A 5-Year R&D Programme on Experimental Technologies

CERN

Experimental Physics Department

DRAFT 1.04 (public)

25 September 2018

Table of Contents

Status of the document

chapter	title	status	comment
Ch. 1	Exec. summary	To be written	At the very end
Ch. 2	Introduction	Complete draft	
Ch. 3.	Requirements	FCC-hh added, CLIC/FCC-ee reworked. HL-LHC extended	By Werner. By Patrick and Lucie
Ch. 4.	WP1, Silicon	Complete draft	revised on 20/09 (following meeting on 14/09)
Ch. 5.	WP2, Gas	Complete draft	Revised on 21/09
Ch. 6.	WP3, calo + light based	Complete draft	Close to final
Ch. 7.	WP4, mechanics	Complete draft	Minor revision (Corrado/Antti), 20/09
Ch. 8.	WP5, electronics	Complete draft	Close to final
Ch. 9.	WP6, links	Complete draft	Close to final
Ch. 10.	WP7, software	Complete draft	Close to final
Ch. 11.	WP8, magnets	Complete draft, updated 17/09	Close to final, Prioritization needed for cost saving.
Ch. 12.	Budget overview		To be updated at the very end
Ch. 13.	Organisation	Complete draft	Wait for feedback
Ch. 14.	Summary & conclusions	To be written	
Ch. 15	Acknowledgements	To be written	
Ch. 16.	Resource spread sheets		To be updated and reformatted

1 Executive Summary

INCOMPLETE DRAFT !!!

CERN’s Experimental Physics Department has defined an R&D programme on experimental technologies which starts in 2020, gradually ramps up in 2021 and extends until 2025.

The programme covers technological R&D activities in the domains detectors, electronics, software and intimately connected systems like mechanics, cooling and experimental magnets. It optimizes current technologies and pushes their performance limits, explores new concepts and makes use of the latest innovations in materials, production and processing technologies.

The results will be building blocks, demonstrators and prototypes which shall form the technological basis for new experiments and experiment upgrades beyond the LHC phase-II upgrade scheduled for the long shutdown LS-3.

The development of new experiment specific detectors, electronics components etc. is in general not covered by the R&D programme. It is expected that these specific activities will be defined at a later stage by the respective collaborations and be financed through their own budget lines.

…

2 Introduction

Progress in experimental physics relies often on advances and breakthroughs in instrumentation, leading to substantial gains in measurement accuracy, efficiency and speed, or even opening completely new approaches and methods.

Given the complexity of modern particle physics experiments, the life cycles from conception to full exploitation are measured in decades, and even just the upgrade of an existing detector may require 10 years. At this moment in time, the landscape of particle physics at the high energy frontier is well defined until the High Luminosity upgrade of the LHC (HL-LHC) which will be implemented in the long shutdown LS-3 (2024-2025). This shutdown will also see large-scale and fundamental changes in ATLAS and CMS, which concern almost all parts of the experiments. ALICE and LHCb undergo major upgrades already in LS-2 (2019-2020). While the detector R&D for the LS-2 upgrades is largely completed, the R&D for the LS-3 upgrades is in full swing and will still continue for a couple of years.

Beyond LS-3, the experimental options are manifold. While the full exploitation of the potential of the HL-LHC is the clear top priority for the next 15 years, a number of studies for a major post-LHC project at CERN are being pursued: CLIC, FCC-hh, FCC-ee. On a global scale, this is complemented by advanced design studies of an International Linear Collider for precision studies of the properties of the Higgs boson. In addition there may be new fixed target experiments or upgrades. Clarifications and possibly prioritization are expected from the 2019-20 update of the European strategy for particle physics. We therefore propose at this stage an R&D programme that concentrates on advancing key technologies rather than developing specialized applications.

The foreseen strategic R&D of the CERN groups will focus on technologies and fields of expertise which will be crucial for future experiments in Particle Physics. In analogy with the importance of the development of high field magnets and high gradient accelerator structures for future accelerators, we have identified key technologies and indispensable expertise without which future experiments cannot be built. In these technologies we have to pursue the R&D and also follow the developments in industry. The knowledge and expertise within the CERN groups in these critical areas needs not only to be maintained, but also further developed through ambitious R&D projects. CERN as the central European Laboratory for Particle Physics plays a major role in providing and maintaining this capability. Due to the complexity and related significant involvement of infrastructure and personnel, in particular engineers, for some technologies CERN has become the only place where this R&D is pursued. In the proposed programme for the strategic R&D at CERN we are concentrating on these technologies. All of the proposed R&D will certainly be done in collaboration with outside institutes, making use of expertise elsewhere and avoiding duplication. Excellent examples for such collaborative work are the existing RD50 and RD51 collaborations for the development of Silicon and Gas detectors.

This proposed EP departmental programme for Strategic R&D will start in 2020, ramp up in 2021, and extend until 2025, at least for its initial definition.

The programme covers technological R&D activities in the domains of detectors, electronics, software and intimately connected aspects such as mechanics, cooling and experimental magnets. It will optimize current technologies and push their performance limits, exploring new concepts and making use of the latest innovations in materials, production and processing technologies.

The results will be building blocks, demonstrators and prototypes which shall form the technological basis for new experiments and experiment upgrades beyond the LHC Phase-II upgrade scheduled for the long shutdown LS-3.

The development of new experiment-specific detectors, electronics components etc. is in general not covered by this Strategic R&D programme. It is expected that those specific activities will be defined at a later stage by the respective collaborations, and be financed through their own budget lines. Often, there will be a "grey area" of limited duration, during which the strategic and experiment-specific R&D will co-exist.

2.1 Instrumentation R&D in the HEP community

R&D in HEP instrumentation, including computing and software, is often organized in phases, from conceptual studies, via proof-of-principle and demonstrators, to full scale prototypes. Phase by phase, the technological complexity and the scale of the involved resources increases. Collaborative structures form in order to profit from joint human and technical resources, as well as from specialized equipment and facilities. Depending on technology and scale, specialized companies get involved in the R&D process – either at a very early stage (e.g. for silicon sensors) or relatively late, when components which were developed in-house need to be replicated in large numbers and at affordable cost.

In certain domains, namely radiation hard silicon sensors and micro-pattern gas detectors, large R&D collaborations have formed (RD50 and RD51), in which research teams, representing a sizable part of the community, exchange their experience and know-how, perform joint projects and develop common tools for detector simulation, readout and characterization. This approach has proved to be highly efficient and greatly boosted the progress in the concerned domains, often to the direct benefit of the experiments. The fact that the LHCC assesses the results and approves the work-plans of the R&D collaborations ensures a certain level of coherence with the needs of the major upgrade projects and new experiments. On the other hand, the quality label 'LHCC approved' allows the collaboration members to apply for dedicated resources,

2.2 Detector R&D at CERN

At CERN, R&D is often performed by mixed teams of people from the experiments and the support groups in the EP department DT, ESE and SFT. Apart from being a partner in the above mentioned collaborative R&D efforts, CERN serves the community through the access to the PS and SPS test beam facilities and through numerous services provided via the EP support groups.

The detector technology group EP-DT provides to the whole CERN community a number of services and facilities which support detector operation and R&D efforts. Examples are the wire bonding and reliability testing labs, the irradiation facilities (hadrons and gammas) and the thin film and glass workshop. The EP-ESE group develops and maintains common or dedicated electronic systems and components for the experiments at CERN. In addition, it provides for the whole CERN community technological support for IC design in various deep sub-micron technologies and organizes multi-project wafer submissions. Similarly, the EP-SFT group develops and maintains common scientific software for the physics experiments in close collaboration with the EP experimental groups, the IT department and external HEP institutes. SFT plays major roles in the ROOT, GEANT and LHC Computing Grid (LCG) projects.

2.3 Organisation of the process

The management of the EP department decided in autumn 2017 to launch a process with the goal of defining a new strategic R&D programme on experimental technologies. A steering committee (SC) was set up, chaired by the department head M. Krammer. The members of the steering committee were: P. Farthouat (ESE), R. Forty (DHH), F. Hahn (DHH[†]), P. Janot (FCC-ee), L. Linssen (CLIC detector), P. Mato (ESE), W. Riegler (FCC-hh), B. Schmidt (DT). C. Joram was appointed study coordinator.

The personnel of the EP Department was informed about the initiative in a kick-off meeting[1] on 20 November 2017, in which the status and future needs of the 4 LHC experiments as well as of future hadron and lepton colliders were discussed. Furthermore, the 8 main R&D themes proposed by the SC were discussed, along with the process organisation and the timeline.

Convenors were appointed for each of the 8 R&D themes with the mandate to form working groups and hold meetings with the aim to explore current limitations, challenges and possible R&D directions. Participation to the working groups was unrestricted and included many external colleagues. The average WG size was 81 persons (min. 15, max. 127).

A 1-day R&D workshop[2] was held on 16 March 2018 at CERN, to which more than 450 people registered, a fraction of them participated by video conferencing. The convenors summarized the material collected in the working group meetings and discussed possible R&D directions.

In the following months, through an iterative process between the convenors and the steering committee, the most relevant R&D topics were selected, work plans prepared, including detailed lists of milestones and deliverables as well as resource estimates. In parallel the preparation of this document started.

A second R&D workshop, held on 25 September at CERN, was devoted to presentations of the selected topics and work plans.

[†] Deceased in March 2018

[1] https://indico.cern.ch/event/677108/

[2] https://indico.cern.ch/event/696066/

3 Requirements of the next generation high energy physics experiments

3.1 LHC detector upgrades beyond LHC Phase II

The four large LHC experiments are carrying out major upgrades in the forthcoming Long Shutdowns (LS) of the LHC. ALICE and LHCb will undergo major upgrades already in LS2, scheduled for 2019 and 2020, during which ATLAS and CMS have planned only minor upgrades, referred to as Phase I. During LS3, scheduled for 2024-2026, ATLAS and CMS will undergo their major Phase-II upgrades. R&D in view of these upgrades will be completed by 2020 and is therefore not a subject of this R&D proposal.

The HL-LHC programme is designed to deliver a total of 3 ab^{-1} of integrated luminosity to both ATLAS and CMS by 2035-2040. The detectors will have to cope with instantaneous luminosities of $5x10^{34}/cm^2/s$, leading to a number of interactions per crossing of up to 200. Where possible, substantial margin has been included in the design of the upgraded detectors to ensure that the experiments would retain their full performance also in case the instantaneous luminosity would rise to $7.5x10^{34}/cm^2/s$, and the integrated luminosity would become 4 ab^{-1}. In particular, an extended longevity of about 50% has been considered for the sub-detectors for which further upgrades or improvements would be prohibitive in terms of costs, complications and risks. However, for sub-detectors that have a relatively easy access for maintenance, the currently available technologies barely match the HL-LHC requirements. For those sub-detectors, further upgrade beyond Phase II and replacements of detector parts might be needed during the HL-LHC program and will have to be envisaged if the operation of HL-LHC is pushed to its limits. In this case, the use of improved technologies would not only be beneficial, but even crucial to maximize the physics reach of the experiments.

One Examples are the timing layers foreseen in the endcaps of ATLAS and CMS, which enables 4D reconstruction of primary vertices. The enhanced ability to separate primary interactions results in a significantly improved statistical power for most physics analyses. Low-Gain Avalanche Silicon Detectors (LGAD) are the technology foreseen for the timing layers. With irradiation, LGAD sensors require a higher bias voltage in order to maintain adequate gain and time resolution, which is better than 30ps for non-irradiated sensors. At the nominal fluence expected at the edge of the rapidity acceptance of η=3, the resolution is expected to become worse than 50ps after 3 ab^{-1} of integrated luminosity at the highest possible bias voltage. It is therefore conceivable that the innermost modules will have to be replaced during the HL-LHC program, using a possible improved fabrication process that might yield enhanced radiation tolerance and sensors with higher granularity. The R&D related to this will be discussed in chapter 4 of this document.

Another area where the LHC detectors would benefit of potential advancements in technology concerns data links for the readout of the Inner Tracker systems. Since light sources are at present neither radiation tolerant nor small enough to be integrated at the module level, electrical links are required to carry the data sufficiently far away from the interaction point to a position where optical conversion can take place. Silicon photonics is a technology allowing to integrate optical links with front-end electronics, moving the radiation-sensitive light source away from the extreme radiation zones. The technology has the demonstrated potential to achieve a radiation tolerance 1-2 orders of magnitude higher than present optical links, with scalable bandwidth capabilities. It is therefore a most appealing option for possible further improvements of the Inner Tracker Systems of ATLAS and CMS. This will be discussed in chapter 9 of this R&D proposal.

The LHCb collaboration submitted in 2017 an Expression of Interest[3] for a second upgrade, envisaged for LS4 around 2030. The proposal is to upgrade the detector in order to take full advantage of the flavour-physics potential of the HL-LHC and to cope with luminosities of up to 2 x $10^{34}/cm^2/s$, thus 10 times more than the Phase-I upgrade currently under preparation. Performing flavour physics at such a luminosity presents significant experimental challenges and requires further R&D. The number of interactions per crossing will be around 50, which leads to much higher particle multiplicities and rates than is the case for the Phase-I upgrade. Radiation damage also becomes a greater concern for several sub-detectors. At very high pile-up, fast-timing information becomes an essential attribute for suppressing combinatorial background and for enabling time-dependent CP-violation measurements. The required R&D will be discussed in several of the following chapters.

Also the ALICE collaboration is in the process of submitting an Expression of interest[4] for a future upgrade of its Inner Tracking System (ITS), beyond the one now under preparation. This upgrade will provide a large improvement of the tracking precision and efficiency at low transverse momentum. Combined with a large reduction of the material budget in the region close to the interaction point this will lead to a significant advance in the measurement of low momentum charmed hadrons and low-mass di-electrons in heavy-ion collisions at the LHC. This upgrade will be based on recent innovations in the field of silicon imaging technology, which open extraordinary opportunities for a novel vertex detector consisting of cylindrical layers. It is based on curved wafer-scale ultra-thin silicon sensors, featuring an unprecedented material budget of 0.05 % X_0 per layer, with the innermost layer positioned at only 18 mm radial distance from the interaction point. The required R&D is strongly related to the concepts discussed in Chapter 4 of this document.

Finally, software must be developed further to support the event reconstruction and analysis in the high multiplicity heavy ion environment or at the expected event rates during the coming decades of the HL-LHC operation. Some ideas related to intra- and inter-event parallelism and GPU usage for the reconstruction in pre-defined detector regions are discussed in chapter 10 of this R&D proposal.

3.2 Detector requirements of a Future Circular Hadron Collider experiment

The FCC-hh collider will deliver pp collisions at a peak luminosity of $30 \cdot 10^{34}$ $cm^{-2}s^{-1}$, which is 6 times larger than the luminosity of the HL-LHC, leading to a pileup of 1000. The planned integrated luminosity is about 30 ab^{-1}, 10 times larger than for the HL-LHC. These numbers indicate that detectors at the FCC-hh have to deal with data rates and radiation levels that are again 1-2 orders of magnitude larger than the numbers at the HL-LHC.

The first layers of the silicon trackers for the Phase-II upgrades of the ATLAS and CMS experiments will experience a hadron fluence of $10^{16}cm^{-2}$ during the HL-LHC operation, which is at the limit of present day silicon sensor technology. This corresponds to the radiation level at the FCC-hh for a radius of 20cm. For smaller radii this number rises significantly and reaches a level of $8 \cdot 10^{17}cm^{-2}$ at the innermost layer. Significant R&D efforts to develop sensors that can handle such radiation levels are therefore needed.

---

[3] Expression of Interest for an LHCb Upgrade II, CERN/LHCC 2017-003
[4] Expression of Interest for an ALICE ITS Upgrade in LS3, ALICE-UG-2018-01

The present detector concepts foresee a position resolution of about 7 um for the vertex detector and about 2% of X_0 of material budget per layer, including services.

In addition to the radiation hardness, the innermost layers experience huge hit rates of up to 10 GHz / $cm^{-2}s^{-1}$. Transporting such large amounts of data without excessive use of power and related cooling infrastructure and material, requires significant R&D on data links.

The pileup numbers of 1000 will require the use of high precision timing of tracks down to the 5-10 ps level. The development of these sensors together with readout electronics that allows to preserve such timing precision in a large system requires dedicated developments.

Radiation hardness is also a crucial topic for calorimetry. Liquid Argon calorimetry as used by ATLAS is a natural candidate for a detector at the FCC-hh. The need for significantly increased granularity requires however a dedicated R&D effort for this technology. The use of silicon for electromagnetic calorimetry will be benchmarked by the CMS Phase-II upgrade.

The radiation levels in the barrel hadron calorimeter will allow the use of 'traditional' scintillators with iron absorbers. The readout with SiPMs for the increased granularity does however need R&D.

The hit rates in the muon system do not go much beyond the numbers in the HL-LHC muon systems. It seems therefore feasible to use gas detector technology similar to the one employed at present at the LHC. The large surface of these muon systems would however profit significantly from an industrialization of the detector construction.

The FCC-hh reference detector foresees a solenoid of 5m bore diameter and a magnetic field of 4T, together with two smaller forward solenoids. The cryogenics plant for this magnet system is foreseen to sit on the surface.

Calorimetry and muon system will be digitized at the full bunch crossing rate of 40MHz and the data will be shipped off the detector at 200-300 TByte/s. Reading also the tracker at the full bunch crossing rate of 40 MHz would result in a data rate of almost 800 TByte/s. Whether it is feasible to readout such a large amount of data or whether a L1 trigger has to reduce this readout rate will depend on the R&D progress on these topics over the next decade.

3.3 Detector requirements for future e^+e^- experiments at the FCC and CLIC

Several high-luminosity / high-energy e^+e^- colliders are currently under study. The CERN-hosted studies, FCC and CLIC, aim for centre-of-mass (CM) energies in the range 88-365 GeV and 350-3000 GeV, and for luminosities up to 460 and 6 x 10^{34} $cm^{-2}s^{-1}$, with two (or four) and one interaction regions, respectively. Both colliders aim at measuring precisely the properties of the Higgs boson and the top quark, both produced so far only in hadron collisions. In particular, they have access to the Higgs potential, either via the precise measurement of the single Higgs production cross sections at 240 and 365 GeV for the FCC, or that of the double Higgs production at 3 TeV for CLIC. The measurement of all electroweak precision observables around the Z pole and the WW threshold for the FCC, and a set of measurements at high energy for CLIC, will increase the high-mass sensitivity to physics beyond the standard model, making use of the availability of transversally or longitudinally polarised electrons and positrons. The FCC tunnel is designed to subsequently host a hadron collider with a CM energy of 100 TeV. Worldwide, two other e^+e^- collider projects are under development, both focussed on the measurement of the Higgs properties: the International Linear Collider (ILC) in Japan, with a CM energy of 250 GeV (upgradable to

500 GeV), and the Circular Electron-Positron Collider (CEPC) in China, with a CM energy in the range 91 -240 GeV. Table 1 lists a few basic FCC and CLIC collider parameters, relevant for the design of the detectors.

Table 1: Basic FCC and CLIC collider parameters with relevance for the design of the detectors.

Facility and energy stage (GeV)	FCC-ee 91.2	FCC-ee 161	FCC-ee 240	FCC-ee 365	CLIC 380	CLIC 1500	CLIC 3000
Luminosity $cm^{-2}s^{-1}$	$4.6 * 10^{36}$	$5.6 * 10^{35}$	$1.7 * 10^{35}$	$3.1 * 10^{34}$	$1.5 * 10^{34}$	$3.7 * 10^{34}$	$5.9 * 10^{34}$
Train freq. (Hz)	N/A	N/A	N/A	N/A	50	50	50
# bunches / train	N/A	N/A	N/A	N/A	352	312	312
Bunch spacing (ns)	< 20	163	994	3396	0.5	0.5	0.5

At linear colliders, the beams arrive in bunch trains. At CLIC, the bunch trains last some 150 ns, comprising around 300 bunches separated by 0.5 ns. During each bunch train one can expect at most one hard e^+e^- collision, while many background particles from beamstrahlung will be spread in time along the 150 ns. The CLIC time structure allows for triggerless readout of full bunch trains. It also allows the on-detector power to be turned off during the inter-train periods (power pulsing) and thereby reduce on-detector cooling needs. Beam-induced backgrounds increase strongly with centre-of-mass energy. Therefore 3 TeV operation can be considered as the most challenging case for CLIC. The presence of beam-induced backgrounds imposes hit timing capability of 1ns accuracy in the calorimeters and time stamping at the 10 ns level in the tracking. The design of the CLIC detector foresees small readout cells in order to limit maximum occupancies to 3% (integrated over the bunch train, safety factors included). This leads to a maximum cell size of 25*25 μm^2 in the vertex detector and trip lengths in the range 1 mm to 10 mm for a 50 μm nominal strip pitch in the silicon tracker. Readout cells in the calorimeters will be small. This will not only allow for accurate jet reconstruction through particle flow analysis (PFA), but it will also provide an indispensable means to efficiently recognise particles from beam-induced background in the data after PFA reconstruction.

At circular colliders, the bunch spacing is orders of magnitude larger than at linear colliders. Synchrotron radiation, however, is an important source of background. At the FCC, the machine-detector interface is designed to ensure that, even at 365 GeV, this background is optimally suppressed in the detector region. At the Z peak, the unprecedented luminosity, the large cross-sections and the 20 ns bunch spacing (table Table 1) result in large data rates, due in particular to background particles from beamstrahlung. Operation at 91 GeV can therefore be considered the most challenging for sustaining these rates in the FCC-ee detector. There are good indications that hit rates at FCC will allow for rather generous readout integration times at the ~1 μs level such that, for an optimised tracking performance, a minimal material budget may outweigh the timing requirements. Current estimates of the data rates also indicate that a triggerless readout of the detector should be possible. This experimental environment, vastly different from that of a linear collider, and the larger number of interaction regions (from 2 to 4), might call for interesting R&D and optimization to get the best physics performance, and might lead to significantly different detector concepts.

The CLIC detector and the two detector concepts currently studied for the FCC are general-purpose devices designed to provide excellent performance for all known e^+e^- physics processes as well as for

Beyond Standard Model (BSM) phenomena, including an optimal preparation for the unexpected. These considerations lead to the following basic detector requirements:

- Transverse impact parameter resolution d_0 at the level of 5 μm for single tracks in the central detector with p_T in excess of a few GeV, and corresponding longitudinal impact parameter z_0 better than 8 μm, to deliver efficient and pure b-quark and c-quark tagging;
- Adequate calorimeter granularity (e.g., transverse, longitudinal, time segmentation, and beyond) and tracker as transparent as possible to allow for optimal particle-flow reconstruction
- Jet energy resolution σ_E/E better than 5% for light-quark jet energies of ~50 GeV, improving to better than 3.5% for jet energies above ~100 GeV;
- Track momentum resolution σ_{pT}/p_T^2 of 2×10^{-5} GeV^{-1} for high-energy minimum-ionising particles in the central detector region, in particular to best determine the Higgs production cross section in the Hl^+l^- final state or for the precision measurement heavy states decaying into leptons;
- Muon (polar and azimuthal) angular resolution better than 100 μrad (at the FCC), for the precise determination of the luminosity spectrum and the absolute alignment of the tracker with respect to the beam axes;
- Lepton identification efficiency well above 95% over the full range of energies;
- Hadron identification capabilities (π, K, p, …), especially for flavour physics at the FCC.
- Detector coverage for electrons down to very low angles (~10 mrad at CLIC).

These requirements are mostly fulfilled for the CLIC detector with a 6-layer vertex detector providing a 3 μm single point resolution, combined with a 6-layer silicon tracker with 7 μm single point resolution. The amount of material in the vertex detector has to be kept as low as 0.2%-0.3% X_0 per layer, while ~2% X_0 per layer is foreseen in the tracker. In the electromagnetic calorimeter (ECal) silicon active layers with $5*5$ mm^2 cell sizes in a 40-layer tungsten absorber stack are proposed, while the hadron calorimeter (HCal) foresees $3*3$ cm^2 scintillator tiles with SiPM readout in a steel absorber stack. HCal comprises 60 layers (7.5 Λ_I) in CLIC, to ensure shower containment at the higher CLIC energies. For muon identification purposes a handful of detector layers with moderate performance requirements are inserted in the return yoke of the CLIC solenoids, generating a magnetic field strength of 4T. Compared to LHC, radiation levels in the e^+e^- detectors are much lower, typically 10^4 times below the LHC levels. Only the small forward electromagnetic calorimeters, which surround the beam pipes in the 10-100 mrad forward angular range, will be exposed to high radiation levels. Doses up to 1 MGy and neutron fluxes up to 10^{14} per year are expected in the most inner layers for the beam calorimeter (Beamcal) at CLIC.

For the FCC, a version of the CLIC detector named CLD was studied, with dimensions scaled to the smaller energies and smaller magnetic field strength (2T). No optimization was undertaken so far to exploit the different, and often favourable, experimental environment, or to reduce the cost, while keeping or even improving the performance. The achieved performance was demonstrated to be adequate for the Higgs and top precision measurements. Table 2 summarises a number of basic detector parameters for the tracking and calorimeter systems of the CLD and CLIC detectors.

A bolder and possibly more cost-effective design, named IDEA, is also being studied for the FCC. In IDEA, the emphasis is put on the tracker transparency, with a short-drift wire chamber able to separate hadron species by cluster counting from 112 layer measurements corresponding to a total of 1.5% X_0, and a light four-to-seven layer vertex detector based on the ALPIDE detector chip planned for the ALICE ITS (0.3% X_0 per layer). The tracker is surrounded by a thin (1 X_0) superconducting solenoid delivering a 2T field and acting as a pre-shower, itself sandwiched between two outer silicon layers. A highly segmented dual-readout calorimeter, with very good intrinsic discrimination between muons, electrons/photons, and hadrons, is envisioned towards excellent jet energy resolution and particle-flow reconstruction. Sustained R&D is welcome to optimize the drift chamber and dual-readout calorimeter towards the stringent requirements of the ultra-precise FCC measurements.

The possibility of hosting four interaction points, and therefore four detectors, is under study at the FCC. The particular choice of the CLD and IDEA concepts, motivated by the wish to explore the technology and cost spectra, is of course not unique. The optimization of these two concepts must continue, but other concepts might actually prove to be better adapted to the FCC physics programme and need to be studied as we move towards FCC detector proposals.

Table 2: Basic detector parameters for the tracking and calorimetry of the CLD and CLIC detectors.

Parameter	CLD	CLIC
Vertex, hit position resolution (μm)	3	3
Vertex, maximum silicon pixel size (μm^2)	25∗25	25∗25
Vertex, hit time-stamping capability (ns)	10 - 1000	10
Vertex, max. material budget per layer (X_0)	0.3%	0.2%
Vertex, inner radius (mm)	17	31
Tracker, hit position resolution (μm)	7	7
Tracker, maximum silicon cell size ($\mu m * \mathrm{mm}$)	50∗(1-10)	50∗(1-10)
Tracker, hit time-stamping capability (ns)	10 - 1000	10
Vertex, max. material budget per layer (X_0)	2%	2%
Tracker, outer radius (cm)	215	150
ECal cell size (mm^2)	5∗5	5∗5
ECal hit time resolution (ns)	1	1
HCal cell size (mm^2)	30∗30	30∗30
HCal hit time resolution (ns)	1	1

For the second interaction region at FCC-ee, the IDEA detector concept is proposed. Its tracking system is composed of a 4-7 layer vertex detector in MAPS technology, followed by a very light drift chamber and an outer silicon layer. The tracker is surrounded by a thin superconducting solenoid with a 2T field, a 1-2 X_0 preshower detector and a dual read-out calorimeter (Cherenkov and scintillation), followed by the instrumented yoke for muon detection. Detailed requirements for the drift chamber and the dual readout calorimeter of the IDEA detector are currently still under study.

3.4 Other experiments

In parallel to the experimental activities at the high energy frontier, a range of further experiments are attempting to probe the standard model and search for physics beyond it at the intensity and/or precision frontiers. These lower energy experiments are either based on intense extracted beams, impinging on a fixed target to produce high flux beams of known or unknown secondary particles, or, at extremely low energies, fall into the domain of exotic atoms (AD, PSI) or nuclei (ISOLDE), which have a sensitivity to BSM physics through very high precision, or, finally, searches for (possibly) naturally occurring dark matter candidates (axions, dark photons). The detector requirements, and consequently the needs for detector R&D, in these three areas are very disparate, and it is mainly the first group (and to small extent the last group) of experiments, at the intensity frontier, that has requirements that have an extensive overlap with R&D efforts in HEP instrumentation. Among these, several are at the level of LOI's submitted to the Physics Beyond Colliders working group. Three major areas targeted by these conceptual designs for the period after LS3, and that are often still in the planning stage, are:

1) Tests of QCD building on existing experiments (COMPASS, NA60++, NA61++) without major new hardware developments, or new proposals (MuonE) relying on state of the art (but existing) ultra-thin silicon tracking detectors (such as ALICE ALPIDE). Nevertheless, vertexing (including in the case of active targets) in particular benefits very much from R&D on monolithic active pixel sensors, stitching & low material budgets, as well as radiation hardness.
2) Dark matter appearance searches, such as SHiP, where currently, the required sub-detectors are at a first level of prototyping. Challenges faced by this category of experiments reside more in a thorough understanding of all potential backgrounds, and thus benefit from improvements to Geant4 in terms of processing speed (with of the order of 10^{20} protons on target being assumed for the full experimental data set) and detailed description of low energy processes (e.g. including neutrons).
3) Experiments selecting a small number of interesting topologies out of a very high flux primary or secondary beam. LFV searches (KLEVER, TauLFV) are a typical example for this class of experiments, and the challenges are very precise timing (~50 ps), combined with excellent kinematics reconstruction (and thus very little multiple scattering), for tracking/vertexing detectors, as well as similar timing requirements (<100 ps, as well as high radiation tolerance of > 100 MRad) for electromagnetic calorimetry.

In a very different area, that of searches for dark matter of astrophysical origins (CAST, IAXO), novel detection technologies based on microwave cavities embedded in strong magnetic fields (RADES) or on opto-mechanical force sensors (KWISP) mostly lie outside the focus of HEP detector R&D. However, several axion detection techniques rely on detection of X-rays (produced via Primakoff effect in strong magnetic fields) via Micromegas or solid-state X-ray detectors. Here, the main challenges are those of very low noise and sub-keV thresholds (~ 200 eV) for the low energy X-rays expected from e.g. chameleons.

4 Silicon Detectors (WP1)

4.1 Main development goals and overview of requirements

The Silicon WP targets the development of new detector technologies meeting the challenging requirements of the vertex and tracking detectors at future CERN facilities. Particular emphasis will be put on developments with applications for the HL-LHC and fixed-target experiments where the installation maps to the 5-year time scale of the EP R&D programme.

In general, tracking and vertexing detectors for future experiments will require at least an order of magnitude more radiation hardness compared to conditions at the LHC. This is particularly true of detectors in closest proximity to the interaction regions, loosely referred to as vertexing detectors. They will also require significantly enhanced hit rate capability and the ability to handle very high data throughput. A particular goal of the R&D for these innermost regions is the addition of timing information to the individual hits, allowing time tagging of tracks and primary vertices and aiding pattern recognition in high occupancy environments. Tracking detectors, which in general cover larger areas, will need an R&D effort focussed on cost effective radiation hard sensors and module technologies. The addition of timing information will also be crucial for these detectors for primary vertex tagging and time of flight measurements. A particular challenge for tracking detectors at future ee and Heavy Ion experiments is the push for ultimate limits on measurement precision, which will be achieved with ultra-small pixels and very thin detection layers. In general, the challenge of the most intense tracking regions will be addressed by hybrid pixel detectors, and the breakthrough technology for tracking is expected to come from CMOS sensor technology developments, which are currently being pushed to unprecedented levels of radiation hardness and rate capabilities.

Approximate requirements for the central tracking volume at the different collider experiments are given in the table below.

Parameter / Exp.	LHC	HL-LHC	SPS	FCChh	FCCee	CLIC 3 TeV
Fluence [$n_{eq}/cm^2/y$]	N x 10^{15}	10^{16}	10^{17}	10^{16} - 10^{17}	<10^{10}	<10^{11}
Max. hit rate [$s^{-1}cm^{-2}$]	100 M	2-4 G	8G	20 G	20M ***)	240k
Surface inner tracker [m^2]	2	10	0.2	15	1	1
Surface outer tracker [m^2]	200	200	-	400	200	140
Material budget per detection layer [X_0]	0.3%*) - 2%	0.1%*) - 2%	2%	1%	0.3%	0.2%
Pixel size inner layers [μm^2]	100x150-50x400	~50x50	~50x50	25x50	25x25	<~25x25
BC spacing [ns]	25	25	>10^9	25	20-3400	0.5
Hit time resolution [ns]	<~25–1k*)	0.2**)–1k*)	0.04	~10^{-2}	~1k ***)	~5

*) ALICE requirement **) LHCb requirement ***) At Z-pole running

The specific combination of competing requirements is different for each of the future applications. A broad and integrated detector R&D programme is therefore needed, advancing a variety of detector technologies while simultaneously addressing system-integration aspects and developing the corresponding testing and simulation infrastructure.

4.2 State-of-the-art in silicon tracking detector technology

The requirements for the current LHC experiments and the HL-LHC upgrades, as well as recent developments for the SPS experimental programme, are met by a variety of silicon tracking detector technologies, which represent the state-of-the art and will be the starting point for this R&D programme. Hybrid pixel detectors with pixel areas down to 50x50 μm^2, withstanding radiation exposure up to 10^{16} n_{eq}/cm^2, particle rates up to several Ghits $s^{-1}cm^{-2}$ have been developed for the LHC phase I/II upgrades of LHCb, ATLAS and CMS. It has been shown by NA62 that hybrid pixel detectors can reach a time resolution of the order of a few hundred picoseconds for a pixel area of 300x300 μm^2. Monolithic Active Pixel Sensors (MAPS) based on CMOS technology with pixel areas down to 28x28 μm^2 featuring a material thickness of 0.3% of a radiation length, X_0, per layer have been developed for the phase I ALICE upgrade. In this context a depleted version of this technology (DMAPS) has been developed. ATLAS is now pursuing R&D on DMAPS for the Phase-II ITK upgrade and currently qualifies them for radiation exposures of 10^{15} n_{eq}/cm^2 and hit-rate capability of >2MHz/m^2.

4.3 Requirements of future upgrades and experiments at future colliders

The tracking detectors for future experiments at hadron colliders will require yet another order of magnitude more radiation hardness compared to the conditions at HL-LHC. At the same time their hit-rate capability needs to be significantly enhanced together with their ability to handle very high data throughput. Future upgrades of innermost layers at pp-experiments at HL-LHC will aim at reducing material significantly <1%X_0 as well as pixel sizes below 25x100/50x50μm^2 for even better tracking performance. Beyond hybrid pixel detectors, this R&D will explore monolithic CMOS sensors incorporating complex readout architectures in small-feature size CMOS technologies as an option to meet these challenges. Specialty hybrid pixel sensors developments target highest rate and timing requirements in conjunction with dedicated FE-ASICs.

High-rate and low-material-budget requirements as well as the need for a large angular coverage will necessitate a focused R&D in novel sensor-interconnection and module concepts. In particular, the integration of serial power systems as well as light-weight and high-bandwidth data transmission for monolithic and hybrid radiation hard sensors solutions will have to be addressed.

The tracking detectors for future ee-experiments or for soft-physics in hadron colliders, on the other hand, will focus on very high spatial measurement precision, to be achieved with ultra-small pixels and very thin detection layers. The innermost layers will need to provide small pixel pitch (< 25 μm) and reduced material budget (down to 0.1% X_0) in order to achieve the best possible impact-parameter resolution. The required performance in terms of spatial resolution, material budget and data rates calls for beyond state-of-the-art sensor technologies in small-feature size integrated CMOS technologies or specialty processes for hybrid silicon sensors.

Incorporating the measurement of the single-hit time at the nanosecond level in a fine-pitch (order of 25x25 μm^2) pixel detector will allow to resolve pile-up in a high track density and interaction rate environment. Such a time resolution is in reach with advanced hybrid and monolithic CMOS process technologies.

In the case of future flavour physics experiments, a time resolution down to a few tens of picoseconds will need to be achieved in the vertex detector and in combination with extremely high data throughputs (300 Gb s^{-1} cm^{-2}). Achieving such a time resolution will require a combination of fine-pitch hybrid pixel detector layers with dedicated coarser timing detectors with intrinsic gain, such as Low Gain Avalanche Detectors (LGAD).

4.4 Prospects for enhanced detector performance

Specialty processes for radiation-hard sensors with minimized inactive area, very small pixel sizes, fast signal collection and very high time resolution will be developed for hybrid detectors in the inner-most layers, as well as for dedicated timing layers needed for pile-up suppression. Fast sensors with high spatial granularity and able to withstand irradiation doses of the order of 10^{16} n_{eq}/cm^2 are the prerequisite to achieve the required performance. The WP will perform design optimisation and characterisation of high granularity pixel detectors based on thin planar active-edge sensors with pixel sizes down to 25x25 μm^2. In addition, fast sensors based on LGAD and 3D sensor technologies will be investigated. The sensor performance under irradiation will be studied and interpreted with the help of device simulations. Cooling requirements to operate those sensors up to the highest radiation level will be assessed.

Current CMOS pixel technology can cover the requirements of the HL-LHC in terms of radiation hardness up to levels of the order of 10^{15} n_{eq} / cm^2. Due to their simplified construction and intrinsically lower power consumption over hybrid pixel modules, they offer a substantially lower material budget, cost advantage as well as reduced assembly time. Further R&D for innermost layers of pp-experiments will extend their radiation hardness to 5-10x10^{15} n_{eq} / cm^2. Hits rates at innermost layers will require the design of sophisticated readout architectures in small-pitch (~25μm) pixels and complex periphery circuits in future DMAPS using small feature-size CMOS processes.

Moreover, one of the features offered recently by CMOS imaging sensor technologies, called stitching, will allow developing a new generation of large-size MAPS with an area up to the full wafer size. The reduction of the sensor thickness to values below 50 μm opens the possibility to exploit the flexible nature of silicon to implement large area curved sensors. In this way a cylindrical layer of silicon-only sensors can be constructed. The will allow the construction of vertex detectors with unprecedented low values of material thickness (<0.1% X_0), uniform coverage and very high spatial resolution (about 3μm).

Using medium feature-size CMOS processes ($\geq$90 nm), the WP will develop initially monolithic depleted CMOS pixel sensors targeting fluences of 1-2 x 10^{15} n_{eq} / cm^2 and hit rates of hundreds of MHz/cm^2. The WP will develop suitable CMOS sensor technologies as well as demonstrator modules for integration to tracker systems of future experiments. Smaller feature-size processes (<90 nm) promise significant advantages in signal speed and logic density. Using suitable processes, the WP will target in a second step the ultimate low-mass monolithic sensor performance with small pixels for high spatial resolution at the innermost layers, where fluences of 5-10 x 10^{15} n_{eq} / cm^2 and hit rates of >3 GHz/cm^2 are expected.

Novel small feature-size CMOS technologies will allow to design readout circuitries that can cope with the increased data throughputs, while achieving a low power consumption both in the matrix and at the periphery. Such circuits can be incorporated in both hybrid and monolithic detectors. More in general, these technologies will allow for an optimization of the analogue and digital circuitries for low power consumption, while simultaneously achieving small pixel sizes and nanosecond timing. An average power dissipation of below 50 mW/cm^2 is required for applications with forced air-flow cooling systems.

At larger radii the large size of the tracker system (up to 400 m^2) requires a new construction approach: away from labour-intensive one-by-one module construction to industrialized processing of silicon sensors and modules. Simplicity in construction can be achieved through post-processing with minimal in-house assembly.

Electrical services for data transmission are already now the limiting factor for off-detector readout. Optical transmission directly from chip through technologies like silicon photonics will help to overcome this limitation. Novel methods of sensor-to-sensor data transmission and module integration will be developed in synergy with the WP on data transmission, to meet these requirements.

A fundamental understanding of the sensor performance and the radiation effects is an essential part of the design and process optimization. This requires the development of flexible characterization infrastructure, as well as advanced simulation tools.

4.5 Activities within the Work Package:

The Silicon WP will develop over the course of the 5 years EP-R&D programme a portfolio of enabling technologies for future highest-performance and large-area silicon detector systems. Four main activities are foreseen, targeting specific aspects of the overall development goals:

1. Hybrid sensors with advanced features for small pixels, high-resolution timing and high-rate applications will be developed within the *Novel Hybrid Silicon Detectors* activity.
2. The activity *Depleted Monolithic Sensors* pursues sensor developments suitable for the requirements of the large-area outer tracker layers, as well as the highest performance requirements of the inner trackers.
3. New module integration and assembly concepts for hybrid and monolithic sensors, as well as the necessary infrastructure, will be developed within the *Module* activity.
4. Detector simulations and modelling of radiation damage, as well as the development of dedicated characterization setups and flexible data-acquisition systems for testing purposes, will be pursued within the *Simulation and Characterization* activity.

Some of the activities are closely linked to other Work Packages and existing detector and R&D collaborations. Synergies will be exploited in particular with the Work Packages on Detector Mechanics, IC technologies and High Speed Links.

The following sections present detailed work plans for each of the activities, including deliverables, as well as the foreseen resources for personnel and materials. A summary of the resources needed to cover each of the activities is given in Tab. x.

4.5.1 Novel Hybrid Silicon Detectors:

The Hybrid-Pixel Sensors activity focuses on novel sensor concepts with advanced features to be used in hybrid assemblies with separate high-performance readout ASICs. Such hybrid pixel detectors remain an important technology option for future CERN projects with need for very high rate and radiation capability, small pixel size and high-accuracy time measurement. Target development goals include sensors with built-in charge multiplication for very fast timing applications (tens of picoseconds), sensors with enhanced lateral drift and trench designs with minimized inactive edges.

Designs with various cell sizes (starting from 25x25 μm^2) will be implemented and tested in view of the different target applications. Sensor thicknesses down to 50 μm are foreseen, to achieve very low material-budget. Particular emphasis will be put on radiation hardness at the levels required in the very harsh environments of the inner detectors at future hadron colliders.

The activity will contribute to the design optimization of future sensors through simulations and testing of prototypes. Existing readout ASICs as well as ASICs currently under development (e.g. CLICpix2, Timepix3, Velopix, Timepix4, RD53A) will be used as test vehicles for assessing the performance of various sensor designs.

Specific ASIC development for very high speed hybrid pixel sensors and fine-pitch pixels will operate as closely as possible in line with the ongoing R&D efforts and has significant overlap with the IC and High Speed Readout work packages.

Development of specific items for a fast timing hybrid silicon tracker will be covered in this working group. It will comprise the definition of a suitable data packaging format to suit pattern recognition needs of a high speed pixel timing tracker, as well as the development of proof-of-principle techniques to achieve required local time resolution in the ASIC. In addition, ASIC development should be tested in experiment-like environment.

Design optimisation and characterisation of high granularity sensor based on thin planar sensors active edge technologies, with pixel size down to 25x25 μm^2 on one side and of fast sensors based on LGAD and 3D sensors technologies on the other side will be performed. Their behaviour under irradiation at levels of 10^{16} n_{eq}/cm^2 will be studied and interpreted with the help of TCAD simulation.

In the context of high-precision timing, a major challenge of the system level design is the proof-of-principle application of fine timed devices within a large scale system. In order to investigate this thoroughly, a phased test-beam programme is proposed, which will be of value beyond this work package, for any timing detector development. This programme will be based on the timing telescope developed within the Simulation and Characterization activity.

The achievement of these research goals shall be demonstrated in the following deliverables:

- Test results from thinned fine-pitch planar sensors with optimized trench design
- Radiation qualification of LGAD pad sensors
- Radiation qualification of fine-pitch planar sensors with optimized trench design
- Post-irradiation test results from LGAD pixel sensor assemblies
- Test results of front-end circuits for precise timing and fine-pitch pixels
- Proof-of-principle application of fine timed tracking devices within a large scale test system;

It is expected that this activity will profit from a close collaboration with a large community of external institutes and existing collaborations, in particular with the RD50 collaboration for radiation-hard semiconductor devices. The corresponding high-performance ASIC and interconnect developments will be coordinated within the IC Technologies WP.

The resource allocation (see table in the annex) includes limited funds for contributions to MPW sensor submissions and post processing of sensors and ASICs.

4.5.2 Monolithic Sensors:

The *Monolithic Sensors* activities foresee the development of monolithic CMOS sensors for the innermost radii for maximum performance and for the outer-layers as cost effective pixel trackers with high granularity and low-material budget.

These developments are targeted through sensor prototyping in (a) medium node size processes (>90nm) and (b) small node size processes (<90nm). Initial developments will start with radiation hard monolithic sensor developed in a >90nm size process to establish sensor designs needed for near future applications. In view of further enhancing the performance (data rates, pixel size), smaller feature size technologies (<90 nm) will be evaluated in a second phase by developing small prototype circuits.

The activities focus on the following objectives:

1. Development of radiation-hard pixel designs and exploration of suitable processes for depleted radiation-hard CMOS sensors. Optimized sensor electrode structures for minimal capacitance and best radiation hardness.
2. Optimal front-end and periphery architectures for low noise / low power; optimized front-end for high-radiation with pixel geometries adapted to the different target applications (10 to 30 μm squared pixels, elongated pixels for outer tracker layers);
3. Optimization of pixel layout and front-end circuit for sub-nanosecond time resolution;
4. New architectures and high-speed signal transmission for high data rates;
5. Data handling and trigger: digital data processing at module or stave end;
6. Power-pulsing features optimized for low duty cycle of linear accelerators;
7. Reticle Stitching to increase the sensor size up to $14x14cm^2$;

The achievement of these research goals shall be demonstrated in the following deliverables:

- Development of radiation hard ($\geq 10^{15}$ n_{eq}/cm^2) monolithic sensors in medium feature size CMOS process;
- Development of sensors in medium feature-size CMOS process for smallest pixel and X_0;
- Development of stitched sensors in medium feature-size CMOS process;
- Small-size test circuit for high-precision timing measurement
- Qualification of small feature-size CMOS processes to address high data rate/low power and smallest pixel, prototyping of high-speed readout architectures and periphery required for highest data-rates and complex trigger/readout schemes;

The construction of these technology demonstrators will naturally interface to the development of other WPs (e.g. mechanics/cooling, data transmission) and provide the possibility of system-level integration experience.

4.5.3 Module development

The module R&D is closely linked to the R&D on novel hybrid and monolithic pixel detectors and focusses on the development of pixel modules and their integration for future applications. This entails the use of hybrid and monolithic pixel sensors/assemblies as described in the previous sections.

The goals can be summarized as follows:

- Study of interconnection technologies and integration concepts for hybrid and monolithic pixel detectors
- Development of module concepts for ultra-thin silicon pixel detectors
- Development of module concepts integrating photonic chips
- Study of module integration to overall detector systems (including cooling and powering)

Links to other activities and work packages:

The work will be closely linked to the developments for hybrid and monolithic pixel detectors. Certain activities, such as interconnection studies or the development of ultra-thin pixel modules can be started immediately with already existing pixel chips/assemblies (e.g. Velopix, ALPIDE, MALTA, RD53A). In a second phase novel chips and assemblies as result of this R&D initiative will be used to build demonstrator modules and study their integration.

Close collaborations are foreseen with the work-packages on IC technologies (WP5), high speed links (WP6) and detector mechanics (WP8).

Objectives:

- *Study of die-to-die interconnection* techniques to achieve highly integrated modules, using RDLs (Redistribution Layers) and interconnection techniques such as Cu-Cu bonds and anisotropic conductive adhesives; validation in a first phase for general R&D and prototype building using monolithic pixel prototype chips.
- Development of *very thin hybrid pixel modules* using fine pitch bump bonding, ASIC to wafer bonding techniques, stress compensation layers and alternative interconnection technologies such as anisotropic conductive adhesives.
- *3D integration of modules for hybrid and CMOS pixel detectors*, including stacking, but also combining electrical and mechanical connections in one step as well as the integration of support/cooling and/or signal/power structures for better thermal management.
- *2.5D integration for hybrid pixel modules* (i.e. rerouting of signals using interposer structures) to improve routing requirements as needed for high performance timing detectors.
- *Integrated pixel modules* with novel methods of sensor integration to serial *powering systems* and novel photonics devices for *data transmission*.
- *Thinning and dicing studies on hybrid detectors and monolithic CMOS sensors* including definition of QA procedures. Studies on novel dicing techniques allowing to reduce and optimizing the cut region, thinning studies on how to control the warp of these ultra-thin dies (50 μm or less).

Deliverables:

- Demonstrator modules of large area monolithic sensors using die-to-die data and power transmission.
- Demonstrator module of an ultra-thin wrapped monolithic pixel module.
- Validation of very thin hybrid pixel assemblies with fine-pitch micro-bump bonds and 2.5D interposer structure.
- Assembly and test of silicon photonics device with pigtails and in a small package.
- Development of a highly integrated module with photonic chip, electrical driver/receiver.
- Validation of the different elements of 3D integrated modules in terms of radiation hardness, including mechanical and cooling structures using serial powering and using light weight fast data transmission. In a second stage radiation testing of a prototype 3D integrated module

An update and extension of existing infrastructure will be crucial for the activities in this work package and the goal to develop and build novel pixel modules. This entails the provision of adequate cleanrooms, metrology and inspection instrumentation as well as assembly tools (see list in table).

4.5.4 Simulation and Characterization:

The Simulation and Characterization activity aims for a fundamental understanding and optimization of the performance of prototypes developed within the different sensor activities. This will be achieved through detailed characterization, modelling and simulation, including the effect of radiation exposure to the levels expected at future hadron colliders.

The activity will conceive and operate specialized characterization tools, such as advanced Transient Current Techniques, micro-focused x-ray and beam telescopes. This includes also a flexible readout system suitable for laboratory and test-beam measurements of the various detector prototypes, which will be of great importance for making the characterization of new designs more efficient. Novel sensor concepts for radiation monitoring at extreme fluences $>10^{16}$ n_{eq}/cm^2 will be developed, which are required for accurate dose estimates in irradiation tests as well as for monitoring purposes at future hadron colliders. A fundamental understanding and modelling of radiation damage will be achieved through characterizations of test structures and sensor prototypes. The resulting models will then be implemented in simulation tools.

A new high-rate beam telescope architecture will be developed which exploits the 200ps timing precision in the Timepix4 ASIC. This can be combined with very precise timing planes to investigate fast timing detectors. Algorithms for precise track time reconstruction and pattern recognition will be developed and tested using the prototype timing layers. As the ASICs are upgraded to match the programmes for future applications, the telescope system will correspondingly be upgraded to be able to probe timing issues with higher precision. The telescope will also be exploited to investigate issues of very high rate data transfer, using as a baseline the 180 Mhits/cm^{2}s available from Timepix4 and then extending this as more high-rate chips become available. The interplay between the pre-processing and output data-rate will be studied and optimized. The telescope can also be used to investigate system aspects related to the very dense power and signal environment, such as cross talk issues related to the close proximity of a very large number of high speed drivers.

A novel Monte Carlo simulation tool will be further developed and maintained, based on existing expertise within the different EP groups. This tool combines Geant4 simulations and TCAD device simulations with parametric simulations of the charge transport and readout response. Special emphasis will be put on the detailed treatment of the transient behaviour, which is of particular importance for sensor types aiming at very high time resolution. Simulations of the data stream will be performed for the optimization of the data pre-processing, encoding and readout. These simulations will give input on crucial items such as the number of required bits, the information share among a super pixel structure, the encoding style and so on. The studies, which will be based on Monte Carlo simulations and a detailed modelling of the readout chain, can be performed for a general inner pixel tracker and then refined to target specific applications.

The achievement of these research goals shall be demonstrated in the following deliverables:

- Upgraded TPA-TCT characterization setup commissioned.
- High-resolution beam telescope with picosecond time resolution and flexible readout system commissioned.
- Radiation monitors for fluences >10^{16} n_{eq} / cm^2 validated.
- Radiation models validated with TCT and x-ray measurements
- Simulation tool validated with TCT, x-ray measurements and beam tests

The activity will be closely linked with the sensor development activities and will also profit from a close collaboration with a large community of external institutes.

Overview of the activities in WP1

Novel silicon sensors – Hybrid-Pixel Sensors	**Hybrid readout ASICs**
- Sensors for timing (4D tracking at high rate) and novel structures o LGAD, silicon for high-precision timing o Thin planar active-edge sensors o Radiation hardness studies and novel monitoring sensors 1 specialty run/y and post processing + hybridization of sensors	- Development of specific front-end circuits for precise timing and for fine-pitch pixels - Data readout and encoding studies for pattern recognition and high-speed pixel timing 3 MPW submissions over 5 years

Monolithic sensors (medium feature size ≥90 nm):	**Monolithic sensor (small feature size <90 nm):**
- Radiation hard depleted sensors for $\geq 10^{15}$ n_{eq}/cm^2 - Medium/high rate architectures (> few x 100 MHz/ cm^2) - small pixel size sensors with very low power dissipation (<25 μm pitch) - stitched sensors from 4x4 to 14x14 cm^2 - flexible thinned sensors / curved configurations	- highest performance for spatial resolution and ns-timing - architectures for highest data rates (>2 GHz/ cm^2) compatible with innermost layers at HL-LHC - commonly needed periphery blocks for data-encoding/transmission and complex trigger/readout schemes - minimized power consumption for minimal material and sensor powering circuits.
Eng Run every 18mo MPW 1-2/y	

Module (sensor integration)	**Module (assembly)**
- Micro-bump bonding assembly - Fine-pitch ACF - 3D integration to modules - sensor interconnection for high speed @ minimal material - 2.5D integration silicon interposer - photonics packaging and integration into module	- wrapped sensors modules - QA for modules - Flex, tools, readout, vacuum
Module (Infrastructure) - Setup and infrastructure for silicon handling (cleanroom) - Analysis tools (SRP etc.) - Pick place for interconnection - Automated inspection systems for large areas - X-ray inspection system for fine pitch	

Simulation and Characterization
- Simulation of sensor and readout: charge deposition, transfer, digitization, data encoding; combination of device and Monte-Carlo simulations - Modelling + simulation of radiation damage - Characterization tools: Advanced TCT, beam telescopes, flexible readout systems for laboratory and beam tests Material for characterization and long term investment

5 Gas based detectors (WP2)

Gas based detectors will remain a key technology for radiation detection in particle physics experiments. They provide low-mass, relatively cheap, relatively easy-to-build and radiation hard detector solutions for specific measurements. In addition, they intrinsically provide an amplification of the signal by gas amplification, thus require less on-detector electronics, and provide excellent single-particle sensitivity compared to other detectors.

At the LHC, all four major experiments (ATLAS, CMS, ALICE and LHCb) are extensively using gas based detectors, various technologies which are based on the need for trigger and bunch crossing tagging (Gas Electron Multipliers GEM, Micro-MEsh Gaseous Structure detectors MicroMegas, Multiwire Proportional Chambers MWPCs, Resistive Plate Chambers RPC, Thin Gap Chambers TGC), for high-rate tracking and particle identification (Straw Tube Detectors, Time Projection Chambers TPC, Drift Tubes, Cathode Strip Chambers CSC) and for single photon detection (Multi-Wire Proportional Chambers with CsI photocathodes).

At CERN, also the non-collider experiments NA61 (proportional chambers as beam position monitors, TPC as large volume tracking device), NA62 (Straw Tubes for tracking of charged particles originating from the decay region), NA64 (MicroMegas and straw tubes for electron track measurements), COMPASS (GEMs and MicroMegas for small area tracking as well as planar drift chambers for large area tacking) and CAST (MicroMegas and Integrated Grid detectors InGrid for single X-ray detection) are widely using gas based detectors.

The upgrades of the LHC detectors as well as new detectors for future collider and non-collider experiments continue to rely on gas based technologies.

In ATLAS currently the replacement of the present first stations in the forward regions, consisting of MicroMegas and small-strip Thin Gap Chambers (sTGC) with a total active surface of more than 2500 m^2, and for CMS, the addition of triple-GEM detectors in front of the existing Cathode Strip Chambers (CSC) with more than 200 m^2 are in full swing. Future upgrades of the muon systems of the experiments might include replacement of the detectors as the RPCs which will have reached the end of their (expected) lifetime in the harsh conditions of the LHC or an upgrade of especially the forward muon detector to match the segmentation, resolution and angular acceptance of the central precision trackers which will be installed in LS3 for the LHC High Luminosity upgrade.

Experiments which are currently under planning or in the scientific review process, as the ILC or FCC rely a large central TPC in case of the ILC as well as on a design with gas based muon detectors. These muon systems will cover active areas larger than $1000m^2$ as in the case of the FCC.

Common challenges for such future muon systems are the high expected particle rates, which for the FCC-hh are expected in most regions to be below $10kHz/cm^2$, which is very well within the technical capabilities of the ATLAS MicroMegas and sTFCs, however can reach o be up to 500 kHz/cm^2 in the forward region for radii less than 1m. Moreover, due to the very high luminosities the requirement on the time resolution of the muon detectors have become more severe and for timing layers, resolutions less than 1ns are now considered.

The challenges for gas based muon detectors for non-collider experiments are less demanding. For example, the proposed non-collider experiment SHIP experiment considers to use as a muon spectrometer to identify the muons produced in neutrino interactions and in tau decays and to complement the muon momentum measurement performed in the magnetised target with RPCs and drift tubes. These detectors will need to operate in an environment of particle rates up to $4kHz/m^2$, which is orders of magnitude lower than the rates expected to LHC, ILC or FCC experiments, thus progress in the research and development of gas based collider detectors will also bring benefit to systems designed for the non-collider experiments.

However, a common issue for many gas based detectors is the need of new eco-friendly gas mixtures. New possible candidates will need to be found to replace SF_6, $C_2H_2F_4$ (for RPCs) and CF_4 (mainly for GEMs).

With the focus on large area gas based muon detectors, the main requirements for their use in future collider experiments can be summarised as follows:

- the most important task is the identification of muons with highest efficiency, order of 99% over a large solid angle. This requires at least three space points along a muon track;
- to resolve bunch crossings and background, time resolutions below 1ns need to be reached;
- standalone muon trigger capabilities, e.g. for a fast level-1 trigger response, should be possible;
- depending on the performance of the inner tracking system, the momentum resolution might be required to reach about $\sigma_{p_T}/p_T^2 \sim 1\text{-}2 \times 10^{-5}\ GeV^{-1}$. With a magnetic field of 2 to 4 Tesla and a few muon stations at a radius larger than 5m, this translates to a required space resolution of a few hundred microns;
- minimal number of electronics channels, which can be possible via a clever geometry of the detector and/or the sensor element, adapted to the tracking resolution needs in the particular detector area (e.g. expect need of higher resolution in the end-caps);
- another key issue, because of the large active area surfaces is that the detectors can be mass producible by industry.

In institutes, universities and collaborations worldwide, a rich R&D programme is carried out to address the issues mentioned above and to develop new technologies for gas based detectors. A very prominent endeavour is carried out by INFN on RPCs, which are widely used in particle physics experiments and because of their excellent time resolution are very good candidates for future muon systems. Another highly visible and successful example is the RD51 collaboration, where in close collaboration with CERN, dedicated R&D is carried out on micropattern gaseous detectors, which are considered to be a key technology for future collider experiments.

To complement the ongoing developments, EP R&D activities on gaseous detector technologies will focus on issues which are less prominently covered, which make use of the large infrastructure at CERN and which tackle issues arising for the LHC upgrades and for future collider experiments.

- Activity 1: Solutions for large area gas based detector systems
  Reliable and efficient mass production of all parts of large area gas based detectors is mandatory for any future detector. In the current Phase-1 upgrade of the LHC experiments, it becomes visible that problems with mass production of the detectors, jeopardises construction schedules and brings the entire project to risk. As in most cases, the final detectors are assembled at CERN, it is in CERN's interest to ensure reliable and efficient mass production in time. New solutions for large area

systems should be addressed in this activity, specifications and procedures should be developed, prototypes build and tested.

- Activity 2: Tools for gas based detector R&D
  The R&D to reduce costs and environmental impacts of gas mixtures for gas based detectors should be strengthened. R&D on this topic is already present at CERN in the EP-DT-FS gas service team, however these efforts need to be extended to ensure that the results achieved are transferred to the community and into the tools used by the community. The extension shall include gas studies and analysis, documenting and cataloguing the results as well as the implementation of the results to the simulation and modelling of gas based detectors, electronics and instrumentation.

- Activity 3: Development of novel technologies
  This activity aims to explore new solutions for future developments of gaseous detectors. It will focus on new materials, new fabrication techniques and new concepts and explores the possibilities, expertise and tools in EP's enlarged PCB workshop. The techniques offer unique opportunities for fast prototyping and might give rise to many novel applications, as excellent, fast timing.

In the following sections each activity will be described in more details. The summary on deliverables, milestones, required resources (human resources and material) is attached in the Excel file.

5.1 Activity 1: Solutions for large area gas based detector systems

Future collider experiments will continue to rely on large area gas based detectors for the detection and measurement of muons. These detectors will have to cover active areas order of a few thousand square meters. The majority of the large components of these detectors will need to be produced by industry in reliable and efficient mass production.

To complement the ongoing research in the field of gas based detectors, where promising technologies are explored on the basis of small prototypes, EP R&D in this activity shall focus on scaling up these small prototypes to full size prototypes.

For a given promising technology, as GEMs, MicroMegas or µRWELL detectors, full size prototypes shall be designed, build and tested with the focus on a number of questions:

- Exploration and documentation of the size limits of the various parts in industry, investigation of possible partners;
- Study of the advantages/disadvantages of a large single detector or a segmented detector of the identical size. These studies should not only include mechanical properties but also performance of the detector in test beams and comparison with simulations;
- Comparison of the performance of a small prototype with a full size prototype. Again, these studies should not only include mechanical properties but also performance of the detector in test beams and comparison with simulations;
- The use of new materials as composites shall be explored and included into the design of the large area detector;
- Detector mechanics plays a crucial role in this context. Novel solution and novel material (composite as an example) can offer interesting solution;
- The design of the large area system shall in addition explore to minimise the number of services (gas, cooling, High Voltage) and as well minimise the number of electronic channels

without compromising precision measurement capabilities and exploit the different approaches of embedded versus distributed electronics.

Error! Reference source not found. illustrates the use of resistive layers for increased stability and robustness of the chamber operation using Micromegas and mRWELL technology as examples.

Insert figure for deliverables

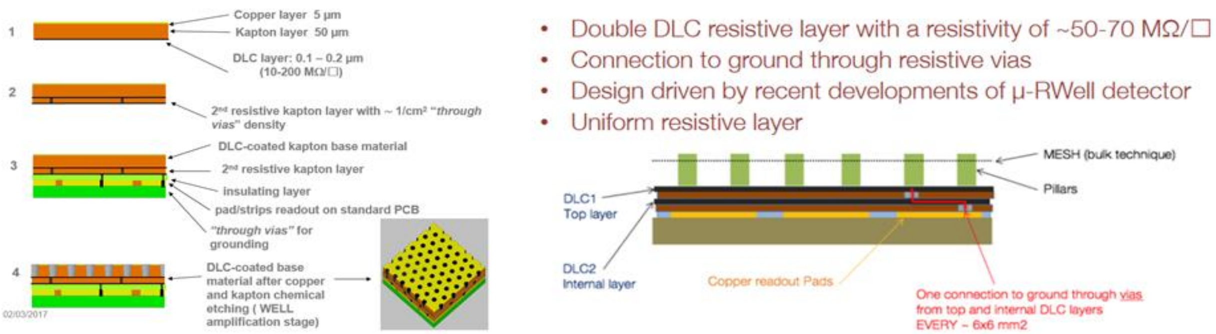


Figure 1: Use of Diamond like Carbon (DLC) layers in MicroMegas and µRWELL detectors

5.1.1 Work plan

Collaborating partners for the activity include EP-DT, with contributions from the PCB workshop and the engineering and technical staff. With the progress in the activity, outside partners from industry but also from the institutes involved in gas based detectors can be expected. To provide an initial nucleus of the team, several CERN staff need to be involved and to guide the activity, with about one FTE per year.

5.2 Activity 2: Tools for gas based detector R&D

This activity aims to strengthen the current R&D environment at CERN, with the goal to foster the tools needed for successful developments and prototyping. Areas of contributions should be:

- Gas analysis and gas studies;
- Simulation and modelling.

5.2.1 Gas analysis and gas studies

A common issue for all gas based detectors is the need of specialised gas mixtures, which are chosen according to the requirements of the measurements and/or the environment and conditions, the detectors operate in.

Within the EP Department, there are already activities ongoing to explore new eco-friendly gas mixtures or new, efficient recirculation systems, e.g. for the various RPCs used at the LHC experiments and foreseen for the HL-LHC. To foster and complement this ongoing activity, it is suggested to continue and even expand the studies on radiation hardness and outgassing properties of materials in different gas mixtures, where EP played a major role during the design and construction phase of the initial LHC experiments. The interest of the collider collaborations – because of increased radiation levels - and beyond-collider experiments focusses on new gas mixtures and new materials in detector components and mechanics.

It is suggested to upgrade the existing possibilities for gas and material studies, with improved monitoring, controlling devices such as pressure regulators, flow meters, and appropriate X-ray sources to perform such studies and measurements.

The activity will add to ongoing EP efforts as the contributions to RD51and the developments for eco-friendly gas mixtures or new recirculation systems. And the activity will provide input the simulation and modelling tools, which are used in the community for gas based detectors world-wide.

Insert figure for deliverables

5.2.2 Simulation and modelling

New measurements and developments in detector technologies are continuously raising new aspects that need to be modelled and simulated. Simulations are in general an excellent approach to better understand our detector and the underlying physics processes. They are crucial for optimisation of a detector and for trying new configurations beyond current limits.

Error! Reference source not found. shows a few examples of state-of-the-art simulation results obtained with the commercial COMSOL software, while Figure 3 illustrates electric field and transparency simulations of GEM structures.

The following points shall be addressed in detail in the simulations: discharges, ion diffusion, behaviour of resistive detectors, signal development and signal processing.

CERN has always played a strong and leading role in all aspects of simulation of gas based detectors. This activity strengthens this role and provides a central point of maintaining and expanding modelling tools, as Garfield, Heed, Magboltz, Degrad, GEANT4, COMSOL, Field (Finite elements, boundary elements) and signal induction and electronics simulation.

The activity ensures that the key tools for all other EP activities on gas based detectors are available, and in addition provides a common interest and links with ongoing gas based detector R&D at CERN (RD51) and the teams in the universities and institutes around the world.

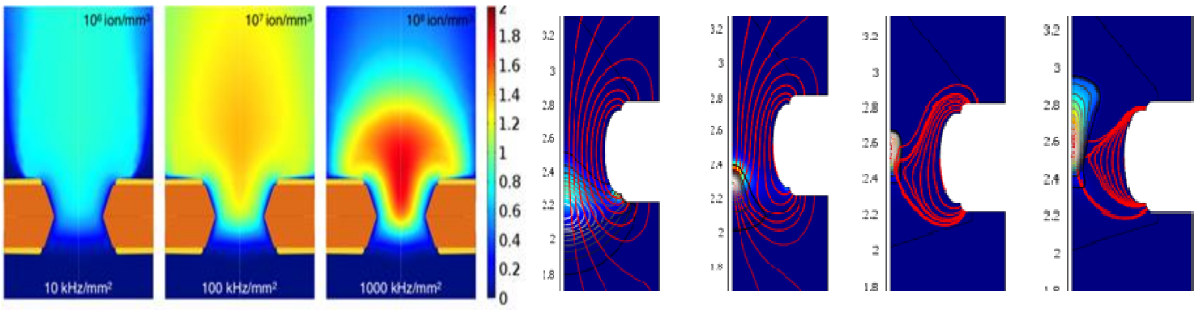


Figure 2: Simulation and Modelling with COMSOL: Left: Space Charge effects at high rate in GEM. Right: Surface ion density evolution in a discharge in GEM.

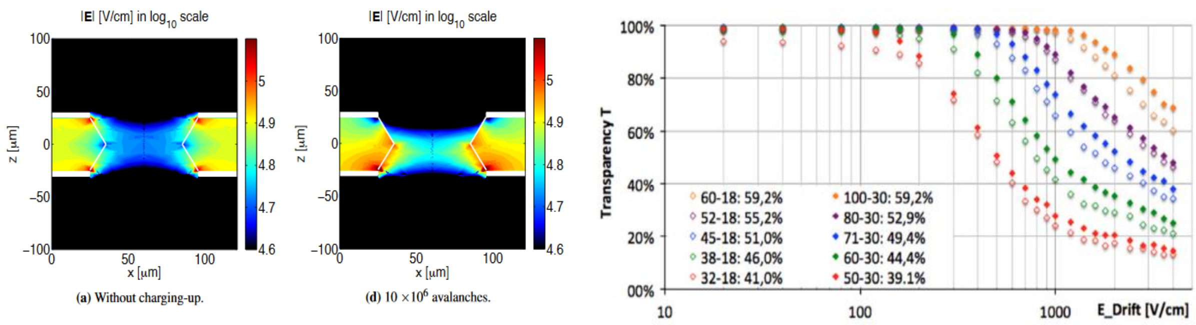


Figure 3: Simulation and Modelling with Ansys and Garfield: Left: Charging up of GEM holes studies. Right: Electron transparency of different Micromegas meshes.

5.2.3 Electronics and instrumentation

To efficiently carry out the proposed R&D, electronics support will be mandatory. In particular, R&D on fast timing gas based detectors, a proposed in 1.3, development of novel technologies, requires specialised and – up to now – non-available systems, which need to be developed. As well, for solutions in large scale detectors, as described in 1.1, a close collaboration to electronics expert is needed, e.g. to find solutions for optimising the number of channels for large detectors.

Thus close collaboration between detector physicist and electronics expert is vital, as well as sufficient and versatile equipment.

It is suggested to foster supporting electronic systems that can be used in laboratory and for medium scale setups as in test beams or for small scale experiments.

Several main lines shall be linked to these activities:

- Single Channel Signal Processing: Fast & precise timing single channel readout;
- Instrumentation: precise ammeter (floating, fast readout), Single channel spectroscopy & trigger lines;
- Multichannel ASIC DAQ (Synergies with EP-DT-DI, EP-ESE): Multipurpose DAQ based on existing solutions.

5.2.4 Work plan

To provide an initial nucleus of the team, several CERN staff need to be involved and to guide the activity, with about one FTE per year.

5.3 Activity 3: Development of novel technologies

Progress in manufacturing techniques, i.e. photolithographic structuring techniques, led to the development of MicroPattern Gaseous Detectors (MPGDs). These detectors are now widely used in high energy physics experiments and industrial and medical instrumentation.

New techniques will allow for new solid converters, which allow high efficiency detectors, high resistivity, stable operation and especially fast timing of signals. The ongoing work in EP-DT-GDD on this topic should be fostered, even extended, with the goal to reach robust, radiation hard photo cathodes and to build a small area prototype.

Also, the next breakthrough for gas based detectors might result from the maturing 3D printing as well as dry plasma, LASER, ink-jet printing can offer unique tools to produce functional structures, which would allow novel specialised and up-to-now unthinkable geometries, and would give rise to manifold opportunities for complex 3D integration of conductive channels, embedded resistive elements, fine-grained multidimensional readout structures and electrical signal routing.

Also, novel structures for amplification can be build and tested. Here electron emitters and protection of photocathodes are two possible examples.

The new printing technologies would also allow faster and cost-efficient production of prototypes, which will allow - in combination with optimised detector design via simulation, resulting from Activity 2 - a fast turnaround for detector development.

At CERN, in the EP department, the new and specialised PCB laboratory, offers unique opportunities to prototype such new prototypes. The feasibility of building a gas based detector should be explored and - in combination with Activity 2 - its outgassing behaviour and radiation hardness of the used materials can be studied.

The proposed activity uses the unique infrastructure of CERN and will give rise to many novel applications.

Insert figure for deliverables

5.3.1 Work plan

Synergies with other groups at CERN, as EN-MME, the Vacuum group of the TE department and the BE department on coatings exist and should be strengthened.

5.4 In case of additional resources available: Activity 4: Fast gaseous photo detectors

Exploring synergies between current technological advancements in gas based detectors and in optical sensors [2] will open new opportunities for fundamental research but also for applications outside our field.

The advantages of gas based detectors, low material budget, the large dynamic range and the radiation hardness, will be combined with the high granularity of optical sensors. Together with a fast data acquisition, see Activity 2, Electronics and instrumentation, and fast image processing, unique and breakthrough solutions for beam monitoring and event by event imaging can be achieved. Particle physics experiments, accelerators and experiments, as well as hadron therapy applications will profit.

This additional activity will require as extra resources one fellow and one doctoral student plus 100kCHF per year.

Part of this activity have been proposed in the framework of ATTRACT. However, substantial and additional support by the EP Department would allow for a highly interesting and visible R&D project with applications beneficial for HEP and society.

5.5 Summary

Future particle physics experiments will rely on gas based detectors. To ensure that these detectors fulfil the requirements of their future applications, as well as to start new developments, a set of three R&D activities for the CERN EP Department is proposed. These activities concentrate on CERN's and EP's expertise and infrastructure, and are orthogonal to ongoing R&D projects at CERN and in outside institutes. The activities cover large area systems, which will be needed for future collider and beam dump experiments, strengthen the important common tools used by the community, simulations, and exploit novel fabrication technologies, which will use unique EP infrastructure.

5.6 References

[1] J. Bortfeldt, et al. "PICOSEC: Charged particle timing at sub-25 picosecond precision with a Micromegas based detector," Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 12 2017. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0168900217313499http://arxiv.org/abs/1712.05256

[2] B. W. Pogue, "Technology: Ultrafast imaging takes on a new design," Nature, vol. 516, no. 7529, pp. 46–47, 12 2014. Available at: http://www.nature.com/doifinder/10.1038/516046a

[3] M. Capeans, "Aging and materials: lessons for detectors and gas systems," Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, vol. 515, no. 1-2, pp. 73–88, 12 2003.

6 Calorimetry and light based detectors

6.1 RD1: R&D for future high-granularity noble liquid calorimetry (towards FCC-hh)

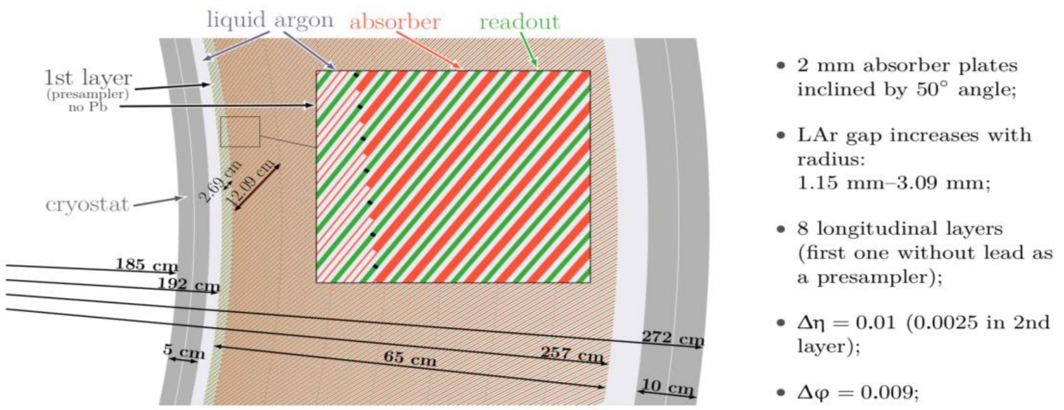
High granularity noble liquid calorimetry will be essential for future accelerator experiments (radiation hardness, stability, high resolution energy measurement, high position resolution, timing resolution, high granularity for 3D imaging, pile-up suppression, particle ID, jet substructure,…). It is part of the reference design of an FCC-hh experiment presented in the FCC CDR. Due to the high radiation environment a fully passive calorimeter with read-out electronics sitting behind the calorimeter outside the cryostat is the preferred choice, leading, however, to long transmission lines of the signals.

We propose 4 research activities (A, B, C and D):

6.1.1 Activity A: PCB development and test-beam module

The granularity of noble liquid calorimeters can be easily adjusted to the needs by finely segmented read-out electrodes (multi-layer PCBs). Such electrode PCBs need to be designed, simulated, produced and tested. Special focus has to be given to the resulting electronics noise of the full system including read-out electronics (CERN, BNL). The idea is to exclusively rely on warm electronics that can be maintained/refurbished during shut-downs, although this leads to long transmission lines and a large number of signal feedthroughs. It is planned to also study the feasibility of such an approach with the test-beam program (including signal attenuation along the transmission lines). As a fall-back solution, cold electronics inside the cryostat (preamplifiers) could be envisaged later on. The final granularity needed will be defined by performance requirements which will be simulated using FCC SW. For this purpose the FCC SW will need some further developments such as the implementation of particle flow or other novel reconstruction techniques. Based on the obtained results a small test module will be designed, produced and tested at the test-beam (2023). LAr is the baseline choice for the moment, but other liquids (e.g. LKr) will be studied in simulation.

The design of a test module which will be needed to evaluate the feasibility of a multi-layer PCB + long transmission lines read-out including performance measurements will be developed in the coming 3 years. The conceptional idea is to build a small-size O(60cm x 60cm x 60cm) prototype of the below calorimeter (see picture, radii and dimensions in the sketch are from the FCC-hh detector, not from



the testbeam module).

A test cryostat (LAr TB cryostat, or cryo lab) will be used for the cool-down.

6.1.2 Activity B: Study and tests of timing resolution

Noble liquid calorimeters have intrinsically good timing resolution due to their fast signal rise-time and their homogeneous active material. Timing resolution will be essential for future applications in accelerator experiments, limits of MIP timing and timing resolution of showers, involving the full read-out chain, will be explored in simulation and optimized. The goal would be to measure the timing resolution also in the testbeam (using the test module introduced in task A). This aspect will have to be studied thoroughly in preparation of the testbeam and taken into account at the design of the test module. It will be necessary to carefully choose the FE electronics adapted for such a measurement as well as the necessary set-up in the beam line.

6.1.3 Activity C: Measurements of LAr properties

In parallel it is essential to measure and simulate LAr properties and calorimeter performance under high ionization rates covering space charge build-up, initial and bulk recombination, surface charge accumulation and the role of impurities. Test-beams are planned at Protvino and CERN by a collaboration of 6 institutes, the so-called HiLum2 collaboration. CERN will be participating with its infrastructure, but will keep its contribution low here.

6.1.4 Activity D: Feed-through development

The large granularity will require an increased signal density at the feedthroughs (FT) of up to 20-50 signals/cm^2 which is a factor ~5-10 more than in ATLAS (ATLAS used gold pin carriers sealed in glass). Novel technologies have to be developed with industry (CERN cyo lab, BNL). High density feedthroughs for cryogenic applications are not specifically limited to FCC-hh calorimeters. We will e.g. profit from synergies with neutrino experiments in which collaborators at BNL are involved. A FT design for a neutrino experiment will be adapted to FCC-hh needs.

6.1.5 Collaboration with other institutes

Some preliminary discussions with other collaborators have started: For the planned test module (task A), collaborators at BNL have agreed to provide read-out electronics (adaptation from ATLAS LAr Phase II Upgrade Electronics). Planning of the HiLum2 and LArPulse test-beams is going ahead by a collaboration of 6 institutes (activity C). BNL has also shown interest in feedthrough R&D (activity D), where a FT design based on PCBs developed for neutrino experiments will be adapted. The CERN cryo lab will also participate in activity D. LAL/Orsay will participate in the electrode design and the FE electronics (activity A).

6.2 R&D for future scintillator based calorimeters

Scintillator based calorimetry is under consideration for many calorimeters of future accelerator experiments due to its cost effectiveness and moderate radiation hardness which makes it an ideal choice for hadronic calorimeters in high energy physics experiments such as FCC-hh, FCC-ee, CLIC and ILC. On top of that it is also considered for the LHCb ECAL Upgrade II, with more challenging radiation requirements of up to $3{\cdot}10^{15}$ n/cm^2 and TID of 3 MGy (CERN/LHCC 2017-003). All such calorimeters will profit from excellent timing resolution to suppress pile-up, in the case of LHCb 20-50 ps are required. CERN has a long expertise on this type of detectors, future R&D will largely profit from that. We propose 2 research activities which are aimed at two different experiments, with overlapping requirements; we will therefore largely profit from synergies between the two activities (A and B):

6.2.1 Activity A: LHCb ECAL

LHCb ECAL: The radiation hardness of suitable scintillation detector materials needs to be thoroughly assessed in terms of scintillation characteristics, light yield, and transmission using various radiation sources providing gammas, protons and neutrons. The expected radiation environment can make it necessary to operate the photodetectors such as SiPM at low temperatures (-30°C to -40°C) and therefore it requires to study radiation hardness of scintillating materials and photodetectors at different temperature. For fast timing, the full detector readout chain has to be optimized in terms of light detection and timing characteristics. This requires time resolution studies on various scintillating materials and on photo detectors, optimization of light collection, shape of the material, etc...

R&D on radiation hard crystals is in full swing. In collaboration with Russian institutes, some first YAG crystals as well as GAGG crystals have been ordered for optical studies, radiation studies, timing studies as well as first test-beam studies with a SpaCal prototype to validate some Monte Carlo simulation. A collaboration with crystal producers that are contributing to our R&D by delivering a variety of samples with different doping, etc has been set up. First discussions were very fruitful and have shown that many questions have to be clarified and long lasting R&D is needed to hopefully produce radiation hard (up to 3 MGray) and fast (tens of picoseconds) crystals that would be suitable for calorimetry in the longer term future.

As far as the question of readout is concerned, the ongoing R&D of fast electronics in other collaborations is of course followed with interest. In recent years many efforts have been done for the development of fast timing detection with resolution below 50ps not only for HEP but also for many industrial applications such as TOF-PET, LIDAR. Many developments are going on, improving timing photodetector in particular for SiPM by all producers together with academic groups and many electronic ASICs are or have been developed also for fast timing. In case of HEP for future experiments radiation tolerance above to 10^{15} n/cm^2 will be required. R&D has started in the framework of Barrel CMS timing layer, CMS HCAL, CMS HGCal but need to be pursued. Also some R&D on new technologies such as radiation hard GaAs diodes has been started.

We will have a much better understanding about our next milestones by fall, once we have received the first crystals and had time to evaluate their performance. A technical student has been hired to start in September with optical measurements.

6.2.2 Activity B: FCC-hh TileCal

FCC-hh TileCal: Due to the relatively modest radiation requirements (TID 8kGy in the tiles) the reference design makes use of organic scintillator tiles read out by wave-length shifting fibres and SiPMs to profit from a factor 4 increase in lateral granularity with respect to ATLAS TileCal. The proposed R&D will be done in close collaboration with industry and several institutes part of the ATLAS TileCal collaboration and will make use of the infrastructure of the TileCal lab in B175 at CERN: Identification and qualification measurements of components before and after radiation (tiles, WLSs, SiPMs, calibration systems), optimization of the optics concept (WLS, coupling to SiPMs), optimization of mechanics,... An ATLAS spare mechanics module will be re-instrumented with FCC-hh components to do tests with cosmic muons and possible tes tbeam measurements (profiting from ATLAS TileCal table and test beam infrastructure).

The HCAL Tile FCC-hh calorimeter will clearly profit from the R&D on raw materials ongoing in the framework of CMS HGCal as well as in other experiments, in particular for more radiation hard, fast and highly efficient components (scintillating tiles, SiPMs and WLS fibres (if fibres will still continue to be used in CMS HCAL uprade).

However, the optics/mechanics concept prosed for FCC-hh Tile calorimeter, inspired by the ATLAS TIleCal, shows quite large differences with respect to CMS or CALICE/ILC hadron calorimeters:

- The scintillating Tiles are oriented parallel to the incoming beams at eta=0

Long fibres are used to bring the light to the outer radius where Si-PMs will be located and therefore suffering much less from radiation levels. The Si-PMs will be in extractable drawers to allow easy access for maintenance during the life time of the experiment

- A Cesium source calibration system is proposed that runs inside the Tiles over many Kilometers of pipes.

The proposed R&D for the FCC-hh Tile hadron calorimeter, will mostly be focused on the optimisation of the optics concept inspired by ATLAS TileCal, for the best compromise between amount of light, best uniformity across the tiles surface and minimal crosstalk between the millions of Tile volumes arriving through the fibres to the Si-PMs. These studies will be done using optical components in test benches and real module prototypes in a later stage.

The FCC-hh fellow presently working in the Tile FCC-hh calorimeter will cover the period up to end 2019.

The main priority of the fellow activity up to now and over the next months is the performance simulation studies with single pions and jets to optimize the main parameters of the calorimeter layout in combination with the EM calorimeter and tracker. The fellow should start soon spending a small part of her time in lab measurements in parallel of the simulation studies.

6.3 R&D for Si based calorimetry for a CLIC detector and CLD detector at FCC-ee

The CLIC detector and the CLD detector at FCC-ee propose very similar highly granular calorimeter designs, which are optimized for Particle-Flow Analysis (PFA). The calorimeters comprise compact sandwich structures for the electromagnetic (ECAL) and hadronic (HCAL) sections in a barrel and end-cap geometry located inside the central detector solenoid. The new CMS highly granular endcap calorimeter HGCal for the HL-LHC phase-2 upgrade will comprise similar technologies. Therefore much will be learned for the CLIC/CLD calorimetry through the HGCal development and construction in the coming years, such as: sensor development and procurement, detector integration, cooling integration (without power pulsing), calibration, full system aspects, mass production. In this context, the CERN EP-LCD group currently participates in the CMS HGCal project as a means to pursue calorimetry R&D for CLIC and aims to continue this strategy. The main differences between CMS HGCal and CLIC reside in the readout timing and the power pulsing. At CLIC, power pulsing will result in a strong reduction factor in heat dissipation between the sandwich layers. This allows for passive conductive cooling along the absorber plates of the calorimeter stack, while active cooling will be applied to concentrator cards at the edge of the detector segments. The power pulsing enables a larger effective density of the calorimeter and more compact particle showers.

We propose 3 research activities (A, B and C):

6.3.1 Activity A: Continuation of CLIC/CLD R&D through participation in CMS HGCal

Continue the calorimeter R&D for CLIC/CLD through participation in CMS HGCal at the current resource level throughout 2019-2022.

6.3.2 Activity B: Engineering studies on electronics and mechanics

Drawing on the CMS HGCal experience pursue engineering (mechanical + electronics) design studies for CLIC/CLD, both for ECAL and HCAL, in order to present realistic designs ranging from the module level up to the system and integration level during the years 2020-2022. This task could be pushed to a later date, e.g. 2022.

6.3.3 Activity C: Build a few realistic CLIC/LCD ECAL modules

Build and test a few realistic CLIC/CLD ECAL modules, including sensors, electronics, absorbers, power pulsing (for the CLIC case), cooling and services during the years 2022-2025. This activity could be pushed to a later date, e.g. 2023.

6.4 R&D on RICH detectors for future high energy experiments

Cherenkov-light based detectors, and in particular RICH detectors, are occupying a place more and more essential in high-energy experiments, in which non-destructive, positive particle identification is required.

CERN has a tradition in carrying out R&D in the field and hosted major actors for many years, who helped defining methods and goals. Indeed, CERN people led R&D and detector implementation in various experiments, as a most recent example the two RICH detectors of LHCb. These have not only brilliantly shown their critical role inside the experiment, but also clearly indicated the future potentialities of this technique. With the present LHCb RICH, single-photon Cherenkov resolution was shown to be better than 0.7 mrad. In a well-focussed R&D, a better than 0.2 mrad resolution could be demonstrated, even in presence of high event multiplicities and complex topologies. Moreover, owing to their optical focusing and Cherenkov effect geometry, all Cherenkov photons produced by a particle in a RICH detector reach the photodetector plane at exactly the same time, independent of where and when on the particle path they have been emitted, if the detector optical geometry is aberration-free. This makes them as ideal timing detectors with possible time resolutions in the picosecond range (Nucl. Instrum. Methods Phys. Res., A 876 (2017) 194-197). All these elements have to be capable of sustaining accumulated radiation doses in excess of ~50 kGy.

- Therefore, it seems fit to propose continuing to pursue a strong R&D activity on RICH detectors, specifically:
- New photodetectors, single-photon sensitive, with high blue-green QE spectrum, picoseconds capable, to be carried out with the relevant industry: Candidates are SiPMs and vacuum technology photodetectors;
- New radiator materials, spanning from gases to aerogel, to metamaterials and photonic crystals (which exhibit a so-called quantum Cherenkov effect);
- New optical materials for (light-weight) mirrors (in cooperation with WG4) and optical coatings and elements;
- New mechanical techniques, cryogenic optical boxes (containing photodetectors) and carbon-fibres based structures (synergy with WG4);
- New front-end electronic ASICs with picoseconds time resolutions and high-rate capabilities (WG5 synergy).

This comprehensive RICH R&D programme will be tailored to demonstrate all aspects of an ultimate performance RICH detector concept which could then be implemented in the LHCb RICH Upgrade II (LS4). Activities have already started, especially in simulation, demonstrating the validity of such approach. Several institutes have shown a keen interest in collaborating and in contributing under CERN leadership (CERN-LHCC-2017-003 and therein cited articles).

In the context of the proposed technological R&D programme, CERN will concentrate on the development of optical hardware and low-temperature systems for the photodetectors, assuming that these will be SiPM detectors, whose dark noise rate – increased due to radiation damage - can be mitigated via its operational temperature. CERN has a long tradition and the required infrastructure for the development of mirrors with enhanced reflectivity (DELPHI, COMPASS, LHCb, NA61) and also for the production of light weight optical structure based on composite materials. In the Thin Film and Glass lab of the EP-DT group, dedicated vacuum coating plants as well as reflectometers for the characterisation of the reflective films are available.

The development of mirror substrates on carbon fibre composite basis will mitigate the dependence on a world-wide single supplier. The development will strongly profit from a cooperation with WG4 (mechanics) and access to the composite lab in the EP-DT group where specific infrastructure and in particular expertise is available for the design, production and testing.

Similarly, the development of compact container structures for the operation of SiPMs at very low temperatures, will profit from the expertise and infrastructure in WG4. Assuming that these structures will be based on CF composites, WG4 can provide help in terms of material selection, production and low temperature testing.

The remaining parts of the comprehensive RICH R&D Programme will be carried out by external Institutes from the LHCb collaboration. The results of this R&D will constitute the basis of the new LHCb RICH system foreseen for Upgrade II in LS4. A scale-model prototype would be implemented in the LHCb phase Ib (following LS3) Upgrade as a test system for the successive full scale detector to be ready in LS4. Approximately 2-3 years after the LS2 RICH upgrade we foresee the official launch of a new LHCb RICH upgrade project and the availability of specific CERN R&D funds.

6.5 R&D on plastic scintillating fibres trackers

A special place in light-based detectors is taken by the plastic scintillating fibres technique, in the fact that the fibre can be used for tracking and calorimetry purposes.

For tracking, arrangements of fibres in projective layers, each providing precise space-vector information (rather than a point) for a relatively low material budget, is a unique feature, available at a low cost. At the end of the 80ies, it became clear that glass-based fibres (used in a few target-based experiments) would not work at high rates and luminosity environments, due to their time response, presenting a long tail of light. Moreover, the UA2 experiment showed how crucial was the photodetector system in such applications. Development of plastic scintillating fibres started vigorously in the framework of the coming hadron collider C. D'Ambrosio, "Central tracking in high luminosity future colliders", in "Supercolliders and Superdetectors", Eds W. Barletta and H. Leutz, World Scientific Publishing Co. (1993)[5,6] due in addition to an interested automotive industry, low costs for big coverage, low material budget and first encouraging results from SSC studies. Two R&D projects were launched at CERN under the umbrella of the DRDC, RD1 and RD7, for calorimetry and tracking respectively. Both projects greatly advanced the technique and set properties, performances and limitations of the technique, which meanwhile has been used mainly in calorimetry.

---

[5] *C. D'Ambrosio, "Central tracking in high luminosity future colliders", in "Supercolliders and Superdetectors", Eds W. Barletta and H. Leutz, World Scientific Publishing Co. (1993)*

[6] *C. D'Ambrosio, T. Gys, H. Leutz and D. Puertolas, "Particle tracking with scintillating fibres", I.E.E.E. Trans. Nucl. Sci., vol. 43, nº3,(1996), p. 2115*

That is until recently, when the LHCb Upgrade decided to build a new tracker based on plastic SciFi with again an important contribution from CERN. The LHCb tracker uses fibres of 0.25 mm diameter with fluorinated double-cladding, which was developed here at CERN, and cooled SiPMs as photodetectors. It's the enormous progress in SiPMs and in particular the availability of fine pitch arrays of SiPMs which makes this new generation of SciFi detectors possible[7]. A fibre tracker will still be used in the next LHCb proposed upgrade (Upgrade II, LS4), possibly complemented by a silicon tracker in the highest pseudo-rapidity regions. The main challenges are to obtain a sufficiently high light yield in order to guarantee high hit efficiency, spatial resolution well below 100 um, which calls for small fibre diameter, and finally a sufficiently high tolerance of ionising radiation.

Three areas surely deserve attention and may be capable of delivering major advances for future high-energy experiments, if a strong R&D was stimulated upon:

1) Studies of high precision compact fibre tracker concepts for the next generation of high-energy experiments, namely future colliders, but not exclusively; these studies would be essential to address specific requirements and designs for the rather different collider types;
2) Single photon sensitive detectors with high sensitivity and granularity and improved radiation hardness;
3) Fibre development; scintillation mechanisms, light yield and transport, new cost effective fabrication techniques, new activation and wavelength shifting mechanism (dopants) and, last but not least, radiation resistance.

Conceptual fibre tracker studies (1) will be performed in the collaborations and do not require resources from this R&D programme. Progress in photodetectors (2) will profit from enormous efforts in numerous projects in HEP (e.g. calorimetry) and other domains, e.g. medical imaging, biomedical and automotive applications and will therefore not be specifically pursued in this R&D programme. However, improvements of the fibres themselves is very specific and would be of great interest also for light-based calorimeters.

We therefore propose to concentrate mostly on specific fibre developments and address the items mentioned in point 3. Such developments rely on tight cooperation with a very limited number of fibre producers available today (two!) and specialised research institutes in the domain of polymers and organic photonics. Such co-operations were established in the context of the LHCb SciFi project and already led to results[8]. CERN has dedicated labs and equipment as well as the expertise required for this activity.

A promising direction is the development of so-called Nanostructured-Organo-silicon-Luminophores (NOL) scintillators, which have demonstrated higher light yield and faster decay time than conventional fibres. Questions like long term stability and radiation tolerance need to be addressed. Another rewarding goal is the simplification and hopefully cost reduction of scintillator tile and fibre production by using 3D printing techniques. The main challenge is the preservation of the optical performance and geometrical precision.

---

[7] *C. Joram, G. Haefeli and B. Leverington, Scintillating Fibre Tracking at High Luminosity Colliders, 2015 JINST 10 C08005*

[8] *O. Borshchev, A.B.R. Cavalcante, L. Gavardi, L. Gruber, C. Joram, S. Ponomarenko, O. Shinji and N. Surin, Development of a New Class of Scintillating Fibres with Very Short Decay Time and High Light Yield. 2017 JINST 12 P05013*

Given the time scale of the envisaged LHCb upgrade in LS4 and the overall resource situation, we propose the continuation of the NOL development and a proof of principle of the fabrication of single fibres and fibre arrangements (e.g. a 10 x 10 cm^2 x-y matrix) by 3D printing. We expect these developments to happen in the shadow of ongoing work in the LHCb SciFi project and to require a minimal financial support.

7 Detector mechanics and cooling (WP4)

7.1 Introduction

The mechanics of the future HEP detectors has to cope with a wide range of demanding requirements. In a simplified scheme we can group future detectors in hadron collider detectors and lepton collider detectors. Hadron detectors propose exceptional new large dimensions and unprecedented radiation level, while lepton detectors require high spatial resolution and very low material budget while radiation damage will be less a concern.

For the mechanics, this translates into competing requirements on minimum space use, complex geometries, low mass, high precision and high stability. Furthermore, the increasingly harsh environmental conditions for the hadron detectors will impose severe constraints on the materials used, as the detectors must remain stable and reliable while going through thermal cycles and absorbing significant radiation doses. Radiation levels will also drive cooling solution for the innermost detectors. While gas cooling at ambient temperature can be considered for lepton experiments, liquid or two phase cooling systems will be needed for detectors in hadron experiments to reach low temperature and limit radiation damage induced leakage currents.

Hereafter a selection of possible R&D activities is proposed:

- Activity 1: Low mass mechanical structures for future HEP Experiment
  - Task-1 Low mass mechanics for future Tracker Detectors
  - Task-2 Low mass composite cryostat for future HEP experiment: Calorimeters and Detector Magnets
- Activity 2: New detectors-infrastructure interfaces and services architecture for automated installation and maintainability
- Activity 3: High-performance cooling for future detectors

7.2 Low mass mechanical structures for future HEP Experiment

Low mass mechanics for sensors’ support and thermal management represents a major challenge for future tracking detectors that will have to cope with stringent requirement on material budget in the innermost layers and large surface coverage for the outermost layers. Whether it is to dissipate the heat generated by readout sensors and other electronic components, or to extend the service life of sensors in a radiation environment, integrated cooling will drive the structural design criteria.

In parallel, low mass mechanics for the reduction of cryostat thickness both for future liquid argon based electromagnetic calorimeters and for helium cooled detector magnets, shall be investigated by considering alternative production technologies and materials.

7.2.1 Task-1: Low mass mechanics for future Tracker Detectors

Low mass detector mechanics with integrated cooling systems have been developed and studied at CERN by the Detector Technologies group (DT) of the Experimental Physics (EP) department. In the framework of the upgrade programs for the Tracking System during the long shutdowns (LS2, LS3) different technologies have been investigated:

1. Cold Plates made of high thermal conductivity carbon fibre laminates embedding polyimide capillaries for water leak less system.
2. Cold Plates made of high thermal conductivity graphite-based material with metallic (titanium, stainless steel or copper-nickel) pipes for high pressure evaporative system
3. Microchannels embedded in silicon or polyimide substrate for vertex detector both for single-phase or two-phase cooling fluids.

The Cold Plate with polyimide capillaries (1) was chosen for a water leak less system and has been fabricated for installation in the ALICE ITS during LS2, while polyimide microchannel (3) was studied as alternative. The metallic pipe options (2) with evaporative CO_2 are being studied for both the ATLAS ITK and the CMS Tracker upgrades for LS3. The NA62-GTK has adopted the silicon microchannel (3) as a solution with liquid C_6F_{14} while the LHCb VeLo will combine the same technology with evaporative CO_2.

The use of CMOS and stitching technologies for silicon pixel chip sensors will open new opportunities in vertex detectors, in large area tracking detectors and in digital calorimeters: improved spatial and time resolution, reduction of power dissipation and lower material budget and large cost saving due to low production costs. A synergy with WP1 is foreseen to identify future technologies for inner tracking sensors.

In the innermost layers of future Vertex lepton collider detectors, the reduction of material budget and the mechanical stability should be pursued by:

- -eliminating active cooling and rely on air or gas cooling; possible for low dissipated power (<20mW/cm^2) and low radiation level, in lepton collider detectors.
- -minimizing active cooling material through new optimised micro capillary or peripheral cooling design, in lepton collider detectors.
- -eliminating on detector electrical substrate; possible if the sensor covers the full stave length (stitching) and connectivity is provided at sensor edge.
- -providing self-supporting sensors by exploiting the flexible nature of thin silicon (<50µm).

In hadron collider Vertex detectors stringent cooling requirements, on the removal of dissipated heat and on the minimisation of radiation damages, will require the development of new heat exchanger substrates to achieve better performance and lower temperatures. Additive manufacturing and other advanced manufacturing techniques will be studied for the fabrication of ultralight microchannel substrates. 3D printing of different materials including metals and ceramics engineered for CTE compatibility will be explored to overcome the limitations of present technologies.

The additive manufacturing techniques will be reviewed with respect to alternatives technologies based on carbon composite material, such carbon microvascular heat exchangers made of carbon fibre structures embedding capillaries (polyimide, low mass micro-pipes, …) for high pressure.

The use of graphene and carbon nanotubes, embedded in carbon composite materials to take advantage of the exceptional intrinsic properties of the nanoparticles, will be investigated in an attempt to enhance the mechanical and thermal properties of the composite materials.

For the outer layers of future trackers both for hadron and lepton colliders, the large areas, the costs, the assembly and the QA will drive the mechanics design choices.

A “lego” modular concept, based on a modular substrate, to serve one or a limited number of chip (stitched) sensors, will allow for single module test and replacement, while it will pose the design challenge in the module’s electrical and hydraulic interconnections. Additive manufacturing will be considered for both the heat exchanger substrates and fluidic interconnection.

Alternatively, the research of technologies that can be scaled to large areas without joints shall be investigated. Ideally a continuous structural/electrical/cooling substrate with a flexible shape, interconnecting 50µm MAPS shall provide a cheap fully integrated solution. Cheap and disposable substrate such as carbon fibre structures embedding polyimide pipes will be exploited.

At the same time the material investigation shall be extended to cheaper carbon composites that can be processed with cheaper processes for large detector volumes, especially relevant respect to the new detector dimensions; i.e. out of autoclave curing that represent a promising faster and more cost-efficient process.

Furthermore, organic materials used in composite mechanical structures will be exposed to unprecedented high radiation level in hadron detectors and will suffer from their loss of mechanical, electrical, optical and chemical properties as a result of accumulated radiation dose. Detailed investigation and qualification to radiation load shall drive the material choice. Carbon Fiber Reinforced Plastic (CFRP) materials, with different resin systems than epoxy, for high radiation shall be investigated, e.g. CFRP-Cyanate ester, CFRP-Cyanate Siloxane, CFRP-Polyimide, CFRP-Peek, thermoplastic prepreg.

In the context of the European project AIDA-2020, EP-DT is leading a Networking Activity focusing on "New support structures and micro-channel cooling" (WP9). This has granted a recognized leadership position to EP-DT, in particular in the field of micro-structured cold plates, which has allowed for effective synergies and has attracted external funds. The AIDA-2020 project will end in mid-2020 and a new large project prosecuting the scientific programme of AIDA-2020 will be submitted to a dedicated call in 2021. Following the good success of the activities conducted in WP9, a Work Package focusing on the extension of the same class of technical issues beyond HL-LHC is planned in the new submission. Internal CERN funds allocated to the R&D on these issues will again pose EP-DT in a leading position and largely facilitate synergies with external teams.

Potential additional co-funding schemes may appear as a result of the seeding effect on this Task and will be actively explored.
Examples are:

- the Collaboration Agreement signed between CERN and NTNU (the Norwegian Institute of Technology) where common interest towards advanced electronic thermal management technologies can be developed;
- the Marie Curie MSCA-ITN-2019 initiative, being prepared for a call in early 2019 to get PhD students at CERN, for a period of 3 years, on Additive Manufacturing R&D technologies.

7.2.2 Low mass composite cryostat for future HEP experiments:

Calorimeters and Detector Magnets

To meet the design goal for minimum radiation length, thus strongly reducing material wall thicknesses and mass of next-generation cryostats for detector magnets and calorimeter cryostats, Carbon Fibre Reinforced Plastic (CFRP) will be explored and compared to advanced metal or hybrid honeycomb structures. A synergy with WP3 and WP8 is foreseen to study the application of these new technologies to HEP detectors cryostat.

Liquid Argon (LAr) calorimetry is considered one reference technology for future Electromagnetic calorimeter (ECAL) because of its intrinsic radiation hardness and stability as well as the successful application in the ATLAS experiment. Development towards ultra-thin superconducting solenoid magnets for high energy particle detector is being carried out. Both applications are based on the need of a cryostat to guarantee the operative temperatures.

Both calorimeter's and magnet's cryostats have a toroidal geometry with cylindrical inner and outer walls. In the calorimeter, the cylinder of the cryostat's inner bore is the most critical, based on the requirement of minimum material in front of the detector. On the contrary, for the magnet the outer cylinder is the most demanding. Indeed, even if the requirement of minimum material applies to both inner and outer cylinders, buckling effects in the outer cylinder must be considered in the design, due to the vacuum inside the cryostat.

In order to fulfil the competing requirements of minimum wall thickness and high strength for the cryostat walls, composite materials shall be considered.

Cryostat for super-cold liquid fluid is still the purview of metals. But in order to decrease the thickness and material budget, lightweight and strong composite materials shall be considered. During years the concerns have been potential leaks, due to microcracking of traditional carbon/epoxy composite laminates at cryogenic temperatures. Microcracks can occur in any laminate because of the difference between the axial and transverse coefficients of thermal expansion (CTE) in each ply.

Similar application can be found in aerospace industry. The fuel tanks responsible for launching rockets into space have been metal for decades with major downside the weight. NASA has recently announced plans for new launch vehicles and crew exploration vehicle (CEV) that may use a pressure-fed propulsion system with incorporated composite tanks. The Composite Cryo-tank Technology Demonstration Project (CCTD) was part of the Space Technology Program and the Game Changing Development (GCD) Program for NASA. The development and demonstrations outlined in the CCTD Program were based on the relevant aerospace industrial experience over the last 20 years. NASA worked with four competing industrial partners—ATK, Boeing, Lockheed Martin, and Northrop Grumman during the design phase of the project. Four conceptual designs differing in materials, structures, manufacturing processes were assessed through coupon testing and finite element stress analysis. NASA selected a 5.5-m diameter demonstrator liner less tank in CCTD Phase II which has been manufactured by Boeing. The composite cryo-tank achieved 30% saving in weight and 25% in cost, compared with a baseline aluminium alloy cryo-tank.

In a similar way the Cryogenic Hypersonic Advanced Tank Technologies (CHATT) project contributed to significant progress in the design of composite tanks for cryogenic propellant applications in Europe. The project CHATT is a part of the European Commission’s Seventh Framework Programme. The main objective was to investigate carbon fibre reinforced composite material for cryogenic fuel tank applications. Four different subscale CFRP-tanks have been designed, manufactured, and tested. Cylindrical tank with liner by DLR (D=1m, L=3m); Cylindrical tank without liner by FOI/SICOMP (tubes several dimensions); Complex shape tank with liner by TU Delft (complex combined spheres shape); Dry wound cylindrical tank with liner by ALE (D=0.29m, L=0.57m).

Space X has designed, developed, and fabricated a composite LOx tank, which is a key component of interplanetary transport system (ITS). The tank is 12m in diameter and represents the largest composite vessel ever produced.

Therefore industry is developing composite tanks that offer great potential weight benefits for space applications. Given the great variety of approaches and materials under development, the future of these applications looks promising. The application in HEP detector should profit from this development and investigate how to tailor these new processes and materials for Detector application.

A close collaboration with Aerospace Industries and Institutes involved in the cryotank development programmes (NASA, ATK, Space-X, ESA, Airbus,..) shall be envisaged for technologies review, consultancy and production assistance.

Specific aspects of the emerging technologies that shall be investigated are listed here below.

- Investigate manufacturing process i.e. specific fibre placement technique and curing processes.

- ISFP, in situ fibre placement, which can produce net-thickness laminates, without the need for vacuum bag debulking or autoclave cure.
- UTL, new debulking ultrasonic method tape lamination to accomplish laminate consolidation. The ultrasonic energy provide excellent compaction while depositing the carbon fibre tapes.
- OOA, out of autoclave process, with a lower curing temperature, the resin system is suitable for vacuum-bag-only curing and produce the quality equivalent to the autoclave process, with minimum porosity and competitive mechanical properties. Improving the OOA materials architecture and fibre placement processes should reduce porosity, and eliminate permeability.
- Review and identify materials: microcrack-resistant fibre/resin system for towpreg (prepregged carbon tow) developed for cryogenic applications. Carbon/resin material systems, such as IM7/8552 epoxy, IM7/F650 bismaleimide and IM7/5250-4 BMI and Cytec's CYCOM 5320-1, a toughened epoxy prepreg resin designed for out-of-autoclave manufacturing of primary structure.
- Review and identify liner and permeability technical solutions
- Porosity can be limited by the use of a permeation barrier film. Liner-less tanks have been developed by working with a variety of carbon fibres in combination with toughened epoxies and cyanate esters. Thin-ply composite structures offer many advantages in composite tank manufacture. They are far more resistant to the formation of microcracks. Also, tougher resins have been developed that offer protection against microcracks (may be used in conjunction with the thin plies). Hybrid laminates are demonstrating the same performance as the thin plies. Excellent permeability results are achieved by both method.
- Review and identify thermal insulation: the broad classes of insulation systems to review include foams (including advanced aerogels) and multilayer insulation (MLI) systems with vacuum. The MLI systems show promise for long-term applications. Structural configurations evaluated include single and double-wall constructions, including sandwich construction. Lightweight, low-conductivity insulation is obviously necessary to maintain such a large temperature gradient.

Specific R&D programs shall be launched to develop design aspects peculiar of HEP cryostats design:

- Cryostat feed-trough
- Cryostat thermal insulation
- Cryostat interface to calorimeter or magnet and related loads
- Cryostat interface to the experiment
- Cryostat radiation loads

The validation of materials and technologies choices, based on production and characterisation of test samples, shall bring to the production of a scaled size cryostat Engineering model (about 1m3 volume) to demonstrate feasibility and to validate design choices and compare to advanced metal or hybrid honeycomb structures.

7.3 New detectors-infrastructure interfaces and services architecture for automated installation and maintainability

Design of present HEP detectors relies on optimized procedures such that installation, maintenance, repair and dismantling work does not lead to an effective dose exceeding ALARA (As Low As Reasonably Achievable) requirements.

Radiation levels in future hadron collider and radiation-cooling times will limit future operational scenarios, this should lead to revised detector design to account for shielding and remote opening/manipulation and access.
As an example, towards the end of the FCC-hh operation, the dose rate levels are around 1 mSv/h in the entire tracker cavity after about 1 week of cooling time, and the values do not decrease significantly for 1 month or 1 year of cooling time. This radiation comes mainly from the highly activated calorimeters, so the detector opening and the placement of shielding must be automated to a large extent in order to limit the dose for personnel.

In general, independently from the specific HEP experiment, new detectors must be designed to be easily maintained and possibly robot friendly to maximize detector accessibility and decrease personnel exposures to hazards.
Layout and interface to automated systems/robots for maintenance and early intervention should be foreseen at the design level. A new concept of detector-infrastructure interface and services connectivity to ease detectors remote handling will be key for the definition of the detector segmentation and accessibility.

The R&D program shall start from the identification of possible available automated/robotic solutions, compatible with the needs of future detectors, to drive the definition of their installation and maintenance strategies and bring to the identification of common automated platforms, mechanism i.e. manipulator systems. The focus of this program will be the design of the detectors interfaces to the automated Remote Manipulator System (RMS), and the design of the interfaces for services automated engaging and disengaging, Services Umbilical Mechanism Assembly (SUMA).

After the detector module/component extraction from the experiment by the RMS and SUMA, the possibility to intervene remotely, with an On Detector Robot Systems (ODRS), shall be as well investigated and interfaces to robot developed.

In addition the use of new advanced technologies like augmented reality, shall be studied to help in a fast and reliable identification of the intervention environment and decrease human exposure to radiation.

The validation of the identified robotic solutions and the development of the RMS, SUMA, ODRS will require the construction and setup of a laboratory: HEP Robot Lab.

Possible collaboration with CERN HSE for all aspect related to safety and intervention in Highly Activated Area, as well with CERN EN- SMM for sharing the know-how on mechatronics.

Possible collaboration with ETH Zurich Department of Informatics, Institute of Neuroinformatics, Robotics and Perception Group is being investigated.

7.4 High-performance cooling for future detectors

The cooling system for any Inner Tracking System in all collider detectors primarily has to remove efficiently the heat generated in the detector, typically dominated by the front-end electronics and some power dissipated in the active sensors. This defines the required cooling power and cooling system dimensioning. The investigation will be done in cooperation with WP1 and WP3.
In hadron collider detectors, the cooling system has the additional task of keeping the silicon sensors at a required cold operating temperature to limit radiation damage-induced leakage currents. Low temperature liquid or two phase cooling systems will be in particular mandatory for detectors in the future hadron collider experiments, due to the extremely high radiation levels expected. In these cases, also a possible implementation of SiPM's will be subject to the availability of deep cold (yet not at cryogenics level) cooling systems. The required operating temperature, the dissipated power and the thermal impedance between coolant and sensor will define the required coolant temperature.

On the other hand, cooling at ambient temperature is a viable solution for future lepton collider experiments, where extreme stability and material budget minimization are the most stringent engineering requirements. In this case, air cooling can be envisaged under certain conditions for detectors characterized by very low power dissipation, as recently demonstrated by the STAR detector at RICH. In parallel, active liquid cooling systems, operated at room temperature, with minimal impact on material budget, will be investigated for a more effective solution in complex or packed detector geometries.

The current state-of-the-art in hadron collider experiments is two phase evaporative cooling with CO_2 fluid for inner tracking detectors. Relevant experience and an important standardization approach to CO_2 cooling have been pursued through the collaboration among groups from different experiments, and a centralized CO_2 cooling service has been established in the EP department. Within few years the evaporative CO_2 has grown to be the baseline cooling technology for the HL-LHC detectors.
However, the operating temperature is limited by the freezing point of CO_2 (-55°C) and pressure/temperature losses in the cooling circuitry and in the cooling plant. For HL-LHC detectors the target "on-detector" evaporation temperature is -40°C, and a substantial lowering of this temperature does not appear feasible.

The next generation trackers for higher radiation levels, covering increasingly large surface areas and using higher channel densities, will require more powerful cooling systems and also lower coolant temperatures, probably well below -40^{o}C. In parallel, the requirements on low mass detectors will persist. Due to its intrinsic limitation on freezing point, pure CO_2 may not be a viable option anymore and replacements need to be found. Among these, CO_2/N_2O mixtures seem to be extremely promising, but basic studies about the boiling properties of these mixtures are still missing.

As a more general long-term perspective, the use of environmental friendly cooling fluid must be investigated. Hydrofluorocarbon (HFC) and Perfluorocarbons (PFC) are being progressively substituted in industries by hydrofluoroolefeins (HFOs) and Fuoroketons (FK), which have a very low Global Warming Potential (GWP). However, effective substitution refrigerants of new generation (in particular for very low temperatures) are still an issue of active R&D. All new synthetic refrigerants, above mentioned, will need to be qualified for application in future detectors, in terms of material compatibility and radiation resistance at the different levels required by lepton or hadron collider experiments. For these synthetic refrigerants R&D effort of EP will focus on the detector cooling requirements and thermal performance validation, while EN CV will be in charge of the fluids qualification.

This activity will in parallel produce a reduction of the total environmental footprint of detector cooling systems installed at CERN. As such, it would be reasonable to envisage a co-funding scheme via the CEPS. Furthermore, in the context of the collaboration just launched between CERN and NTNU (the Norwegian Institute of Technology), the part of work on natural refrigerants might also gain access to co-funding schemes from NTNU.

Identification of new coolants and development of the needed cooling units will be essential but not enough. Once the cooling power is generated at the proper temperature in the plant, the coolant has to be efficiently transferred to the detector structures. Cold transfer lines in hadron collider detectors need to be insulated from the surroundings and installed in congested spaces. In all cases, the large detector dimensions will call for an increased integration of the cooling system to minimise number of parallel lines. Minimal material budget pipework compatible with the selected refrigerant are also to be qualified for lepton collider detectors. New layout architecture shall be studied, jointly with the development of cheap and radiation hard sensors for pressure and flow readings on large number of instrumented lines.

8 Integrated Circuits (WP5)

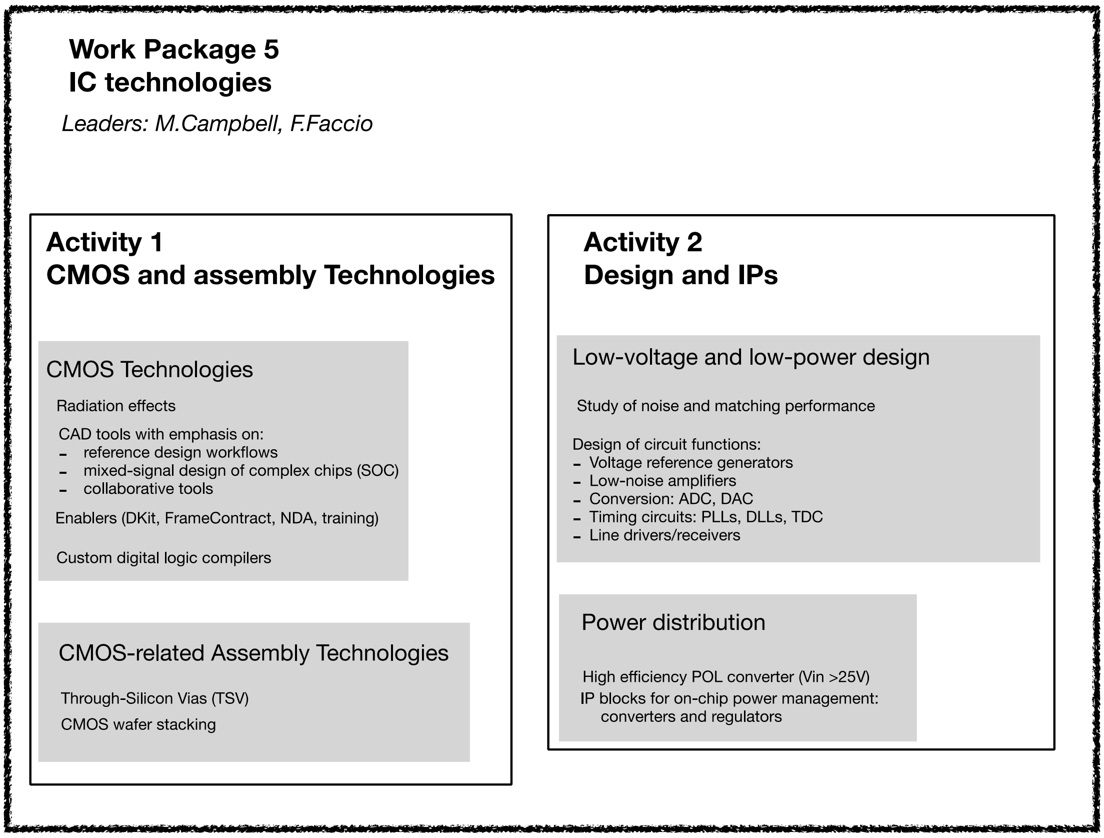
The High Energy Physics ASIC design community is currently designing in 130nm and 65nm commercial-grade CMOS technologies. Meanwhile industry is ramping up the production in 7nm FINFETs, and is developing prototypes in 5nm. ASICs for HEP should follow the microelectronics industry in order to benefit from the intrinsic density of more downscaled transistors and the also intrinsic high speed and lower power consumption. The need to follow industry is also motivated by the fact that these newer technologies only will surely be available in the future, whereas older process lines are susceptible to be discontinued. The new technologies present advantages but also challenges that have to be addressed in the context of an R&D activity:

- The newest technologies use 3-D geometries of transistors (FINFETs) that are new to the community, or geometries with discrete device sizes. This has an impact on (1) the electrical performance of the transistor, (2) its radiation hardness (3) its layout for manufacturability and (4) the usable design practices.
- Scaling the transistor dimensions is usually accompanied by a downscaling of the voltage supply to limit the electric field inside the physical device. This requires novel design techniques for signal processing that have been developed by industry.
- Downscaling has an impact on variability and noise (since the channel of the transistors is smaller, random dopant fluctuation from device to device, for example, can create a large mismatch). Moreover, the noise and mismatch parameters evolve with radiation.
- The cost of designs increases (in particular, the cost of the masks), making it essential to reach first working silicon.
- The complexity of the design kits also increases. As an example, the number of Design Rule Check rules (DRC) approximately doubles for every new technology generation.
- Computer Aided Design (CAD) Tools become more essential and more complex and require a specialization for their efficient use.
- Layout becomes more complex due to advanced lithographic techniques involved in the fabrication. Layout awareness by designers can improve the yield of the fabricated circuits.

Industry has also made very significant advances in assembly technologies, and our community has only marginally benefitted from them. The potential improvements to detector systems with the adoption of through-silicon vias or wafer-level bonding (wafer stacking) are enormous and certainly deserve a detailed investigation.

Last but not least, the opportunities for substantial improvements of our detector systems from these recent technologies can be fully exploited only by concentrating most of the system's functions in single and large ASICs, that become full Systems-on-Chip (SOC). These circuits also embed power distribution elements, and have to be designed by a large number of engineers that share a common platform via collaborative CAD tools.

To cover all these topics, the R&D work package on IC technologies is structured in 2 main activities, each composed by two themes as illustrated in the following chart.



8.1 CMOS and assembly technologies

This Activity is aimed at providing the HEP community with a solid infrastructure in state-of-the art CMOS technologies for the design of complex mixed-mode Application-Specific Integrated Circuits (ASICs), as well as for the assembly of these circuits in advanced electronics systems.

a. CMOS Technologies

A first detailed survey of the CMOS technologies available at the time of starting the R&D will be made, keeping into account the projected future long-term accessibility. This will include classic planar 28nm technologies and the more advanced FinFETs that replaces them ubiquitously as from the 16nm generation.

The technologies having been selected in this first survey will be evaluated to understand their natural radiation tolerance. The target radiation levels will be determined by the machine where the ASICs will be eventually deployed (CLIC, HE-LHC, FCC, …). This will lead to the choice of a mainstream and a backup technology for the future ASIC design. If necessary, special radiation tolerant design techniques will be developed to increase the radiation tolerance. While the detailed study of the radiation effects in the mainstream technology will continue, the infrastructure necessary for the design of complex mixed-signal circuits will be prepared.

The infrastructure includes the necessary enablers to access the technology in Multi-Project Wafer or dedicated engineering runs. The technology provider will be contacted to establish a commercial frame contract and the necessary Non-Disclosure Agreements to enable collaborative design work will be signed. This follows the model already very successfully used in our community in the last two decades.

Another necessary element of the infrastructure concerns the modern CAD tools enabling successful first-silicon design of even large Systems-On-Chip (SOCs, these are large ASICs embedding all the elements of a full system). Our community is just starting to use this type of tools, and still lacks the widespread competence – in particular for digital circuitry that represents the vast majority of the functions in modern mixed-signal chips and SOCs. Design teams working on such demanding projects obviously exceed the number of engineers in a single HEP institute, therefore the tools and culture for collaborative design have to be promoted.

To address these needs, a common Design Platform will be developed comprising of an integrated Mixed-Signal Design Kit, along with a set of well-established reference Design Workflows. The Mixed-Signal Design Kit will integrate the foundry Physical Design Kit with standard cell libraries to facilitate analogue, digital and mixed signal design. The reference Design Workflows will give the designers all the necessary information in the form of setup scripts, instructions and examples for using the Mixed -Signal design Kit to perform specific design tasks. Special attention will be devoted to the hierarchical digital back-end implementation workflow to enable the design of complex System On Chip ASICs. The development of the common Design Platform will be outsourced to industrial vendors specializing on this domain.

To facilitate the mitigation of radiation effects on the selected technology, dedicated radiation tolerant design techniques will be developed and elementary IP blocks (IO pads, ESD protection structures, SRAM memories, etc.) with enhanced radiation tolerance will be developed in collaboration with industrial vendors. Custom digital logic compilers will be developed to mitigated SEU effects that are expected to be particularly prominent in these very advanced technologies. Device simulation models with radiation performance parametrization will be developed to facilitate analog simulations with radiation performance degradation estimates. We foresee the need for the purchase of advanced EDA tools for standard cell library characterization, advanced design power analysis and SIP (System In Package) design. The acquisition of additional software license packages is also needed to enable processing parallelism and reduce processing times that are expected to be particularly high for complex SOCs.

To disseminate the technical information and expertise in our community, customized training courses will be developed and offered to designers in external institutes and universities. The courses will include advanced technology information as well as hands-on training in the use of the Mixed-Signal Design Kit and the reference Design Workflows. The development of these courses will be done in collaboration with industrial vendors.

At the end of the R&D phase, all this infrastructure will be maintained as core activity.

b. Assembly Technologies

Hybrid pixel detectors remain the detector of choice at the heart of the large general purpose LHC detectors and for the LHCb VELO upgrade. These detectors permit the use of the latest high-density CMOS processes which are combined with separate optimised semiconductor detectors to deal with the extreme rates foreseen in the innermost tracking layers (up to 3GHz/cm^2). The high component density of the latest CMOS processes permits, in the case of ATLAS and CMS, local hit storage at the pixel (or super-pixel) level and the selection of only triggered events for readout. In the case of the LHCb VELO, triggerless readout is required and the VELOpix chip is able to deal with a hit rate of up to 0.5 GHz/cm^2. Sensor substrates are optimised to deal with the very challenging radiation environment (up to 10^{16} neutrons/cm2 in the case of ATLAS and CMS). While there has been and continues to be impressive progress with monolithic pixels, hybrid pixels will probably continue to be necessary in environments where ultimate performance is required. One of the main arguments against the continued use of hybrid pixels is the cost associated with flip chip bump bonding of ASIC and sensor together. This cost is primarily driven by the lack of volume in production which precludes the savings associated with industrial scale processing. Bump deposition at the required pitch is carried out on fully processed wafers in specialised institutes and companies. Wafer dicing is followed by component picking and inspection, steps which are still done manually by operators. Flip chip assembly is carried out one chip at a time on a machine requiring manual supervision. Unless volumes increase substantially these costs are unlikely to drop substantially in the coming years. In the image sensor industry, a different approach - based on wafer stacking - is being used for high-end sensors. In these processes image sensor wafers are connected to CMOS readout wafers permitting assembly costs at a fraction of those of flip chip bump bonding. For the time being these processes are not accessible to our community. One of the medium term aims of this part of the work package is to start prototyping using these processes and ultimately to design a hybrid pixel detector. Note that this proposal would involve the use of industry standard processes with little or no modifications to the production steps.

The "assembly technologies" theme of WP5 will address specifically the 2 following issues:

- TSV processing of finished very fine feature size wafers in a way which is compatible with bump bonding will be developed. This is a topic which needs to be addressed as soon as the mainstream technology is chosen and a full wafer populated with a large chip becomes available. LHCb (or future detectors such as TauFV at SHiP) will require readout rates which can only be addressed by the use of TSV's to avoid the bottleneck associated with bringing all data to one side of a chip.
- Accessing one of the commercial wafer stacked CMOS lines is also a medium-term aim of this activity. To begin with, contacts will be sought with foundries and, if successful, test structures will be implemented to check the radiation tolerance of the sensor layers used. If the sensor is radiation hard (or can be hardened with little process modification) test chips can be implemented. It should be said that this activity is relatively high risk but also with a great potential to provide low cost high performance pixel layers.

8.2 Design and IPs

This activity is aimed at the design of circuit functions that are needed for the development of complex mixed-signal ASICs and SOCs, and of power management blocks.

a. Low-voltage and low-power design

The challenges associated to the adoption of more advanced CMOS technologies are addressed in this theme with the purpose of (1) evaluating ASIC technologies, (2) designing circuit building blocks and characterizing them on silicon, (3) encouraging the participation of other institutes from the HEP ASIC design community and (4) disseminating the know-how produced by this effort in order to maximize the probability of having first-time working silicon designs.

The detailed objectives are the following:

- Build-up experience in the use of the mainstream CMOS technology (selected in Activity 1, Theme 1) for analogue and digital design, and disseminate the know-how in the HEP community.
- Design and characterize the building blocks required in complex HEP circuits. Provide guidelines to the designers in the community (documentation/web site). A preliminary list of building blocks is shown below. The blocks are classified according to their functionality in existing circuits for HEP.

- Front-end:
  - Amplification, filtering and discrimination (A/D conversion) for 2-D readout circuits. (Charge sensitive amplifier, shaper and comparator for sensors with input capacitance <100fF and leakage current per pixel <20nA).
  - Amplification, filtering and discrimination (A/D conversion) for a 1-D readout circuit (strip detectors).
  - Input stage and discrimination for the readout of detectors with intrinsic amplification for timing layers (SiPMs, MCPs).
  - Voltage references.
- Module controller:
  - Analog to Digital Converter (e.g. with the sigma delta architecture), Digital to Analog Converters, Temperature monitor.
- Data transmission and timing
  - PLLs, DLLs, TDC.
  - Line drivers/receivers (the specifications of these blocks should be done in collaboration with WP6 (High speed links)).

b. Power Distribution

The complex SOC circuits that will be developed in the mainstream CMOS technology (selected in Activity 1, Theme 1) will be divided into different power domains, each with sub-1V supply voltage. Other components of the system, such as optical transceivers, might instead need larger supply voltages (2.5V). To satisfy the requirement for different voltage domains from a single higher-voltage line, a scheme that reduces the amount of cables from outside the detector, different power distribution circuits are needed. This theme is focused on the development of these circuits: a stand-alone DCDC converter rated for an input voltage of 25V or more, and IP blocks in the mainstream technology to be made available to SOC designers.

A radiation and magnetic field tolerant DCDC Point-Of-Load (POL) converter with a maximum input voltage of 12V has been recently already developed in a 0.35um commercial technology, and is being deployed in a large number of LHC detector systems. The availability of this old technology in the long run is not guaranteed at all, hence a more performant successor has to be developed in the near future. As a first step, the radiation tolerance of commercially available high voltage (HV) technologies will be measured to find the best match to the new HEP needs. These technologies can be based on Silicon (Si) or Gallium Nitride (GaN), where today the most important industry developments are concentrated. A particular focus will be addressed to the technologies allowing a larger input voltage, since ideally the new POL should allow for input voltages up to 25V, that would translate in a twofold reduction of the current in the long cables from the remote power supplies. It is expected that the technology investigation, leading to a choice, will take at least one year because it involves design and irradiation measurements of dedicated test structures. All radiation effects need to be taken into account: total ionizing dose, displacement damage and single event effects. Once the most suitable technology is chosen, several DCDC prototypes will be designed, integrated and tested (electrically and for radiation effects). The converter topology will be chosen to optimize the efficiency and total mass (size of the external components required), with a target conversion ratio of 25V to 1.8V-2.5V. The full development is projected to take several prototype iterations stretching for four years, due to the complexity in ensuring reliable handling of the large current commutation and robustness to radiation-induced damage in high-voltage technologies. For instance, immunity to Single Event Effect (no latch-up, no more than 10% change in the output voltage, no undesired power cycles) requires specific tests with heavy ion beams and often the help of pulsed laser beams to localize the sensitive nodes.

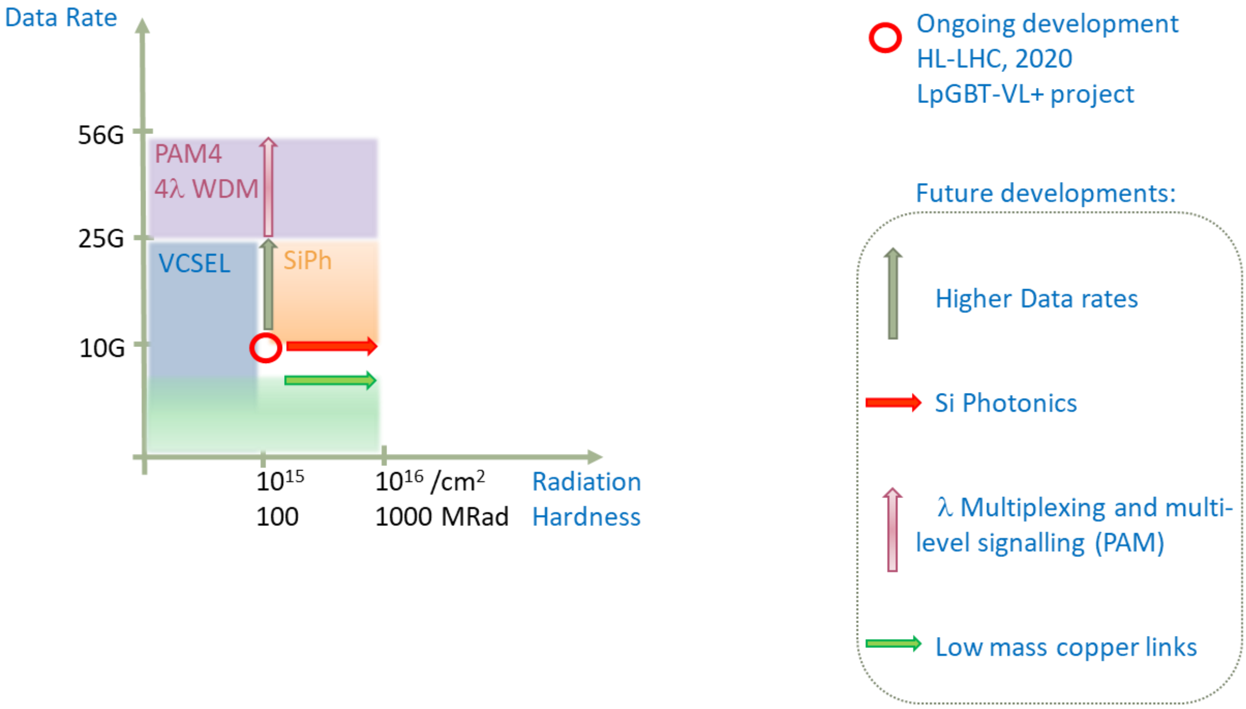
The second objective of this Theme is the development of a set of power IP blocks in the mainstream technology: fully integrated DCDC converters (capacitor and/or inductor based) and linear regulators. The DCDC converters will work as second stage, converting the 1.8V-2.5V from the first stage to the required voltage of the analog (1V) and digital (<0.8V) circuitry. The input voltage will depend on the available I/O transistors in the mainstream technology, and the converters will work at very high frequency to reduce the inductor and capacitor dimensions. Linear regulators can be useful as low-dropout elements to provide power to very sensitive circuit blocks. All these IP will be designed in the chosen mainstream CMOS technology, documented and made available to designers in the HEP community.

9 High speed links (WP6)

During the requirements gathering phase for WP6, three lines of R&D activities were identified: ASICs, FPGAs and Optoelectronics. These activities have the potential to significantly enhance the data-rate and/or radiation hardness of the data transfer systems which will be implemented beyond HL-LHC.

The Figure below indicates that data rates beyond 25 Gb/s (and multiples of this if using multiplexing schemes), and resistance to doses and fluences beyond 1 Grad and 10^{16} particles/cm^2 are possible targets for an R&D program on high speed links.

For reference, the ongoing LpGBT and VL+ development projects for HL-LHC are indicated with a red circle. This circle marks the hard limit of the technologies used today. R&D must take place to move away from this point and enable high performance links beyond HL-LHC.



9.1 Limitations of HL-LHC Data Transfer Systems and proposed further development paths

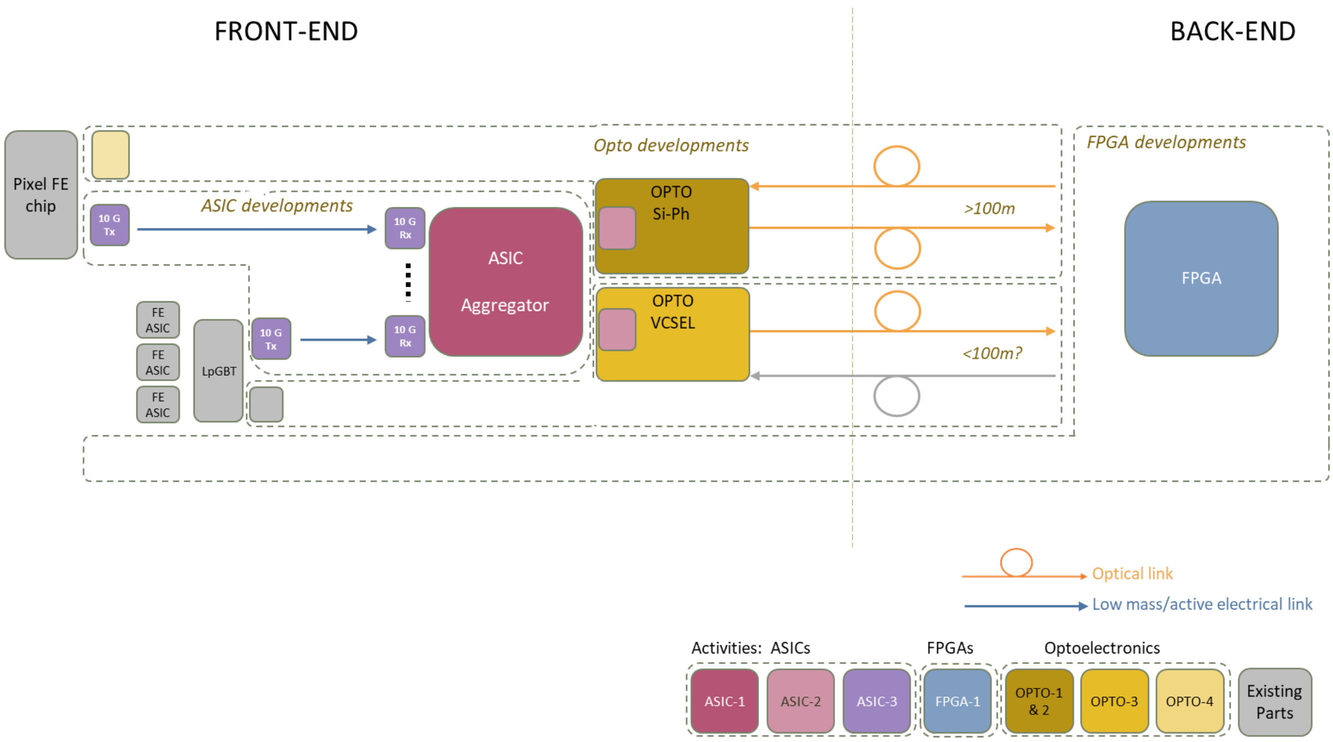
The links being developed for HL-LHC are limited in data rate to 10 Gb/s and their optical transceivers cannot survive fluences beyond 5×10^{15} particles/cm^2. This is problematic already for HL-LHC detectors where the pixel optoelectronics for instance has to be deported to the first strip layer (or above) leading to the use of massive lower-bandwidth copper cables. Another problematic example is the case of the CMS HGCal detector, where the huge amount of data to be shipped off-detector with limited link bandwidth will impose the installation of a large number of costly optical links.

Experiments in future accelerators will demand more bandwidth (especially when considering the trend towards triggerless readout systems) and in some cases higher radiation hardness.

The WP6 project will be generic, aiming at developing a limited set of technologies considered essential to build experiments beyond HL-LHC. They will target higher data rates and better radiation resistance. They will not result in chipsets or components dedicated to specific high-energy physics detectors, but rather in prototype ASICs and component demonstrators which will be designed and fabricated as building blocks for future targeted projects.

Three fronts must be opened to develop post HL-LHC technologies, articulated as three parallel activities in this work package: ASICs, FPGAs and Optoelectronics.

The figure below indicates how these three development lines (differentiated by colour) fit together to form a link transferring data between front- and back-end, building on the existing base of components developed for HL-LHC (LpGBT, LpGBT-FPGA and VL+, in grey colour).



9.2 Activities

Three development activities constitute WP6, as described in more detail below: ASICs (Activity 1), FPGAs (Activity 2) and Optoelectronics (Activity 3). ASICs and Optoelectronics activities (1 and 3) are broken down into tasks that constitute independent efforts while still relying on mutual synergies to produce the required development result. The FPGA activity (2) spans all of the ASICs and Optoelectronics activities as it will provide the basis for emulating and testing the functionalities targeted by the R&D program.

Activities and resources requirements are given for a 5-year time-span (2020-2025), but depending on resources availability a second development phase (2025-2030) will have to be considered. Tasks are numbered in order of priority (1 being the highest priority, for instance ASIC-1). “Low priority” is to be interpreted in the specific CERN-EP context (taking into account project history, in-house expertise, synergy with on-going activities, etc.) and not as a qualitative judgement on the value of the task (for instance ASIC-3 or OPTO-4). Link developments require parallel progress on all activity fronts. Thus, no priorities are set among activities; only tasks are prioritized within a given activity. The table below summarizes the tasks and their priorities.

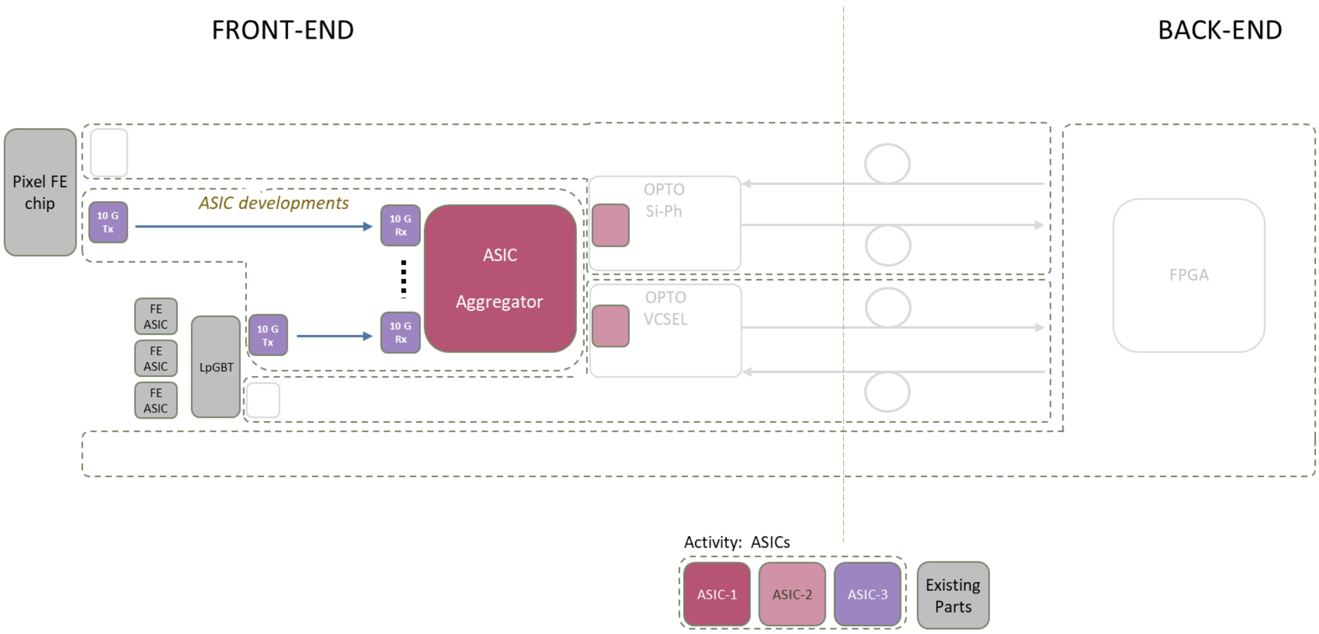
Activity	Task-Priority	Description
ASICs	ASIC-1	Very high data rate aggregator/transmitter
	ASIC-2	Optoelectronics drivers
	ASIC-3	Low-mass electrical cable transmission (active cable)
FPGA	FPGA-1	FPGA-based system testing and emulation
OPTO	OPTO-1	Silicon Photonics System & Chip Design
	OPTO-2	Silicon Photonics Radiation Hardness
	OPTO-3	Next-generation VCSEL-based optical link
	OPTO-4	Silicon Photonics packaging

For each task, an analysis was performed to check:

- If it is or can be (partly) covered in collaboration with partner institutes (see for instance ASIC-3),
- If it is or can be (partly) funded by other projects or CERN departments (see for instance OPTO-1).

Tasks were resource-loaded and prioritized taking the results of this analysis into account.

9.2.1 Activity 1: ASICs



Task ASIC-1: Very high data rate aggregator/transmitter

Feasibility study and design of very high data rate transmitters in advanced CMOS technologies. The project draws on the use of a 28 nm CMOS technology and aims at developing serializers, low jitter PLLs, 28/56 Gb/s PAM4 transmitters, pre-emphasis circuits and phase-aligners. This task will allow breaking the 10 Gb/s limit of the currently used 65 nm CMOS technology, it is carried out in cooperation with KU Leuven and SMU (TBC).

Task ASIC-2: Optoelectronics drivers

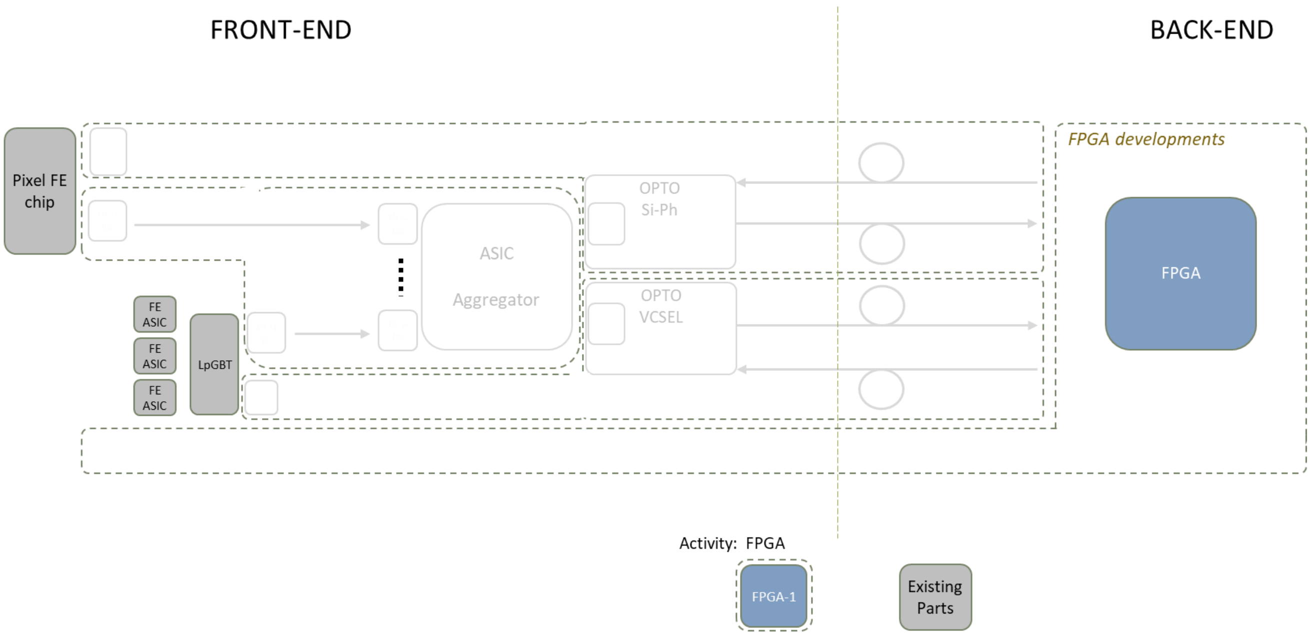
Feasibility study and development of very high speed driver circuits for VCSELs and Silicon Photonics Modulators in synergy with WP5-IC technologies, WP6-Opto-1 and WP6-Opto-3. This task will link activities 1 and 3, enabling demonstration of optical data transmission beyond 10 Gb/s. This task is carried out in cooperation with INFN and SMU (TBC).

Task ASIC-3: ASICs for low-mass electrical cable transmission (active cables)

Feasibility study of ASICs for high data rate transmission over low mass electrical cables. The study will investigate high speed signaling on low-bandwidth cables putting emphasis on the modulation format (possibly PAM4), pre-emphasis and equalization circuits. This task allows aggregation of multiple distributed data sources to one single high-data rate transmitter (task ASIC-1).

This development has priority 3 and is carried out mostly by collaborating institutes (TBD). CERN contributes to coordination, subsistence and submission costs.

9.2.2 Activity 2: FPGA

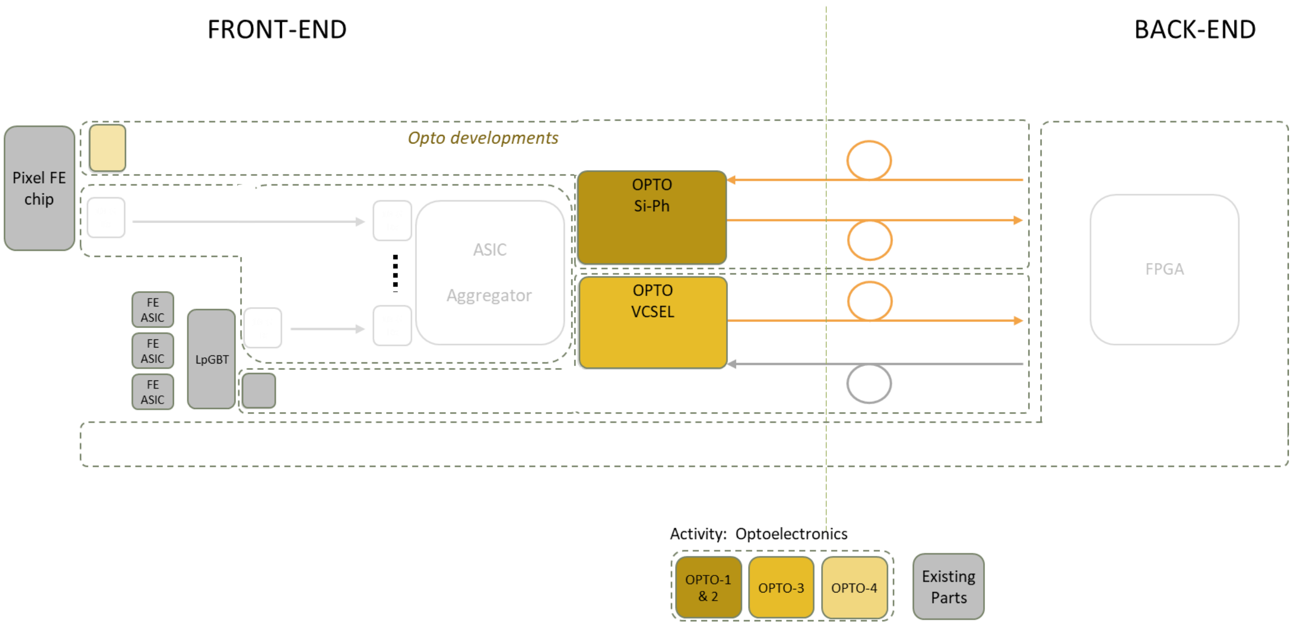


Task FPGA-1: FPGA-based system testing and emulation

Selection of FPGA-based hardware and development of code to perform high-level emulation of ASICs, functional verification of designs and testing of components and systems.

This activity spans across ASICs and Optoelectronics activities.

9.2.3 Activity 3: Optoelectronics



Task Opto-1: Silicon Photonics System & Chip Design

Investigation of system architectures and Si-Photonics components in order to design a front-end chip for a Si-Photonics based readout system. Such systems are of interest in particle physics experiments and accelerator beam instrumentation requiring higher bandwidth and radiation tolerance as well as lower mass and power consumption at the very front-end. This task must start as early as possible due to the prospective nature of this R&D, in order to assess technology feasibility and usability for HEP and keep time margin to investigate a fallback if necessary (for instance Opto-3 and ASIC-3). The potential benefit of silicon photonics technology is very big, but the challenges and risks need to be assessed immediately.

This activity is carried out in cooperation with INFN Pisa, KIT and CERN-BE (TBC).

Task Opto-2: Silicon Photonics Radiation Hardness

Investigation of radiation hardness of Si-Photonics components, based on existing components as well as potential new designs. Silicon photonics can possibly bring optics to the innermost detector areas thanks to its promising radiation hardness. This task will possibly break the radiation limits of currently used VCSEL-based links. It will be carried out in cooperation with Bristol University (TBC).

Task Opto-3: Next-generation VCSEL-based optical link

Investigation of feasibility of implementing up to 28G VCSEL-based links, possibly including CWDM (Coarse Wavelength Division Multiplexing) and/or PAM4. This will require understanding the technology limitations in terms of reach (is 100m possible?), radiation tolerance and associated penalties, voltage headroom in VCSEL driver, fiber transmission penalties, etc. This task investigates an evolutionary path complementary to Task Opto-1 and unlocks high data rates for very short distances. It however will not enable higher radiation resistance as the limits of VCSELs have been attained at HL-LHC already.

Task Opto-4: Silicon Photonics Packaging

Investigation and proof of feasibility for packaging Si-Photonics components in view of use in detector front-end systems. The major effort on this project will be staged to come later in the R&D program, should the technology be successfully validated. Nevertheless some packaging budget is necessary immediately to support the prototyping effort of other tasks and is included in OPTO-1 and OPTO-2.

Developing packaging solutions for photonic circuits is a challenging task as no mature and standard commercial solution is currently available which will match the compactness and low-mass requirements of tracking HEP detector. This workpackage must thus remain visible and ready to be activated as soon as possible in order not to jeopardize the development results achieved by other tasks.

10 Software (WP7)

10.1 Introduction

Software forms a critical part of the HEP programme, in the generation and simulation of physics events, in the data acquisition systems and triggers of the experiments, right through to the reconstruction and analysis phases. Future accelerators, such as CLIC and FCC, plan to increase physics reach through precision and higher rates. Software must be developed to support the lifecycle of the associated experiments, from design and conception to data taking, reconstruction and analysis. Support for these future physics programmes puts even greater demands on software than today, with greatly enhanced precision and event rates needed for simulation, combinatorial explosions for reconstruction in high pile-up environments and massive data volumes to be handled for analysis across our distributed computing infrastructure.

One of the defining features of the software landscape today comes from the gradual slowing of Moore’s Law and the stall in clock speed for microprocessors. This means that performance improvements for software have to solve two fundamental problems:

- to increase throughput, make more use of parallelism by running on multiple cores and utilising the wide vector registers that are available on modern hardware;
- to adapt to different processing architectures, such as GPUs and FPGAs, where performance gains in recent years have far outstripped those on traditional CPUs.

In addition, mass storage systems, which deliver our data to the processors have become far more hierarchical, and algorithms and processing frameworks need to adapt to the new characteristics of solid state storage, which is quite different from magnetic disks. All these problems are intimately linked as they often require fundamental re-design of algorithms from traditional serial implementations. In addition to this change to the core of HEP software, the way in which HEP processes data in heterogeneous and geographically dispersed computing centres needs to adapt to the anticipated rates and technology changes we expect in the future. These problems are covered in some considerable detail in the HEP Software Foundation’s Roadmap for HEP Software and Computing[9].

Software support for new experiment concepts needs to be available from the start of the design process. This requires the integration and testing of many pieces of software from the HEP community and the wider open source world that in itself is a vital and non-trivial support task for all R&D activities, akin to laboratory facilities for hardware R&D.

In undertaking all of this software R&D work we adapt to, work with and integrate developments in industry and other scientific communities. E.g., in the field of Machine Learning (ML) where many exciting new techniques will be important for HEP.

We propose five activities which are software R&D topics in critical areas for CERN’s scientific programme and an additional activity to provide turnkey software stacks to support future experiments.

[9] A Roadmap for HEP Software and Computing R&D for the 2020s, The HEP Software Foundation, https://arxiv.org/abs/1712.06982.

10.2 Faster Simulation

Monte Carlo event simulation is a vital tool for the design, construction and running of any high-energy physics experiment. The computing resources needed to produce the required amount of simulated data are growing with the energy and the luminosity of the particle accelerators and are starting to exceed the available computing budget. Without enough Monte Carlo statistics, the accuracy of the physics analyses will decrease, cutting into the sensitivity to find new physics. Already for the Run 3 of LHC, the simulation demands for some of the LHC experiments will require an order of magnitude speed-up of the simulation applications and this number will only increase for future accelerators like HL-LHC and in particular the FCC and HE-LHC studies.

There are ongoing R&D activities that aim to explore the possibilities of 'vectorisation' of the particle transport code by grouping particles together and applying vectorised processing available on modern processors. It is becoming clear now, however, that those techniques will not be sufficient to provide the necessary performance increase. Currently the only known way to achieve the required simulation capability is to use different techniques where traditional particle transport is totally or partially replaced by parameterisations. The experiments are developing 'hybrid' simulation solutions where different parts of the Monte Carlo production chain are replaced by other methods, trading some precision for CPU performance. This can extend from substituting single computationally heavy tasks in the full simulation with faster solutions up to performing the simulation, without traditional particle transport, of the entire detector.

Traditional parametric simulations are 'hand written', detector- or particle-specific and are typically derived from test beam data or from single-particle detector responses simulated in Geant4. Data generation is an active field of research in Machine Learning (ML). In the recent past, several techniques have been proposed to train generative models, i.e., neural networks capable of learning the main features of a dataset and producing new examples similar to those provided for training. Thanks to these promising technologies new possibilities have emerged, where trained neural networks take the place of computing-intensive stages of HEP event simulation with much faster inference procedures. The use of ML techniques can range from replacing some CPU-intensive calculations, such as sampling from complex probability distributions, full (sub)detector response simulation, the replacement of the entire simulation and reconstruction steps with a neural network, or even direct production of analysis relevant quantities. The R&D activity in some of these directions has already started and is showing very promising results. In order to be useful to future experiments, however, these early results have to be developed into reusable software components with well understood systematic uncertainties.

We plan for three work packages that can deliver new, break-through solutions: detector response simulation, combined fast simulation and reconstruction, and fast parameterisation of CPU-intensive physics processes.

10.3 Reconstruction for High Particle Multiplicity Environments

Event reconstruction in p-p collisions at high luminosity (HL-LHC, HE-LHC and FCC-hh with a pile-up of 200 and more) or in a high multiplicity heavy ion environment suffers substantially from increased event complexity. Due to its combinatorial character, track reconstruction is the most compute-intensive part. The foreseen vertex density often hinders the separation between particles stemming from the primary hard-scatter vertex and pile-up vertices when using current algorithms. In addition, calorimeters have to adopt a high granularity design in order to withstand the harsh radiation levels and disentangle the signal event from the very large pile-up background.

New detector types for tracking and calorimetry are being developed and will require updated reconstruction algorithms. The next generation of time-based tagging of particles paves the way for a broader usage of timing detectors for a future FCC-hh detector, where vertex reconstruction, and potentially calorimetry, could heavily rely on timing detection devices. Recent developments (e.g. ATLAS dense environment and CMS “jet core” tracking) are making progress in particularly pile-up environments like those expected at HL-LHC and FCC-hh. However, they are computationally infeasible on the full phase space. This necessitates physics- and/or environment-driven track reconstruction setups in the future: e.g., special disappearing track search and dense tracking algorithms in a region specifically triggered or identified by a targeted analysis.

Serial processing on single cores is not a cost-effective solution for the event complexity and data rates of future experiments. Parallel processing and hardware acceleration can increase the event throughput. R&D for concurrent reconstruction algorithms can be decoupled from detector specifics to a certain extent and can thus be done across experiments. This will prevent duplication of work on general questions regarding algorithm feasibility, data structures and appropriate software patterns.

While concepts and examples exist for intra- and inter-event parallelism (e.g. CMS framework) and GPU usage for the reconstruction in pre-defined detector regions (e.g. ALICE HLT), several problems, such as the ambiguity solving for geometric decomposition remains largely unsolved. Vectorisation in track reconstruction is particularly difficult due to its branching character. Domain decomposition must support data-driven dynamic processing of, e.g., dense regions with special algorithms.

For highly granular calorimeters (HGCAL), naive reconstruction algorithms exploring many combinations among all possible paths are expected to fail at the anticipated event complexity, due to combinatorial explosion. New techniques and algorithms spanning several fields – from computation geometry to clustering, machine learning, graph theory, and modern computer architectures – must be planned and designed, taking into account the information from the surrounding tracking and timing detectors.

Objectives of this R&D line include both advances in reconstruction software to exploit modern parallel hardware, as well as the adaptation to new detector concepts which are particularly designed for the high particle multiplicity. The following tasks would be performed over the time of 5 years:

- Identification of common algorithms and subprograms suited for vectorisation, parallelism, and GPU usage, development of a prototype and a reference implementation including appropriate data structures.
- Development of a generic library that implements several clustering algorithms in a concurrent form.
- Development and formulation of the mathematical framework for 4D detectors (including timing) and 6D track model, transport and fitting. Extension of the current Kalman-based track- and vertex fitting approaches with time information.
- Implementation of a testbed for concurrent tracking with timing information. Parallel ambiguity solving for concurrent tracking and use of vectorised backends for geometry and linear algebra.
- Development of dynamic, physics driven domain decomposition of the problem for parallel processing so that algorithms and compute time can be assigned according to the multiplicity and event complexity in individual detector regions.

- Extension and application of tracking concepts to HGCAL reconstruction.
- Validation and optimization of prototypes with software for HL-LHC, CLIC or FCC-hh.

10.4 Efficient Analysis Facilities

Analysing collision data efficiently is essential for HEP. Since the LHC start-up, the time needed between datasets' arrival and the delivery of scientific results was greatly reduced. Analysis software significantly improved and approaches to analysis were streamlined: for example, analysis trains were introduced by experiments to combine analysis steps from different users and execute them together, reducing access to the same input data. Nevertheless, such improvements will not be sufficient in the future. Detectors at future hadron colliders will lead to one to two orders of magnitude data rate increases and a veritable escalation of data complexity. The increase poses an unprecedented challenge to the HEP data processing chain. The question of how to analyse data volumes at the HL-LHC and FCC-hh scale is not yet answered and is crucial for the success of these endeavours. What is clear is that future complexity cannot be handled by requiring more advanced programming skills from researchers. Already their time and focus are dissipated understanding how the analysis should be implemented in code rather than what steps are needed for an optimal study.

The EP department already has significant expertise in software development, I/O patterns of large datasets and high throughput analysis. Building on this knowledge we would undertake R&D in three specific areas: increasing the data reading rate; developing programming models that boost scientists' productivity; helping to design specialist *Analysis Facilities* specifically targeting this workflow.

We would embrace a filesystem-less approach that evolves the way HEP data is read today. Complementing the concept of dataset as an ensemble of files, it proposes object storage, a data architecture widely adopted in the Big Data industry for its reliability and lower cost. Moreover, its flat organisation and scale-out model are an excellent match for the expected increase in data size. Stored objects will represent batches of datasets' rows and columns, the content of which will be managed by the ROOT I/O subsystem. Such a granularity allows one to provide just the needed data to a certain analysis being executed, also in parallel, without looping over (or worse, transfer over the network) entire files just to read a small portion thereof.

Following Function as a Service (FaaS) and functional programming principles, an analysis facility would deliver a framework to express analyses as chains of high-level operations or functions such as filtering, histogramming or calculation of derived quantities. Uncomplicated access to the Analysis Facility is assured both through traditional means (e.g. interactive login) and modern ones such as web interfaces. These interfaces assist explorative, interactive programming as well as the submission of analyses that are grouped into structured wagons to be organised in analysis trains. Well-designed interfaces also enable to dynamically plug-in resources, such as clusters or heterogeneous accelerators, to optimise the execution of CPU-intensive analysis-related tasks such as fits or neural networks' training.

The full potential of these developments is maximised by a tight integration with existing computing farms. We would deliver a library to distribute computations on the Analysis Facility, supporting both interactive and train modes. This latter approach is evolved not only to avoid replicating data accesses but also to eliminate replicated work such as filtering. In addition, based on data popularity at an overall farm level, caching of datasets or parts thereof can be exploited.

10.5 Frameworks for Heterogeneous Computing

Due to the higher event complexity and increased throughput, the next generation of HEP experiments will require significantly more computing resources than today. To achieve the expected processing throughput within an acceptable budget, it will become mandatory to take a "heterogeneous computing" approach, coupling general processing CPUs with more efficient devices (GPUs, FPGAs, others) running dedicated workflows. In fact, this is the direction that national laboratories and supercomputers are taking, in order to achieve "exascale computing" capabilities. To take advantage of these resources - whether within dedicated centers like HLT farms, or opportunistic resources like national labs - the next generation of experimental frameworks will need to support integrating resources of different types within and across compute nodes. Failing to solve this problem will condemn HEP to CPU only processing and severely limit our physics reach.

In this R&D line, we will develop a toolkit for heterogeneous computing that will allow existing HEP experiment frameworks to integrate accelerator resources and to address key questions of efficiency and robustness. The most general and flexible model for component interaction is to use the message passing pattern, so as to retain an abstraction that allows adaptation to specific (as yet unknown) hardware types and to different experiment software. Decoupling the processing into individual components as a set of “microservices” is a popular paradigm that matches industrial trends; importantly this offers flexibility in scaling these building blocks to be task specific or to control whole nodes.

When processing clusters consist of different types of hardware, not all of which can run every algorithm, using the resource pool efficiently becomes a challenge. The data driven message-based approach allows connecting components with different latency and throughput profiles: for example, messages can be batched by a pre-processor to provide suitable work units to a device, which amortizes the costs of moving data. We anticipate scheduling along multiple processing paths to match the resource profile, e.g., process on a fast GPU if it is available, and fall back to a CPU if the GPU is busy. This flexibility helps avoid stalls and bottlenecks. To achieve good performance in such an environment, it is imperative to avoid global synchronization as much as possible. In a later stage of the R&D line we will extend the problem of scheduling against a fixed resource (like an HLT farm) to the problem of provisioning from a flexible resource pool (such as a cloud-based interface). This solution needs to be tested and developed for throughput efficiency and to respect resource limitations, such as memory exhaustion.

Monitoring needs to be built into the system from the beginning. It must be possible to establish the health of the system and to optimise performance by providing inputs to the scheduler. Likewise, the system’s design should not assume success: workflows must be available to cope with failure without human intervention, minimising data loss at acceptable processing costs.

This R&D project will have a close relationship to the algorithmic studies in the Reconstruction and Simulation R&Ds, that develop code that can run on accelerator devices. It will work closely with the experiments to ensure that developments can be integrated into existing software frameworks (usually task based) that manage processing components, such as CPU based multi-core servers.

10.6 Multi-Experiment Data Management

The anticipated growth rates of experimental data in the future greatly exceed the infrastructure growth rate from technology alone. Alongside the already prodigious data volume increases for HL-LHC, new experiments such as SKA and DUNE will share this data volume challenge and likely much of the storage and network infrastructure used by the CERN experiments. At the same time many smaller communities and experiments do not want to lose efficient access to these same resources. Thus a more dynamic shared use of the available storage and network capacities is needed, which is able to orchestrate, synchronise, and adapt itself across multiple experiments with competing usage patterns.

Data management has been strongly experiment-specific up to now, but will need a solution with a similar common approach as computing. We propose this R&D effort to ensure fair use of available resources across multiple experiments and to give the software applications and frameworks the possibility to make better use of the available resources. This problem has been extensively reviewed within the HSF and WLCG and put forward as an important challenge for the long-term developments in HEP computing and beyond. The experiment software groups in EP have spearheaded these data management developments with products such as Rucio, DIRAC, and AliEn.

For efficient data management across experiments there are two main objectives that need to be achieved: throughput guarantees and latency hiding. For throughput, the experiments will get the novel possibility to dynamically claim storage and network for their workflows, with estimations on satisfiability and deadlines to reduce resource inefficiencies. The system will arrange the requests for data lifetime and data movement within these claims and schedule the necessary actions on the underlying infrastructure with respect to all experiments' requirements. If free resources are detected, experiments will gain the ability to get access to overflow data and network allocations, which would otherwise be inaccessible to them. The second metric, latency, targets users doing interactive analysis of experiment data, which interleaves with the organised data activities. The ad-hoc delivery of smaller size data products to analysis facilities happens on the same networks that are configured for the scheduled, high-throughput streams. We propose to integrate the storage and network infrastructure with the projected analysis activity to dynamically pre-empt resources and automatically adapt path routing for under/over-capacity networks. If these workflows are taken into account in advance, then their required data can be delivered and cached favourably to increase physics analysis. Especially the transport from data archives on cost-effective tape systems to high-throughput analysis-level facilities will benefit greatly. This will require interaction with the software frameworks, applications, and the infrastructure layers, thus there are strong links to other software R&D lines.

10.7 Turnkey Software Stacks for Future Experiments

Detector studies for future colliders critically rely on well-maintained software stacks to model detector concepts and to understand a detector's limitations and physics reach. These software stacks resemble the offline software of a running experiment, including event generation, detector response simulation, reconstruction algorithms, analysis tools, and distributed computing resource management. In contrast to the software suite of running experiments, detector studies tools must be lightweight and be able to rapidly adapt to detector design changes and varying collider conditions. Moreover, the software must handle a wide range of detail during the detector development lifecycle, from first estimates based on a coarse-grained geometry during the inception phase to detailed physics studies using sophisticated reconstruction algorithms on simulated event data.

Existing experiment software stacks, such as the LHC experiment frameworks, are highly customized to a specific experiment, which makes them complex to operate and maintain and too difficult to reuse with the much more limited computing effort available to the study groups for future detectors. Individual HEP libraries, on the other hand, solve particular problems, such as geometry description, track reconstruction, or data serialisation and plotting, but still require significant effort to integrate into a stack that can be used by an experiment. This lead in the past to the creation of multiple independent solutions, which are quite pragmatic, but non-optimal and incomplete. An example at CERN is the CLIC software based on the software used for the ILC studies, and the FCC software which has its origin in the software of the LHC experiments. While both of them tried to share as many components as possible, there is a significant duplication of effort.

The goal of this project is the development of a single turnkey software stack that can be used for the detector studies of both FCC and CLIC communities. A large challenge is in identifying a maximum subset of detector-independent data structures and algorithms, in particular in identifying common parts of the event data model, which is a precondition for applying common reconstruction algorithms. A practical approach is required towards documentation, software dependencies and detector-specific plugin interfaces such that a low maintenance stable software core is readily usable for established and new detector study groups.

In a first phase of this project the existing software stacks used by the CLIC and FCC study groups should be streamlined and merged. In a second phase, the resulting software stack should be prepared for reuse by new detector study groups. A third work package should investigate currently used data management and resource scheduling tools and attempt to integrate them with the offline software stack. This project will establish and maintain close relationships to the development teams of various HEP libraries and tools inside and outside CERN EP as well as to the CLIC and FCC development groups. A full software stack used by detector study groups is an important complement to targeted software R&D efforts insofar it provides a realistic test bed for novel methods and algorithms.

11 Detector magnets (WP8)

Detector magnets and magnet systems are key components of future experiments. The following table summarises the current main design parameters of magnets for future general purpose experiments. The parameters of the existing central solenoids in ATLAS and CMS are given for comparison.

Table: Magnet parameters, general purpose experiments at present and future colliders

Collider	FCC-hh	FCC-hh	FCC-hh	FCC-ee	FCC-ee	CLIC	LHC	LHC
Detector concept	baseline	baseline	alter-native	IDEA	CLD	baseline	CMS	ATLAS
Magnet type	central solenoid	forward solenoid	forward dipole	central solenoid	central solenoid	central solenoid	central solenoid	central solenoid
Location w.r.t. calorimeter	behind	N/A	N/A	in front	behind	behind	behind	in front
B-field (T)	4	4	4 Tm	2	2	4	3.8	2
Inner bore radius (m)	5.0	2.6	N/A	2.1	3.7	3.5	3	1.15
Coil length (m)	19	3.4	N/A	6	7.4	7.8	12.5	5.3
Current (kA)	30	30	16.6	20	20 or 30	~20	18.2	7.7
Current density A/mm2	7.3	16.1	27.6	??	??	13	12	
Stored energy (GJ)	~12.5	0.4	0.2	~0.2	~0.5	~2.5	2.3	0.04
Mat. budget incl. cryostat				~1 X_0		<1.5 λ		
Cavern depth (m)	≤ 300	≤ 300	≤ 300	≤ 300	≤ 300	~100	100	~75

In order to cope with the partly tremendously increased requirements, challenges in different domains need to be addressed.

Five work packages have been defined in Working Group 8 to cover Detector Magnet R&D for future Experiments. They are presented successively:

8.1: Advanced Magnet Powering for high stored energy detector magnets,

8.2: Reinforced Super Conductors and Cold Masses,

8.3: Ultra-Light Cryostat Studies,

8.4: New 4 tesla General Purpose Magnet Facility for Detector Testing,

8.5: Innovation in Magnet Controls, Safety & Instrumentation.

11.1 Advanced Magnet Powering for high stored energy detector magnets

Detector magnets of the next HEP Experiments generation, such as the ones for CLIC and FCC, will be installed in specific environments and infrastructures that significantly differ from those of past and present HEP experiments. We see deeper experimental caverns in the range of 300 to 400 m underground, specific garage positions for detector maintenance, much larger dimensions, much large stored energies and magnet operating currents up to 40 kA.

Therefore, new developments are necessary for the powering and associated cooling circuits of these future detector magnets. Studies shall lead to understanding and defining the new technical requirements in a broad approach beneficial for the various HEP projects where CERN is involved.

Demonstrated and fully qualified technical solutions have to be made available for powering these superconducting magnets in both a stable and a sustainable manner, fulfilling requirements of magnetic field stability and magnetic field availability for data tacking during physics runs, while minimizing energy consumption in an effort to be more economical and ecologically sound.

In this perspective, an R&D program has been defined to address the following issues considered essential for achieving better magnet system performance:

1) Compact and Fast Protection Current Breakers;

2) Free Wheel System (FWS) limiting magnet charge cycles and allowing faster recoveries;

3) Persistent Current Switch (PCS) allowing large energy savings and less magnet down time;

4) Compact, high performance Quench Protection Dump Units;

5) Maximum Energy Extraction Studies allowing much faster magnet recovery;

6) Cryogenics HTS Current Bus Lines allowing remote on-surface powering.

Ad. 1, 4 and 5. Superconducting magnets for future detectors will have 10 to 20 GJ stored magnetic energy and large inductance. The powering and quench protection circuits have to be engineered accordingly. Magnet and superconducting lines protection studies shall demonstrate technical concept and their requirements to find answers to these challenges. Few issues are critical and shall be developed: (1) New compact fast protection current breakers (common effort with TE/MPE); (2) Compact High-Performance Quench Protection Dump Unit; (3) Maximum Energy Extraction studies.

Ad. 2. The feasibility of free wheel systems will be studied and the technical requirements defined. The free wheel mode shall allow minimizing the downtime of the magnet, leaving the possibility for intervention on magnet sub-system while the magnet stays energized. The availability of a free wheel mode shall also extend operational time at nominal field to ensure magnet availability for physics runs over the entire accelerator lifetime, and to preserve the lifetime of the magnet by limiting the mechanical cycles induced by stress due to magnetic forces when the magnet is energized.

Ad. 3. In addition, the feasibility of a persistent current switch is assessed, in particular for what concerns both the magnetic field stability necessary for the detector operation, and the aspects of stability and protection for high current applications up to 40 kA. Both low-temperature superconductor and HTS shall be envisaged at the study phase to define the technical requirements in order to converge to an optimal solution. A high-current switch towards persistent mode is developed, with a design that can be adapted to future magnet configurations. This development will make it possible to avoid ohmic loss and associated running costs in the normal conducting bus lines, which may go up to 1 MW level.

Ad. 6. Superconducting magnets for future detectors in 350 m deep caverns will be cooled and energized from the surface requiring availability of proven technical solutions for 400 meter long and vertical superconducting links, a combined cryogenic helium line and 40 kA class superconducting current feed and return lines. Flexibility of such combined lines shall be assessed and demonstrated. The task is to design such a combined busbar/cryo-line cooled by the helium gas supplied from the return line of the magnet coil cryo-circuit, including its implementation, and show with a representative demonstrator its feasibility and safety for incorporation in the detector magnet's electrical circuit. The design may be based on ReBCO CORC high temperature superconductor, which is affordable in this case, like in current leads, due to the limited length. It is noted though that the technical requirements for the superconducting links for a detector magnet are essentially different from those powering accelerator magnets using energy extraction within seconds. For detector magnets the link has to survive the magnet ramp down time ultimately with very little or no cooling for 2 to 5 hours. The up-to 40 kA HTS bus line design will benefit from recent developments lead by CERN-TE department for the 18kA HTS power lines.

Maintenance requirements of these systems (FWS, PCS, cryo feed lines, protection circuits) shall be identified in the studies, in view to understand the intervention times and the associated overall downtime of the future detector.

11.2 Reinforced Super Conductors

The next generation detector magnets will require very high yield strength Al stabilized and reinforced NbTi/Cu conductors. Examples are magnets for CLIC, all variants of FCC.

This need is not only expressed for large bore high field detector magnets, but also for detectors with the design goal of a 2-4T solenoid cold mass with a radiation length less than 1 X0, allowing a few centimetres of Al alloy in cold mass and conductor only. In addition, the solenoid support cylinder needs to be minimized or even suppressed. The technology is relevant for any new detector with a solenoid positioned inside the calorimeter, such as LHeC/FCC-eh or the FCC-ee when using the IDEA detector concept.

Seriously considered is using an Al-Ni doped co-extruded NbTi-Cu cable, reinforced by welding with high yield strength Al alloy of the 7000 series, as for example Al7068.

The project comprises the mechanical designs of cold mass and conductor, quench dump studies, conductor development including friction-steer and electron-beam welding exercises. Short conductor demonstrator units will be made and tested to qualify them for use in the magnets.

A first EP iteration on reinforced conductor extrusion was performed in 2011 with little means. This shall be continued, first with the material remaining at CERN, then at a later stage by purchasing new materials. Some constraints are expected on the amount of material to be purchased as the manufacturers can only supply raw materials above a minimum threshold quantity, for production reasons. As a first step, only reinforcement material shall be purchased for welding and metallurgic characterization tests. These tests will provide the mechanical, electrical and microstructural characterization of the welding procedure. Tests on samples shall be done at room temperature and 4K.

The R&D program that will be established shall identify and propose manufacturing routes, in view to produce sample lengths with industry that can be adapted for scaling up to production for future detector magnet conductors.

The reinforced conductor studies shall therefore cover:

1. Design of high strength reinforced conductors, in combination with quench studies,

2. Conductor demonstrator manufacturing and testing, mechanical and SC properties,

3. Cold mass design: minimum thickness support cylinder, new thin cooling circuits, cold mass supports and electrical connections.

11.3 Ultra-Light Cryostat studies

To meet the design goal for minimum radiation length, thus strongly reducing material wall thicknesses and mass of next-generation cryostats for detector magnets and calorimeter cryostats and in-detector structures in general, carbon fibre reinforced polymeric-based composites will be explored and compared to advanced metal or hybrid honeycomb structures. Technology, and materials development of cryogenic fuel tanks will be incorporated. Thin-ply hybrid laminates and out-of-autoclave curing are projected as candidate materials and process. A table top demonstrator will be built. This study will be coordinated by WG4, based on the technical requirements provided by WG8.

The technical requirements will cover the vacuum tightness, the loads applied to the cryostat, the dimensional tolerances, the surface state, the ageing effects, and in particular the resistance to radiation, chemicals, mechanical impacts.

The requirements concerning the feedthroughs for the cryogenics, the power circuit and the instrumentation cable connections shall be established, together with the support system of the magnet and its thermal shields.

The study shall also cover the assembly scenario of the coil into the cryostat, in particular it shall specify the support points of the cryostat for its transport and handling during insertion of the coil and thermal screens. Technical requirements and solutions for the support of the fully loaded cryostat in the detector shall be established, together with other detector loads that can be added to the cryostat.

11.4 New 4 tesla General Purpose Magnet Facility for Detector Testing

The new cutting-edge high-energy particle detectors of the future accelerators have to work in 4-T magnetic field. For testing detector units and performing calibration with magnetic field, a general purpose 4-T test facility is required and will replace or complement the outdated systems available at CERN's North area. The magnet shall be installed on a beam line and the facility shared among collaborations to which CERN is contributing.

The Conceptual Design Study of such a magnet will be achieved in the frame of this R&D activity of WP8. The study will define the characteristics of the facility and prepare the technical specification for its construction. Specific R&D studies shall validate the design and allow integration of the innovative technologies, particularly including the studies led within the frame of this WP8. The type of magnet (solenoid, dipole, Helmholtz coil arrangement, etc.) will be defined according to the expressed needs.

The magnet shall offer a typical inner duty volume of about one cubic-meter. The target is to design a magnet with a maximum field of 4 Tesla at the magnet centre, in order to be able to test detector chambers, electronics and other components with and without beam. The facility is also intended for the calibration of magnetic sensors at 4-T to be latter used on field mapper of future detectors. The field homogeneity within the duty volume shall be specified based on the requests of the potential users from the CERN test beam community. These users shall be identified at an early stage. The teams from CLIC and FCC detectors shall be included in the list of potential users.

This facility will allow to perform tests with the full range of magnetic conditions in a detector, both with a constant field value up to 4-T, and with variable field conditions that are met during ramp up or magnet discharge, with the possibility to adjust the ramp up rate to the typical values met with detector magnets. The direction of the field with respect to the beam line will be defined. The change of the field polarity shall be possible. The study will also provide the requirements to change the orientation of the magnet by 90° with respect to the beam line, to have the magnetic field either aligned or perpendicular to the beam line.

The supporting structure of this magnet shall act as a yoke and therefore it will contribute to shield the experimental areas surrounding the magnet stray field. This support and yoke structure shall be designed to leave full and easy access inside the magnet duty volume. The access to this duty volume shall always be possible without moving or modifying the yoke structure and the magnet support structure. The stray field shall be compatible with the CERN Safety instructions.

An example of such a construction is the M1 magnet of the test beam facility located in the North area.

The Device Under Test (DUT) shall be inserted into the magnet inner duty volume with a nonmagnetic table moved on rails. The tables shall provide at the minimum the degrees of freedom to translate the DUT in one direction inside the magnet and to orientate the DUT around 2 axis. A preliminary design of such a table is part of the study, including the proposal of a remote positioning control.

The magnet will be superconducting. The study will first focus on low temperature superconductor (such as NbTi), then widening the scope on the feasibility to use high temperature superconductor for comparison with NbTi. The superconductor type shall be reinforced.

The magnet will be cooled at cryogenics temperature by indirect cooling mode through conduction cooling from a helium circuitry on the cold mass. The helium circulation shall be obtained either by thermosiphon mode or forced flow. For NbTi superconductors, the cooling shall be obtained by boiling helium at 4K.

The study will also cover the energy extraction analysis for faster magnet recovery.

The study will assume the magnet sub-systems (vacuum pumping system, cryogenics, power supply, control and safety systems) will be designed from off-the-shelf equipment, in order to limit the costs both on development and maintenance. In particular, for what concerns the powering of the magnet, power converters designed and developed at CERN by the TE-EPC group shall be considered.

The space needed for this facility will be specified:

- Inside the experimental area: space for the magnet and around it for handling and loading of the DUT, space for racks and services for the DUT,

- Outside the experimental area: space for the powering and protection circuit, refrigerator, vacuum pumping units, control room with racks, distribution cabinets for water cooling, electrical supply, compressed air.

The study will list the technical services necessary for the facility (magnet and its sub-systems, experimental area): electrical power, water cooling. As this magnet is intended to replace existing facility(ies), as a first approximation, it is not expected an increase of the load on the electrical and cooling networks in the experimental hall.

The control system shall be compatible with the CERN UNICOS (UNified Industrial Control System) framework used to develop industrial supervision and control applications. This will allow in the future the maintenance and operation of such a facility by the teams in charge of other magnets and detectors in EP department and CERN.

Note: magnet construction itself, commissioning and installation on beam line is NOT included, as this has to go on another budget. Estimated cost of the bare magnet (depending on free bore and length is between 5 and 7M.

The work shall therefore cover:

1. Definition of the requirements together with the CERN test beam community,

2. Perform the full design of such a magnet, as a test ground to work on a full system, including control systems and instrumentation, quench protection, persistent mode and free wheel options.

11.5 Innovation in Magnet Controls, Safety & Instrumentation

A next generation of innovative magnet controls, safety system and instrumentation is anticipated for running the next generation of detector magnets for improved capacity, autonomy, and reliable interfacing to external systems, detectors, accelerator, and mains infrastructure. The requirements shall be established, and simulation, prototyping and validation performed. Instrumentation for future detector magnets is to be defined at an early stage based. The upgrade of existing instrumentation is considered and new technologies shall be assessed. In parallel a review of new magnet instrumentation is pursued, promising detectors selected and field tested for qualifying them for detector magnet operation regarding robustness, aging effects, reliability and availability.

It is proposed in the frame of the WG8 to restrict the studies to 3 domains: quench detection, magnet control systems, magnetic measurements.

11.5.1 Quench protection: requirements, sensors, electronics:

The quench propagation in HTS is slower than in LTS with lower resistive voltage developed, requesting electronics with faster response time and lower voltage threshold, with increased noise reduction.

The study will cover problems related to the increase of the quench detection sensitivity at any changes of the operating current in the detector magnets due to eddy currents effect in the cold mass and high purity conductors.

Another important activity will be linked to the quench detection of low voltage elements of magnet electrical circuit such as coil joints, superconducting bus bars and connections to the current leads where further development of the reliable fast response superconducting quench detectors is required.

11.5.2 Magnet control: specification and requirements, interfaces:

The study will provide the technical requirements for future magnet control and safety systems: expected number and type of signals, interfaces, reduced response time, increased noise filtering. Suitable front end and back end electronics shall be identified from latest SCADA technologies and data processing systems. Fats quench detection systems shall be investigated.

11.5.3 Instrumentation: magnetic measurement:

The topics of interest expressed within the WG8 cover the magnetic measurement and instrumentation in magnetic field.

It is proposed to launch a study of the magneto resistive (MR) sensors. Their performances, their sensitivity in high fields, their radiation hardness, shall be studied. Other MR flavours shall be investigated.

Another subject of interest is the investigation of motion actuation in high magnetic field for scanning tables with piezoelectric motors.

It is also proposed to study an update to the Controller Area Network (CAN) bus used in EP for the field mapper and field measurement with Hall probes, e.g. with CAN–FD (Flexible Data rate).

12 Budget Overview

Only in the CERN internal version.

13 Organisational Aspects

Strategy

The R&D will be carried out by fellows and students supervised by staff with a high degree of competence and experience in the concerned domains. Typically, the staff members devote a 20% fraction of their time to this role. The activities will be embedded in existing work environments. This ensures an efficient transfer of the competence and experience at the beginning of the R&D programme, the availability of appropriate lab space, specialized instrumentation and technical know-how, and last but not least, a sustained growth of knowledge and expertise in the working groups.

Structure

In the implementation phase we foresee to maintain the same breakdown of the R&D programme into 8 work packages. Every work package will be led by a WP leader, appointed by the steering committee. Every work package consists of typically a handful distinct activities. On the proposal of the WP leader, the steering committee will appoint activity leaders.

The activity leaders are fully involved in the research activity and are responsible for the efficient and targeted implementation of the work plans. The WP leaders are responsible for the overall progress and coherence of the WP and the optimal use of the attributed resources.

The steering committee will appoint an overall coordinator who closely follows up all R&D activities, monitors its progress and use of resources, and agrees with the activity and WP leaders on any adaptations concerning work plan, timeline or resources which may arise.

Co-operation

Co-operations with groups in and outside the lab are an efficient way of optimizing the use of resources and infrastructures. In many domains well-established links to external groups exist and co-operations have already been tentatively agreed.

In the fields of radiation hard silicon and micro pattern gas detectors, RD50 and RD51 are fully-established and LHCC reviewed R&D collaboration, in which large parts of the silicon and gas detector communities exchange their experience and combine their efforts in common projects. The official status as a CERN R&D collaboration gives its member institutes the possibility to apply for dedicated funding. We expect that some of the R&D activities presented in this document will be carried out by CERN personnel under the umbrella of RD50 and RD51 and stimulate cooperation and additional external resources.

Monitoring and reporting

The size and wide thematic scope of the presented R&D programme require a systematic approach to monitoring and reporting. A set of milestones and deliverables were defined for each of the activities, typically one of each per year. While a deliverable is a physical object, a completed design, or a built prototype, milestones are just project checkpoints which allow to measure progress.

Apart from the regular meetings of the work packages, the progress of the R&D programme will be presented in a yearly public meeting and documented in a public annual report.

14 Summary and conclusions

15 Acknowledgements

We want to thank all colleagues – at CERN and from external institutes - who actively participated to this process by contributing ideas and feedback. Their experience and views were essential for this process.

We are particularly grateful to the work package convenors. They have collected, filtered and processed a wealth of ideas and proposals, made and defended their choices, presented their work programme at the workshops and finally wrote them down in this document.

Finally we express our gratitude to the CERN management for their support and encouragement.

Manfred Krammer, Christian Joram

16 Deliverables and resource spread sheets

This document is available in two version. The content of this section is version-dependent.

The public version includes spread sheets which list, for every activity, milestones and deliverables.

The CERN-internal version serves as basis of resource discussions with the management. It contains in addition resource spread sheets.

R&D work plan

WG	1 - Silicon Sensors	Activity	1.1

Short description: Novel Silicon Sensors – Hybrid-Pixel Detectors

Long description: The Hybrid-Pixel Sensors activity focusses on novel sensor concepts with advanced features to be used in hybrid assemblies with separate high-performance readout ASICs. Target development goals include sensors with built-in charge multiplication for very fast timing applications (10s of ps),

	date (count month from start of R&D)	item
Deliverables (max. 5)	18	Test results from thinned fine-pitch planar sensors with optimised trench design
	36	Radiation qualification of sensors with intrinsic gain
	40	Radiation qualification of fine-pitch planar sensors with optimised trench design
	56	Post-irradiation test results from LGAD segmented sensor assemblies
	60	Test results of front-end circuits for precise timing and for fine-pitch
Milestones (max. 5)	6	Submission of fine-pitch planar sensors with optimised trench design
	12	Submission of optimised sensors with intrinsic gain
	36	Submission of LGAD pixel sensors
	48	Pre-irradiation test results from LGAD segmented sensors
	54	Proof-of-principle application of fine timed tracking devices within large-scale test system;

	WP ID	common items
Cooperation with other WPs?	5	ASIC+sensor interconnection

	Group	nature / volume
Cooperation with ext. groups	RD50	Radiation-hardness qualification
	Timepix4	Test chip for pixelated timing sensors
	RD53/ESE	Test chip for planar sensors
	LHCb	Timing tracker, perf. optimisation, beam tests, hybridisation
	CMS	System-level integration, optical transmission
	CLICdp, FCCee, FCCh	Performance optimisation, beam tests, hybridisation

R&D work plan

WG: 1 - Silicon Sensors | **Activity**: 1.2

Short description: Monolithic CMOS sensors

Long description: The Monolithic CMOS sensor activity focuses on the development of radiation hard and/or highest resolution CMOS sensors for future trackers. We envisage the development of depleted CMOS sensors in high radiation environments for pp-collisions and smallest pixel CMOS sensor for Heavy-Ion and ee tracking applications. Radiation-hard CMOS sensors will be developed for two ranges of radiation hardness: up to 2e15 neq and for > 2e15 neq. Small pixel CMOS sensors for Heavy-Ion and ee will focus on lowest possible power consumption, X0 and good timing capability (O(ns)). Reticle stitching is a common goal for all

Deliverables (max. 5)

date (count month from start of R&D)	item
16	Rad hard CMOS sensors/medium pixel size (2e15 neq - 2Mhz/mm2)
26	Prototype of wafer-scale chip in medium feature-size CMOS process
30	Small-size test circuit for high-precision timing measurement
36	Prototype chip in medium feature-size CMOS process for smallest
50	Qualification of small feature-size CMOS processes to address high data rate/low power and smallest pixel

Milestones (max. 5)

10	Submission of rad hard CMOS sensors/medium pixel size (2e15 neq - 2Mhz/mm2)
20	Submission of wafer-scale chip in medium feature-size CMOS process
24	Submission of small-size test circuit for high-precision timing
30	pixel and X0
40	Submission of small feature-size CMOS test chips for high data rate / low power and smallest pixel

Cooperation with other WPs?

WP ID	common items
5	ASIC+sensor interconnection

Cooperation with ext. groups

Group	nature / volume
ATLAS	
ALICE	
RD53/ESE	
DT	
RD50	
CLICdp, FCCee, FCChh	

R&D work plan

WG	1 - Silicon Sensors	Activity	1.3

Short description: Module concepts for hybrid and CMOS pixels

Long description: This activity focusses on the study and development of new modules for hybrid and CMOS pixel detectors. The two main areas are highly integrated module assembly techniques (including chip-to-chip connections, 3D integration of electrical/mechanical and cooling aspects, 2.5D integration for high performance modules) and the study of ultra-thin modules (including thinning, dicing and wrapping).

	date (count month from start of R&D)	item
Deliverables (max. 5)	18	Test results from large area sensors with Redistribution Layer
	36	Thinning and dicing results for ultra-thin sensors
	40	Test of 2.5D integrated pixel modules
	50	Irradiation qualification of 3D integrated modules and glues
	56	Development of a module with photonic chip and electrical driver/receiver
	60	Final QA procedure for ultra-thin pixel modules
Milestones (max. 5)	6	Submission of CMOS wafers with Redistribution Layer
	12	Submission of components and post processing for 2.5D integrated hybrid modules
	18	Submission of dedicated CMOS wafers for thinning and dicing for ultra-thin modules
	36	Preparation of 3D integrated modules and dedicated glue study
	40	Assembly of silicon photonics device with fibre pigtails in suitable small package
	48	Setup and validation for QA of ultra-thin modules

	WP ID	common items
Cooperation with other WPs?	5	ASIC+sensor interconnection
	6	Photonics chips
	8	3d-integrated modules

	Group	nature / volume
Cooperation with ext. groups	RD50	Radiation-hardness qualification
	Timepix4	Test chip for pixelated timing sensors
	RD53	Test chip for planar sensors
	LHCb	Performance optimisation, beam tests, hybridisation
	CLICdp, FCCee, FCCh	Performance optimisation, beam tests, hybridisation

R&D work plan

WG: 1 - Silicon Sensors | **Activity** 1.4

Short description:	Simulation and Characterisation
Long description:	The Simulation and Characterization activity aims for a fundamental understanding and optimization of the performance of prototypes developed within the different sensor activities. This will be achieved through detailed characterization, modelling and simulation, including the effect of radiation exposure to the levels expected at future hadron colliders. Dedicated simulation, characterisation and radiation-dose monitoring tools will be developed within the activity.

	date (count month from start of R&D)	item
Deliverables (max. 5)	12	TPA-TCT setup commissioned.
	24	High-resolution (spatial, timing) beam telescope and flexible readout system commissioned.
	36	Radiation monitors for fluences >10^16 validated.
	48	Radiation models validated with TCT, x-ray measurements
	56	Simulation tool validated with TCT, x-ray measurements and beam tests
Milestones (max. 5)	6	Workshop on Simulation tools.
	12	Release of flexible readout system.
	18	Simulation tool validated for pre-irradiated sensors.
	20	Design review for new radiation monitors.

	WP ID	common items
Cooperation with other WPs?		

	Group	nature / volume
Cooperation with ext. groups	RD50	Radiation-hardness modelling
	ATLAS, CMS, ALICE, LHCb, CLICdp, FCC	Characterisation, validation of simulation.

R&D work plan

WG	3 - Calorimetry and light based detectors	Activity	3.1

Short description: R&D for future high-granularity noble liquid calorimetry

Long description: High granularity noble liquid calorimetry will be essential for future accelerator experiments. It is part of the reference design of an FCC-hh experiment presented in the FCC CDR. Due to the high radiation environment a fully passive calorimeter with read-out electronics sitting behind the calorimeter outside the cryostat is the preferred choice, leading, however, to long transmission lines of the signals.

We propose 4 research activities:

A: The granularity of noble liquid calorimeters can be easily adjusted to the needs by finely segmented read-out electrodes (multi-layer PCBs). Such electrode PCBs need to be designed, simulated, produced and tested. Based on the obtained results a small test module will be designed, produced and tested at the testbeam (2023).

B: Limits of MIP timing and timing resolution of showers, involving the full read-out chain, will be explored in simulation and optimized. Measurements in testbeam.

C: In parallel it is essential to measure and simulate LAr properties and calorimeter performance under high ionization rates covering space charge build-up, initial and bulk recombination, surface charge accumulation and the role of impurities.

D: The large granularity will require an increased signal density at the feedthroughs (FT) of up to 20-50 signals/cm2 which is a factor ~5-10 more than in ATLAS (ATLAS used gold pin carriers sealed in glass). Novel technologies have to be developed with industry.

Deliverables (max. 5)

date (count month from start of R&D)	item
Q3/2020	Small size prototype electrode produced for electrical measurements (noise, cross talk, coherent effects, capacitances, ….) (A)
Q4/2020	Production of high sig. density FT flange for vacuum and cold tests and electrical testing (D)
Q4/2021	Full FT with foreseen signal density (D)
Q2/2023	Small size test module for test-beam measurements (A)

Milestones (max. 5)

Q4/2019	Design and spice-simulation of multi-layer electrodes (A)
Q4/2019	Design of possible high signal density FT flange with O(100) connections (D)
Q2/2022	Design of small-size test module for testbeam measurements (A)
Q2/2021	Testbeam measurements LArPulse if necessary on top of Protvino testbeam (C)
Q3/2023	Testbeam measurements (A)

Cooperation with other WPs?

WP ID	common items
WG4, WG8	R&D on low material (low radiation length) cryostat

Cooperation with ext. groups

Group	nature / volume
BNL	BNL wants to participate in activities A (FE-electronics for testbeam) and D (FT design based on PCB)
Prague Charles Univ.	
LAL/Orsay	Activity A, PCB design and FE electronics
HiLum2 collaboration (6 institutes)	Measurements of LAr parameters in testbeams at Protvino and at CERN (activity C)

R&D work plan

WG	3 - Calorimetry and light based detectors	Activity	3.2

Short description: R&D for future scintillator based calorimeters

Long description: Scintillator based calorimetry is under consideration for many calorimeters of future accelerator experiments. We propose 2 research activities which are aimed at two different experiments, with overlapping requirements; we will therefore largely profit from synergies between the two activities:

A: LHCb ECAL: The radiation hardness of suitable scintillation detector materials needs to be thoroughly assessed in terms of scintillation characteristics, light yield, and transmission using various radiation sources providing gammas, protons and neutrons. The expected radiation environment can make necessary to operate the photodetectors such as SiPM at low temperatures (-30°C-40°C) and therefore it requires to study radiation hardness of scintillating materials and photodetectors at different temperature. For fast timing, the full detector readout chain has to be optimized in terms of light detection and timing characteristics. This requires time resolution studies on various scintillating materials and on photo detectors, optimization of light collection, shape of the material, etc...

B: FCC-hh TileCal: Due to the relatively modest radiation requirements (TID 8kGy in the tiles) the reference design makes use of organic scintillator tiles read out by wave-length shifting fibres and SiPMs to profit from a factor 4 increase in lateral granularity with respect to ATLAS TileCal. The proposed R&D will be done in close collaboration with industry and several institutes part of the ATLAS TileCal collaboration and will make use of the infrastructure of the TileCal lab in B175 at CERN: Identification and qualification measurements of components before and after radiation (tiles, WLSs, SiPMs, calibration systems), optimization of the optics concept (WLS, coupling to SiPMs), optimization of mechanics,...

Deliverables (max. 5)

date	(count month from start of R&D) item
Q4/2023	Prototype design (A)

Milestones (max. 5)

Q4/2019	Tests in B175 with WLS and SiPMs (B)
Q4/2020	Decision on detector concept: SPACAL or others like Shashlik (A)
Q2/2021	Decision on possible materials and photodetectors (A)
Q1/2022	Re-instrumentation of ATLAS spare mechanics module (B)
Q2/2023	Otimisation of selected material (A)

Cooperation with other WPs?

WP ID	common items

	Group	nature / volume
Cooperation with ext. groups	ATLAS TileCal collaboration	Use of infrastruct. in B175, synergies for hardware tests (B)

R&D work plan | WG | 3 - Calorimetry and light based detectors | **Activity** | 3.3

Short description: R&D for Si based calorimetry for a CLIC detector and CLD detector at FCC-ee

Long description: The CLIC detector and the CLD detector at FCC-ee propose very similar highly granular calorimeter designs, which are optimized for Particle-Flow Analysis (PFA). The calorimeters comprise compact sandwich structures for the electromagnetic (ECAL) and hadronic (HCAL) sections in a barrel and end-cap geometry located inside the central detector solenoid. The new CMS highly granular endcap calorimeter HGCal for the HL-LHC phase-2 upgrade will comprise similar technologies. Therefore much will be learned for the CLIC/CLD calorimetry through the HGCal development and construction in the coming years. The main differences between CMS HGCal and CLIC reside in the readout timing and the power pulsing. At CLIC, power pulsing will result in a strong reduction factor in heat dissipation between the sandwich layers. The power pulsing enables a larger effective density of the calorimeter and more compact particle showers.

We propose 3 research activities:

A: Continue the calorimeter R&D for CLIC/CLD through participation in CMS HGCal at the current resource level throughout 2019-2022.

B: Drawing on the CMS HGCal experience pursue engineering (mechanical + electronics) design studies for CLIC/CLD, both for ECAL and HCAL, in order to present realistic designs ranging from the module level up to the system and integration level during the years 2020-2022. This task could be pushed to a later date, e.g. 2022.

C: Build and test a few realistic CLIC/CLD ECAL modules, including sensors, electronics, absorbers, power pulsing (for the CLIC case), cooling and services during the years 2022-2025. This task could be pushed to a later date, e.g. 2023.

Deliverables (max. 5)

date (count month from start of R&D)	item
Q4/2024	Realistic modules built for tests in testbeams (C)

Milestones (max. 5)

Q4/2022	Realistic design of CLIC/CLD module (B)
Q4/2022	Realistic system integration of CLIC/CLD module (B)
Q4/2023	Design of realistic modules to be built (C)

Cooperation with other WPs?

WP ID	common items

	Group	nature / volume
Cooperation with ext. groups	CMS HGCal collaboration	
	CALICE collaboration	

R&D work plan

WG	3 - Light based detector	Activity	3.4

Short description: R&D on RICH detectors for future high energy experiments

Long description:

Development of optical hardware and low-temperature systems for the photodetectors;
* Development of light-weight mirros with enhanced reflectivity.
* Development of a thermally insulated and gas tight photodetector housing allowing to low-temperature operation of SiPMs.

Deliverables (max. 5)

date (count month from start of R&D)	item
12	First prototypes high precision carbon-fibre based optical mirrors (spherical and flat)
18	first protptyp photodetector box
30	Mini RICH detector to be tested in beam lines (LHCb RICH supported)

Milestones (max. 5)

9	material and tooling procured
12	test set-up prepared
24	design of mini-RICH set-up completed

Cooperation with other WPs?

WP ID	common items
WG4	design, production and tetsing of composite structures

Cooperation with ext. groups

Group	nature / volume
LHCb RICH	photodet, Asics, electronics, DAQ, software, new radiators
Liubliana	photodetectors and system tests
TBC	system tests and non-LHC experiments

R&D work plan

WG: 3-Light based detetors | **Activity** 3.5

Short description:	R&D on plastic scintillating fibre trackers
Long description:	Fibre development; scintillation mechanisms, light yield and transport, shorter decay time, new cost effective fabrication techniques, new activation and wavelength shifting mechanism (dopants), and radiation resistance.

Deliverables (max. 5)

date (count month from start of R&D)	item
12	High light yield fibres
24	proof of principle 3D fibre printing
36	x-y matrix of 3D printed fibres

Milestones (max. 5)

Cooperation with other WPs?

WP ID	common items	

Cooperation with ext. groups

Group	nature / volume
Kuraray, Saint Gobain	Sample development
Polymer Institute	Luminophore development
3D printing companies	Sample development
LHCb SciFi team	NOL studies

R&D work plan

WG	4 - Detector Mechanics	**Activity**	4.1.1

Short description: **Low mass mechanics for future HEP Vertex/ Tracker Detectors**

Long description: Low mass mechanics for sensors' support and thermal management represents a major challenge for future HEP trackers. The detectors design will have to cope with unprecedented requirements on minimum material budget and thight stability in lepton collider and with extremely high radiation levels and large surface coverage in hadron colliders. The program shall be pursued by the developement of ultralight mechanical substrates for gas cooled vertex detectors, and of 3d print microchannel/carbon-composite-vascular heat-exchangers for fluid cooling of large surface trackers. Substartes moudularity and mechanical and hydraulic interconnectivity will be addressed. The different alternative designs will be validated through the production and testing of breadboard, engineering and qualification models.

Deliverables (max. 5)

date (count month from start of R&D)	item
12	Report on identified techonologies and materials for detector thermo-mechanical substrate, and status of thermo-fluid models
24	Thermo-mechanical substrates design, based on identified technologies. Substrate Breadboard models. Report on characterisation tests.
36	Substrate Engineering models. Report on characterisation tests.
48	Substrate Qualification models. Report on characterisation tests.
60	Substrate Qualification models. Final Report on comparative performances

Milestones (max. 5)

12	Identify future technologies for inner tracking sensors (WG1). Investigate integrated thermo -mechanical substratesd design: - lightweight gas cooling for lepton vertex detector -3d print microchannels cooling for hadron tracking detectors. - carbon vascular heat exchanger for tracking detector - substrate mechanical and hydraulic interconnection, "lego" concept
24	Build and characterise substrates breadboard models.
36	Build and characterise substrates engineering models.
48	Build and characterise substrates qualification models.
60	Characterise qualification models, compare different alternative designs.

Cooperation with other WPs?

WP ID	common items
1	sensors and detector layout

Cooperation with ext. groups

Group	nature / volume
CERN-EN	Material and structure characterisation

EPFL, INFN, LBNL, Swiss Space Center	Potential for cooperation with several external Institute
ESA, Airbus, Gilat	Review of similar technologies for satellite and antenna thermal management applications.
AVS, NLR, CEA, Airbus, Bradford Engineering, Diabatix	Horizon 2020-SPACE-2018-2020, Innovative Mechanically Pumped loop for ACtive Antennae
HLL-MPI Munich, IFIC Valencia, FBK, CNM, CSEM, Fraunhofer, Sintef	Network of collaboration in the frame of the large European Project following AIDA-2020 and other projects
MSCA-ITN-2019	Marie Curie MSCA-ITN-2019

R&D work plan

WG	4 - Detector Mechanics	Activity	4.1.2

Short description: **Ultra Radiation Thin Cryostats for Magnets & Calorimeters (Joint with W3 and W8)**

Long description:

In order to meet the design goal for minimum radiation length of next-generation cryostats for detector magnets and calorimeter cryostats, Carbon Fiber Reinforced Plastic (CFRP) will be explored and compared to advanced metal or hybrid honeycomb structures. Technology and materials development of cryogenic fuel tanks for aerospace application will be incorporated. Thin-ply hybrid laminates and out-of-autoclave curing are projected as candidate materials and process. A scaled size Carbon Composite Cryostat Engineering model will be built.

Deliverables (max. 5)

date (count month from start of R&D)	item
12	Report on identified techonologies and materials. Design of HEP cryostat based on carbon composite. Alternative design based on Aluminum sandwich honeycomb.
24	Report on CFRP design validation based on numerical FEA and experimental test on samples. Report on CFRP vs Al sandwich cryotank design. Cost estimate for ultra-light Cryostat for calorimeter and magnet
36	Scaled size ultra-light Cryostat Engineering model (1m3).
48	Scaled size ultra-light Cryostat Engineering model (1m3).
60	Design and Qualification Test report.

Milestones (max. 5)

12	Investigate status of cutting edge technologies developed for aerospace LH2 and LOX carbon composite cryo-tanks. Develop design of HEP cryostats based on carbon composite materials and compare with metallic options, including aluminium sandwich.
24	Validate design/materials/technology choices through Finite Element Analysis, test specimen, cryostat samples for specific interfaces. CFRP vs Al sandwich cryotank design assesment. Provide a cost estimate for most promising ultra-light Cryostat designs, both for detector calorimeters and magnet.
36	Production readiness of Scaled Size ultra-light Cryostat Engineering model
48	Production completion of Scaled Size ultra-light Cryostat Engineering model
60	Qualification test

Cooperation with other WPs?

WP ID	common items
3	Fully integrated joint project
8	Fully integrated joint project

Group	nature / volume

Cooperation with ext. groups	NASA, ATK, Boeing, Lockheed Martin, NorthropGrumman SpaceX, ALE, AeroSpatiale, ESA, Airbus, RUAG, DLR	Review of similar technologies for space tanks, consultancy. Parts production assistance.
	Institutes, Companies	Placing small material development projects, demonstrator production.

R&D work plan WG | 4 - Detector Mechanics | **Activity** | 2

Short description: **Dedetectors-infrastructure interfaces and services architecture for automated installation and maintainability**

Long description:

Design of present HEP detectors relies on optimized procedures such that installation, maintenance, repair and dismantling work does not lead to an effective dose exceeding ALARA (As Low As Reasonably Achievable) requirements.
Radiation levels in future hadron collider and radiation-cooling times will limit future operational scenarios, this should lead to revised detectors design to account for shielding and remote opening/manipulation and access. Independently from the specific HEP experiment, new detectors must be designed to be easily maintained and possibly robot friendly to maximize detector accessibility and decrease personnel exposures to hazards. Layout and interface to automated systems/robots for maintenance and early intervention should be foreseen at the design level. A new concept of detector infrastructure interfaces and services connectivity shall ease remote handling.

Deliverables (max. 5)

date	(count month from start of R&D) item
12	Report on Detectors integration/ maintanace needs and strategies. Report on industrial automated and robotic system compatible with the needs of future remote detector handling
24	Principle Design of common solutions for detectors' interface -to automated Remote Manipulator System (RMS), for detector handling -to Services Umbilical Mechanical Assembly (SUMA), for service connection -to On Detector Robot System (ODRS), for on detector remote intervention
36	Engineer Design of common solutions for detectors' interface
48	Production of test articles for solution testing
60	Report on identified solution and experimental validation of test articles

Milestones (max. 5)

12	Identification of integration and maintenance strategies. Identification of industrial solutions and cutting edge technologies of automated and robotic system compatible with the needs of future remote detector handling and maintainace.
24	Development of the Design of common solutions for detectors' interface
36	Construction of HEP Robotics Lab for solution testing
48	Engineer Design of a common solutions for detectors interface. HEP Robotics Lab equipped for validation of the proposed design solution
60	Experimental validation on test articles of the proposed solutions in HEP Rob Lab

Cooperation with other WPs?

WP ID	common items

Group

nature / volume

Cooperation with ext. groups	CERN-EN	material and structure characterisation/ robotics
	CERN HSE	radiation environment
	ETH-Zurich	robotic
	NASA	robotic
	ESA	Robotics, RDV & docking
	University	potential for cooperation with several Departements

R&D work plan

WG	4 - Detector Mechanics	Activity	3

Short description: **High-performance cooling for future detectors**

Long description: Environmental friendly, radiation resistant, single-phase and phase-changing coolants for new operative requirements of future detectors. Cooling pipework and instrumentation for large distributed systems adapted to the different challenges posed by detectors at future hadron or lepton colliders.

Deliverables (max. 5)

date (count month from start of R&D)	item
12	Report on selected candidate fluids and their potential target application, ranking in term of priority for closer need in time
24	Report on selected advanced instruments and flexible pipework to be engineered
36	Published reports (and papers) on thermo-fluid properties of advanced natural refrigerants usable in future experiments
48	Report on radiation tolerance of new synthetic refrigerants and their limits of apllicability in different detector classes
60	Tested prototypes (demonstrators) of advanced cooling systems for different needs

Milestones (max. 5)

12	Selection of candidate fluids (synthetic and natural) for single-phase and phase-changing applications
24	Preliminary tests on new advanced instruments and insulated pipework. Pre-selection of best candidates for engineering.
36	Quality step forward in the understanding and modeling of thermo-fluid properties of new (advanced) natural refrigerant suited for detector applications
48	Completed irradiation campaigns on new classes of synthetic refrigerants
60	Build and test reduced scale prototypes of the future advanced systems for the different needs of experiments

Cooperation with other WPs?

WP ID	common items
WP1	Optimal cooling fluid and instrumentation
WP3	Optimal cooling fluid and instrumentation

Cooperation with ext. groups

Group	nature / volume
EN-CV, 3M, Honeywell Fluids	Radiation tolerance studies on new synthetic refrigerants with low environmental footprint. Impact on plant components from new refrigerants. Activity lead by EN-CV with EP-DT cooperating and coordinating with experiments for their needs

NTNU, Sintef, GE Global Research	Studies on the boiling properties of N_2O and CO_2/N_2O mixtures in harsh environment. Studies on heat transfer and pressure drop characterisitcs of CO_2 at supercritical conditions, and on the required minimal material budget pipework. The work can leverage on the (unique) state-of-the-art experimental facilities exisiting in EP-DT and on the high level of expertise of the external partners.
HB Products, NTO, MPI Munich	Studies on advanced affordable instrumentation and vacuum insulated pipework. Prototype fabr/ testing.

R&D work plan

WG	5 - IC technologies	**Activity**	5.1a

Short description: CMOS Technologies

Long description: Survey of advanced CMOS Technologies, radiation tolerance evaluation, radiation tolerant design techniques. Frame contracts for technology access. Development of common platform(s) for ASIC design, specialized EDA tools, digital macro block development and common repository. Legal framework for HEP labs access to technologies, tools and macro blocks. Training and technology dissemination to HEP labs.

Deliverables (max. 5)

date (count month from start of R&D)	item
24	Preliminary radiation evaluation survey report
36	Final radiation evaluation survey report
48	Commercial frame contracts & common design platform
60	Technology access legal framework for HEP institutes and training sessions

Milestones (max. 5)

12	Obtain access to technologies and submit test devices for evaluation
36	Perform Radiation Evaluation studies
48	Frame contracts for selected technologies and common design platform(s)
60	Legal framework for HEP institutes and technology dissemination

Cooperation with other WPs?

WP ID	common items

Cooperation with ext. groups

Group	nature / volume

R&D work plan

WG	5 - IC technologies	Activity	5.1b

Short description: Assembly technologies suitable for future hybrid pixel detectors

Long description: A bottleneck in the output rate of conventional hybrid pixel readout chips is the column wise readout architecture. Future high performance readout chips will use TSV's to overcome this limitation. TSV processes compatible with the chosen new mainstream CMOS processs will be developed. Another task is accessing commercial wafer stacking processes which combine image sensor wafers with standard CMOS .

Deliverables (max. 5)

date (count month from start of R&D)	item
36	PDK for chosen stacked-Si process available
40	TSV processed mainstream wafers -1st lot
60	TSV processed mainstraem wafers 2nd and 3rd lots
60	stacked-Si chips available

Milestones (max. 5)

24	Appropriate stacked-Si process identified
30	First submission of mainstream wafers to TSV processing
36	First test chip in stacked-Si submitted
54	Large stacked-Si chip submitted

Cooperation with other WPs?

WP ID	common items

Cooperation with ext. groups

Group	nature / volume
LHCb	Design of 'picoPIX' chip (upgrade of VELOpix)
Future project tbd	Definition and design of large stacked-Si chip

R&D work plan

WG: 5 - IC technologies — **Activity**: 5.2a

Short description: Low voltage low power design

Long description: Activity conceived with the objective of (1) evaluating ASIC technologies, (2) design and implementation of circuit building blocks that should be characterized on silicon, (3) encourage the participation in this programme to institutes in the HEP ASIC design community and (4) disseminate the programme accumulated know-how in order to maximize the probability of having first-time working silicon designs.

Deliverables (max. 5)

date (count month from start of R&D)	item
30	1. ASIC in the mainstream technology containing IP blocks: (1) Voltage references, temperature monitor, DACs for biasing purposes (2) CSA, shaper and comparator for the readout of 2D detectors and (3) circuits for the readout of detectors with intrinsic amplification for timing layers (SiPMs, MCPs)
42	2. ASIC in the mainstream technology optimizing circuits in deliverable (1) and incorporating new IP blocks: (1) Data transmission circuits (line drivers and receivers) and a (2)PLL (specifications to be discussed with WP6)
54	3. ASIC in the mainstream technology optimizing the Data transmission circuits and the PLL (in deliverable (2)). Integration of an ADC circuit.
60	Documentation of the designed IP blocks and the results of the electrical characterization.

Milestones (max. 5)

Cooperation with other WPs?

WP ID	common items

Cooperation with ext. groups

Group	nature / volume
NIKHEF	Line drivers, receivers, PLLs (existing collaboration in the framework of the LHCb Velopix chip)
UB	Design of blocks for amplification, filtering and discrimination (A/D conversion) for a 1-D readout circuit for fast timing. (Existing collaboration in the framework of the FastIC project)

R&D work plan

WG: 5 - IC technologies

Activity 5.2b

Short description: Radiation hard circuits for future experiments' power distribution

Long description: Development of components for a modular power distribution system in two step-down stages: a first stage in Si or GaN technologies to provide 1.8-2.5V from an input voltage of 25V, and a second stage macroblock to be embedded in front-end chips for on-chip conversion and regulation.

Deliverables (max. 5)

date (count month from start of R&D)	item
60	High voltage (25V) rad-hard DCDC converter for high conversion ratio
60	On-chip 1.8V-2.5V to 1V DCDC converters and linear regulators in mainstream tech

Milestones (max. 5)

date	item
12	Choice of the suitable Si or GaN technology for high voltage converter
24	Development of first prototype for the 25V DCDC Converter
36	First prototype of linear regulator and DCDC converter in mainstream technology
48	Reliability and large scale irradiation campaign

Cooperation with other WPs?

WP ID	common items

Cooperation with ext. groups

Group	nature / volume

R&D work plan

WG: 6 - High Speed Links

Activity: 6.1.1

Short description:	ASIC-1 Very high data rate aggregator/transmitter
Long description:	Feasibility study and design of very high data rate transmitters in advanced CMOS technologies.

Deliverables (max. 5)

date (count month from start of R&D)	item
20	Low jitter PLL: Performance report (including irradiation TID and SEU)
32	Serializer: performance report (TID + SEU), Final specifications
56	Transmitter: Performance report

Milestones (max. 5)

12	Low jitter PLL (submission)
24	Serializer and PAM4 demonstrator ASIC (submission)
36	
48	28/56 Gbps transmitter (fully functional) (submission)
60	

Cooperation with other WPs?

WP ID	common items
5	IC technologies

Cooperation with ext. groups

Group	nature / volume
KU - Luven (TBC)	PLL design
SMU (TBC)	PAM 4

R&D work plan

WG	6 - High Speed Links	**Activity**	6.1.2

Short description:	ASIC-2 Optoelectronics drivers
Long description:	Development of very high speed drivers for VCSELs and External modulators

Deliverables (max. 5)

date	count month from start of R&D item
32	Laser driver: Performance report (TID + SEU)
50	Modulator driver: performance report (TID + SEU)

Milestones (max. 5)

12	Technology and topology selection for the VCSEL driver
24	28 Gbps NRZ and 56 Gbps PAM4 laser driver (submission)
42	28/56 Gbps NRZ modulator driver (submission)

Cooperation with other WPs?

WP ID	common items
5	IC technologies

Cooperation with ext. groups

Group	nature / volume
SMU (TBC)	VCSEL drivers
INFN (TBC)	Modulator drivers

R&D work plan

WG	6 - High Speed Links	**Activity**	6.1.3

Short description:	ASIC-3 ASICs for low-mass electrical cable transmission (active cable)
Long description:	Feasibility study of 28nm ASICs for high data rate transmission over low mass cables.

Deliverables (max. 5)

date	count month from start of R&D item
12	System study: signalling, pre-emphasis/equalization and FEC coding
32	Transmitter ASIC performance report (TID + SEU)
50	Receiver ASIC: performance report (TID + SEU)
60	Final proposal on signaling, FEC coding and Architectures

Milestones (max. 5)

24	Transmitter ASIC submission (PLL, pre-emphasis, NRZ and PAM4)
42	Receiver ASIC submission (CDR and equalization)

Cooperation with other WPs?

WP ID	common items

Cooperation with ext. groups

Group	nature / volume
tbd	low mass cables study (phy)
tbd	ASIC design & system studies

R&D work plan

WG	6 - High Speed Links	**Activity**	6.2.1

Short description:	FPGA-1 FPGA-based system testing and emulation
Long description:	High-level emulation of ASICs, functional verification of designs, testing of components and systems.

Deliverables

(max. 5)

date	count month from start of R&D item
3	FPGA evaluation platforms - batch 1
12	Firmware for emulation
24	Firmware for testing
24	FPGA evaluation platforms - batch 2

Milestones

(max. 5)

12	full emulation with FPGA-to-FPGA of NRZ or PAM-4 28/56 Gbps links
24+	development of test environments for ASICs/optoelectronic devices
…	delivered by WG6 / activities 1 and 3

Cooperation with other WPs?

WP ID	common items

Cooperation with ext. groups

Group	nature / volume

R&D work plan

WG	6 - High Speed Links	Activity	6.3.1

Short description: OPTO-1 Silicon Photonics System & Chip Design

Long description: Investigation of system architectures and SiPh components in order to design Front-End chip for SiPh-based readout system.

Deliverables (max. 5)

date	(count month from start of R&D) item
12	System Architecture & Chip design proposal
27	Test Chip 1 test report
45	Test Chip 2 test report

Milestones (max. 5)

12	System feasibility demonstrated in simulation
14	Test Chip 1 Design Review and submission
33	Test Chip 2 Design Review and submission
51	System feasibility demonstrated in lab

Cooperation with other WPs?

WP ID	common items

Cooperation with ext. groups

Group	nature / volume
Pisa (TBC)	Driver chip design, exchange of design info/models
KIT (TBC)	SiPh chip design reviews
CERN-BE (TBC)	Long distance radiation tolerant links in HL-LHC

R&D work plan

WG	6 - High Speed Links	Activity	6.3.2

Short description: OPTO-2 Silicon Photonics Radiation Hardness

Long description: Investigation of radiation hardness of SiPh components, based on existing IP building blocks from CERN and/or industry as well as potential new designs.

Deliverables (max. 5)

date count month from start of R&D	item
6	Radiation Test Method
24	Radiation Test results for each SiPh component
48	Radiation damage model for each SiPh component

Milestones (max. 5)

12	Radiation test chip defined and submitted
30	Radiation test results reported at conference (e.g. NSREC, RADECS)
54	Radiation damage model reported at conference (e.g. NSREC, RADECS)

Cooperation with other WPs?

WP ID	common items

Cooperation with ext. groups

Group	nature / volume
Bristol University (TBC)	PhD supervision

R&D work plan

WG	6 - High Speed Links	Activity	6.3.3

Short description: OPTO-3 Next-generation VCSEL-based optical link

Long description: Investigation of feasibility of up to 28G VCSEL-based links, possibly including CWDM and/or PAM4.

Deliverables (max. 5)

date (count month from start of R&D)	item
6	Test method description for 28Gb/s NRZ/PAM4/CWDM
12	Market survey for 28G modules and components, including CWDM variants
36	Radiation test data for 28G VCSEL components
48	Module test results

Milestones (max. 5)

12	System feasibility shown in simulation
24	Device models available for driver chip design
48	28G link feasibility assessment complete

Cooperation with other WPs?

WP ID	common items

Cooperation with ext. groups

Group	nature / volume

R&D work plan

WG	6 - High Speed Links	Activity	6.3.4

Short description: OPTO-4 Silicon Photonics packaging

Long description: Investigation and proof of feasibility for packaging SiPh components for use in detector front-end systems.

Deliverables (max. 5)

date	(count month from start of R&D) item	

Milestones (max. 5)

Cooperation with other WPs?

WP ID	common items
1	Si detectors

Cooperation with ext. groups

Group	nature / volume

R&D work plan

WG	7 - Software	Activity	7.1

Short description: Faster simulation

Long description: The goal of this R&D activity is to develop novel, faster simulation techniques, assuring the necessary speed-up required to provide enough Monte Carlo statistics for the adequate accuracy of physics analysis in future experiments. Using Machine Learning (ML)-based technologies, new possibilities have emerged where trained neural networks take place of computing-intensive stages of HEP event simulation. The use of ML techniques can range from replacing some CPU-intensive calculations, such as sampling from complex probability distributions, to full (sub)detector response simulation. Even the replacement of entire simulation and reconstruction steps with a neural network, or direct production of analysis relevant quantities can be envisaged. We plan, therefore, for three work packages that can deliver new, break-through solutions: fast detector response simulation, combined fast simulation and reconstruction, and fast parameterisation of CPU-intensive physics processes.

Deliverables (max. 5)

date (count month from start of R&D)	item
18	ML-based algorithms to replace computational expensive physics models
36	Generic fast-simulation tools for different detector classes
48	Integration mechanism for new fast simulation tools
60	ML-models to predict combined effect of simulation and reconstruction

Milestones (max. 5)

12	Review and evaluation of available ML generative models.
20	Demonstator of ML-based physics process simulation.
36	Prototype of concrete detector fast simulation.
54	Prototype of ML-based combined simulation and reconstruction.

Cooperation with other WPs?

WP ID	common items

Cooperation with ext. groups

Group	nature / volume

R&D work plan

WG: 7 - Software

Activity: 7.2

Short description: Reconstruction for high particle multiplicity environment

Long description: Event reconstruction in p-p collisions at high luminosity (HL-LHC, HE-LHC and FCC-hh with a pile-up of 200 and more), or in a high multiplicity heavy ion environment, suffers substantially from increased event complexity. Due to their combinatorial character, track reconstruction and clustering in high granularity calorimeters are hereby the most compute-intense parts. In this R&D project we would like to address both issues by introducing novel ideas in tracking (e.g. 6D Kalman Filter) and providing working, stand-alone clustering libraries that could be either integrated directly in HEP frameworks or used as a reference.

Deliverables (max. 5)

date (count month from start of R&D)	item
12	Review of existing clustering and reconstruction algorithms for concurrent execution, identification of potential and limitations of currently deployed algorithms and data structures. Development of mathematical framework for 6D track reconstruction.
24	Test implementation of geometry divided concurrent reconstruction based on typical HEP track seeding and track following approach, with first prototype for coherent overlap resolving. Extension with timing detectors including full 6D track reconstruction and including timing at clustering level for calorimeters.
36	Extension to environment driven setup with different track reconstruction setups (eventual algorithms) depending on the detector and physics environment. Technical and timing evaluation of overhead losses and potential gain w.r.t to purely sequential reconstruction.
48	Investigation of GPU based track reconstruction, clustering and track seeding, and prototype integration into high granular calorimetry: full inner tracker and calorimeter clustering and tracking setup for HL-LHC and the FCC-hh study.
60	Finalisation and refining of implementation, encapsulation of drop-in solution software, coordination with experiments for eventual integration and publication.

Milestones (max. 5)

9	Review of current clustering and track reconstruction algorithms for concurrent execution concluded, mathematical framework to 6D numerical parameter propagation and extension timing extension of the Kalman filter.
18	Prototype of a geometry based concurrent track reconstruction and cross-reference of performance w.r.t to a sequential setup established. 6D Kalman filtering prototype done. Prototye of standalone, concurrent, clustering algorithms library.

30	Prototype of an environment driven concurrent track reconstruction and cross-reference of performance w.r.t. conventional setup established.
46	Characterization and performance comparison of different clustering algorithms, in different PU conditions and for several particle types (charged hadrons, electrons, photons, neutrals). Demonstrator SW for ID and high granularity detector reconstruction, with concurrent steering and data flow implemented.
60	Finalization and documentation of estatblished SW prototypes, coordination with experiments for eventual re-integration into SW environment of the experiments.

Cooperation with other WPs?

WP ID	common items
7	Strong link to turnkey systems for integration

Cooperation with ext. groups

Group	nature / volume
CMS Collaboration	HGCal software reconstruction
ATLAS Collaboration	ACTS Software project/Tracking SW

R&D work plan

WG	7 - Software	Activity	7.3

Short description: An Efficient Analysis Facility

Long description: Despite great advances in analysis productivity in LHC Runs 1 and 2, future hadron colliders will bring orders of magnitude increases in recorded events at far greater complexity. Analysis at this scale cannot be solved by scaling today's solutions, but is crucial for the success of CERN's scientific programme, even for the HL-LHC. This future scaling and complexity cannot be handled by requiring more advanced programming skills from researchers. Already now, their time and focus are dissipated understanding how the analysis should be implemented in code rather than what steps are needed for an optimal study.

Cultivating and developing EP expertise in software development, I/O patterns of large datasets and high throughput analysis, we propose to address these concerns along three R&D lines: increase of data reading rate, forging of programming models that boost scientists' productivity and contribution to specialised data centres' creation, Analysis Facilities, influencing their design.

The project can be divided in two stages:

1) redesign and reimplement ROOT IO components for high throughput, filesystem-less based data analysis;
2) for a prototype analysis facility, focus on usability and backend engine.

Deliverables (max. 5)

date (count month from start of R&D)	item
12	First prototype integration of ROOT IO with object stores
36	Assessment of current HEP analyses programming models and future prospects
48	Design and implementation of interfaces for high throughput HEP data analysis

Milestones (max. 5)

24	ROOT IO subsystem able to read and write from/to object stores and not only files
36	Deployment of prototype analysis facility, rudimentary access command line only
48	Mechanism for dynamic, on demand provision of resources
60	Prototype analysis facility using object store as data pool, accessible from the web

Cooperation with other WPs?

WP ID	common items
WP7-5	Fine grained treatment of HEP columnar datasets

	Group	nature / volume
Cooperation with ext. groups	IT-ST	Access to a large scale object store over the network
	Experiments analysis teams	Usecases, feedback about user experience
	Openlab	Technology watch, cooperation with companies
	EP-SFT	SWAN and ROOT teams, for analysis web interface and core software

R&D work plan

WG	7 - Software	Activity	7.4

Short description:	Frameworks For Heterogeneous Computing
Long description:	In this R&D line, we will develop a toolkit for heterogeneous computing that will allow existing HEP experiment frameworks to effectively integrate accelerator resources and to address key questions of efficiency and robustness. We will use a message passing interface, so as to retain an abstraction that allows adaptation to different hardware types and to different experiment software. Use of multiple possible execution paths will be allowed, essential to increase the efficiency of resource usage. We will develop a monitoring infrastructure that will enable the system's performance to be characterised and provide the information to scheduling components. Robust handling of failure modes will be studied. First versions of the library will target fixed resource pools, such as HLT farms. Later extensions will allow

Deliverables (max. 5)

date (count month from start of R&D)	item
12	Design report
18	Prototype for CPU based system, single channel
24	Prototype for CPU/GPU colocated systems
36	Support for multiple hosts and resource selection
48	Support for dynamic provisioning of resources

Milestones (max. 5)

date	item
9	Survey existing libraries and frameworks
15	Core functionality for IPC available
18	Interfaces for integration with exisiting frameworks
42	Benchmark of different access patterns (CPU vs GPU, local vs remote, ..

Cooperation with other WPs?

WP ID	common items
7	Strong links to analysis facilities, experimental stacks, simulation and reconstruction projects.

Cooperation with ext. groups

Group	nature / volume
ALFA/O2 Collaborati	Framework Integration (ALICE)
Gaudi Collaboration	Framework Integration (ATLAS/LHCb)
CMS Collaboration	Framework Integration (CMS)
Fermilab SCD	Heterogenous framework for LHC and neutrino
CERN OpenLab	Future accelerator technologies, links to industry

R&D work plan

WG	7 - Software	Activity	7.5

Short description: Multi-Experiment Data Management

Long description: The LHC experiments are anticipating a massive increase of their data needs from triggering to offline by 2026, and new large experiments at the scale of HL-LHC are coming online such as SKA and DUNE, competing for the same resources. The current static interfaces and their operation will not scale to that level. A more dynamic, shared use of the available heterogeneous storage and network capacities is required that is able to orchestrate and adapt across multiple experiments with competing usage patterns.

This R&D will explore methods for fair use of the available resources through two complimentary efforts:
(1) dynamically claim and release storage and network for organized experiment workflows
(2) dynamically preempt storage and network to meet ad-hoc analysis deadlines

Deliverables (max. 5)

date (count month from start of R&D)	item
12	Quality of Service specification and interf. for data managm./storage
24	Implement storage and network interf. and first vertical integration
36	Orchestration of high-rate data transfer across two experiments
48	Deadline-aware analysis activity with dynamic resource allocation
60	N-way exp. orchestration with full resource preemption for analysis

Milestones (max. 5)

12	Quality of Service specification document
24	Vertical slice ready with all interfaces available
36	Demonstration of increased storage space and throughput
48	Demonstration of reduced latency and analysis deadline scheduling
60	Final report

Cooperation with other WPs?

WP ID	common items
WG7	The "Efficient Analysis Facility" directly interacts and benefits from this R&D

Cooperation with ext. groups

Group	nature / volume
CERN IT-ST & IT-CS	Ongoing developments for network, storage, and transfer infrastructure
SKA (via U. Manches	Data management for Radioastronomy
IceCube & LIGO (via	Data management for Neutrino and Astronomy
DUNE (via RAL)	Data management for Neutrino
CMS (via CERN and F	Currently evaluating Rucio for adoption

R&D work plan

WG	7 - Software	Activity	7.6

Short description: Turnkey Software Stacks for Future Experiments

Long description: The goal of this project is the development of a single turnkey software stack that can be used for the detector studies of the FCC and CLIC communities and later extended to other users. The project will work towards identifying a maximum subset of detector-independent data structures and algorithms, in particular in identifying common parts of the event data model (a precondition for applying common reconstruction algorithms). The project will develop appropriate documentation and guidance for developers working on common software projects so as to ease their integration. The development of detector-specific plugin interfaces will allow the low maintenance stable software core to be readily usable. Full integration of algorithms and validation, from geometry to physics results, is envisaged for the detector concept studies.

The fully scoped project allows us to develop a core stack and integrate all of the detector concepts under study, ensuring not only technical functionality but proper integration of new algorithms and validation of the results. If the project is funded at a lower level then the full integration and physics validation will be lost, but the core software stack will be delivered.

The work package is primarily aimed at supporting detector study R&D programs rather than producing core software R&D results.

Deliverables (max. 5)

date (count month from start of R&D)	item
12	Streamlined common stack for detector development, with adaptors for CLIC to Gaudi framework
12	Fully functioning distributed computing components for full scale validation within production environment and continuous testing
24	Validation of physics performance in the new stack: fully functioning simulation and reconstruction system for current CLIC and FCC detectors
42	Simulation and reconstruction for additional CLIC and FCC detector models
60	Turnkey software stack for the use by other experiments

Milestones (max. 5)

6	Understand commonalities and differences in FCC and CLIC stacks, identified distributed computing requirements
9	Design report for common CLIC/FCC stack
18	Run CLIC reconstruction using Gaudi
24	Run Pandora PFA in FCC-ee studies

WP ID common items

Cooperation with other WPs?		
	7	Delivery of common testbed environment for all software R&D

Cooperation with ext. groups	Group	nature / volume
	FCC	Critical alignment with the group for delivery of the working stack
	CLIC	Critical alignment with the group for delivery of the working stack
	HSF	Common build and packaging tools

R&D work plan

WG	Activity
8 - Detector Magnets	8.1

Short description: Advanced Magnet Powering for high-stored energy detector magnets.

Long description: Superconducting magnets for future detectors will have very large stored magnetic energy and will be housed in deep underground caverns. The magnet powering and quench protection circuits have to be engineered accordingly. Few issues are critical and new technical solutions shall be developed and demonstrated.

Deliverables (max. 5)

date (count month from start of R&D)	item
12	Feasibility Study of various Magnet Powering Modes. Recent Technology Study Report based on literature research.
24	Technical Requirements Report and Conceptual Design Report based on Simulation and some model R&D. Selection of demonstrators.
36	Technical design and Engineering Report. Construction of short demonstrator models and testing (2 years).
48	Continued R&D on demonstrators and testing.
60	Final report.

Milestones (max. 5)

12	Review of options and study report finished.
24	Technical requirements and Conceptual Design of system and demonstrators finished.
36	Technical design finished and construction of demonstators in progress.
48	Test report of demonstrators.
60	Final report, evaluation, outlook and conclusion.

Cooperation with other WPs?

WP ID	common items

Cooperation with ext. groups

Group	nature / volume

R&D work plan

WG	8 - Detector Magnets	Activity	8.2

Short description: Reinforced Super Conductors and Cold Masses

Long description: Design goal is a 2-4T solenoid cold mass with radiation length less than 1 X0. This requires very high yield strength Al stabilized and reinforced NbTi/Cu conductors. The project comprises cold mass and conductor mechanical design, quench dumps studies, conductor development and demonstrator tests.

Deliverables (max. 5)

date	(count month from start of R&D) item
12	Review study reinforcement options, thin cold mass design report.
24	Short sample productions, welding technology, and characterization
36	Short sample productions, welding technology, and characterization.
48	Selected conductor unit length production and coiling/bending test.
60	Reporting, evaluation and outlook.

Milestones (max. 5)

12	Review study report.
24	Short sample test reports.
36	Short sample test reports.
48	Long unit test report.
60	Test coil report, final report, batch of samples made.

Cooperation with other WPs?

WP ID	common items

Cooperation with ext. groups

Group	nature / volume
EN/MME-MM	Materials and Conductor characterization work.
CEA-Saclay	Conductor design and testing.

R&D work plan	WG	8 - Detector Magnets	Activity	8.3

Short description:	Ultra Light Cryostat Studies
Long description:	Achieving the design goal of minimum radiation length, requiring strongly reduced material wall thicknesses and mass of next-generation cryostats for detector magnet, requires to study carbon fibre reinforced polymeric-based composites. These will be explored and compared to advanced metal or hybrid honeycomb structures.

Deliverables
(max. 5)

date	(count month from start of R&D) item

Milestones
(max. 5)

Cooperation with other WPs?

WP ID	common items
4	Fully integrated joint project

Cooperation with ext. groups

Group	nature / volume
ESA, Airbus, NASA, Boeing, Lockheed Martin, ATK, Northrop Grumman, SpaceX, Technologya, Perm Machinostroitel.	Review of similar technologies for space tanks, consultancy. Parts production assistance.
Institutes, Companies.	Placing small material development projects, demonstrator production.

R&D work plan WG 8 - Detector Magnets **Activity** 8.4

Short description: New 4T General Purpose Magnet Facility for Detector Testing

Long description: New cutting-edge high-energy particle detectors in future accelerators have to work in 4 T magnetic field. For testing detector units on a beam line, a 4-T test facility is required and will replace or complement the outdated systems available at CERN's North area. The facility will be shared by collaborations to which CERN is contributing.

Deliverables (max. 5)

date (count month from start of R&D)	item
12	Magnet design (1 year).
24	Magnet subsystems design and integration: powering circuit, cryo, vac, cryostat, support system (1 year).
36	Demonstrators testing, control, instrumentation, powering (1 year).
36	Final Report of Design and Specification.

Milestones (max. 5)

12	Magnet conceptual design report.
24	Magnet Technical Specification and procurement documents. `
36	Final report Design and Technical Specification.

Cooperation with other WPs?

WP ID	common items

Cooperation with ext. groups

Group	nature / volume

R&D work plan

WG	Activity
8 - Detector Magnets	8.5

Short description: Innovation in Magnet Controls, Safety & Instrumentation

Long description: New and Innovative magnet controls, safety systems and instrumentation is anticipated for running the next generation of detector magnets for improved capacity, autonomy, and reliable interfacing to magnet-external systems, . Requirements shall be established, simulation, prototyping and validation performed.

Deliverables (max. 5)

date (count month from start of R&D)	item
12	Report on future needs for magnet control systems (1 year).
24	Conceptual design, simulations, prototyping of new control systems and instrumentation (2 year).
36	Simulation and validation tests (1 year).
48	Final report.

Milestones (max. 5)

12	Definition of future needs for control systems, interfaces, instrumentation. Survey on the development in industry.
24	Conceptual design completed.
36	New controls and instrumentation validated.
48	Final report submission.

Cooperation with other WPs?

WP ID	common items

Cooperation with ext. groups

Group	nature / volume