Strategic R&D Programme on Technologies for future Experiments

An initiative of the CERN EP department

- Concept
- Process
- Scope and themes
- Budget
- Implementation

https://ep-dep.web.cern.ch/rd-experimental-technologies
(you find some more links there)

What have these things in common ?

EP R&D

Versatile links

DC-DC converters

GBT

On-detector powering

RD51

MPGD fabrication techniques

GIF++

Virtualisation

PS Irrad upgrade

ASICs in 130 nm technology

Multi core architectures

EP R&D

1. They play major roles in the LHC phase-I/II upgrades
2. They were initiated/boosted during the ''White Paper'' R&D program

(2008-2011)

Versatile links

DC-DC converters

GBT

On-detector powering

RD51

MPGD fabrication techniques

GIF++

Virtualisation

PS Irrad upgrade

ASICs in 130 nm technology

Multi core architectures

White Paper R&D program, based on an initiative of CERN DG Robert Aymar in 2006.
R&D budget in PH department ~20 MCHF (60% of what was asked). Program chaired by Lucie Linssen.

A bit of history (for the younger generation)

In the 1990s, we had a large-scale R&D program, monitored by the Detector R&D Committee (DRDC)

EP R&D

http://committees.web.cern.ch/Committees/obsolete/DRDC/Projects.html

RD-1	Scintillating fibre calorimetry at the LHC.	
RD-2	Proposal to study a tracking/preshower detector for the LHC.	
RD-3	Liquid argon calorimetry with LHC-performance specifications.	
RD-4	Study of liquid argon dopants for LHC hadron calorimetry.	
RD-5	Study of muon triggers and momentum reconstruction in a strong magnetic field for a muon detector at LHC.	
RD-6	Integrated high-rate transition radiation detector and tracking chamber for the LHC.	
RD-7	Proposal for Research and Development on a central tracking detector based on scintillating fibres.	
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RD-18	New fast and radiation hard scintillators for calorimetry at LHC.	★ Crystal Clear Collaboration. KT collaboration contract
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RD-47	High energy physics processing using commodity components HEP PC).	
RD-48	Further work on radiation hardening of silicon detectors.	
RD-49	Proposal for studying radiation tolerant ICs for LHC .	
RD-50	Development of Radiation Hard Semiconductor Devices for Very High Luminosity Colliders	★ LHCC monitored
RD-51	Development of Micro-Pattern Gas Detectors Technologies	★ LHCC monitored
RD-52	Dual-Readout Calorimetry for High-Quality Energy Measurements	
RD-53	Next generation of readout chips for the ATLAS and CMS pixel detector upgrades	★ LHCC monitored

★ active

Concept

- Experimental landscape beyond upgrades in LS3 is vague (with some exceptions). Update of ESPP (2018-2020) may give some hints … or not.
- Current studies like FCC (hh/ee), ILC, CLIC, give us relatively clear ideas what the experimental challenges may be.
- Development cycles are long: O(decade).
- R&D for LHC phase-II upgrades comes to an end around 2020
- Detector R&D requires expertise, experience and infrastructure. It can't be switched off/on but requires a certain continuity.

➡ **Define a 'strategic' technological R&D programme, rather than an experiment specific programme.**

(Experiment specific features will be added at a later stage and require different funding paths.)

Concept (2)

EP R&D

- We are defining an (initial) 5-year R&D programme of the CERN EP department, in close connection with external institutes (synergy / complementarity).
- R&D shall cover various detector technologies, infrastructure, electronics, software and experimental magnets
- EP activities shall focus on areas
  - where EP has very significant expertise and infrastructure
  - where EP plays a leading/unique role
  - which will be key for the success of future projects
  - Where a failure could be a showstopper
- Program will be adapted whenever experimental roadmap is updated.

Process

EP R&D

Lots of input from community, also from external groups

Some interaction with community; negotiations with steering committee

Work on full and short version of R&D document

20 Nov 2017

Kick-off meeting

- Announce idea
- Requirements

16 March 2018

R&D workshop I

- 8 working groups
- Ideas & Options

25 September 2018

R&D workshop II

- Selected topics
- Concrete work plans
- R&D report (draft)

1 Nov 2018

EP retreat

- Presented plan and budget, Fabiola present

18 Dec 2018

Deadline

- input to ESG

R&D themes

Working Groups → packages	Convenors
WP 1: Silicon detectors	Heinz Pernegger, Luciano Musa, Petra Riedler, Dominik Dannheim
WP 2: Gas detectors	Christoph Rembser, Eraldo Oliveri
WP 3: Calorimetry and light based detectors	Martin Aleksa, Carmelo D'Ambrosio
WP 4: Detector Mechanics^{++}	Corrado Gargiulo, Antti Onnela
WP 5: IC technologies	Federico Faccio, Michael Campbell
WP 6: High Speed Links	Paolo Moreira, Francois Vasey
WP 7: Software	Graeme Stewart, Jakob Blomer
WP 8: Detector Magnets	Herman Ten Kate, Benoit Cure

Steering committee

Philippe Farthouat, Roger Forty, Patrick Janot, Christian Joram (coordinator), Manfred Krammer (chair), Lucie Linssen, Pere Mato, Burkhard Schmidt, Werner Riegler

WP1: Silicon detectors

EP R&D

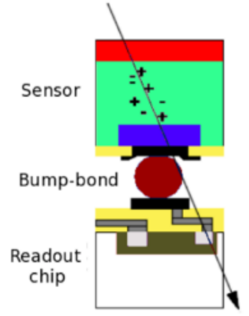
Parameter \ Experiments	LHC	HL-LHC	SPS	FCChh	FCCee	CLIC 3 TeV
Fluence [$n_{eq}/cm^2/y$]	N x 10^{15}	10^{16}	10^{17}	10^{16} - 10^{17}	<10^{10}	<10^{11}
Max. hit rate [$s^{-1}cm^{-2}$]	100 M	2-4 G****)	8G****)	20 G	20M ***)	240k
Surface inner tracker [m^2]	2	10	0.2	15	1	1
Surface outer tracker [m^2]	200	200	-	400	200	140
Material budget per inner 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*)	40 ps	~10^{-2}	~1k ***)	~5

- In general, at least an order of magnitude more radiation hardness than at LHC.
- High time resolution O(10ps)
- High hit rate / data rate
- Very low material budget

Convenors: Dominik Dannheim, Luciano Musa, Heinz Pernegger, Petra Riedler. Contributions from: Duccio Abbaneo, Michael Campbell, Victor Coco, Paula Collins, Michael Moll, Walter Snoeys + many from outside CERN

Module development

Interconnection technologies, integration concepts for pixel detectors, ultra-thin modules, highly integrated systems with high speed readout (photonics) and powering



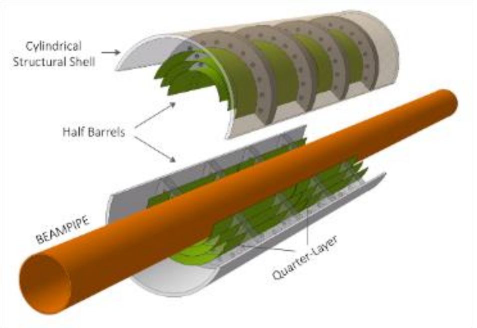
With 3D and LGAD sensors

Novel hybrid pixel detectors

Small pixels,
timing and high rate,
tile-able, minimize dead areas, radiation hardness

Monolithic pixel detectors

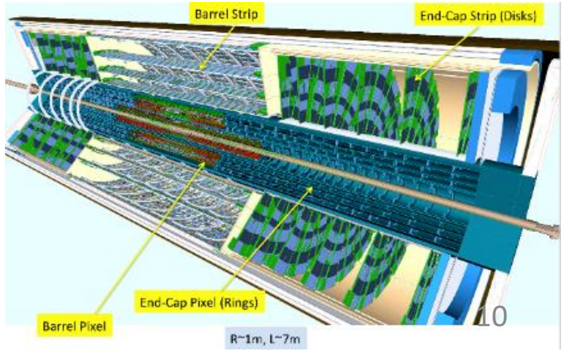
Depleted sensors,
low material budget,
large areas @ reduced cost, small pixels,
radiation hardness,
high rate



CMOS

Very high resolution, very low mass

very high radiation and rates



Simulation and characterization

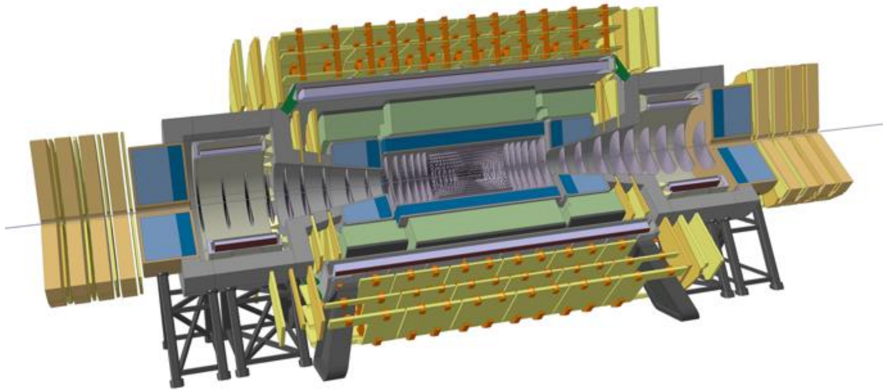
Simulation and modelling of detector response + radiation hardness, dedicated setups for characterization

In tight co-operation with RD50

WP2: Gas Detectors

EP R&D

- Any future large scale HEP experiment will rely on gas detectors.
- Areas may be huge! ➔ Need reliable cost effective technologies



Active areas (m^2)	
Micromegas and sTGCs	>2’000
GE1/1, GE2/1, ME0	>200
FCC-hh (Barrel, forward, very forward)	~10’000, 3’000,300

It depends how one counts

- A large part of the community is well connected via RD51. CERN plays a central role in this collaboration (management, test beam, lab space, test electronics & DAQ development). But CERN expertise is concentrated on very few people.
- Use of environment unfriendly gases has become an issue and must be addressed (similar for cooling fluids).

Convenors: Eraldo Olivieri, Christoph Rembser

Activity 1: Solutions for large area gas based detector systems

Experience: industrial production of large quantities of large area detectors is still difficult

Design, build & test full size prototypes (GEMs, MicroMegas or µRWELL) with focus on

- Industrialisation
- Performance scaling
- New materials, minimised services, minimised channels, embedded/distributed electronics

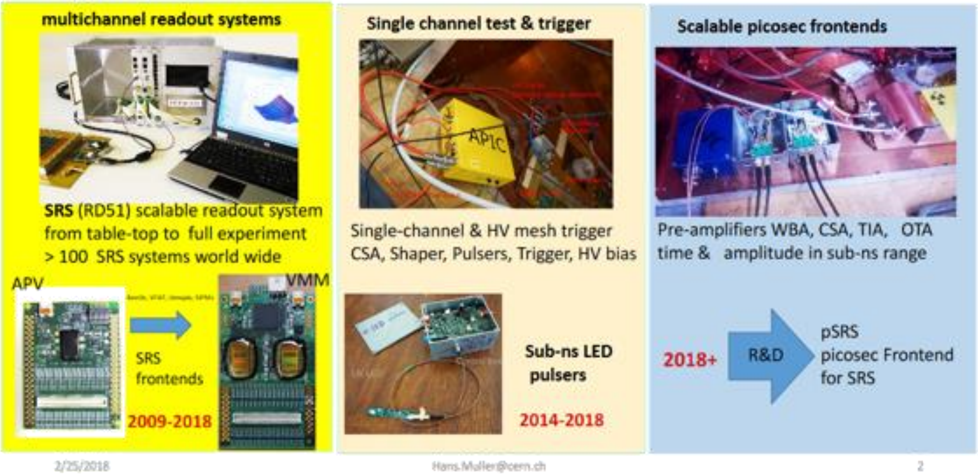
Activity 2: Tools for gas based detector R&D

- Gas analysis and gas studies;
- Simulation and modelling;
- Electronics and instrumentation (for characterisation and testing);

Garfield, Heed, Magboltz, Degrad, GEANT4, COMSOL, Field (Finite elements, boundary elements).

Activity 3: Development of novel technologies

- Very fast gas detectors (based on C-effect + photocathodes)
- Need long life photocathodes
- Explore additive production techniques (incl. 3D printing)



In case additional resources available:

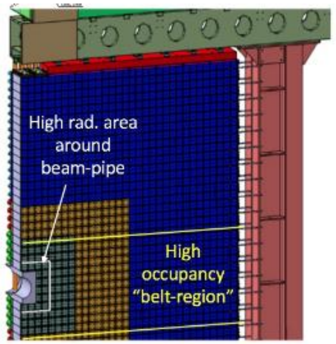
Activity 4: Fast optical read readout.

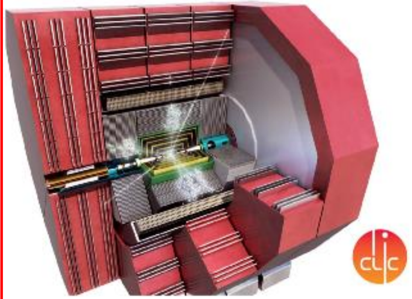
WP3: Calorimetry & Light Based Det's.

'Potential clients'

Light Based Det's.:
- Scintillating fibre technology
- Ring Imaging Cherenkov (RICH) detectors

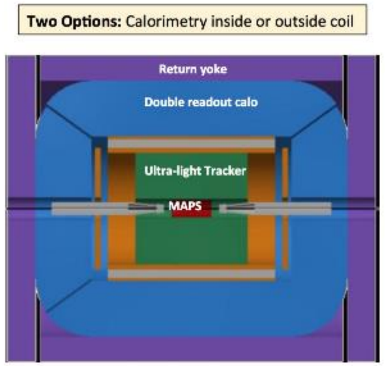
LHCb Upgrade II (2031): 3MGy, $3 \cdot 10^{15}$ n. require timing + good σ_E



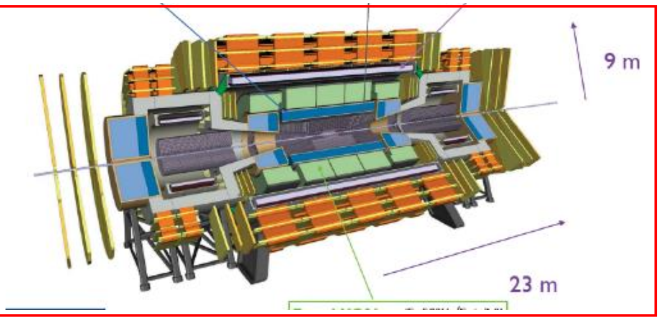


CLIC/ILC calorimeters optimized for Particle Flow (CALICE)

FCC-ee
excellent jet energy resolution, particle ID, Particle flow or dual readout



FCC-hh: extreme pile-up (up to 1000) High radiation ($2x10^{16}$ - $5x10^{18}$ n) in forward region), high granularity, high resolution, good timing

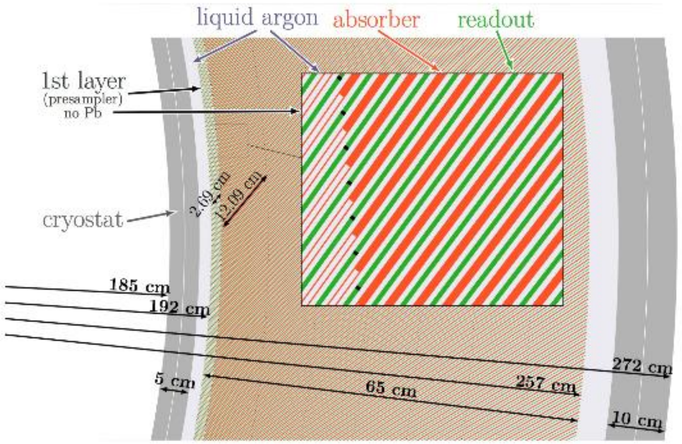


Convenors: Martin Aleksa and Carmelo D'Ambrosio

Activities

1) **High granularity noble liquid calorimetry (LAr),** reference design for FCC-hh, but potentially also interesting for FCC-ee.

   Electrode design, time resolution, LAr properties, high ionisation rates, cryogenic feedthroughs.



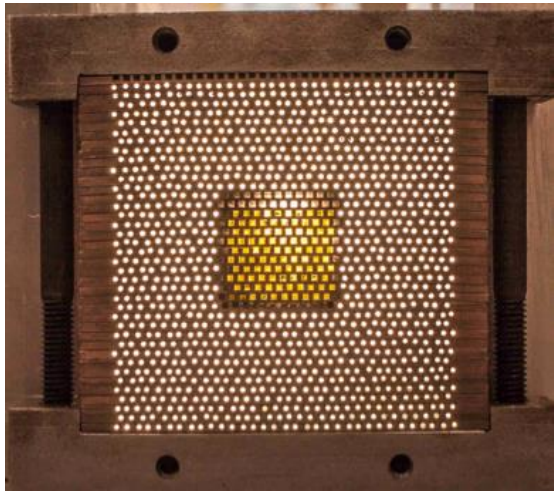
2) **Scintillator based calorimetry**. Good choice for hadronic calorimetry in FCC-hh,ee, CLIC, ILC, SHiP and LHCb ECAL upgrade II

   Material R&D (scint, WLS), photodetectors (SiPM) at low temperatures, calo type, timing. Profit from RD18 (Crystal Clear) expertise!

   Concentrate initially on 2 technologies

   - Tile-cal like HCAL (FCC-hh)

   - SPACAL ECAL studies (LHCb motivated).



LHCb test beam module (SPACAL) with various crystal and plastic fibre types

3) **High-granularity silicon-based sampling calorimeters** optimised for particle flow in CLICdet and CLD@FCC-ee.

   Much can be learned through the CMS HGCAL @ HL-LHC project, which we support!

   Further more specific studies shall follow at a later stage.

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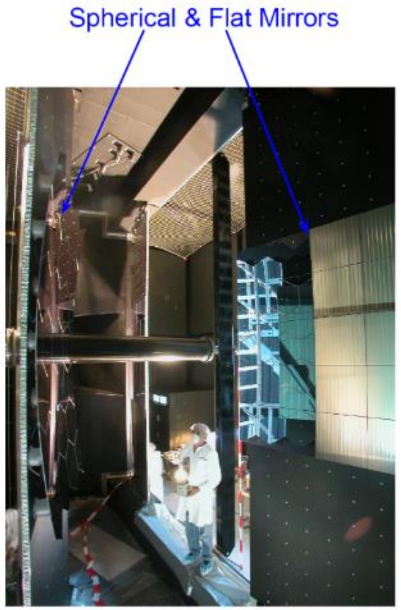
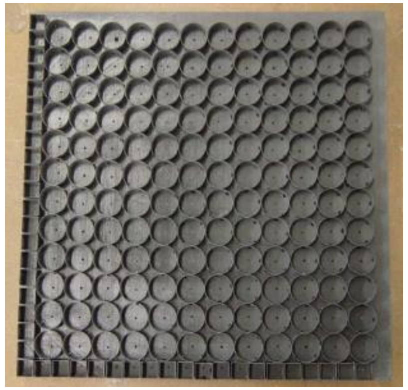
RICH and SciFi





LHCb intends to upgrade its RICH system for Run 5 (2031), entailing lots of challenges: optics, photodet's (SiPM), mirrors, mechanics, FE electronics.

It was agreed to concentrate on 2 aspects <u>for which CERN has specific expertise and infrastructure</u>:

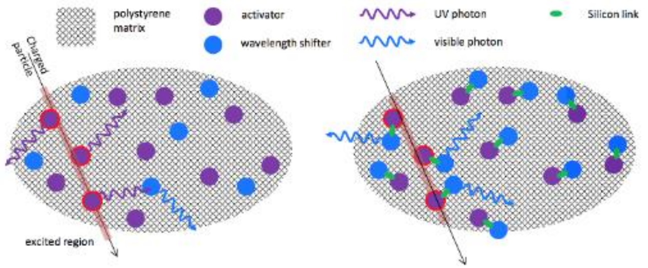
- **Light weight (CF) optical mirrors**
- **Special mechanics for photodetector housing** (at very low temperature).

The remaining aspects are covered by LHCb collaboration.

LHCb is currently building the world's largest SciFi tracker.
Modifications/upgrades are foreseen in LS3 and LS4

Two small activities are proposed, in the shadow of LHCb SciFi work

- Improve quality (light yield, speed) of scintillating fibres (e.g. NOL scheme)



- Investigate feasibility of fibre production by 3D printing

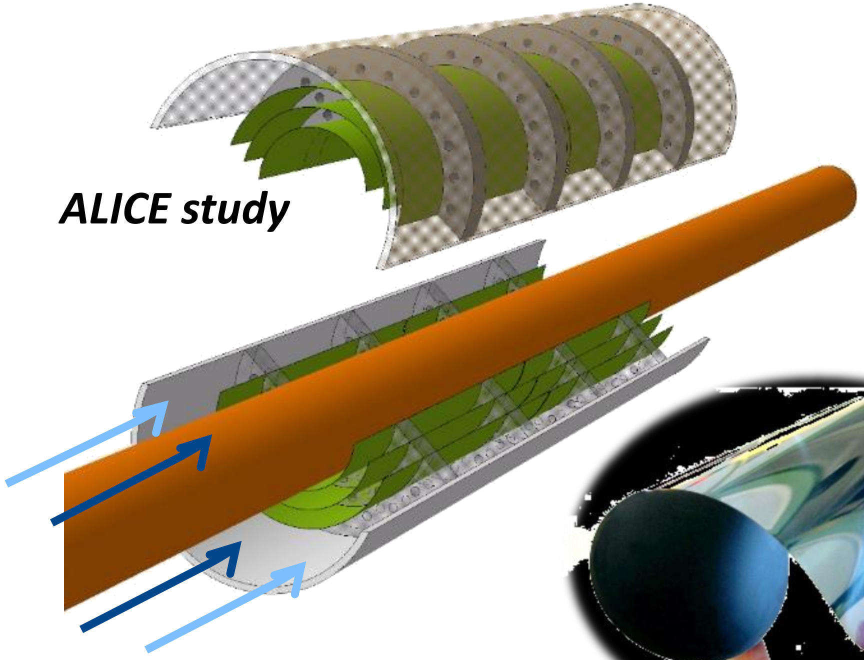
WP4: Detector Mechanics^{++}

- Structure Design
- Cooling Design
- Materials
- Processes
- Integration
- Installation
- Maintenance
- Environment and Stability

➢ **Activity 1** **Low mass mechanical structures for…**

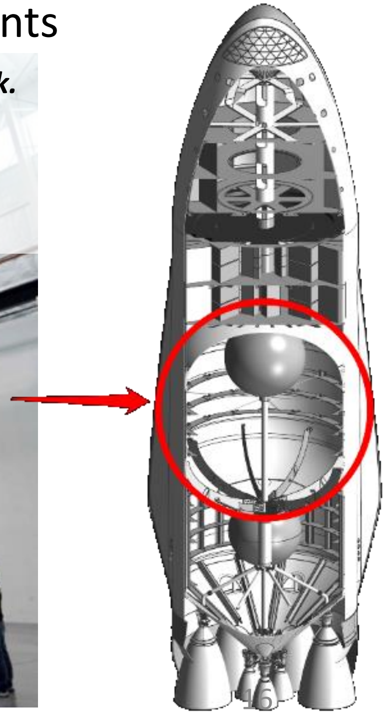
Task-1 **… future Tracking Detectors**

Task-2 **… future cryostats for Calorimeters and Detector Magnets**



Air flow cooling

Learn from latest industrial developments

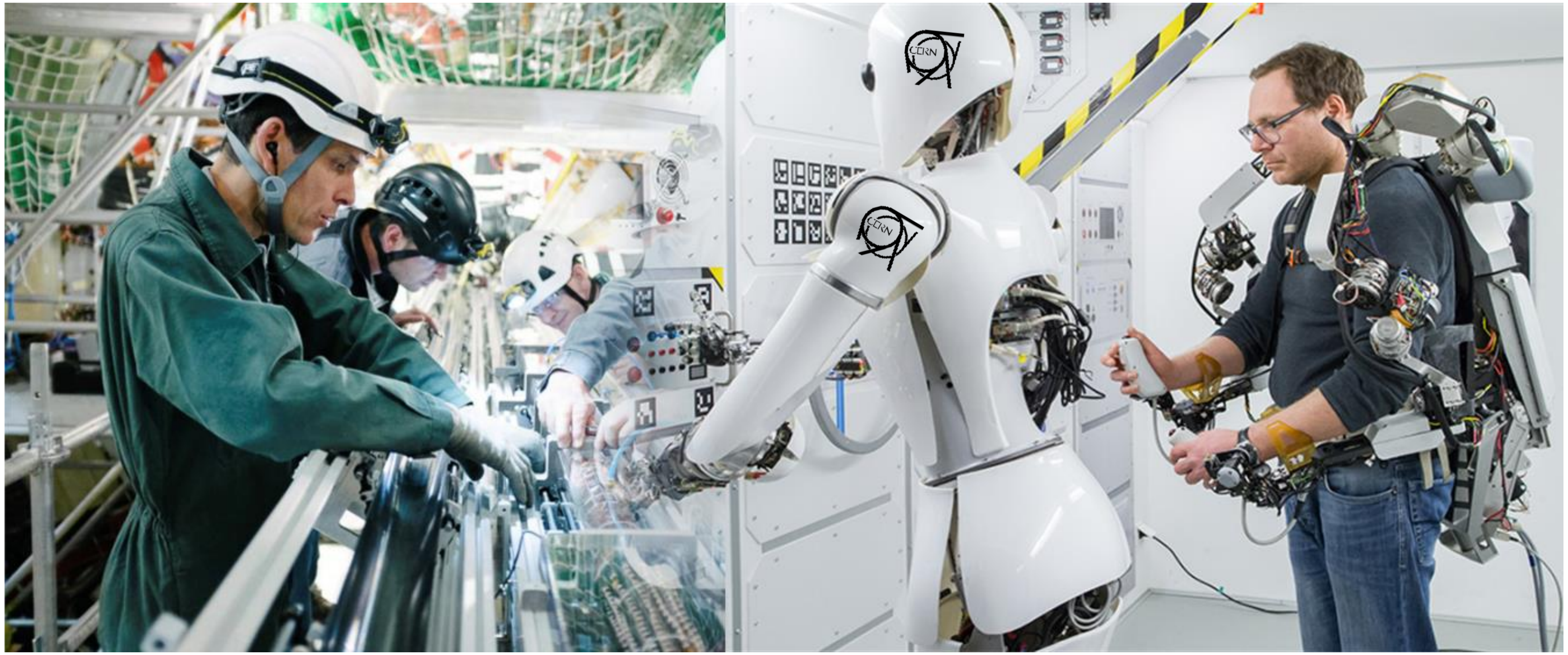


Convenors: Corrado Gargiulo and Antti Onnela

➢ Activity 2 New detector interfaces and services architectures for automated installation and maintainability in future high radiation environments

EP R&D

Today ➔ Tomorrow (or later)



At a certain moment such technologies will be badly needed. However, for the time being, we aren't sure that we have the budget.

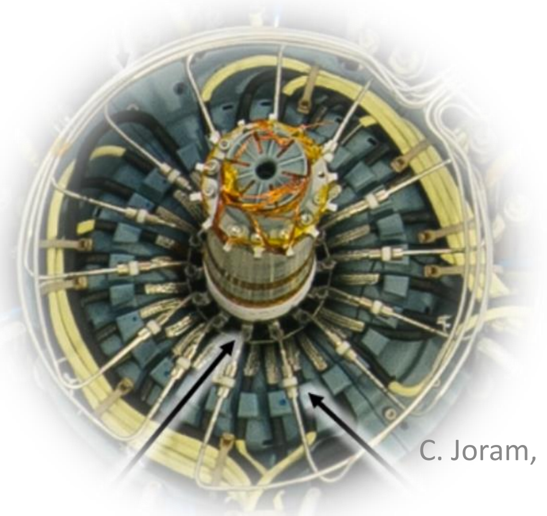
➢ Activity n.3 High-performance cooling for future detectors

- Future lepton collider: operation at ambient temperature may be a viable solution → 'simple' air cooling or liquid cooling for complex detector geometry
- Future hadron collider: more powerful cooling and also lower coolant temperature:

  → CO_2/N_2O are promising coolants, which are in addition environment-friendly

- **Cooling pipework and instrumentation** for large distributed systems

Cold transfer lines *in hadron collider detectors need to be* ***insulated*** *from the surroundings and installed in congested spaces.*



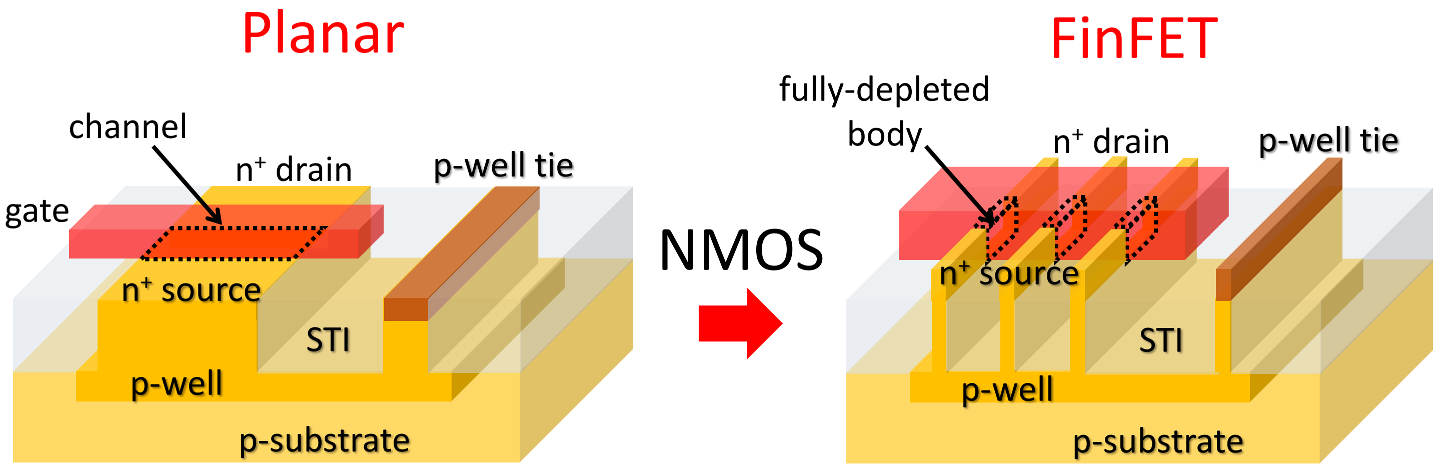
Minimize material budget of pipework

R&D on cheap and rad hard sensors *for pressure and flow reading*

WP5: Integrated Circuits

- Large parts of HEP community rely on CERN as technology platform (toolkits, libraries) and entry point to foundries

- Current HEP ASIC designs are in 130 and 65 nm technology ⇐⇒ industry is already at 7 nm (and below)
- Following the evolution should give performance increase (e.g. higher IO speed), but requires VERY substantial resources and efforts
- Standing still is anyway no option, as currently used processes will become unavailable.
- Below 22 nm, transistors are produced in FinFET technology, complicating design and fabrication process significantly.



1. Chose and evaluate technology → 2. Develop building blocks for ASICs

EP R&D

Survey technologies:
- 28nm planar
- 16nm FinFET

Activity 1
CMOS and assembly Technologies

CMOS Technologies

Radiation effects

CAD tools with emphasis on:
- reference design workflows
- mixed-signal design of complex chips (SOC)
- collaborative tools

Enablers (DKit, FrameContract, NDA, training)

Custom digital logic compilers

CMOS-related Assembly Technologies

Through-Silicon Vias (TSV)

CMOS wafer stacking

TSV increase data throughput. WP will bring TSV technology to 28 nm on 12'' wafers

Longer term: wafer stacking may make bump bonding obsolete

Activity 2
Design and IPs

Low-voltage and low-power design

Study of noise and matching performance

Design of circuit functions:
- Voltage reference generators
- Low-noise amplifiers
- Conversion: ADC, DAC
- Timing circuits: PLLs, DLLs, TDC
- Line drivers/receivers

Power distribution

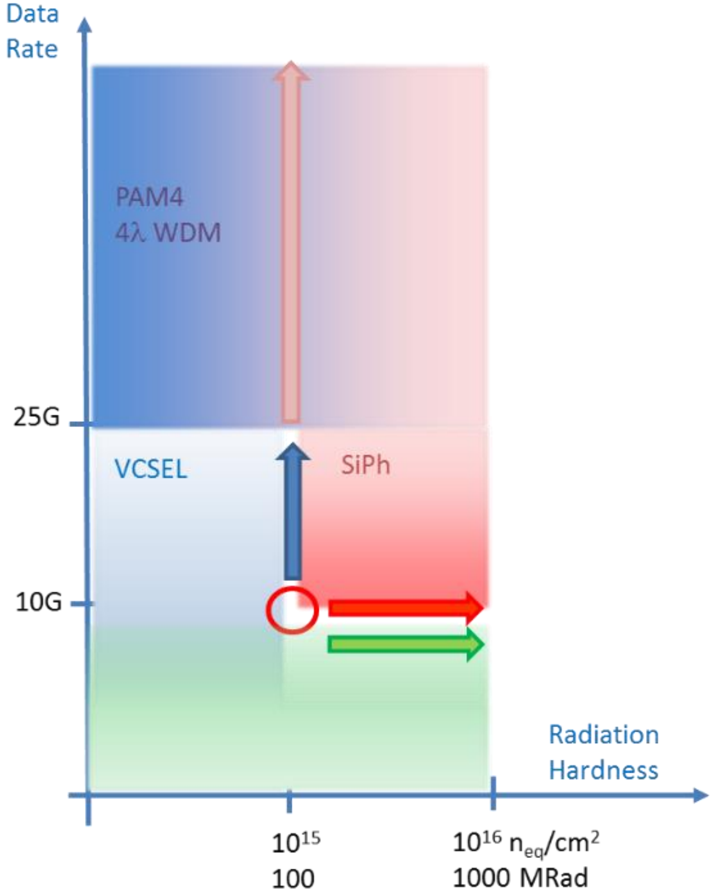
High efficiency POL converter (Vin >25V)

IP blocks for on-chip power management: converters and regulators

Improve on existing FEAST2 DCDC converters. Increased voltage rating (25V), rad hard, small, B-tolerant

WP6: High Speed Links

- Under development for HL-LHC: lpGBT 10 Gbps SER/DES + VCSEL drivers + TIA (65 nm)
- How to go beyond 10 Gbps and cope with higher radiation levels?



Ongoing development
HL-LHC, 2020
LpGBT-VL+ project

Future developments:

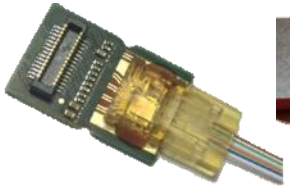
- Higher Data rates
- Si Photonics
- λ Multiplexing and multi-level signalling (PAM)
- Low mass copper links

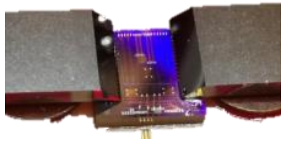
3 R&D activities were identified:

- ASICs

- FPGAs

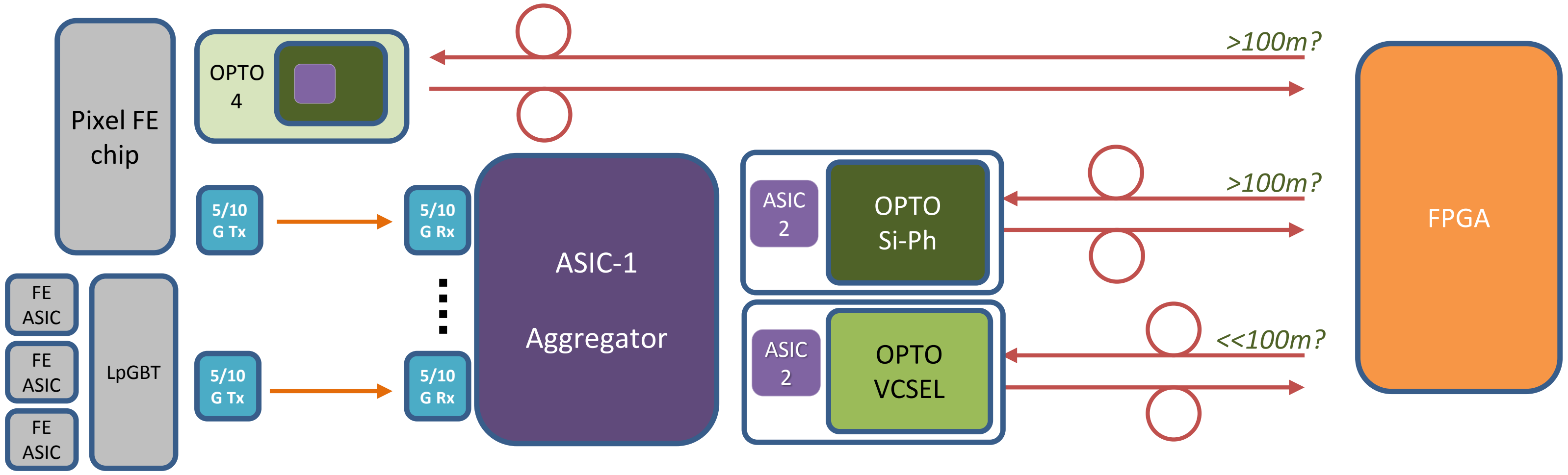
- Optoelectronics



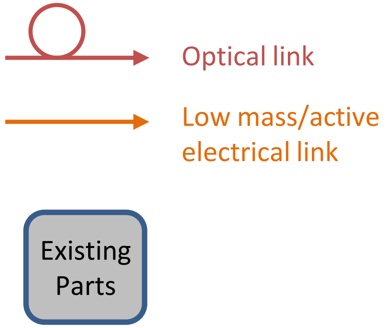


Convenors: P. Moreira and Francois Vasey

EP R&D



Activity	Task	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 & 2	Silicon Photonics System & Chip Design
		Silicon Photonics Radiation Hardness
	OPTO-3	Next-generation VCSEL-based optical link
	OPTO-4	Silicon Photonics packaging



WP7: Software

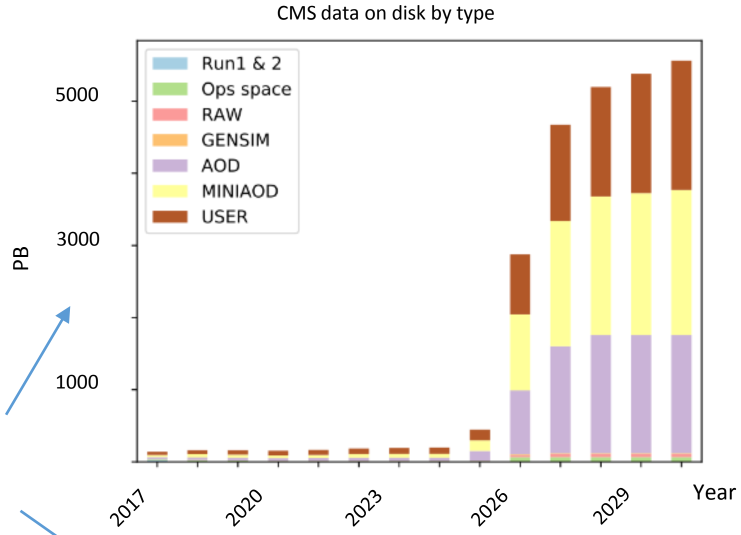
Major HEP Software Challenges for the 2020s

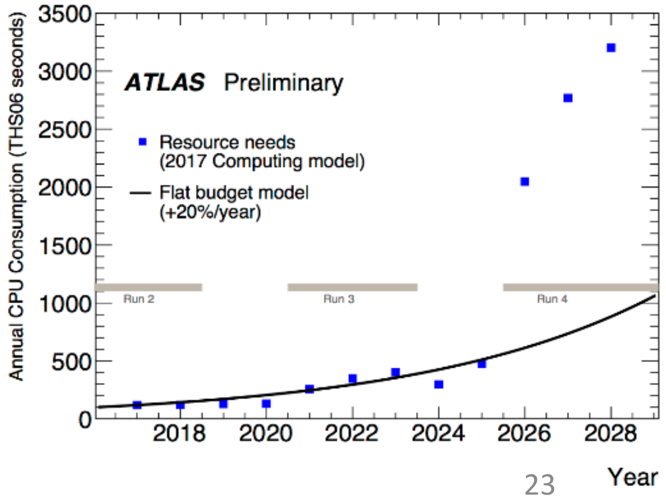
1. An order of magnitude higher event rates and event complexities at future hh colliders
2. Changing hardware landscape
   Specialized and more parallel processors and storage devices
3. …

Whatever the future, we pass through the HL-LHC on the way

HEP Software Foundation Community White Paper maps out that path

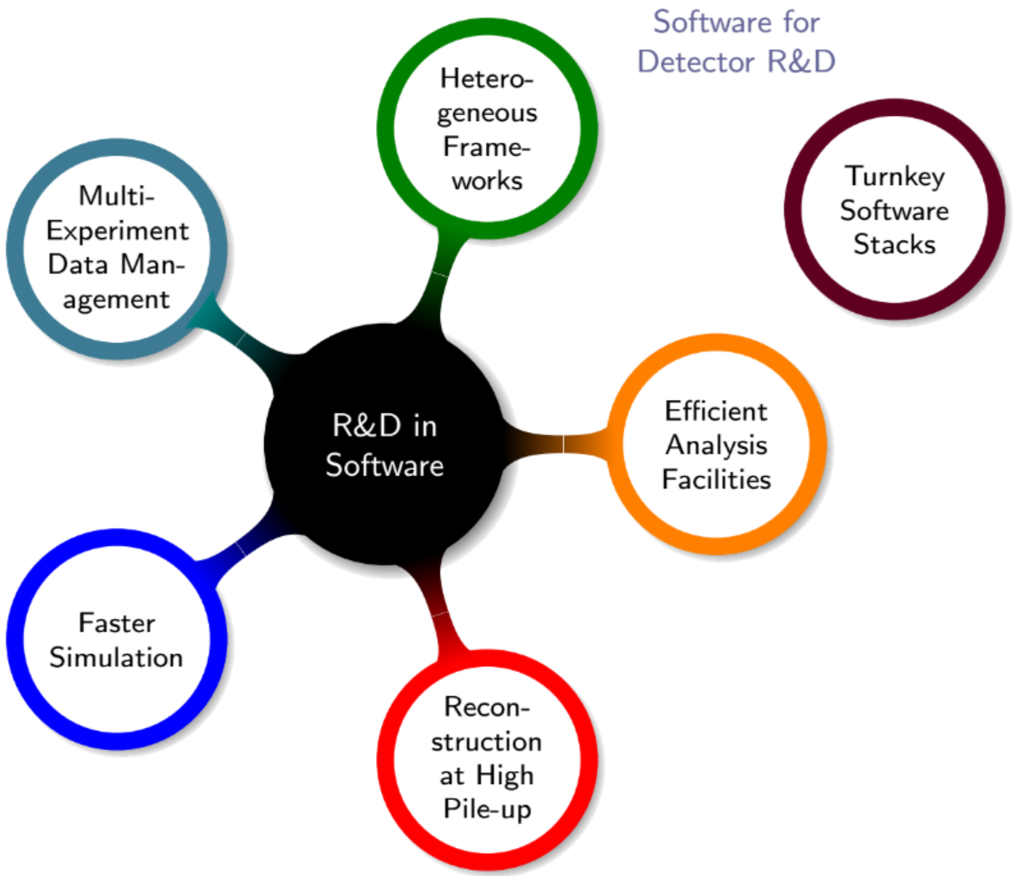
HL-LHC is far from being a solved problem for software and computing





Convenors: Graeme Stewart and Jakob Blomer

- 5 research lines addressing HEP software challenges
- Turnkey software stacks supporting of detector studies



Simulation: aim for 1 order of magnitude speed-up

Reconstruction: algorithms, hardware, ML for tracking with ultrahigh pile-up

Analysis: smart dataflow and bookkeeping to cope with 1-2 order of magn. higher event numbers and complexity.

Heterogenous computing: Use of hardware accelerators (GPU, FPGA, TPU, ASIC, etc.) across a large number of nodes

Data management across experiments: allows dynamic resource sharing. Examples are Rucio, DIRAC, ALiEN

Turnkey Software Stacks: Aim at a low-maintenance common core stack for FCC and CLIC that can “plug-in” a detector concept under study

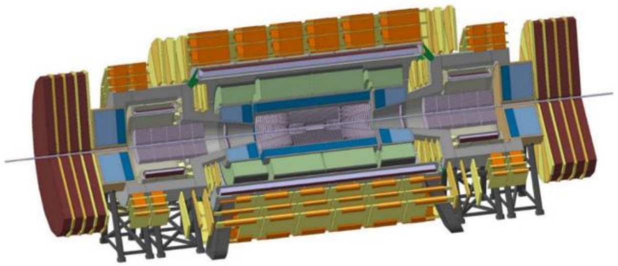
WP8: Detector Magnets

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

5 proposed activities

1. Advanced Magnet Powering for high stored energy detector magnets
2. Reinforced Super Conductors and Cold Masses
3. Ultra-Light Cryostat Studies
   Coord. By WP4 (mechanics)
4. New 4 tesla General Purpose Magnet Facility for Detector Testing
   Only study, no construction
5. Innovation in Magnet Controls, Safety & Instrumentation

R&D will use above 4T magnet as use case.



FCC with very large barrel and forward 4T solenoids

Convenors: Herman Ten Kate and Benoit Cure

1. **Advanced Magnet Powering for high stored energy detector magnets →** to improve stability and quench protection, reduce recovery and energy consumption.

2. **Reinforced Super Conductors and Cold Masses →** basis for building very low X_0 magnets (if solenoid inside e.m. calo).

3. **Ultra-Light Cryostat Studies**

→ part of a more general study in WP4 for light weight vessel structures (LAr calo, magnets, cryo SiPM box).

Design will be influenced by above technologies

CMS – 20 kA switch breakers for powering and discharging lines.

4. **New 4 T General Purpose Magn Facility for Detector Testing →** many detectors and equipment will have to work at 4 T. Today, there is no adequate test infrastructure available. Only design study is part of R&D. Budget O(10 M) for construction must come from a different source.

5. **Innovation in Magnet Controls, Safety & Instrumentation →** Sensors, electronics, DAQ for quench protection, magnet control, magnetic measurements

Instrumentation development can use 4T facility as use case.

Budget

Working groups estimated - for the agreed 5-year workplans - their needs in terms of

- material
- longer term investment (lab, instruments)
- fellows
- Students

These were scrutinized and squeezed by the steering group.

➔ Total budget request: 62.9 MCHF, i.e. 12.6 MCHF p.a. (fellows/students converted to money)
100 k p.a./ 50 k p.a.

In parallel, CERN management created, from 2020 on, a budget line “RDD - R&D for future detectors” and sources it with ~6 MCHF p.a. with a promise for ~8 MCHF p.a.

Problem: a part of the 8 MCHF is used to pay staff salaries. → For the time being, we are lacking a substantial part of the budget.

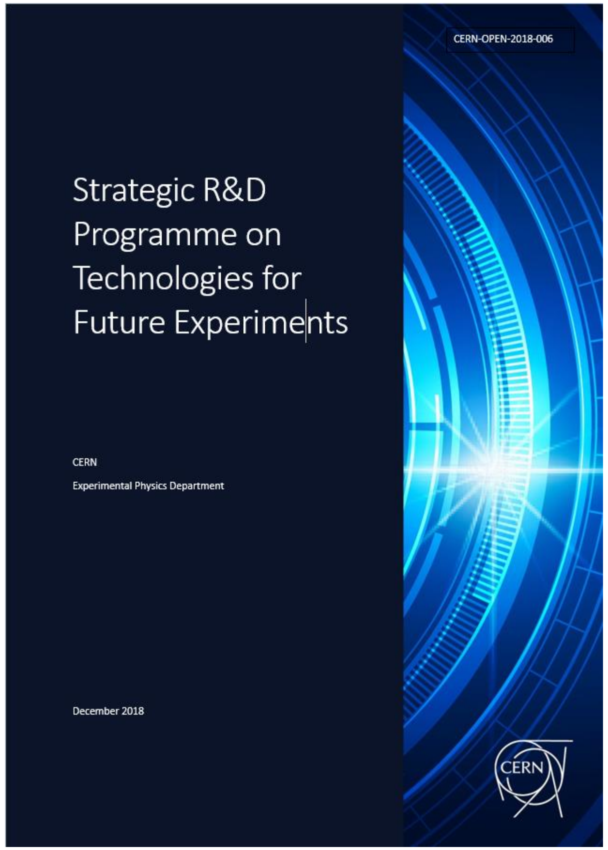
Implementation

EP R&D

- We intend to launch activities in 2020 and to ramp up to full speed during 2021.
- The main part of the R&D work is done by fellows and students, embedded in existing work environments (groups, labs, equipment, experience). We don't create a EP-RD group!
- The fellows are supervised by experts (staff), who devote a fraction (typically 0.1-0.3) of their time. Σ=22 FTE identified, distributed over some 70-80 people. We don't count them in the budget!
- Work is structured in 8 work packages and 38 activities, with WP and Activity leaders, who are also responsible for the smooth integration and supervision of the fellows and students.
- Need to find ways to give team of R&D fellows and students a common identity. Active webpage, team internal seminars and training,…
- Continuous follow-up and yearly progress reports. An 'R&D coordinator' is needed.
- Steering committee stays in place and is responsible for overall success.

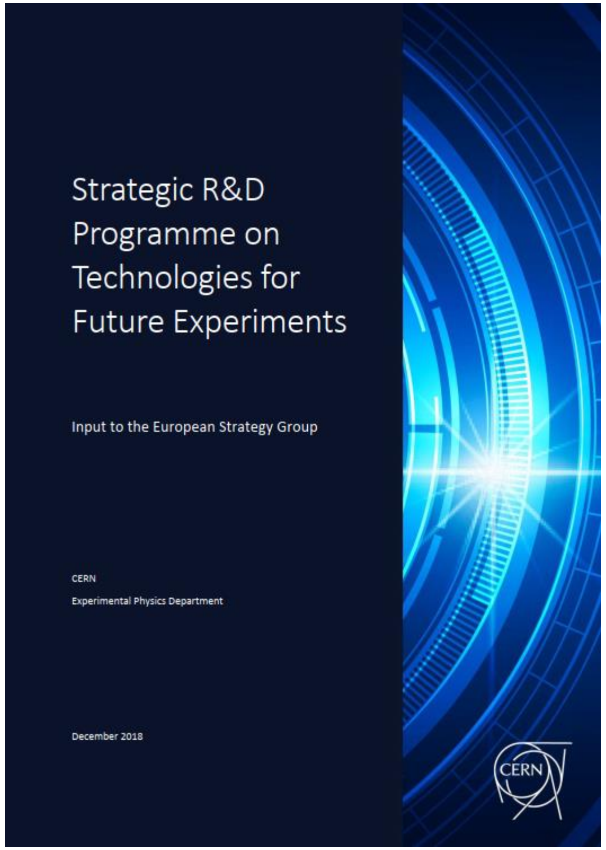
EP R&D

Documentation



R&D report, CERN-OPEN-2018-006, ~100 pages

https://cds.cern.ch/record/2649646



Input to the European Strategy Group, 10 pages
→ see EP R&D website

What's next ?

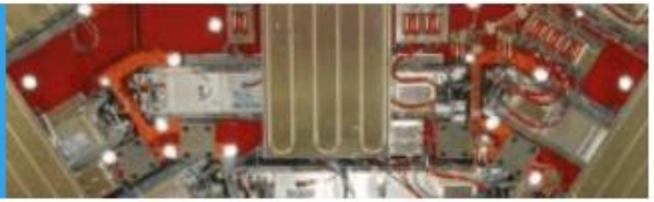
EP R&D

- Keep the momentum !
- Keep management under pressure to find more money. We are convinced that this R&D programme is needed!
- Vague idea of an R&D day in 2019. Invite community to present their plans. Discuss common activities, sharing of equipment, samples, …
- Consider to establish some R&D collaborations like RD50, RD51, … e.g. for detector mechanics, monolithic Si detectors, ASICs, … should bring in more people and allows external groups to request funding.

Also interesting …

EP R&D

ECFA-DP
ECFA Detector Panel



European Survey on Detector R&D

Phil Allport, Ariella Cattai, Silvia Dalla Torre, Doris Eckstein, Els Koffeman, Lucie Linssen, Laurent Serin, Arno Straessner

(The ECFA Detector Panel http://ecfa-dp.desy.de)

11. November 2018

- Scope: Particle and astro-particle physics
- Addressing R&D topics but also questions related to career opportunities and challenges
- 30 questions, 700 respondents.

ECFA Detector Panel Report

P. Allport, A. Cattai, S. Dalla Torre, D. Eckstein, E. Koffeman, L. Linssen, L. Serin, A. Straessner

The ECFA Detector Panel
(http://ecfa-dp.desy.de/ - ecfa-dp@desy.de)

Input to the European Strategy Group, 10 pages