ECFA Detector R&D Roadmap

21.2.2022

Susanne Kuehn, CERN
Overview

• The ECFA Detector R&D Roadmap process
• Overview of future facilities considered in the Roadmap and R&D organisation
• Examples on R&D of several detector technologies
  – Gaseous, Liquid and Solid State Detectors
  – Calorimetry, Particle identification and photon detectors, Quantum and emerging technologies
  – Microelectronics, Integration, Training
• Observations – General Strategic Recommendations
• Summary

Disclaimer: by far not complete list and coverage of all Detector R&D areas. Many specific talks in the sessions of the VCI.
“Organised by ECFA, a roadmap should be developed by the community to balance the detector R&D efforts in Europe, taking into account progress with emerging technologies in adjacent fields” *

The community should define a global detector R&D roadmap that should be used to support proposals at the European and national levels” *

Process organised by Panel and nine Task Forces with input sessions and open symposia, surveys with wide community consultation (1359 registrants)

Thank you for all input, contributions and comments!

* 2020 European Particle Physics Strategy Update https://europeanstrategyupdate.web.cern.ch/
Overview of future facilities

- Many different future facilities proposed/foreseen based on accelerators and non-accelerators
- Focus on the technical aspects of detector R&D requirements given the 2020 EPPSU deliberation document listed “High-priority future initiatives” and “Other essential scientific activities for particle physics” as input

The dates used in these diagrams have a deliberately low precision, and are intended to represent the earliest ‘feasible start date’ (where a schedule is not already defined), taking into account the necessary steps of approval, development and construction for machine and civil engineering. They do not constitute any form of plan or recommendation, and indeed several options presented are mutually exclusive.

Furthermore, the projects mentioned here are usually limited to those mentioned in the 2020 EPPSU, although it should be noted that detector R&D for other possible future facilities is usually aligned with that for programmes already listed.

The facilities are aligned with recently published Accelerator R&D Roadmap http://arxiv.org/abs/2201.07895

→ Many detector concepts at different future facilities
Task Forces started from the future science programme to identify main detector technology challenges to be met (both mandatory and highly desirable to optimise physics returns) and estimated the period over which the required detector R&D programmes may be expected to extend.

Within each Task Force created a time-ordered technology requirements driven R&D roadmap in terms of capabilities not currently achievable. It is also noted that in many cases, the programme for a nearer-term facility helps enable the technologies needed for more demanding specifications later, providing stepping stones towards these.

Developed and defined “Detector R&D Themes” (DRDTs) to highlight the most important drivers for research in each technology area and “Detector Community Themes” (DCTs) in the context of the training area (TF9).

General strategic recommendations for our field are collected in the chapter of general observations and considerations.
Detector R&D organisation

• Looking in the past:

Detector R&D

• From 1986, vigorous CERN programme with 40 MCHF funding from Italian government (Zichichi’s LAA Project)
• CERN Detector R&D Committee set up mid 1990. By March 1992: 35 proposals, 24 approved – involving 800 people in 170 institutes

Several processes conducted/ongoing to organise the Detector R&D (more details in spare slides)

– Technology oriented RD Collaborations: RD18, RD42, RD50, RD51, RD53, …
– US Basic Research Needs report and Snowmass Instrumentation Frontier process
– CERN EP R&D
– AIDAInnova
– ECFA Detector R&D Roadmap (Slides, Webpage)
– ….

Detector R&D readiness should not be the determining factor in the future of particle physics
Gaseous detectors

- Gaseous detectors: from Wire/Drift Chamber → Time Projection Chamber (TPC) → Micro-Pattern Gas Detectors

- Primary choice for large-area coverage with low material budget & dE/dx measurement (TPC, Drift chamber) & TOF functionality (MRPC, PICOSEC)

**Detector Readiness Matrices of each Task Force chapter** focus on the extent to which the R&D topic is *mission critical* to the programme than the intensity of R&D required

  - Must happen or main physics goals cannot be met
  - Important to meet physics goals
  - Desirable to enhance physics reach
  - R&D need being met
Gaseous detectors: area and timing

- Upgrades to a number of systems used at the LHC for tracking, muon spectroscopy and triggering have **taken advantage of the renaissance in gaseous detectors** (esp MPGDs)
- New generation of TPCs use MPGD-based readout: e.g. ALICE Upgrade, T2K, ILC CepC
- **Gaseous detectors offer very competitive timing** through e.g.
  - **Multi-gap Resistive Plate Chambers** (down to 60 ps time resolution) (ALICE TOF Detector, Z.Liu, NIM A927 (2019) 396)
  - An enabling emerging R&D: **Micromegas with timing** (PICOSEC concept)

  
  \[ \sigma \sim 25 \text{ ps per track} \]

*Many developments emerged from the R&D studies within the RD51 Collaboration*
Gaseous Detectors: eco-friendly gases

- 92% of emission at CERN related to large LHC experiments
- Thanks to gas recirculation GHG emission already reduced by > 90% wrt. to open mode systems!
- Many LHC gas systems with gas recuperation

Possible alternatives to GHG gases

- Alternative gases:
  - A lot of work especially in RPC community to search for alternative to C₂H₂F₄
  - Not an easy task to find new eco-friendly gas mixture for current detectors
The DRDTs of Task Force 1 Gaseous detectors

- The faded region acknowledges the typical time needed between the completion of the R&D phase and the readiness of an experiment at a given facility.
- Stepping stones are shown to represent the R&D needs of facilities intermediate in time.
- It should be emphasised that the future beyond the end of the arrows is simply not yet defined, not that there is an expectation that R&D for the further future beyond that point will not be needed.
Liquid detectors

- The DRDTs are

- Several large-scale and many small-scale experiments running or foreseen with liquid detectors

Underground Dark Matter Experiments – small and rare signals
R&D for multi-ton scale noble liquids:

- Target doping and purification
- Detector components radiopurity and background mitigation

Note: Developments in this field are rapid and it is not possible today to reasonably estimate the dates for projects requiring longer-term R&D.

Modified from L. Baudis

ARIA underground purification system for argon (DarkSide-20k)
Low-radioactivity argon: extraction (Urania plant, 330 kg/d), purification (ARIA facility, 10 kg/d)

Distillation columns for krypton and radon, material screening and selection, radon emanation
Solid State Detectors

- Many different silicon detector technologies for particle tracking have been developed over the last four decades:

  - Silicon strips
  - Multiplexing ASICs
  - CCDs

  DELPHI  
  CDF  
  CMS

- Remarkable: every decade the instrumented areas have increased by a factor of 10 while the numbers of channels in the largest arrays have increased by a factor of 100

- Solid state detectors more and more used for calorimetry and time-of-flight

They lead to these DRDTs:

New Challenges (see Detector Readiness Matrix in spare slides):

- Vertex detectors with low mass, high resolution (Target per layer spatial resolution of $\leq 3 \, \mu m$ and $x/x_0 \leq 0.05\%$ for FCC-ee), low power and high radiation hardness (up to $8 \times 10^{17} n_{eq}/cm^2$ for pp-colliders)

- Trackers: affordable sensors with low mass, high resolution, low power

- Large area and granular devices for calorimeters

- Detectors with ultra-fast timing ($O(10-100 \, ps)$) for PID, TOF

- Fully integrated with electronics, mechanics, services, …
CMOS MAPS

- Monolithic sensors combining sensing and readout elements
- Example: For FCC-ee vertex detector targeting spatial resolution per layer of ≤ 3µm and \( \frac{x}{x_0} \leq 0.05\% \), essential to have low power. Plus radiation-hardness up to \( 8 \times 10^{17} n_{eq}/cm^2 \) for pp-collider.

**CMOS MAPS for ALICE ITS3 (Run 4):**
(LOI: CERN-LHCC-2019-018, M. Mager)
- Three fully cylindrical, wafer-sized layers based on curved ultra-thin sensors (20-40 µm), air flow cooling
- Very low mass, < 0.02-0.04% per layer

**MIMOSA @ EUDET BeamTest Telescope → 3 µm track resolution achieved**

**Large area: stitching INMAPS process**

**Radiation hardness of MAPS:** From ALPIDE to MALTA/Monopix with modified Tower Jazz 180 nm process

\( \rightarrow \) Up to 97% efficiency after fluence of \( 1 \times 10^{15} n_{eq}/cm^2 \)

To achieve higher radiation hardness: Hybrid technologies with thin, 3D-structures (columns/trenches) silicon and/or high bandgap materials (e.g. diamond) are mostly considered for really high radiation environments.
Silicon timing detectors

LGAD: Fill factor & performance improvements

- Two opposing requirements:
  - Good timing reconstruction needs homogeneous signal (i.e. no dead areas and homogeneous weighting field)
  - A pixel-border termination is necessary to host all structures controlling the electric field

- Several new approaches to optimize/mitigate followed:

For LGADs, three main foundries (CNM, FBK, HPK), more producers interested

Time information hugely beneficial to suppress pile-up in pp-collisions

Areas of LGAD developments within RD50 Collaboration:
- Timing performance (~ 25 ps for 50 μm sensors)
- Fill factor and signal homogeneity
- Position resolution is about 5% of the distance between electrodes O(5-15 μm) (AC-LGAD)
- Radiation Hardness (~2x10^{15} n_{eq}/cm^2)
- Performance Parameterisation Model

Many more details in Nicolo Cartiglia’s invited talk on Friday

21.2.2022
ECFA Detector R&D Roadmap - Susanne Kuehn
**PID and Photon Detectors**

- **Particle Identification** (PID) essential to identify decays when heavy flavour are present: everywhere. *Used are dE/dx, Time-of-Flight and Cherenkov radiation*

- Many developments on vacuum photon detectors, solid state, gas-based and superconducting photon detectors

- Challenges for example for **SiPMs**: the high dark count rate and moderate radiation hardness prevented their use in RICH detectors where single photon detector required at low noise

- Challenges for **MCP-PMTs** is their price and they are not tolerant to magnetic fields, similarly **Large-Area Picosecond Timing Detectors** (LAPPD) which are promising but need in addition pixellation
Examples of trends in proximity focusing aerogel radiator RICHes:

- **Combination of proximity focusing RICH + TOF with fast new photon-sensors** → MCP-PMT or SiPM using Cherenkov photons from PMT window

- Use of focusing configuration, e.g. ARICH (Belle), Forward RICH (Panda)

- RICHes with proximity focusing: thin radiator (liquid, solid, aerogel) and low momenta

- **Time-Of-Flight (TOF) detectors**: use prompt Cherenkov light, fast gas detector

- RICHes with focalisation: extended radiator (gas), mandatory for high momenta

Cherenkov photons from PMT window can be used to positively identify particles below threshold in aerogel

P. Krizan @INSTR2020
T. Credo, 2004 IEEE NSS/MIC Conference Record

DRDTs:
Quantum and emerging technologies

- Quantum Technologies are a rapidly emerging area of technology development to study fundamental physics
- The ability to engineer quantum systems to improve on the measurement sensitivity holds great promise
- Many different sensor and technologies being investigated: clocks and clock networks, kinetic detectors, spin-based, superconducting, optomechanical sensors, atoms/molecules/ions, interferometry, ...
- Several initiatives started at CERN, DESY, UK, ...

Example: potential mass ranges that quantum sensing approaches open up for Axion searches

DRDTs

Many more details in Michael Doser’s invited talk on Friday
Calorimetry

- R&D in calorimetry has a particularly long lead-time due to the duration of the stage for experiment specific final prototyping, procurement, production, assembly, commissioning and installation.

- DRDTs:
  - **DRDT 6.1:** The enhanced electromagnetic energy and timing resolution most relevant in next decade for upgrades of ALICE and LHCb.
  - Example: MAPS based SiW ECALs

**ALICE FoCAL**
- ALPIDE CMOS sensor based 3cm×3cm area 24 layer stack

**CALICE**
- Integrated front-end and digital electronics
- 15 layers with 15360 channels
- 2.1 mm (x11) and 4.2 mm (x3) tungsten
- Culmination of 10 years of prototyping

Good energy resolution

https://aitanatop.ific.uv.es/aitanatop/siwecal-tb2021/
Calorimetry

**DRDT 6.2: Particle Flow based on high granularity calorimeters** particularly important for $e^+e^-$ Higgs-EW-top factories and to be considered for EIC. Separation of signals by charged and neutral particles in highly granular calorimeters.

**Options are:**

- **Dual-readout** (e.g. DREAM/RD52 Collaboration, **FCC-ee IDEA**): $f_{EM}$ from absorber with combined scintillator parallel plates for non-relativistic (hadronic) component and Cherenkov for relativistic (EM) component (PMMA fibres);

- **High granularity LAr/LKr**: LAr proven technique but high granularity challenging;

- **Finely segmented crystals** (**RD18 Collaboration**);

- **Particle Flow based “tracking calorimeter”** concept with very fine sense element segmentation for precise reconstruction of each particle within the jet. Up to $\sim 100$M channels and 10000 m$^2$ active elements

**DRDT 6.3: Extreme radiation hardness and pile-up rejection** critical for FCC-hh in particular

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With thanks for help to Roman Pöschl, Fabrizio Salvatore and Nige Watson

From P. Allport

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21.2.2022
Electronics

- **Precision timing** (TOF; 4D-tracking), **ultra-high granularity** and improved signal **resolution** all come at a cost in terms of data handling, processing, complexity and power.
- These inevitably **require exploiting the latest advances in commercial microelectronics and high-speed links.**
- The need for bespoke solutions for even modest radiation or magnetic fields is a further problem as these are not commercial drivers, with HEP at best a niche low volume market.
- For example: Long time to develop radiation tolerance in 65 nm O(Grad) and large cost → technology is not straightforward;

  RD53 Collaboration
  (65 nm ASIC for HL-LHC)

- HEP Community now looks into 28 nm for the future and dedicated 130/65 nm technologies for monolithic pixels

However, increasing sophistication, entry **cost and complexity** demand **radically different approaches** to those historically adopted by the HEP community
Much of the ECFA Detector R&D Roadmap is dedicated to discussion of the need for better organisation and coordination across Europe to cope with these considerable challenges.

The DRDTs are:

- **DRDT 7.1**: Advance technologies to deal with greatly increased data density
- **DRDT 7.2**: Develop technologies for increased intelligence on the detector
- **DRDT 7.3**: Develop technologies in support of 4D- and 5D-techniques
- **DRDT 7.4**: Develop novel technologies to cope with extreme environments and required longevity
- **DRDT 7.5**: Evaluate and adapt to emerging electronics and data processing technologies
Integration

• DRDTs:

  • Investigation of **novel superconductors for magnet systems** as well as support of expert design capabilities and modelling software for future experiments is vital.
  
  • **Cooling technologies** for cryogenics and low-mass heat removal from on-detector electronics and semiconductor sensors require dedicated generic R&D activities.

  • **Ultra low mass, stable, precision mechanics** and **machine detector interface design** are major topics.

Example: Pipe/cooling design
Training for instrumentation

- A structured training programme shall support the scientists in their career
- Increase participation of young scientists, in particular graduate students, in leading-edge instrumentation R&D, and to foster growth of future HEP instrumentation experts who can compete for permanent positions

Possible structure of a training plan recommendation

Personnel, retention and training of detector experts are detailed in the ECFA Detector R&D Roadmap as mandatory to the success as well as the long-term health of experimental particle physics as a whole.
General Strategic Recommendations

• GSR 1 - Supporting R&D facilities
It is recommended that the structures to provide Europe-wide coordinated infrastructure in the areas of: test beams, large scale generic prototyping and irradiation be consolidated and enhanced to meet the needs of next generation experiments with adequate centralised investment to avoid less cost-effective, more widely distributed, solutions, and to maintain a network structure for existing distributed facilities, e.g. for irradiation

• GSR 2 - Engineering support for detector R&D
In response to ever more integrated detector concepts, requiring holistic design approaches and large component counts, the R&D should be supported with adequate mechanical and electronics engineering resources, to bring in expertise in state-of-the-art microelectronics as well as advanced materials and manufacturing techniques, to tackle generic integration challenges, and to maintain scalability of production and quality control from the earliest stages.

• GSR 3 - Specific software for instrumentation
Across DRDTs and through adequate capital investments, the availability to the community of state-of-the-art R&D-specific software packages must be maintained and continuously updated. The expert development of these packages - for core software frameworks, but also for commonly used simulation and reconstruction tools - should continue to be highly recognised and valued and the community effort to support these needs to be organised at a European level.

• GSR 4 - International coordination and organisation of R&D activities
With a view to creating a vibrant ecosystem for R&D, connecting and involving all partners, there is a need to refresh the CERN RD programme structure and encourage new programmes for next generation detectors, where CERN and the other national laboratories can assist as major catalysts for these. It is also recommended to revisit and streamline the process of creating and reviewing these programmes, with an extended framework to help share the associated load and increase involvement, while enhancing the visibility of the detector R&D community and easing communication with neighbouring disciplines, for example in cooperation with the ICFA Instrumentation Panel.
General Strategic Recommendations

• **GSR 5 - Distributed R&D activities with centralised facilities**

Establish in the relevant R&D areas a distributed yet connected and supportive tier-ed system for R&D efforts across Europe. Keeping in mind the growing complexity, the specialisation required, the learning curve and the increased cost, consider more focused investment for those themes where leverage can be reached through centralisation at large institutions, while addressing the challenge that distributed resources remain accessible to researchers across Europe and through them also be available to help provide enhanced training opportunities.

• **GSR 6 - Establish long-term strategic funding programmes**

Establish, additional to short-term funding programmes for the early proof of principle phase of R&D, also **long-term strategic funding programmes to sustain both research and development of the multi-decade DRDTs** in order for the technology to mature and to be able to deliver the experimental requirements. Beyond capital investments of single funding agencies, international collaboration and support at the EU level should be established. In general, the cost for R&D has increased, which further strengthens the vital need to **make concerted investments**.

• **GSR 7 – “Blue-sky” R&D**

It is essential that adequate resources be provided to support more speculative R&D which can be riskier in terms of immediate benefits but can bring significant and potentially transformational returns if successful both to particle physics: unlocking new physics may only be possible by unlocking novel technologies in instrumentation, and to society. Innovative instrumentation research is one of the defining characteristics of the field of particle physics. **“Blue-sky” developments in particle physics have often been of broader application and had immense societal benefit.** Examples include: the development of the World Wide Web, Magnetic Resonance Imaging, Positron Emission Tomography and X-ray imaging for photon science.
General Strategic Recommendations

• **GSR 8 - Attract, nurture, recognise and sustain the careers of R&D experts**

Innovation in instrumentation is essential to make progress in particle physics, and **R&D experts are essential for innovation**. It is recommended that ECFA, with the involvement and support of its Detector R&D Panel, continues the **study of recognition with a view to consolidate the route to an adequate number of positions with a sustained career in instrumentation R&D** to realise the strategic aspirations expressed in the EPPSU. It is suggested that **ECFA should explore mechanisms to develop concrete proposals in this area and to find mechanisms to follow up on these in terms of their implementation**.

Consideration needs to be given to creating sufficiently attractive remuneration packages to retain those with key skills which typically command much higher salaries outside academic research. It should be emphasised that, in parallel, society benefits from the training particle physics provides because the knowledge and skills acquired are in high demand by industries in high-technology economies.

• **GSR 9 - Industrial partnerships**

It is recommended to **identify promising areas for close collaboration between academic and industrial partners**, to create international frameworks for exchange on academic and industrial trends, drivers and needs, and to **establish strategic and resources-loaded cooperation schemes on a European scale to intensify the collaboration with industry**, in particular for developments in solid state sensors and micro-electronics.

• **GSR 10 – Open Science**

It is recommended that **the concept of Open Science be explicitly supported in the context of instrumentation**, taking account of the constraints of commercial confidentiality where these apply due to partnerships with industry. Specifically, for publicly-funded research the default, wherever possible, should be open access publication of results and it is proposed that the Sponsoring Consortium for Open Access Publishing in Particle Physics (SCOAP³) should explore ensuring similar access is available to instrumentation journals (including for conference proceedings) as to other particle physics publications.
8 page synopsis brochure prepared for less specialist audience
Summary

• The ECFA Detector R&D Roadmap has been prepared by a large team of internationally recognised leaders in this area with access to a much wider pool of other instrumentation experts. It has been the product of wide community consultation with very broad participation.

• The draft document was iterated with the RECFA delegates and National Contacts with numerous helpful comments received from committees looking at this in a number of countries and very valuable feedback from neighbouring disciplines where there are strong synergies between instrumentation needs.

• The results of all the feedback have been implemented in the final 248 page version and additional non-expert 8 page synopsis which was formally approved by Plenary ECFA on 19th November 2021.

• Many technological challenges and several examples were presented in this talk → Highlighting the need for a lot of further Detector R&D

• Mission critical for different facilities means different things.

• Major R&D funding for the LHC detector R&D programme was in place from 1986. Without the required investment in detector R&D the opportunities the future facilities offer will be squandered.

• The next step will be for mechanisms to be proposed for implementing the final recommendations.
Thank you!

Acknowledgment
Phil Allport, Laura Baudis, Kerstin Borras, Corrado Gargiulo, Sunil Gowala, Christian Joram, Manfred Krammer, Thomas Peitzmann, Roman Pöschl, Frank Simon, Maxim Titov, the ECFA Roadmap Panel
**Snowmass Instrumentation Frontier:** The Snowmass Process is organized by the DPF of the American Physical Society: [https://snowmass21.org](https://snowmass21.org)
- Identify and document a vision for the future of particle physics (PP) in the US in a global context
- Communicate opportunities for discovery in PP to broader community and to the (US) government.
- Aim for Snowmass Book and online archive by end of 2022

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<th>Snowmass Report « Community-Driven »:</th>
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<tbody>
<tr>
<td>IF Frontier Summary: 40 pages</td>
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<td>(Written by TG members including early careers)</td>
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<tr>
<td>Snowmass Report</td>
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<tr>
<td>Executive Summary: ~10 pages</td>
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<tr>
<td>Introduction</td>
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<td>10 Frontier Executive Summaries</td>
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<td>Executive Summaries of Multi-Frontier Topics</td>
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<tr>
<td>Conclusion</td>
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<td>Snowmass Summary Report (~50 pages)</td>
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<td>Frontier Summaries (~400 pages with 10 Frontiers)</td>
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<td>Multi-Frontier Topic Summaries (~50 pages)</td>
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<td>Snowmass Book ~500 pages</td>
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<td>Topical Group Reports: short reports</td>
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<td>Reports of Multi-Frontier Topics</td>
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<td>Contributed Papers = White Papers</td>
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<td>References</td>
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**DOE-BRN Report** published (Sep. 2020)
[https://science.osti.gov/hep/Community-Resources/Reports](https://science.osti.gov/hep/Community-Resources/Reports)
CERN EP R&D

- Following tradition of DRDC (LHC Phase-0), White Paper R&D (LHC Phase-I)
- Target beyond approved LHC upgrades: e.g. FCC-ee/eh/hh
- Strong links/overlap with RD50, RD51, RD18 and AIDAinnova

See materials at [https://ep-rnd.web.cern.ch](https://ep-rnd.web.cern.ch)
**EU: AIDAinnova Project and Detector R&D for Higgs Factories**

**New AIDAinnova Call / Objectives:**
- Support research *infrastructure* networks developing and implementing a *common strategy/ roadmap* including technological development required for improving their services through *partnership with industry*
- Support *incremental innovation* and cooperation with industry
- Complementarity to ATTRACT
- Increased focus on industrial partners
- No Transnational Access Proposed
- Funding 10 M€ for 4 years

**Higgs Factory Detector R&D**

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<tr>
<th>Detector Technology</th>
<th>Linear &amp; Circular Colliders common R&amp;D</th>
<th>Differences</th>
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<tbody>
<tr>
<td>All</td>
<td>test infrastructure prototype electronics software for reconstruction and optimisation</td>
<td>readout rates power and cooling requirements</td>
</tr>
<tr>
<td>Silicon Vertex and Track Detectors</td>
<td>highest granularity and resolution, timing ultra-thin sensors and interconnects simulation and design tools low-mass support structures cooling micro-structures</td>
<td>emphasis on timing (background) and position resolution</td>
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<tr>
<td>Gaseous Trackers and Muon Chambers</td>
<td>ultra-light structures for large volumes industrialisation for large area instrumentation eco-friendly gases</td>
<td>DC and TPC presently considered only at some colliders</td>
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<tr>
<td>Calorimeters and Particle ID</td>
<td>highly compact structures and interfaces advanced photo-sensors and optical materials ps timing sensors and electronics</td>
<td>emphasis on granularity and stability DR and LAr presently only considered for circular</td>
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**Some targeted applications:**
- Higgs Factories
- ATLAS, CMS LS4, ALICE, LHCb LS3 pre-TDR
- Accelerator-based neutrino experiments

F. Sefkow: [https://indico.cern.ch/event/932973/contributions/4066737/attachments/2140131/3606033/Ainnova-HiggsF-FSefkow20201110.pdf](https://indico.cern.ch/event/932973/contributions/4066737/attachments/2140131/3606033/Ainnova-HiggsF-FSefkow20201110.pdf)
Technology oriented R&D Collaborations

- Originally: "Cell" approach, oriented to select the different LHC experiment detector technologies within CERN DRDC program (90’s): [http://committees.web.cern.ch/Committees/obsolete/DRDC/Projects.html](http://committees.web.cern.ch/Committees/obsolete/DRDC/Projects.html)

- **Today: Successful approach to streamline efforts/resources, handle new techniques and common components to on-going detector engineering challenges/production:**
  - RD18 Crystal Clear, inorganic scintillators for crystal electromagnetic calorimeters at LHC
  - RD42 CVD Diamond radiation detector development
  - RD50 Radiation hard semiconductor devices for very high luminosity colliders
  - RD51 Development of Micro-Pattern gas detectors technologies
  - RD53 Pixel readout chip for ATLAS and CMS (65 nm) at HL-LHC

- In general, large collaborations of interacting institutes, mostly EU-based with world-wide participation

- Good model, allows to consolidate resources, especially people

- CERN is central, but support needed from other labs and agencies

- **Detector R&D Programs –originally focused on ILC and CLIC Linear Colliders** to exploit complementary/commonalities of technological developments for different facilities

- **CALICE high granularity electromagnetic and hadronic calorimeters (since 2001 for ILC)**
  - CALICE enabled high granularity calorimetry for CMS HL-LHC upgrade
ECFA Detector R&D Roadmap

Main Document published (approval by RECFA at 19/11/21 [https://indico.cern.ch/event/1085137/]) and 8 page synopsis brochure prepared for less specialists audience
ECFA Detector R&D Roadmap: Technologies

- Within each Task Force created a time-ordered technology requirements driven R&D roadmap in terms of capabilities not currently achievable. It is also noted that in many cases, the programme for a nearer-term facility helps enable the technologies needed for more demanding specifications later, providing stepping stones towards these.

- The principle is that for the earliest feasible start dates of a proposed facility (including those which are still considered in the EPPSU, but would be mutually exclusive):
  - the basic detector R&D phase is not the time limiting step, i.e. that R&D is started sufficiently early and prioritised correctly to meet the needs of the long-term European particle physics programme in its global context;
  - the outcomes of the R&D programme are able to provide the necessary information on the feasibility and cost of future deliverables to allow such decisions to be made.

- Developed and defined “Detector R&D Themes” (DRDTs) to highlight the most important drivers for research in each technology area and Detector Community Themes (DRDTs) in the context of the training area (TF9).

- The relevant Task Forces have then identified a set of detector R&D areas which are required if the physics programmes of experiments at these facilities are not to be compromised.
Main report: “Recent initiatives with a view towards strategic R&D on detectors are being taken by CERN’s EP department and by the ECFA detector R&D panel, supported by EU-funded programmes such as AIDA and ATTRACT. Coordination of R&D activities is critical to maximise the scientific outcomes of these activities and to make the most efficient use of resources; as such, there is a clear need to strengthen existing R&D collaborative structures, and to create new ones, to address future experimental challenges of the field beyond the HL-LHC. Organised by ECFA, a roadmap should be developed by the community to balance the detector R&D efforts in Europe, taking into account progress with emerging technologies in adjacent fields.”

Deliberation document: “Detector R&D programmes and associated infrastructures should be supported at CERN, national institutes, laboratories and universities. Synergies between the needs of different scientific fields and industry should be identified and exploited to boost efficiency in the development process and increase opportunities for more technology transfer benefiting society at large. Collaborative platforms and consortia must be adequately supported to provide coherence in these R&D activities. The community should define a global detector R&D roadmap that should be used to support proposals at the European and national levels.”

Extracted from the documents of 2020 EPPSU, [https://europeanstrategyupdate.web.cern.ch/](https://europeanstrategyupdate.web.cern.ch/)

More roadmap process details at: [https://indico.cern.ch/e/ECFADetectorRDRoadmap](https://indico.cern.ch/e/ECFADetectorRDRoadmap)
Thanks also due to the expert Input Session speakers, respondents to the Task Force surveys, the 121 Symposia presenters, the 1359 Symposia attendees and the 44 APOD TF topic specific contacts.
Organisation

May 2020
EPPSU mandate to ECFA to develop a roadmap for detector R&D efforts in Europe

Sep 2020
Structure in place with Detector R&D Roadmap Panel

Dec 2020
Task Forces active

Website:
https://indico.cern.ch/e/ECFADetectorRDRoadmap

Expert & Community Consultation

Feb 2021
Collection of requirements of future facilities & projects

Feb/March 2021
Questionnaires of Task Forces to national contacts

Task Forces liaise with experts in
• ECFA countries
• adjacent disciplines
• industry

March-May 2021
Open Symposia

Drafting Roadmap & Feedback

May 2021
Task Forces collate input from symposia

25-28 May 2021
Drafting sessions
• opening session with all experts involved
• plenary & parallel sessions with Task Force members
• final session of Roadmap Panel

July 2021
Near final draft shared with RECFA*

30 July 2021
Presentation at Joint ECFA-EPS session

August 2021
Collect final community feedback*

October-December 2021
Detector R&D Roadmap Document circulated for approval to ECFA in Nov 2021 and presentation to Council in Dec 2021
Links for Roadmap Process

https://indico.cern.ch/event/957057/page/21633-mandate (Panel Mandate document)

https://indico.cern.ch/event/957057/page/21653-relevant-documents

https://home.cern/resources/brochure/cern/european-strategy-particle-physics


https://aidainnova.web.cern.ch (linking research infrastructures in detector development and testing)

https://attract-eu.com/ (ATTRACT: linking to industry on detection and imaging technologies)

https://ecfa-dp.desy.de/public_documents/ (Some useful documents from the ECFA Detector Panel)
Concepts of Picosecond (a few 10’s) Timing Detectors

- Several types of technologies are considered for “Picosecond-Timing Frontier”:
  - Ionization detectors (silicon detectors or gas-based devices)
  - Light-based devices (scintillating crystals coupled to SiPMs, Cherenkov absorbers coupled to photodetectors with amplification, or vacuum devices)

Examples of timing detectors at a level of ~ 30 ps for MIPs and ~ 100 ps for single photons
## Liquid detectors

<table>
<thead>
<tr>
<th>Readout development</th>
<th>2022-2025</th>
<th>2025-2030</th>
<th>2030-2035</th>
</tr>
</thead>
<tbody>
<tr>
<td>Higher energy resolution</td>
<td>2.1</td>
<td></td>
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<tr>
<td>Lower energy threshold</td>
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<td></td>
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<tr>
<td>Expand wavelength sensitivity</td>
<td>2.1</td>
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<table>
<thead>
<tr>
<th>Measurement strategy</th>
<th>2022</th>
<th>2025</th>
<th>2030</th>
<th>2035</th>
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<tbody>
<tr>
<td>Fine granularity</td>
<td>2.2</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>$dE/dx$ (combine modalities: charge, light, heat, acoustics)</td>
<td>2.2</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Target properties</th>
<th>2022</th>
<th>2025</th>
<th>2030</th>
<th>2035</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid doping and purification (87 - 200K)</td>
<td>2.3</td>
<td></td>
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<tr>
<td>High pressure</td>
<td>2.3</td>
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<table>
<thead>
<tr>
<th>Scaling up challenges</th>
<th>2022</th>
<th>2025</th>
<th>2030</th>
<th>2035</th>
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<tbody>
<tr>
<td>Detector services (e.g. cryogenics) and integration</td>
<td>2.4</td>
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<tr>
<td>Large arrays (sensors)</td>
<td>2.4</td>
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<tr>
<td>Low power</td>
<td>2.4</td>
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<td></td>
<td></td>
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<tr>
<td>Detector components radiopurity and background mitigation</td>
<td>2.4</td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

- Must happen or main physics goals cannot be met
- Important to meet several physics goals
- Desirable to enhance physics reach
- R&D needs being met

21.2.2022

ECFA Detector R&D Roadmap - Susanne Kuehn
Liquid detectors: Underground Dark Matter experiments

- Variety of DM experiments with small and rare signals need extreme control of background sources (radiopurity) coupled with high sensitivity and discrimination of signal from residual backgrounds

- R&D for multi-ton scale noble liquids:
  
  **Target properties**
  
  - Low-radioactivity argon: extraction (Urania plant, 330 kg/d), purification (ARIA facility, 10 kg/d)
  - Fast purification in liquid phase for large e-lifetime (removal of O₂ and H₂O impurities) → high light and charge yield; radon-free filters

- R&D for multi-ton scale noble liquids: **Detector performance and background control**
  
  - Single phase versus two-phase TPCs
  - Distillation columns for krypton and radon, material screening and selection, radon emanation
  
  R&D on sealed TPC for DARWIN; JINST 16 P01018 (2021)

---

ARIA underground purification system for argon (DarkSide-20k)

ARIA underground purification system for argon (DarkSide-20k)

LXe purification system (5 L/min LXe, faster cleaning; 2500 slpm) for XENONnT

Low-radioactivity argon: extraction (Urania plant, 330 kg/d), purification (ARIA facility, 10 kg/d)
Quantum and emerging technologies

ECFA Detector R&D Roadmap - Susanne Kuehn
### Calorimetry

**ECFA Detector R&D Roadmap - Susanne Kuehn**

- **Low power**
- **High-precision mechanical structures**
- **High granularity 0.5x0.5 cm² or smaller**
- **Large homogeneous array**
- **Improved ele. resolution**
- **Front-end processing**

- **High granularity (1–5 cm²)**
- **Low power**
- **Low noise**
- **Advanced mechanics**
- **Em. resolution 0%(E/E)**

- **High granularity (1–10 cm²)**
- **Low hit multiplicity**
- **High rate capability**
- **Scalability**

- **High granularity**
- **Rad-hard photodetectors**
- **Dual readout tiles**

- **High granularity (PFA)**
- **High-precision absorbers**
- **Timing for z position**
- **With C/S readout for DR**
- **Front-end processing**

- **Lateral high granularity**
- **Timing for z position**
- **Front-end processing**

- **Up to 10¹⁰ nₑ/cm²**
- **> 10¹⁵ nₑ/cm²**
- **< 3%/E**

**Legend**
- Must happen or main physics goals cannot be met
- Important to meet several physics goals
- Desirable to enhance physics reach
- R&D needs being met

**Timeline**
- **< 2050**
- **2035-2040**
- **2040-2045**
- **>2045**

**Note:**
- DRBT: Detector R&D Beyond the Standard Model
### Integration

- Detector Readiness Matrix

#### Detector Readiness Matrix

<table>
<thead>
<tr>
<th>Component</th>
<th>DBDT</th>
<th>&lt; 2030</th>
<th>2030-2055</th>
<th>2055-2040</th>
<th>&gt; 2045</th>
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<td>UL solenoid</td>
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<tr>
<td>Dual solenoid</td>
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<tr>
<td>High field dipole</td>
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<tr>
<td>T below CO₂</td>
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<tr>
<td>Gas cooling</td>
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<td>He-T with head load</td>
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<tr>
<td>Microchannel</td>
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<td>Cooling tubes</td>
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<td>TECs</td>
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<td>Non out-gassing</td>
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<td>Lightweight</td>
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<td>Feedthroughs</td>
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<td>Moveable vertex tracker</td>
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<td>MEMS ar flow</td>
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<td>4D BIB</td>
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<td>Radiation high level</td>
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<td>Polarization</td>
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<td>HV supply for field cage</td>
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<td>Purification systems</td>
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</tbody>
</table>

**Legend:**
- Red circle: Must happen or main physics goals cannot be met
- Orange circle: Important to meet several physics goals
- Yellow circle: Desirable to enhance physics reach
- Green circle: RD&D needs being met
Integration

- DRDTs:
  - Investigation of novel superconductors for magnet systems as well as support of expert design capabilities and modelling software for future experiments is vital.
  - Cooling technologies for cryogenics and low-mass heat removal from on-detector electronics and semiconductor sensors require dedicated generic R&D activities.
  - Ultra low mass, stable, precision mechanics and machine detector interface design are major topics

Example: IRIS tracker concept
Example of future detectors at accelerators

- Busy events
- Require hardware and software triggers
- High radiation levels

• One of the many challenges: radiation hardness. Radiation levels of e.g. 300 MGy/5-6 \(10^{17} \text{n}_{\text{eq}}/\text{cm}^2\) in first tracker layers go well beyond what any currently available microelectronics can survive (\(\leq \text{MGy}\)) and few sensor technologies can cope beyond \(\sim 10^{16} \text{n}_{\text{eq}}/\text{cm}^2\)

\[\Rightarrow\] Detector R&D essential
Largest challenge is that radiation levels go well beyond what any currently available microelectronics can survive ($\leq$ MGy) and few sensor technologies can cope beyond $\sim 10^{16}n_{\text{eq}}/\text{cm}^2$ (HL-LHC vertex layers)

[Image of future detectors at accelerators]

[Diagram showing the FCC-hh CDR with various components labeled]

Exception: Forward calorimeter goes to higher $\eta \rightarrow$ bigger factor
Summary on ECFA Detector R&D Roadmap

- The ECFA Detector R&D Roadmap has been prepared by a large team of internationally recognised leaders in this area with access to a much wider pool of other instrumentation experts.
- It has been the product of wide community consultation with very broad participation.
- The draft document was iterated with the RECFA delegates and National Contacts with numerous helpful comments received from committees looking at this in a number of countries.
- We also have benefited from very valuable feedback from neighbouring disciplines where there are strong synergies between instrumentation needs.
- The main messages were presented to the particle physics community at the ECFA Plenary Session of the EPS-HEP2021 Conference and remain unchanged in those shown on 19th November 2021.
- The results of all the feedback have been implemented in the final 248 page version and additional non-expert 8 page synopsis which was formally approved by Plenary ECFA on 18th November 2021.
- These were then presented to the CERN Scientific Policy Committee and Council last week by the Chair of ECFA and we understand they have been very well received, with the SPC congratulating the Roadmap Panel and endorsing the recommendations.
- The next step will be for mechanisms to be proposed for implementing the final recommendations.