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Strategic R&D Programme on Technologies for Future Experiments

CERN

Experimental Physics Department

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1 Executive Summary

Instrumentation is a key ingredient for progress in experimental high energy physics. The Experimental Physics Department of CERN has defined a strategic R&D (Research and Development) programme on technologies for future experiments. Provided the required resources can be made available it will start in 2020 and initially extend over five years. The selection of topics and the established work plans are the result of a transparent and open process, which lasted 14 months and involved several hundred of physicists and engineers at CERN and in the broader HEP community.

The landscape of particle physics at the high energy frontier is well defined until the High Luminosity upgrade of the LHC (HL-LHC) scheduled for the long shutdown LS3 (2024-2026). 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, these efforts complement advanced design studies for an International Linear Collider that could be hosted in Japan, and plans for the CEPC in China, for precision studies of the properties of the Higgs boson. In addition, there may be new fixed target and beam dump experiments or upgrades explored under the Physics Beyond Colliders initiative hosted by CERN. Clarifications and possibly prioritization are expected from the 2020 update of the European strategy for particle physics.

The above studies have served as guideposts to assess the future experimental challenges and define the directions of the principal R&D lines. For hadron colliders the main challenges come from the very high luminosity operation, leading to extreme pile-up, track density, radiation loads and data throughput. The addition of high precision timing information on several subdetectors appears as a promising strategy. Future e^+e^- colliders call rather for unprecedented precision in vertexing and tracking, combined with very low material budgets and highly granular calorimetry. These primary challenges for the detector design are complemented by equally demanding challenges in the domains of electronics, mechanics, magnets and cooling. Also the sheer volume of generated data and the need for adequate Monte-Carlo samples call for new approaches in software development.

The foreseen strategic R&D described in this document focuses on those technologies and fields of expertise that will be crucial for any future experiments in particle physics and in which CERN groups have significant if not unique expertise. In analogy with the importance of the development of high field magnets and high gradient accelerating structures for future accelerators, we have identified key technologies and indispensable expertise without which future experiments cannot be built.

The results of this R&D will be building blocks, demonstrators and prototypes, which will form the technological basis for new experiments and experiment upgrades beyond the LHC Phase-II upgrades scheduled for the long shutdown LS3.

Previous similar initiatives, the DRDC projects[1] in the 1990's and the White Paper R&D programme[2] (2008-2011), have been instrumental in providing the technologies which are presently in use at the LHC experiments or which will be deployed in the coming LHC upgrades (Phase-I and Phase-II). Examples of the achievements of the White Paper R&D programme are the validation of the CMOS 130 nm technology, the GEM single mask technique, radiation hard optical links and DC-DC converters. It is

[1]http://committees.web.cern.ch/Committees/obsolete/DRDC/Projects.html
[2]L. Linssen, CERN LHC upgrade R&D projects and irradiation plans, LHCC upgrade session, 1 July 2008. https://indico.cern.ch/event/36149/

evident that without these timely and well-coordinated R&D efforts the LHC experiments would not have been possible.

A large part of the required R&D work will be carried out jointly with external groups from universities and research labs. This cooperation will be based on organically grown networks and relations, but also exploit the dynamic and efficient structures like the RD50 and RD51 collaborations. For many developments, close cooperation with industrial partners is absolutely crucial.

The R&D programme is structured around eight work packages (WP) with sets of sub-activities, which target specific challenges. These comprise developments in

- Silicon vertexing and tracking detectors, with a focus on hybrid and monolithic pixel detectors.
- Micropattern gas detectors, including the development of environment friendly gases.
- Calorimetry and light based detectors, such as RICH and scintillating fibres.
- Detector mechanics, from lightweight structures to carbon-fibre reinforced cryostats, as well as high performance detector cooling.
- Integrated circuits, in particular exploration and radiation validation of CMOS technologies in 28 and 16 nm technologies and development of the essential IP blocks.
- Faster and more radiation-hard optical links, including the exploration of silicon photonics.
- Simulation and analysis software, exploiting advanced hardware and programming techniques.
- Magnets for experiments, from low mass superconducting cables to controls and safety aspects.

Some activities, such as radiation hard electronics, detector magnets and detector cooling, are technologically complex and require significant infrastructure and a sustained level of engineering resources. It should be noted that for some technologies, CERN has become the only place where such R&D is pursued. Its adequate weight in the programme is therefore of strategic importance for the whole HEP community.

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

2 Introduction

Progress in experimental physics often relies 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 their 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 LS3 (2024-2026). 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 LS2 (2019-2020). While the detector R&D for the LS2 upgrades has largely been completed, the R&D for the LS3 upgrades is in full swing and will still continue for a few more years.

Beyond LS3, 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 2020 update of the European strategy for particle physics. An R&D programme is therefore proposed at this stage that concentrates on advancing key technologies, rather than developing specialized applications.

The programme covers technological R&D activities in the domains of 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 proposed programme focuses on areas where the EP department has significant expertise and infrastructure and plays already a leading or unique role. The identified technologies are key for the success of future projects and a discontinuity of the R&D could become a showstopper for experiments in the future. The results will be building blocks, demonstrators and prototypes, which will form the technological basis for new experiments and experiment upgrades beyond the LHC Phase-II upgrade scheduled for the long shutdown LS3.

This proposed EP departmental programme for Strategic R&D will start in 2020 and extend until 2024, at least for its initial definition.

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, reviewed by the relevant committees and financed through their own budget lines. The Strategic R&D, however, will lay solid foundations for the technologies needed. 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 typically 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 industrialized for replication 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[3] and RD51[4]), 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 good 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 and services provided by the EP Department

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 that support detector operation and R&D efforts. Examples are the wire bonding and reliability testing labs, the irradiation facilities (hadron and gamma) 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 and beyond. Examples are the radiation hard fast optical links and DC-DC converters. 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. EP-SFT plays major roles in the ROOT, GEANT and LHC Computing Grid (LCG) projects.

[3] https://www.cern.ch/rd50/
[4] http://rd51-public.web.cern.ch/

2.3 Organization 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 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 steering committee conceived an open and transparent process that would allow for bringing in ideas in a bottom-up way and allow for a broad participation of the HEP community.

The personnel of the EP Department was informed about the initiative in a kick-off meeting[5] on 20 November 2017, in which the status and future needs of the 4 large LHC experiments as well as of future hadron and lepton colliders were discussed. Furthermore, the 8 main R&D themes proposed by the Steering Committee were discussed, along with the process organization and timeline.

Convenors were appointed for each of the 8 R&D themes with the mandate to form working groups (WG) and hold meetings with the aim to explore current technological 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[6] was held on 16 March 2018 at CERN, for 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. A first complete draft of the present report was presented.

A short summary of this report (max. 10 pages) will serve as input to the European Strategy Group in view of the 2020 update of the European Strategy for Particle Physics.

[†] Deceased in March 2018
[5] https://indico.cern.ch/event/677108/
[6] 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 $5x10^{34}$ $cm^{-2}s^{-1}$, 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 $7.5x10^{34}$ $cm^{-2}s^{-1}$, 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.

An example is the timing layer 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 30 ps 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 50 ps 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, possibly using an 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 optical links to be integrated 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 [1] for a second upgrade, envisaged for LS4 around 2030. It proposes 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} $cm^{-2}s^{-1}$, thus 10 times higher 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.

The ALICE collaboration is also in the process of submitting an Expression of Interest [2] for a future upgrade of its Inner Tracking System (ITS), beyond the one now under preparation. This upgrade will provide a further large improvement of the tracking precision and efficiency at low transverse momentum. Combined with a substantial 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 30×10^{34} $cm^{-2}s^{-1}$, which is 6 times larger than the luminosity of the HL-LHC, leading to a pile-up 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 will 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.

A 100 TeV proton collider serves as a discovery machine as well as a precision measurement machine. The factor 7 increase in energy over the present LHC increases the mass reach by a similar factor. The much larger cross sections for SM processes together with the higher luminosity lead to a significant increase in measurement precision. The detector must therefore be able to measure multi-TeV jets, leptons and photons from heavy resonances with masses up to 50 TeV, while at the same time measuring the known SM processes with high precision and being sensitive to a broad range of BSM signatures at moderate p_T.

To gain some elementary insight into the scale and the requirements of a general purpose detector at the FCC-hh collider, a ‘reference detector’ was developed as part of the FCC study. This detector concept does not represent a specific choice for the final implementation, but it serves as a concrete example used for subsystem and physics studies and that allows identification of topics where dedicated R&D efforts are needed. The detector has a diameter of 20 m and a length of 50 m, comparable to the dimensions of the ATLAS detector. It uses a 4 T central solenoid of 10 m bore diameter and a forward magnet system consisting of smaller solenoids or dipoles. Silicon tracking, Liquid Argon based electromagnetic and hadron calorimetry as well as scintillator based hadron calorimetry in the barrel region are chosen as reference technologies. These technologies will still need significant R&D efforts in order to be applicable to the FCC-hh environment.

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 20 cm. For smaller radii this number rises significantly and reaches a level of $8\times10^{17}cm^{-2}$ at the innermost layer. Significant R&D efforts are therefore needed to develop sensors that can handle such radiation levels.

The present detector concepts foresee a position resolution of about 7 µm 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 pile-up 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 such timing precision to be preserved 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 5 m bore diameter and a magnetic field of 4 T, together with two smaller forward solenoids. The cryogenics plant for this magnet system is foreseen to sit on the surface. Several components of this system need to be developed.

Calorimetry and the muon system will be digitized at the full bunch crossing rate of 40 MHz and the data will be shipped off the detector at 200-300 TB/s. Reading also the tracker at the full bunch crossing rate of 40 MHz would result in a data rate of almost 800 TB/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-ee 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 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. For 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 1 ns accuracy in the calorimeters and time stamping at the 10 ns level in the tracking. The design of the CLIC detector [3] [4] 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 strip 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 [5]. 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 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, calls 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-ee 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_{p_T}/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 4 T. 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 innermost 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 (2 T). 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 summarizes 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 2 T 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 to provide excellent jet energy resolution and particle-flow reconstruction. Sustained R&D will be necessary to optimize the drift chamber and dual-readout calorimeter towards the stringent requirements of the ultra-precise FCC measurements.

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 should 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 ($\mu m \times$ 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

3.4 Other experiments

In parallel to the experimental activities at the high energy frontier, a range of further experiments are probing the standard model and searching 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 study [6]. 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 the ALICE ALPIDE). Nevertheless, vertexing (including in the case of active targets) in particular will benefit strongly 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 will 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 typical examples 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 the 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.

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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. We also put emphasis on technologies that could find applications at the HL-LHC and fixed-target experiments where the installation maps to the initial 5-year time scale of the EP R&D programme.

In general, tracking and vertex detectors for future experiments will require at least an order of magnitude more radiation hardness compared to conditions at the LHC [1][2]. This is particularly true of detectors in closest proximity to the interaction regions, loosely referred to as vertex 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 e^+e^- 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 [3]. 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 are given in Table 3.

Table 3: Approximate requirements for the central tracking volume at the different collider experiments.

Parameter / Exp.	LHC	HL-LHC	SPS	FCC-hh	FCC-ee	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$^{****)}$	8 G$^{****)}$	20 G	20 M $^{***)}$	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 $[\mu m^2]$	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 ****) max. output rate for LHCb/high intensity flavour experiments: 300-400 Gbit/s/cm^2

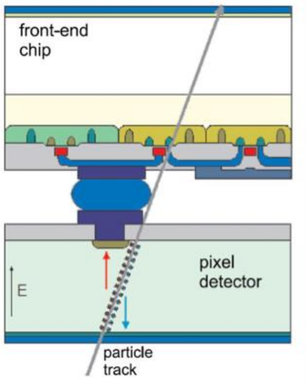
The specific combination of competing requirements is different for each of the future applications. A broad and integrated detector R&D programme is therefore needed, advancing a variety of detector technologies while simultaneously addressing system-integration aspects and developing the corresponding 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 [4]. Hybrid pixel detectors (see Figure 1a) 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. Prototypes of hybrid detectors for CLIC have been produced based on ASICs in 65 nm process technology with a pixel size of 25x25 μm^2. 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. LHCb has designed a dedicated ASIC to withstand an output bandwidth of more than 16 Gb/s for the Phase-I upgrade. Monolithic Active Pixel Sensors (MAPS) (see Figure 1b) 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 [5]. 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 capabilities of >200 MHz/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 [6][7]. To meet these challenges, this R&D will explore hybrid pixel detectors and monolithic CMOS sensors incorporating complex readout architectures in small-feature size CMOS technologies. Specialty hybrid pixel sensor developments target the highest rate and timing requirements in conjunction with dedicated FE-ASICs. Radiation-hard monolithic CMOS sensors with small pixel pitch (~25x25 µm) and high hit-rate architectures aim at significant performance improvement for future upgrades of the innermost layers.



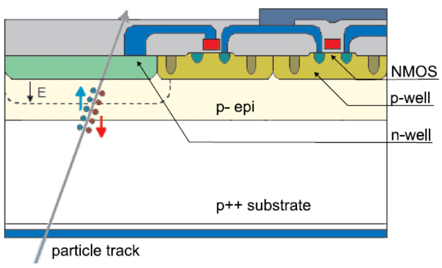


Figure 1: Schematic views of hybrid (a) and monolithic (b) pixel detectors [N. Wermes / Univ. Bonn].

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 lightweight and high-bandwidth data transmission for monolithic and hybrid radiation hard detector solutions will have to be addressed.

The tracking detectors for future e^+e^- 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 pile-up to be resolved 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 need to 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 [9][10] Due to their simplified construction and intrinsically lower power consumption than hybrid pixel modules, they offer a substantially lower material budget, cost advantage as well as reduced assembly complexity. Further R&D for the innermost layers of pp-experiments will be needed to 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 (~25 μm) pixels and complex periphery circuits in novel future DMAPS using small feature-size CMOS processes.

Moreover, one of the features offered recently by CMOS imaging sensor technologies, called stitching (see Figure 2), will allow developing a new generation of large-size MAPS with an area up to the full wafer size [11]. In this technology, the reticles which fit into the field of view of the lithographic equipment are placed on the wafer with high precision, achieving a tiny but well defined overlap. 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 could be constructed. This would 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) [12].

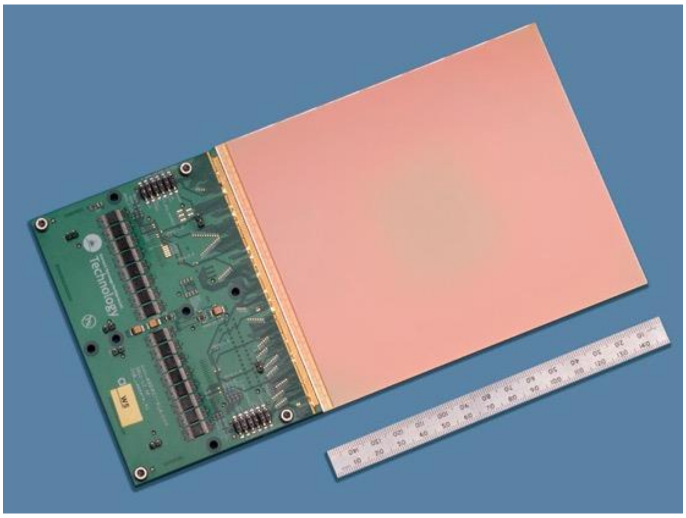


Figure 2: Wafer-scale stitched imaging sensor with an active area of 140x140 mm² [N. Guerrini, RAL].

Using medium feature-size CMOS processes (≥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 (below 65 nm) CMOS technologies will allow readout circuitries and high-rate output serializers to be designed which can cope with the increased data throughputs, while achieving a low power consumption both in the matrix and at the periphery. Other front-end blocks which are of common application include fast front ends and clock distribution elements. Both hybrid and monolithic applications would benefit from the small feature size which allows sophisticated readout architectures to be implemented in small pitch (25 um) pixels. More generally, 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. For applications requiring extreme speed and time-stamping, for example in high rate flavour experiments, CMOS technologies with feature-size down to 28 nm might allow timing precision of down to 10s of picoseconds, with the associated local oscillators and suitable methods for clock distribution and calibration throughout the ASIC.

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 the chip through technologies like silicon photonics will help to overcome this limitation [4]. 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. 3D integration and interposer layers will allow the necessary functionality to be incorporated while allowing ASIC tiling on the modules.

A fundamental understanding of the sensor performance and the radiation effects is an essential part of the design and process optimisation. 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 the table at the end of this chapter.

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 (see Figure 3).

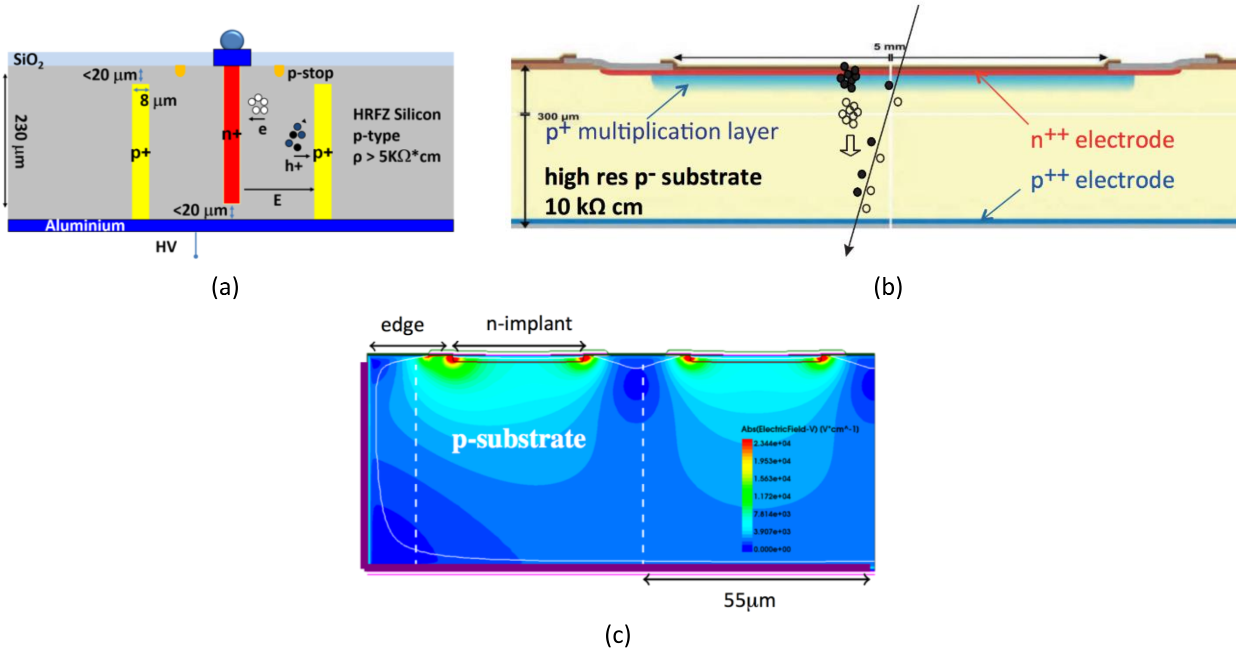


Figure 3: Schematic view of 3D (a) and LGAD (b) sensors indicating the different implantations [arXiv:1806.01435, Rep. Prog. Phys. 81 066101]. Schematic view of an active edge (c) silicon pixel sensor showing the electric field distribution in the edge region and over two 55 µm wide pixel cells [CERN-THESIS-2016-311].

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.

In parallel, a specific ASIC development for very high-speed hybrid pixel sensors and fine-pitch pixels will be pursued. The design of generic 28 nm IC blocks for analog front-end and high-speed data serializers, with output bandwidth of 10 Gb/s, will be carried out within the IC WP. In this activity we will develop, through Multi-Project-Wafer (MPW) submissions, a demonstrator based on a 28 nm CMOS process to demonstrate the end-to-end design of a 25x25 μm^2 pixel matrix, with fine timing and high data throughput rate. It will include the analog front-end, digital matrix and a single high-speed data link. In parallel, a potential digital architecture, which can be suitably matched to a fast readout scheme distributed over a full scale ASIC, will be developed. The demonstrator will be used both to test the ultimate timing performance of the sensors but also will serve as a readout base for the second stage of a dedicated beam telescope.

System level development, such as the definition of a data packaging format to meet pattern recognition needs of a high speed pixel timing tracker, or the development of proof-of-principle techniques to achieve required local time resolution in the ASIC, will be investigated. In the context of high-precision timing, a major challenge of the system level design is the demonstration 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.

Design optimisation and characterisation of high granularity sensors based on thin planar-sensor active edge technologies, with pixel size down to 25x25 μm^2 on one side and of fast sensors based on LGAD and 3D sensor 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 simulations.

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.

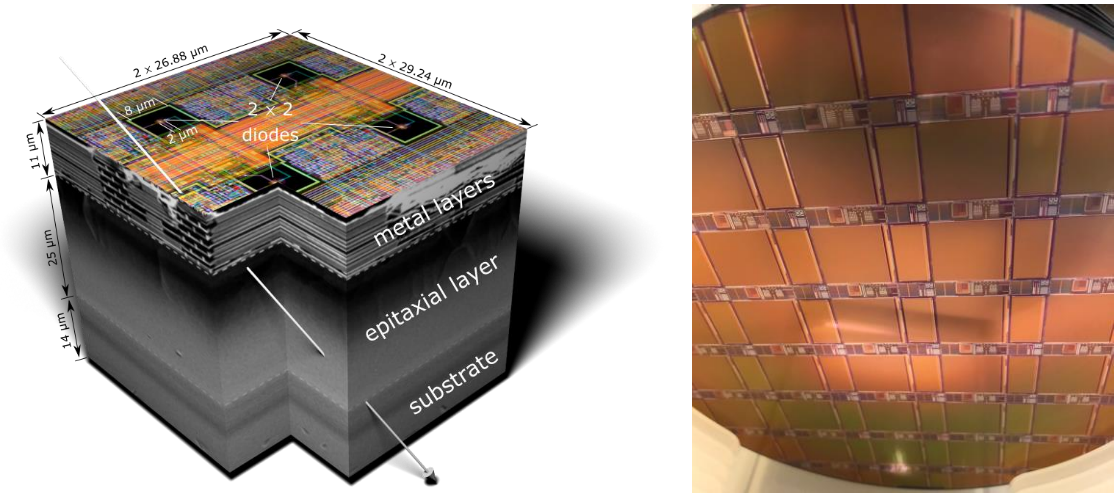
It is expected that this activity will profit from a close collaboration with a large community of external institutes and existing collaborations, in particular with the RD50 collaboration for radiation-hard semiconductor devices. The corresponding high-performance ASIC and interconnect developments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

The resource allocation (see table in the annex) includes limited funds for contributions to MPW sensor and ASIC 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 (see Figure 4).

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 sensors developed in a >90nm size process to establish sensor designs needed for near future applications [13]. 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.



(a) (b)

Figure 4: Schematic view of the cross section of a monolithic pixel chip (ALPIDE) indicating the CMOS metal layers and the eptitaxial and substrate silicon (a). Photograph of a MALTA/MONOPIX monolithic pixel chip wafer (b).

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 (see Figure 5);
- 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 resulting from 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 (WP4).

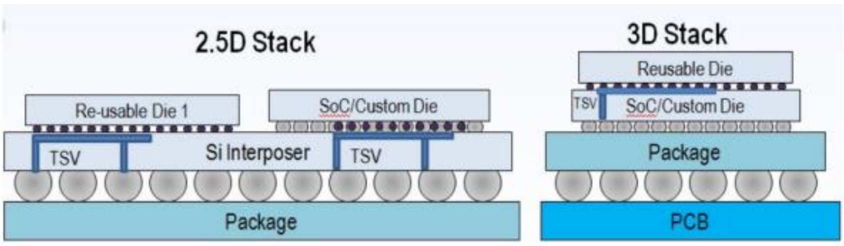


Figure 5: Schematic view of a 2.5 D integration using side-by-side chip placement on a passive interposer vs. a 3D integration of several chips [Ref: https://iew2015.wordpress.com/track_2-5d-and-3d-integration/].

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 the cut region to be reduced and optimized, thinning studies on how to control the warp of these ultra-thin dies (50 μm or less).

Deliverables:

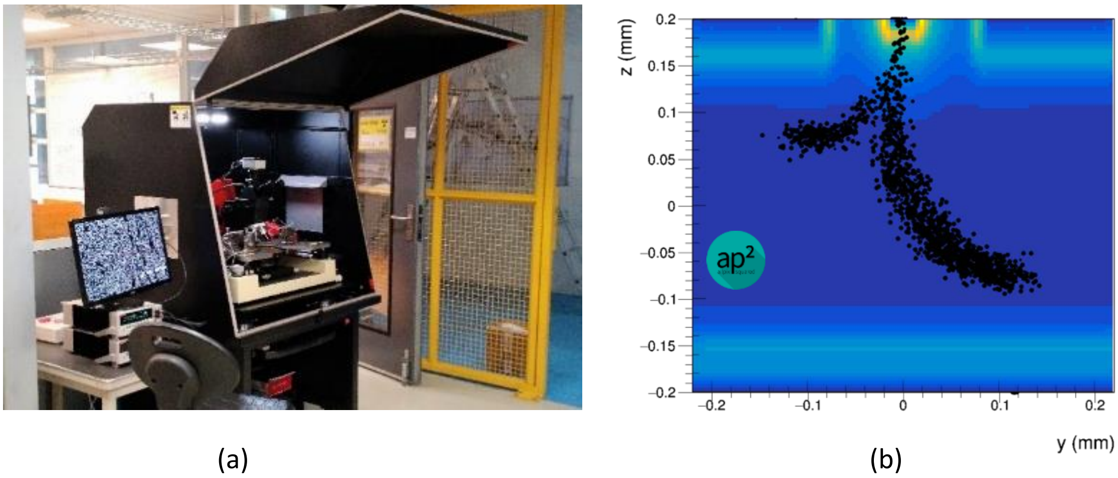
- Demonstrator modules of large area monolithic sensors using die-to-die data and power transmission;
- Demonstrator module of an ultra-thin wrapped monolithic pixel module;
- Validation of very thin hybrid pixel assemblies with fine-pitch micro-bump bonds and 2.5D interposer structure;
- Assembly and 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 lightweight 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 (Figure 6a). 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 [14]. 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 (see Figure 6b).



(a) (b)

Figure 6: Picture of a probe-station in the CERN irradiation facility (a) and simulation of charge deposition and propagation inside an under-depleted High-Voltage CMOS sensor (b).

A new high-rate beam telescope architecture will be developed which exploits the 200 ps 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 [15]. This tool combines Geant4 simulations and TCAD device simulations with parametric simulations of the charge transport and readout response. Special emphasis will be placed 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.

Table: 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 ○ LGAD, silicon for high-precision timing ○ Thin planar active-edge sensors ○ 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 - minimised power consumption for minimal material and sensor powering circuits.
Engineering Run every 18 months MPW 1-2/y	

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5 Gas based detectors (WP2)

5.1 Introduction and overview

Gas based detectors will remain a key technology for radiation detection in particle physics experiments. They provide excellent performances for large area, low mass, radiation hard, relatively cheap and rather easy-to-build detector solutions. Through gas amplification they can intrinsically achieve a large signal-to-noise ratio, releasing requirements in readout electronics and providing excellent single-particle sensitivity.

All four major LHC experiments (ALICE, ATLAS, CMS and LHCb) are extensively using gaseous detectors. Depending on the needs, various technologies are used. Examples are for triggering and bunch-crossing tagging Gas Electron Multipliers (GEM), Micro-Mesh Gaseous Structures (MicroMegas), Multiwire Proportional Chambers (MWPC), Resistive Plate Chambers (RPC), Thin Gap Chambers (TGC), for high-rate tracking and particle identification Straw Tube Detectors, Time Projection Chambers (TPC), Drift Tubes (DT), Cathode Strip Chambers (CSC) and for single photon detection MWPCs with CsI photocathodes.

Non-collider experiments at CERN also rely on gas based detectors. NA61 is using proportional chambers as beam position monitors and a TPC as large volume tracking device. NA62 has Straw Tubes for tracking of charged particles originating from the decay region. NA64 is using MicroMegas and Straw Tubes for electron track measurements. COMPASS uses GEM based detectors and MicroMegas for small area tracking and planar drift chambers for large area tracking. CAST depends on MicroMegas and Integrated Grid detectors (InGrids) for single X-ray detection.

Gaseous detector technologies are part of the ongoing LHC upgrades as well as part of the R&D activities for future collider and non-collider experiments.

In ATLAS currently the replacement of the present first muon 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. ALICE is replacing the MWPC readout of the TPC with a quadruple GEM solution.

Existing systems will have to be replaced or complemented in the future. For example, the upgrade of especially the forward muon detectors might be required to match the segmentation, resolution and angular acceptance of the central precision trackers that will be installed in LS3 for operation in the HL-LHC era. Replacements might be needed as the expected end of lifetime of several existing systems, RPCs for example, will be reached due to the harsh radiation conditions.

Experiments for the ILC or FCC, currently under consideration or in the scientific review process, all rely on large area muon systems and, specifically for the ILC, in large area central TPC. Muon detectors will cover active areas greater than 1000 m^2 for FCC experiments. A common challenge will be the high rate capabilities. While most of the FCC-hh regions are below 10 kHz/cm^2 (well within the technical capabilities of the current LHC upgrade solutions), the forwards regions with radii less than 1 m can reach 500 kHz/cm^2. In addition to the challenges of the high rates, requirements on time resolution will be more severe due to the very high luminosities. Time resolution of the order of ns and less will become important for most of the muon systems, and depending on the trigger requirements of the detectors even smaller time resolutions down to 25 ps are considered.

Progress in the research and development for gaseous detectors for the HL-LHC, ILC or FCC experiments will naturally bring benefit to the design of non-collider experiments, especially as the challenges for gas based muon detectors in non-collider experiments are typically less demanding. The proposed SHiP experiment for example, considers RPCs in the muon spectrometer downstream of the experiment to identify the muons produced in neutrino interactions or in tau decays and currently plans the use of straw tubes to complement the muon momentum measurement close to the magnetised target. These detectors will need to operate in an environment of particle rates up to 4 kHz/m^2, which is orders of magnitude lower than the rates expected at LHC, ILC or FCC experiments.

A common issue for many gas based detectors is the need of eco-friendly gas mixtures. In the context of CERN's environmental policy, the CERN Environmental Protection Steering Board (CEPS) is following up on the environmental impact of gas based detection systems. New eco-friendly gas mixtures or novel solutions for the gas system and in the detector need to be investigated: a few critical examples to be replaced are SF_6, $C_2H_2F_4$ for RPCs or CF_4 mainly for timing GEMs [1].

Focusing on large area muon systems, because of the unique role played by gaseous detectors in this context, requirements for future collider experiments can be summarised as follows:

- muon identification with highest efficiency over a large solid angle, and at least three space points along a muon track;
- to resolve bunch crossings and background, time resolutions below 1 ns 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 σ_{p_T}/p_T^2 ~ 1-2 x 10^{-5} GeV^{-1}. With a magnetic field of 2 to 4 Tesla and a few muon stations at a radius larger than 5 m, this translates to a required spatial resolution of a few hundred microns;
- minimal number of electronics channels, e.g. achieved by clever readout geometry of the detector and/or the sensor elements and a versatile readout, adapted to the specific requirements coming from the covered area (barrel or end-caps);
- detector production preferably manageable by industry.

Institutes, universities and collaborations worldwide, are carrying out rich R&D programmes to address the above-mentioned issues and to develop new technologies for gaseous detectors. A very prominent endeavour is carried out for instance by INFN on RPCs, which are widely used in particle physics experiments and which, because of their excellent time resolution, are very good candidates for future muon systems. Dedicated R&D on micro-pattern gaseous detectors, considered a key technology for future collider experiments, is successfully carried out by the international RD51 [2] collaboration in close collaboration with CERN.

To complement the ongoing developments, EP R&D activities on gaseous detector technologies will focus on issues that are less well covered, which make use of the large infrastructure at CERN, e.g. the new PCB workshop, test beams and the Gamma Irradiation Facility GIF++, and which tackle issues arising for the LHC upgrades and for future collider experiments.

Three main lines of activities are proposed:

- Activity 1: Large area gaseous detector systems.

Reliable and efficient mass production of all parts of large area gas based detectors is mandatory for any future detector. The current Phase-I upgrade of the LHC experiments show 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. With this activity, new solutions for large area systems should be addressed, specifications and procedures should be developed, tested and documented. This activity is based on development, building, testing and comparing several prototypes and comparing their reliability and performance.

- Activity 2: R&D Framework and Tools.

The aim of this activity is to foster tools required for future detector developments and for prototype design and evaluation. It will focus on strengthening the R&D environment at CERN. Gas studies and analysis, simulation and modelling, electronics and instrumentation will be subjects of this activity. Large interaction with the community (e.g. RD51) will be pursued and priority will be given to what is already under development and supported at CERN. A few examples are activities for environmental protection and gas analysis in EP-DT-FS, activities for gaseous detector simulation as Garfield in EP-DT-DD, and activities for gaseous detector front end electronics and instrumentation in EP-DT-DD/DI.

- Activity 3: Novel technologies

This activity aims to explore new solutions for future detector developments. Novel materials as well as new fabrication techniques will be tested on small prototypes. The use of solid converters for fast and precise timing measurements and 3D-printing of amplifying structures are two examples. This activity will enlarge CERN expertise in fields such as nanotechnologies and material science, fields that are not exhaustively covered today and which might bring high potential for future applications.

In the following sections, each activity will be described in more detail. The summary of deliverables, milestones, required resources (both human and material) is attached in the annex.

5.2 Large area gaseous 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 of a few thousand square meters. The majority of the large components of these detectors will most likely be produced by industry in reliable and efficient mass production.

To complement the ongoing research in the field of gaseous detectors, where promising technologies are explored on the basis of small prototypes, R&D in the EP Department will focus on scaling up these prototypes to full size muon detectors.

Considered technologies are GEMs, MicroMegas or the new µRWELL. Simulation studies will drive the detector design and will be used to understand the results obtained. The evaluation of a technology will be based on the achieved (long-term) performance (in test beams, irradiation and cosmic stands) and comparison with small size prototypes will serve as reference of the scaling-up process.

Several aspects will be explored and considered:

- Novel solutions and new materials in detector structures, for example Diamond-like-Carbon (DLC), see Figure 7, and in the mechanics, such as composite materials;

- Studies for the optimal size of the detector—large single detector or a segmented detector—in terms of detector performance, production, construction and integration will be performed. Also for detector services, gas, cooling, high voltage, strategies will be developed to minimise their impact on the final system;
- To ensure that possibilities for detectors are feasible from the industrial production side, a survey of size limits coming from production and industry will be done. Investigation of possible production and construction partners will be carried out as well.

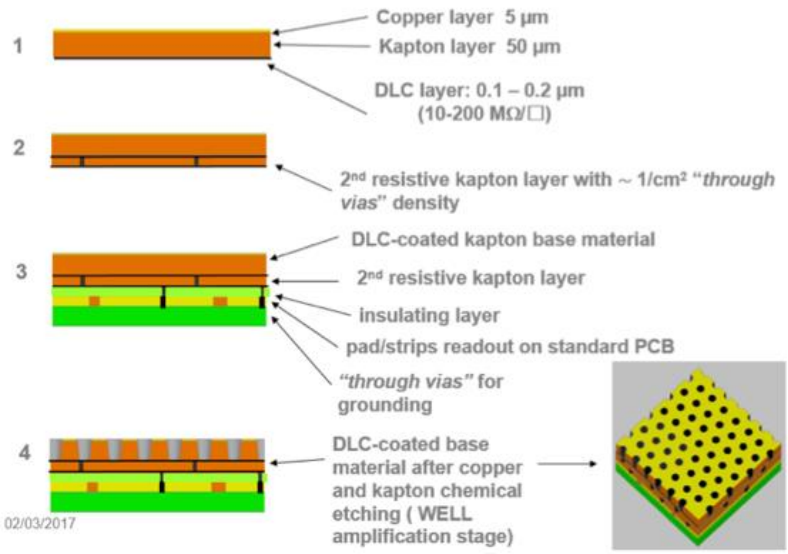

Figure 7: Example of the use of resistive layers made of Diamond like Carbon (DLC) layers in a micro-resistive well (µRWELL) [3] detector to increased stability and robustness of the chamber operation.

Deliverables

Deliverables of this activity are:

- a prototype, size in the order of a m^2, of a single stage detector for high rate condition, larger than 1 MHz/cm^2, based on resistive electrodes;
- a prototype, size in the order of 100 cm^2, of a detector with embedded/integrated readout electronics for a thin detector and a high granularity readout;
- a prototype, size in the order of a m^2, of a multistage detector for conditions with high rates, larger than 1 MHz/cm^2;
- a prototype, size in the order of 100 cm^2, of a detector with discrete and distributed RPC-like readout electronics;
- finally, after five years of activity, a report summarising the achievements.

5.3 R&D Framework and Tools

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. Promoting and supporting such activities will also provide a common framework, which outside communities will use. Areas of contributions should be:

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

Gas analysis and gas studies

Gaseous detectors need specialised gas mixtures to achieve performances compatible with the requirements. The interests of collider collaborations and of beyond-collider experiments focus on stable long-term operation that might be affected by ageing and radiation, thus specialised gas mixtures have to be chosen. However, environmental impact of gases has become an important issue and the search for new eco-friendly gas mixtures or for new and efficient recirculation systems, e.g. for the various RPCs used at the LHC experiments and foreseen for the HL-LHC, becomes mandatory. To foster and complement ongoing activity in EP, it is suggested to continue and even expand 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 [4]. It is proposed to upgrade the existing setups for gas and material studies, with improved monitoring, controlling devices (pressure regulators, flow meters, etc.) and appropriate radioactive sources. The activity will provide input the simulation and modelling tools, which are used in the community for gas based detectors world-wide.

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 understanding a detector and the underlying physics processes. They are crucial for optimisation of a detector and for trying new configurations beyond current limits. Fig. 2 shows an example of state-of-the-art simulation results obtained with commercial COMSOL software. The following points shall be addressed in detail in the simulations: discharges, ion diffusion, behaviour of resistive detectors, signal development and signal processing.

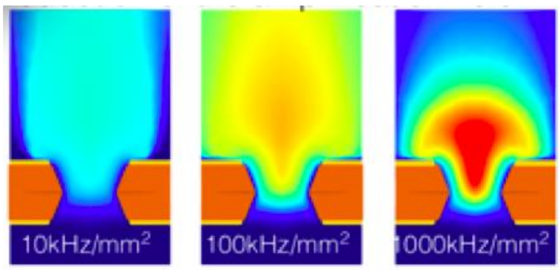

Figure 8: Example of simulation and modelling with COMSOL: Space Charge effects at high rate in a GEM detector.

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 [5], 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.

Electronics and instrumentation

To efficiently carry out the proposed R&D, support for on-detector electronics will be mandatory. In particular, to proceed with developments for fast timing gaseous detectors, as proposed in Activity 3 (novel technologies), specialised and – up to now – unavailable systems are required to be developed. As well for solutions in large scale detectors (Activity 1), a close collaboration with electronics expert is vital, e.g. to find solutions for optimising the number of channels for large detectors.

The aim of the activity is also to develop supporting electronic systems that can be used in a laboratory or for medium-scale setups such as in test-beams or small-scale experiments [6].

Examples of equipment needed are:

- For single channel signal processing: development of front-end electronics for a fast and precise timing single channel readout;
- For instrumentation: a high voltage monitoring and discharge protection system, high resolution floating pico-ammeters;
- A Multipurpose Data Acquisition System (DAQ) based on a multichannel ASIC DAQ.

Deliverables

Deliverables of this activity are:

- A framework and support for modelling and simulation, using tools such as Garfield, Heed, Magboltz, Degrad, Geant4, COMSOL, Field;
- A prototype of single channel readout for fast and precise timing;
- Laboratory space, equipment and database for outgassing studies and measurements on new material and components;
- A DAQ system for laboratory, test-beam and small experiments;
- Finally, after five years of activity, a report summarising the achievements.

5.4 Novel technologies

Material science, manufacturing processes and electronics are fields with continuous progress and exciting developments. For gaseous detectors these developments might offer breakthrough ideas and solutions for future detectors. Progress in manufacturing techniques such as photolithographic structuring techniques in the past led to the development of Micro-Pattern Gaseous Detectors (MPGD). These detectors are now widely used in high-energy physics experiments. Industrial and medical instrumentation may also profit from future developments. R&D activities where CERN is already involved and that will be strengthened by the EP R&D program are outlined below.

Solid Converters

Solid-state physics and material science nowadays offer several possibilities of creating new materials with very specific and controllable properties. Gaseous detectors can profit from this in the context of solid converters (photocathodes, secondary emitters), and new converters would overcome several limitations. Recent developments, as shown in Figure 9 for precise and fast timing with MPGD (MicroMegas with Cherenkov radiators and CsI photocathodes) indicate how promising this research can be. After having proved the principle of achieving less than 25 ps time resolution measured for minimum ionizing particles [7], radiation hardness and robustness of the photocathode are now the focus of future studies. The ongoing work in EP-DT-DD/GDD on this topic should be fostered, or even extended, with the goal to reach robust, radiation-hard photo cathodes and to build a small area prototype.

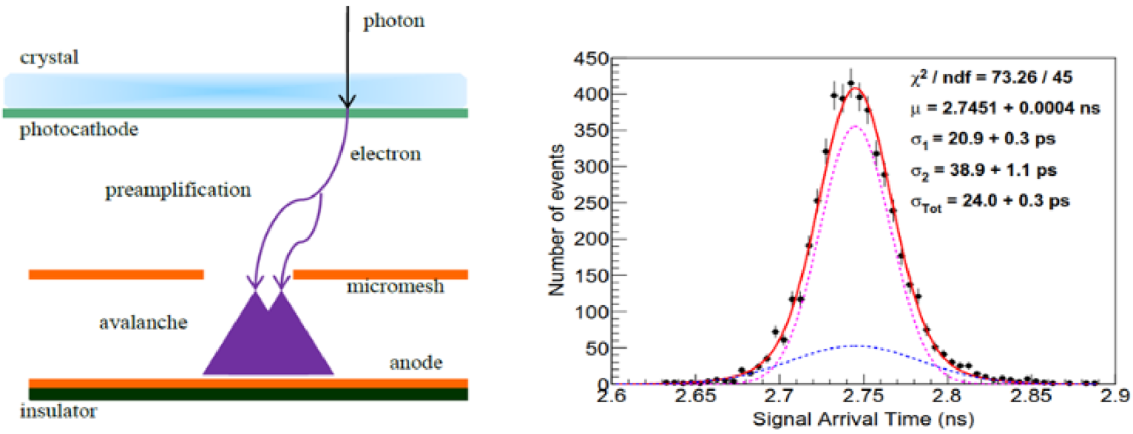

Figure 9: Concept of a Picosec detector as proposed in [2]. Cherenkov radiator, CsI photocathodes and gaseous amplifying stage are based on MicroMegas. Left: Detector layout. Right: measured time resolution (less than 25 ps) with minimum ionizing particles and with a 3 mm MgF_2 radiator and an 18 nm CsI photocathode.

New Manufacturing techniques

The next breakthrough for gas-based detectors might result from new manufacturing processes. 3D-printing [7] as well as dry plasma, LASER, or ink-jet printing can offer unique tools to produce functional structures, which would allow novel specialised and up-to-now unthinkable geometries. Manifold opportunities exist for complex 3D integration of conductive channels, embedded resistive elements, fine-grained multidimensional readout structures and electrical signal routing. The new printing technologies could 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 develop 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 materials used shall be studied.

The proposed activity uses the unique infrastructure of CERN and should give rise to many novel applications. Access to new technologies, expertise and knowledge from different communities will be enabled via existing links with other laboratories such as EPFL. Recognizing the advantages of having infrastructure and expertise in house[1], this activity could lead eventually to future and long term investment at CERN for specific infrastructure.

Fast Optical readout

This activity will explore synergies between current technological advances in gaseous detectors and electronics, specifically imaging sensors [9]. Future perspectives are opening new opportunities for fundamental research but also for applications outside our field. Advantages of gaseous detectors such as low material budget, large dynamic range and radiation hardness, combined with the high granularity of optical sensors, represent a unique possibility for detection systems. Breakthrough solutions for beam monitoring and event-by-event imaging are today considered a real possibility because of the progress achieved on fast image acquisition (from tens of kHz to MHz) and on-board processing. Particle physics experiments, accelerators as well as applications for society, such as hadron therapy, will profit from these studies.

Deliverables

Deliverables of this activity are:

- A test Stand for studying photocathodes: determination of the quantum efficiency in vacuum and gas, as well as ageing characterisation;
- A prototype of a gaseous detector build using novel techniques such as 3D-printing;
- A prototype of optical readout with a fast imaging camera and on-board fast image processing;
- A test stand for secondary emitter studies and characterisation;
- Finally, after five years of activity, a report summarising the achievements.

5.5 Summary

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

[1] The EP-DT-EF Micro Pattern Technology (MPT) Workshop at CERN is one of the best examples, with several new developments coming out at CERN because of the unique expertise in an inspiring environment.

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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, due to its radiation hardness, stability, high resolution energy measurement, high position resolution, timing resolution and high granularity, for 3D imaging, pile-up suppression, particle ID, jet substructure and more. It is part of the reference design of an FCC-hh experiment presented in the FCC CDR [1]. 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 easily be 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. 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 a 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 software. For this purpose, the FCC software 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 (in 2023). LAr is the baseline choice for the moment, but other liquids (e.g. LKr) will be studied with simulation.

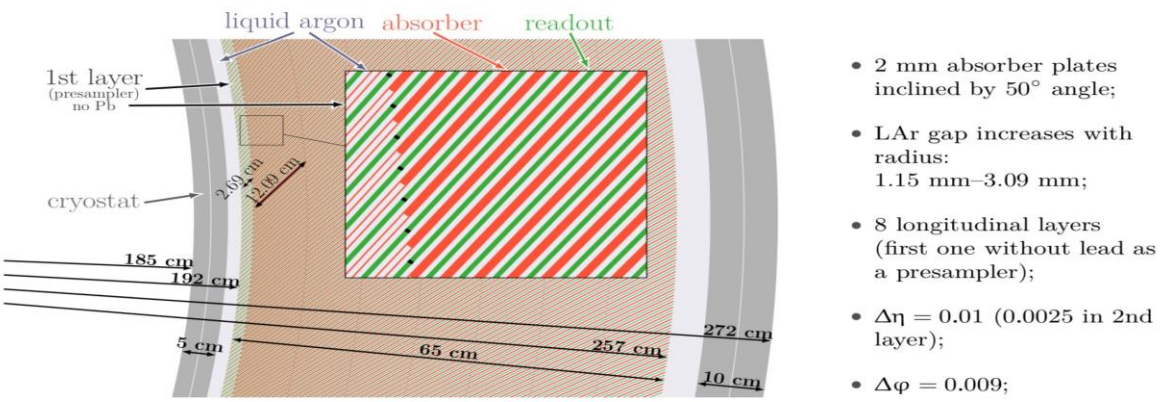

Figure 10: Cross-section of the FCC-hh reference detector electromagnetic barrel calorimeter.

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

A test cryostat (LAr test-beam 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, and the limits of MIP timing and the 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 test-beam (using the test module introduced in task A). This aspect will have to be studied thoroughly in preparation of the test-beam and taken into account at the design of the test module. It will be necessary to choose carefully 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 will be 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. The CERN participation will be with its infrastructure, but it is expected to keep the contribution low here.

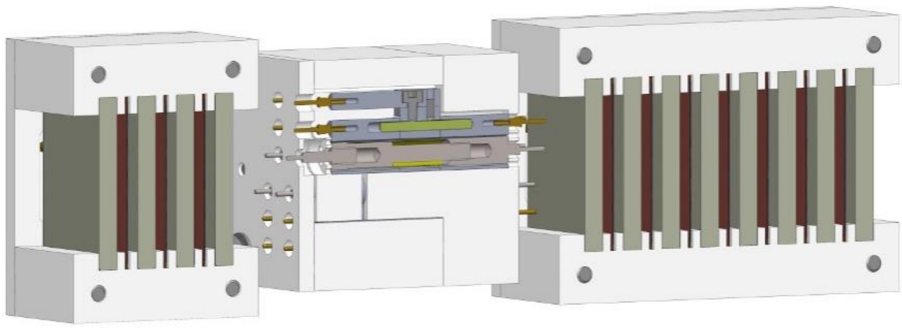

Figure 11: Sketch of a proposed set-up for a test-beam at CERN. Electrons in the test-beam enter this drawing from the right. The parallel tungsten plate calorimeter on the right initiates an EM shower which reaches shower max at the location of the PEEK matrix containing four rod-tube electrodes. One such rod-tube electrode is exposed in this cut-away drawing. Another parallel tungsten plate calorimeter downstream of the PEEK matrix helps determine shower fluctuations. Two such set-ups would operate in one cryostat next to each other (one with a Sr-90 source embedded inside the tubes to produce high ionization rates, the other one without for reference).

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 cryo lab, BNL). High density feedthroughs for cryogenic applications are not specifically limited to FCC-hh calorimeters. We will for example profit from synergies with neutrino experiments in which collaborators at BNL are involved. An 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 with a collaboration of 6 institutes (activity C). BNL has also shown interest in feedthrough R&D (activity D), where an 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). LAPP Annecy and CPPM in Marseille are evaluating the possibility of joining this R&D effort (interests in PCB design, Simulation and software and feedthrough design).

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 [2], with more challenging radiation requirements of up to 3×10^{15} n/cm^2 and TID of 3 MGy. 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 two 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 upgrade

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), it is therefore required to study radiation hardness of scintillating materials and photodetectors at different temperatures. 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.

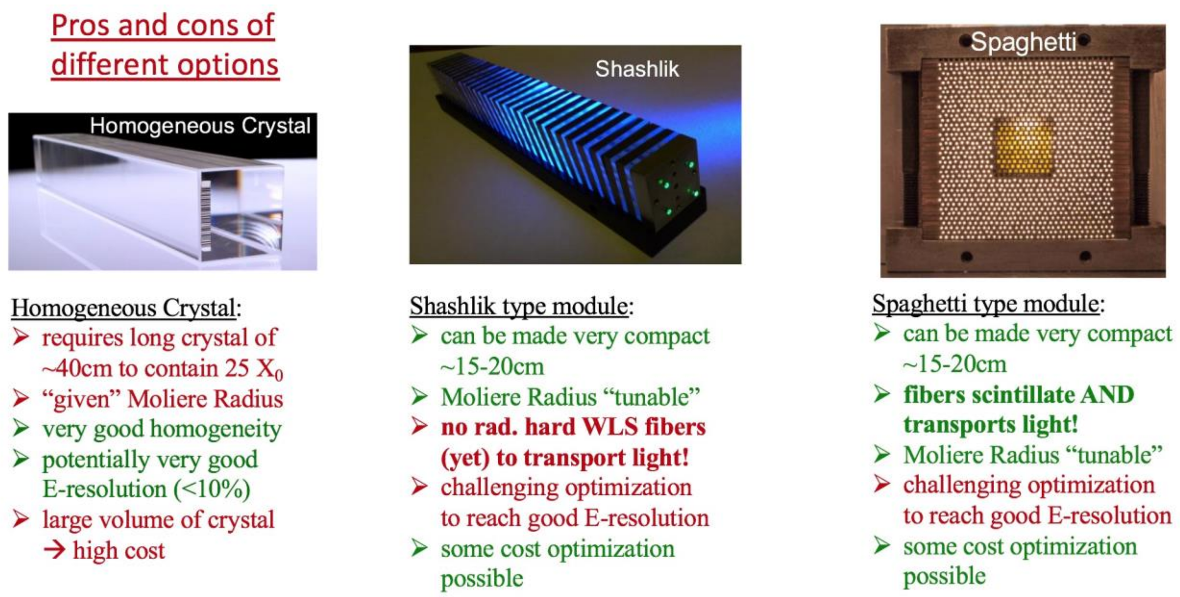

Figure 12: Different options for an LHCb ECAL upgrade.

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 [3]. A collaboration with crystal producers that are contributing to the 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 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 readout is concerned, the ongoing R&D of fast electronics in other collaborations is followed with interest. In recent years a lot of effort has been invested in the development of fast timing detection with resolution below 50 ps 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 SiPMs by all producers together with academic groups and many electronic ASICs are being, 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 needs to be pursued. Some R&D on new technologies such as radiation hard GaAs diodes has also been started.

6.2.2 Activity B: FCC-hh TileCal

Due to the relatively modest radiation requirements (TID 8 kGy in the tiles) the reference design for the FCC-hh TileCal makes use of organic scintillator tiles read out by wave-length shifting fibres and SiPMs, to achieve a factor 4 increase in lateral granularity with respect to the ATLAS TileCal. The proposed R&D will be done in close collaboration with industry and several institutes that are part of the ATLAS TileCal collaboration. It will make use of the infrastructure of the TileCal lab in B175 at CERN for 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, etc. An ATLAS spare mechanics module will be re-instrumented with FCC-hh components to make tests with cosmic muons and possibly test-beam measurements (profiting from the ATLAS TileCal table and test beam infrastructure).

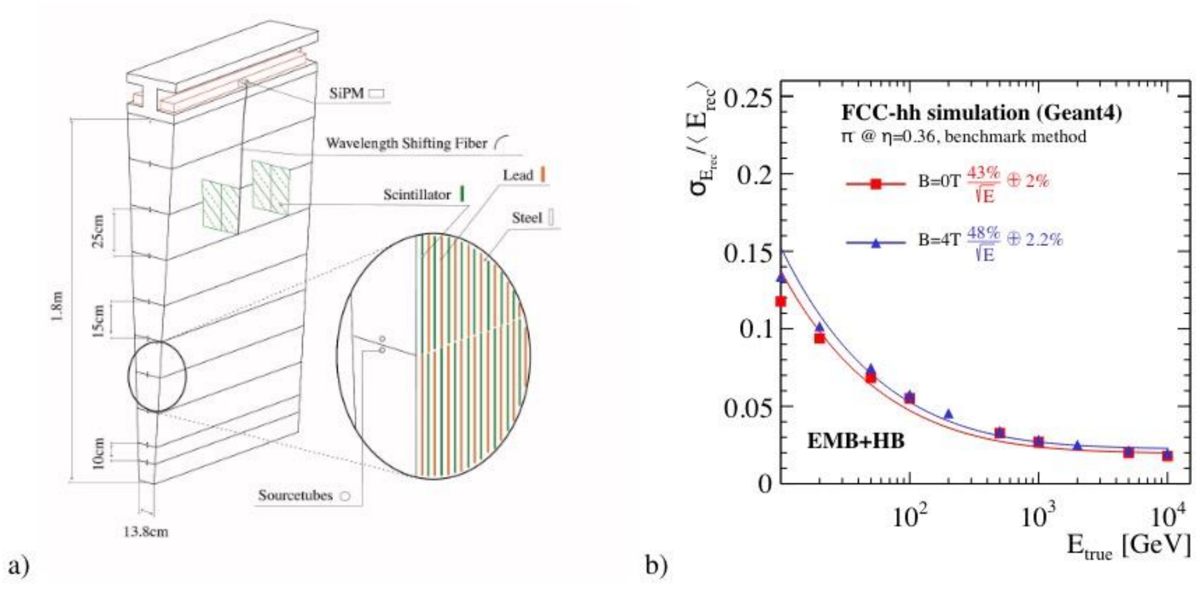

Figure 13: a) Proposed layout for an FCC-hh barrel HCAL. The technology is based on scintillators similar to the ATLAS TileCal. b) First simulation results of the combined single pion resolution.

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

- The scintillating tiles are oriented parallel to the incoming beams at η=0.
- Long fibres are used to bring the light to the outer radius where SiPMs will be located and therefore suffer much less from radiation levels. The SiPMs will be in extractable drawers to allow easy access for maintenance during the lifetime 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 a TileCal-like hadron calorimeter will mostly be focused on the optimisation of the optics concept inspired by ATLAS TileCal, for the best compromise between the amount of light, best uniformity across the tiles surface and minimal crosstalk between the millions of tile volumes arriving through the fibres to the SiPMs. 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 on the Tile FCC-hh calorimeter R&D will cover the period up to end 2019. The main priority of the fellow's activity is 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 with the simulation studies.

6.3 R&D towards Si based calorimetry for CLIC, FCC-ee and FCC-hh

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 active layers are built of silicon sensors or scintillator tiles coupled to Silicon Photomultipliers. Similarly, highly granular calorimetry with silicon sensors is a promising option for FCC-hh.

The new CMS highly granular endcap calorimeter HGCal [4] for the HL-LHC Phase-II upgrade will comprise similar technologies. Therefore, much will be learned for the CLIC/CLD calorimetry [5] 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, and 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.

The activity descriptions B and C below currently focus on CLIC/CLD, and do not yet include specific FCC-hh aspects. Depending on the CMS HGCal experience and on strategic decisions concerning future colliders, activities B and C may be reshaped in the future.

Table 4: Comparison of proposed silicon pad sensors for HGCal, CLICdet and CLD.

	Total Surface of Silicon Pad Sensors (m^2)	Cell Size (mm^2)
CMS HGCal	600	5 – 10
CLICdet ECAL	2500	5 x 5
CLD ECAL	4000 (tbd)	5 x 5

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 and 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 start date, e.g. 2022.

6.3.3 Activity C: Build a few realistic ECAL modules for e^+e^- experiments

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 start 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 an increasingly essential place 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 has hosted major actors for many years, who helped defining methods and goals. Indeed, CERN people have led R&D and detector implementation in various experiments, as a most recent example the two RICH detectors of LHCb. These have not only 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 of 0.7 mrad has been achieved. 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 on the particle path they have been emitted, if the detector optical geometry is aberration-free. This makes them ideal timing detectors with possible time resolutions in the picosecond range [6]. All the detector elements have to be capable of sustaining accumulated radiation doses in excess of ~50 kGy, if they are to be used in hadron colliders.

Table 5: Mean number of photoelectrons expected for saturated rings, N_{pe}, and contributions to the Cherenkov angle resolution for single photons, σ_γ, for the current detectors and the Phase-I upgrade and Upgrade II of LHCb. The range in N_{pe}, and in the chromatic and total resolution for RICH 1 in Upgrade II corresponds to whether or not filters are employed to exclude the higher frequency light. The RICH 2 Upgrade-II values are with filters.

	RICH 1			RICH 2		
	Current	Phase I	Phase II	Current	Phase I	Phase II
N_{pe}	32	42	60–30	24	22	30
σ_γ [mrad]						
Chromatic	0.84	0.58	0.24–0.18	0.48	0.31	0.10
Pixel	1.04	0.44	0.15	0.35	0.19	0.07
Emission	0.76	0.37	0.10	0.27	0.27	0.05
Total	1.60	0.78	0.30–0.24	0.65	0.45	0.13

There is a strong interest in flavour physics results from the current experimental programme at the LHC, and future colliders are expected to also include an important flavour-physics programme. Therefore, it seems fitting 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, picosecond 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 could exhibit so-called quantum Cherenkov effects);
- New optical materials for (lightweight) mirrors and optical coatings and elements;
- New mechanical techniques, cryogenic optical boxes (containing photodetectors) and carbon-fibre (CF) composite based structures;
- New front-end electronic ASICs with picosecond time resolutions and high rate capabilities.

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

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 development and production of lightweight optical structures 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 worldwide single supplier. The development will strongly profit from cooperation 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 vessel structures for the operation of SiPMs at very low temperatures will profit from the expertise and infrastructure of the EP-DT group and of CERN at large. Assuming that these structures will be based on CF composites, we shall seek 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 for designing the new LHCb RICH system foreseen for Upgrade II in LS4. A scale-model prototype would be implemented in the LHCb Phase-Ib upgrade (following LS3) as a test system for the successive full-scale detector to be ready in LS4. Approximately 2-3 years after the current RICH upgrade in LS2, 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: among other applications, fibres 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 80s, it became clear that glass-based fibres (used in a few fixed target experiments) would not work in high rate and luminosity environments, due to their time response, presenting a long light tail. Moreover, the UA2 experiment showed how the photodetector system was crucial in such applications. Development of plastic scintillating fibres started vigorously in the framework of the coming LHC [7][8][9], due in addition to an interested automotive industry, low costs for large coverage areas, 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.

That is until recently, when the LHCb upgrade decided to build a new tracker based on plastic scintillating fibres (SciFi) with an important contribution from CERN. The LHCb tracker uses fibres of 0.25 mm diameter with fluorinated double-cladding, which was developed at CERN in collaboration with Kuraray (Japan), and cooled SiPMs as photodetectors. It is the enormous progress in SiPMs, and in particular the availability of fine pitch arrays of them, which makes this new generation of SciFi detectors possible [10]. A fibre tracker is also proposed to be used in the next LHCb upgrade (Upgrade II, LS4), possibly complemented by a silicon tracker in the highest 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 µm, which calls for small fibre diameter, and finally a sufficiently high tolerance of ionising radiation.

Three areas certainly deserve attention and may be capable of delivering major advances for future high-energy experiments, if a strong R&D is 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.

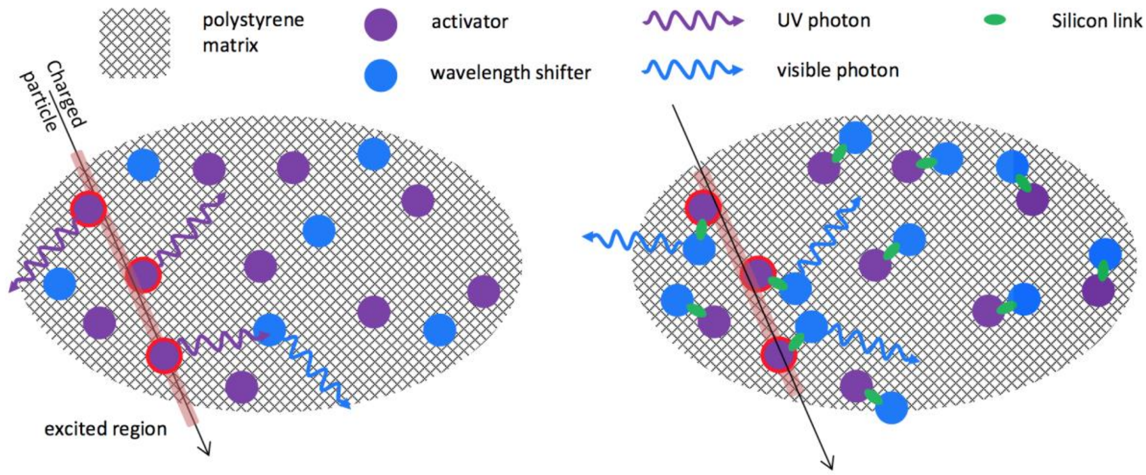

Figure 14: Schematic of the NOL principle. While in a standard organic scintillator (left) energy is transferred from the activator to the wavelength shifter molecules by radiative processes, the two molecules are joined by a silicon link. This allows for a more efficient non-radiative energy transfer.

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 (only 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 [11]. 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, shown in Figure 14, 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.

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.

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7 Detector mechanics (WP4)

7.1 Introduction

The mechanics of the future HEP detectors will have 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 exceptionally large dimensions and unprecedented radiation levels, while lepton detectors require high spatial resolution and very low material budget, with radiation damage being less a concern (Figure 15).

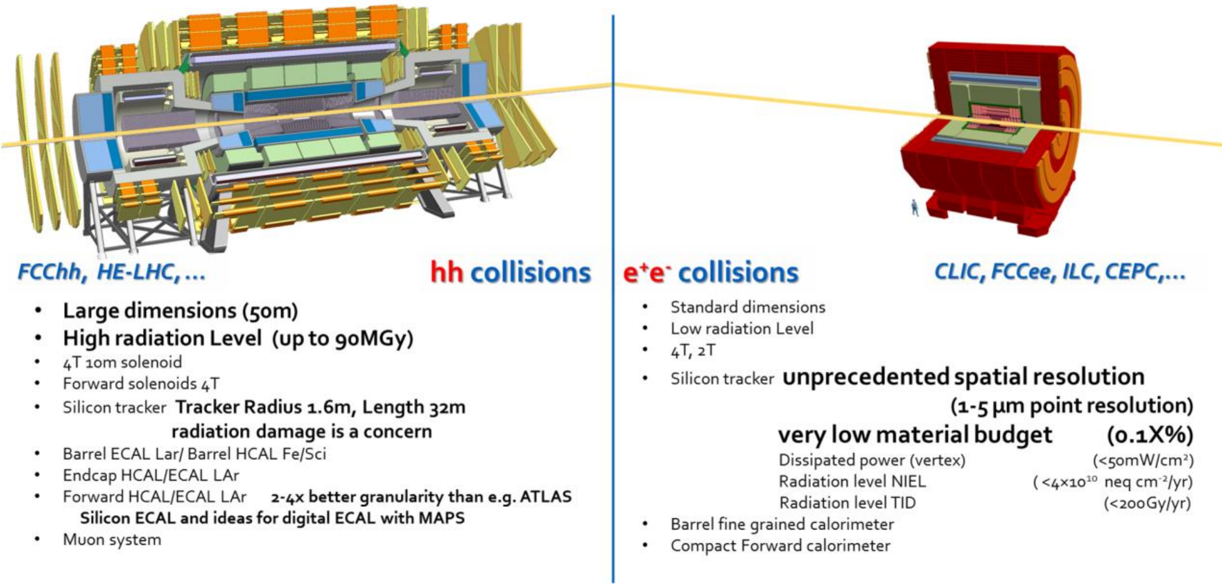

Figure 15: The mechanics of the future HEP detectors has to cope with a wide range of demanding requirements.

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 and electronics power densities will also drive cooling solutions 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.

To address the future detector mechanics needs a selection of targeted R&D activities is proposed:

- Activity 1: Low mass mechanical structures for future HEP Experiments
    - 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 interfaces and services architecture for automated installation and maintainability;
- Activity 3: High-performance cooling for future detectors.

There is a wide interest on these proposed activities, beyond CERN, in several Institutes and companies worldwide. Already existing initiatives, like the annual Forum on Tracking Detector

Mechanics, provide relevant opportunities for launching of R&D collaborations. This EP R&D initiative raises the interest in developing this further.

7.2 Low mass mechanical structures for future HEP Experiments

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 LHC experiments' Tracking Systems different technologies have been investigated:

1. Cold Plates made of high thermal conductivity carbon fibre laminates embedding polyimide capillaries for water leak less system (Figure 16) [1], [2];
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], [4];
3. Microchannels embedded in silicon or polyimide substrate for vertex detector both for single-phase or two-phase cooling fluids (Figure 17) [5], [6].

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.

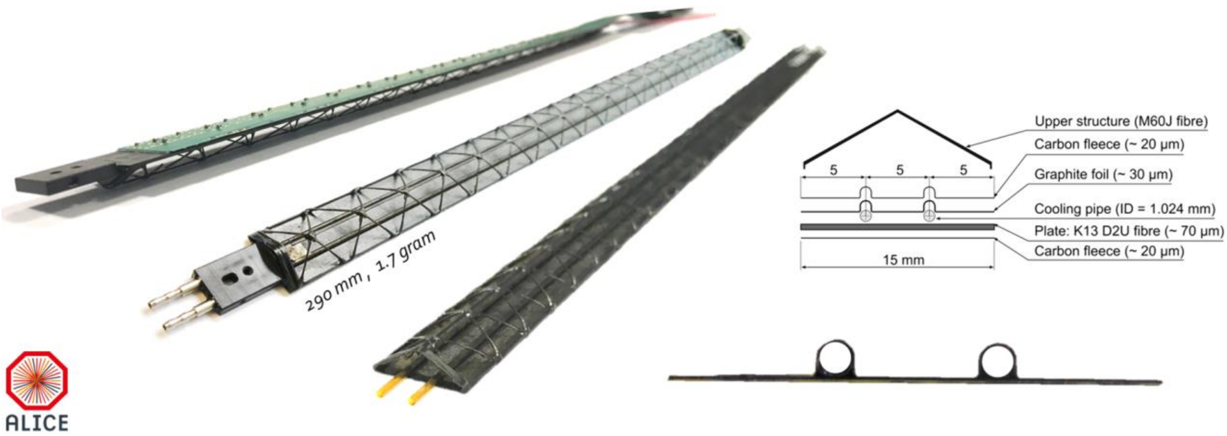

Figure 16: Cooling Substrate: ALICE ITS Inner Barrel Stave, High thermal conductive carbon microvascular substrate with embedded polyimide tubes.

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.

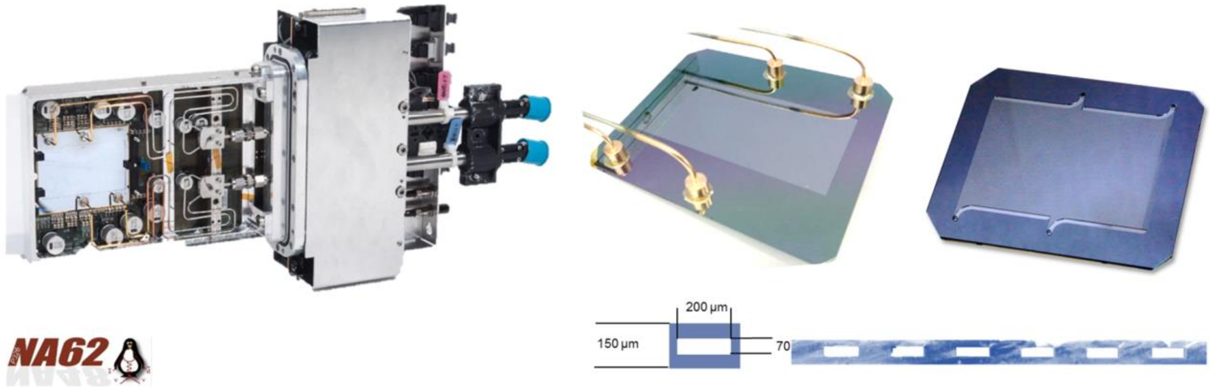

Figure 17: Cooling Substrate: Na62 GigaTracker module. Silicon microchannel [7].

For the innermost layers of future lepton collider vertex 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 (<20 mW/cm^2) and low radiation levels;
- minimizing active cooling material through new optimised micro capillary or peripheral cooling design;
- 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 (<50 µm).

In hadron collider vertex detectors stringent cooling requirements, on the removal of dissipated heat and on the minimisation of radiation damage, will require the development of new heat exchanger substrates to achieve better performance and lower temperatures. Additive manufacturing and other advanced manufacturing techniques are to be studied for the fabrication of ultralight microchannel substrates. 3D printing of different materials including metals and ceramics engineered for CTE compatibility need to be explored to overcome the limitations of present technologies (Figure 18).

The additive manufacturing techniques will be reviewed with respect to alternative technologies based on carbon composite materials, such carbon microvascular heat exchangers made of carbon fibre structures that embed capillaries (polyimide, low mass micro-pipes, etc.) compatible with high pressure.

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

For the outer layers of future trackers, both for hadron and lepton colliders, large areas need to be covered with detectors, and therefore the costs, the assembly aspects and the QA will be essential for the mechanics design choices.

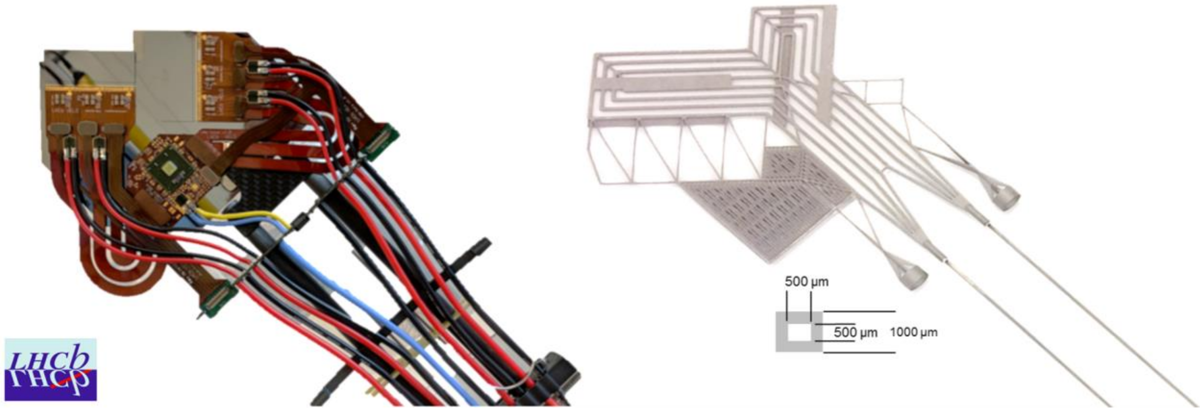

Figure 18: Cooling Substrate. LHCb VELO module with a prototype of the cooling substrate in grade 2 Titanium. Obtained by additive manufacturing (Direct Metal Laser Melting). The final substrate that will be installed in the detector is based on silicon microchannels [6].

A “lego” concept, based on a modular substrate, to serve one or a limited number of (stitched) chip sensors, would allow for single module test and replacement. The challenges with such concept are with the electrical and hydraulic interconnections.

- Substrates with miniaturised closed loop heat pipe, operated in standalone mode, and transporting the heat from the sensors to a primary cooling loop without any hydraulic interconnections will be investigated to reduce system complexity;
- Additive manufacturing methods are to be considered for both the heat exchanger substrates and fluidic interconnection.

Alternatively, cheap and disposable cooling substrates with a flexible shape, interconnecting 50 µm MAPS based on carbon-fibre structure embedding polyimide pipes could provide a cheap fully integrated solution.

Material investigations shall be extended to cheaper carbon composites that can be processed more cheaply for large detector volumes, especially relevant for the new, increased detector dimensions: i.e. out-of-autoclave curing that represents a promising faster and more cost-efficient process.

Organic materials used in composite mechanical structures will be exposed to unprecedented high radiation levels in hadron detectors and will suffer from loss of mechanical, electrical, optical and chemical properties. Detailed investigation and qualification to radiation load shall drive the material choice. To meet the requirements Carbon Fibre Reinforced Plastic (CFRP) materials with different resin systems than epoxy, e.g. CFRP-Cyanate ester, CFRP-Cyanate Siloxane, CFRP-Polyimide, CFRP-Peek, thermoplastic prepreg, will be investigated.

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 place EP-DT in a leading position and greatly facilitate synergies with external teams.

Potential additional co-funding schemes may appear as a result of the seeding effect of 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 and hybrid honeycomb structures. A synergy with WP3 and WP8 is foreseen to study the application of these new technologies to HEP detector cryostats.

Liquid Argon (LAr) calorimetry is considered one reference technology for future Electromagnetic calorimeter (ECAL) because of its intrinsic radiation hardness and stability demonstrated in the successful application in the ATLAS experiment. Development towards ultra-thin superconducting solenoid magnets for future HEP experiments is being carried out. Both applications need cryostats to guarantee the low operating temperatures.

Both calorimeter and magnet 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 mass and thickness applies to both inner and outer cylinders, buckling effects in the outer cylinder, due to the vacuum inside the cryostat, must be considered in the design.

Cryostats for super-cold liquid fluids are still the purview of metals, but in order to decrease the thickness and material budget, lightweight and strong composite materials should be considered. During recent 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 significant difference between the axial and transverse coefficients of thermal expansion (CTE) in each ply.

Similar applications can be found in aerospace industry [8], [9], [10]. The fuel tanks used in rockets have been metal for decades, with a 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 [11]. 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 and manufacturing processes were assessed through coupons 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 cryotank achieved 30% saving in weight and 25% in cost, compared to a baseline aluminium alloy cryotank.

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 [12], [13]. The project CHATT is a part of the European Commission's Seventh Framework Programme. The main objective was to investigate carbon fibre reinforced composite materials for cryogenic fuel tank applications. Four different subscale CFRP-tanks have been designed, manufactured, and tested. Cylindrical tank with liner by DLR (D=1 m, L=3 m); Cylindrical tank without liner by FOI/SICOMP (tubes of several dimensions); Complex shape tank with liner by TU Delft (complex combined spheres shape); Dry wound cylindrical tank with liner by ALE (D=0.29 m, L=0.57 m).

Space X has designed, developed, and fabricated a composite LOx tank, which is a key component of interplanetary transport system (ITS). The tank is 12 m in diameter and represents the largest composite vessel ever produced (Figure 19) .

Figure 19: Left: ATLAS Liquid Argon Hadronic Calorimeter Cryostat in Aluminium Alloy. Right: SpaceX ITS LOx cryotank in Carbon Composite.

Industry pursues 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 applications.

A close collaboration with Aerospace Industries and Institutes involved in the cryotank development programmes (NASA, ATK, Space-X, ESA, DLR, Airbus, etc.) shall be envisaged for technology 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 tape lamination method to accomplish laminate consolidation. The ultrasonic energy provides excellent compaction during depositing of the carbon fibre tapes;
- OOA, out-of-autoclave process, with a lower curing temperature, in which the resin system is suitable for vacuum-bag-only curing and produce 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 structures;
- Review and identify liners and other permeation barrier solutions;
- Review liner-less tanks that 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 methods;
- Review and identify thermal insulation: the broad classes of insulation systems to review include foams (including advanced aerogels) and multilayer insulation (MLI) systems combined 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 address design aspects that are specific to HEP cryostats:

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

The validation of material and technology choices, based on production and characterisation of test samples, shall be followed by production of a scaled size cryostat Engineering model (about 1 m^3 volume) to demonstrate feasibility, to validate design choices and to compare against advanced metal or hybrid honeycomb structures.

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

Following the ALARA (As Low As Reasonably Achievable) objectives the design of present HEP detectors relies on optimizing installation, maintenance, repair and dismantling work to minimize effective dose on personnel.

Radiation levels in future hadron collider and radiation-cooling times will limit operational and maintenance scenarios, and call for revised detector designs to account for shielding, remote opening/manipulation and limited (short) human access [14]. 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 an extension to 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 of 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 (Figure 20). Accesses and interfaces enabling use of automated systems/robots for maintenance and repair interventions need to be foreseen already 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.

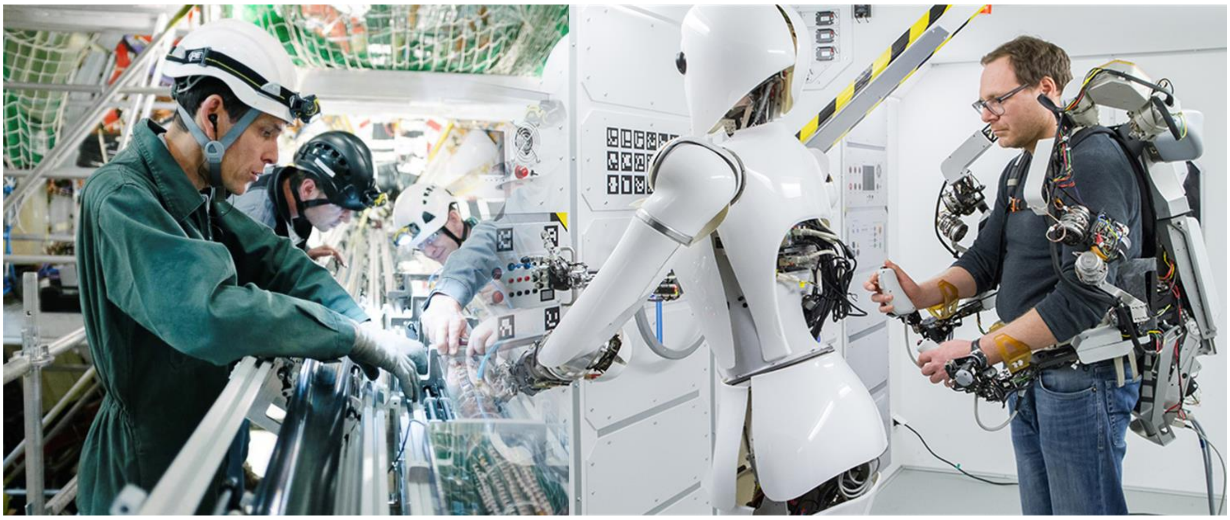

Figure 20: Radiation levels in future hadron collider and radiation-cooling times will limit future operational scenarios. This should lead to revised detector designs to account for shielding and remote access and manipulation.

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 to identify suitable automated platforms and manipulator systems. The focus of this program will be the design of detector interfaces for an automated Remote Manipulator System (RMS), and the design of the interfaces for services automated engaging and disengaging, Services Umbilical Mechanism Assembly (SUMA) (Figure 21).

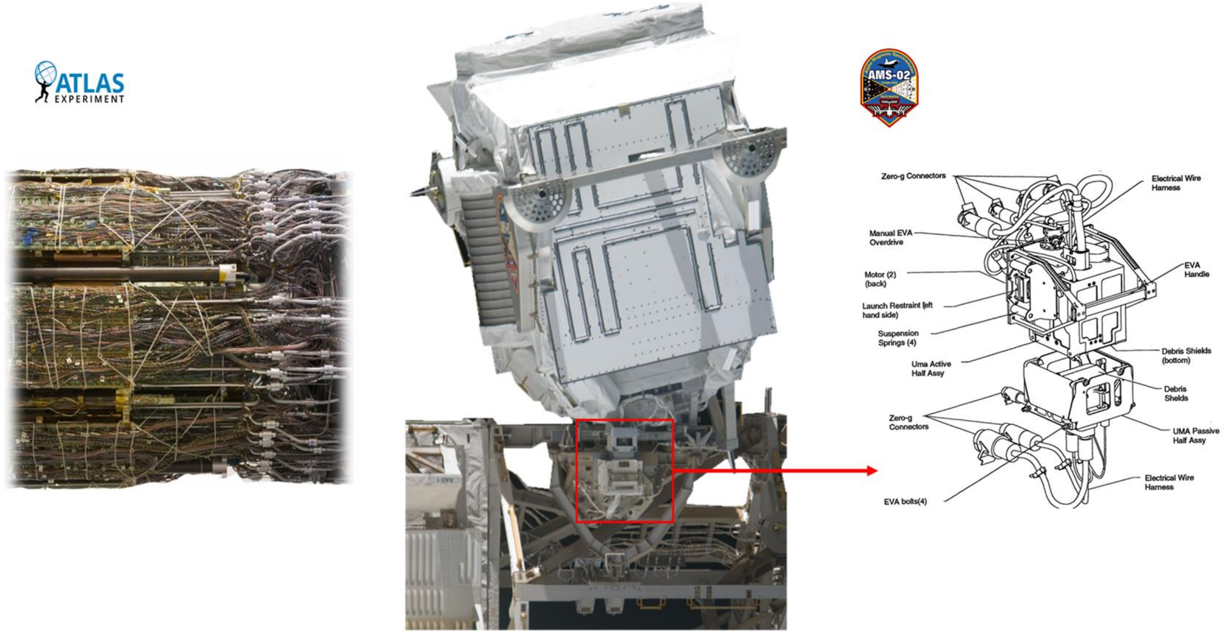

Figure 21: Service Umbilical Mechanism Assembly (SUMA) for connections minimization and automation. Left, typical HEP detector service connection, right HEP Space based detector with on single port for service connection [15], [16].

After the detector sub-structure/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 for robots developed.

In addition, the use of new advanced technologies like augmented reality shall be studied for fast and reliable identification of the intervention environment (such as where are the hot areas) and to help with the intervention work in order to 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: an HEP Robot Lab.

Possible collaboration is foreseen with CERN HSE for all aspect related to safety and intervention in Highly Activated Areas, as well with CERN EN-SMM for sharing the know-how on mechatronics. Possibilities for collaboration are being investigated with ETH Zurich Department of Informatics, Institute of Neuroinformatics, Robotics and Perception Group as well as Tampere University of Technology, Laboratory of Automation and Hydraulics, Cognitive Robotics and Department of Signal Processing, Computer Vision.

7.4 High-performance cooling for future detectors

The cooling system for any Inner Tracking System in all collider detectors has to remove efficiently the heat generated in the detector and to keep the detector in needed operating temperature. The thermal load is typically dominated by the front-end electronics and some power dissipated in the active sensors, auxiliary electronics and cables. To match the future needs the investigations on cooling will be done in cooperation with WP1 and WP3.

In hadron collider detectors, the cooling system has the essential task of keeping silicon sensors at a required cold operating temperature which helps limiting the radiation damage-induced leakage currents. A possible implementation of silicon photo-multipliers (SiPM) in hadron collider detectors will also call for deep cold (though not yet cryogenics level) cooling. Low temperature liquid or two-phase cooling systems need to be used in all these cases. 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 the radiation levels are lower. There, 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 RHIC. 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 for inner tracking detectors in hadron collider experiments is two-phase evaporative cooling with CO_2 fluid. Relevant experience and an important standardization approach to CO_2 cooling have been pursued with groups from different experiments, and a centralized CO_2 cooling service has been established in the EP-DT group [17]. Within a few years the evaporative CO_2 has grown to be the baseline cooling technology for the HL-LHC tracking detectors. However, the operating temperature of CO_2 is limited by its freezing point of -55°C and by 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. 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°C. In parallel, the requirement for 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 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 the above mentioned new synthetic refrigerants 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-DT 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 CERN Environmental Protection Steering board (CEPS). Furthermore, in the context of the collaboration just launched between CERN and NTNU (the Norwegian Institute of Technology), the work on natural refrigerants might also gain access to co-funding schemes from NTNU.

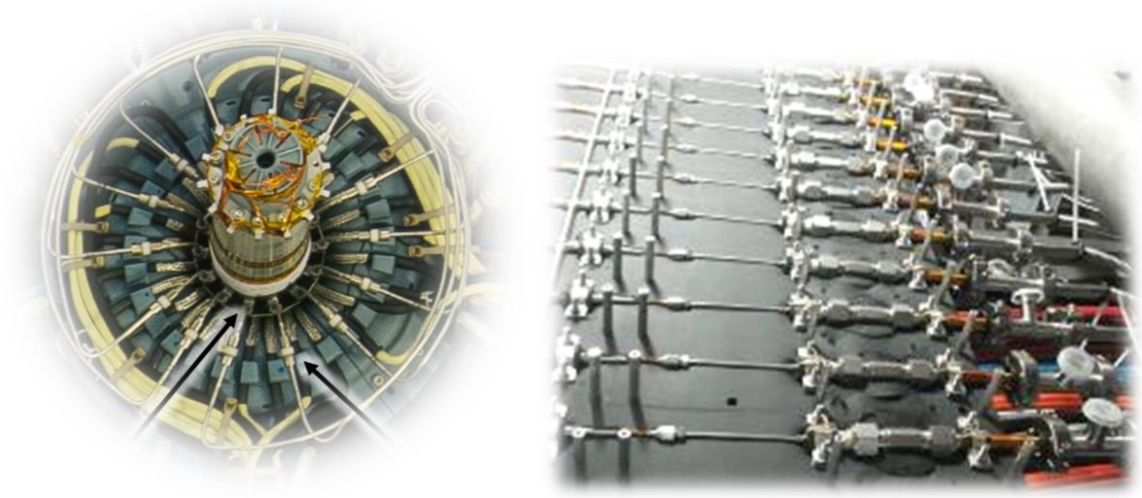

Figure 22: Higher radiation levels and new coolants will require identification and validation of suitable hardware and instrumentation solutions for the cooling circuits.

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 the 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.

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8 Integrated Circuits (WP5)

The High Energy Physics ASIC design community is currently designing in 130 nm and 65 nm commercial-grade CMOS technologies [1]. Meanwhile industry is ramping up the production in 7 nm FINFETs, and is developing prototypes in 5 nm [2][3]. ASICs for HEP should follow the microelectronics industry in order to benefit from the intrinsic density of more downscaled transistors and also the intrinsic high speed and lower power consumption. The need to follow industry is also motivated by the fact that only these newer technologies 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 3D geometries of transistors (FINFETs, shown in Figure 23) 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 a working chip in the first iteration;
- 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.

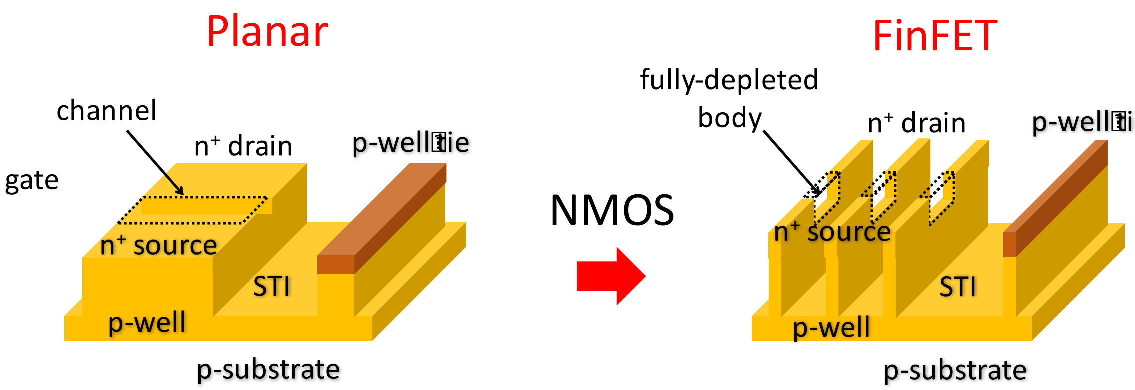
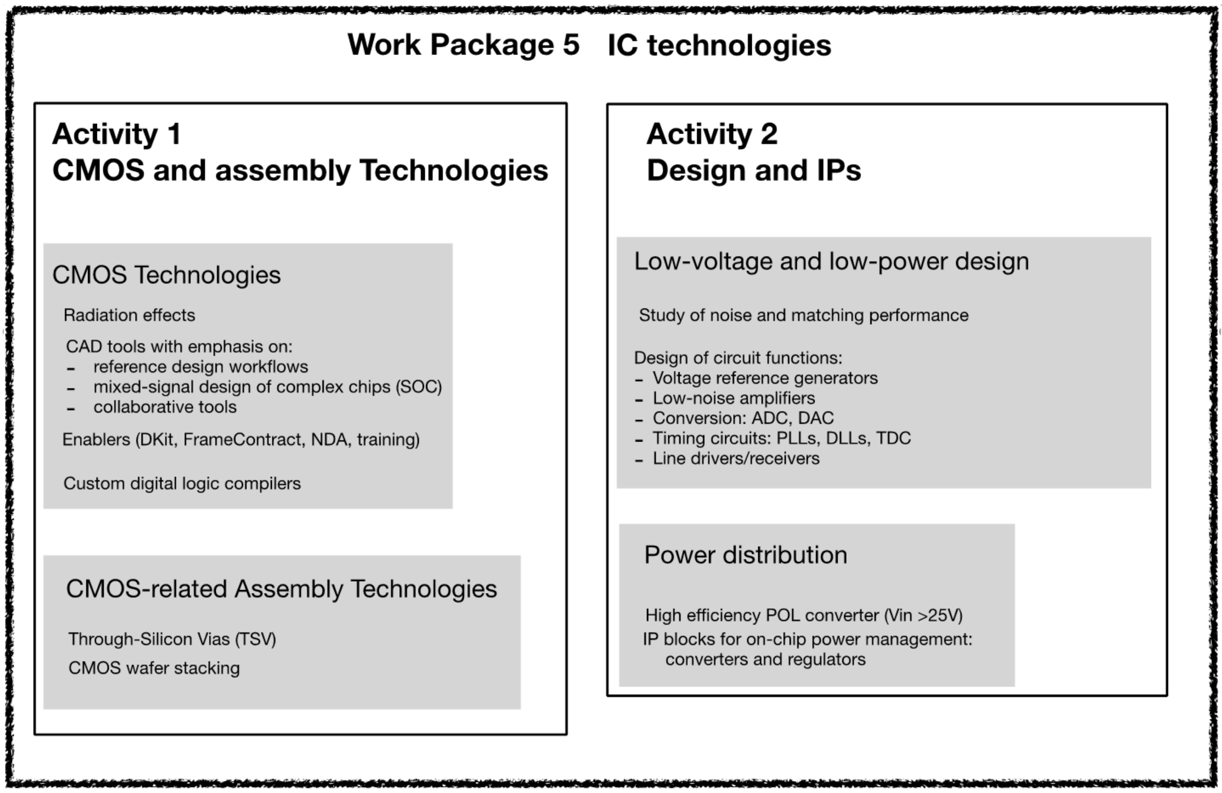


Figure 23: Moving from planar to FinFETs below the 22 nm node. The structure of the transistor is very different, with dramatic consequences on the design practices and tools [4][5][6].

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 [7][8].

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 28 nm technologies and the more advanced FinFETs that replaces them ubiquitously as from the 16 nm 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, etc.). 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 [9][10]. 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 mitigate 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, 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 future LHCb VELO upgrade [11]. 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 3 GHz/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/cm^2 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 that 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 that 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 will be developed in a way that is compatible with bump bonding. This is a topic that 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 that can only be addressed by the use of TSVs 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. This need emerges from the increasing complexity of technologies, as illustrated in *Figure 24*.
- 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 2D readout circuits. (Charge sensitive amplifier, shaper and comparator for sensors with input capacitance <100 fF and leakage current per pixel <20 nA).
    - Amplification, filtering and discrimination (A/D conversion) for a 1D 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, most of which with sub-1 V supply voltage. Other components of the system, such as optical transceivers, might instead need larger supply voltages (2.5 V). 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 (see *Figure 25*). This theme is focused on the development of these circuits: a stand-alone DC-DC converter rated for an input voltage of 25 V or more, and IP blocks in the mainstream technology to be made available to SOC designers.

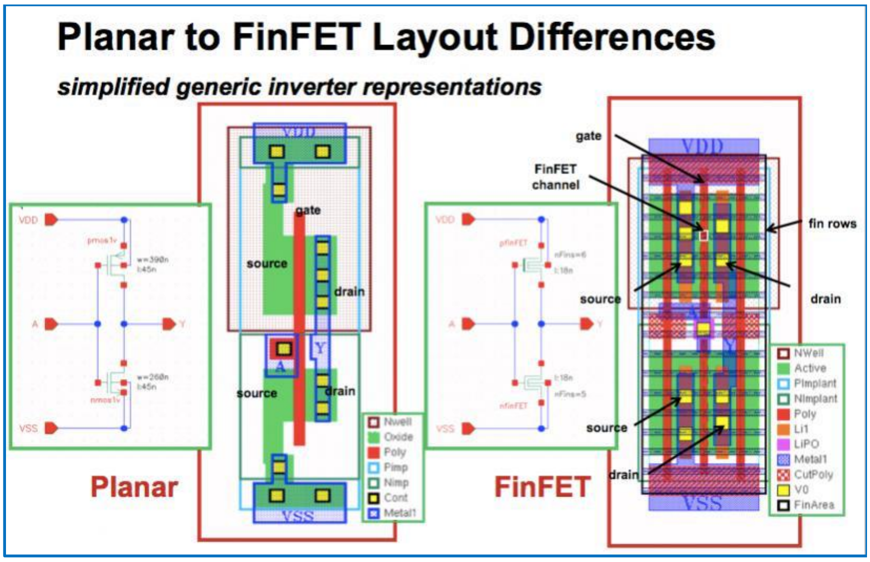


Figure 24: The increased complexity in more advanced CMOS technologies is evident from this comparison of the layout of a simple inverter in a planar (down to 22 nm) and a FinFET (from 20 nm) process. The number of layers necessary for fabrication is considerably increased in FinFETs, and precise rules dictate the patterning in most layers.

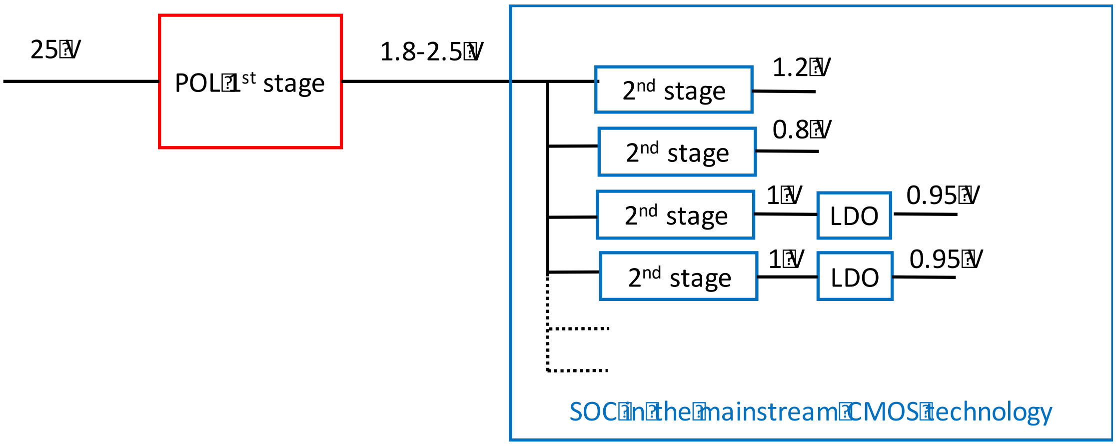


Figure 25: Power distribution scheme for a System-On-Chip with multiple voltage domains. The 1st stage POL will be developed in a high-voltage technology, while the other elements in the mainstream CMOS technology.

A radiation and magnetic field tolerant DC-DC Point-Of-Load (POL) converter with a maximum input voltage of 12 V has been recently already developed in a 0.35 µm commercial technology, and is being deployed in a large number of LHC detector systems [12]. The availability of this old technology is not guaranteed at all in the long run, 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 [13]. 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 25 V, which 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 DC-DC 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 25 V to 1.8 V-2.5 V. 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 DC-DC converters (capacitor and/or inductor based) and linear regulators. The DC-DC converters will work as second stage, converting the 1.8 V-2.5 V from the first stage to the required voltage of the analog (1 V) and digital (<0.8 V) 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.

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9 High speed links (WP6)

Three lines of R&D activities have been identified to bring the performance of high-speed data links to the levels required by future detectors: ASICs, FPGAs and Optoelectronics. These activities have the potential to significantly enhance the data-rate and/or radiation hardness of the data transfer systems that will be implemented beyond HL-LHC.

Figure 26 highlights 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 [1][2] 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.

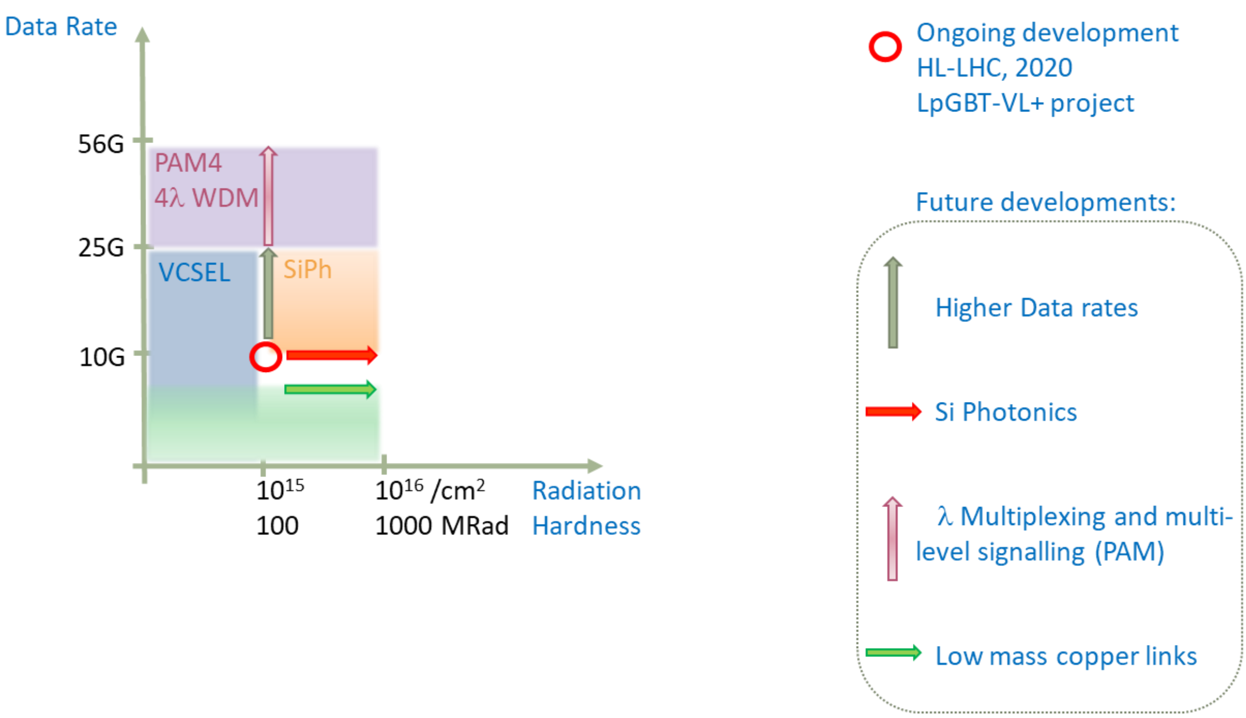


Figure 26: Current performance (red circle) and development space for high-speed links.

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

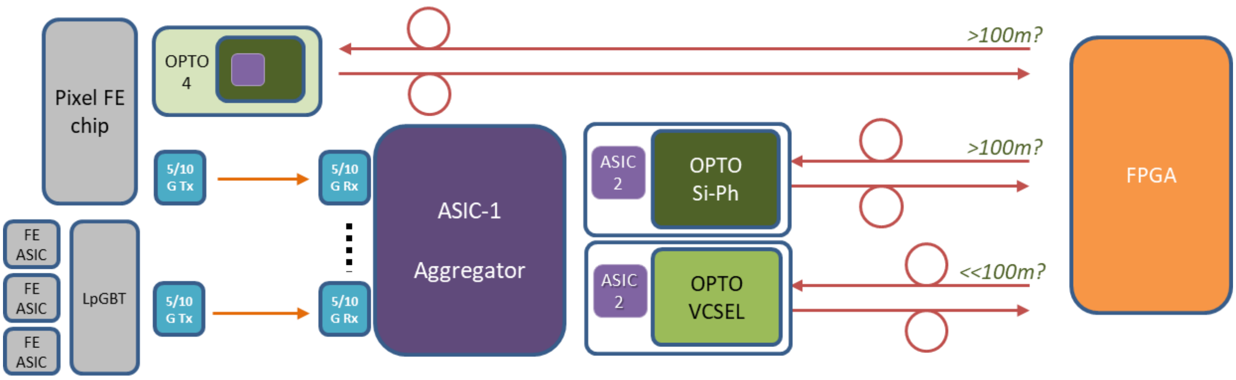
The links being developed for HL-LHC are limited in data rate to 10 Gb/s and their optical transceivers cannot survive fluences beyond 5x10^{15} particles/cm^2 [3][4]. This is problematic already for HL-LHC detectors where the pixel optoelectronics for instance has to be deported to the first strip layer (or above) leading to the use of massive lower-bandwidth copper cables [5]. Another example is the case of the CMS HGCal detector, where the huge amount of data to be shipped off-detector with link bandwidths limited to 10 Gb/s will impose the installation of a large number of costly optical links.

Experiments in future accelerators will demand even 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. However, they will not result in chipsets or components dedicated to specific high-energy physics detectors, but rather in prototype ASICs and component demonstrators that will be designed and fabricated as building blocks for future targeted projects.

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

Figure 27 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).



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

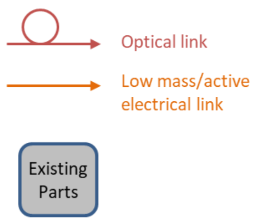


Figure 27: Schematic representation of a high-speed link between front-end and back-end.

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 (2020-2024, 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 assessment of 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.

Table 6: Overview of proposed tasks and 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

The ASICs activity targets 28 Gb/s to 56 Gb/s link data rates, a significant step upwards from the 10 Gb/s achieved by the chipset under development for HL-LHC. It will be carried out in synergy with WP5 where the most suitable and radiation resistant technologies will be selected and characterized. The ASICs will be operated in the front-ends of the detectors and will perform aggregation, serialization/ deserialization and driver/receiver functions.

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 will be carried out in cooperation with KU Leuven and SMU.

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 will be carried out in cooperation with INFN and SMU.

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 will be carried out mostly by collaborating institutes. CERN contributes to coordination, subsistence and submission costs.

9.2.2 Activity 2: FPGA

The backend of the link is located in the counting room where Commercial Off The Shelf (COTS) electronics can be used. The performance of high-end state-of-the-art FPGAs is already matching the data rate targets of activity 1 (ASICs) and FPGAs are the best candidates for interfacing to front-end serializers/deserialisers. No custom hardware developments are foreseen for backend link electronics, but a large effort is required to develop code and master the tools associated to high performance FPGAs.

Activity 2 evaluates FPGAs, develops associated firmware and software, and surveys the market for new products and features. It is crucial that both activities 1 and 2 develop compatible capabilities and grow in synergy. FPGA activity 2 will be key to benchmarking, testing and operating the high-speed link system.

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

Optoelectronics is key to transferring data between front- and backend. 28 Gb/s links for future experiments will hit distance and radiation resistance limits which need to be investigated, understood and mitigated. Activity 3 covers both legacy VCSEL-based technology and the more advanced but immature Silicon Photonics technology in order to maximize the reach of the R&D effort.

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 suitability 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 soon. This activity will be carried out in cooperation with INFN Pisa, KIT and CERN-BE.

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.

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

Investigation of feasibility of implementing up to 28 Gb/s 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 100 m possible?), radiation tolerance and associated penalties, voltage headroom in VCSEL driver, fibre transmission penalties, etc. This task investigates an evolutionary path complementary to Task Opto-1 and unlocks high data rates for very short distances. However, it 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 detectors. This work package 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.

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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, 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 [1]. This challenging trend begins already with the HL-LHC, as illustrated in Figure 28.

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 (Figure 29) [2]. 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 the 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 [3]. 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

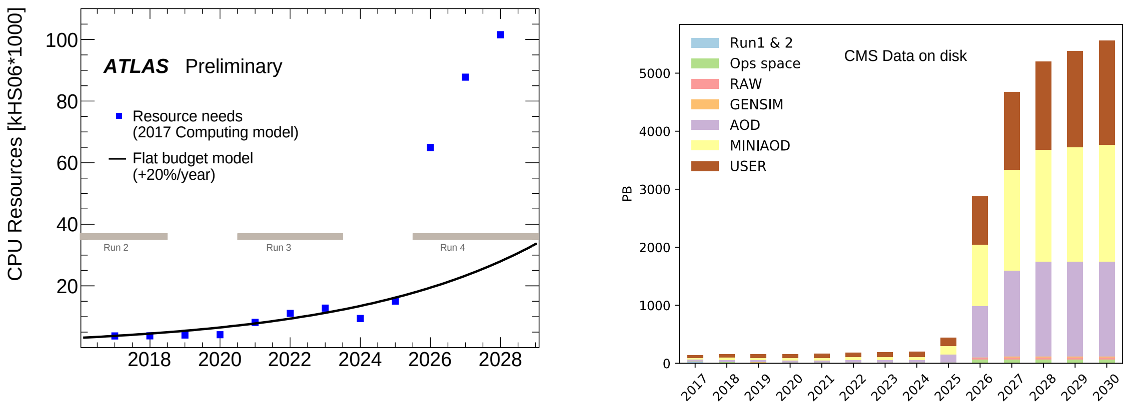

Figure 28 - Plots of the CPU and Disk requirements for general purpose LHC experiments in the HL-LHC era, illustrating the step change in resources from accelerator upgrades. These plots show the naïve application of the Run 2 computing models, which simply underlines the need for software and computing investment. Already the experiments have made improvements from these 2017 estimates. From HSF CWP Roadmap [1].

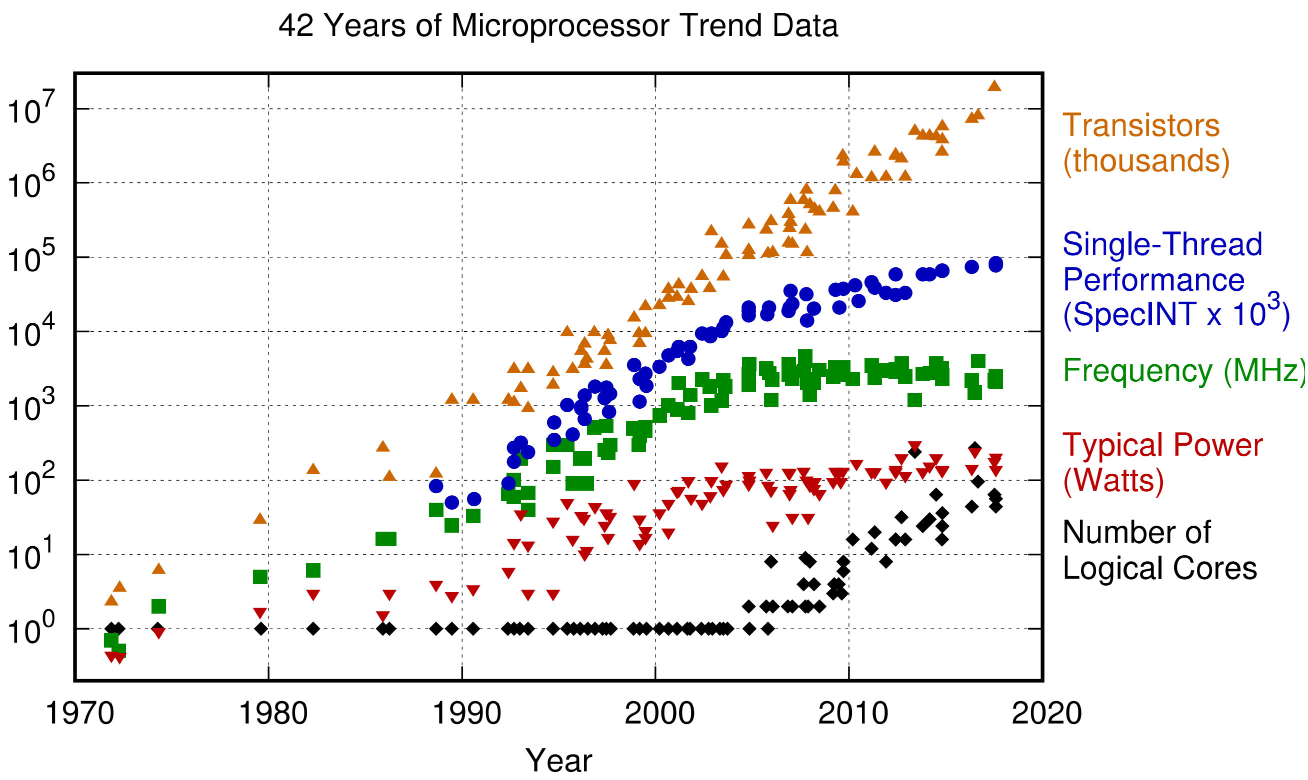

Figure 29 – Microprocessor trend data showing the limit reached for clock frequency and the consequent limitation in single core performance. Original data to 2010 collected and plotted by M. Horowitz, F. Labonte, O. Shacham, K. Olukotun, L. Hammond, and C. Batten. New data collected for 2010-2017 by K. Rupp, https://github.com/karlrupp/microprocessor-trend-data. CC-BY 4.0.

data in heterogeneous and geographically dispersed computing centres needs to adapt to the anticipated rates and technology changes we expect in the future.

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. An example is 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.

10.2 Faster Simulation

Monte Carlo event simulation is a vital tool for the design, construction and running of any high-energy physics experiment [4]. 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. This technique, combined with effective use of accelerators and HPC systems, may provide significant speed up to detector simulation applications, although not sufficient to fully satisfy the needs of all experiments. Currently the only known way to achieve the additional 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 [5]. 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 (Figure 30) with well-understood systematic uncertainties.

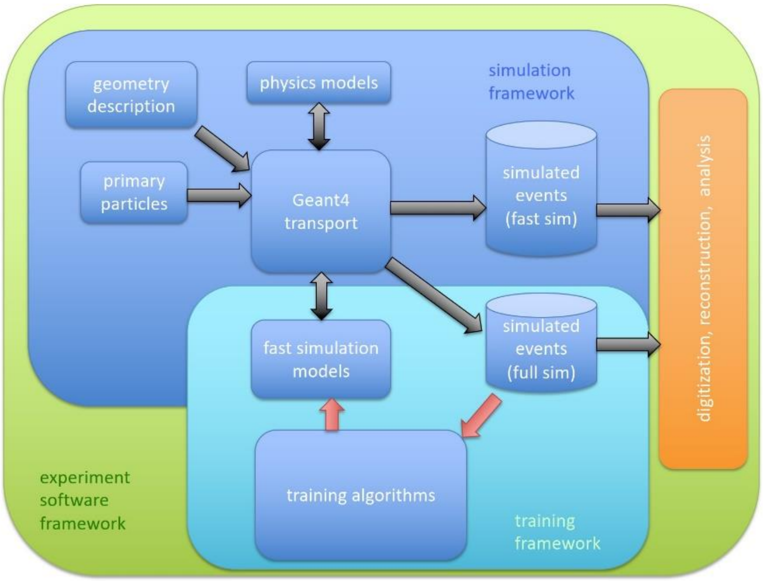

Figure 30 – Illustration showing the integration of machine learning training and inference into the classical workflow.

The effort on fine-grained parallelisation based on vectorisation and data locality will be complemented with 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 [6]. 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. the CMS framework) and GPU usage for the reconstruction in pre-defined detector regions (e.g. the 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 (e.g. the CMS 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 that 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 back-ends 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 dataset 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 [7]. 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 network 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 [8]. To take advantage of these resources—whether within dedicated centres 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 activities, 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 [1]. 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 [9]. 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 led 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.

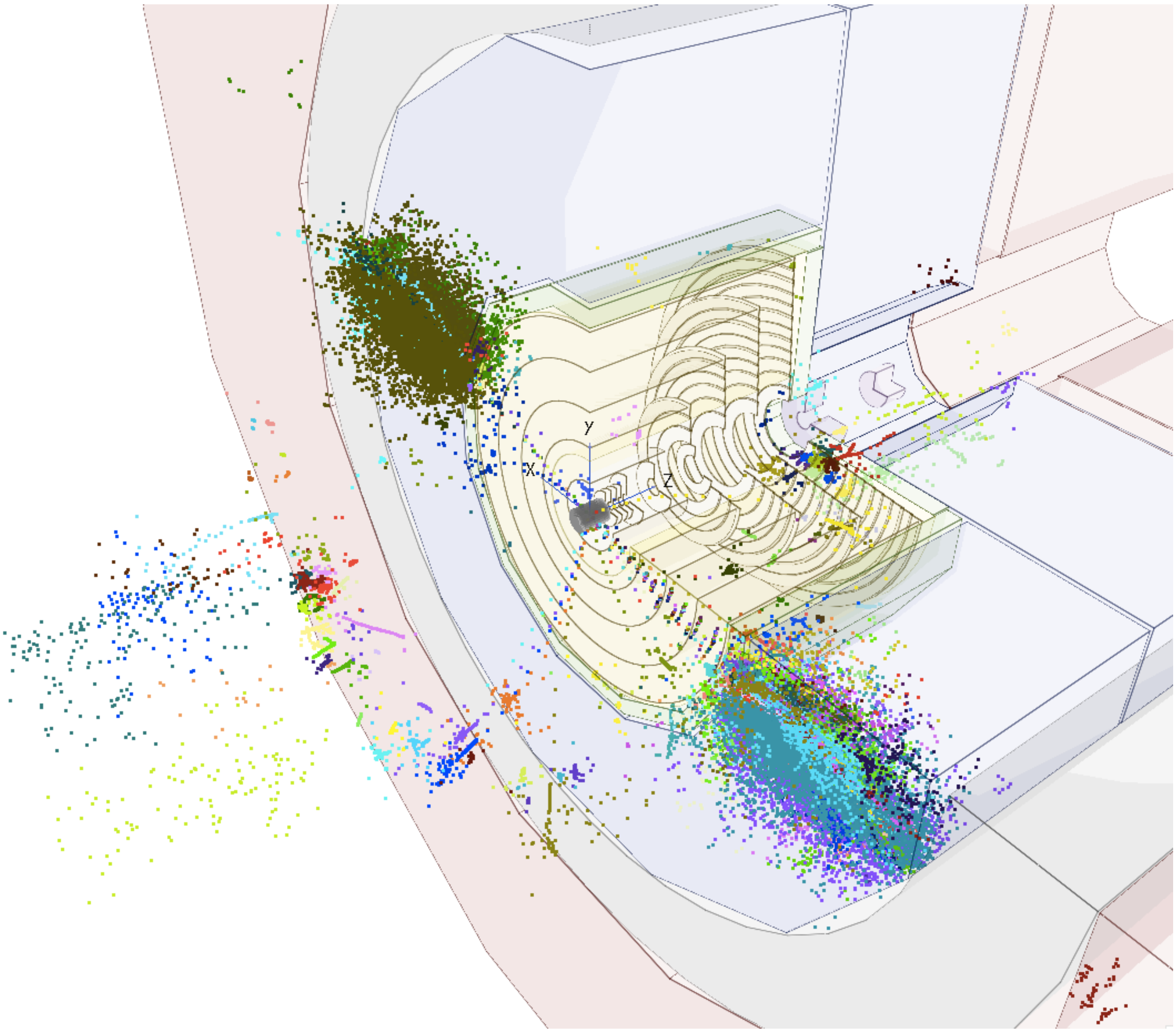

Figure 31 – Already early detector studies require a fairly complete simulation and reconstruction software chain, as in this example for studying jet tagging capabilities with 5TeV b-jets in FCC-hh, but using the CLIC software and the FCC vertex tracker, combined in the CLIC detector model.

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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 [1][2][3] . The parameters of the existing central solenoids in ATLAS and CMS are given for comparison [4][5].

Table 7: 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/mm^2	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 in some cases tremendously increased requirements, challenges in different domains need to be addressed.

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

- Advanced Magnet Powering for high stored energy detector magnets;
- Reinforced Super Conductors and Cold Masses;
- Ultra-Light Cryostat Studies;
- New 4 tesla General Purpose Magnet Facility for Detector Testing;
- 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, see Figure 32, 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 larger 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.

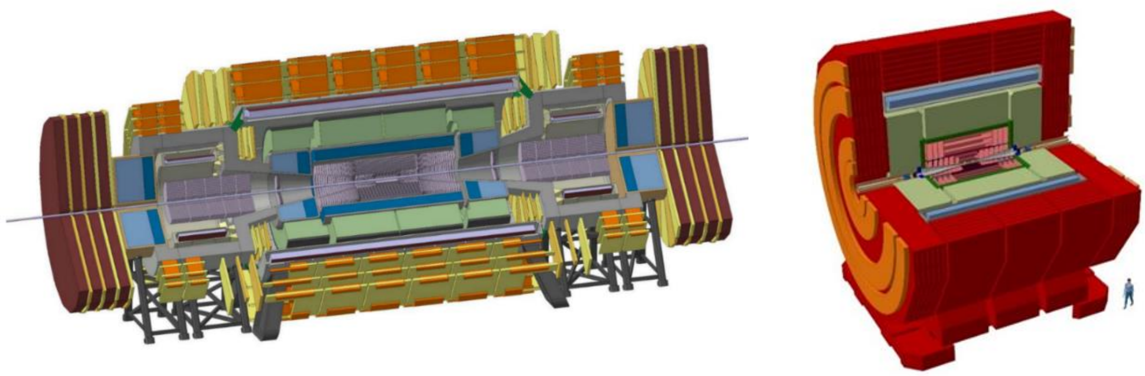

Figure 32 : Two detectors: the FCC-hh (left) and the CLICdp (right).

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. A few issues are critical and shall be developed:

(1) New compact fast protection current breakers (common effort with TE/MPE):
To withstand the large magnet current, large, sturdy and redundant switch breakers will be used. This might be an issue for integration layouts with detector on-board platform. Based on the requests and the specific time constants of the future HEP magnets, technical solutions shall be identified and validated.

(2) Compact High-Performance Quench Protection Dump Unit:

The design shall take into account the operational requirements and constraints of future HEP magnets (reliability, integration, availability, recovery time, costs, etc.). Dump circuits with either passive or active cooling shall be considered.

(3) Maximum Energy Extraction studies:
These generic studies will cover magnet discharges, quench propagation, fault case scenario, with finite-element simulations, and provide a design of the energy extraction system adapted to the future HEP magnets (heaters, quench back).

Ad. 2. The feasibility of free wheel systems will be studied and the technical requirements defined. An optimized design for the large detector magnet applications shall be proposed. The free wheel mode shall allow minimizing the downtime of the magnet, leaving the possibility for intervention on magnet sub-systems 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. Such a system is being currently developed for the CMS magnet and adapted to its powering circuit (Figure 33), with an implementation planned during LS2 [6].

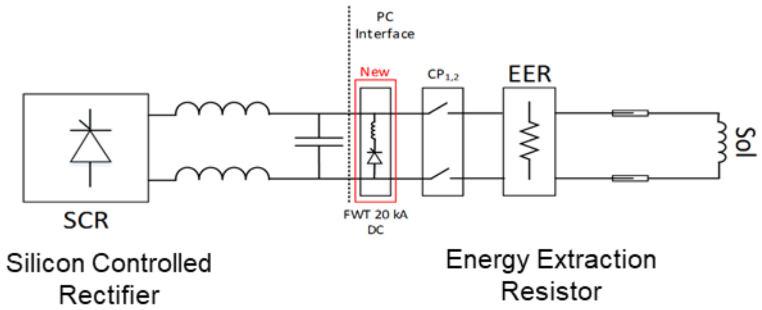

Figure 33: The Free Wheel Thyristor system on the CMS magnet powering circuit.

Ad. 3. In addition, the feasibility of a persistent current switch will be 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. As the large magnet have resistive splices, the study will indicate the typical field decrease time-dependence in persistent mode. Solutions for field and magnet current measurement in persistent mode will be identified. 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 demonstrator towards persistent mode will be developed, with a design that can be adapted to future magnet configurations, made either with low T_c superconductor or HTS. 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. The up-to 40 kA HTS bus line design will benefit from recent developments lead by CERN-TE department for the 18 kA HTS power lines of the HL-LHC accelerator [7]. 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 study of these cryogenics HTS current bus lines will be initiated at a later stage of the proposed EP R&D program.

Maintenance requirements of these systems (FWS, PCS, cryo feed lines, protection circuits) shall be identified in the studies, in view of understanding 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 the magnet for CLIC and all variants of FCC magnets.

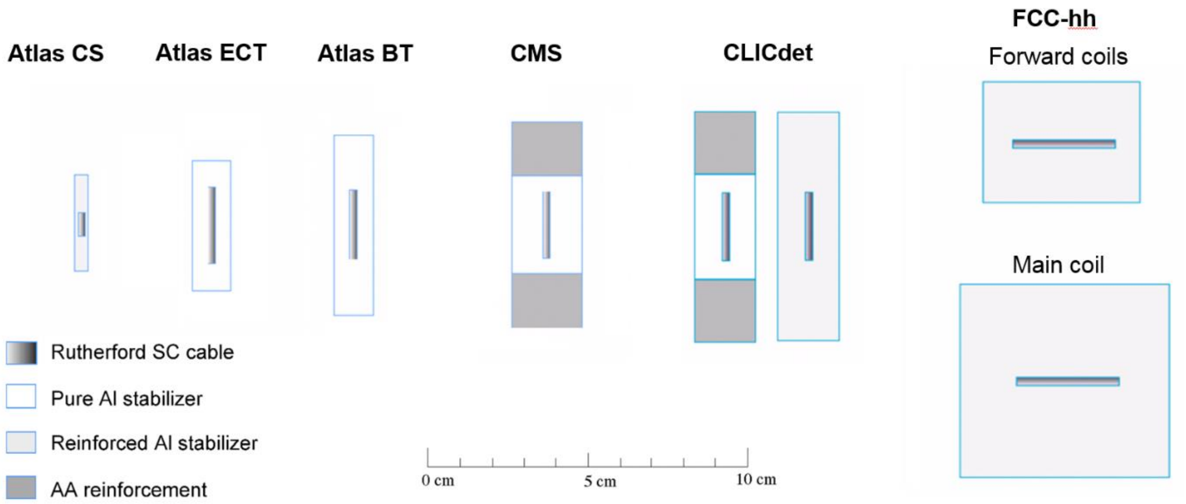

Figure 34: Comparison of existing and conceptual superconductors with both stabilizing and reinforcement options.

This need is not only expressed for large bore high field detector magnets (Figure 34), but also for detectors with the design goal of a 2-4 T solenoid cold mass with a radiation length less than 1 X_0, 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 (see Figure 35), such as LHeC/FCC-eh or the FCC-ee when using the IDEA detector concept [8].

Using an Al-Ni doped co-extruded NbTi-Cu cable is seriously considered, reinforced by welding with high yield strength Al alloy of the 7000 series, for example Al7068 [9][10].

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.

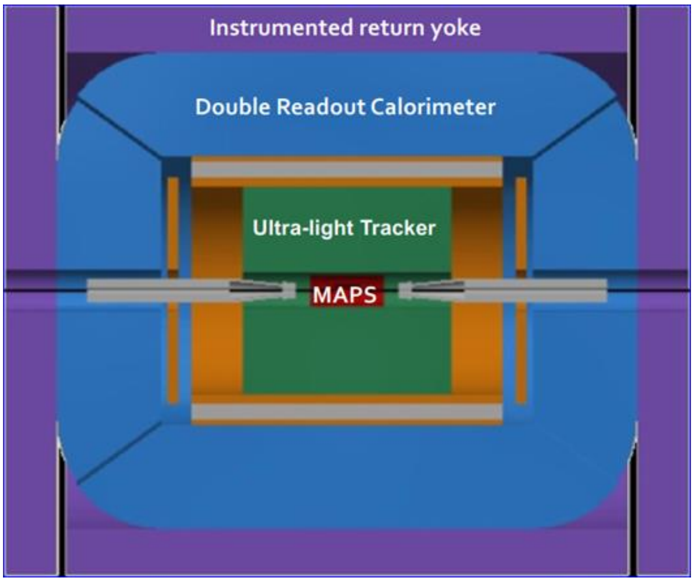

Figure 35: Innovative thin solenoid positioned inside the calorimeter and around the tracker.

A first EP iteration on reinforced conductor extrusion was performed in 2011 with little means (Figure 36) [11]. 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 welds, at room temperature and 4 K.

Figure 36: Cold work of an Al-0.1wt%Ni stabilized conductor with an Atlas-BT cross section (CLICdp studies).

The R&D program that will be established shall identify and propose manufacturing routes, in view of producing 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.

This activity is foreseen at a later stage of the R&D program, possibly for the second 5-year phase.

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 developed for 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. Deliverables and milestones are listed in the WP4 on detector mechanics R&D activities.

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, and 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 (see examples in Figure 37). The magnet shall be installed on a beam line and the facility shared among collaborations to which CERN is contributing.

Figure 37: Beam line test facilities in use in EHN1: the 3-T CMS-M1 magnet (left), and the 1.9-T Morpurgo dipole (right).

The Conceptual Design Study of such a magnet will be achieved in the frame of this WP8 R&D activity. 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 needs expressed.

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 later used on a 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, including the teams from CLIC and FCC detectors.

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 with 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 CMS-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 axes. 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, concerning 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, and compressed air.

The study will list the technical services necessary for the facility (magnet and its sub-systems, experimental area): electrical power, and water cooling. As this magnet is intended to replace existing facilities, 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.

It is noted that the magnet construction itself, commissioning and installation on the beam line is not included in the frame of this EP R&D program, as this will have to go on another budget. Estimated cost of the bare magnet (depending on free bore and length) is in the range of 5 to 7 MCHF.

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, ageing 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, and magnetic measurements. They will be applied to the 4 T general-purpose test facility as a use case.

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.

Fast quench detection systems shall be investigated.

The study will also 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 (Figure 38).

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.

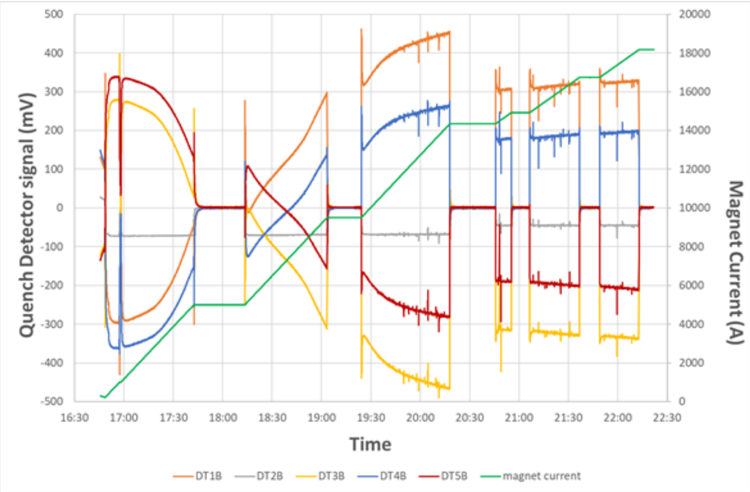

Figure 38: Quench detector signals during a ramp-up of the CMS magnet.

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, and increased noise filtering. Suitable front end and back end electronics shall be identified from latest SCADA technologies and data processing systems. The needs for the interfaces with the other control systems (vacuum, cryogenics, detector, beam, safety, etc.) will be defined.

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).

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12 Organizational Aspects

Strategy

The R&D will largely 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. Each work package consists of typically a handful of 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 the work plan, timeline or resources which may arise.

Co-operation

Co-operations with groups in and outside CERN 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 collaborations, 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 R&D collaborations like RD50 and RD51, and stimulate cooperation and additional external resources. The R&D in other work packages may give rise in time to the establishment of new R&D collaborations.

Monitoring and reporting

The size and wide thematic scope of the presented R&D programme will require a systematic approach to monitoring and reporting. A set of milestones and deliverables have been 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 project checkpoints which allow progress to be measured.

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.

13 Conclusions

We have defined a strategic R&D programme focused on technologies that we consider crucial for future experiments at the high energy frontier. The initiative follows the tradition of previous R&D programmes that made fundamental and vital technological contributions to the current LHC experiments and their upgrades. Given the multitude and complexity of the challenges ahead, the initiative is timely and would ensure continuity following the LHC Phase-II R&D efforts. Support for this initiative from the European Strategy Update process would be crucial.

To be effective and efficient, the implementation of this programme relies on two factors:

1. Appropriate funding throughout its lifetime, in terms of materials and investments but also in terms of experienced researchers, postdocs and students. A condensed version of this document is being sent as input to the European Strategy Update process, which we hope to lead to a strong statement of support.
2. Sustained cooperation with partners from the HEP community. Motivated by the great success of R&D collaborations like RD50 (radiation hard silicon detectors) and RD51 (micro-pattern gas detectors), we could see this model also applied to other areas.

14 Acknowledgements

We would like 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 developing the process.

We are particularly grateful to the work package conveners. 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 written them down in this document.

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

Manfred Krammer, Christian Joram

15 Workplans and resource estimates

For each R&D activity, spreadsheets with short descriptions of the workplans, deliverables and milestones, as well as detailed resource estimates have been prepared. This information has been collected in an annex document and is for internal purposes only.


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