PROCEEDINGS OF SCIENCE

Detector R&D, collider experiments

D. Contardo

Institut de Physique des 2 Infinis de Lyon UMR 5822
CNRS - Université Claude Bernard Lyon 1
Campus LyonTech-La Doua
Bâtiment Dirac - 4 rue Enrico Fermi
69622 Villeurbanne Cedex, France
didier.claude.contardo@cern.ch

Detector R&D is addressed here in the context of experimental concepts developed for future e-e and h-h colliders. Performance goals and operation conditions driving the detector designs are briefly reminded. The R&D needed and the technology trends to provide appropriate technical solutions are then discussed, based on the state-of-the-art detectors prepared for ongoing experiment upgrades. The outline is by experimental sub-systems used for tracking, calorimetry, particle identification, precise time of flight measurements and muon measurements. Eventually, hints on ancillary component developments are mentioned.

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1. Introduction

Future High Energy Physics programs were widely discussed at the recent Granada Symposium organized by the CERN Council in preparation of the update of the European Strategy for Particle Physics in 2020 [1]. The colliders proposed to succeed to the HL-LHC were at the heart of these discussions. These projects include: e-e linear colliders, the ILC proposed in Japan and the CLIC proposed at CERN; and circular colliders in a 100 km tunnel that can house either e-e or h-h[1] accelerators, respectively the FCC-ee and FCC-hh proposed at CERN and the SpeC and SppC proposed in China. Detailed scenarios proposed for the energy and luminosity planning at these colliders can be found in [2][2].

At e-e colliders, due to the small physics process cross-sections data rates and irradiation are not an experimental issue. The detectors can operate with continuous readout (w/o physics trigger) and relatively long signal integration time of O(μs). An experiment at CLIC would however requiring signal timing precisions ≃ 1 and 5 ns respectively for the calorimeters and the tracker to reduce the larger beamstrahlung background expected at the highest beam energies envisaged. In case of linear colliders, the low frequency of bunch trains will allow power pulsing and airflow cooling of the on-detector electronics to minimize material in the tracking systems and optimize the sampling fraction in calorimeters.

At h-h colliders, the collision rates can reach 30 GHz with an average pile-up of a thousand proton-proton collisions in a same bunch crossing. In these conditions, the data rates will be O(x10) those encountered at HL-LHC and, for a 20 ab^{-1} integrated luminosity, the detectors will suffer up to 30 to 100 times larger radiation fluences and total integrated doses (TID), respectively at the inner radii of the tracker and calorimeters.

The main challenges for experiments will be to provide unprecedented measurement precision for lepton collisions, and unprecedented rate and radiation tolerance capabilities for proton collisions.

Experiments proposed for e-e colliders feature a supra-conducting solenoid magnet[3] housing the pixel vertex detector, the outer tracker and the calorimeters[4]; followed by the muon systems embedded in the magnet return yokes. At linear colliders two push-pull experiments can be considered at the same interaction point, while circular colliders can profit from two experiments operating in parallel. Three detector concepts have therefore been proposed with some different technology options. The ILD and SiD experiments for ILC [3] consider respectively a Time Projection Chamber (TPC) and a full Si-Sensor for the outer tracker. The CLICdet at CLIC[5] [4] and the CLD for FCC-ee [5] are adapted from the SiD design, while the CepC baseline detector [6] is similar to the ILD. All these detectors contemplate high granularity calorimetry. IDEA [5] is the third concept developed for the FCC-ee, proposing to use a Drift Chamber (DC) in the outer tracker and dual readout calorimetry.

[1] h-h refers to proton and ion beams. This contribution focuses on the most demanding p-p case.
[2] A summary of the main beam characteristics influencing experiment designs can be found in the oral presentation of this contribution at https://indico.cern.ch/event/577856/
[3] Experiments feature 2 to 5 T magnets depending on tracker technology choices and beam constraints.
[4] Only the IDEA detector proposal considers calorimetry outside of the solenoid magnet.
[5] Due to the higher beam background, a single experiment with a full Silicon tracker is considered at CLIC.

PoS(EPS-HEP2019)698

For h-h colliders, a single experimental concept has been developed so far for a p-p general purpose experiment[6] [7]. It features three supra-conducting unshielded solenoid magnets at 4 T and covers a pseudorapidity range up to 6, the barrel(endcap) magnets have diameters of 10(6) m. The tracker is a full silicon device and Liquid Argon calorimetry is foreseen to sustain the highest radiation levels in the forward region.

2. Tracking systems

The tracking performance requirements at e-e colliders are a transverse momentum resolution $\sigma(p_T)/p_T^2 \simeq 3 \times 10^{-5}\,\mathrm{GeV}^{-1}$ (for $p_T \simeq 100$ GeV) and an impact parameter[7] resolution $\sigma(d_0)/d_0 \simeq 2/3\text{-}5/10\text{-}20$ μm (at 100/10/1 GeV and 90°). This is a factor 5 improvement compared to LHC. The tracker configurations of the different experiments are optimized to meet these goals considering the technologies proposed and the specific beam conditions at the different colliders.

At p-p colliders, high intrinsic detector precision is also needed in order to minimize mis-association of tracks to their vertex of origin in the huge pile-up of collisions. Track transverse momentum and impact parameter resolutions are however expected to be worse than at e-e experiments by about a factor two, due to the larger material budget and radius of the inner layers (imposed by particle rates and irradiation levels).

A summary of the tracker configuration parameters considered for the different experiments can be found in the oral presentation of this contribution[8]. In the following we consider the most demanding case of pixel Silicon sensor developments. Presently two main types of systems exist. In the hybrid designs, Si-sensors can be depleted at high voltages and pixels(strips) are bump(wire) bonded to the readout electronics. These designs provide the best radiation tolerance and allow the highest electronics density for high rate capabilities. In the Monolithic Active Pixel (MAP) designs, the readout electronics is directly grown on the silicon-substrate in a relatively standard microelectronics process[9]. These designs provide the lightest systems with the best spatial resolution, but are limited in rate capabilities and radiation tolerance.

State-of-the-art hybrid systems have been developed for the upgrades of ATLAS, CMS and LHCb; and LHCb will install in 2020 the first vertex detector with n-in-p sensors of 200 μm thickness and a pixel size of 55 x 55 μm^2, providing a 10 μm resolution (fig. 1). Such sensors are expected to maintain full detection efficiency up to 2×10^{16} 1 MeV neq/cm^2 fluence[10]. A common frontend ASIC was developed for ATLAS and CMS in a 65 nm technology to achieve a few GHz/cm^2 digital output rate[11] and to sustain a TID up to 0.5-1 GRad.

State-of-the-art MAP systems have been built for the ALICE upgrade at LHC and for the BELLE-2 upgrade at SuperKEKB (fig. 1). The ALICE ALPIDE sensors are produced in a 180 nm CMOS technology, their thickness is 50 μm with a pixel size of 28 x 28 μm^2 for a resolution of 5 μm. An 0.3% fraction of radiation length (X_0) per layer has been achieved. The readout is binary with zero-suppression and an integration time of 5 μs. The radiation tolerance is 2×10^{13} 1 MeV neq/cm^2 and 3 MRad, limited by the absence of depletion in the bulk of the sensor. The

[6] Similarly to the LHC program, 4 experiments are proposed at future h-h colliders, two general purpose p-p physics experiments, a dedicated flavor physics p-p experiment at lower luminosity and a Heavy Ion physics experiment.
[7] d_0 is the track distance of closest approach to the interaction vertex in the direction transverse to the beam.
[8] https://indico.cern.ch/event/577856/
[9] MAPs avoid the expensive bump bonding process needed in the hybrid pixel design.
[10] This would only satisfy radiation tolerance requirements for a future p-p collider experiment at radius ≳ 30 cm.
[11] Digital readout provides signal amplitude information while binary is a yes/no answer compared to the threshold set in the frontend ASIC.

PoS(EPS-HEP2019)698

BELLE-2 vertex detector uses a DepFET technology. The sensor thickness is 75 μm with a pixel size of 50 x 50 μm^2 for a resolution of 15 μm. 0.2 % of X_0 per layer was achieved. The binary readout is continuous with a time integration of 20 μs. Despite low voltage depletion of the sensor bulk in this technology, the fluence tolerance is similar to the CMOS standard process at 2 x 10^{13} neq/cm^2 with a slightly higher dose rate tolerance of 10 MRad.

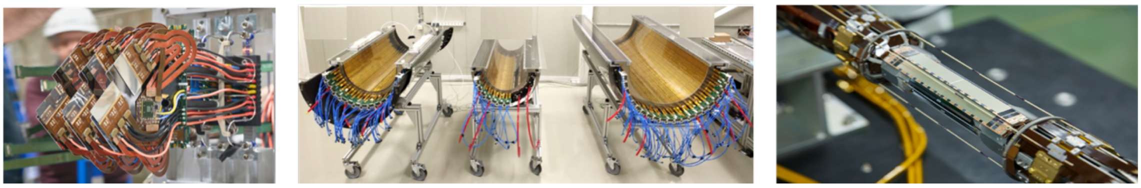

Figure 1: Prototype of a portion of the LHCb vertex detector (left), layers 4,3,5 of the ALICE Inner Tracking System (center), BELLE-2 vertex detector (right).

For future detectors, the main challenge will be to develop Silicon-systems able to achieve together as much as possible of the following features: few μm hit position resolution, $\lesssim 0.2\%$ X_0 per layer, time resolution of few ns or less[12], rates up to 10's of GHz/cm^2 and radiation tolerances up to 10^{18} 1 MeV neq/cm^2 and 10's of GRads.

Hybrid design developments have two main focus, thinner sensors with smaller pixels for improved resolution and possibly higher radiation tolerance; and alternative to bump bonding for cheaper connection to the ASIC chips. MAPs main studies are of similar nature for improved resolution, on short integration time and higher rate capabilities of the readout, and on process variants for increased radiation tolerance. Several demonstrators have recently been produced along these lines (fig. 2)[13]. They show that reaching a spatial resolution $\lesssim$ 5 μm likely requires pixels smaller than 25 x 25 μm^2 for thin sensors (50 μm) even with a digital readout[14]. A 200 MHz/cm^2 readout rate has been achieved in CMOS MAPs with a time precision $\simeq$ 5 ns, as required for CLIC. Modified CMOS process referred to as HV/HR CMOS have been developed to allow depletion of the Si-sensors. They provide an order of magnitude improvement in fluence and dose tolerance up to $\simeq$ 2 x 10^{15} 1 MeV neq/cm^2 and few 100 MRad. CMOS MAPs are therefore excellent candidates for e-e collider applications. However, at the inner radius of a CLIC detector an hybrid solution may still be needed to reach the necessary readout rate of 6 GHz/cm^2. ASIC bump-bonding is this case appears challenging for pixel size down to 25 x 25 μm^2. Initial tests of ASIC connection in a SoI via technique or with capacitive coupling with a conductive glue have started but the studies are still at an early stage. It has to be noticed that fine pitch 3D interconnection techniques may allow to separate analog and digital readout functionalities both in the hybrid and MAP designs. A further step needed toward p-p collider tracking systems will be a substantial increase in radiation tolerance for any devices, particularly for MAPs as even with the recent improvements above-mentioned they would only marginally meet the requirements for an outer tracker layer. Use of a deeper sub-micron technology process for MAPs may be a solution to improve all performance parameters. A proposal for a HL-LHC upgrade of the ALICE ITS is emerging considering a 65 nm technology to produce 20 μm thick MAPs with 10 x 10 μm^2 pixels.

[12] Better time resolution for Silicon-sensors is discussed in the MIP Time of Flight detector section.
[13] Their specifications can be found in the oral presentation of this contribution at https://indico.cern.ch/event/577856/
[14] Digital readout allows to interpolate the track position from the charge sharing across channels.

At this very small thickness, radiation length could be further reduced and flexibility of the sensors may also allow to consider cylindrical detector designs instead of flat module tiles.

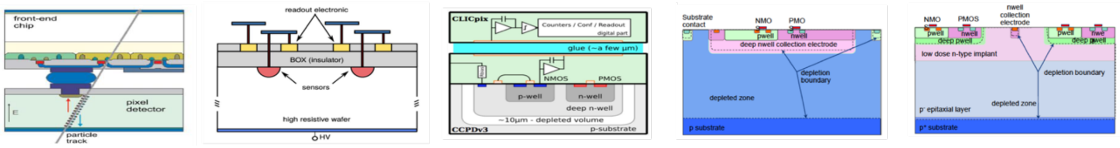

Figure 2: Designs used in pixel sensor demonstrators[13], from left to right: planar hybrid (CLICpix), SoI sensor/ASIC interconnection (Cracov), HV-CMOS MAPs capacitive coupling to digital readout (CLIC CD3P), modified HV CMOS MAPs process (ATLASPix), Modified HR-CMOS process (ALICE, CLICTD, MALTA).

3. Calorimetry

3.1 High Granularity Calorimeter

A jet energy resolution of 4-3% in the range 50-100 GeV is a crucial requirement at e-e colliders to distinguish Z and W hadronic decays. To meet this goal, the CALICE collaboration has developed the High Granularity Calorimeter (HGC) and Particle Flow (PF) concepts. In the PF jet energy reconstruction, the energy deposits in the hadron calorimeter associated with tracks and photons can be subtracted and only the $\simeq$ 10% remaining neutral hadrons energy fraction is provided with lower resolution by the hadron calorimeter. The HGC design with fine longitudinal and transverse segmentation provides a 3D shower topology for optimal subtraction of track and photon energies.

Simulations to optimize the CALICE calorimeter design have shown that with proper choice of the segmentation parameters and of the absorbers[15] the expected jet energy resolution can be achieved. The proposed technologies for the active layers are hybrid Silicon-pad sensors in tungsten absorber for the electromagnetic section, and scintillator or Resistive Plate Chambers (RPC) in stainless steel absorber for the hadronic part. Test of realistic prototypes have shown that the necessary energy resolutions can be achieved, respectively $\sigma(E)/E\ (e/\gamma) \simeq 17\%/\sqrt{E} \oplus 1\%$ and $\sigma(E)/E\ (\pi) \simeq 44\%/\sqrt{E} \oplus 2\%$.

At p-p colliders, a HGC design can also provide a unique mean to mitigate the effect of collision pile-up on the jet energy measurements. CMS has adopted the CALICE concept to replace the present endcap calorimeters for the HL-LHC upgrade. To further mitigate pile-up effects, the 4th dimension has been added with a time measurement of the energy deposit in each cell/channel of the frontend ASIC chip, with a 50 ps precision (see also section 7).

The CMS HGC characteristics are close to the CALICE optimizations (fig 3). Recent developments have focused on producing state-of-the-art prototypes of first 8” Silicon-pad sensors and the very complex ASIC readout chip. The hadronic section of the calorimeter is based on small scintillating tiles readout with SiPMs as in the CALICE AHCAL design option. Developments are in final choice of scintillators, injection-molded polystyrene or casted PVT tiles, and packaging of SiPMs for best cooling efficiency. Recently a full shower tower calorimeter portion was tested in beam with intermediate CMS components for the electromagnetic section

[15] See the oral presentation of this contribution at https://indico.cern.ch/event/577856/

and CALICE AHCAL layers in the hadronic part. The measurements are in good agreements with the simulations.

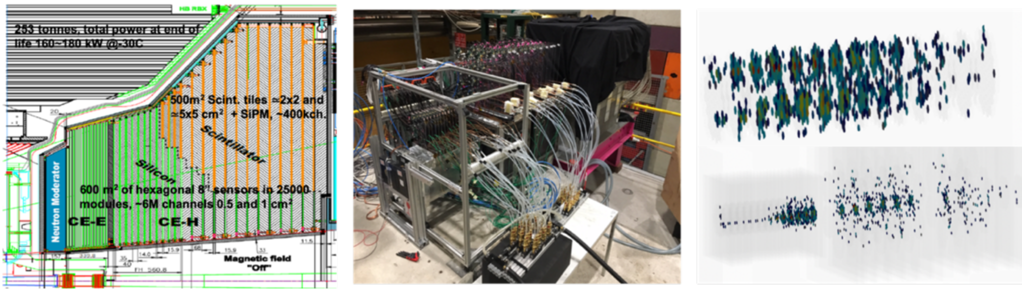

Figure 3: CMS HGC design (left), test set-up of a full calorimeter tower (center) and measured showers of 2 close-by electrons and of a π of 300 GeV (top and bottom right).

High Granularity Calorimetry is now well established for e-e colliders experiments and can benefit from the advances of the CMS detector for device engineering. A remaining challenge for future experiments will be in the unprecedented scale of the detector areas. At p-p colliders, the possible pseudorapidity coverage of a HGC would depend on radiation tolerance improvements of all components, including Si-sensors, scintillators, SiPMs[16] and readout electronics. A further step in high granularity could be to use MAP sensors, possibly allow particle counting. A first small size calorimeter prototype has been realized with the MIMOSA MAPs and ALICE is proposing a forward HGC calorimeter for HL-LHC (FoCAL), where few layers would be equipped with MAPs. MPGDs could also provide very fine segmentation in the lower rate and radiation environment of a hadronic calorimeter section (see section 6).

3.2 Liquid Argon and scintillating tiles calorimeters

A Liquid Argon (LAr) calorimeter is a natural proposal for a future p-p experiment as it is intrinsically radiation tolerant. It would provide appropriate electromagnetic resolutions, estimated to $\sigma(E)/E$ $(e/\gamma) \simeq 10\%/\sqrt{E} \oplus 0.7\%$ and $\sigma(E)/E$ $(\pi) \simeq 50\%/\sqrt{E} \oplus 3\%$ up to relatively high pseudorapidity. The challenge will be in increasing the granularity by about a factor 10, compared to the state-of-the-art ATLAS calorimeter, to mitigate collision pile-up effects. A straight inclined structure design has been proposed with 8 longitudinal segmentations and a cell size $\Delta\eta \times \Delta\phi \simeq 0.01(0.025) \times 0.01(0.025)$ in the electromagnetic(hadronic) section. The development of the multilayer readout strip Printed Circuit Board, and of the feedthrough to house the electronics outside of the cryogenic volume are some of the engineering challenges. In the barrel region, the LAr calorimeter could be completed with a hadronic vertical scintillating tile calorimeter, also similar to the ATLAS design but with a x 4 increased granularity.

3.3 Other calorimeter designs

A dual readout calorimeter based on the DREAM/RD52 concept has been proposed for the FCC-ee IDEA experiment. In this design, longitudinal Cerenkov and scintillating fibers, typically of 1 mm diameter and 1.5 mm pitch are alternately embedded in the absorber. The Cerenkov light is only produced by the electromagnetic shower component and this design provides an event by

[16] Presently, the lower radiation tolerance of scintillators and SiPMs is defining the location of the transition region with Silicon-sensors in the CMS HGC design.

event information to correct the difference in the electromagnetic and hadronic response, and the energy non-linearity, typical of hadronic shower measurements[17]. A small size prototype has recently shown promising resolutions: $\sigma(E)/E \simeq 10(30)\%/\sqrt{E} + 1\%$ for $e/\gamma(\pi)$. Major challenges for DUAL Calorimetry will be to develop a projective geometry, to possibly introduce some depth segmentation, either with fibers starting a different depth or extended use of timing information, and to introduce a dense readout of the fibers at the back of the calorimeter, for instance with SiPMs.

The LHCb collaboration is proposing a second experimental upgrade to further increase the accepted luminosity at the HL-LHC. A new electromagnetic calorimeter will be needed with improved radiation tolerance to $\simeq$ 300 MRad, and time resolution of $\simeq$ 50 ps to mitigate pile-up effects. Shashlik and Spaghetti configurations, respectively with crystal tiles and wave length shifting fibers, or crystal fibers, are considered.

Homogenous electromagnetic calorimetry is used in CMS, non-collider experiments and medical applications, it could remain an option for future colliders, particularly if fine granularity can be implemented. the TICal development with crystal fibers may provide a solution allowing at the same time a precise measurement of the shower timing.

Examples of the various designs are presented in fig. 4. R&D is mostly in improving radiation tolerance and time resolution. Developments have started to investigate nano-particle technologies to produce crystals or organic scintillator materials, for instance nano-crystals with tunable wavelength emission and Organo-Silicon Luminophor for improved wavelength shifting and light transmission.

Figure 4: From left to right, IDEA DREAM calorimeter concept and prototype, Shashlik and Spaghetti calorimeter options for LHCb, Homogenous Intelum Time Imaging Calorimeter.

4. Cherenkov detectors for particle identification

Cerenkov detectors are extensively used for particle identification in flavor and heavy ion experiments at colliders. They can also provide precise time of flight information. The Belle-2 collaboration as recently upgraded its endcap Ring Imaging Cherenkov (RICH) with a 4-layers aerogel focusing design providing a 4σ π/K separation at 4 GeV with a 20 cm expansion region (fig. 5). In the barrel part of the detector, where available space is even more limited, an extension of the Detection of Internal Reflection Cherenkov (DIRC) concept of the BABAR experiment has been developed. It is called the Time Of Propagation detector, as the particle identification is performed through the arrival time of the Cherenkov light produced in quartz bars readout with Micro Channel Plate Photo Multiplier Tube (fig. 5). A resolution of 80 ps is expected with a Single Photon Time Resolution of the MCP-PMT of 40 ps. At HL-LHC, LHCb foresees a mixed design,

[17] *These effects are referred to as the "compensation" issue in usual sampling calorimeters that cannot discriminate electromagnetic and hadronic components. In a HGC, the fine segmentation allows compensation based on the different topologies of these two components.*

the TORCH detector capable to identify particles both through the internal reflection angle and the time of flight measurements (fig. 5). The target is to cover a momentum range of 2-10 GeV with a time resolution of $\simeq$ 15 ps with MCP-PMT readout (for an average of 30 photons/track). Main developments for Cherenkov light detection are on one hand in new materials, for instance photonic crystal nano-structures and on the other hand on improved MCP-PMT with increased sensitivity to UV and SPTR $\lesssim$ 10 ps (see also section 5).

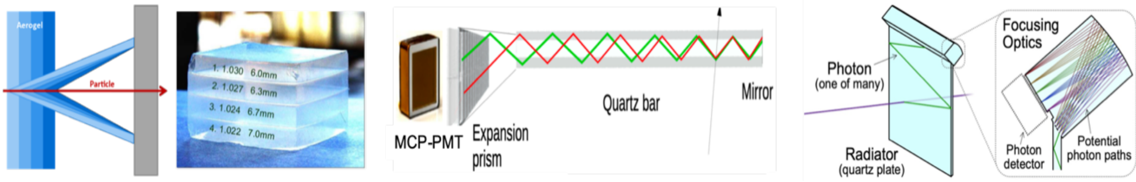

Figure 5: Belle-2 ARICH (left) and TOP (center), LHCb TORCH (right)

5. Minimum Ionizing Particle Time of Flight detectors

Precise time of flight measurement is a mean for particle identification, but also a new paradigm to mitigate confusions in track associations to vertices in presence of large collision pile-at p-p colliders[18]. While the tracking system can identify the track z-origins with a precision of 10 µm to a mm, depending on momentum and polar angle, their precise ToF measurement can discriminate those produced in close-by collisions but at different times in the p-p bunch crossing. HL-LHC simulations have shown that a MIP ToF resolution of $\simeq$ 30 ps would allow recovering a vertex purity equivalent to a 50-effective pile-up at a real pile-up of 200.

ATLAS and CMS upgrades will implement thin layers of MIP ToF detectors in the available space between the tracker and calorimeters. CMS will cover the full acceptance of the experiment, while ATLAS will cover only the most difficult forward regions. A layer of LYSO crystals with SiPM readout in the CMS barrel layer will fulfil requirements for time precision and radiation tolerance. The time resolution will mostly degrade, due to the Dark Current Rate (noise) increase in SiPMs. This degradation will remain tolerable up to a fluence $\simeq 2\ 10^{14}$ 1 MeV neq/cm^2 for operation at -30° C with adequate annealing periods at room temperature. This would not be sufficient in the endcaps where both ATLAS and CMS will use the new Low Gain Avalanche Diode (LGAD) Silicon technology. A LGAD sensor is a regular planar Si-sensor with a thin layer of doping implant below the collection pads to provide small amplification (fig. 6). With present sensors of 50 µm thickness and $\simeq$ 2 mm^2 pads, the time resolution has been shown to be limited by Landau signal fluctuations to $\simeq$ 25 ns. An avalanche gain of 10 to 20 is considered sufficient to maintain a timing precision $\lesssim$ 50 ps. This can be achieved up to a fluence $\simeq 2\ 10^{15}$ neq/cm^2 operating at -30° C and increasing the bias voltage up to 800 V. To improve the resolution the ATLAS and CMS detectors will feature two double sided layers providing between 2 and 3 hit measurements per track[19].

At future p-p colliders, with a 1000 pile-up, a similar performance as at HL-LHC is expected to require a time precision of 5-10 ps. R&D for scintillator devices are in materials of increased

[18] Precise ToF measurement is becoming a new paradigm for all detector technologies. Scintillating devices are of particular interest for their ability to measure photons and therefore to identify the position of a positron decay for instance in medical Positron Emission Tomography, or in some non-collider experiments such as the MEG-II upgrade.
[19] 3 hits is for ATLAS, where LGADS will suffer more radiation than in CMS due to a slightly higher pseudorapidity coverage.

light yields particularly for fast UV components, in conjunction with improved SiPM Photon Detection Efficiency at these wavelengths. New materials and smaller pixel are also investigated to reduce SiPM DCR after irradiation. Monolithic Digital CMOS SiPMs with electronics readout of each pixel are also becoming available, possibly allowing photon counting and improved SPTR. Achieving smaller time resolution with LGAD would likely need to reduce sensor thickness and also pad size to contain the capacitance noise. The present LGAD fill factor is ≃ 85%, limiting the detection efficiency and the ability to develop a pixel design. Ongoing improvement developments are on trenches between electrodes (as in SiPMs, see fig. 6), and/or AC coupling devices. To increase radiation tolerance, new materials and process for the amplification layer implant are considered, this may also improve time resolution if higher gains can be reached at lower voltages.

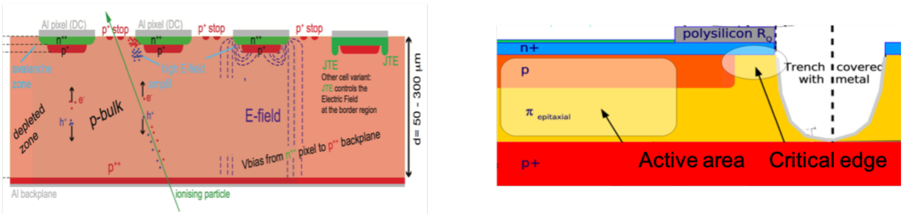

Figure 6: LGAD (left) and SiPM (right) sensor designs

Alternative technology developments that have shown capability for high MIP ToF precision include Hyper-Fast-Silicon deep depleted Avalanche Photo Diodes, MCP-PMT operated in secondary emission mode or equipped with a Cherenkov radiator coated with a photocathode material, and a similar design with a Micro-Megas readout (see section 6). For HL-LHC, ALICE is proposing a Fast Interaction Trigger detector of ≃ 30 ps resolution with modules of quartz Cherenkov radiators readout by MCP-PMTs. Dedicated studies are on-going to also develop more efficient and radiation tolerant photocathode materials.

Achieving ultimate time precisions ≲ 10 ps will likely require multilayer devices, and also non-trivial developments of the readout electronic and of the reference clock distribution systems for which best current precision levels are respectively ≃ 20 and 10 ps.

6. Micro-Pattern Gas Detectors

Although conventional technologies[20] will continue to be used for muon detection with improved designs, the recent R&D trend has naturally been to develop higher granularity detectors and hybrid designs for improve performance. The main breakthroughs have been with the Gas Electron Multipliers (GEM) and the Micro-Megas (MM) designs, now commonly used in operating experiments and/or their upgrades, both for muon detection and Time Projection Chambers readout. With MPGDs, hit position and time resolutions ≃ 50 µm and few ns have been achieved with rate capabilities up to 10's of MHz/cm^2. This was enabled by the new amplification scheme of these designs and by the Printed Circuit Board technology progress.

New devices (fig. 7) are being developed to ease fabrication, for instance with a single amplification stage in a GEM-like design; to further reduce the granularity to pixel scale levels for improved spatial resolution and rate capability, in conjunction with development of new

[20] Cathode Strip Chambers, Drift Tubes, Resistive Plate Chambers.

resistive layer materials for AC coupling readout. In the MM design, a first monolithic detector (InGrid) has been realized with a mesh grown directly on a Medipix pixel chip using a CMOS technology, a resolution of $\simeq$ 20 µm has been achieved with initial prototypes. An application of MPGDs with pixel size readout could be cluster counting in TPCs proposed at e-e colliders to improve the dE/dx resolution[21]. As mentioned in section 3-4, MPGDs are also good candidates for high granularity calorimetry and for precise timing measurements.

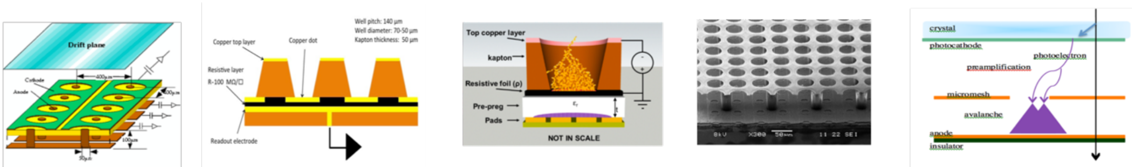

Figure 7: New MPGD developments, from left to right: the µPIC, the µ-Resistive-Well and the Resistive-Plate-Well design variants of a single GEM-like layer device; the InGrid CMOS design, and a MM equipped with a Cherenkov radiator coated with a Photocathode.

With new environmental legislations on greenhouse gas emission, a strong R&D effort is required to replace the Hydro-Fluoro-Carbons commonly used in gas mixtures. Hydro-Fluoro-Olefin now used in refrigerant systems are candidates, however not providing sufficient performance at this stage. This situation may favor for future experiments designs that would not not require HFC. Long lead tests will also be needed to demonstrate radiation tolerance at future p-p colliders far beyond the maximum levels of 3 to 5 x HL-LHC integrated luminosity presently established. Eventually, building large size detectors was shown to be challenging with the recent ATLAS and CMS upgrades. New fabrication techniques are investigated, including 3D printing and inkjet laser printing (a candidate for flexible PCB designs).

7. Ancillary components

Signal readout and processing electronics are critical elements of all detector performance. While Back-End electronics progress are fully driven by commercial application and they must be closely tracked through board prototyping, frontend ASIC chips need specific R&D as their complexity is increasing with channel density, rates, and data treatment features. Characteristics of chips developed for HL-LHC must mostly fulfill needs for e-e collider experiments, although a step further in deeper sub-micron technology may be needed for MAPs to reach the ultimate hit resolution envisaged. As well, at a future p-p collider, the pixel detector channel density together with the much higher rates and radiation tolerance will require a deeper sub-micron technology than the 65 nm presently used. The choice of technology should consider long term availability, cost and complexity (timescale) for developments. A 28 nm process appears to be a good option, and a deepest Fin-FET technology could also be a line of investigation for the areas of most demanding radiation tolerance. As mentioned in section 2, 3D interconnectivity of different functionality ASICs would be very beneficial to develop hybrid designs optimized to specific requirements. Developments in this domain are at an early stage in HEP and must benefit from

[21] Cluster counting techniques are also envisaged for Drift Chambers with GHz level readout sampling. This can improve the track time-position correlation and therefore the spatial resolution (for instance in the on-going MEG-II experiment upgrade and for the IDEA proposal at FCC-ee).

commercial application progress. Future photonics, multiple amplitude modulation and wireless directional antenna devices could provide the necessary data transfer increase.

Mechanical structures and services are of utmost importance in allowing extremely compact and light systems with demanding specifications for precision, stability and thermal behaviours. Several new materials are being studied among which good candidates are Carbon composites with graphene and Carbon nanotubes, CFRP with new resins. To allow simplified designs and fabrication process, 3D printing techniques may become a new paradigm. Cooling is also a specific area of developments as lower temperatures, bellow the typical -40° achieved with present CO_2 bi-phase cooling plants, would increase radiation tolerance in all solid-state devices. An efficient air flow cooling will also be needed at e-e collider experiments. Small size and light pipes and connections or cooling channels embedded in sensitive elements, as in LHCb silicon sensors, are other developments toward light and compact integrated systems. Low mass cryostats for supra-conducting magnets and for LAr calorimetry could also substantially contribute to material mass reduction.

8. Summary and outlook

Detectors for future collider experiments will require substantial performance improvements compared to the state-of-the-art systems developed for recent detector upgrades. For e-e experiments, technical solutions that can provide the expected performance are mostly existing, but a strong R&D effort will be needed to engineer the final detector designs. New technology R&D should still provide further improvements and will be mandatory to fulfill requirements at a future p-p collider, with major challenges in data rates and radiation tolerance. The general trends toward enhanced performance are in use of nanomaterials, deep submicron fabrication process and integration and hybridization of the different system functionalities. To proceed with R&D, wide international programs offer opportunities to raise funds and to build on synergies within an outside HEP. The European ATTRACT and AIDA-2020 initiatives are aimed at bringing together fundamental research and industrial communities to develop future detectors and imaging devices for several applications. CERN R&D programs dedicated to detectors used at collider experiments also offer an excellent framework to share expertise and federate contributions of the whole HEP community [8].

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PoS(EPS-HEP2019)698