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Luminosity and Forward Detectors for LHC upgrades

Gabriele Chiodini[*†]
INFN sezione di Lecce, via Arnesano, Lecce - 70310 - Italia
E-mail: gabriele.chiodini@le.infn.it

This paper discusses the challenge related to luminosity and forward physics measurements at ATLAS and CMS experiments after the scheduled LHC luminosity upgrades. The topics covered are not at all exhaustive of the subject but focus on activities where italian groups are involved. In addition, the author research interest in fast timing detector with tracking capability is the guiding principle of the report. Particular emphasis is given to the need of upgrading the existing detectors, in term of granularity and radiation resistance, and of pushing state-of-the-art technology to add fast timing to tracking information in the same device. Two Cherenkov based detectors for luminosity measurement (LUCID for ATLAS) and beam background monitoring (HBM for CMS) are briefly described as examples of systems placed far from the beams. Instead, near the beams, solid state devices, such as diamond detectors, are employed for luminosity measurements. In this respect, the evolution from particle counting mode to tracking mode configurations (DBM for ATLAS and PLT for CMS) is emblematic of the paradigmatic change of view needed to cope with high pile-up. The ambitious goal of forward detectors to take data in normal run condition, in order to accumulate statistics for precision EW coupling measurements and search for BSM heavy objects, is delineated. The need to develop new sensors and electronic chains to achieve very good time resolution is illustrated. The effort on diamond detectors capable to replace Cherenkov based timing detector for forward physics is clearly stated. The report concludes depicting one of the most promising new technology intended to face the challenge of a device with hundreds of micron space resolution and tens of ps time resolution: the Ultra Fast Silicon Detector (UFSD).

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[*]Speaker.
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1. Introduction

Luminosity and forward detectors at general purpose experiments, such as ATLAS and CMS at LHC, share the feature to cover a small, or a very small, portion of the geometrical phase-space. This is in contrast to the other detectors of the apparatus, where a full azimuthal coverage and a large eta coverage are required in the transverse and forward directions, respectively. From this respect, these detectors share more similarities with a fixed target experiment than a collider experiment: relatively easy access and a short intervention time, in case of failure or when new upgrades are available, and groups involving a limited number of persons.

The upgrades planned for the Large Hadron Collider (LHC) are aspected to happen in three phases (phase 0 in 2013/14 and run II, phase I in 2018 and run III, phase 2 in 2022/23 and run IV), foreseeing a global increase of luminosity by a factor ten. Correspondingly, the different sub-detectors of ATLAS and CMS must be improved, upgraded, or replaced, in order to keep the same physics performances. Differently from the central detectors, the luminosity and forward detectors have upgrade plans only for phase 0 and phase I, respectively.

The increase in luminosity provides a challenging environment also for luminosity detectors, and in order to cope with higher and higher particle rates and radiation levels also these detectors must be upgraded. Anyway, for the specific characteristics mentioned above, the R&D time and the construction phase for the luminosity detectors are expected to be quite fast and affordable, in terms of time, cost and personal. This makes more efficient to draw an upgrade project as latest as possible, in order to profit from the accumulated experience on luminosity measurements at LHC and on technological advances, which are continuously pushing performance in many directions (new materials, radiation resistance, granularity, timing, ...).

Until now and for all run II, the forward detectors in ATLAS and CMS could take data only in special LHC optics configuration, where a large beta is set at the interaction regions and event pile-up is not present. Instead, for run III is aspected and planed that these detectors should be capable to run in normal LHC optics cnfiguration, where a small beta is set at the interaction regions and event pile-up will occur. Finally, for run IV, new superconductive quadrupole triplets and compensating magnets are needed around the interaction region to squeeze further the beta parameter by setting-up the crab waist collision schema. The insertion of cryogenic lines and magnets around the forward region will make more difficult to design forward detectors for phase II, just to mention the uncertainty on the background environment and the small space clearance left for detectors and services. Likely, the performance and physics measurements which are going to be reached with these detectors for run II running in normal conditions are essential before to speculate for any upgrade scenario for HL-LHC in a useful manner.

2. Luminosity detectors

Precision physics require precise luminosity determination and at LHC upgrades the issues are going to be exacerbated due to higher rates, pile-up and machine background levels. Luminosity measurements will require new detector geometry and optimisation for LHC phase 0 and I and, likely, improved or new detector technologies for HL-LHC.

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Horizontal and vertical separation beam scans are used to measure the luminosity absolute scale, but the instantaneous relative luminosity is measured continuously by several detectors placed in different position around the interaction region and made of complementary technologies. Cherenkov based detectors are placed at large distance from the interaction point and covers a large area, solid state detectors are placed at small distance from the interaction point and covers a small area, but in principle they should extract the measurements of the same physical quantity. Of particular interest, it is also the relative bunch-by-bunch luminosity useful for accelerator diagnostics and optimisation.

2.1 Cherenkov based detectors

LUCID is a dedicated luminosity monitor in the ATLAS experiment placed around the beam-pipe on both forward ends of the interaction point [1]. It is composed of 16 photomultipliers (PMTs) and 4 quartz fiber bundles. The PMTs detect charged particles crossing their quartz window and fibers, where Cherenkov light is produced. Digital hits are produced when the signals are above the front-end threshold. LUCID measures bunch-by-bunch luminosity exploiting event- and hit-counting algorithms and uses pointing geometry to reduce the signal from secondary particles below the front-end threshold. In fact, secondary particles are presumably crossing the detector element with a large crossing angle, than with a much shorter active path with respect to parallel particles (see Fig. 1b). Anyway, this solution is not very robust against the presence of multiple crossing of secondary particles in one detector element. In fact, the sum of two or more secondary signals can be large enough to overcame the threshold, introducing a non-linear bias in the determination of the luminosity (see Fig. 1c). Multiple hit effects can happen for detector elements too close to the interaction point, where the track density is very high, or at very high luminosity, as foreseen in phase 0 for LUCID. Also the strong ageing reached by the PMTs forced the upgrade of LUCID detector. In fact, the aspected issues related to higher particle rate levels, due to both luminosity and energy increase, and to the installation of the new aluminium beam pipe are:

- Event counting saturation
- PMT ageing
- Signal non-linearity

and the proposed solutions are:

- smaller PMT diameter size: from 15 mm to 10 mm or even smaller.
- lower PMT gain: from 10^6 to 10^5
- integrate the signal to have charge information too.

Consequently, LUCID replaced all the PMTs, the fibers were shortened to 1.5 m length and a new front-end electronics was developed. New algorithms, based on the measured charge released in the PMTs, are foreseen for the upgraded, in addition to the old algorithms based on digital information only.

The CMS experiment created a new project to deal with the upgrades of luminosity mesurements, beam monitoring and beam protection called BRIL (Beam Radiation Instrumentation and Luminosity, [2]). The project comprises: a new pixel luminosity telescope, an upgraded Fast Beam Conditions Monitoring based on diamond sensors, a fraction of the forward HCAL and a new direction-sensitive quartz Cherenkov counters with excellent time resolution. This integrated approach was triggered by the relevance and complexity of the measurements. For example machine induced background, mainly relativistic particles originating from interactions of the beam with residual gas atoms in the beam-pipe or with collimators, must be kept at low level to obtain high quality data from tracker and muon detectors. This motivated the construction of a new Beam Halo Monitoring (BHM) based on Cherenkov signals, which are insensitive to photon and neutron cavern background and to non-relativistic particles. In addition, the directionality of the Cherenkov light cone is very effective in separating the correlated background of the two beams. This BHM consists of several rings of direction-sensitive quartz Cherenkov counters placed at a large radial position from the beam-pipe and installed in phase 0, where the radiator face opposite to the PMT entrance window does not reflect the light (see Fig. 1a).

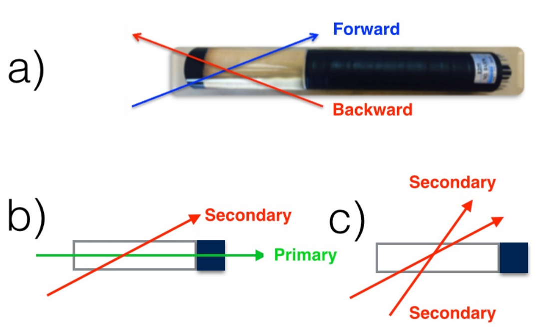

Figure 1: Strategies used by beam halo and luminosity detectors to reduce the particle background rate by employing the directionality of the incoming particle.

2.2 From particle counter mode to tracking mode

Pad diamond sensors provided luminosity measurements for ATLAS and CMS with a precision of about 2% in run I. These detectors were operated in particle counting modes, differently from BABAR and CDF experiments which were operate in DC current mode, in order to cope with the nominal luminosity of LHC. In addition, the ATLAS BCM diamond detectors were capable to perform precise time-of-flight (ToF) measurements and distinguish primary collisions from parasitic or secondary collisions. Anyway, the luminosity increase and the bunch spacing reduction from 50 ns to 25 ns might cause saturation of such solid stated detectors. Hence, new detectors, called PLT (Pixel Luminosity Telescope, [3]) for CMS and the DBM (Diamond Beam Monitor, [4]) for ATLAS, were designed to handle the increased number of collisions taking place starting from phase I. Both detectors are pixel detectors instrumented with the same front-end chip of the central pixel detector of the experiment. The CMS final decision was to use the more traditional Silicon sensors (instead of mono-crystalline diamond sensors) of 5.2x12 mm2 size bump bonded to the PSI chip. ATLAS, instead, uses polycrystalline pixel diamond sensors of 18x21x0.5 mm2 size bump bonded to FEI4 chip. The choice of diamond as a radiation-hard sensor material will ensures the stability and durability of the detector throughout its lifetime.

The luminosity measured by the pixel telescopes is based on the reconstruction of particle tracks originating from collision region. This is performed by three pixel sensors stacked one behind the other with the purpose to monitor the instantaneous (bunch-by-bunch) luminosity with a precision of 1% without saturation. The luminosity telescopes are placed in the forward region close to the beam pipe. The mechanical structures holding the three single chip pixel modules are show in Fig. 2 for both experiments. The DBM system houses eight DBM telescopes, approximately placed 1 m away from the collision region and about 9 cm from the beam, four for each side and covering the region $3.2 < \eta < 3.5$. The PLT system is comprised of two arrays of eight small-angle telescopes situated on either side of the interaction point about 1.75 m away and 5 cm from the beam.

The luminosity telescope have limited timing capability, being able to discriminate only hits from different bunch-crossing but not from different pile-up vertexes. Likely, for the phase II upgrade, where an average of 200 primary vertexes per crossing is aspected, the only tracking capability will not able to distinguish tracks from different primary vertex and very fast timing of tens of ps will help a lot to keep pile-up background under control.

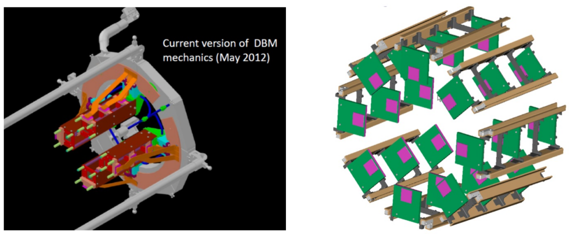

Figure 2: Mechanical drawing of one side of the luminosity pixel telescopes named DBM and PLT installed in ATLAS and CMS, respectivelly.

3. Forward detectors

The ATLAS and CMS physics program could be extend by selecting p-p collisions at LHC where the protons remains intact (forward protons) and a central system X is produced. These processes proceed mainly by the Feynman diagrams of Fig. 3, which turn LHC in a gluon-gluon collider (a) and a photon-photon collider (b). Measuring the invariant mass of the two tagged protons is possible to trigger on the production of resonances, new particles and W/Z pairs.

The studies of these processes are proposed for phase I in ATLAS by the AFP collaboration [6] and in CMS by the TOTEM/PPS collaboration [7]. The apparatus require high precision tracking and timing detector at about 220 m upstream and downstream of the interaction point to detect protons scattered at small angles and with small momentum losses. The tracking detector must measure the proton fractional momentum losses in the range $0.02 < \eta < 0.2$ (corresponding to central mass from few hundreds GeV to few TeV) with a precision of about 4-5 GeV in the invariant mass.

It is crucial to integrate high total luminosity to study processes with cross-sections of few fb, such as EW anomalous coupling and possible BSM heavy objects. This is possible only collecting

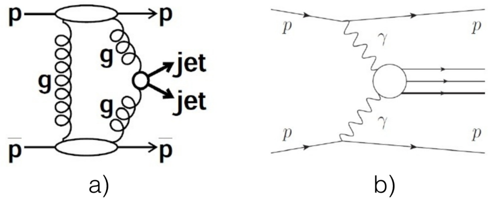

Figure 3: Central Exclusive Production via the exchange of di-gluon system (a) and EW production of a central system X by two photons exchange (b).

data in normal LHC physics runs, with a tracker very much radiation hard (solid state pixel detector) and with a timing detector capable to tag protons with 10 ps time precisions (high pile-up conditions make primary vertex separation necessary). The area covered by these detectors is quite small, about 2x2 cm2, with an irradiation highly non-uniform, having a hot spot of about 5x10^{15} p(7.5 TeV)/cm2, and an active area very close to the beam, 2-3 mm are are need to have good acceptance.

3.1 Edge-less pixel Silicon detectors

The baseline technologies for AFP tracking are hybrid Silicon pixel detector with edge-less 3D sensors equipped with FE-I4 readout chip. This is the second time that 3D Silicon sensors are used in HEP experiment after ATLAS IBL.

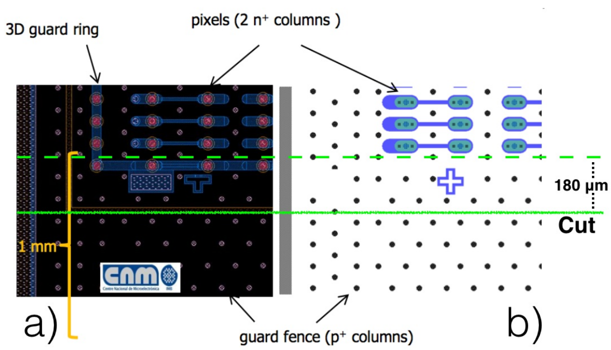

Figure 4: Edge termination of 3D Silicon sensors fabricated by CNM (a) and FBK (b) for ATLAS IBL for phase 0.

Fig. 4 shows the FE-I4 3D IBL sensors made by CNM and FBK consisting of 336x80 pixels of 50x250 μm^2 with p-type bulk and 2 n+ columns per pixel. It is imperative to have the sensor edge facing the beam as shorter as possible, in order to comply with the beam requirements on background, because the detectors behave like collimators. The edge termination is different for the two technologies: CNM termination consists in 3D guard ring of n+ columns with p+ ohmic-column fence and FBK, instead, has only p+ ohmic-column fence. An edge cut down to 100-180 μm is done with standard diamond-saw, but also sensors with Scribe-Cleave-Passivate (SCP) cuts were investigated with promising results. The edge length should be compare with FE-I4 chip edge dead region, which extends about 80 μm. In testbeams a stable efficiency up to last pixel was measured for both sensors, but for FBK the efficient edge extended about 80-85 μm beyond the boundary of pixel cells due to the absence of the guard ring.

3.2 Large beta run and fast timing

The single diffraction, which produces a single forward proton, is about 10% of the total cross section at LHC. In a high-pile up environment an occurrence of two single-diffraction interactions in the same bunch crossing can easily fake an interaction of interest, which yields two forward protons. The rejection of this background is possible by measuring the arrival time difference of the forward protons in the two arms with picosecond accuracy and ensure that is compatible with the vertex location measured from the ATLAS inner detector. A 10 ps time-of-flight resolution translates into a 2.1 mm vertex resolution (a $\sqrt{2}$ reduction factor comes from the two time measurements). The simulations shown that a 10 ps time-of-flight measurement provides a background rejection factor around 20.

The AFP baseline timing detector is named QUARTIC and consists in quartz (fused silica) bars positioned at the Cherenkov angle with respect to the proton directions. The radiators are placed along x, to add granularity, and along z, to have multiple timing measurements for achieving the 10 ps resolutions. The Cherenkov light travels up to the bar ends and is converted to a signal by a new generation of Microchannel Plate Photomultiplier Tubes (MCP-PMTs). The goal of the electronics is to preserve the signal shape information dominated by the excellent MCP-PMT response (about 20 ps per bar) and derive the best possible timing. The baseline AFP readout chain is made of a low-noise RF voltage amplifier, followed by a custom made constant-fraction discriminator (CFD) and a high-precision TDC based on the HPTDC chip [8]. The CFD, the TDC and the reference clock add each one a 5 ps time dispersion per channel which must be added in quadrature to the final time resolution. In Fig. 5 the various components and their locations are depicted. Anyway, the best performing readout chain is based on the new generation of Fast Waveform Digitizer, but the CFD method described here is very close to optimal and the only one fully built and successfully tested in testbeam. The requirements on the Waveform Digitizer chip are quite demanding: 1 GHz input bandwidth, zero dead time at the LHC, sampling clock of 10 Gs/s, 12 bit ADC in order to obtain an offline timing resolution less than 10 ps. A specific ASIC is under development for AFP and TOTEM, called SAMPIC [9], which is based on the experience of successfully prototypes.

4. High risk high impact R&D

At the higher luminosity of LHC phase I a higher pixelisation of the timing detector will be required in order to fight the large pile-up environment. For this reason, several R&D activities on timing detector based on diamond and Silicon sensors were started.

4.1 Fast timing with diamond detectors

An extensive R&D program is pursued by several groups to replace the QUARTIC timing detector with diamond detectors to solve the main limitations: photodetector radiation damage, large detector size and high occupancy. In fact, between the most interesting features of this material there are the very high tolerance to big radiation doses, the intrinsic speed of the collected signal and the fine segmentation in pixels or strips.

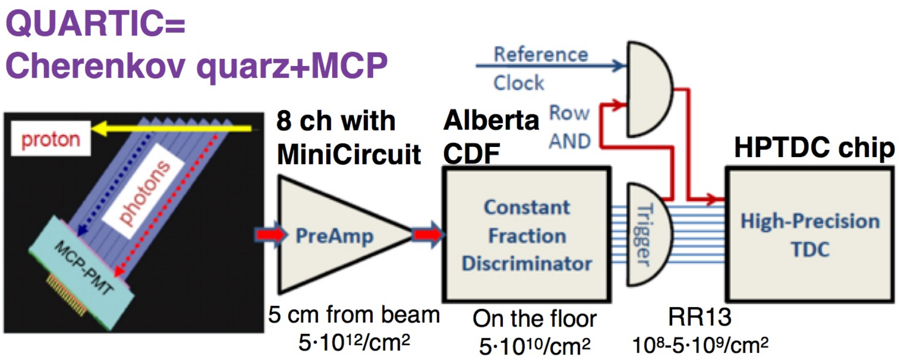

Figure 5: Complete detector and electronic chain of QUARTIC AFP fully tested with laser setup and in testbeam resulting in a 22 ps per quartz bar time resolution for a minimum ionizing particle. Below the different electronic blocks is also reported the amount of total radiation dose aspected.

CVD diamond-sensor detectors are already successfully used in nuclear physics for time-of-flight measurements of relativistic ions (atomic number Z>1), in which the signal intensity is high, reaching time resolutions of the order of tens of ps. This result suggests the possibility of using diamond detectors for time-of-flight applications also for minimum-ionizing particles for which the time resolution is limited only to a few hundred ps [10]. Assuming a readout electronics chain capable to correct for time walk error and with a negligible time digitization error (employing for example very fast constant fraction discriminators and TDCs, for on-line corrections, or very fast waveform digitizers, for off-line corrections) we can estimate the achievable time resolution using the formula [11]:

$$\Delta t = \frac{t_{rise}}{S/N}, \tag{4.1}$$

where t_{rise} is the signal rise time, approximately given by the maximum between the charge collection time and the electronics rise-time, S is the collected charge in diamond due to a crossing ionizing particle, and N is the electronic noise, which for diamond is just the front-end noise, because the leakage current is negligible. To improve the time resolution is necessary to act on one of the following conditions: decrease the signal rise time, decrease the noise and increase the signal. Such goals require the developing of low-noise and high-speed front-end electronics and the use of innovative geometrical and circuital configurations.

Two innovative solutions have been proposed recently in literature, see Fig. 6 a) and c). In the first solution a Multi-Layer-Crystal-Detector (MLCD) concept is proposed using M layers of thin diamond sensors (fast collection time independent from M) readout in parallel (signal increased M times) [12]. The MLCD idea relies on a custom made front-end electronics, featuring a low and constant electronic noise for input capacitance up to few nF, thanks to a new design solution using SiGe transistors. In the second solution a sensor with 3D electrodes is proposed [13]. In such electrode configuration the charge is collected very fast for small pitch but with the signal still proportional to the sensor thickness, allowing a reduction of the collection time without compromising the signal level. The 3D diamond sensors have been successfully built and extensively tested. A more conservative approach, proposing a solution that could be built with the existing technology, is the idea to boost strongly the signal, without affecting the noise and the collection time, by placing several diamond layers parallel to the tracks, one on top of each other , see Fig. 6 b).

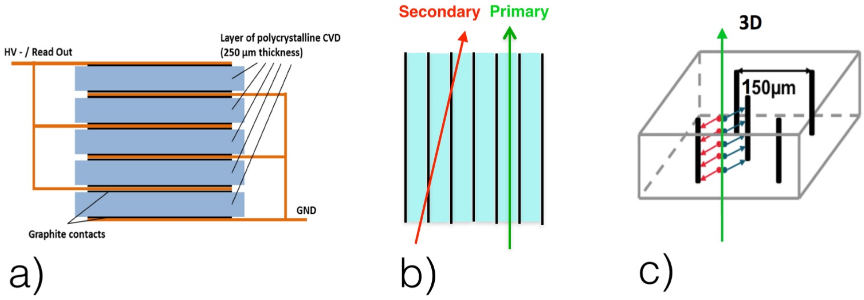

Figure 6: New diamond detector configurations explored by different groups to boost the signal amplitude and/or to reduce the charge collection time in order to reach a time resolution of tens of ps for a minimum ionizing particle: a) Multi-Layer-Crystal-Detector, b) Grazing diamond and c) 3D diamond sensor.

A final, but important consideration is that, in recent years, there are two vendors [15] selling large size detector-grade poly-crystal diamond sensors, making the procurement of the material less risky and, likely, less expensive.

4.2 The 4D pixel detector challenge

We already meet two situations where devices with very fast timing resolution of about 10 ps and precision space information of about 10 μm are strongly desirable. This 4D pixel detector is very challenging and in my opinion should be one of highest priority R&D for experiments at the future colliders with a lot of applications in other fields too.

The existing pixel detector with the best timing performance is the one used by the Giga-Tracker of NA62 experiment [16]. In the front-end readout chip the arrival time of the discriminated signal for each pixel cell is corrected with time-over-threshold information. A time resolution below 200 ps with 200 μm thick fully depleted Silicon sensor was achieved. A thickness reduction of the sensors should help in reaching the final resolution of the built-in TDC, which is below 100 ps. It is evident that to reduce further the timing precision not only the front-end electronics should be improved (likely this is possible with ultra-sub-micron CMOS technology) but also the sensor technology.

A very promising development is the "Low Gain Avalanche Detectors (LGAD)" project of the RD50 collaboration. It consists in a Silicon detector similar to traditional pixel or strip sensors (100 % filling factor and low noise rate), but with a much larger signal (thanks to a moderate internal gain of about 10-20). The gain is achieved by adding below the junction electrode an extra doping layer, where a high electric field of about 300 kV/cm, close to the breakdown voltage, is obtained (see Fig. 7). The n-in-p structure proposed by CNM collects electrons which have a charge multiplication gain (α_e=0.7pair/μm) higher than holes (α_h=0.1pair/μm) in the extra layer. Anyway, most of the signal is induced by the drift at the opposite electrode of the holes produced in the extra layer and a thin Silicon layer (50-100 μm) is required to keep time resolution small. Radiation hardness of multiplicative structures is of general concern. In fact, a decrease of about

20 % in gain after an irradiation of 10^{14} n/cm2 was observed in the first LGAD prototypes. Likely, this is due to boron disappearance and the next structures will be doped with Gallium.

The LGAD approach can be extended to any Silicon structure, not just pads, and this is the effort strongly pursued by the "Ultra Fast Silicon Detector (UFSD)" collaboration [17] . This is an intermediate approach with respect to the two previous described strategies: high gain (MCP and SiPm), where radiation hardness is the limiting factor, and no gain (Silicon and diamond sensors) where the signal-to-noise ratio is the limiting factor. This reflects also in the electronic chain where sensors with gain privilege a VA+CFD+TDC readout and sensors with no gain a FAST CSA+WAVEFORM DIGITIZER.

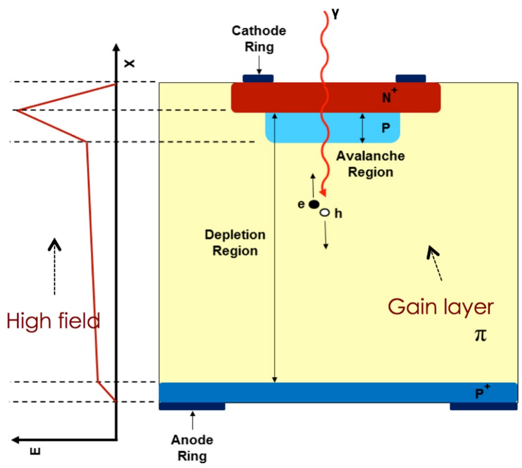

Figure 7: The n-in-p structure of Low Gain Silicon Detectors where the gain in the avalanche region is kept small (G ≈ 10-20) with respect to APD (G ≈ 50-500) or SiPm (G ≈ 10^5) devices.

5. Conclusions

Luminosity detector upgrade with high granularity and timing resolution are needed for LHC upgrades and HL-LHC. Forward detector for diffractive physics running in nominal optics configuration at LHC are already beyond the limit of the available technologies. In this respect, it is important to tackle the technical difficulties by a staged approach going from high β runs with low primary vertex multiplicity to low β runs with high primary vertex multiplicity and later from phase I to phase II.

The above mentioned challenges are well suitable for small size detectors and pave the way to more ambitious project, such as the instrumentation of large eta region with large size detectors having tracking and timing capability. Moreover, these detectors and measurements are an ideal place for students and young physicists to acquire direct and rewarding experience in state-of-the-art technologies, in detector design, construction and operation, and in collider physics analysis. Finally, a lot of synergy (between experiments and sub-detectors) and spin-off (medical, space and imaging) can be envisaged for these new ideas and technologies.

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