

# 4-Dimensional Trackers

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## 1 Introduction

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Precision Timing information at the level of 10-30ps is a game changer for detectors at future collider experiments. For example, the ability to assign a time stamp with 30ps precision to particle tracks will allow to mitigate the impact of pileup at the High-Luminosity LHC (HL-LHC). With a time spread of the beam spot of approximately 180ps, a track time resolution of 30ps allows for a factor of 6 reduction in pileup.

Both ATLAS and CMS will incorporate dedicated fast-time detector layers for the HL-LHC upgrade [1, 2]. Timing information will be even more important at future high energy, high luminosity hadron colliders with much higher levels of pileup. For example, one of the key challenges at a future 100 TeV p-p hadron collider will be the efficient reconstruction of charged tracks in an environment of unprecedented pileup density. A powerful way to address this challenge is by fully integrating timing with the 3-dimensional spatial information of pixel detectors. An integrated 4-dimensional tracker with track timing resolution at the levels of  $\sim 10$ ps can drastically reduce the combinatorial challenge of track reconstruction at extremely high pileup densities [3].

While timing information will be critical to mitigate the impact of pileup, it is not the only way in which it will enhance the event reconstruction of future hadron and lepton colliders. Timing information offers completely new handles to detect and trigger on long-lived particles (LLP) [2, 4], expand the reach to search for new phenomena by providing new handles on the data [2], and enabling particle-ID capabilities for pion/kaon separation at low transverse momentum [2]. 4D devices with coarse timing capabilities at  $\sim$ ns level but with similar granularity as regular tracking devices at the other end of 4D phase space can complement the fast timing layers for an enhanced overall 4D tracking.

The optimal design of future 4D trackers will involve three key considerations: sensors with adequate spatial and time resolution, low power and low noise readout electronics, and overall detector layout, including material considerations. Significant R&D is required to understand how to best design 4D trackers and how all these aspects will impact physics performance.

The following sections describe specific considerations for the integration of timing within tracking detectors at various future collider detectors and upgrades of existing experiments.

## 1.1 Hadron colliders: HL-LHC and FCC-hh

Valentina Maria Martina Cairo

The Inner trackers of the ATLAS and CMS Experiments at the Large Hadron Collider (LHC) will be upgraded to cope with the extreme conditions of the High-Luminosity phase of the LHC, currently foreseen to take place towards the end of 2027.

[Add something about CMS?]

The CMS Experiment is planning to install a MIP Timing Detector (MTD) with different sensor strategies in the barrel and endcap regions. The barrel will rely on scintillator crystals and silicon photomultipliers, whereas the endcap timing layer (ETL) will consist entirely of silicon sensors. [2]

Jenni: The motivation and physics cases for the CMS timing detector endcap are essentially the same as for ATLAS, so perhaps this section can just be combined for the two experiments. J: I think CMS also estimates that the inner tracker/pixels need to be replaced after some years in the HL-LHC, but I don't know if it has been planned to include timing also in the IT at that point.

The ATLAS Inner Detector, currently based on both silicon and gaseous technologies, is planned to be replaced by a full-silicon Inner Tracker (ITk) [5, 6]. ATLAS will also be installing a High Granularity Timing Detector [1] in the forward pseudorapidity region, which will help mitigate the effects of pileup interactions and distinguish between collisions occurring close in space but well-separated in time. Due to the high radiation dose in proximity of the interaction point, the two innermost pixel layers of the ITk will have to be replaced after a certain number of years of data taking. This represents a unique and exciting opportunity for the physics community to study the impact that fast-timing through 4D tracking would have on challenging physics cases (Higgs pair production, Vector Boson Fusion production of Higgs bosons decaying to invisible particles, etc) if used in the ATLAS barrel region. This would allow to bring in technological innovation and fully exploit the potential of HL-LHC by complementing the capabilities of the HGTD. Even a single pixel barrel layer with timing capabilities could be a vast improvement in terms of performance and physics results, but detailed simulation studies are needed to evaluate the potential of such detector layout and eventually probe its feasibility. The time resolution needed to substantially boost the ATLAS performance is to be evaluated along with the amount of material introduced in the tracker with the usage of 4D silicon modules by means of tracking performance feat as well as more complex objects such as b-jets.

Beyond HL-LHC, one of the key challenges in the design of Future hadronic Circular Colliders (FCC-hh [7]) arises from an increased number of pile-up events  $O(1000)$ , up an order of magnitude more than at the HL-LHC. This implies that particle tracking and identification of vertices based on traditional 3D tracking would be extremely difficult, making a very clear case for the usage of 4D technology in all tracking layers. In fact, with trackers providing timing information, in addition to the longitudinal position measurement, the pile-up discrimination power opens up in 2 dimensions, time and space, and one key question to answer is again what timing resolution per track is needed. As shown in Fig. 1, studies on primary vertexing at the FCC-hh demonstrate that 2D vertexing with an extreme timing resolution of 5–10 ps per track is essential to keep the levels of effective pile-up<sup>1</sup> under control at large pseudorapidities ( $|\eta| > 3$ ) which would otherwise reach level of tens or hundreds leading to large merging effects in vertex reconstruction and large confusion in vertex selection.

At the same time, the higher energies and luminosities typical of the FCC-hh, pose very stringent constraints on the detector design itself, for instance on the radiation hardness of the silicon modules, limiting either the lifetime of the inner detector or the number of suitable technologies.

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<sup>1</sup>Effective pile-up is defined as the number of pile-up vertices which effectively lead to a confusing assignment of low  $p_T$  tracks to the original primary vertex

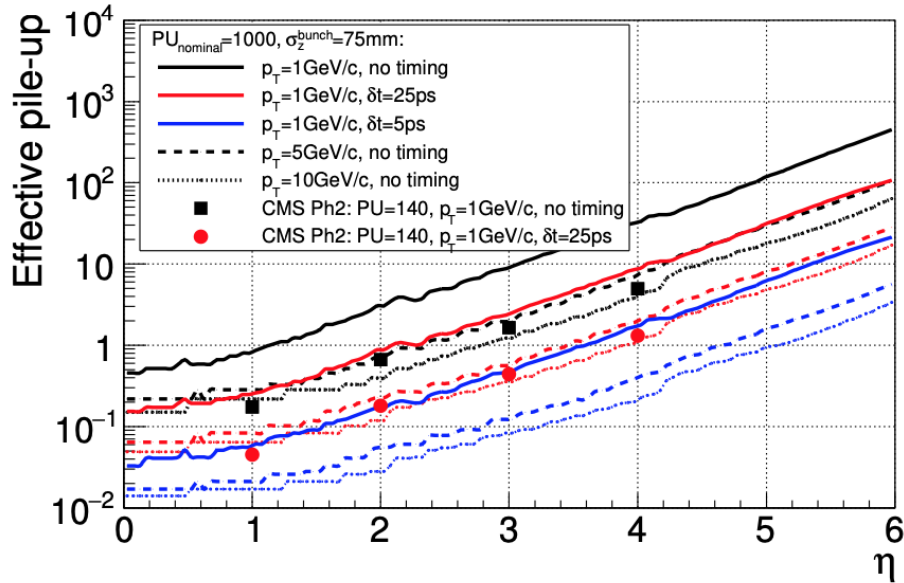


Figure 1: From Ref. [8]. An effective pile-up in the FCC-hh tracker. Several options of timing resolution per track in 2D vertexing are assumed: no timing (black),  $\delta t = 25$  ps (red) and  $\delta t = 5$  ps (blue). Several  $p_T$  values are shown: 1 GeV/c (solid), 5 GeV/c (dashed) and 10 GeV/c (dotted). For reference the effective pile-up for CMS Phase 2 layout,  $p_T = 1$  GeV/c and nominal pile-up=140 is added.

82 In the layouts under study [7], the beampipe is supposed to have a radius of 20 mm, and at 25 mm  
 83 the radiation levels are of the order of 0.4 GGy after 30  $ab^1$  and approximately 1 MeV neq fluence  
 84 ( $6 \times 10^{17}$  per  $cm^2$ ), which corresponds to approximately 30 times (600 times) more radiation com-  
 85 pared to HL-LHC (LHC), making none of the existing technologies suitable, but rather requiring  
 86 dedicated Research and Development efforts targeting extreme timing resolutions and radiation  
 87 hardness.

## 88 1.2 $e^+e^-$ colliders: ILC, CLIC, C<sup>3</sup> (?)

89 Valentina Maria Martina Cairo, Lucie Linssen

90 The usage of 4D tracking technology at  $e^+e^-$  colliders is subject to very different conditions  
 91 compared to that of experiments at hadron machines: both the numbers of collisions per beam  
 92 crossing and the radiation levels are orders of magnitude lower, but the physics measurements are  
 93 normally targeting very high precision, imposing track parameter resolutions to be extremely good,  
 94 thus requiring very low passive material in the vertexing and tracking detectors.

95 Most of the studies performed so far focus on the usage of time at the ns resolution level as  
 96 part of the object reconstruction chain, while studies of potential applications of precision timing at  
 97 the ps level are still to be further investigated in  $e^+e^-$  colliders. Both aspects will be summarised  
 98 below.

99 The International Linear Collider (ILC) [9] is a proposed 20 km  $e^+e^-$  linear collider at the  
 100 energy frontier, with a initial baseline center-of- mass energy of 250 GeV. Two detector concepts  
 101 have been studied at the ILC: the Silicon Detector (SiD) and the International Large Detector  
 102 (ILD).

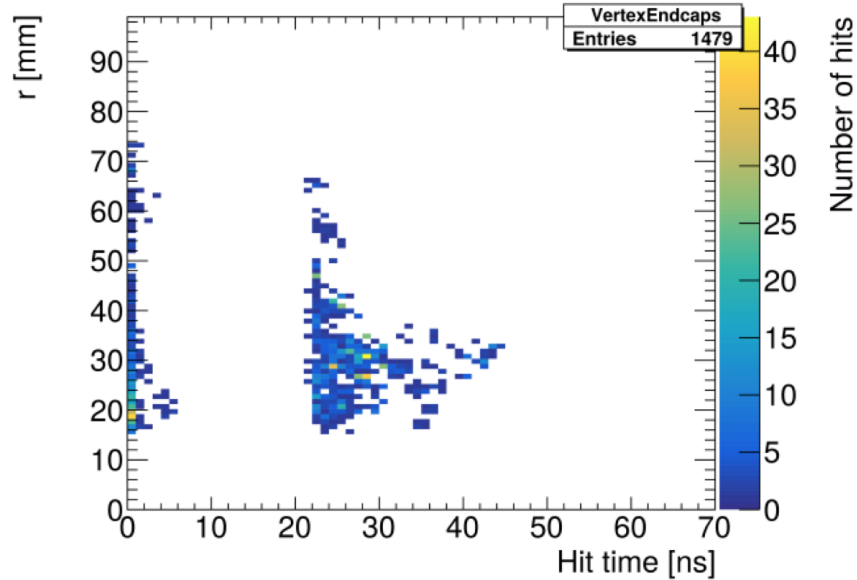


Figure 2: From Ref. [10]. The time distribution of beam background hits in the SiD Vertex Detector Endcap.

103 SiD is a compact detector based on a powerful silicon pixel vertex detector, silicon tracking,  
 104 silicon-tungsten electromagnetic calorimetry (ECAL) and highly segmented hadronic calorimetry  
 105 (HCAL). SiD also incorporates a 5T solenoid, iron flux return, and a muon identification system.  
 106 The choice of silicon detectors for tracking and vertexing ensures that SiD is robust with respect  
 107 to beam backgrounds or beam loss, provides superior charged-particle momentum resolution, and  
 108 eliminates out-of-time tracks and backgrounds. The recent developments in fast-timing detectors  
 109 could bring in improvements to the SiD layout, as described in Ref. [10]. Timing layers with  
 110 resolutions at the level of the nanosecond could be used in the HCAL to help suppress backgrounds.  
 111 Fig. 2 shows a clear distinction between the time of the collision hits and that of background hits.

112 Better time resolutions would instead make it possible to exploit time-of-flight (TOF) for low-  
 113 momentum particle identification (PID) if timing layers were added to the tracking system or in  
 114 between the tracker and the ECAL. Fig. 3 shows that, in SiD, a TOF system with time resolution  
 115 of 10 ps allows for PID up to a momenta of a few GeV.

116 The ILD concept has been designed as a multi-purpose detector for optimal particle-flow (PFA)  
 117 performance. Its tracking systems differs from the SiD one: a high-precision vertex detector is  
 118 followed by a hybrid tracking system, realised as a combination of silicon tracking with a time-  
 119 projection chamber (TPC). The complete system, along with a calorimeter, is located inside a 3.5  
 120 T solenoid.

121 Particle identification in the ILD can be carried out by the TPC using  $dE/dx$  information but  
 122 studies have been conducted [11] on the possibility of improving PID via a TOF system. As a proof  
 123 of concept a possible TOF estimator is computed, which uses the first ten calorimeter hits in the  
 124 ECAL that are closest to the straight line, resulting from extrapolation of the particle's momentum  
 125 into the calorimeter, assuming an individual time resolution of 100 ps per hit. Fig. 4 shows the  
 126 complementary between  $dE/dx$  and TOF information at the ILD.

127 The momentum range in which the particle identification using TOF is effective depends on the  
 128 time resolution. More detailed studies [12] show that smaller time resolutions do boost the PID  
 129 reach in the low momentum regime, but the momentum range covered via TOF for PID remains

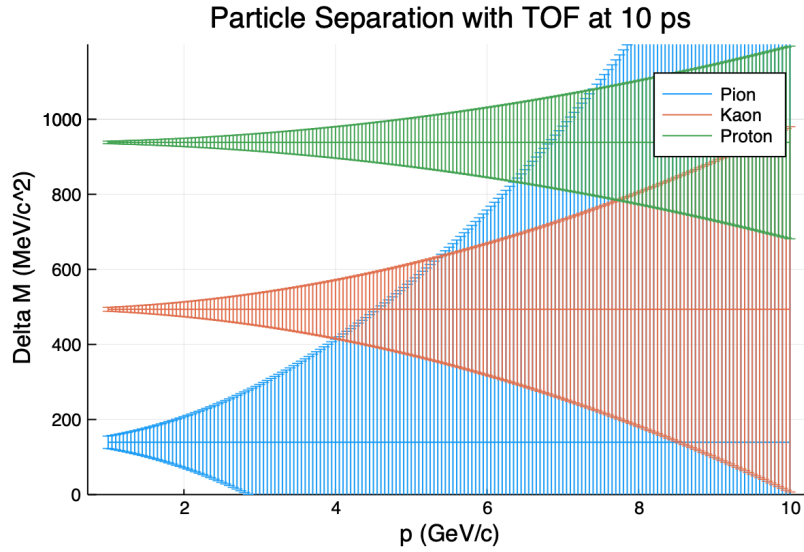


Figure 3: From Ref. [10]. Mass resolution for a time-of-flight system with a performance of 10 ps in SiD.

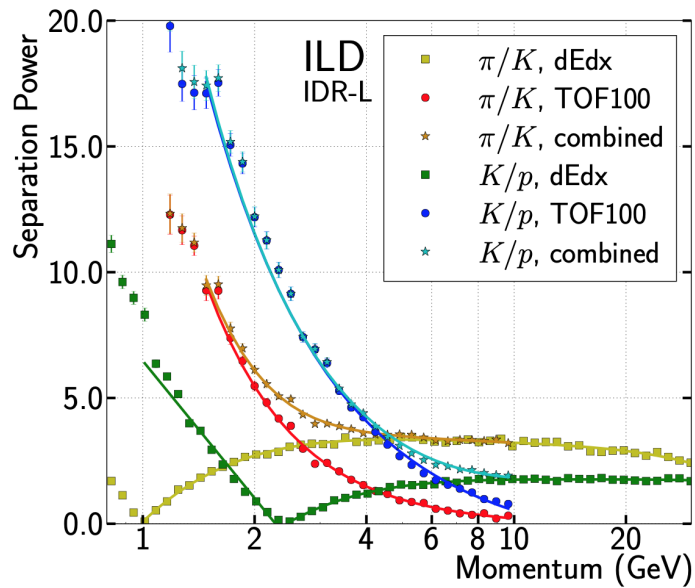


Figure 4: From Ref. [11]. Particle separation power for  $\pi/k$  and  $K/p$  based on the  $dE/dx$  measurement in the TPC and on a time-of-flight estimator from the first ten ECAL layers. The separation power obtained when the information from the two systems is combined is also shown.

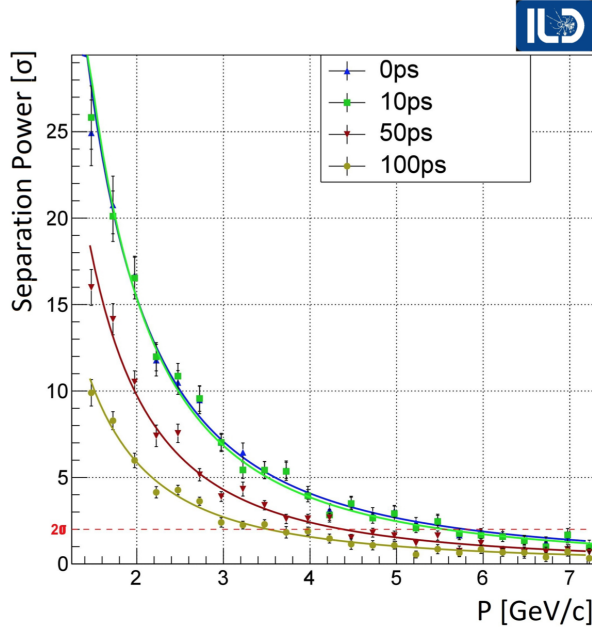


Figure 5: From Ref. [12]. Separation power between kaons and pions as a function of momentum assuming different time resolutions for a time-of-flight system in ILD.

130 limited, as one can see in Fig. 5. Dedicated PID detectors would have to be installed to discriminate  
 131 pions from kaons at high momenta and more information about related studies can be found in [?].

132 The Compact Linear Collider (CLIC) [13, 14] is another proposed  $e^+e^-$  machine featuring a  
 133 future multi-TeV collider. Two detector concepts are designed based on those studied for the ILC.  
 134 The timing requirements at CLIC are driven by the levels to which the background degrades the  
 135 physics performance of the detector. Assuming that the occupancies in the elements of the tracking  
 136 detectors are sufficiently low that efficient track reconstruction is possible, there is unlikely to be  
 137 a significant impact on the quality of the reconstructed tracks. Hence the main impact of the  
 138 background will be on the reconstruction of jets. From detailed studies (see Section 2.5 in Ref. [13])  
 139 on the  $W$ -boson mass resolution in simulated  $W \rightarrow qq$  decays, it was concluded that at CLIC the  
 140 required hit-time resolution must be below 5 ns in the tracking and vertexing detectors and at most  
 141 1 ns in the calorimeters. This hit-time information is used during the reconstruction of particle-  
 142 flow objects, which starts with track reconstruction by using only tracker hits within a 10 ns time  
 143 window around the physics event and then combines them with information from calorimeter hits.  
 144 As a result, all the particle-flow objects (charged and neutral) have sub-ns time resolution and this  
 145 information can be used to remove particles from beam-induced background via both momentum  
 146 and timing cuts as a function of the angular region and of the particle type.

147 Dedicated 4D tracking studies with ps-level resolution in some of the tracking layers have not  
 148 yet been performed in CLIC. It has to be noted though that CLIC assumes to run at 380 GeV and  
 149 above, thus the impact of fast timing in a TOF system is expected to have less added value for  
 150 CLIC than for  $e^+e^-$  collisions at lower centre-of-mass energies.

### 151 1.3 Muon Collider

152 Hannsjörg Weber, Sergo Jindariani

153 Experiments at muon colliders have huge potential. A muon collider as a Higgs factory might

154 allow to directly measure the mass and width of the Higgs boson at highest precision [15]. On  
155 the other hand, muon colliders have a potential to achieve collision energies of tens of TeV with a  
156 relatively small size for a collider ring, thus reaching way further than  $e^+e^-$  colliders and having  
157 a physics reach on-par with hadron colliders with hundreds of TeV in collision energy [16]. The  
158 current timeline to complete the accelerator R&D and be ready for the construction of a muon  
159 collider is estimated to be earliest in the latter part of the 2030s [17].

160 The major challenge for a muon collider experiment is that muons are unstable particles and  
161 naturally decay. The decaying muons within the colliding beams will create, for each beam crossing,  
162 a spray of hundreds of million particles entering a muon collider experiment. Out of those, an order  
163 of a million particles is charged. This multiplicity of particles entering the detector volume is  
164 expected after the muon collider experiment has already been shielded by so-called nozzles in the  
165 forward region, blocking the volume of  $|\eta| \lesssim 2.5$ . The background induced by these particles is  
166 commonly referred to as the beam-induced background (BIB) [18]. The BIB primarily consists of  
167 low energy photons and neutrons with a small fraction of charged hadrons, muons and electrons  
168 also present.

169 The presence of the BIB puts stringent requirements on a tracking detector. Firstly, the high  
170 number of particles entering the detector region leads to high levels of radiation and thus detectors  
171 need to be radiation hard, similarly to the detectors at hadron colliders. Secondly, hits produced  
172 by the BIB particles complicate data readout and make track reconstruction at the muon collider  
173 a very challenging task.

174 Yet, as the decay of muons is a stochastic process, several advantageous design aspects for  
175 tracking detectors can be thought of to suppress the impact of the BIB. Most of the BIB particles  
176 enter the detector from the two forward regions and do not originate in the collision area. Precise  
177 timing of detector hits would be able to reduce the BIB by a large fraction as we only need to  
178 consider hits consistent with the collision time. Furthermore, if timing of the hits can be correlated  
179 among adjacent layers of a tracking detector, a further filtering can be done by only considering  
180 hits consistent with being produced by the same particle. Initial studies indicate that single hit  
181 resolutions of 20-30 ps are sufficient to reduce the BIB to a manageable level. Additional suppression  
182 can be achieved if the tracker can obtain directional information, as for example is being done with  
183 the  $p_T$  modules of the CMS outer tracker upgrade for the HL-LHC [19]. Besides the requirements  
184 of precise timing and directionality, also a high spatial resolution is needed to achieve a low detector  
185 occupancy. Simulation studies show that small pixels at a size of about  $(25 \mu\text{m})^2$  are needed at the  
186 innermost layers of a tracking detector while even at the outermost layers strips with length of at  
187 most few cm are required [20].

188 These requirements on small pixels/strips with precise timing and directional information will  
189 allow to not only handle the BIB, but will also enable a muon collider experiment to take high  
190 quality data for precision measurements and searches for new physics at highest energies [21].  
191 Therefore, there is a high need of R&D efforts towards 4D (and 5D) tracking within the muon  
192 collider community.

## 193 1.4 Electron Ion Collider

194 Zhenyu Ye

195 The Electron-Ion Collider (EIC) [1] is a new accelerator facility to be built at Brookhaven  
196 National Laboratory in the United States. In 2031, the machine will begin colliding high-energy  
197 electron beams with high-energy proton and ion beams to study the spatial and spin structure of  
198 nucleons and nuclei. Due to the small  $ep$  and  $eA$  cross-sections, the collision rate at the EIC will  
199 be 500 kHz or less with a total particle production rate of about 4 million per second. Therefore,

200 the requirement on the irradiation tolerance and occupancy of the detectors at the EIC will be  
201 considerably relaxed than those at the hadron colliders.

202 AC-coupled LGADs have been widely included in the submitted EIC detector proposals. In the  
203 barrel (endcap) region, precise timing and spatial information will be provided by single (double)  
204 layer of AC-LGADs for particle identification and track reconstruction, while in the far-forward  
205 (p/A-going) direction, AC-LGADs will be used to detect high-momentum hadrons near the beam  
206 line. These detectors need to provide a single hit timing resolution better than 30 ps and depending  
207 on the location a single hit spatial resolution between 15 to 150  $\mu m$ . The detector designs need to  
208 incorporate low material budgets, e.g.,  $\sim 1\%$   $X_0$  per layer in the barrel region. These impose a great  
209 challenge to the performance of AC-LGAD sensors, front-end readout ASIC, off-detector electronics,  
210 as well as the mechanical and cooling system design. A R&D project has been established to develop  
211 a common approach for these detectors so that they can share the same design to the extent possible.

212 [1] Science Requirements and Detector Concepts for the Electron-Ion Collider: EIC Yellow Re-  
213 port, BNL-220990-2021-FORE, JLAB-PHY-21-3198, LA-UR-21-20953, arXiv:2103.05419 (2021).

## 214 **2 Sensor technologies**

215 Simone Mazza, Ryan Heller, Ron Lipton, Gabriele Giacomini, Doug Berry, Jennifer Ott, Valentina  
216 Maria Martina Cairo

### 217 **2.1 Advanced LGAD designs**

218 LGADs, AC-LGADs, Trench-isolated LGADs, Buried Gain LGADs, Deep Junction LGADs, 3D

219 The most prominent class of 4D sensors proposed for future trackers are based on an evolu-  
220 tion from LGAD sensors developed for the HL-LHC. LGADs are thin silicon sensors with modest  
221 intrinsic gain, and achieve 30 ps or better time resolution in mm scale pads. Standard LGADs,  
222 however, rely on Junction Termination Extensions to interrupt the gain layer between channels,  
223 which introduce inactive regions. As a result, LGADs cannot be simply miniaturized to a pitch  
224 appropriate for tracking.

225 Several sensor concepts have been proposed and demonstrated to make LGAD sensors suitable  
226 for tracking. Many of these fall in the category of AC-LGADs, which feature continuous gain  
227 layer, a resistive n+ surface layer, and AC-coupled readout electrodes. Because the gain layer is  
228 uninterrupted, AC-LGADs achieve a fill factor of 100%, and electrodes can be designed with smaller  
229 pitch and size than standard LGADs. A key feature of AC-LGADs is the signal sharing between  
230 electrodes, which can be used to obtain position measurements with resolution much smaller than  
231 (bin size)/ $\sqrt{12}$ . One major advantage of AC-LGADs is that they can obtain the spatial resolution  
232 necessary for future colliders with a coarser pitch and hence a reduced number of readout channels.

233 Recent test beam measurements have demonstrated that AC-LGADs can achieve simultaneous  
234 30 ps and 5  $\mu m$  resolution with strips of pitch 100-200  $\mu m$  [22]. This spatial resolution represents a  
235 factor of 5-10 improvement beyond what would be obtained in binary readout, thanks to the sharing  
236 of signals between adjacent channels. Other studies have demonstrated similar performance [23]  
237 [24].

#### 238 **2.1.1 AC-coupled LGADs**

239 Ryan: Move some of description from general section here, add some test beam results.

240 Simone: add some UCSC laser results and simulations, non conventional geometry

241 AC-LGADs have several parameters that can be tuned to optimize the sensor response to the  
242 specific application. The geometry of the electrodes in terms of pitch and pad dimension is the  
243 most important one, however also the N+ sheet resistivity and the dielectric thickness between N+  
244 and electrodes influence the charge sharing mechanism. All of the AC-LGAD parameters affect  
245 the way the charge is shared, therefore it is necessary to balance the properties to achieve the best  
246 time and spatial resolution in respect of the channel density and occupancy. These parameters  
247 need to be studied with simulation softwares, such as TCAD Silvaco or Sentaurus, to have a good  
248 representation of the observed sensor performance. Simulations with TCAD software are important  
249 to compare with existing prototype data and to help in optimizing the design.

250 The top metal of the electrodes in AC-LGADs sits on the oxide layer with no underlying  
251 structure. Thanks to the simple layout it is possible to arrange the metal of the electrodes in  
252 any shape and size, allowing to optimize the geometry to tune the charge sharing to the specific  
253 application. For example circles and crosses instead of metal square could simplify and enhance the  
254 reconstruction process. Furthermore electrodes can be shaped to have different charge sharing in  
255 the X and Y direction (e.g. micro-strips) to optimize the channel density to the sensor resolution  
256 in both directions. A proof of principle of metal electrodes modification process, executed at BNL,  
257 was made [25]. The procedure was successful showing that the top geometry of AC-LGADs can be  
258 modified, a universal design can be then produced and etched to the specific application.

### 259 **2.1.2 Buried Layer LGADs**

260 Radiation campaigns showed that LGADs with deep and narrow gain layers are radiation harder  
261 than LGADs featuring shallower and broader gain layers. Gain layers are generally obtained by  
262 means of ion implantations which can implant boron at a maximum depth of about  $2\ \mu\text{m}$  using very  
263 high and not easily available implantation energies. Furthermore, deeper implants are generally  
264 broader than shallower implants. A way to circumvent the problem, at the expense of a complication  
265 in the process, is to implant the boron layer at low energy and then to bury it under a few microns  
266 of epitaxial layer, obtaining in this way a deep and narrow gain layer (if high thermal cycles are  
267 avoided in the subsequent process. The method can be applied to either standard DC-coupled  
268 LGADs or AC-LGADs. A first fabrication has been completed but suffered from a high leakage  
269 current due to a poor epitaxial deposition. Another fabrication is on-going.

### 270 **2.1.3 Trench-insulated LGADs**

271 A way to avoid AC-LGADs and still have a high fill-factor in fine-pitch devices is to use narrow  
272 trenches to separate the pixels (or strips). The deployment of such trenches all around the electrodes  
273 allows to get rid of the JTE, to bring the gain layer closer to the edge of the n-plus implants, and  
274 to bring the pixels close together. Dead areas of a few microns have been demonstrated in FBK  
275 productions.

### 276 **2.1.4 Double Sided LGADs for 5D Tracking**

277 The Double Sided LGAD (DS-LGAD) adds a readout layer to the p-side of the LGAD structure.  
278 This allows for double-sided readout with the p side reading out the slower-drifting holes. For a  
279 device with the bulk thickness large compared to the pixel pitch the p-side readout can function as a  
280 mini time projection chamber with the drift time providing information on the depth of origin of the  
281 charge cloud. The signal p-side collects two components, holes from the primary ionization followed  
282 by the larger number of holes generated at the gain layer. This provides a unique signature of the  
283 pattern of charge deposit within the device (figure AAAA). The fast rise signal can be read by a

284 large area cathode, limiting the number of complex, power hungry fast amplifiers and digitizers. The  
285 p-side provides a large, slower signals that can be read out with electronics with lower complexity  
286 and power consumption.

287 The characteristics of the thick ( $> 5 \times pitch$ ) DS-LGAD are sensitive to the interplay between  
288 the device thickness, gain layer location and doping, and the applied voltage. In a buried layer  
289 device the depth and doping of the gain layer sets the operating point and the drift field. These can  
290 be tuned to achieve the required characteristics. Diffusion width and time of arrival of the holes  
291 from gain layer amplification can then be used to provide excellent position and good track angle  
292 resolution. Operation will be a compromise as these thicker devices will have worse time resolution  
293 than thin LGADs and may be more sensitive to radiation effects on doping levels.

### 294 **2.1.5 Deep-Junction LGADs**

295 The “Deep-Junction LGAD” (DJ-LGAD) [26] is a new approach to the application of controlled  
296 impact-ionization gain within a silicon diode sensor. The term “deep-junction” arises from the  
297 use of a p-n semiconductor junction buried several microns below the surface of the device. The  
298 buried junction is formed by abutting thin, highly-doped p+ and n+ layers, with the doping density  
299 chosen to create electric fields large enough to generate impact ionization gain in the narrow buried  
300 junction region. Additionally, the doping densities chosen for the p+ and n+ layers are balanced so  
301 that when the sensor is fully depleted, the electric field outside of the junction region, while large  
302 enough to saturate the carrier drift velocity, is significantly less than that require to create impact  
303 ionization gain. This preserves the electrostatic stability at the segmented surface of the detector,  
304 thus in principle permitting the production of DC-coupled LGADs with arbitrarily fine granularity.  
305 No JTE structure is required for a DJ-LGAD array, as the buried gain layer ensures a uniform gain  
306 performance across channels. The DJ-LGAD approach is seen to hold significant promise towards  
307 the development of a highly-pixelated DC-coupled silicon diode sensor with substantial internal  
308 gain and precise temporal resolution.

### 309 **2.1.6 Thin LGADs**

310 Thin sensors can be a useful technology to apply in very high radiation environment [27, 28]. In  
311 the late years a saturation of the charge trapping effect in silicon was observed [29]. However  
312 at a fluence of  $10^{17} - 10^{18}$  a standard 300 um silicon detector would still need several thousand  
313 volts to deplete. For a thin sensor instead the full depletion at very high fluence can happen at  
314 much lower voltages: 500 V of full depletion for a 50 um sensor at  $10^{17}$ . The collected charge for  
315 thin sensors, however, would be too small to be efficiently detected by readout electronics. Thin  
316 LGADs can be used thanks to the intrinsic charge multiplication, it was shown that sufficient gain  
317 is observed until a few  $10^{15}$  for time resolution measurements purposes but less gain is necessary  
318 for hit detection only. Furthermore at high fluences gain in the bulk “p” region of the sensor can be  
319 activated by increasing the bias voltage applied to the sensor. These statements gives an indication  
320 of the radiation hardness properties of thin LGADs even at extreme fluences for hit detection. An  
321 example of extreme fluence would be a tracking system very close to the interaction point in future  
322 hadron colliders.

## 323 **2.2 3D**

324 Timespot trench 3D sensors for timing

## 2.3 MAPS

Fine spatial resolution and course time resolution: CMOS MAPS. Coordinate with CMOS paper Valentina: for Malta, there is public material here we can use as a reference (including a section on timing) <https://twiki.cern.ch/twiki/bin/viewauth/Atlas/MaltaApprovedPlots> and also this CERN EP RD seminar: <https://indico.cern.ch/event/1074066/2-measurement-results-from-fas>

## 2.4 Comparison of sensor technologies

Tradeoffs for different sensors: high occupancy? material budget? rad hardness?

## 2.5 Induced Current Detectors

An induced current detector uses the same sensor as a traditional silicon detector but utilizes small pixel pitch and 3D integration (3DIC) techniques to create a low-capacitance pixel unit cell and readout chain. This not only limits the amount of noise in the system but also enables the detection of the induced current as described by the Schokley-Ramo theorem [30, 31]. The Schokley-Ramo current is the current induced at the readout electrode from mobile charge carriers within the sensor. It has a very fast rising edge ( $\sim 15$  ps) [32] and can be used to precisely timestamp track hits. The Schokley-Ramo current is dependent on the weighting field within the sensor and the depth of charge deposition. As a direct result, it has a complicated bi-polar signal shape that integrates to zero over the course of several nanoseconds. This signal combined with the drift current creates a pulse shape that is dependent on the charged particle's angle of incidence.

A detector that is sensitive to the effects of the Schokley-Ramo current has two critical features: precise ( $\sim 15$  ps) time resolution and angle of incidence information [33]. The precise time resolution is useful in many different collider experiments and can be used for either vertexing or particle identification via a time-of-flight (TOF) measurement. The angular information is a more novel feature but still useful feature. First it can be used to quickly identify particles with large transverse momentum ( $p_T$ ) for an L1 trigger, as high- $p_T$  particles have high angles of incidence. Second it can be used to greatly increase the speed of track reconstruction because the angular information greatly reduces the number of pixel hits that must be considered when track seeds are generated. These capabilities make it a very attractive detector technology for future collider experiments and requires the continued investment in advanced ASIC design and 3DIC techniques.

## 3 Electronics

While readout prototypes for the timing detectors at the HL-LHC upgrades have demonstrated performance in line with requirements, applying similar techniques in trackers presents several challenges. High granularity requirement of future trackers will require readout ASICs with smaller pixel sizes compared to present generation, maintaining power consumption levels similar to present designs without timing extraction. Accommodating the additional required electronics for timing extraction, i.e. Time to Digital Converters (TDCs) [34] and memories together with the typical pixel circuitry of present trackers, in pixels at pitches on the order of tens of microns will require the adoption of deeper low power and fast technology nodes beyond 65nm. The entire pixel electronics will need to be designed with low power techniques and with novel timing extraction architecture. In addition, the high luminosity of future hadron colliders will require trackers capable to survive in extreme radiation environments (accumulating a dose of up to 30 GRad and  $10^{18}$  neutrons/cm<sup>2</sup>)

366 Because of these aspects, state-of-the-art low power CMOS and Bi-CMOS technology targeted for  
367 the mmW communication industry are of particular interest. These includes FDSOI technologies  
368 which could potentially open a path to monolithic readouts at very fine pitch. These technologies  
369 are also of interest in other HEP applications for their demonstrated performance at deep cryogenic  
370 temperatures.

371 **This might be suitable here**

372 It is important to stress that the read-out philosophy of standard PIN silicon sensors and  
373 UFSD is different. In PIN sensors, the maximum current happens just after the passage of the  
374 particle while in UFSD the current increases for the duration of the electron drift time, then there  
375 is a plateau, and finally decreases. This peculiar signal shape limits the useful bandwidth of the  
376 amplifier. The amplifier bandwidth affects both noise and slope and, ideally, the higher BW the  
377 lower the jitter. However, the intrinsic time response of UFSD sensors sets the upper limit to the  
378 maximum reachable slope that the analog output can exhibit. As a consequence, the bandwidth  
379 should be chosen to be the minimum value that retains the intrinsic sensor speed while keeping the  
380 noise low. The bandwidth defines the signal shaping of the front-end and its optimum value for  
381 timing is obtained when the amplifier shaping time equals the sensor peaking time.

382 **Useful text to incorporate?**

383 Advances in detector technology and the direction of HEP experiments and applications require  
384 the development of new specialized readout electronics. Experimental demands include some com-  
385 bination of high rep rates (order of ns dead time), below 10 ps time of arrival (TOA) resolution,  
386 low power (between 0.1 mW and 1 mW per channel), and high dynamic range (for some specific  
387 application up to a few 1000s).

### 388 **3.1 Current timing chips**

389 brief discussion of ALTIROC, ETROC (Ryan), capabilities and limitations

### 390 **3.2 FAST family of ASICs**

391 **Keep or remove?**

392 In the past several years the FAST effort had the goal of designing an ASICs tailored to the read-  
393 out of Ultra-Fast Silicon Detector. TOFFEE [35], the first prototype, has been produced in 2016,  
394 FAST1 in 2018 [36], and FAST2 [37] in 2020. This family of ASICs aims to provide a 25 ps time  
395 resolution with rates up to 200 MHz and has been designed in a 110 nm CMOS commercial tech-  
396 nology node. In every iteration of the production the architecture has been improved to optimize  
397 the chip performance. Starting from FAST2 a analog-only version of the chip have been produced.  
398 The next foreseen production is FAST3, which is based on the studies performed on FAST2 with  
399 expand linearity of the output dynamic range. In parallel to FAST3, the ASIC UFSD\_ALCOR has  
400 been designed. It includes the optimized front-end stage used in FAST3\_Analog, a discriminator  
401 stage, time to digital converter (TDC), and a digital control unit. Each channel can measure the  
402 Time of Arrivals (ToA) and Time of Threshold (ToT) of a pulse signal with a least significant bit  
403 of 25 ps. FAST3 and UFSD\_ALCOR are almost completed and will be manufactured in the first  
404 half of 2022.

### 405 **3.3 SiGe amplifiers**

406 A possible path to achieve O(10 ps) time resolution is an integrated chip using Silicon Germanium  
407 (SiGe) technology. Using DoE SBIR funding, Anadyne, Inc. in collaboration with University of  
408 California Santa Cruz has developed a prototype SiGe front end readout chip optimized for low

409 power and timing resolution, with 0.5 mW per channel (front end and discriminator) while retaining  
410 10 ps of timing resolution for 5 fC of injected charge. In the process some insight was developed  
411 into the challenges and potential performance of SiGe front end ASICs for future R&D effort.  
412 The developed single pre-amplifier stage and what is effectively a Time Over Threshold (TOT)  
413 discriminator topology is suitable for low repetition rate and quiescent power and sub 10 ps timing  
414 resolution applications. Some practical considerations for selecting a process for future R&D include  
415 the size and power efficiency of the CMOS transistors for the back-end electronics and diminishing  
416 performance gains of higher speed SiGe transistors. The currently available SiGe processes offer  
417 130 nm CMOS at a minimum. Transistors faster than 25 GHz have little signal to noise or power  
418 improvements to offer when designing readout systems for signals in the 1-2 GHz regime ultra-fast  
419 silicon detectors operate in. Moving to faster and smaller SiGe transistors may only introduce  
420 unnecessary design challenges such as poor transistor matching, low breakdown voltages, higher  
421  $V_{be}$ , etc. The current prototype is designed in a 10 GHz process. Significant R&D efforts would be  
422 required to determine how much timing resolution, power consumption and dead time performance  
423 could be improved by moving to a specific 20-30 GHz process.

### 424 **3.4 Full digitization chip**

425 University of California Santa Cruz is currently working with Nalu Scientific to design and fabricate  
426 a high channel density and scalable radiation-hard waveform digitization ASIC with embedded in-  
427 terface to advanced high-speed sensor arrays such as e.g. AC-LGADs. The chip is being fabricated  
428 with TSMC's 65nm technology using design principles consistent with radiation hardening and tar-  
429 gets the following features: picosecond-level timing resolution; 10 Gs/s waveform digitization rate  
430 to allow pulse shape discrimination; moderate data buffering (256 samples/chnl); autonomous chip  
431 triggering, readout control, calibration and storage virtualization; on-chip feature extraction and  
432 multi-channel data fusion; reduced cost and increased reliability due to embedded controller (reduc-  
433 tion of external logic). Existing readout approaches, such as AltiROC and the newer TimeSPOT1  
434 , promise good-to-excellent timing resolution and channel density, and use a TDC-based measure-  
435 ment for signal arrival times and time-over-threshold (ToT) for an indirect estimate of integrated  
436 charge. However, these readout strategies will likely adversely impact the ability to provide sub-  
437 pixel spatial resolution and are typically have difficulty compensating for environmental factors such  
438 as pile-up, sensor aging, and radiation; timing precision can also be adversely impacted by factors  
439 such as timewalk, baseline wander and waveform shape variations. Here, instead, full waveform  
440 digitization will be used, which is expected to be more robust against a variety of adverse factors  
441 which can affect timing and spatial precision. The initial iteration of the readout chip (v1) was  
442 recently (Jan 2022) fabricated for 50 um AC-LGADs. Later versions of the chip will be designed  
443 for 20 um pixel arrays and also test the minimum pitch feasible for a single-channel readout using a  
444 one-to-one pixel-input channel mapping. The final version of the chip will feature a transimpedance  
445 amplifier input stage able to be fine-tuned (or tunable) in order to accommodate high-density sensor  
446 arrays using technologies other than AC-LGADs.

### 447 **3.5 28nm CMOS technology TDC design**

448 CERN's EP RD WP5: CMOS Technologies [38] survey has promoted the selection of 28nm CMOS  
449 node as the next step in microelectronics scaling for HEP designs. The choice was based on  
450 radiation-hardness studies [39], frequency and cost of MPW runs and strong presence on the market.  
451 Furthermore, the 28nm technology is at least twice as fast and allows circuit densities around 4-5  
452 times higher than the previously employed 65nm node, making it a good candidate for design of

453 high granularity 4D trackers. One of the critical circuit blocks necessary to enable 4D operation  
454 in trackers are low-power and compact Time-to-Digital Converters (TDC) capable of high time-  
455 measurement precision. SLAC has stated the design of TDCs in 28nm technology node with target  
456 time resolutions of 10-50ps. The plan is to submit the first prototype for fabrication at the end of  
457 this year.

### 458 3.6 Chips comparison

459 Write something about the different approach performances

## 460 4 Layout

461 A major next step towards 4D tracking at future hadron colliders is the study of how to best  
462 combine timing with spatial information. The fine spatial tracking resolution demand towards  
463 small pixel with low material budget and low power may make it impractical to instrument finest  
464 timing capabilities on all layers. On the other hand, 4D devices with still fine spatial granularity  
465 and integrated some coarse timing capabilities can potentially allow a versatile mixture of layers  
466 with different balance of spatial and timing resolution to serve an optimal overall 4D tracking for  
467 the wide range of applications. The addition of timing information to every pixel hit might not be  
468 the approach that leads to the best performance. Alternative approaches such as alternating spatial  
469 with timing layers, or 4D with 3D layers could help improve the overall physics performance.

470 Another aspect of detector layout is related to the physics drivers motivating its development.  
471 For example, improved and fast charged track reconstruction, heavy flavor ( $b/c$ ) tagging, and  
472 particle-flow reconstruction under very high pileup density will require 4D information in the inner  
473 layers, whereas LLP and time-of-flight particle ID capabilities, including the possibility of strange-  
474 tagging [40–43], will benefit from 4D information in the outer layers. LLP applications would  
475 demand continuous timing coverage and could benefit from modest timing resolution in more layers  
476 without stretching timing dynamic range. Future  $e^+e^-$  collider vertex detector backgrounds are  
477 predominantly back-scattered bremsstrahlung particles from downstream magnets and collimators  
478 with  $\sim$ ns range delays. 4D tracking devices with fine spatial resolution and modest timing resolution  
479 in other layers could significantly enhance the overall performance.

480 Other key considerations are tracking material and pseudorapidity coverage. The additional  
481 material required to go from 3D to 4D tracking will have an impact on the track-time association  
482 efficiency and mis-association rate. Whereas a lower track-time efficiency will simply reduce the  
483 potential gains from timing information, the wrong assignment of times to tracks is particularly  
484 problematic as in this case the 4D reconstruction will perform worse than 3D. The impact of  
485 showering of particles within the tracking material might be partially mitigated with the use of  
486 advanced algorithms based on graph neural networks or other deep learning techniques but this  
487 will require a long term study. In the case of future lepton colliders, material in the tracking  
488 detector has to be minimized to not degrade  $p_t$  and impact parameter resolution, posing additional  
489 constrains on the incorporation timing information [?]

## 490 5 Key areas for future R&D

491 Ariel Schwartzman, Simone Mazza, Su Dong, + additional contributors

492 Valentina: Maybe something of what is written above for ATLAS could go here? Or we can  
493 highlight there already that this is a key area for future R&D, making a sort of recommendation

494 to the particle physics community.

495 **6 Summary**

496 Need executive summary 1 page

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