Expression of Interest
Towards Time of Flight MCMOS tracking layers for a detector at FCC-ee

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1 Introduction

We express interest to prepare a Time of Flight (ToF) system based on Monolithic CMOS (MCMOS) sensors to enhance the physics reach of the FCC-ee detectors. The target is to achieve a 30 ps precision on Minimum Ionizing Particles in sensors providing the position precision required for tracking. We present the possible implementations in an overall detector concept, technical solutions investigated at Irfu and IP2I, and plans for simulation studies and to design the system mechanics and services.

2 Implementations of ToF layers in a FCC-ee detector concept

Many physics studies at FCC-ee require Particle Identification (PID). Without being exhaustive, one can mention the measurements of Higgs decays to fermion [1], flavor physics studies [2] or Heavy Neutral Lepton mass measurement [3]. In this EoI we consider PID using the combination of Time of Flight (ToF) and the measurement of dE/dx (or cluster counting, dN/dx) from a Large Gas Volume Detector (LGVD).

A LGVD can provide very good particle identification, however with a poor π/K separation around $p \simeq 1$ GeV where their energy loss is crossing. A performant ToF detector is therefore required to mitigate this issue both in the barrel and forward and backward regions. In the barrel region, at a magnetic field of 2 Tesla, the best π/K separation would be achieved with a detector located behind the LGVD at a radius of 2.2 m. One(two) layer(s) would enable the required robustness and performance. A surface of up to $\simeq 200$ m^2 may be needed. The overall detector performance would be greatly optimized if the ToF layers can also provide the position precision required.

At 2 Tesla, tracks with transverse momentum (p_t) lower than 0.66 GeV would not reach a ToF barrel layer positioned at 2.2 m. The dE(dN)/dx in the LGVD would still allow to identify the particles, but with a momentum cutoff of 0.12 GeV for an inner radius of 40 cm. A ToF layer of 30 ps precision located at 15 cm would ensure a 3σ π/K separation from 0.045 GeV to 0.66 GeV in complement of the momentum coverage of the 2.2 m layer(s).

At 3 Tesla, tracks with $p_t \leq 1$ GeV would not reach a radius of 2.2 m. A possible location for the timing layer would then be at the entry of the LGVD at a radius of $\simeq 35$ cm, that would ensure a $> 4\sigma$ π/K separation up to 1 GeV.

A further advantage of an inner ToF layer is that it could mitigate the uncertainty of about 40 ps on the timing of the Interaction Point due to the beam size.

The MCMOS technology considered here could also be implemented as front layers of a Si/W electromagnetic calorimeter as it may help to improve π_0/γ identification and also improve the overall timing performance. It could also be a good candidate for a 5D-digital luminosity calorimeter based on shower particle counting.

3 Development of 5D high precision MCMOS sensors

Sensors based on industrial CMOS processes are very attractive for future experiments, that will need production of active areas ranging from few square meters to hundreds of square meters. CMOS processes are widely used in the micro-electronics industry, making these processes relatively cheap and allowing easy production of significant detector surface. The sensor diode, the analog front-end and digital processing electronics can all be integrated into the same substrate, suppressing the need of costly connection to the readout electronics.

Provided the analog front-end and the sensor diode are adequately optimized, it is possible to develop sensors with moderate position resolution of a few 100 microns, but with a time resolution of the order of 50 ps on a single MIP. As an example, the MiniCactus V1 sensor reaches a resolution of 65 ps on MIPs with a 0.5 by 1 mm pixel [4], and the more recent MiniCactus v2 reaches 60 ps for a 0.5 by 0.5 mm pixel. These sensors have been developed with the LFoundry LF15A 150 nm process.

To further improve the time resolution, a possibility is to add an intrinsic gain in the sensor itself, before any processing by the analog front-end. This can be done in the form of a buried PN-junction. First tests of this concept are expected by mid-2025 with the LF15A process.

The timing precision of MCMOS sensors has also been investigated in a different foundry process, TPSCo 65 nm, allowing a relatively different sensor configuration. A similar performance of $\simeq 60$ ps was reached and this design can provide high position precision. IP2I is planning to develop in this technology an asynchronous readout implementing the high precision ToA and ToT features[1] required to enable the timing measurement.

In the framework of the DRD3 collaboration, Irfu and IP2I will contribute to the studies aiming to find the best compromise in terms of technology, time resolution, position resolution and power consumption[2]. At the same time developments of low power readout architecture will be pursued in the DRD7 collaboration program[3].

It is expected that by the end of the first 3-4 years of these R&D the most promising design(s) and technology alternative(s) are identified to narrow down the following R&D steps.

4 System aspects

The ToF layers must minimize the amount of dead materials in any implementation in the detector concept. This constraint is the most stringent for layers in the tracking volume. The system needs to be hermetic with light, precise and stable mechanical structures to ensure proper control of systematic uncertainties. IP2I and Irfu are interested to study a bent design based on large area sensors; as an alternative a more conventional stave design can be considered[4]. Special care will be taken to study the power consumption management and the impact of the required cooling on the amount of dead materials. Once a work plan is established, IP2I and Irfu will join the new DRD8 collaboration proposed for studies in this field.

5 Simulation studies

The R&D work will be supported by simulation studies, implementing the ToF layers at different positions in an overall detector concept. This will allow to establish physics-driven benefit of the precision timing and requirements both for timing and position precision as a function of the implementation radius. Full simulations will be important to evaluate the data flows, for readout architecture design, and the realistic system performance.

Some of these studies are already underway at Irfu and IP2I in the framework of the FCC-ee Physics Experiment and Detector working group. The appropriate software developments will be integrated in the common simulation framework to the benefit of the community.

6 Outlook

PID will be a major physics enabler at future FCC-ee experiments and ToF tracking layers could extend the performance and momentum coverage below 3 GeV. IP2I and Irfu have competences and experience to develop such a system with related R&D work and simulations studies already started. The existing infrastructures at both laboratories[5] would allow major contributions to the prototyping and production of large elements of the system.

References

[1] Hao Liang et al. *Jet-Origin Identification and Its Application at an Electron-Positron Higgs Factory.* `https://arxiv.org/abs/2310.03440`. 2024.

[2] Roy Aleksan and Luis Oliver. $\overline{\mathrm{B}}_{d,s} \to \mathrm{K}^{*0}\overline{\mathrm{K}}^{*0}$ *decays, a serious problem for the Standard Model.* `https://arxiv.org/abs/2312.07198`. 2024.

[3] Roy Aleksan et al. *Timing-based mass measurement of exotic long-lived particles at the FCC-ee.* `https://arxiv.org/abs/2406.05102`. 2024. arXiv: `2406.05102 [hep-ph]`.

[4] *MiniCACTUS: A 65 ps Time Resolution Depleted Monolithic CMOS Sensor.* Vol. 70. 11. Nuclear Science Symposium 2022. IEEE Transactions on Nuclear Science, Oct. 2023.

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[1] Time of Amplitude for precision timing and Time over Threshold to provide signal amplitude and in turn time-walk correction.

[2] The CERN Detector Research and Development collaboration 3 is dedicated to solid state detectors. Its program includes other R&D efforts with similar goals in LFoundry 110 nm and TowerJazz 180 nm processes, and in the SiGe technology.

[3] The CERN Detector Research and Development collaboration 7 is dedicated to detector electronics.

[4] Both types of designs are being studied for Vertex Detectors, but on a much smaller scale.

[5] these infrastructures served for production of large scale detectors for the ATLAS and CMS High Luminosity LHC upgrades.

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