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Electron Ion Collider

Preliminary Design Report
(this report only contains TOF part)

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multi-chapters

Chapter 8

Experimental Systems

8.1 Experimental Equipment Requirements Summary

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8.2 General Detector Considerations and Operations Challenges

8.2.1 General Design Considerations

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8.2.2 Backgrounds and Rates

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8.2.3 Radiation Level

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8.3 The ePIC Detector

8.3.1 Introduction

Hello, here is some text without a meaning [1].

Figure 8.1: Test Figure.

8.3.2 Magnet

Requirements

Requirements from physics: Add text here.

Requirements from Radiation Hardness: Add text here.

Requirements from Data Rates: Add text here.

Justification

Device concept and technological choice: Add text here.

Subsystem description:

General device description: Add text here.

Sensors: Add text here.

FEE: Add text here.

Other components: Add text here.

Requirements from Data Rates: Add text here.

Implementation

Services: Add text here.

Subsystem mechanics and integration: Add text here.

Calibration, alignment and monitoring: Add text here.

Status and remaining design effort:

R&D effort: Add text here.

E&D status and outlook: Add text here.

Other activity needed for the design completion: Add text here.

Status of maturity of the subsystem: Add text here.

Environmental, Safety and Health (ES&H) aspects and Quality Assessment (QA planning: Add text here.

Construction and assembly planning: Add text here.

Collaborators and their role, resources and workforce: Add text here.

Risks and mitigation strategy: Add text here.

Additional Material Add text here.

8.3.3 Tracking

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8.3.3.1 The silicon trackers

Requirements

Requirements from physics: Add text here.

Requirements from Radiation Hardness: Add text here.

Requirements from Data Rates: Add text here.

Justification

Device concept and technological choice: Add text here.

Subsystem description:

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Performance

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Risks and mitigation strategy: Add text here.

Additional Material Add text here.

8.3.3.2 The MPGD trackers

Requirements

Requirements from physics: Add text here.

Requirements from Radiation Hardness: Add text here.

Requirements from Data Rates: Add text here.

Justification

Device concept and technological choice: Add text here.

Subsystem description:

General device description: Add text here.

Sensors: Add text here.

FEE: Add text here.

Other components: Add text here.

Performance

Implementation

Services: Add text here.

Subsystem mechanics and integration: Add text here.

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Collaborators and their role, resources and workforce: Add text here.

Risks and mitigation strategy: Add text here.

Additional Material Add text here.

8.3.4 Particle identification

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8.3.4.1 The time-of-flight layers

Requirements and Justifications

Requirements from physics: With single hit timing resolution of 35 ps from the Barrel TOF (BTOF) and 25 ps from the Forward TOF (FTOF), the TOF detector system can provide particle identification for low momentum charged particles, e.g., π-K separation at the 3σ level for $p_T < 1.2$ for $-1.3 < \eta < 1.3$, and $p < 2.5$ GeV/c for $2 < \eta < 3.7$, respectively. By combining the PID information for low momentum particles from the TOF detectors and high momentum particles from Cherenkov detectors, ePIC will have excellent PID capability over a wide momentum range in a nearly 4π acceptance, which is crucial to achieve the goals of the EIC physics program. Besides precise timing resolution, AC-LGAD sensors can also provide precise spatial resolution (30 μm), and thus aid track reconstruction and momentum determination. The requirements on the timing and spatial resolutions, as well as the material budgets (1 % and 5 % X/X_0 for BTOF and FTOF) are being evaluated in EPIC MC simulation to find the optimal configuration without over-designing these detectors. Table 8.1 summarizes the required timing and spatial resolution together with material budgets, covered area, channel counts and sensor dimensions. Figure 8.2 shows the BTOF

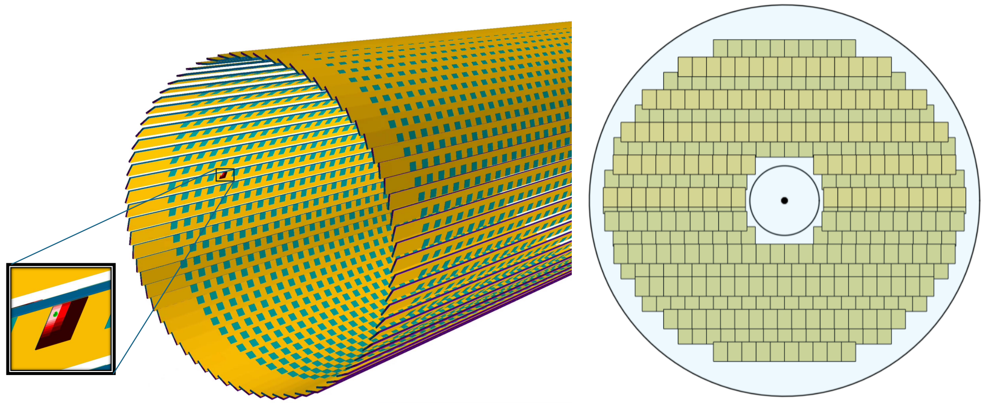


Figure 8.2: Geometries of BTOF with insert of sensor and charge sharing distribution (left) and FTOF (right).

and FTOF geoemetry with an insert on sensor with a simulation of charge sharing. Fig. 8.3 shows the performance of the TOF detector in the form of $1/\beta$ as a function of particle momentum p in PYTHIA DIS simulation events. Together with other PID detectors, we are able to demonstrate that the ePIC PID performance which includes the TOF detectors as one of the integral components meets the requirements.

subsystem	Area (m^2)	dimension (mm^2)	channel count	timing σ_t (ps)	spatial σ_x (μm)	material budget (X0)
Barrel TOF (BTOF)	10	0.5*10	2.4M	35	30 ($r\ \phi$)	0.01 (2)
Forward TOF (FTOF)	1.4	0.5*0.5	5.6M	25	30 (x, y)	0.05

Table 8.1: Required performance for physics and proposed configurations. Barrel TOF (BTOF) is strip structure along beam direction (1cm) while Forward TOF wall (FTOF) pixel size is 0.5mm.

Requirements from Radiation Hardness (Simone): Much work has been done to characterize and improve the radiation resistance of LGAD gain layers to meet the requirements imposed by forward timing at the LHC [2] (up to $2.5 \times 10^{15}\ n_{eq}/\text{cm}^2$). However, no studies have yet been done on the effect on AC-LAGDs of even the modest levels of radiation expected for ePIC sensors. The fluence expected for the lifetime of the ePIC experiment is significantly less than in previous experiments, as seen in Fig. 8.4 and Tab. 8.2. It is safe to assume that the maximum foreseen fluence for ePIC will be $< 10^{12}$ Neq. The highest fluence between raw and Neq fluence was considered, as the standard NIEL correction is not applicable for some aspects of LGAD radiation damage. Because of the sensitivity of the sensor performance to the value of the N+ sheet resistance (a feature absent from the conventional LGADs made use of for the LHC), it is possible that AC-LGADs may be significantly less radiation tolerant than their conventional cousins. Indeed, N-type doping is known to be particularly sensitive to hadronic irradiation, with N-bulk sensors inverting to P-bulk before exposure of even 1×10^{14} is accumulated. Furthermore, LHC sensors are designed to run at -30C to reduce the post-radiation leakage current, while in ePIC, the sensors will be operated

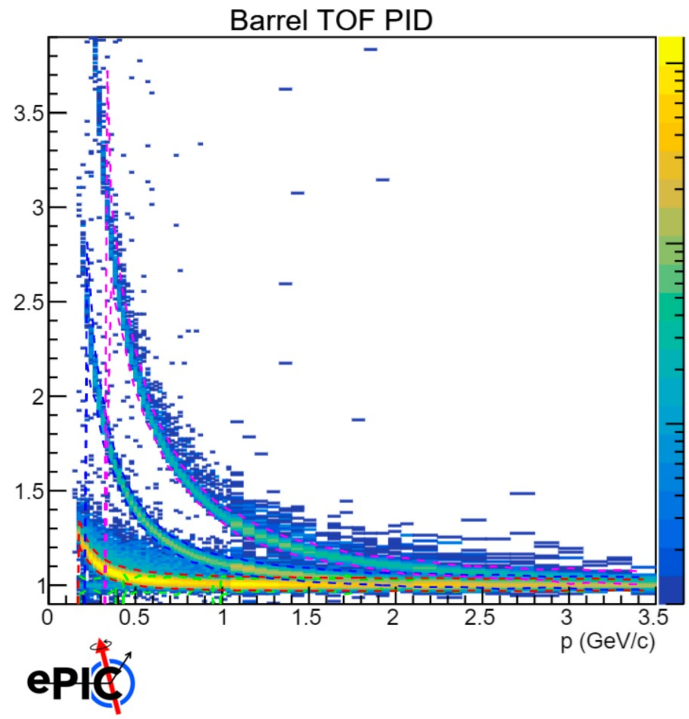


Figure 8.3: simulation performance with PYTHIA DIS events.

at room or slightly lower temperatures for the experiment's lifetime. The leakage current increase due to radiation damage for the fluence in ePIC has to be low enough not to trigger a thermal run-away combined with the power dissipation from the readout chip, especially for the forward and end-cap region where the chips are bump bonded on top of the sensors.

RAW fluence			
System	Average	Min	Max
Barrel	5.4×10^9	3.4×10^9	5.9×10^{10}
End-cap	1.3×10^{10}	5.1×10^9	1.6×10^{11}
B0 trackers	3.9×10^{10}	3.3×10^9	1.8×10^{11}
NEQ fluence			
System	Average	Min	Max
Barrel	3.6×10^9	1.1×10^9	1.3×10^{11}
End-cap	1.2×10^{10}	3.2×10^9	8.4×10^{10}
B0 trackers	4.5×10^{10}	2.7×10^9	4.2×10^{11}

Table 8.2: RAW and NEQ fluence per system

Therefore, a radiation exposure run was performed before the EIC LGAD design was finalized. Several sensors from HPK and BNL were irradiated at FNAL ITA facility (400 MeV protons) and at the TRIGA reactor in Ljubljana (MeV-scale neutrons) to probe radiation effect from ionizing and non-ionizing particles. The radiation exposure would be done in steps, allowing potential charge-collection pathologies, should they exist, to be mapped out for the development of models and corrections. By studying the sensor performance before and after irradiation, the change in N+

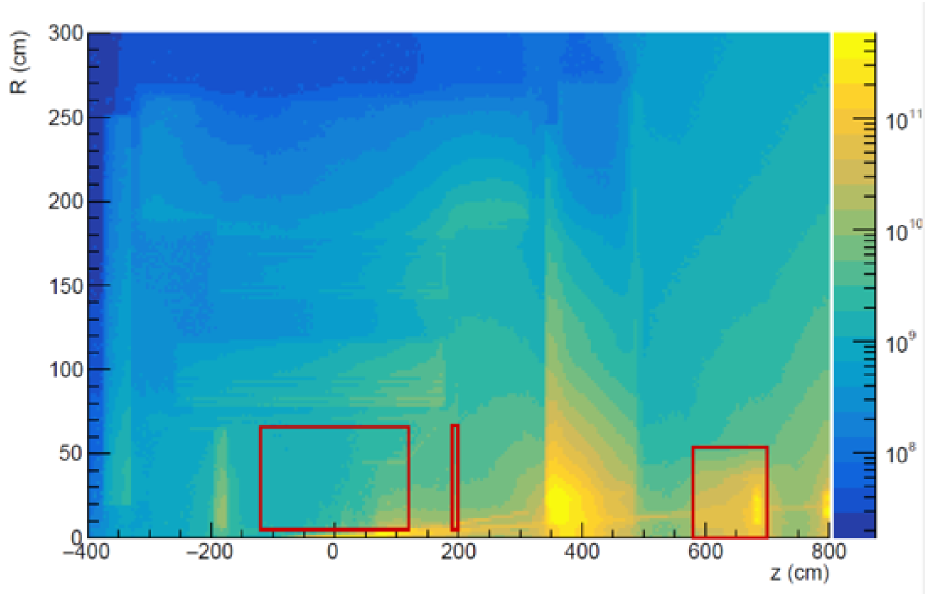


Figure 8.4: Fluence accumulated for the lifetime of the ePIC detector. Red squares highlight the barrel, end-cap, and B0 trackers detectors. What is assumed in this plot? What's lifetime and luminosity?

resistivity can be characterized, and this particular risk can be addressed. Sensors irradiated with 1 MeV neutrons were received in the Summer of 2024 and tested; the results are encouraging, as seen in the following sections. Sensors were irradiated at the FNAL ITA facility but are still cooling down from the activation; they will likely be tested in early 2025.

Requirements from Data Rates: The readout electronics (sensors and ASICs) of the Barrel TOF (BTOF) and Forward TOF (FTOF) differ significantly so we present the rate requirements separately for both of these sub-components. On top of that, the phase space coverage is different (mid-rapidy vs forward rapidity) which mandates different particle rate and background calculations.

FTOF

The FTOF simulation shows an average of 2 particles hitting FTOF per collision at the highest luminosities. At the 500 kHz collision rate this amounts to a 1 MHz particle rate on the surface of FTOF disk. Since FTOF is expected to contain 5.8 million channels the average hit frequency per channel is 0.2 Hz. Due to charge sharing of the AC-LGAD pixels we expect a particle hit to occupy 9 (or 3x3) channels of the readout ASIC

BTOF

The BTOF simulations show an average of 5 particles hitting BTOF per collision. At the 500 kHz collision rate this amounts to a 2.5 MHz particle rate on the surface of the BTOF barrel. BTOF contains 2.4 million channels which give an average hit frequency per channel of 1 Hz. Due to charge sharing of the AC-LGAD strips we expect a particle to occupy 3 strips/channels of the readout ASIC.

Electronics Noise

Noise measurements have consistently shown a rate of 30 Hz per channel. Such a noise rate is achieved with a 5-sigma cut and is deemed to be even somewhat pessimistic but this is the number we plan to use during these calculations.

Data Rates

We will assume a typical CERN-developed ASIC's zero-suppressed data format which is: 32 bits header, Nx32 bits of channel data (ADC, TDC, ch Id) and 32 bits trailer. Such data formats are used in e.g. HGCROC which is a precursor to our expected ASICs.

For FTOF the expected rate of bits per second per ASIC is thus:

0.2 Hz (particle rate) X 11 x 32 (bits for 9 hits) X 1024 (channels) == 72 kbs At the same time the noise rate is: 30 Hz (noise rate) X 3 x 32 (bits for a single hit) X 1024 (channels) == 3000 kbs

Summing up these 2 contributions we arrive at the per-ASIC data rate of 3.1 Mbs. For the worst case of 28 ASICs per RDO (or fiber) = 87 Mbs per fiber link to DAQ. While for the total FTOF sub-detector of 212 RDOs we reach 18 Gbs.

For BTOF a similar calculations shows:

1 Hz (particle rate) x 5 x 32 (bits for 3 hits) X 128 (channels) == 21 kbs While the noise rate is 30 Hz (noise) x 3 x 32 (bits for a single hit) X 128 (channels) == 370 kbs

Summing up these 2 contributions we reach the total data rate per-ASIC of 390 kbs.

Since an RDO reads out 64 ASICs per stave we expect a rate per RDO (or fiber) of 24 Mbs. For the entire BTOF which contains 288 staves we reach a total rate requirement of 7 Gbs.

We note that these rates are very small and well within the reach of ASICs, interconnects as well as fiber interfaces of our electronics and DAQ. We also note that the data rates are dominated by the electronics noise which we can control by raising or lowering the various ADC or TDC thresholds of the ASIC thus adjusting the system performance even ASIC-to-ASIC if required.

Device concept and technological choice: AC-coupled Low-Gain Avalanche Diode (LGAD) is a new silicon sensor technology. Signals produced by charged particles in the sensor active volume are amplified via an internal p+ gain layer near the sensor surface. Signals induced on a continuous resistive n+ layer on top of the p+ gain layer, are AC coupled to patterned metal readout electrodes, which are on the sensor surface and separated by a dielectric layer from the n+ layer. The internal signal amplification and thin active volume enables precise timing measurement, while charge sharing among neighboring electrodes can provide precise position measurement. The AC-LGAD technology has been chosen to use for particle identification, tracking, and far-forward detectors at EIC where precision timing and spatial measurements are needed.

Subsystem description:

General device description: The BTOF consists of 144 tilted staves, each of which is made of two half staves with a total length of around 270 cm sitting at a radial position around 65 cm. AC-LGAD strip sensors are mounted on low mass Kapton flexible printed circuit boards (FPCs), and are wire-bonded with front-end ASICs. The FPCs are glued onto mechanical structures made from low density Carbon-Fiber (CF) materials, and bring power and input/output signals to the sensors and ASICs. The heat generated by the frontend ASICs are removed by an embedded Aluminium cooling tube in the CF structure. The FTOF consists of detector modules made from AC-LGAD pixel sensors bump-bonded with front-end ASICs. These detector modules are mounted from both sides onto a thermal-conductive supporting disk with embedded liquid cooling lines located around 190 cm away from the center of the experiment. Since the irradiation flux at the EIC is much smaller than that at the LHC, it is assumed that the radiation damage will not be a concern and the AC-LGAD sensors can be operated at room temperature.

Sensors: The sensors identified for the TOF timing layer are AC-coupled LGADs (AC-LGADs) that can provide exceptional position resolution and timing resolution [3–5] while maintaining low channel density. The barrel TOF will employ strip sensors 1-2 cm long with a pitch of 500-1000 um and a strip width of 50 um. The sensor thickness will likely be 50 um to reduce the input capacitance to the pre-amplifiers. Nevertheless, 30 um thick strip sensors are still under investigation. The full sensor size will be 4x3.2 cm or 3.2x2cm with 1 cm segments. The End-cap TOF and Far Forward will both employ pixel AC-LGADs with a pitch of 500-1000 um and pixel size 50-150 um. The thickness of the pixel sensors will be 20 um to maximize the time resolution reach, as the input capacitance is not a concern for small pixels. The prototype full-size sensor will be 1.6x1.6 cm with 16x16 or 32x32 pixels. All cited full-size geometries were produced for the first time in the most recent HPK fabrication that was received at the time of writing. Results on the full prototype production are expected by the end of the year. Studies on smaller-scale devices are presented in the following section **??**.

FEE: The FEE for AC-LGAD based detectors is focused on the development of an ASIC and service hybrid. The EICROC project by the French group is focused on designing ASICs for reading fine-pixelated AC-LGAD sensors, optimized for EIC Far-Forward detectors like B0, OMD, Roman Pots, as well as FTOF. The first version, EICROC0, is a 4x4 channel ASIC with 0.5x0.5 mm^2 pixel size, featuring components like a transimpedance preamplifier, 10-bit TDC for timing, 8-bit ADC for amplitude measurement, and an I2C slow control interface. It is designed for low capacitance and sensitivity to low charges (2 fC), operating with 1 mW per channel, and targeting 30 ps timing and 30 μ m spatial resolution. The prototype is currently under testing, with noise issues being addressed for future iterations. The next version, EICROC1 (expected in 2025), will feature a 16x8 channel configuration, followed by the final 32x32 channel version for full-scale implementation.

Flexable Printed Circuit boards: The Flexible Printed Circuit (FPC) is used to read out data and distribute power to the sensors and ASICs. In the acceptance region, a material budget of 1% X/X_0 is required, meaning the FPC material should be as minimal as possible. Additionally, the FPC must be 135 cm in length. To meet these stringent requirements, careful consideration of the FPC material is necessary, as signal loss is expected with such a long FPC, especially if using polyimide, a standard material in FPCs. The sPHENIX experiment encountered a similar challenge with their Inner Tracker (INTT), a silicon sensor tracker, and successfully addressed it by using Liquid Crystal Polymer (LCP) instead of polyimide as the dielectric material. This technology will be adopted for our detector as well.

Stave design: Barrel staves are divided into two half-staves, with services and connections coming from the outer side. The half-staves consist of a support structure with an integrated cooling pipe, flexible printed circuit (FPC), sensors, and ASICs. Sensors and ASICs are mounted on both the front and back sides of the half-stave, making it double-sided, with enough overlap to achieve 100% efficiency in the stave direction. The lateral overlap and tilting ensure 100% efficiency in the direction parallel to the staves. In total, there are 16 sensors and 32 ASICs on each side of the half-staves.

Other components: Add text here.

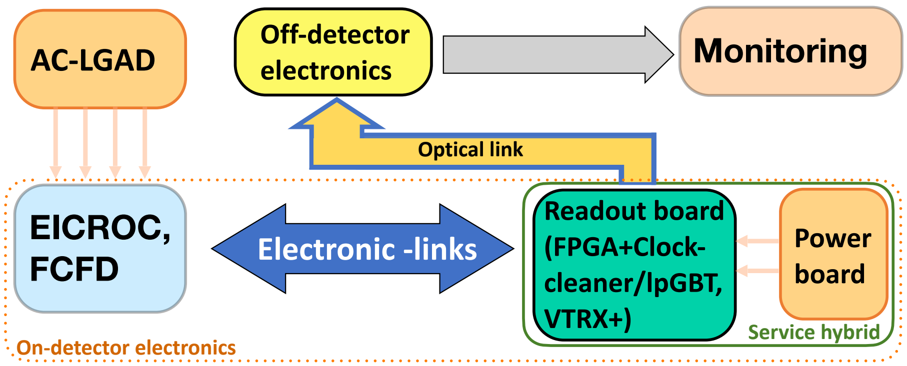


Figure 8.5: Schematic of the AC-LGAD sub-system readout chain. Each component is undergoing design, (pre-)prototyping, testing under various environments, and customization to meet the specific requirements of individual subsystems.

Performance The AC-LGAD systems, including the BTOF, FTOF, and far-forward systems (Roman Pots, OMD, and B0 tracker), share a common readout chain currently under development. Performance evaluations are being conducted in various laboratory environments as part of the ongoing R&D efforts. A schematic of the full readout chain is shown in Fig. 8.5. The effort can be divided into to parts: 1) integrating the sensors with ASIC, 2) development of the readout-board and power board.

Assemblies of 4x4 AC-LGAD pixel sensors with 500×500 μm^2 pixelation and 30 μm thickness, and 4x4 EICROC0 ASICs, were completed by the BNL, IJCLab, OMEGA, and Hiroshima groups on test-boards developed by IJCLab/OMEGA. Testing included scans of the analog and digital components using charge injection and beta particles from a Sr-90 source, resulting in a measured jitter of 8-9 ps for charges above 20 fC. Both wire-bonded and flip-chip assemblies were developed for various characterizations. Additional tests using Transient Current Technique (TCT) laser scans were conducted to map out charge distribution, and various tests are still ongoing. Targeting the Ac-LGAD strip sensors for BTOF, the Fermilab and UIC teams have been developing ASICs. Tests showed precise timing from LGAD sensors, favoring Constant Fraction Discriminator (CFD) for its better performance with smaller signals. The first single-channel CFD-based ASIC (FCFDv0) achieved 30 ps timing precision. A 6-channel prototype (FCFDv1) was later developed for AC-LGAD sensors, demonstrating 11 ps time resolution in initial tests. Ongoing test beam campaigns are focused on reducing noise and optimizing performance with AC-LGAD strip sensors. ORNL is developing flexible Kapton PCBs for TOF applications, where sensors and mockup ASICs will be glued, wire-bonded, and co-cured onto a composite structure at Purdue for evaluation. Flip-chip options will be available soon, aiming to support low-cost sensor-ASIC hybridization techniques.

In FY24, BNL, LBNL, and Rice developed a prototype board (ppRDO) for precise clock distribution and ASIC integration for AC-LGAD systems. Key milestones, including schematic designs, part orders, PCB layout, and initial testing, were completed ahead of schedule. Firmware development and performance tests on clock-cleaning, jitter, and power distribution are ongoing. The collaboration aims to continue in FY25, focusing on the development of a readout board (RBv1) and power board (PBv0) for AC-LGAD systems, supporting TOF applications and ensuring DAQ compatibility. The ppRDO includes three components: 1) FPGA, 2) clock cleaner, and 3) SFP+ module. Future versions will adopt lpGBT to replace the FPGA and clock cleaner, and VTRx+ to replace the SFP+ module, improving performance, radiation hardness, and integration.

Implementation

Services: Electric power is distributed to the detector components via the Power Board (PB), which is part of the Service Hybrid (SH). The SH also includes the functionality of the Readout Board (RDO). In the case of BTOF, one SH supports 32 sensors and 64 ASICs, with SHs placed on both sides of the stave. For FTOF, several types of SHs are used, covering 12, 24, or 28 sets of sensors and ASICs. The SH is mounted directly on the sensors and ASICs.

subsystem	item	quantity	diameter (mm)	lengths (m)	description
BTOF	FEE LV	24	20	15–25	Rack to Panel, 8AWG (24 AWG sense pairs)
BTOF	FEE LV	72	6.3	8	panel to detector, Alpha PN: 2424C SL005
BTOF	FEE HV	18	14	15–25	Rack to Dist. Panel
BTOF	FEE HV	144	1.5	8	panel to sensor
BTOF	cooling tubes	144x2	5	> 2.6	supply/return from panel to stave (Aluminum)
BTOF	cooling tubes	4x2			supply/return to panel
FTOF	FEE LV	212	9.04	25	supply/return LV from FEE to Rack
FTOF	FEE HV	14	14	25	rack to dist. panel
FTOF	FEE HV	212	2.42	10	panel to sensor
FTOF	cooling tubes	2x2	5		supply/return from panel to detector (Aluminum)
FTOF	cooling tubes	2			supply/return to panel

Table 8.3: Summary of BTOF and FTOF low voltage and high voltage powersupply cables to distribution panels and then to the detector FEE.

Low Voltage (LV) and High Voltage (HV) cables are connected to the PB, where multiple DC-DC converters step down or adjust the voltages as needed. HV is applied to groups of multiple sensors, rather than distributed individually to each sensor. The size of each sensor group is determined by the design of the sensors and the electronics. Table 8.3 summarizes the service (cables and tubes) necessary for TOF detectors.

A liquid cooling system is employed to control the temperature of the detector. For the BTOF

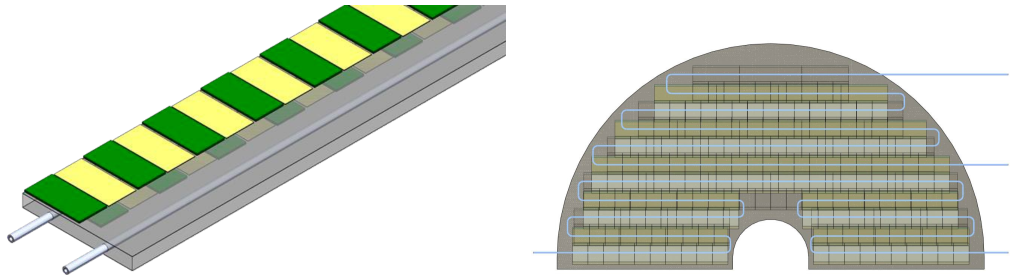


Figure 8.6: schematic drawings of one BTOF stave (left) and half of the whole FTOF (right) cooling pipes.

stave, one or two cooling pipes are integrated into the support structure, with liquid flowing in one direction along the length of the stave. In FTOF, a winding liquid pipe is integrated into the support structure. The flow rate and pipe diameter are determined by the amount of heat generated and the detector's performance requirements, though the pressure must remain below the surrounding air pressure to ensure safe operation. Fig. 8.6 shows a single BTOF stave with cooling pipe (left) and half of the FTOF structure with cooling pipe (right).

Subsystem mechanics and integration: BTOF is a barrel geometry located at radius of 63cm from z=-115cm to z=+174cm along the beam direction as shown in Fig. 8.7. Both detector subsystems have 7.5cm space in radial direction for BTOF and in beam direction for FTOF. The three engagement rings (each of 5mm width) hold the BTOF detector to the global structure. A concept was developed for stave mounting mechanism on engagement rings by clips with staves at 18 degree angle. Staves are removable individually for easy maintenance. Table 8.4 lists the positions relative to the global ePIC geometry.

subsystem	Z_{min} (cm)	Z_{max} (cm)	inner radius (cm)	outer radius (cm)	stave angle
Barrel TOF (BTOF)	-112.5	176.5	62	69.5	18^o
Forward TOF (FTOF)	185	192.5	10.5	60	0

Table 8.4: BTOF is a barrel geometry surrounding the beam while FTOF is a wall on the hadron side (positive Z).

Calibration, alignment and monitoring: Wei: Add text here.

Status and remaining design effort: eRD112 and eRD109

eRD112: Sensor R&D effort A brief summary of eRD112 activities is reported in this section, for a more detailed review of the sensor development effort consult the 2024 erd112 report document. HPK sensors from the latest production have been tested at the Fermilab test beam facility; the results are summarized in Ref. [3]. The summary best results are reported in Fig. 8.8. The same HPK production was tested in laboratory with focused laser TCT and showed similar results as

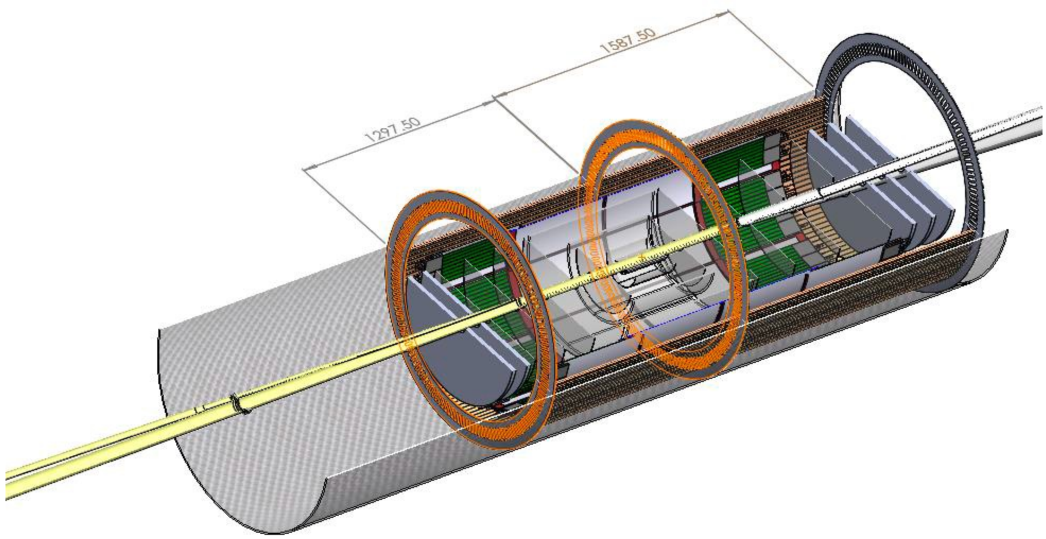


Figure 8.7: Barrel TOF supporting mechanic structure with engagement rings. The width of the three engagement rings is 5mm.

reported in Ref. [4]. The presented strip sensors (Fig. 8.8, Left) show a constant time resolution of around 35 ps, which is within the requirements for the ePIC TOF. The strip reconstructed position resolution is between 10-20 μm, which is also within the ePIC TOF requirement of 30 μm. The best result for pixel sensors (Fig. 8.8, Right) shows an homogeneous time resolution of 20-25 ps, well within ePIC TOF requirements. The position resolution instead is 20-70 μm across the device; the charge-sharing mechanism allows for precision reconstruction in between metal electrodes, but the resolution is significantly worse for hits directly on the metal electrodes.

The position resolution requirement for ePIC end-cap TOF is 30 μm. Therefore, pixel technology needs to be refined to meet the requirements. The new HPK production (expected by the end of the year) includes smaller electrode sizes and larger gaps between electrodes that could provide good reconstruction across the sensor. However, it was observed that a larger gap decreases the total S/N between electrodes, which might degrade the overall performance of the sensors. Results from a BNL production provide a promising alternative to square metal pixels. The S/N is better across the sensor for a cross-shape electrode given the same central metal shape, allowing for better reconstruction using charge sharing. HPK did not include cross-shape geometry in the latest production, but it might be included in the next one. Another producer of cross-shaped AC-LGADs is Fondazione Bruno Kessler (FBK). The FBK prototypes were investigated with a laser TCT, and a similar behavior was observed for cross-shaped devices [5].

The sensors irradiated at the Triga Reactor with 1 MeV neutrons were received in Spring 2025 and characterized both for electrical proprieties (capacitance and current over voltage) and with the laser TCT station. Gain degradation can be probed with measurements of capacitance over voltage by identifying the gain layer depletion point (V_{GL}). Fig. 8.9, Left, shows the change in the gain layer for the irradiated HPK AC-LGADs from several wafers, with different N+, oxide and active thickness, up to 1×10^{15} Neq; in the region of interest for ePIC $< 10^{13}$ Neq the gain layer is unchanged. The charge-sharing proprieties after irradiation were tested using a focused IR laser

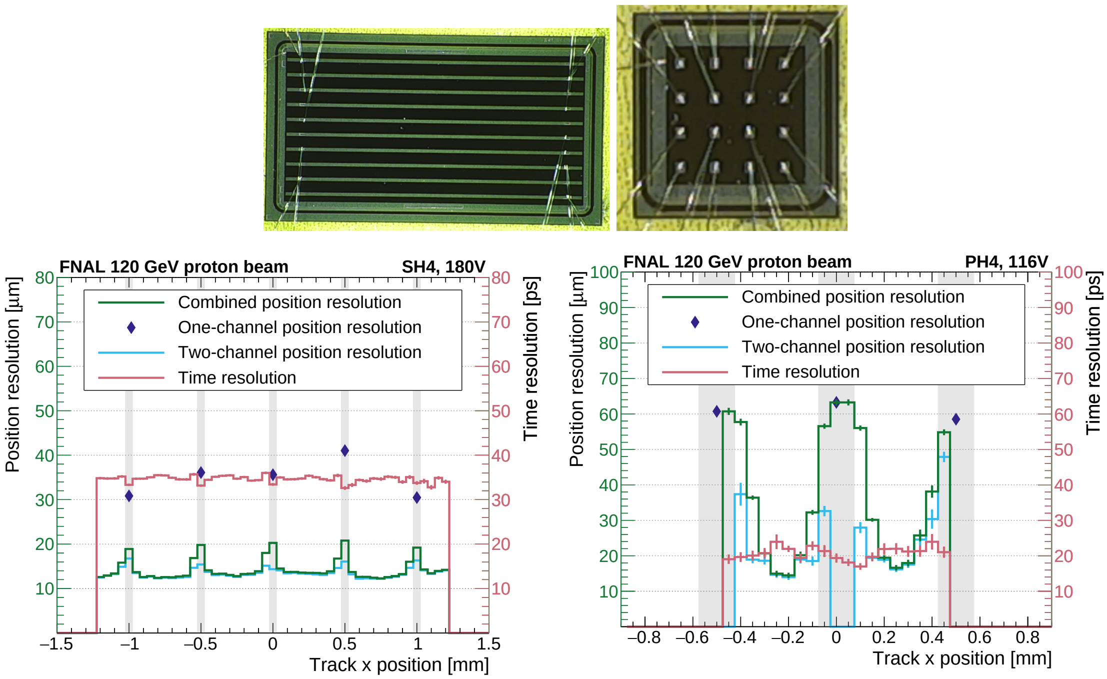


Figure 8.8: Left: Picture and beam test results for HPK strip sensor, 1 cm long, 500 μm pitch, and 50 μm strip width. Right: Picture and beam test results for HPK pixel sensor, 4x4, 500 μm pitch, and 150 μm strip width. Plots from Ref. [3].

in the laboratory. As seen in Fig. 8.9, Right, the spatial response of the sensor is unchanged after irradiation up to 5×10^{14} Neq. The current increase in the irradiated HPK sensors is also negligible until $< 10^{13}$ Neq, as shown in Fig. 8.9, Bottom. The measurements were done at room temperature; therefore, no cooling will be necessary to reduce the dark current, which would increase the sensor power dissipation in ePIC. In conclusion, no change in the behavior of the sensors is expected during the lifetime of the ePIC detector due to radiation damage.

eRD109: readout R&D effort A more detailed review of the electronics development effort can be found in the 2024 eRD109 report document. In the following section, a brief summary will be provided.

The development of the EICROC0 chip is proceeding as planned. In 2024, an updated PCB ("2024" PCB), has been designed by OMEGA. This updated PCB features improved testability and grounding, as well as the removal of supplementary PLLs. The chip shows good homogeneity between channels and Jitter <35 ps for an injected charge of >4 fC, both for the pre-amplifier and for the discriminator output, as seen in Fig. 8.10, Left. A large correlated noise still remains with the updated "2024" PCBs (already observed in the "2023" PCB), which leads to large TDC jitters, over 50 ps, when by design, the TDC jitter is expected to be of the order of 10 ps. Nevertheless, the intrinsic performance of the preamplifier, the TDC, and the ADC, taken individually, is confirmed to be in agreement with the design and within the ePIC detector specifications.

The Fermilab team has continued the development of the FCFD ASIC prototype and, in FY23, has designed the first multi-channel prototype with this approach, labeled as FCFDv1. Numerous technical improvements were implemented based on the experience with FCFDv0, aimed at addressing the stability and performance of the system. The FCFDv1 ASIC was submitted for

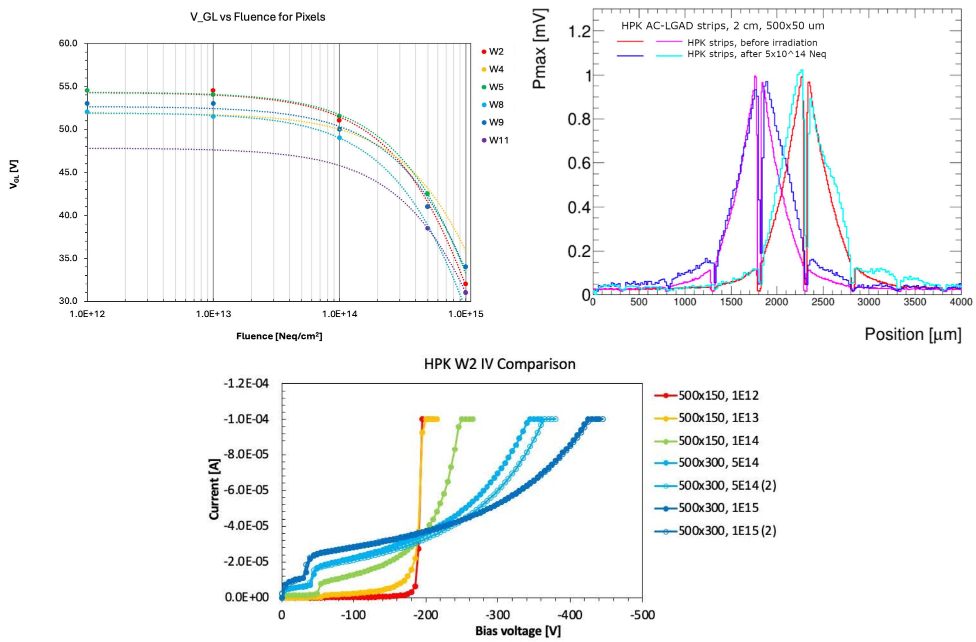
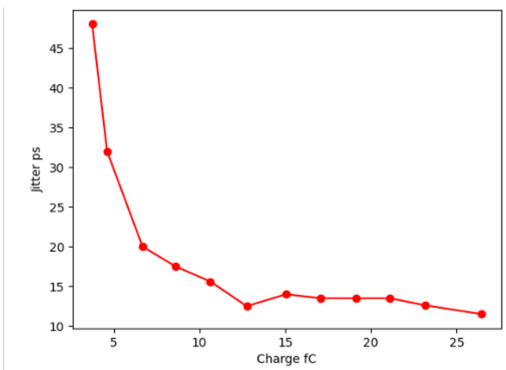


Figure 8.9: Left: Degradation of the gain layer for AC-LGADs of several wafer (with different N+, oxide and active thickness) from HPK latest sensor production, showing no change in gain layer doping up to 10^{13} Neq, which is an order of magnitude over the ePIC TOF radiation requirement. Sensors were irradiated at the TRIGA reactor (Lubjiana) with 1 MeV neutrons. Right: Normalized comparison of response profile of two nearby strips for two HPK 2 cm length, 500 μm pitch, 50 μm strip width: one before irradiation and one after 5×10^{14} Neq, even if the total signal is degraded (hence the unevenness after normalization) the charge sharing profile is unchanged. likely will update the plot with latest results from this week Bottom: Current over voltage measurement for irradiated HPK sensors.

production in September 2023, and received in January 2024. A specialized readout board was designed to accommodate the FCFDv1 connected to the EIC-module size AC-LGAD sensor. Initial measurements of the performance were done using internal charge injections performed with an LGAD-like signal. With input capacitance ∼3.5 pF a time resolution of around 11 ps was achieved, as shown in Fig. 8.10, Right. Test beam campaigns have been performed to study the performance of the FCFDv1 with AC-LGAD sensors attached to them, both of them in June 2024. The newly introduced amplitude readout was found to function well, and results show 100% efficiency when combining neighboring strips. The analysis of the test-beam data is ongoing at this time.

E&D status and outlook: E&D activities

Thermo-Mechanical demonstrator: The fabrication of a demonstrator stave following the double-sided design, as seen in Fig. 8.12, is ongoing. The demonstrator will be a thermal/mechanical demonstrator of the assembly procedure and chip/sensor power dissipation. A mock-up stave, example in Fig. 8.11, will be co-cured with a readout flex with a cooling pipe in the center, and a series of Si heather and full-size HPK sensors from the latest production will glued to the stave, then wire-bonded together and to the readout flex. The demonstrator will be used to probe the power dissipation, the temperature gradient across the stave, and the mechanical assembly procedure.



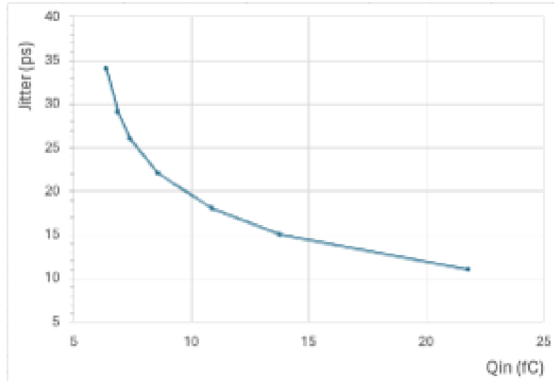


Figure 8.10: Left: EICROC Discriminator jitter versus the injected charge, determined from data on an oscilloscope. Right: FCFD Jitter measurements with 3.5 pf input capacitance and charge injection. Plots from the erd112 and erd109 2024 reports.

Demonstrator results are expected by Q1 2025.

Figure 8.11: Assembled stave prototype at Purdue.

E&D status and outlook: Add text here.

Other activity needed for the design completion: Add text here.

Status of maturity of the subsystem: Add text here.

Environmental, Safety and Health (ES&H) aspects and Quality Assessment (QA planning: From eRD112 on QA:

We also carried out QA long-term and stress-test reliability studies of LGADs as a stepping-stone towards studies on AC-LGADs. The tests were conducted in an ambient chamber at various environmental conditions. We kept the sensors under bias voltage over periods of weeks, at different temperatures, ranging from -60 to +80 degrees Celsius and under different humidity conditions. Under these extreme conditions we carried out I-V scans. At intervals of time between temperature cycles, we also collected signals from beta particles from a Sr-90 source at room temperatures to study any deterioration in noise or charge collection. The results were presented at IEEE conference: While we saw an impact of humidity and temperature on current and breakdown voltage, the sensors recovered their original performance in subsequent cycles. In addition, we also studied the impact of passivation on sensors to minimize charge build-up and early mortality. We confirmed that passivation is critical to minimise the impact of humidity on sensors and prevent early mortality. Such tests were critical after issues have been observed in silicon sensors used for tracking detectors in other experiments, such as those at the HL-LHC. As part of our QA strategy, we also sent to colleagues of UNM BNL-made AC-LGADs to have them irradiated at various fluences in a proton beam at ITA, in a gamma beam at SANDIA and with neutrons at the TRIGA reactor. The first results are shown in the previous sections.

For both sensors and readout chips, it is imperative to evaluate the yield of the test productions to adjust the final production orders. The QA plans to evaluate the yield of the sensor productions are as follows: each produced sensor will be tested in the laboratory in a probe station with simple current over voltage (IV) and capacitance over voltage (CV) tests. AC-LGADs have a single point of DC connection on the N+, so only 1 or 2 needles are necessary for the test; a probe card is not necessary for QA. The IV test will allow us to check the current level and the breakdown voltage for each produced device; the current level has to be $<< 1\mu A$ to not introduce power dissipation issues. The breakdown voltage of all devices has to be within 10%? to avoid issues in the HV distribution. The CV test will allow to probe the gain layer depletion voltage and demonstrate that all devices have homogeneous gain; for LHC prototypes[2], the gain homogeneity was within 1%. A selection of devices from the full production will be characterized by mounting them on analog front-end boards with laser TCT and at test beam facilities to ensure the homogeneity of the charge-sharing response. does it make sense to add yield number from previous HPK production? I guess they were terrible... Do we have some yield number from BNL?

this is just a first stab, correct if wrong To evaluate the yield of the chip (EICROC, FCFD) productions, a sample of chips from each batch will be tested and probed for homogeneity in all the channels using a calibration input. All channels have to be within 10%? of homogeneity. A selection of chips will be coupled (wire bonded or bump bonded) with a matching working sensor and mounted on a prototype PCB to probe correct and homogeneous operation in a realistic configuration. Then the boards will be tested with a laser TCT or at test beam facilities.

Once the state of sensors, readout chips, and flex is advanced, a fully loaded demonstrator stave is envisioned. The mounting procedure will already be tested during the assembly of the thermo-mechanical demonstrator. The full demonstrator will then be tested with radioactive sources in laboratory or at test beams.

Construction and assembly planning: The BTOF detector has a cylindrical shape, consisting of 144 tilted staves. These staves are assembled at designated sites within class-7 or higher clean rooms before being transported to BNL for final construction. Each stave is approximately 270 cm long and is divided into two half-staves of 135 cm. A half-stave includes a support structure with an integrated cooling pipe, a flexible printed circuit (FPC), sensors, and ASICs. The sensors and ASICs are mounted on both sides of the half-stave, with 16 sensors and 32 ASICs on each side. Wire-bonding is used to connect the ASICs to the sensors and electronics. Only components that pass various quality inspections—such as visual checks, metrology, and electrical tests—proceed to the assembly stage. During the half-stave assembly, FPCs are glued onto both sides of the support structure (Fig.8.12 (a)). To ensure precise alignment, a specialized tool is used, featuring pins and holes that guide the placement of the FPC and the correct application of glue. Once one side has been attached and cured, the other side is assembled. After assembly, the staves undergo both electrical and mechanical tests. Subsequently, sensors and ASICs are installed on one side using alignment tools similar to those used during the FPC mounting process (Fig.8.12 (b)). These tools help position the components and apply adhesive. Electrical connections are verified, and the ASICs are bonded to the sensors using wire-bonding, followed by wire encapsulation (Fig.8.12 (c)). When attaching components to the opposite side, a fixture is employed to maintain the necessary clearance. Upon completing the installation on both sides (Fig.8.12 (d)), the final round of testing is conducted. Fully tested staves are then shipped to BNL for integration into the global support structure of the ePIC detector, which contains 144 slots for precise alignment of the staves within the global coordinate system.

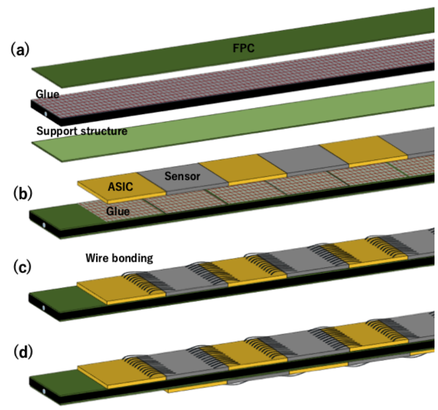


Figure 8.12: Assembly process of BTOF stave.

The FTOF is constructed in a double-sided disk shape by combining square modules. Each module includes 4 sensors, 4 ASICs, a module board, and an Aluminum Nitride (AlN) base plate, which acts as a thermal conduit to the cooling system. The modules are connected to a service hybrid (SH) that consists of a power board (PB) and a readout board (RDO). Three different configurations of SH are used, depending on the number of modules being supported: 3 modules (RB3), 6 modules (RB6), and 7 modules (RB7). In total 780 modules, 28 RB3s, 34 RB6s, and 70 RB7s, are used to make disk shape. Sensor and ASIC are connected by bump-bonding. The module board is connected to the ASICs through wire bonding and has a connector to interface with the RDO. Assembly of the modules occurs in class-7 (or higher) clean rooms, while the PB and RDO can be assembled under standard conditions. The assembly of each module begins with the connection of one sensor to one ASIC using bump-bonding technology (Fig.8.13 (a)). Automated machines are used for sensor and ASIC placement, alignment, and bonding. After bonding, the electrical performance of the sensor-ASIC hybrids is tested. Following this, 4 sensor-ASIC hybrids are glued onto the base plate (Fig.8.13 (b)). The module board is then mounted on the ASIC side of the hybrids by glue, using a dedicated tool to ensure precise alignment. After the mounting, ASIC is connected to the module board by wire-bonding, followed by wire encapsulation. The modules undergo thorough quality checks before moving on to SH assembly. The RDOs and PBs are manufactured using standard circuit board techniques and come with dedicated connectors for integration. SHs are available in configurations supporting 3, 6, or 7 modules, with the RDO and PB connected via dedicated interfaces (Fig.8.13 (c)). Once assembled (Fig.8.13 (d)), the modules and SHs are tested for connectivity and performance. After passing all tests, the modules and SHs are shipped to BNL, where they are attached to the disk-shaped support structure. Specialized tools ensure the accurate placement of the components. Modules and SHs are mounted on both sides of the support structure to eliminate acceptance gaps between sensors. When installing the modules and SHs on the opposite side, a fixture is used to maintain the required clearance between components. Finally, the fully assembled disk is installed into the ePIC detector.

Collaborators and their role, resources and workforce: Table 8.14 shows the participating institutes with their role, the contact person and potential commitments. This shows substantial participation by the international collaborators outside of the U.S.. We also anticipate substantial funding support from the international collaborators for the BTOF detector as well.

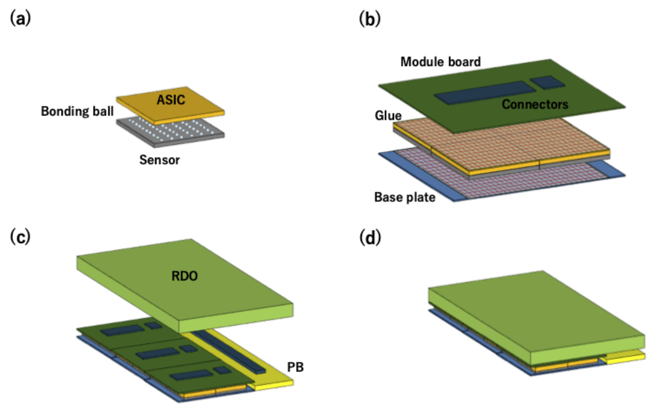


Figure 8.13: Assembly process of FTOF modules. RB3 type is shown as an example.

Risks and mitigation strategy: Our R&D results (eRD112) show that the performance of the sensors would meet our requirements. Those studies were done with smaller chip dimension. The production for R&D study with full-size sensor chip is underway. There is a potential risk that the performance of sensors with larger size would be worse. The mitigation is to reduce the sensor size.

The HPK sensors for R&D (eRD112) is of small quantity. A mass production would be a risk in terms of chip yield and schedule delay. The mitigation is to explore other possible production sites (Taiwan/FBK).

FCFD ASIC design (eRD109) currently only has analog signal readout. The design and test of the digitization component is underway and expected to have first pass early next year. Additional resource may be need to mitigate potential schedule delay and cost increase. In addition to the baseline chips EICROC and FCFD, third-party ASICs are also taken into consideration: FAST (INFN Torino), AS-ROC (Anadyne Inc. + UCSC), and HPSoC (Nalu + UCSC). The most advanced one is the High-Performance System-on-Chip (HPSoC) ASIC, designed by Nalu Scientific [6], in close collaboration with SCIPP, and fabricated in 65 nm CMOS by TSMC. HPSoC comprehends a fast analog front end and, unique to all other current LGAD readout ASICs, will capture the full signal waveform at a sampling rate of 10-20 GS/s. Together, these are expected to address the EIC goal of 25 ps timing resolution or better per measured space point. V2b of the chip has a working digital back-end and is currently under review.

We have performed heat conductivity and cooling simulations, and R&D test on cooling capacity (currently with PED funding). Those show promising outcome for meeting the cooling needs. The potential risk is that the cooling capacity is not sufficient to maintain a stable and relatively uniform temperature. A possible mitigation strategy is to use different material for cooling pipe with better heat conductivity and higher flow rate.

Additional Material

8.3.4.2 The proximity focusing RICH

Requirements

Institute	Contact Person	NOW (TDR->Project)
Brookhaven National Laboratory	Prithwish Tribedy tribady@bnl.gov	DAQ readout chain readout, sensor-ASIC integration, sensor with FF AC-LGAD; EICROC testing
Fermi National Accelerator		FCFD ASIC (no ePIC)
Los Alamos National Laboratory	Xuan Li xuanli@lanl.gov	
Rice University	Wei Li wl33@rice.edu	B/FTOF FEE?, Backend electronics (postdoc) , simulation and reconstruction
Oak Ridge National Laboratory	Oskar Hartbricht hartbricho@ornl.gov	sensor-ASIC integration, frontend electronics (waffle probing), module assembly
Ohio State University	Daniel Brandenburg Brandenburg.89@osu.edu	BTOF/FTOF: module assembly; backend electronics
Purdue University	Andreas Jung anjung@purdue.edu	Module assembly
Univ. of California, Santa Cruz	Simone Mazza simazza@ucsc.edu	Sensor, sensor-ASIC integration, module assembly (no in-kind)
University of Illinois at Chicago	Olga Evdokimov mailto:evdolga@uic.edu	
Hiroshima University	Kenta Shigaki shigaki@hiroshima-u.ac.jp	FTOF EICROC testing, sensor testing (30%), simulation
RIKEN	Yuji Goto. goto@bnl.gov	BTOF: module assembly
Shinshu University	Kentaro Kawaide kawade@shinshu-u.ac.jp	Sensor testing, simulations
University of Tokyo	Taku Gunji gunji@cns.s.u-tokyo.ac.jp	DAQ streaming readout
South China Normal University	Shuai Yang syang@scnu.edu.cn	
Univ of Sci. and Tech. of China	Yanwen Liu	
Indian Institute of Tech., Mandi	Prabhakar Palni prabhakar.palni@unigoa.ac.in	FTOF Module Assembly/QA, sensor testing
National Inst. of Sci. Edu. Res.	Ganesh Tambave ganesh.tambave@niser.ac.in	Module Assembly
National Central University		FF AC-LGAD (sensor QA)
National Cheng-Kung University	Yi Yang yiyang@ncku.edu.tw	Mechanics and cooling systems
National Taiwan University	Rong-Shyan Lu rslu@phys.ntu.edu.tw	FF AC-LGAD; module assembly
Univ. Técnica Federico Santa María		Simulations
LBNL	Zhenyu Ye yezhenyu2003@gmail.com	BTOF ASIC testing; SH
Kent State University	Zhangbu Xu zxu22@kent.edu	Simulation, readout test, machine shop (in-kind)
Nara	Takashi Hachiya hachiya@cc.nara-wu.ac.jp	BTOF module assembly/validation/FPCB

Figure 8.14: Collaboration institutions and their responsibilities.

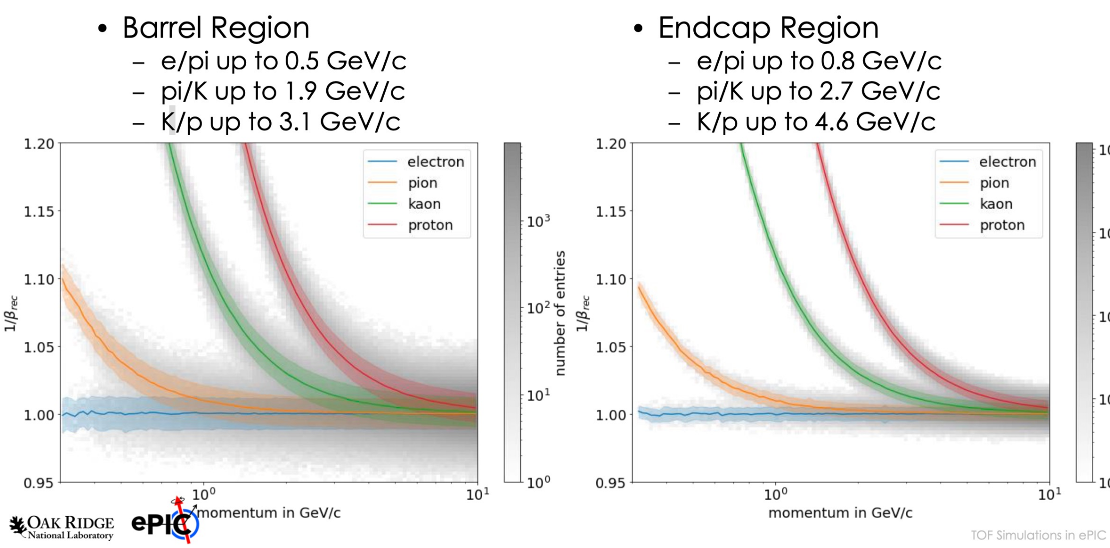


Figure 8.15: simulation of $1/\beta$ as a function of particle momentum for BTOF and FTOF performance.

Requirements from physics: Add text here.

Requirements from Radiation Hardness: Add text here.

Requirements from Data Rates: Add text here.

Justification

Device concept and technological choice: Add text here.

Subsystem description:

General device description: Add text here.

Sensors: Add text here.

FEE: Add text here.

Other components: Add text here.

Performance

Implementation

Services: Add text here.

Subsystem mechanics and integration: Add text here.

Calibration, alignment and monitoring: Add text here.

Status and remaining design effort:

R&D effort: Add text here.

E&D status and outlook: Add text here.

Other activity needed for the design completion: Add text here.

Status of maturity of the subsystem: Add text here.

Environmental, Safety and Health (ES&H) aspects and Quality Assessment (QA planning: Add text here.

Construction and assembly planning: Add text here.

Collaborators and their role, resources and workforce: Add text here.

Risks and mitigation strategy: Add text here.

Additional Material Add text here.

8.3.4.3 The high performance DIRC

Requirements

Requirements from physics: Add text here.

Requirements from Radiation Hardness: Add text here.

Requirements from Data Rates: Add text here.

Justification

Device concept and technological choice: Add text here.

Subsystem description:

General device description: Add text here.

Sensors: Add text here.

FEE: Add text here.

Other components: Add text here.

Performance

Implementation

Services: Add text here.

Subsystem mechanics and integration: Add text here.

Calibration, alignment and monitoring: Add text here.

Status and remaining design effort:

R&D effort: Add text here.

E&D status and outlook: Add text here.

Other activity needed for the design completion: Add text here.

Status of maturity of the subsystem: Add text here.

Environmental, Safety and Health (ES&H) aspects and Quality Assessment (QA planning: Add text here.

Construction and assembly planning: Add text here.

Collaborators and their role, resources and workforce: Add text here.

Risks and mitigation strategy: Add text here.

Additional Material Add text here.

8.3.4.4 The dual radiator RICH

Requirements

Requirements from physics: Add text here.

Requirements from Radiation Hardness: Add text here.

Requirements from Data Rates: Add text here.

Justification

Device concept and technological choice: Add text here.

Subsystem description:

General device description: Add text here.

Sensors: Add text here.

FEE: Add text here.

Other components: Add text here.

Performance

Implementation

Services: Add text here.

Subsystem mechanics and integration: Add text here.

Calibration, alignment and monitoring: Add text here.

Status and remaining design effort:

R&D effort: Add text here.

E&D status and outlook: Add text here.

Other activity needed for the design completion: Add text here.

Status of maturity of the subsystem: Add text here.

Environmental, Safety and Health (ES&H) aspects and Quality Assessment (QA planning: Add text here.

Construction and assembly planning: Add text here.

Collaborators and their role, resources and workforce: Add text here.

Risks and mitigation strategy: Add text here.

Additional Material Add text here.

8.3.5 Electromagnetic Calorimetry

Add text here.

8.3.5.1 The backward endcap electromagnetic calorimeter

Requirements

Requirements from physics: Add text here.

Requirements from Radiation Hardness: Add text here.

Requirements from Data Rates: Add text here.

Justification

Device concept and technological choice: Add text here.

Subsystem description:

General device description: Add text here.

Sensors: Add text here.

FEE: Add text here.

Other components: Add text here.

Performance

Implementation

Services: Add text here.

Subsystem mechanics and integration: Add text here.

Calibration, alignment and monitoring: Add text here.

Status and remaining design effort:

R&D effort: Add text here.

E&D status and outlook: Add text here.

Other activity needed for the design completion: Add text here.

Status of maturity of the subsystem: Add text here.

Environmental, Safety and Health (ES&H) aspects and Quality Assessment (QA planning: Add text here.

Construction and assembly planning: Add text here.

Collaborators and their role, resources and workforce: Add text here.

Risks and mitigation strategy: Add text here.

Additional Material Add text here.

8.3.5.2 The barrel electromagnetic calorimeter

Requirements

Requirements from physics: Add text here.

Requirements from Radiation Hardness: Add text here.

Requirements from Data Rates: Add text here.

Justification

Device concept and technological choice: Add text here.

Subsystem description:

General device description: Add text here.

Sensors: Add text here.

FEE: Add text here.

Other components: Add text here.

Performance

Implementation

Services: Add text here.

Subsystem mechanics and integration: Add text here.

Calibration, alignment and monitoring: Add text here.

Status and remaining design effort:

R&D effort: Add text here.

E&D status and outlook: Add text here.

Other activity needed for the design completion: Add text here.

Status of maturity of the subsystem: Add text here.

Environmental, Safety and Health (ES&H) aspects and Quality Assessment (QA planning: Add text here.

Construction and assembly planning: Add text here.

Collaborators and their role, resources and workforce: Add text here.

Risks and mitigation strategy: Add text here.

Additional Material Add text here.

8.3.5.3 The forward endcap electromagnetic calorimeter

Requirements

Requirements from physics: Add text here.

Requirements from Radiation Hardness: Add text here.

Requirements from Data Rates: Add text here.

Justification

Device concept and technological choice: Add text here.

Subsystem description:

General device description: Add text here.

Sensors: Add text here.

FEE: Add text here.

Other components: Add text here.

Performance

Implementation

Services: Add text here.

Subsystem mechanics and integration: Add text here.

Calibration, alignment and monitoring: Add text here.

Status and remaining design effort:

R&D effort: Add text here.

E&D status and outlook: Add text here.

Other activity needed for the design completion: Add text here.

Status of maturity of the subsystem: Add text here.

Environmental, Safety and Health (ES&H) aspects and Quality Assessment (QA planning: Add text here.

Construction and assembly planning: Add text here.

Collaborators and their role, resources and workforce: Add text here.

Risks and mitigation strategy: Add text here.

Additional Material Add text here.

8.3.6 Hadronic Calorimetry

Add text here.

8.3.6.1 The backward endcap hadronic calorimeter

Requirements

Requirements from physics: Add text here.

Requirements from Radiation Hardness: Add text here.

Requirements from Data Rates: Add text here.

Justification

Device concept and technological choice: Add text here.

Subsystem description:

General device description: Add text here.

Sensors: Add text here.

FEE: Add text here.

Other components: Add text here.

Performance

Implementation

Services: Add text here.

Subsystem mechanics and integration: Add text here.

Calibration, alignment and monitoring: Add text here.

Status and remaining design effort:

R&D effort: Add text here.

E&D status and outlook: Add text here.

Other activity needed for the design completion: Add text here.

Status of maturity of the subsystem: Add text here.

Environmental, Safety and Health (ES&H) aspects and Quality Assessment (QA planning: Add text here.

Construction and assembly planning: Add text here.

Collaborators and their role, resources and workforce: Add text here.

Risks and mitigation strategy: Add text here.

Additional Material Add text here.

8.3.6.2 The barrel hadronic calorimeter

Requirements

Requirements from physics: Add text here.

Requirements from Radiation Hardness: Add text here.

Requirements from Data Rates: Add text here.

Justification

Device concept and technological choice: Add text here.

Subsystem description:

General device description: Add text here.

Sensors: Add text here.

FEE: Add text here.

Other components: Add text here.

Performance

Implementation

Services: Add text here.

Subsystem mechanics and integration: Add text here.

Calibration, alignment and monitoring: Add text here.

Status and remaining design effort:

R&D effort: Add text here.

E&D status and outlook: Add text here.

Other activity needed for the design completion: Add text here.

Status of maturity of the subsystem: Add text here.

Environmental, Safety and Health (ES&H) aspects and Quality Assessment (QA planning: Add text here.

Construction and assembly planning: Add text here.

Collaborators and their role, resources and workforce: Add text here.

Risks and mitigation strategy: Add text here.

Additional Material Add text here.

8.3.6.3 The forward endcap hadronic calorimeter

Requirements

Requirements from physics: Add text here.

Requirements from Radiation Hardness: Add text here.

Requirements from Data Rates: Add text here.

Justification

Device concept and technological choice: Add text here.

Subsystem description:

General device description: Add text here.

Sensors: Add text here.

FEE: Add text here.

Other components: Add text here.

Performance

Implementation

Services: Add text here.

Subsystem mechanics and integration: Add text here.

Calibration, alignment and monitoring: Add text here.

Status and remaining design effort:

R&D effort: Add text here.

E&D status and outlook: Add text here.

Other activity needed for the design completion: Add text here.

Status of maturity of the subsystem: Add text here.

Environmental, Safety and Health (ES&H) aspects and Quality Assessment (QA planning: Add text here.

Construction and assembly planning: Add text here.

Collaborators and their role, resources and workforce: Add text here.

Risks and mitigation strategy: Add text here.

Additional Material Add text here.

8.3.7 Far forward detectors

Add text here.

8.3.7.1 The detectors in the B0 bending magnet

Requirements

Requirements from physics: Add text here.

Requirements from Radiation Hardness: Add text here.

Requirements from Data Rates: Add text here.

Justification

Device concept and technological choice: Add text here.

Subsystem description:

General device description: Add text here.

Sensors: Add text here.

FEE: Add text here.

Other components: Add text here.

Performance

Implementation

Services: Add text here.

Subsystem mechanics and integration: Add text here.

Calibration, alignment and monitoring: Add text here.

Status and remaining design effort:

R&D effort: Add text here.

E&D status and outlook: Add text here.

Other activity needed for the design completion: Add text here.

Status of maturity of the subsystem: Add text here.

Environmental, Safety and Health (ES&H) aspects and Quality Assessment (QA planning: Add text here.

Construction and assembly planning: Add text here.

Collaborators and their role, resources and workforce: Add text here.

Risks and mitigation strategy: Add text here.

Additional Material Add text here.

8.3.7.2 The roman pots and the off-momentum detectors

Requirements

Requirements from physics: The Roman pots and Off-Momentum Detectors need to cover an angular region from $\sim$0 to 5 mrad. For the Roman pots, achieving acceptance down to 0 mrad is impossible due to the presence of the hadron beam itself, so the low-θ (low-p_T) acceptance is essentially entirely driven by the focusing quadrupoles (machine optics) before and after the interaction point. For IP-6, the choice of low-β^* optics to maximize luminosity means the 10σ transverse size of the beam at the Roman pots location is larger, worsening the acceptance at the expense of high luminosity. Conversely, a choice can be made to reduce luminosity to improve low-θ acceptance at the Roman pots location. Given this set of operational parameters for the machine itself, it is required that the sensor packages have minimal dead area at the edges to take maximum advantage of the machine optics during data taking runs.

For resolution, the detectors must deliver p_T-resolution better than 10%.

Requirements from Radiation Hardness: Maximal radiation doses are shown to be ¡ 10^{12} 1 MeV neutron equivalaent for NIEL radiation, while ionizing doses are around 1 krad for the Roman pots region of ePIC.

Requirements from Data Rates: Rates during normal operations, with expected vacuum of 10^{-9} mbar, are a few Hz/channel.

Justification

Device concept and technological choice: Add text here.

Subsystem description:

General device description: The Roman pots and off-momentum detectors are both vacuum-based silicon sensors arranged into two stations for fully reconstructing protons at various magnetic rigidities, where rigidity here refers to the fraction of the momentum the proton has with respect to the steering dipoles design orbit momentum.

Sensors: AC-coupled low-gain avalanche diodes (AC-LGADs) are the technology of choice for these two subsystems due to their capabiltity to provide both high-precisions space and time information.

FEE: Add text here.

Other components: Add text here.

Performance

Implementation

Services: Add text here.

Subsystem mechanics and integration: Add text here.

Calibration, alignment and monitoring: Add text here.

Status and remaining design effort:

R&D effort: Add text here.

E&D status and outlook: Add text here.

Other activity needed for the design completion: Add text here.

Status of maturity of the subsystem: Add text here.

Environmental, Safety and Health (ES&H) aspects and Quality Assessment (QA planning: Add text here.

Construction and assembly planning: Add text here.

Collaborators and their role, resources and workforce: Add text here.

Risks and mitigation strategy: Add text here.

Additional Material Add text here.

8.3.7.3 The zero degree calorimeter

Requirements

Requirements from physics: Add text here.

Requirements from Radiation Hardness: Add text here.

Requirements from Data Rates: Add text here.

Justification

Device concept and technological choice: Add text here.

Subsystem description:

General device description: Add text here.

Sensors: Add text here.

FEE: Add text here.

Other components: Add text here.

Performance

Implementation

Services: Add text here.

Subsystem mechanics and integration: Add text here.

Calibration, alignment and monitoring: Add text here.

Status and remaining design effort:

R&D effort: Add text here.

E&D status and outlook: Add text here.

Other activity needed for the design completion: Add text here.

Status of maturity of the subsystem: Add text here.

Environmental, Safety and Health (ES&H) aspects and Quality Assessment (QA planning: Add text here.

Construction and assembly planning: Add text here.

Collaborators and their role, resources and workforce: Add text here.

Risks and mitigation strategy: Add text here.

Additional Material Add text here.

8.3.8 Far backward detectors

Add text here.

8.3.8.1 The luminosity system

Requirements

Requirements from physics: Add text here.

Requirements from Radiation Hardness: Add text here.

Requirements from Data Rates: Add text here.

Justification

Device concept and technological choice: Add text here.

Subsystem description:

General device description: Add text here.

Sensors: Add text here.

FEE: Add text here.

Other components: Add text here.

Performance

Implementation

Services: Add text here.

Subsystem mechanics and integration: Add text here.

Calibration, alignment and monitoring: Add text here.

Status and remaining design effort:

R&D effort: Add text here.

E&D status and outlook: Add text here.

Other activity needed for the design completion: Add text here.

Status of maturity of the subsystem: Add text here.

Environmental, Safety and Health (ES&H) aspects and Quality Assessment (QA planning: Add text here.

Construction and assembly planning: Add text here.

Collaborators and their role, resources and workforce: Add text here.

Risks and mitigation strategy: Add text here.

Additional Material Add text here.

8.3.8.2 The low Q^2 taggers

Requirements

Requirements from physics: Add text here.

Requirements from Radiation Hardness: Add text here.

Requirements from Data Rates: Add text here.

Justification

Device concept and technological choice: Add text here.

Subsystem description:

General device description: Add text here.

Sensors: Add text here.

FEE: Add text here.

Other components: Add text here.

Performance

Implementation

Services: Add text here.

Subsystem mechanics and integration: Add text here.

Calibration, alignment and monitoring: Add text here.

Status and remaining design effort:

R&D effort: Add text here.

E&D status and outlook: Add text here.

Other activity needed for the design completion: Add text here.

Status of maturity of the subsystem: Add text here.

Environmental, Safety and Health (ES&H) aspects and Quality Assessment (QA planning: Add text here.

Construction and assembly planning: Add text here.

Collaborators and their role, resources and workforce: Add text here.

Risks and mitigation strategy: Add text here.

Additional Material Add text here.

8.3.9 Polarimeters

Add text here.

8.3.9.1 The electron polarimeters

Requirements

Requirements from physics: Add text here.

Requirements from Radiation Hardness: Add text here.

Requirements from Data Rates: Add text here.

Justification

Device concept and technological choice: Add text here.

Subsystem description:

General device description: Add text here.

Sensors: Add text here.

FEE: Add text here.

Other components: Add text here.

Performance

Implementation

Services: Add text here.

Subsystem mechanics and integration: Add text here.

Calibration, alignment and monitoring: Add text here.

Status and remaining design effort:

R&D effort: Add text here.

E&D status and outlook: Add text here.

Other activity needed for the design completion: Add text here.

Status of maturity of the subsystem: Add text here.

Environmental, Safety and Health (ES&H) aspects and Quality Assessment (QA planning: Add text here.

Construction and assembly planning: Add text here.

Collaborators and their role, resources and workforce: Add text here.

Risks and mitigation strategy: Add text here.

Additional Material Add text here.

8.3.9.2 The proton polarimeters

Requirements

Requirements from physics: Add text here.

Requirements from Radiation Hardness: Add text here.

Requirements from Data Rates: Add text here.

Justification

Device concept and technological choice: Add text here.

Subsystem description:

General device description: Add text here.

Sensors: Add text here.

FEE: Add text here.

Other components: Add text here.

Performance

Implementation

Services: Add text here.

Subsystem mechanics and integration: Add text here.

Calibration, alignment and monitoring: Add text here.

Status and remaining design effort:

R&D effort: Add text here.

E&D status and outlook: Add text here.

Other activity needed for the design completion: Add text here.

Status of maturity of the subsystem: Add text here.

Environmental, Safety and Health (ES&H) aspects and Quality Assessment (QA planning: Add text here.

Construction and assembly planning: Add text here.

Collaborators and their role, resources and workforce: Add text here.

Risks and mitigation strategy: Add text here.

Additional Material Add text here.

8.3.10 Readout Electronics and Data Acquisition

Requirements

Requirements from physics: Add text here.

Requirements from Radiation Hardness: Add text here.

Requirements from Data Rates: Add text here.

Justification

Device concept and technological choice: Add text here.

Subsystem description:

General device description: Add text here.

Sensors: Add text here.

FEE: Add text here.

Other components: Add text here.

Performance

Implementation

Services: Add text here.

Subsystem mechanics and integration: Add text here.

Calibration, alignment and monitoring: Add text here.

Status and remaining design effort:

R&D effort: Add text here.

E&D status and outlook: Add text here.

Other activity needed for the design completion: Add text here.

Status of maturity of the subsystem: Add text here.

Environmental, Safety and Health (ES&H) aspects and Quality Assessment (QA planning: Add text here.

Construction and assembly planning: Add text here.

Collaborators and their role, resources and workforce: Add text here.

Risks and mitigation strategy: Add text here.

Additional Material Add text here.

8.3.11 Software and Computing

Requirements

Requirements from physics: Add text here.

Requirements from Radiation Hardness: Add text here.

Requirements from Data Rates: Add text here.

Justification

Device concept and technological choice: Add text here.

Subsystem description:

General device description: Add text here.

Sensors: Add text here.

FEE: Add text here.

Other components: Add text here.

Performance

Implementation

Services: Add text here.

Subsystem mechanics and integration: Add text here.

Calibration, alignment and monitoring: Add text here.

Status and remaining design effort:

R&D effort: Add text here.

E&D status and outlook: Add text here.

Other activity needed for the design completion: Add text here.

Status of maturity of the subsystem: Add text here.

Environmental, Safety and Health (ES&H) aspects and Quality Assessment (QA planning: Add text here.

Construction and assembly planning: Add text here.

Collaborators and their role, resources and workforce: Add text here.

Risks and mitigation strategy: Add text here.

Additional Material Add text here.

8.4 Detector Integration

Add text here.

8.4.1 Installation and Maintenance

Add text here.

8.5 Detector Commissioning and Pre-Operations

Add text here.

References

[1] R. Abdul Khalek et al. “Science Requirements and Detector Concepts for the Electron-Ion Collider: EIC Yellow Report”. In: *Nucl. Phys. A* 1026 (2022), p. 122447. DOI: 10.1016/j.nuclphysa.2022.122447. arXiv: 2103.05419 [physics.ins-det].

[2] *Technical Design Report: A High-Granularity Timing Detector for the ATLAS Phase-II Upgrade*. Tech. rep. Geneva: CERN, 2020. URL: https://cds.cern.ch/record/2719855.

[3] I. Dutta et al. “Results for pixel and strip centimeter-scale AC-LGAD sensors with a 120 GeV proton beam”. In: (July 2024). arXiv: 2407.09928 [physics.ins-det].

[4] C. Bishop et al. “Long-distance signal propagation in AC-LGAD”. In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 1064 (2024), p. 169478. ISSN: 0168-9002. DOI: https://doi.org/10.1016/j.nima.2024.169478. URL: https://www.sciencedirect.com/science/article/pii/S0168900224004042.

[5] L. Menzio et al. “First test beam measurement of the 4D resolution of an RSD pixel matrix connected to a FAST2 ASIC”. In: *Nucl. Instrum. Meth. A* 1065 (2024), p. 169526. DOI: 10.1016/j.nima.2024.169526. arXiv: 2402.01517 [physics.ins-det].

[6] C. Chock et al. “First test results of the trans-impedance amplifier stage of the ultra-fast HPSoC ASIC”. In: *Journal of Instrumentation* 18.02 (2023), p. C02016. DOI: 10.1088/1748-0221/18/02/C02016. URL: https://dx.doi.org/10.1088/1748-0221/18/02/C02016.