EIC Detector R&D Proprosal

The eRD108 Consortium

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Project ID: eRD108

Project Name: Development of EIC ePIC MPGD Trackers.

Brookhaven National Laboratory (BNL): Craig Woody

CEA Saclay: Francesco Bossù, Maxence Vandenbroucke

Florida Institute of Technology (FIT): Marcus Hohlmann

Istituto Nazionale di Fisica Nucleare (INFN Roma Tor Vergata): Annalisa D'Angelo

University of Virginia (UVa): Huong Nguyen, Nilanga Liyanage

Temple University (TU): Matt Posik, Bernd Surrow

Thomas Jefferson National Accelerator Facility (JLab): Kondo Gnanvo

Vanderbilt University (VU): Sourav Tarafdar

Project Members:

BNL: B. Azmoun, A. Kiselev, M. Purschke, C. Woody

CEA Saclay: F. Bossù, A. Francisco, M. Vandenbroucke

FIT: M. Hohlmann, P. Iapozzuto

INFN: A. D'Angelo, A. Fantini, B. Benkel

JLab: K. Gnanvo

TU: M. Posik, B. Surrow

UVa: H. Nguyen, N. Liyanage

VU: S. Tarafdar, V. Greene, J. Velkovska

Contact Person: Kondo Gnanvo; kagnanvo@jlab.org

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1 Introduction

We propose R&D on Micro-Pattern Gaseous Detectors (MPGDs) for the recently re-designed tracking system of the EIC project detector ePIC. One type is the micro Resistive-Well (µRWELL) detector, the second is the Micromegas (MM) detector. We propose to:

1. Pursue the study of a cylindrical Micromegas for the Inner MPGD layer in the ePIC central barrel tracker for timing and pattern recognition.
2. Develop large rectangular µRWELLs for an outer MPGD layer in the ePIC central barrel tracker in front of the DIRC for timing and pattern recognition as well as to help the measurement of the track incidence angles on the DIRC.
3. Develop large disk-shaped µRWELLs for timing and pattern recognition in the ePIC tracker endcap.

1.1 Risks addressed

The proposed R&D addresses various risks in the development of the ePIC detector for the EIC project:

- Pattern recognition performance in the barrel and endcap region of ePIC trackers based on Si detectors alone is insufficient with the limited number of silicon layers.
- The slow integration time of the Si trackers means that the ePIC trackers in both barrel and endcap need to be complemented by MPGD layers to provide additional fast timing capabilities.
- Particle ID under-performs because reconstruction in DIRC devices suffers if the impact point and direction of the charged particle producing the Cerenkov radiation are not known precisely enough.
- Scaling up detectors from small proof-of-principle prototypes to large full-size production modules often poses problems with HV stability and gain uniformity related to insufficient stiffness and robustness of large modules. This is exacerbated if there is an additional requirement of a thin-gap gas volume and low mass for the large detectors as is the case for ePIC.

1.2 Risk mitigation approach in proposed R&D

It is well known that spatial resolution of standard MPGDs rapidly degrades with particles crossing the detector at large angle from the normal due to the long ionization charge trail produced these particles along their path in the gas volume. Moreover, the Lorentz force effect of the magnetic field of the solenoid also adversely impact the spatial resolution. Thin Gap µRWELL technology complemented by GEM pre-amplification is identified as the best approach to address position resolution challenges of the ePIC MPGD trackers. We will leverage our ongoing effort [1] as part of the EIC generic R&D, to investigate the issues related to stability and performance associated to mechanical structures of large and low-mass Thin Gap MPGDs.

The risks with respect to HV stability and gain uniformity related to stiffness and robustness of large modules are mitigated by researching a number of different candidate materials and designs with full-size prototype gas-envelope/foil-support structures, i.e. mock-up detectors.

2 Micromegas Barrel Tracker

2.1 What was proposed for FY23

For the FY23 R&D cycle, the research program was twofold. First, we planned to complete the studies on the 2D readout structures on small prototypes and test them in an electron beam at MAMI in Mainz (Germany). The second part of the program was the design and building of a scale-1 prototype with the dimension of a CLAS12 Micromegas tile and a longer mock-up with dimensions about 50x100cm^2.

2.2 What was achieved in FY23

In preparation for the beam test at MAMI (June 5th–11th 2023), several prototypes with an active area of about 12x12cm^2 have been assembled in Saclay. Using the technique of a bulk Micromegas on a stretched Kapton foil to minimize the material budget, the prototypes consists of a stack of different "amplification Kapton" foils (AK), i.e. the stretched foil with the resistive ink and a micromesh, and a readout flexible PCB with the 2D readout pattern (readout Kapton, RK). This stack is stretched on a carbon frame, allowing for minimal material budget in the active region down to 0.2% of X0. An example of a stack of RK and AK after the bulk process is shown on the left in Figure 1. The RKs have been designed in Saclay and then produced at CERN. The resistive layer and the assembly has been done in Saclay. An example of a complete prototype is shown at the center of Figure 1.

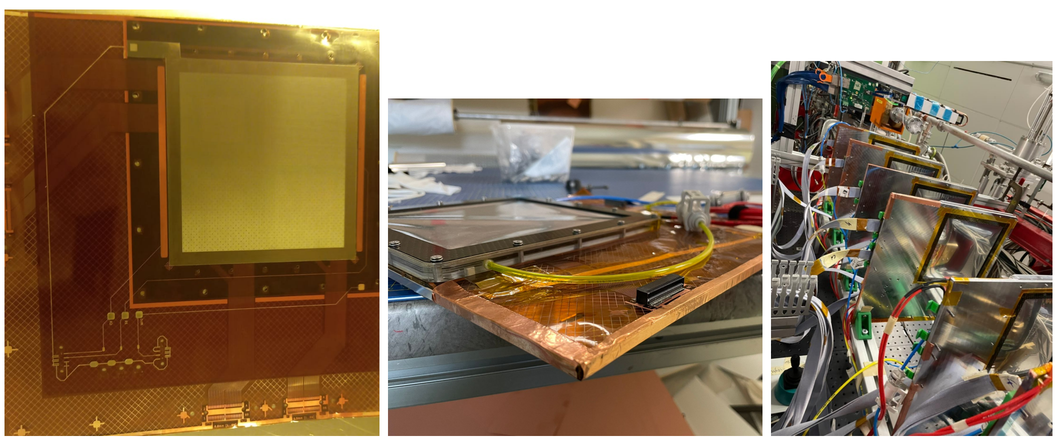

Figure 1: (left) Stack of the readout Kapton and the amplification Kapton foils that has been bulked with a micromesh. (center) Fully assembled prototype. (right) Beam test setup in MAMI.

At the beam test, prototypes with different resistive layer patterns and different readout patterns have been tested. In particular, we tested orthogonal strips with variable pitch between 0.5 and 1.5 mm, orthogonal strips of 1 mm in pitch but variable inter-strip gaps to check the signal sharing between the two coordinates, and ASACUSA-like patterns with different pitches from 0.8 mm to 2 mm. The set of detectors placed on the moving platform at the MAMI test beam facility is shown on the right of Figure 1. The reference tracker consists of four plans of silicon pixel spare ladders from the ALICE MFT (ALPIDE technology) that has been assembled in Saclay. A second week of beam test in MAMI is under discussion for October 2023 that would allow us to refine the analysis of the 2D patterns and tests different resistive layers.

The goal of the full-scale prototype studies is to check the performance and uniformity of the chosen combination of resistive layer and RK patterns over a large active area. To simplify the design phase, we reused the CAD drawings of a CLAS12 Micromegas tile and fitted in the new readout layers. Since the curvature radii of MMs in an EIC detector will be bigger than those in CLAS12 (50 - 70 cm in radius), a larger size and curvature mock-up tile is also planned to check its mechanical stability. The design work is ongoing.

2.3 R&D plans and funding requests for FY24

The R&D plans for FY24 will aim at addressing some challenges that the new ePIC configuration for the inner Micromegas barrel layer presents us. The new configuration of the MPGD systems of the ePIC detector has been discussed on June 15th 2023 and it is shown in Figure 6. The inner barrel cylindrical Micromegas layer consists of three cylindrical sections that cover the pseudorapidity region $|\eta| < 1.5$. In this design, particles will cross the forward and backward sections with impinging angles larger than 30 degrees. As a consequence, two aspects should be considered: keeping a good spacial resolution in the longitudinal direction and keeping the material budget low.

2.3.1 Gas mixture optimisation for thin-gap Micromegas:

In a standard 3 mm gap Micromegas, particles crossing the drift gap with angles larger than 30 degrees will create primary electrons over several millimeters in z. In order to minimize this effect one can explore two techniques. Either trying to reconstruct the trajectory of the particle by measuring the time of arrival of the signals on different strips, the so called micro-TPC mode, or one can try to minimize the space of formation of primary electrons by minimizing the conversion gap. The latter needs a careful choice of gas mixture that can provide enough primary electrons on a short path to be easily detected.

In FY24, we want to optimize argon-based gas mixtures to maximise the number of primary electrons. We propose to modify the Micromegas prototype design in order to have a 1-mm drift gap that will be tested with several fractions of argon and isobutane. Other quenchers such as pentane can also be explored.

2.3.2 Thin support material for cylindrical Micromegas:

The second aspect regards the support material and the structure of cylindrical Micromegas. Although, the 2D Micromegas tiles can be build with a material budget of about 0.5% of X_0 (for orthogonal tracks), particles crossing with large angles will traverse more material and the minimization of the material budget in conjunction with large detectors will be explored. In continuation with the large size mock-up under investigation in FY23, we propose to different materials than FR4 for the cylindrical PCB. In particular we want to focus on the possibility of using a thin carbon fiber cylindrical support that can be compatible with the stretched bulked Micromegas.

2.4 Milestones and Timeline for FY24

2.4.1 Milestones for the gas mixture optimisation:

- Design of the a new chamber of the prototype with 1-mm drift gap - 3 months
- Procurement of materials - 5 months
- Prototype assembly - 6 months
- Tests of gas mixtures - 8 months

2.4.2 Milestones for thin support material for scale-1 prototype:

- **Design of the support structure** - 6 months
- **Procurement of the carbon fiber structure** - 9 months
- **Assembly with the mock-up** - 10 months

- **Mechanical tests** - 12 months

3 Cylindrical µRWELL prototype

3.1 What was planned for FY23?

We planned to design and produce the components for two half-cylindrical µRWELL prototypes by late 2022. The design of two composite µRWELL/2D-readout flexible PCBs was to be done at Jefferson Lab and BNL in collaboration with experts of the MPT PCB workshop at CERN and was expected to be completed by the end of October 2022, with production to start in November 2022. The plan was to 3D-print the mechanical frame parts at FIT. The fabrication of the two composite PCBs was expected to be completed and shipped to FIT in April 2023 for the final assembly into two half-cylinders in May 2023. The prototype was to be tested in a 120 GeV proton beam at Fermilab in June 2023.

We also planned to partially equip the prototype with VMM3a ASICs during the beam test. All components needed to produce the VMM3a-SRS DAQ system, including an SRS minicrate, FEC, DVM, and four VMM3a hybrid cards were acquired and initial testing of components with RCDAQ software began in October 2022. During the configuration setup of the system, we identified communication issues between the VMM3a hybrids and the FEC cards. In communications between BNL and CERN experts, it was determined that our VMM3a hybrid cards were early prototypes and were not compatible in their current form with the rest of our SRS-DAQ system. As a result we were not able to implement a VMM3a-based DAQ system.

3.2 What was achieved in FY23?

The detector R&D largely progressed according to plan in FY23. Fig. 2 shows our final designs of two composite µRWELL/2D-readout foils with capacitive-sharing readout strips in U-V geometry, one with straight strips (JLab design, left) and one with zigzag strips (BNL design, center); both foils were produced at CERN and delivered to us (right) .

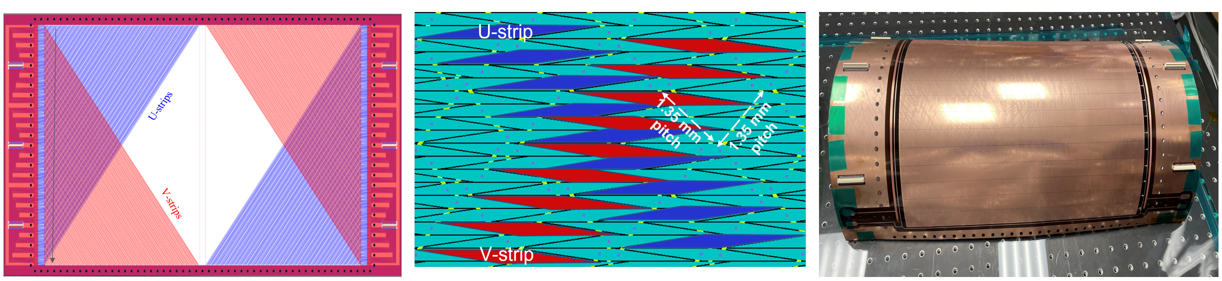

Figure 2: Readout designs with U-V strip geometry and capacitive-sharing. Left: Straight strips. Center: Zigzag strip. Right: Composite µRWELL/readout foil produced at CERN during detector assembly.

The final mechanical design of the detector prototype is shown in Fig. 3 (left). The composite µRWELL/readout foil (copper color) is sandwiched between an inner clamp frame (blue) and a central spacer frame (green) that creates a 3 mm drift gap. A cathode drift foil (silver) is sandwiched between the central spacer frame and an outer clamp frame (yellow). Readout connectors for the front-end electronics are soldered onto the µRWELL/readout composite foil. The drift foil is cut from 125 µm aluminized mylar foil. The frames are 3D-printed PLA material. The detectors were assembled at FIT in May 2023 (Fig. 3 right).

The two detector halves were installed on a rotational mount and placed in a 120 GeV proton beam at the Fermilab test beam facility in June 2023 with small 10cm × 10cm GEM detectors upstream and downstream of the cylindrical detector to create a tracking telescope (Fig. 4).

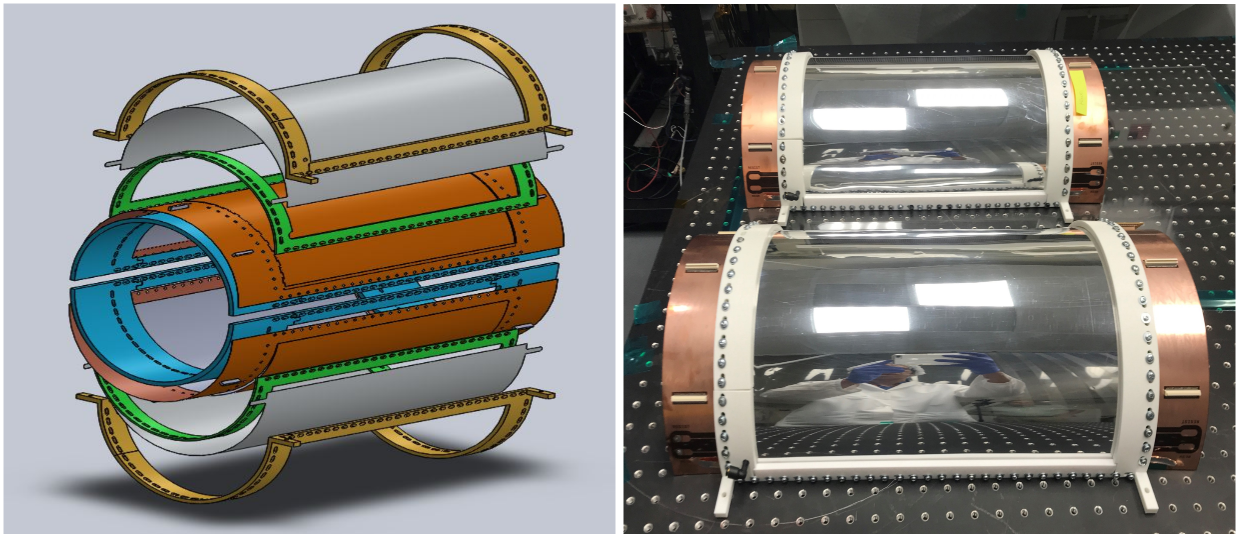

Figure 3: Left: Exploded view of cylindrical µRWELL detector design. Right: Two fully assembled detector half-cylinders. For scale: The hole pitch on the optical table that the detectors rest on is one inch.

During the initial commissioning phase, when the detector was flushed for several days with dry nitrogen gas to remove humidity from the µRWELL foil, we observed that small dents had formed in the drift foil, likely due to thermal expansion and gravitational sagging. This compromised the integrity of the drift gaps and prevented us from applying full high voltage. After some investigation, this problem was eventually overcome temporarily by drastically increasing the gas flow to create an overpressure in the detector that removed the dents and allowed us to continue HV training. Unfortunately, by the time this issue was resolved, the FNAL director had issued an order to stop all beam activities at the lab due to various safety and security issues encountered in other sections of the lab. Since beam did not return by the end of our assigned test period, we were not able to collect data with the detector.

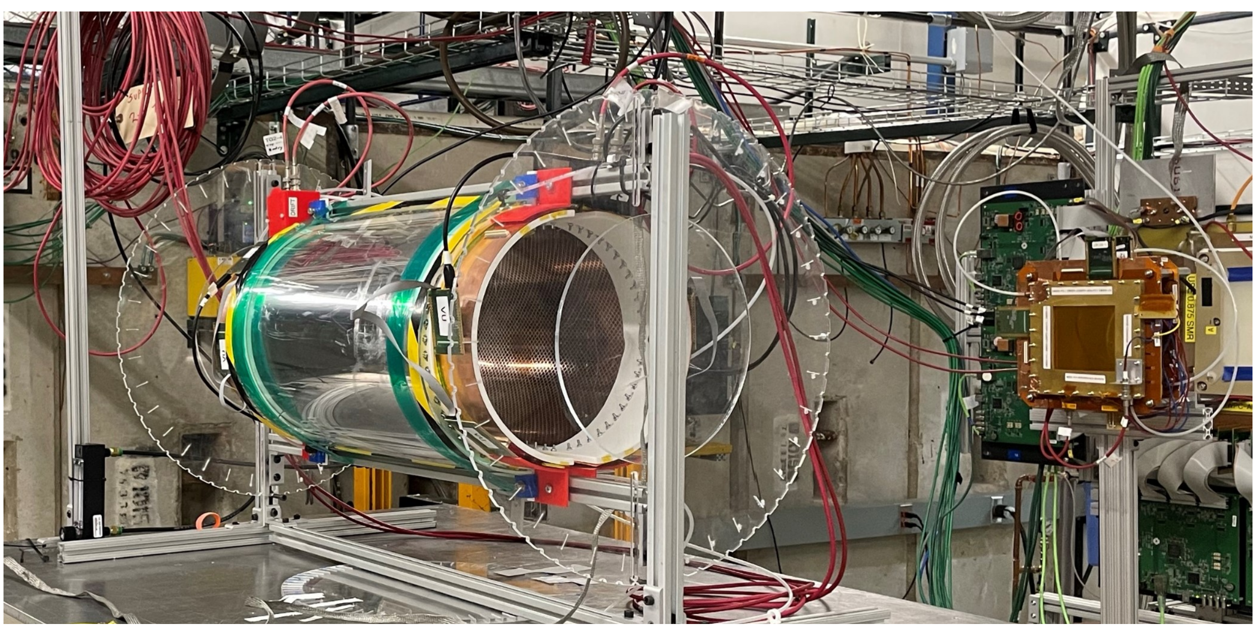

Figure 4: Cylindrical µRWELL detector and small downstream GEM tracking detectors placed in proton beam at FNAL testbeam facility (June 2023).

3.3 R&D Plans and Funding Request for FY24

We will investigate how to stabilize the drift foil and make the detector fully operational on an opportunistic basis. Potential remedies are employing a thicker drift foil, adding an axial rib that stiffens the outer clamp, or gluing the drift foil to a backing made from honeycomb material. If this succeeds, we will commission the detector and test it with radioactive sources, cosmics, and X-rays in our labs. As this detector was intended as a backup for the baseline cylindrical micromegas detector in ePIC with the intention to complete this line of inquiry in fall 2023, no further funding is requested for FY24.

4 ePIC endcap µRWELL layers

4.1 Motivation for endcap µRWELL layers

In May 2023, MC simulations showed that the ePIC tracking configuration in the endcap regions of the ePIC detector, which will experience the highest backgrounds in the experiment, will not provide enough hit points in the $|\eta| > 2$ region for good pattern recognition (Fig. 5 top).

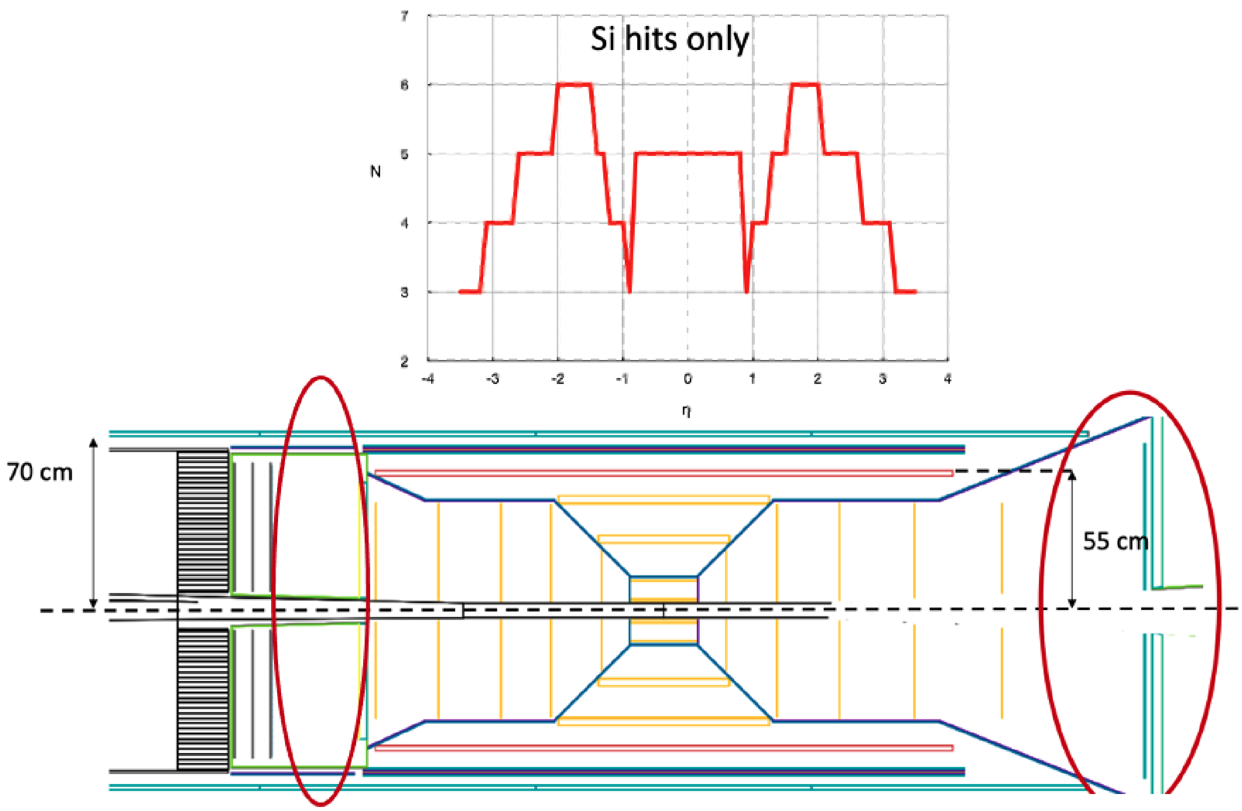

Figure 5: Top: Expected hit distribution with only Si trackers at endcap based on fast simulation [https://indico.bnl.gov/event/19481/]. Bottom: ePIC tracker geometry before June 2023.

In order to overcome this issue, in June 2023 the collaboration added two planar MPGD trackers in each endcap of the ePIC baseline tracker design (Fig. 6). This will not only increase the number of hit points available for pattern recognition, but will also complement the slower Si hits with fast hit points taking advantage of MPGD timing resolutions on the order of $\sim$ 10 ns, which will aid in background rejection.

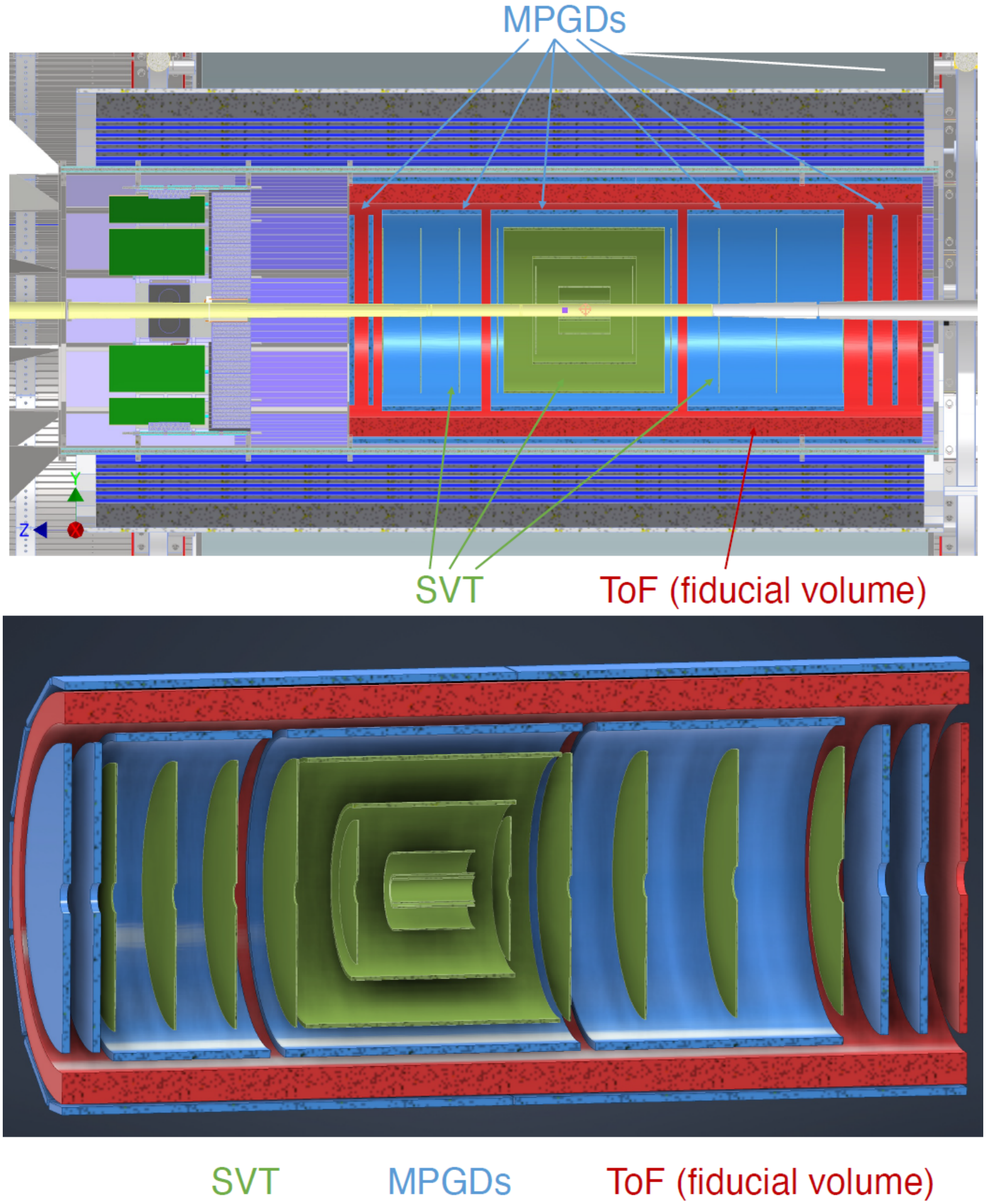

Figure 6: New ePIC tracker geometry (June 2023) with additional MPGD layers (light blue) that were recently introduced into the baseline design of the detector. Top: R-z view. Bottom: Cut-away view.

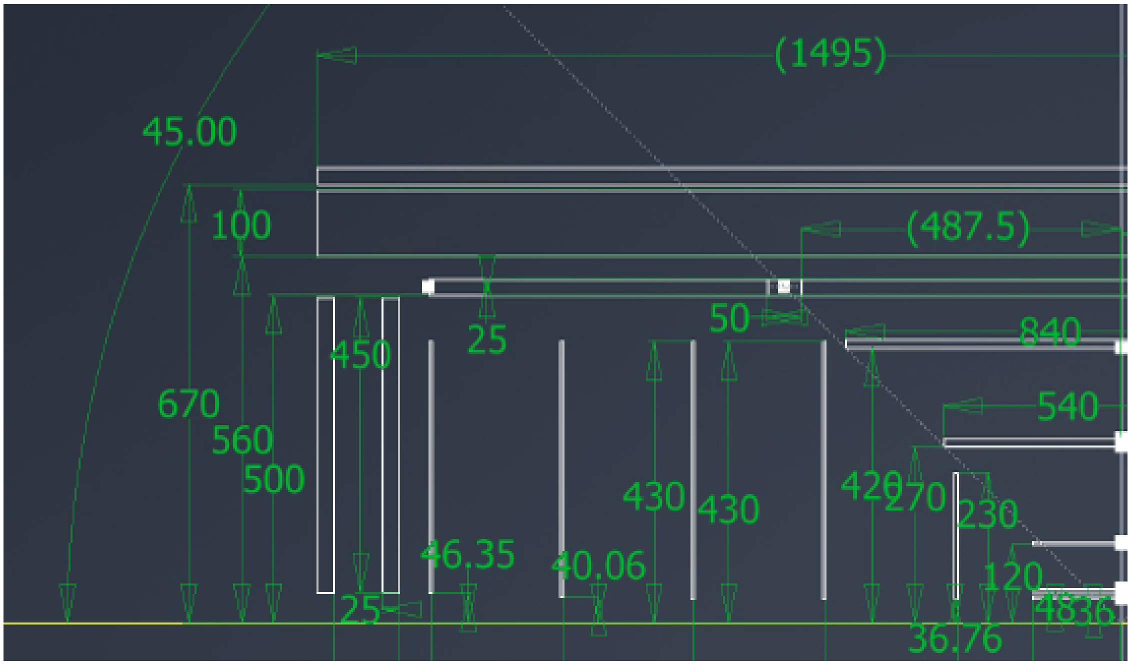

Figure 7: Subdetector dimensions in one quadrant of the current ePIC tracker design.

The new endcap MPGDs are circular disks with a central hole for the beam pipe. Fig. 7 shows that the backward endcaps have a radius of 500 mm and that the central hole has a radius of 50 mm. The forward endcap MPGDs have the same outer radius, but a center hole that has a radius of about 70 mm. As the width of the Cu-kapton foil base material for the µRWELL restricts one dimension of a µRWELL detector to about 550 mm, an implementation of the endcap MPGD trackers with µRWELLs would consist of two half-circular disks with "D-shaped" cut-outs for the beam pipe (Fig. 8).

4.2 R&D Plans and Funding Request for FY24

As EIC CD-2 and CD-3 are projected to be at the same date, with a corresponding major review assumed to occur in January 2025, EIC R&D will presumably stop before the end of 2024. This leaves one year or less for conducting R&D on the new endcap disks depending on when FY24 funds become available. This is not enough time to develop, build, and test a complete prototype as design, production, and delivery of just one new µRWELL foil will most likely take close to a year at the CERN MPT shop. **Consequently, we propose to focus on designing a two-dimensional readout with low channel count and on developing a low-mass but robust mechanical design for the full-size semi-circular detector geometry (Fig. 8).**

The newly joining INFN group, in collaboration with TU, will perform circuit layout work for the readout design. A two-dimensional read-out scheme for a half-circular geometry has never been implemented on µRWELL detectors before and poses a number of design issues that require detailed study. There are a number of possible options that could be suitable to optimize the resolution, acceptance, material budget minimization, and detector robustness:

- readout segmentation: radius and azimuthal coordinates vs. (X,Y) geometry;
- reduced number of readout channels: capacity sharing vs. traditional charge collection;
- 2D-readout optimization: charge sharing among 2 readout layers vs. two 1D readout layers;
- performance impact of electronics position layout: on-detector vs. off-detector using flex cabling.

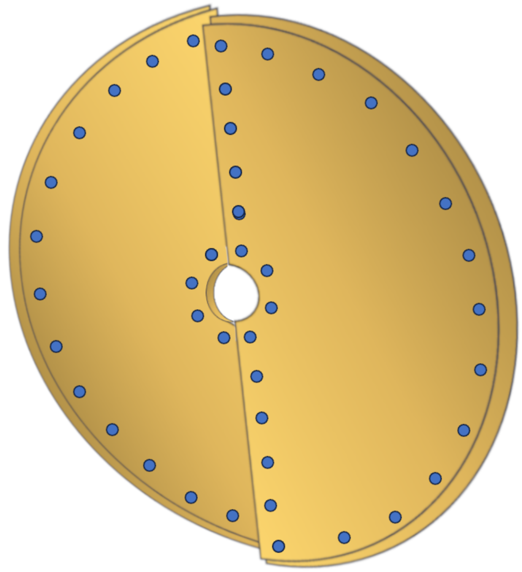

Figure 8: Conceptual design example for an MPGD endcap disk with stacked overlapping half-disks to maximize acceptance.

The INFN group will collaborate with the TU group to optimize the conceptual design of the endcap readout. INFN, in collaboration with TU, will be in charge of the CAD drawing of the multiple layers that will be needed to produce the µRWELL detector printed circuit. We request funding for a Ph.D. student at INFN to work on CAD under the supervision of an INFN expert.

The FIT and Vanderbilt groups will design, build, and test full-size prototype gas-envelope/foil-support structures, i.e. mock-up detectors, made from light materials and test them for stiffness and robustness to ensure integrity of the drift gap and gas tightness.

Specifically, FIT will investigate how carbon fiber (CF) material can be employed to this task and how charging up of the conductive CF material near HV electrodes can be avoided or mitigated. This is an issue that we previously encountered in eRD6 R&D with a large-size trapezoidal Triple-GEM detector made with CF frames. Due to the proximity of the drift cathode to the frames, the HV on the drift induced charges on the CF when the CF was electrically floating or grounded. The resulting field led to discharges between the drift and the frames. This could only be mitigated by putting the CF frames at a -2kV potential, which allowed us to operate the detector. Due to safety concerns this approach is clearly not feasible for a production detector running in a large experiment. We will investigate how to design a CF gas-envelope/foil-support structure for the semi-circular detectors that does not charge up. We will test this by installing a drift foil and a Cu-kapton foil as a stand-in for the µRWELL foil in the prototype gas envelope and applying HV. Using the same prototype, we will also investigate how best to stretch and support a drift foil over the 1m diameter of the detector to ensure uniformity of the drift gap size across the disk area, HV stability, and gas tightness.

Vanderbilt will explore the possibility of using very thin FR4 with a honeycomb sandwich and Delrin as gas enclosure. These two materials being insulators will help in mitigating the issue of charging up of Carbon Fiber. However, the ease of machining and also the hygroscopic nature of these materials need to be investigated with a mock-up structure for the gas enclosure. The gas tightness of the gas enclosure will be tested by using long-term gas flow through these sealed gas enclosures and monitoring both oxygen and water content in the circulated gas by using oxygen and humidity sensors. The same prototype will be used for testing various stretching techniques for drift cathode along with GEM foil to maintain a uniform drift gap along with High Voltage stability for the same.

We request funding for a Ph.D. student at FIT to work on the CF mock-up detector design, construction, and test and for materials to construct the mock-up detector.

4.3 Person-power required and available for FY24

- 0.5 FTE for CAD drawing; **Ph.D. student to be supported by this proposal;**
- 0.6 FTE for CF mock-up detector design, construction, and test; **Ph.D. student Pietro Iapozzuto available at FIT and to be supported by this proposal;**
- 0.4 FTE for readout design and optimization; 0.25 FTE research scientist from TU (in-kind) + 0.15 FTE research scientist from INFN (in-kind);
- 0.2 FTE for technical coordination and student supervision; INFN staff (in-kind);
- 0.2 FTE for CF R&D technical coordination and student supervision; FIT faculty (in-kind);
- 0.2 FTE for mock-up detector design, construction and test; research scientist from VU (in-kind).

4.4 Milestones and Timeline for FY24

Note: DJFR = Date JLAB Funding Received

Milestones related to the readout design:

- Design concepts definition for the endcap readout scheme (INFN, TU) - DJFR + 6 months
- CAD design of the endcap detectors readout (INFN, TU) - DJFR + 12 months

Milestones related to the mechanical design:

- Design of mock-up detector completed (FIT, VU) - DJFR + 4 months
- Construction of mock-up detector completed (FIT, VU) - DJFR + 8 months
- Test of mock-up detector completed (FIT, VU) - DJFR + 12 months

5 ePIC outer barrel µRWELL layer

5.1 Motivation for barrel µRWELL layers

The inner and outer MPGD based barrel layers address the same issues described in Sec. 4.1, providing fast timing hit information to aid in pattern recognition and provide signal-background discrimination. Additionally, the outer MPGD barrel layer will be located just in front of the hpDIRC, whose geometry will mimic that of the hpDIRC bars as illustrated in Figure 9, to provide a precision hit point to better determine the angle of the track entering the PID volume. This additional information will allow the hpDIRC PID reconstruction better determine the direction of the charged particle producing the Cherenkov radiation, and ultimately yield better PID performance. For this reason, the outer MPGD layers is required to have excellent spatial position resolution capabilities over the full pseudo-rapidity range covered by the hpDIRC in the barrel region. To achieve this level of performance, we plan to develop large-area and low-mass planar thin gap µRWELL prototypes with hybrid amplification GEM-µRWELL technology [1] with the focus on developing narrow support frame support structures and optimizing the cabling and services geometry requirement to simultaneously maximize detector acceptance and minimize integration challenges.

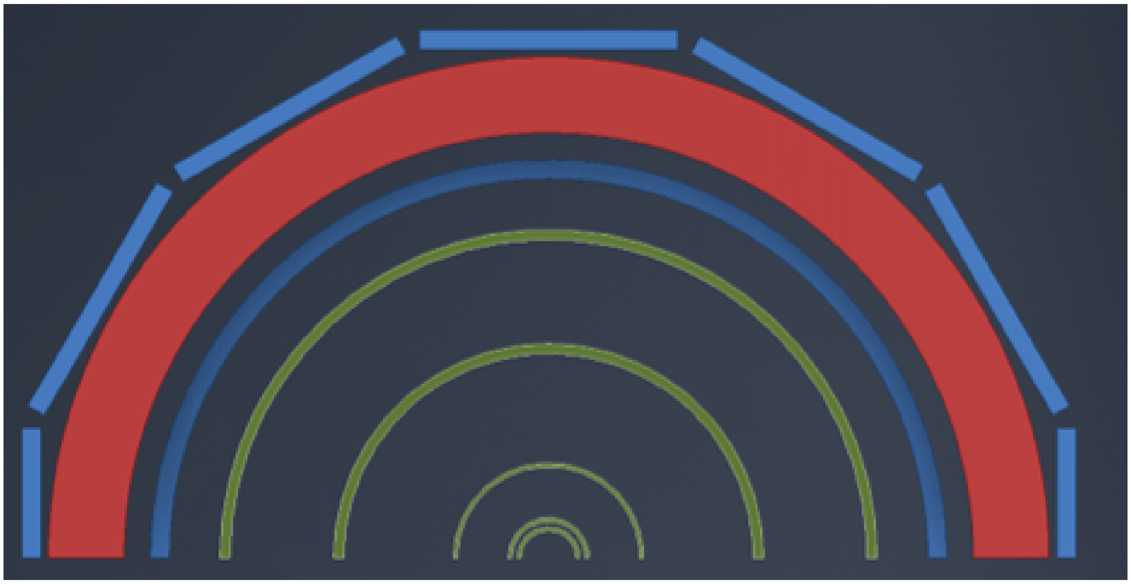

Figure 9: Front view of new ePIC tracker geometry (June 2023) indicating the MPGD layers (light blue) that were recently introduced into the baseline design of the detector. (Note that the ToF fiducial volume is indicated in red.)

5.2 R&D Plans and Funding Request for FY24

We propose to develop a low-mass, full-size (30 cm × 150 cm) planar detector aimed at achieving high spatial resolution and efficiency using the hybrid amplification GEM-μRWELL technology. Our proposal has two main focuses: (1) designing and building a full-size prototype to address challenges related to the stability of a large-size detector, while maintaining thin gaps (as small as 1mm) between the drift, GEM, and μRWELL layers, and (2) designing a two-dimensional μRWELL readout that conforms to the mechanical design of the prototype, thereby maximizing the active area of the detector.

The UVA group has successfully built various large-sized (120cm × 55cm, 150cm × 40cm) triple-GEM detectors with a 3mm drift gap for multiple physics experiments at JLab. These detectors rank among the largest detectors ever constructed and operated in nuclear particle physics experiments worldwide. However, developing a low-mass, high-efficiency, large-size detector with a 1 mm drift gap presents the next level of challenge. To investigate the stability of this detector's performance, the JLab and UVA groups will collaborate on the design and construction of a prototype. The prototype will utilize honeycomb, a low-mass material, as the main support frame for the detector. It will incorporate a standard Cu-kapton drift foil, a GEM foil, and a Cu-kapton foil as a mock-up μRWELL foil. Additionally, we will develop a stretcher and a foil stretching technique to ensure the flatness of each foil and maintain a uniform gap between adjacent layers in the detector. To evaluate the detector's stability, we will conduct HV tests on the prototype, varying the mixture ratios and flow rates of Ar/CO2 gas, as well as monitoring the gas pressure inside the prototype.

Both UVa and JLab groups will actively participate in the building and testing of the prototype. Simultaneously, the JLab group will concentrate on designing the two-dimensional μRWELL foil. For the UVA group, we are seeking funding to acquire the necessary materials for constructing the proposed Outer Barrel Planar Thin Gap Hybrid GEM-μRWELL prototype. Additionally, we request funding to support a Ph.D. student at UVA who will be responsible for designing and fabricating the prototype.

5.3 Person-power required and available for FY24

- Design the outer Barrel µRWELL readout scheme and GEM foil - 0.05 FTE (JLab scientist);
- Prototype CAD drawing, construction, and testing - 1 FTE (0.75 FTE by UVa PhD student supported by this proposal and 0.25 FTE by UVa undergrad student);
- Overall coordination of mock-up prototype design, construction and tests - 0.05 FTE (JLab scientist);
- Technical coordination of mock-up prototype construction, tests & student supervision - 0.3 FTE (0.15 FTE by UVa Faculty and 0.15 FTE by UVa Scientist);

5.4 Milestones and Timeline for FY24

Note: DJFR = Date JLAB Funding Received

Milestones related to the readout design:

- Design the outer µRWELL, readout scheme and GEM foil (JLab) - DJFR + 6 months

Milestones related to the mechanical design:

- Design of outer µRWELL mock-up prototype (UVa, JLab) - DJFR + 3 months
- Construction of outer µRWELL mock-up prototype completed (UVa) - DJFR + 8 months
- Test of the prototype (UVa - JLab) - DJFR + 12 months

6 Funding profile and split among the institutions for FY24

A breakdown of the funding request is shown in Tab. 1. In the case of university requests, fringe and indirect costs are included in the numbers in the table. A detailed breakdown of the request for each institution can be found in an excel sheet available at this link: Detailed Budget Breakdown (Google Sheet).

Table 1: **FY24 Budget request – Money matrix (includes overheads and IDCs).**

Institution	Endcap	Inner Barrel	Outer Barrel	Total per institution
BNL	-	-	-	$0
FIT	$36,218	-	-	$36,218
INFN	$25,000	-	-	$25,000
JLab	-	-	$22,500	$22,500
Saclay	-	$35,000	-	$35,000
TU	-	-	-	$0
UVA	-	-	$46,515	$46,515
VU	$14,925	-	-	$14,925
TOTAL	$76,143	$35,000	$69,015	$180,158

References

[1] K. Gnanvo et al. *Development of Thin Gap MPGDs for EIC Trackers.* https://www.jlab.org/sites/default/files/eic_rd_prgm/files/2022_Proposals/20220725_eRD_tgMPGD_Proposal_final_EICGENRandD2022_23.pdf. Generic EIC-related Detector R&D Program. 2022.