# eRD112 FY23 Report and FY24 Proposal on EIC AC-LGAD R&D

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## 1 Executive Summary

We requested $461k funding support and received the approval of $250k to work on AC-LGAD sensor and mechanical structure R&D for EIC AC-LGAD detectors in FY23. Below we summarize what we have done in FY23 and what we propose to do in FY24.

In FY23, we worked on several sensor productions at BNL instrumentation division (BNL-IO). Some of the sensors were characterized in the labs and at Fermilab test beam facility (FTBF). The previously reported issue of gain non-uniformity with BNL-IO production [6] has been significantly improved by continuously rotating the wafers during the implantation. This was first demonstrated by the sensors from the BNL production (6/2022-9/2022 and 6/2022-12/2022). These sensors were tested at FTBF in January 2023, followed by another test beam campaign in April 2023 for strip and pixel sensors from a newer BNL-IO production (8/2022-3/2023).

In FY23, we received prototype sensors from Hamamatsu (HPK) through a joint production with KEK through US-Japan collaboration. This is the first production for EIC by HPK, utilizing the knowledge and experience from their work for US-Japan collaborative R&D efforts in developing AC-LGAD sensors for High Energy Physics. The sensors were tested at FTBF in June 2023, where good timing resolution down to 35 (20) ps and spatial resolution below 20 um have been observed with strip (pixel) sensors. More detailed investigation to characterize the HPK sensors, and examine their irradiation tolerance has been planned.

In FY23, we have also worked on prototyping low-mass mechanical structure to achieve the 1% $X_0$ material budget requirement for the barrel TOF. A first prototype has been produced. Its mechanical property was measured and compared to finite element analysis results. More prototypes will be produced and analyzed using the remaining FY23 fund.

In FY24, we propose to continue the work to optimize the sensor design with the goal of improving the timing resolution and reducing the number of channels through prototyping with BNL-IO and HPK, and developing low-mass mechanical structure to meet the material budget requirement for the forward TOF and B0 tracker. We also propose to start looking into detector module design and assembly, by working with multiple vendors to produce module-size prototype sensors, investigating sensor-ASIC integration, and assembling prototype detector modules. These will be needed by the CD2/3 review.

Our total budget request in FY24 is $424k, as summarized in the table below. In the follow sections we give a detailed report on the FY23 work and FY24 proposal.

| Inst. | Labor (k$) | M&S (k$) | Total (k$) |
|---|---|---|---|
| BNL | 56 | 75 | 121 |
| UIC/FNAL | 20 | 20 | 40 |
| UCSC | 31 | 4 | 35 |
| Purdue | 30 | 5 | 35 |
| NCKU | 0 | 18 | 18 |
| HPK production | - | 80 | 80 |
| FBK production | 15 | 70 | 85 |
| Total | 152 | 272 | 414 |

Table 1: eRD112 total budget request for AC-LGAD R&D in FY24.

## 2 EIC AC-LGAD Detector Specifications

MC simulation studies have been performed for the EIC project detector using the latest simulation framework. This allows us to refine the AC-LGAD detector specifications as shown in Table. 2 below. The changes include the timing resolution of the barrel TOF from 30 to 35 ps, the material budget of forward TOF from 0.08 to 0.025 $X_0$, and the spatial resolution of B0 tracker from 140 to 20 $\mu m$. These define the R&D goals for individual detectors but we will continue to explore common designs for these detectors where possible to reduce cost and risk.

| | Area ($m^2$) | Time resolution | Spatial resolution | Material budget |
|---|---|---|---|---|
| Barrel Time-of-Flight | 10 | 35 ps | 30 $\mu m$ in $r \cdot \phi$ | 0.01 $X_0$ |
| Forward Time-of-Flight | 2.2 | 25 ps | 30 $\mu m$ in $x$ and $y$ | 0.025 $X_0$ |
| B0 Tracker | 0.07 | 30 ps | 20 $\mu m$ in $x$ and $y$ | 0.01 $X_0$ |
| Roman Pots | 0.14 | 30 ps | 140 $\mu m$ in $x$ and $y$ | no strict req. |
| Off-Momentum Detectors | 0.08 | 30 ps | 140 $\mu m$ in $x$ and $y$ | no strict req. |

Table 2: Specifications of AC-LGAD detectors for EPIC, the EIC project detector. The timing and spatial resolutions are given for single hits, while the material budgets are given per detector layer.

# 3 eRD112 FY23 Report

## 3.1 eRD112 FY23 Report - BNL

The wafers with AC-LGAD strips, whose processing began in summer 2022, were completed. Wafers from this batch are either 20 or 50 $\mu$m thick and with p-type high resistivity epitaxial substrate. These include strips and pixel geometries. An effort was made to address the non-uniformity issue measured on previous batches: the gain implantation was performed with the wafer continuously rotating, to average out the small variations in the gain dose delivered to the wafer.

A summary of the geometrical characteristics and multiplicity per wafer of the devices in this batch is given in Tab. 3.

| multiplicity | strip/pixel length (mm) | pitch ($\mu$m) | non-metal gap ($\mu$m) |
|---|---|---|---|
| 7 | 0.5 | 500 | 400 |
| 7 | 0.5 | 500 | 450 |
| 4 | 10 | 500 | 400 |
| 4 | 10 | 500 | 450 |
| 4 | 10 | 700 | 600 |
| 4 | 10 | zig | zag |
| 5 | 25 | 500 | 400 or 450 |
| 5 | 25 | 500 | 400 |

Table 3: List of AC-LGAD strip geometries produced by BNL.

After completion of the processing, wafers have been diced, devices have been tested at the probe station and those working have been distributed to the collaboration. Pictures of devices diced from the wafers are shown in Figure 1.

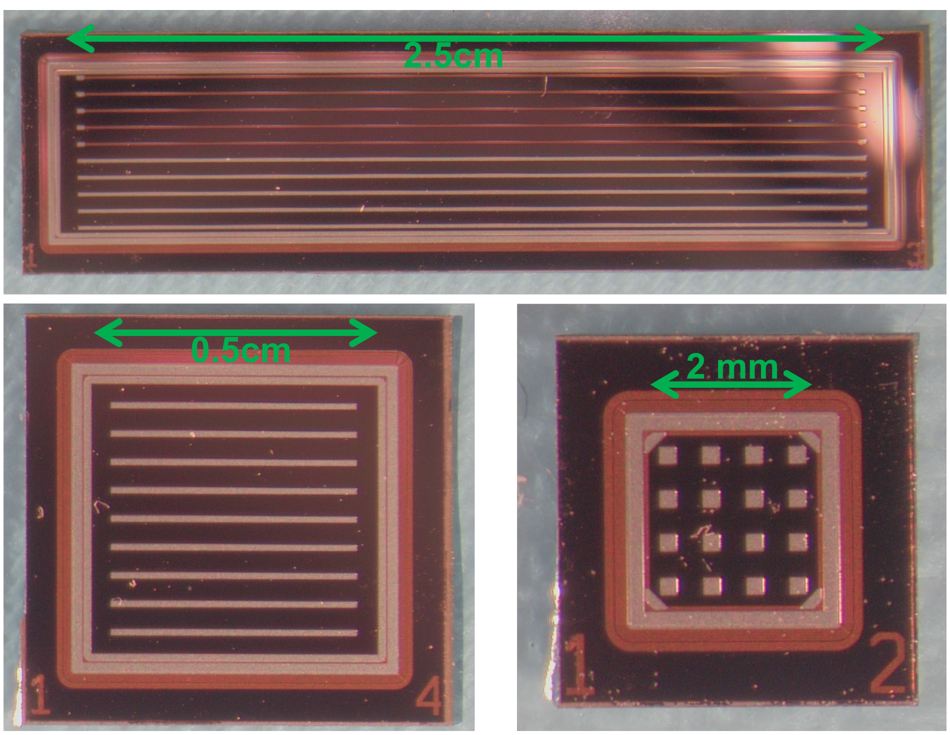


Figure 1: picture of some of the AC-LGAD strips and pixels inserted in the layout used for the wafers fabricated in FY23.

Furthermore, BNL fabricated a batch of EICROC-compatible AC-LGADs, such that the sensors can be bump-bonded to the ASIC. High-resistivity epitaxial p-type wafers with 20, 30 and 50 $\mu$m active thickness have been used, which make use of the standard wafer processing deployed in all LGADs and AC-LGADs produced by BNL. The process flow follows the one developed in previous years, with the exception of the passivation layer: in the old batches a photosensitive polymide layer was used, while in this new batch (and in the future ones) a dielectric stack of nitride and oxide (deposited by means of PECVD) has been used. Such sensors have a geometry compatible with the EICROC whic is a pixelated ASICs with a 4x4 pixel matrix and a pitch of 500 $\mu$m. Due to the small dimensions of the sensors, several of these structures have been placed on the wafers, allowing a variety of layout variations in the design. Such variations, include the size of the metalization of the electrodes (an in turn the non metalized gap size) and the geometry of the electrodes. They are summarized in the following:

- 4x4 arrays of 100 $\mu$m wide metal squares;
- 4x4 arrays of 200 $\mu$m wide metal squares;
- 4x4 arrays of 400 $\mu$m metal crosses, with 100 $\mu$m diameter inner circle for wire/bonding or bump-bonding;
- 4x4 arrays of 100 $\mu$m diameter metal circles surrounded by a 200 $\mu$m square frame.

A picture of some examples of such sensors is shown in Figure 2, together with the whole 4" wafer.

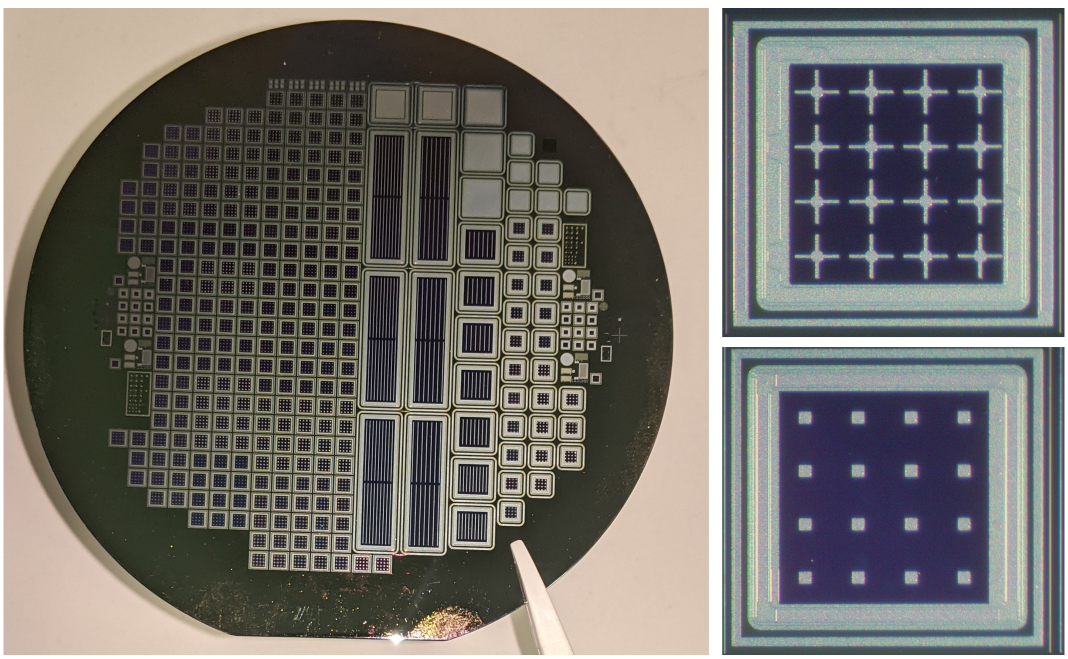

Figure 2: picture of the 4" wafers populated with small AC-LGAD sensor arrays compatible with EICROC0 chips. On the right there are examples of such sensors: arrays of crosses and 100-$\mu$m wide square pixels.

Besides the above-mentioned small-size pixel sensors with a geometry that is compatible with the bump-bonding with an EICROC0, the wafer is populated with other types AC-LGADs with larger areas or different pitches to study the uniformity of the charge collection on larger structures and study the charge sharing at different pitches, as listed below:

- devices with active area of 2 cm x 0.5 cm, with 1 cm long AC strips, either at a pitch of 700 $\mu$m or 500 $\mu$m: two 1-cm long strips are placed parallel the longer side of the device, 2-cm long;
- square devices with active area of 0.5 cm x 0.5 cm, with 0.5 cm long AC strips, either at a pitch of 700 $\mu$m or 500 $\mu$m;
- other test structures for process qualification.

Devices, after being selected by means of static characterization at the probe station (I-V and C-V scanns), have been distributed to the collaboration.

Additional wafers are under production. They feature a different metal layout that takes into consideration the inputs receive by the collaboration. This change requires only the redesign and the purchase of two new photolithographic masks of the the metal and the opening of the passivation for the top (and final) layers of a wafer. The rest of the design and the process is unchanged.

Furthermore, additional wafers are in fabrication and feature a gain with a higher implantation dose, in an attempt to increase the gain of the device (now limited to 60 for DC-LGAD).

## 3.2 eRD112 FY23 Report - UIC/FNAL

The UIC and FNAL team has led the experimental study of prototype AC-LGAD sensors. The results on the first centimeter-scale AC-LGAD strip sensors produced by BNL-IO for EIC, which were reported in the last year report [6], have been published in a journal article [7].

In FY23, UIC and FNAL groups conducted a series of test beam campaigns to characterize sensors produced by BNL-IO and HPK at FTBF (see Fig. 3). These include the long strip sensors from the BNL-IO production (6/2022-9/2022 and 6/2022-12/2022) that were tested at FTBF in January 2023, strip and pixel sensors from the BNL-IO production (8/2022-3/2023) that were testsed at FTBF in April 2023, and strip and pixel sensors from the first HPK production that were tested at FTBF in June 2023.

Excellent hit efficiency, timing resolution down to 20 (34-35) ps and spatial resolution below 20 um across the whole sensor have been observed with HPK E-type pixel (1-cm long strip) sensors with 500 $\mu m$ pitch, as shown in Fig. 4. A systematic difference (not shown) has been observed between the E-type and C-type HPK sensors, with the latter exhibiting smaller signal amplitude (by about 1/3) and worse timing resolution (37-41 ps) that can be attributed to more signal sharing due to smaller resistivity in the n+ layer. No noticeable difference has been observed in the timing resolution between strip sensors with different AC-coupling capacitance (240 vs 600 pF/mm$^2$) or different metal width. We note that sensors from BNL-IO typically exhibit a smaller signal amplitude (by about 1/2) and worse timing resolution (40-44 ps) than the HPK E-type sensors, but close to the HPK C-type sensors.

These preliminary results of HPK sensors represent a significant improvement w.r.t the results presented in our previous report based on the first BNL sensors [7]. They are close to the specifications for EIC AC-LGAD detectors listed in Table. 2, i.e. 25 (35) ps timing resolution and 20 $\mu m$ resolution for pixel (strip) sensors. More detailed analysis and follow-up studies including TCAD simulations, lab and irradiation tests have been planned, as discussed in the FY24 proposal.

An infrared laser test stand at UIC has been calibrated to give the same signal amplitudes as the test beam. In such conditions, we have observed (not shown) similar level of timing and spatial resolutions from the laser-induced signals as those from test beam. We will utilize this test stand in future sensor characterization studies, allowing a fast feedback on sensor performance before dedicated test beam campaigns which are not always readily available.

## 3.3 eRD112 FY23 Report - UCSC

In the area of sensor development, in FY23 the Santa Cruz Institute for Particle Physics (SCIPP) at UC Santa Cruz (UCSC) contributed to studies geared towards the understanding of charge sharing and position resolution for AC-LGADs, and the effects of strip geometry on these characteristics. The group made use of several techniques to provide feedback to labs developing and fabricating AC-LGADs, including lab-bench measurements of electronic characteristics (CV, IV) and sensor response (making use of a highly-focused, fast pulsed laser system) and test beam data from the FNAL test beam facility. Furthermore, the group refined 2D and 3D sensor simulations in two proprietary TCAD frameworks (SILVACO and Synopsys Sentaurus) that are showing promise to be able to guide further optimization of sensor parameters for EIC applications.

For the laser Transient Current Technique (TCT) testing sensors are mounted on Fermilab 16-ch testing boards and read out by a fast oscilloscope (2 GHz, 20 Gs). The goal of the measurement is to emulate the signals from charged particles but in a more convenient laboratory setting with a faster turnaround. The downside is that the laser cannot penetrate the metal electrodes, therefore the sensors can only be studied in between the metal. Sensors mounted on boards are excited with an infrared (IR) 1064 nm pulsed laser with a pulse temporal width of 400 ps. The laser beam is

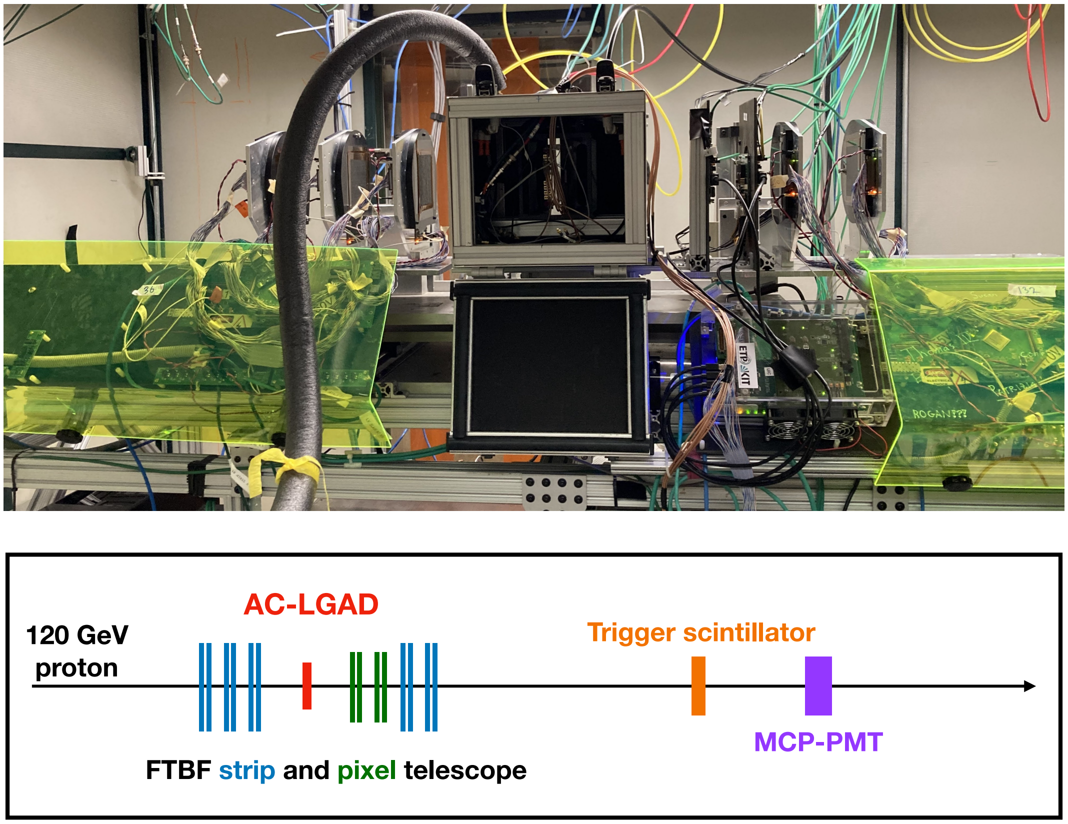


Figure 3: Picture (top) and diagram (bottom) of the FTBF silicon telescope and reference instruments used to characterize AC-LGAD performance. The telescope comprises five pairs of orthogonal strip layers and two pairs of pixel layers, for a total of up to 14 hits per track.

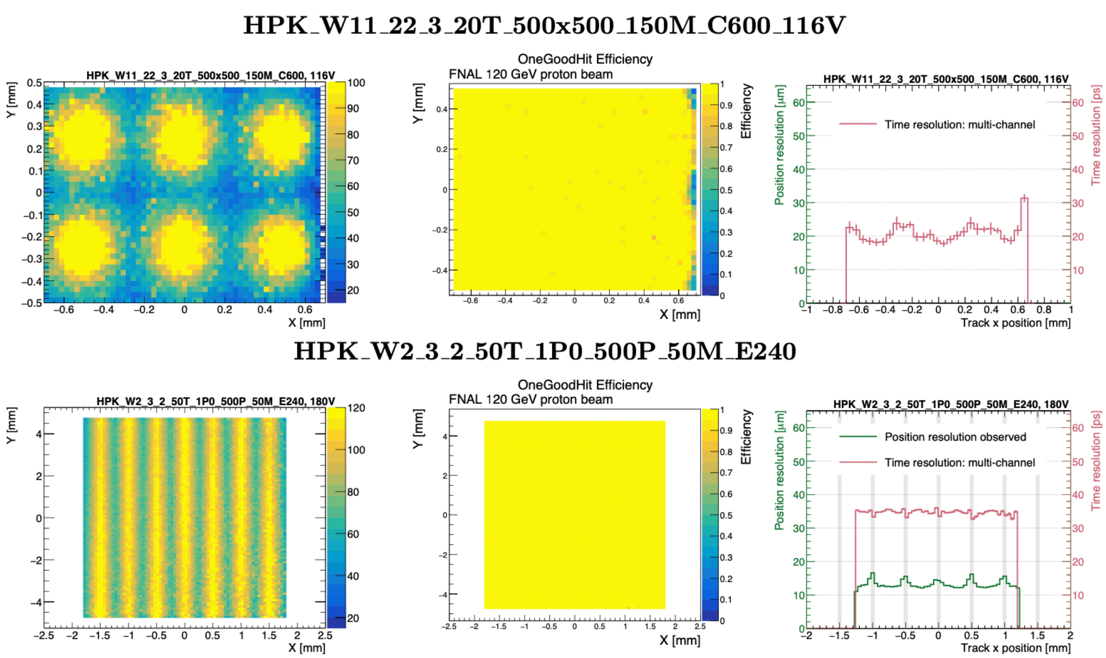


Figure 4: Performance of a HPK pixel (top) and strip (bottom) sensors measured in the FTBF test beam. Left: signal amplitude; Middle: efficiency; Right: timing (and spatial) resolution.

focused by a lens system that can produce a laser spot of 10-20 $\mu m$ on the surface of the sensor. The analog board is mounted on X-Y moving stages so the response of the sensor as a function of laser illumination position can be evaluated. X-Y 1D/2D scans of the sensors are taken with the system: for each position in the position grid, an average waveform is registered for each readout channel. The characteristic charge-sharing properties of AC-LGADs were probed for strips of different width, pitch, and length. Issues of non-uniformity in the sensor response, diagnosed as non-homogeneities in the sensor gain layer, have been improved in the recent BNL sensor productions compared to the sensors tested in FY22. An acceptable level of nonuniformity will have to be defined by the collaboration.

Strip sensors with varying strip lengths and pitch from a BNL AC-LGAD prototype production were characterized using the TCT test bench. From this production, sensors were produced with thicknesses of 50 and 20 $\mu m$, strip lengths of 0.5, 1, and 2.5 cm, and strip widths from 100-300 $\mu m$. Direct comparisons of similar geometries show that longer strips have increased charge sharing. For 50 $\mu m$ sensors, charge sharing was measured to be significant up to the second neighboring channel for strip lengths of 1 cm and reduced for the shorter 0.5 cm strip lengths as shown in Figure 5 (right). For 20$\mu m$ thick sensors, the effect of charge sharing was significant up to the second neighboring channel, but was similar between the two strip lengths as shown in Figure 5 (left). For the sensors fabricated with 2.5 cm strip lengths, significant charge sharing was observed up the fifth neighboring channel. Thus, it can be concluded that in order to ensure sufficient signal height and timing resolution, unless significant reduction in charge sharing could be achieved e.g. by increasing the N+ layer resistivity, the longest acceptable metal length for AC-LGAD strips in the ePIC detector is likely limited to around 1 cm. This is currently the barrel-TOF sensor baseline.

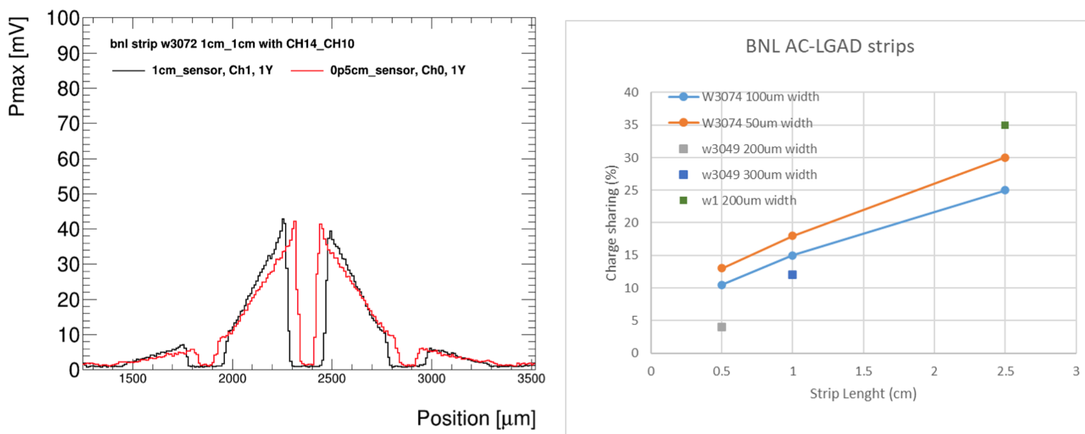


Figure 5: (Left) Effect of charge sharing for BNL sensors with thickness of 20 $\mu m$ with strip lengths of 0.5 cm and 1 cm. (Right) Summary plot of charge sharing % after the first neighbor as a function of strip length, for several 20 $\mu m$ and 50 $\mu m$ BNL prototypes.

Several BNL prototypes were electrically characterized in a probe station. The AC capacitance of the AC strips and the inter-strip capacitance were measured for several strip lengths and pitch/width. It was found that AC capacitance can go up to 100s of pF and generally increases with strip length and width. The inter-strip capacitance has a similar behavior in the tested prototype, but is higher than the corresponding AC capacitance, with the highest value measured at around 1000 pF. All tested wafers from BNL exhibit a large (orders of magnitude) frequency dependence on both AC and interstrip capacitance that is still to be understood, as various sensor capacitances are essential inputs to the front-end electronics design.

3D sensor simulations with TCAD were further improved to study the impact of various AC-LGAD design parameters on signal sharing. Increased doping in the N+ layer had been found already earlier in 2D simulations to increase the charge sharing as shown in Figure 7 (left). It was now more firmly established that 3D simulations are needed to observe the increased charge-sharing effect with longer strip lengths observed in the experimental data, and fine-tune the sensor simulation models accordingly. In this process, the studies were still focused on 50 $\mu m$ thick sensors. Figure 7 (middle;right)

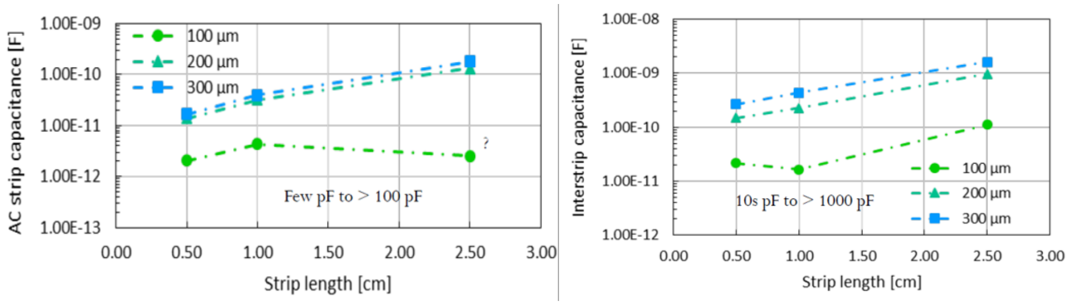


Figure 6: AC strip capacitance (left) and inter strip capacitance (right) for several AC-LGAD strip prototypes from BNL.

demonstrate the strongly increased charge sharing for strip lengths of 2 cm. It was also determined that the signal induced away from the electrode had a longer time delay with higher resistances of the N+ layer, ultimately affecting the time of arrival of the signal.

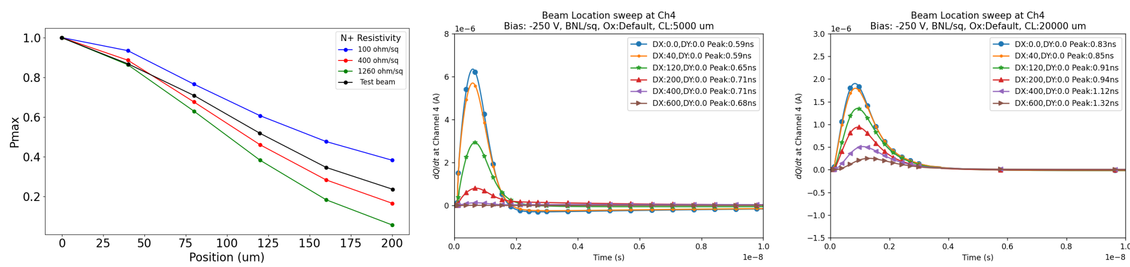


Figure 7: Simulations of charge sharing for a 50 $\mu m$ AC-LGAD with variations in the resistance of the N+ layer (left). The impact of strip length on signal sharing is pronounced (middle - 5 mm, right - 2 cm). Results were obtained using the 3D TCAD Sentaurus simulation framework.

## 3.4 eRD112 FY23 Report - Purdue

In FY 2023 Purdue received k$15+5 in R&D funds to study the mechanical design of the barrel TOF support staves. The funds only arrived in April 2023 and by the time of this report (June 2023) we have been able to manufacture a very first prototype of the stave. Figure 8 shows the first prototype of the barrel TOF stave under load of one pound with a deflection of 1.7cm for a 1.35m long stave. We used FEA simulations tied to the loading test data and determined that a full length stave of 2.4m length only supported at either end is deflecting by around 5cm which will break the structure. Additional support by the larger cylindrical support structure of the barrel TOF can mitigate that deflection down to around 700 micrometer.

We have subjected the prototype structure to loading test using a realistic scenario and compared to FEA studies as well. The actual results and the FEA studies have been highly useful in composing the PED request submitted in 2023. As of the date of submission of this report no thermal tests had been done, but we anticipate these to happen in the coming months.

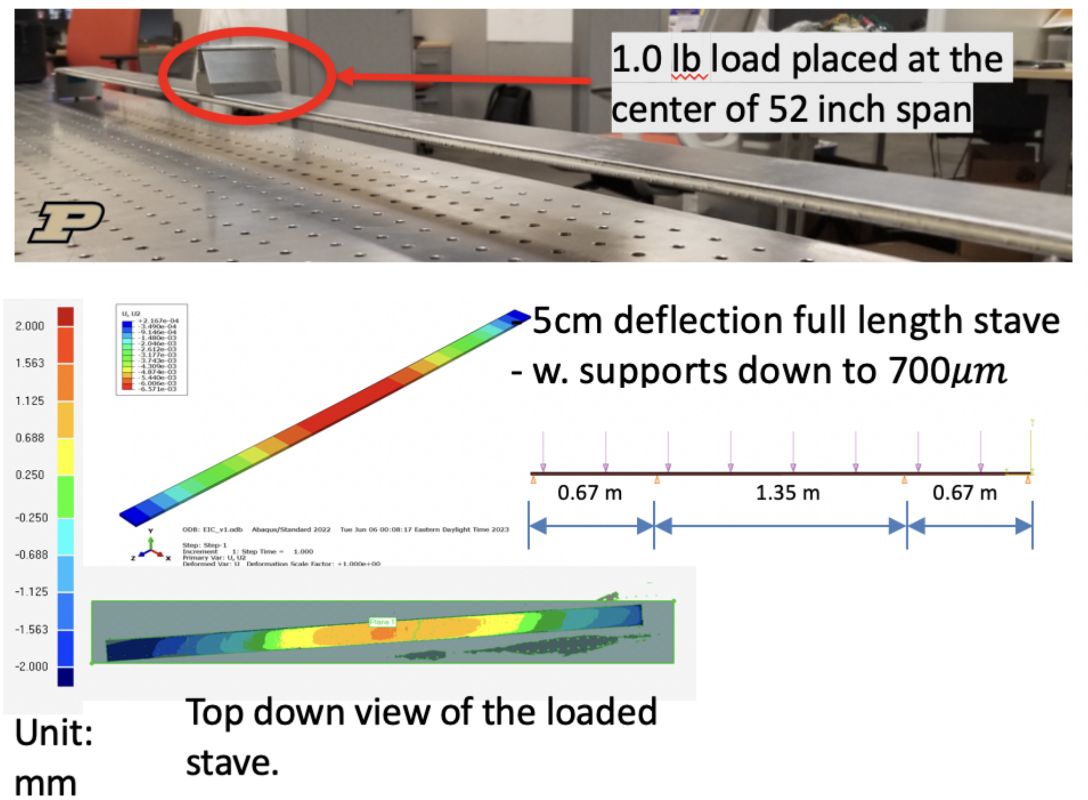


Figure 8: First prototype of the barrel TOF stave structure under load and compared to results determined by an FEA.

# 4 eRD112 FY24 Proposal

## 4.1 eRD112 FY24 Proposal - BNL

The BNL effort in eRD112 is multi-faceted. It includes the following broad activities:

- Design and fabrication of AC-LGAD sensors,
- Testing of AC-LGAD sensor performance,
- Sensor Quality Assurance (QA),
- Assembly and testing of readout electronics.

### 4.1.1 AC-LGAD Design and Fabrication

BNL will continue the **design and fabrication of batches of AC-LGADs** in its class-100 clean-room dedicated to silicon sensor processing. Sensors will be designed and fabricated with optimized geometries and improved process to meet the requirements emerging from the collaboration inputs.

Batches will be fabricated on the standard p-type silicon epitaxial substrates used in previous BNL productions and will feature different active thicknesses, such as 20, 30 and 50 $\mu$m. The design will be modified according to the requests of the collaborators, which are based on the experimental results obtained in laboratory and test-beam measurements. Therefore, new masks sets will be designed and then purchased for the top metal layer of a wafer, which implements the electrode segmentation of the sensors. If tests of the latest batches still in fabrication are successful, the gain layer implant energy will be increased to augment the gain to values greater the one hundred. Experimental results showed that a larger gain is needed as in AC-LGADs the signal from a particle hit is induced to several adjacent electrodes, with lower amplitudes in all of them than in DC-coupled LGADs. A modified implant dose of the resistive n-layer can also be accommodated, to fine tune such signal sharing among nearby electrodes. For example higher implantation doses on the n-layer lead to lower resistivity and in turn a larger signal sharing, which may be beneficial in some applications, e.g. barrel TOF. It must be stressed that variations in the dose of the n-resistive layer will require modification of the gain layer dose too. This can be, to a certain extent, simulated in TCAD; simulations will be carried on at BNL, using the TCAD Silvaco platform, but it is wise to check results with collaborators running the same simulations on a different software (e.g. UC Santa Cruz, running simulations on TCAD Synopsys platform). To help the accuracy of the simulations, SIMS tests will be carried out to measure the actual doping profiles on sacrificial sensors and input this information into the simulations.

Various and optimised strip geometries will be designed to outperform the geometries of old batches, which have been extensively studied in collaborating laboratories and at test beams. Aim of the optimization is timing, while keeping the number of read-out channels as small as possible, in an effort to limit the power budget. In addition, pixel geometry will be varied for an optimization of the signal sharing, e.g. varied pitch, and timing. Pixel sensors bump-bond compatible with the available read-out chips (most notably EICROC) will be produced.

Another requirement raised by the collaboration is the use of a double metal to re-route the signals from the strips to the read-out chips. As the ASICs will be mounted parallel to the strip, a second metal layer will connect a strip to a pad at the border of the sensor. From here, short wire bonds will make connections to the input pads of the ASICs. Such solutions avoids the use of large bonding pads scattered on the length of the metal AC-strips, which may be very narrow to maximise the signal sharing. Such a novel double metal design will avoid the use of long (and impractical) aluminum wire-bonds, which may deteriorate the signal quality, especially for timing.

### 4.1.2 AC-LGAD wafer and sensor testing

After fabrication, **devices will be tested for functionality** by means of current-voltage and capacitance-voltage characterizations (I-V and C-V) and then distributed to collaborators for further detailed testing. At BNL, not only the static characterization at the probe station, but also functional tests with laser beams (TCT scans) and with radioactive sources, such as Sr-90 etc., will be carried out. More specifically, we will be using an IR lnd a red laser to measure gain and uniformity of the signal. and Sr-90 to test the response to minimum-ionising particles

#### 4.1.3 Quality Assurance tests for AC-LGAD sensrs

We also plan to carry out **QA long-term and stress-test reliability studies** of AC-LGADs in an ambient chamber at various environmental conditions. More specifically, we will test AC-LGADs kept under bias voltage over periods of months, at different temperatures, ranging from $-60°$ C to $+180°$ C and under different humidity conditions. Under these extreme conditions we will carry out I-V and C-V scans and collect signals from beta particles from a Sr-90 source to study any deterioration in noise or charge collection. In addition, we will study and optimise means of transportation of the sensors to minimise charge build up and early mortality. Such tests hare 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 plan to test BNL-made sensors post-irradiation**. We have developed a collaboration with UNM and Los Alamos that allows us to irradiate AC-LGADs at various fluences in a proton beam at LANSCE and in a gamma beam at SANDIA, and then test them in a cold probe station that we have re-furbished at BNL: post-irradiation I-V and C-V scans at cold temperatures, i.e. $-30°$ C.

#### 4.1.4 Assembly and readout characterisation of AC-LGADs with ASICs

In addition, the BNL team will **assemble and test modules of EICROC and AC-LGAD, either bump- or wire-bonded**, for characterizing the read out functionalities of the assembly of the sensor+ASIC. Several of these assemblies will be distributed to collaborators in the consortium and a sufficient number of them will be kept at BNL for in-house testing with pulse generators, lasers and radioactive sources. So far BNL has been the only institute outside the developers in France to test the EICROC0 ASIC. The plan is for BNL to build expertise in such testing and then propagate the acquired knowledge to collaborating institutes.

#### 4.1.5 BNL summary

In summary, for FY24 we propose to perform the following tasks:

- Design and fabrication of AC-LGAD strip sensors with optimized geometry for timing;
- Optimization of geometry and process parameters to reduce the number of channels in AC-LGAD detectors;
- Fabrication of pixel sensors with optimized geometry for timing and signal-sharing compatible with the read-out ASICs being developed;
- Introduction of second metal for re-routing of signals.
- QA tests after irradiation with protons and gammas;
- QA stress-tests in different and extreme environmental conditions;
- Assembly and testing oc AC-LGAD+EICROC modules.

#### 4.1.6 BNL budget request

Here follows a table with the funding request by the BNL team for the above-mentioned activities.

| Inst. | Activity | FTE | Budget (k$) |
|---|---|---|---|
| BNL | 2 batches of Sensor design/fabrication | mult. | 75 |
| BNL | Wire/bump-bonding, module assemblies | 0.10 (Tech) | 20 |
| BNL | wafer dicing, testing, test-board/module testing | 0.10 (Tech) | 20 |
| BNL | sensor QA and ASIC testing | 0.25 (UG) | 6 |
| Total | | | **121.0** |

Table 4: BNL FY24 budget request for eRD112 activities that serve the whole consortium, including sensor fabrication, sensor+ASIC module and test-board assemblies, wire- and bump-bonding, sensor QA tests as well as ASIC testing. All entries in thousands of dollars.

## 4.2 eRD112 FY24 Proposal - UIC/FNAL

UIC/FNAL team has led the work on characterizing BNL and HPK AC-LGAD prototype sensors with infrared laser and beam and delivered the relevant results to quantify the sensor performance in timing/spatial resolutions and gain uniformity, as described in section 3.2. In FY24, we will continue such work on prototype sensors. We request $25k at the same level as last year to cover the cost, as outlined in Table. 5 below.

| Resource | Task | FTE (%) | Budget (k$) |
|---|---|---|---|
| UIC Faculty | coordination, detector design | 15 | 0 (in-kind) |
| FNAL Scientist | coordination, lab/beam tests | 5 | 0 (in-kind) |
| Postdocs | lab/beam tests | 20 | 0 (in-kind) |
| Graduate Students | Sensor simulation, lab/beam test | 50 | 0 (in-kind) |
| Undergraduate Student | 3D printing | 15 | 0 (in-kind) |
| Electric Technician | test board assembly | - | 15 |
| Materials and Supplies | test beam setup | - | 5 |
| Travel | beam test | - | 5 |
| Total | - | - | **25** |

Table 5: UIC budget request for FY24 on sensor R&D. All entries in thousands of dollars.

In addition, we propose to look into sensor/ASIC integration options that enable connecting strip sensors and pixelated frontend ASICs, or pixel sensors and pixelated frontend ASIC with different pixel sizes. This effort was included in our previous proposal last year but was not included in the final request to allow funding support to other more urgent requests at that time. We believe this would be faciliate testing of various sensors with the same ASIC in the current R&D phase, and provide a possible solution for sensor/ASIC integration in the construction phase. We will design and fabricate Silicon- or PCB-based interposers, which will be bump-bonded to pixelated ASICs from one side and then wire- or bump-bonded to strip or pixel sensors with different pitch sizes from the other side. We request $15k to cover the cost, as outlined in Tabl. 6 below.

| Resource | Task | FTE (%) | Budget (k$) |
|---|---|---|---|
| Electrical Engineer | interposer design | 5 | 5 |
| Graduate students | interposer testing | 25 | 0 (in-kind) |
| M&S | interposer fabrication and bonding | - | 10 |
| Total | - | - | **15** |

Table 6: UIC budget request for FY24 on sensor/ASIC integration. All entries in thousands of dollars.

The UIC/FNAL deliverable in FY24 will include:

- Lab/beam testing results for new AC-LGAD sensors from BNL and HPK.
- Prototype interposers that connect strip/pixel sensors with pixelated frontend ASIC.

## 4.3 eRD112 FY24 Proposal - UCSC

As a collaboration, the EIC detector groups are pursuing timing resolution for minimum-ionizing particles that is significantly better than has been achieved for large HL-LHC applications. We have yet to demonstrate a detection system, or a clear path towards one, that can do meet stated EIC goals. Thus, integrated R&D must continue on both sensor technologies and readout schemes.

As FY24 approaches, a number of sensor design issues and production concerns remain unresolved:

- In order to achieve the required timing resolution, it may be necessary to reduce intrinsic charge-deposition fluctuations by making use of thinner (20 $\mu$m vs. 50 $\mu$m bulk) sensors; the exploration of the performance of 20 $\mu$m sensors is intertwined with the availability of adequately optimized readout systems, and is thus in the early stages of exploration
- Optimal fabrication parameters, especially the N+ sheet resistance, have yet to be determined

- The radiation hardness of AC-LGAD sensors needs to be verified
- There is currently only one commercial institution (HPK) participating in the development of AC-LGAD sensors for the EIC. In order to minimize risk for the eventual final production run, the standard practice is to work with multiple vendors to develop production-level capabilities for the fabrication of full-size sensors.

Here, we propose a program that can leverage a body of ongoing effort to help provide an efficient path towards the optimization of AC-LGAD sensors for applications in the EIC TOF-PID system and to engage a medium-scale semi-private vendor (Fondazione Bruno Kessler (FBK), Trento, Italy) in the process of engineering production-scale sensors for the EIC.

### 4.3.1 Detection System Characterization and Issues

Because sensor performance is enmeshed with the characteristics of the readout circuitry, it will be necessary to test prototypes as they become available both with standard "benchmarking" readout (SCIPP single-channel board, FNAL 16-channel board) as well as with the evolving readout ASICs as they become available. Figure 9 shows, for example, the PCB developed at SCIPP to interface the HPSoC prototype with sensor prototypes. Similar systems are available as SCIPP for testing new sensor prototypes with the ASROC and FAST chips, and SCIPP would readily include testing with the EICROC as part of its proposed program for FY24 if the collaboration felt it helpful.

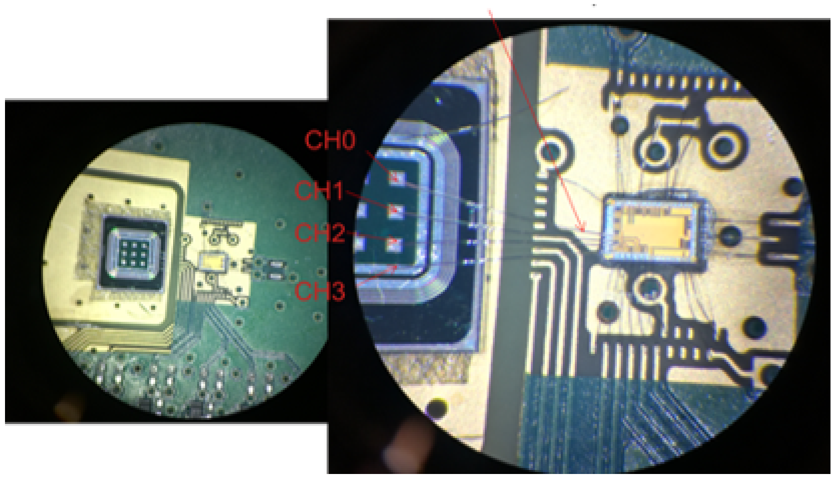


Figure 9: Micrographs of the prototype HPSoC ASIC, assembled on its characterization board, with its four inputs bonded to pixels in a 3x3 AC LGAD array.

During FY24, sensor development is expected to continue, with a corresponding need to characterize the sensors and their interfacing with readout schemes, and to provide guidance for the final refinement of sensor properties and to qualify prototypes as production-ready. A new set of HPK prototypes from the EPIC production run is expected soon, and the sensor R&D program continues at BNL. An important part of the characterization studies will be the evaluation of the uniformity of the sensor response across the wafer, and the identification and evaluation of problematic areas. Through its seminal role in the development of AC-LGAD technology, as well as its participation in the development of sensors for the timing layers for the ATLAS and CMS detectors, the SCIPP group brings a deep expertise to bear upon the LGAD detector characterization and development program.

In addition, as the development of the sensors and their readout electronics matures, a new level of system development and integration issues will arise. Scaling from small-scale to full-scale prototypes will need to be verified, and the development of hybrids, interconnect strategies and signal transport and transmission schemes will need to be worked out. Again, the SCIPP group has a deep expertise from its work on various ATLAS tracking systems, including the HGTD, and will be a natural partner in the development and review of proposed approaches.

#### 4.3.2 TCAD Studies

TCAD simulation studies have emerged as an important tool in the development and use of advanced sensor systems. Over the past two years, the SCIPP group has developed and tuned simulation models of LGAD sensors in both the Silvaco and Sentaurus packages, and have begun to develop confidence in these models as design tools. For example, Figure 7 shows the result of a TCAD simulation of AC-LGAD charge-sharing behavior as a function of the sheet resistance of the N+ layer and strip length. The simulation of the N+ shows good reproduction of the general shape of the charge-spreading function, and an ability to provide an approximate measure of the N+ sheet resistance of a physical sensor, which is generally not well known during fabrication.

Fabrication parameters such as sheet resistance, gain layer doping level, etc., provide a large space from which an optimum must be derived. Increasingly, we are confident that TCAD can provide important guidance in navigating that space. In FY24, simulations will focus on 20 $\mu$m bulk sensors, the intended default sensor thickness for ePIC agreed upon during FY23. Our simulation studies will be directed towards remaining open questions in sensor geometry design: determining the optimal strip width at a pitch of 500 $\mu$m in the barrel TOF to complement test beam data, as well as examining the potential increase in pixel pitch for the endcap TOF AC-LGAD layer from 500 to 700 $\mu$m, which holds promise to reduce the number of readout channels in ePIC. We collaborate closely with BNL on this work and will provide simulation studies to guide their further refinement of their upcoming prototype sensor runs.

#### 4.3.3 Irradiation Studies

Much work has been done to characterize and improve the radiation resistance of LGAD gain layers, in order to meet the requirements imposed by forward timing at the LHC (up to $2.5 \times 10^{15}$ $n_{eq}/\text{cm}^2$). However, no studies have yet been done on the reaction of AC-LAGDs to even the modest levels of radiation expected for EIC sensors. 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 $1 \times 10^{14}$ is accumulated.

As a result, it is important to execute a radiation exposure run before the EIC LGAD design is finalized. The SCIPP group proposes to collaborate in such a run at the LANSCE accelerator at LANL (500 MeV protons) and lead one at the TRIGA reactor in Ljubljana (MeV-scale neutrons). 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.

Another effort is to attempt 'graded' irradiation of the device: as already stated, even low-fluence irradiation can affect the N+ resistivity, and there might be an aberration effect in the charge sharing if the irradiation is not homogeneous (especially in the case of the forward AC-LGAD detector). This would result in a hit recognition that is skewed in one direction and changes with operation time. The graded irradiation can be performed at LANSCE (the beam profile is shown in Fig. 10, left) to obtain a different fluence between two edges of a large sensor (Fig. 10, right). A 5 mm wide strip detector (of which prototypes from BNL are available) can serve this purpose and have a factor 2 fluence difference in the direction perpendicular to the strip. By studying the sensor performance before and after irradiation the change in N+ resistivity can be characterized and this particular risk can be addressed.

#### 4.3.4 LGAD Fabrication at FBK

The Fondazione Bruno Kessler (FBK), a semi-public semiconductor device manufacturer in Trento, IT, has emerged as one of the primary producers of LGAD sensors for R&D and experimental-scale production. They have a strong track record of following LGAD innovation trends with responsive, collaborative development efforts that produce high-quality prototypes and fully engineered production devices. Engaging them as a participant in the development and procurement of EIC LGADs will both speed up the specification and engineering of the production-scale device and mitigate risk associated with otherwise relying on a single commercial vendor for EIC LGAD sensors.

During the funded FY24 period, we propose to oversee a fabrication of LGAD sensors at FBK. We would begin by working with the EIC LGAD community to define a set of fabrication parameters,

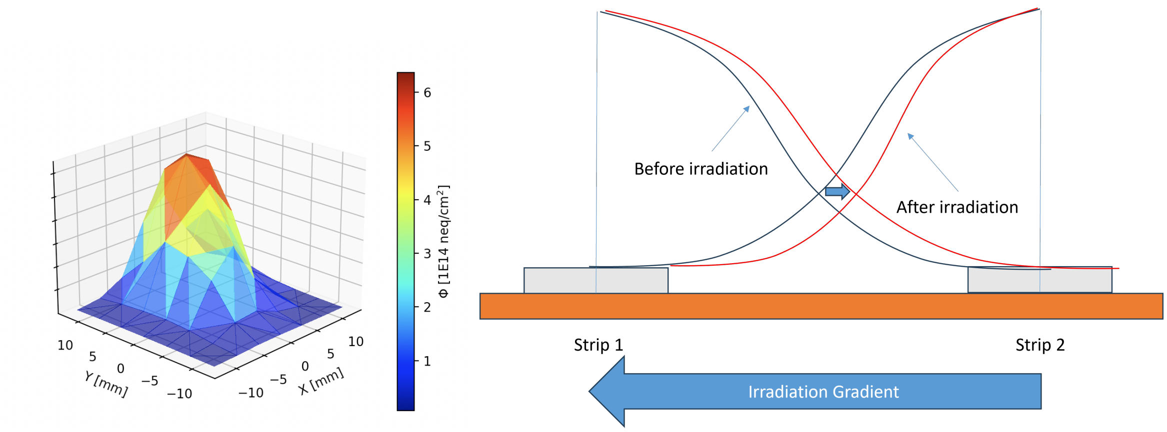


Figure 10: (left) Beam profile at LANSCE for 500 MeV protons. (right) Concept of the charge sharing change with graded irradiation.

| Wafer number | price |
|---|---|
| 5 wafers | $70k |
| 10 wafers | $90k |
| 15 wafers | $100k |

Table 7: Quoted cost of an AC-LGAD production at FBK.

guided by EIC performance requirements and informed by TCAD simulation, to be executed in the FBK run. We would then oversee the process of setting up the run at FBK, providing input and feedback in regular meetings leading up to the beginning of fabrication. We would further act as a point of delivery of the FBK prototypes to all interested EIC collaborators.

For this work, we request $15k to support our work in initiating and overseeing the fabrication run, as well as an amount between $50-100k to be provided to FBK to pay for the cost of the run. The rough cost of the production vs the number of wafers produced is reported in Tab. 7 (unofficial initial quote from FBK).

#### 4.3.5 Summary and Milestones

Significant work at both the R&D and engineering level will be required to develop LGAD sensors for the EIC detector. Much of this work will need to be done in concert with the development of the associated electronic readout. SCIPP can support this work in critical ways, and proposes a program of R&D that leverages existing effort to provide significant contribution to this program at a relatively modest level of support. $35k is requested for work on sensor testing and integration, radiation hardness verification, and design optimization through TCAD simulation. An additional $15k, plus the cost of a sensor fabrication run, would be required to establish FBK as a second commercial vendor for EIC LGAD sensors. Milestones projected for completion in FY24 are as follows:

- TCAD-based optimization of sensor characteristics, especially 20 $\mu$m bulk (December 2023)
- Characterization of BNL prototypes, especially for response uniformity (results within three months of delivery)
- Characterization of EPIC run of HPK LGAD sensors (February 2024)
- Execution and evaluation of radiation damage study (March 2024)
- Design studies for and initiation of an AC-LGAD fabrication run at FBK (March 2024)

| Inst. | Personnel | Months | Percent | Budget (k$) |
|---|---|---|---|---|
| SCIPP | Faculty | 12 | $1 \times 5\%$ | 0 (in-kind) |
| SCIPP | Senior Staff | 12 | $1 \times 5\%$ | 0 (in-kind) |
| SCIPP | Postdoctoral Fellow | 12 | $1 \times 8\%$ | 0 (in-kind) |
| SCIPP | Laboratory Specialist | 12 | 10% | 12.0 |
| SCIPP | Electro-Mechanical engineer | 12 | 8% | 19.0 |
| SCIPP | Material and Supplies | | | 4.0 |
| Total | | | | **35.0** |

Table 8: UCSC/SCIPP budget request for eRD112 sensor characterization for FY24. All entries in thousands of dollars.

| Inst. | Personnel | Months | Percent | Budget (k$) |
|---|---|---|---|---|
| SCIPP | Faculty | 12 | $1 \times 5\%$ | 0 (in-kind) |
| SCIPP | Senior Staff | 12 | $1 \times 10\%$ | 0 (in-kind) |
| SCIPP | Electrical Engineer | 12 | 6% | 10 |
| SCIPP | Laboratory Specialist | 12 | 4% | 5 |
| FBK | Fabrication Run | | | TBD |
| Total | | | | **15.0** + Fab |

Table 9: UCSC/SCIPP budget request for initiation of an AC-LGAD fabrication run at FBK within eRD112 in FY24. All entries in thousands of dollars.

#### 4.3.6 UCSC eRD112 Budgets

### 4.4 eRD112 FY24 Proposal - Purdue/NCKU

Purdue University (US), National Cheng Kung University (NCKU, Taiwan), and Academia Sinica (AS, Taiwan) will collaborate on the design and manufacture of the mechanical support structure for the endcap TOF detector in EPIC. To meet the required precision and material budget of the endcap TOF measurements, carbon fiber composite materials have been proposed for manufacturing the light-weight support due to their high thermal conductivity, strength to mass ratio, and radiation tolerance. The work proposed here is complementary to the PED request submitted by the same team under title “Request for Project Engineering and Design Support for EPIC TOF Detectors” in June of 2023.

For the initial design of endcap TOF layout, a “clam shell” (DEE) design similar to the CMS End Cap Timing Layer has been brought up. In this design, the endcap (back and front) is split into two sections in the beam direction to ease installation. The endcap TOF modules have a total power consumption of about 13.6 $k$W. The main body consists of the mechanical support structure made from carbon fiber, with a cooling non-metallic tube embedded. The challenge of this R&D project will be to reduce the average material budget of the endcap TOF system from 5% to 2.5% or less.

The work proposed here is to push the material budget down by a factor of two or more whilst maintaining optimal thermal and mechanical performance of the endcap support structure. There is basically two directions for this, with the first one being a more state-of-the-art with a sandwich structure and an embedded metal cooling pipe - this is part of the PED request made in June 2023 by the same team. More challenging but even less material is a cutting-edge blue sky R&D concept of a fused 3D-printed and compression molded structure with continuous carbon fibers for heat transfer and an embedded opening/cavity serving as a cooling channel. The proposed R&D project aims to develop the latter one further and Figure 11 shows a first prototype. Apart from scaling the technology to larger sizes, a focus of the R&D project here is to interconnect these structure and reduce the mass in those interconnections. On the other hand, injection molding is another possible method to make such kind of structure. Therefore, comparing the strength and thermal performance and cost from using compression and injection molding methods will also be part of this R&D project.

We expect to have two prototypes, one from compression molding and one from injection molding, of the endcap no-pipe TOF structure delivered in summer of 2024. A cost-effective approach will be adopted by using non-final material instead and the finite element analysis for the optimization of design.

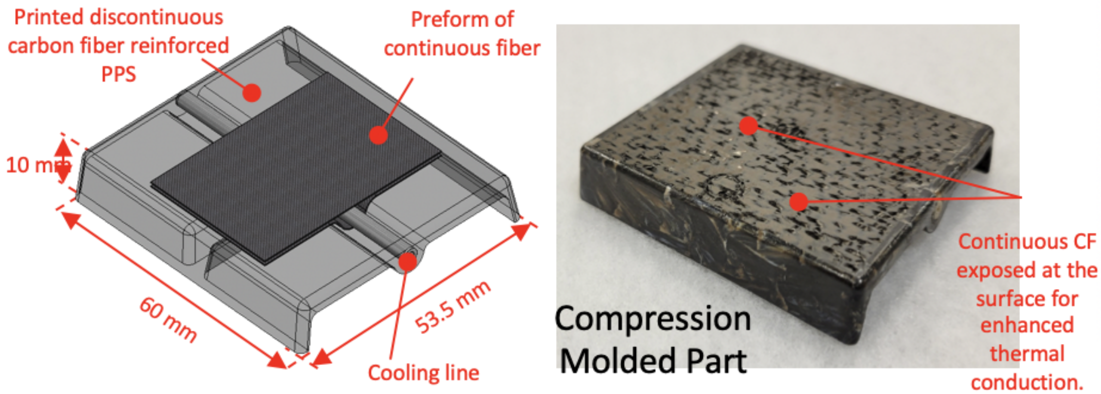


Figure 11: Design and actual prototype for the endcap support structure - more details in the text.

### 4.4.1 Purdue/NCKU budget

The total budget amount requested by Purdue/NCKU team is 53 k$, Tab. 10 contains the breakdown of the budget allocation at the mechanical structure R&D. Manpower at Purdue/NCKU on EPIC: 2 faculties (20% FTE), 1 engineers (10% FTE).

| Inst. | Personnel | Months | Percent | Budget (k$) |
|---|---|---|---|---|
| Purdue | Faculty | 12 | $1 \times 20\%$ | 0 (in-kind) |
| Purdue | Mechanical engineer | 12 | 10% | 30.0 |
| Purdue | Material and Supplies | | | 5.0 |
| NCKU | Faculty | 12 | $1 \times 20\%$ | 0 (in-kind) |
| NCKU | Materials and Supplies | | | 18.0 |
| Total | | | | **53.0** |

Table 10: Purdue/NCKU budget request for FY24. All entries in thousands of dollars.

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