A Fast Timing MAPS detector for the EIC

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July 2023

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1 Introduction

The future Electron-Ion Collider (EIC) to be built at Brookhaven National Laboratory (BNL) plans to host two detectors: the EIC project detector and detector II [1]. The EIC project detector design is under optimization by the ePIC collaboration and the detector II design is to be determined. The current ePIC tracking detector design has a limited number of hits in the forward and backward pseudorapidity region for track reconstruction (see Figure 1). The ePIC tracking detector, which utilizes the 65 nm Monolithic Active Pixel Sensor (MAPS) and Micropattern Gaseous Detector (MPGD) technologies, can not achieve fine spatial resolution (< 20 μm) and fast timing resolution (< 10 ns) within a single technology based detector subsystem. Recent simulation studies have indicated that the average number of hits of reconstructed tracks with the current ePIC tracking detector design is less than 4 in the pseudorapidity regions of $|\eta| > 1.5$ (see Figure 1), which can not provide the desired redundancy for track reconstruction. According to the recent EIC background studies [2], the radiation dose near the beam pipe region is around two to three orders of magnitude higher than the region far from the beam pipe.

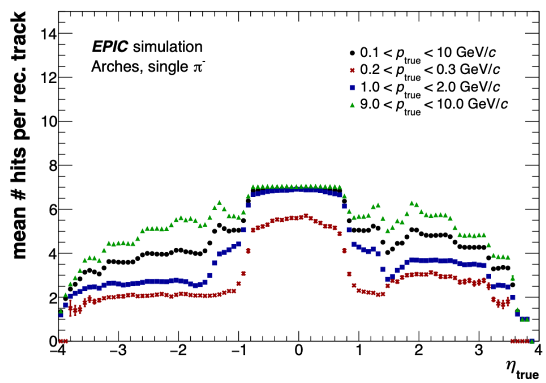
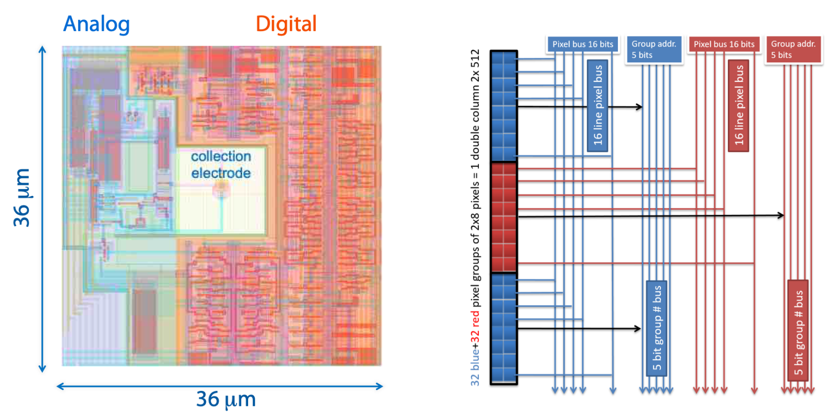


Figure 1: Number of hits per reconstructed track in the ePIC single particle simulation in different track momentum bins.

We propose to develop a Depleted Monolithic Active Pixel Sensor (DMAPS) based tracker either for the ePIC detector upgrade or the EIC detector II. This proposed detector will utilize the MALTA sensor [3] technology to achieve high radiation tolerance, fine spatial resolution and fast timing resolution. It will expand the track reconstruction quality and kinematic reach in both forward and backward pseudorapidity for either the ePIC detector or the EIC detector II. Meanwhile, this detector will help determine the event activity such as measuring the event multiplicity and event plane, which is essential for the EIC e+A physics.

1.1 MALTA technology overview

MALTA is a family of Monolithic Pixel Sensor (MAPS) detectors developed in TowerJazz 180 nm CMOS imaging technology. The pixel has a pitch of 36.4 μm^2 that allows for good spatial resolution, a small collection electrode size (3 µm) that provides minimal capacitance (< 5 fF), and enough spacing to the electronics (3.4 µm) to avoid cross-talk. The read-out of the pixel is asynchronous, without any clock distribution over the matrix, which reduces the power consumption per pixel below 1 µW. The total power consumption per area is 10 mW/cm^2 for the digital domain and 70 mW/cm^2 for the analog domain [3, 4]. Figure 2 shows the MALTA pixel design with the analog and digital charge collection and the asynchronous readout architecture.



(a) (b)

Figure 2: MALTA pixel design with the analog and digital charge collection (left) and the asynchronous readout architecture (right). Figure from [4]

MALTA prototypes were produced on high resistivity 25 µm and 30 µm thick epitaxial silicon. Before irradiation, these samples can reach full depletion at around 10 V. They also have a high signal to noise ratio (~20), where the expected energy deposition of a Minimum Ionizing Particle (MIP) is 1500 electrons, and the noise is lower than a few hundred electrons. The implant design is modified to include an additional low dose n-blanket layer under the deep p-well to improve depletion. And additional process modifications at the pixel edges increase the lateral field configuration and reduce the charge collection time. This is either a 4 µm gap in the n-blanket, or the addition of a 5 µm wide extra-deep p-well.

Additionally, MALTA prototypes have been processed on high resistivity Czochralski (Cz) substrates (3 - 4 kΩ·cm), that can be biased up to 50 V leading to deeper depletion levels, and increased charge collection. All implant designs are available on Cz substrates. Available prototypes are MALTA, MALTA2, and Mini-MALTA. MALTA is a 2x2 cm^2 detector with the original design suffering from complex slow control. Mini-MALTA is a 300x500 pixel prototype that implements a new slow control design. MALTA2 improves the slow control, the front-end design, and it has a matrix size of 288x512 covering an area of almost 1x2 cm^2. In this proposal, we will focus on the detector and stave design based on the MALTA2 sensors.

1.2 CERN MALTA R&D activity

Extensive characterization of the MALTA series sensors has been done at CERN, in laboratory conditions and in beam tests in the past several years. These past tests focus on individual sample testing with established full readout chain. Deep knowledge about the front-end understanding, and radiation hardness qualification, have been achieved based on a series of measurements such as hit efficiency for different MALTA sensors and under different conditions. MALTA2 sensors have been extensively characterized at CERN SPS using the 180 GeV hadron beam. Figure 3 shows the CERN SPS beam test results in-pixel, and average time resolution of a MALTA2 sample with extra-deep p-well. Better than 2 ns timing resolution has been achieved by the MALTA2 sensor. This advanced feature allows the proposed FMT detector, which will be built with the MALTA2 sensors, to perform event by event measurements at the EIC (The EIC has the bunch crossing rate at around 10 ns). Moreover, we expect the MALTA2 sensor can achieve comparable hit spatial resolution and radiation tolerance as the MALTA sensor, which is better than 7 μm hit spatial resolution and better than 1×10^{15} n_{eq} cm^{-2} radiation tolerance.

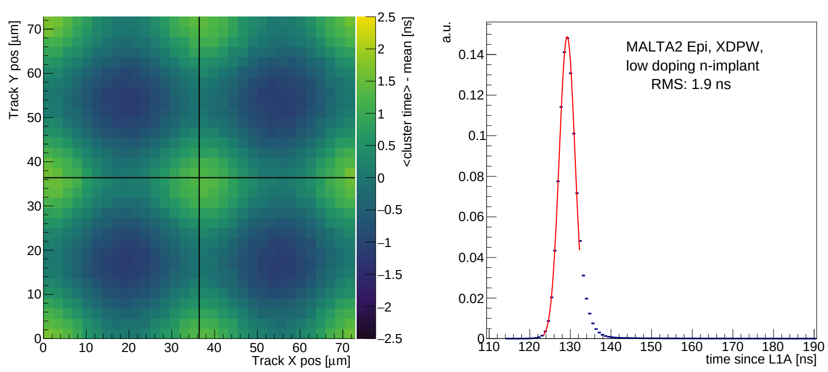


Figure 3: In-pixel timing projected over a 2x2 pixel matrix (left), and time of arrival of leading hit in the cluster with respect to a scintillator reference of a MALTA2 sample with extra-deep p-well front-end modification manufactured on Epi substrate [7].

1.3 LANL MALTA R&D activity

Through collaboration with CERN, the LANL EIC team has established the test bench in lab to characterize the MALTA prototype sensor. The left panel of Figure 4 shows the MALTA sensor bench test setup at LANL, which consists of a MALTA sensor carrier board, the low power supply modules, the trigger unit module and the XILINX KC705 based data processing module. The middle and right panel of Figure 4 shows the threshold and noise scan of part of the MALTA prototype sensor. The threshold over noise ratio is no less than 20 and good uniformity can be achieved by the MALTA sensor. This test setup can be expanded to characterize the MALTA2 prototype sensor and prepare for the MALTA2 stitched sensor stave R&D studies.

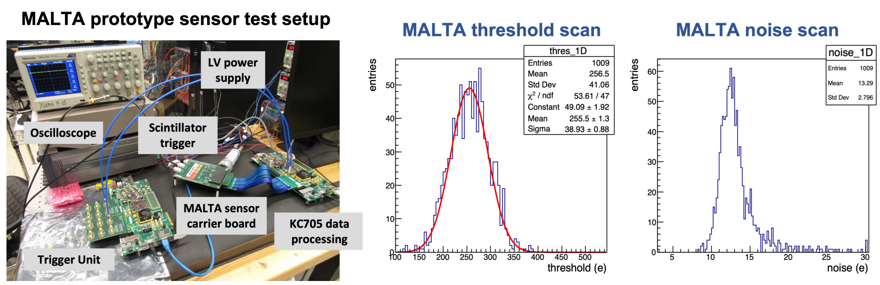


Figure 4: The MALTA sensor bench test setup at LANL (left) and threshold (middle) and noise (right) scan results [5].

2 Project overview

We propose to carry out the detector design and R&D for a proposed fast-timing High-Voltage Monolithic Active Pixel Sensor (HV MAPS) tracking detector (FMT). This detector is based on the MALTA2 sensor (1cm by 2cm active area per sensor). This detector will be placed behind the central tracking sub-detectors and in front of the Particle Identification (PID) detectors either in the ePIC detector or in the EIC detector II. We plan to deliver the detector design of fast-timing MAPS tracker, which has the capability to

- suppress the backgrounds in the track reconstruction by separating different collision events.
- extend the kinematic reach of the tracking capability.
- help determine the event activity of e+A collisions.
- reconstruct long decay particles such as Lambda for flavor physics.

Figure 5 shows the sketch of the proposed FMT implemented in the current design of the ePIC detector. In the initial design, the FMT consists of 2 (or 3)

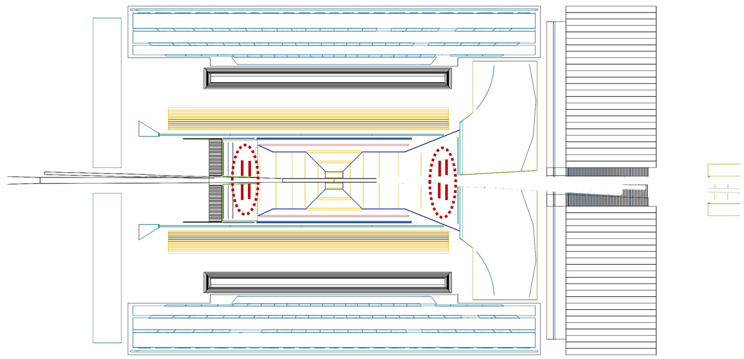


Figure 5: The proposed Fast MAPS tracker (FMT) sketch inside the current ePIC detector design.

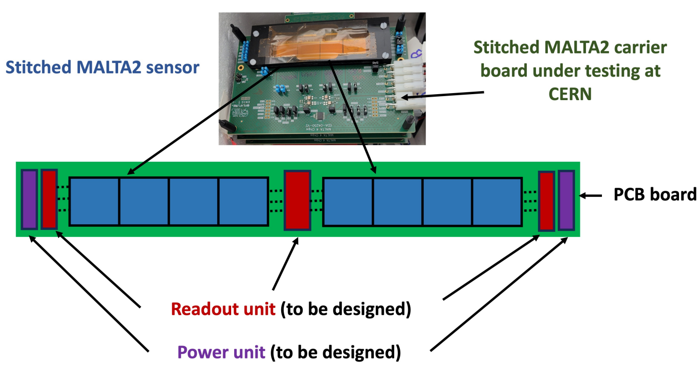


Figure 6: The conceptual design of the proposed MALTA2 stitched sensor stave.

disks in the forward hadron-endcap region and 2 disks in the backward electron-endcap region. The beam crossing angle at the IP6 location of the EIC is 25 mrad. We propose to install the FMT at the EIC IP6 within the z range of 1.4 m to 1.9 m from the primary collision vertex in the hadron-endcap region and -1.3 m to -1.1m range in the electron-endcap region. A single disk of the FMT will be built using a series of MALTA2 staves. How to arrange the staves per disk to provide a 2π azimuthal coverage with minimal material budgets will be one key technical deliverable of this project. A single MALTA2 stave is composed of 2 groups of 4 stitched MALTA2 sensors as shown in Figure 6. The pseudorapidity coverage of the FMT in the hadron beam going direction is around 2.65 to 4.1, which can significantly mitigate the track reconstruction gap as shown in Figure 1. In the electron endcap region, the FMT pseudorapidity coverage is around 2.4 to 3.9. As the ePIC detector design is evolving, we will update the geometry of the proposed FMT accordingly.

The beam crossing angle at the IP8 location of the EIC is 35 mrad. As a second option, we propose to install the FMT at the EIC IP8 within the z range of 1.4 m to 1.9 m from the primary collision vertex in the hadron-endcap region and -1.9 m to -1.4m range in the electron-endcap region. The detector design will be updated when the EIC detector II conceptual design is released. In this proposed detector coverage, the FMT has the pseudorapidity coverage of 2.6 to 3.9 and -3.9 to -2.6 at IP8.

Another key milestone of this project is to deliver a technical design of the MALTA2 stitched sensor stave for the proposed FMT detector. Figure 6 shows the conceptual design of a stave, which consists of two groups of four stitched MALTA2 sensors, with the associated power line and data transmission modules on the same PCB board. The four MALTA2 sensor stitch design has been already tested in [8] using several interconnection techniques including a silicon bridge glued with Anisotropic Conductive Film. Modules have a relatively high production yield and a fully working chip-to-chip communication. The hits from the left most chip are routed to the right most chip from where they are read-out with high hit-efficiency under beam environments compatible to the location of the FMT. The power consumption of this stave will be evaluated and the corresponding cooling and support structure will be designed as well.

We will consider carbon fiber structures in the mechanical design of the MALTA2 stave for the FMT. Carbon fiber possesses a high strength to weight ratio and contributes minimally to the material budget. Additionally, it has been successfully used for the mechanical structure of the MVTX staves that are part of sPhenix in operation at BNL. Mixed phase CO2 will be considered as a potential cooling fluid for its favorable thermodynamic properties and low contribution to the material budget. However, mixed phase CO2 must be operated on the order of 25 bar to achieve a favorable boiling temperature. The cooling tubes will need to be designed to satisfy this pressure requirement. The design of the mechanical structure and cooling will be optimized using FEA.

3 FY24 Work Scope

3.1 Deliverables

We would like to start a two-year project encompassing the proposed FMT detector design, prototype stave assembly and construction, and detector prototype construction and testing. We plan to achieve the following milestones for FY24:

- Develop the technical design for the proposed Fast timing MAPS tracker (FMT) and validate its performance in simulation.
- Develop a mechanical design for the FMT disk using a series of MALTA2 staves to provide a 2π azimuthal coverage with minimal material budget.
- Achieve the first version of the MALTA2 stitched sensor stave technical design for the FMT, which includes the power and data transmission parts

and potentially cooling lines.

- Develop the first prototype MALTA2 stave with down-selected MALTA2 sensors, produce two fully fabricated MALTA2 stitched sensor staves, and characterize their performance in bench tests and potentially beam tests at CERN and LANL.

3.2 Cost Effectiveness

The equipment that is proposed to be acquired in this project will be produced by state of the art electronics fabrication facilities and well qualified technical labor. We will utilize existing R&D labs at CERN and LANL and plan to use the CERN SPS test beam facility to perform the sensor characterization and stave design and development. These labs have well established MALTA sensor test infrastructure and could be expanded for the proposed research in this proposal. Using these existing labs will eliminate the need to use valuable resources for building the same supporting and technical environment in another institution.

This project will support a fraction of the time of one postdoc, one graduate student and one junior mechanical engineer. These junior members will advance their technical skills, be involved in advanced silicon detector technology R&D and become familiar with the EIC detector design developments. Through this project, we will train the next-generation of physicists and engineers for the EIC project.

3.3 Diversity, Equity, and Inclusion

The team consists of staff at different career phases, including senior and mid-career scientists, senior and junior engineers, postdocs and students. This team also has a diverse background and a good balance in gender. The senior colleagues in the team will train the junior colleagues, engineers, postdocs and students to develop their technical skills for advanced silicon detector R&D and EIC detector design. This project will provide a unique opportunity to foster young academics and encourage them to take on leadership roles in this field. The PI and other members of the team will help the junior members play an important role in several key features of the proposed tasks and pave their path for their next career adventure.

4 Budget

Although the EIC generic R&D proposal call is for the next fiscal year, we plan to operate this project in the following fiscal years as well. To achieve the milestones for FY24, a multi-institution team has been formed with colleagues from LANL, CERN and MIT. We will work closely to deliver the detector technical design and utilize the existing R&D labs at CERN and LANL to carry out the proposed sensor/stave characterization and validation.

Table 1: Funding request by function category for three scenarios.

Index	Item	Nominal	Nominal-20%	Nominal-40%
1	Postdoc (student) labor	$54,597	$43,678	$32,758
2	Mechanical engineer labor	$50,895	$40,716	$30,537
3	Electronic engineer labor	$50,895	$50,895	$50,895
4	Technician labor	$18,199	$9,100	$0
5	Travel (beam test)	$8,000	$4,000	$0
6	Stave mechanical M&S	$7,000	$5,600	$4,200
7	Stave PCB fabrication	$7,000	$5,600	$4,200
8	Readout module	$15,000	$15,000	$7,500
	Total	$211,586	$174,589	$130,090

Table 2: Nominal-20% funding request by function category

Index	Item	Nominal-20%
1	Postdoc (student) labor	$43,678
2	Mechanical engineer labor	$40,716
3	Electronic engineer labor	$50,895
4	Technician labor	$9,100
5	Travel (beam test)	$4,000
6	Stave mechanical M&S	$5,600
7	Stave PCB fabrication	$5,600
8	Readout module	$15,000
	Total	$174,589

Table 3: Nominal-40% funding request by function category

Index	Item	Nominal-40%
1	Postdoc (student) labor	$32,758
2	Mechanical engineer labor	$30,537
3	Electronic engineer labor	$50,895
4	Technician labor	$0
5	Travel (beam test)	$0
6	Stave mechanical M&S	$4,200
7	Stave PCB fabrication	$4,200
8	Readout module	$7,500
	Total	$130,090

4.1 Baseline Budget Request FY24

We would like to request funding to cover the part time labor of one postdoc, one graduate student, two mechanical engineers, one electronic engineer, and one technician. The costs of the associated M&S and beam test travel expense are included as well. Table 1 lists the detailed funding request for a nominal budget request as well as 20% and 40% reduced budgets, respectively.

4.2 Reduced Budget Request FY24

Two reduced funding request scenarios have been considered. For the nominal-20% case, the labor cost of the postdoc (student) and mechanical engineers will be reduced to 80%, and technician labor will be reduced to 50% and fewer MALTA2 sensors and staves will be produced. The beam test activity will be reduced accordingly. Table 2 lists detailed costs for the nominal-20% scenario with different function categories respectively. These cost estimations have been included in Table 1 for comparison.

For the nominal-40% case, the labor cost of the postdoc (student) and mechanical engineers will be reduced to 60%, and fewer MALTA2 sensors and staves will be produced. There will be no beam tests to characterize the stave prototype performance. And there will be no technicians to support this project. We will only be able to produce one MALTA stitched sensor stave and work on the bench tests. Table 3 lists detailed costs for the nominal-40% scenario with different function categories respectively.

4.3 Institutions and Contacts

Table 4: Institutions involved and institutional contacts

Topic	Institution	Contact person
FMT detector design	LANL	Xuan Li
	CERN	Carlos Solans
	MIT	Yasser Corrales Morales
Stave design and validation	LANL	Xuan Li
	CERN	Carlos Solans
	MIT	Yasser Corrales Morales
Bench and beam tests	LANL	Xuan Li
	CERN	Carlos Solans
	MIT	Yasser Corrales Morales
Simulation studies	LANL	Xuan Li
	CERN	Carlos Solans
	MIT	Yasser Corrales Morales

Table 4 provides a list of the institutions involved in this proposal and institutional contacts. It covers all areas of interest for FY24, i.e. detector design and sensor R&D. As EIC specific structures will become available and additional institutions will join the efforts, we anticipate further delineations in particular in the area of characterization.

References

[1] R. Abdul Khalek et al., *Science Requirements and Detector Concepts for the Electron-Ion Collider: EIC Yellow Report*, `arXiv: 2103.05419 (2021)`.

[2] Report from Background Task Force, Z. Zhang *et al.*, $https://indico.bnl.gov/event/19501/contributions/76715/attachments/47708/80876/BeamBackground_ePIC_20230526.pdf$

[3] H. Pernegger et al., *First tests of a novel radiation hard CMOS sensor process for Depleted Monolithic Active Pixel Sensors*, JINST **12** (2020) P06008.

[4] H. Pernegger et al., *MALTA-Cz: A radiation hard full-size monolithic CMOS sensor with small electrodes on high-resistivity Czochralski substrate*, `arXiv: 2301.03912 (2023)`.

[5] X. Li et al., *Forward silicon vertex/tracking detector design and R&D for the future Electron-Ion Collider*, PoS PANIC2021 (2022) 084.

[6] M. van Rijnbach et al., *Radiation hardness and timing performance in MALTA monolithic pixel sensors in TowerJazz 180 nm*, JINST **17** (2022) C04034.

[7] G. Gustavino et al., *Timing performance of radiation hard MALTA monolithic Pixel sensors*, `arXiv: 2209.14676 (2022)`.

[8] F. Dachs et al., *Development of a large-area, light-weight module using the MALTA monolithic pixel detector*, NIM A (2023) 167809