A Fast Timing MAPS detector (FMT) for the EIC

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EIC Generic R&D review

Outline

- Questions and Answers
- Proposal overview
  - MALTA2 technical feature
  - Proposed MALTA2 detector module design
  - Proposed R&D plan
- Summary and outlook

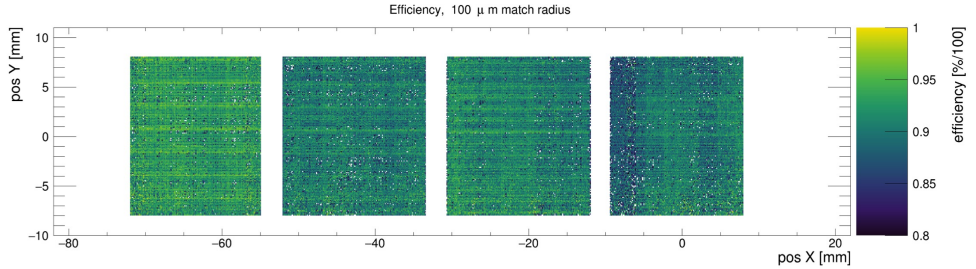
Questions from the review committee

- Q1: What potential risks of this seemingly promising technology are addressed in section 3.1 Deliverables, items 3 and 4? I.e., the stitching and testing of a prototype stave? (Note that Items 1 and 2 involve the detailed design of a Fast MAPS Tracker which seems more appropriate for possible future project R&D.)
- Q2: Are there other potential show-stoppers that must be addressed before this technology could be confidently incorporated into a future EIC project detector? For example, if it were clear that the radiation length of a stave with cooling and power and readout lines was too large, that might suggest related priority topics for the generic R&D program.
- Q3: What are typical hit efficiencies of a full MALTA2 chip?
- Q4: What are potential challenges/risks and mitigation strategies?
- Q5: What are the broader scientific implication of this project?

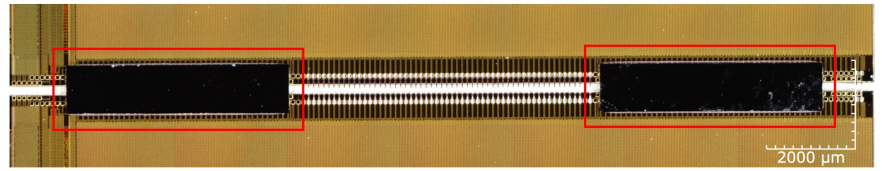
Answer to question 1

- The risk is low to moderate.
- Promising beam test results have been achieved for MALTA quad-module (previous version of MALTA2 sensor).
- We plan to produce the prototype MALTA2 sensor quad-module (4 MALTA2 sensors assembled with either 1) wire bonding from chip to chip or 2) silicon bridge between adjacent chips for data transmission. We plan to perform the R&D about the power distribution arrangement, where the early design has been established in existing MALTA quad modules. The MALTA2 R&D status has been summarized in *https://cds.cern.ch/record/2852748/files/EP_R_D_Annual_Report_2022%20(3).pdf*.
- Critical components such as the MALTA2 sensors and flex PCB boards to build the MALTA2 quad module prototype already exist.
- For the planned the FMT design and integration to the EIC project, we will update the layout of the PCB board and may redesign the power distribution to reduce the material budget of the service part. The MALTA2 sensor and data readout part will very likely remain the same.

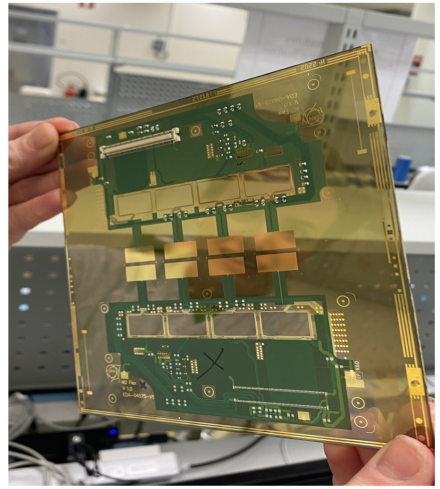
Efficiency of fully enabled MALTA module



Silicon stitching between two MALTA2 chips



MALTA2 flex module PCB

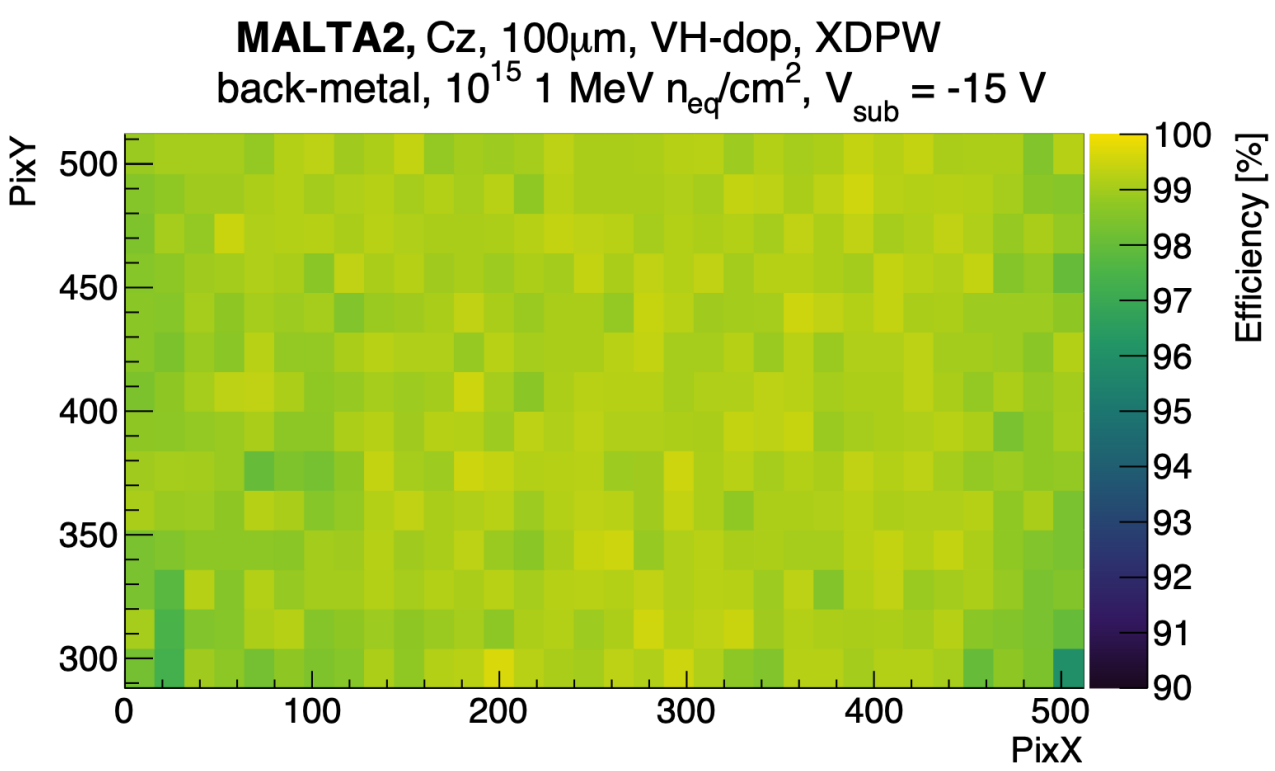


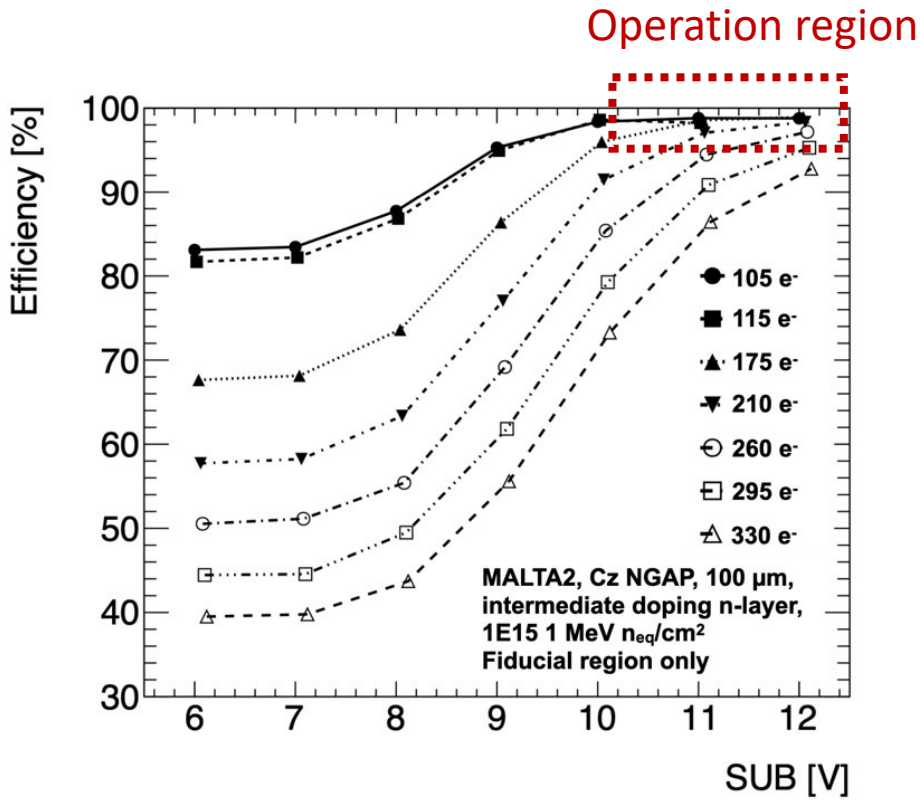
Answer to question 2

- The show-stopper is the service material budget. Depending upon the EIC timing requirement, if the FMT detector only needs 100 ns timing resolution, we plan to utilize the existing MALTA2 sensors. If the material budget of the proposed FMT does not satisfy the EIC project requirement, we need to go for the MALTA3 senor option to further reduce the material budget of the readout and power service, which is in design and not tested yet.
- The radiation length of the active detector volume is not an issue as we can dice the MALTA2 sensor down to 100 μm thickness. The total material budget of the readout and power lines need dedicated R&D to be evaluated, which will be a main component of this project.

Answer to question 3

- The typical hit efficiencies of a full MALTA2 chip is >95% at 10^{15} 1MeV n_{eq}/cm^2. The updated version of MALTA chip: MiniMALTA3 is expected to have 99.9% hit efficiency at 10^{15} 1MeV n_{eq}/cm^2





Answer to question 4

- The potential challenges/risks are how to reduce the service material budget while not impacting too much on the timing resolution of MALTA2 chips.
- Since the current MALTA2 chip can achieve around 2ns timing resolution, which is much faster than the EIC beam bunch crossing rate and collision rate, this provides sufficient adjustment room for a special version of MALTA2 sensor design for the EIC with reduced power lines.
- To mitigate the risk of service material budget, we have the following options:
  - To perform two MALTA2 sensor-based stave designs (details listed later) and select the optimized design with minimum service material budget.
  - Check the feasibility of utilizing MALTA3 sensors, which are under design and will need less service components on chip.
  - Place the proposed FMT in a region which is further away from the collision vertex and less sensitive to the detector material budget. We will perform dedicated simulation studies to evaluate the impact.

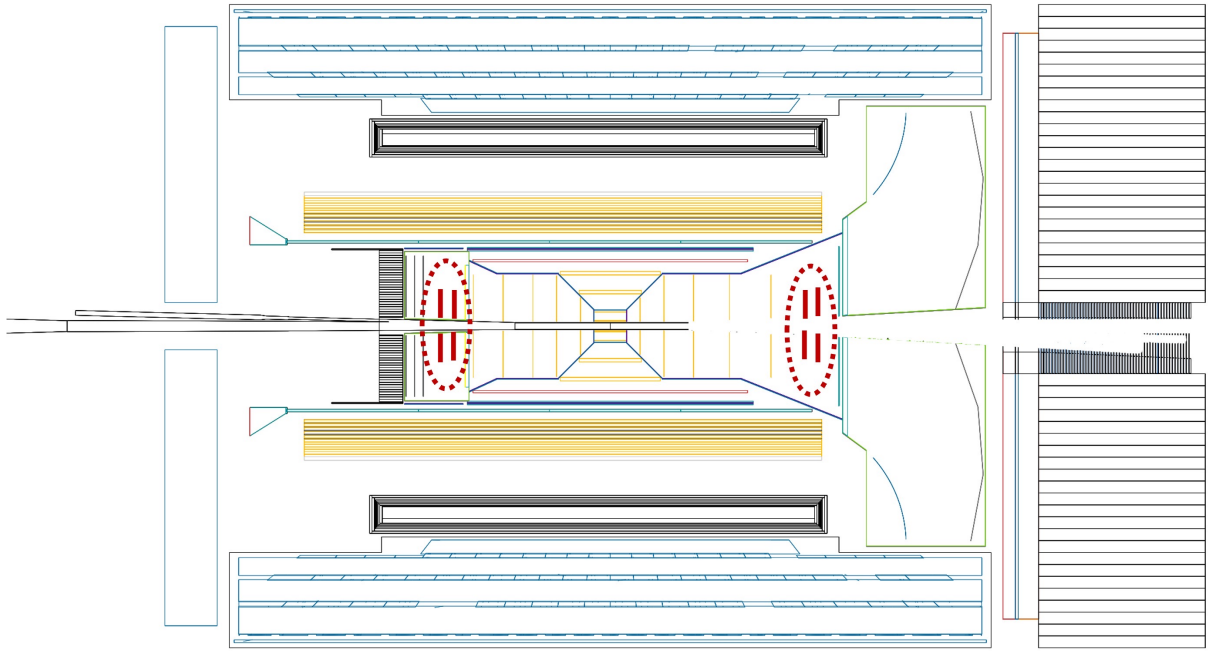
Answer to question 5

- This project introduces a new silicon technology, which can be used to achieve 4D tracking and event by event activity monitoring to enrich the EIC e+A physics capability.
- The proposed detector based on the MALTA2 technology will be compact to save the space for other detector subsystems. Meanwhile, we can achieve ~2 ns timing resolution and ~5 μm spatial resolution with a single MAPS technology, which will save the cost and mitigate the integration risk compared to a multi-technology detector design.

4D MAPS tracking detector for the EIC

- We propose to carry out R&D for a Depleted Monolithic Active Pixel Sensor (DMAPS), i.e., MALTA2, based 4D tracking detector either for the ePIC detector upgrade or the EIC detector II.
- This detector will utilize advanced MALTA2 sensors to achieve fine spatial resolution and fast timing resolution to measure event activity and help improving the track finding in the forward and backward regions.

Current ePIC detector design



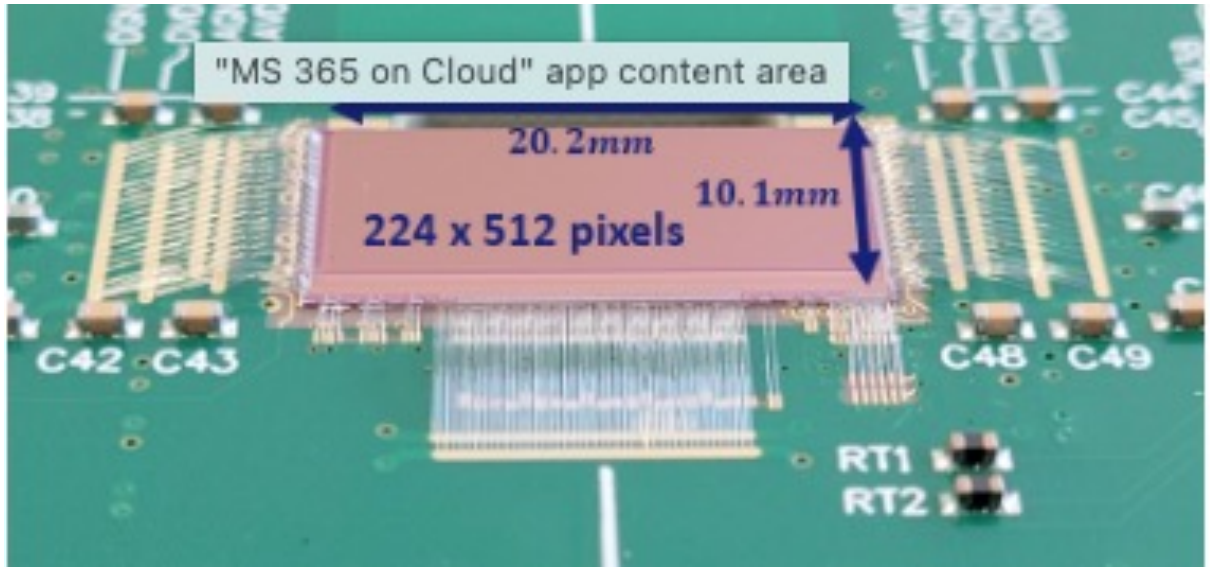
The **proposed fast MAPS tracking detector** will be placed in the hadron/electron endcap region behand the inner tracking detector.

MALTA2 sensor technical feature

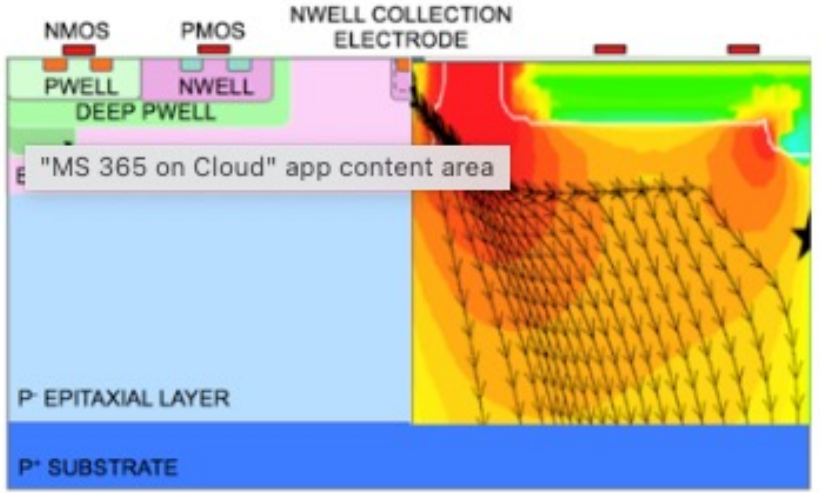
- The MALTA2 prototype sensor made of Tower 180 nm technology is under extensive bench and beam tests with well established readout chain.
- MALTA2 sensor has
  - 20 X10 mm^2 active area,
  - 224 X 512 pixels with 36.4 μm pitch,
  - 10 mW/cm^2 digital power consumption, 70 mW/cm^2 analog power consumption.

IEEE Transactions on Nuclear Science, vol. 69, no. 6, pp. 1299-1309, 2022.

MALTA2 prototype sensor

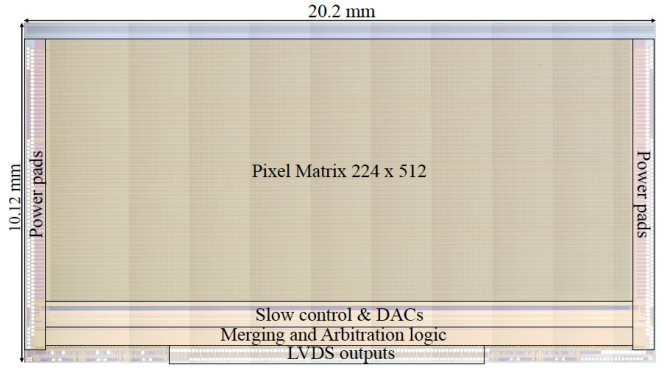


MALTA2 pixel design w/ improved charge collection in the pixel edge

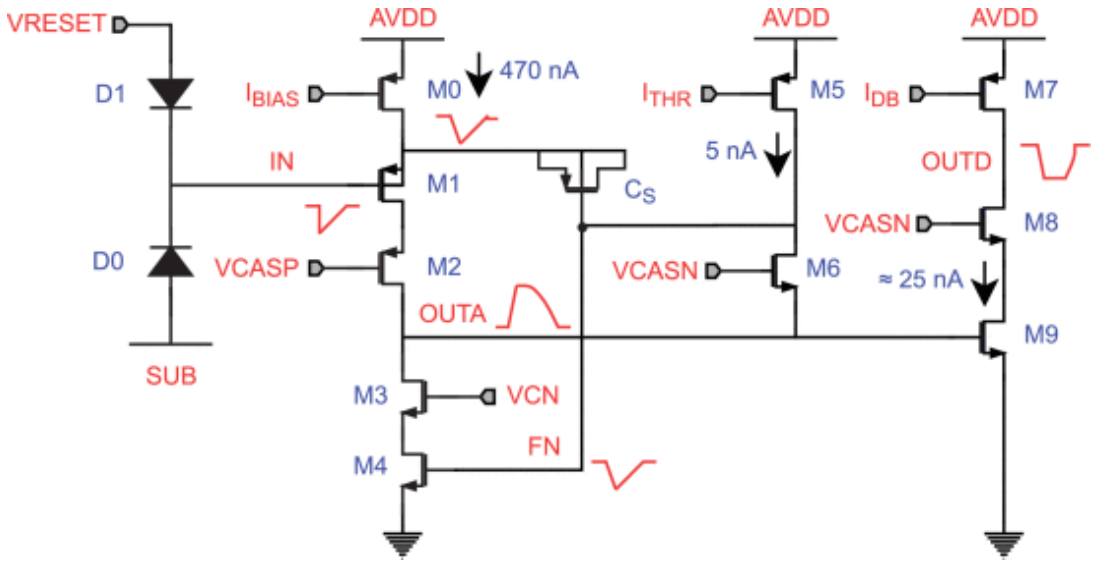


MALTA2 readout scheme

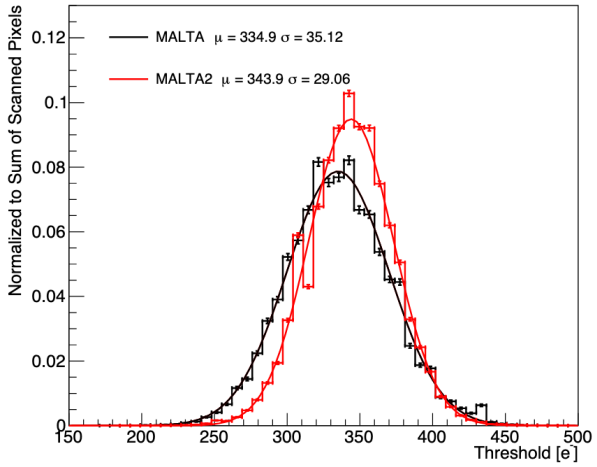
- 40-bit wide data packet transmitted off chip via LVDS drivers, with a maximum speed of 5 Gbps.
- Fully established front-end and back-end readout chain for MALTA2 prototype sensor characterization.



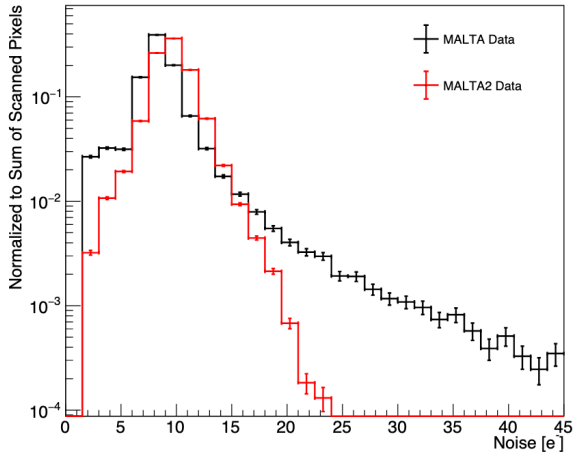
MALTA2 pixel front-end schematic w/ amplification, shaping and digitization



Threshold



Noise



MALTA2 sensor performance (I)

- MALTA2 telescope has been installed at CERN SPS H6B with 5x10^6 particles/spill at 50 kHZ max readout rate:
  - Trigger directly from MALTA sensors
  - Using scintillator for better time reference.
  - 6 tracking planes + 2 DUTs.
  - Can be thinned to 100 μm depth.
- From the latest 2023 SPS beam tests, the MALTA2 sensor can achieve ~2 ns timing resolution and ~5 μm spatial resolution.

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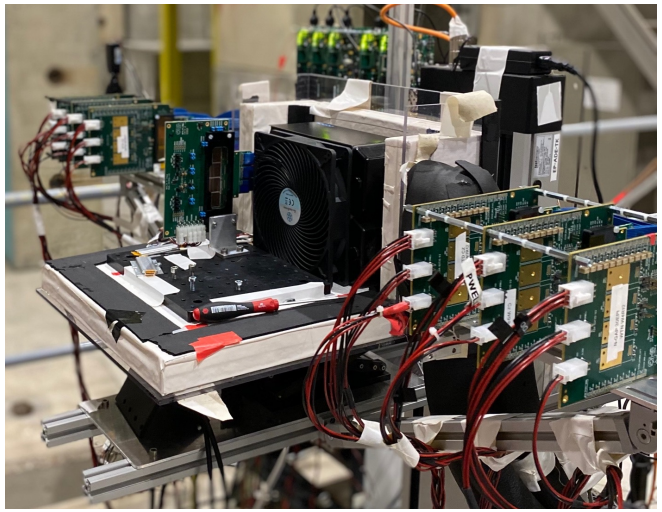
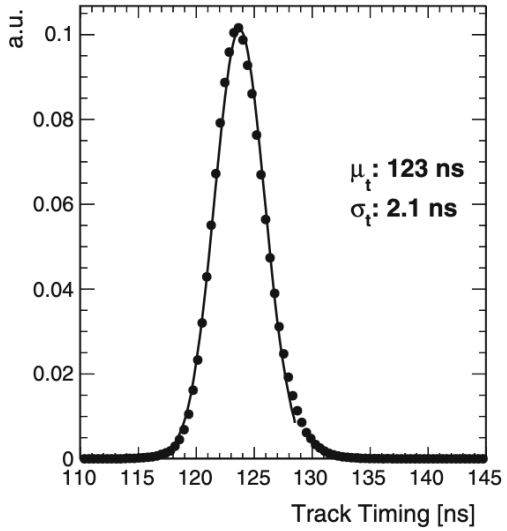
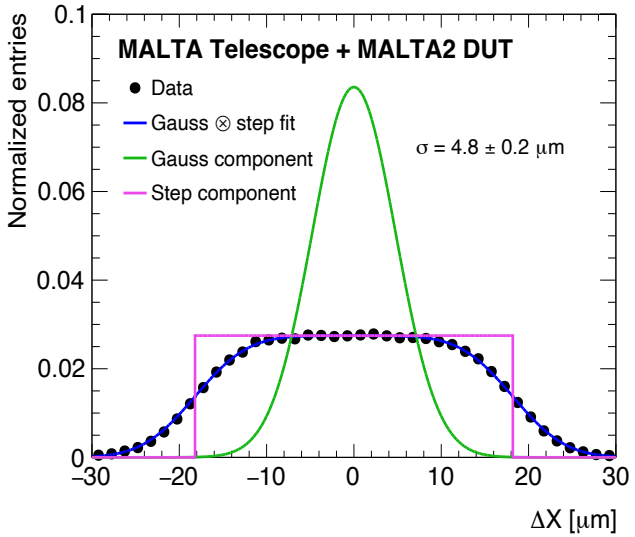
MALTA2 telescope at SPS

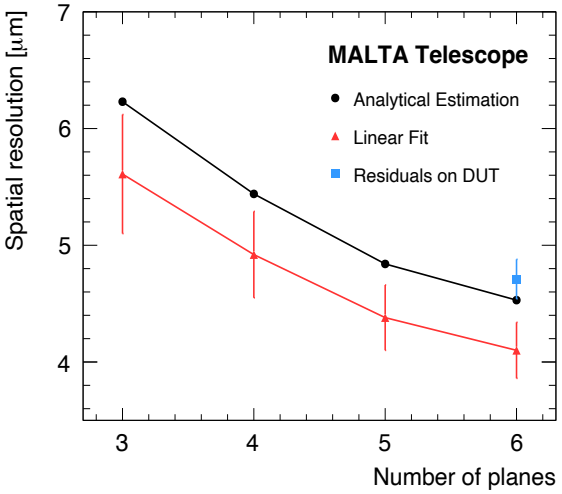


MALTA2 timing Res.



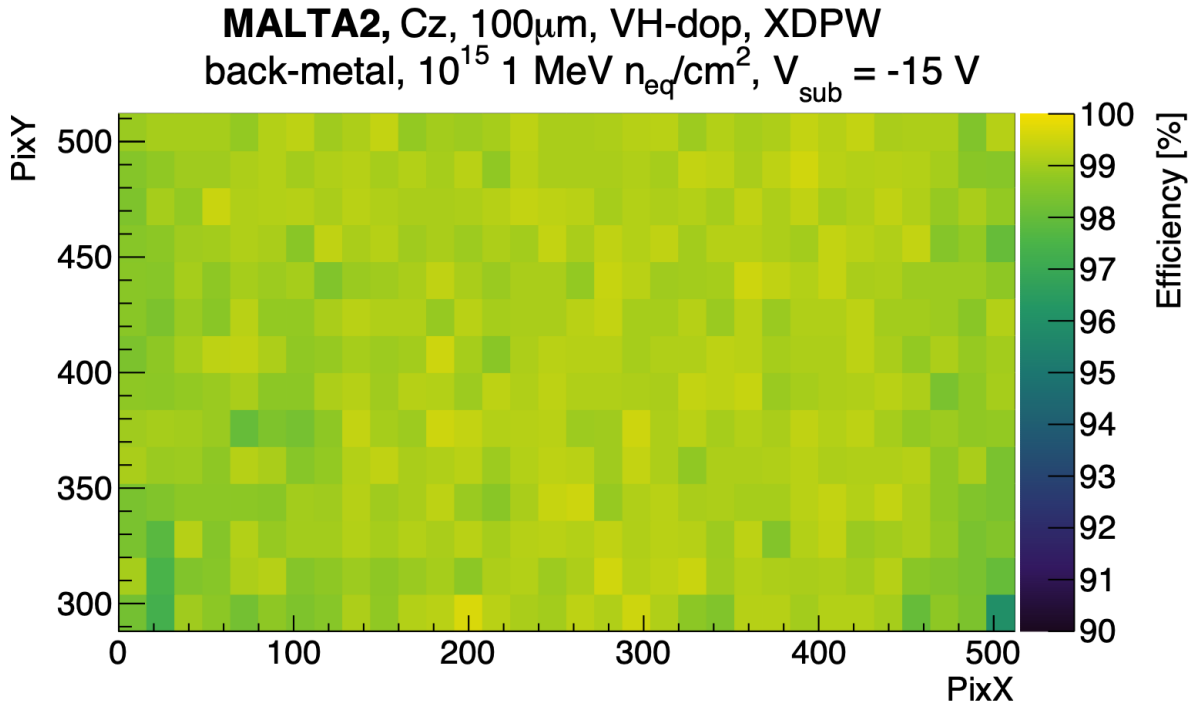
MALTA2 spatial Res.



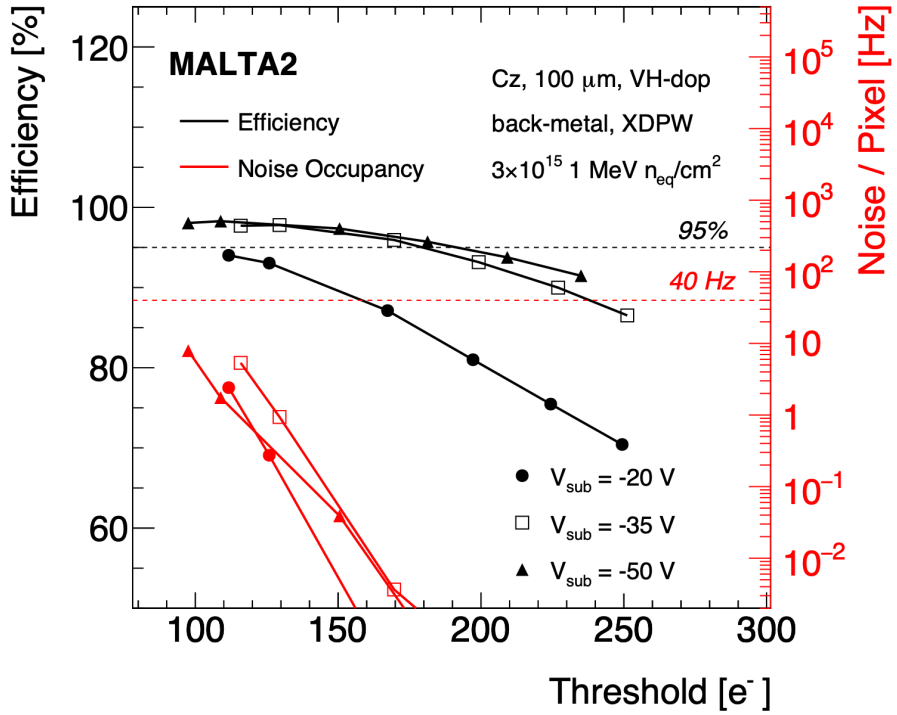


MALTA2 sensor performance (II)

- The MALTA2 sensor is also radiation hard and can be placed close to the EIC beam pipe to measure the event activity.
- Uniform >95% hit efficiency at 10^{15} 1MeV n_{eq}/cm^2 (left).
- Low noise rate even at $3x10^{15}$ 1MeV n_{eq}/cm^2 (right).



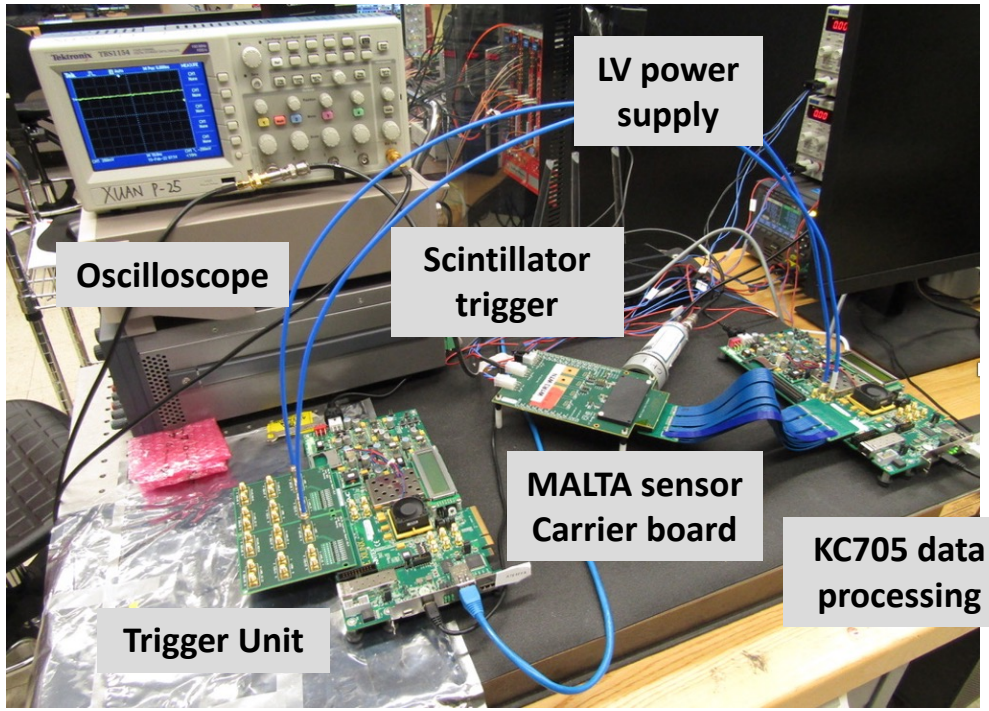
arXiv: 2308.13231



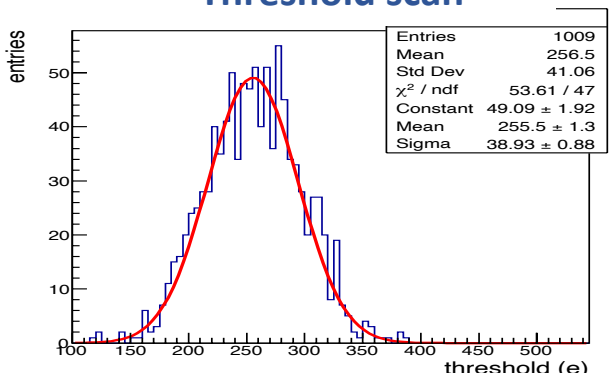
MALTA sensor R&D test at LANL

- A similar test bench like the CERN one has been setup at LANL.
- Threshold and noise scan has been performed for MALTA prototype sensors.
- Successfully suppressing the noise hits with optimized DAC configuration and the hit occupancy has been studied with the ^{90}Sr source tests. Will utilize the same bench for the MALTA2 sensor characterization.

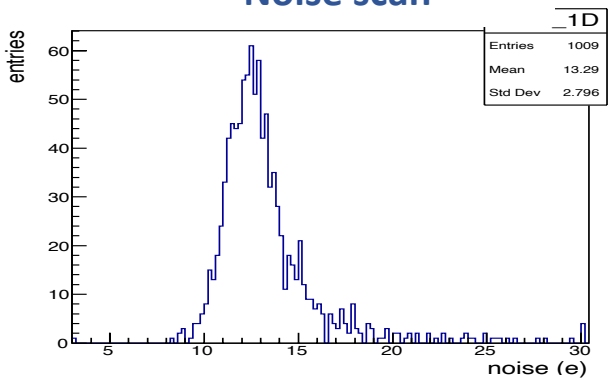
MALTA prototype sensor test setup



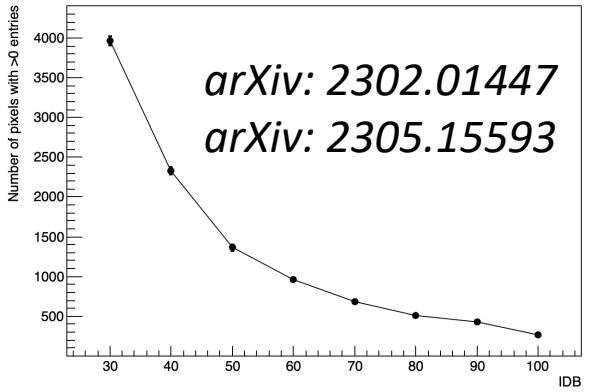
Threshold scan



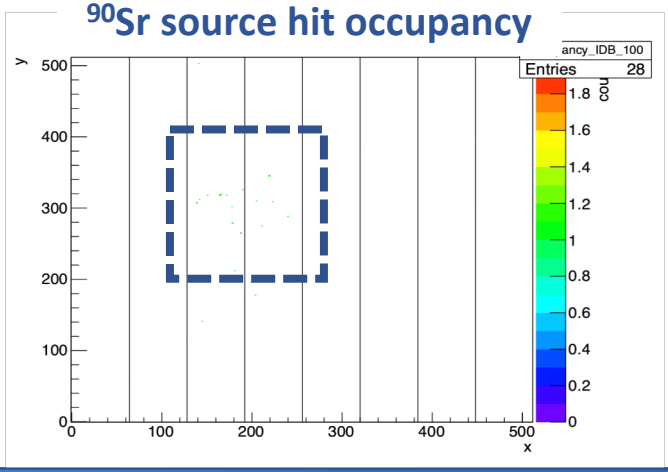
Noise scan



Noisy pixel rate VS IDB value



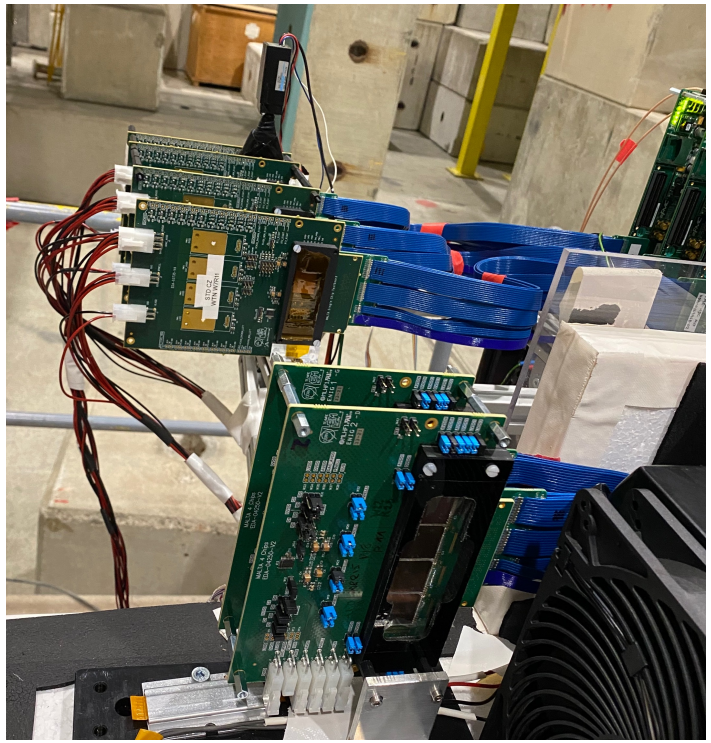
^{90}Sr source hit occupancy



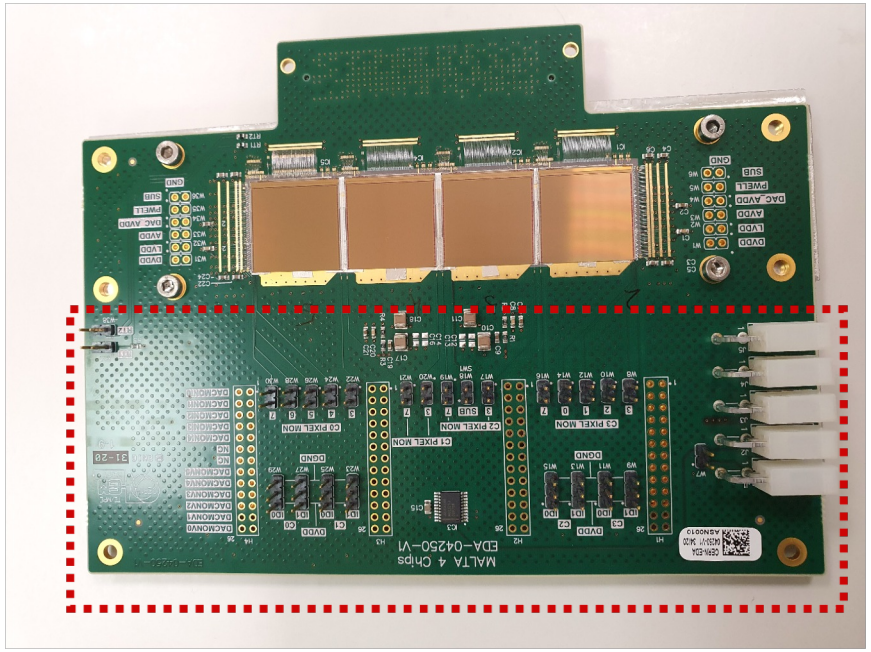
MALTA quad chip development

- A large area MALTA quad chip module has been designed and fabricated. Data of adjacent MALTA sensors can be routed through CMOS output.
- This MALTA quad chip module has been tested at CERN SPS and obtained comparable performance with single MALTA sensors.

MALTA quad-module in MALTA telescope at CERN SPS



MALTA quad-module



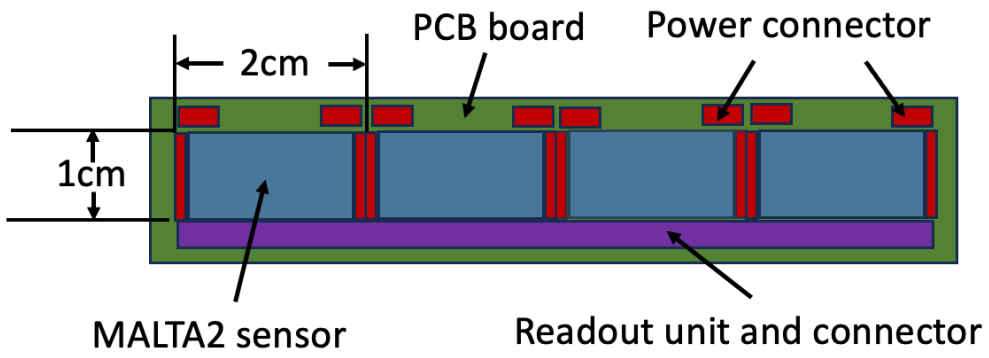
- MALTA2 quad module is in production.
- Plan to reduce the service PCB part (highlighted in red) to make the module fit into a stave-like structure.

Proposed R&D plan (I)

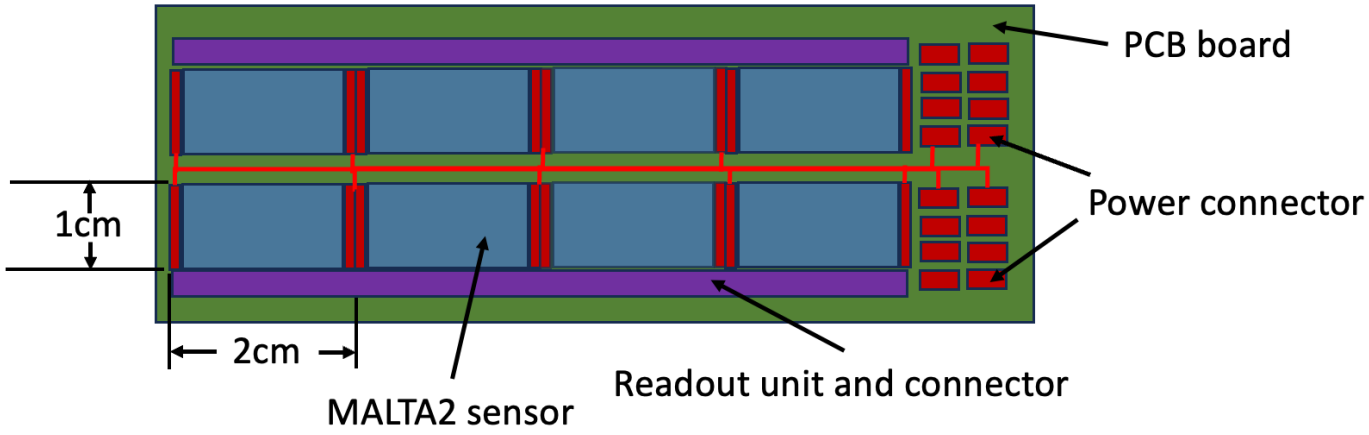
- Utilized the existing LANL and CERN test benches to characterize and down-select good MALTA2 sensors for the quad module production.
- Produce at least two MALTA2 quad modules at CERN.
- Develop the MALTA2 stave design, which consists of one or two MALTA2 quad modules and updated PCB layout which will reduce the service material budget.

Initial sketch of the proposed MALTA 2 stave by Xuan Li (LANL)

MALTA2 stave design option 1



MALTA2 stave design option 2

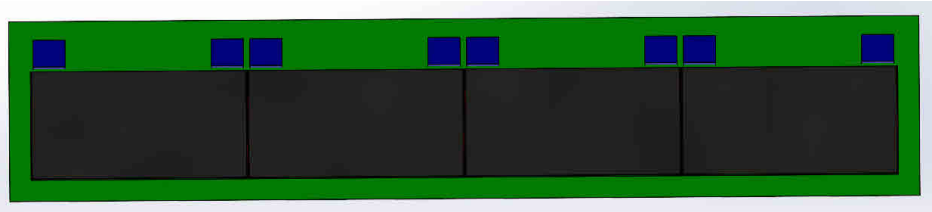


Proposed R&D plan (I)

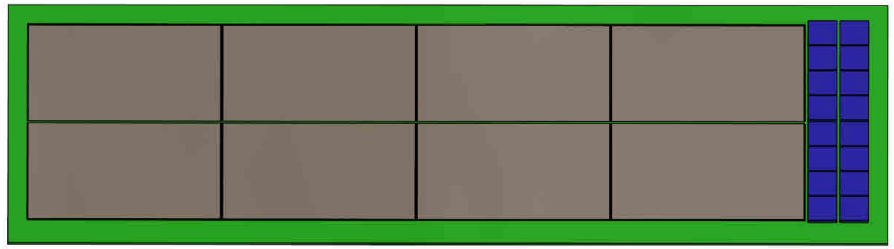
- Initial mechanical design of the MALTA2 stave options with the power connections (readout layout will be designed during this project).

Initial mechanical design of the proposed MALTA2 stave by Walter Sondheim (LANL)

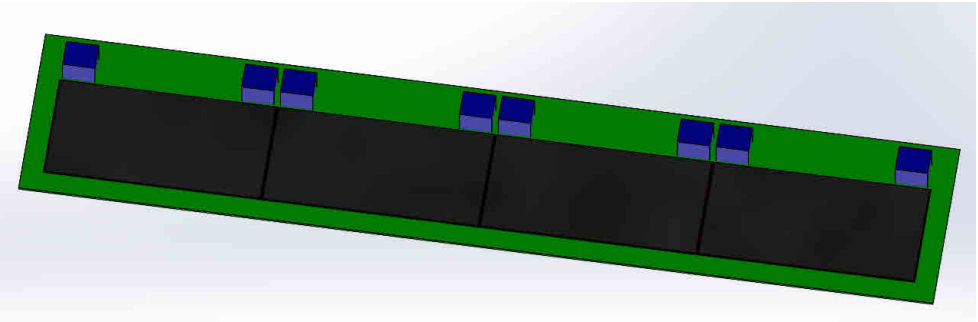
MALTA2 stave design option 1 top view



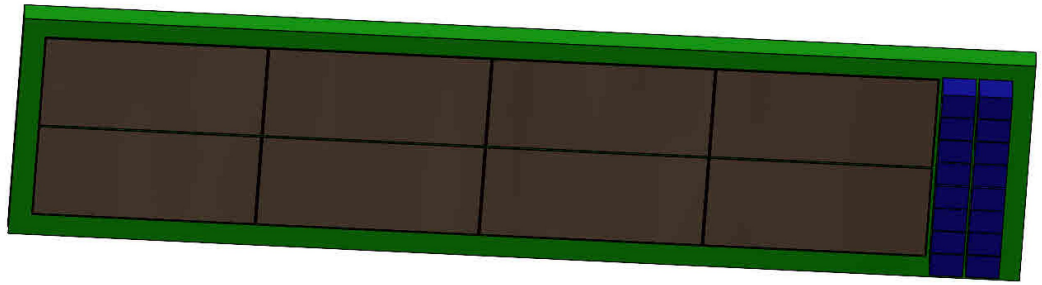
MALTA2 stave design option 2 top view



MALTA2 stave design option 1 3D view



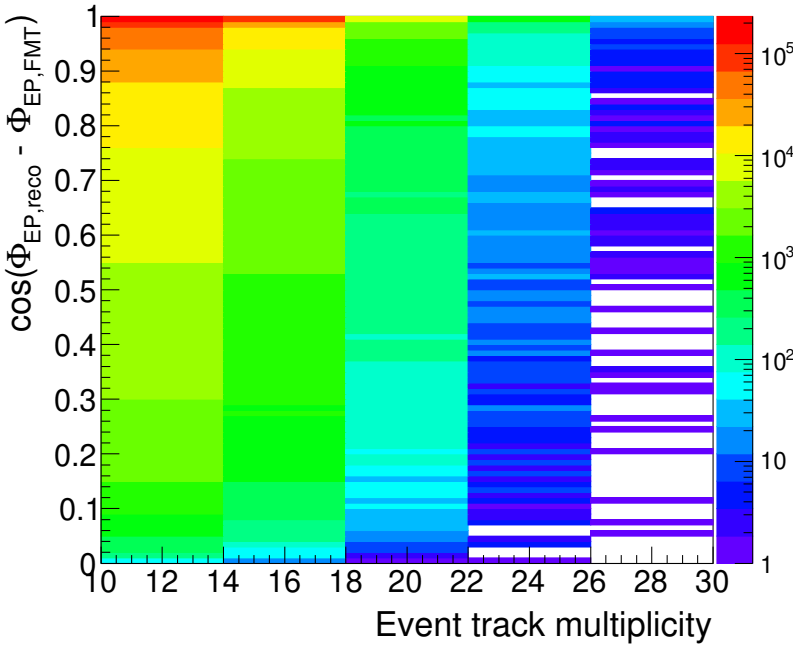
MALTA2 stave design option 2 3D view



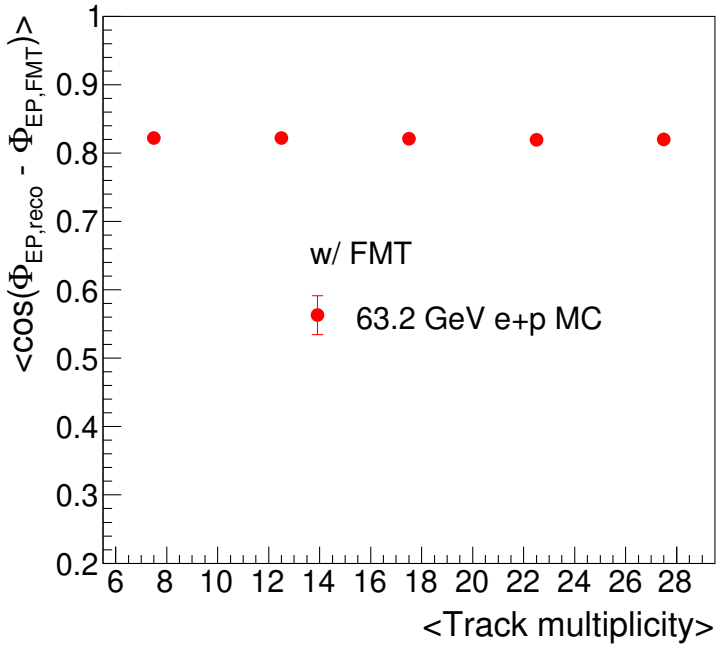
Proposed R&D plan (II)

- Schedule and carry out the beam tests for the MALTA2 quad module (and/or the newly designed MALTA2 stave depending upon its production status). Aim to achieve characterization results for potential publications.
- Perform the technical design of the proposed MALTA2 based Fast Timing MAPS tracking detector (FMT) and validate its performance for the ePIC detector upgrade and/or EIC detector II.

Multiplicity dependent cos(Δ Φ_{EP})



Event Plane Resolution with the FMT

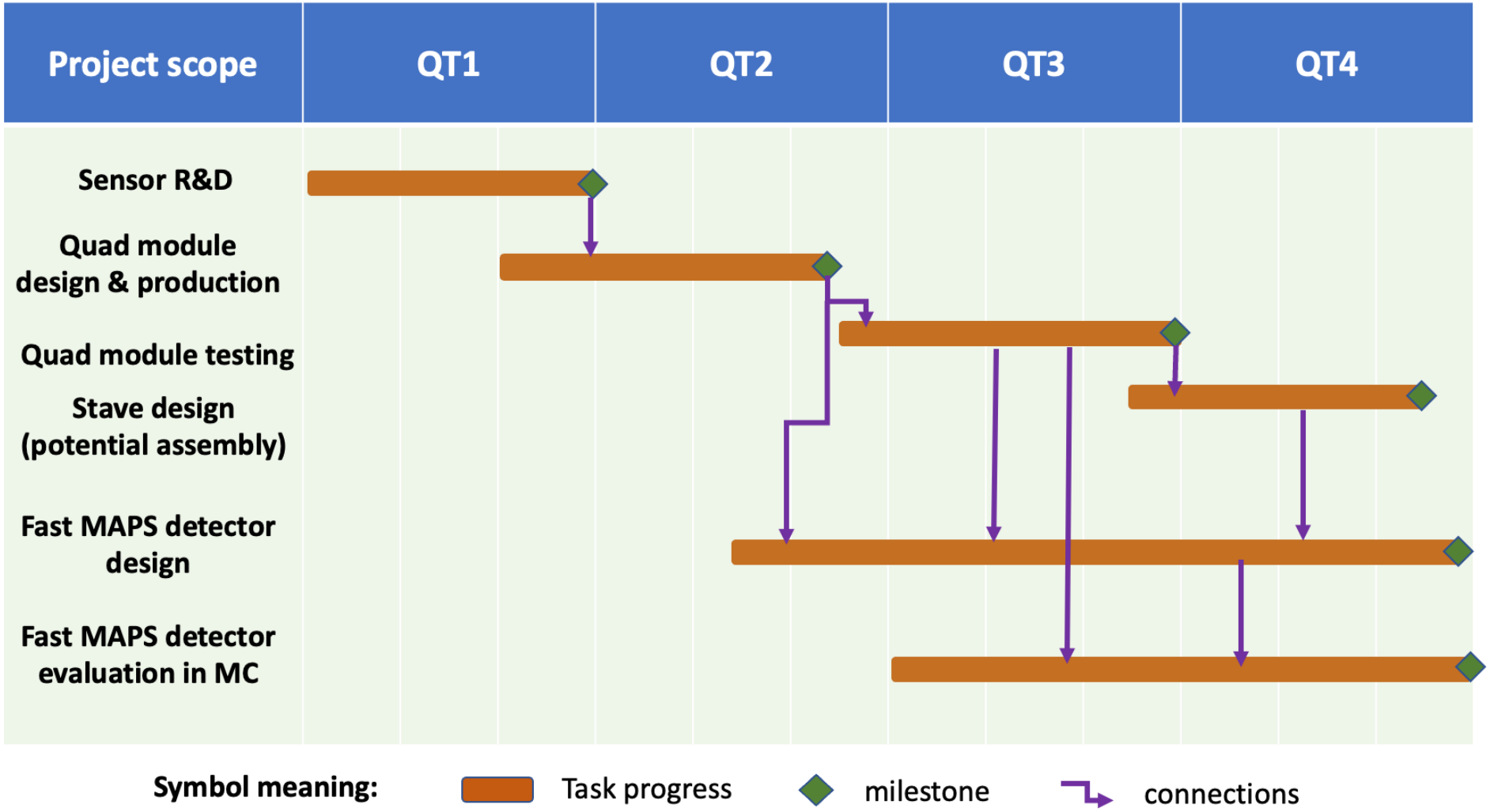


Initial e+p DIS simulation studies to evaluate the event plane resolution provided by the proposed Fast Timing MAPS detector (FMT) by Xuan Li (LANL).

Will expand the studies with latest e+A event generator during this project.

FY24 project timeline and milestones

- The activity timeline and milestones for FY24



Project funding request

- This project is proposed for two years. For FY2024, the project forecast is listed below:

Index	Item	Nominal	Nominal-20%	Nominal-40%
1	Postdoc (student) labor	$54,597 (30% FTE)	$43,678 (24% FTE)	$32,758 (18% FTE)
2	Mechanical engineer labor	$50,895 (20% FTE)	$40,716 (16% FTE)	$30,537 (12% FTE)
3	Electronic engineer labor	$50,895 (20% FTE)	$50,895 (20% FTE)	$50,895 (20% FTE)
4	Technician labor	$18,199 (15% FTE)	$9,100 (7.5% FTE)	$0
5	Travel (beam tests)	$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

Note: the funding request includes the overhead rate at LANL and MIT

Summary and Outlook

- The proposed Fast Timing MAPS detector will utilize advanced MALTA2 technology to provide event activity monitoring for future EIC measurements.
- The proposed R&D will make full use of existing resources and perform innovative detector design and prototype module production.
- We have established a strong collaboration with world-leading scientists and engineers from LANL, CERN and MIT.
- New MALTA sensor, mini MALTA3 (using synchronization memory with 0.78 ns time resolution) could achieve 1ns timing resolution and is much easier for service integration. Will cross-check the status and timeline of the mini MALTA3 sensor for the EIC detector integration as well.

mini MALTA3 sensor design