New Generation Resistive Micromegas for Future Detectors

Paolo Iengo on behalf of the RHUM team

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IFD 2025 - INFN Workshop on Future Detectors

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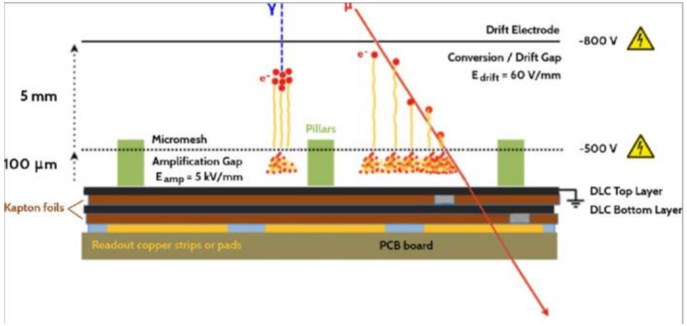
Europe/Rome timezone

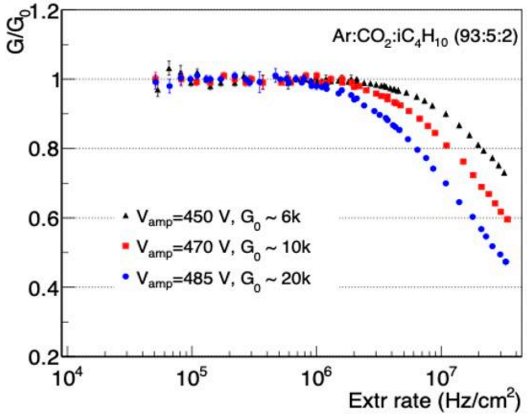
Introduction

- INFN NA and RM3 groups have played a major role in the development and construction of the largest MPGD-based detector system ever built: the Micromegas (MM) detector for ATLAS
- Based on that established experience we started in 2015 an R&D program to further develop the resistive MM with the following objectives
  - Consolidation of the technology for use at future colliders, also aiming at very high rates up to 10 MHz/cm^2
  - Optimization of the spark protection resistive scheme to achieve stable operation at high rate and gain
  - Demonstration of the scalability to large surfaces
  - Exploitation of the robustness and stability of configurations achieved at high rates to redirect R&D efforts towards a simplified and optimized version for operation at low/medium rates
  - Industrialisation/production at industries (ongoing with ELTOS)
- Effort developed within INFN MPGD_NEXT and RHUM projects and RD51/DRD1 collaborations
- Fully aligned with ECFA readmap and strategic themes for future experiments of DRD1

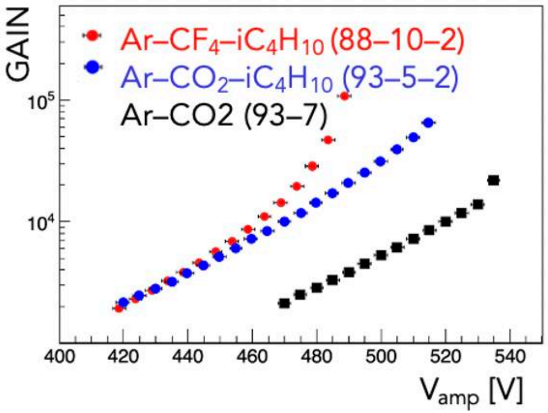
Established results for high rate



Consolidate double DLC layout and pad readout

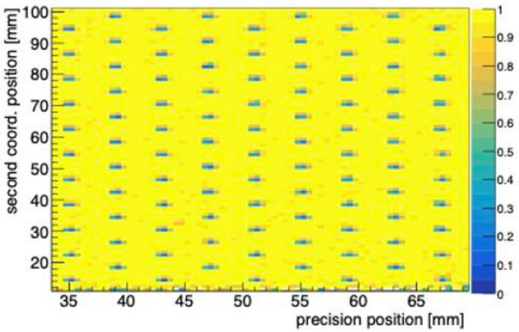


Rate capability measured with X-rays

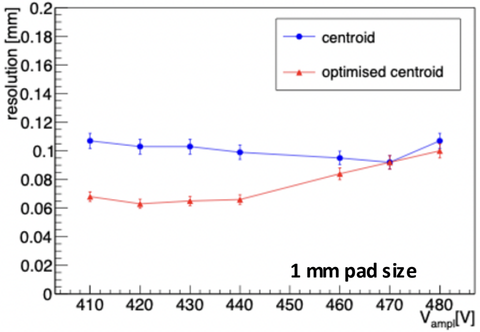


Gain vs HV for different gas mixtures

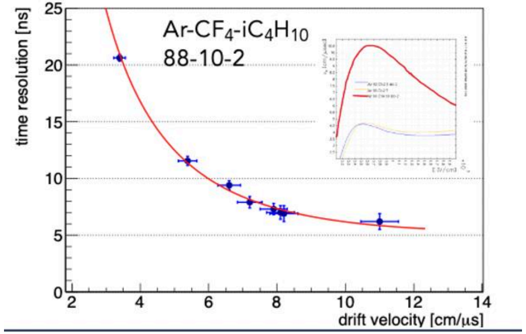
- Result from test with beam



Efficiency map for perpendicular tracks



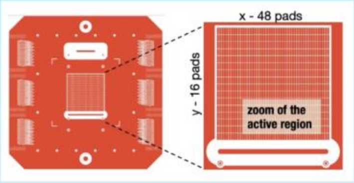
Space resolution down to 65 um:
1/15 of the pad size



Time resolution down to 6 ns

Established results: from small to large size

Small size prototypes

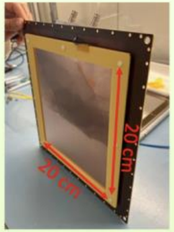


Several resistive layout tested

Active area: 4.8 x 4.8 cm^2 active region
Anode plane pad size: 0.8 x 2.8 mm^2 → 768 pads

48 pads – 1 mm pitch (“x”)
16 pads – 3 mm pitch (“y”)

Medium size prototypes

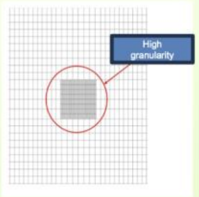


Two detectors:
Paddy400-1 & Paddy400-2

Active area : 20 cm x 20 cm (partial readout in central part, ~40%)
Anode plane pad size: 1x8mm^2 → 4800 pads

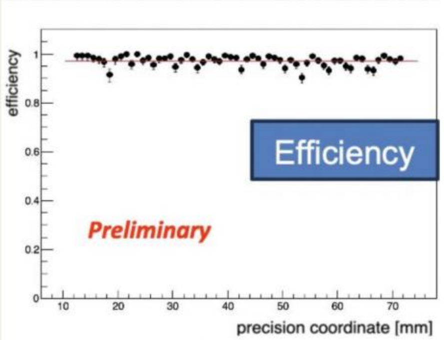
- Tests performed also in “common cathode” configuration

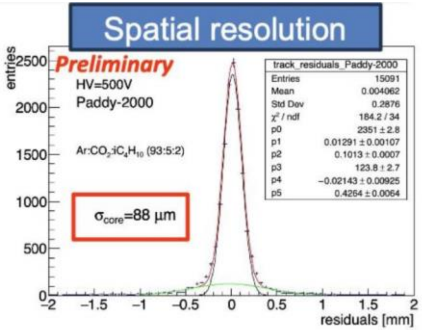
Large size prototypes



Paddy-2000 - “The Big one”

Active area : 50 cm x 40 cm
Anode plane pad size:
Central part
1x8mm^2 → 512 pads
Surrounding area
10x10mm^2 → 2048 pads

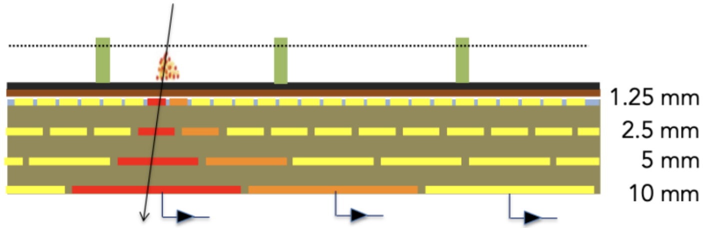




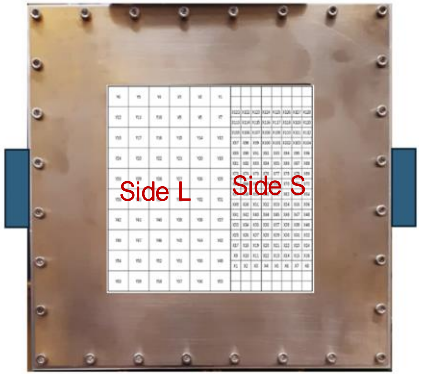
Paddy-2000 dimension fit the needs of detector units for most of applications to future experiments

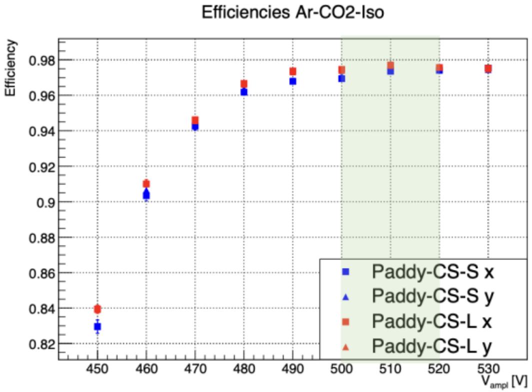
Ongoing activity: low/medium rate

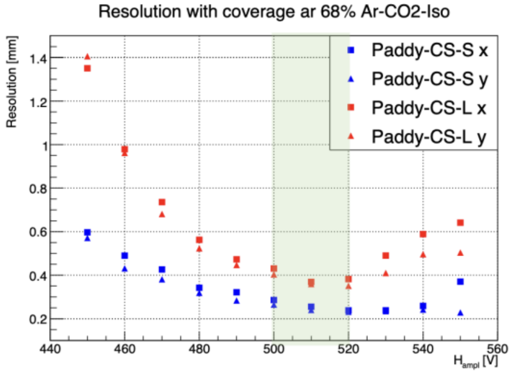
- Single layer DLC: at low rate the double DLC configuration to quickly evacuate the high-density current not needed
  → simplified (and cheaper!) construction
- Capacitive sharing: to reduce number of readout channels while preserving the spatial resolution



Prototype with single DLC and capacitive sharing







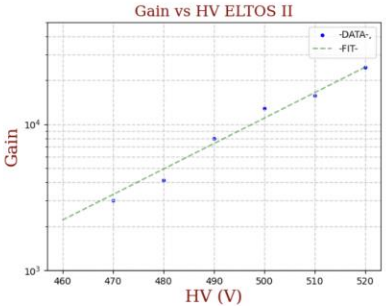
- Top readout layer (direct signal induction): 1.25x1.25 mm^2
- Side L: Four layers / four steps capacitive sharing: 1.25x1.25 mm^2 → 2.5x2.5 mm^2 → 5x5 mm^2 → 10x10 mm^2 readout pads
- Side S: Four layers / three steps capacitive sharing: 1.25x1.25 mm^2 → 2.5x2.5 mm^2 → 5x5 mm^2 → 5x5 mm^2 readout pads

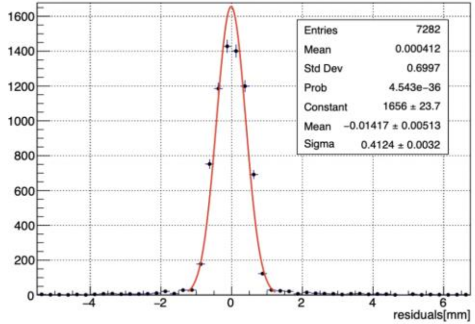
Space resolution:
- 220 um with 5x5 mm^2 pad size (1/23)
- 380 um with 10x10 mm^2 pad size (1/26)

No efficiency lost for the capacitive coupling

Ongoing activity: knowledge transfer

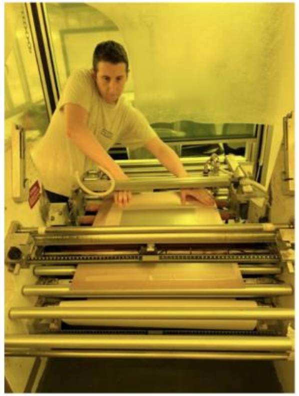
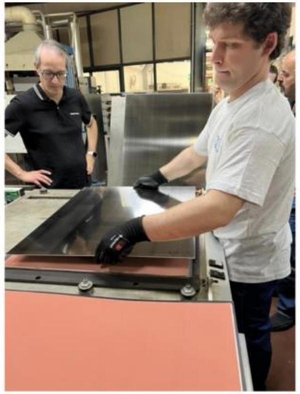
- Future experiments might need mass production.
  Not fully affordable in Institutes: industrialization needed
- Following on the successful experience for the Micromegas for ATLAS we established a collaboration with ELTOS SpA for the KT of DLC resistive bulk-Micromegas
  - Reminder: for ATLAS 1280 m^2 of Micromegas board, not bulk
- The DLC foils can be produced in-house at CERN with the CERN-INFN sputtering machine (trained personnel from our group)
- Single layer DLC 10x10 cm^2 prototypes constructed and tested with good results

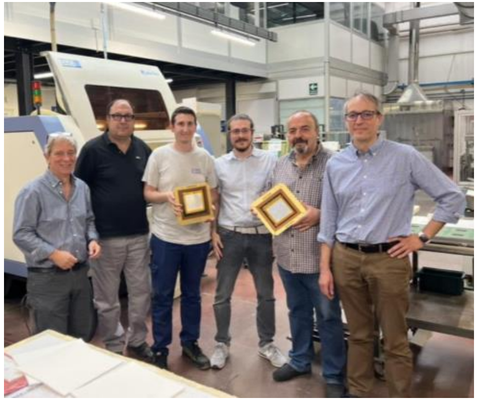




Good stability (gan up to 20k
Space resolution: 400 um with 1.6 mm pad size

Single DLC prototype constructed at ELTOS

Conclusions and Outlook

- DLC resistive Micromegas is a solid technology available for applications to future experiments
  - Excellent performance: gain, stability, time and space resolutions, simple operations
  - High-rate variant (2-layer implementation) up to 10 MHz/cm2
  - Medium/Low-rate variant (single DLC layer) with capacitive sharing for readout channels saving
  - Scalability to large size
  - Industrialization

- HEP applications
  - Very forward extension of muon tracking system at existing experiments
  - Muon tracking/tagger or TPC for next accelerators (FCC, Muon Collider)
    - Expression of Interest submitted for Muon system at FCC-ee ALLEGRO and IDEA
  - Beam-dump experiments
    - Part of the SHADOWS experiment proposal, not approved by CERN in 2024
  - Readout element for sampling calorimeter (see fire talk by L. Generoso)
  - Considered for proton structure/QCD Physics with AMBER (M. Alexeev *et al*)
  - Tracker for the PADME experiment upgrade at LNF, under test (some of the authors + LNF group)

If RHUM can't fix it, you're not using enough RHUM*

RHUM…

…what else?

Thank you!

* l'alcol nuoce gravemente alla salute

The hybrid µ-RWELL: a new high performance resistive MPGD

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[1]INFN - Roma2, [2]INFN - LNF, [3]INFN - Catania, [4]CERN, [5]INFN - Bari

Performance Requirements for the Experiments of the Future

Future High-Energy and nuclear Physics experiments demand improvements in particle detection technologies: unprecedented tracking and timing performance, as well as enhanced robustness in extreme environments

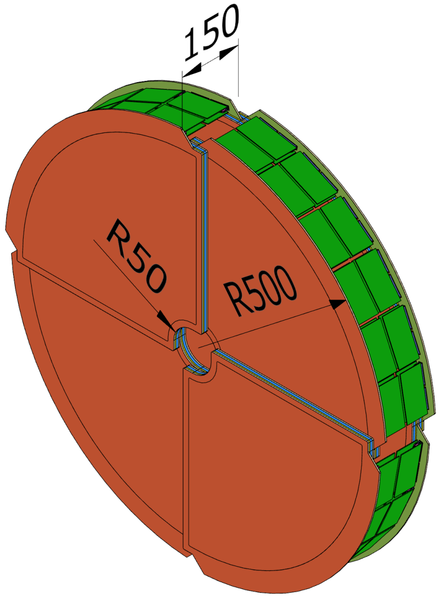
EIC – ePIC Endcap Trackers
INFN Roma2 group

Where:
- Electron Ion Collider (EIC) @ Brookhaven National Laboratory

Main Physics Goals:
- Internal nuclear sctructure
- Confinement
- QCD in non-perturbative regime

Geometry:
- 2 pairs of G-RWELL disks
- Large coverage (pseudo-rapidity |η| > 2)

Performance Requirements	
Time resolution	10 -20 ns
Material budget	$\simeq 1\ \%\ X_0$
Spatial resolution	150 μm
Readout	2D strips
Single detector efficiency	96 – 97%

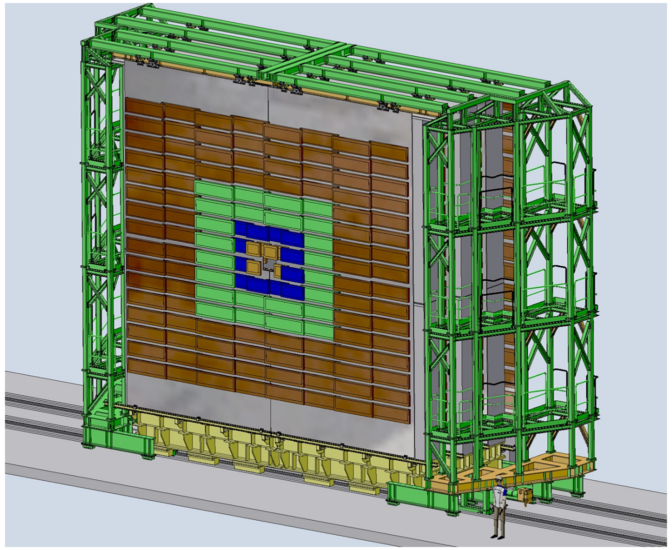


LHCb - Muon System Upgrade
INFN LNF group

Where:
- LHCb @ CERN

Main Physics Goals:
- cp violation
- B physics

Geometry:
- 4 stations for a total of 600 detectors

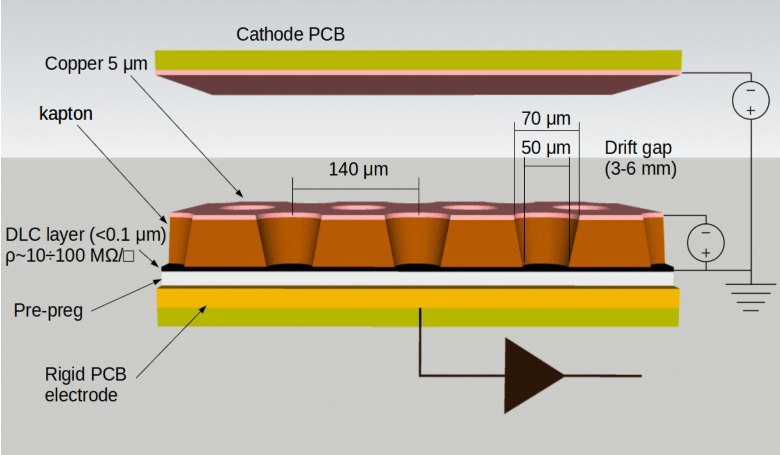


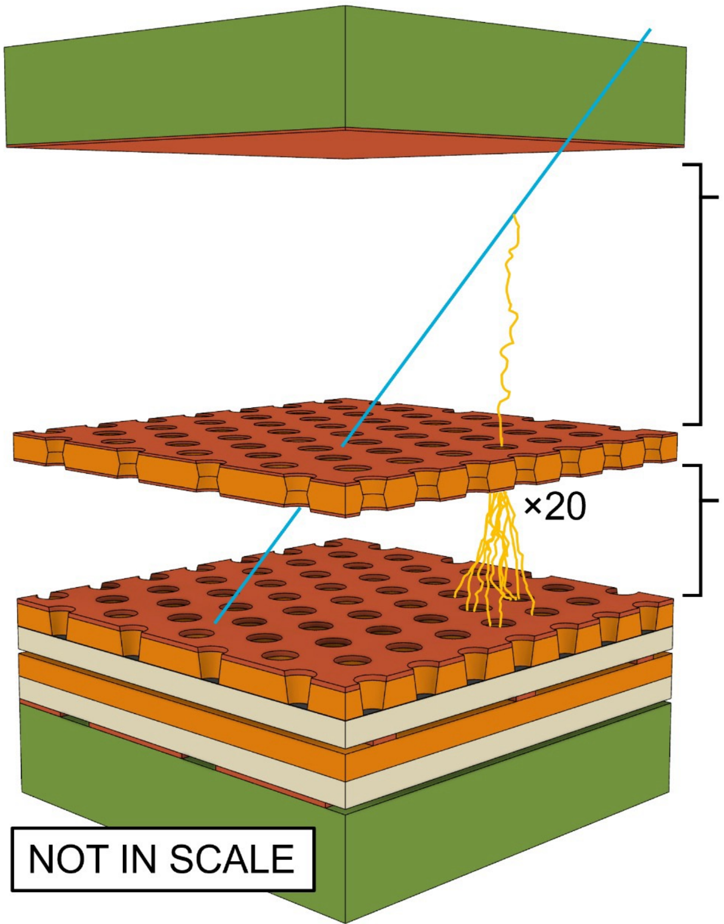
Performance Requirements	
Expected muon flux	1 MHz/cm^2
Rate for FEE channel	700 kHz
Time Resolution	< 5 ns
Readout	Pads

The G-RWELL

The μ**-RWELL** is a single amplification stage **resistive MPGD**(DLC layer w/ ρ ~ 100 MΩ/□)

- Single amplification stage
- Maximum gas gains up to 10^4
- 1D spatial resolution down to 100 μm over a wide range of incidence angles (0–45°)
- Time resolution down to 5–6 ns
- Operation at particle flux exceeding MHz/cm^2





CATHODE
~ 3 mm lightweight support
5 μm copper

DRIFT
6 mm

GEM
5 μm Copper
50 μm Kapton
5 μm Copper

TRANSFER
3 mm → 2 mm in the future

μ-RWELL
10 μm copper
50 μm Kapton
~ 100 nm DLC

R/O
2D strip layout, 600 μm pitch
~ 3 mm lightweight support

GEM + μ-RWELL hybrid (**G-RWELL)** developed for safe operation at a **gas gain larger than 10^4**.
It ensures satisfying performance even with **angled tracks while using a 2D R/O.**

The particle ionizes in both the drift and transfer gas gaps
Two amplification stages:

- into the holes of the GEM foil – gain **20**
- inside the WELL – gain **2'000**

Total gas gain up to ~10^5

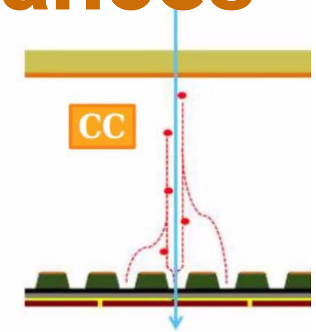
The G-RWELL layout has been characterized using X-rays at LNF and muon/pion beams at the CERN T10- PS beam line, demonstrating exceptional performance and stability.

Tracking Performances

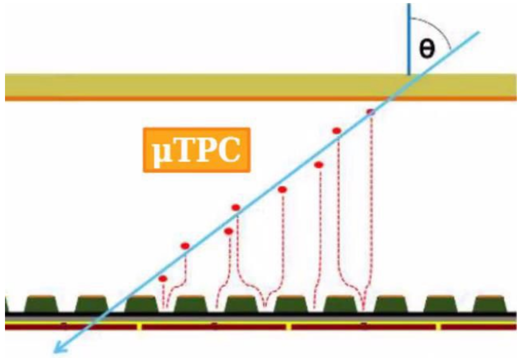
Test beam @PS T10 November 2024

- muon beam 5GeV/c

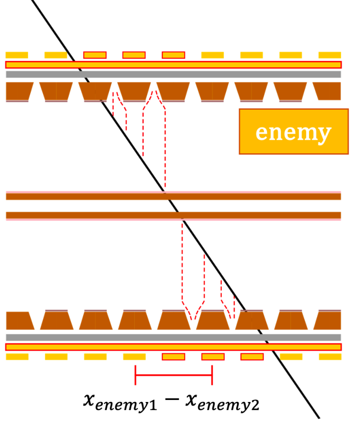
2 G-RWELL prototypes	
Active area	10 x 10 cm^2
Pitch	400 µm
Drift gap	6 mm
Transfer gap	3 mm



Charge Centroid: calculates the position of ionization clusters based on mean position weighted on measured charge



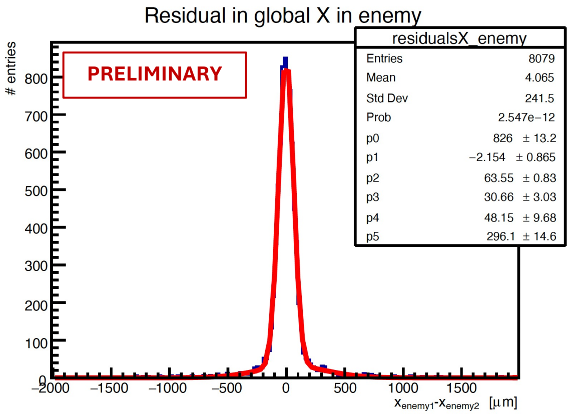
µTPC: tracks are reconstructed with the time of arrival of hits and the drift velocity, the cluster's position is the intercept with a plane parallel to the readout



"**Enemy mode**": evaluates the residual as the distance between the position of the cluster detected by the two adjacent DUTs minimizing the systematic contribution of the tracking devices

PRELIMINARY

Charge Centroid 0°

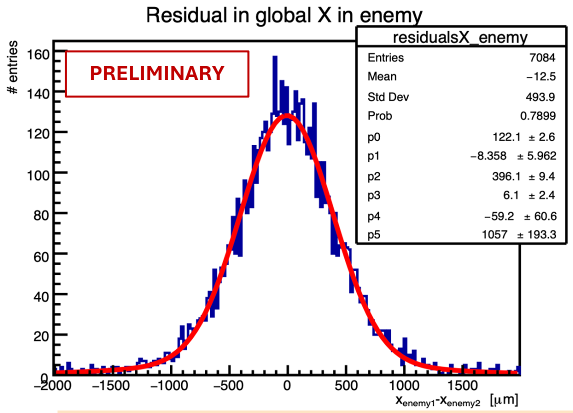


σ = 90 µm

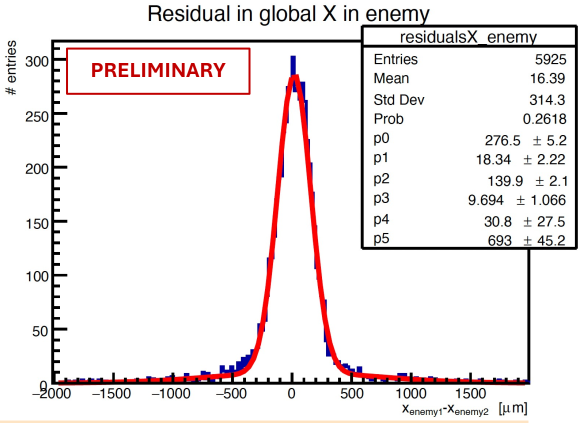
In plateau (eff ~ 96%) :

ΔV_{GEM} = 430 V ΔV_{WELL}= 550 V

Charge Centroid 30°



µTPC 30°



σ = 370 µm **σ = 200 µm**

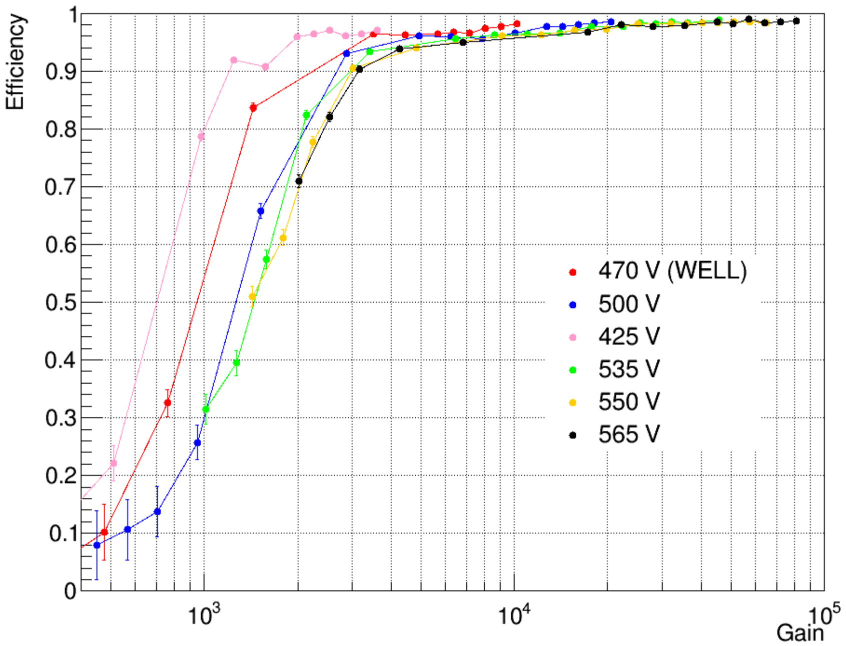
In plateau (eff ~ 96%) :

ΔV_{GEM} = 460 V ΔV_{WELL}= 550 V

Gas mixture	Ar:CO_2:CF_4 45:15:40
Acquisition system	SRS + APV25 + mmDAQ3
Data analysis	Corryvreckan framework

Timing Performances

Preliminary Gas Gain Measurement
@LNF laboratory using an X-ray gun: $G_{TOT} = G_{GEM} \otimes G_{\mu\text{-RWELL}}$
$G_{TOT} \sim 5 \times 10^4$ stopped without any evidence of even the slightest instability



Efficiency plateau >98% at gas gain above 6000

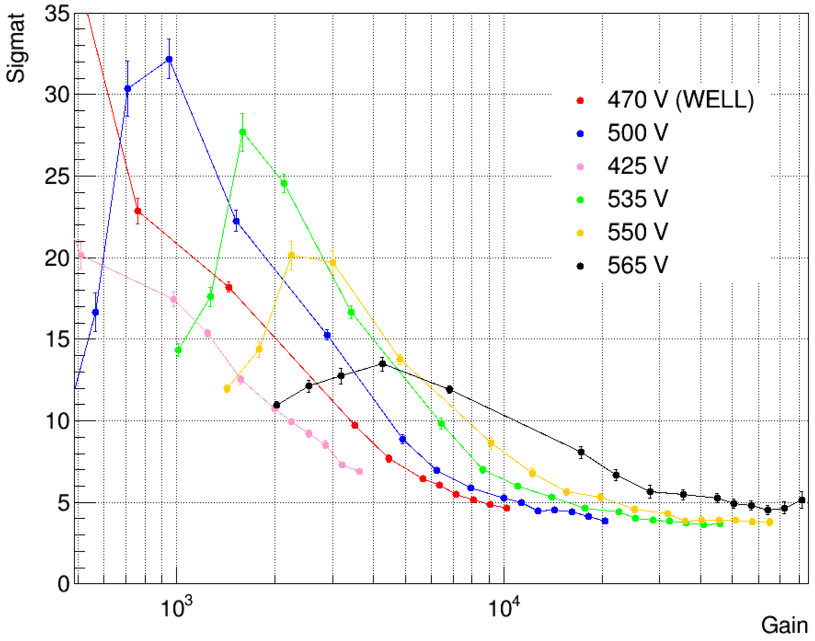
Work from the **DDG INFN-LNF** group

Test beam @PS T10 November 2024
- muon beam 5GeV/c

Gas mixture	$Ar:CO_2:CF_4$ 45:15:40
FEE	FATIC3 ASIC chip (**INFN Bari**)
THR	6 fC for efficiency, 5fC for timing

2 G-RWELL prototypes	
Active area	10 x 10 cm^2
Pad Readout	9×9 mm^2
Drift gap	6 mm
Transfer gap	3 mm

Multiple time resolution curves corresponding to different settings of μ-RWELL amplification stage



time resolution 3.8 ns
G_{TOT} ~3 – 4 x 10^4
$G_{\mu\text{-RWELL}}$ ~1.5 x 10^3
G_{GEM} ~20–25

Differences between different HV_WELL values can be attributed to a well-known effect typical of multi-step amplification stage layouts, commonly referred to as the "bi-WELL effect"

Summary and outlook

Future High Energy and Nuclear Physics challenges, which impose stringent requirements on time and spatial resolution, drive the R&D toward detectors achieving gas gains ≈ 10^5 with high operational stability in harsh environments

The **G-RWELL** is a hybrid detector based on the µ-RWELL, with a GEM preamplification:

- Max gas gain ≈ 10^5
- **Fine 2D tracking** for non-orthogonal tracks, (INFN Roma2).
    - **Spatial resolution < 100 µm** for perpendicular tracks
    - **Spatial resolution ≈ 200 µm** for inclined tracks (performance for incident angles under study)
- **Time resolution ≈ 3.8 ns** (single gap) (INFN LNF)

PRELIMINARY

The G-RWELL sets new performance benchmarks for MPGDs, showing **exceptional stability** and reliability, highlighting its potential for implementation in future High Energy Physics experiments, even in harsh environment.

Next steps foresee the construction of large area G-RWELL prototypes: a quadrant with 50 cm radius for ePIC and a M2R2 30 x 70 cm^2 for LHCb

Apparatus for Meson and Baryon Experimental Research

New large area Micromegas detector and readout ASIC for the AMBER experiment at CERN

M. Alexeev on behalf of the design working group

Università di Torino & INFN Torino

ISTITUTO NAZIONALE DI FISICA NUCLEARE

Apparatus for Meson and Baryon Experimental Research (AMBER,NA66)

2018: Letter of Intent
arXiv:1808.00848

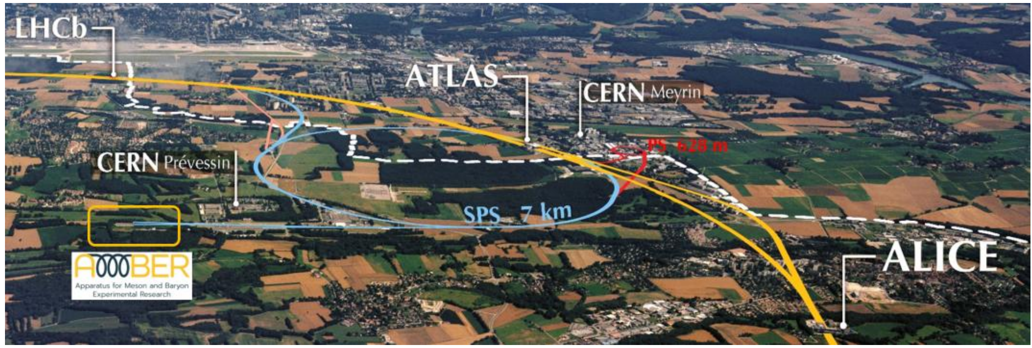
2019: Formation of a Proto-Collaboration

2019: AMBER Phase–1 Proposal
CERN-SPSC-2019-02

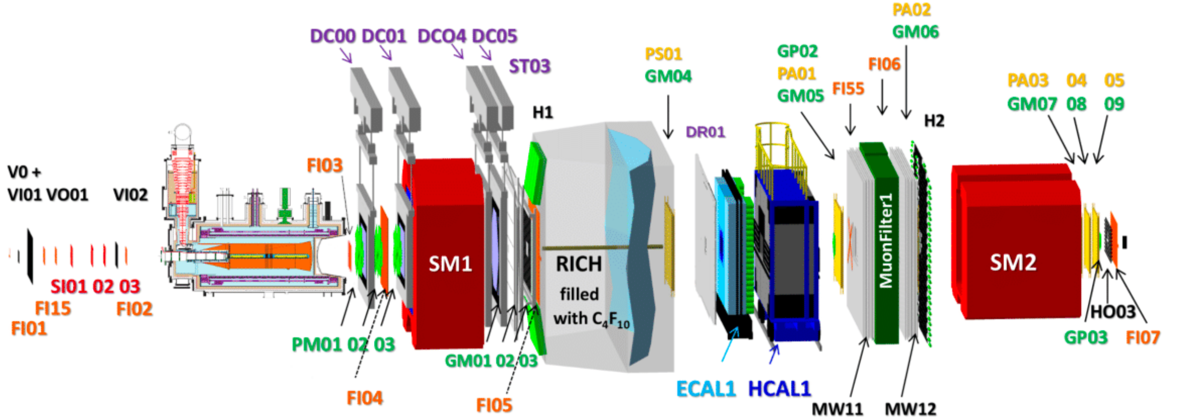
2020: Recommendation of the Proposal by SPSC and approval by Research Board

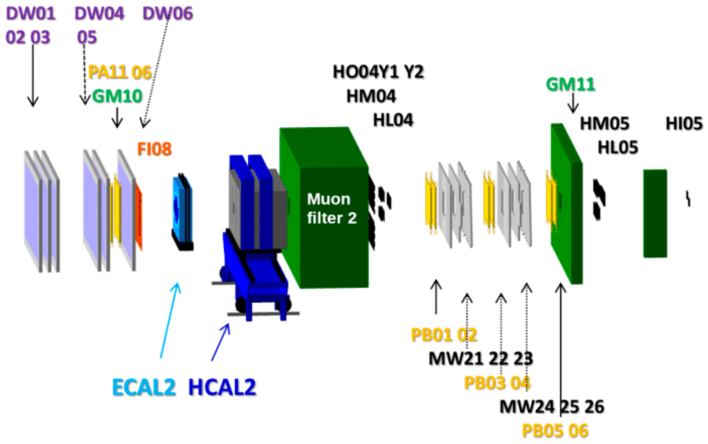
2021,2022: AMBER Pilot Run

2023: Start of AMBER data taking



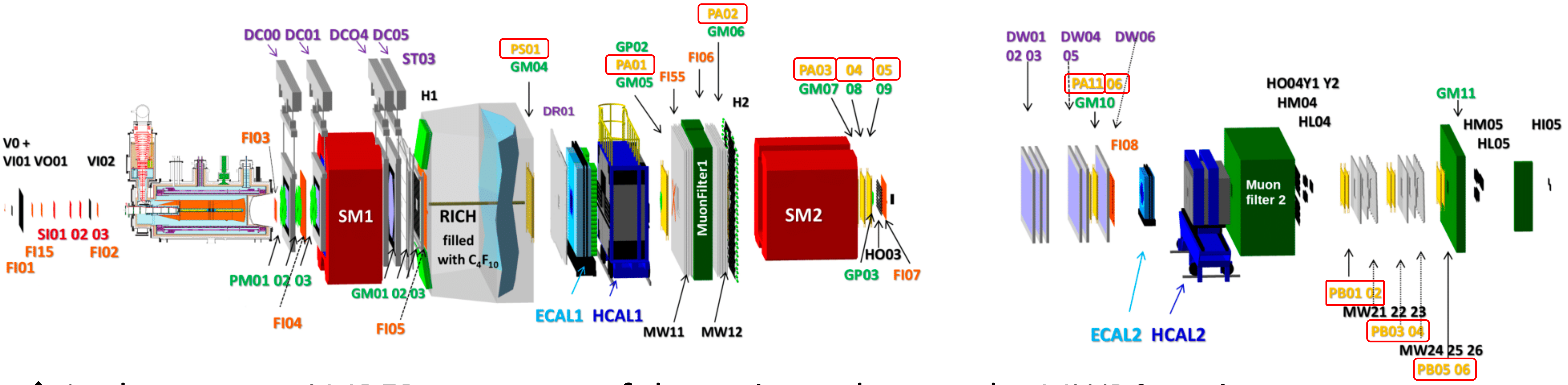
Phase-2 proposal in preparation
Post LS4 ->





Presently 32 institutes from 14 countries, but there is no upper limit on the values.

Why we work on the MM project



❖ In the present AMBER setup one of the main tracker are the MWPC stations

Present situation		Reasonable situation
✓ Triggered DAQ	➡	❑ Trigger less DAQ
✓ Degraded detectors		❑ Maintenance available for a long period of time
✓ Limited Team		❑ Collaboration between, experts, ASIC teams and CERN MPT & GDD workshops

Decided path to the future

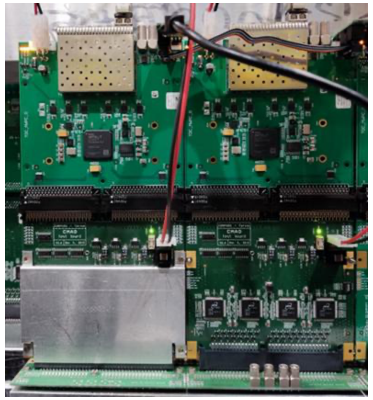
Till 2024

COMPASS MWPCs possible path to the future

After 2024

Existing detectors

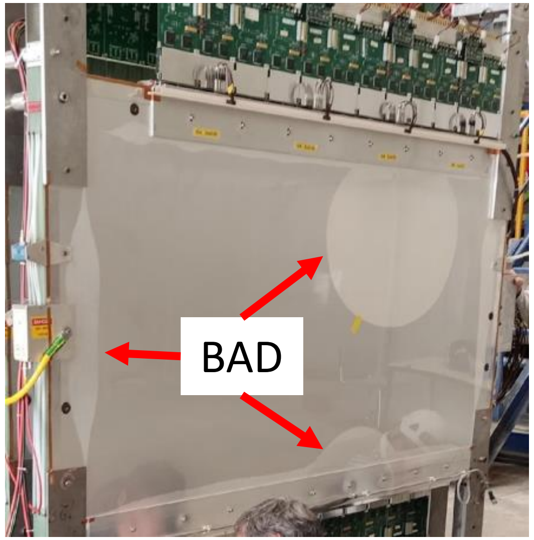
Trigger less DAQ (2025)

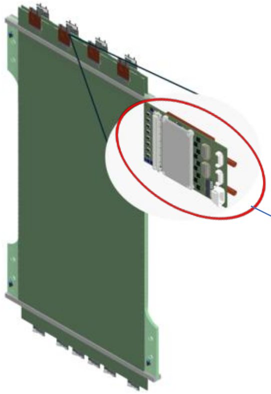


FPGA based

New FE needed

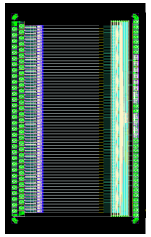
New ASIC





New detectors

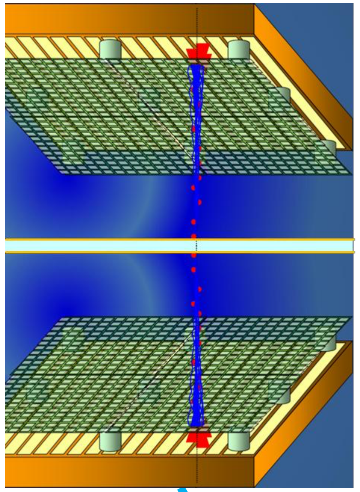
New FE needed



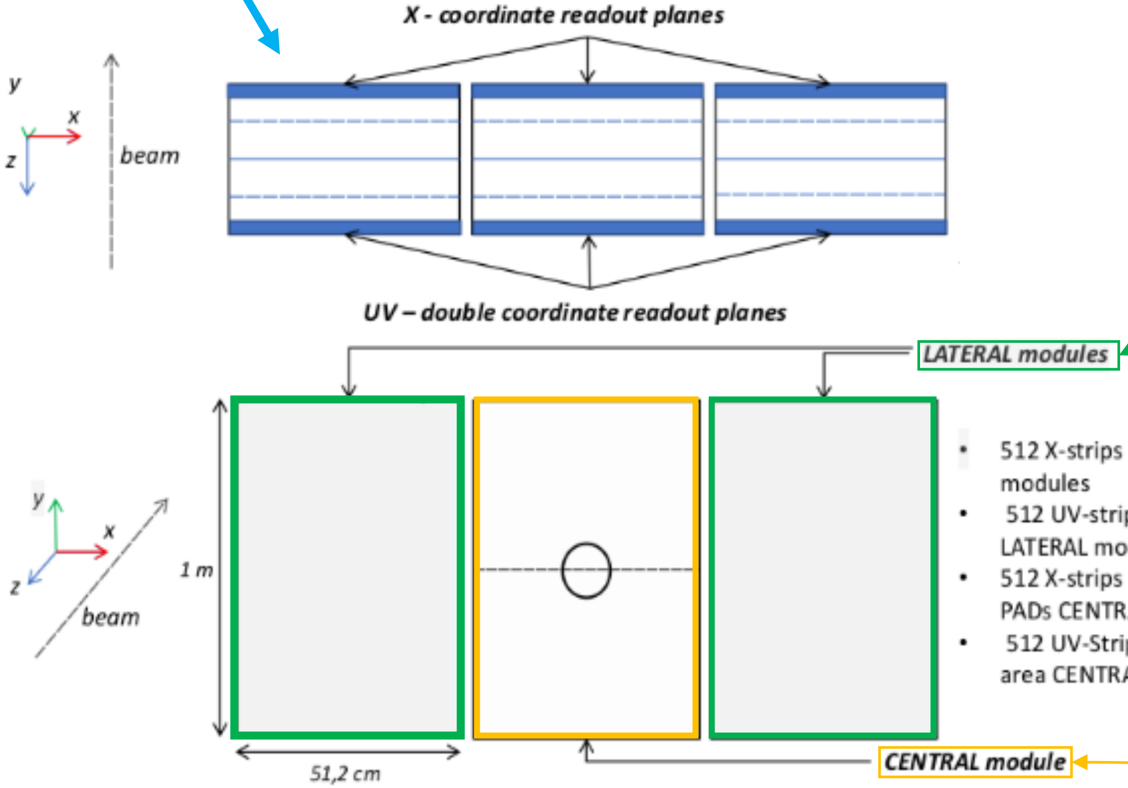
New ASIC

The 2 developments could go together -> **ToRA**

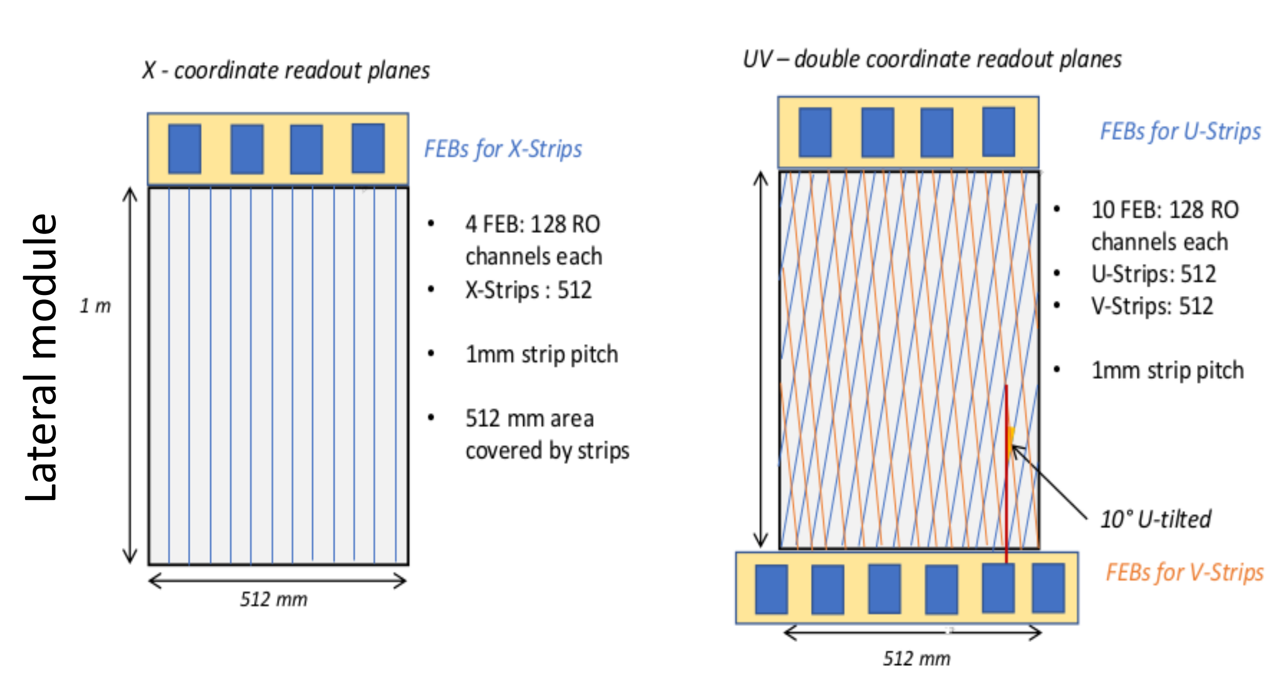
Concept design

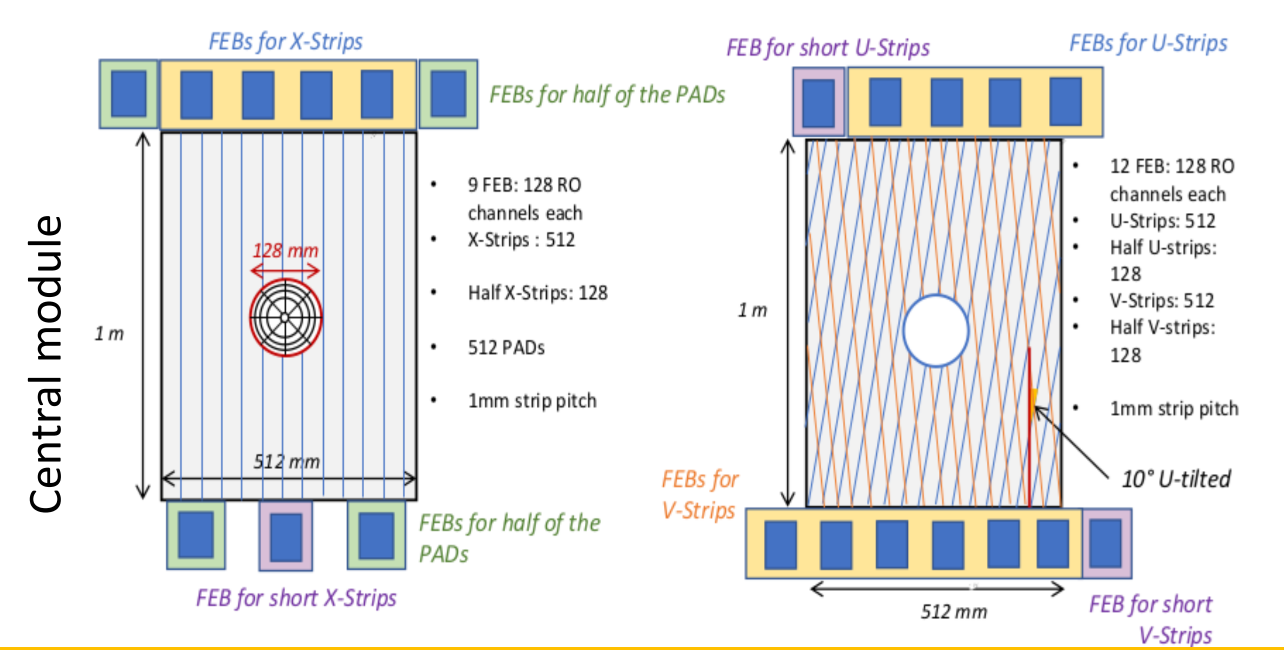


- ➢ common cathode
- ➢ 2 types of modules



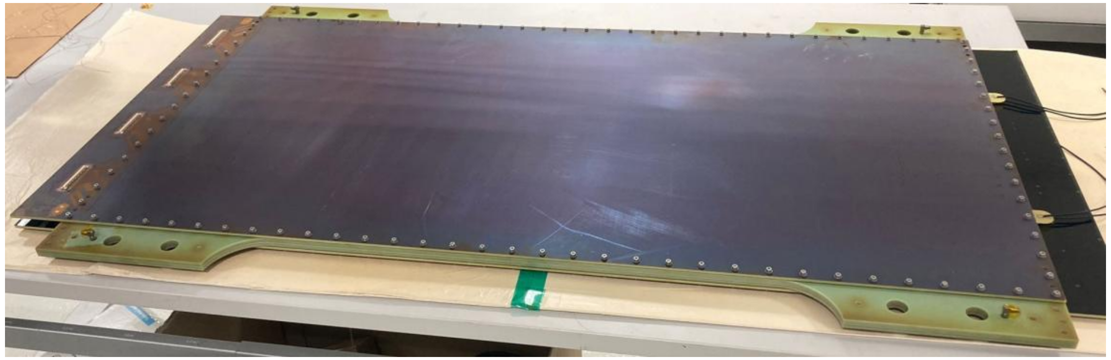
- 512 X-strips LATERAL modules
- 512 UV-strips LATERAL modules
- 512 X-strips + 512 PADs CENTRAL module
- 512 UV-Strips + dead area CENTRAL module



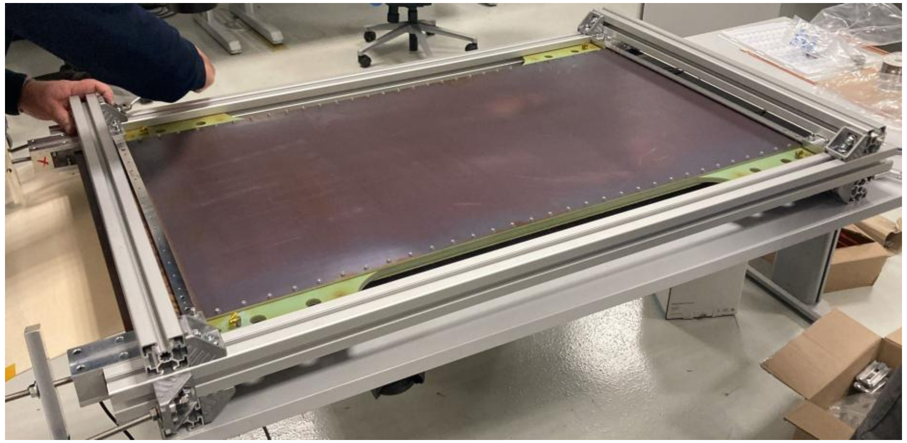


Lateral module prototype testing

Delivered on 11.10.24



Mechanics for transport and suspension mounted
11.10.24



Transported and installed in the AMBER experiment
12.10.24

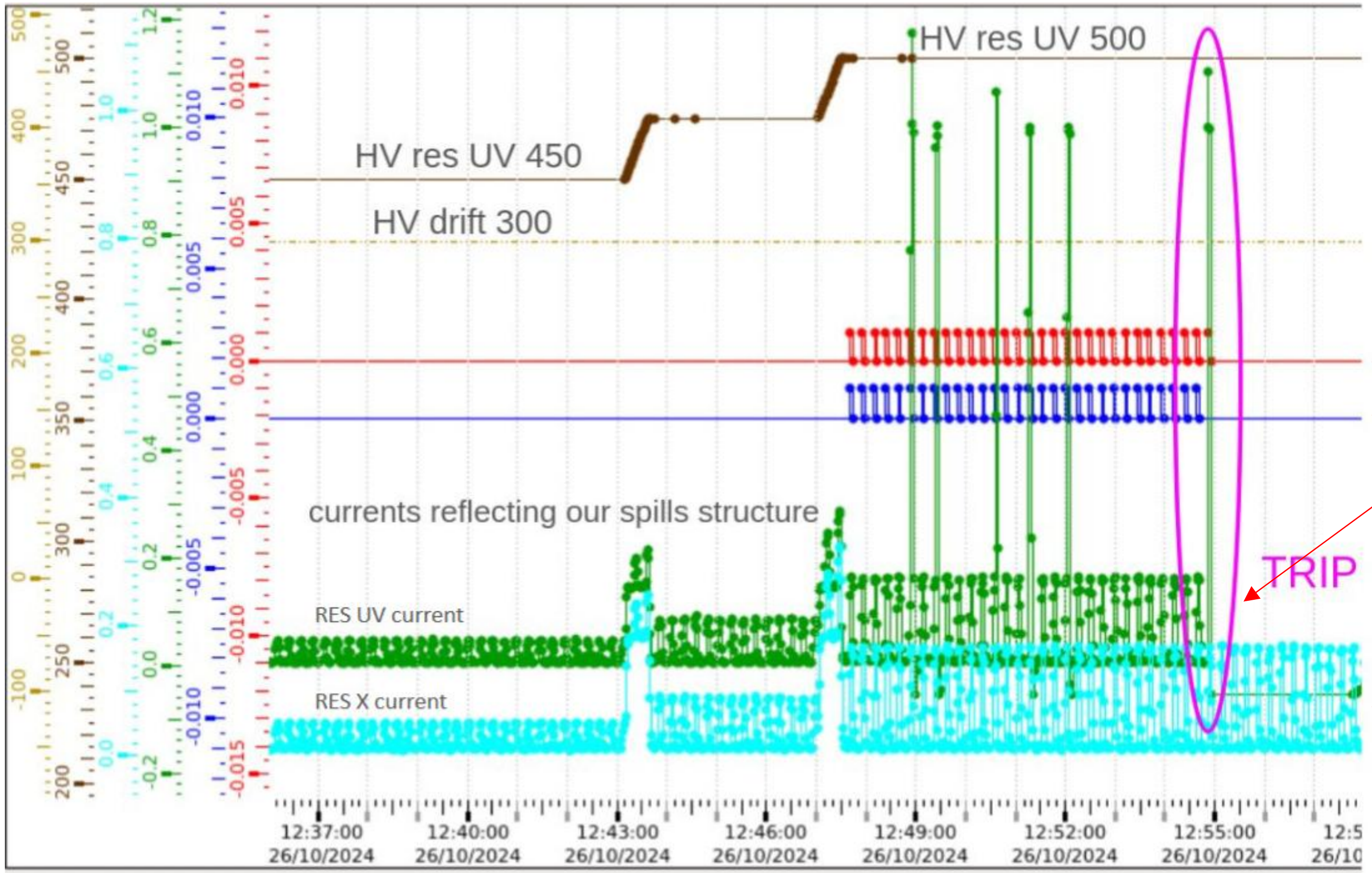
HV stability verified by MPT workshop experts
17.10.24

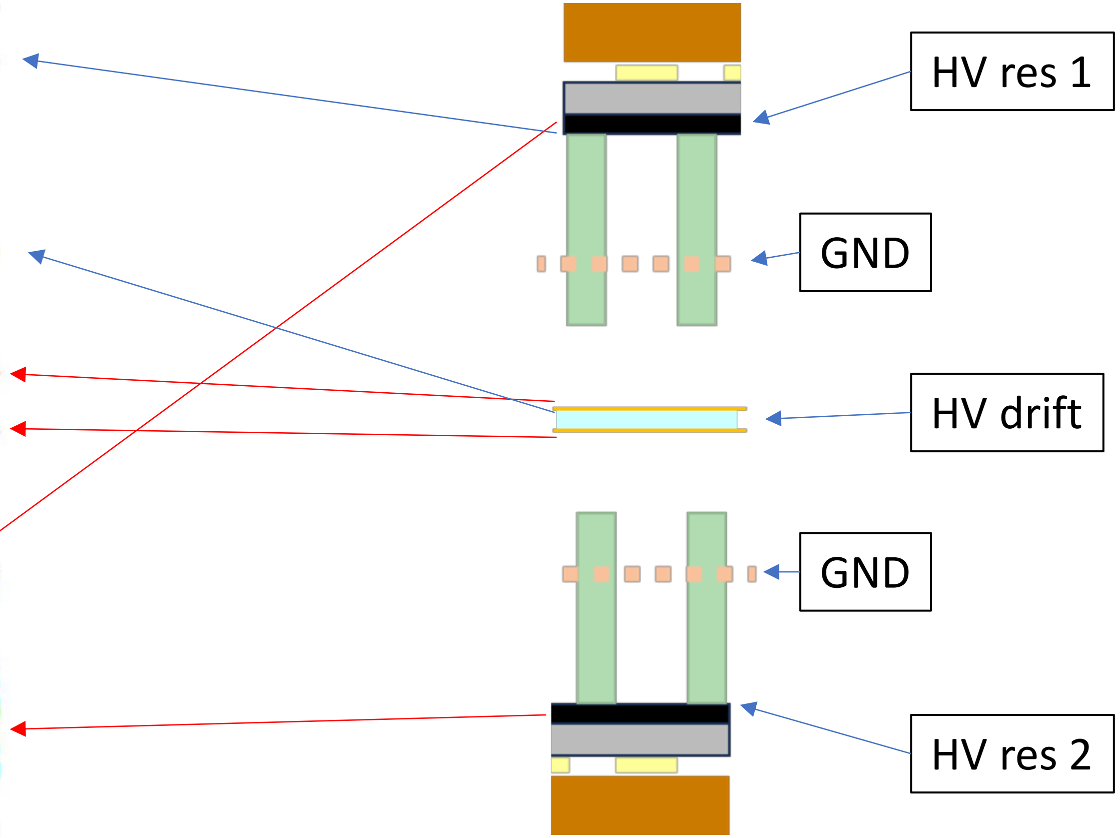
450V resistive layers
325V cathodes planes

resistive UV ~5nA
resistive X ~7nA
drift UV ~1,5nA
drift X ~3nA

We express our gratitude to MPT and GDD labs colleagues and all the community that supports us in the task

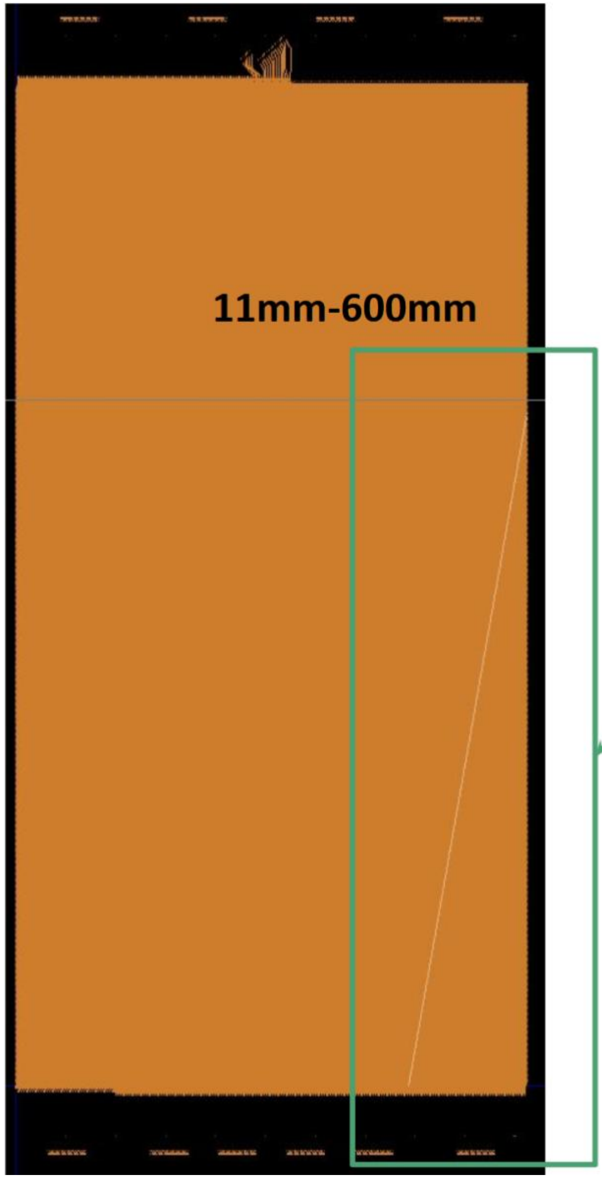
Glimpse of the first operation 1

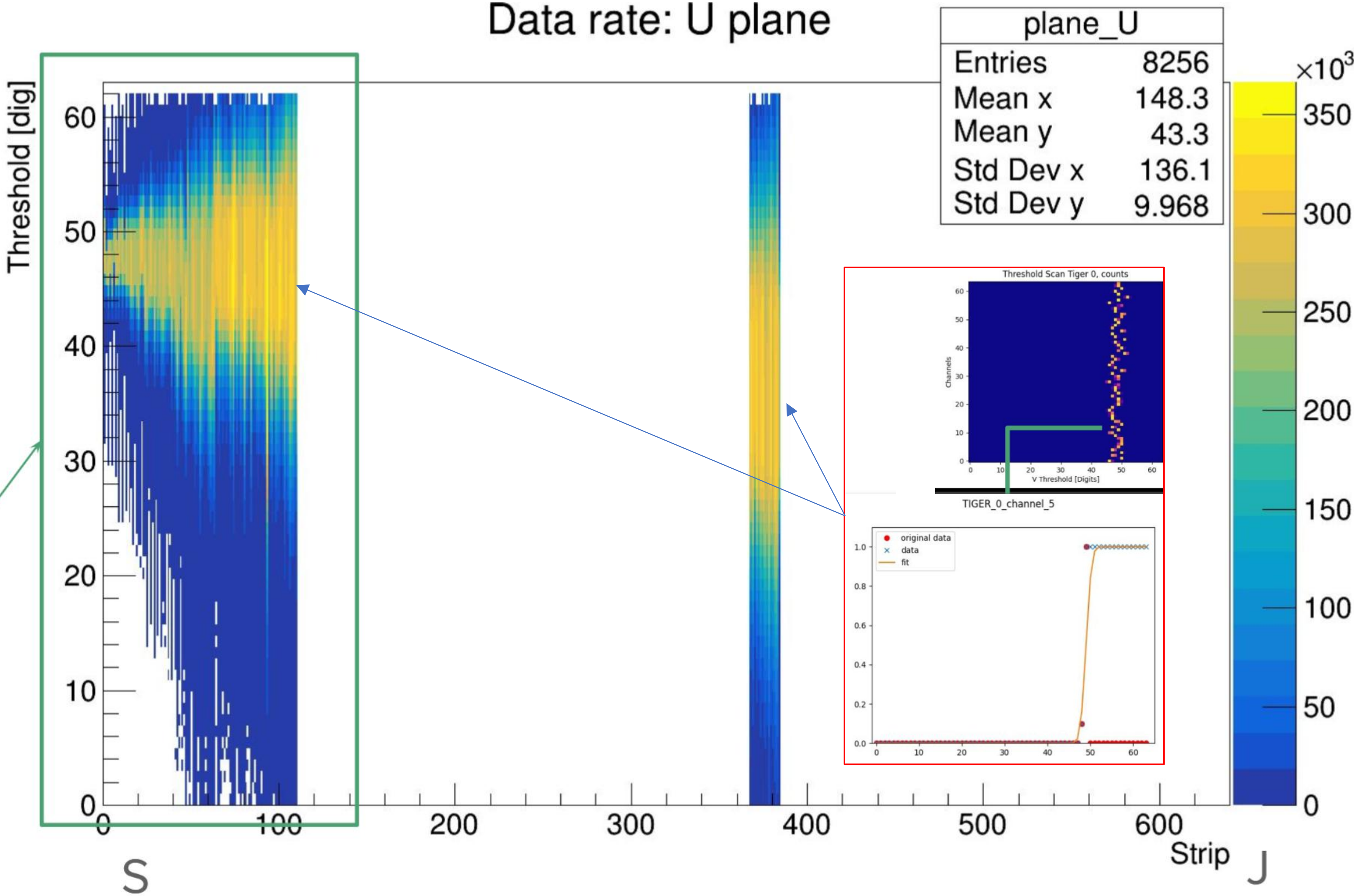




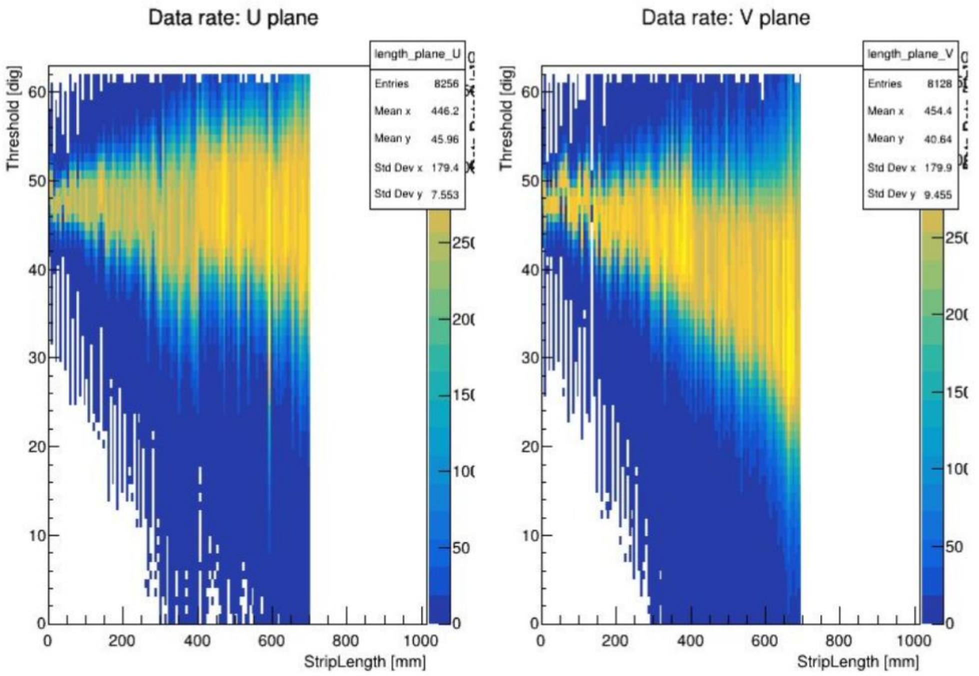
Gain observed

Glimpse of the first operation 2

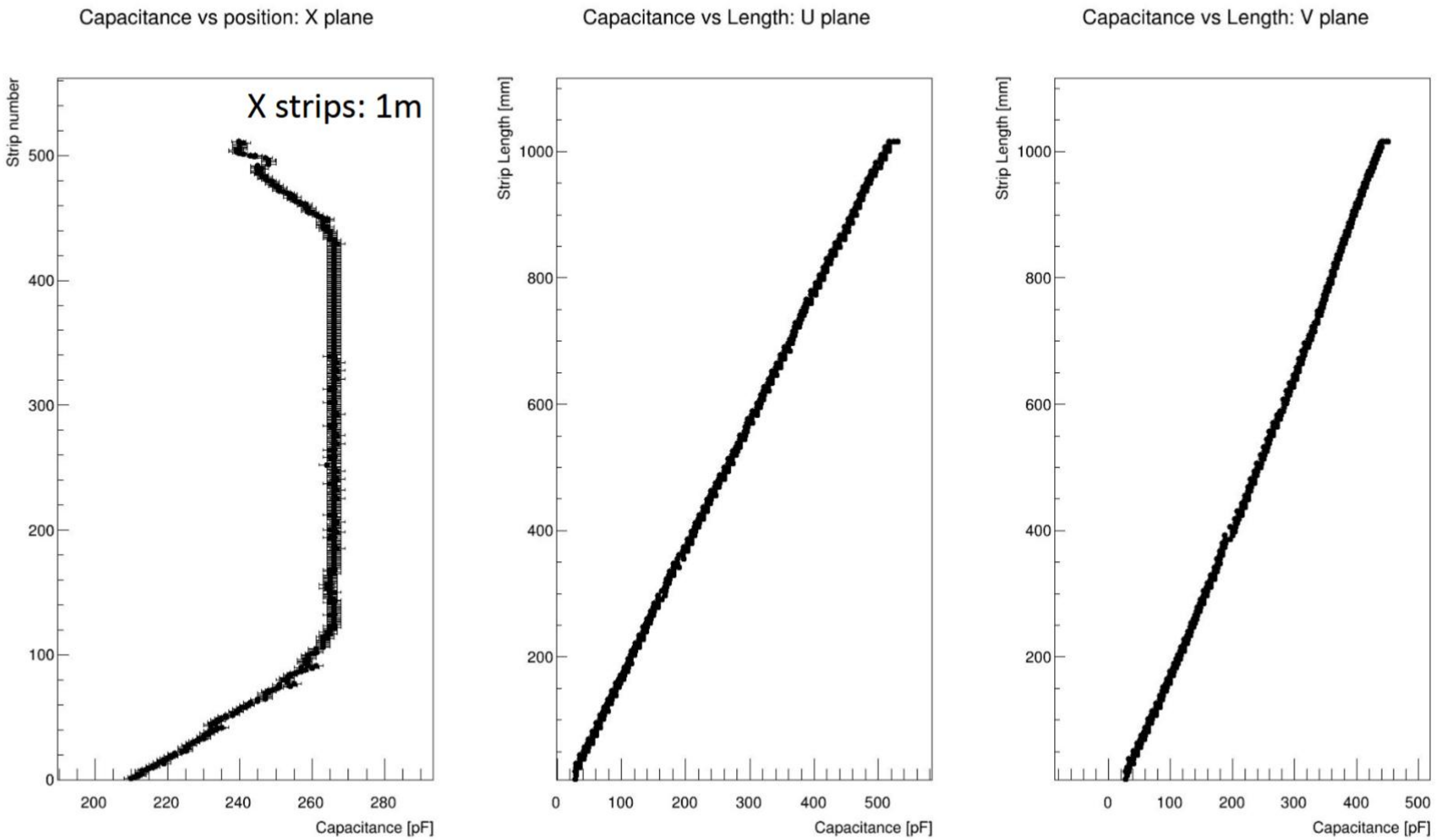




Glimpse of the first operation 4



Why we see such a behaviour



Wider thresholds distributions with longer strips

Strips capacitance measured in Torino

- X strips range: 210-250pF
- U strips range: 30-530pF
- V strips range: 28-450pF

We must update the ASIC design features

21

Chiara Alice - DRD1 collaboration meeting - 10.12.2024

Torino Readout (for) AMBER ASIC

- MPGD and Wire detectors compatible
- Target specific application
- Limited complexity
- Reuse existing solutions (ToASt)
- 65nm
- Two step features design v1, v2

Will depend on the FE optimisation results

Detector	MM	Straw	
Channels/ASIC	64	64	
Power/channel	$\lesssim$ **25**	$\lesssim$10	mW
Input capacitance	$\lesssim$550	20-100	pF
Input charge	1-100	1-1000	fC
Input impedance	$\lesssim$50 Ω	*tbd*	Ω
Max rate	$\lesssim$ **0.5**	$\lesssim$0.18	MHz
Peaking time	**150-500**	**25-150**	ns
Time resolution	1-2	$\lesssim$1	ns
Charge resolution	8	10	bits
Gain	**10-20**	2	mV/fC
ENC @10 pF	500-1000		e^-
ENC ? @550 ? pF	1000-3000		e^-
ENC @60 pF		3000	e^-
Threshold range	*tbd*	0-15	fC
Clock frequency	200	200	MHz

ToRA 2 step design plans

v1(2025-2026)

- Base version aimed at MM (GEM) & STRAW/MWPCs
- Would be sufficient for the AMBER environment
- 4 Gains
- 4 shaping times
- Trigger less
- 1 or 2 revisions depending on performance & testing

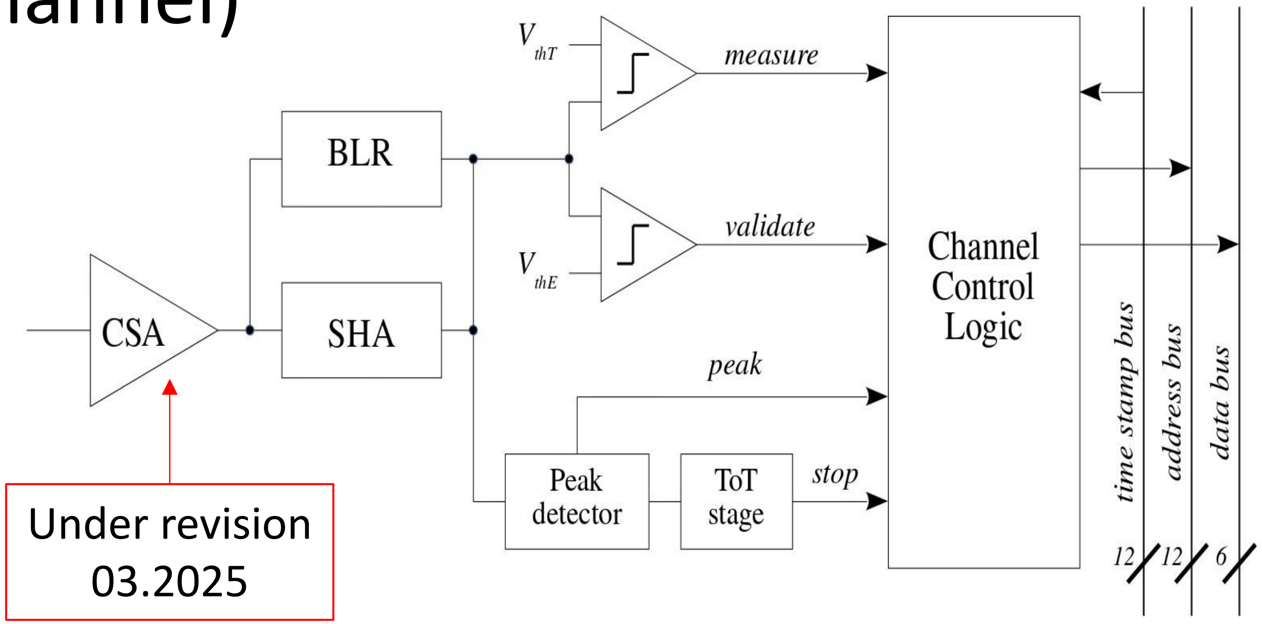
v2 (2026-2028)

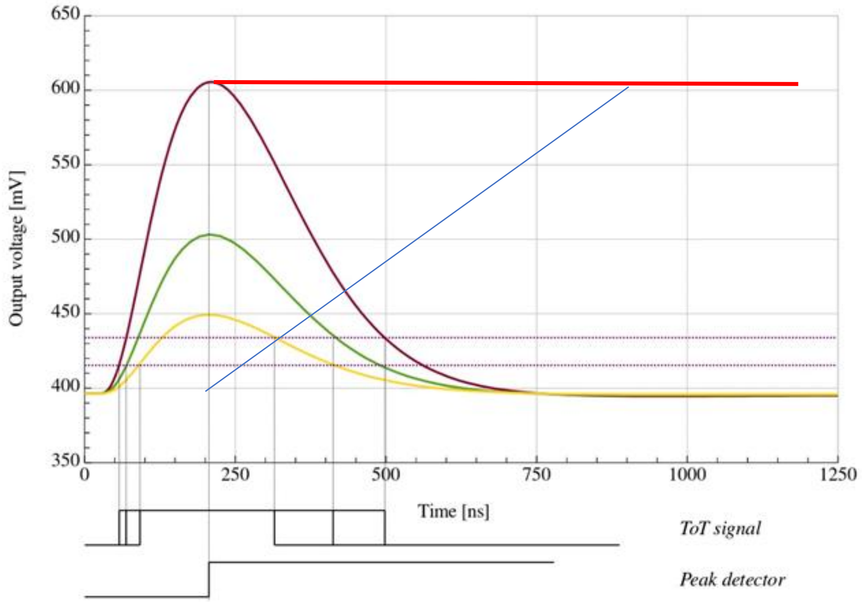
- Actions on the inter-channel analog architecture
- Minor tuning of the channels & Backend

We have a pipeline for 2 submissions that could be (v1_a,v1_b) or (v1_a,v2_a) depending on the v1_a performance

V1, Analog part (single channel)

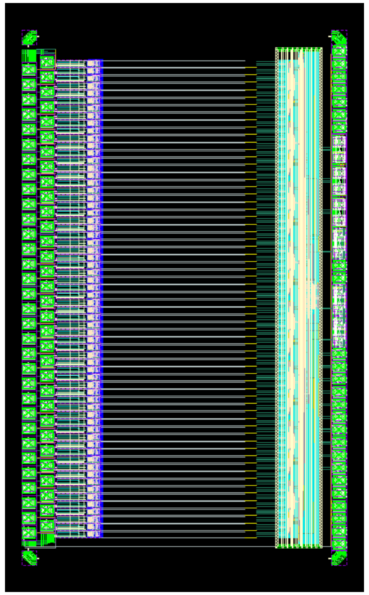
- Charge Sensitive Amplifier
  - Fours gains : 2, 6 (20), 8 (20), 12 mV/fC
  - Both polarities
- Shaper
  - 3rd order, one real and two cc poles
  - Programmable peaking time : 25 (250), 60 (250), 150 and ~500 ns
- Operation
  - Double threshold signal detection
  - Lower threshold for time measurement, higher threshold for validation
  - Peak detector signal
  - ToT & linear ToT measurement
  - Peak holder for charge measurement (via ToT)





V1, Back-end & data link

- Data output in 32 bits or 64 bits words over 200 Mb/s serial links
- It can be configured to use 1 or 2 links
- Frame length is of 20.48 μs at 200 MHz
- Data within a frame are packed within a frame header and a frame trailer
- Frame header contains chip id and frame number
- Frame trailers contains the number of valid samples and CRC



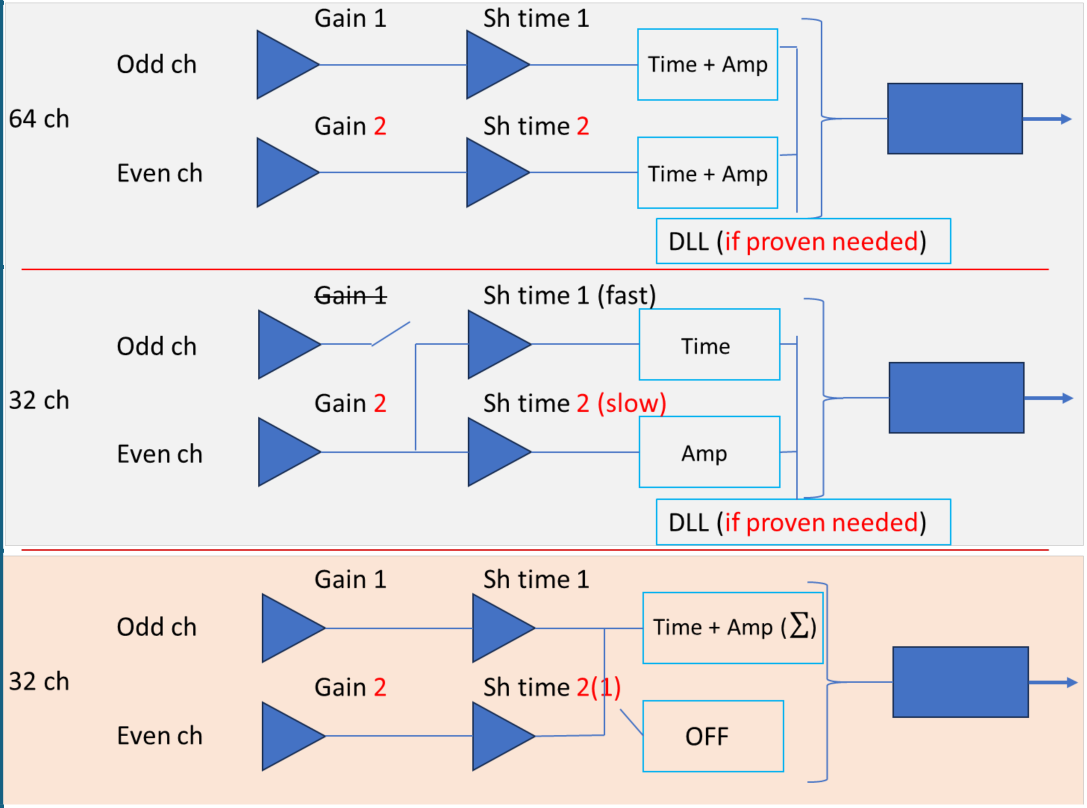
Packet type	Header	Data			
	2 bit	*30 bits*			
Data word 0	10	Region[2:0]	Channel[2:0]	Le[11:0]	Te[11:0]
Data word 1	11	Region[2:0]	Channel[2:0]	Pk[11:0]	ToT[11:0]
Header	01	01	*Reserved[12:0]*	ChipId[6:0]	FrameN[7:0]
Trailer	01	10	DataCnt[11:0]		CRC[15:0]
Sync	00	00	1100 1100 1100	1100 1100 1100	1111

V2 (2026-2028)

- ❖ Odd/even channel individual configuration
- ❖ Odd/even channels interconnections

- ➢ Anode + Cathode separate RO
- ➢ Double branch mode for Wire detectors AMP + 1ns time resolution
- ➢ Signal combination for possible noise rejection and low amplitude

Needs more study



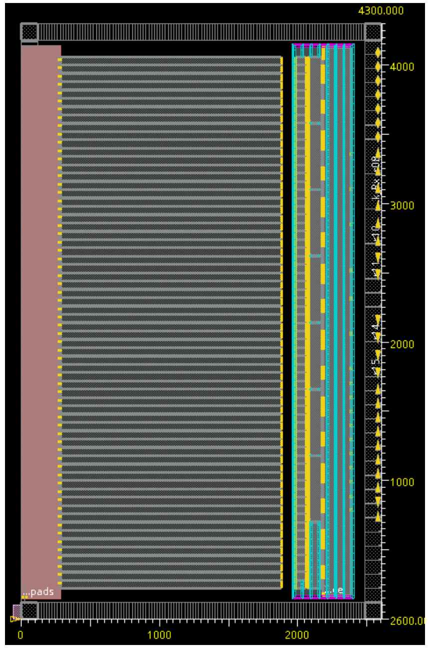
- ❑ If better time resolution is needed
  - Channel or region-level 8-tap delay line
  - Delay controlled by a global DLL
  - Time resolution 180 ps r.m.s.

Next steps

- Detector prototype study and testing in experimental conditions

- ToRA v1 ASIC is aimed at the submission in May

- DAQ modules and FE electronics for ASIC characterization and test on detector are being prepared



Characterization of IXPE Gas Pixel Detectors with the X-ray Calibration Facility

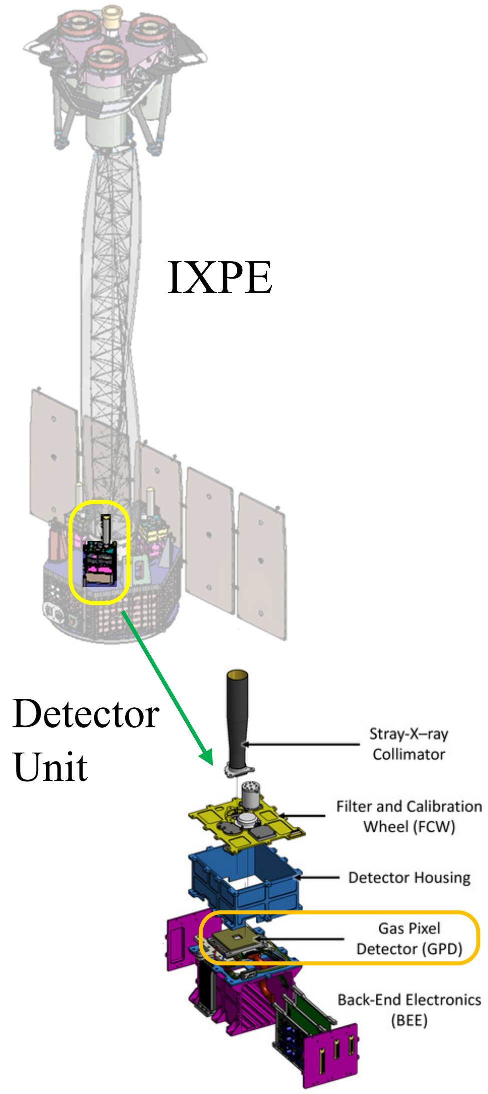
Stefano Tugliani

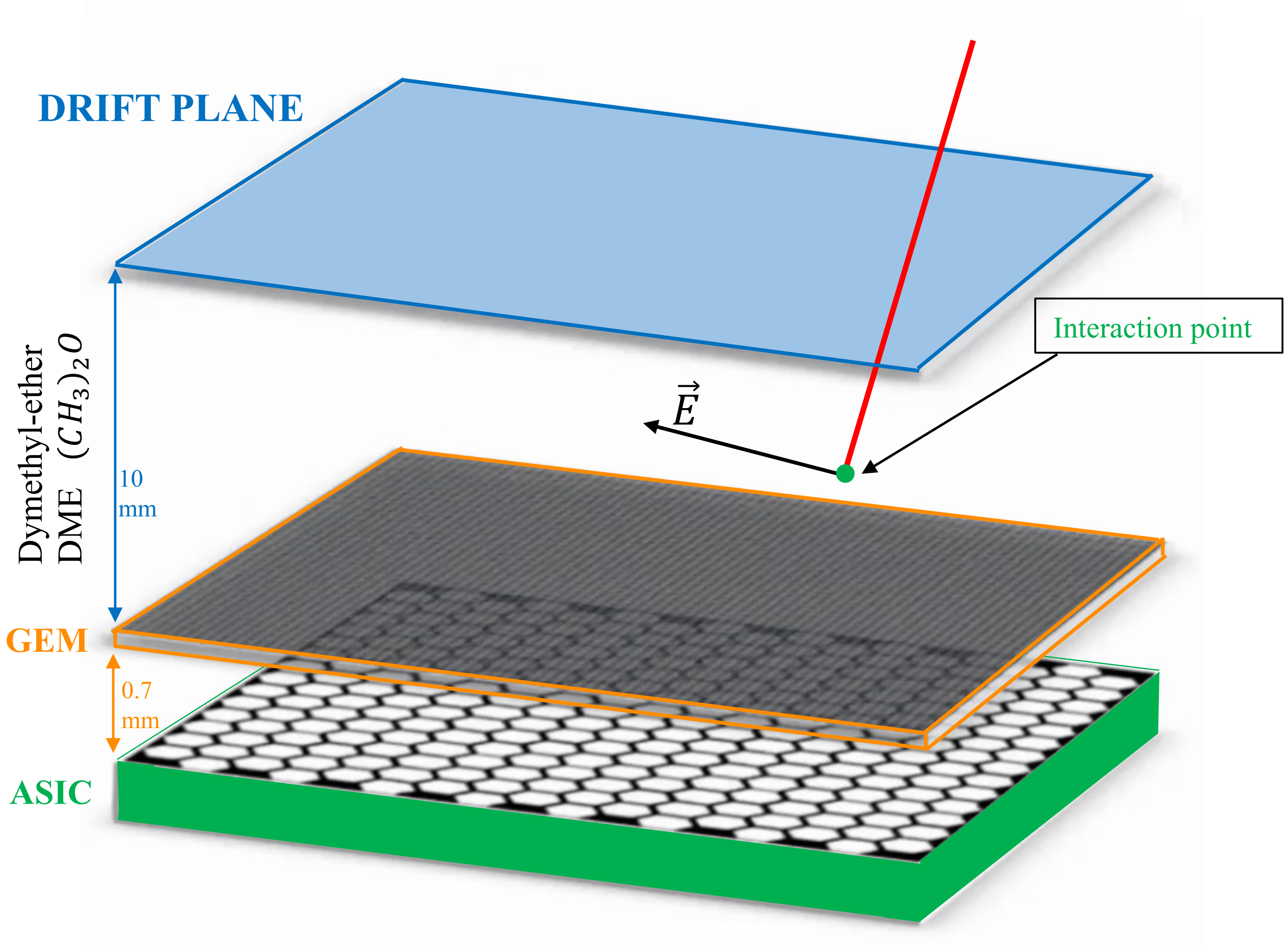
Istituto Nazionale di Fisica Nucleare
SEZIONE DI TORINO

Simone Maldera, Andrea Frassà, Raffaella Bonino, Nicolò Cibrario, Luca Latronico, Alessio Gorgi

18/03/2025

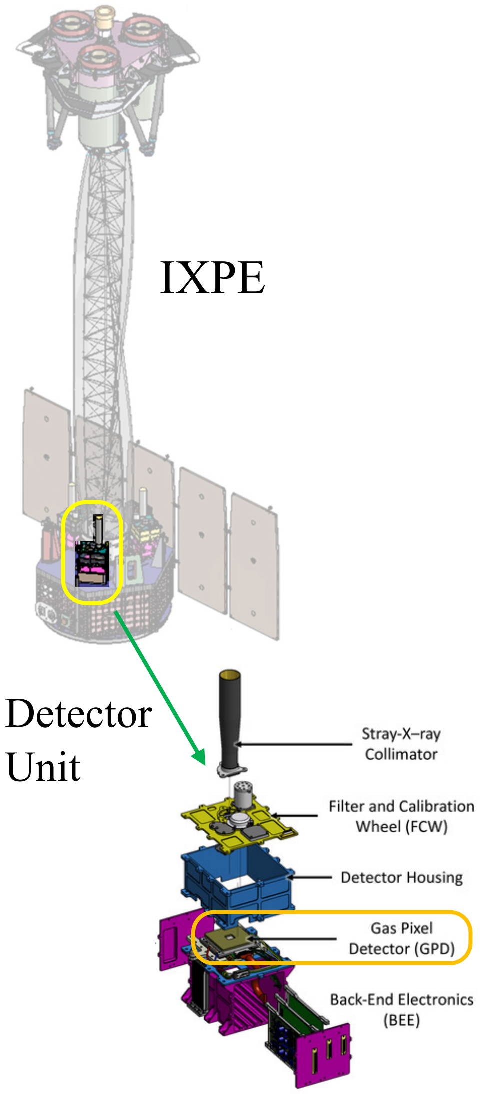
The Gas Pixel Detector GPD

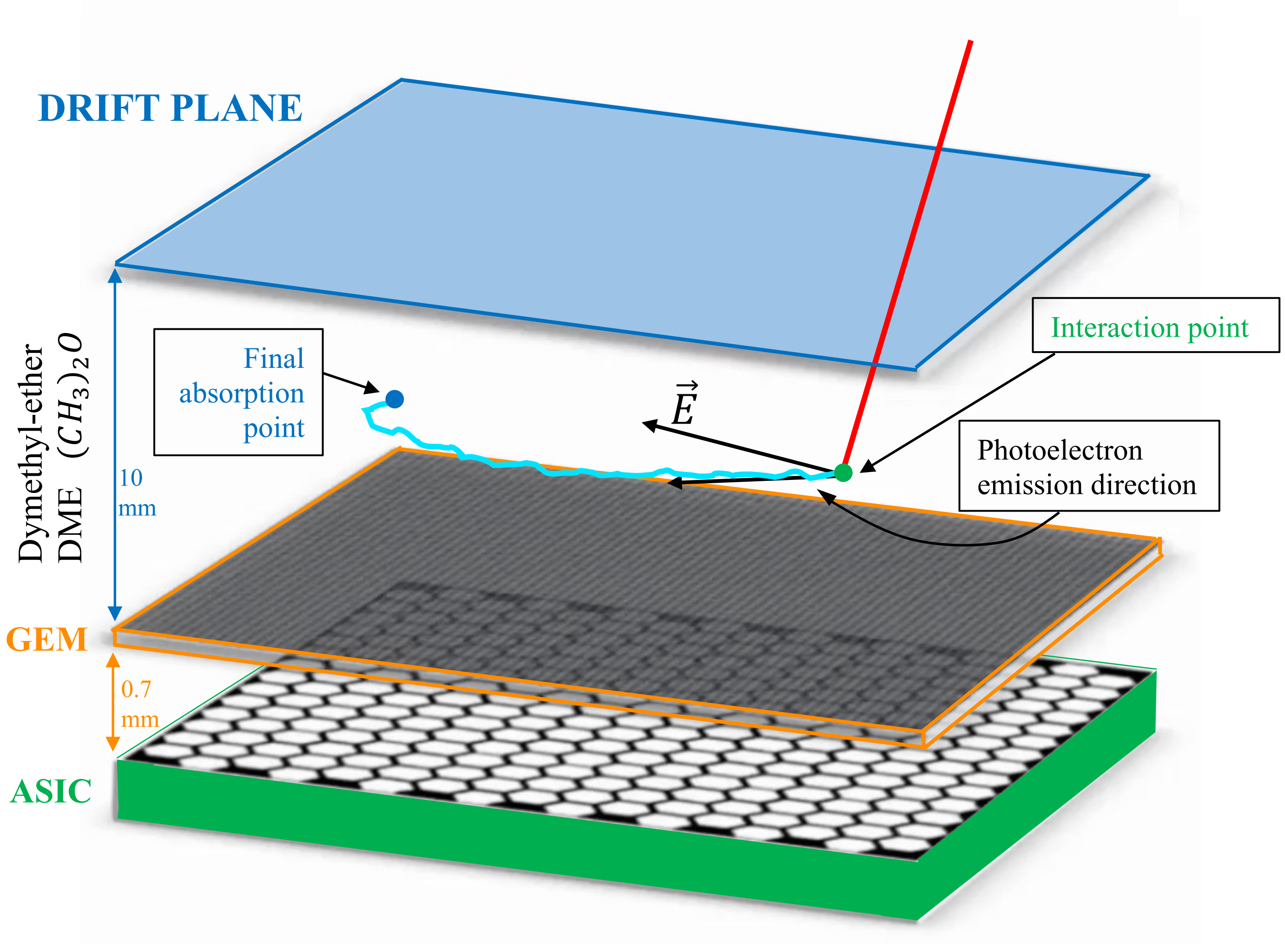




Ref. [2]

The Gas Pixel Detector GPD





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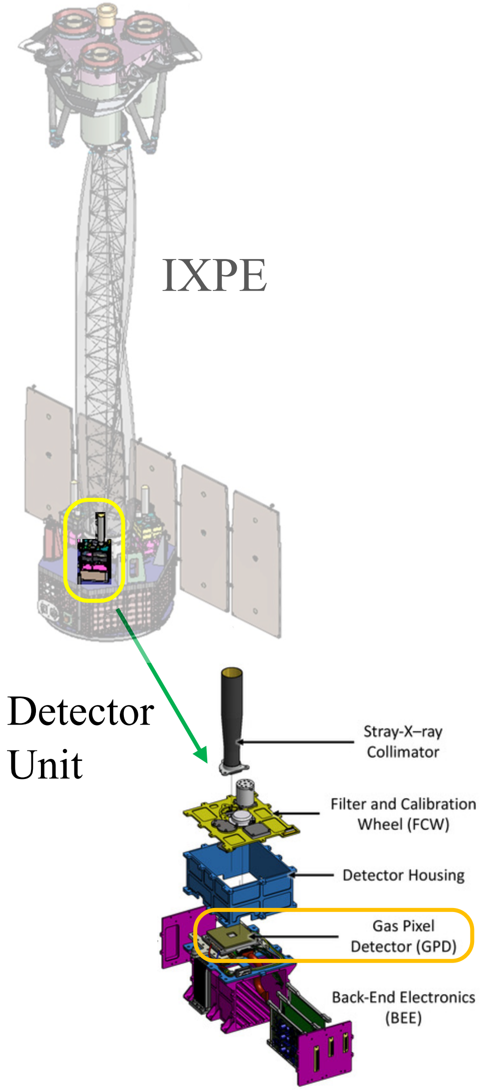

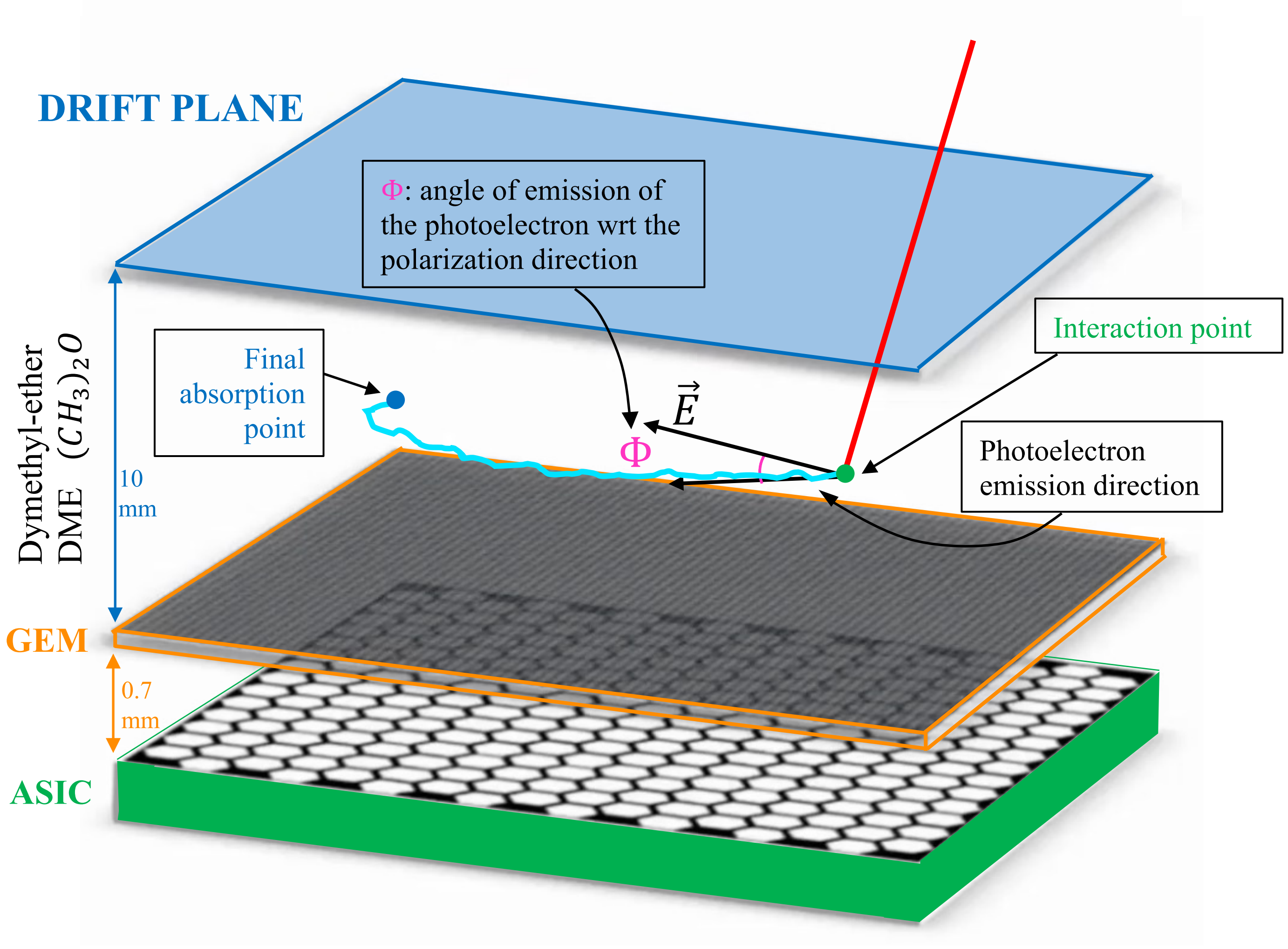

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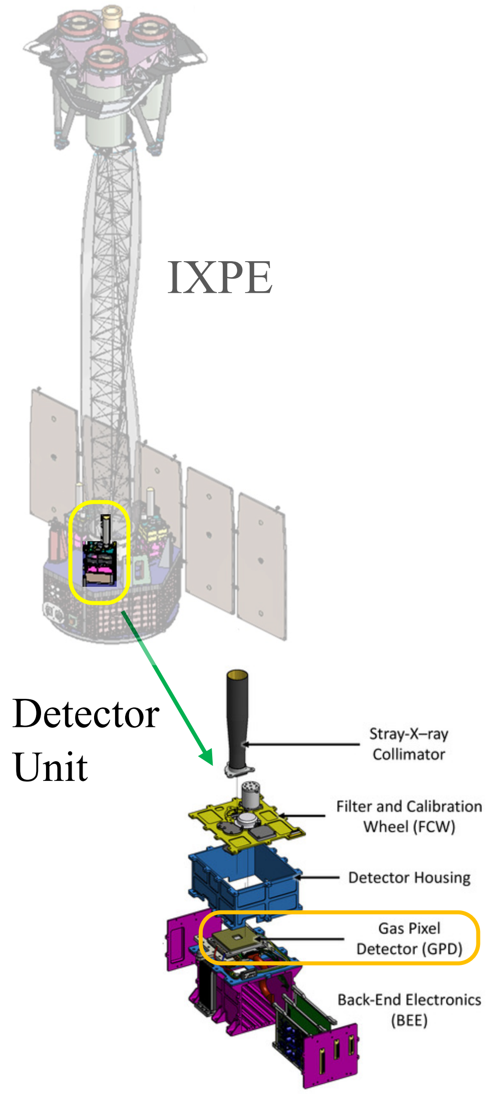

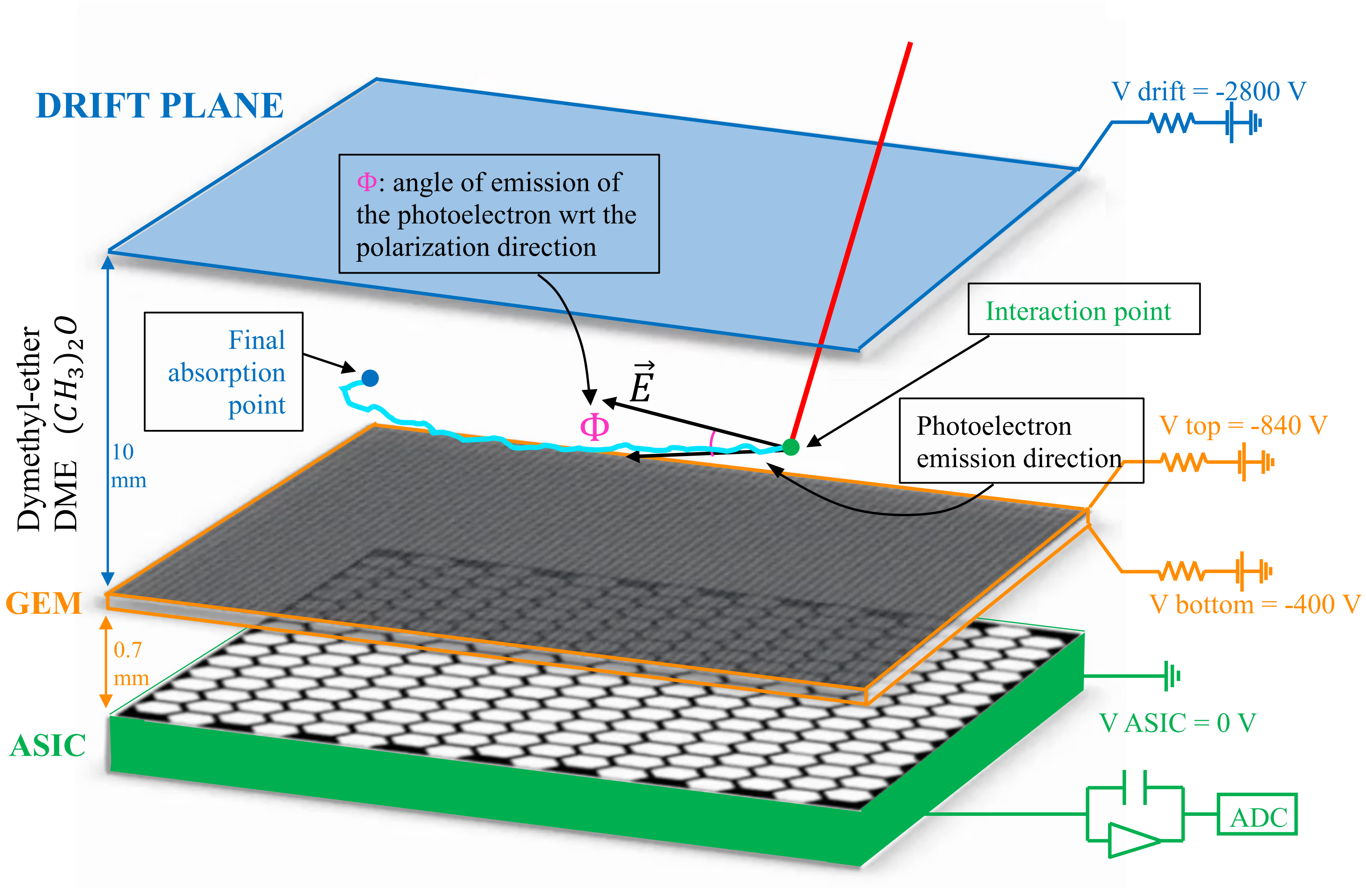

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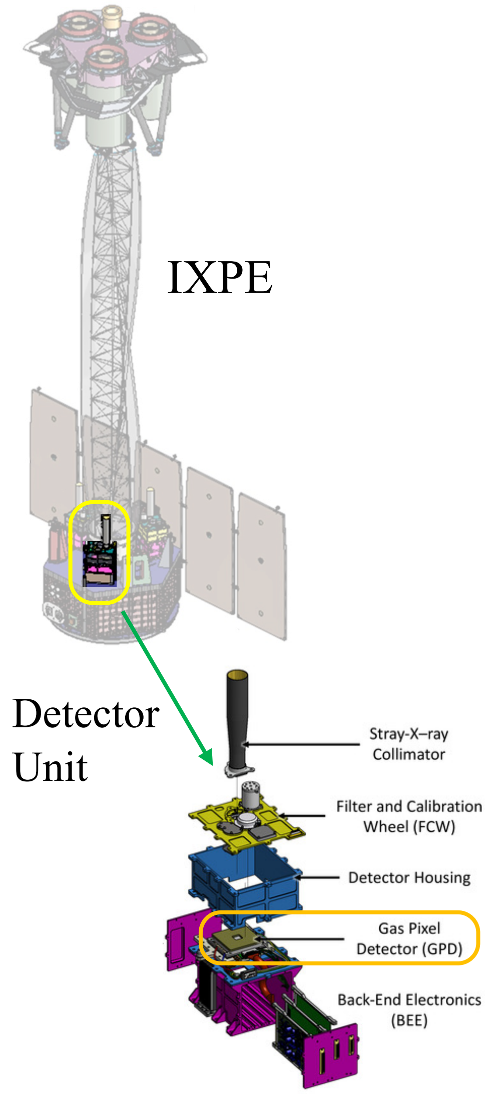

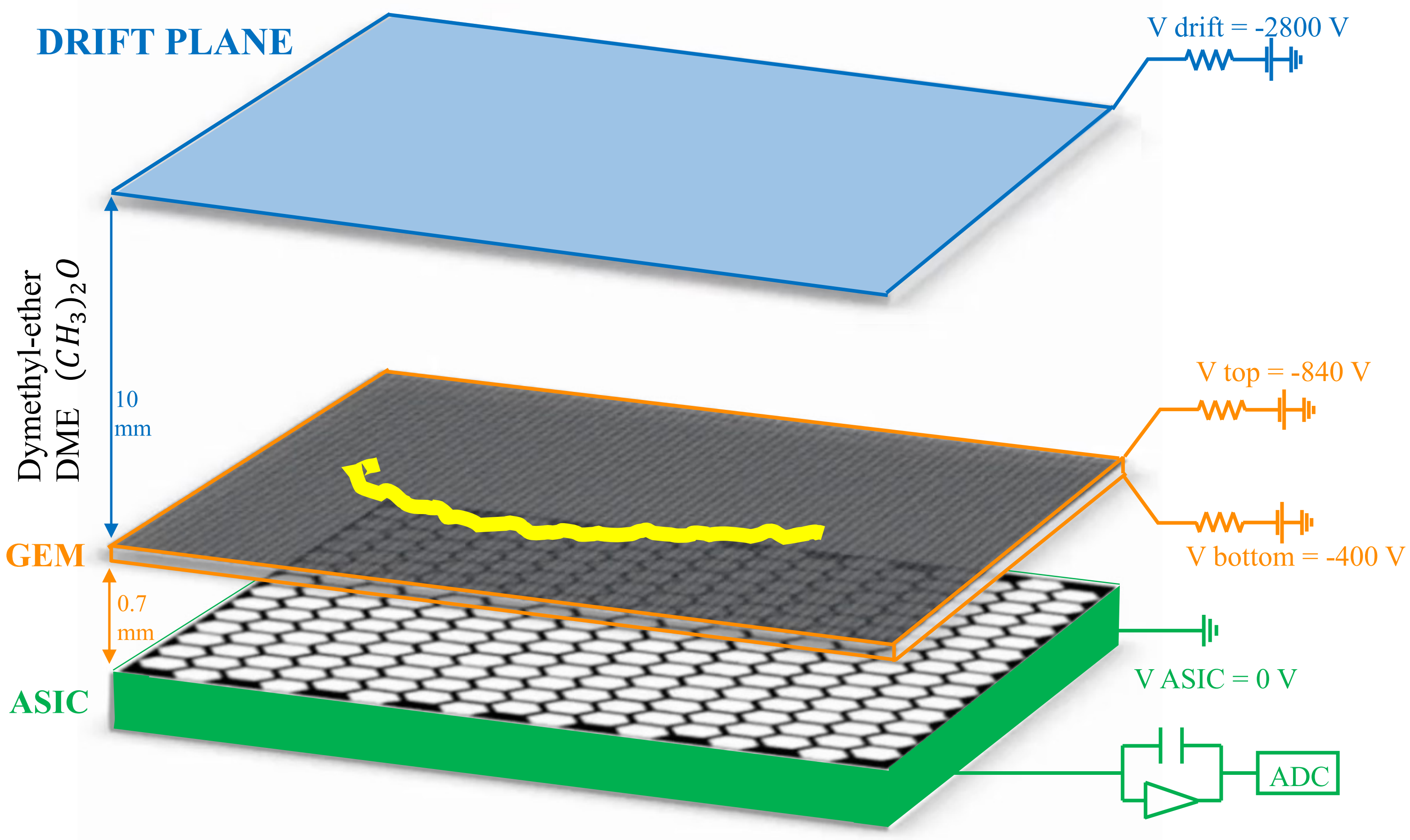

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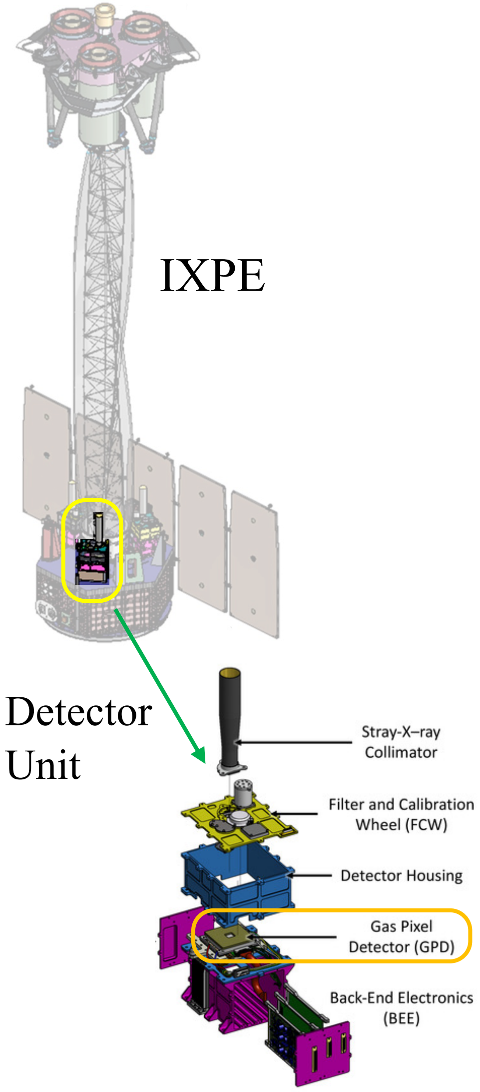

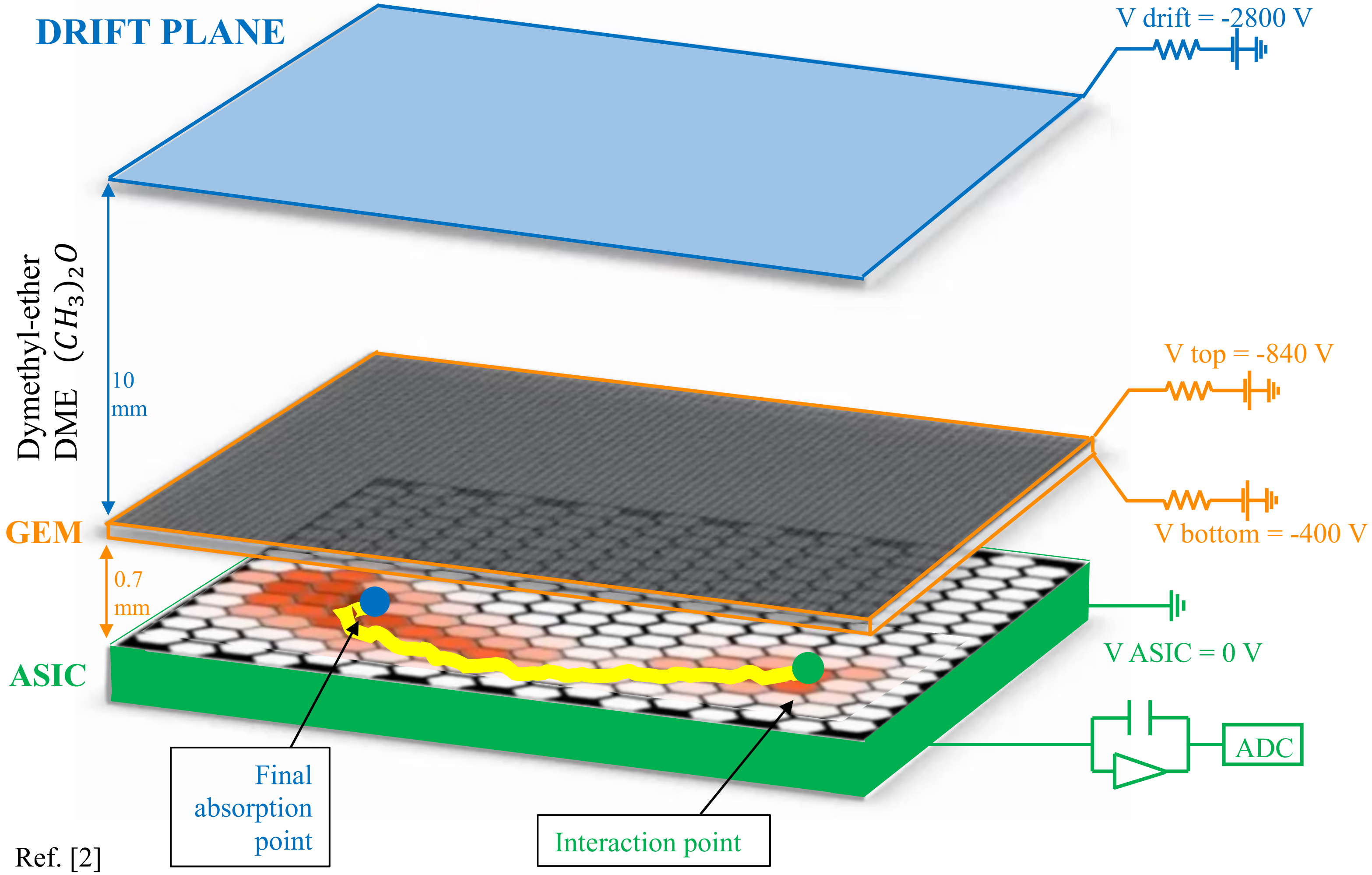

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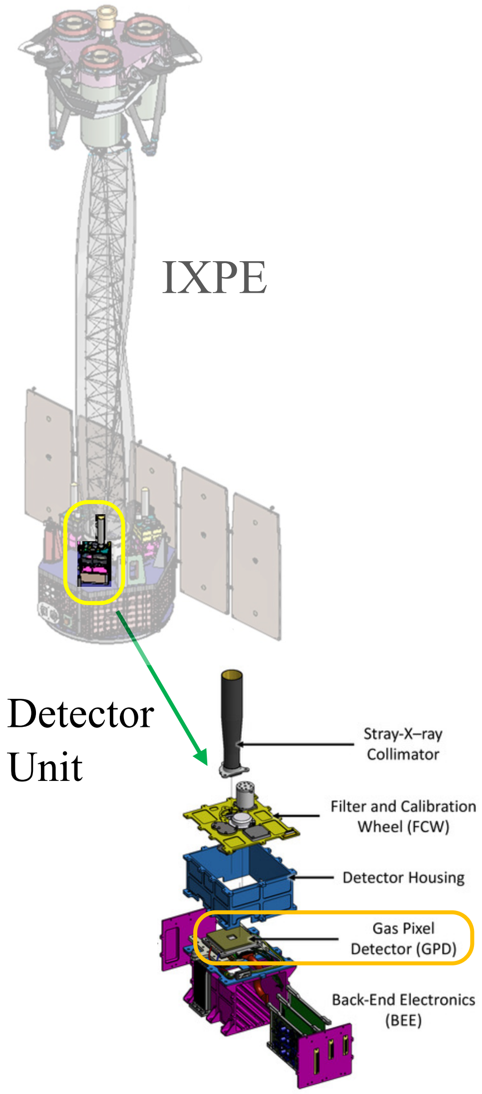
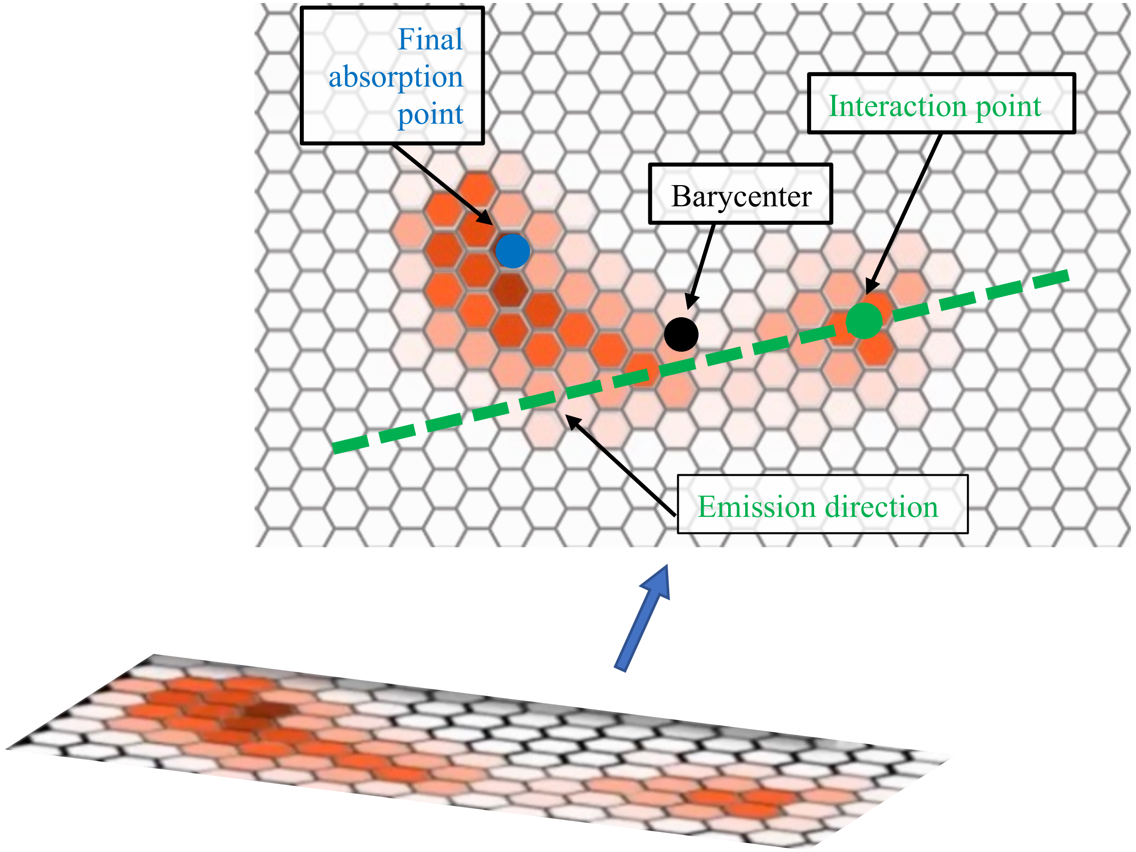
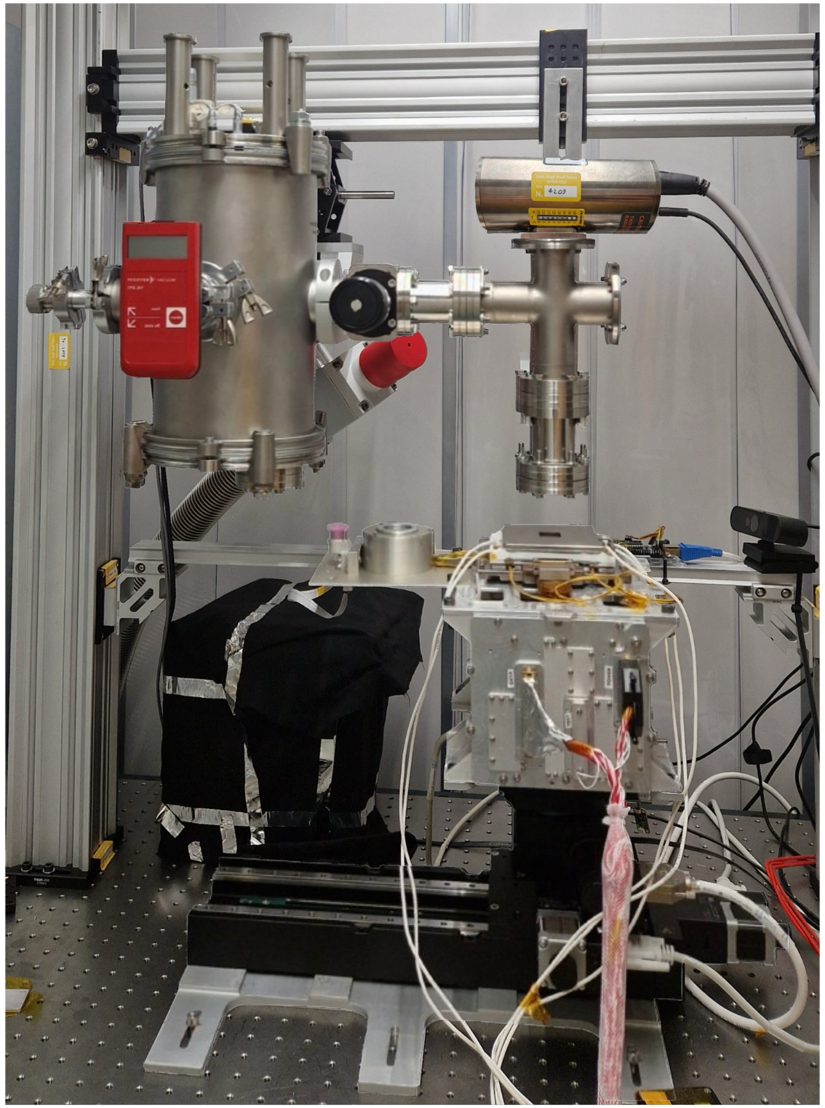




Ref. [2]

The X-ray Calibration Facility

Ref. [2],[5],[6]



The X-ray Calibration Facility

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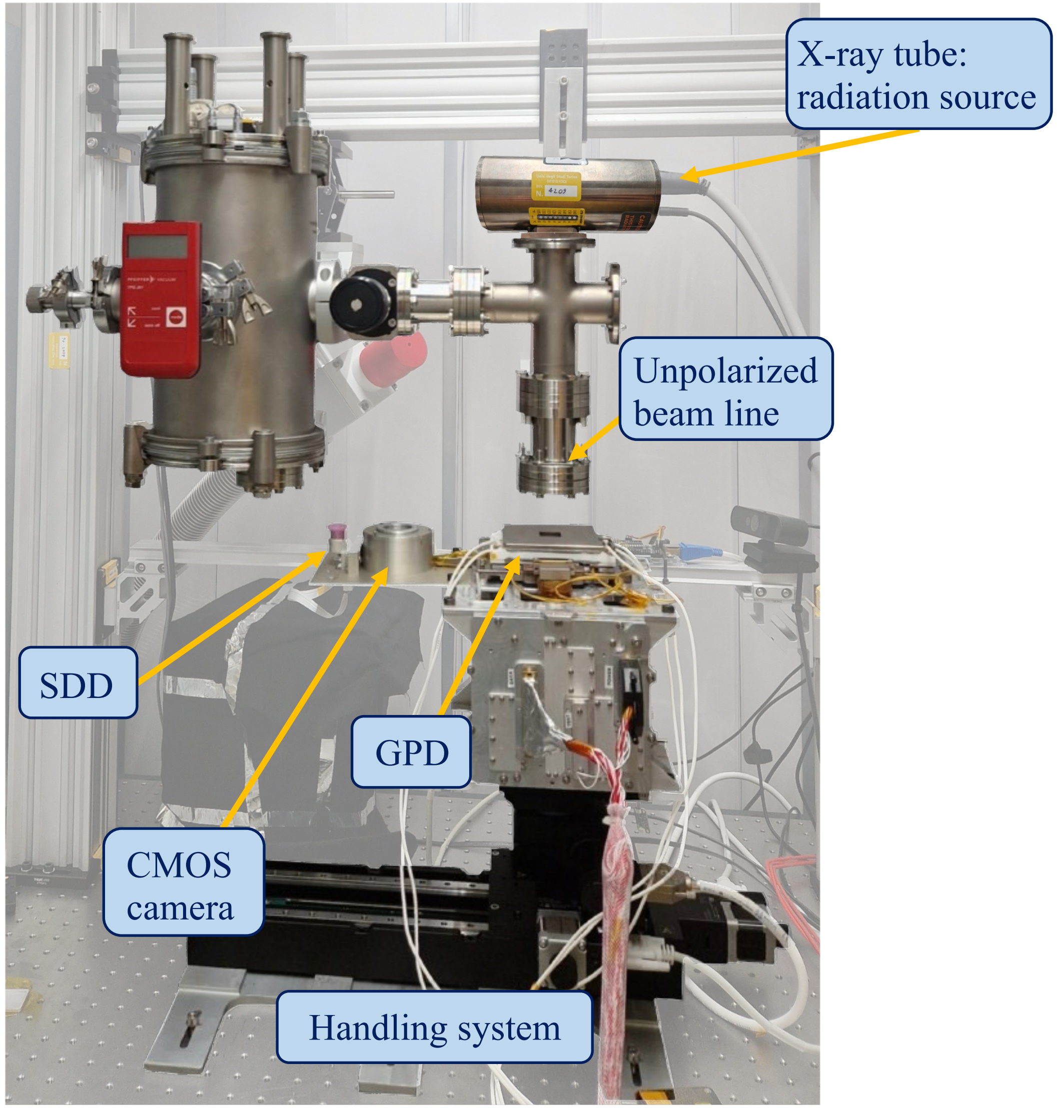

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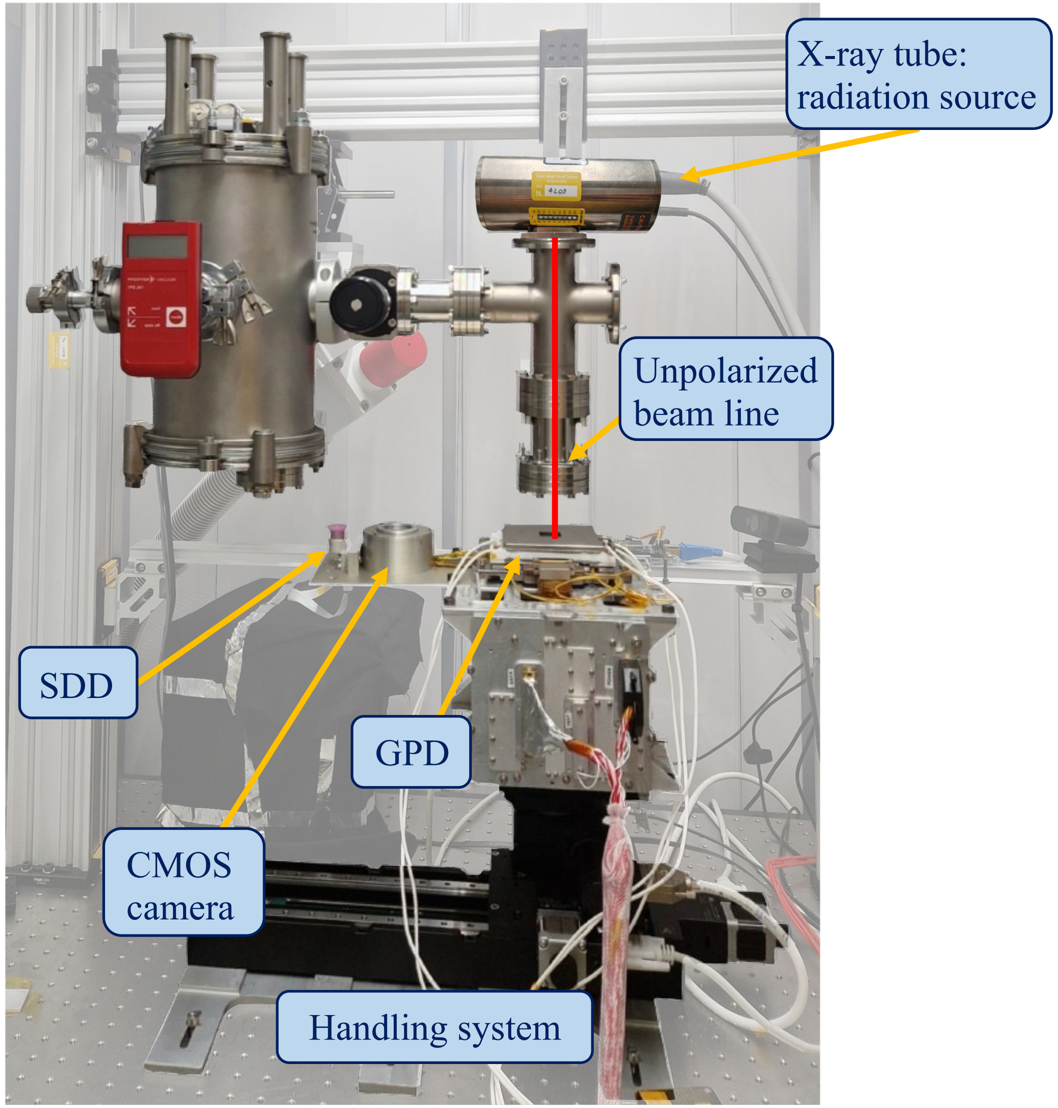

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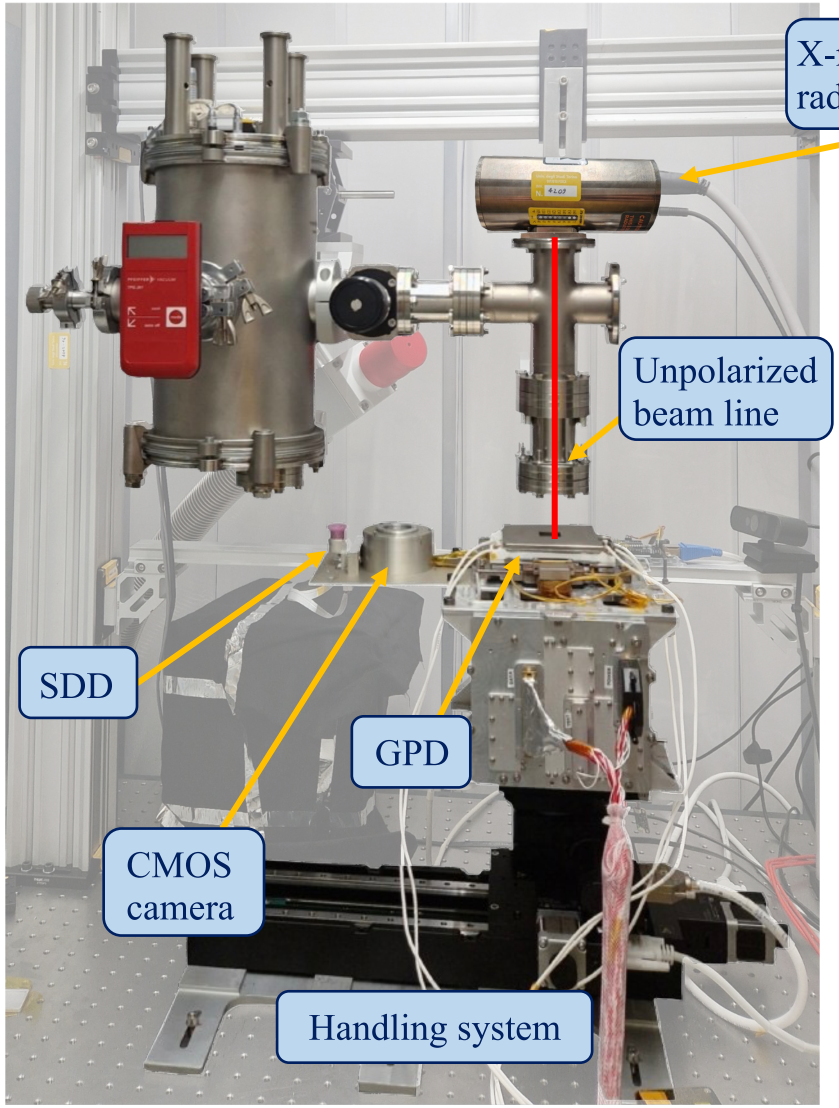
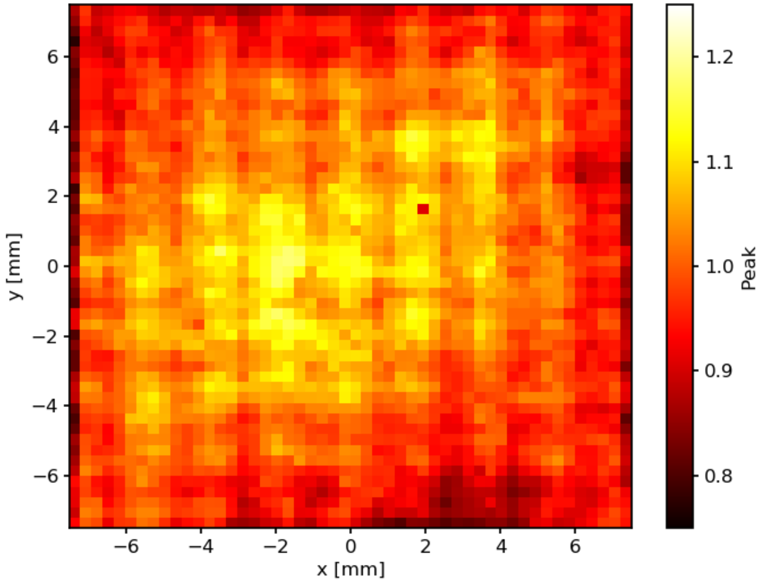


Ref. [2],[5],[6]

Gas Pixel Detectors:
study of **systematic effects** that take place in the detector

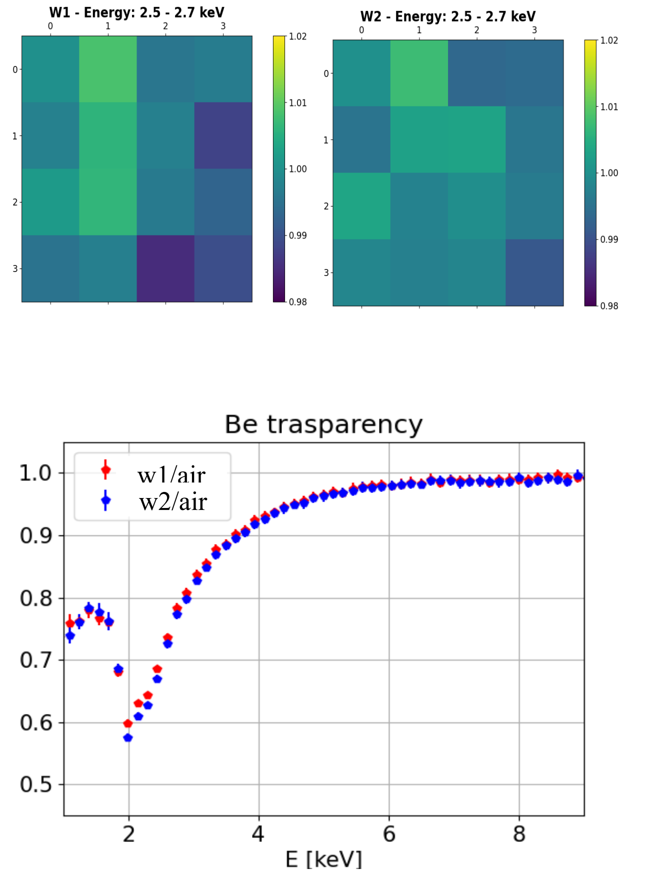
GPD gain map

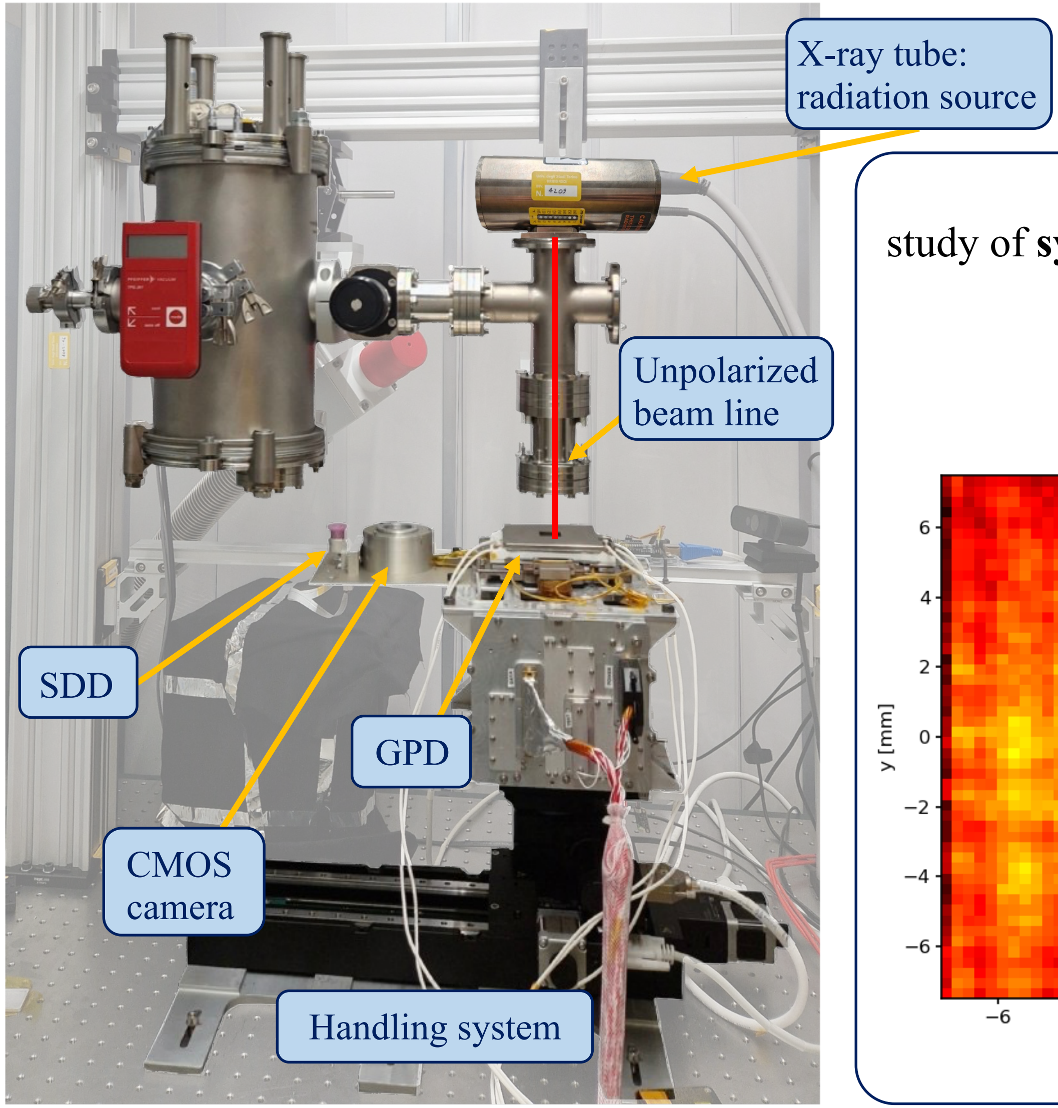


The X-ray Calibration Facility

Ref. [2],[5],[6]

Beryllium windows transparency
measurements for future X-ray detectors





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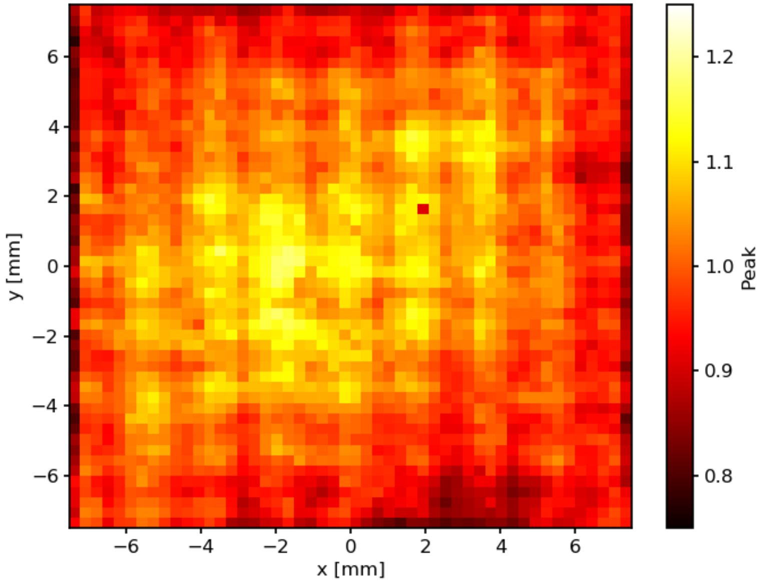
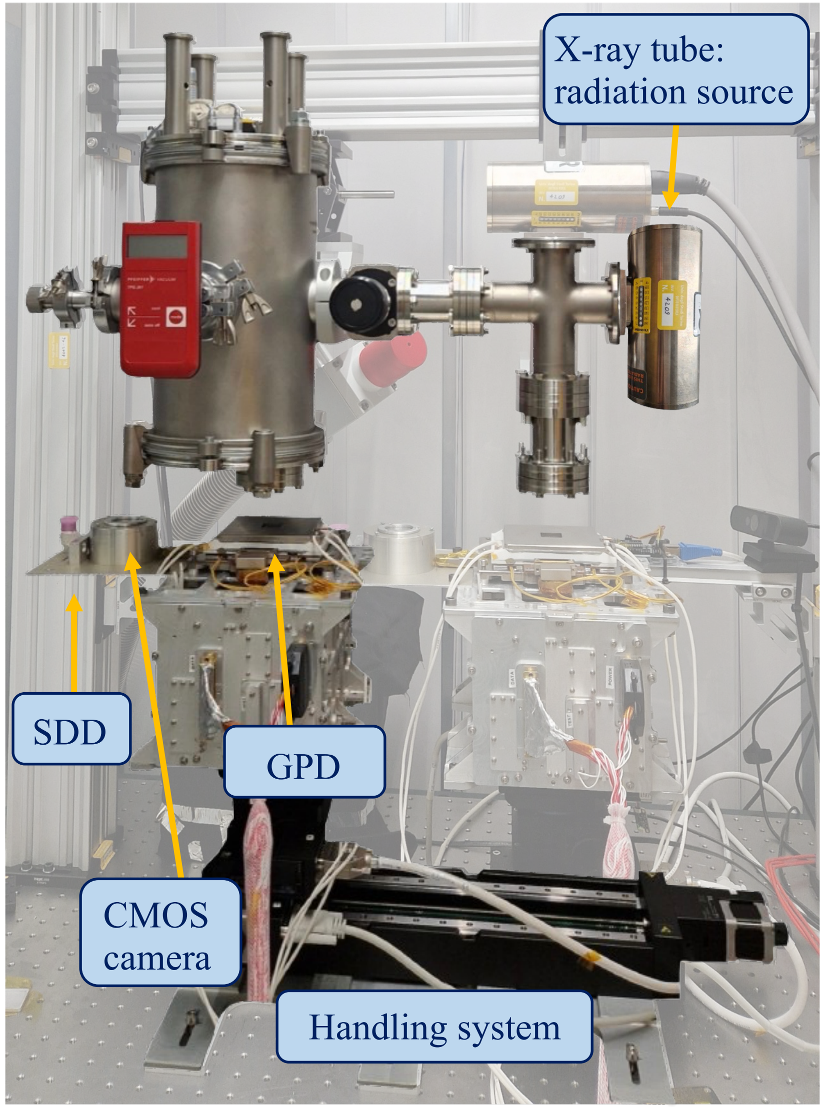


The X-ray Calibration Facility

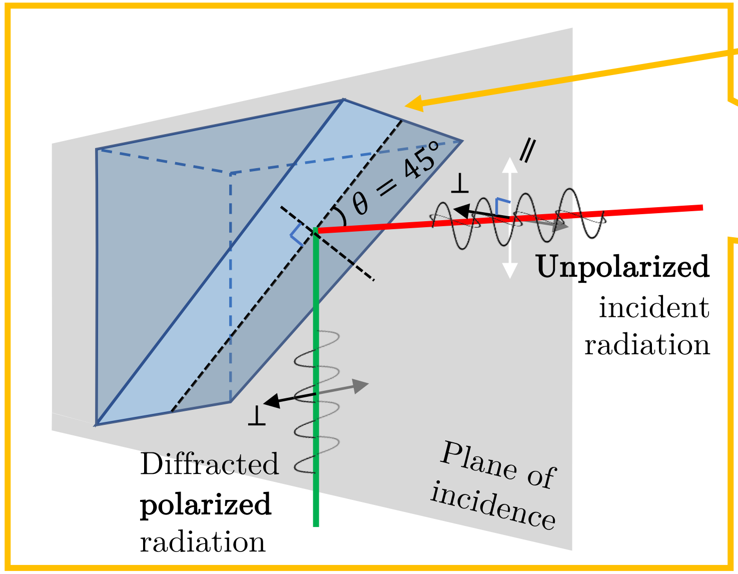
Ref. [2],[3],[5],[6]

Ref. [2],[3],[5],[6]

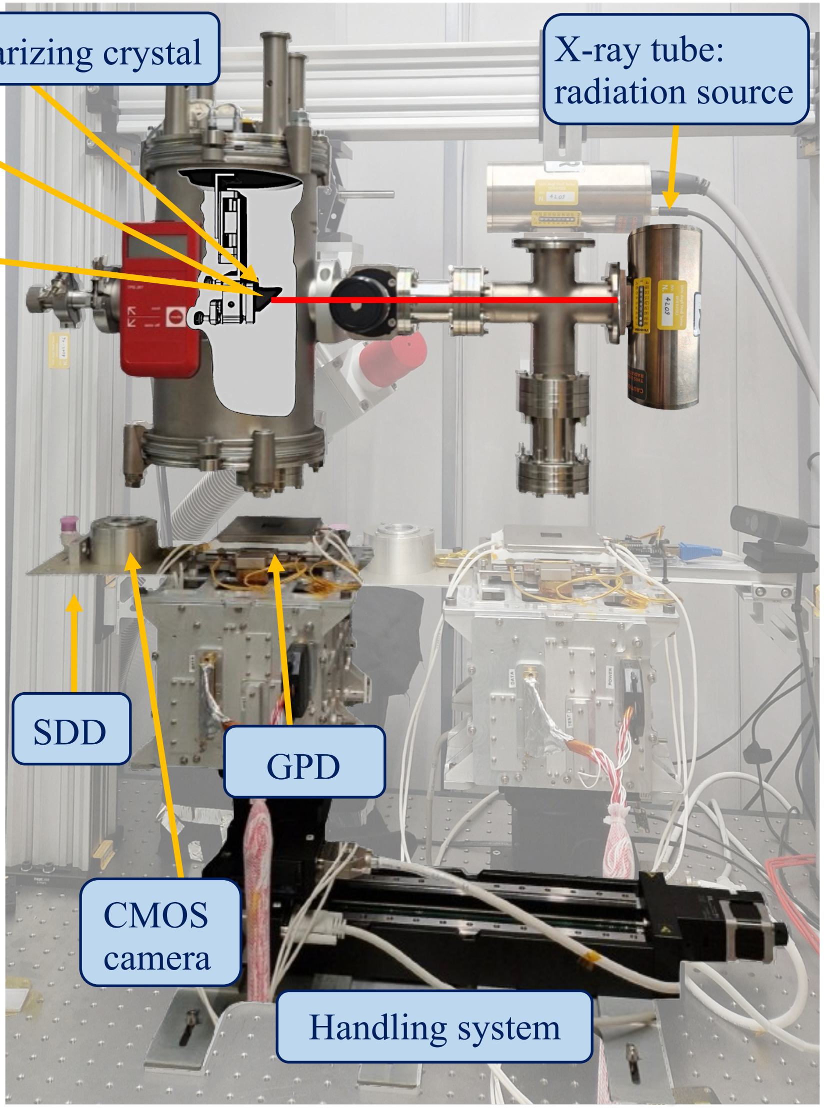
The X-ray Calibration Facility



Ref. [2],[3],[5],[6]



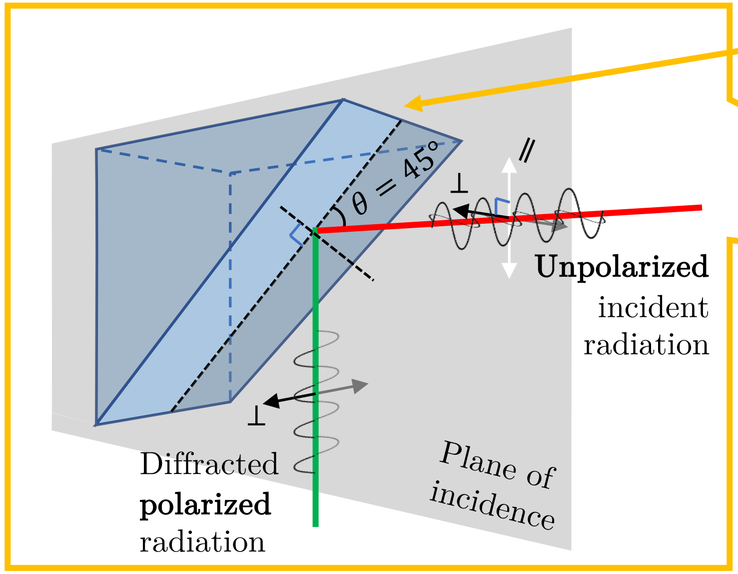
$\theta = 45°$
//
⊥
Unpolarized
incident
radiation
⊥
Diffracted
polarized
radiation
Plane of
incidence

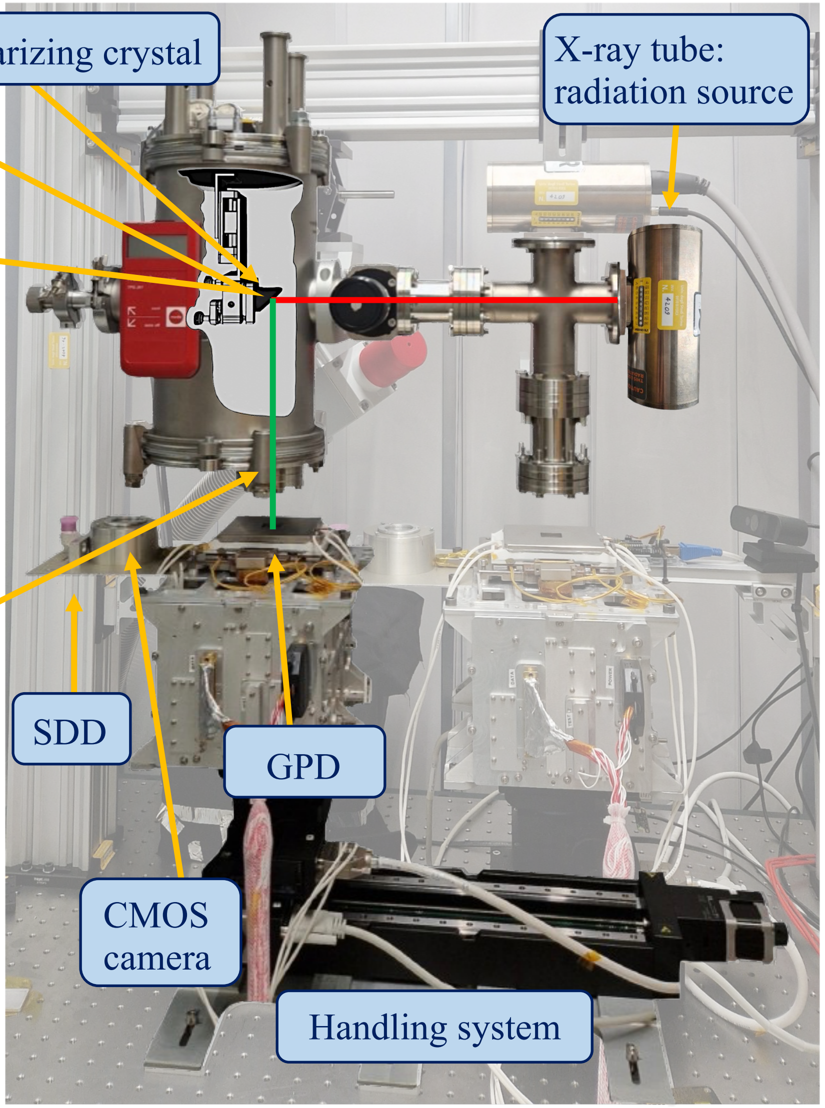


Polarizing crystal
X-ray tube:
radiation source
SDD
GPD
CMOS
camera
Handling system

Ref. [2],[3],[5],[6]

The X-ray Calibration Facility





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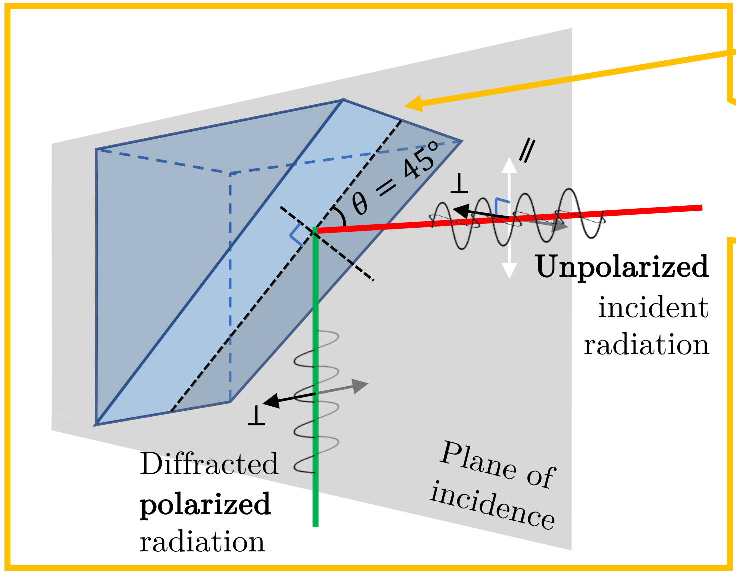
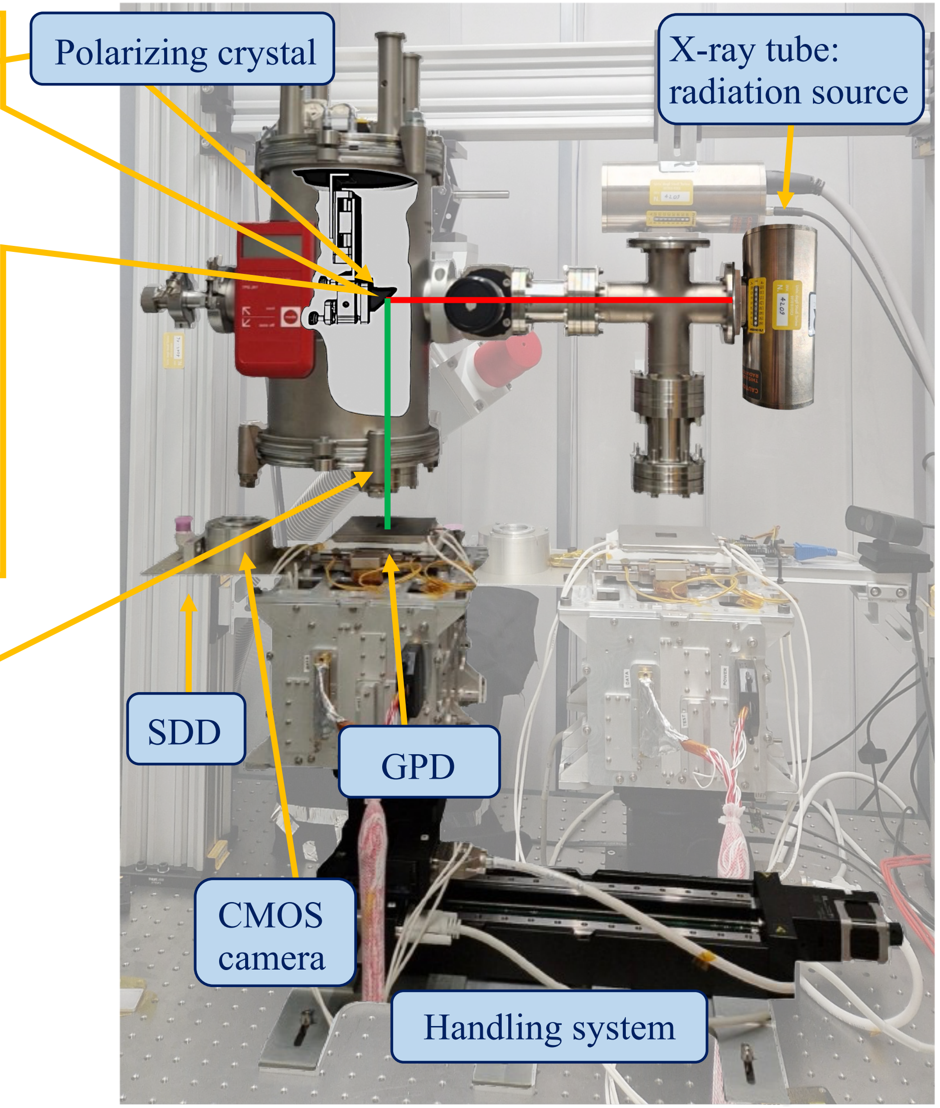
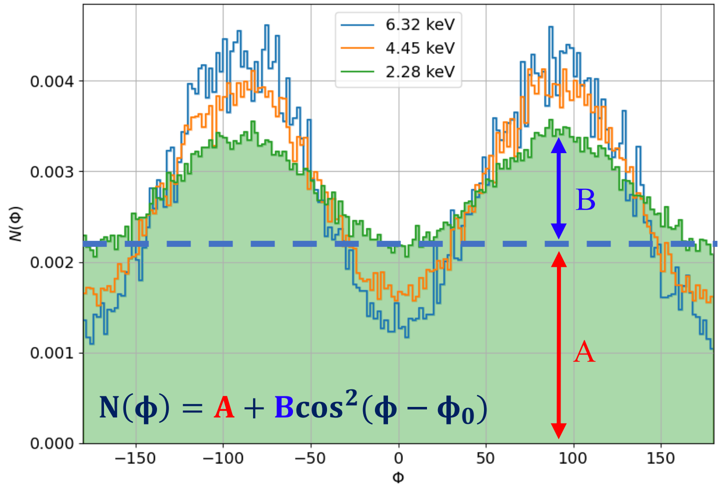




GPD response to the polarization: Modulation factor (response to 100% linearly polarized radiation) vs Energy.



Ref. [2],[3],[5],[6]

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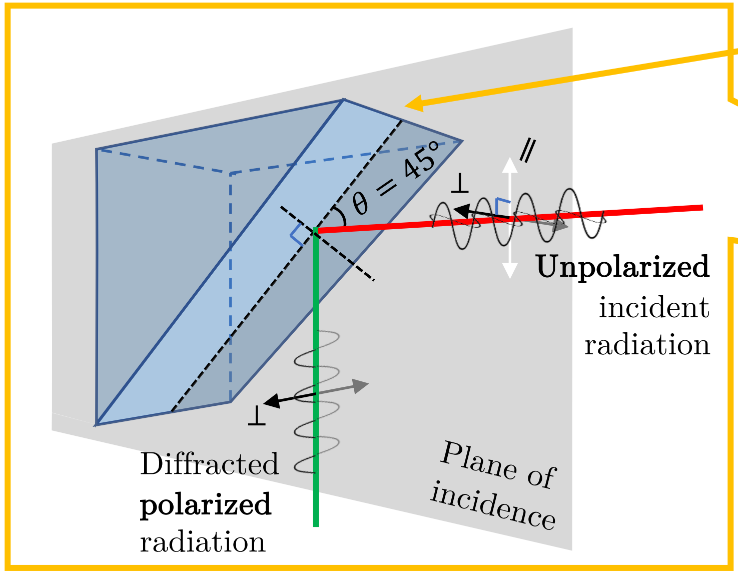

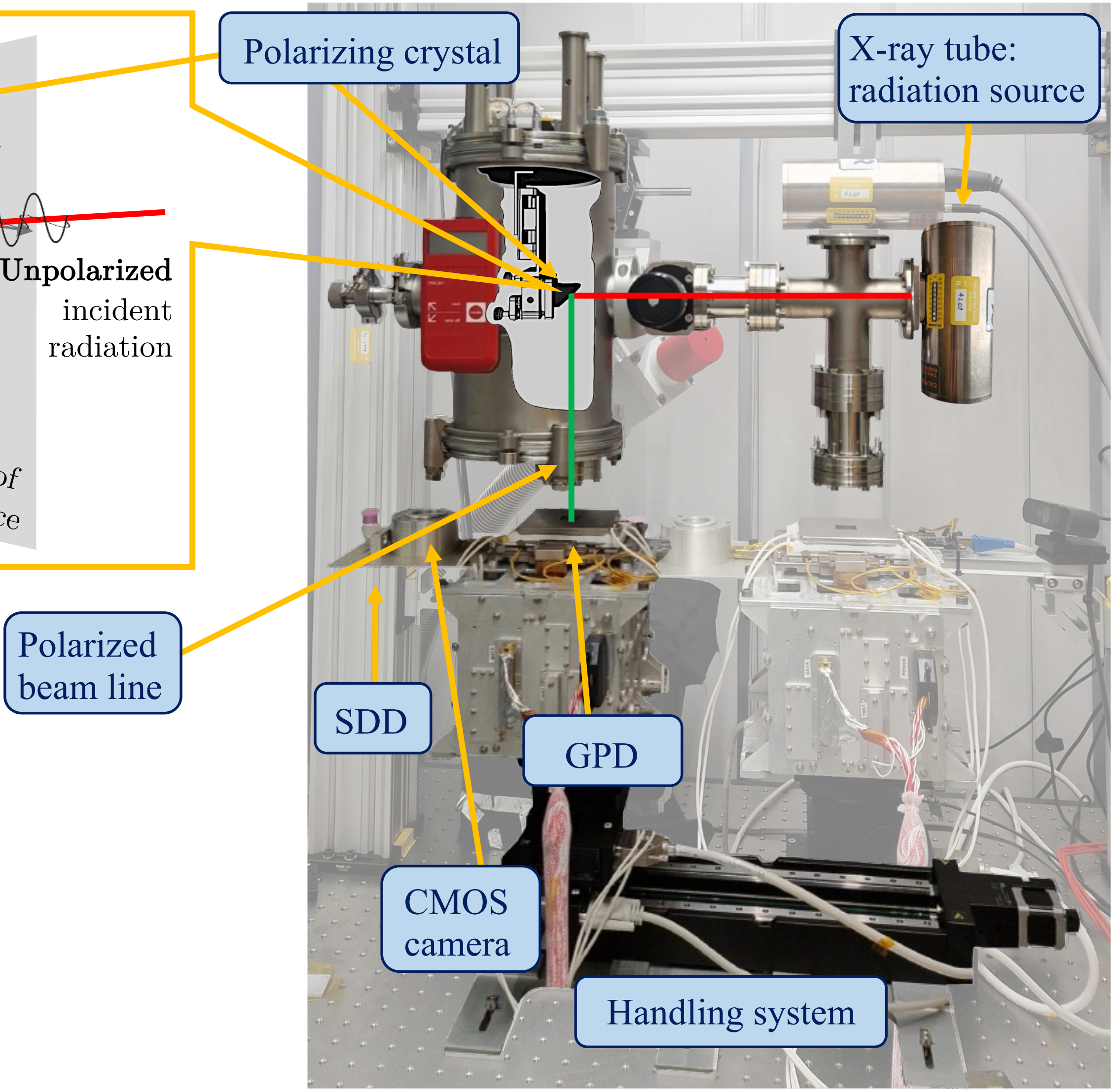

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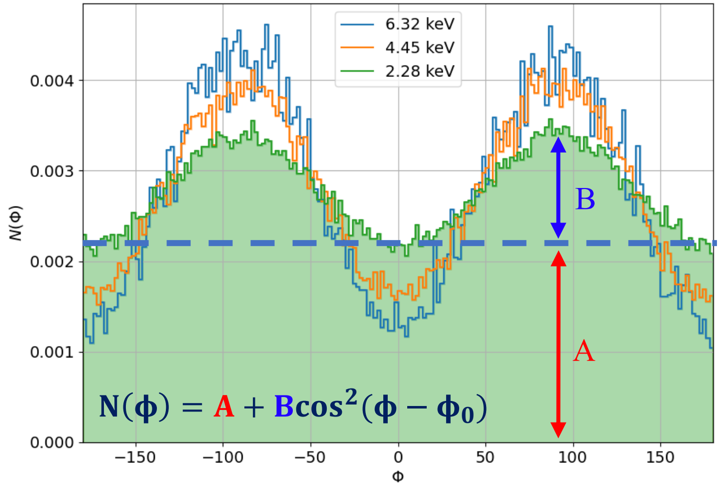
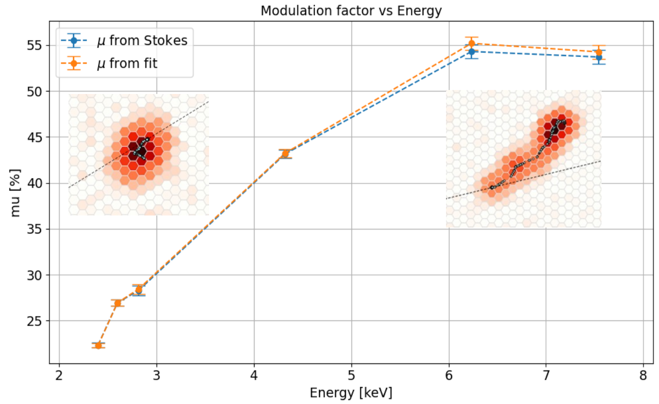




Ref. [2],[3],[5],[6]

THANK YOU FOR YOUR ATTENTION

[1] Weisskopf et al. The Imaging X-Ray Polarimetry Explorer (IXPE): Pre-Launch. 2021. doi: 10.48550/ARXIV.2112.01269. url: https://arxiv.org/abs/2112.01269.

[2] L. Baldini et al. “Design, construction, and test of the Gas Pixel Detectors for the IXPE mission”. In: Astroparticle Physics 133 (2021), p. 102628. issn: 0927-6505. doi: https://doi.org/10.1016/j.astropartphys.2021.102628. url: https://www.sciencedirect. com/science/article/pii/S0927650521000670.

[3] Fabio Muleri Sergio Fabiani. Astronomical X-ray Polarimetry. Aracne, 2014.

[4] Fabio Muleri. “ON THE OPERATION OF X-RAY POLARIMETERS WITH A LARGE FIELD OF VIEW”. In: The Astrophysical Journal 782.1 (Jan. 2014), p. 28. doi: 10.1088/ 0004-637x/782/1/28. url: https://doi.org/10.1088%2F0004-637x%2F782%2F1%2F28.

[5] S. Tugliani et al. “IXPE Gas Pixel Detectors characterization using the X-ray Calibration Facility”. In: Nuovo Cim. C 47.3 (2024), p. 141. doi: 10.1393/ncc/i2024-24141-9.

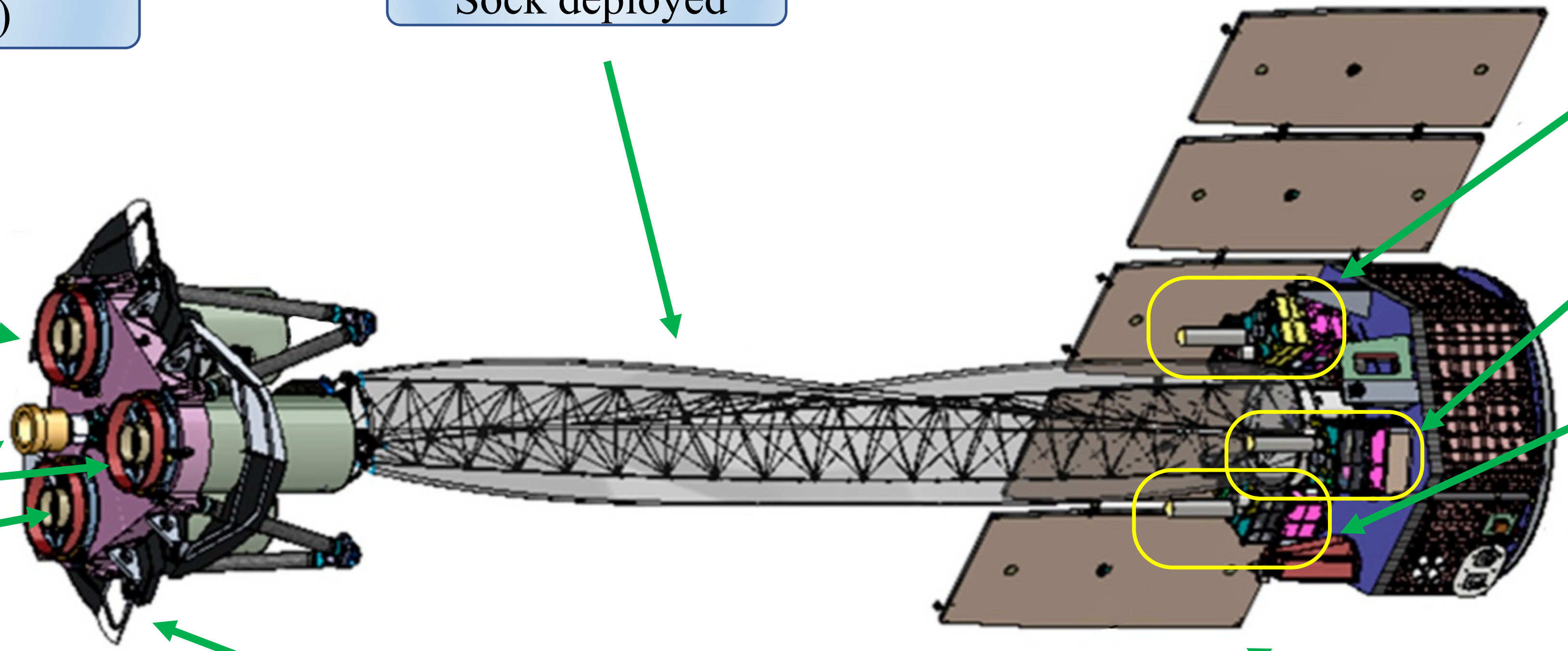
[6] S. Tugliani et al. “IXPE Gas Pixel Detector characterization with the X-ray calibration facility”. In: Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 1069 (2024), p. 169800. issn: 0168-9002. doi: https://doi.org/10.1016/j.nima.2024.169800.

[7] F. Kislat et al. “Analyzing the data from X-ray polarimeters with Stokes parameters”. In: Astroparticle Physics 68 (Aug. 2015), pp. 45–51. doi: 10.1016/j.astropartphys.2015. 02.007. url: https://doi.org/10.1016%2Fj.astropartphys.2015.02.007.

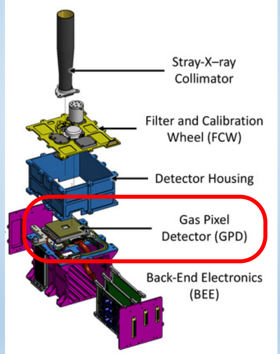
[8] C. Tomaiuolo et al. " Time-dependent instrumental effects in IXPE: Pressure variation and GEM charging inside GPDs ". In: Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 1069 (2024), p. 169881. issn: 0168-9002. doi: https://doi.org/10.1016/j.nima.2024.169881.

Mirror Module Assembly (x3) (Wolter I)

Boom w/ thermal Sock deployed



Detector Unit (x3)



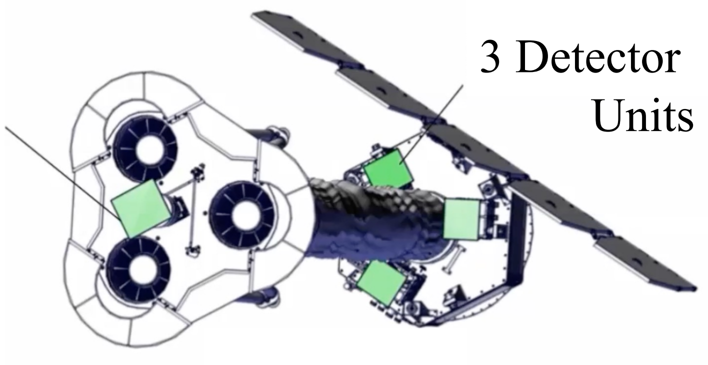
Forward star tracker

X-ray Shields (x3) deployed

Solar array

Ref. [1]

Star Tracker: Celestial Coordinates system



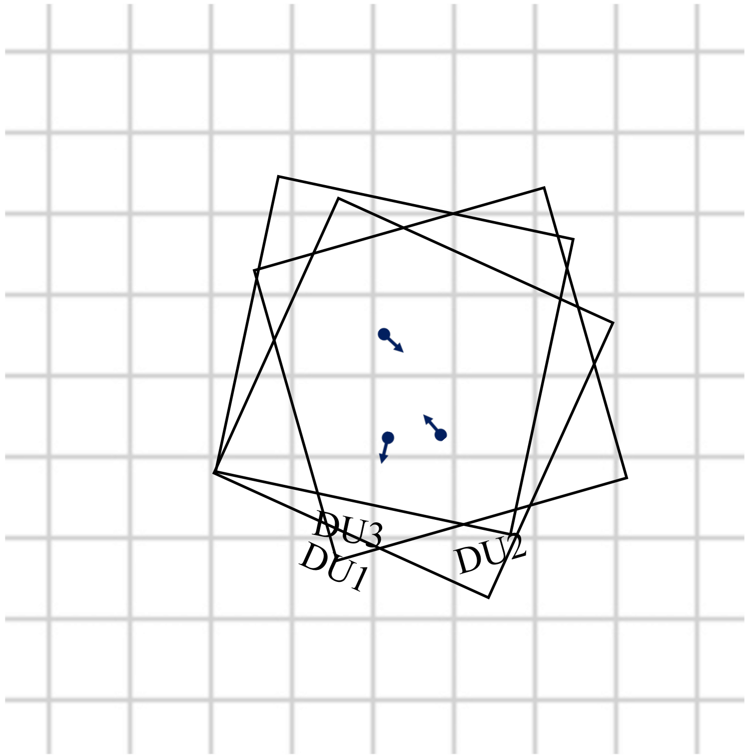
3 Detector Units

Detector Coordinates

Level 1 data: Event reconstruction in detector coordinates

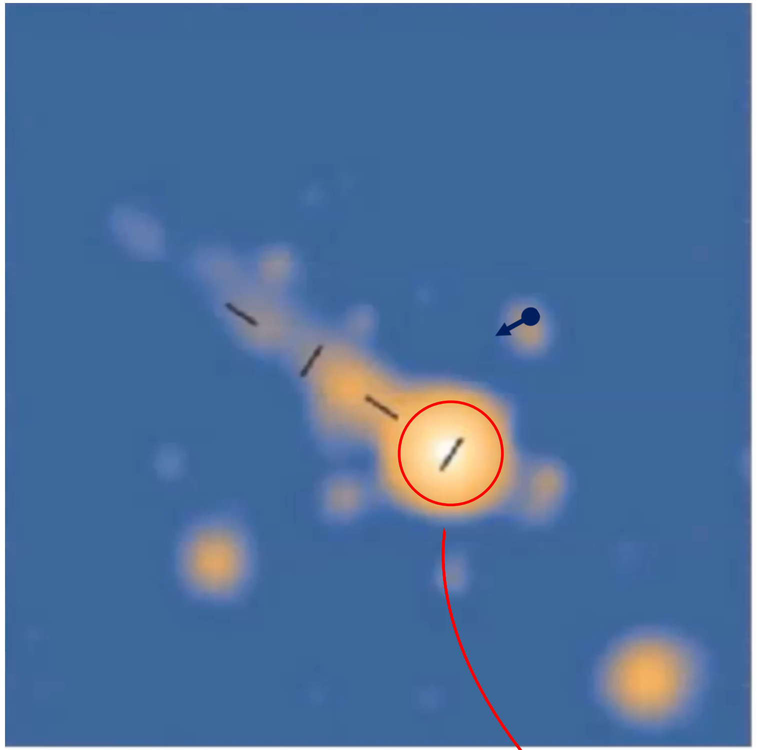
→

Level 2 data: Data in sky coordinates



Celestial Coordinates

IXPE data processing 2



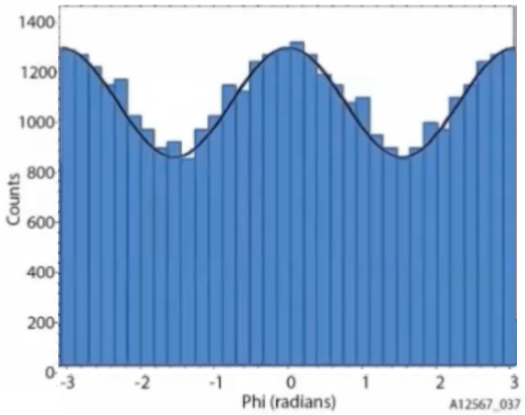
Polarization information: recovered on a statistical basis from the azimuthal distribution of the photoelectron directions of emission.

Photoelectric differential cross section: $\frac{d\sigma}{d\Omega} = r_0^2 \alpha^4 Z^5 \left(\frac{m_e c^2}{E}\right)^{\frac{7}{2}} \frac{4\sqrt{2}\sin^2\theta \boldsymbol{\cos^2\phi}}{(1-\beta\cos\theta)^4}$

Ref. [3], [4], [7]

The total counts are modulated as:

$$N(\phi) = A + B\cos^2(\phi - \phi_0)$$



Azimuthal angle ϕ: photelectron emission direction.

Polarization angle: ϕ_0

Polarization Degree: derived from the Stokes parameters and from

$$\boldsymbol{\mu} = \frac{N_{max}-N_{min}}{N_{max}+N_{min}} = \frac{\mathbf{B}}{\mathbf{2A+B}} \Longrightarrow p_0 = \frac{1}{\mu}\sqrt{\mathcal{Q}^2 + \mathcal{U}^2}$$

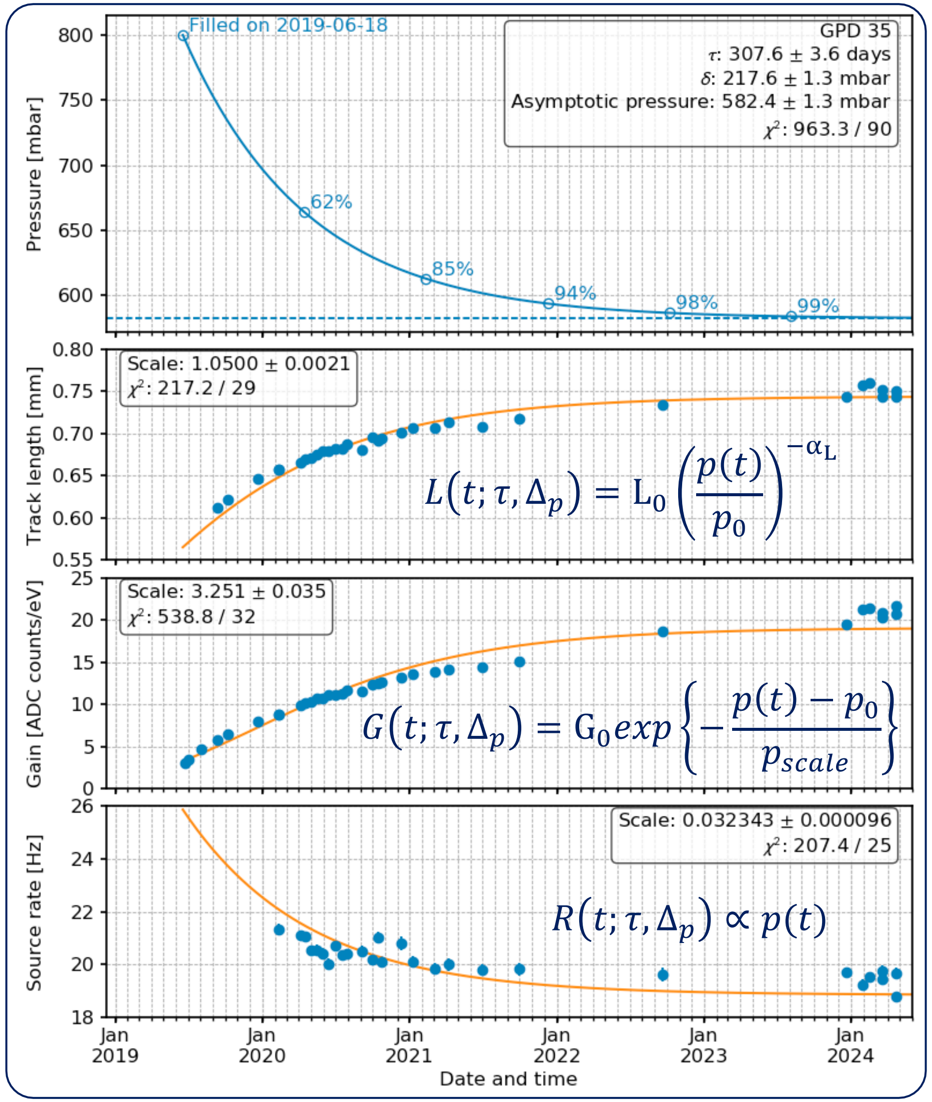
GPD long term studies: secular pressure decrease

Secular decrease of the pressure in the *sealed* gas cell, due to internal adsorption of DME with a time scale of months.

$$p(t;\tau,\Delta_p) = p_0 - \Delta_p(1 - \mathrm{e}^{-(t-t_0)/\tau})$$

The pressure decrease can be retrieved analyzing:

- Increase of track length
- Increase of gain
- Decrease of rate



Ref. [8]

R&D on Plasma-Etched Gas Electron Multipliers for X-ray Polarimetry in Space

A. Lega, D. Novel, C. Sgro', T. Facchinelli, G. Pepponi, M. Boscardin,
L. Baldini, R. Hall-Wilton, R. Iuppa, L. Latronico

IFD 2025 - INFN Workshop on Future Detectors,
Sestri Levante,
17-19/03/2025,

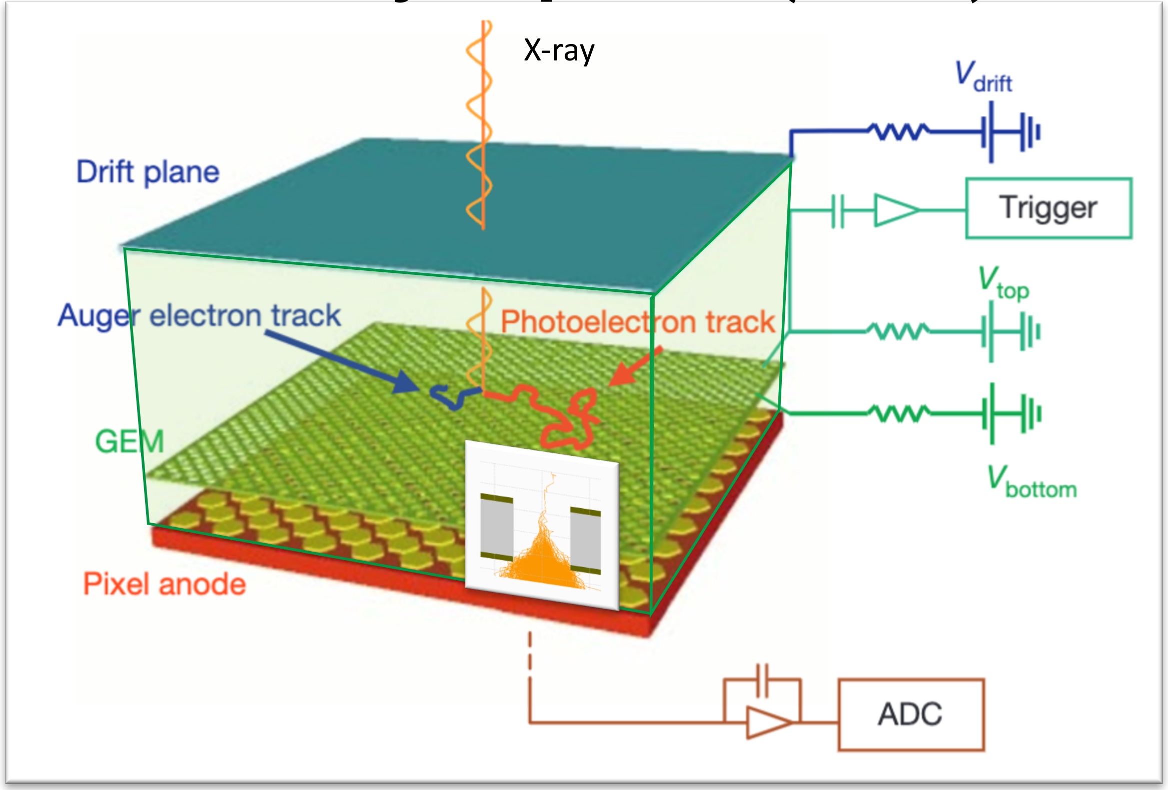
FONDAZIONE BRUNO KESSLER

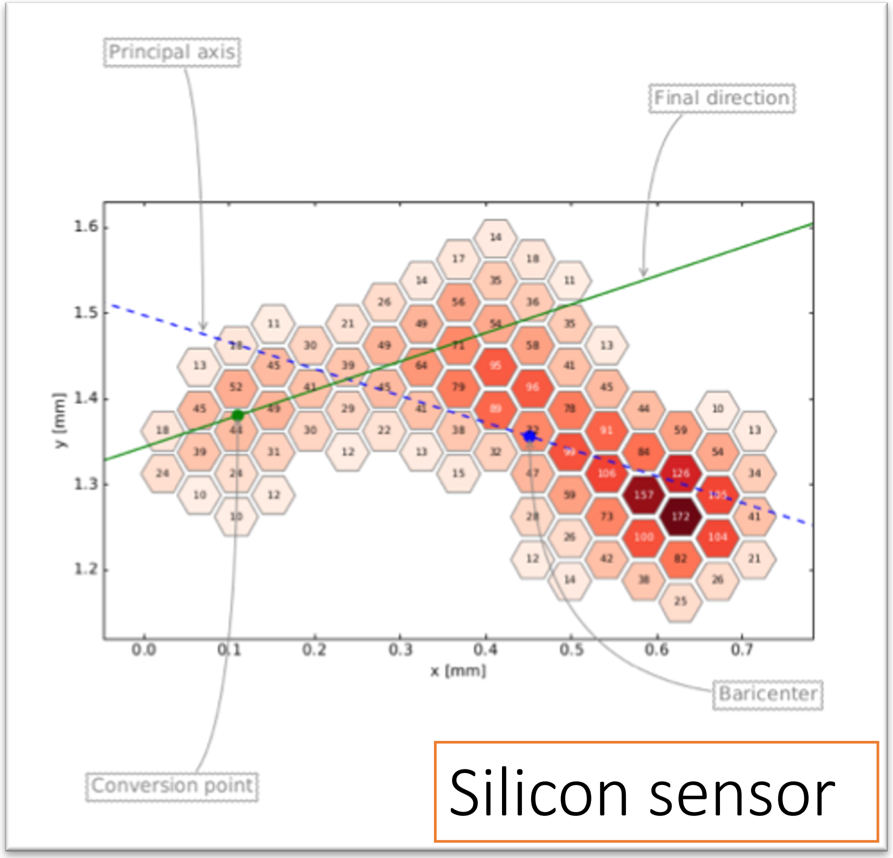
UNIVERSITÀ DI TRENTO

Istituto Nazionale di Fisica Nucleare
TIFPA
Trento Institute for Fundamental Physics and Applications

Gaseous Electron Multipliers

The Gas Pixel Detector (GPD) for the Imaging X-Ray Polarimetry Explorer (IXPE)

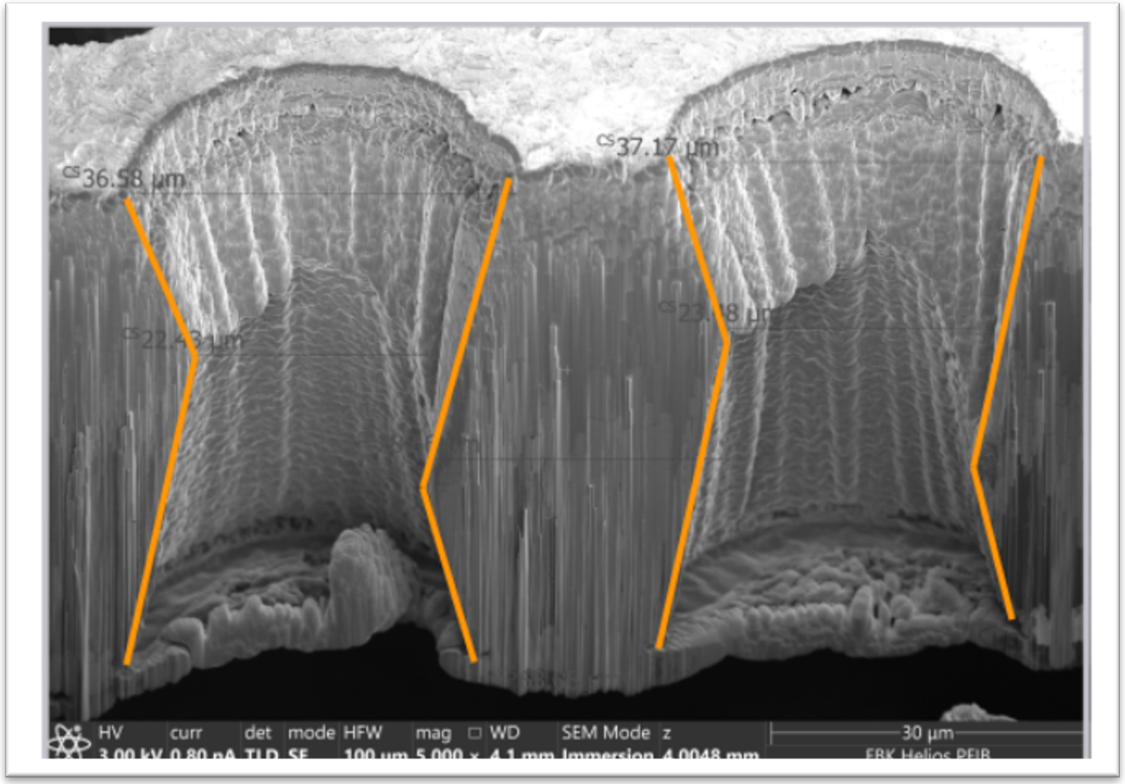


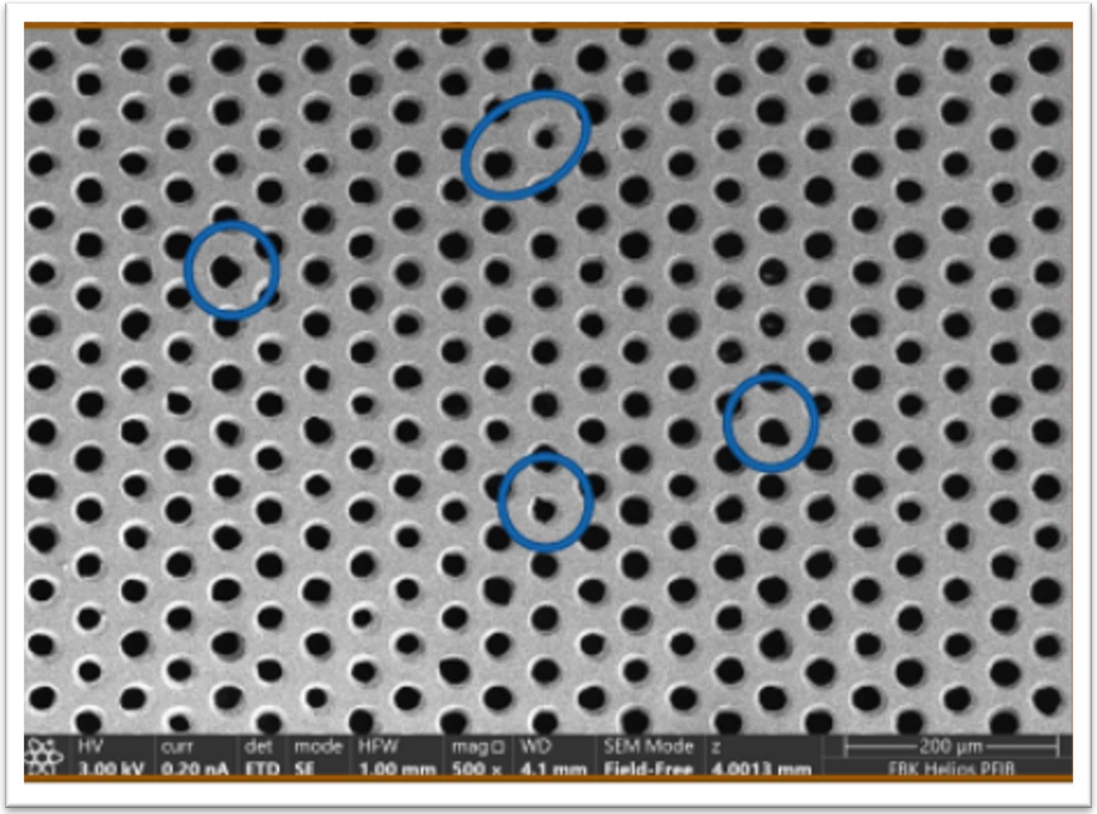


- ❑ Photoelectron direction -> X-ray polarisation
- ❑ Measure polarisation in space is difficult!
- ❑ Electron undergo multiple scattering!
- ❑ Direction is measured in the first 500 μm

Gaseous Electron Multipliers

IXPE GEM holes are not perfect!





- ❑ Holes are not symmetric
- ❑ Diameters are not all equals!

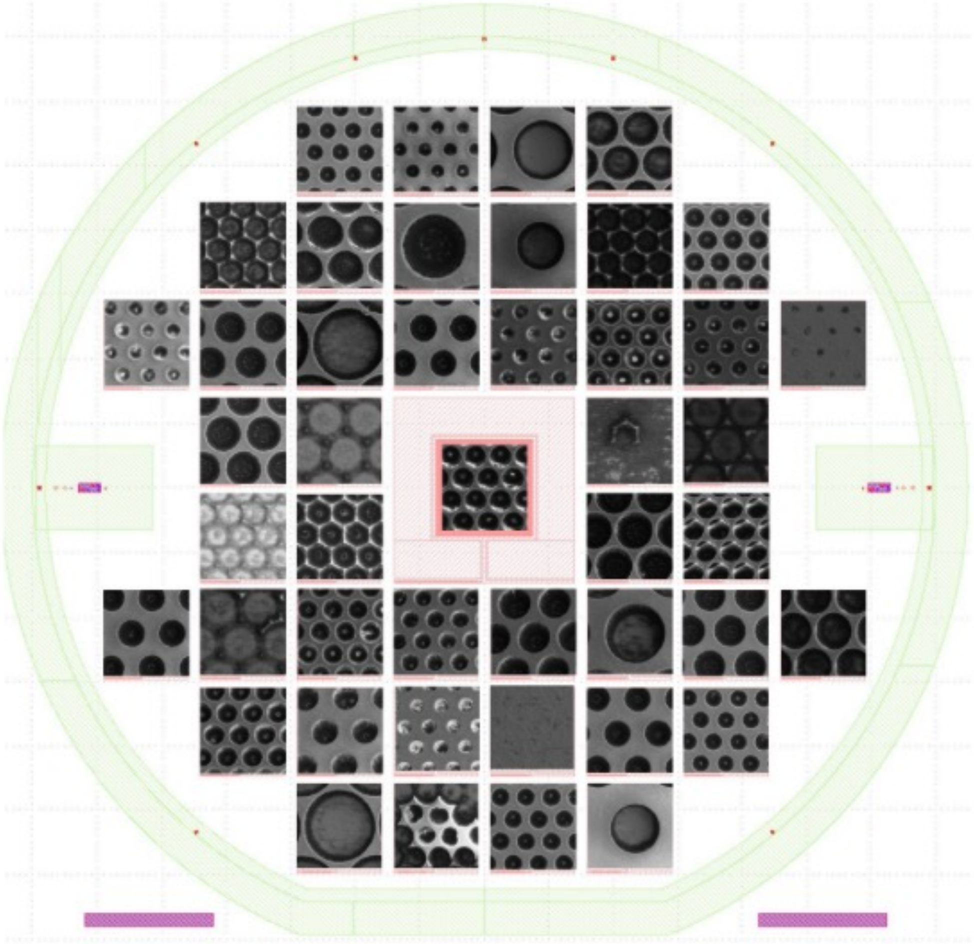
IFD 2025
INFN WORKSHOP ON FUTURE DETECTORS

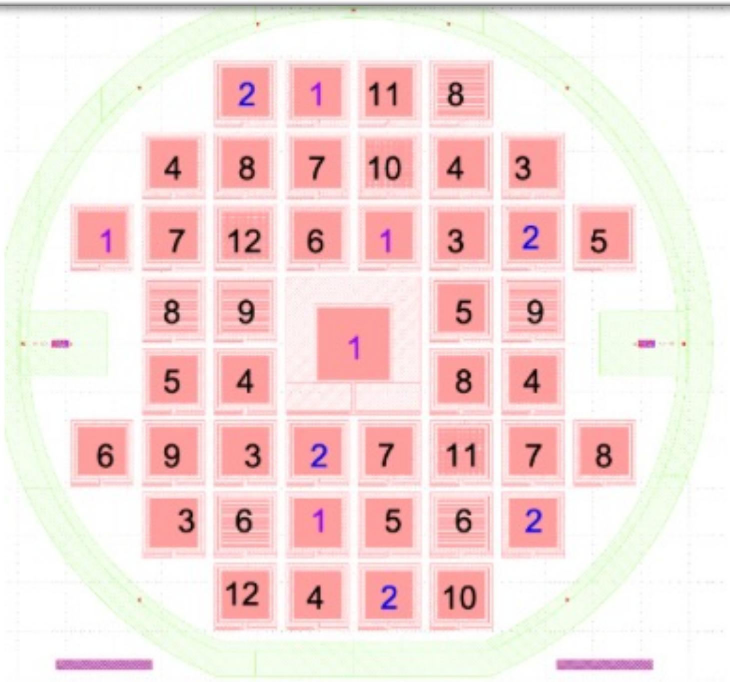
Gaseous Electron Multipliers

GEM holes quality: can we do better?

Configuration	Hole diameter (μm)	Pitch (μm)	Replicates
1	11	50	4
2	14	50	5
3	19	50	4
4	24	50	5
5	29	50	4
6	34	80	4
7	34	80	5
8	44	80	5
9	59	150	4
10	59	150	4
11	84	150	5
12	109	150	2

- ❑ Plasma-based etching approach developed with the know-how of the FPCs
- ❑ Kapton 50 μm
- ❑ Copper 6 μm





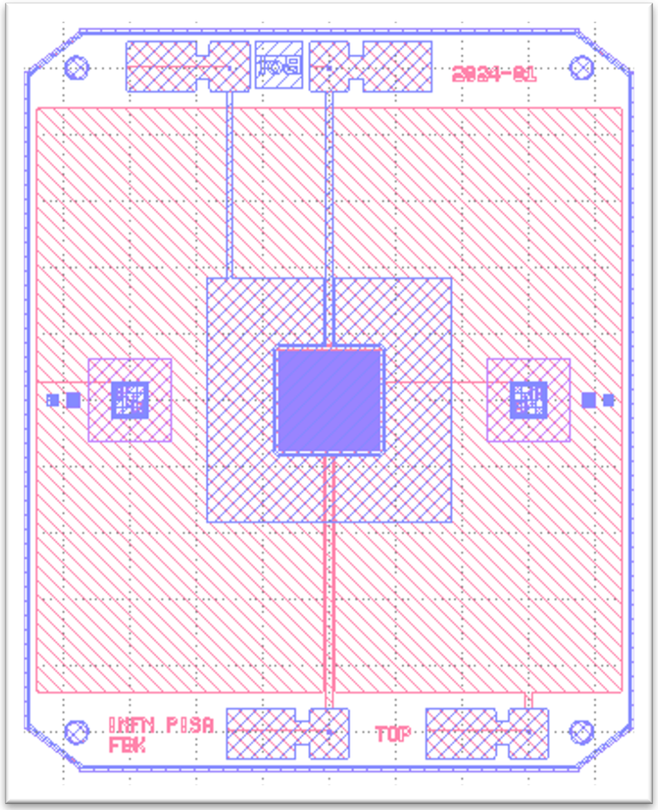
Plasma-based etching approach for GEM detector microfabrication at FBK for X-ray polarimetry in space

Proceeding

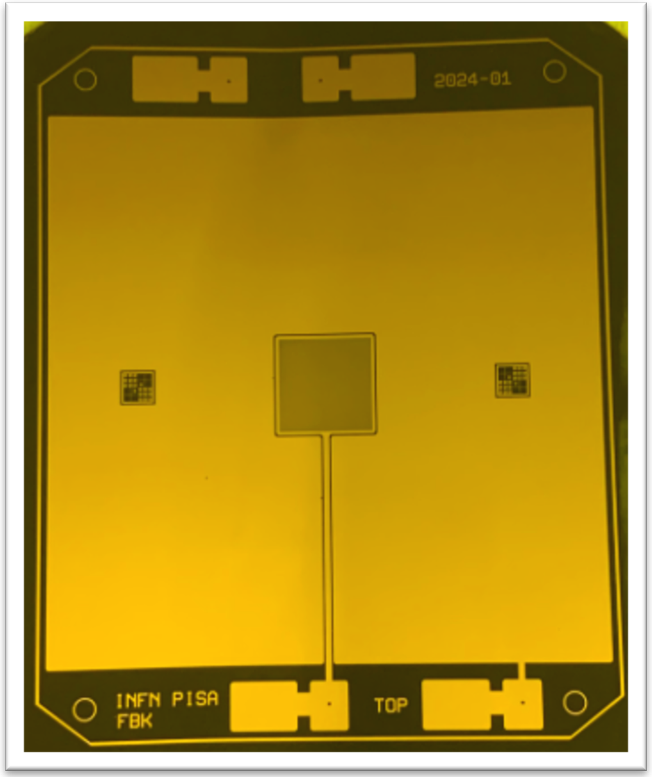
A. Lega, D. Novel, T. Facchinelli, C. Sgrò, L. Baldini, M. Minuti, M. Boscardin, G. Pepponi, R. Iuppa, R. Hall-Wilton and L. Latronico

Gaseous Electron Multipliers

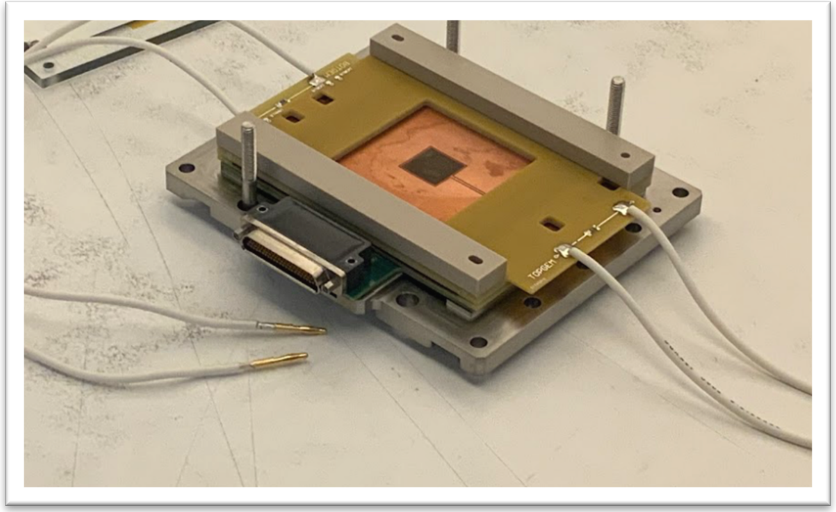
Full GEM design for IXPE



❑ Lithography mask design



❑ First lithography result



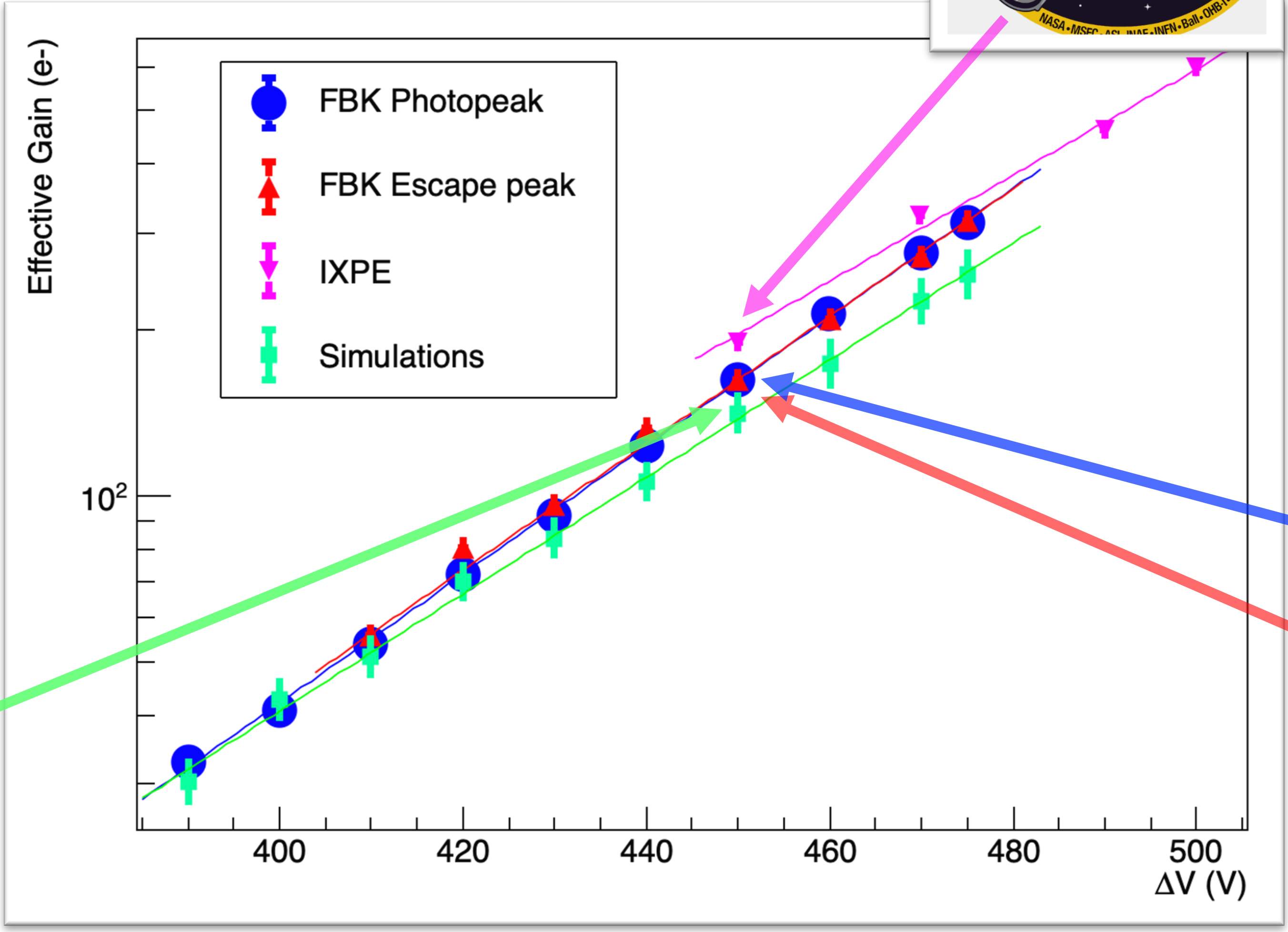
❑ Mechanical assembly with the manufactured GEM

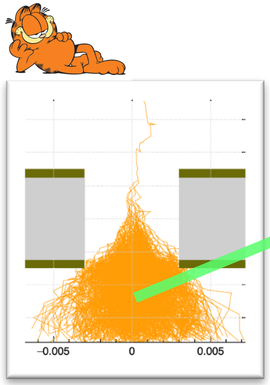
Plasma-based etching approach for GEM detector microfabrication at FBK for X-ray polarimetry in space

Proceeding

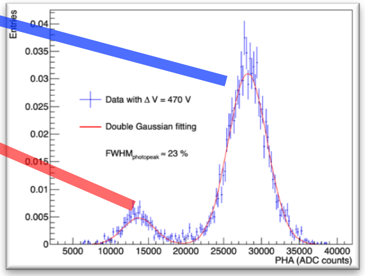
A. Lega[a,b,c,*] D. Novel[a] T. Facchinelli[a] C. Sgrò[d,e] L. Baldini[d,e] M. Minuti[d,e] M. Boscardin[a] G. Pepponi[a] R. Iuppa[b,c] R. Hall-Wilton[a] and L. Latronico[d,e]

Gaseous Electron Multipliers
Full GEM design for IXPE





GIF++ CODE



- SIMILAR GAIN CHARACTERISTICS TO THE ONE MOUNTED IN IXPE!

Plasma-based etching approach for GEM detector microfabrication at FBK for X-ray polarimetry in space

Proceeding

A. Lega, D. Novel, T. Facchinelli, C. Sgrò, L. Baldini, M. Minuti, M. Boscardin, G. Pepponi, R. Iuppa, R. Hall-Wilton and L. Latronico

Thanks for the attention!

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Istituto Nazionale di Fisica Nucleare

TIFPA

Trento Institute for Fundamental Physics and Applications

GSSI GRAN SASSO SCIENCE INSTITUTE

INFN LNGS Istituto Nazionale di Fisica Nucleare Laboratori Nazionali del Gran Sasso

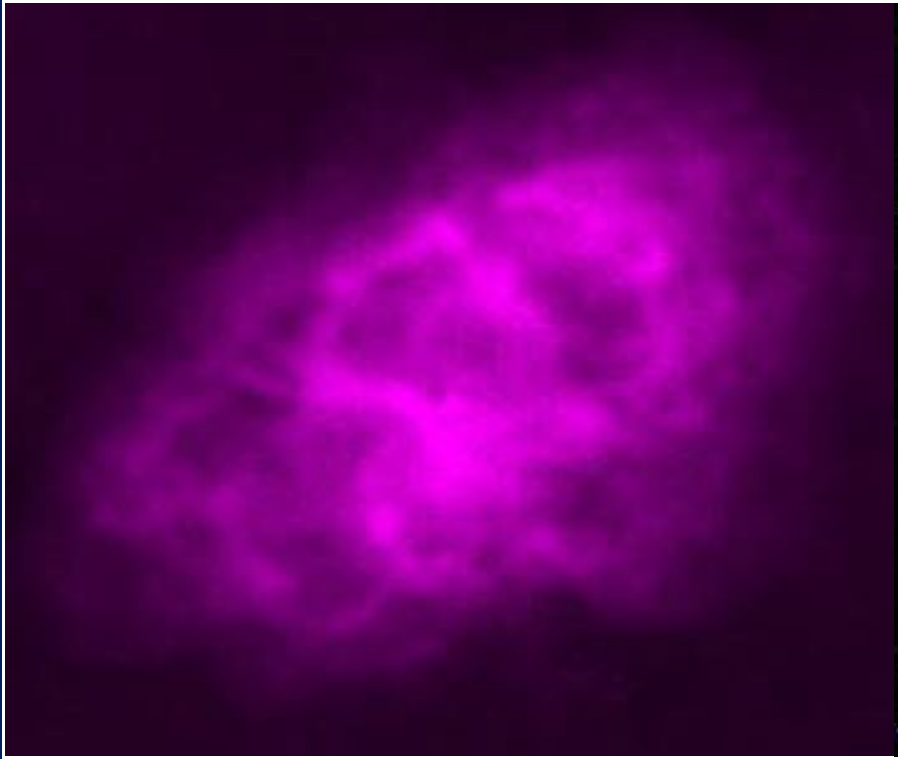
A Large-Volume, Extended Field-of-View TPC for X-Ray Polarimetry

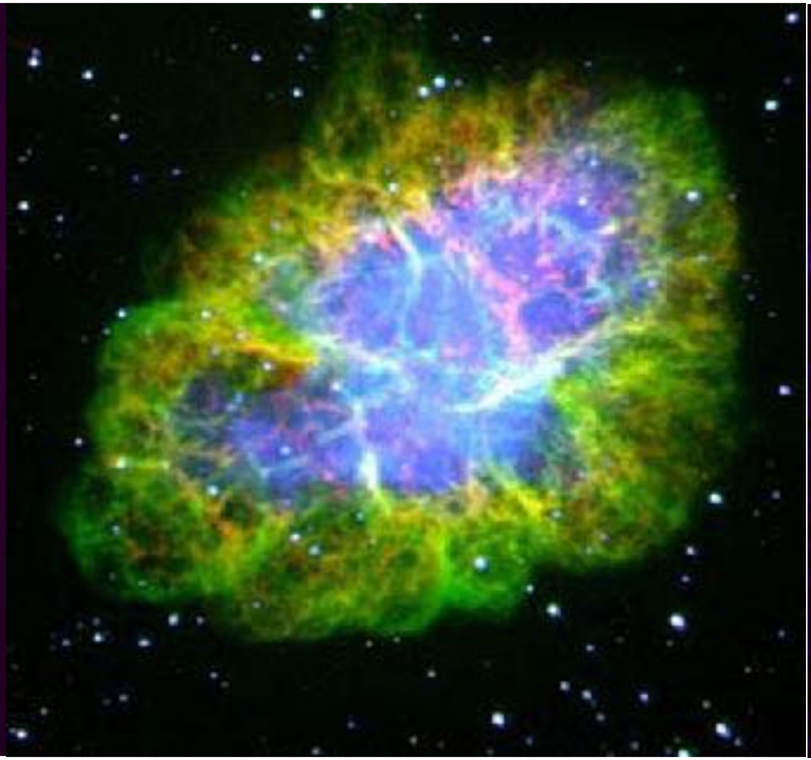
Davide Fiorina[a,b], Elisabetta Baracchini[a,b], Giorgio Dho[c], Paolo Soffitta[d], Enrico Costa[d], Sergio Fabiani[d], Fabio Muleri[d], Giovanni Mazzitelli [c]

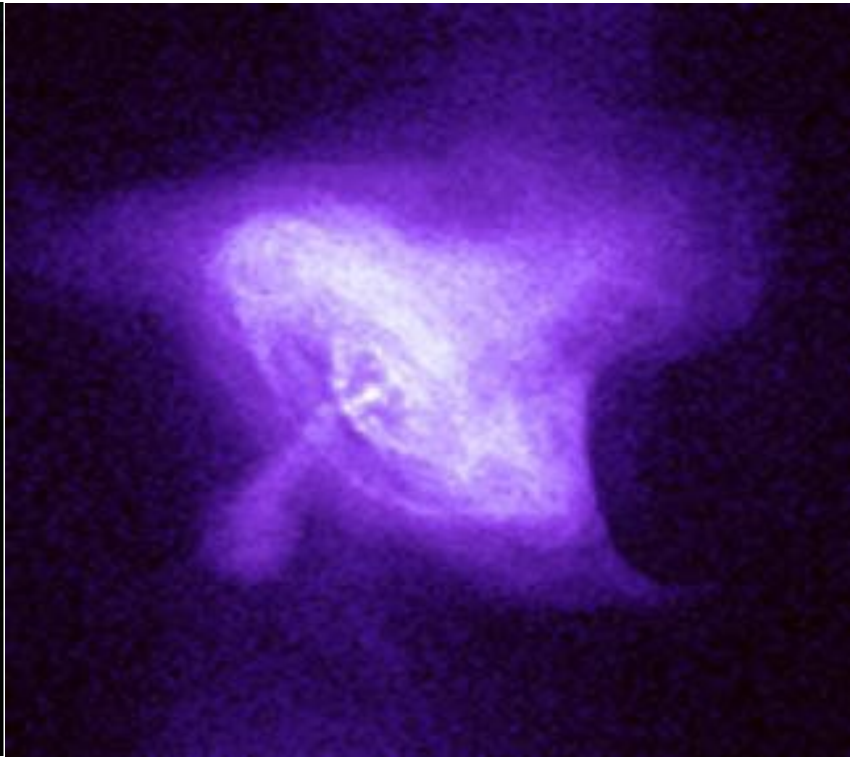
[a]Gran Sasso Science Institute
[b]INFN Laboratori Nazionali del Gran Sasso
[c]INFN Laboratori Nazionali di Frascati
[d]IAPS - INAF Istituto di Astrofisica e Planetologia Spaziali

Polarization in the EM spectrum

M1-Crab nebula







Radio

Optical

X-rays

Widely observed by different missions

First mission dedicated to polarimetry launched in 9 Dec 2021

Why Polarized X-Rays

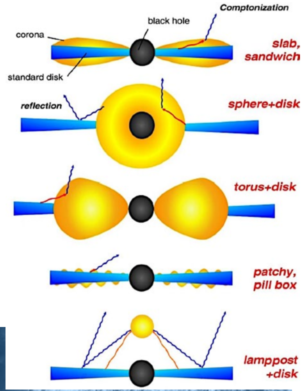
- The polarization of X-rays depends on magnetic field structures, geometry of gas clouds, and fundamental interactions
- Its measurements can unlock knowledge on astrophysical objects no other method can

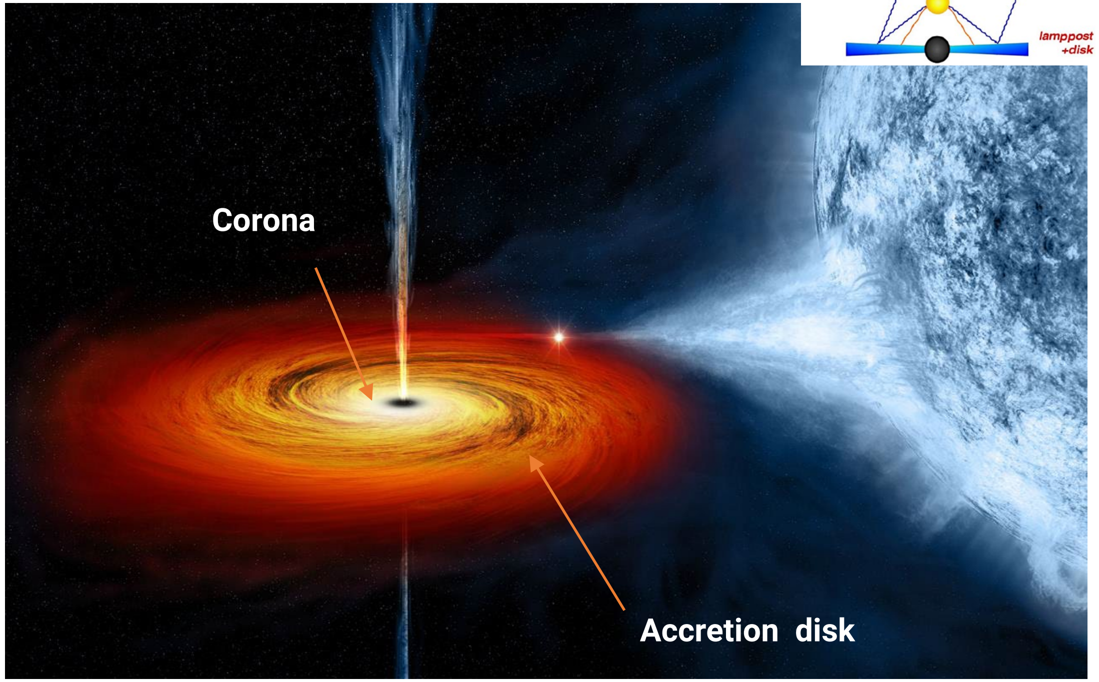
Acceleration mechanisms in jets and shocks

(Blazars, Super Nova Renant)

Shape of coronas and accretion geometry

(Accreting black hole binaries for example)

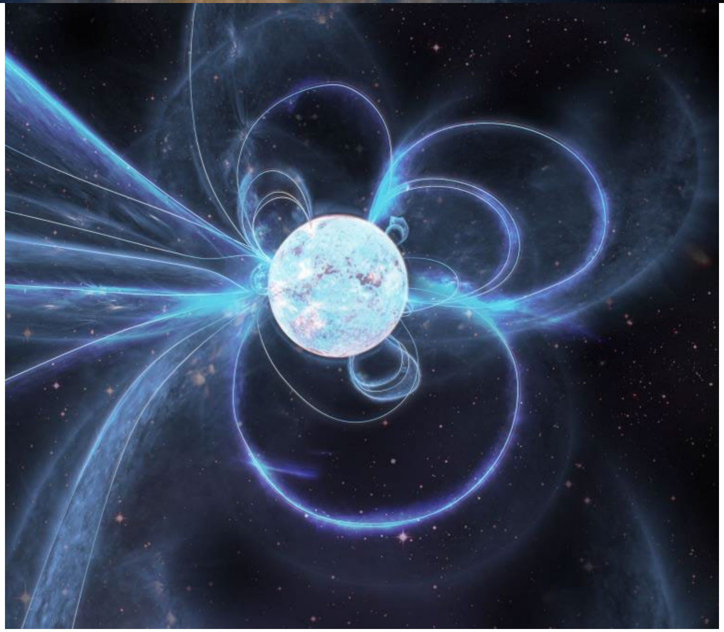




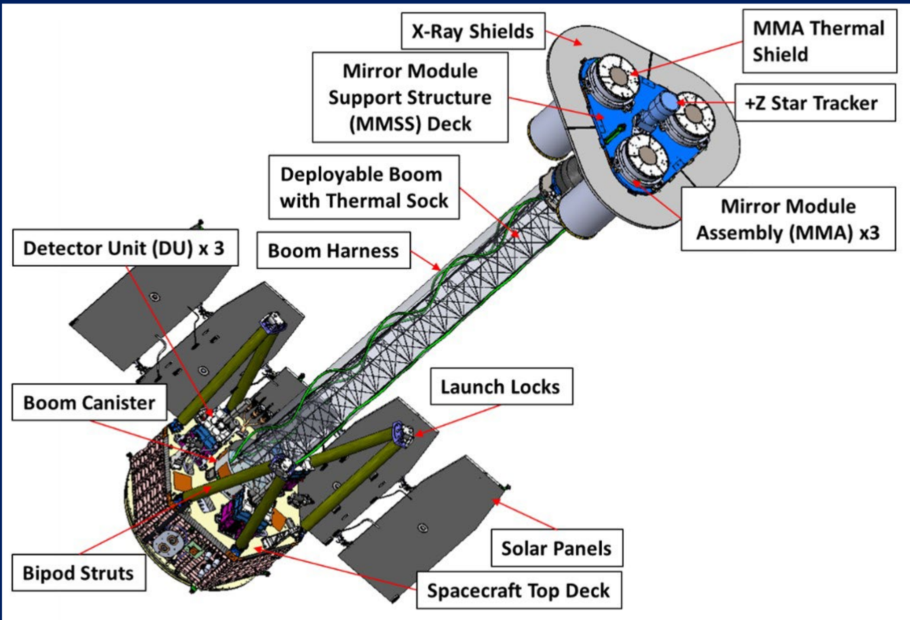
New physics can be searched too (QG, LIV, vacuum birefringence, ALPs)

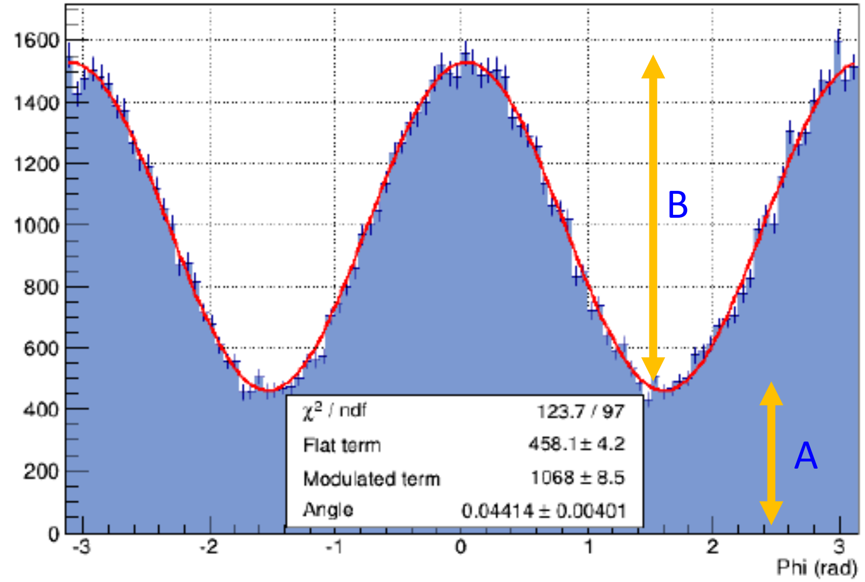
Behaviour in extremely strong magnetic fields

(Magnetars)



IXPE mission





- The Imaging X-ray Polarimetry Explorer (IXPE) was launched in December 2021
- 3 Photoelectric detectors (GPD) in the optics of 3 mirror telescopes (reduces background, focuses sources)
- Onboard calibration system with polarized and unpolarized sources

$$\mathcal{M}(\phi) = A + B\cos^2(\phi - \phi_0)$$

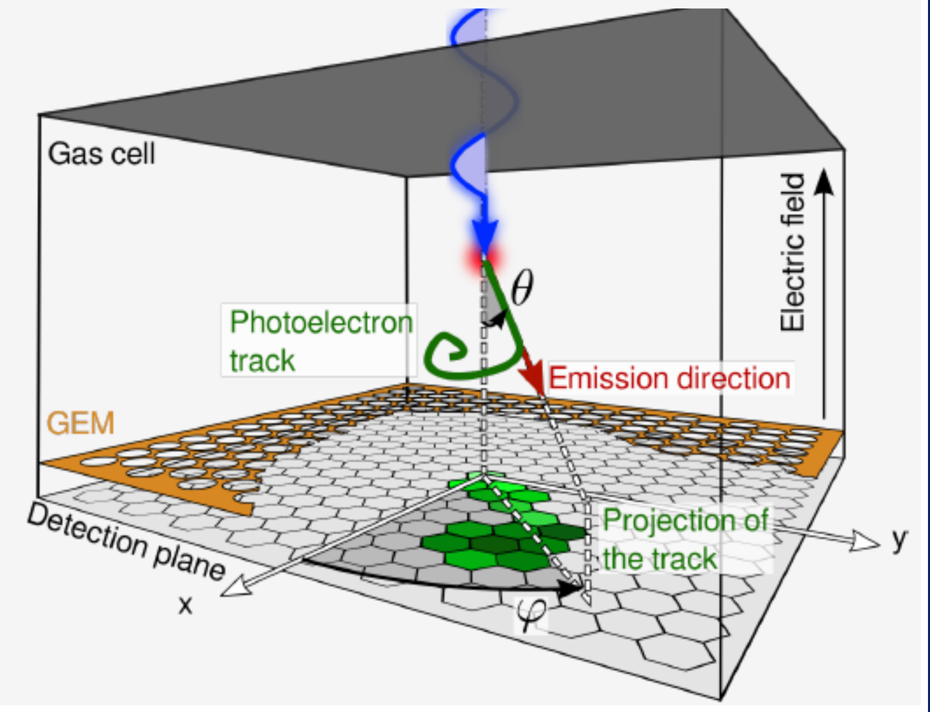
Polarization Angle

$$\mathcal{P} = \frac{1}{\mu}\frac{B}{B+2A}$$

Polarization Degree

Modulation Factor

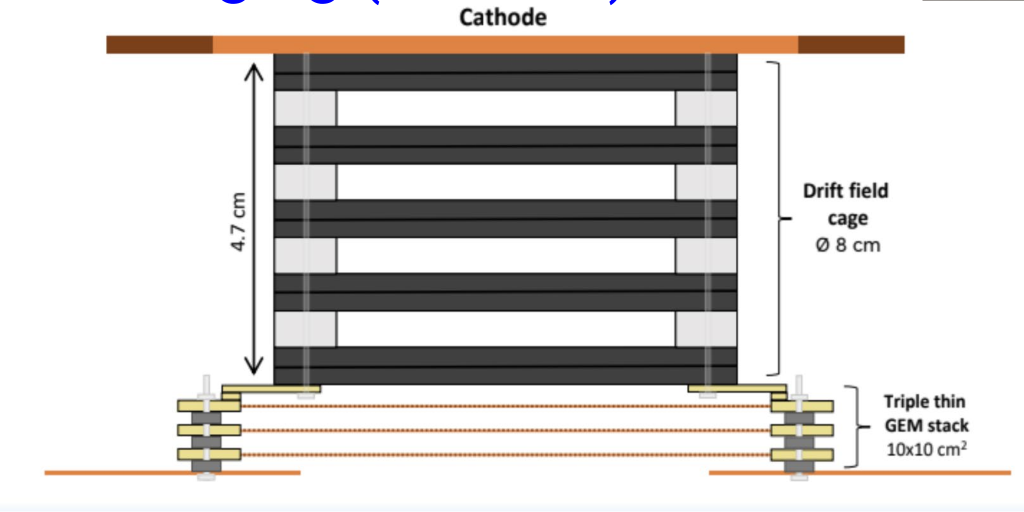
$$\frac{d\sigma}{d\Omega} \propto \cos^2\phi \, \frac{\sin^2\theta}{(1-\beta\cos\theta)^4}$$

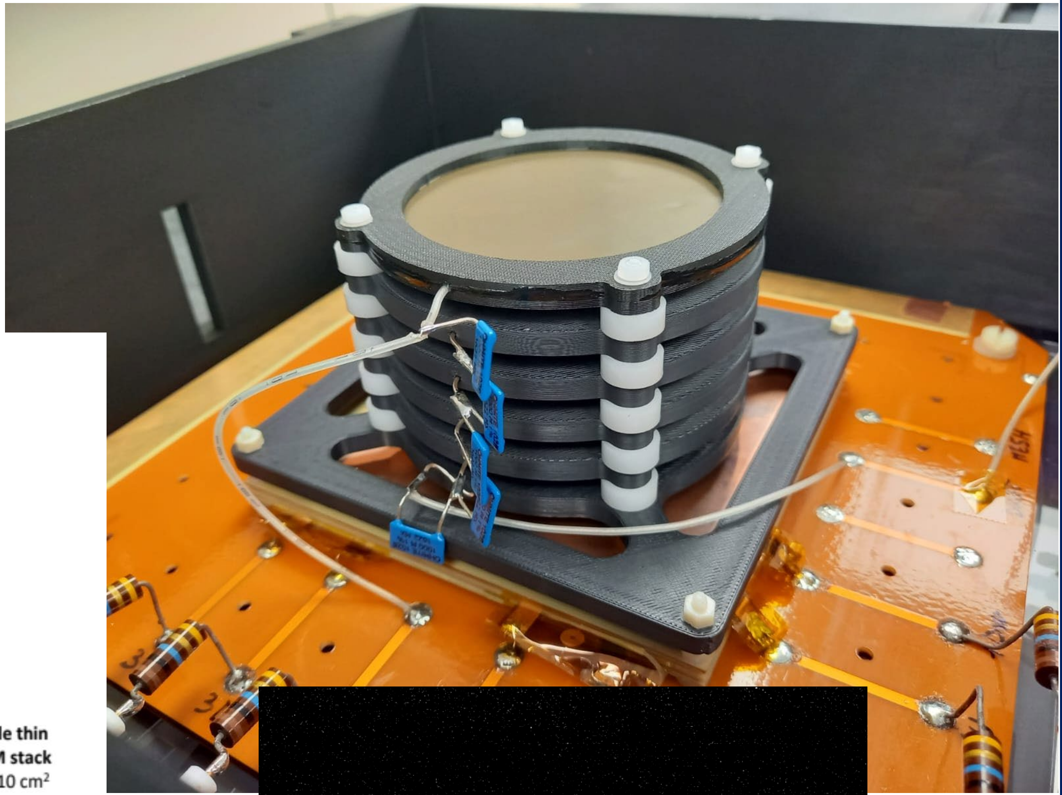


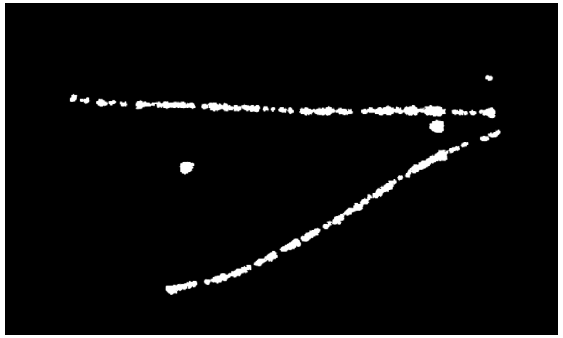
- DME gas @ 0.8 bar (diffusion of ~90-100 $\frac{\mu m}{\sqrt{cm}}$)
- 50 µm thick Be window (transparent to X-rays)
- Single GEM amplification (50 µm pitch)
- Hexagonal custom ASIC pixelated charge detector (10^5 channels)
- Energy resolution 15% @ 6.4 keV
- Position resolution less than 120 µm @ 2 keV

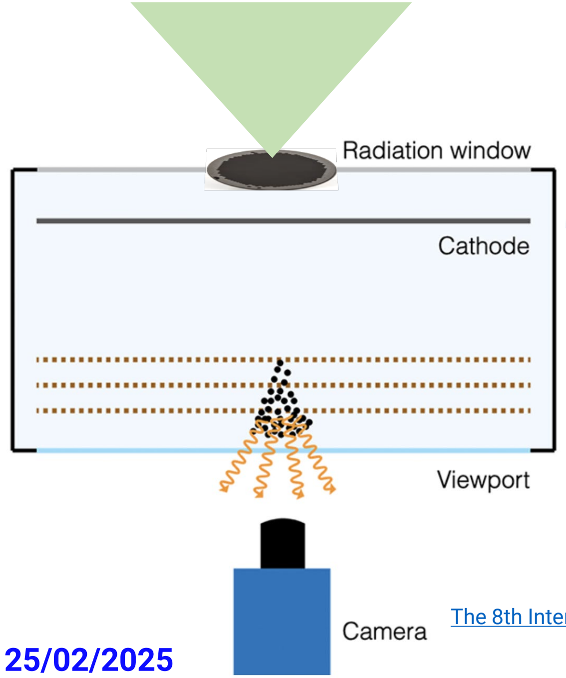
MetalMANGO prototype

- Large FoV ≈ **20°**(IXPE is 0.2°)
- Larger energy band **10-60 keV** (IXPE 2-8 keV)
- ~~**3D imaging** (IXPE 2D)~~





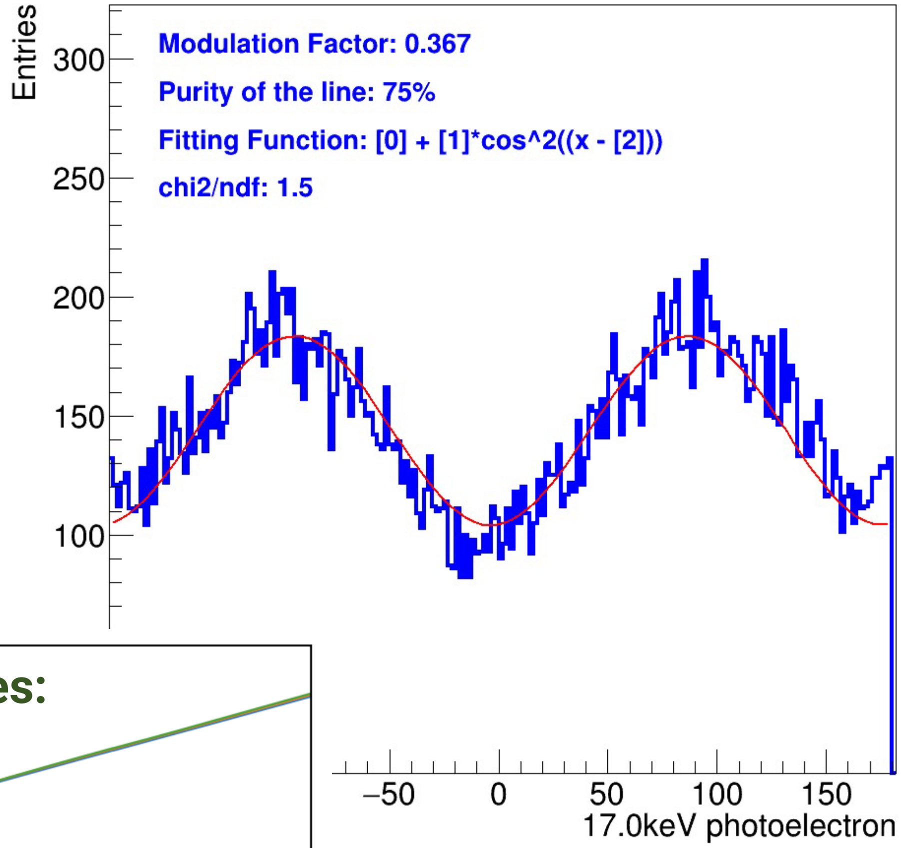


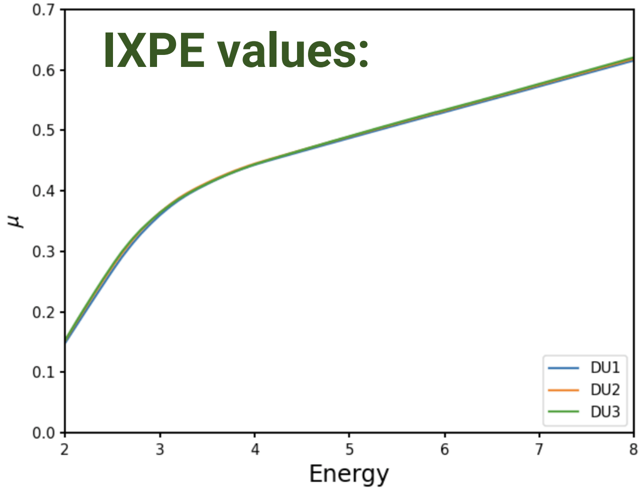


The 8th International Conference on Micro Pattern Gaseous Detectors (MPGD2024) (14-18 October 2024): Development and Preliminary Results of a Large-Volume Time Projection Chamber for X-ray Polarimetry · Indico

Detector Performance

17 keV fully polarized beam





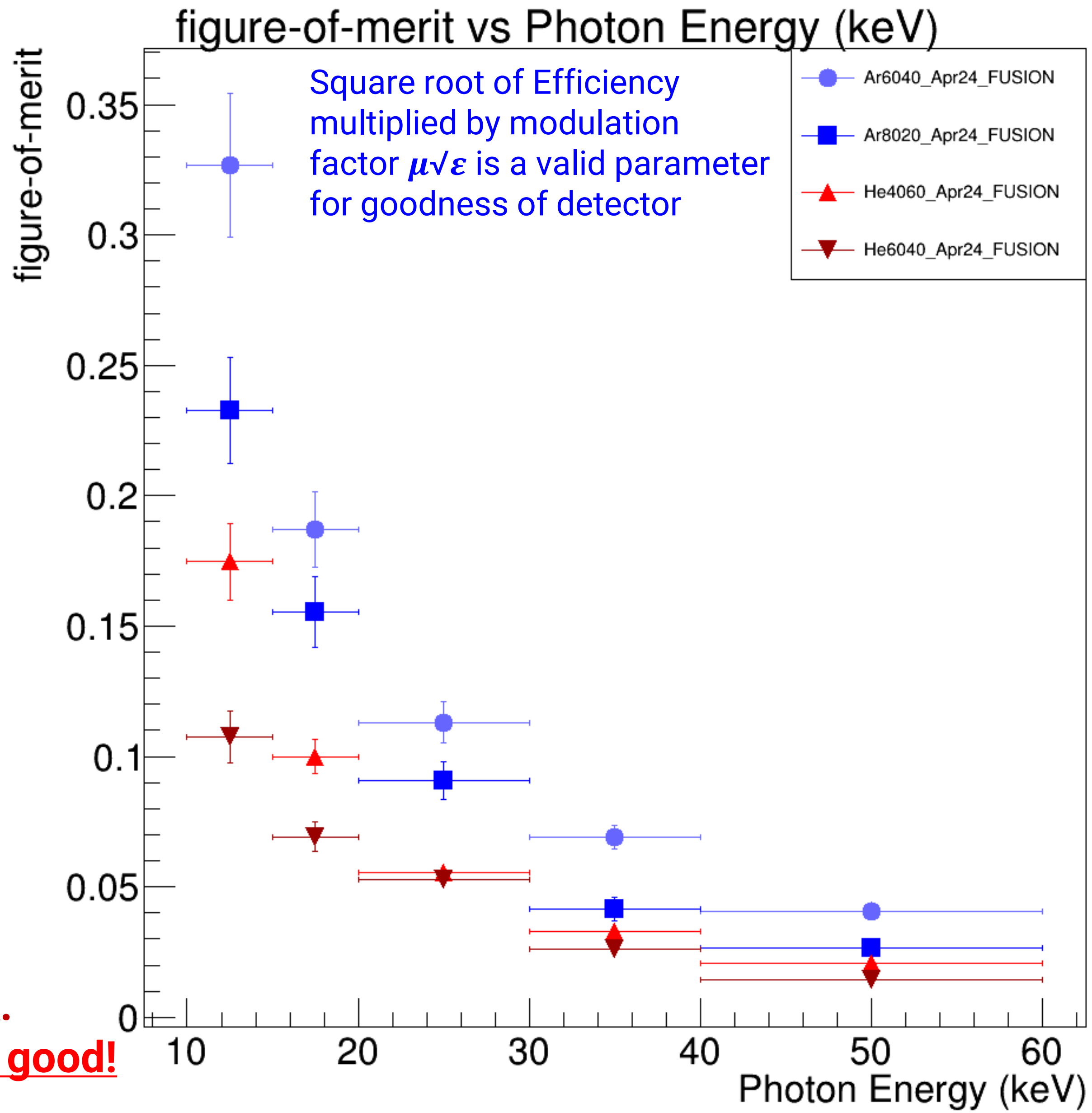
IXPE values:

<u>0.11 @ 2.6 keV</u>

<u>0.074 @6.4 keV</u>

Our value are in the ballpark.

<u>This does not mean we are similarly good!</u>



Founded from ERC in Horizon 2020 program (grant agreement 818744)

Istituto Nazionale di Fisica Nucleare

Towards a large gaseous TPC with optical readout: the CYGNO project

S. Piacentini for the CYGNO collaboration

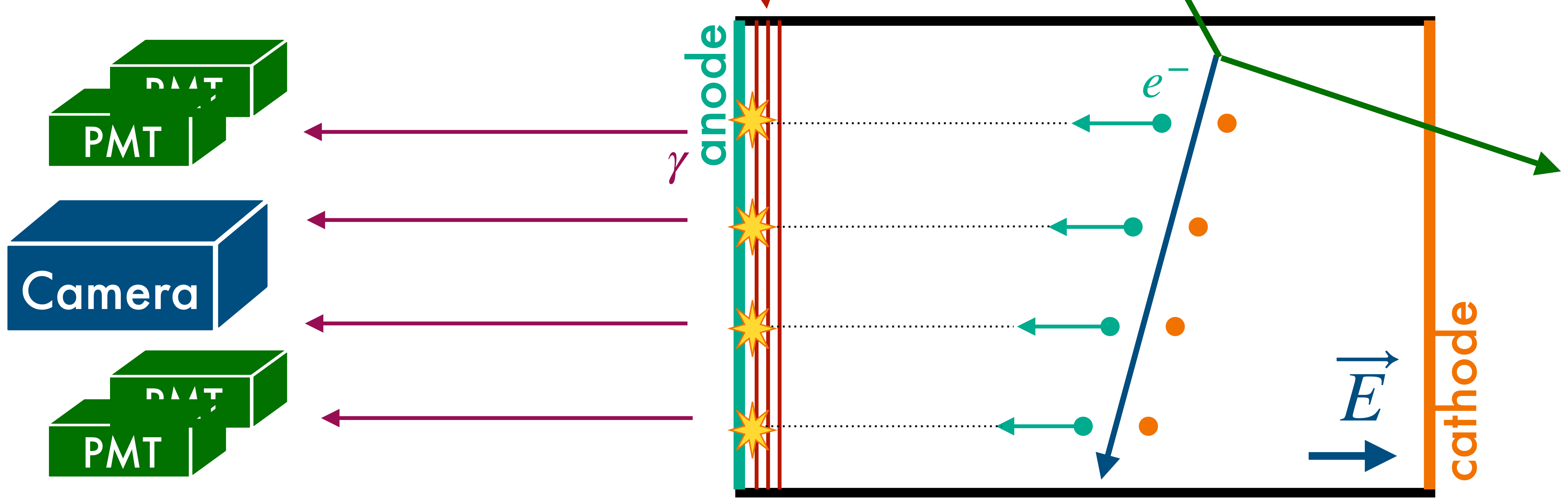
R. Antonietti, E. Baracchini, L. Benussi, S. Bianco, R. Campagnola, C. Capoccia, M. Caponero, L. G. Carvalho, G. Cavoto, I. A. Costa, A. Croce, M. D'Astolfo, G. D'Imperio, E. Danè, G. Dho, F. Di Giambattista, E. Di Marco, J. M. F. dos Santos, D. Fiorina, F. Iacoangeli, Z. u. Islam, E. Kemp, H. P. Lima Jr, G. Maccarrone, R. D. P. Mano, R. R. Marcelo Gregorio, D. J. G. Marques, G. Mazzitelli, A. G. McLean, P. Meloni, A. Messina, C. M. B. Monteiro, R. A. Nobrega, I. F. Pains, E. Paoletti, L. Passamonti, F. Petrucci, S. Piacentini, D. Piccolo, D. Pierluigi, D. Pinci, A. Prajapati, F. Renga, R. J. d. C. Roque, F. Rosatelli, A. Russo, G. Saviano, P. A. O. C. Silva, N. J. Spooner, R. Tesauro, S. Tomassini, S. Torelli, D. Tozzi

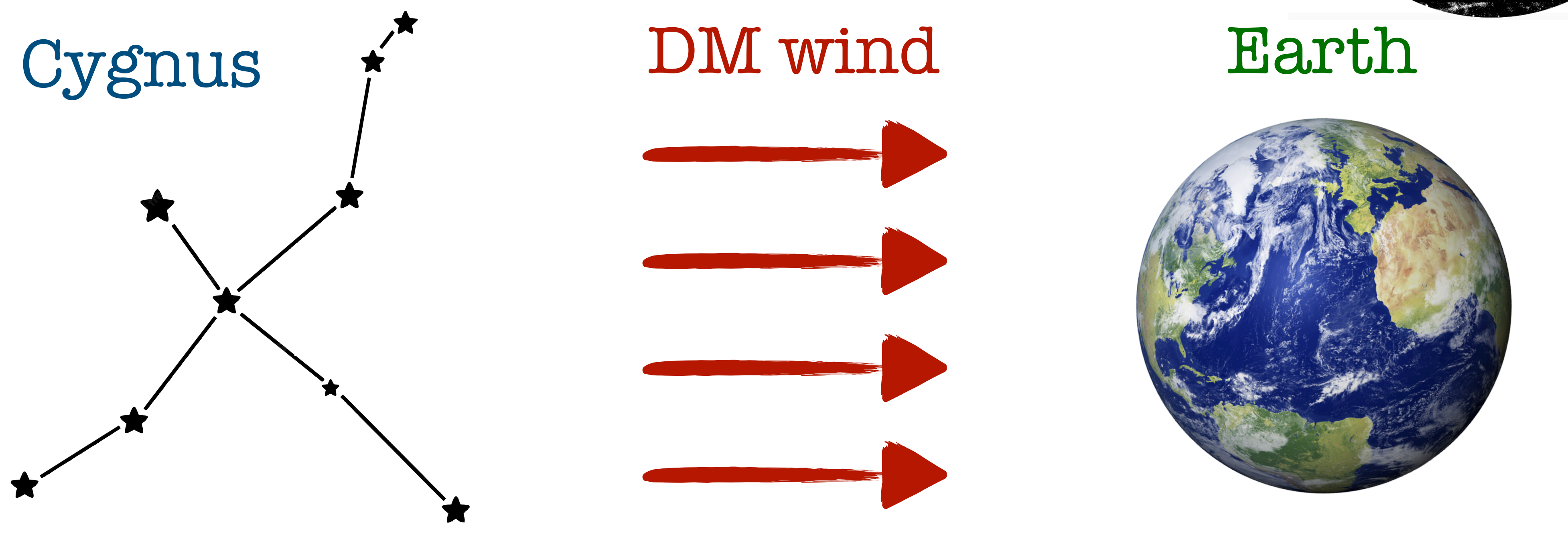
IFD 2025 - INFN Workshop on Future Detectors **18 / 03 / 2025**

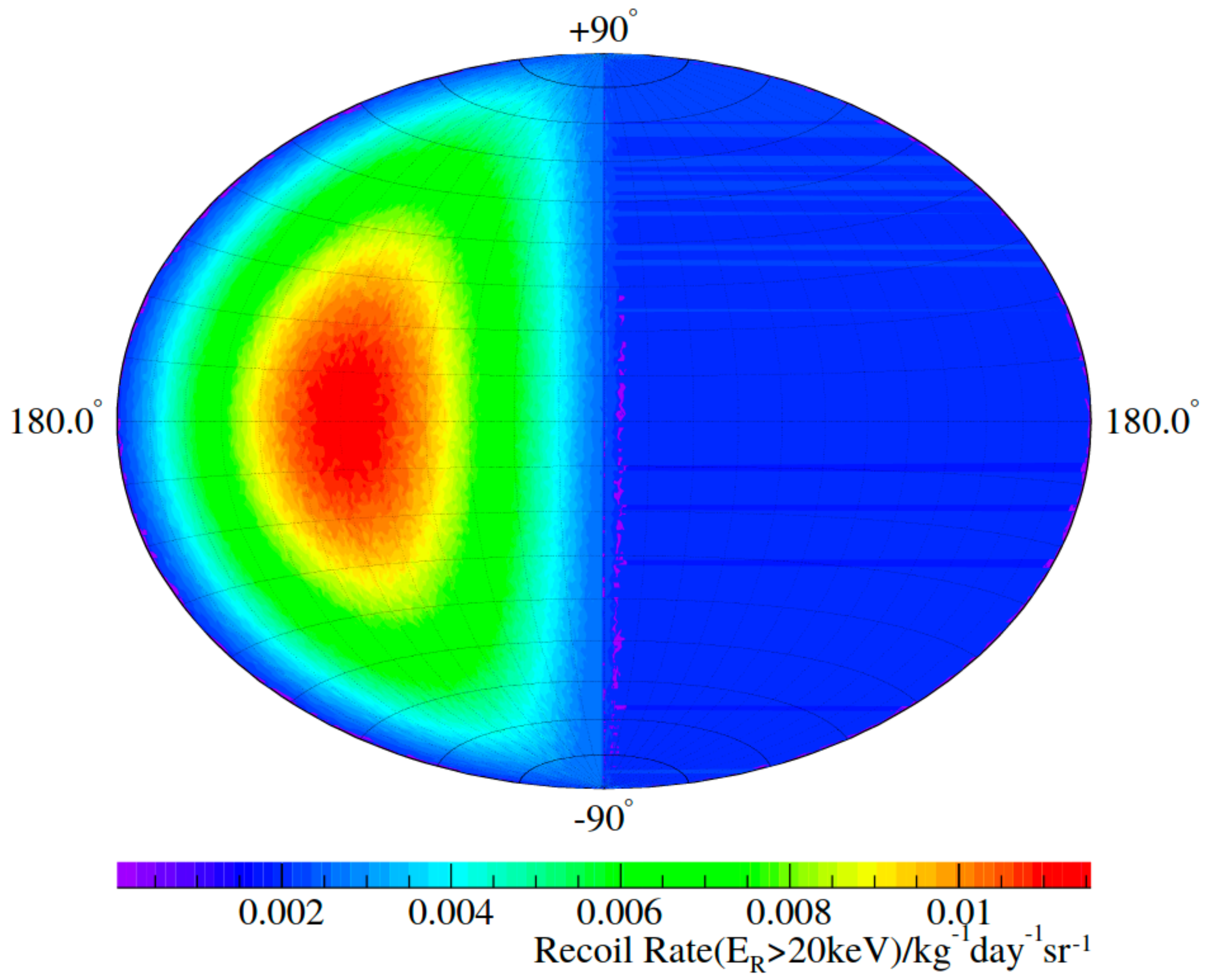
The CYGNO project

- **Aiming for** a large detector for high precision **3D tracking of rare low energy nuclear recoils** (keV) possibly induced by **dark matter** (DM) particles and solar neutrinos
- **Experimental challenges:** rate O(evt/kg/year), background rejection, and energy threshold (keV)
- **Strategy: photograph nuclear recoils** in a (1 atm) He:CF_4 TPC with a GEM amplification stage

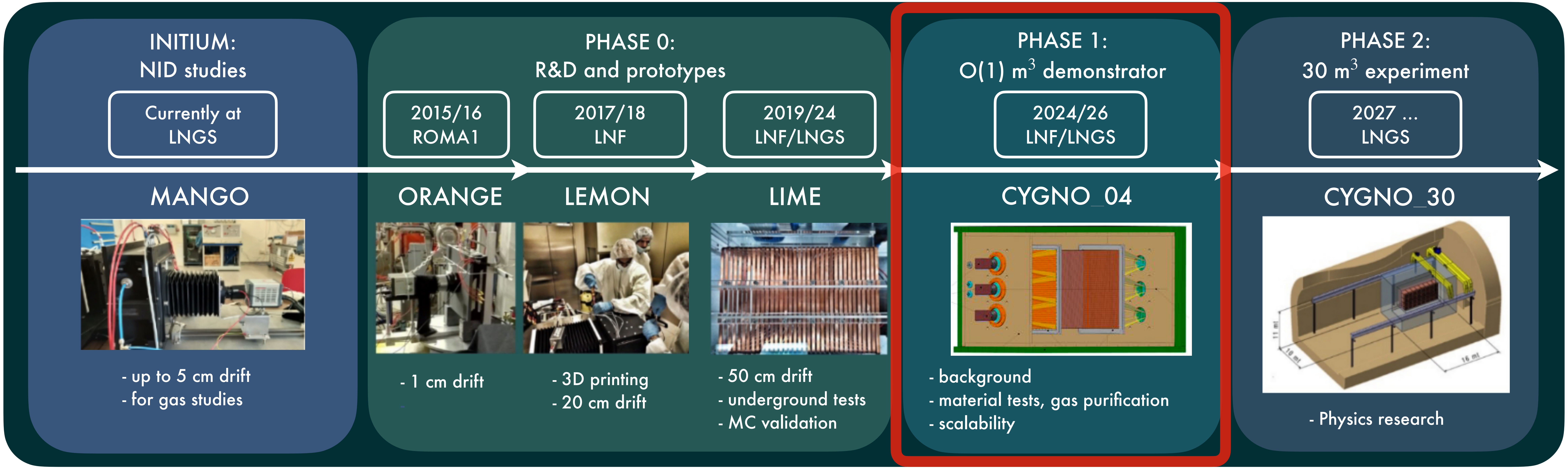
➡ low energy events in 1 atm gas ⇒ visible tracks ⇒ optical readout







The CYGNO timeline

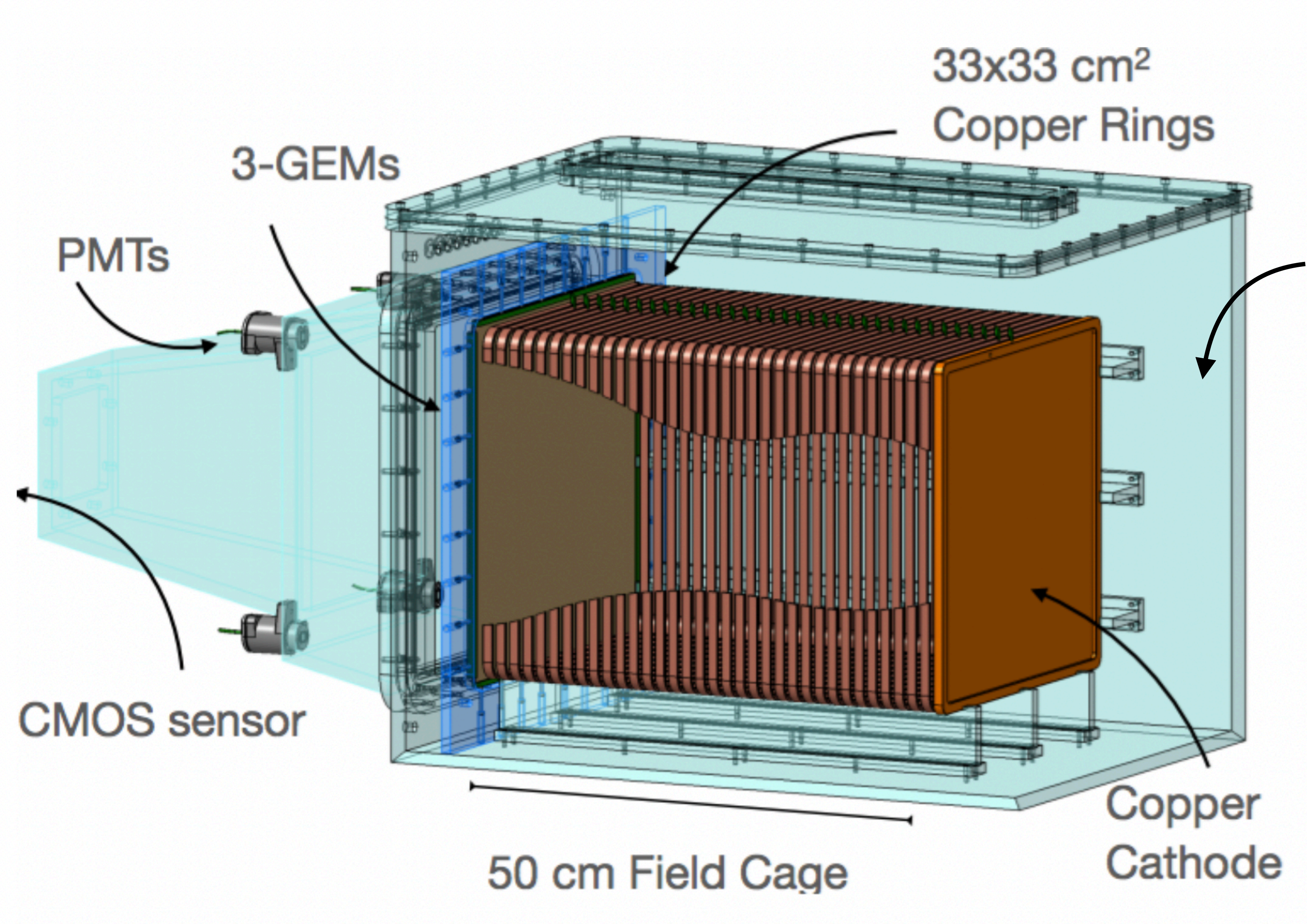


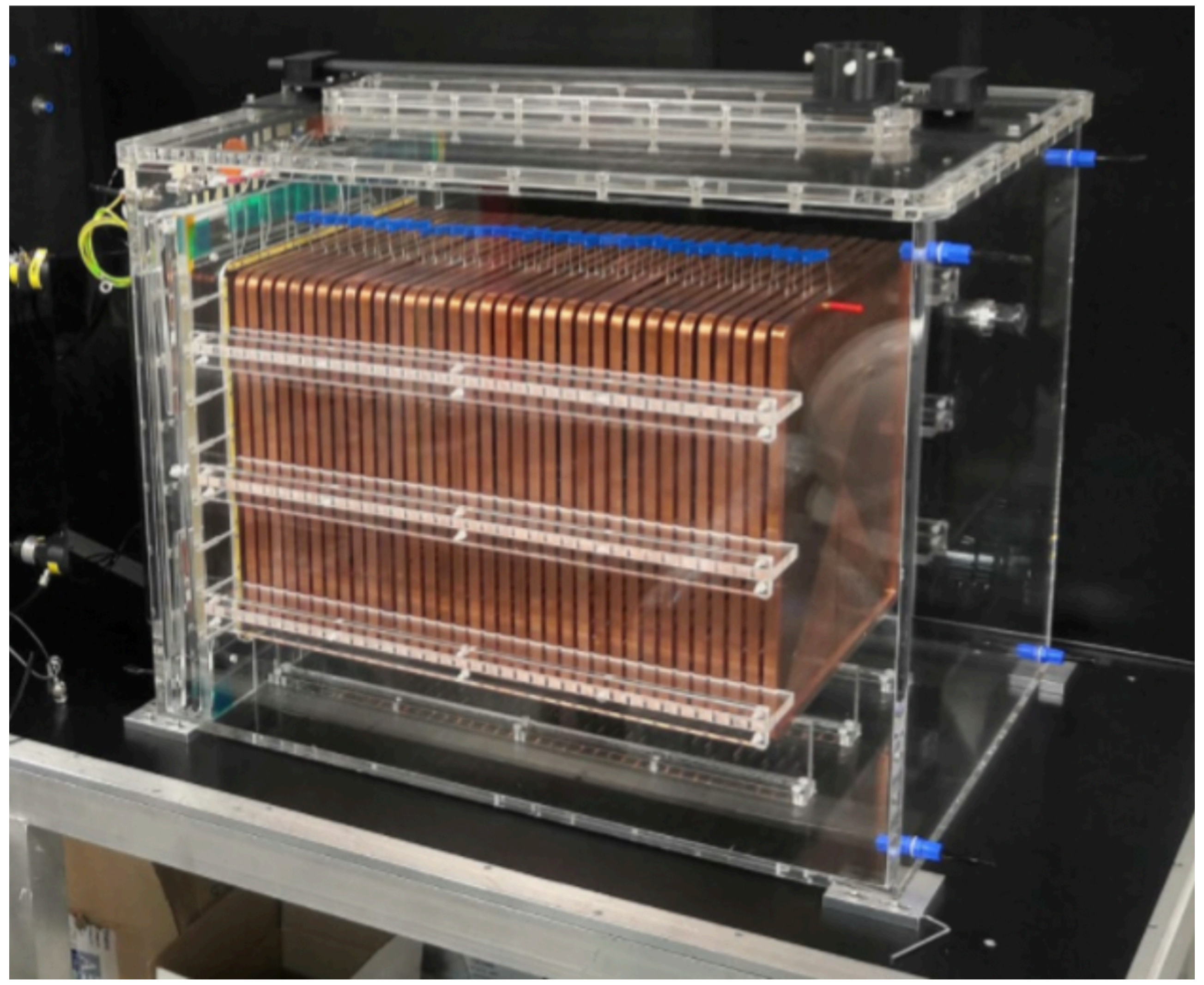
Phys.Lett.B 855 (2024) 138759
Eur.Phys.J.C 83 (2023) 10, 946
Instruments 6 (2022) 1, 6
Measur.Sci.Tech. 32 (2021) 2, 025902
NIM A 999 (2021) 165209

JINST 15 (2020) 12, T12003
JINST 15 (2020) P10001
JINST 15 (2020) P08018
2019 JINST 14 P07011

LIME: Long Imaging ModulE

- Designed at **RM1 and LNF** and built at **LNF**





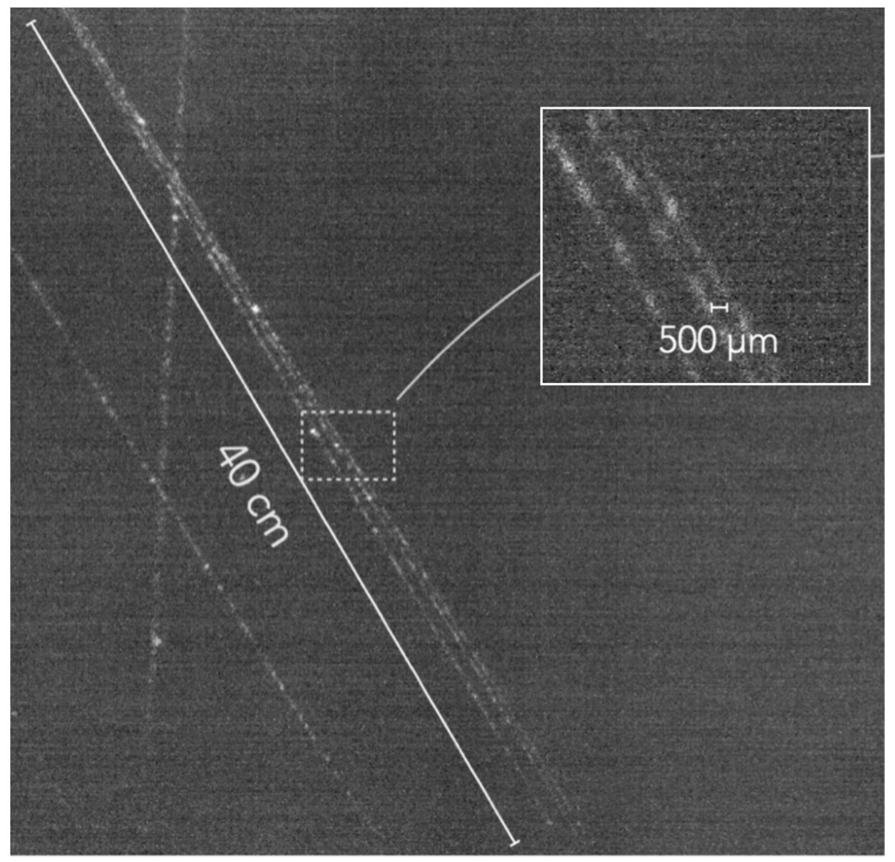
Purpose of LIME:

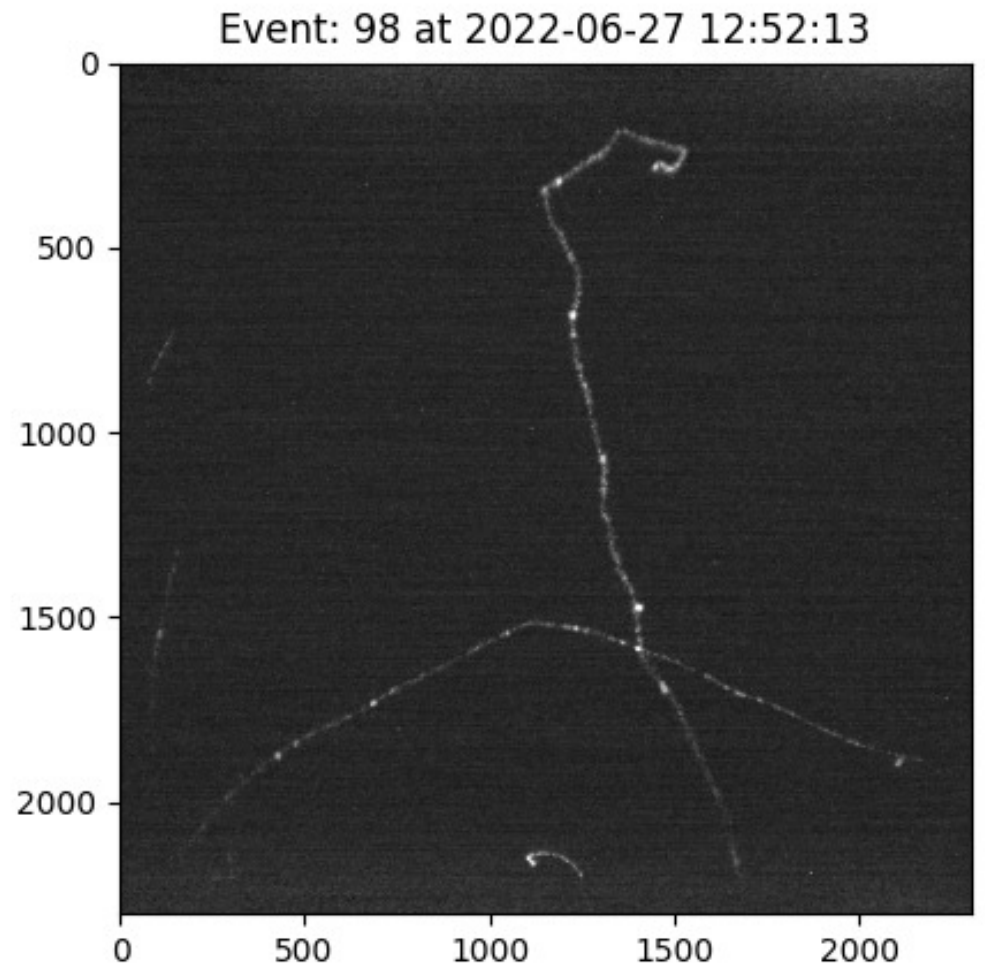
- Prove we can operate such a detector underground
- Study and improve our Monte Carlo simulation

4 Hamamatsu R7378 PMTs

- Copper ring **field cage**, 50 cm **drift**
- 1 **sCMOS** sensor + 4 **PMTs**
- 3 **GEMs** for a 33 x 33 cm^2 sensitive area
- **50 L** sensitive volume

Cosmic rays (overground, no shielding)



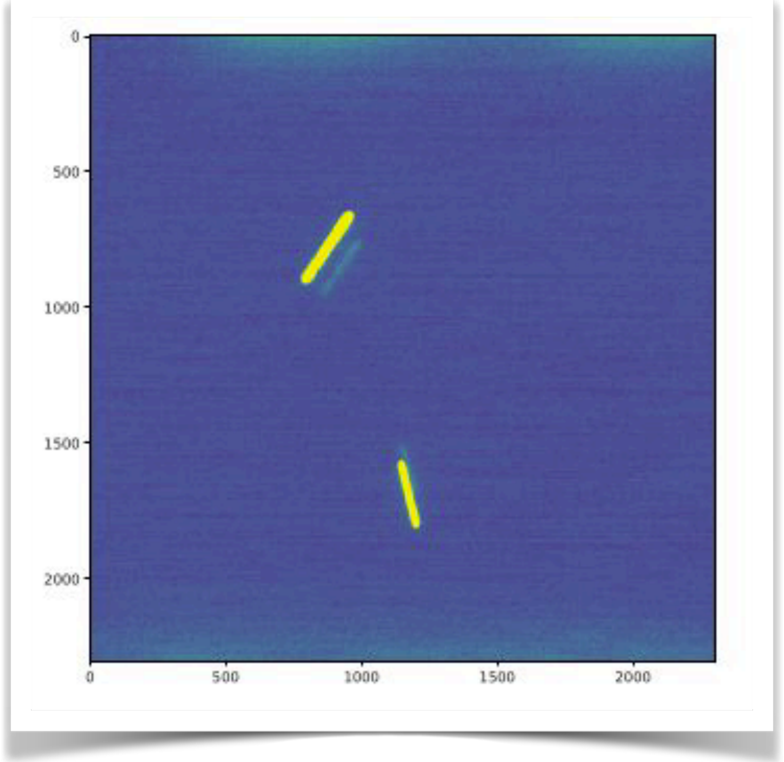


Natural radioactivity (underground, no shielding)

3D reconstruction of alpha tracks

CYGNO Experiment

- Combination of camera and PMT: **full 3D reconstruction**, combining PMT and CMOS
- **Energy ↔ 3D range**



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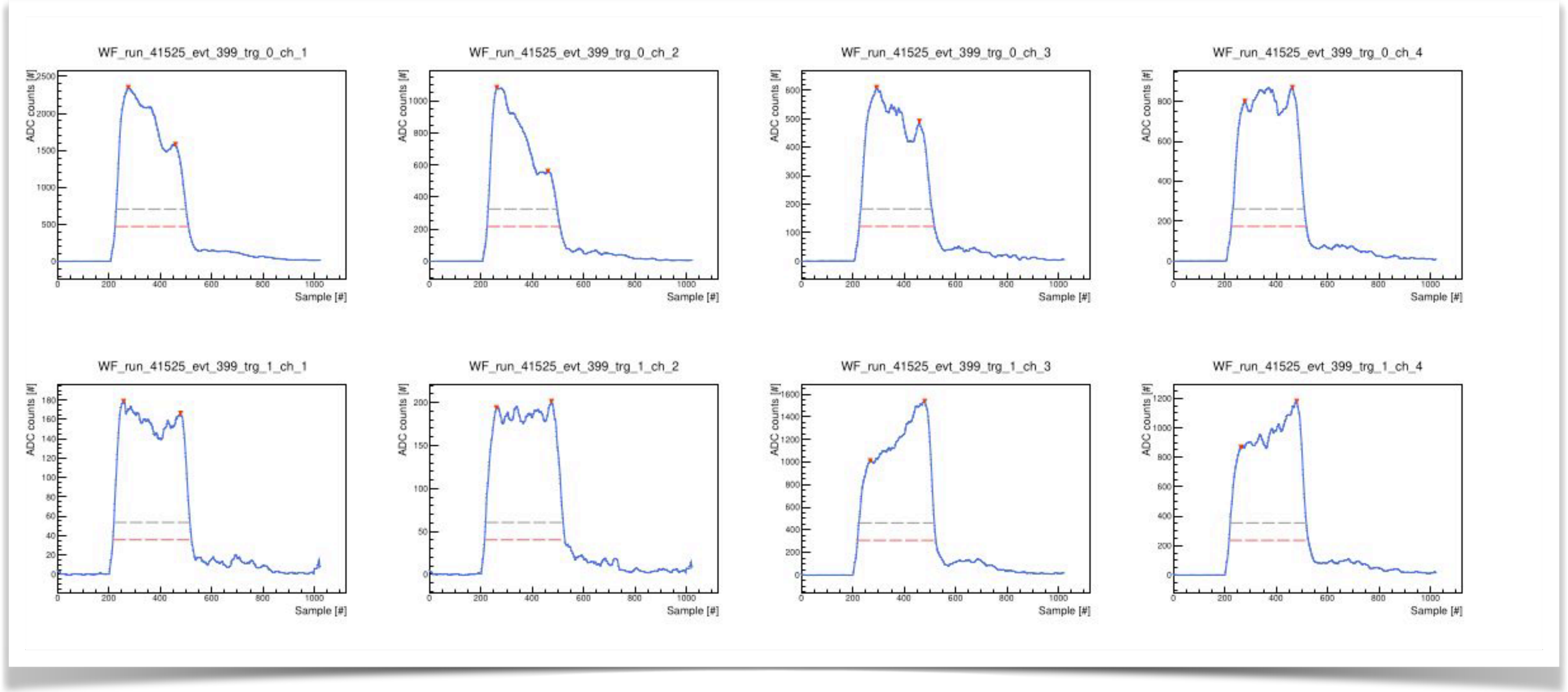
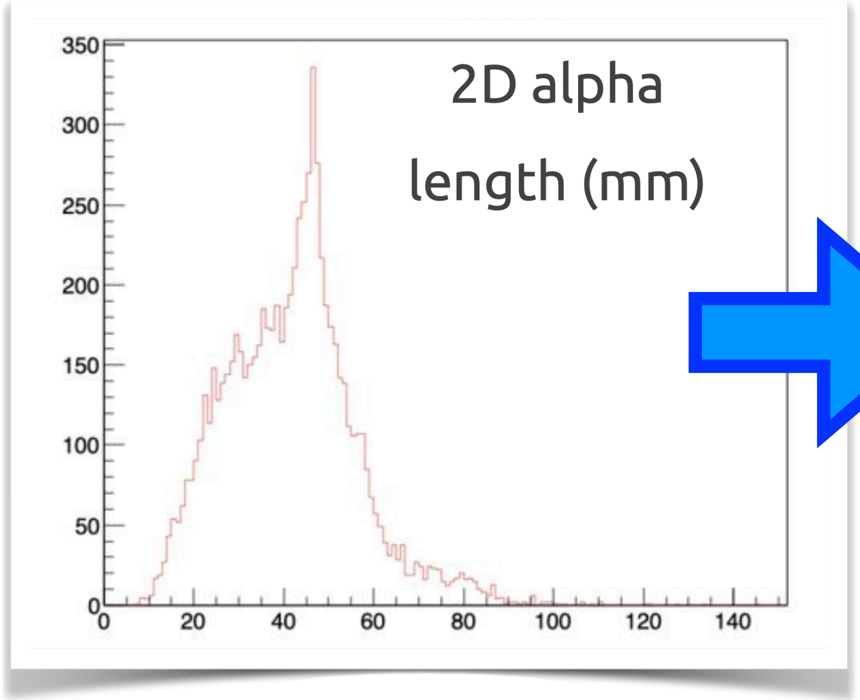
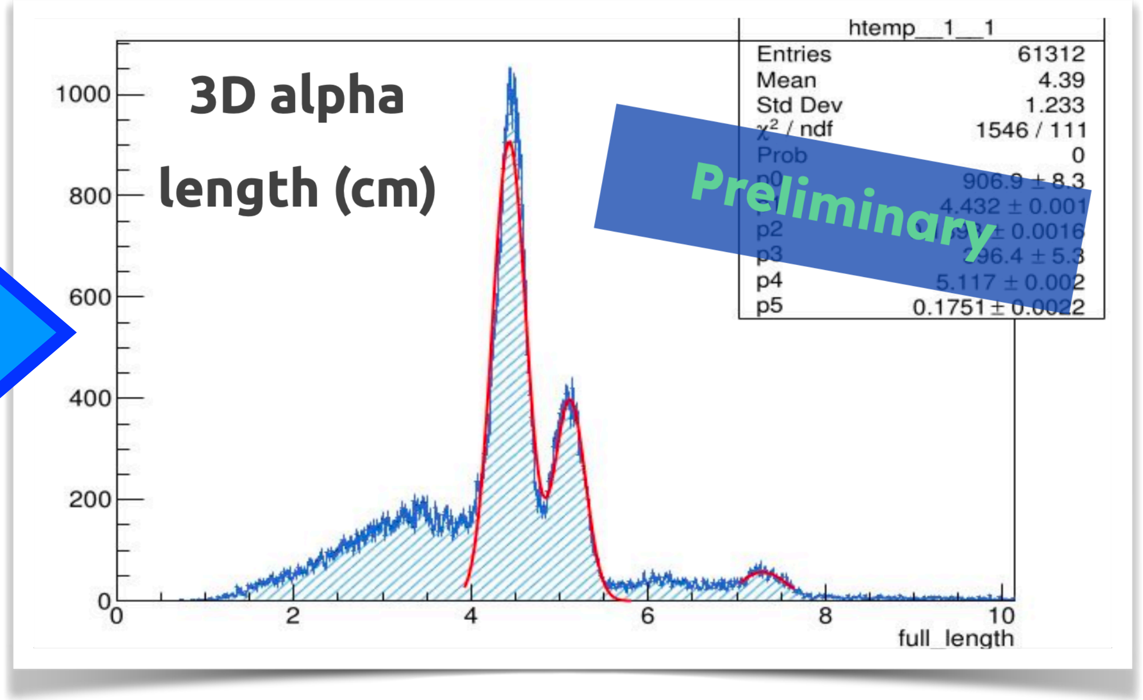
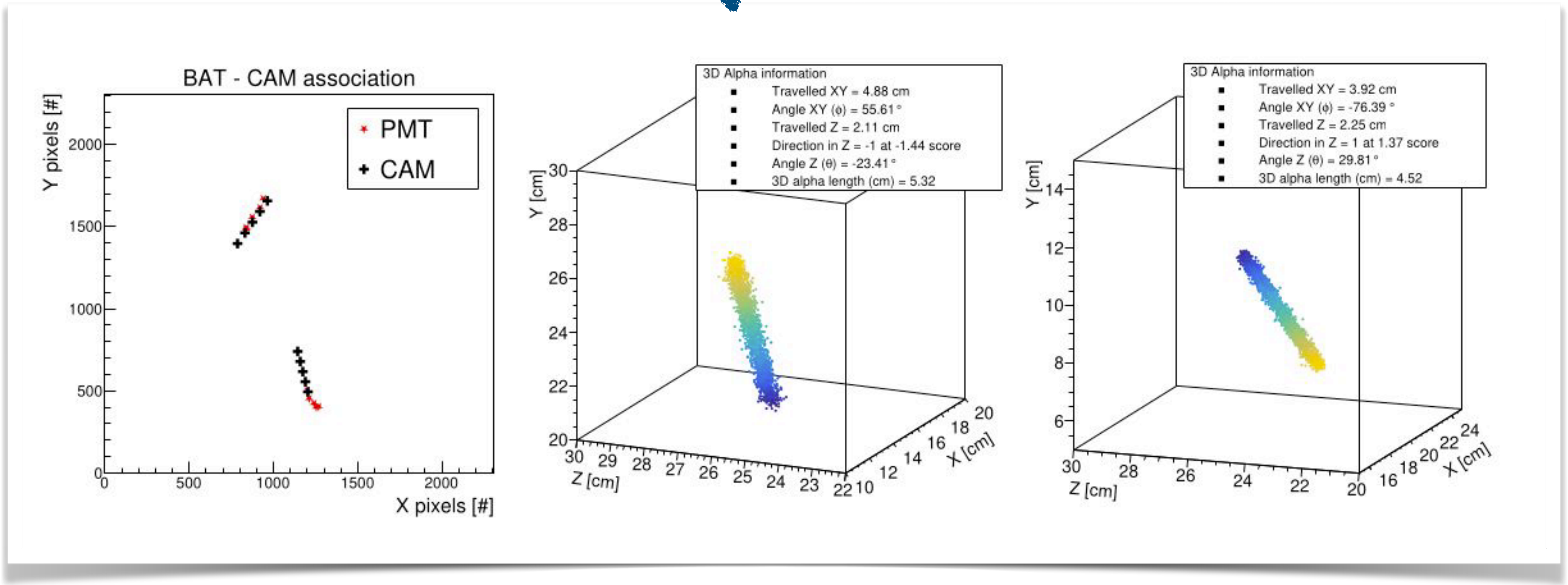






CMOS image + 4 PMTs

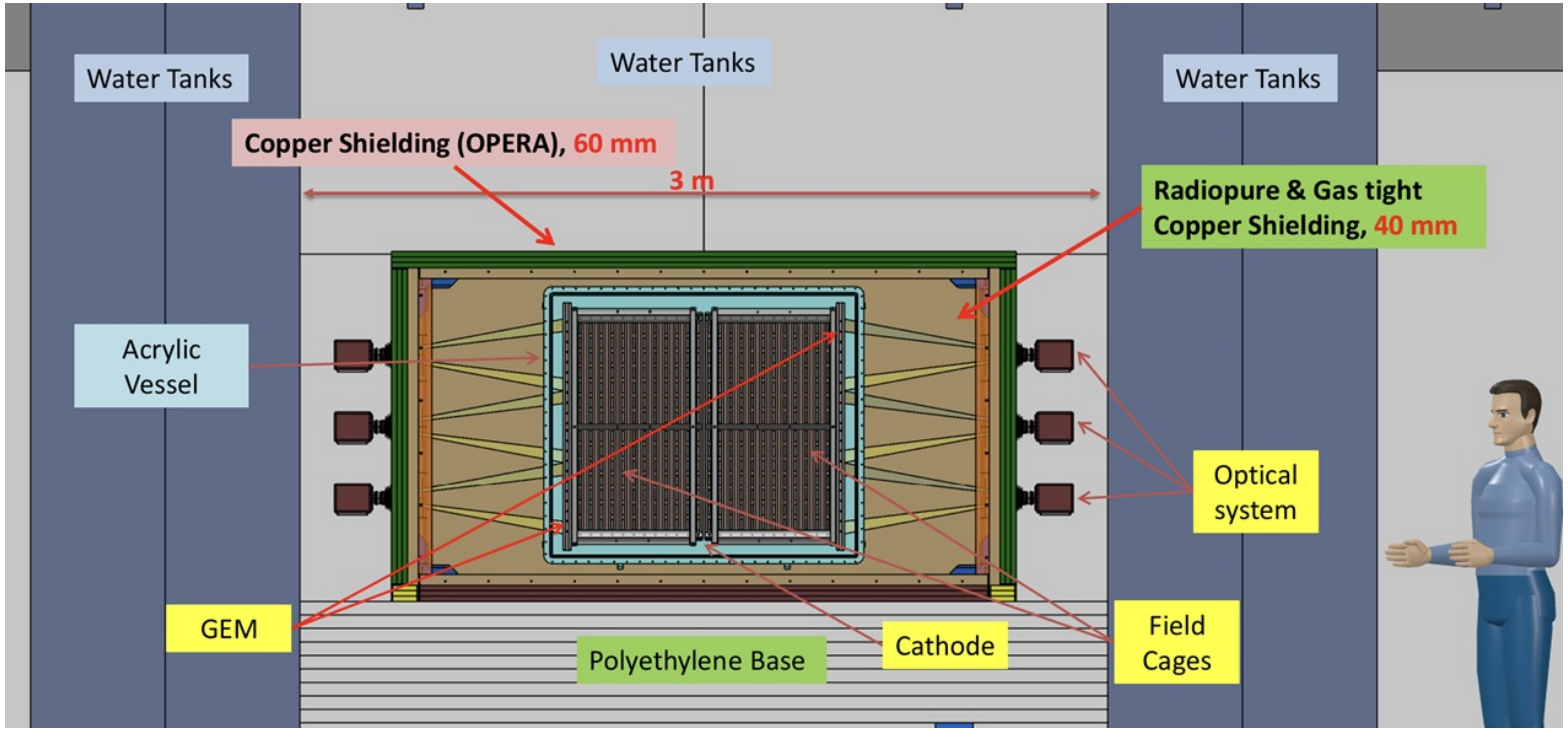
3D length and inclination
of alpha tracks with head-tail



CYGNO PHASE 1: CYGNO_04

CYGNO Experiment

Designed at LNF and to be installed at LNGS

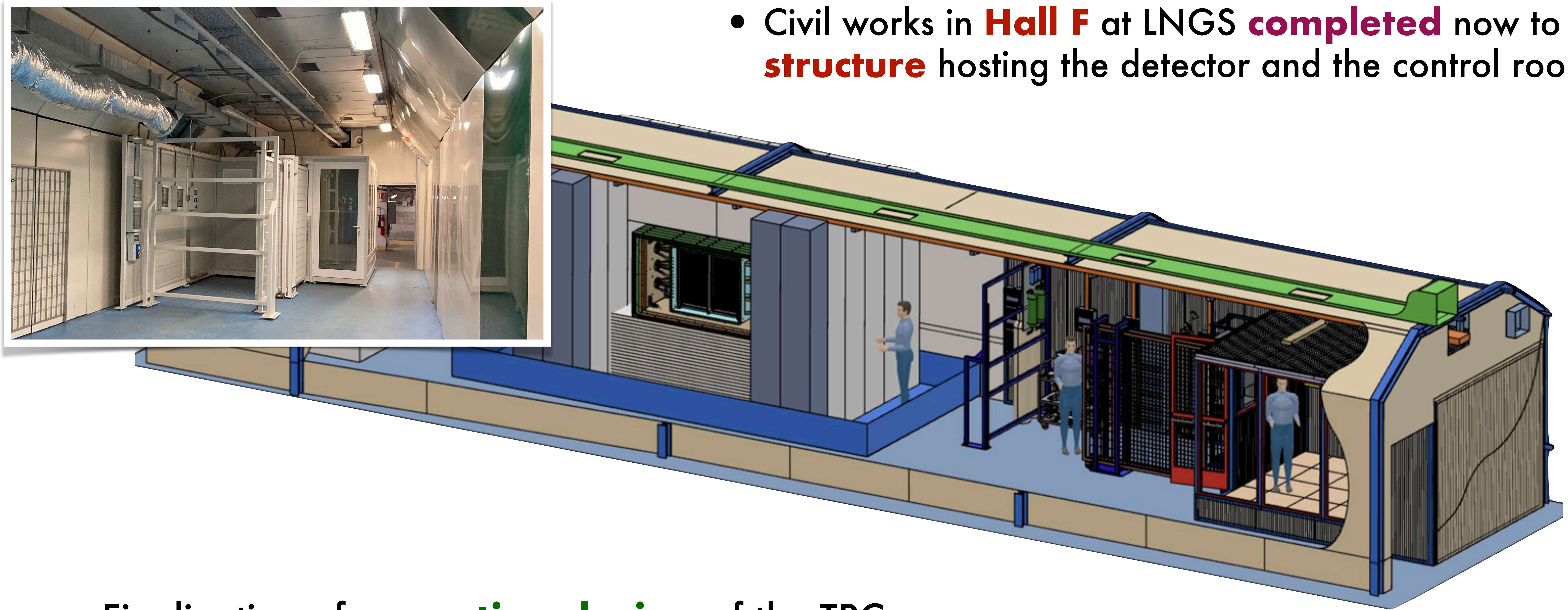


- **Design:**
  - ◉ TPC made of **2 chambers** with a **common cathode**.
  - ◉ Closed by 2 sets of **50 cm x 80 cm triple GEMs**
  - ◉ **Readout** of each GEM side: 3 cameras with rectangular sensors (ORCA Quest) + 8 PMTs
  - ◉ **Vessel:** low radioactivity PMMA
  - ◉ **Shielding:** 10 cm copper + 100 cm water with a polyethylene base

Purpose of CYGNO-04:

- Feasibility large scale detector (radiopure materials, gas purification)
- Demonstrate scalability of the technology

Status of the commissioning



- Civil works in **Hall F** at LNGS **completed** now to **build the structure** hosting the detector and the control room

- Finalization of **executive design** of the TPC
- We plan to be able to **assemble the detector** in place by the beginning of 2026

Eco-friendly RPCs for future HEP applications: an insight into signal shape and rate studies

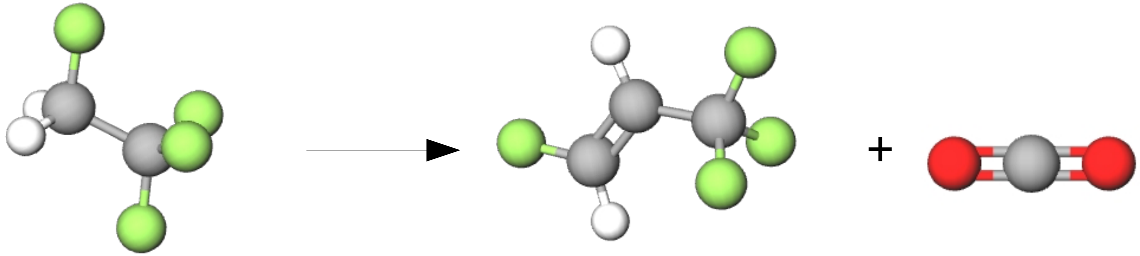
Luca Quaglia[1] *on behalf of the RPC EcoGas@GIF++* collaboration

[1]INFN Torino

RPCs in HEP and their gas mixture

- **Resistive Plate Chambers** (RPCs)
  - Gaseous particle detectors with fast response + low-cost per unit area = ideal detectors for **muon triggering** and **identification** at LHC and future experiments

- Currently employed gas mixture in HEP: > 90% $\mathbf{C_2H_2F_4}$ + i-C_4H_{10} (5-10%) + SF_6 (< 1%)
  - $C_2H_2F_4$ and SF_6 are fluorinated greenhouse gases (F-gases) with a high GWP and are being phased out by the EU
    → Need to find an alternative RPC gas mixture in view of the future (HL-LHC and possibly FCC)
    → Possible solution explored: replace $C_2H_2F_4$ with $C_3H_2F_4$ (HFO) + CO_2



GWP ($C_2H_2F_4$) ~ 1430 GWP (**HFO**-1234ze) ~ 6 GWP (CO_2) = 1

The RPC EcoGas@GIF++ collaboration

- Cross-experiment collaboration

  → It includes **CMS, <u>ALICE</u>, ATLAS, ShiP/LHCb** and the **EP-DT** group of CERN

- Focus the effort for eco-friendly gas mixture studies

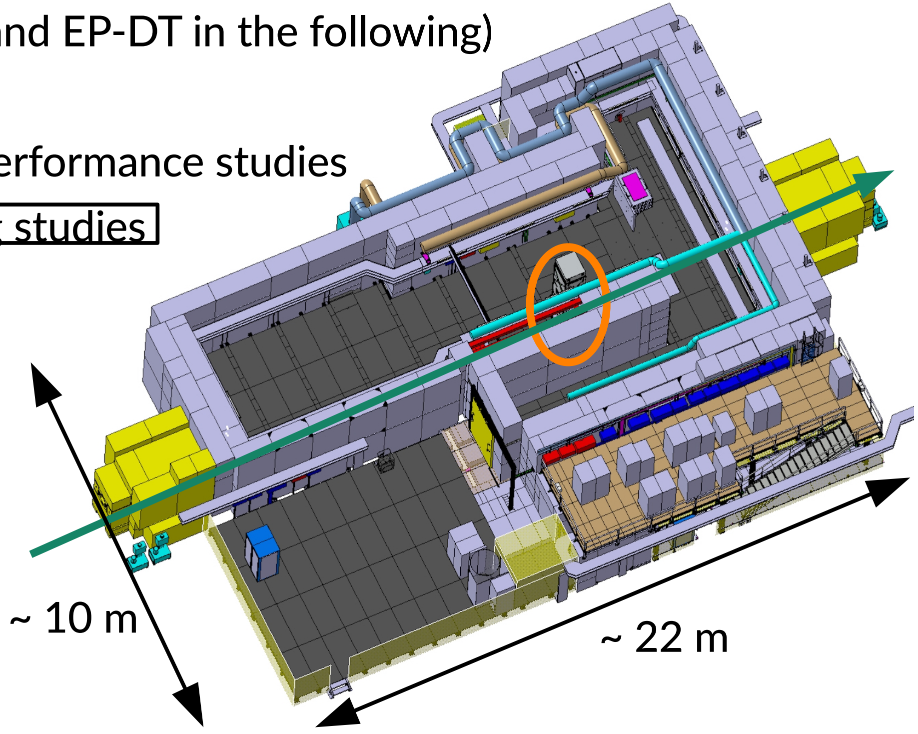
  → One RPC prototype per group (only results from ALICE and EP-DT in the following)

  → Experimental setup loacted @ GIF++ (CERN):

  1) High activitiy ^{137}Cs source for aging tests + μ beam for performance studies

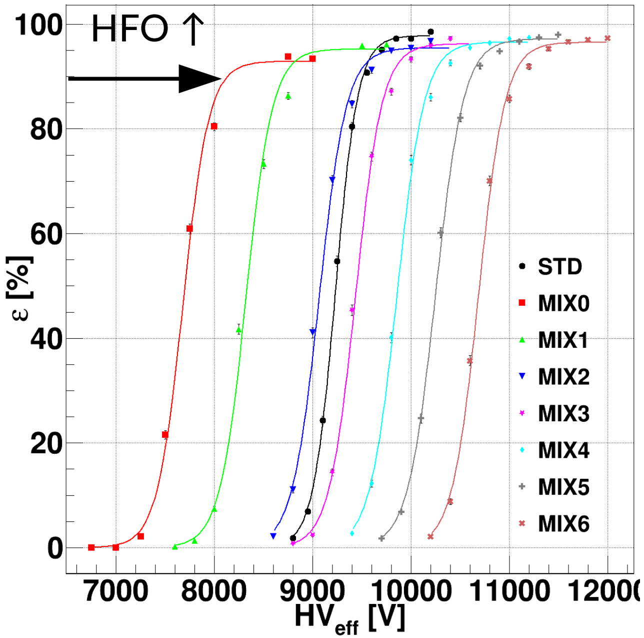
  2) Several mixtures beam-tested and one selected for aging studies

Mixture	$C_2H_2F_4$ %	HFO %	CO_2 %	i-C_4H_{10} %	SF_6 %	GWP
STD	95.2	0	0	4.5	0.3	1488
MIX0	0	0	95	4	1	730
MIX1	0	10	85	4	1	640
MIX2	0	20	75	4	1	560
MIX3	0	25	69	5	1	529
MIX4	0	30	65	4	1	503
MIX5	0	35	60	4	1	482
MIX6	0	40	55	4	1	457



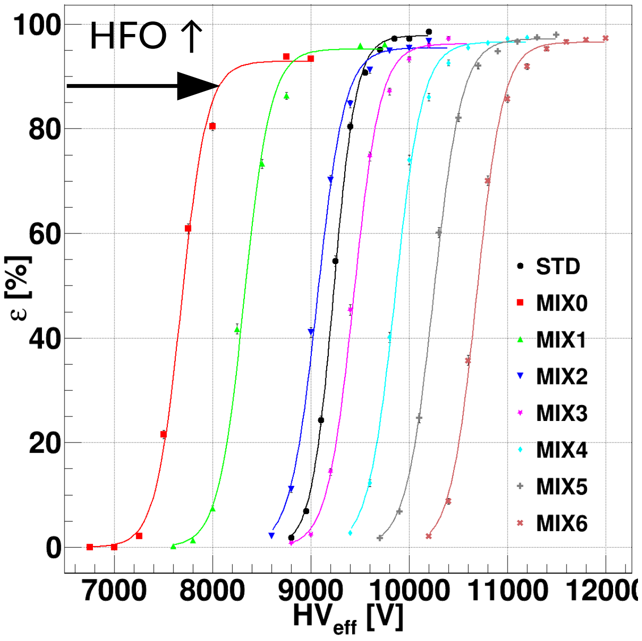
GIF++ facility layout

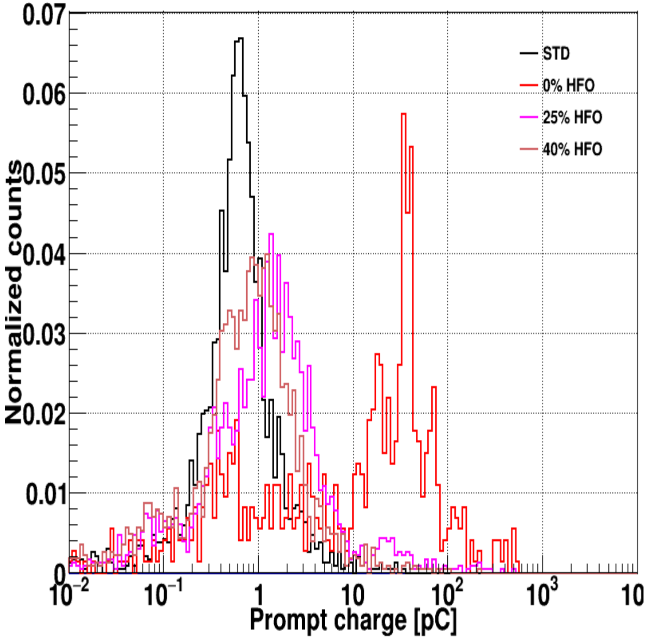
Baseline performance



- Efficiency curves fitted with logistic function to extract
  Working Point (WP) = knee (voltage where efficiency is 95% of its maximum) + 150 V
- Increasing value of **maximum efficiency as the HFO concentration increases** (denser mixture)
- Increase of **WP by ~1 kV for every 10% HFO added to the mixture**

Baseline performance

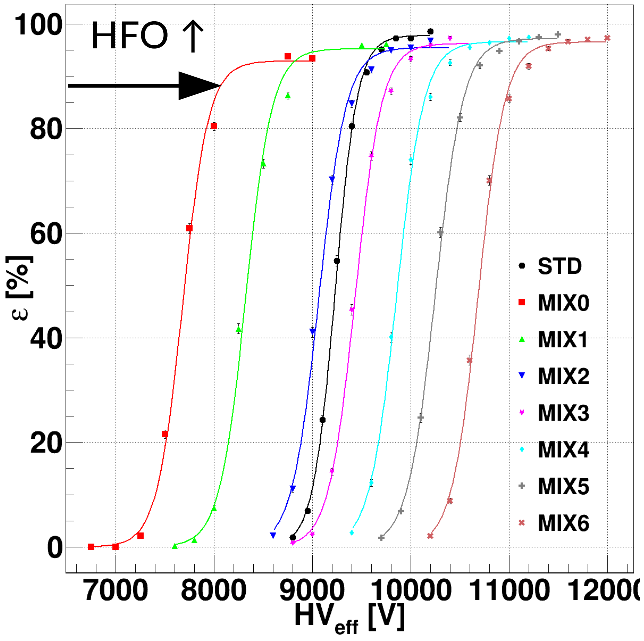


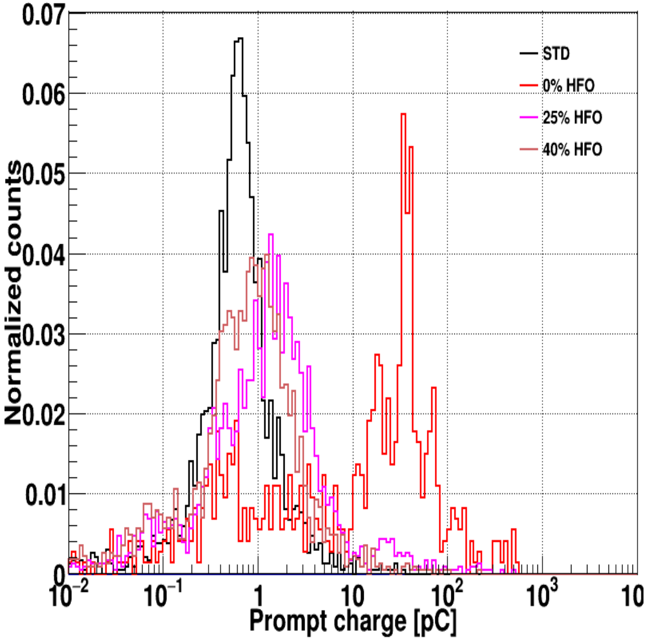


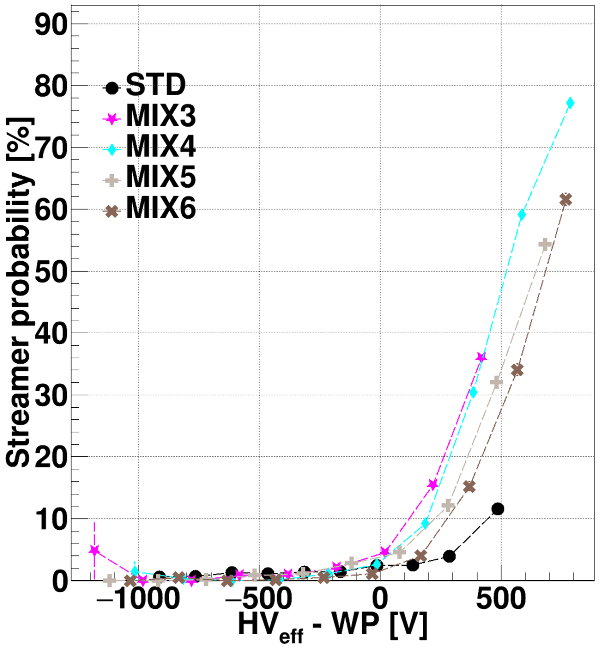
- For HFO-based mixtures, **small signal (avalanche) peak shifted towards higher values** wrt STD
  → Higher absorbed current

- **Large-signals peak generally more populated** than with STD
  → # of streamers decreases as CO_2 concentration decreases (**quenching** effect of more HFO)

Baseline performance







- Large-signal contamination at WP **improves with increasing HFO content**
- At **WP values are similar** to STD
- **Steeper rise** of the curve for voltages above the WP wrt STD

Performance evolution during aging

- **Aging test** ongoing since July 2022 (RPCs powered ON and exposed to ɣ's from the ^{137}Cs source)

- Periodic beam-test campaigns to monitor performance evolution. Example from a 2 mm single gap RPC after integrating ~115 mC/cm^2

Performance evolution during aging

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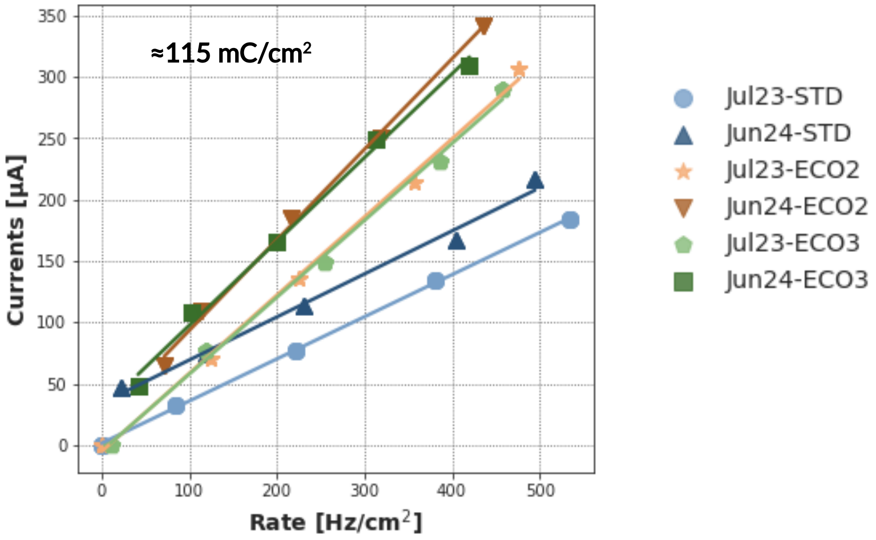
- **Currents under irradiation** slightly higher in 2024 wrt 2023
  → Visible for all mixtures
  → Ohmic current increase potentially related to electrode degradation



EP-DT RPC source on current vs rate at WP.
Comparison between 2023 and 2024 TB

Performance evolution during aging

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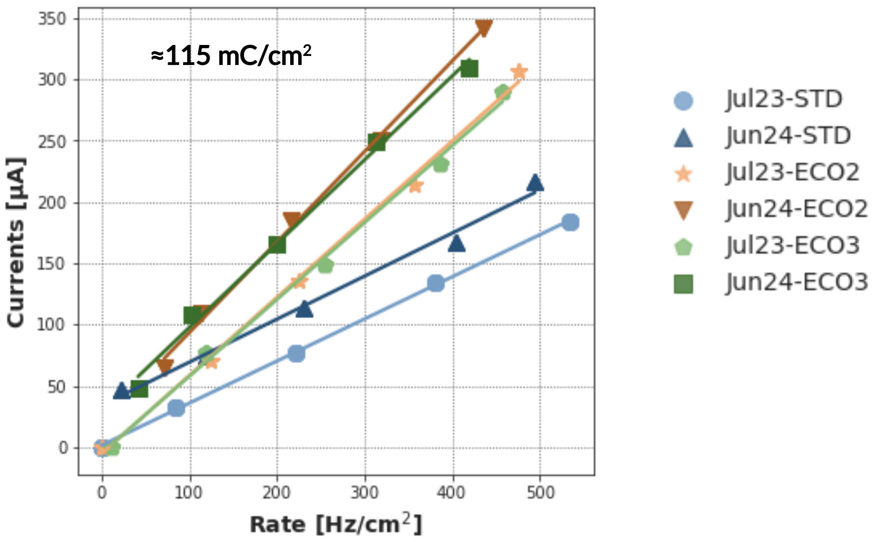
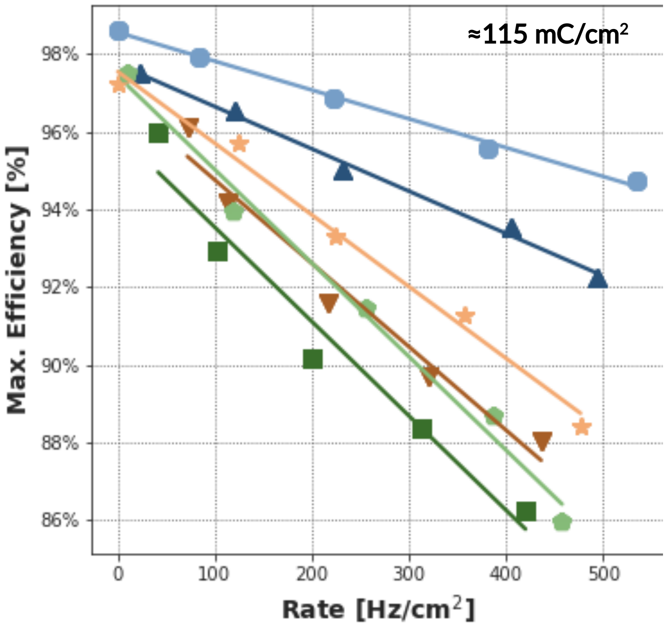
- Periodic beam-test campaigns to monitor performance evolution. Example from a 2 mm single gap RPC after integrating ~115 mC/cm^2
- **Maximum efficiency under irradiation** for same background reduced in 2024 vs 2023 for all mixtures
  - ~2% for all mixtures



EP-DT RPC source on current vs rate at WP.
Comparison between 2023 and 2024 TB



EP-DT RPC maximum efficiency vs background rate.
Comparison between 2023 and 2024

No significant performance degradation observed so far

Aging studies are still ongoing and results from all detectors are being analyzed and compared for similar aging conditions

Foreseen to start studying also alternative gases to SF_6 + chemical anlyses of aged detectors

Paper summarizing the main results is in the pipeline

Thanks for your attention!!!