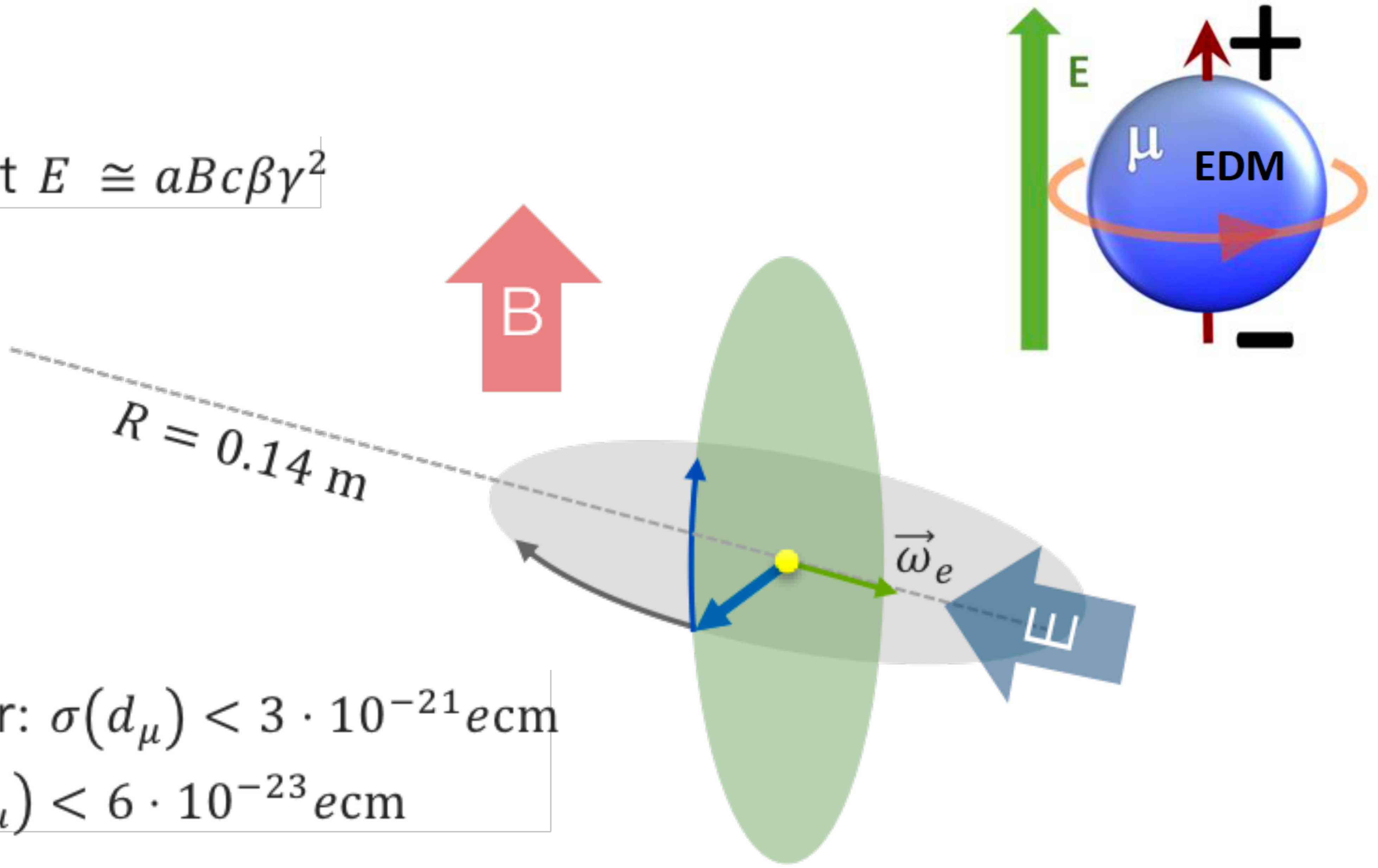
The muEDM experiment at PSI: Report 2023-4 and requests 2025

Angela Papa
Referee meeting, Sept 3rd/2024
CSN1

set $E \cong aBc\beta\gamma^2$



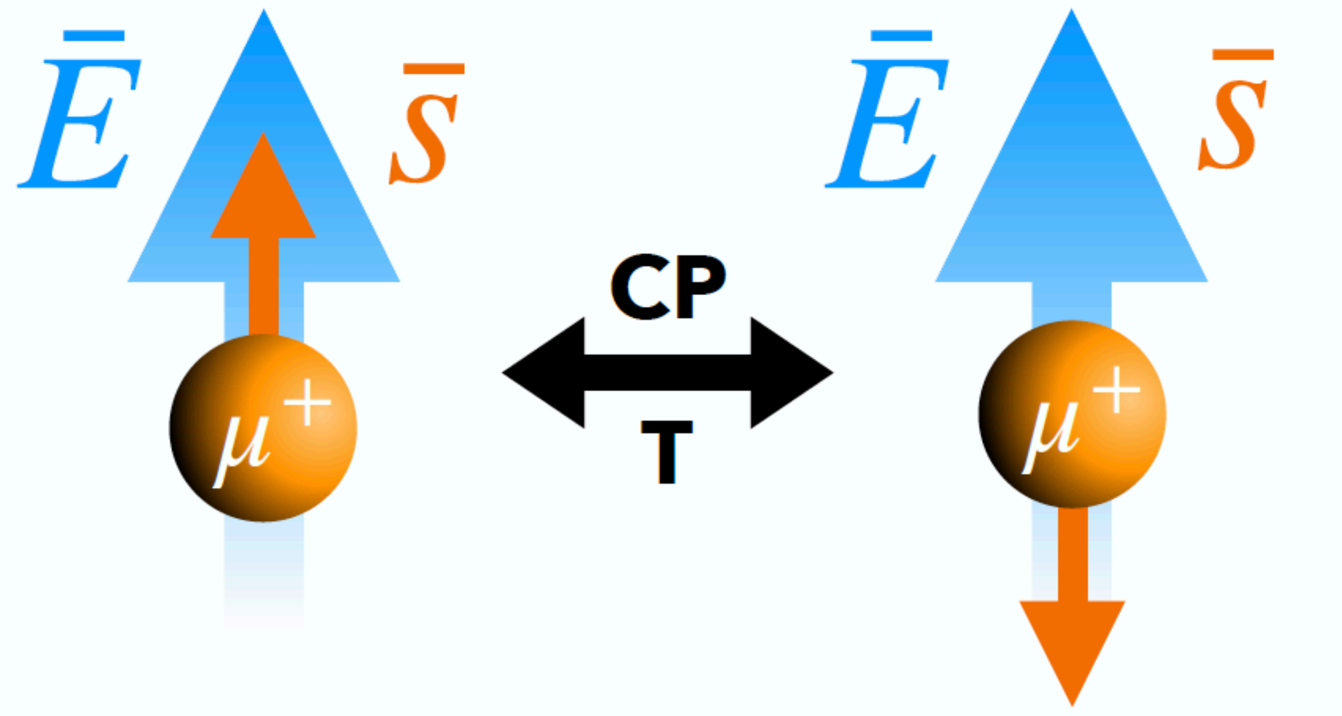
Prescursor: $\sigma(d_\mu) < 3 \cdot 10^{-21} ecm$

Final: $\sigma(d_\mu) < 6 \cdot 10^{-23} ecm$

muEDM dedicated search: Current status and Motivations

- EDMs of fundamental particles are intimately connected to the **violation** of time invariance **T** and the combined symmetry of charge and parity **CP**
- The different EDM searches are sensitive to **different**, **specific** combinations of underlying **CPV sources**
- **Muon unique** feature: the only currently direct accessible EDM of a **naked** fundamental particle and **second** family fermions

A permanent EDM requires T violation, equivalently CP violation by the CPT Theorem.

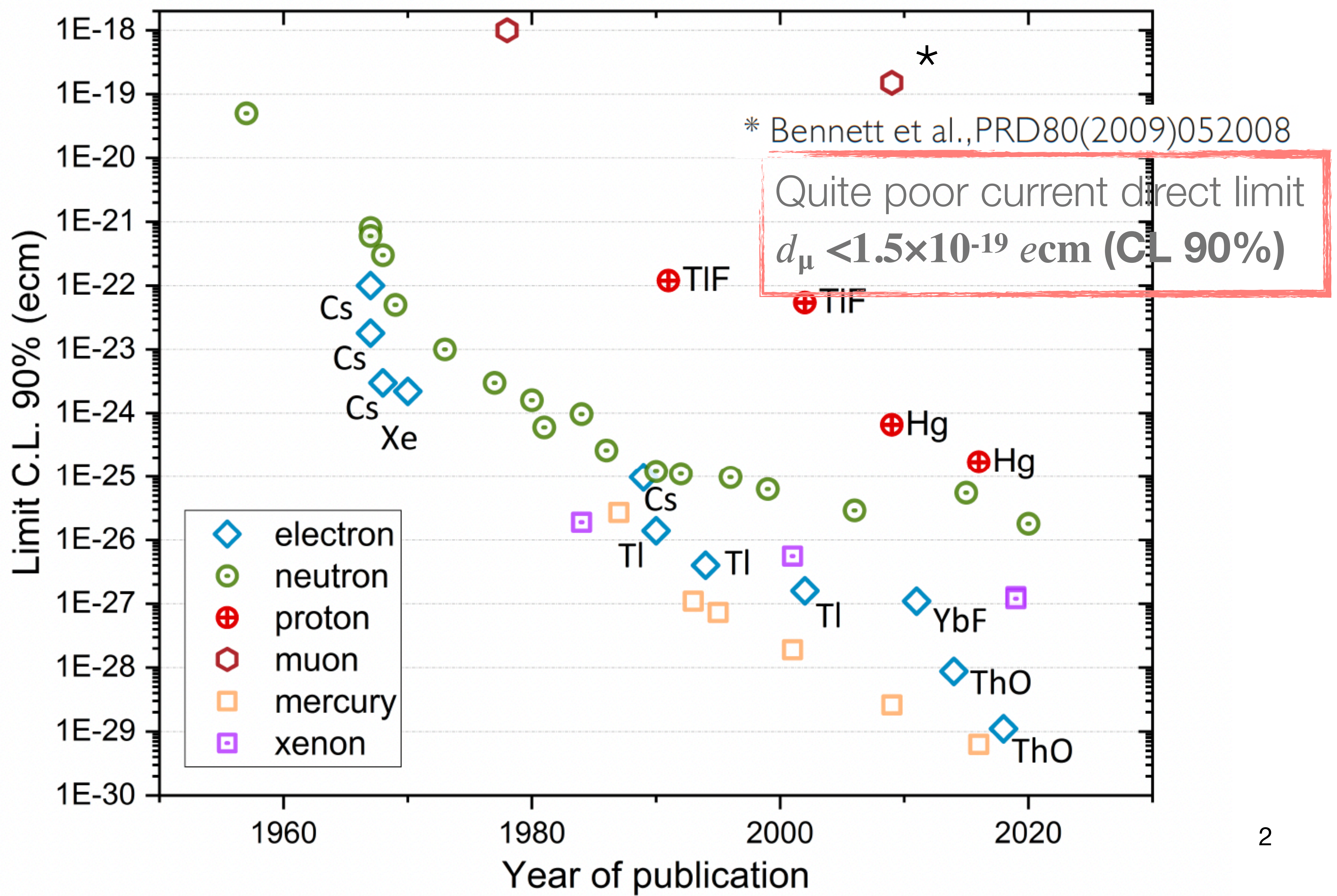


$$H_\mu^{EDM} \overset{\beta\to 0}{\propto} d_\mu \bar{\sigma}\cdot\bar{E}$$

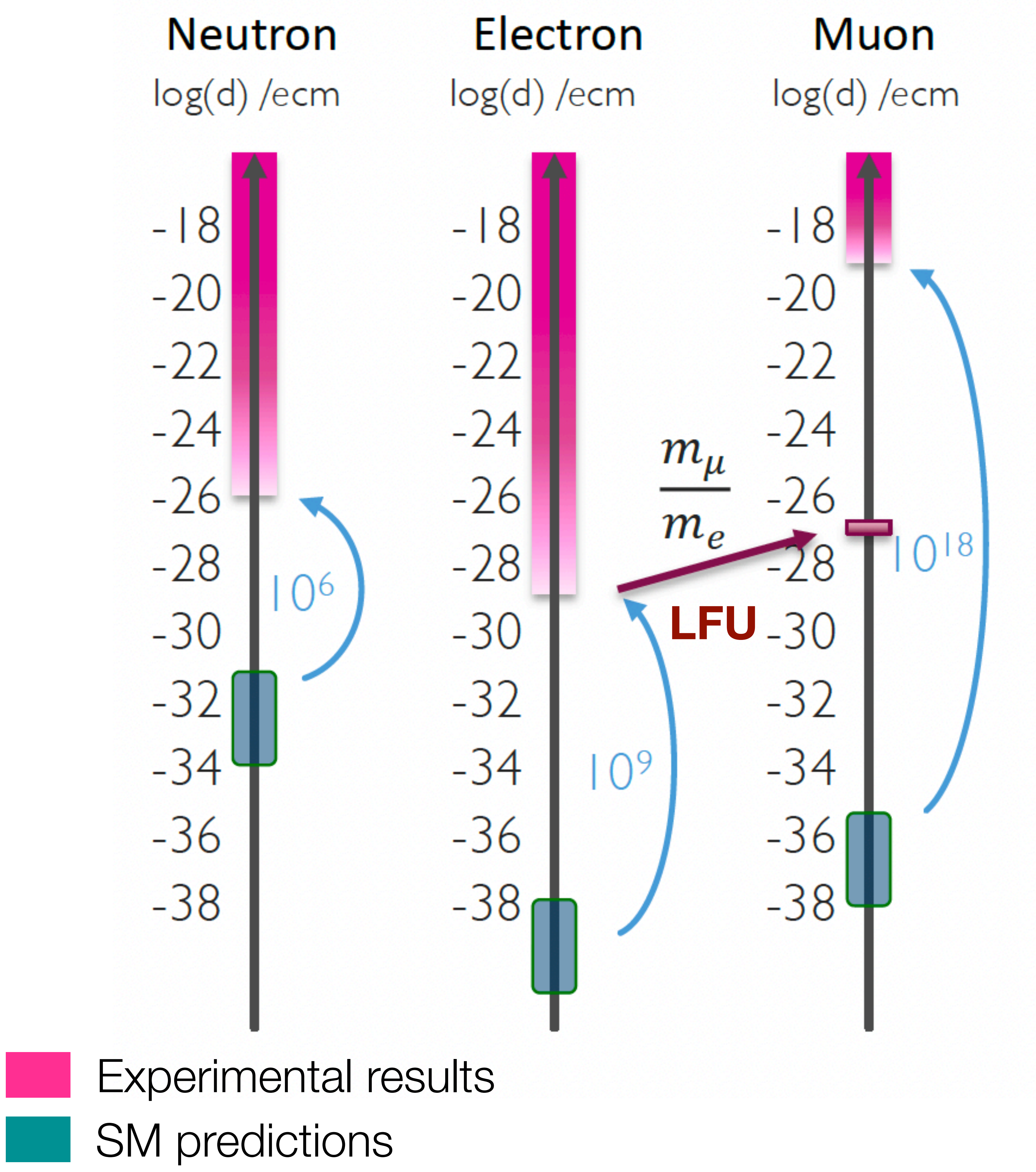
Hamiltonian EDM term is CP violating

SM Prediction: $d_\mu^{SM} = 1.4\times 10^{-38}\, e\,.\,\mathrm{cm}$ (Yamaguchi & Yamanaka, 2020)

$d_e \leq 1.1\times 10^{-29} e\,.\,\mathrm{cm} \overset{LFU}{\Longrightarrow} ? \; d_\mu \leq \frac{m_\mu}{m_e} d_e = 1.6\times 10^{-27} e\,.\,\mathrm{cm}$



muEDM direct search: Why now?



- FNAL/JPARC g-2 experiments aims at $d_\mu \sim O(10^{-21})$ *e*cm (via g-2)
- **Direct muEDM search at PSI in stages:**
  - **Precursors: $d_\mu < 3\times10^{-21}$ *e*cm**
  - **Final: $d_\mu < 6\times10^{-23}$ *e*cm**

Reminder: g-2 experimental approaches

In uniform magnetic field, muon spin rotates ahead of momentum due to g-2 = 0

$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)\right]$$

BNL E821 approach
γ=30 (P=3 GeV/c)

J-PARC approach
$E = 0$ at any γ

$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)\right]$$

$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B}\right)\right]$$

Continuation at **FNAL** with **0.1ppm** precision

Proposed at **J-PARC** with **0.1ppm** precision

The frozen-spin technique

$$\vec{\omega} = \frac{q}{m}\left[a\vec{B} - \left(a + \frac{1}{1-\gamma^2}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right] + \frac{q}{m}\frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)$$

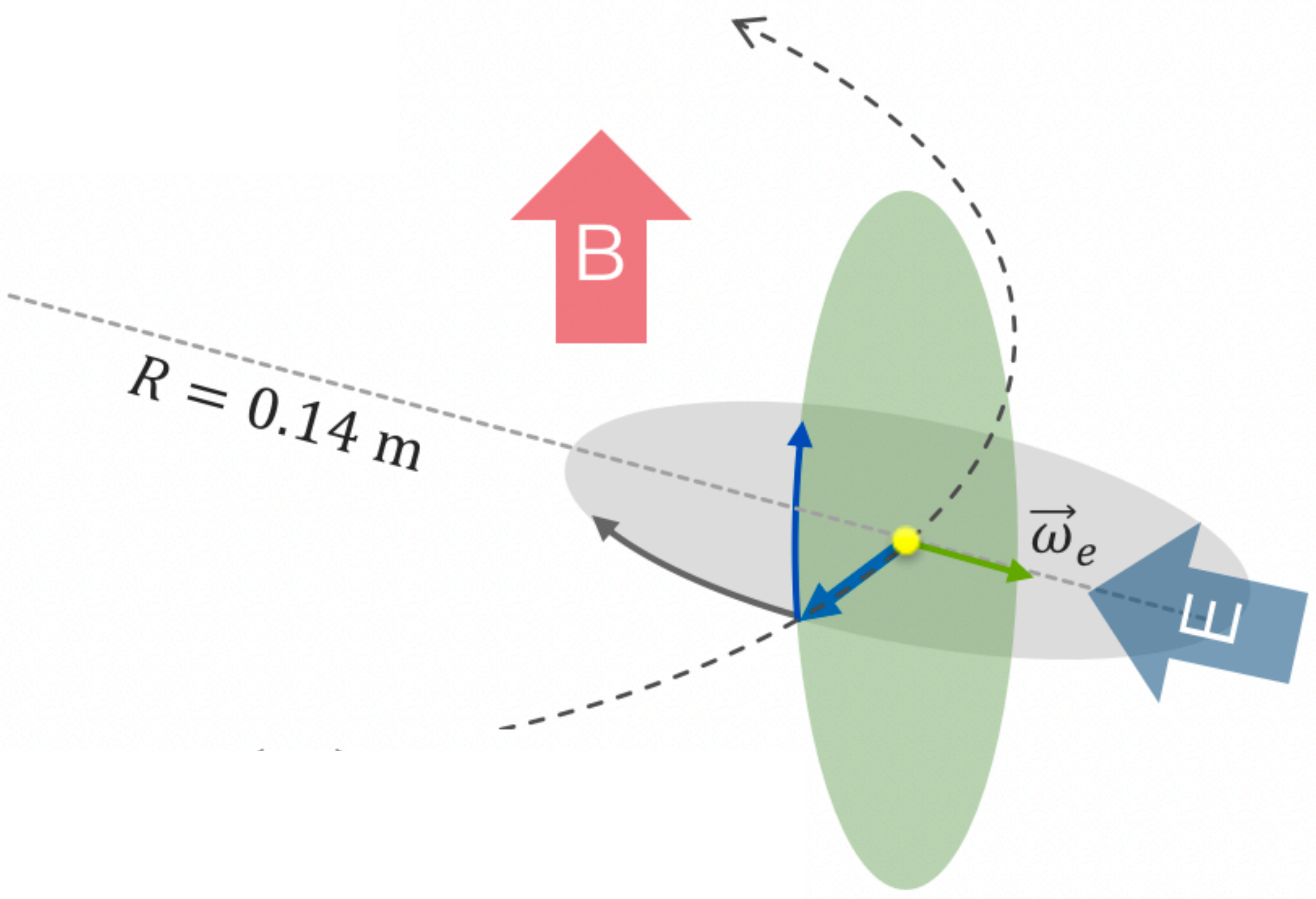
ω_a $\qquad\qquad$ ω_e

- The frozen-spin technique uses an Electric field perpendicular to the moving particle and magnetic field, fulfilling the condition:

$$a\vec{B} = \left(a - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}_f}{c}$$

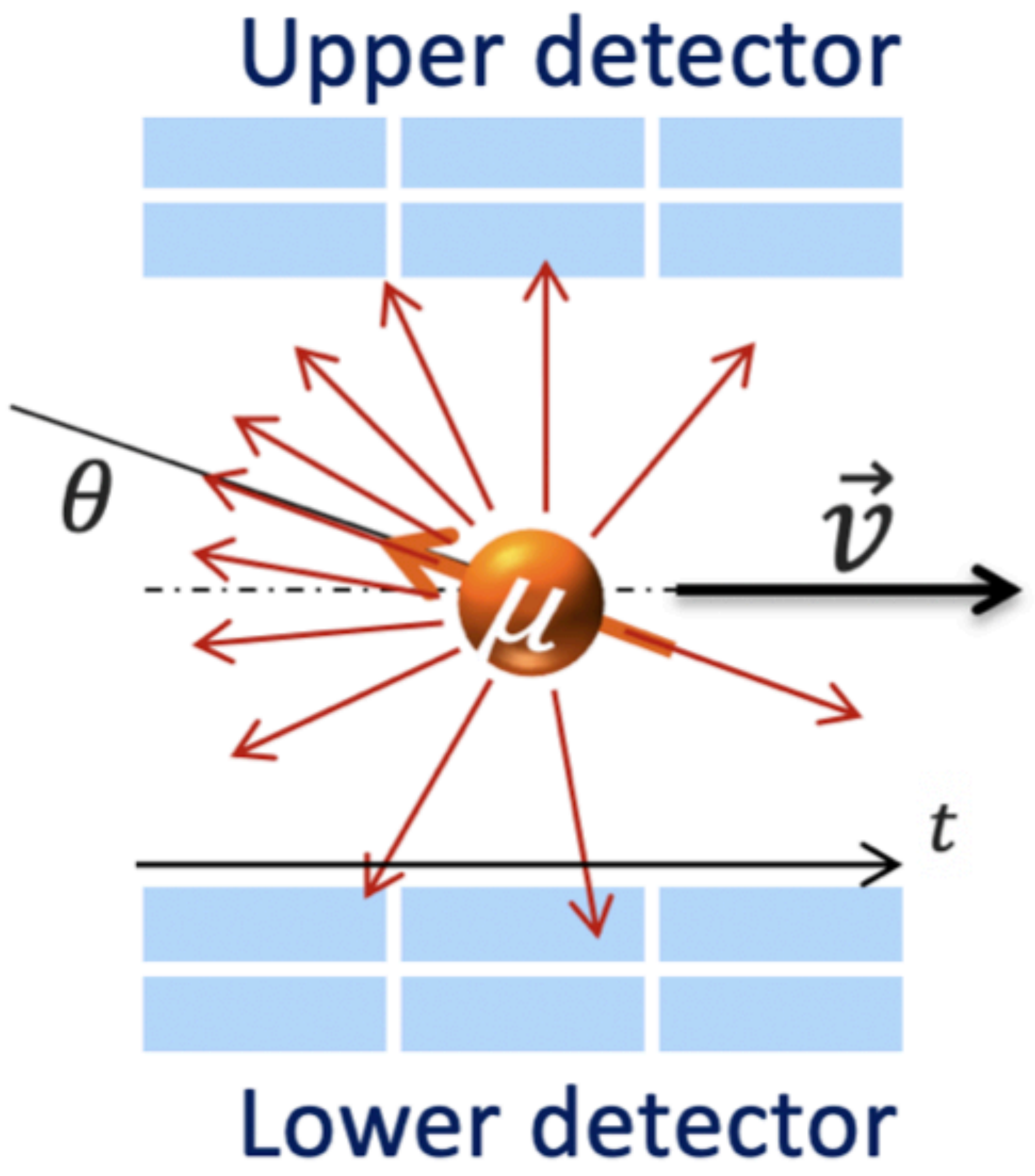
- Without EDM, $\omega = 0$, the spin follows the momentum vector as for an ideal Dirac spin-1/2 particle, while with an EDM it will result in a precession of the spin with $\omega_e \parallel E$

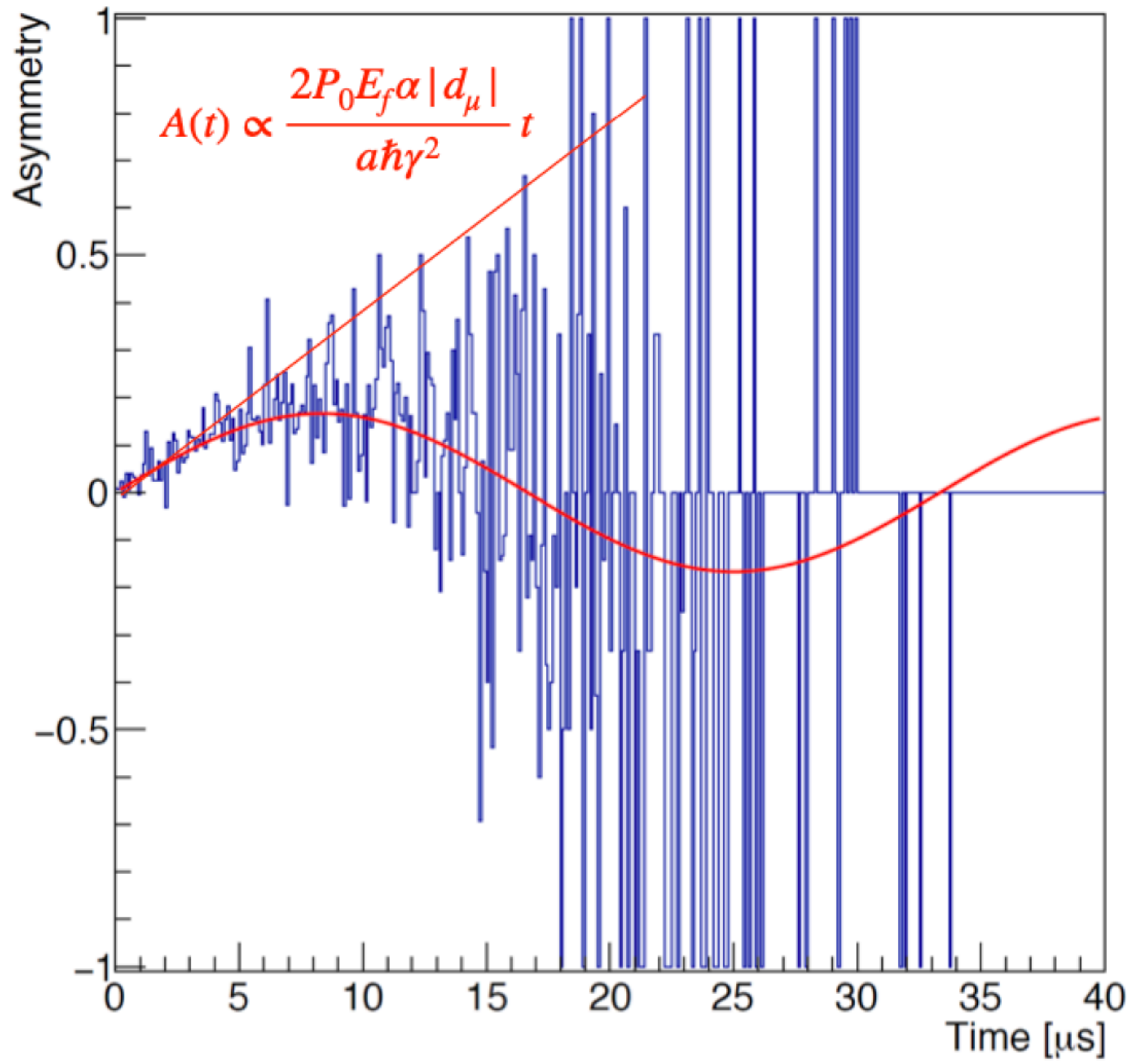
- The sensitivity to a muon EDM is given by the asymmetry up/down of the positron from the muon decay



Signal: asymmetry up/down positron tracks

- Positron are emitted predominantly along the muon spin direction
- The sensitivity to muon EDM is extracted from the **asymmetry up/down** of the **positron** from the muon decay, averaged over the muon decay time distribution (lifetime = $\gamma\tau_\mu$)





- P_0 = initial muon polarisation
- E_f = electric field in the lab frame
- N = number of observed decays
- τ_μ = muon lifetime
- $\boldsymbol{\alpha}$ = mean decay asymmetry (~ 0.3)
- a = anomalous magnetic moment
- γ = gamma factor of the muon

$$A(t) = \frac{N_\uparrow(t) - N_\downarrow(t)}{N_\uparrow(t) + N_\downarrow(t)} \propto \frac{2P_0E_f\alpha|d_\mu|}{a\hbar\gamma^2}t$$

$$\sigma(|d_\mu|) = \frac{d|d_\mu|}{d\bar{A}}\sigma(\bar{A}) \sim \frac{a\hbar\gamma}{2P_0E_f\sqrt{N}\tau_\mu\alpha}$$

Signal: asymmetry up/down positron tracks

- Positron are emitted predominantly along the muon spin direction
- The sensitivity to muon EDM is extracted from the **asymmetry up/down** of the **positron** from the muon decay, averaged over the muon decay time distribution (lifetime = $\gamma\tau_\mu$)

Final muEDM Experiment Sensitivity

μE1 Beamline Flux $2 \times 10^8 \mu^+/s$

Momenta $\gamma = 1.55$

Polarisation $P_0 \approx 0.95$

Av. Decay Asymmetry $A \approx 0.3$

Electric Field $E_f = 2\,\mathrm{MV/m}$

$$\sigma(d_\mu) = \frac{a\hbar\gamma}{2P_0E_f\sqrt{N}\tau_\mu A}$$

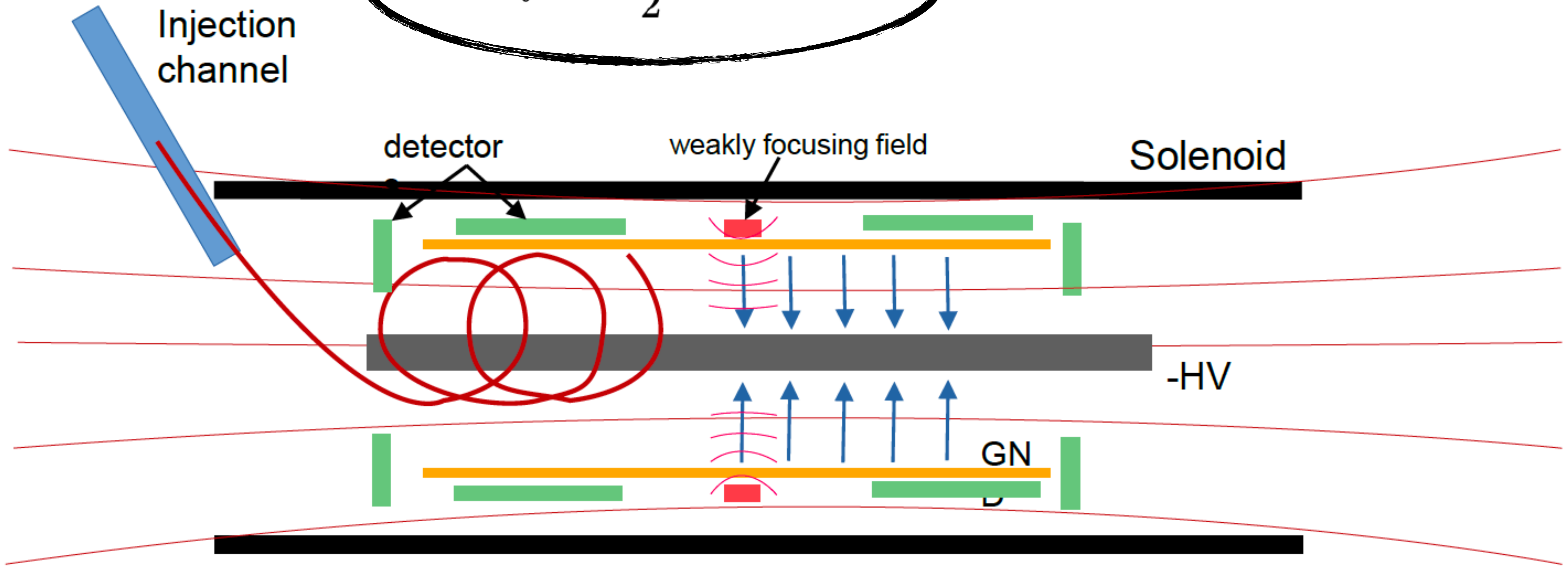
$$\sim 6 \times 10^{-23} e\,.\,\mathrm{cm}$$

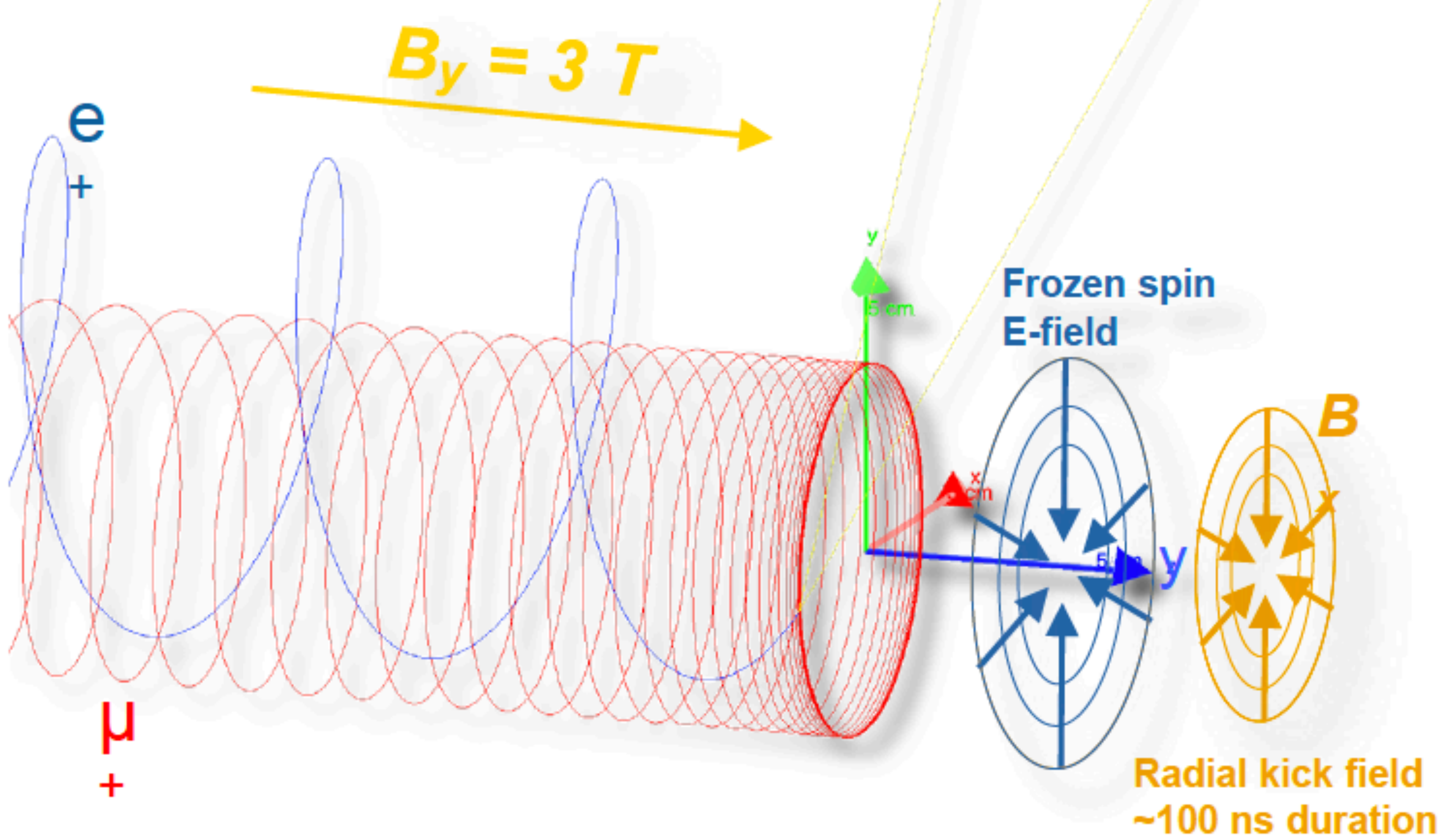
(with $N = 200$ days)

The general experimental idea

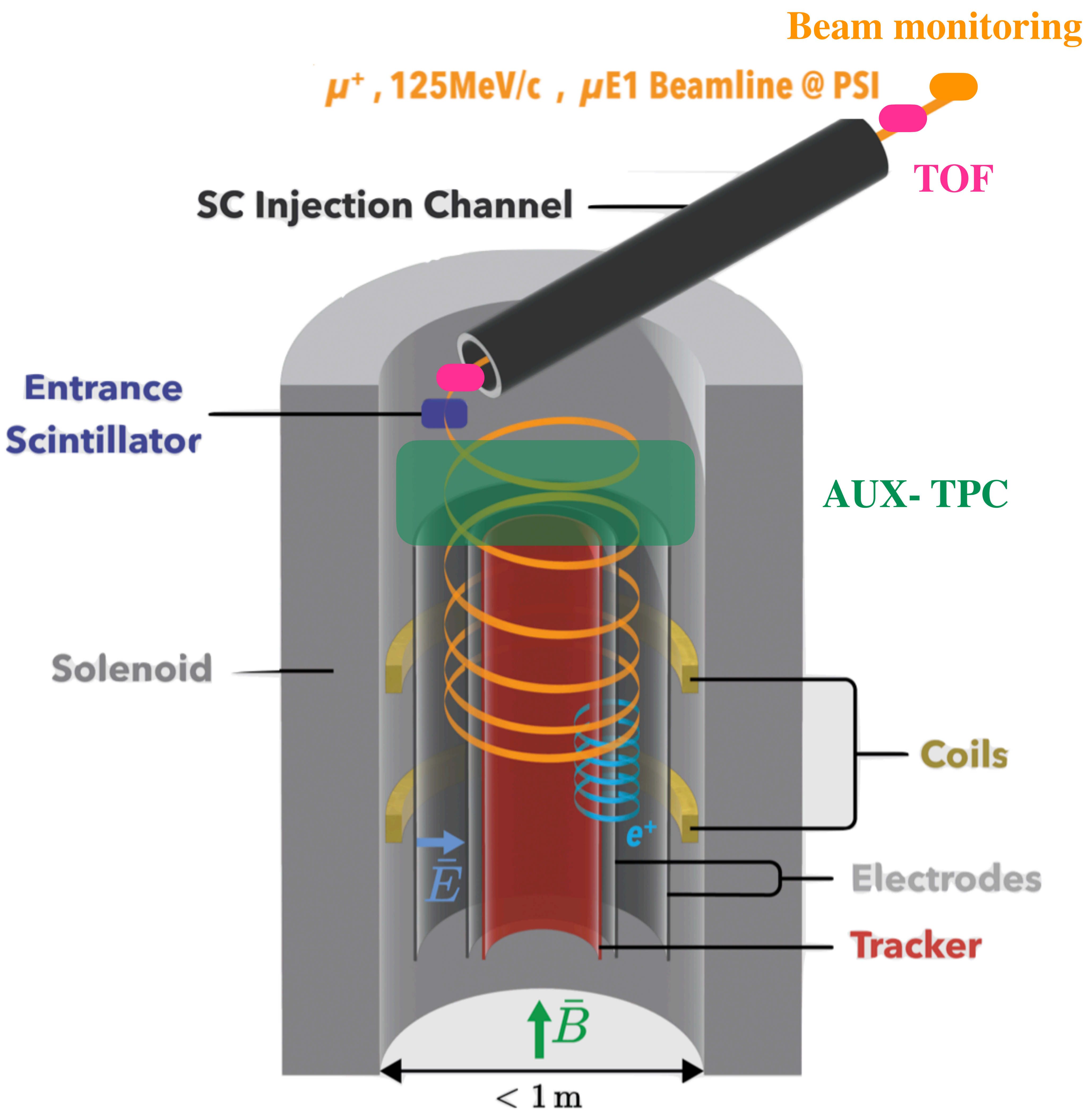
- Muons enter the **uniform magnetic** field region
- A **radial magnetic** field pulse stops them within a weakly focusing where they are **stored**
- **Radial electric** field **“freezes” the spin** so that the precession due to the magnetic dipole moment is cancelled

$$E_f \approx \frac{g-2}{2} Bc\beta\gamma^2$$





The muEDM: All items and INFN involvement

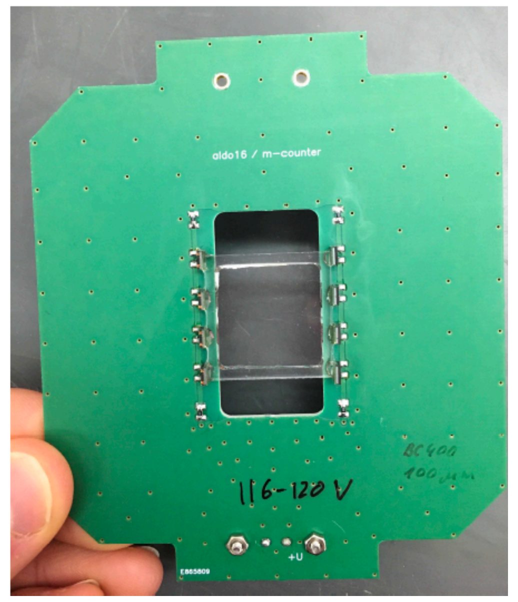


- Muons from pion-decays >> high polarisation p ~95%
- Injection through superconductor channels
- Muon beam detector
- **Time of Flight detector for the systematics**
- Entrance detector (**R&D**) for the kicker
- Magnetic kicker
- Thin electrodes for the frozen spin
- **Positron detector for the g-2 and muEDM signature**
- **AUX detectors** (i.e. **TPC** for the initial experimental settings)
- **TDAQ**
- MC/Analysis

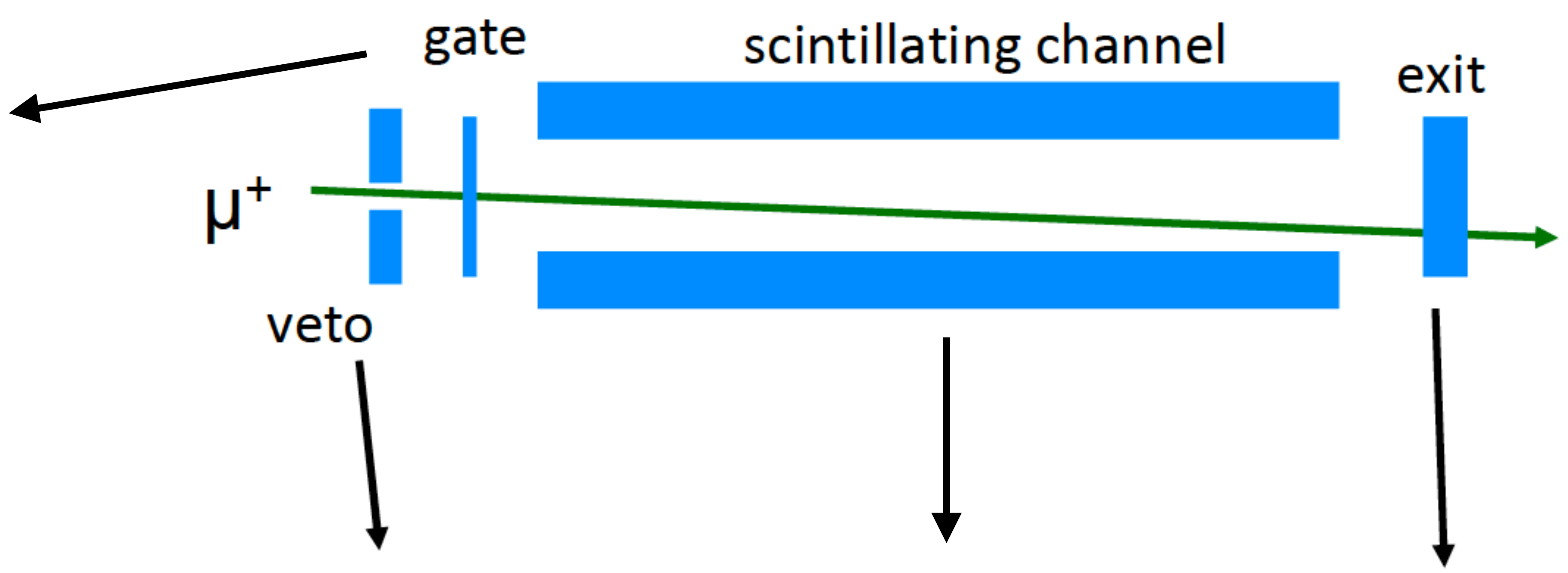
TOF/Entrance detectors v1.0

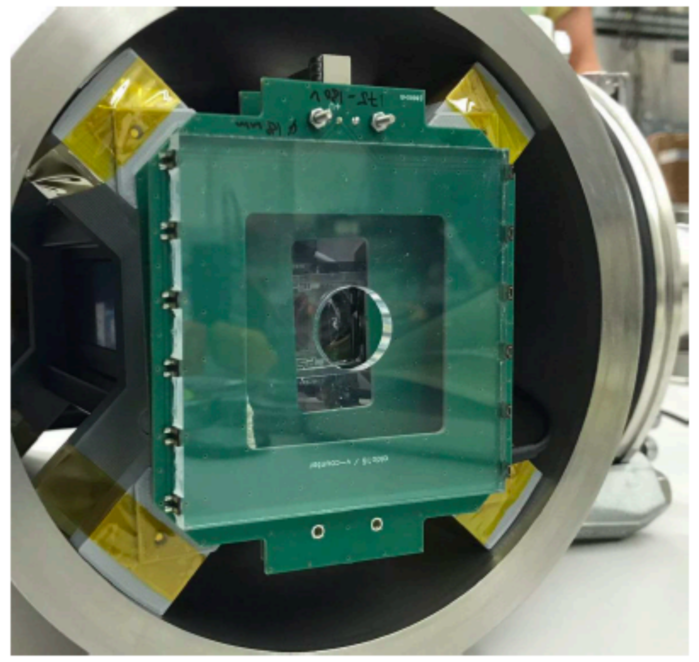
- A **very thin** (<100 um), to minimise the multiple scattering, and **full** efficient (>95%) to store all muons
  - Made of Plastic (BC400) detector coupled to MPPC
- to provide a **fast** trigger pulse for the magnetic kicker (Entrance detector combined with an active aperture veto)
- to keep under control systematic effects for the clockwise and counter clockwise muon injection via a time of flight (TOF) measurement

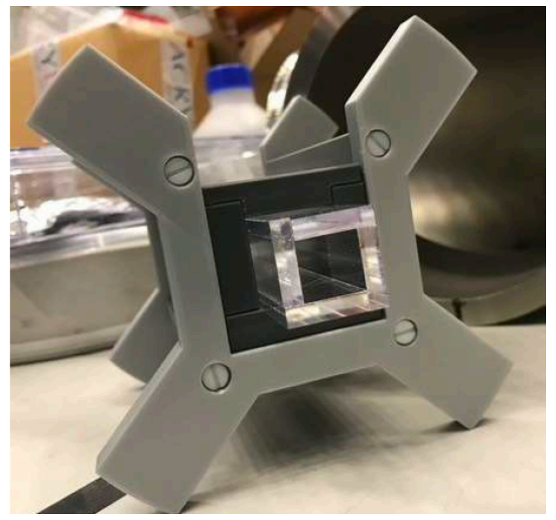
- Prototype: Thin plastic scintillators (10 x 10 x [0.50-0.15] mm3) with anti-coincidence channel - Plastic scintillator bars (5 x 20 x 200 mm3)

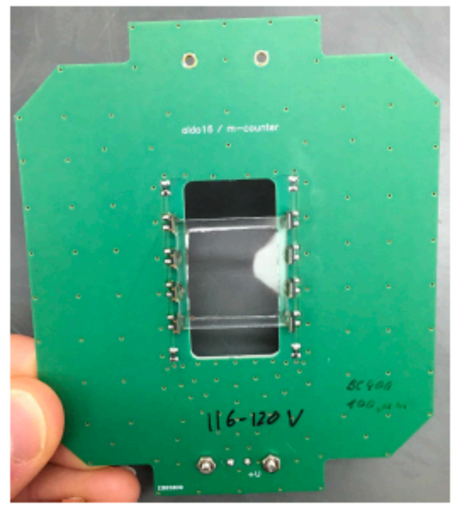


100 um BC-400

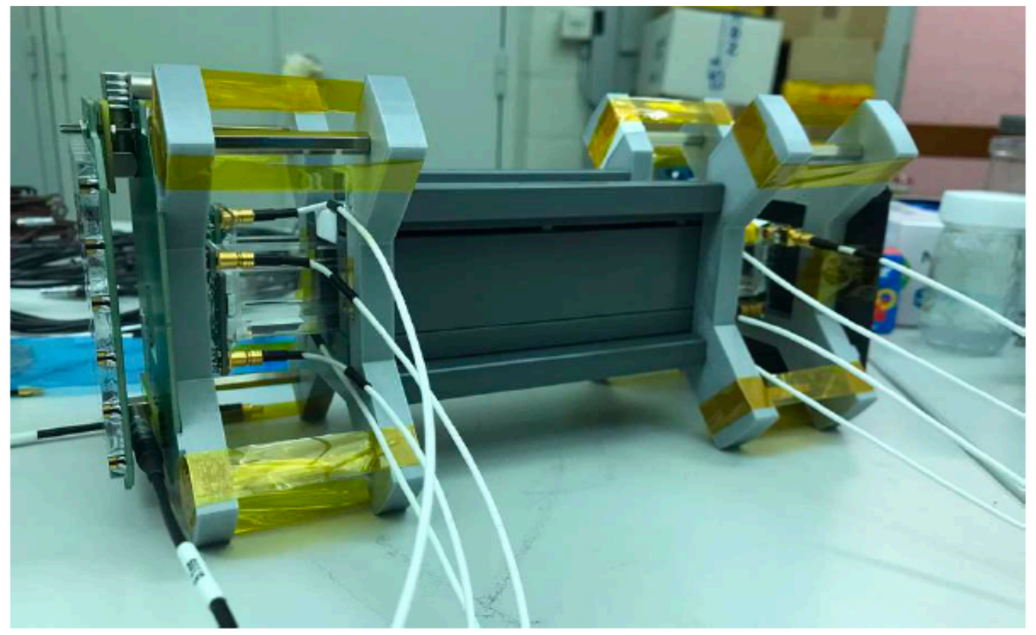






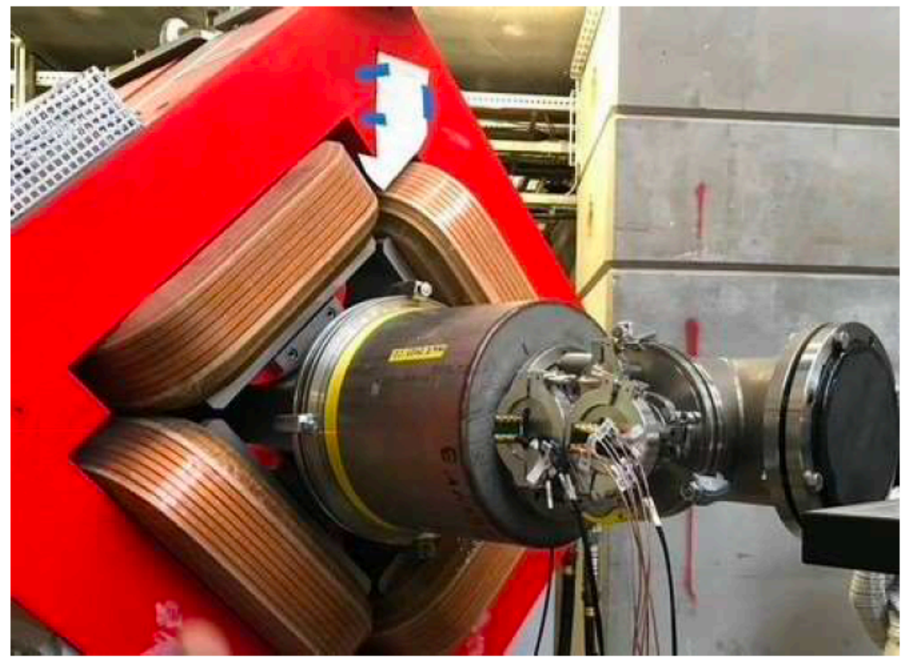


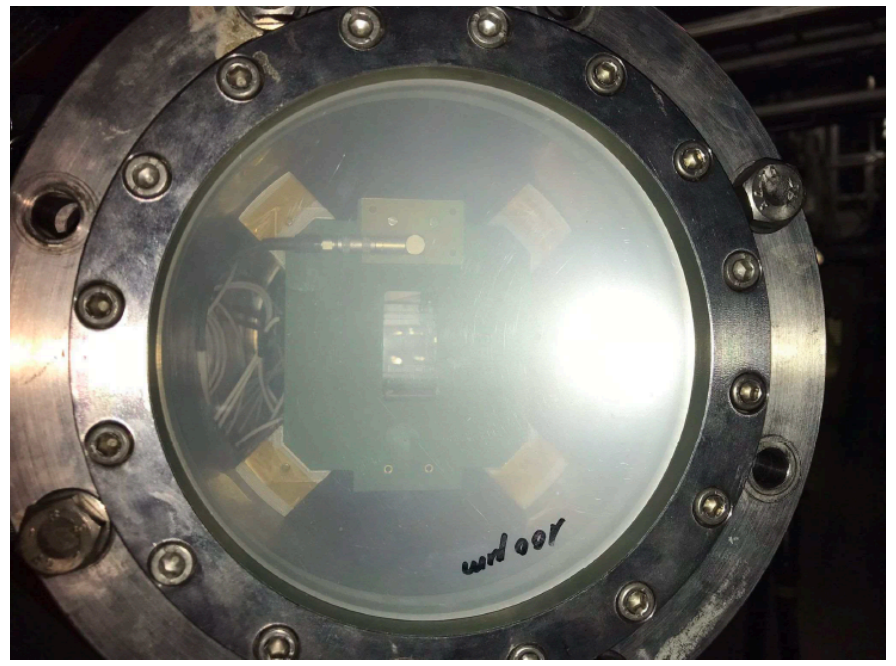
200 µm BC-400



Assembled telescope

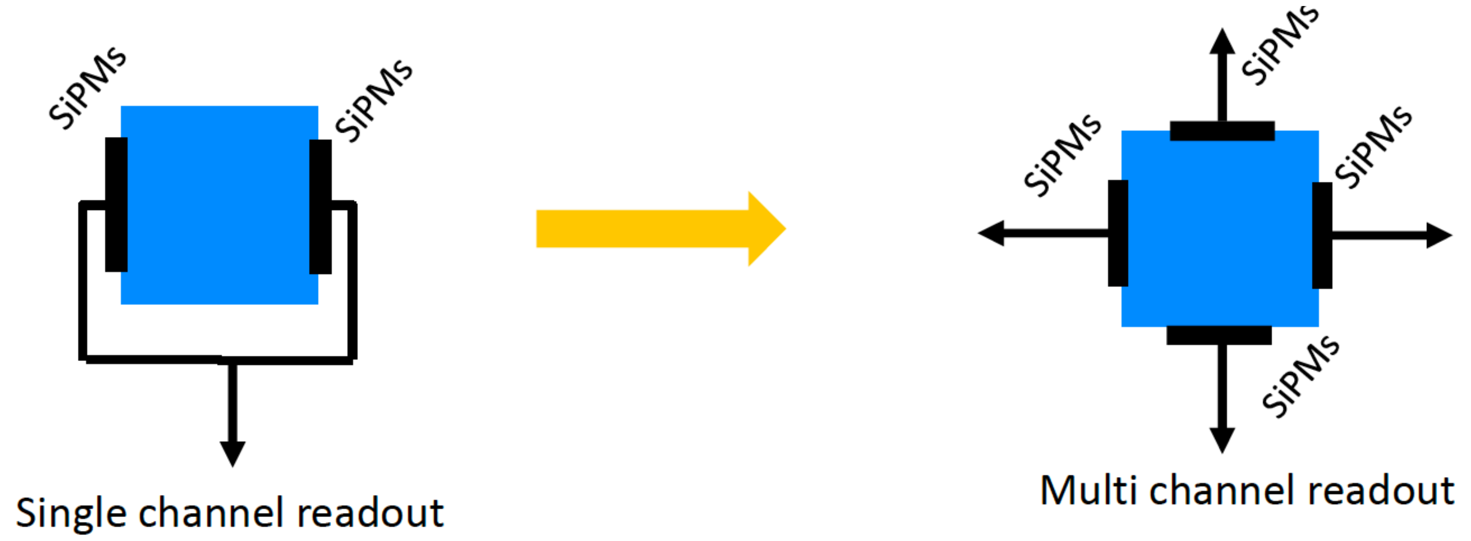
with 28 MeV/c muons

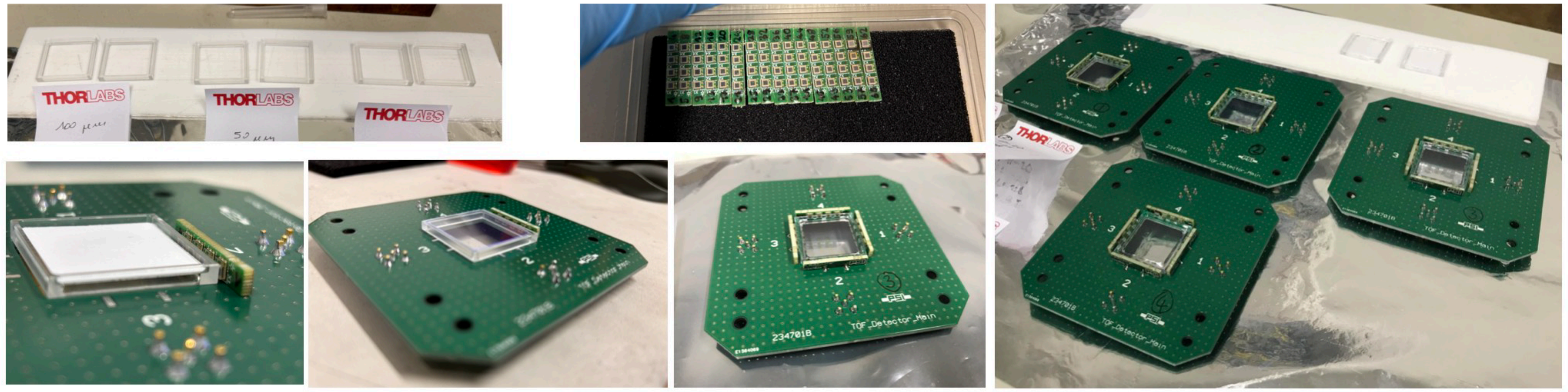




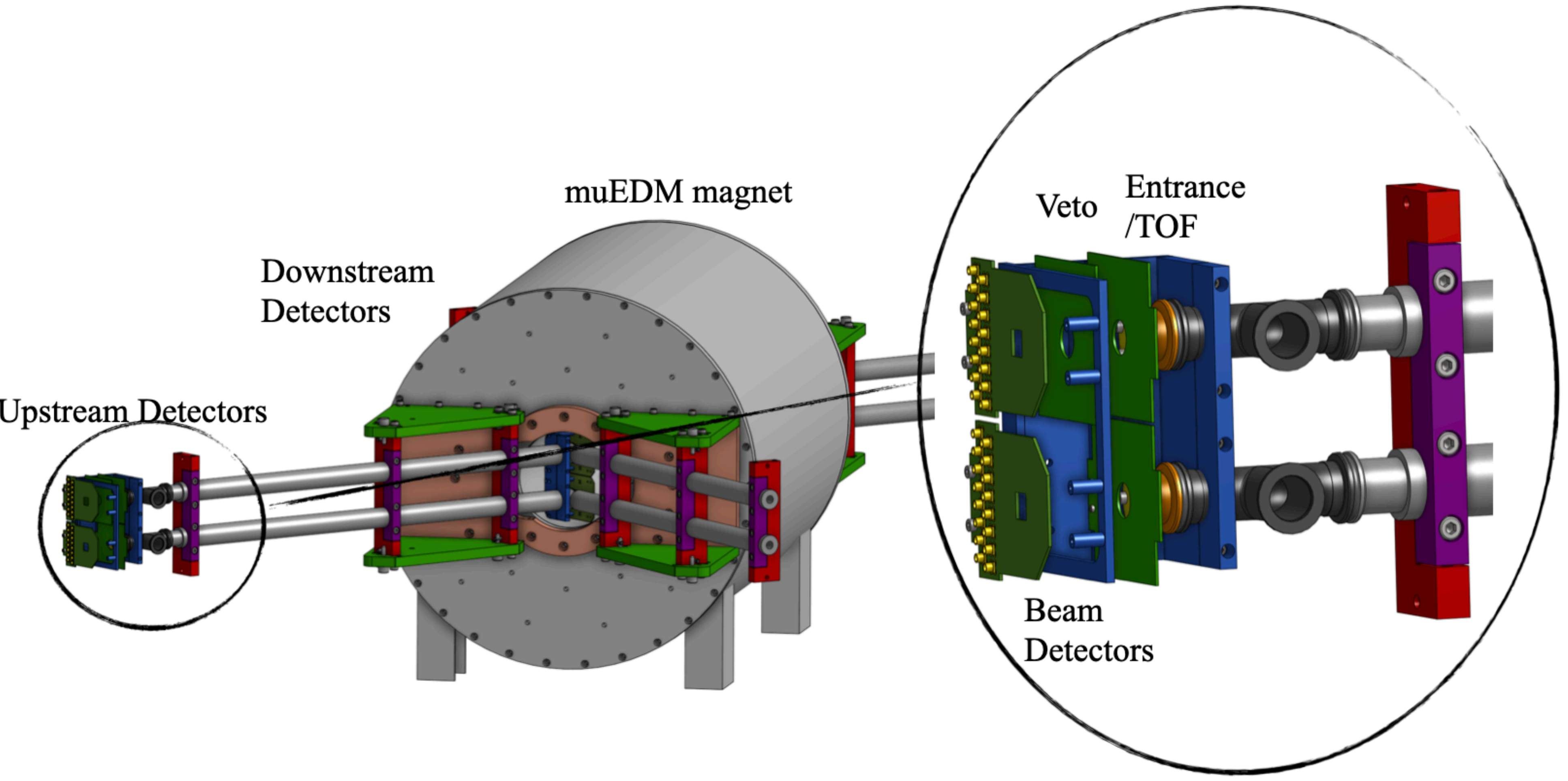
TOF/Entrance detectors v2.0

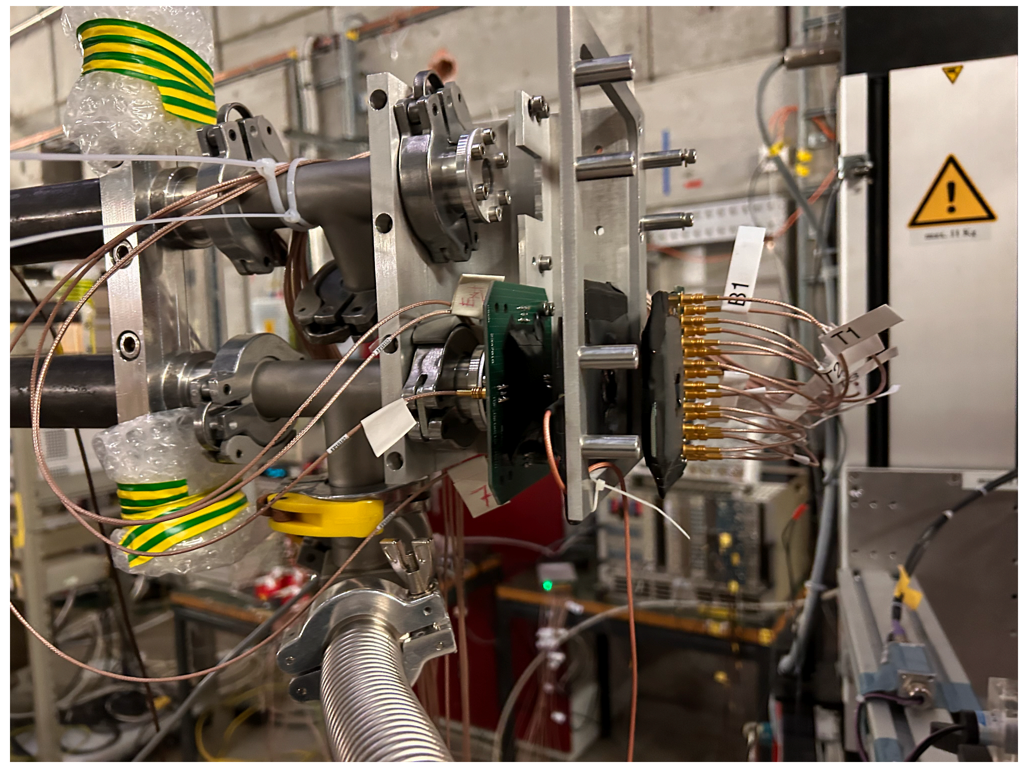
- Multi-channel independent readout
  - To face with small signal and high thermal noise contamination for a full detection efficiency, the signal being correlated pulses the second uncorrected ones
  - Detection efficiency > 98% (100 um) & 65% (50 um) requiring two fired channels (otherwise with one fired channel >99% and >87% respectively)
  - TOF/Entrance detector experiment requirements: **Addressed.** R&D: **Completed!**

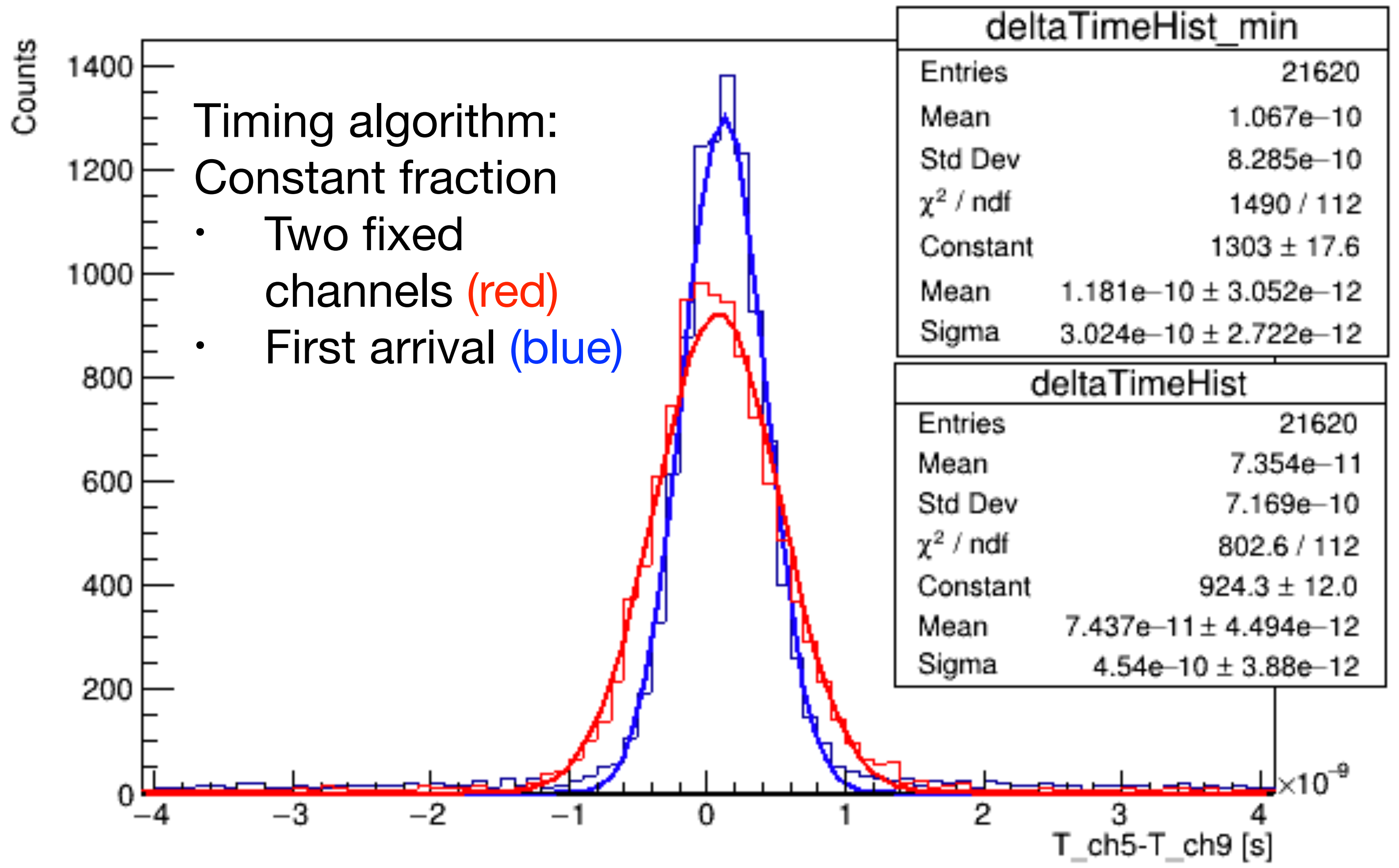




Measured “intrinsic” time resolution: **O(300) ps, as expected!**

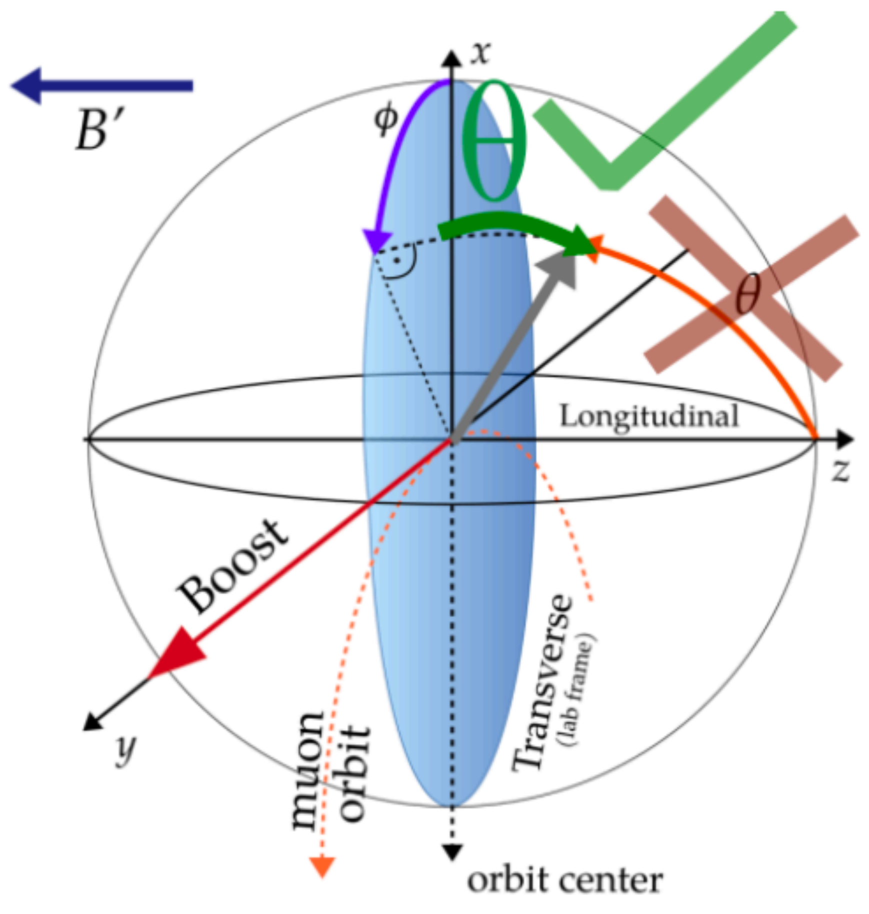


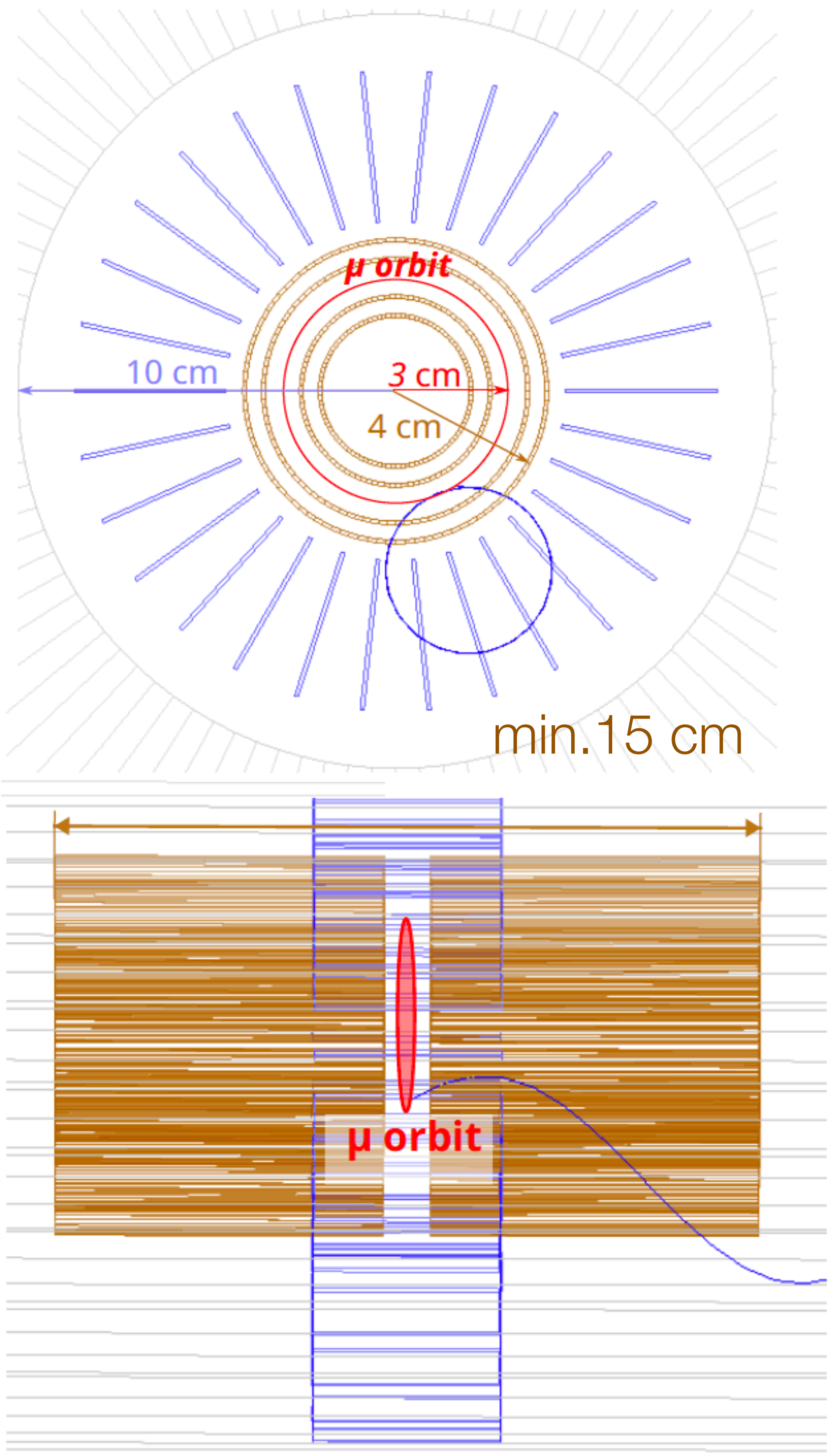




The positron tracker: CHeT

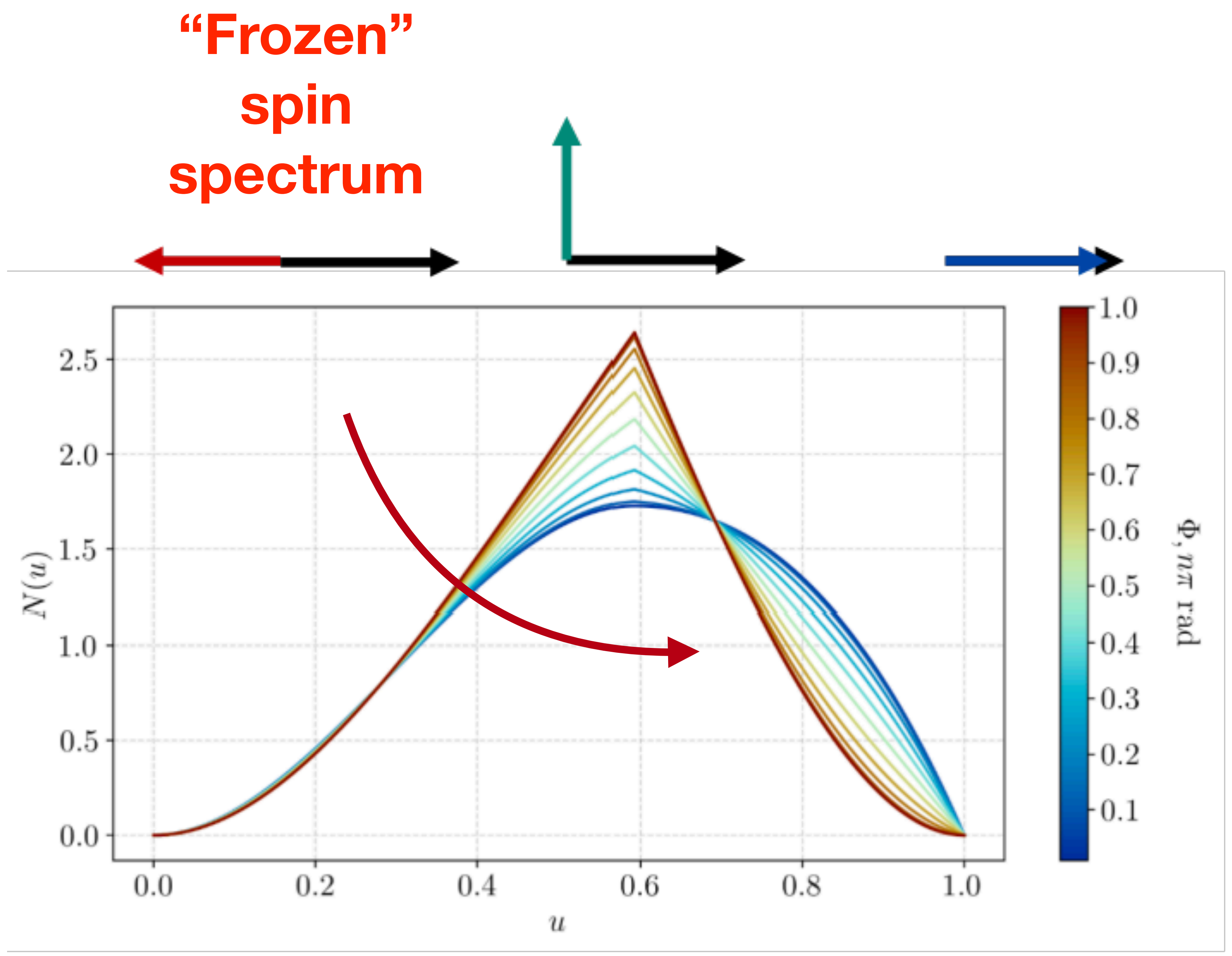
- Very thin (~ **0.1% X_0**) scintillating fibre detector coupled to MPPC for the **g-2** and **EDM** measurement
- Spatial Constraint: 5T magnet bore diameter = **20 cm**
- Detector requirements
  - Timing resolution **< 2 ns**, Position resolution: **O(1) mm**
  - Detection efficiency **O(50%)**
- Track parameters
  - g-2: Need to measure particles emitted with small theta
  - EDM: Need to measure particles emitted with theta ~pi/2
- Geometry
  - **Radial** detector: **30** Petals. Longitudinal-transverse fibres
  - **Cylindrical** detector: **4** Cylindres. Longitudinal-transverse/stereo fibres
- Technology
  - **500um/250um** fibres group in 2x/4x and coupled to **1.3 x 1.3 MPPC** (Hamamatsu S13360-50PE)
  - Readout: **CAEN FERS**
  - Number of channels: **2000 (double readout scheme)**

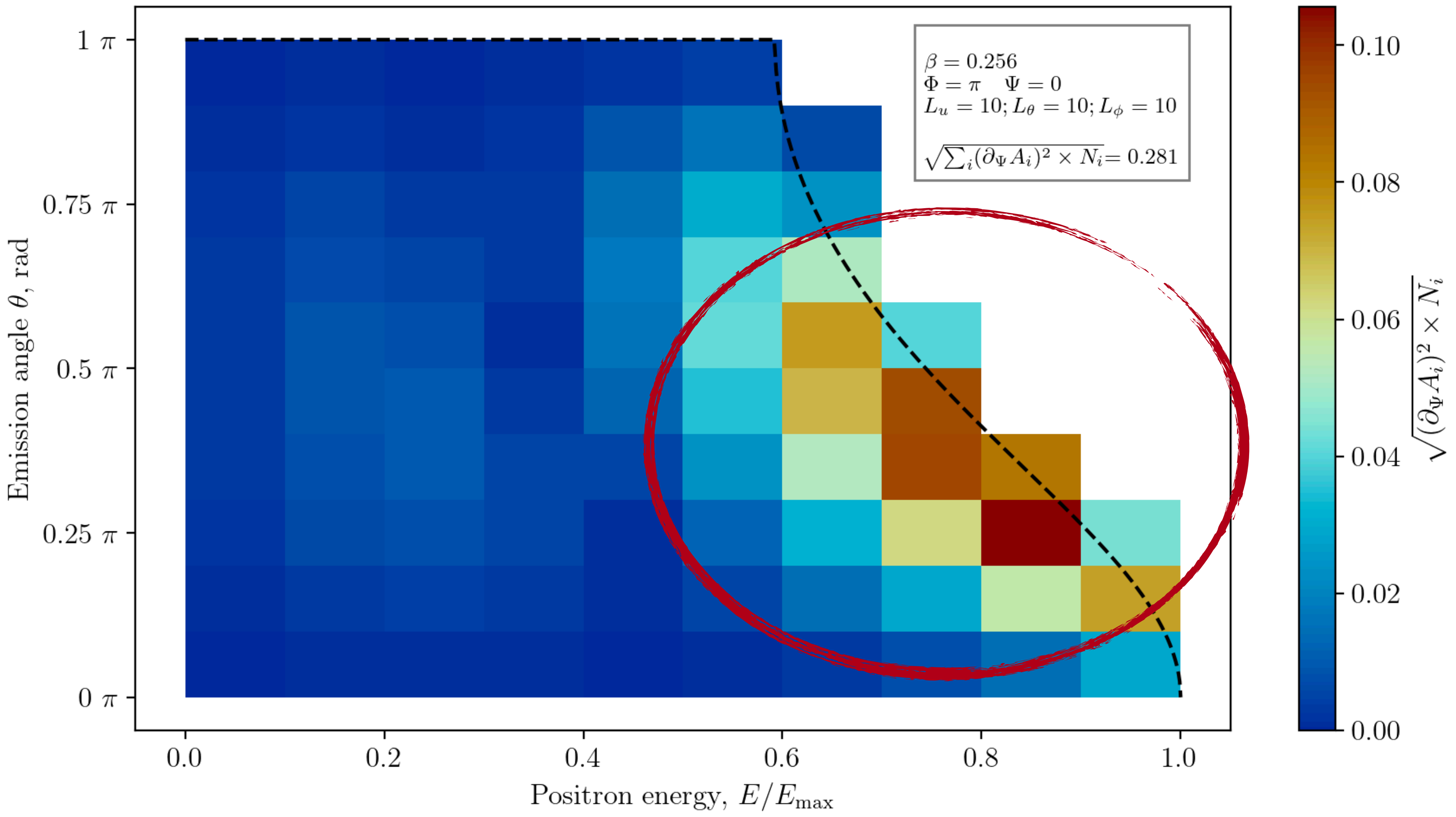


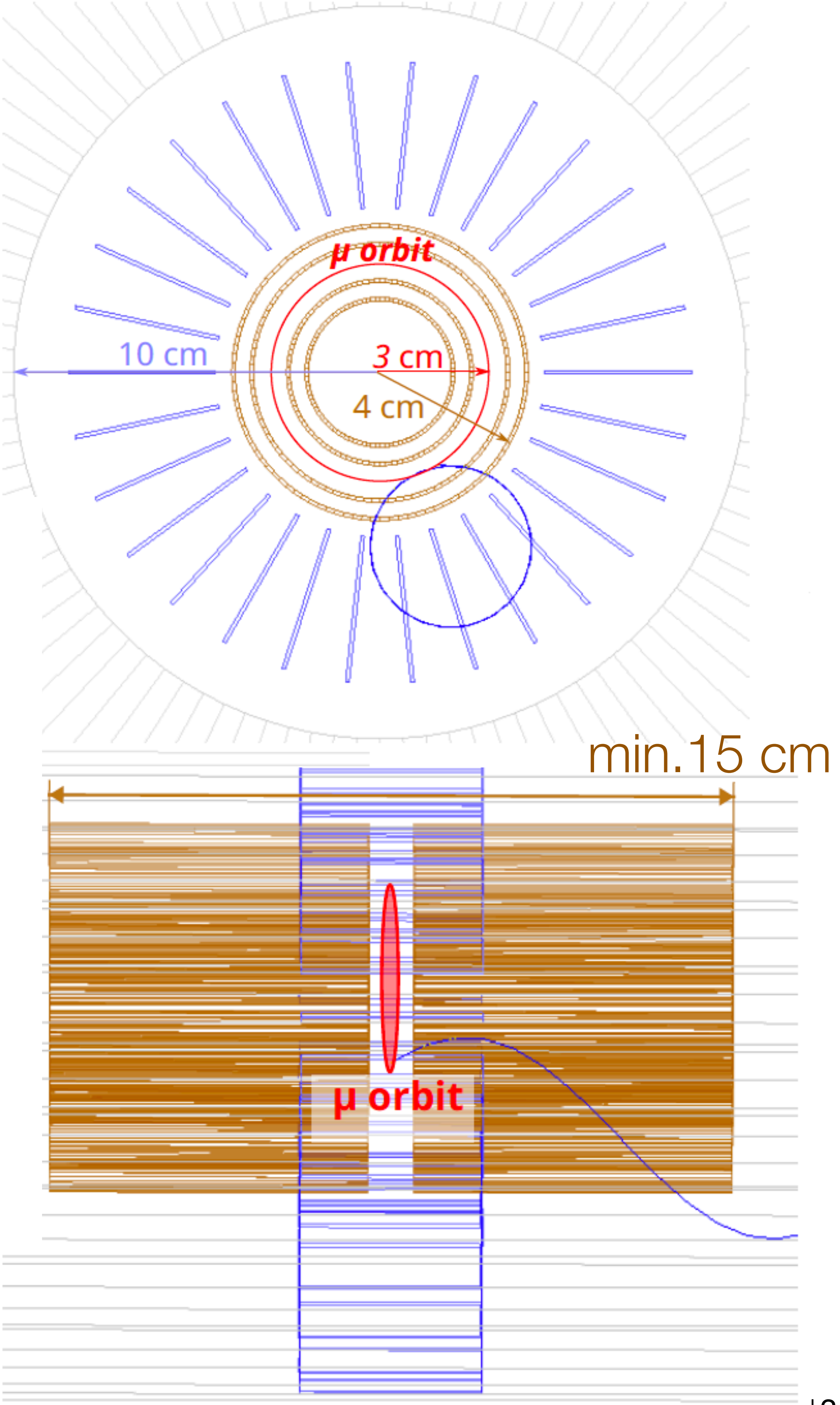


The positron tracker: CHeT

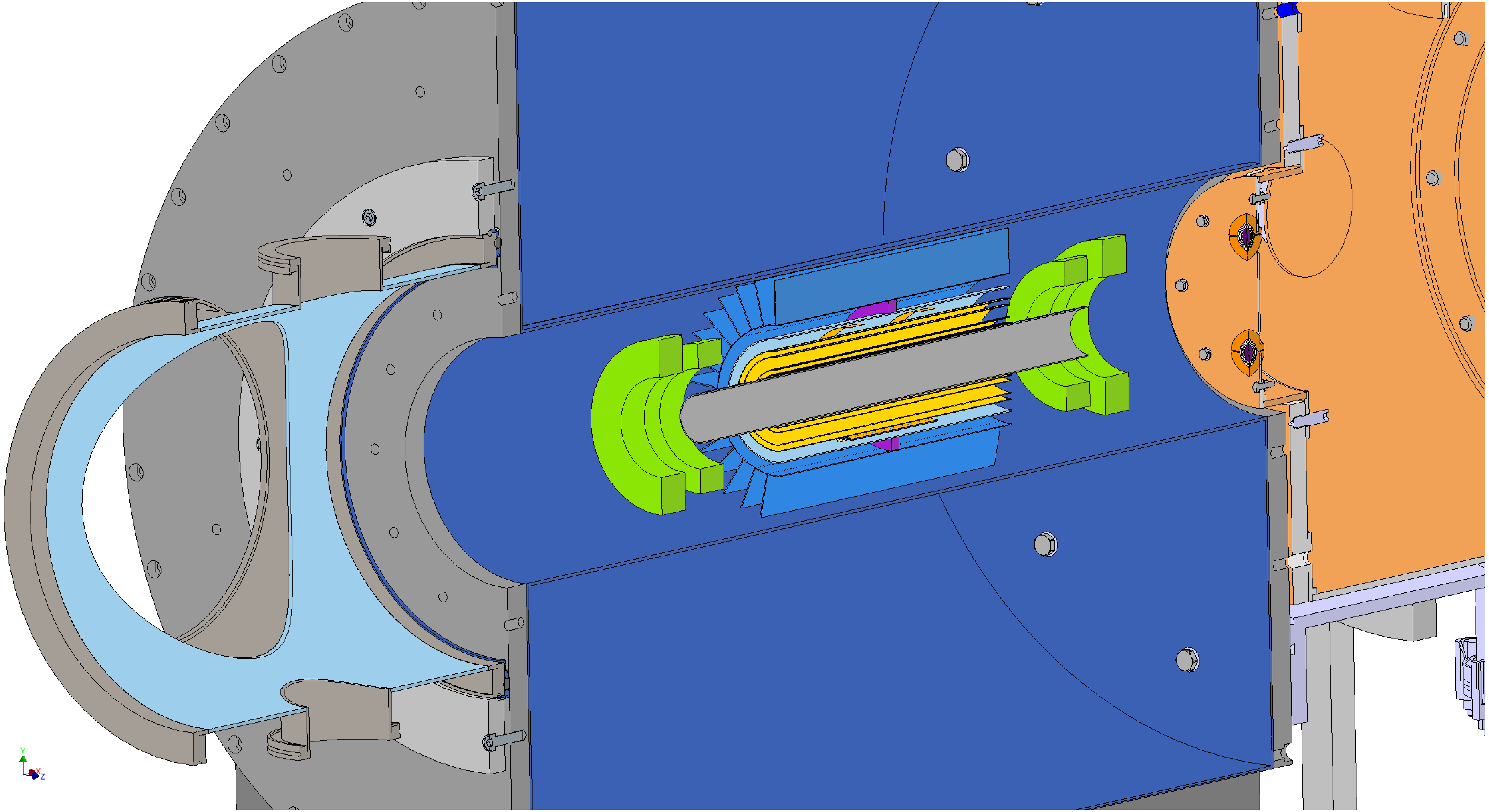
- EDM figure of merit for the Phase I of the experiment



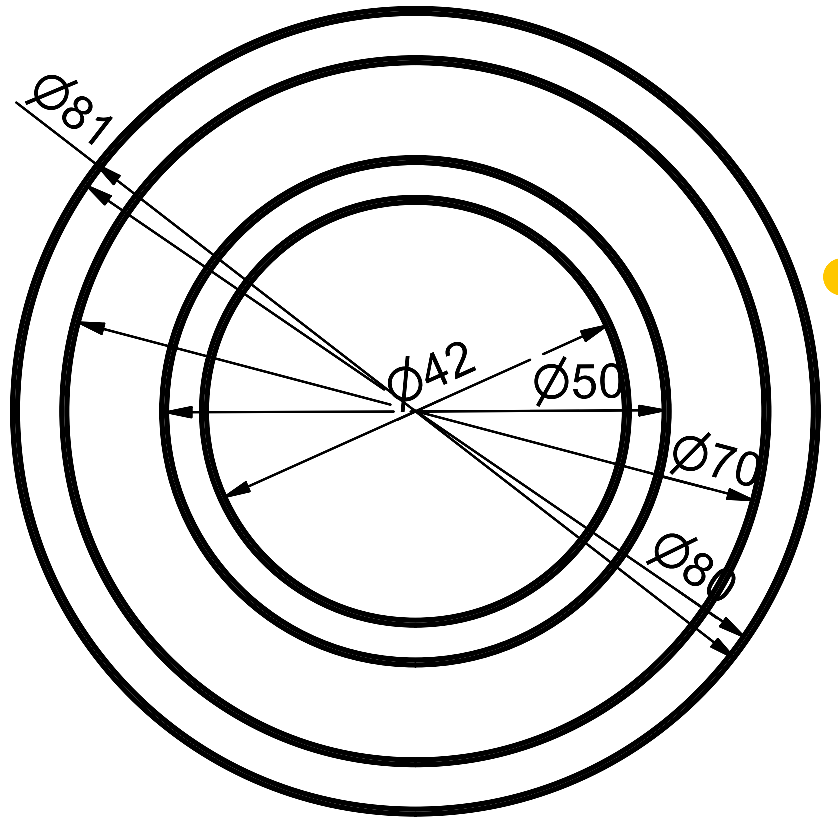


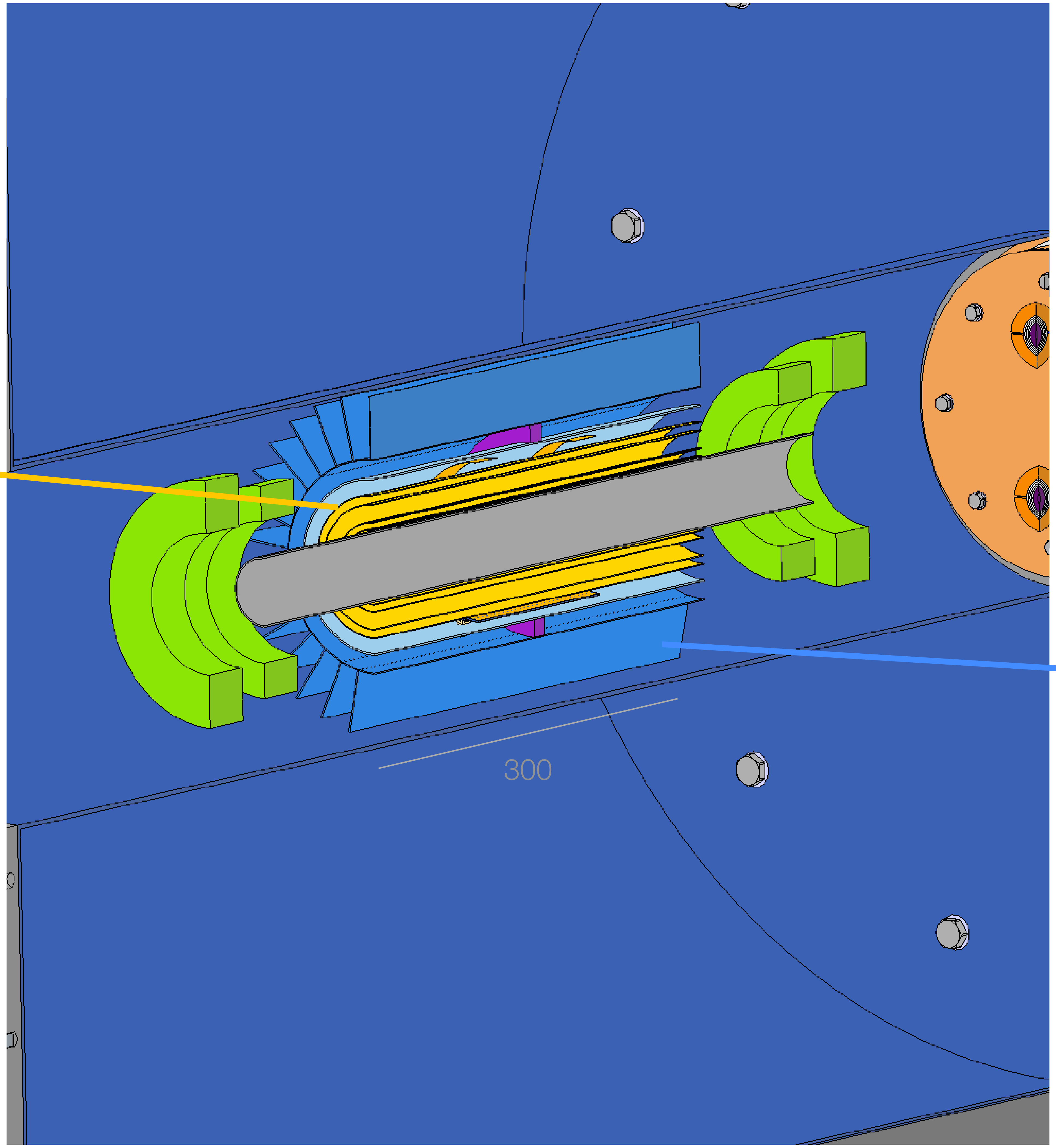


CHeT inside the magnet

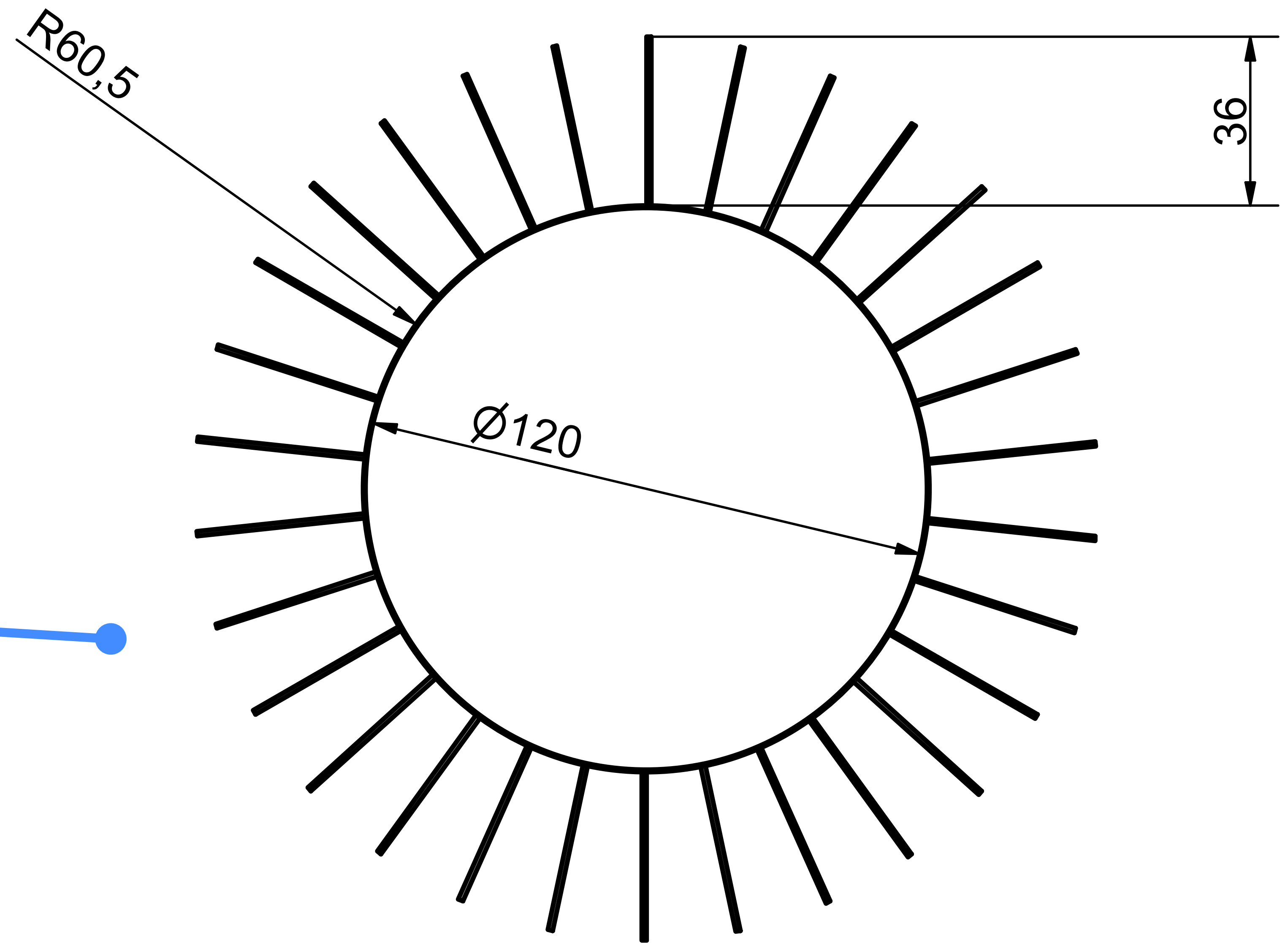


CHeT inside the magnet

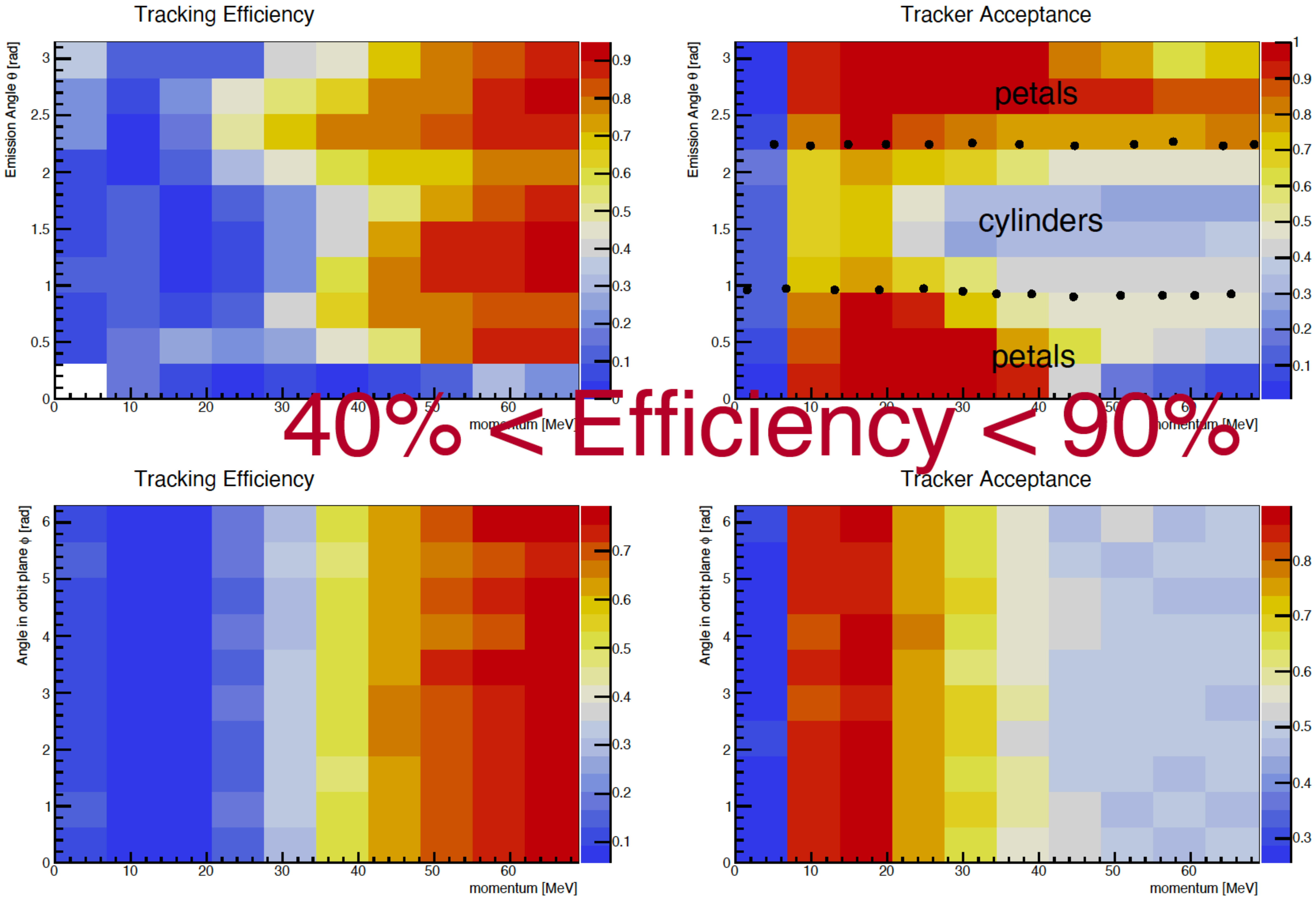




Unit: mm

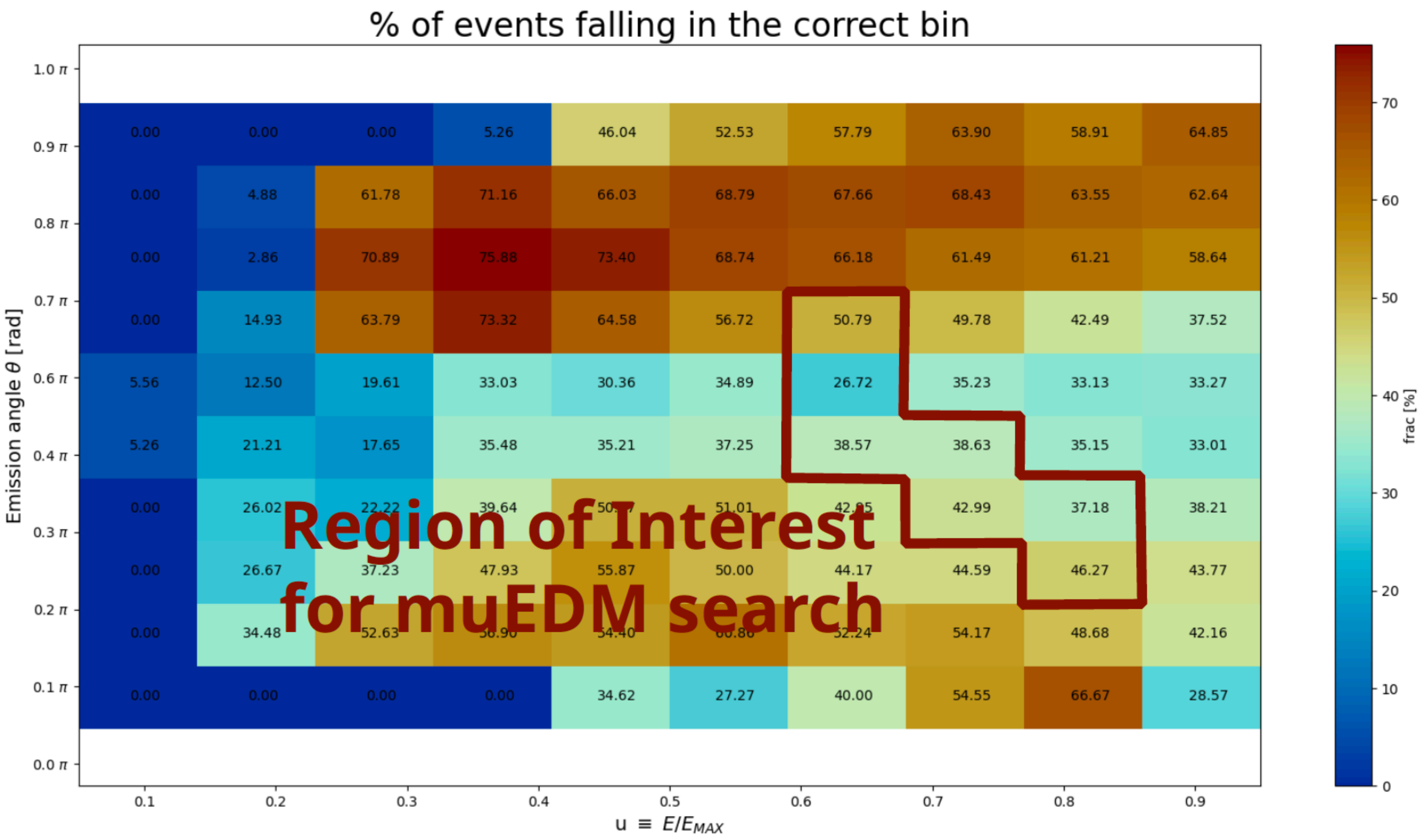


CHeT detector performances: Detector Acceptance



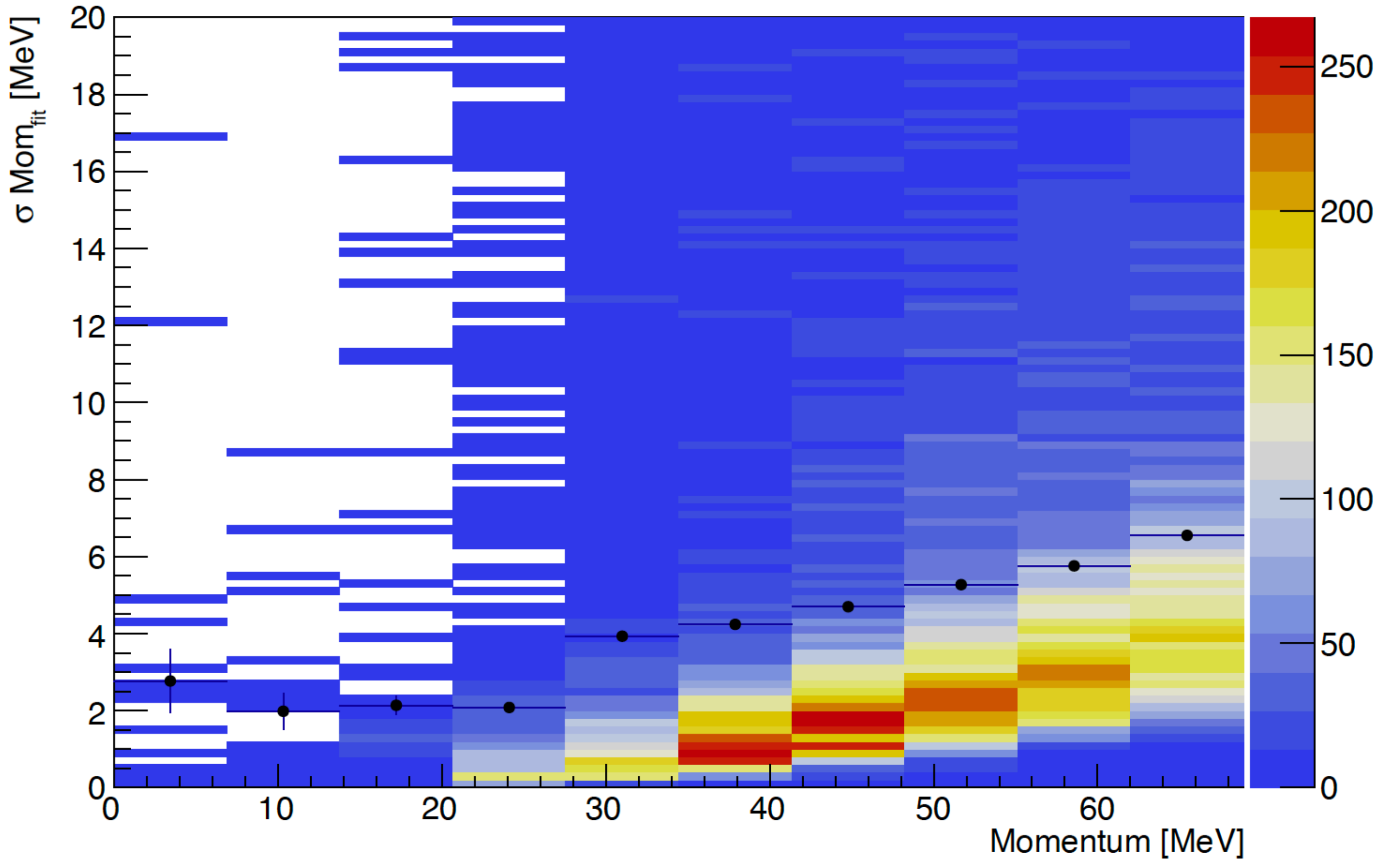
40% < Efficiency < 90%

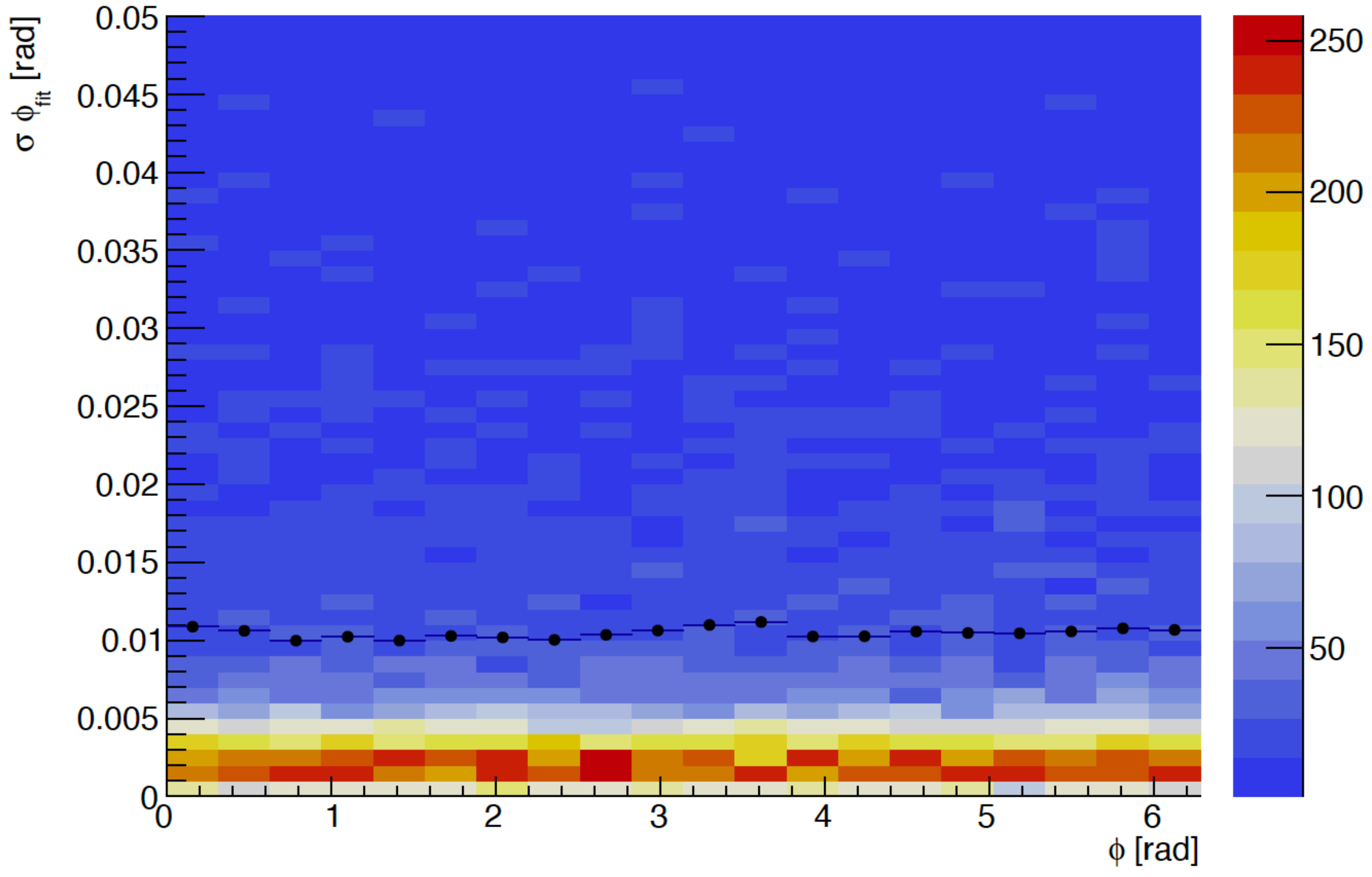
CHeT detector performances: Tracking efficiency

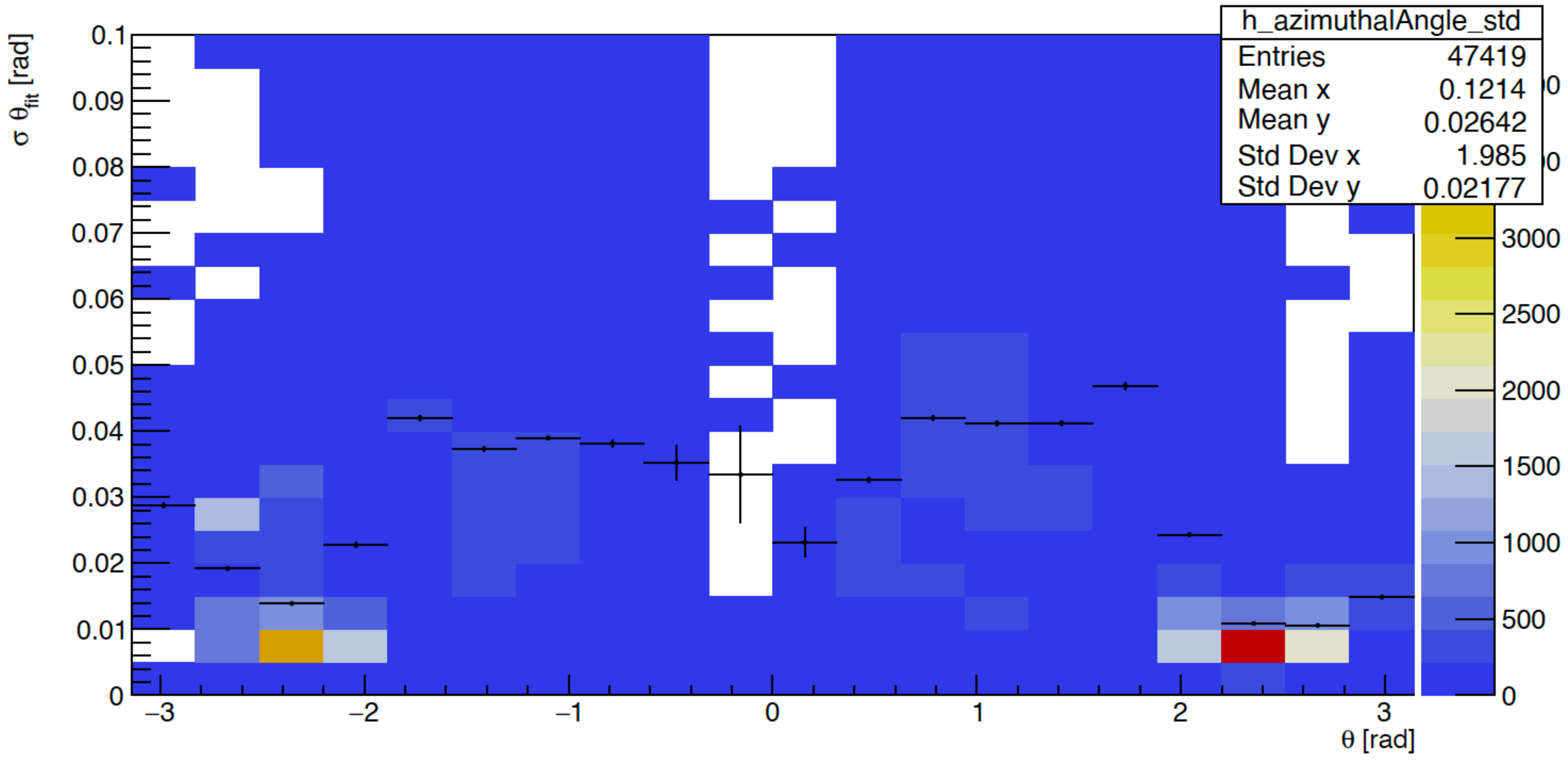


CHeT detector performances: Resolutions

- Achieved typical (using the mode of the distribution instead of the average, which is influenced by bad reconstructed tracks) resolutions of:
- $\sigma_p / p \approx$ 0.05 MeV x p
- $\sigma_\theta \approx$10-30 mrad, worsening for particles emitted along the z axis
- $\sigma_\varphi \approx$ 2-3 mrad

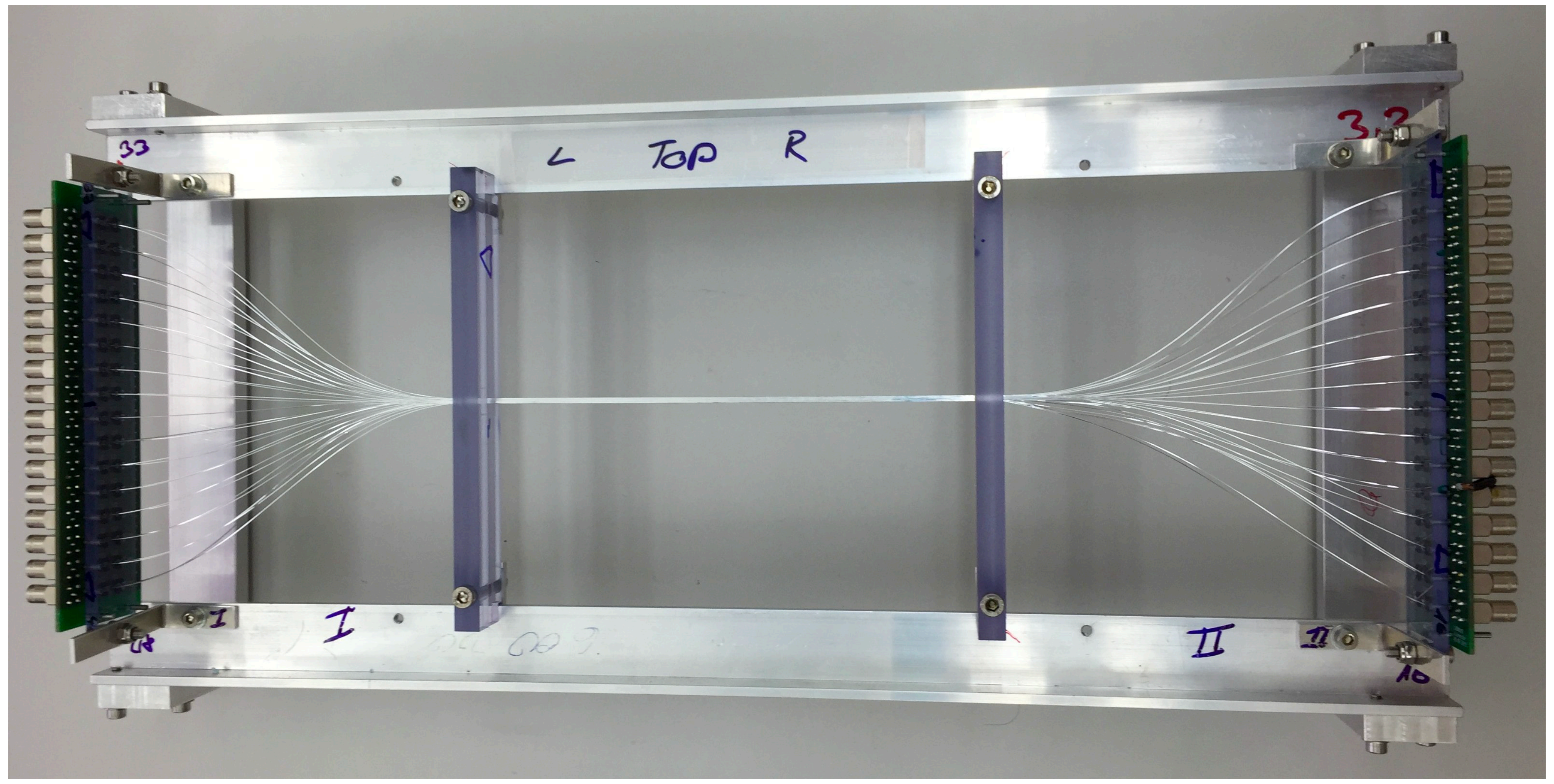


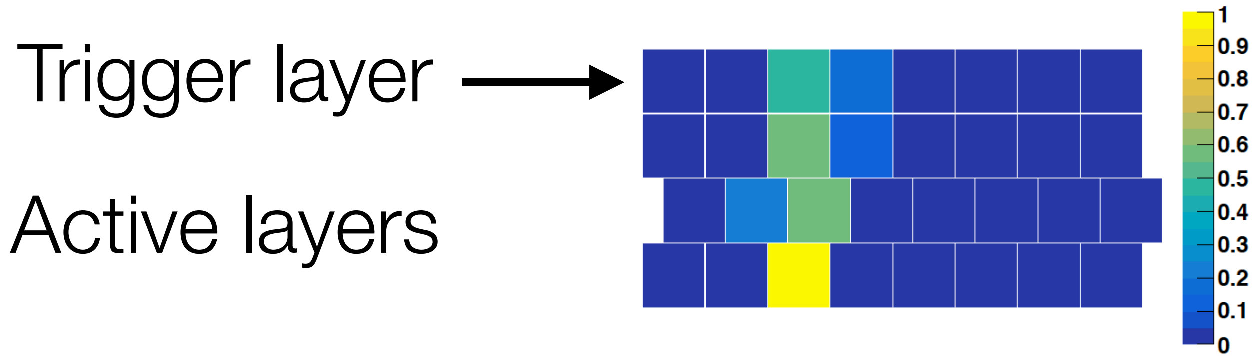




Fibre detector prototype: To assess the basics performances

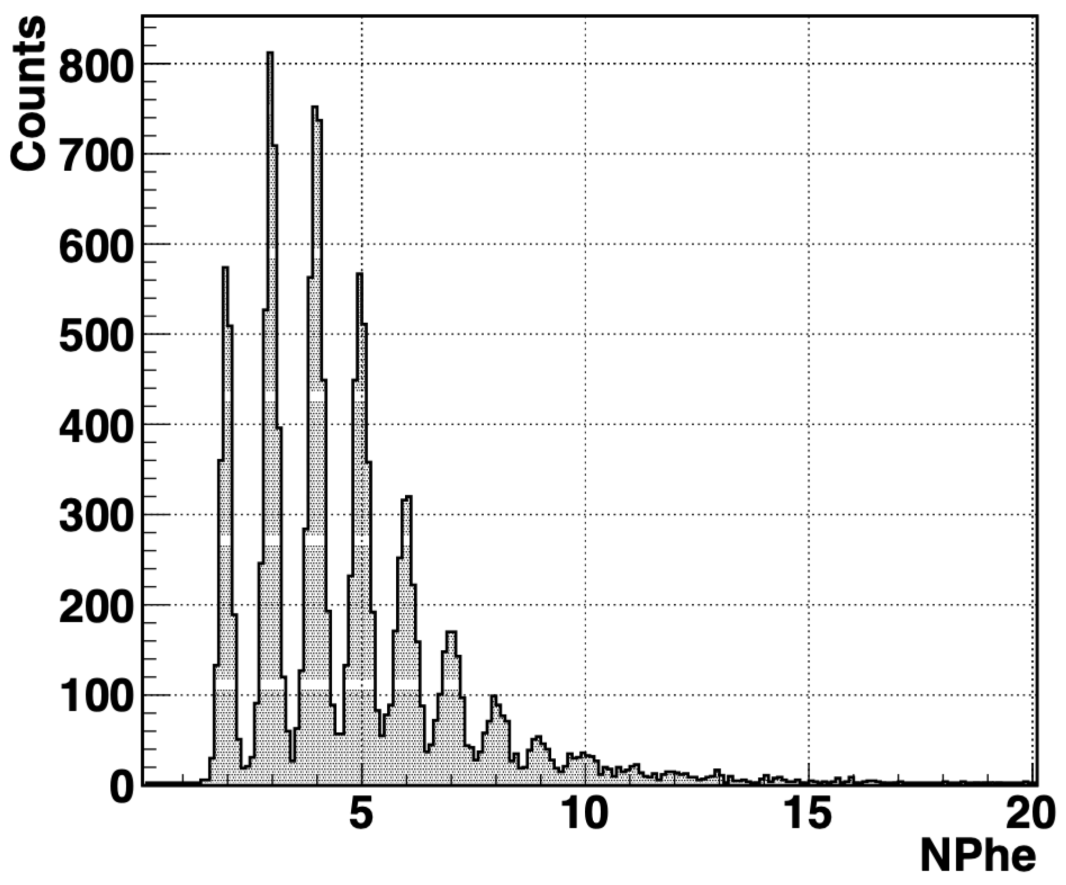
- A fibre bundle (W = 2 mm, L = 300 mm) with a double read-out scheme (left-right)
- 0.25 mm BCF12 Saint Gobain fibre (Aluminum fiber coating)
- Hamamatsu S13360-1350CS SiPM
- DAQ: DRS (5 GSample/s)



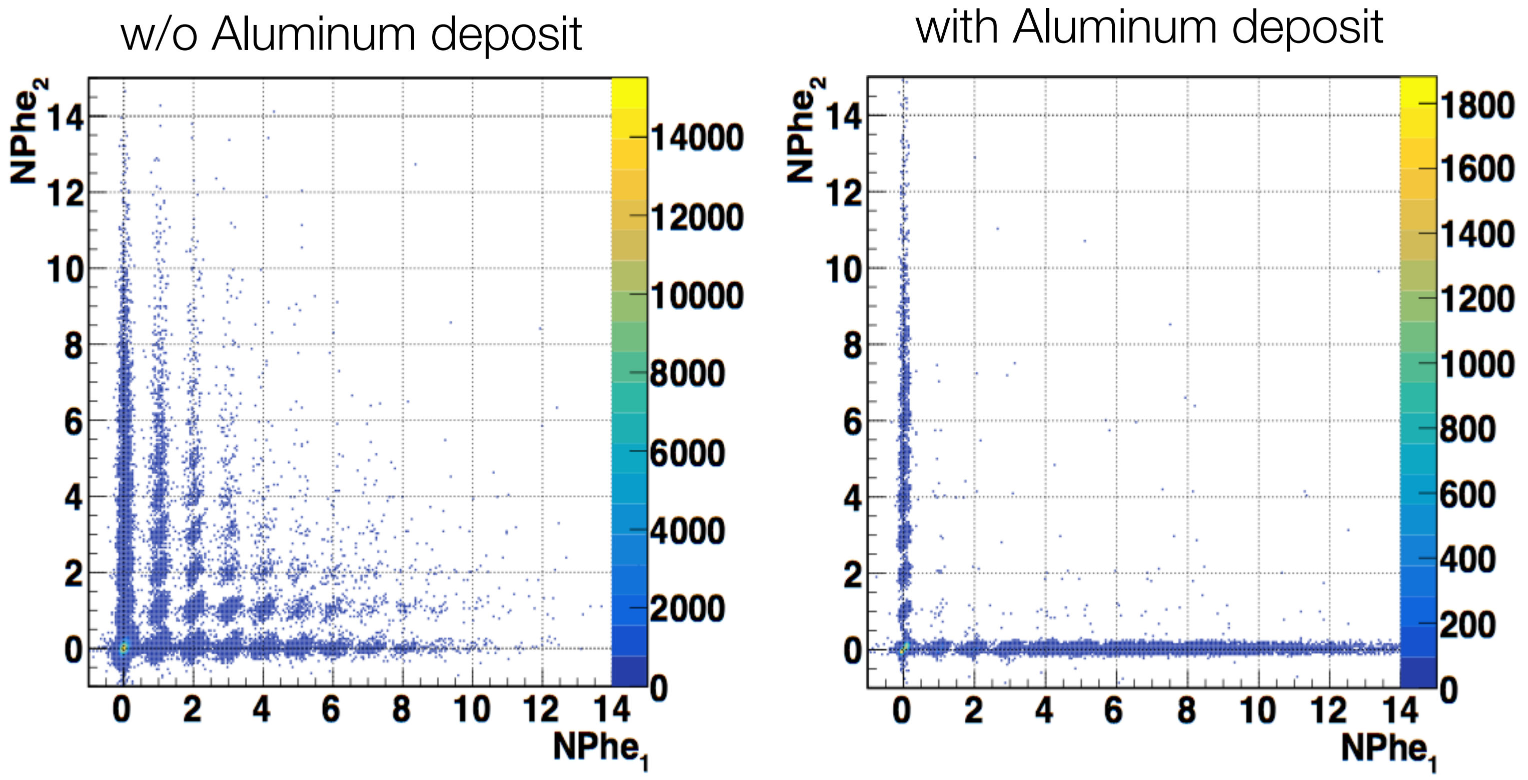


Fibre bundle transverse view

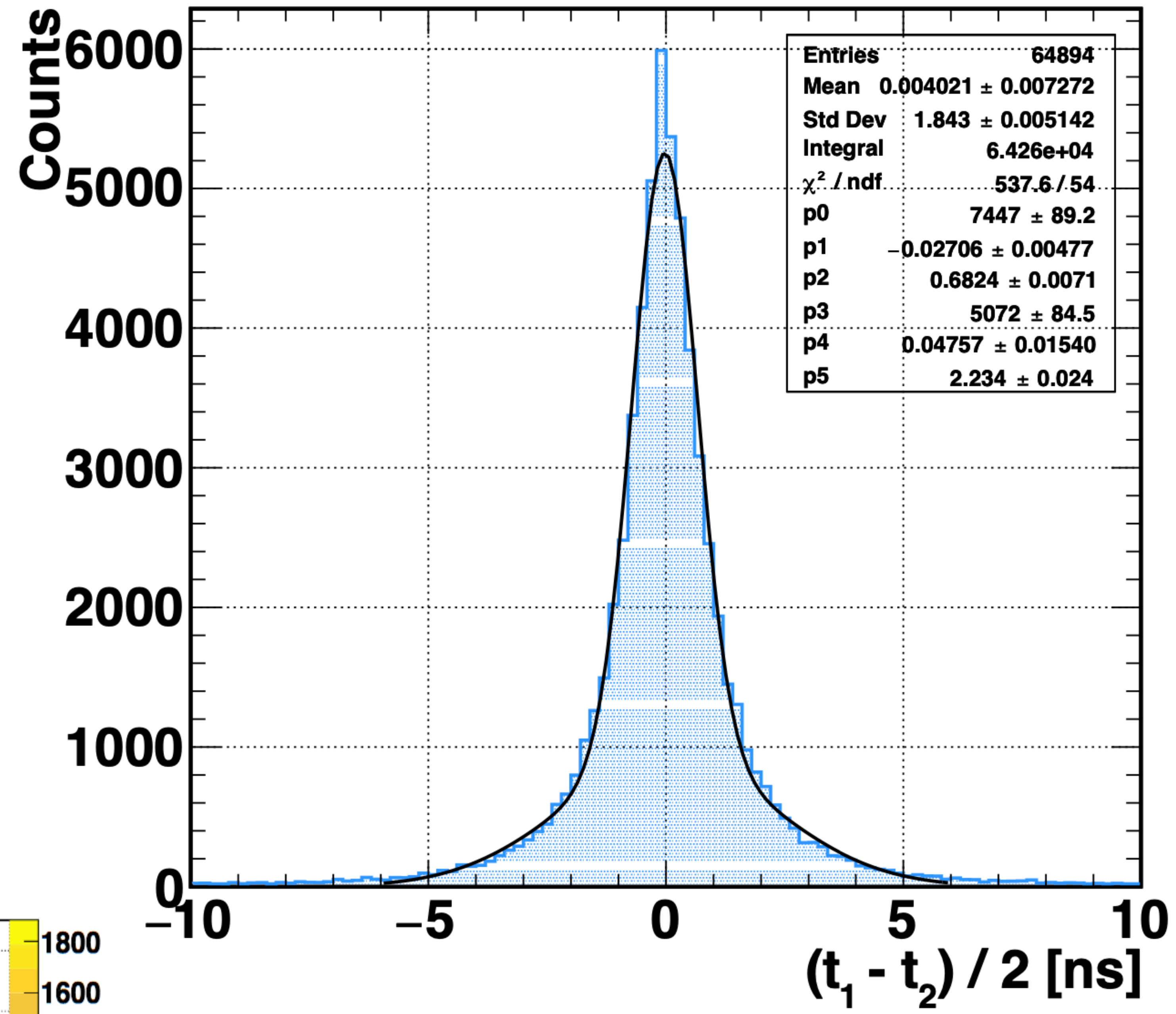
Collected charge/fibre



Fibre Optical cross-talk



Time resolution [**< 1ns**]



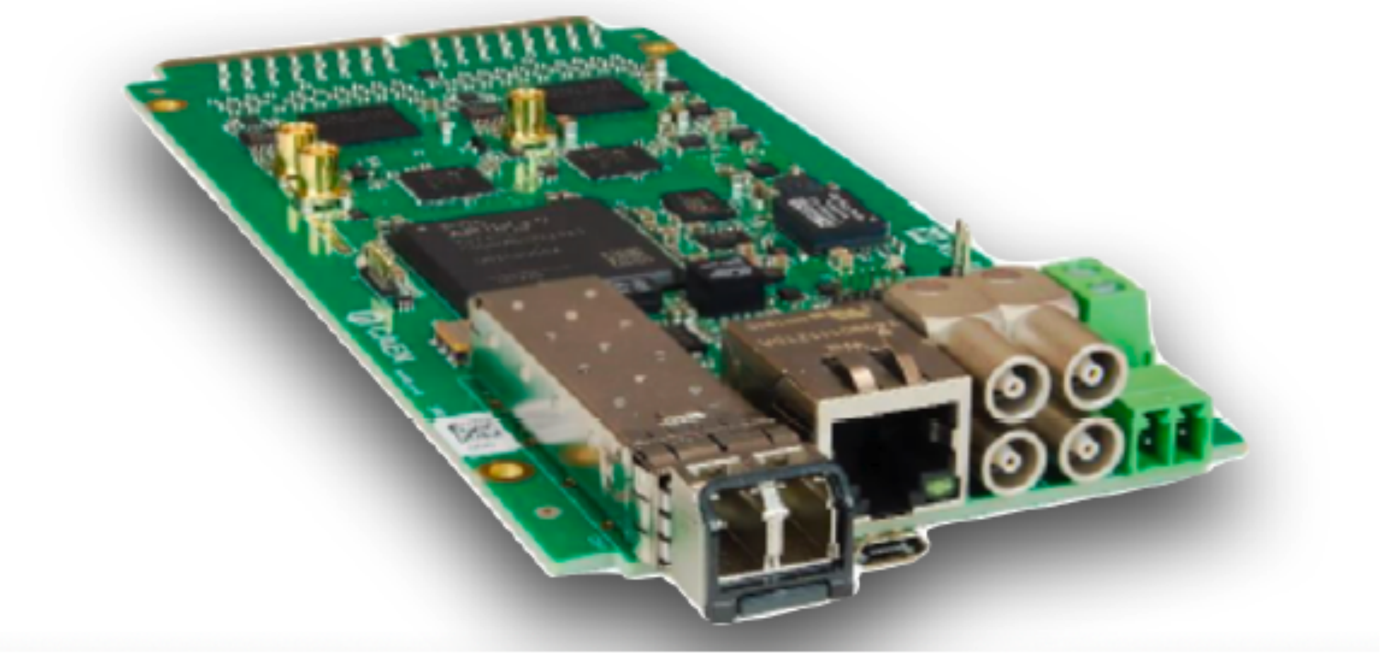
DAQ: CAEN FERS 5200

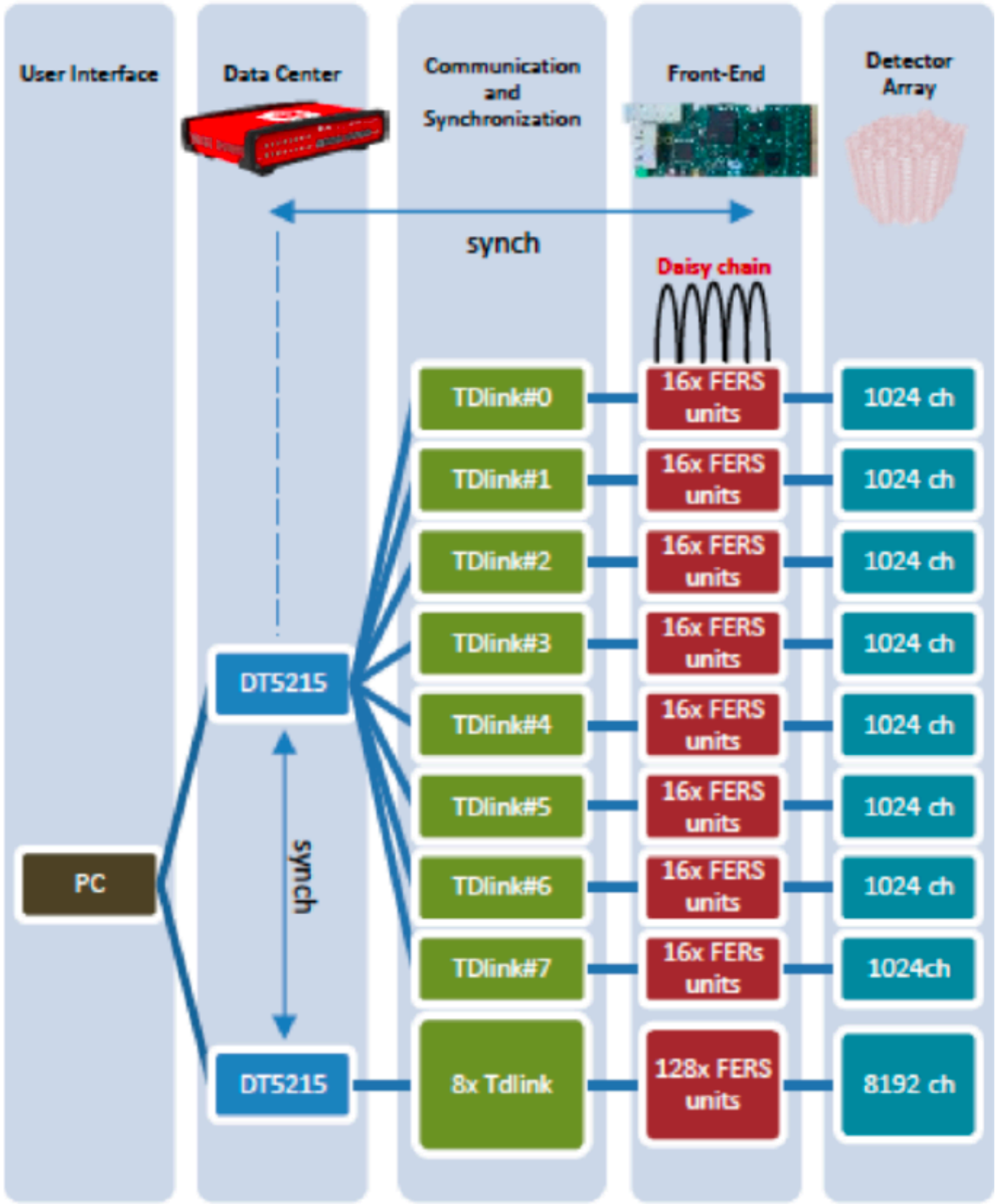
- Platform for the readout of large arrays of detectors including services (i.e. MPPC bias and front-end amplification)

- **Modular** (A520x FERS units- 64/128 channels) + DT5215 Concentrator Board. **Scalability**: from a single standalone FERS units to **8192** channels with Concentrator Board. **Easy-synch**: up to 128 FERS units can be easily managed and synchronized by a single DT5215 Concentrator Board

- Timing**@200ps** level
  - **Time Over Threshold** available

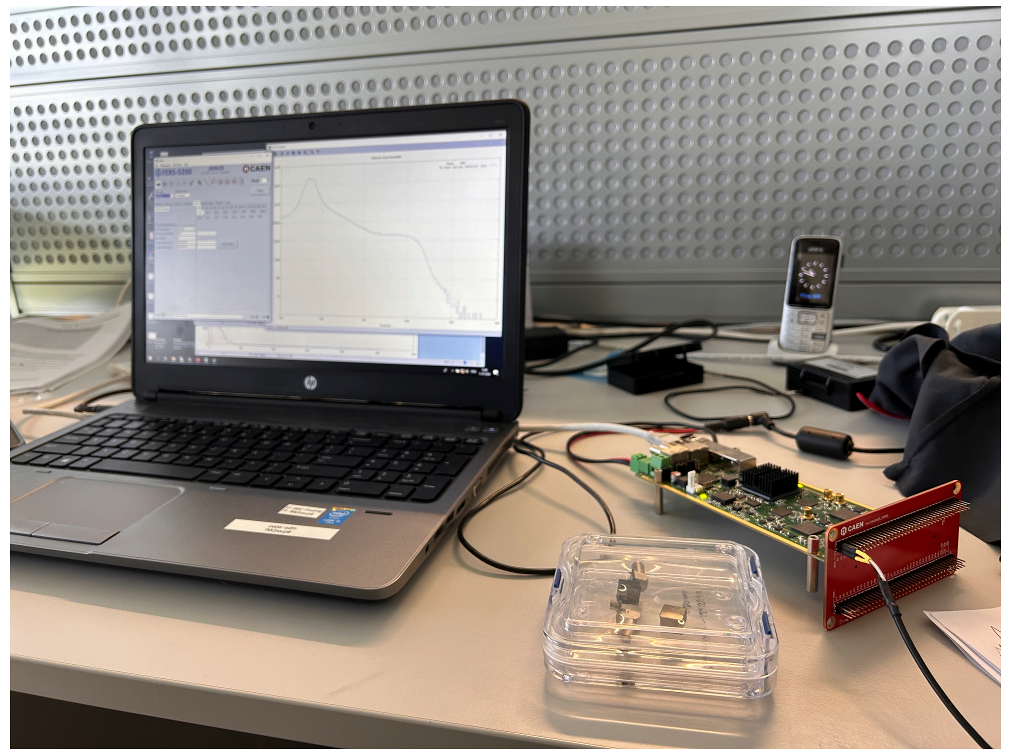
- Read out up > **100 KHz**

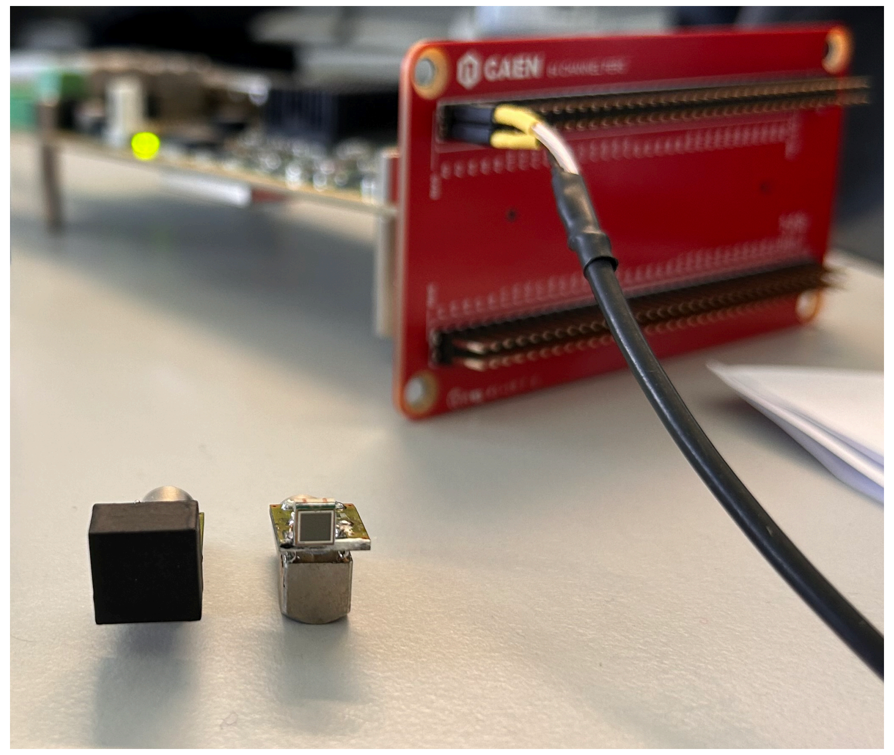




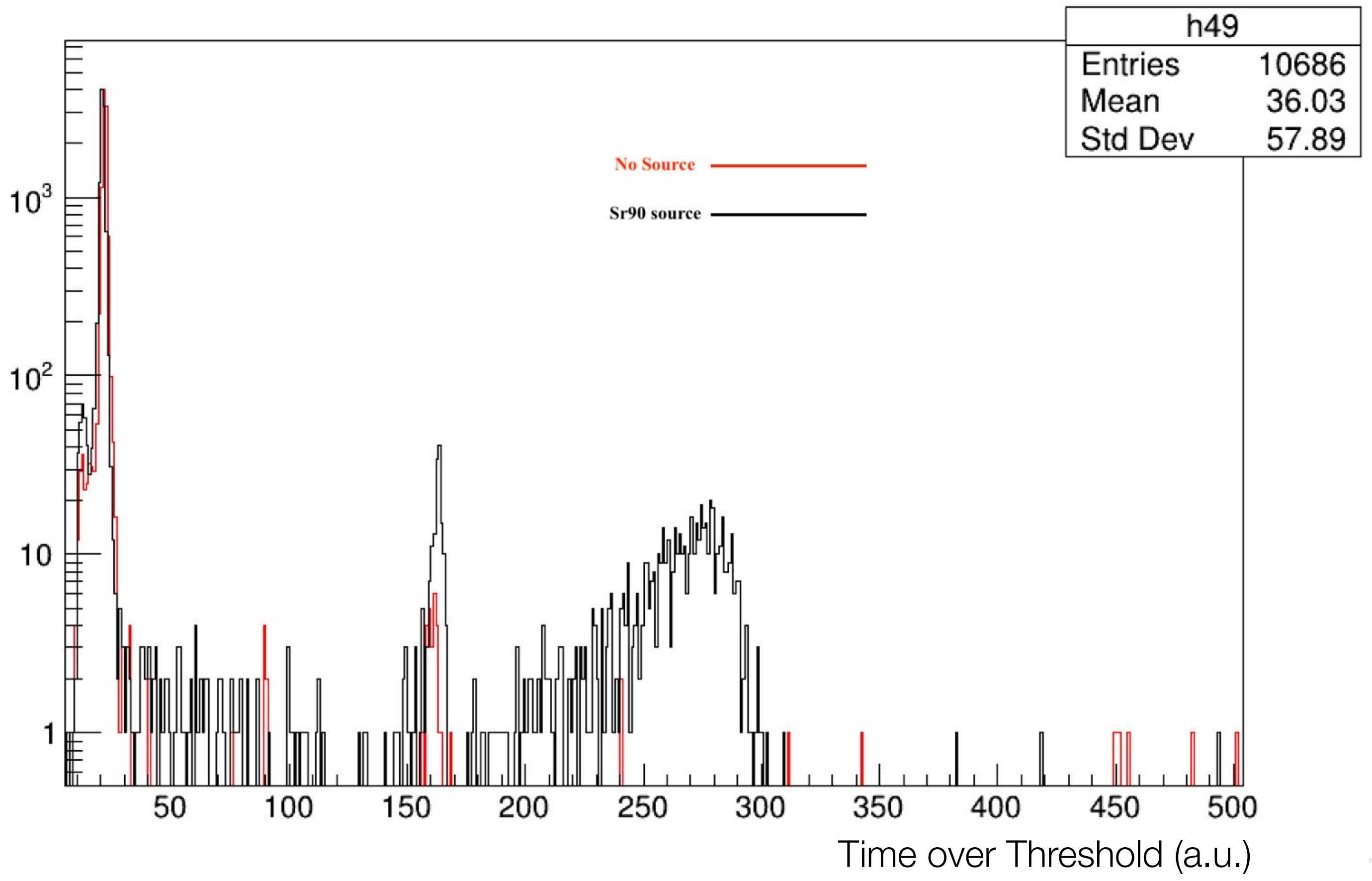
CAEN FERS 5200: First tests in lab

- Janus software for board and DAQ control
- Started to become acquainted with one **borrowed board (INFN-MI)** meanwhile **“our”** has been **ordered** and **received**
    - Plastic scintillator BC200 10x10x5 + MPPC S13360-3050PE + Sr90 source (w/wo) [**done**]
    - Critical is to prove the detection of a few phe (CHeT signal). First test: Dark noise spectrum using the CHeT MPPC [**done**]
    - Prototypes with different fibres (250um, 500um, 1000um) + FERS w/o Sr90 source: **In preparation**

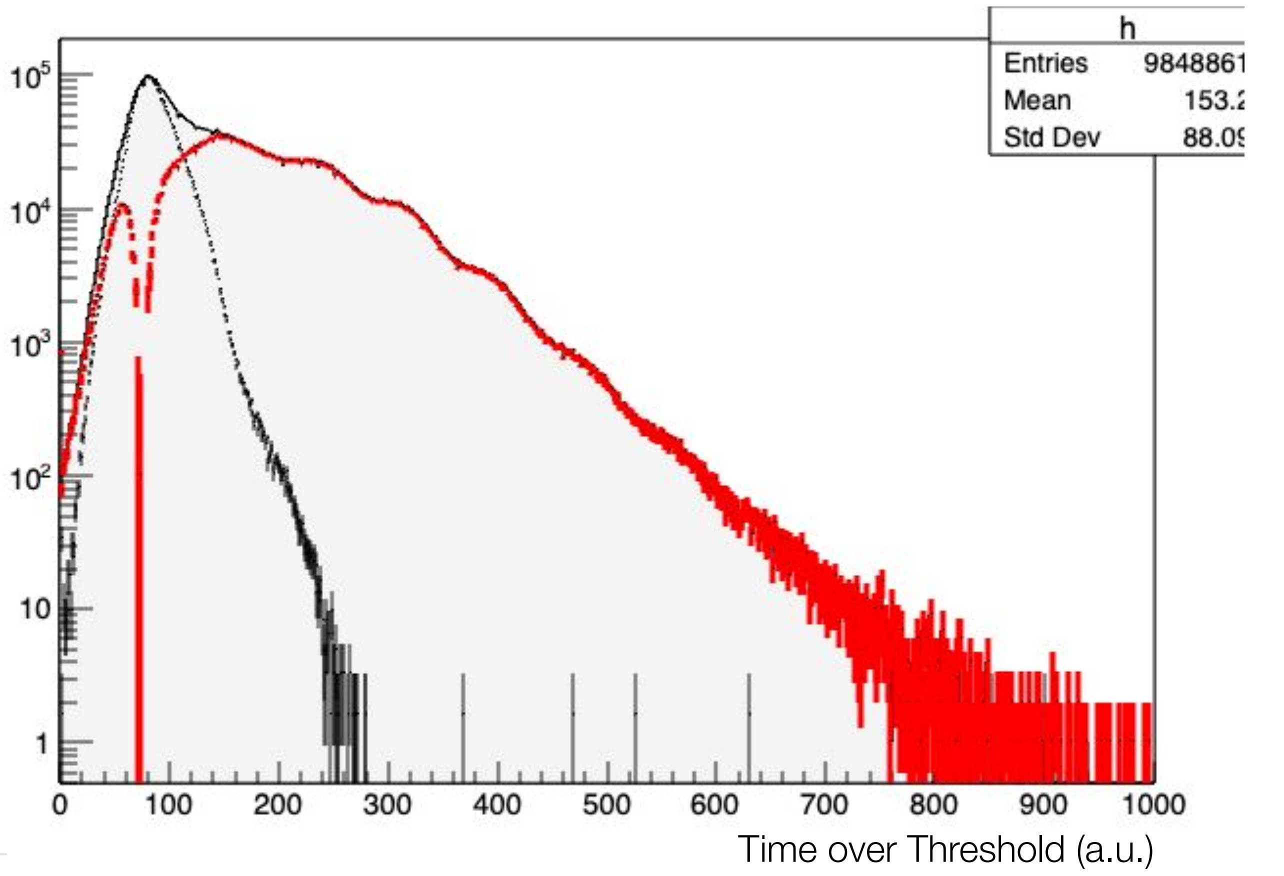




Thick scintillator + Sr90 (w/wo)

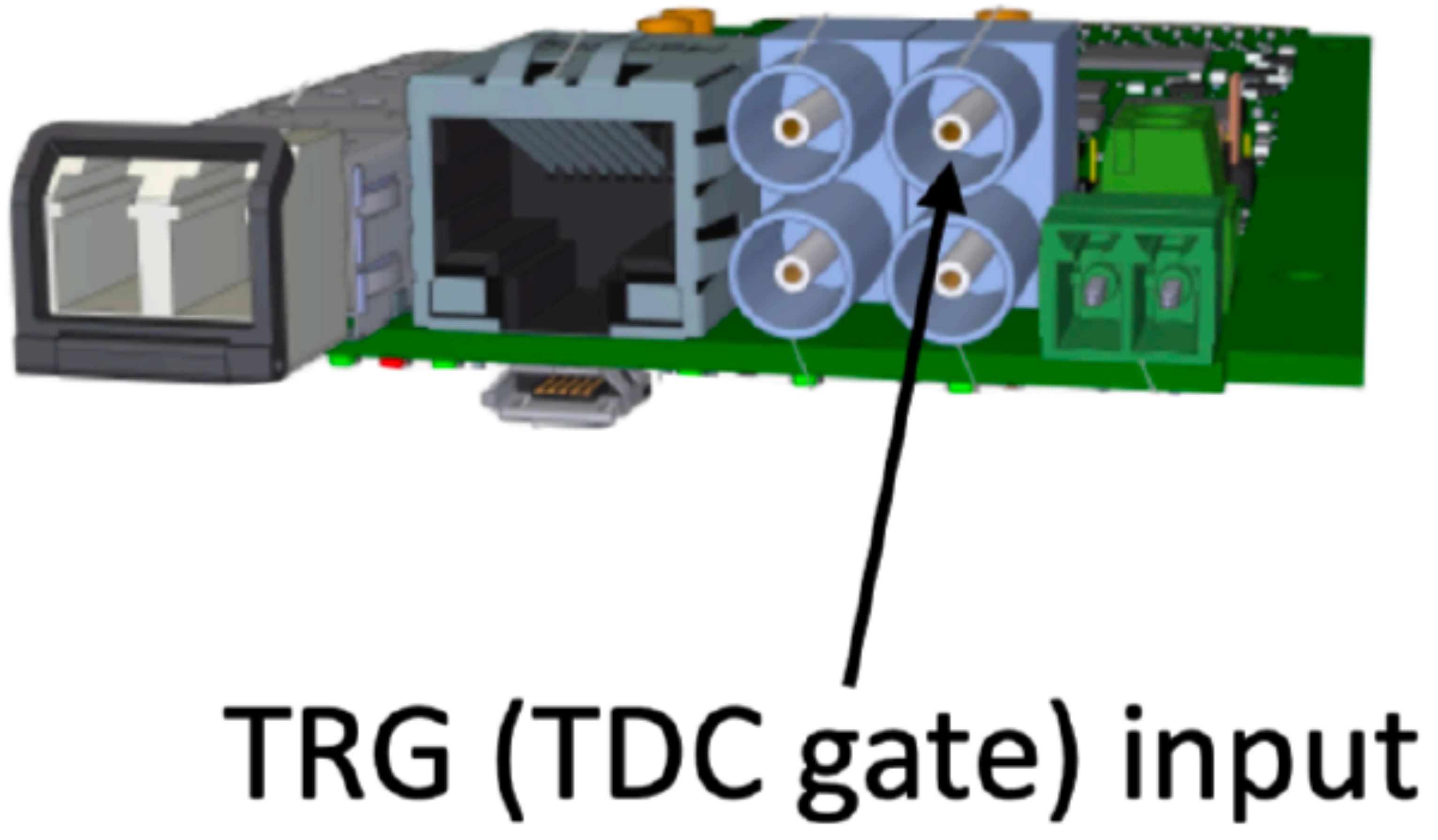


MPPC S13360-1350 HV (w/w-wo)



Configuration for muEDM

- **FERS used for the CHeT readout**
  - **2000** channels default configuration
  - The trigger signal used to open a 20 us gate looking for hits in the fibre-tracker (common start)
    - The signal is received on one of the LEMO input
  - Hits sent in push mode
- **Trigger signal distribution to be designed**
  - **32** copies are needed for **2048** readout channels

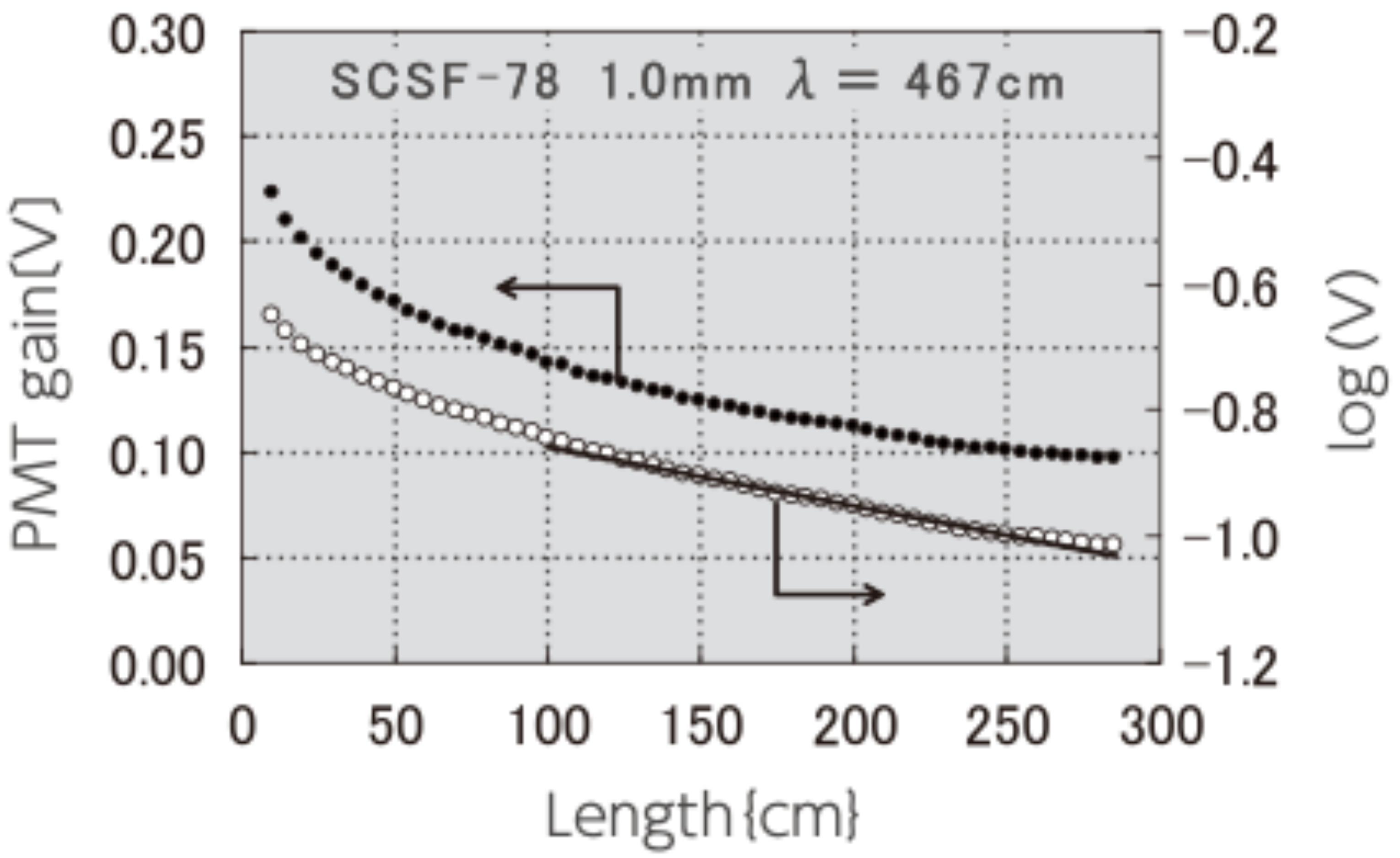


Material procurement: Fibres

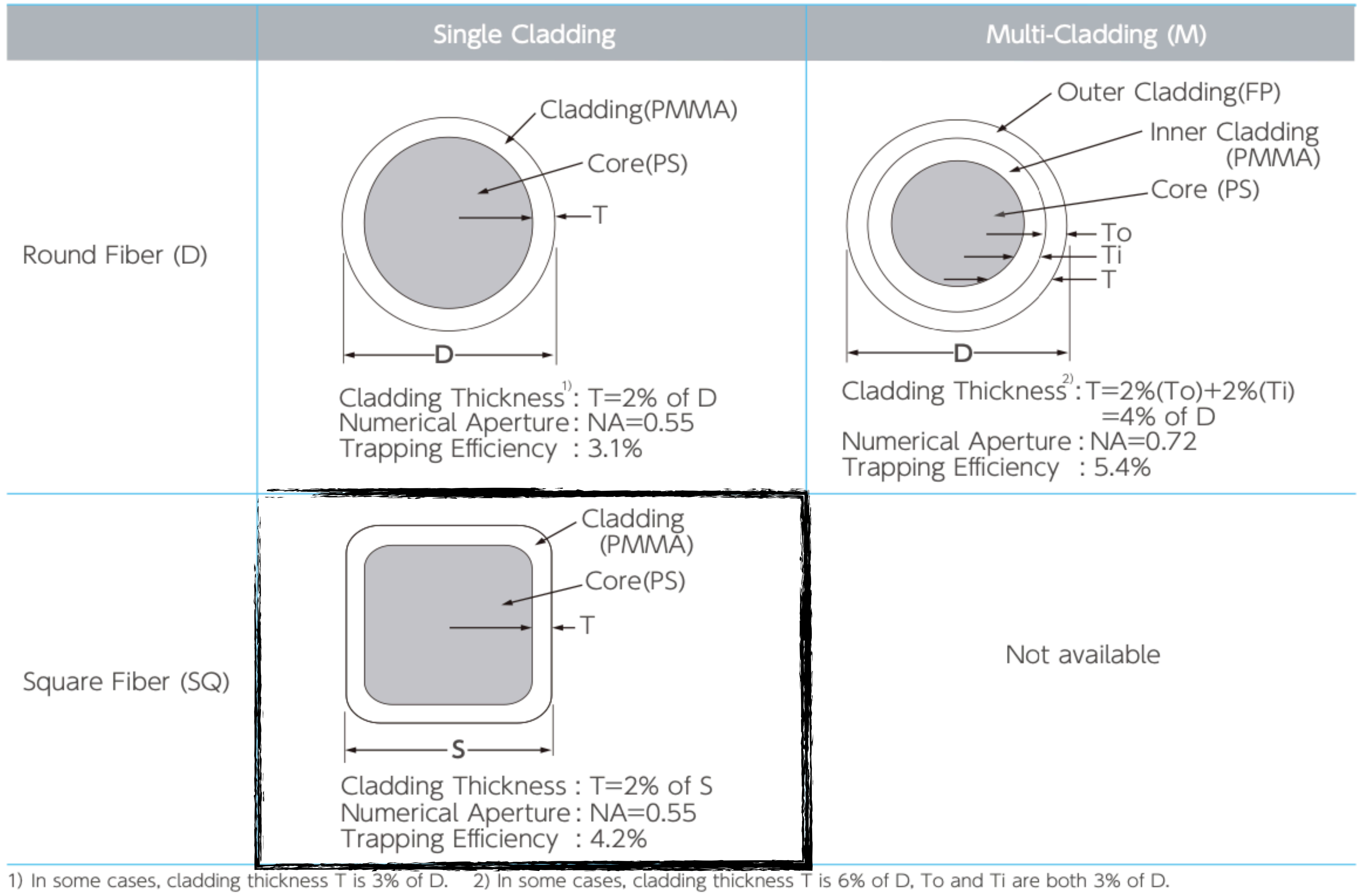
- Fibres: **Received**
- SCSF-78, Square Single Cladding, S-type
- Quantity : MOQ **0.25mm = 3.200m** & **0.5mm=1.200 m**

Formulations[1)]

Description	Emission Color	Emission Spectra	Emission Peak[nm]	Decay Time [ns]	Att.Leng.[2)] [m]	Characteristics
SCSF-78	blue	See the following figure	450	2.8	>4.0	Long Att. Length and High Light Yield
SCSF-81	blue		437	2.4	>3.5	Long Attenuation Length
SCSF-3HF(1500)	green		530	7	>4.5	3HF formulation for Radiation Hardness



Cross-section and Cladding Thickness

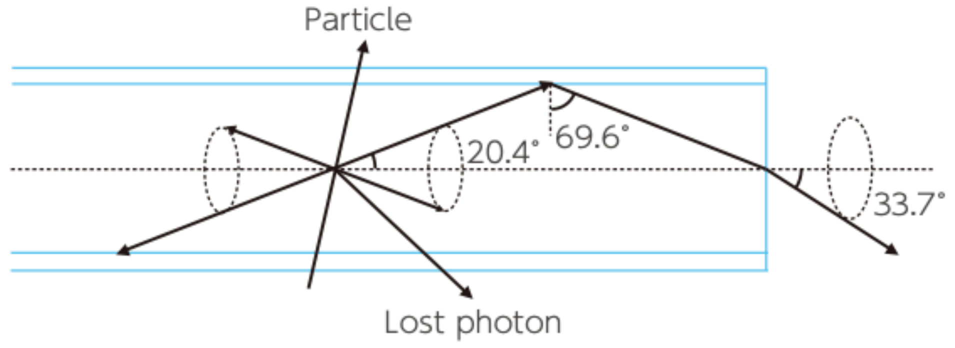


1) In some cases, cladding thickness T is 3% of D. 2) In some cases, cladding thickness T is 6% of D, To and Ti are both 3% of D.

Cladding and Transmission Mechanism

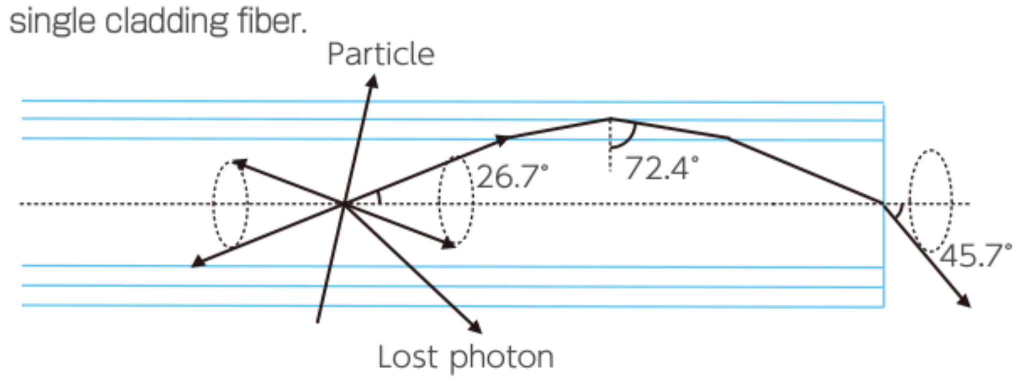
Single cladding

Single cladding fiber is standard type of cladding.



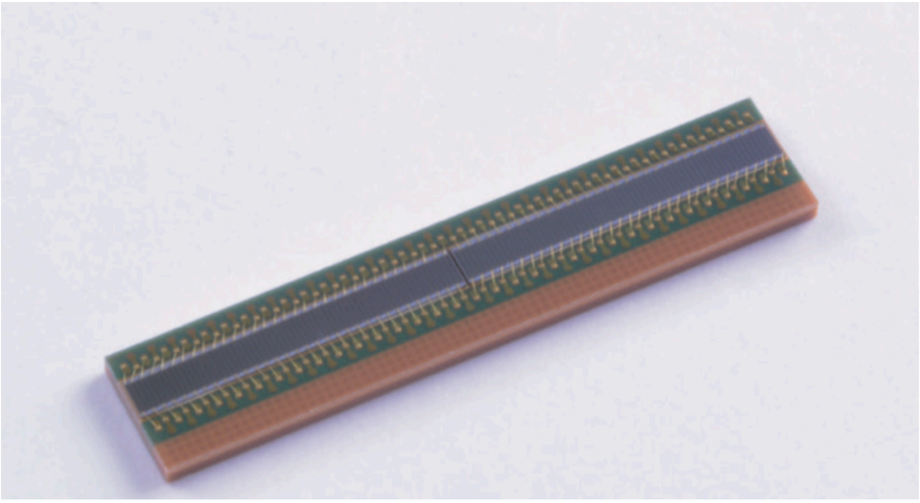
Multi-cladding

Multi-cladding fiber(M) has higher light yield than single cladding fiber because of large trapping efficiency.
Clear-PS fiber of this cladding has extremely higher NA than conventional PMMA or PS fiber, and very useful as light guide fiber.
Multi-cladding fiber has long attenuation length equal to single cladding fiber.

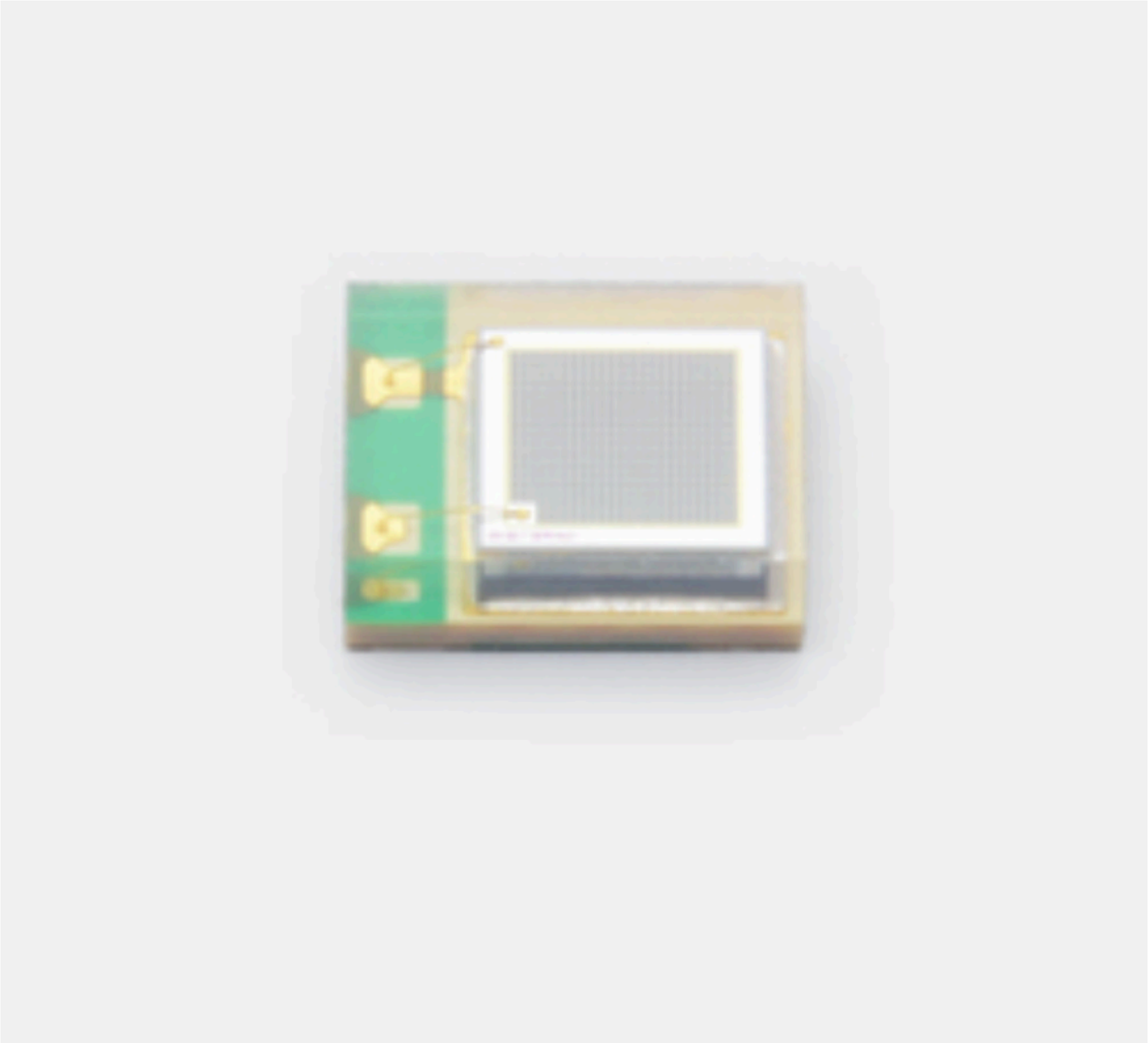


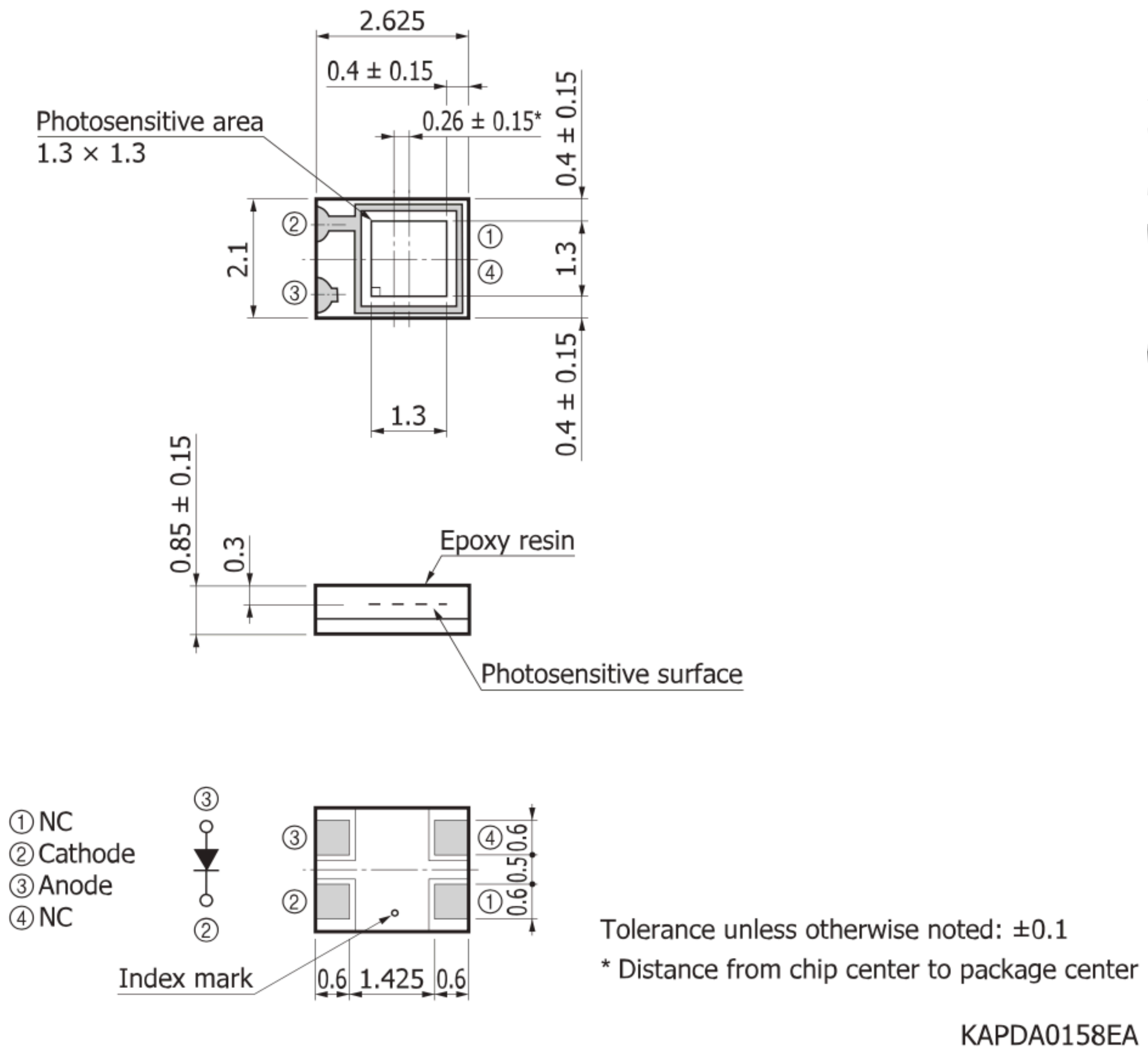
Material procurement: Sensors

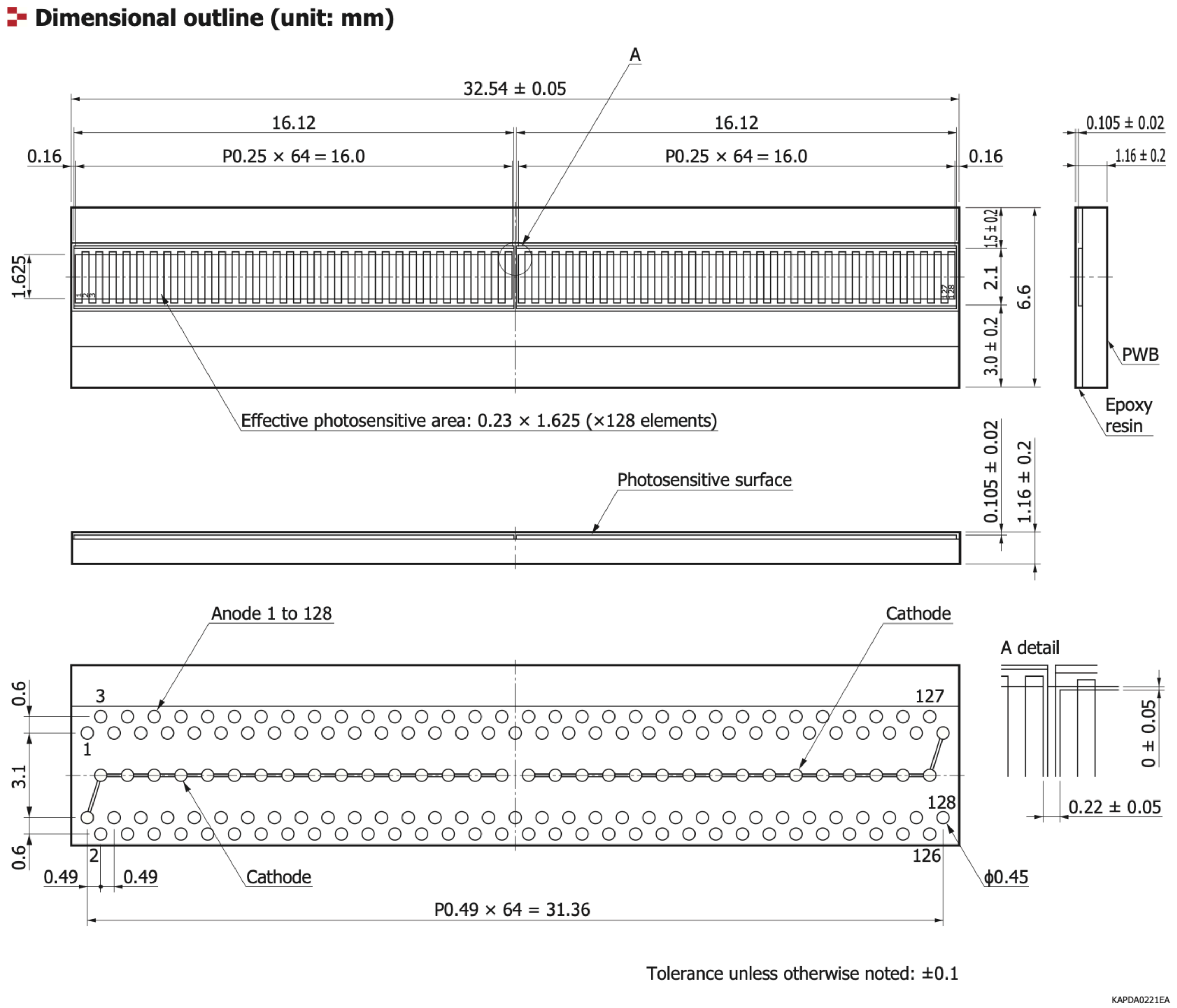
- **2000 MPPC 13360-1350 PE 1.3x1.3 50 um   10 KCHF [strong price reduction wrt to the original ~60 KCHF]**
- Order: **Submitted.** Delivery: **Oct/Nov 2024**
- 200 x 128 array S13552   53 KCHF
- **Ongoing:** PCB board/connector/cables to the FERS



Final choice

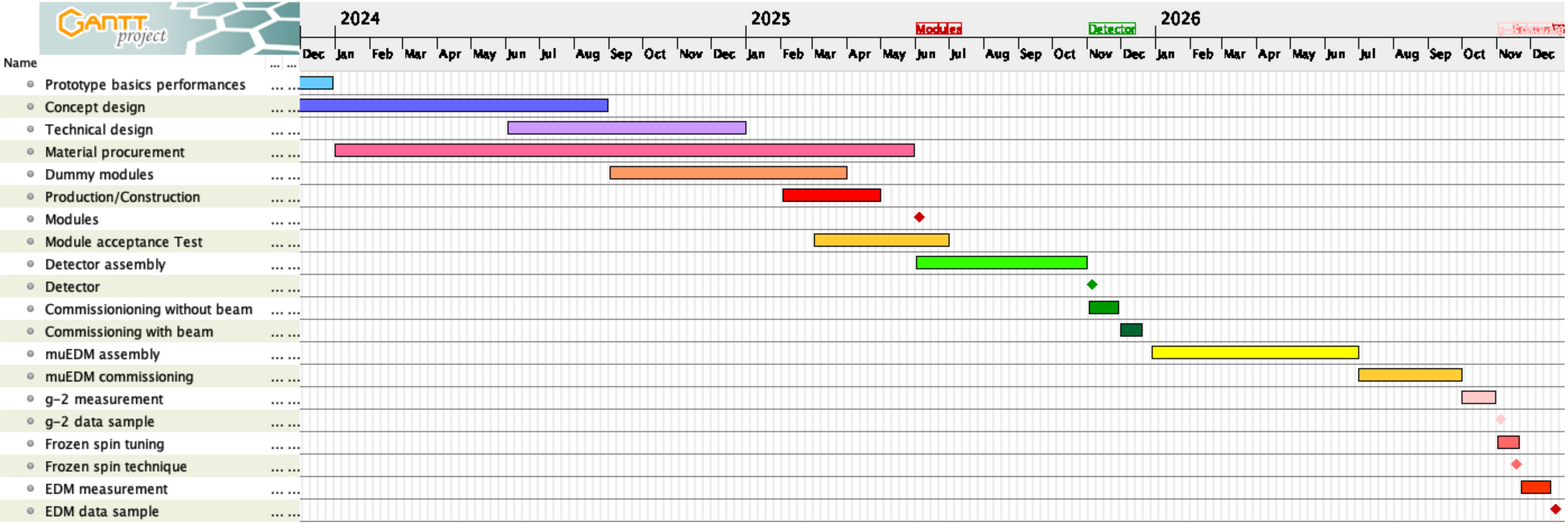






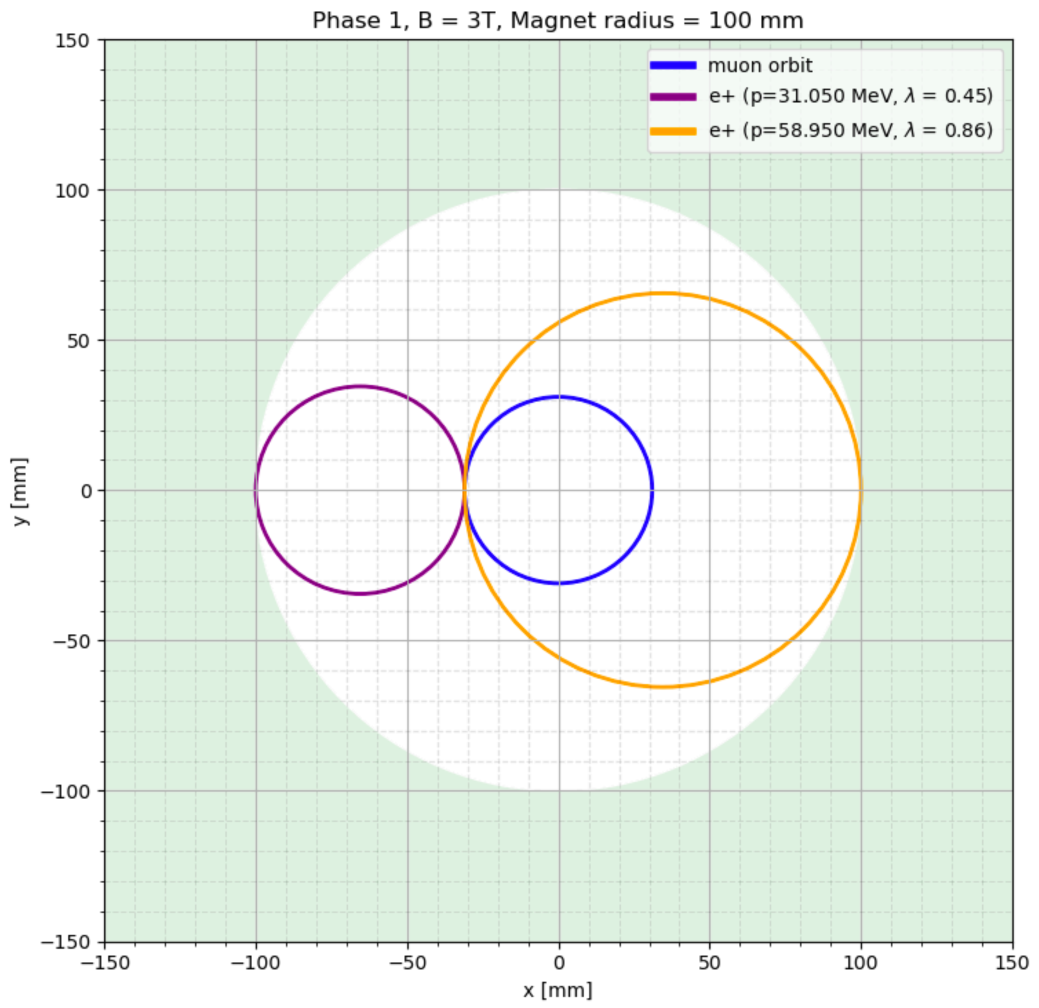
CHeT schedule

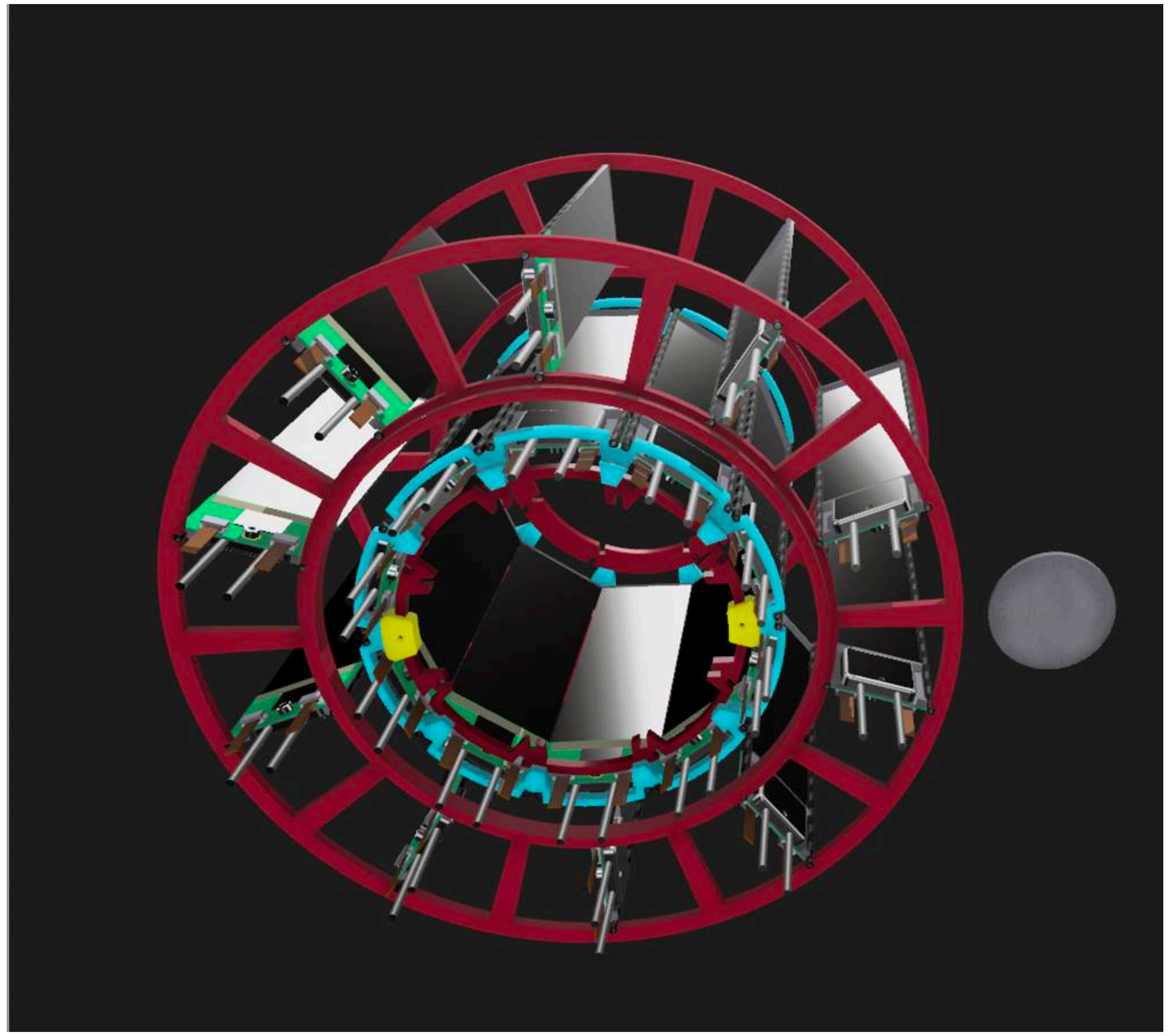
- **Technical** design: End of 2024
- **Construction** + **commissioning**: End of 2025
  - Technical support + workshop + space (Fibre cutting/sputtering/glueing and detector assembly) @ **granted** PSI
- muEDM Phase I (**frozen spin technique proof** + **data taking**): End of 2026

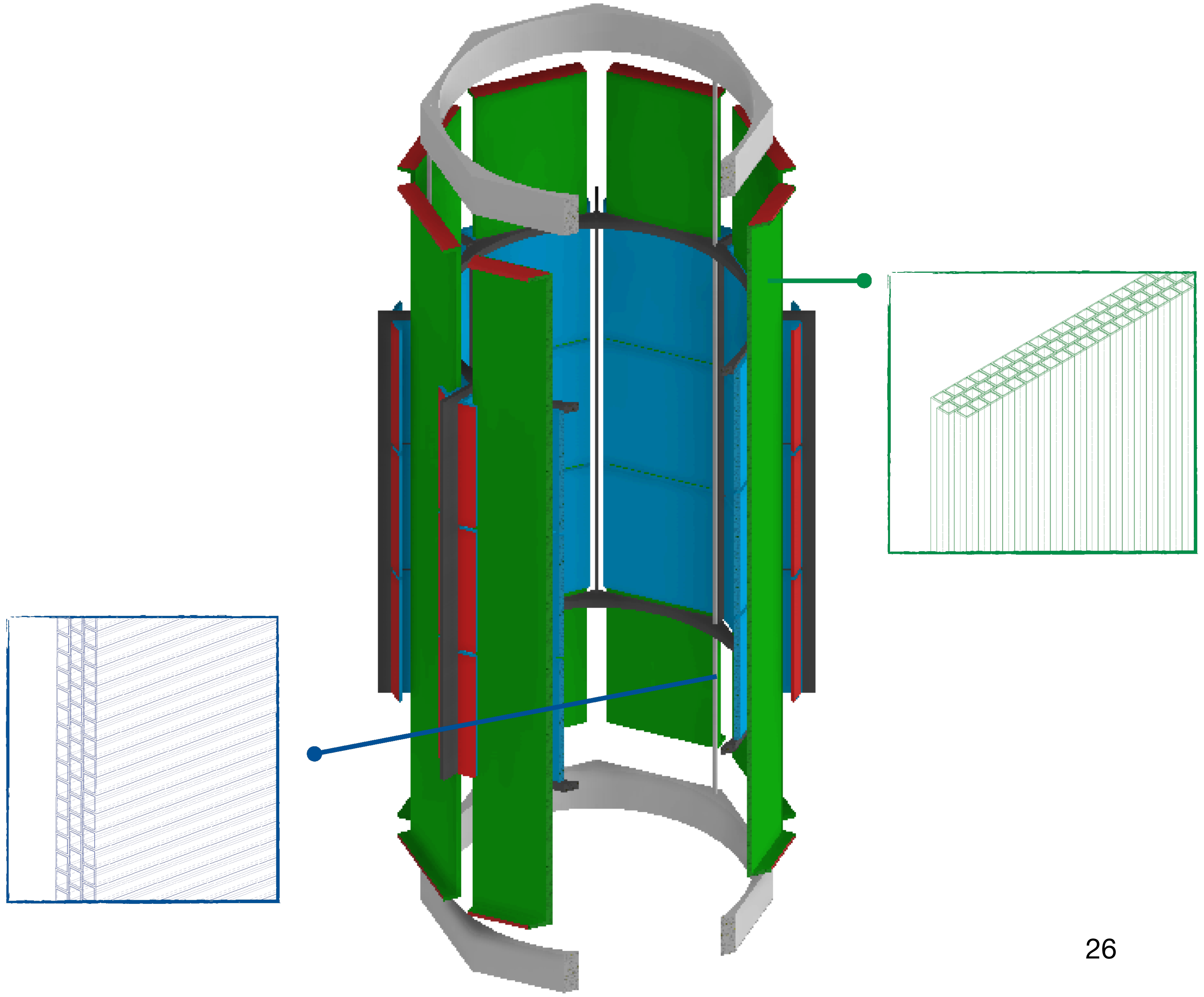


Positron tracker (Original proposal)

- Silicon strip detector (g-2) + SciFi (EDM)
- The performances of the current fibre only design are similar to the original proposal (Same physical program for Phase I)

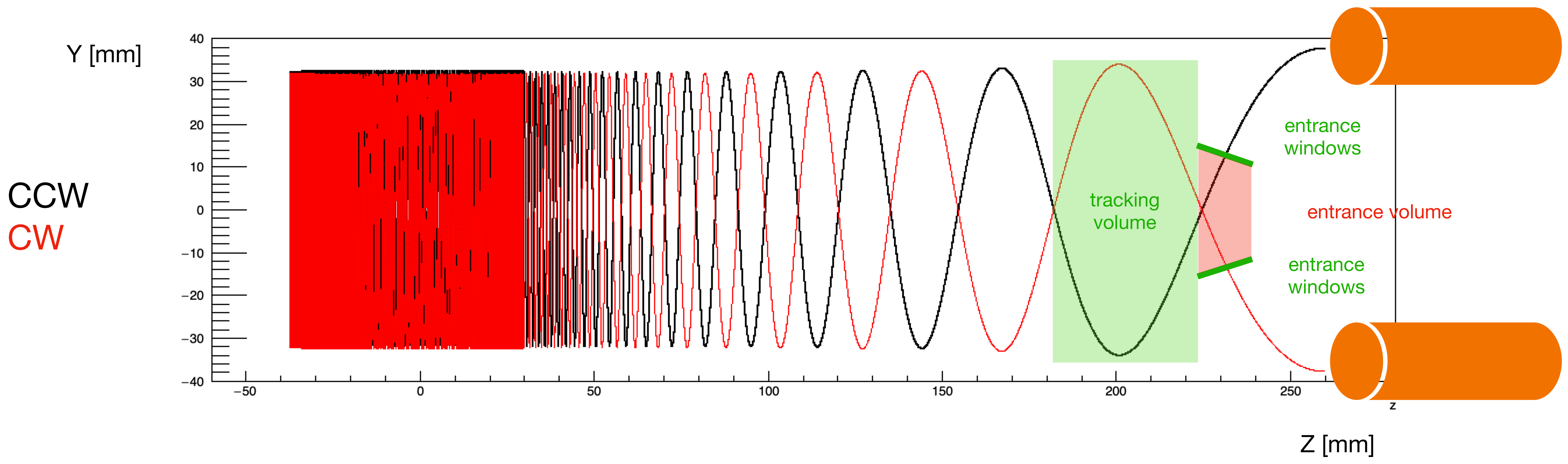




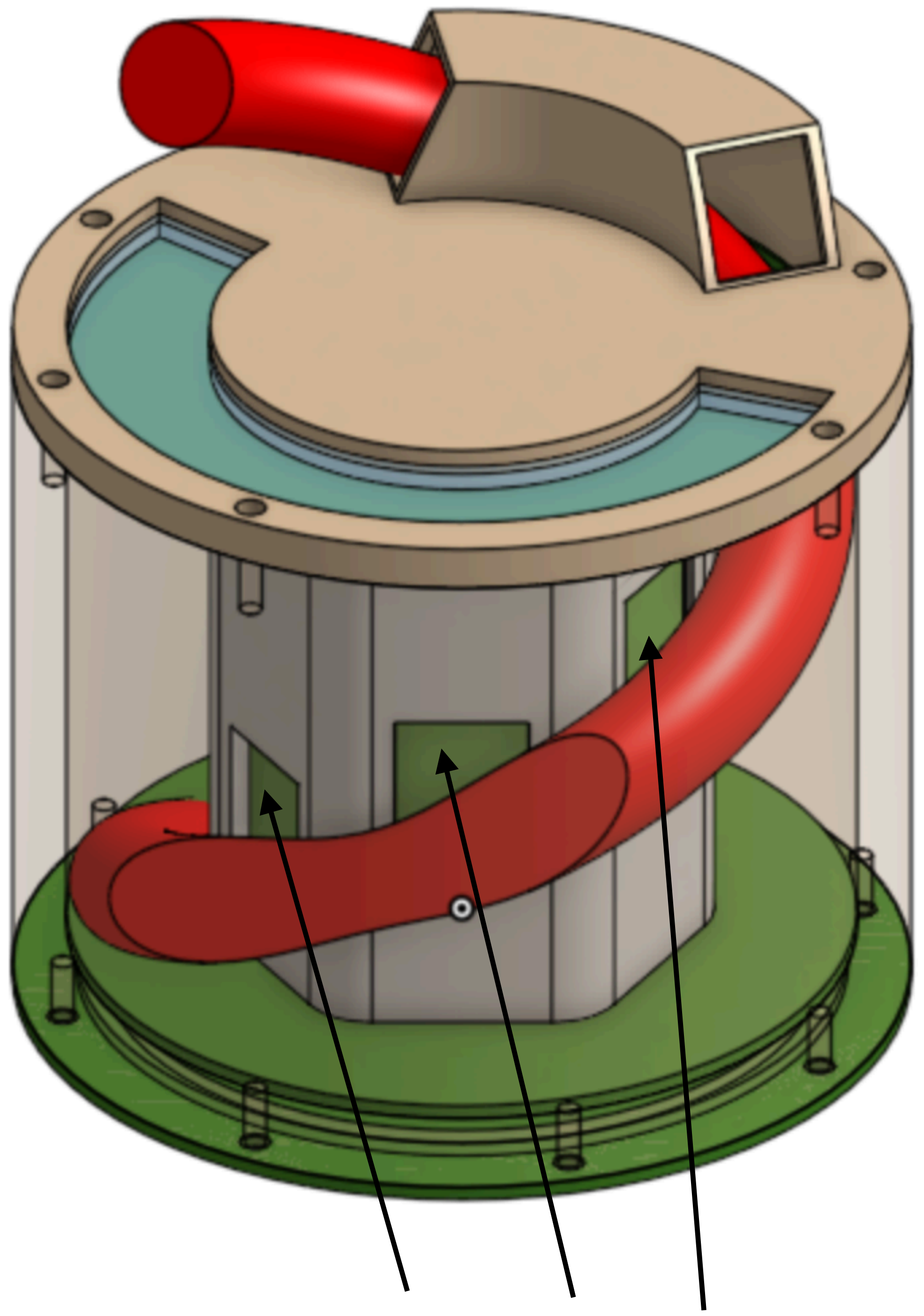


AUX detector: A TPC for muon trajectory characterisation

- Determination of the muon momentum difference between clockwise (CW) and counter-clockwise (CCW) injection within 0.5% precision —> essential for the control of the systematic uncertainties
- Determination of the phase space at the entrance of the magnet —> cross-check the alignment of beam, injection channels and magnet
- Schedule. Construction + commissioning: 2/4+3/4 of 2025. Beam characterisation: 4/4 of 2025



- Small TPC (few cm drift) with GridPix readout in two configurations:
  - longitudinal (optimized for momentum) and radial (optimized for angles)
- Extremely light material budget:
  - 400 nm silicon nitride windows, light helium-based gas mixture

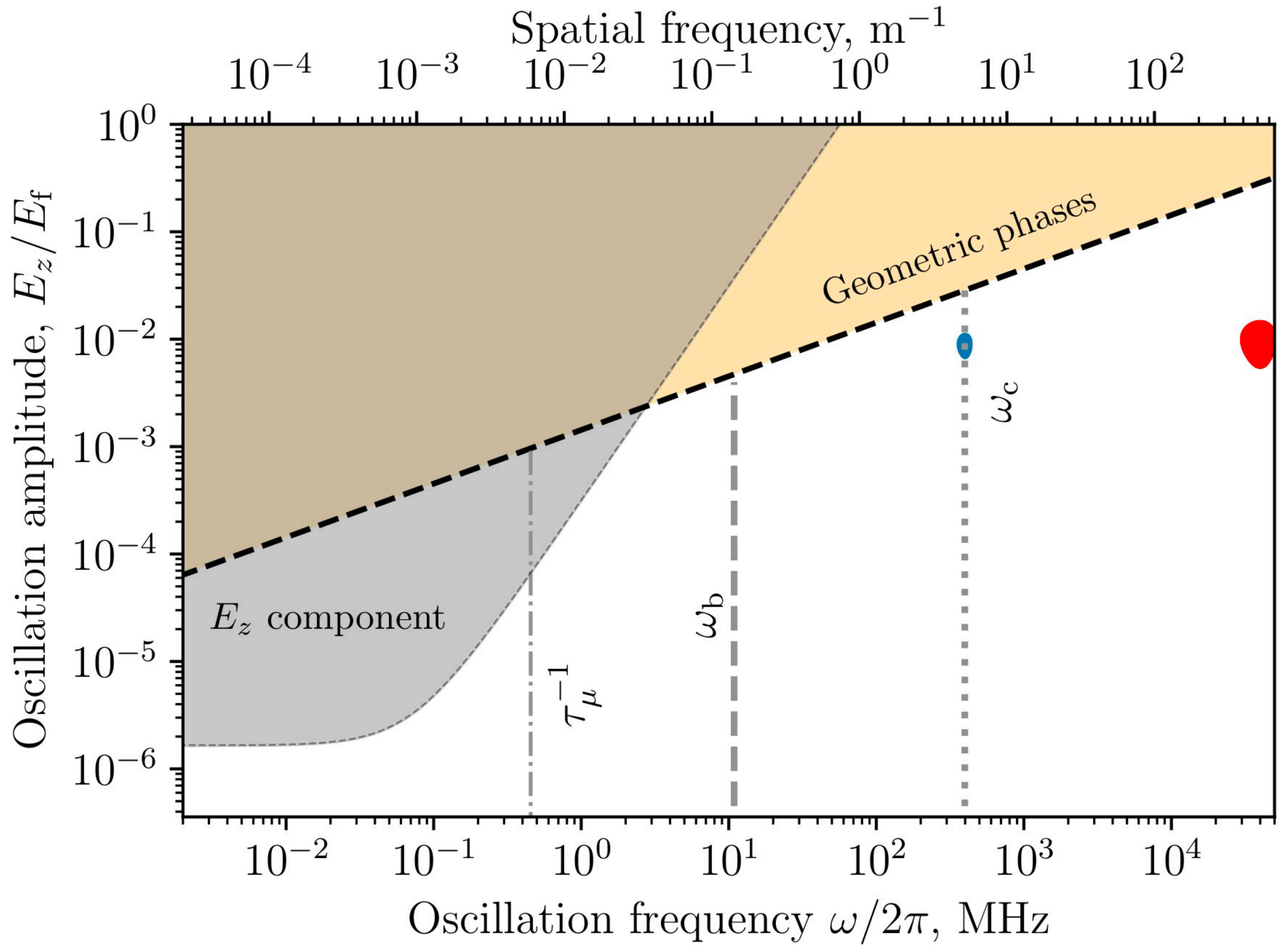


GridPix sensors
(to be duplicated for symmetric CW/CCW tracking)

More about Milestones 2023: Systematic effect study

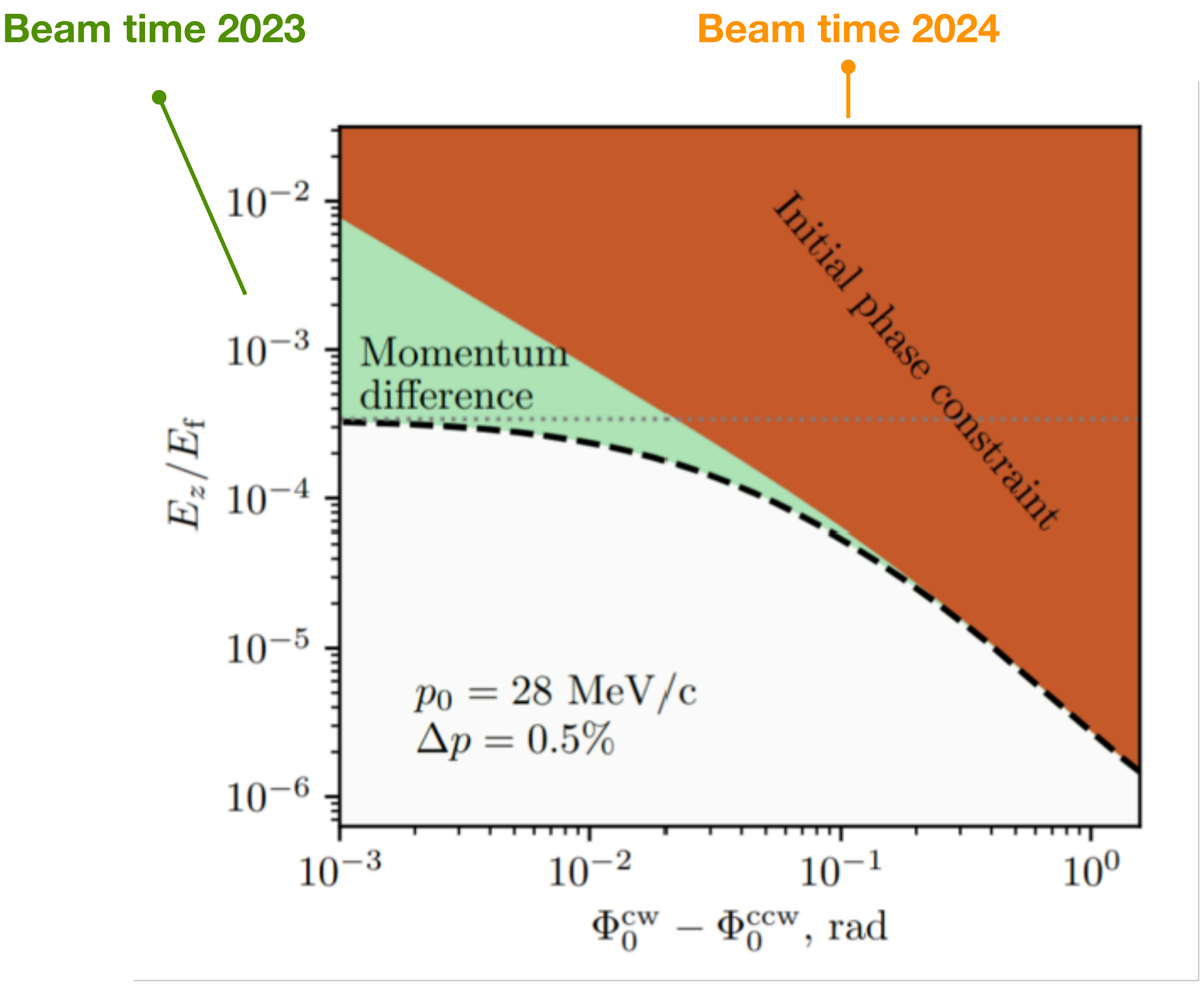
- Finished a comprehensive study on the possible systematic effects due to the anomalous magnetic moment mimicking the EDM signal (Published: EJP C)
- Possible effect due to electric field component perpendicular to muon momentum $\Omega \propto \vec{\beta} \times \vec{E}$
- Significantly mitigated by taking advantage of the CP-violating nature of the EDM and employing counter-rotating beams
  - Systematic stays the same while EDM flips sign

	μ	d	$\mathbf{s}$	$\mathbf{E}$	$\mathbf{B}$	$-d\,\mathbf{s}\cdot\mathbf{E}$	$-\mu\,\mathbf{s}\cdot\mathbf{B}$
parity	+	+	+	-	+	$(++-)=-$	$(+++)=+$
time	+	+	-	+	-	$(+-+)=-$	$(+--)=+$
charge	-	-	+	-	-	$(-+-)=+$	$(-+-)=+$
charge & parity	-	-	+	+	-	$(-++)=-$	$(-+-)=+$



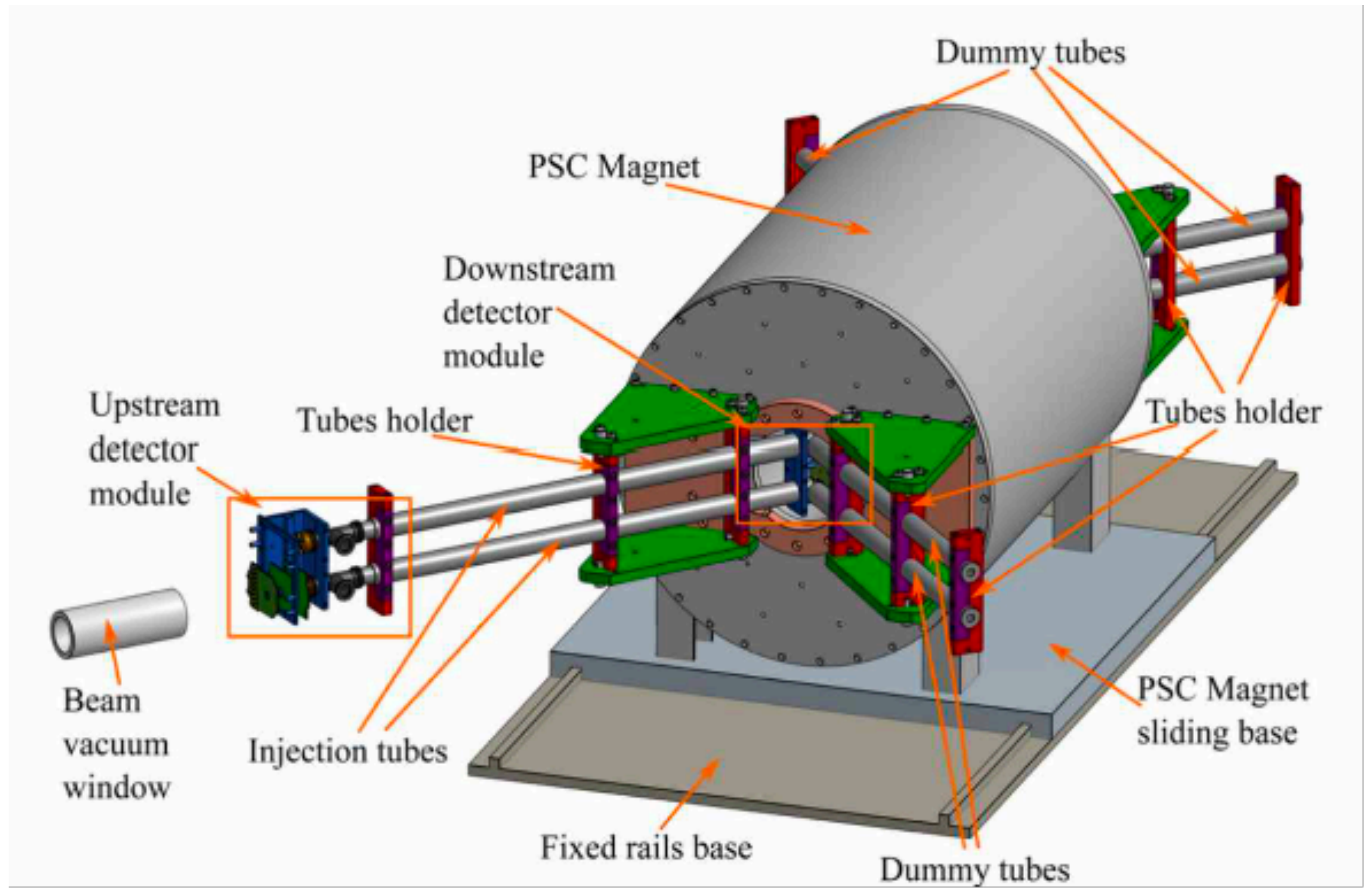
Milestones 2023: Systematic effect

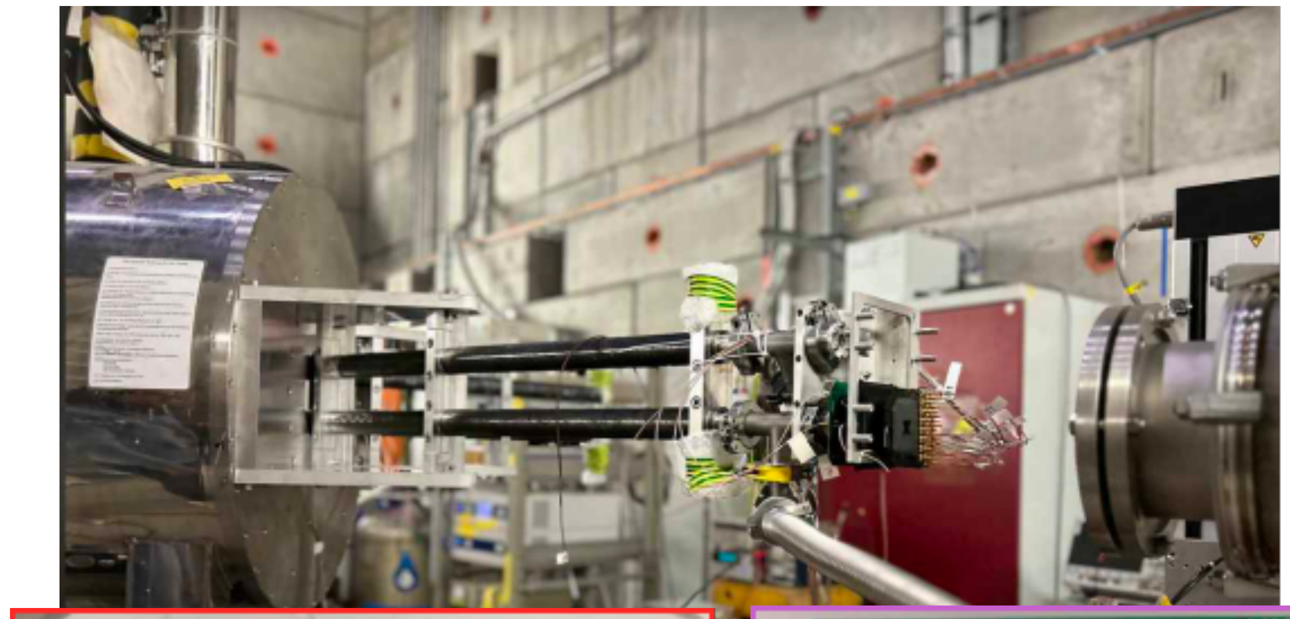
- Cancellation of the systematic effect works only if initial conditions in the positive/negative B-field setup are similar
  - One needs to keep the difference in mean muon momentum **within 0.5%**
  - The difference in mean g-2 phase at the time of injection must be **below 25 mrad**
- Experiment planned to show the control of this parameter
  - Beam time **2023** & 2024

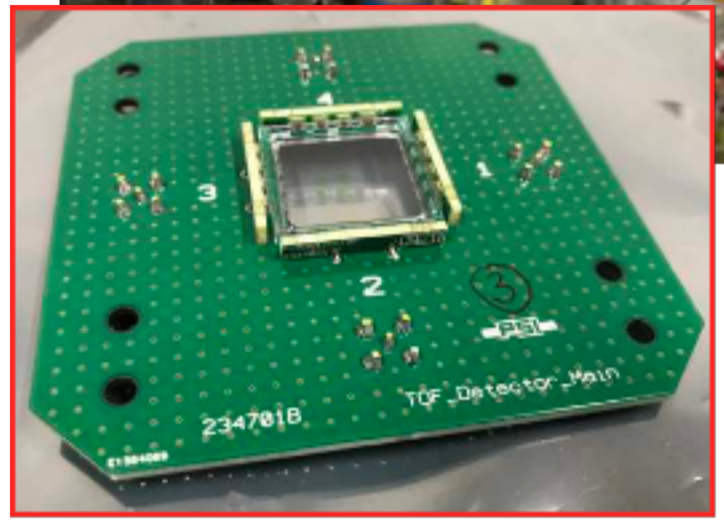


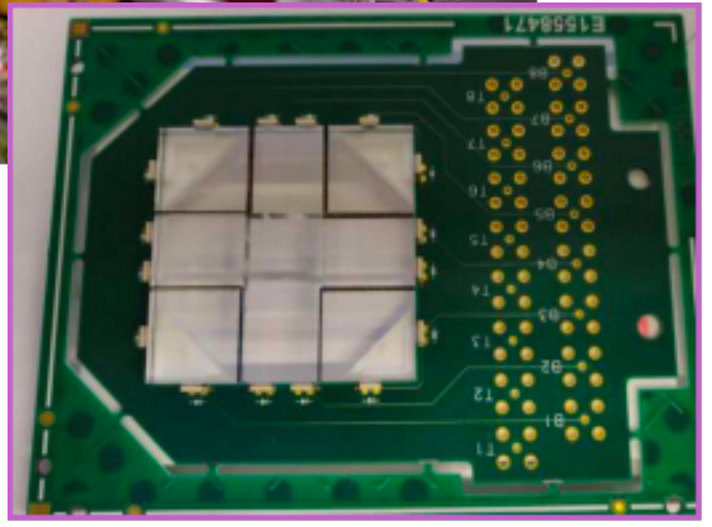
Milestones beam time 2023: All accomplished

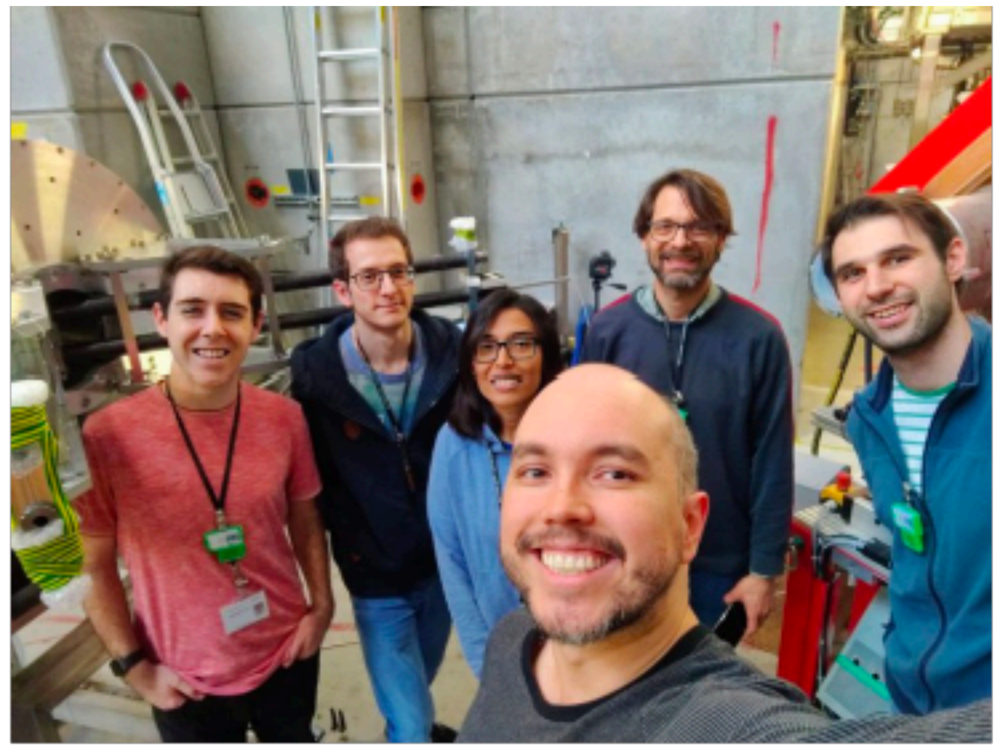
- Show control of the momentum of injected muons by measurements of the **ToF** through injection tubes
- Reproducibility of muon momentum distribution for **positive** and **negative** magnetic field
- Fringe field shielding and hysteresis studies
- Tests of a **beam monitor** to center the beam on the injection channel

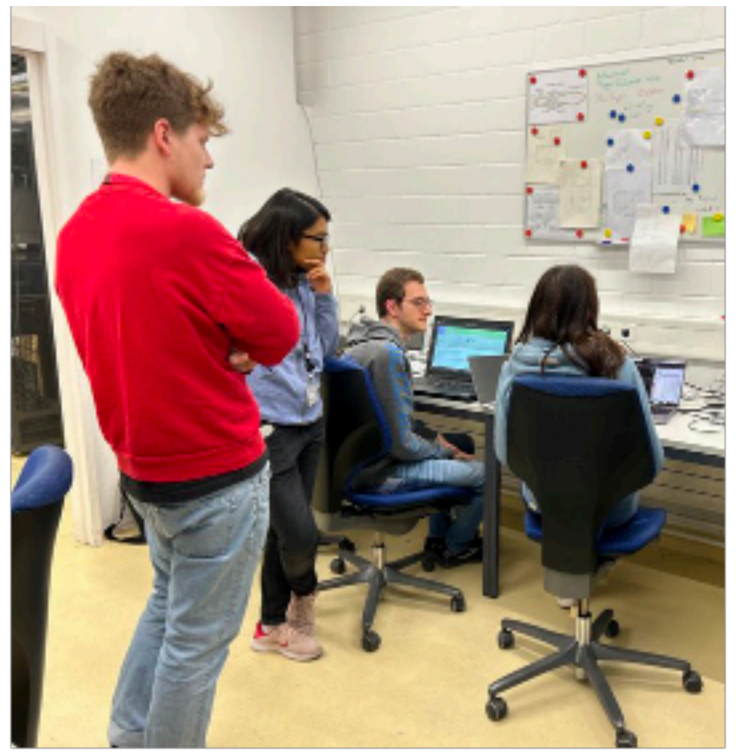






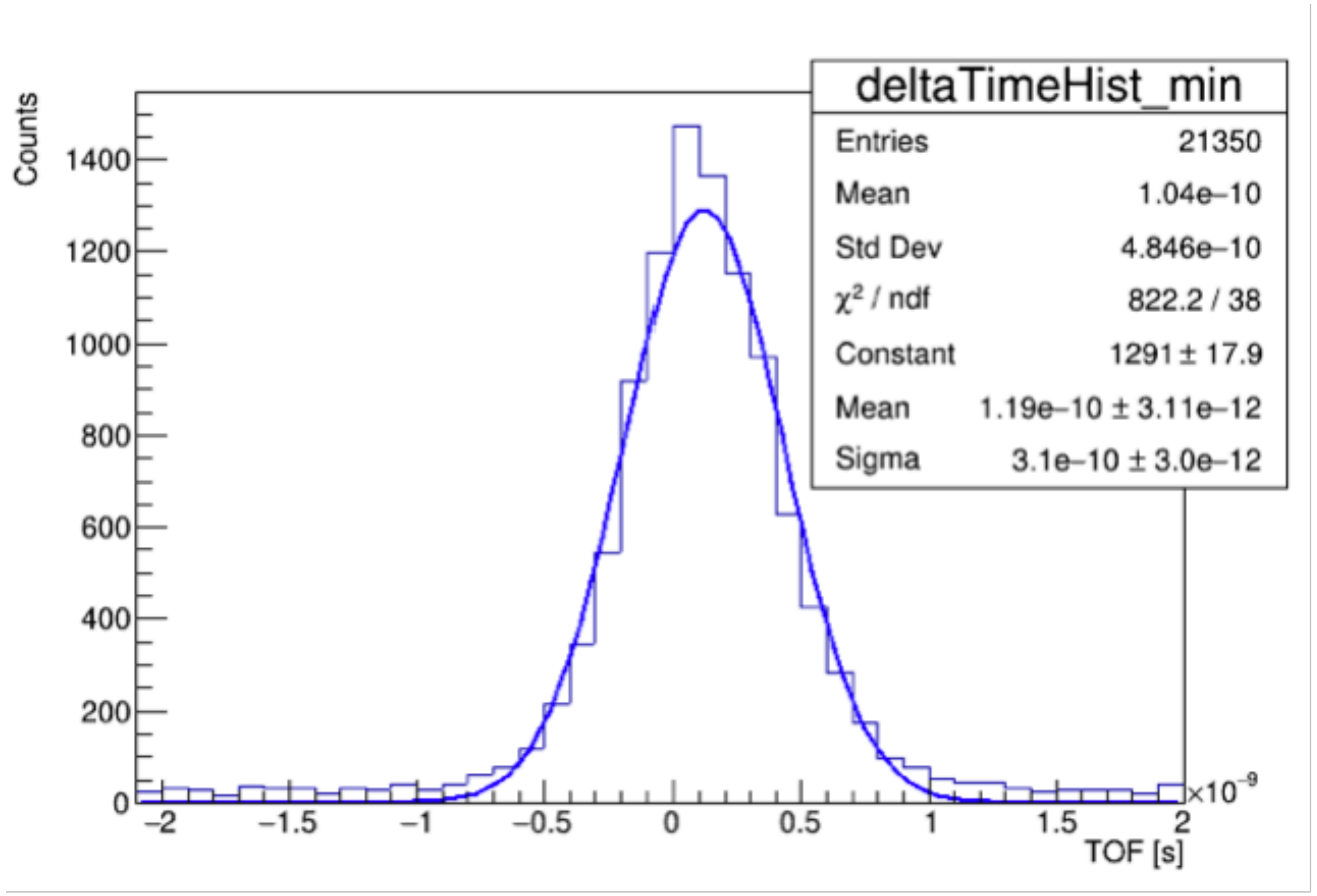


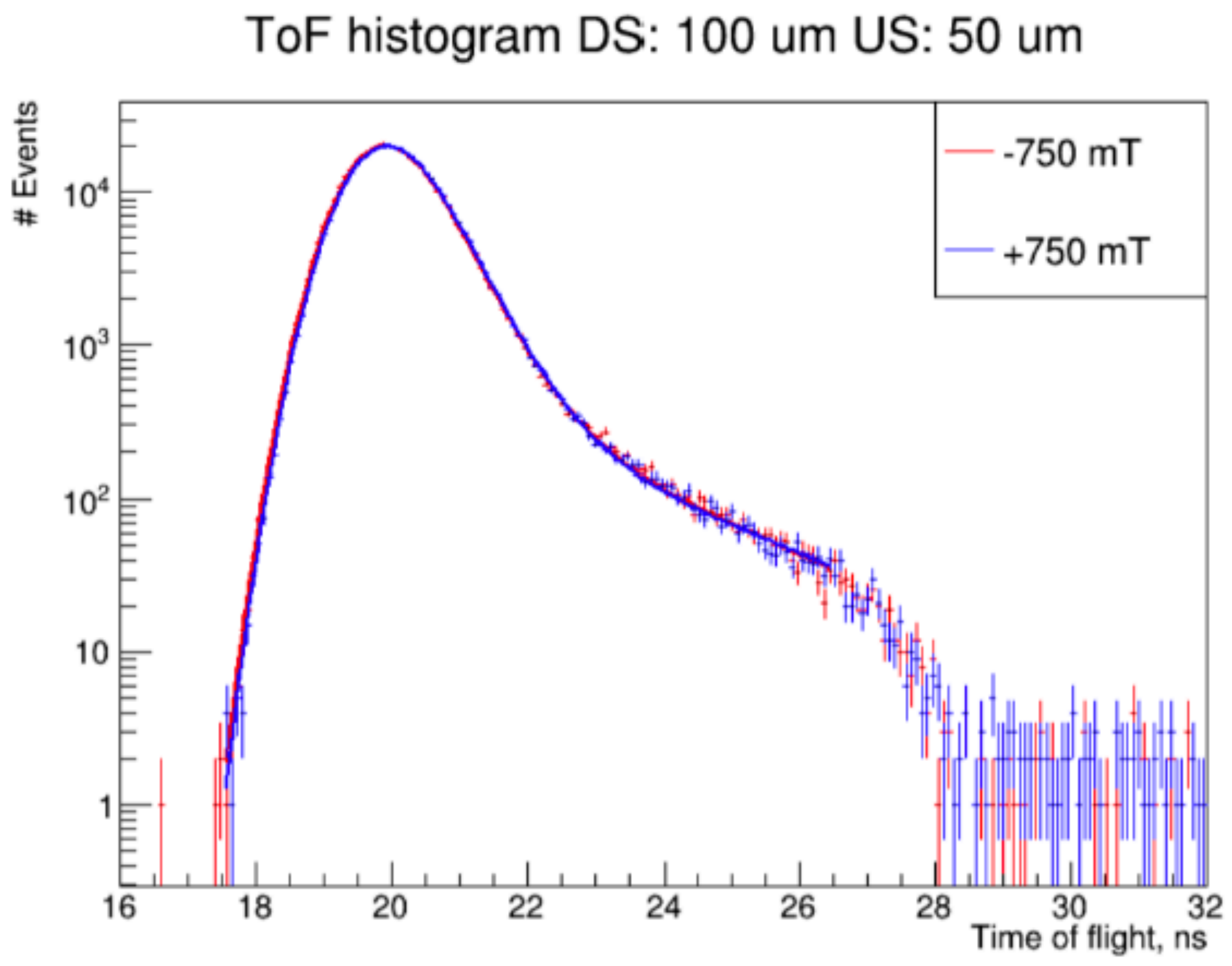




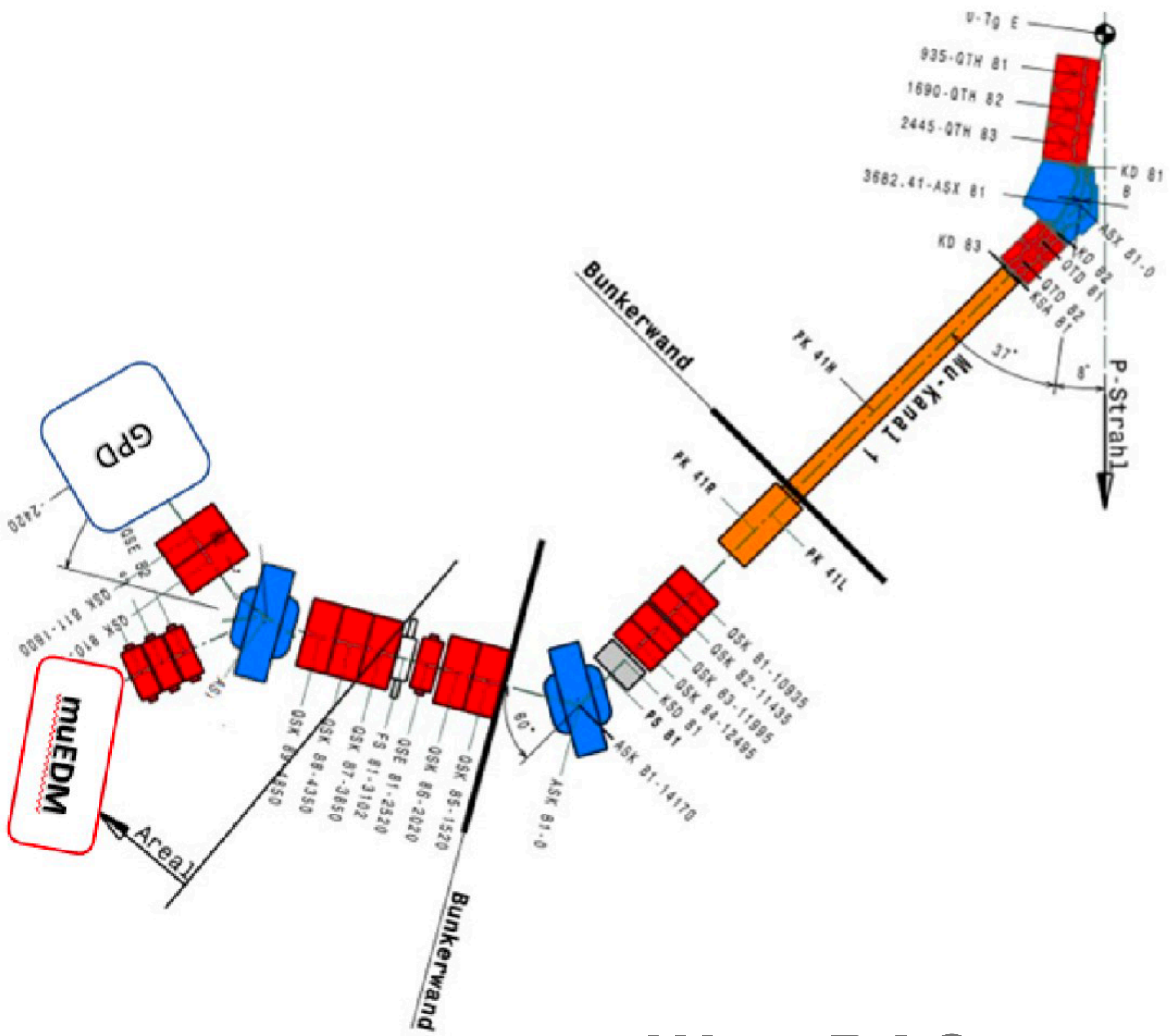
Beam time 2023: Major results

- First results show very good timing resolution on individual muons (**~300 ps**)
- ToF spectra for **positive** and **negative** magnetic field configuration with mean values within less than 0.2% difference
- Strong indications that **momentum control below 0.5%** is achievable



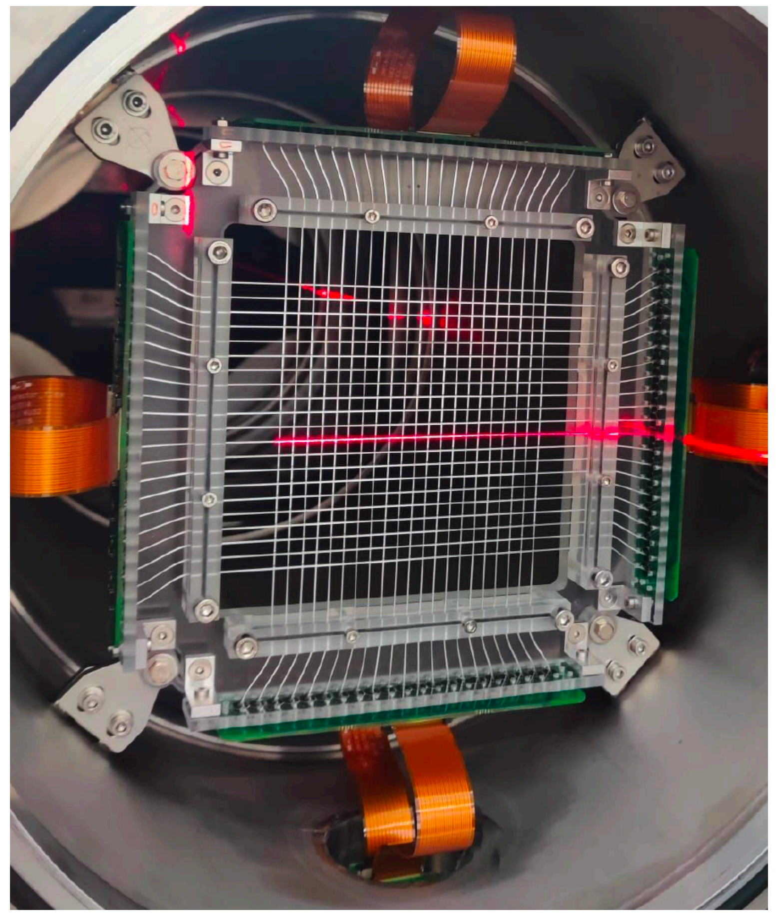


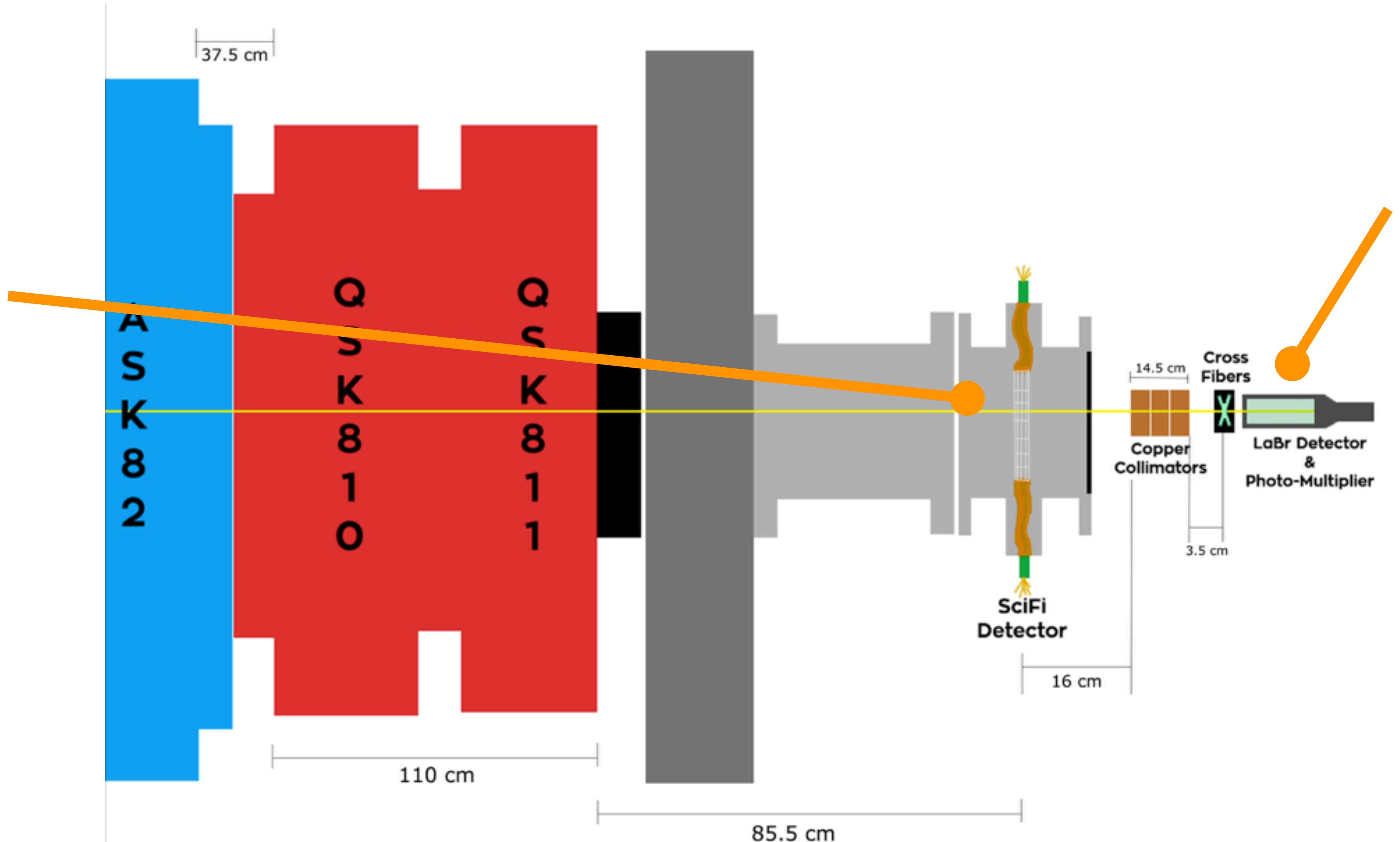
Beam time 2024: muE1 (done)



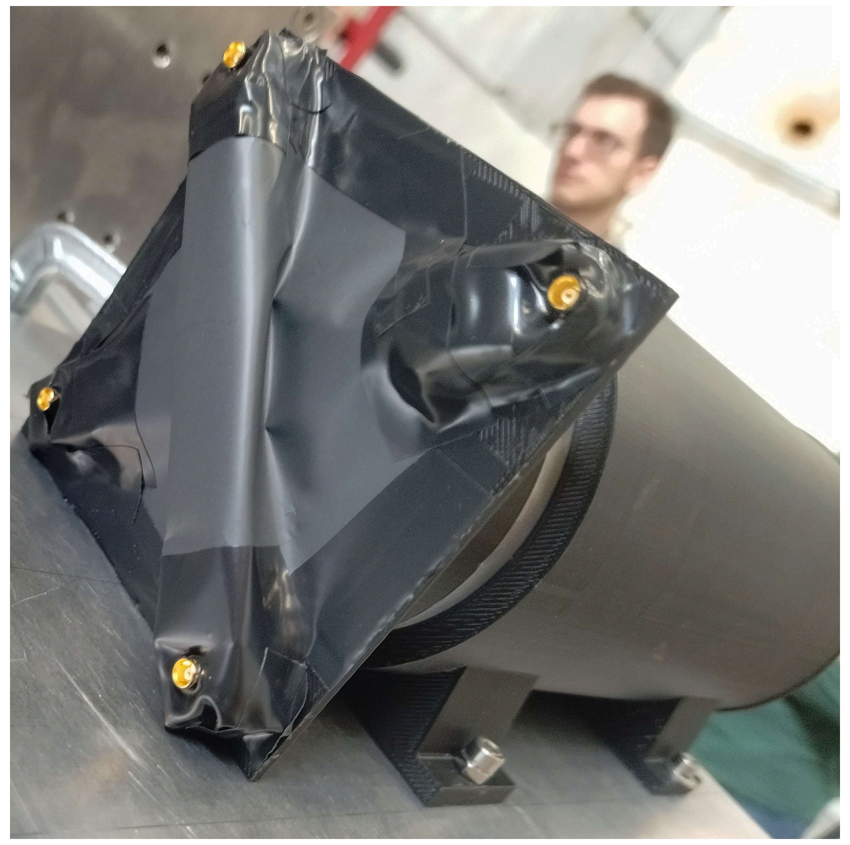
- Goal: Characterize the 4D lateral **phase space of the muE1** beam in Z-configuration
- Z-configuration permits operation of the
  - GPD muSR instrument - GIANT instrument
  - and the **future muEDM** on the same beam line
- **Very successful:** Data analysis ongoing !
  - Our contributions
    - Measurement **technique proposal** (6D phase space + RF reference)
    - **SciFi+BC400X+LaBr** detectors readout with **WaveDAQ** (Trigger+DAQ settings)

SciFi





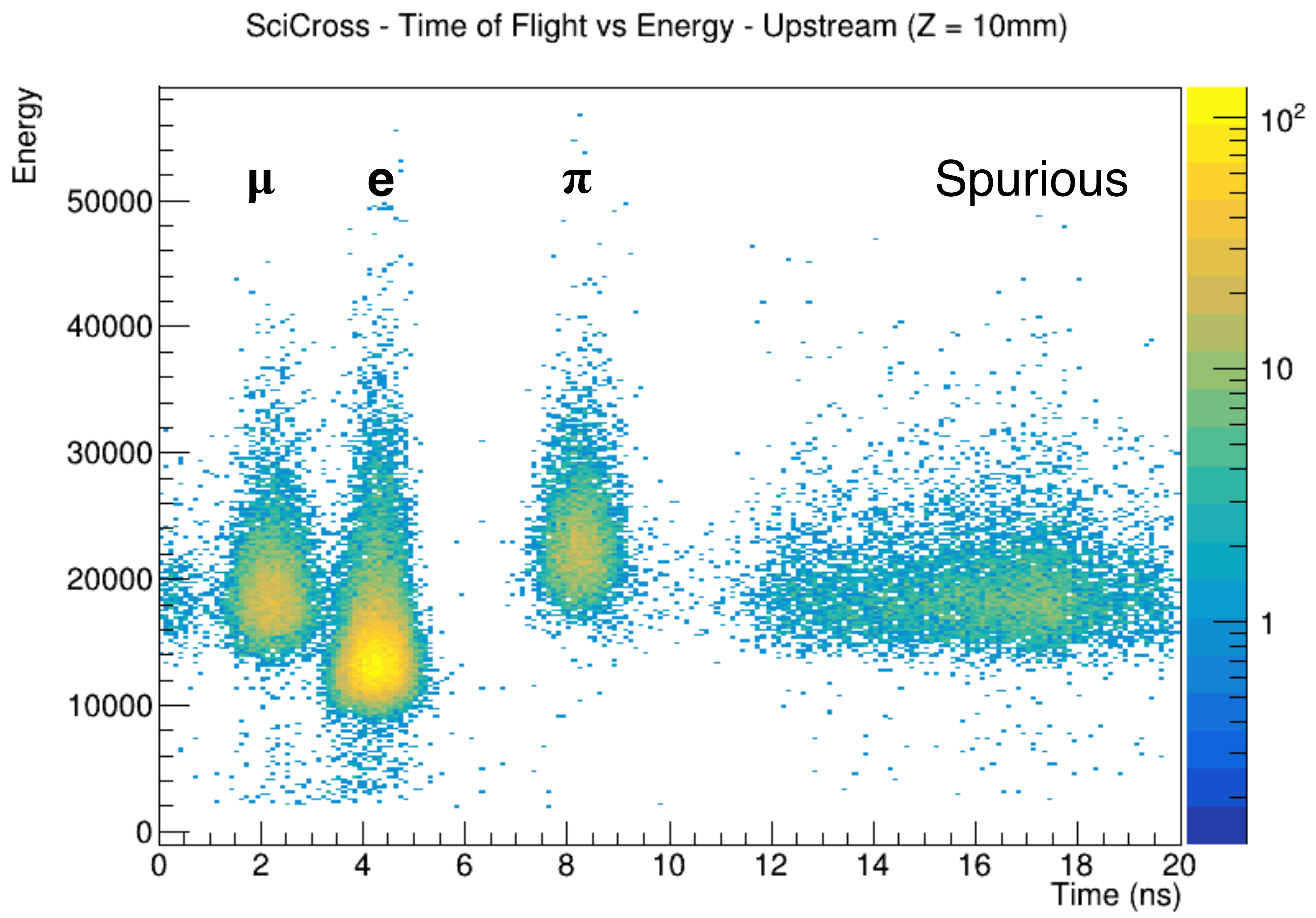
BC400-X & LaBr

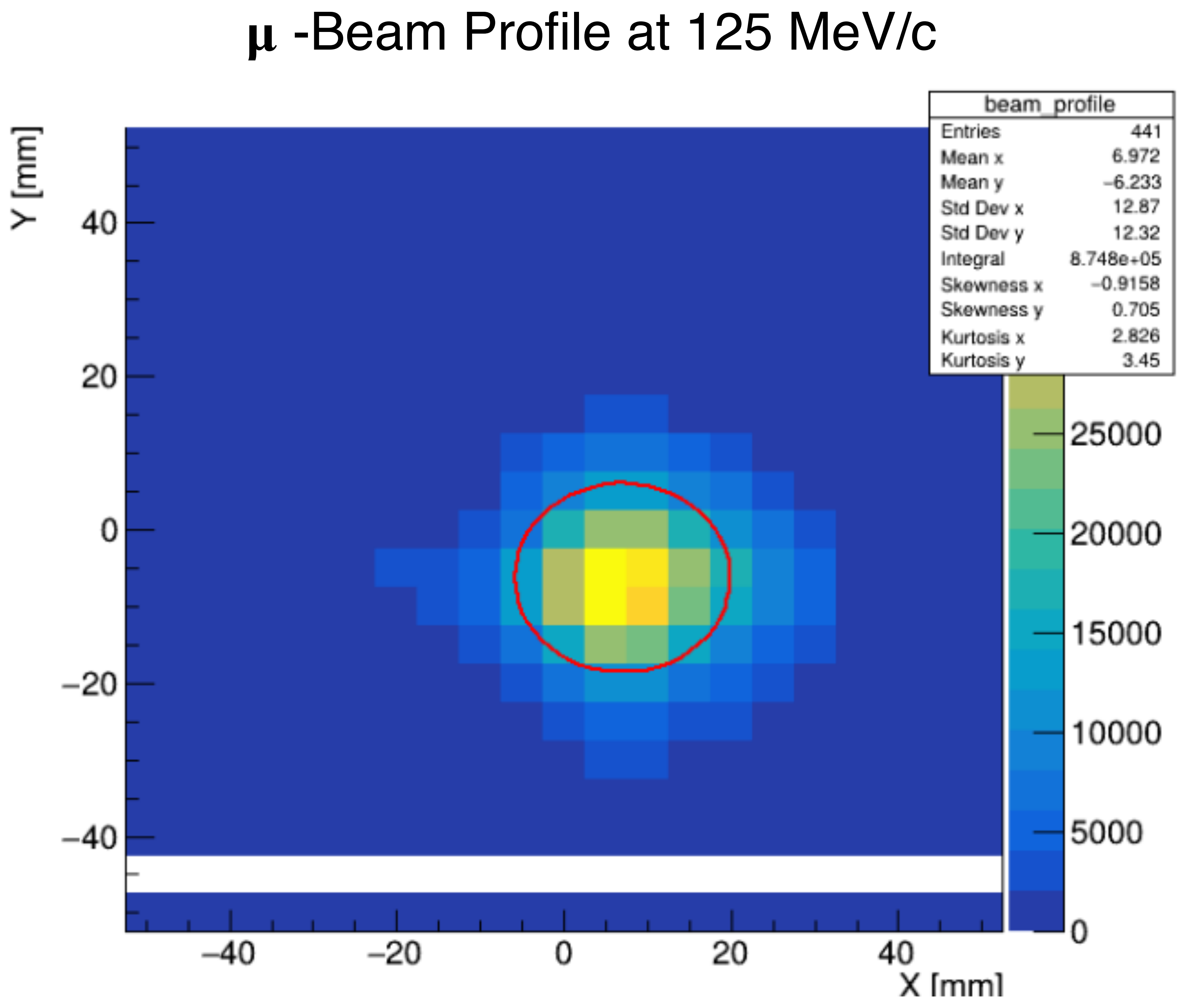


WaveDAQ

Some preliminary results

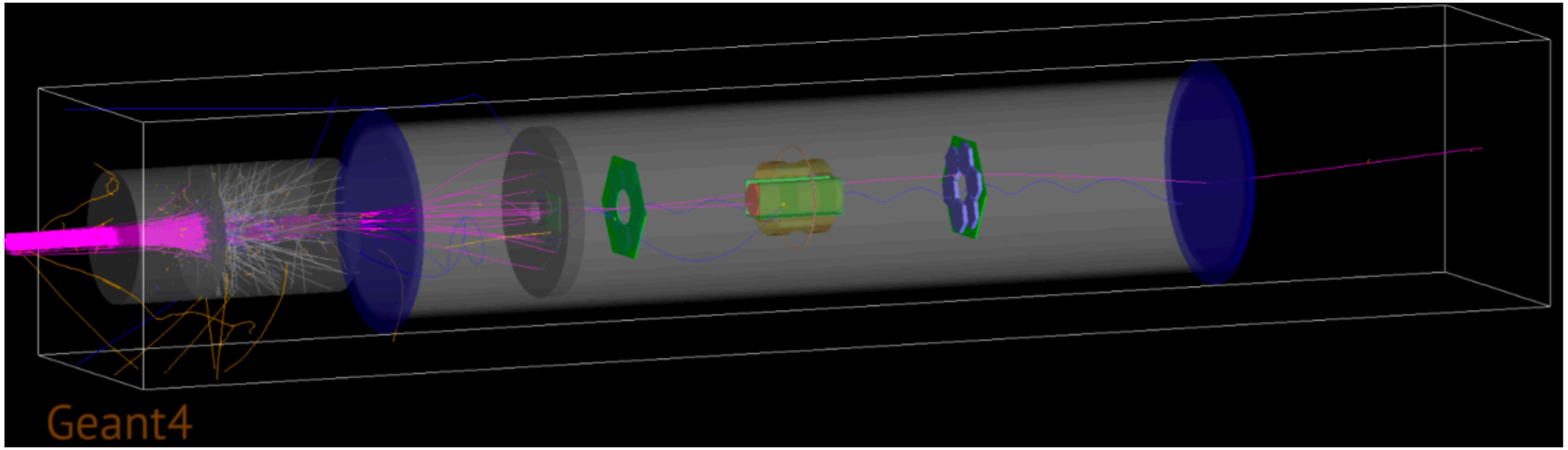
- Clear separation among muons/positrons/pions with RF
- An example of beam profile as measured by SciFi+WaveDAQ

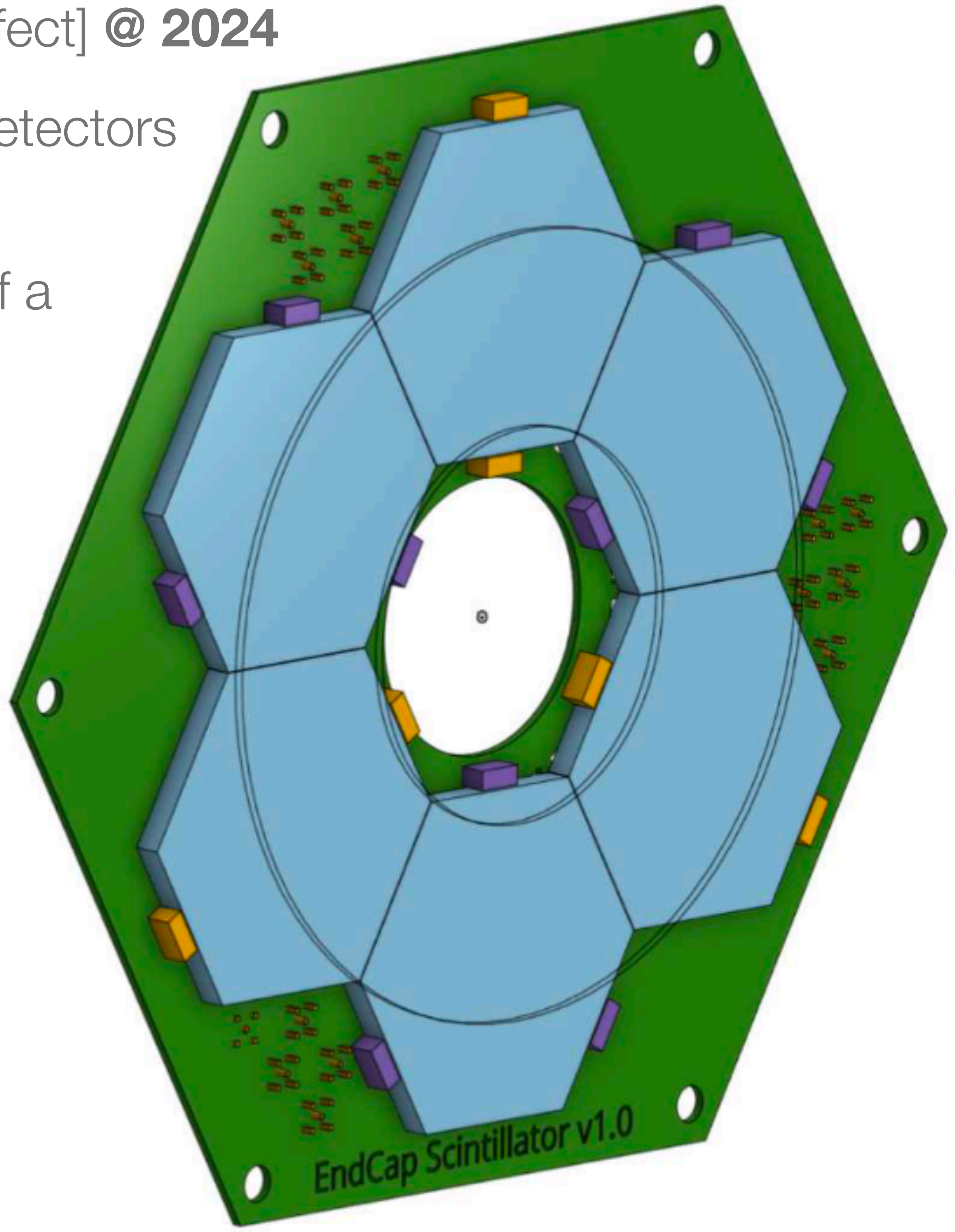




Beam time 2024: piM1

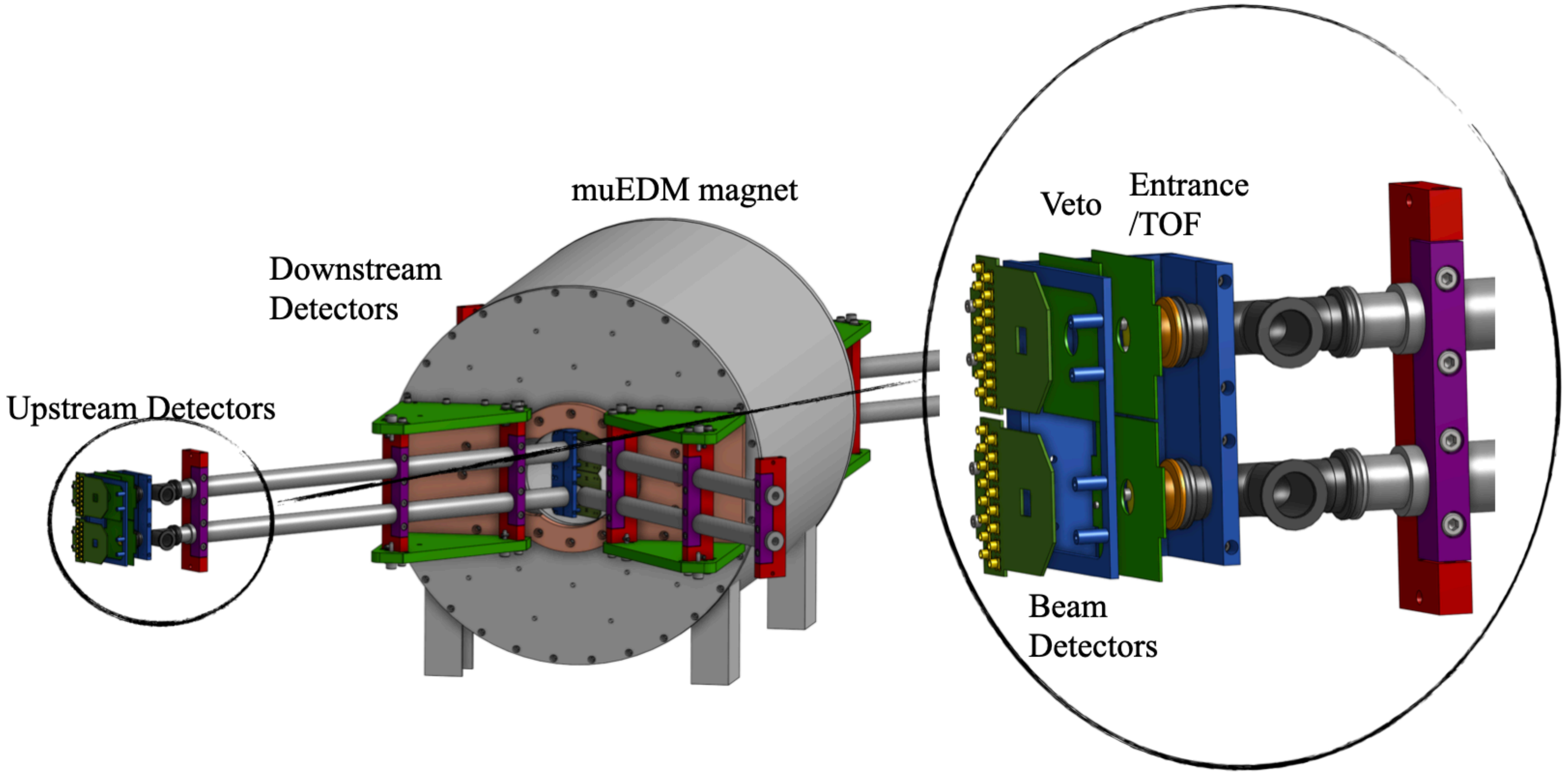
- Test of the Exit detector
- The purpose of the detector is two-fold
  - Optimise the correction coil and kicker current for the best muon spiral injection
  - Study time-dependent detection changes due to the kicker pulse [source of a possible systematic effect] **@ 2024**
- Procedure: Measure the positron decay asymmetry as a function of time post-magnetic kick using two detectors placed on the sides of a stopping target for 200 MeV/c pions inside the 3 T solenoid field.
- Source of uniformly distributed positrons → any asymmetry change correlated to the kick will be a sign of a systematic effect
  - Some dedicated detector already prepared and tested

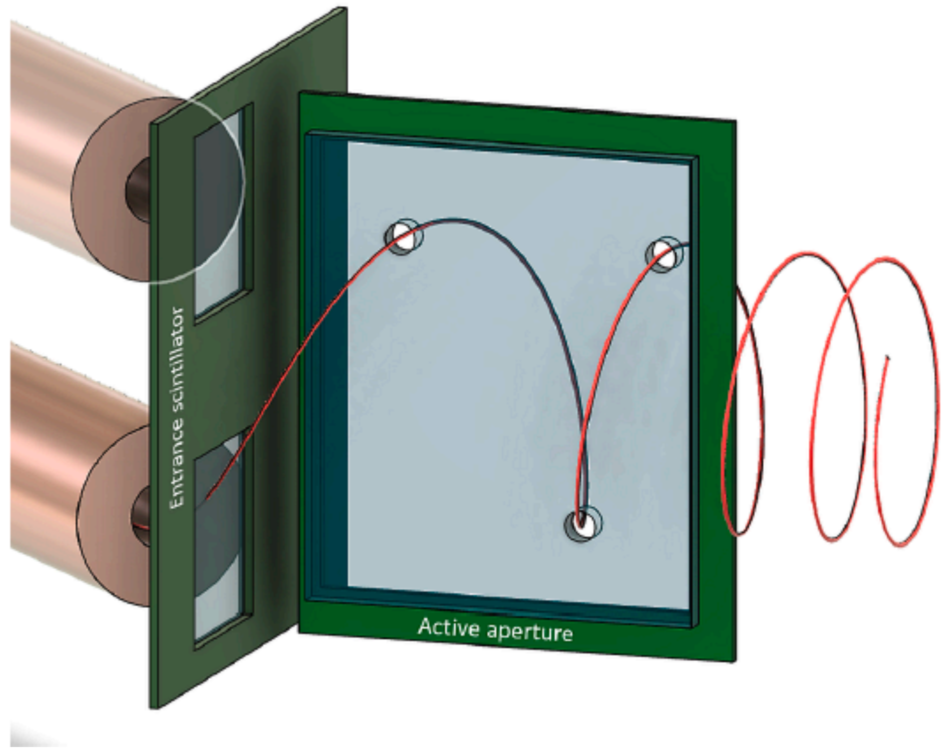


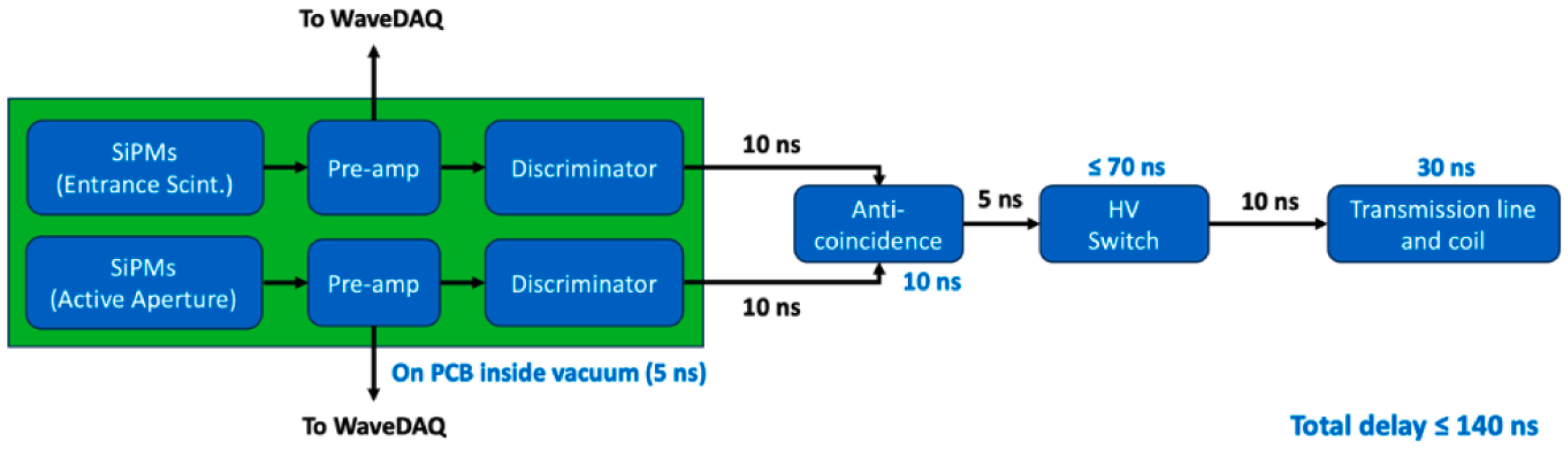


Beam time 2024: piE1

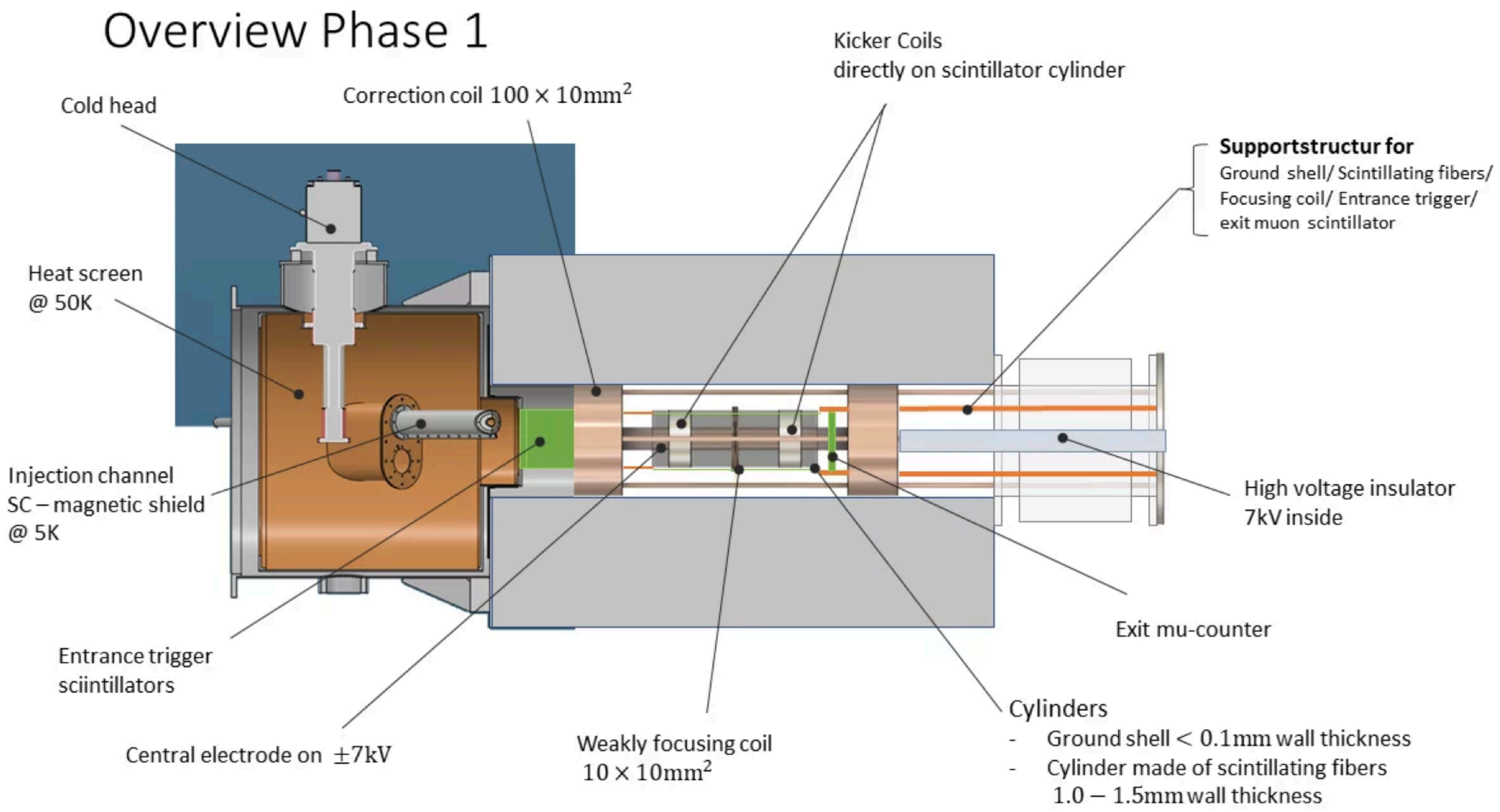
- Test the double injection moving the magnet up/down as expected for the CW and CCW injection
  - Beam monitoring/TOF/Complete Entrance Detectors (including the anti-coincidence)
- Test in final conditions of the trigger from the Entrance detector



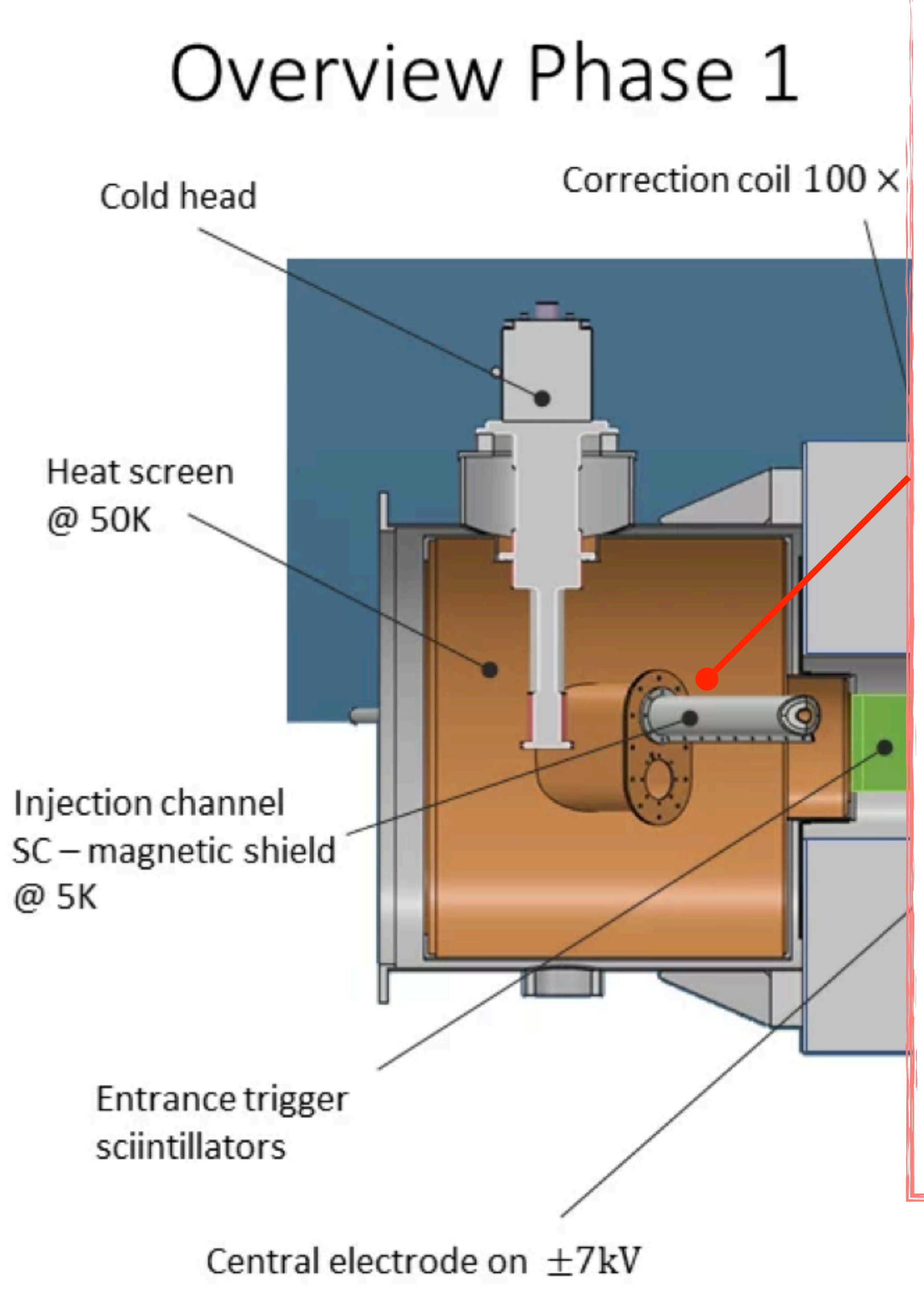




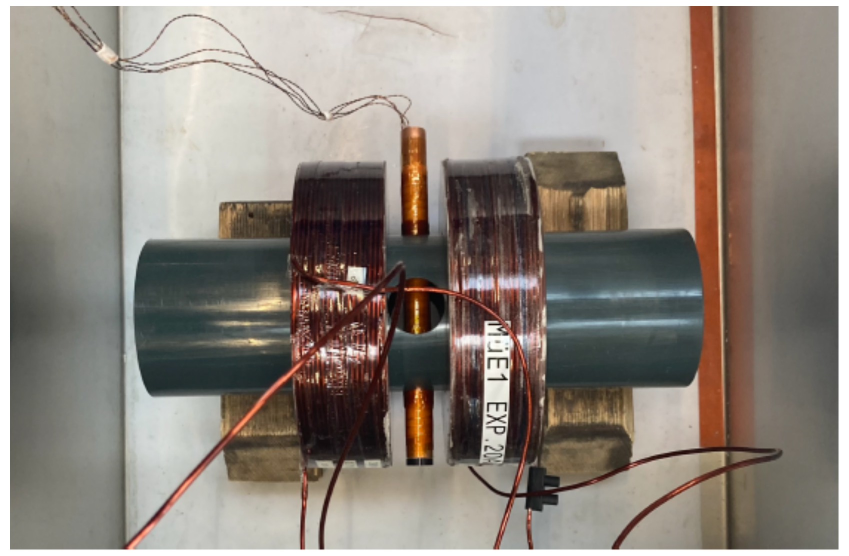
Summary

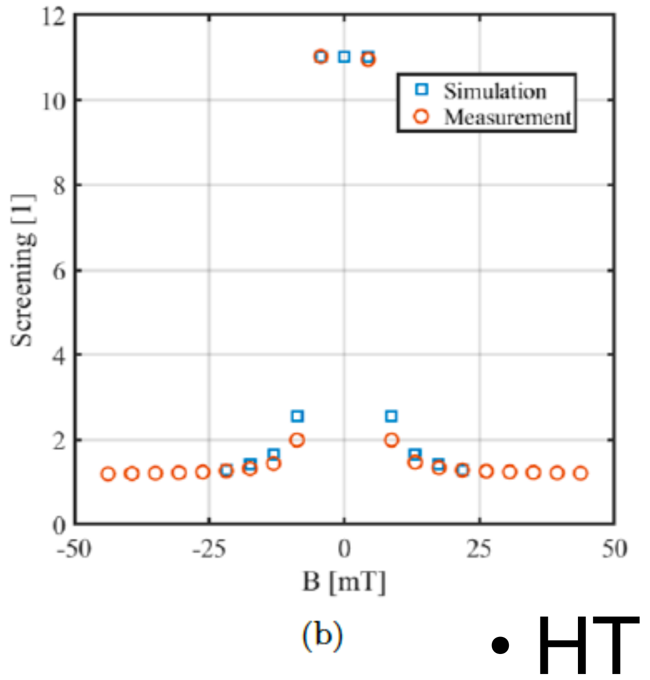

Overview Phase 1
Kicker Coils
directly on scintillator cylinder
Correction coil $100 \times 10\mathrm{mm}^2$
Cold head
Supportstructur for
Ground shell/ Scintillating fibers/
Focusing coil/ Entrance trigger/
exit muon scintillator
Heat screen
@ 50K
Injection channel
SC – magnetic shield
@ 5K
High voltage insulator
7kV inside
Exit mu-counter
Entrance trigger
sciintillators
Central electrode on $\pm 7\mathrm{kV}$
Weakly focusing coil
$10 \times 10\mathrm{mm}^2$
Cylinders
- Ground shell $< 0.1\mathrm{mm}$ wall thickness
- Cylinder made of scintillating fibers
$1.0 - 1.5\mathrm{mm}$ wall thickness

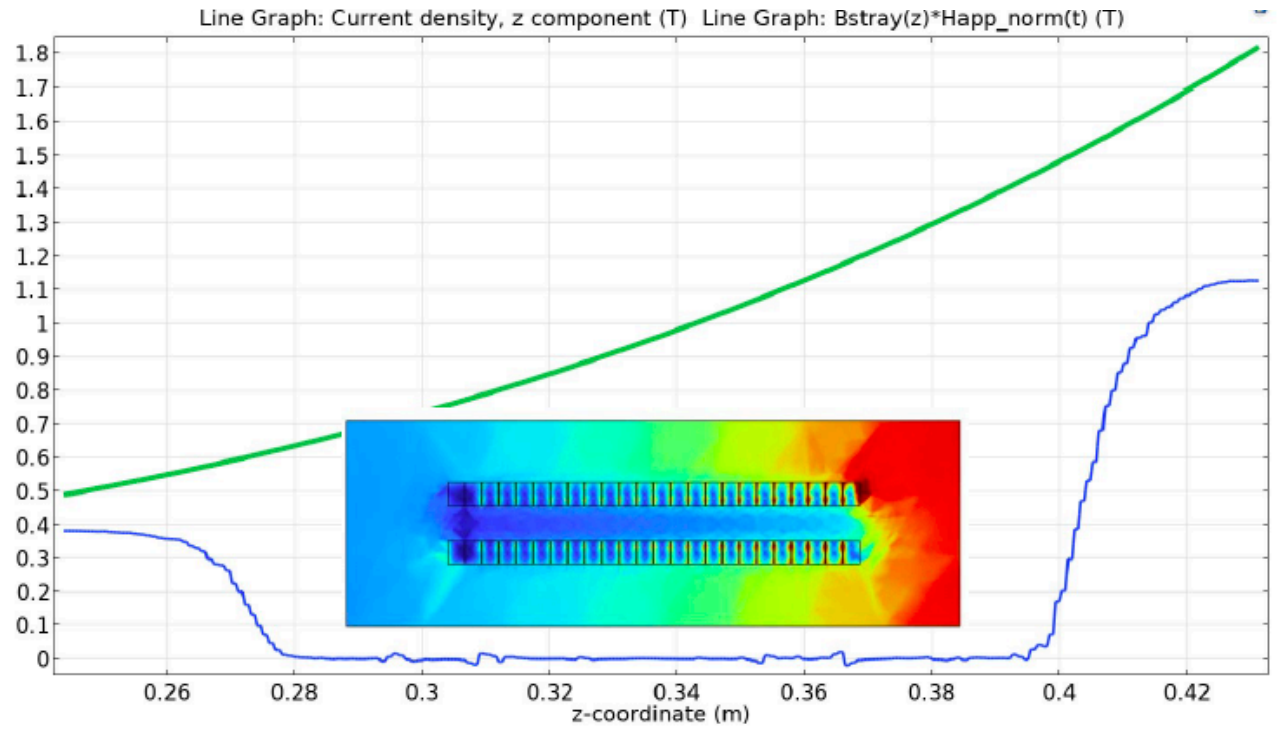
Summary



First SC-prototypes test





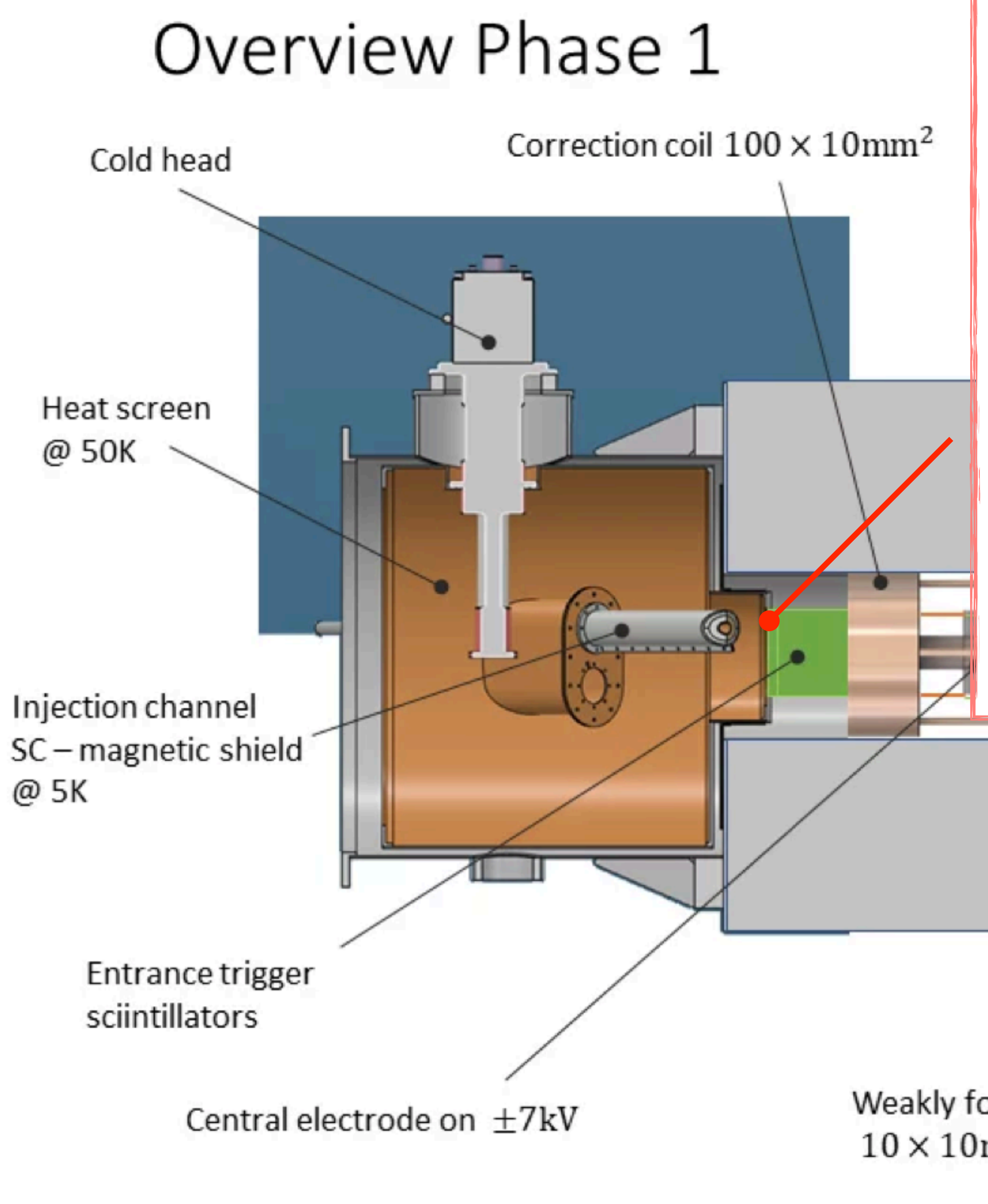


- HT SC YBCO-tape
- HT SC Bi-2223
- Shielding factor demonstrated and in agreement with MC
- Final: HT Bi-2223 + REBCO disks
- Other option: LT Nb-Ti/Nb/Cu SC sheet
- Cryo-cooler: Expected for Feb2025

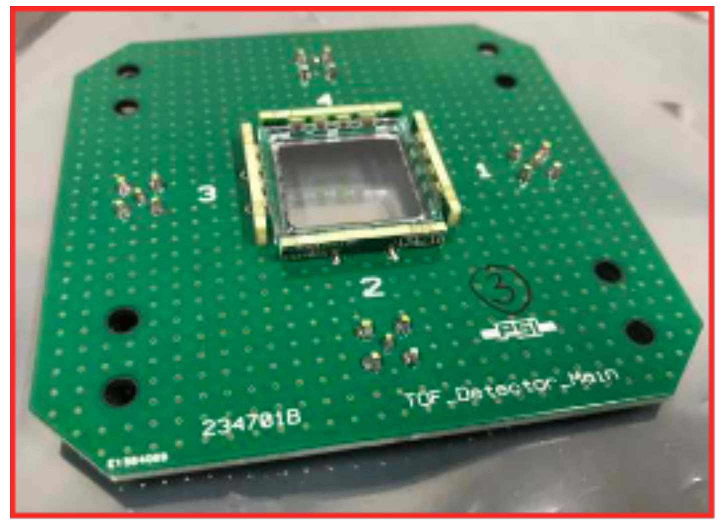
Weakly focusing coil
$10 \times 10 mm^2$

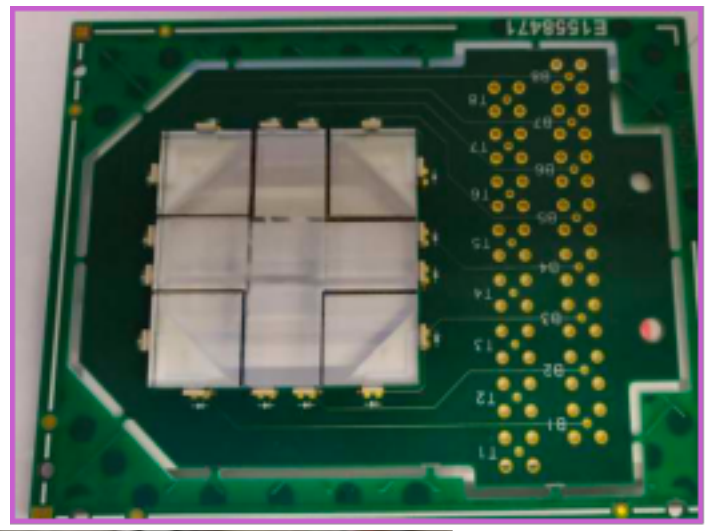
- Ground shell < 0.1mm wall thickness
- Cylinder made of scintillating fibers
$1.0 - 1.5$mm wall thickness

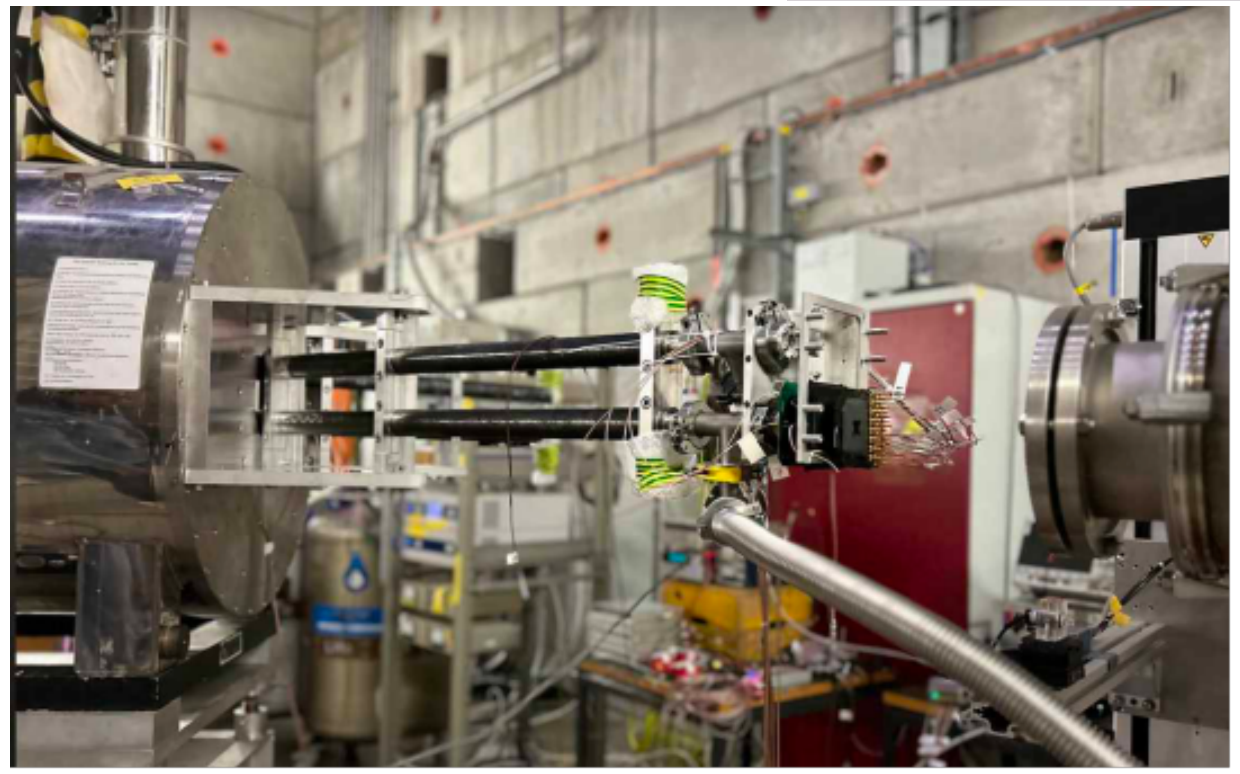
Summary

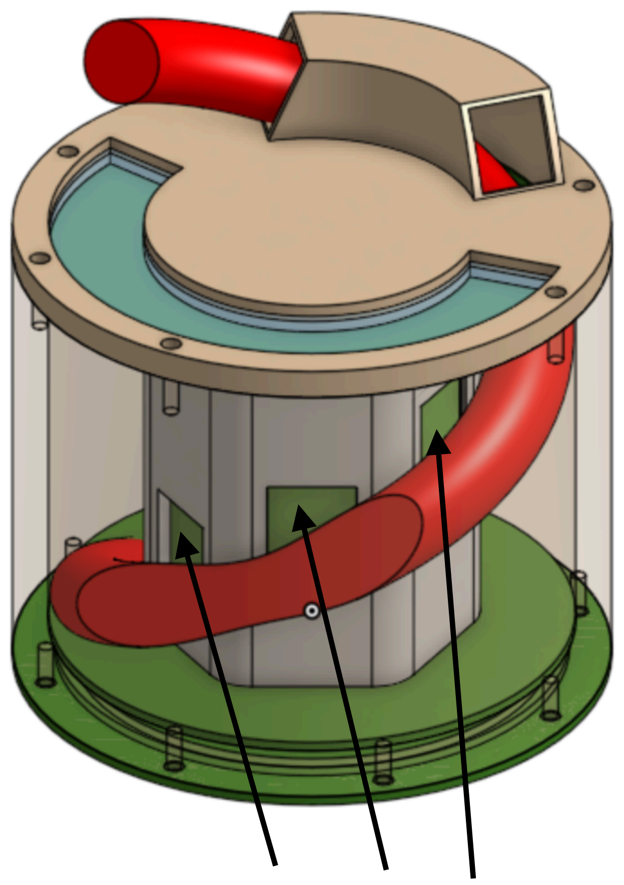


Beam monitoring/Entrance/TOF/ Muon Chamber





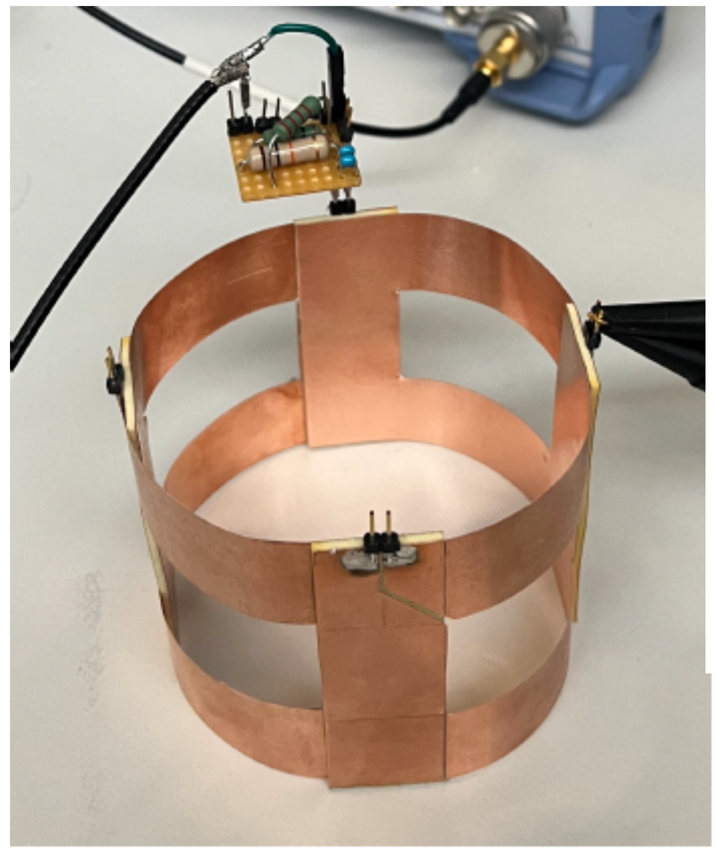


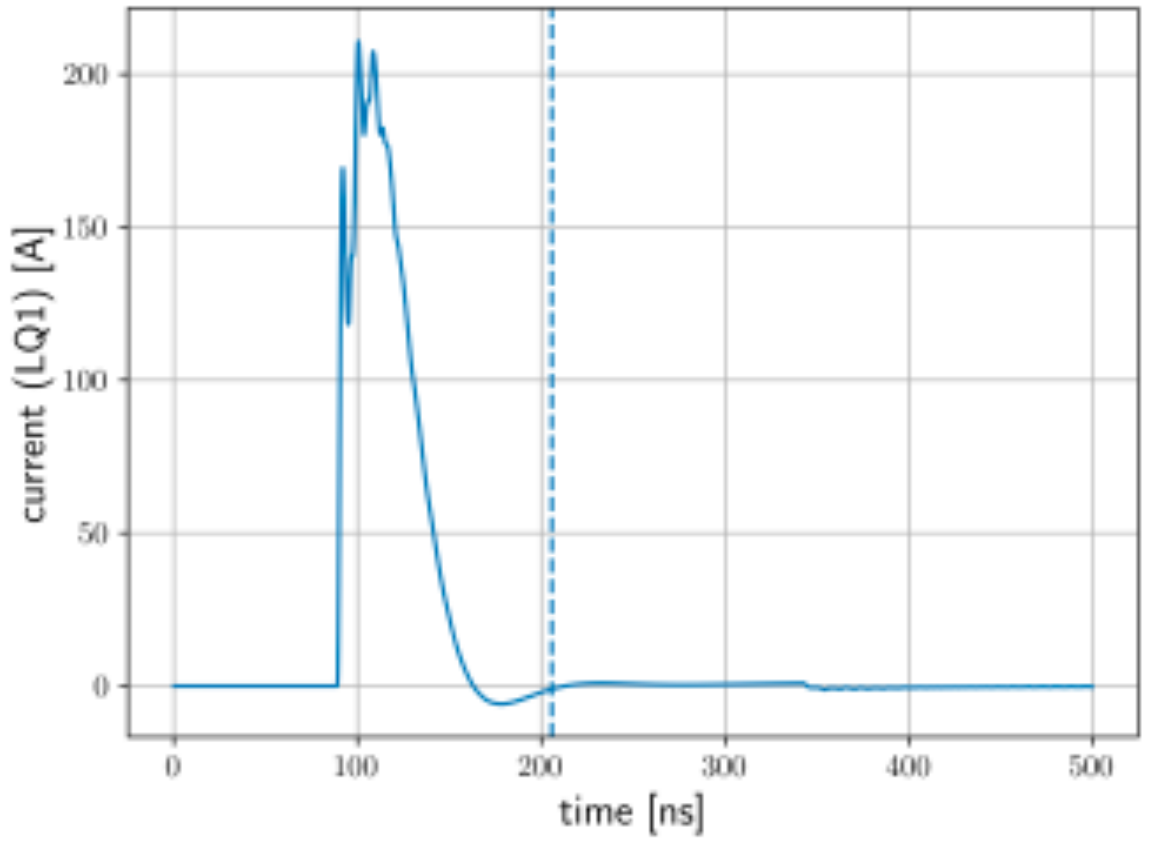


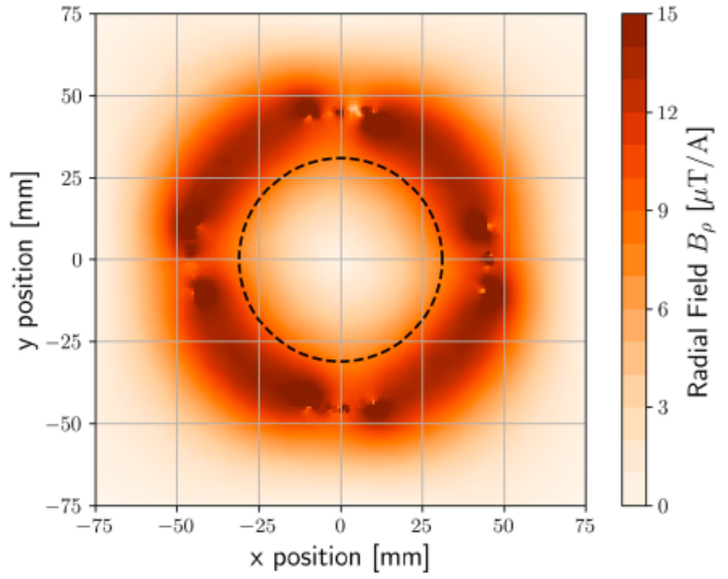
- R&D completed
- Ready for final construction

Summary

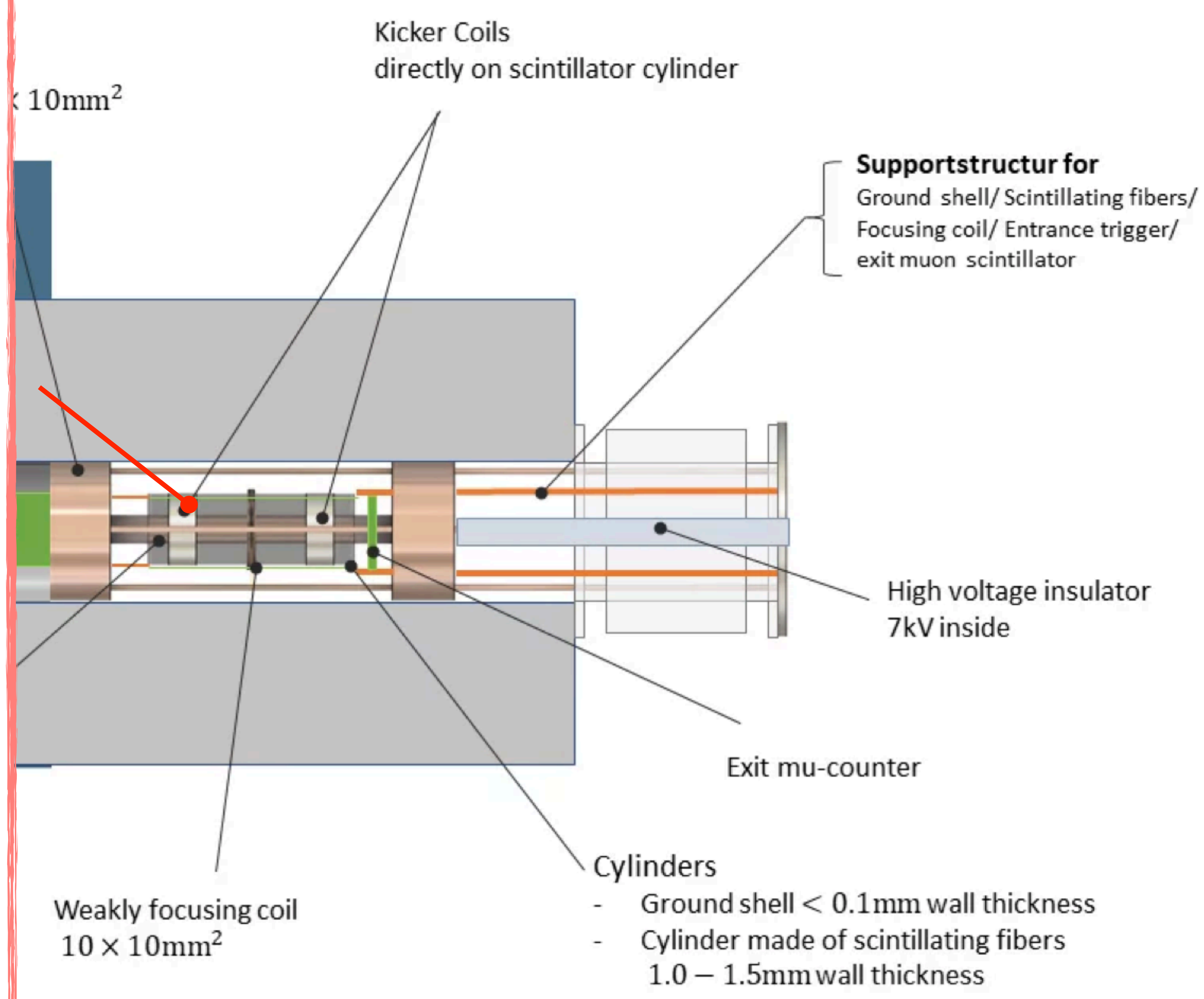
Kicker coils





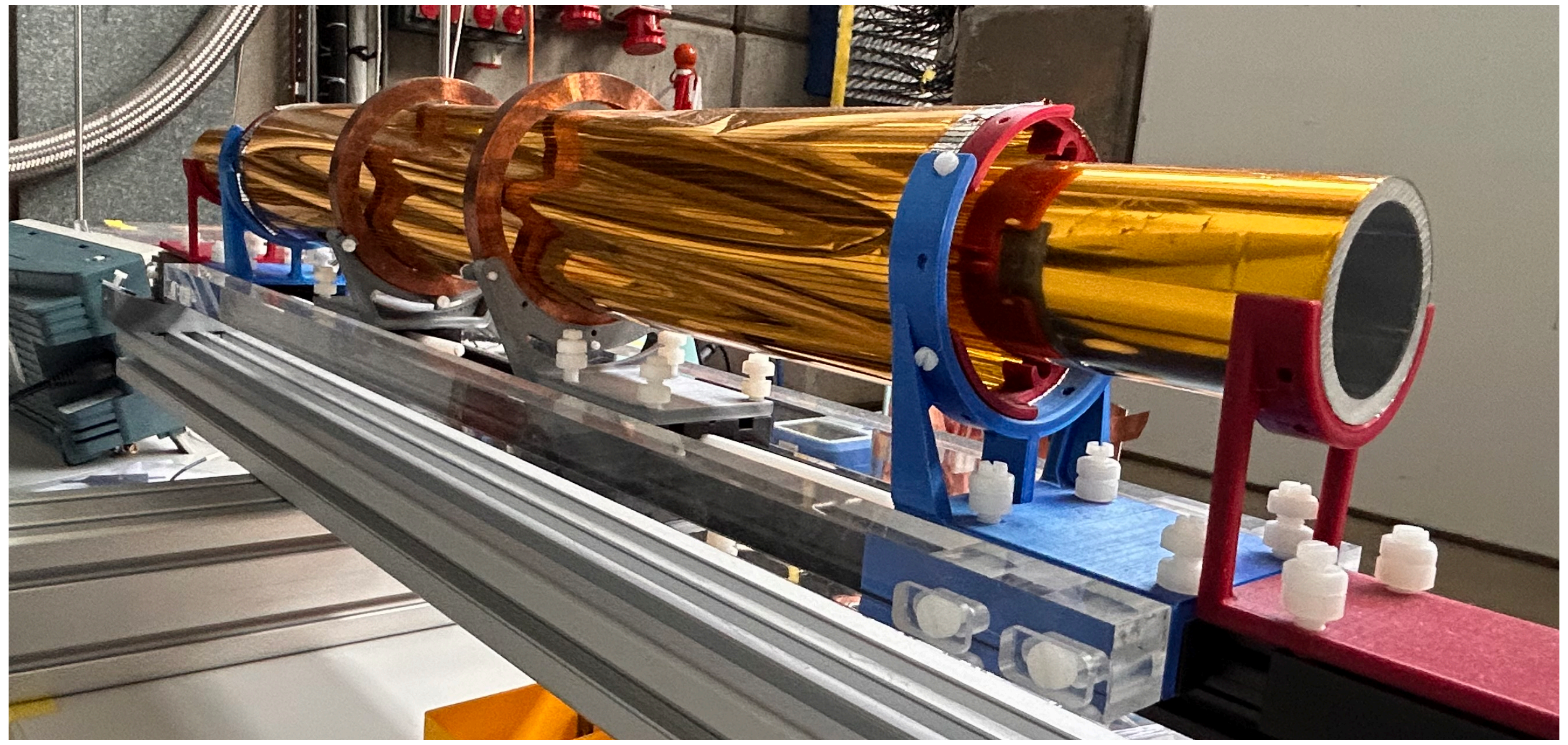


- Coil prototype: built
- Fast kicker circuit in construction: 200 A to be released for ~ 100 ns after ~ 80 ns from the trigger
- Expected “disturbance” test during BT2024
- Kicker final PS: Beginning 2026

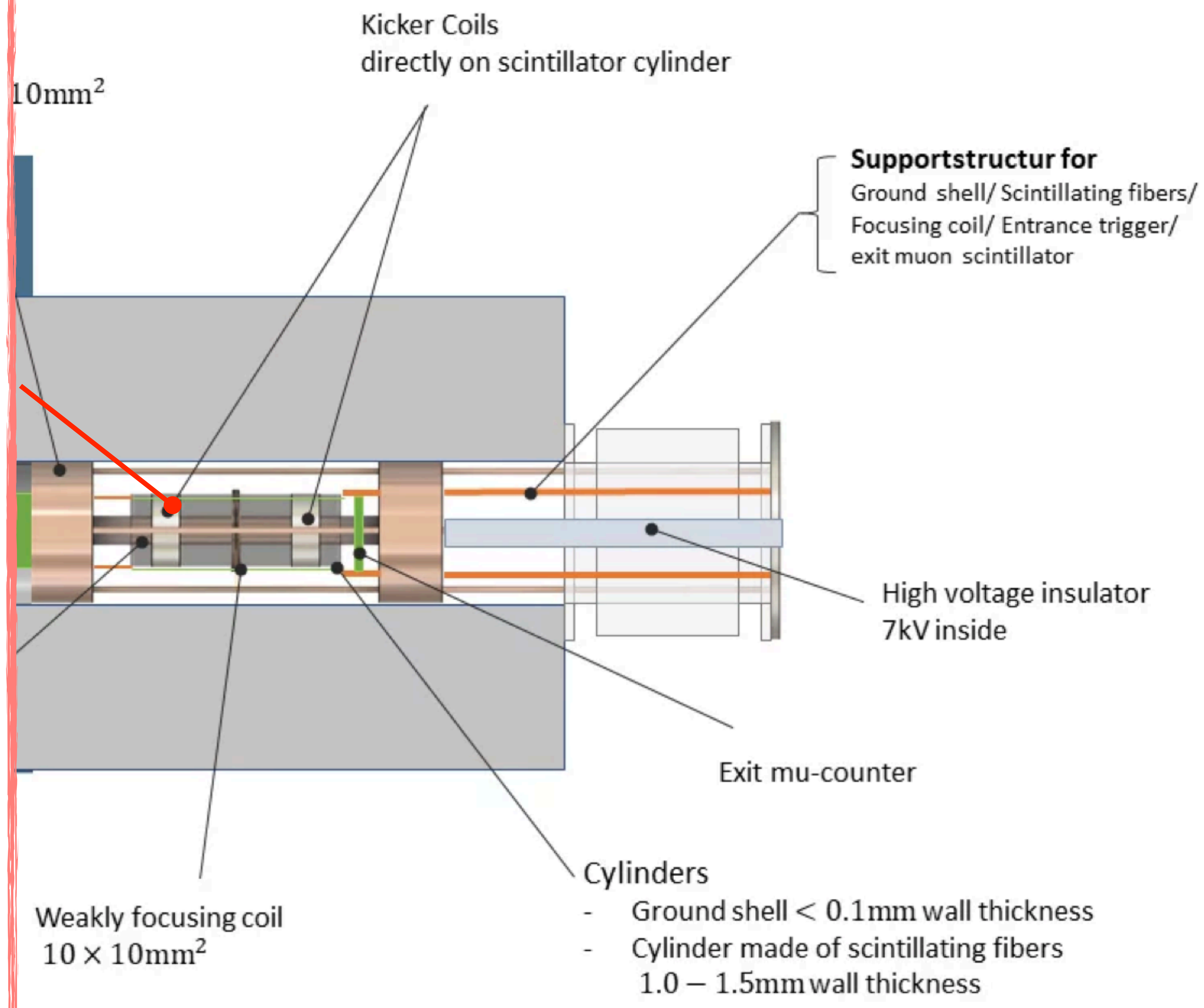


Summary

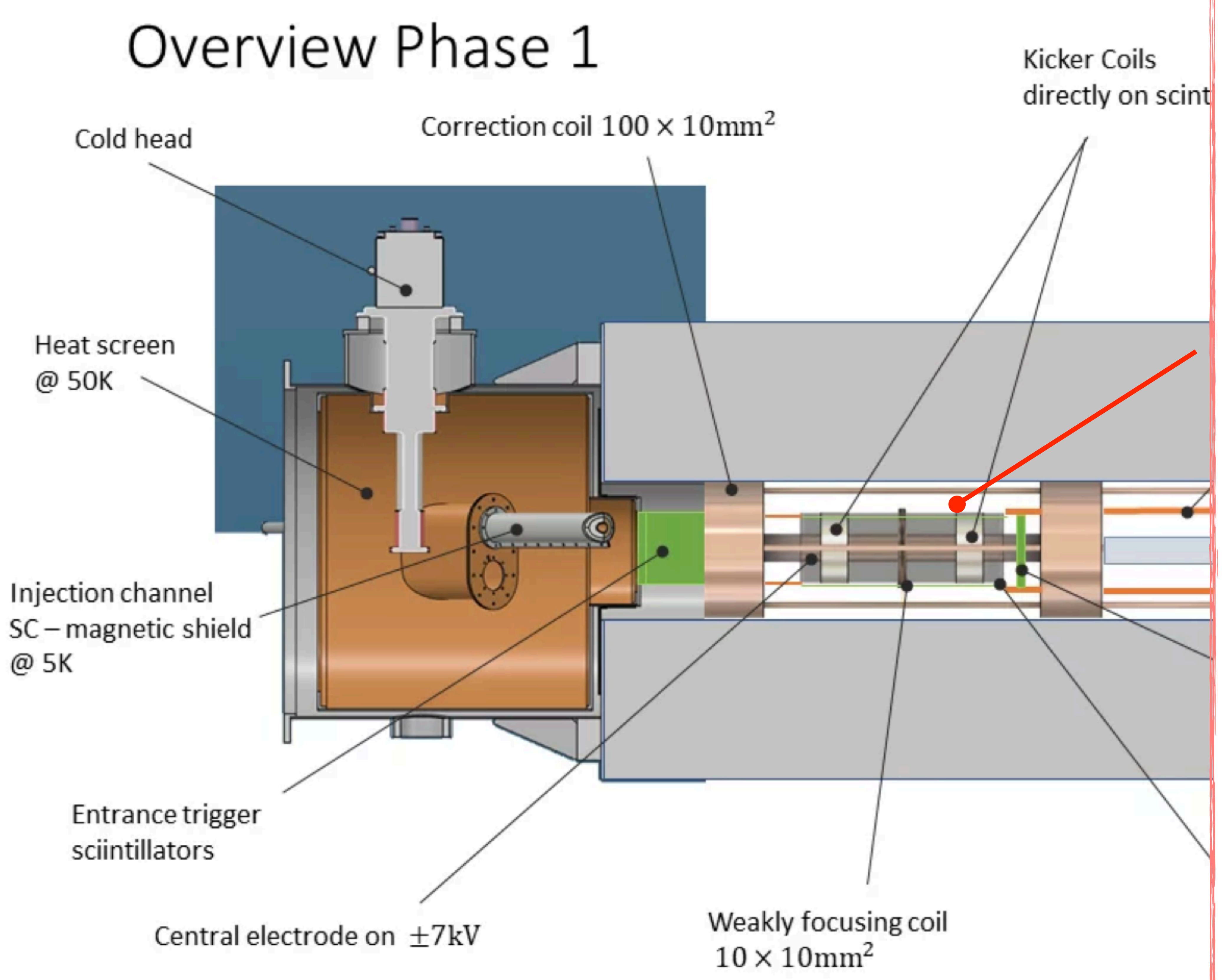
Frozen-spin electrodes



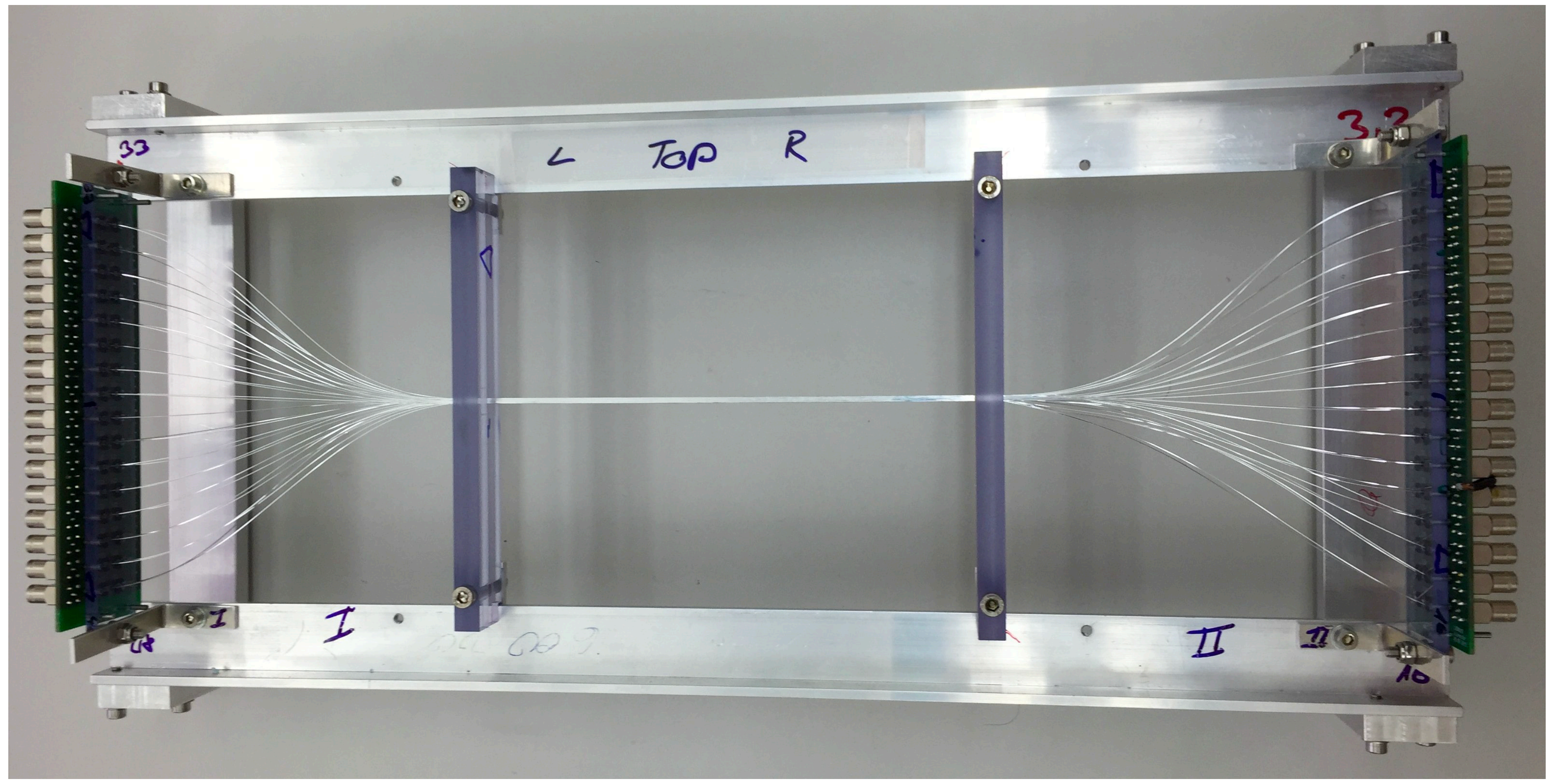
- Electrode prototype: built
- PS: Received
- Dedicated space vere to perform HV test (SLS)
- Assembly of the setup: ongoing
- Test: by Nov 2024



Summary

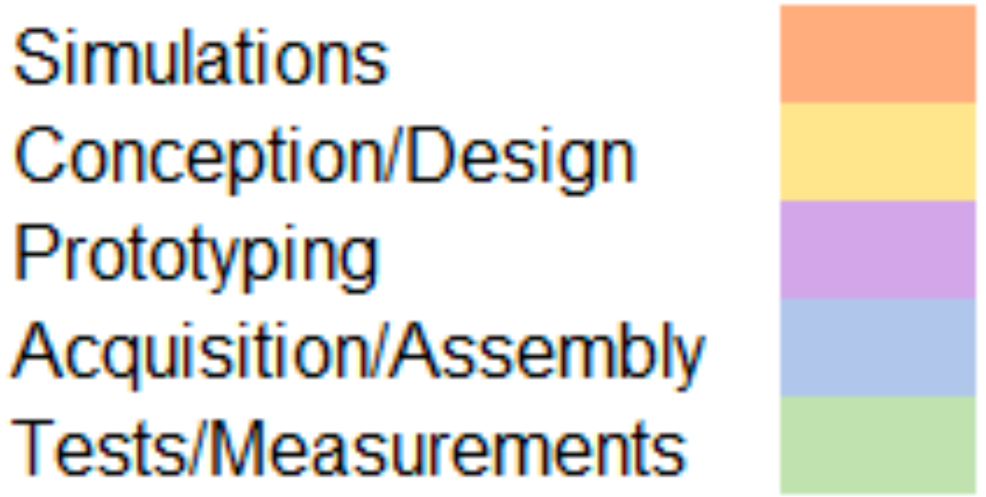


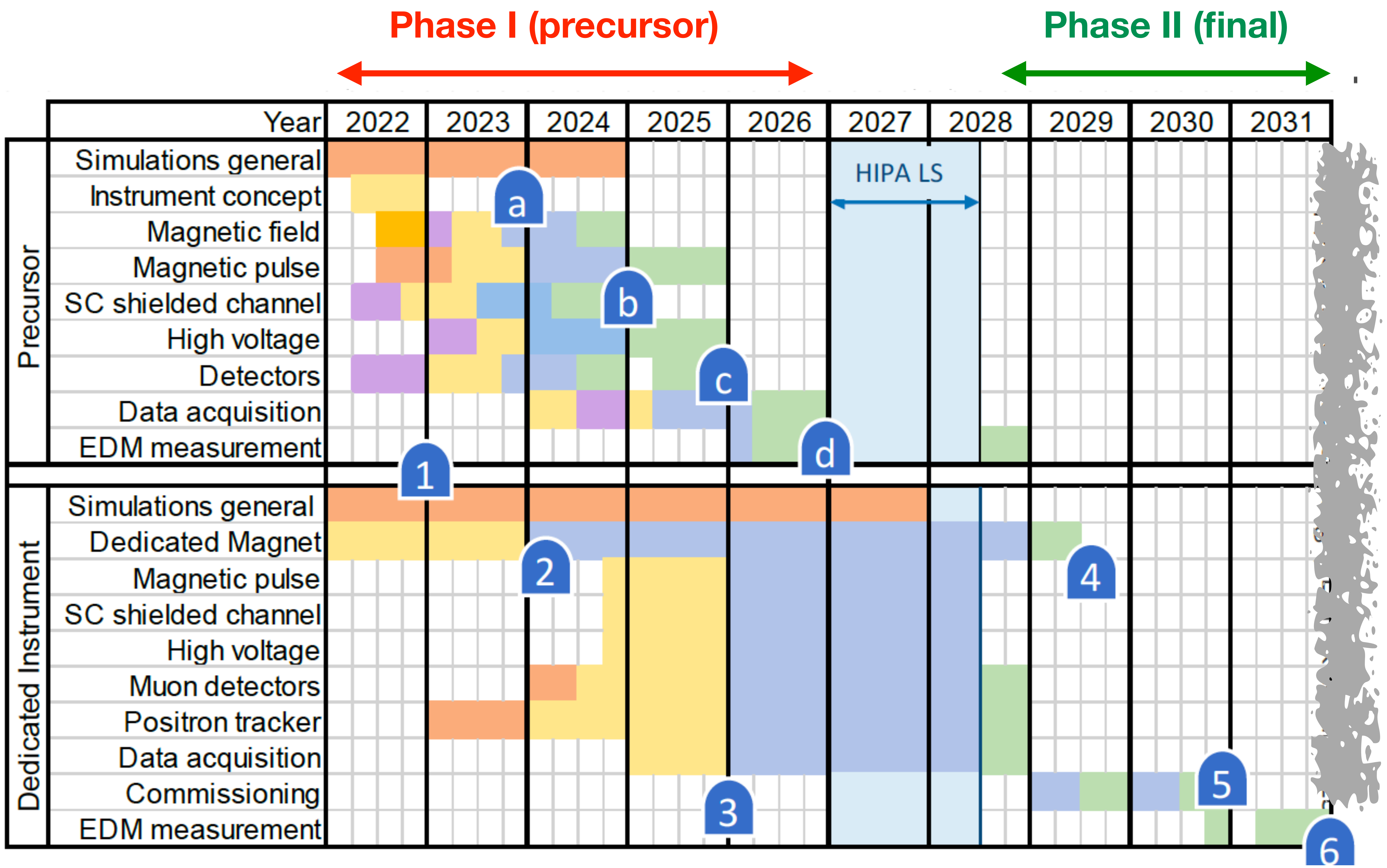
CHeT detector



- CHeT prototype: tested
- CHeT prototype + new DAQ: by 2024
- Technical Design: by 2024
- Material procurement for the final detector: Ongoing
- Modules and commissioning: by 2025

muEDM schedule



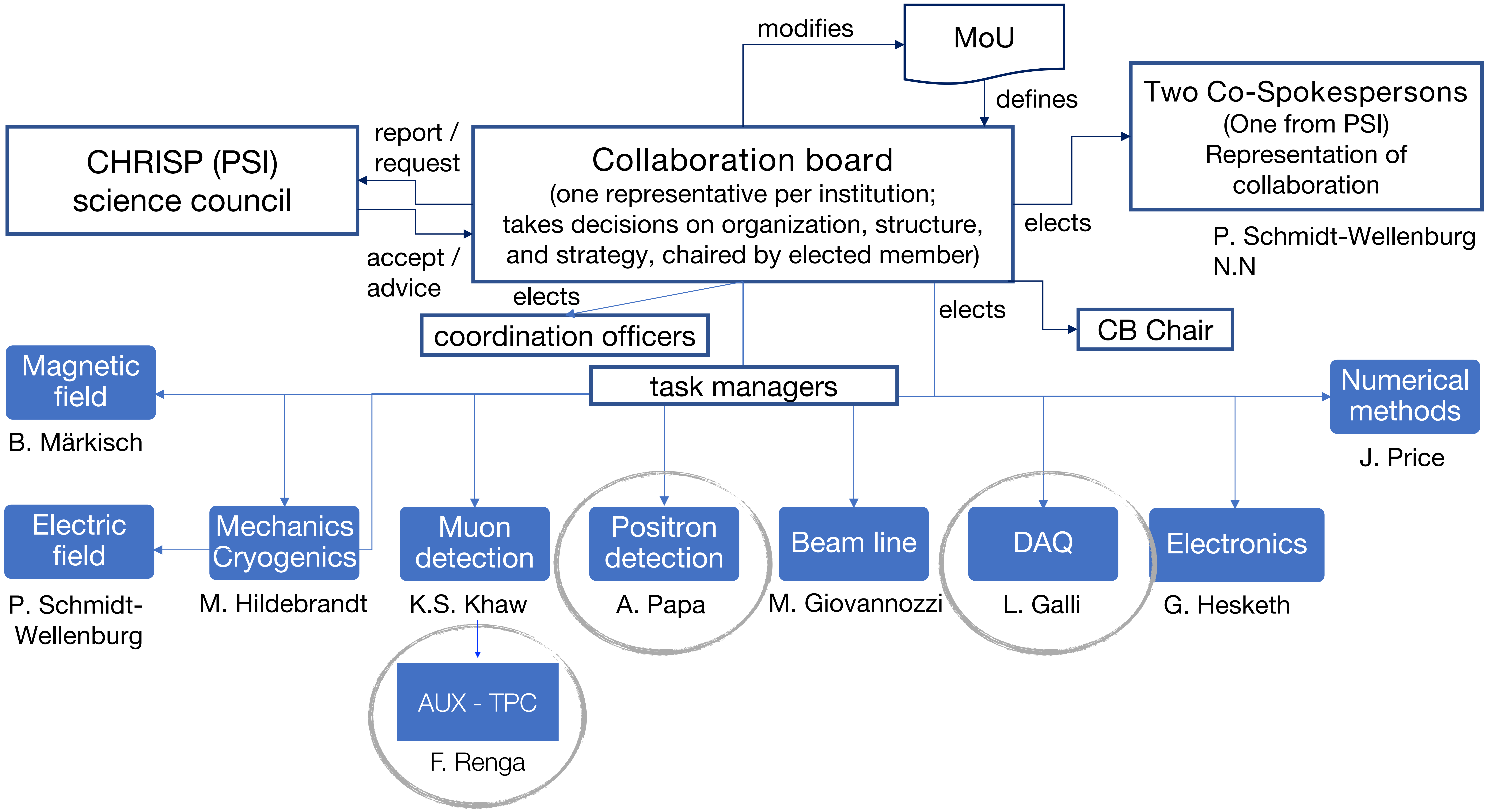


1 Full proposal for both phases to CHRISP committee
2/a Magnet call for tender / precursor design fix
b Precursor ready for assembly/commissioning
3/c Technical design report / frozen spin demonstration
d First data for precursor muEDM
4 Magnet delivered, characterized and accepted
5 Successful commissioning / start of data taking
6 End of data acquistion for muEDM

muEDM projected sensitivity phase I and II

	πE1	μE1
Muon flux (μ^+/s)	4×10^6	1.2×10^8
Channel transmission	0.03	0.005
Injection efficiency	0.003	0.60
Muon storage rate (1/s)	400	360×10^3
Gamma factor γ	1.04	1.56
e^+ detection rate (1/s)	300	90×10^3
Detections per 200 days	8.64×10^9	1.5×10^{12}
Mean decay asymmetry A	0.45	0.3
Initial polarization P_0	0.95	0.95
Sensitivity in one year ($e \cdot$cm)	$<3 \times 10^{-21}$	$< 6 \times 10^{-23}$

Collaboration structure



Estimated cost/item

muEDM feature	Institution	Financial requirements (kEuro)	Existing funding (kEuro)
Cryostat	TUM/ETHZ	200	200
SC shield	TUM/ETHZ/CERN	120	120
muMonitor & muExit	PSI	20	20
muStart TOF	INFN Pisa	5	2
muTrigger	SJTU	10	10
muTPC	INFN Rome	25	5
SciFi tracker	INFN Pisa	40	10
Coils	ASTeC UK	15	
Magnetometry & E-field probe	PSI	60	40
Magnetic-field mapper	PSI/ETHZ	80	40
Magnetic pulse	PSI	180	180
Electric field	PSI	15	15
Mechanics	PSI/ETHZ	30	
Vacuum	PSI/ETHZ	30	15
DAQ	INFN Pisa	180	5
DAQ for beamtime	PSI	30	30
Electronics	PSI	20	10

Cost coverage among Institutes/Nationality

	K [Euro]
Svizzera	635
Italia	230
Germania	120
UK	60
Cina	10

Anagrafica - Pisa & Rome

Pisa

A. Baldini	Research Dir.	0.3
H. Benmansour	Ph.D.	
F. Cei	A. Prof.	0.3
M. Chiappini	Tech. Res.	0.3
A. Driutti	Assistant Prof.	0.1
L. Galli	Researcher	0.2
E. Grandoni	Ph.D.	
G. Gallucci	Researcher	0.6
M. Grassi	Research Dir.	0.2
F. Leonetti	Sch. Holder (+ Ph.D.)	1.0
A. Papa	A. Prof.	0.5
A. Venturini	Ph.D.	
B. Vitali	Ph.D. (*)	
		3.5
Post-Doc	P-D (Not started yet) (**)	1.0
		4.5

(*) PhD thesis defended on May 17th 2024

(**) Post-doc from PRIN. Will start after summer 2024

Rome

G. Cavoto	Full Prof.	0.1
D. Pasciuto	Tech. Res.	0.2
F. Renga	Senior Researcher	0.1
C. Voena	A. Prof.	0.1

0.5

Cost coverage among Institutes/Nationality

	K [Euro]	FTE
Svizzera	635	13.5
Italia	230	5
Germania	120	2.5
UK	60	2
Cina	10	2

Richieste 2025 - Pisa

Capitolo	Descrizione	Parziali (k€)		Totale (k€)	
		Richieste	SJ	Richieste	SJ
apparati	MPPC per il tracciatore: 10 K DAQ FERS: ~~180~~ 163 K (31 schede + concentratore) PCB /connessioni/cavi MPPC-elettronica: 20 K	~~210.00~~ 193	0.00	~~210~~ 193	0
consumo	Metabolismo: 1.5 k x FTE	5.00	0.00	5	0
missioni	Meeting di collaborazione internazionale 8k Meeting di collaborazione italiano 2 k Preparazione apparato 20 K Test beam 30 K	60.00	0.00	60	0
Totale				~~275~~ 258	0

Apparato - Pisa

- 2000 MPPC: **10K** [prezzo da 1000 a 2000: 8K —> 10K]
- DAQ FERS (2000 canali): 31 schede + concertatore: ~~180K~~ -> **163K**
  - La **doppia lettura (2000 canali)** garantisce una **piena efficienza di rivelazione** della singola fibra, e quindi del rivelatore [**dati sperimentali**:SciFi Large Prototype]
- MPPC PCB/connessioni MPPC-FERS: **20K**
  - **Totale:** ~~210K~~ -> **193K**

Missioni e consumo - Pisa

- Missioni:
  - 3 Meeting collaborazione x 4: 8K
  - 1 Meeting collaborazione italiana: 2K
  - Costruzione apparato + assemblaggio
    - Supporto tecnico, spazi e macchine del PSI per il taglio/polishing/incollaggio/sputtering ed assemblaggio delle fibre
    - 8 settimane x 3 FTE = 20K
  - Test del rivelatore (senza fascio/cosmici e con fascio):
    - 8 settimane x 4 FTE = 30 K
  - Totale missioni: **60K**
- Consumo:
  - **5K** (come da tabellina)

Proiezioni Apparato - Pisa 2026

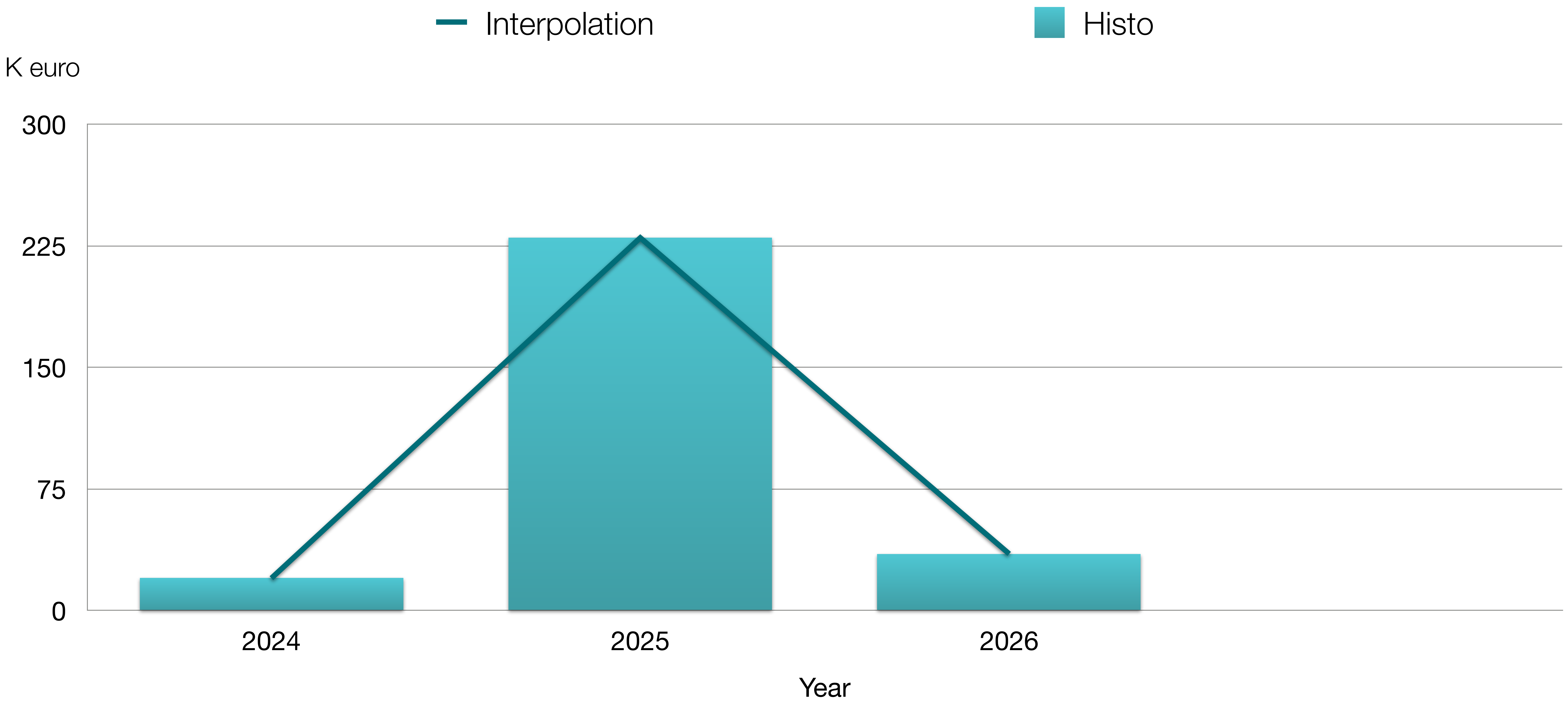
- Maintenance apparato (MPPC/cavi/connettori/PCB): **10K**
- DAQ FERS board: 1 scheda **6K**

  - **Totale: 16K**

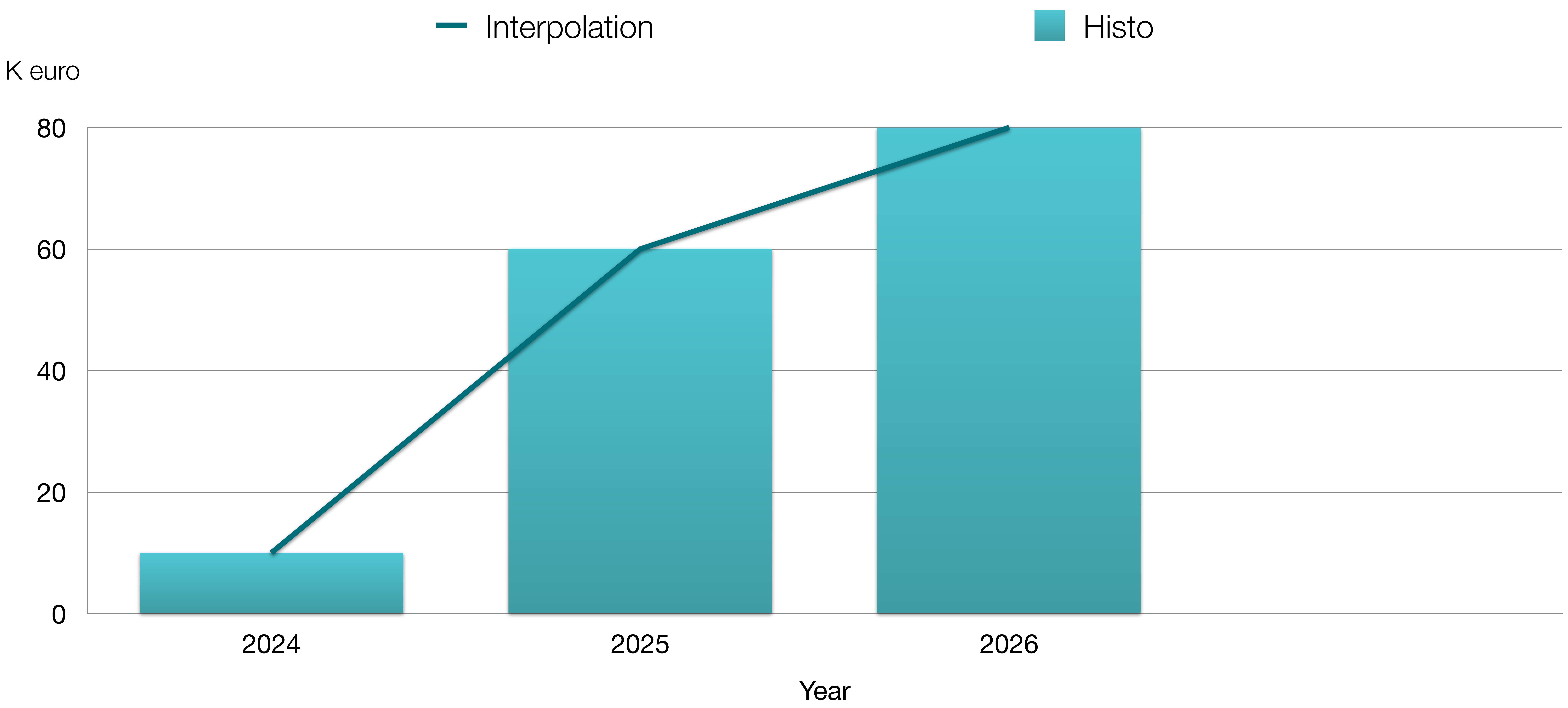
Proiezioni Missioni e consumo - Pisa 2026

- Missioni:
  - 3 Meeting collaborazione x 4: 8K
  - 1 Meeting collaborazione italiana: 2K
  - Assemblaggio finale
    - 6 settimane x 3 FTE = 15K
  - Test del rivelatore (senza fascio/cosmici e con fascio):
    - 16 settimane x 4 FTE = 55 K
  - Totale missioni: **80K**
- Consumo:
  - **10K**

Proiezione evoluzione richieste apparato Pisa+Roma 2024-2026

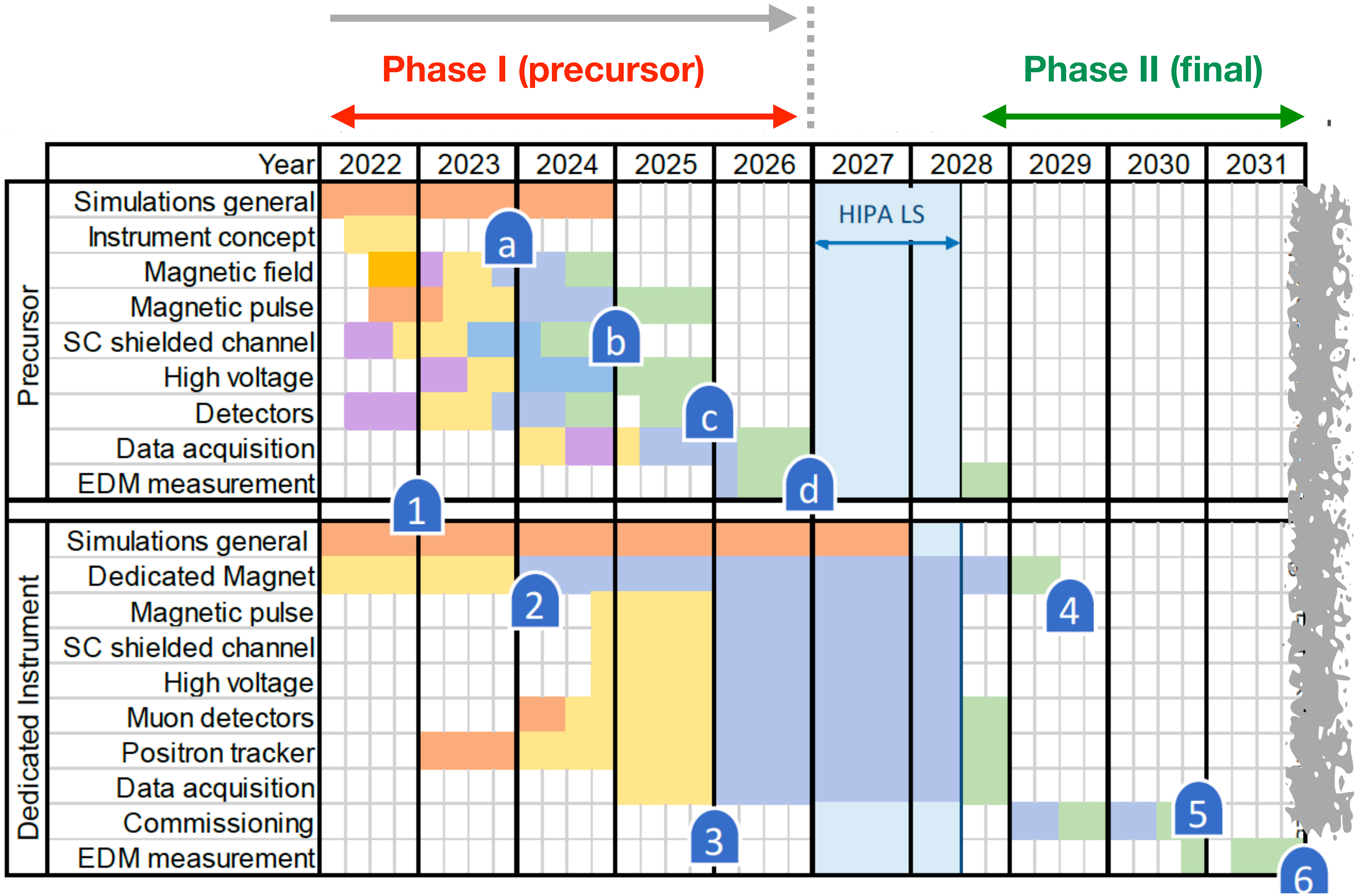


Proiezione evoluzione missioni Pisa+Roma 2024-2026



muEDM schedule

Apparatus. Discussed total O(230) K cost up to here



- Simulations
- Conception/Design
- Prototyping
- Acquisition/Assembly
- Tests/Measurements

1 Full proposal for both phases to CHRISP committee
2/a Magnet call for tender / precursor design fix
b Precursor ready for assembly/commissioning
3/c Technical design report / frozen spin demonstration
d First data for precursor muEDM
4 Magnet delivered, characterized and accepted
5 Successful commissioning / start of data taking
6 End of data acquistion for muEDM

Where we are:

- Proposal of the experiment submitted and accepted by the laboratory
- Special running grants:
  - 1 ERC
  - 1 PRIN (INSIGHTS)
- Looking for enthusiastic collaborators!


PSI Proposal No. R-21-02.1
Status Report of the search for the muon electric dipole moment to INFN

M. Giovannozzi
CERN: Beams Department, Esplanade des Particules 1, 1211 Meyrin, Switzerland

M. Hoferichter
UB: University of Bern, Bern, Switzerland

G. Hiller
UD: University of Dortmund, Dortmund, Germany

R. Appleby, I. Bailey
CI: *Cockcroft Institute, Daresbury, United Kingdom*

C. Chavez Barajas, T. Bowcock, J. Price, N. Rompotis, T. Teubner, G. Venanzoni, J. Vossebeld
UL: University of Liverpool, Liverpool, United Kingdom

R Chislett, G. Hesketh
UCL: University College London, London, United Kingdom

N. Berger, M. Köppel[1], A. Kozlinsky, M. Müller[1], F. Wauters
UMK: University of Mainz - Kernphysik, Mainz, Germany

A. Keshavarzi, M. Lancaster
UM: University of Manchester, Manchester, United Kingdom

F. Trillaud
UNAM: Universidad Nacional Autonma de Mexico, Mexico City, Mexico

B. Märkisch
TUM: Technical University of Munich, Munich, Germany

M. Francesconi
INFN-N: INFN, Napoli, Italy

A. Baldini, F. Cei, M. Chiappini, A. Driutti, L. Galli, G. Gallucci, M. Grassi, A. Papa, A. Venturini[1], B. Vitali[1]
INFN-P: INFN and University of Pisa, Pisa, Italy

G. Cavoto, D. Pasciuto, F. Renga, C. Voena
INFN-R: INFN and University of Roma, Roma, Italy

S.Y. Hoh, T. Hu[1], K.S. Khaw, J.K. Ng[1], Y. Shang[1], Y. Takeuchi, G.M. Wong[1], Y. Zeng[1]
SJTU: Shanghai Jiao Tong University and Tsung-Dao Lee Institute, Shanghai, China

A. Adelmann, C. Calzolaio, R. Chakraborty, M. Daum, A. Doinaki[12], C. Dutsov, W. Erdmann, D. Höhl,[12], T. Hume,[12], M. Hildebrandt, H. C. Kästli, A. Knecht, K. Z. Michielsen[12], L. Morvaj, D. Reggiani, D. Sanz-Beccera, P. Schmidt-Wellenburg[3]
PSI: Paul Scherrer Institut, Villigen, Switzerland

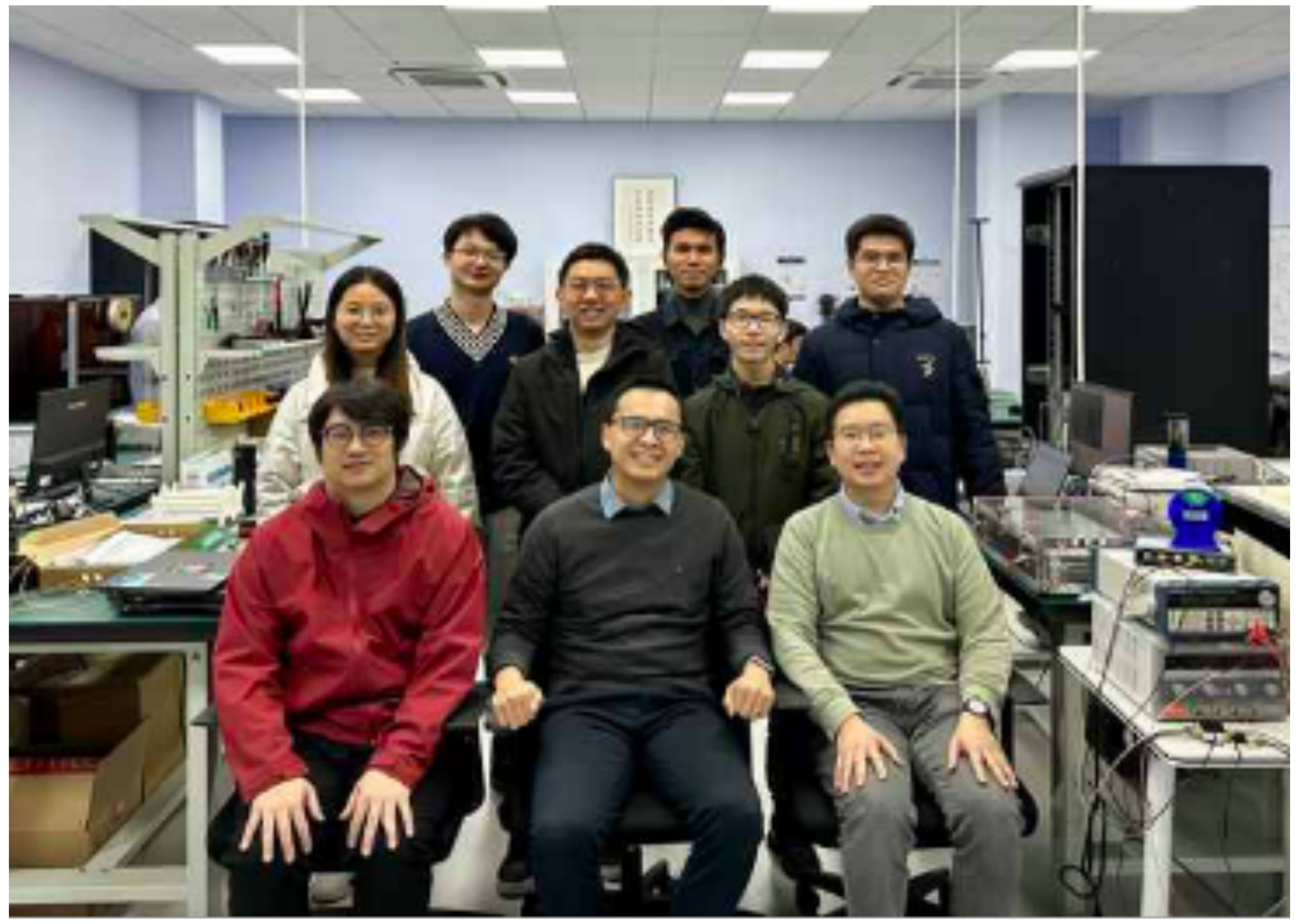
K. Kirch[4]
ETHZ: ETH Zürich, Switzerland

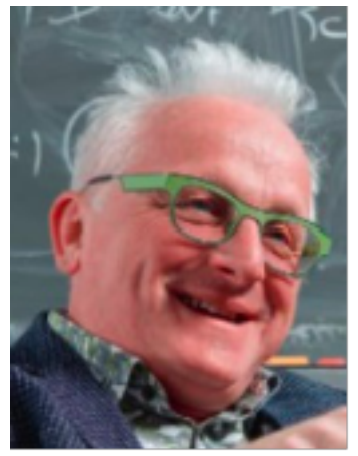
L. Caminada[4], A. Crivellin[4]

Outlook

- Thanks a lot for your attention

- Looking forward a successful 2024 in view of the construction and commissioning of the muEDM Phase I experiment



Back-up

Summary: Systematic effect

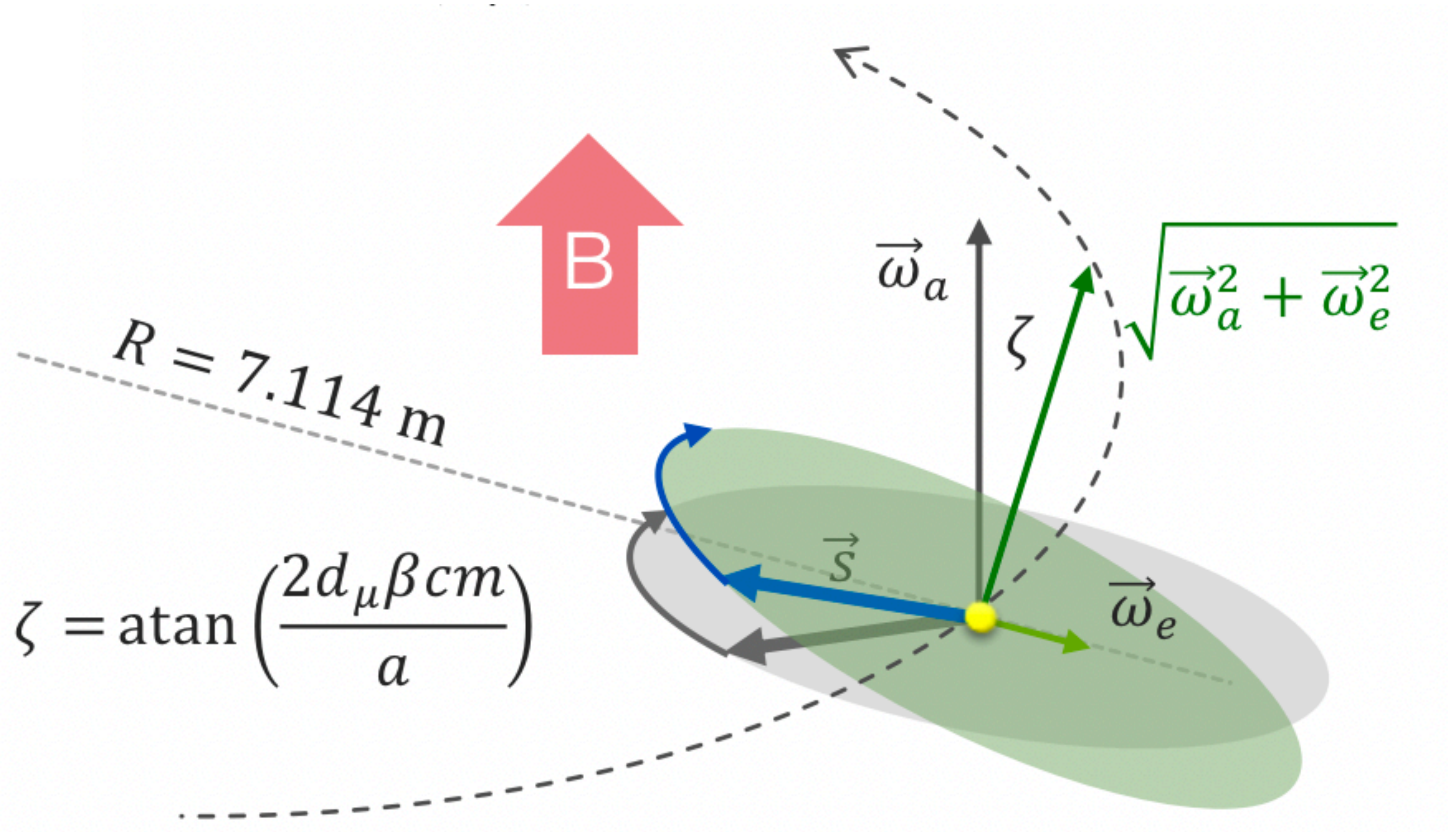
Systematic effect	Phase I		Phase II	
	Expected value (Limit value)	**Syst.** $10^{-21}\ e\cdot$cm	**Expected value (Limit value)**	**Syst.** $10^{-23}\ e\cdot$cm
Radial B-field (ii) @100 kHz	5 µT (140 µT)	0.03	20 µT (40 µT)	0.75
Current flowing through orbit (iii)	< 10 mA (250 mA)	$< 10^{-2}$	< 10 mA (40 mA)	0.3
Longitudinal E-field E_z, (v)	$< 10^{-4} E_f$	–	$< 1.5 \times 10^{-5} E_f$	–
Mean momentum difference Δp, (vi)	0.2% (0.5%)	–	(0.1)%	–
Difference in initial polarisation, (vii)	25 mrad	–	5 mrad	–
Radial E-field adjustment, ($viii$)	0.1%	–	0.01%	–
Main B-field adjustment, ($viii$)	0.01%	–	0.001%	–
CW/CCW orbit displacement	1 mm	–	1 mm	–
$\partial_x E_z$, $\partial_y E_z$	(0.56 kV/m/m)	–	(0.15 kV/m/m)	–
E-field related systematics	–	0.75	–	1.5
Resonant geometrical phase accumulation (xi)	Pitch < 1 mrad Offset < 2 mm	2×10^{-2}	Pitch < 1 mrad Offset < 2 mm	0.15
TOTAL		0.75		1.70

EDM search: From the “frequency” approach…

$$\vec{\omega} = \frac{q}{m}\left[a\vec{B} - \left(a + \frac{1}{1-\gamma^2}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right] + \frac{q}{m}\frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)$$

ω_a ω_e

- i.e. FNAL: The decay positrons are recorded using calorimeters and straw tube trackers inside the storage ring
- The sensitivity to a muon EDM is limited by the resolution of the vertical amplitude, proportional to ζ, of the oscillation in the tilted precession plane
- i.e. J-PARC: even if the technique is different the sensitivity to an EDM is limited by the resolution of the vertical amplitude



…to the frozen-spin technique

$$\vec{\omega} = \frac{q}{m}\left[a\vec{B} - \left(a + \frac{1}{1-\gamma^2}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right] + \frac{q}{m}\frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)$$

ω_a ω_e

- The frozen-spin technique uses an Electric field perpendicular to the moving particle and magnetic field, fulfilling the condition:

$$a\vec{B} = \left(a - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}_f}{c}$$

- Without EDM, $\omega = 0$, the spin follows the momentum vector as for an ideal Dirac spin-1/2 particle, while with an EDM it will result in a precession of the spin with $\omega_e \parallel E$
- The sensitivity to a muon EDM is given by the asymmetry up/down of the positron from the muon decay