Status of the muEDM experiment at PSI

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NuFact 2024 @ Argonne National Laboratory

September 17, 2024

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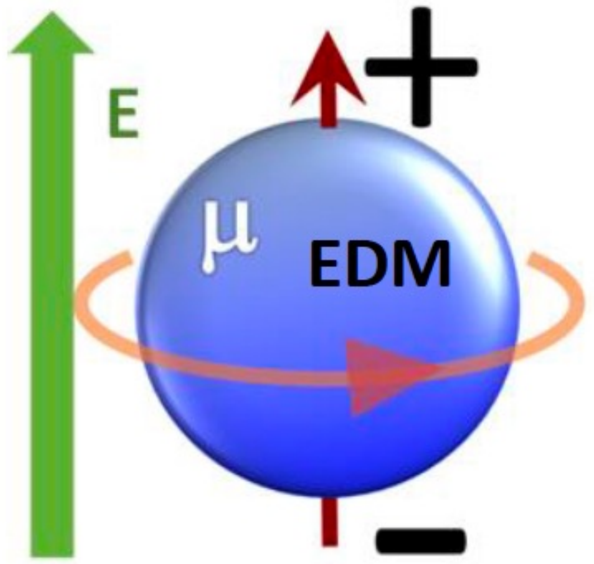
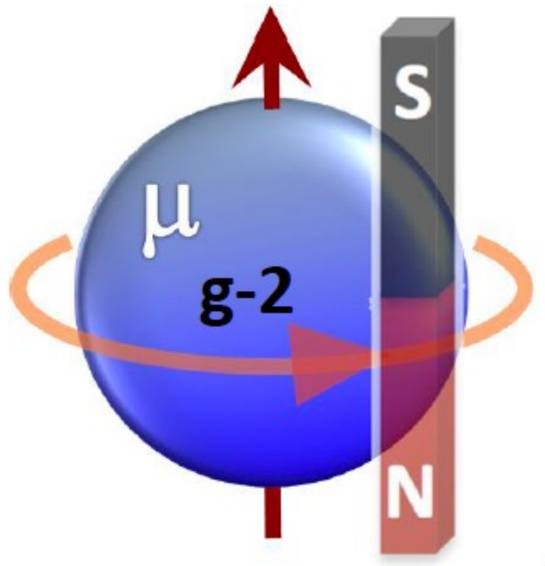
Motivation for EDM searches



$$\vec{d} = \eta \frac{e}{2mc} \vec{s}$$

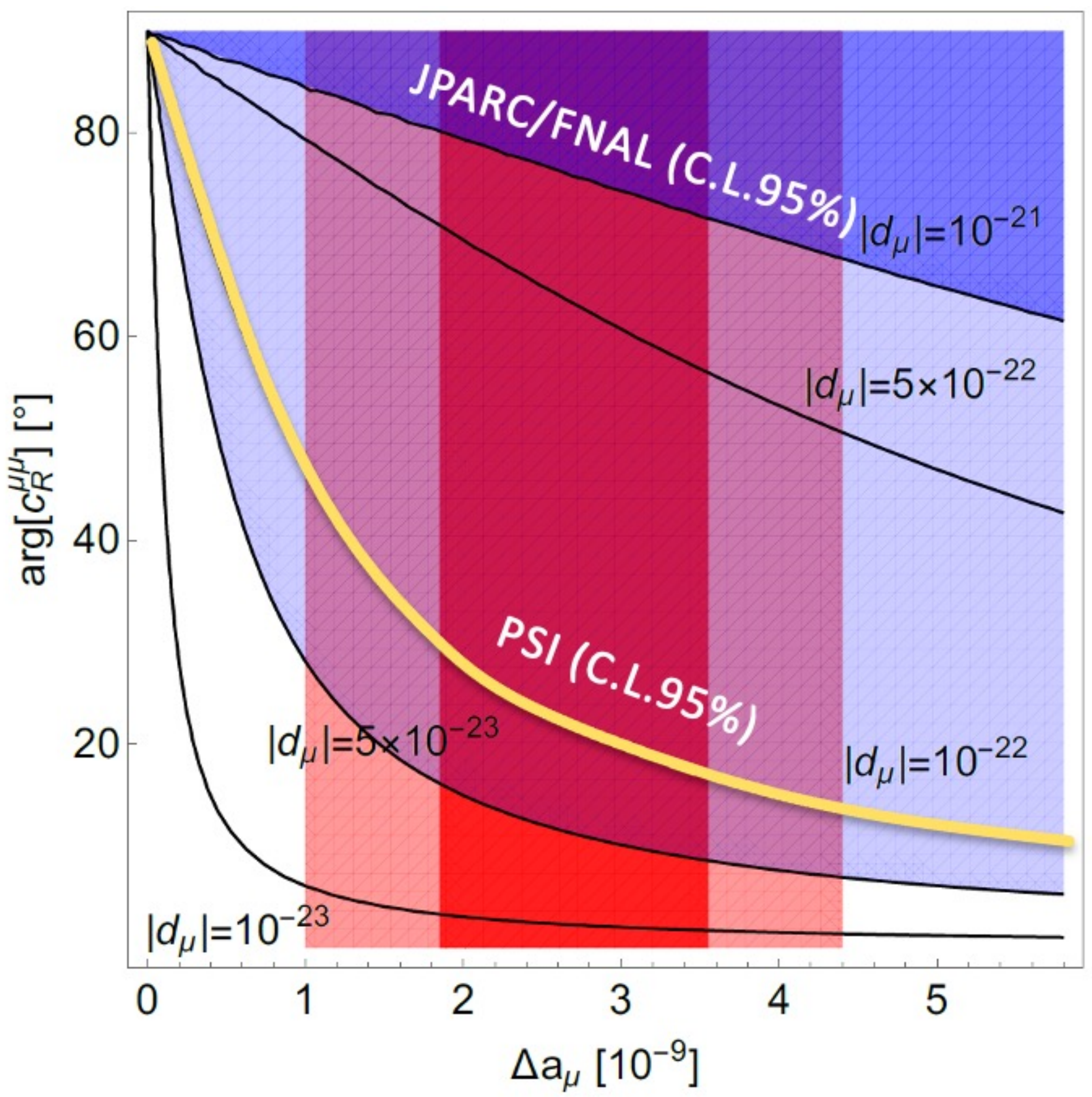


$$\vec{\mu} = g \frac{e}{2m} \vec{s}$$

- Electric dipole moment (EDM) violates time-reversal symmetry and charge-parity (CP) symmetry, assuming CPT invariance.
- Standard Model predicts small EDMs for fundamental particles
  - CKM contribution: $d_\mu^{CKM} \sim 10^{-42}\ \mathrm{e \cdot cm}$, hadronic long-range effect: $d_\mu^{HLR} \sim 10^{-38}\ \mathrm{e \cdot cm}$ PRD 89 (2014) 056006 PRL 125 (2020) 241802
  - Current experimental limit $d_\mu^{\mathrm{BNL}} < 1.8 \times 10^{-19}\ \mathrm{e \cdot cm}\ (95\%\ \mathrm{C.L.})$ PRD 80 (2009) 052008
  - Indirect limit from heavy atom EDM searches $|d_\mu| < 2{\times}10^{-20}\ \mathrm{e \cdot cm}$ PRL 128 (2022) 131803
  - Excellent probes for new physics since it is essentially “background-free”
- Any observed EDM signal is for sure BSM physics! A.D. Sakharov, JETP Lett. 5, 24 (1967)
  - May shed light on the baryon asymmetry in the universe as new sources of CPV are required

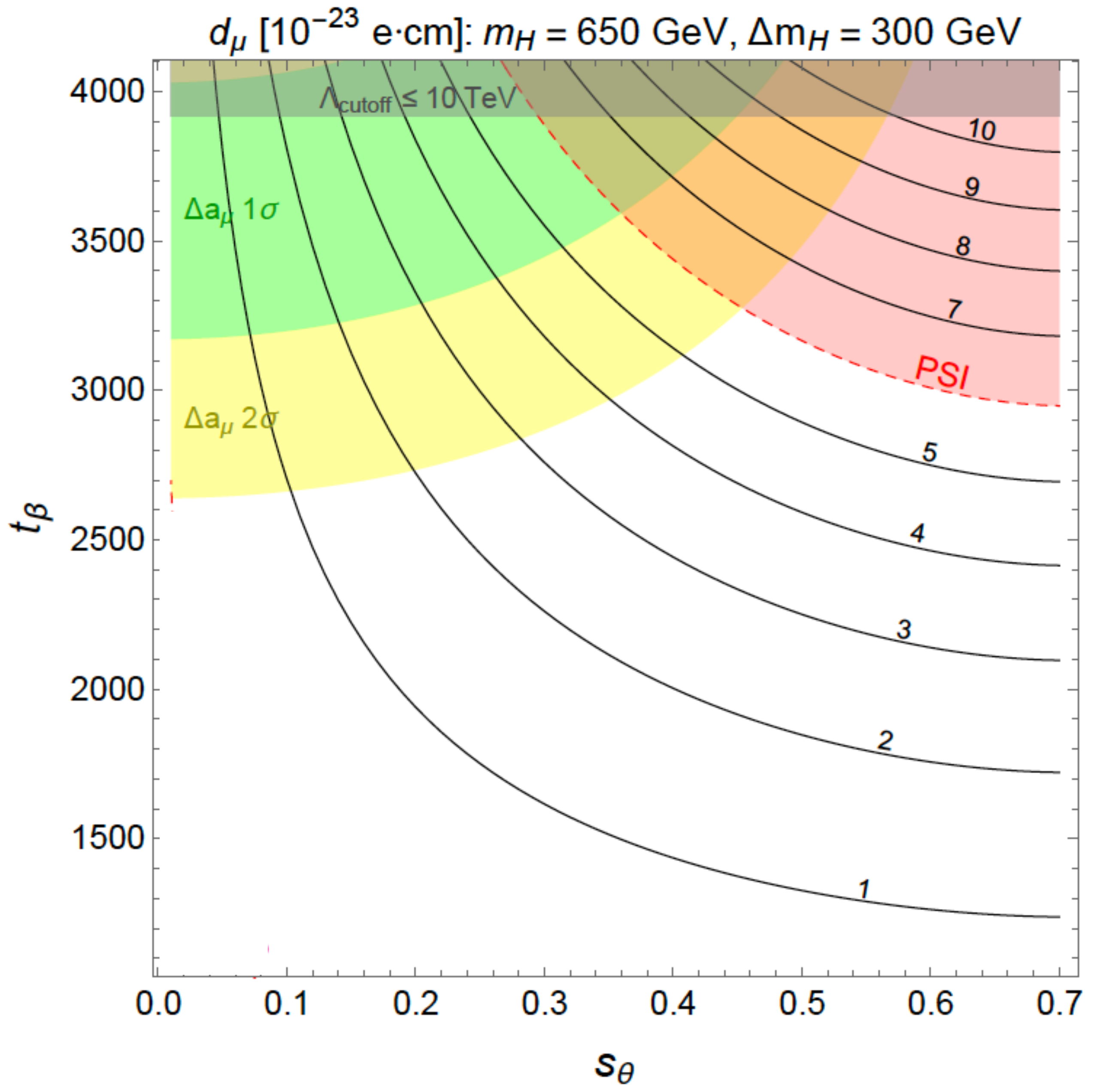
BSM/EFT models with large EDM

EFT Analysis



PRD 98 (2018) 113002

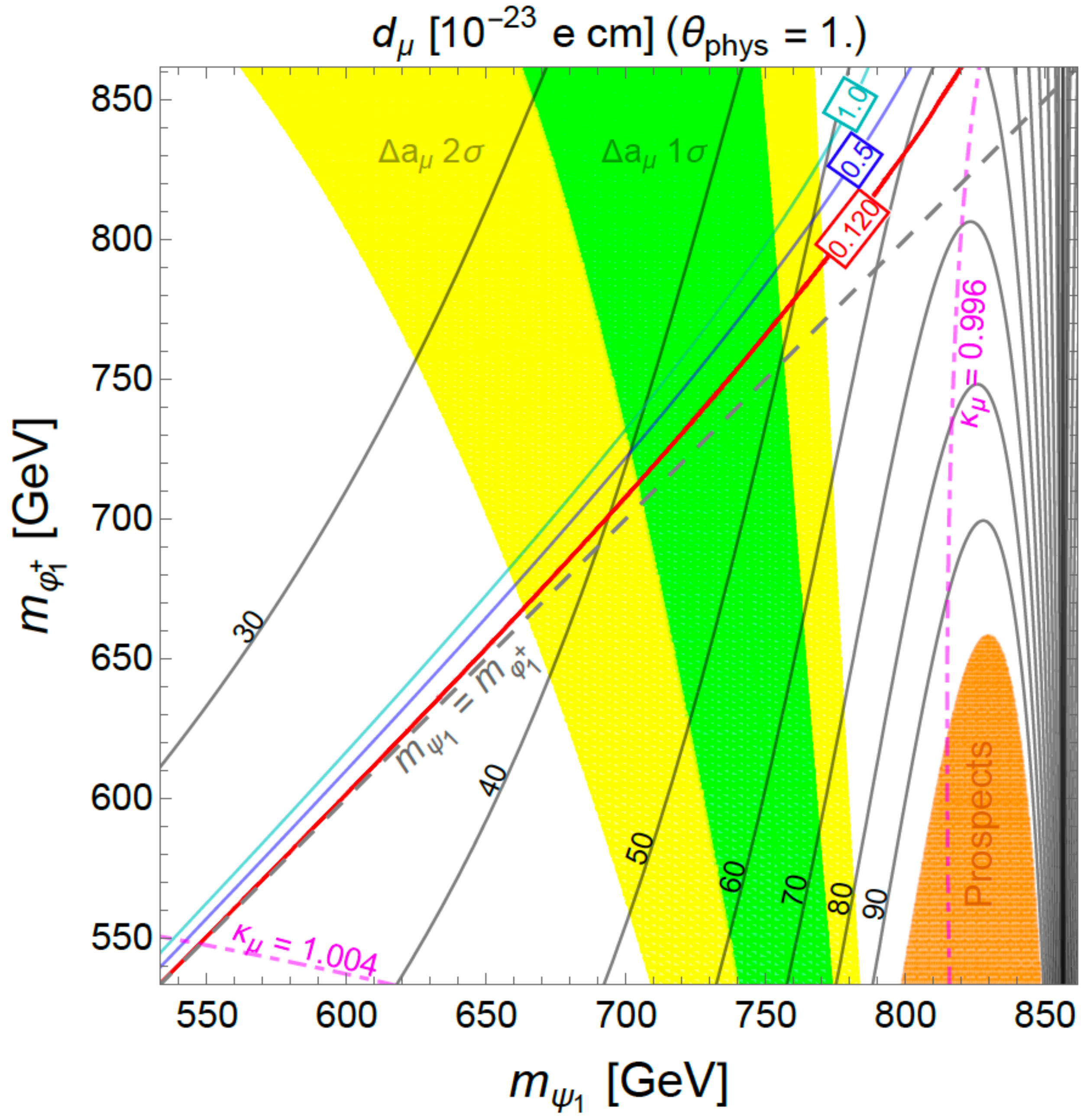
Muon specific 2HDM



Interesting parameter space: $s_\theta \sim 0.35$, tanβ ~ 3700

PLB 831 (2022) 137194

Radiative muon mass model

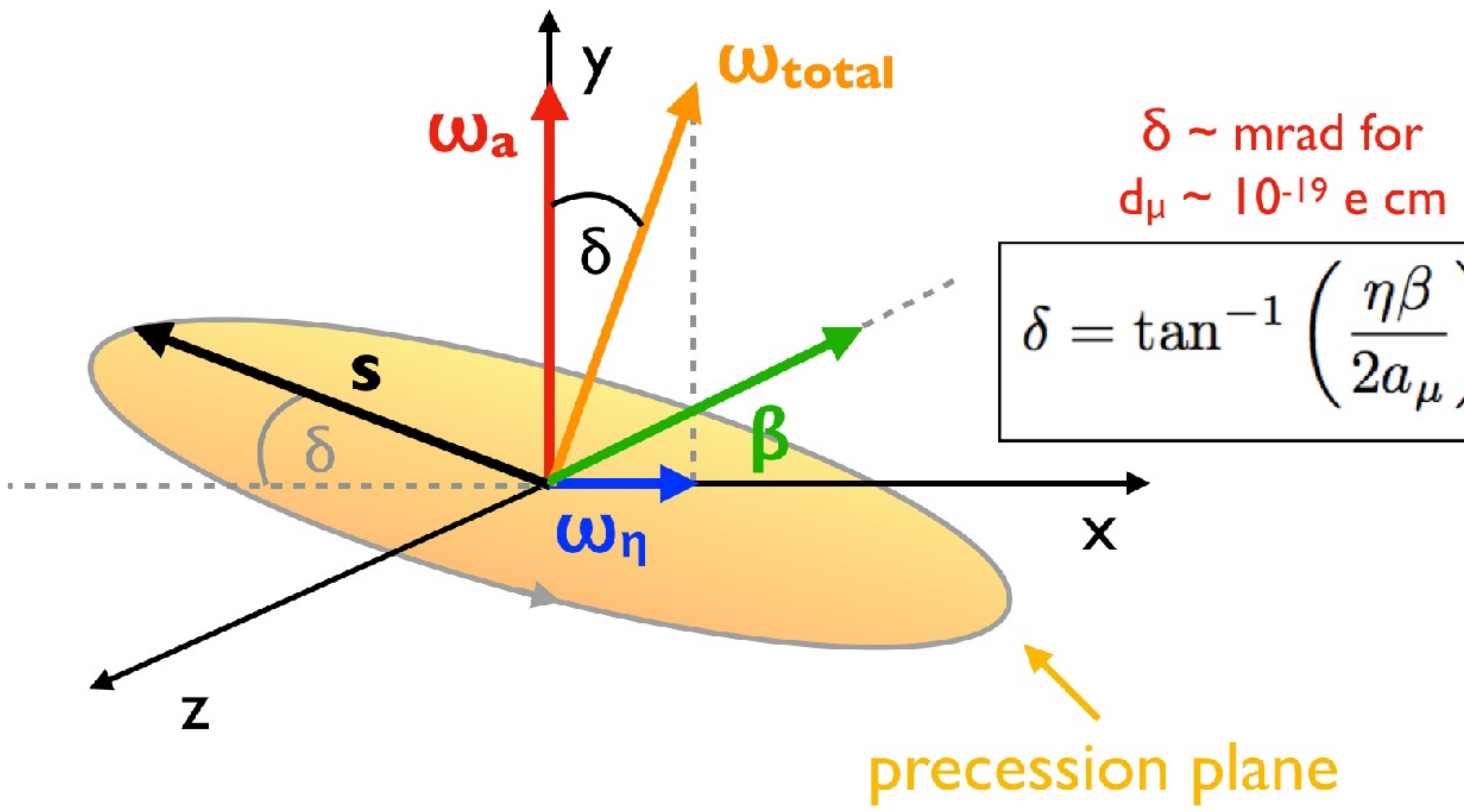


JHEP02 (2023) 234 (4)

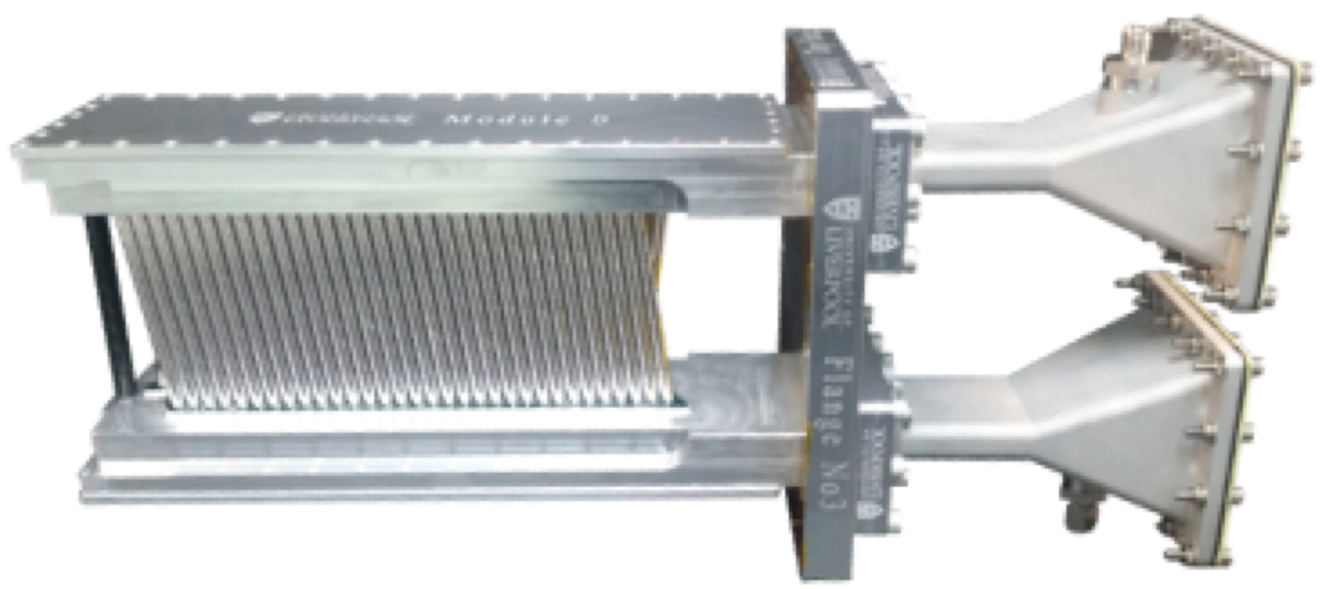
FNAL/J-PARC goal of 10^{-21} e cm probes tiny phase space of BSM models

Going beyond 10^{-21} e cm?

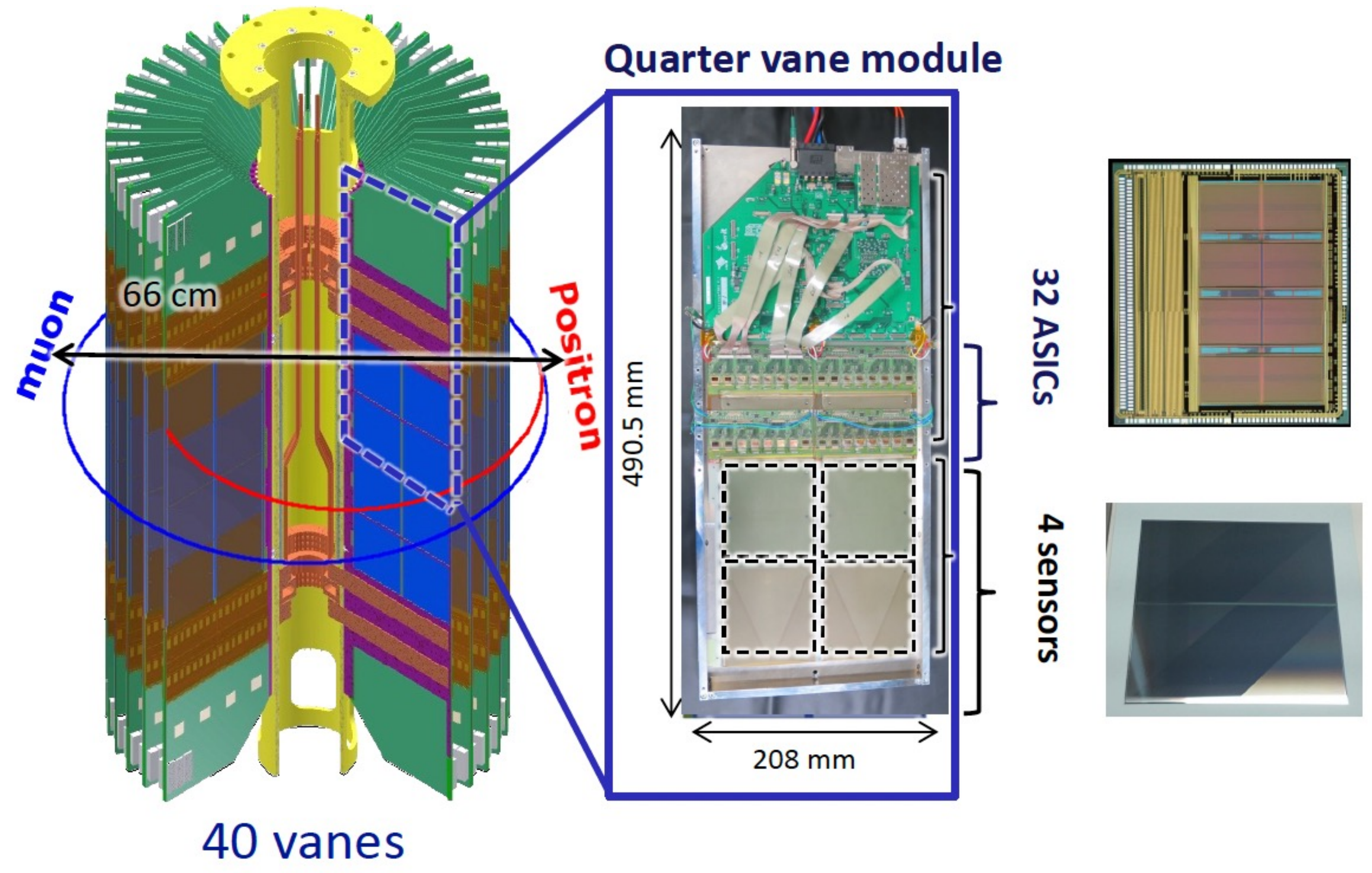
- How can we improve the sensitivity of the muon EDM search?
- In the parasitic g-2 approach, the tilt angle is the limiting factor
- For an EDM below 10^{-21} e cm, it will be very challenging to measure this small angle < μrad (multiple scattering effect + systematic effects like mis-alignment)



$$\delta = \tan^{-1}\left(\frac{\eta\beta}{2a_\mu}\right)$$



Straw trackers
FNAL Muon g-2



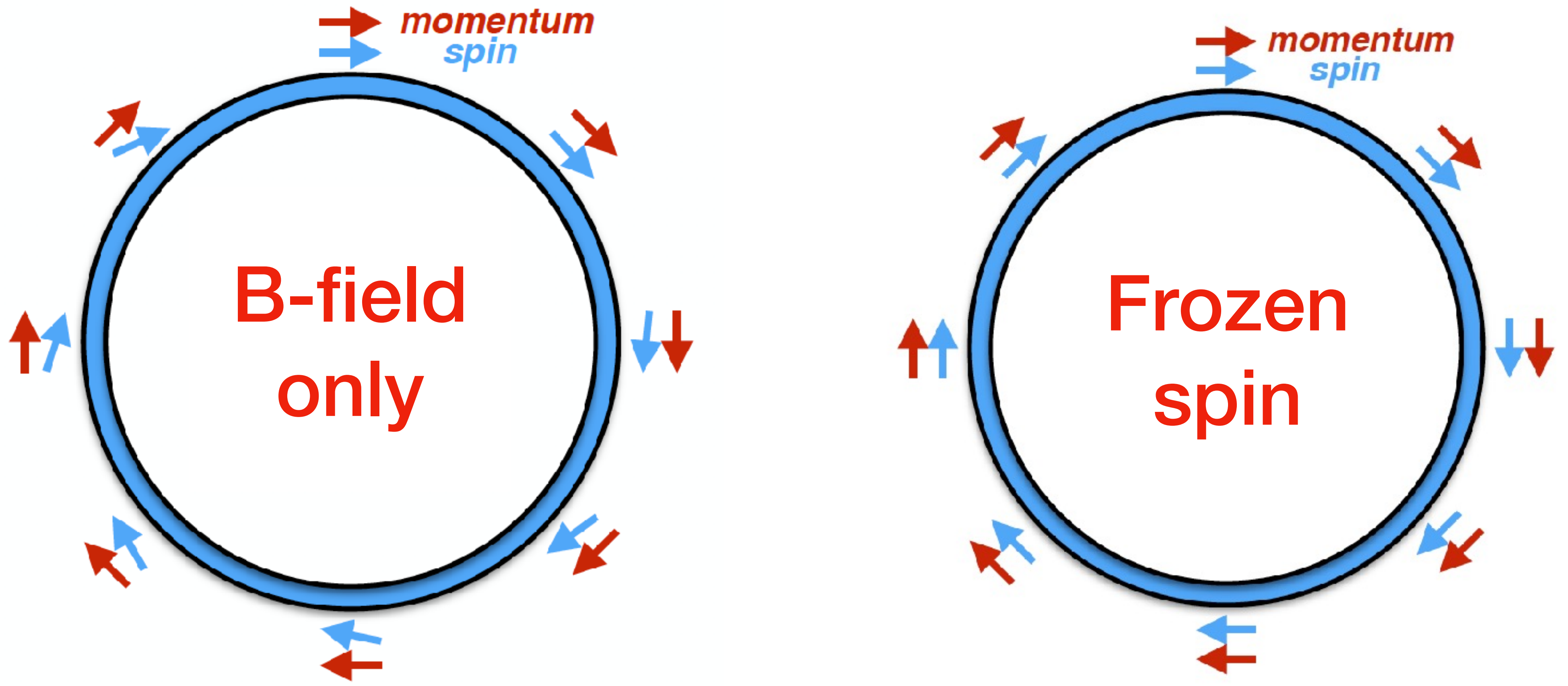
Silicon Strip Detector
J-PARC Muon g-2/EDM

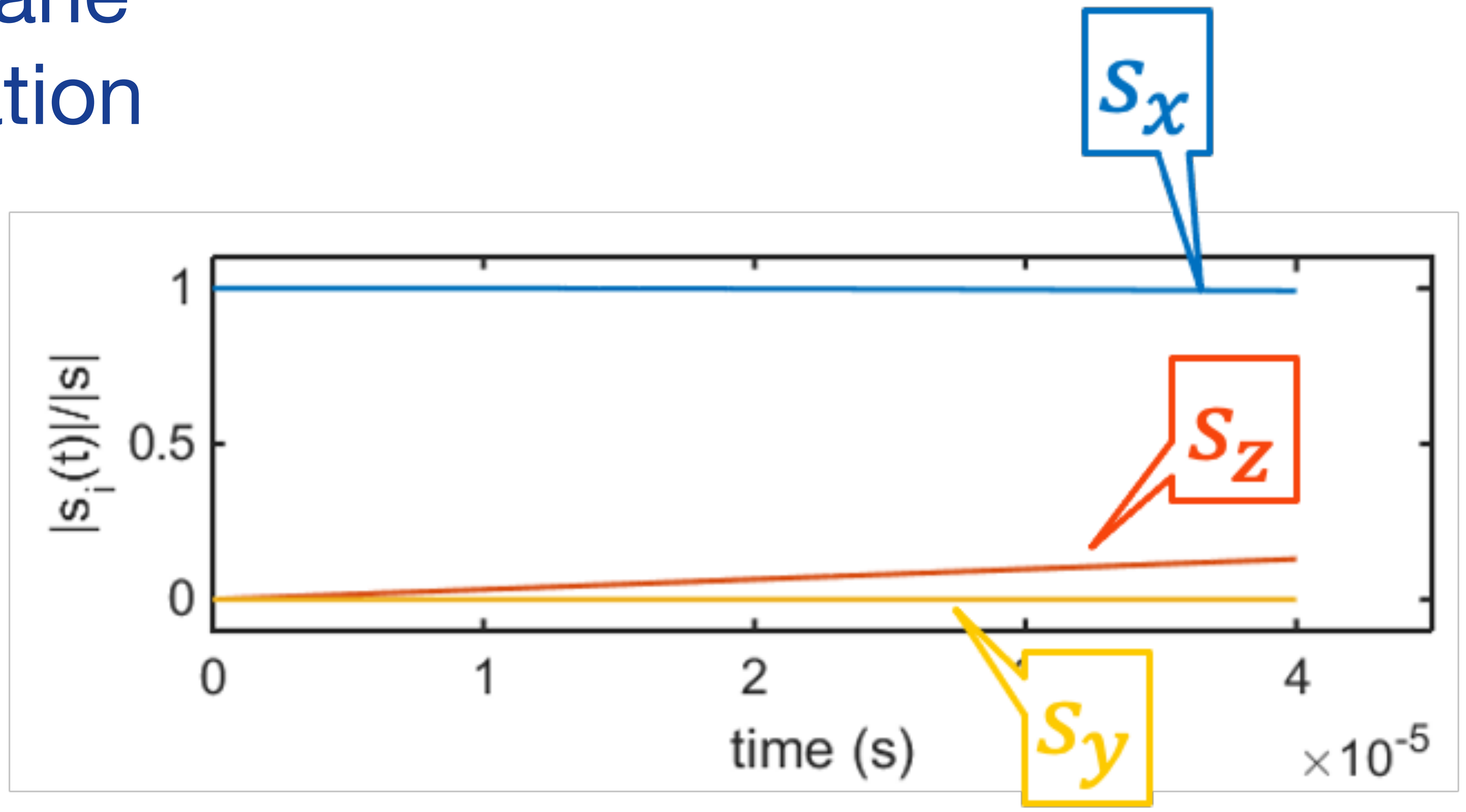
The “frozen-spin” technique

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

ω_a : g-2 ω_η: EDM

- Developed in 2004 for the muon EDM search PRL 93 (2004) 052001
- Freeze g-2 component by applying a radial E-field of ~ **$aBc\beta\gamma^2$**
  → no anomalous precession in the storage plane
  → EDM causes an increasing vertical polarization





Principle of the FS-EDM measurement

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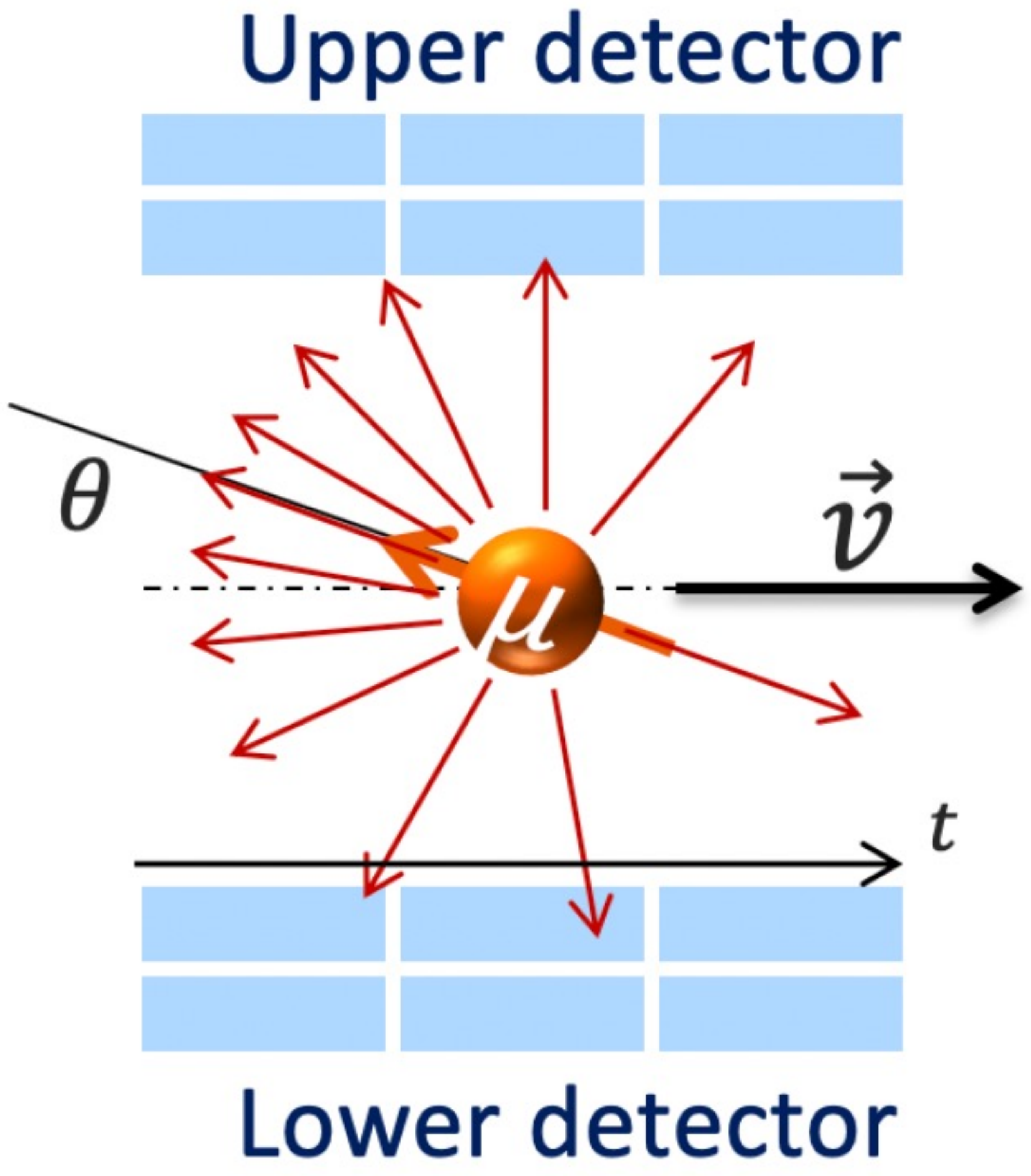
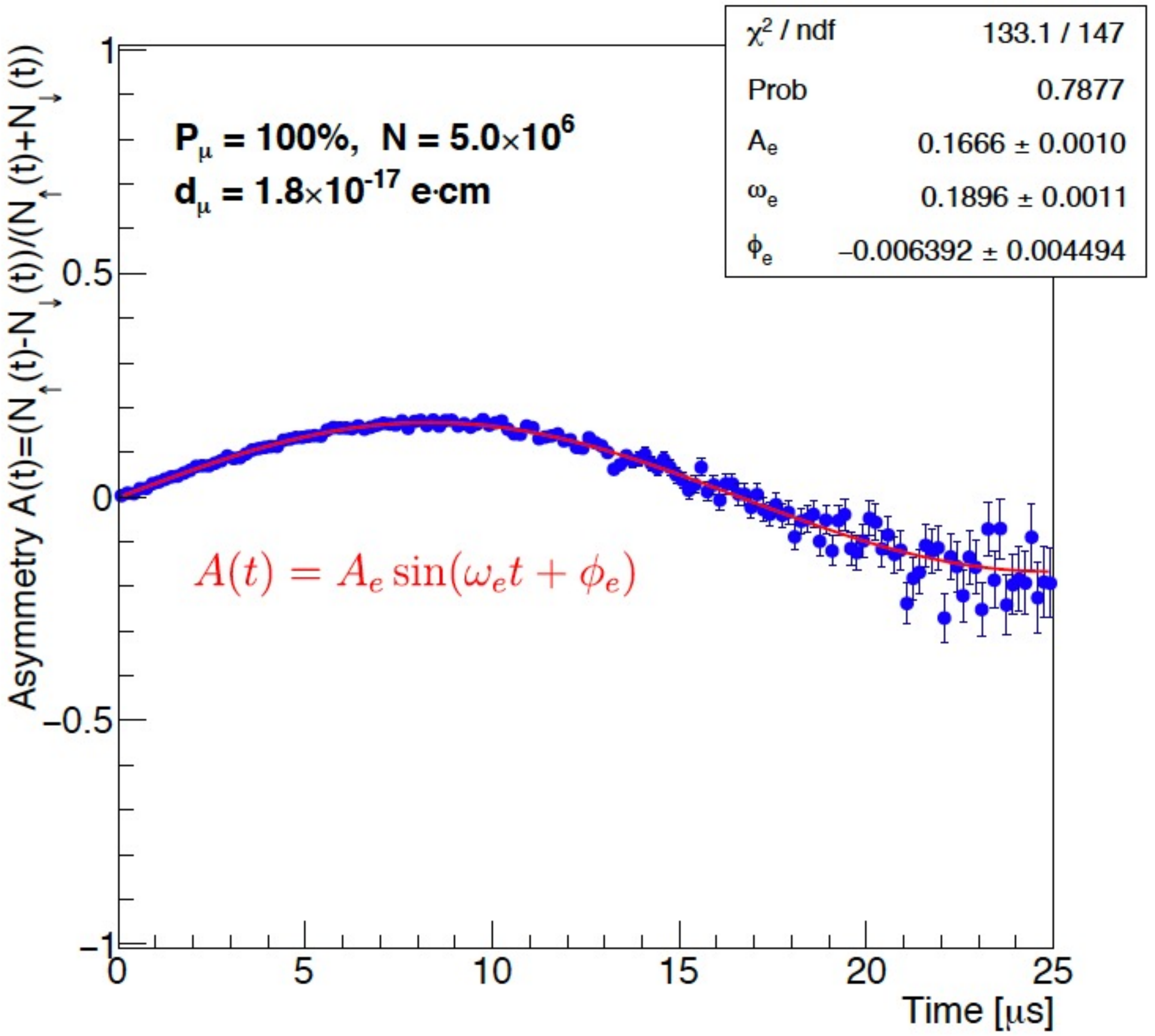
- Up-down asymmetry measured using upper and lower detectors





$$\sigma(d_\mu) = \frac{\hbar \gamma^2 a_\mu}{2 P E_f \sqrt{N}\, \gamma \tau_\mu\, \alpha}$$

P := initial polarization

E_f := Electric field in lab

$\sqrt{N}$:= number of positrons

τ_μ := lifetime of muon

α := mean decay asymmetry

The PSI muEDM Collaboration

CERN
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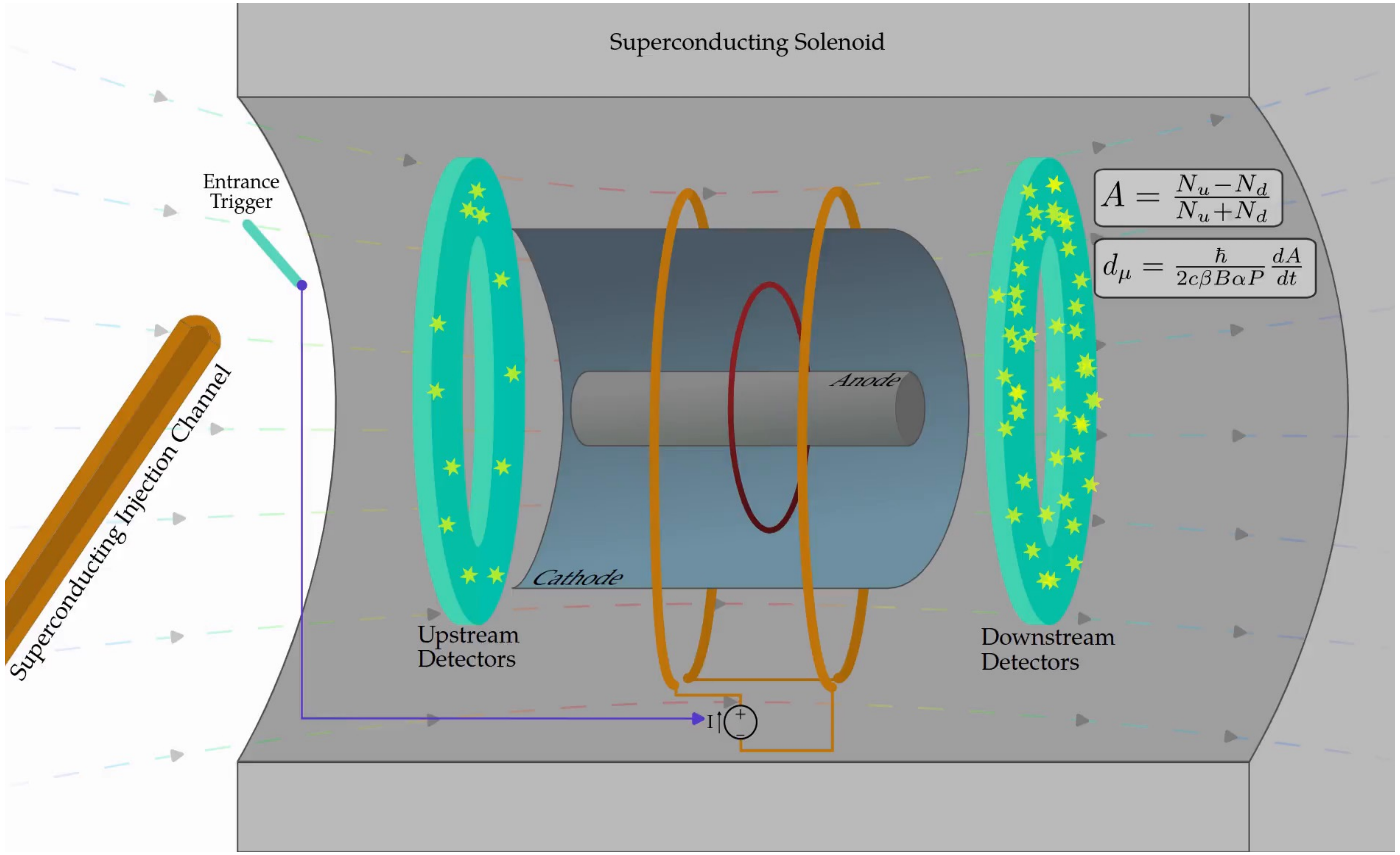
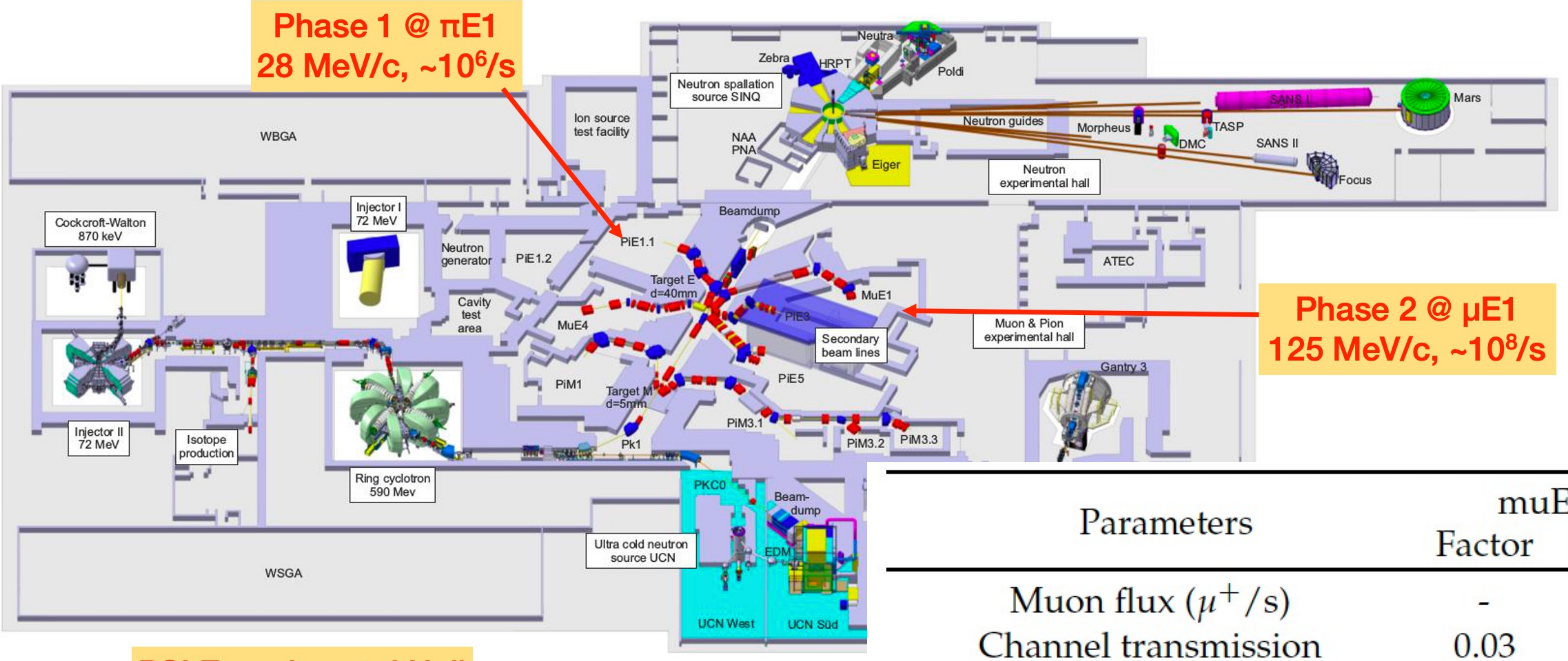
tu technische universität dortmund
The Cockcroft Institute of Accelerator Science and Technology
UNIVERSITY OF LIVERPOOL
UCL
JOHANNES GUTENBERG UNIVERSITÄT MAINZ JG|U
MANCHESTER 1824 The University of Manchester
Universidad Nacional Autónoma de México
Technical University of Munich TUM
INFN
Università di Pisa
SAPIENZA Università di Roma
李政道研究所 Tsung-Dao Lee Institute
PSI
ETH zürich
Universität Zürich UZH

Principle of the FS-EDM measurement

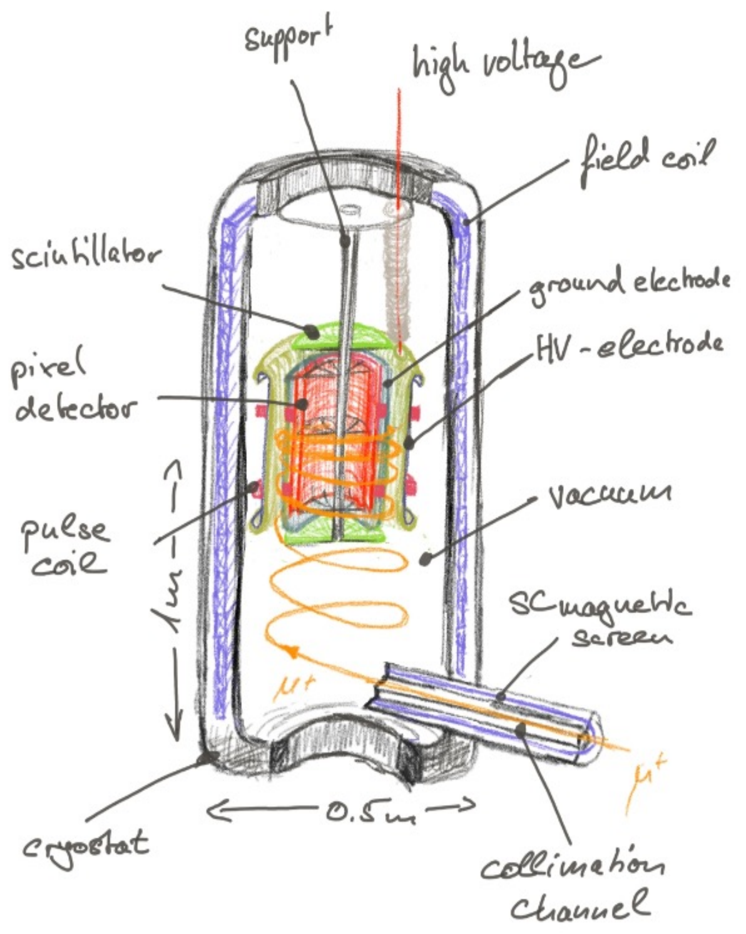


- Muon enters the solenoid through a SC injection channel
- Magnetic pulse kicker stops the muon's longitudinal motion within a weakly focusing field where it is stored
- Radial electric field 'freezes' the spin so that the precession due to the g-2 is cancelled
- Up-down detectors measure the asymmetry of the muon decay

muEDM Phase I and Phase II

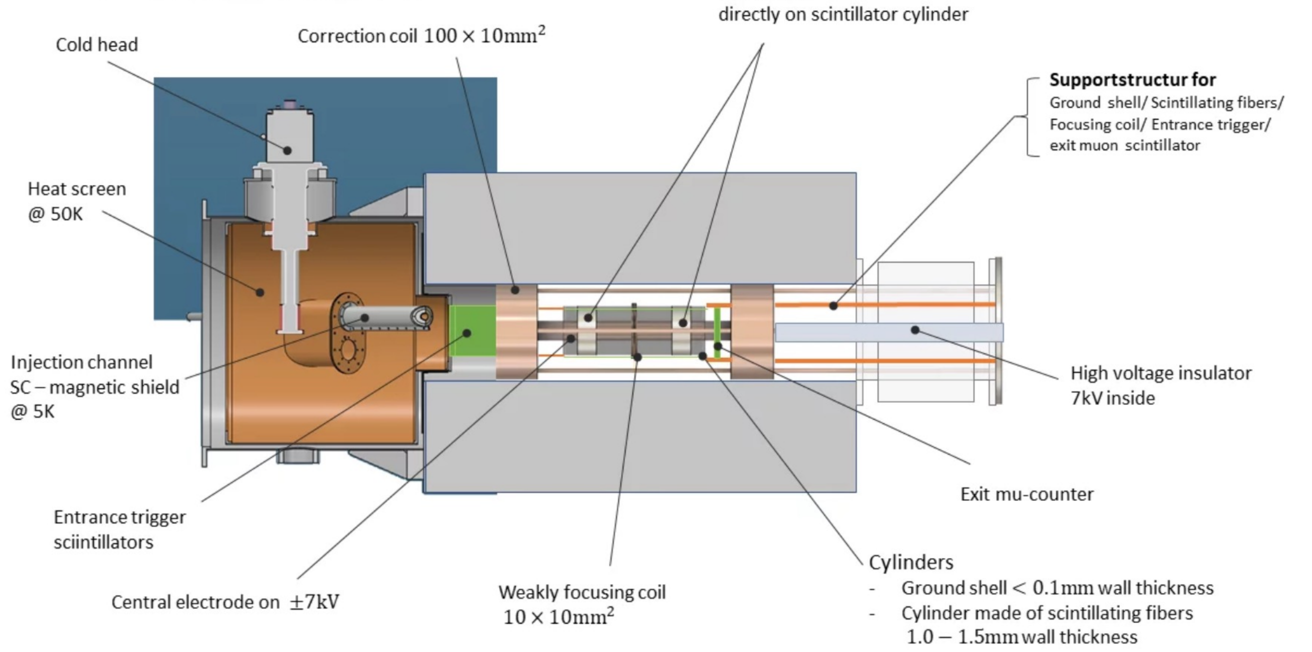


PSI Experimental Hall



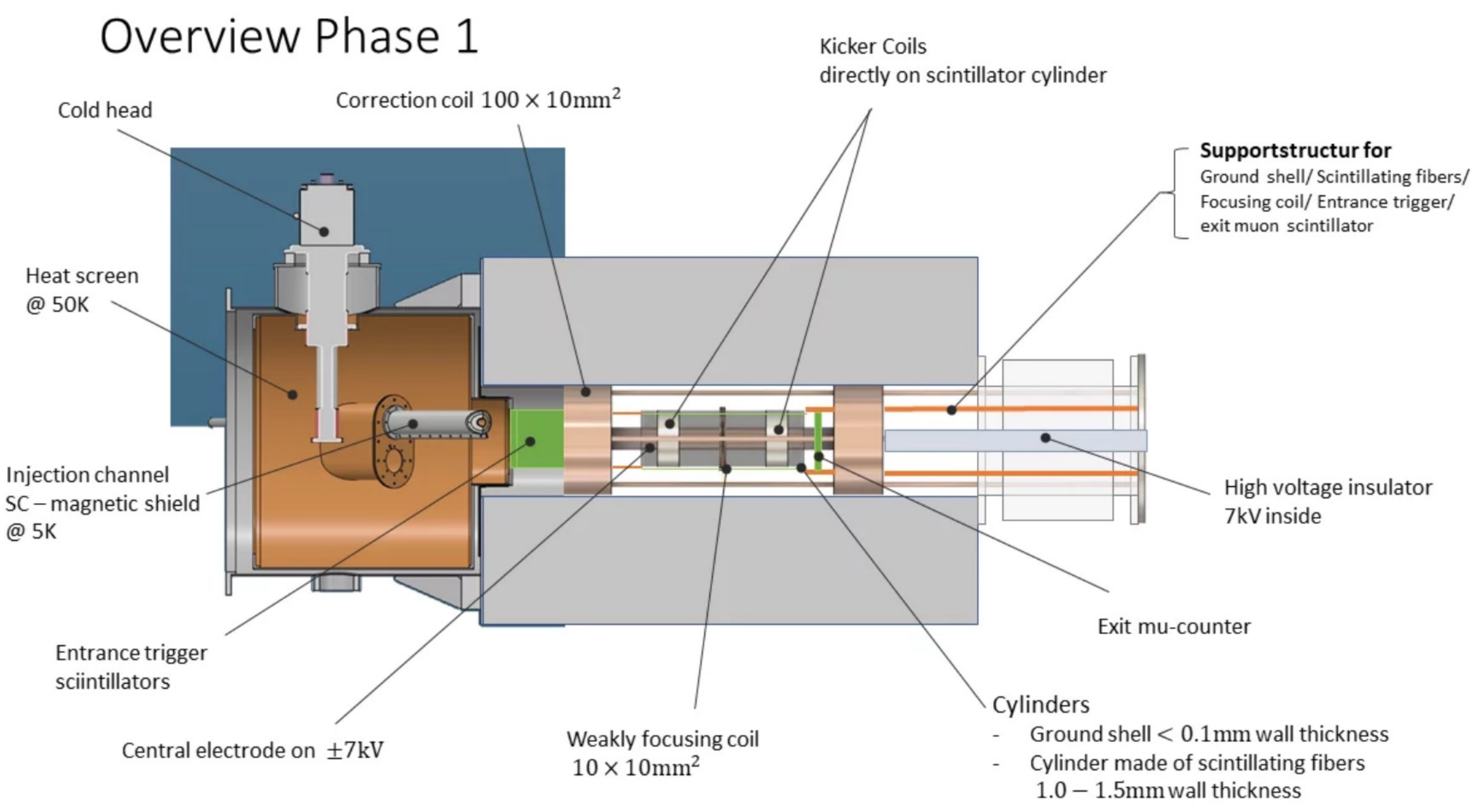
Parameters	muEDM Phase I Factor	muEDM Phase I Event rate [Hz]	muEDM Phase II Factor	muEDM Phase II Event rate (Hz)
Muon flux (μ^+/s)	-	4×10^6	-	1.2×10^8
Channel transmission	0.03	1.2×10^5	0.005	6×10^5
Injection efficiency	0.017	2.0×10^3	0.6	3.6×10^5
e^+ detection efficiency	0.25	5.0×10^2	0.25	9.0×10^4
Detected e^+ per 200 days	8.64×10^9		1.56×10^{12}	
Beam momentum, [MeV/c]	≈ 30		125	
Gamma factor, γ	1.04		1.56	
Storage magnetic field, B [T]	3		3	
Electric field, E_f [kV/cm]	3		20	
Muon decay asymmetry, α	0.3		0.3	
Initial polarization, P_0	0.95		0.95	
Muon EDM Sensitivity [e·cm]	3×10^{-21}		6×10^{-23}	

Overview Phase 1



Overview of muEDM Phase I

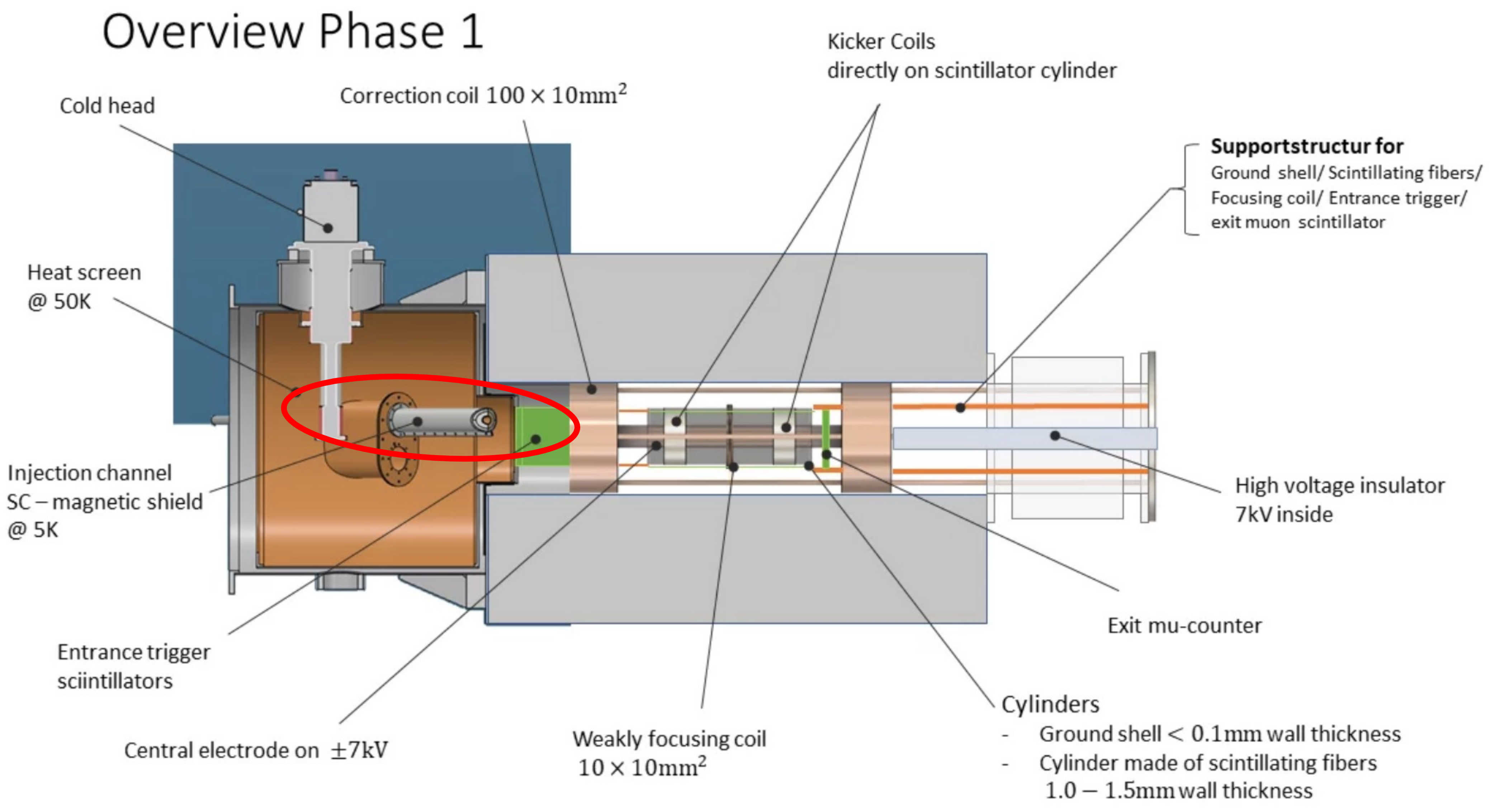
Proof-of-principle of the frozen spin technique



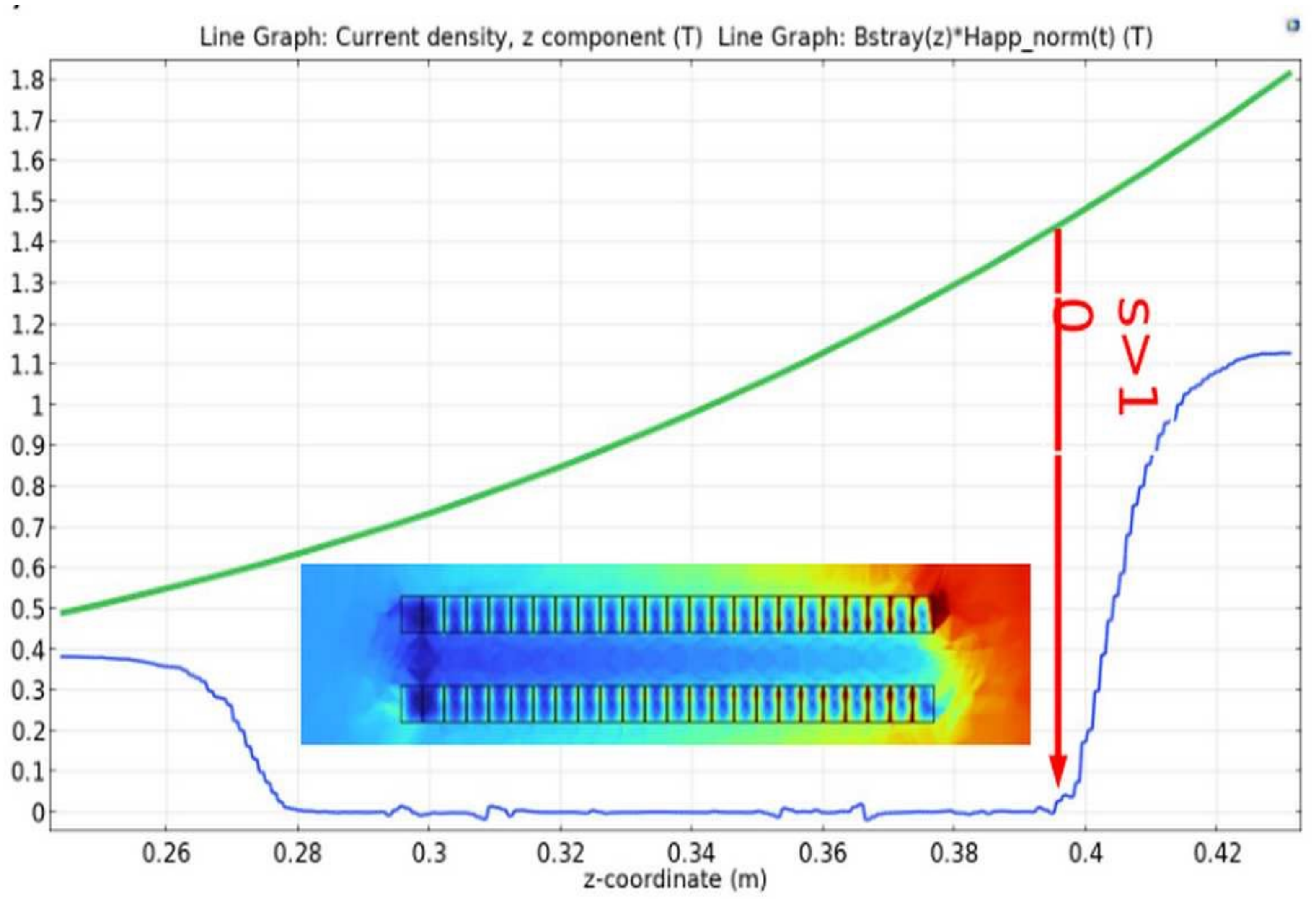
Develop key technologies and design the final instrument

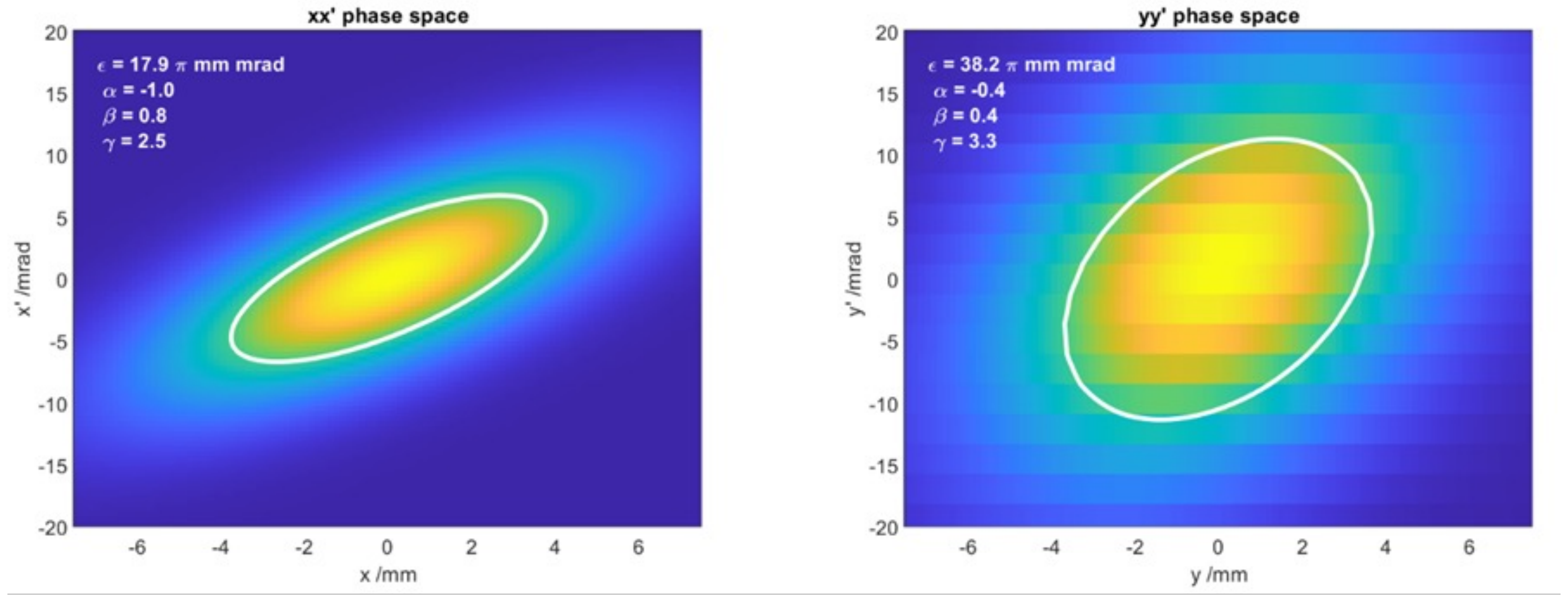
- Full MC model
- Full FEM model
- Analysis and DAQ
- Injection channel made of a superconducting shield
- Pulsed magnetic field to kick muons on a stable orbit
- Nested electrode system with a minimal material budget for the frozen-spin technique

Muon Injection through SC channel



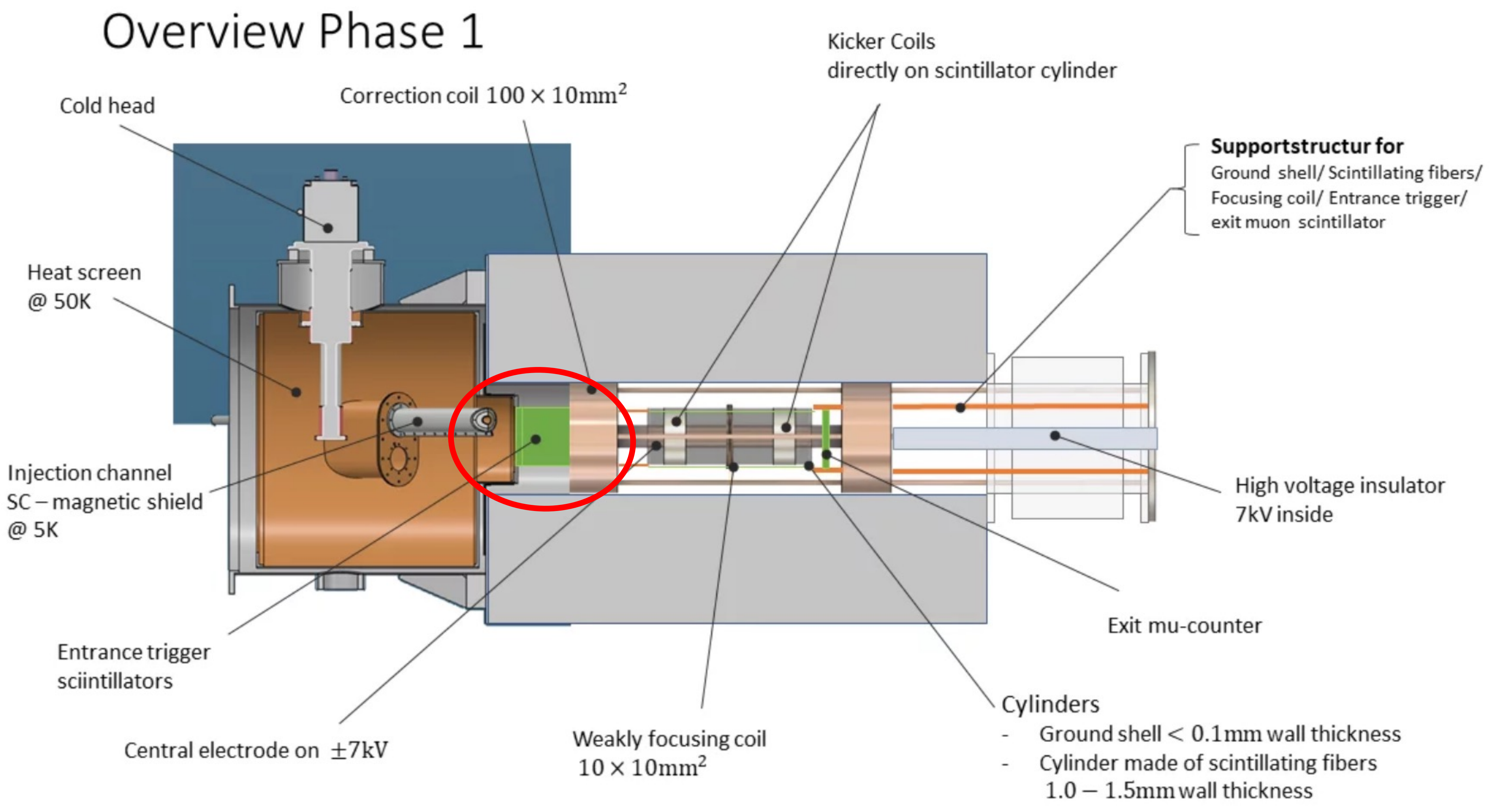
- Long injection channels for beam collimation
- Superconducting material (YBCO) to shield injection channel from fringe field

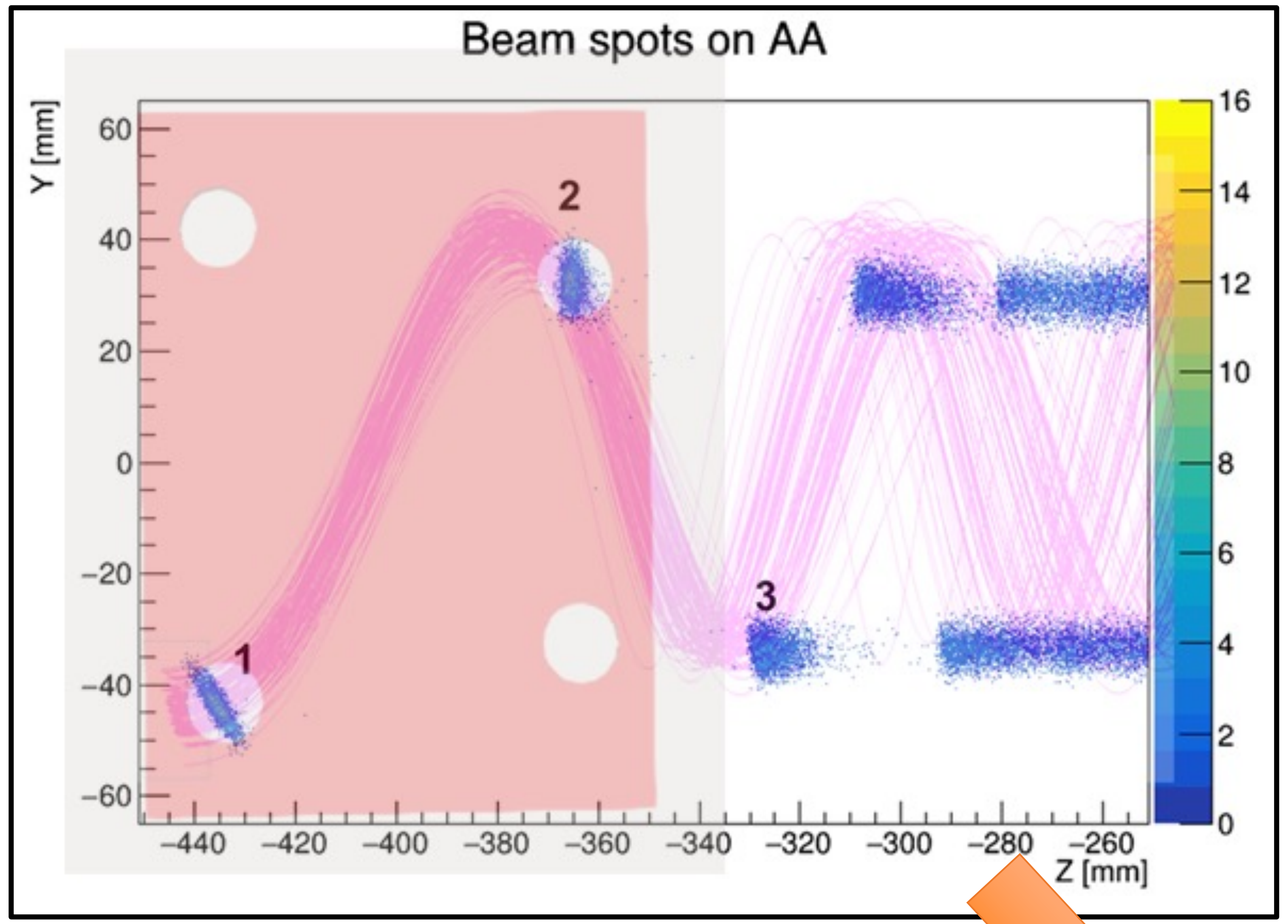




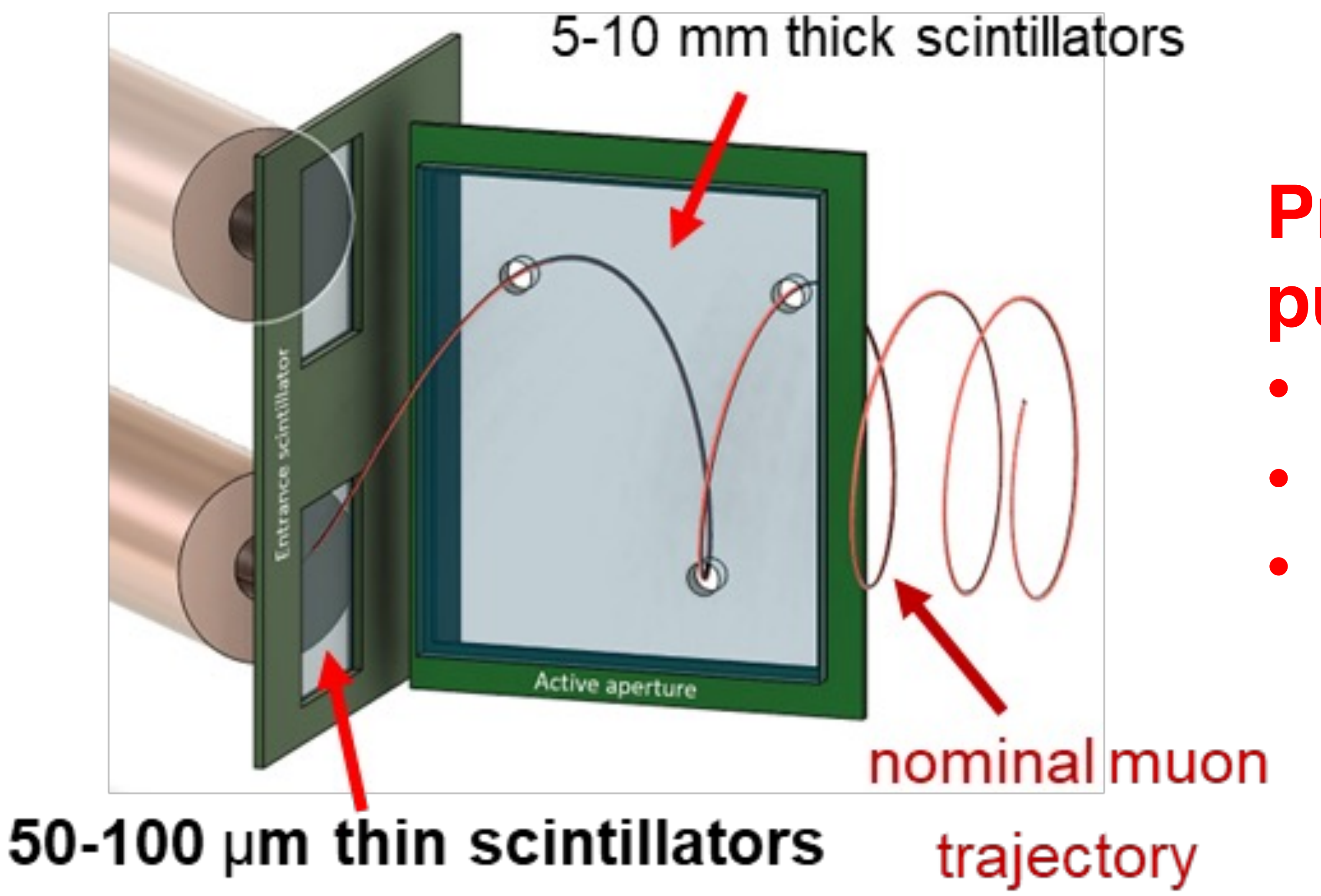
- G4beamline/musrSim to optimize muon injection
- Storage efficiency $\sim 0.5 \times 10^{-4}$

Muon Entrance Detector



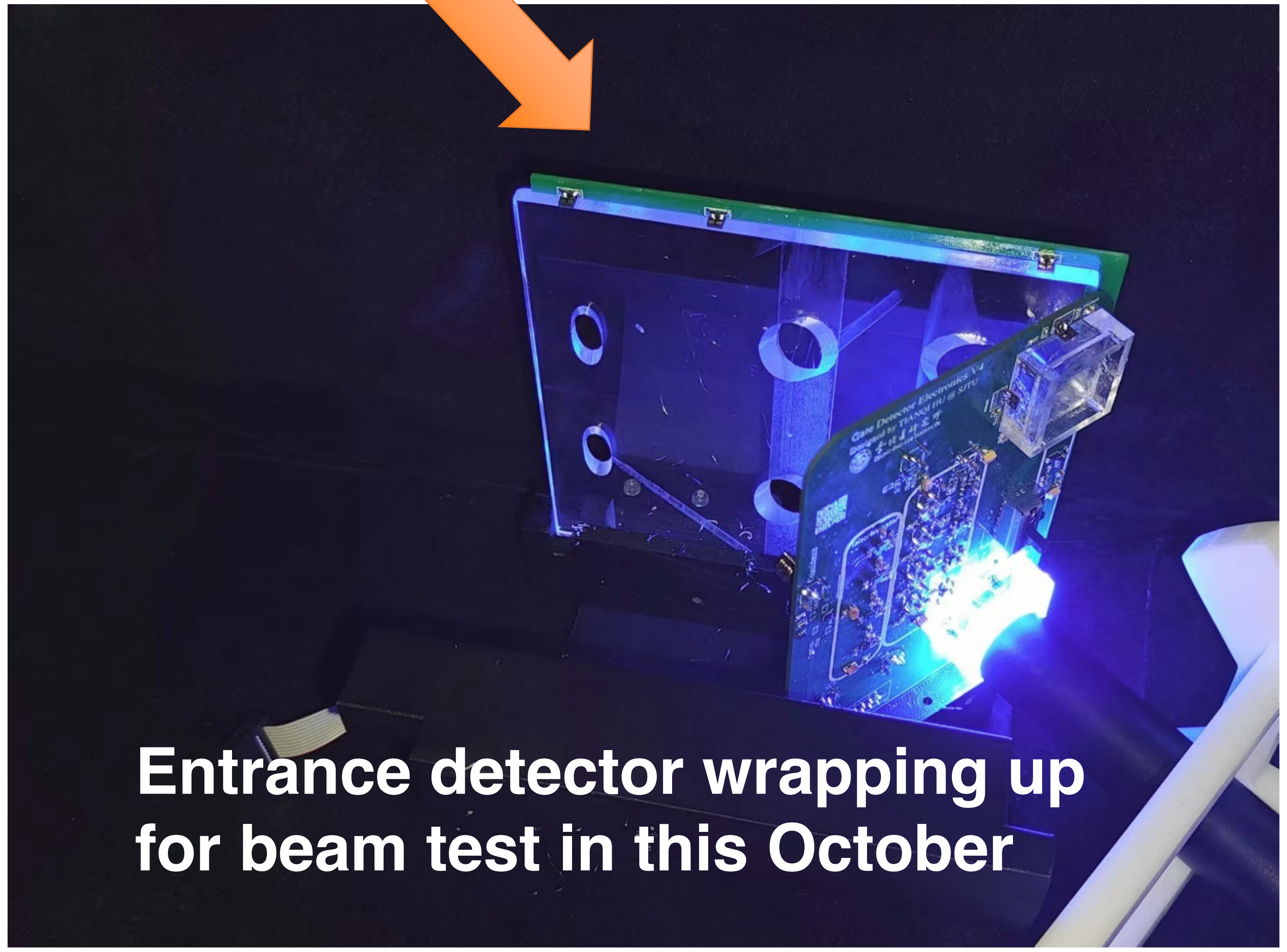


Optimized detector geometry to maximize storage muons

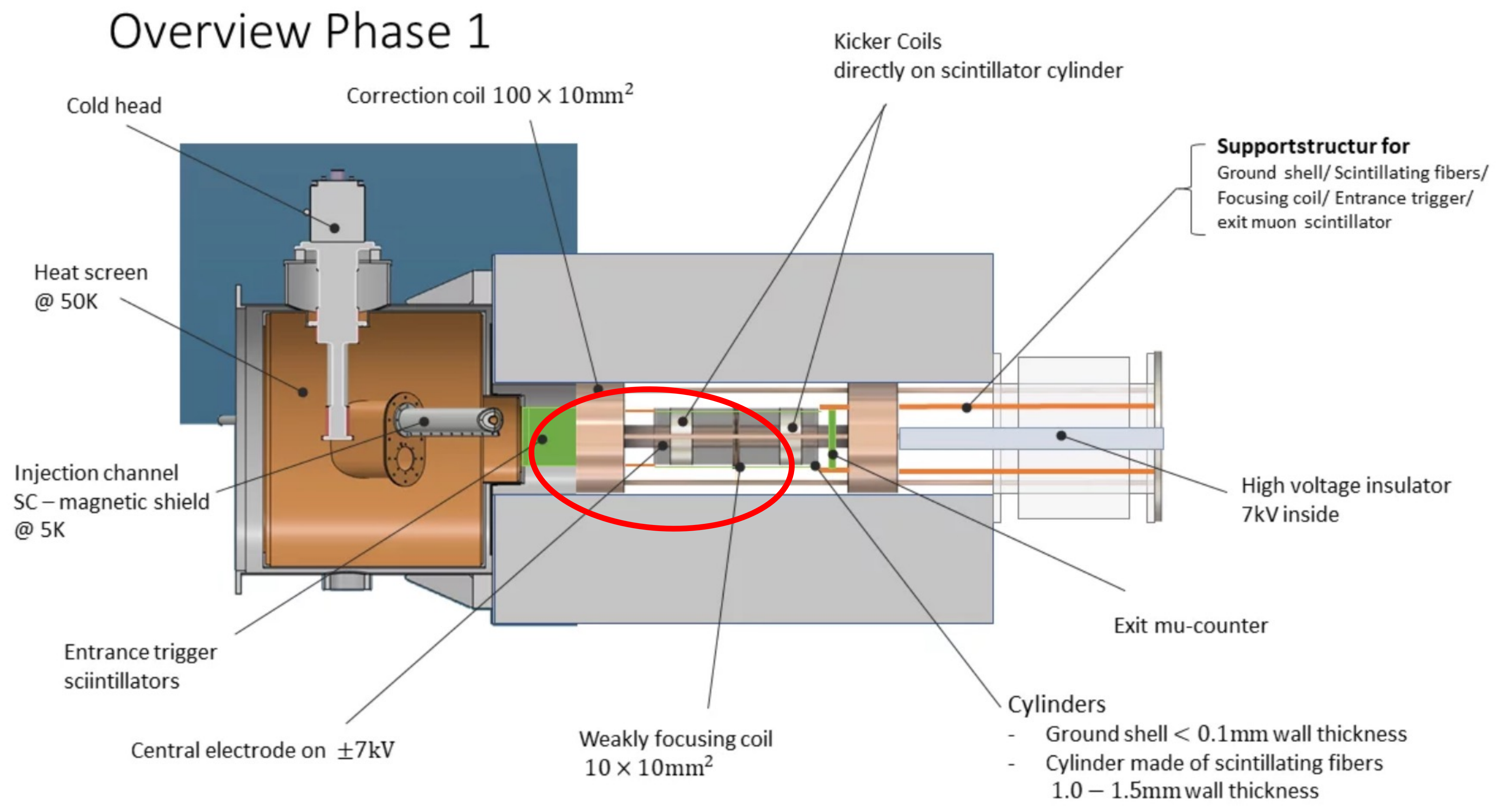


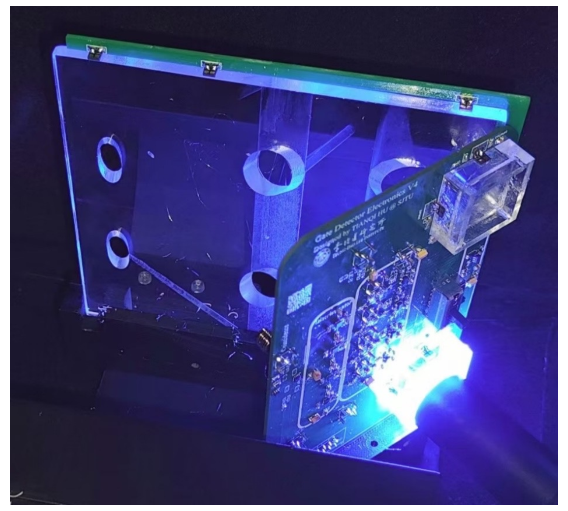
Provides trigger signal of storage pulse kick

- Fast detector
- Only does so for *storable muons*
- Rejects out-of-acceptance muons

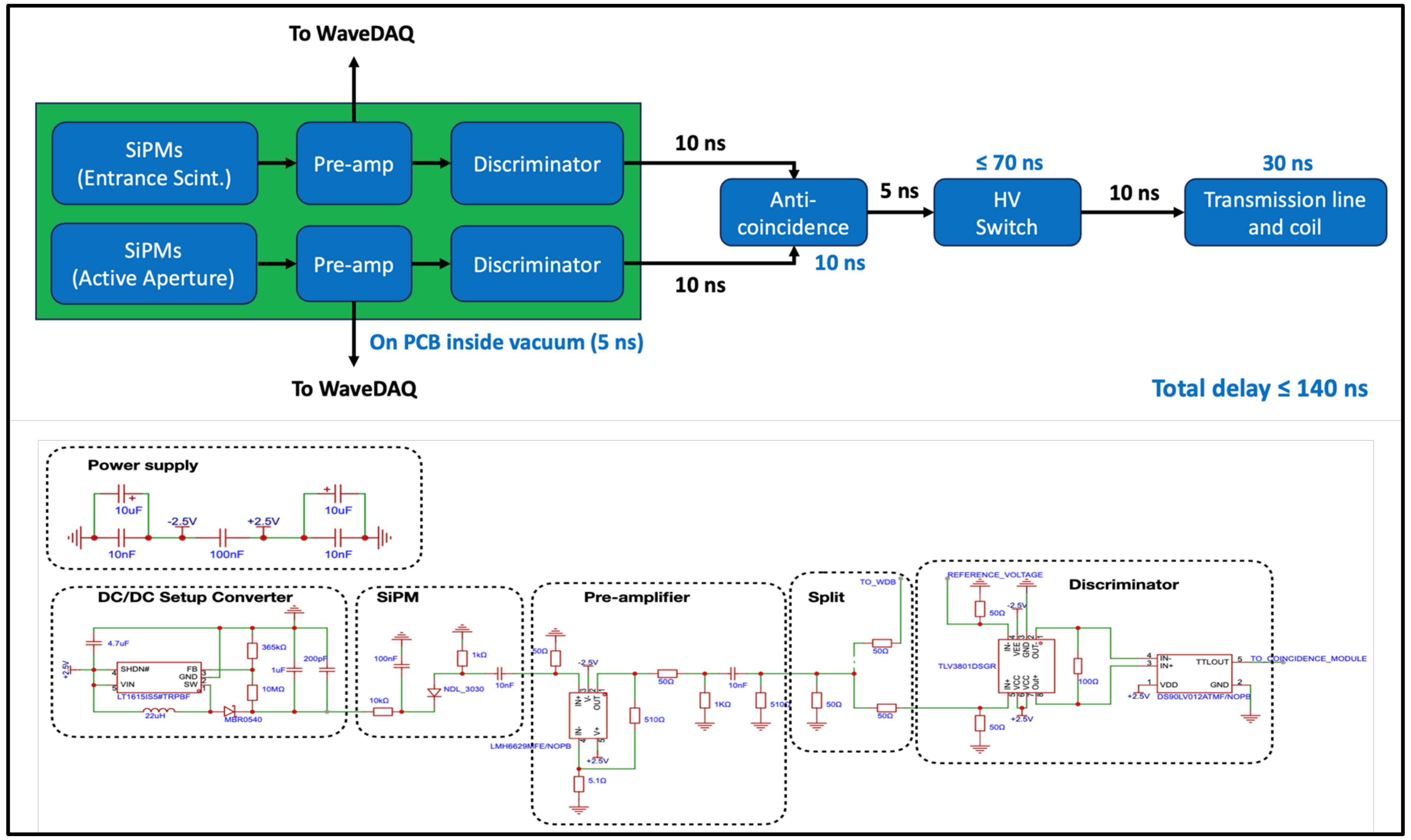


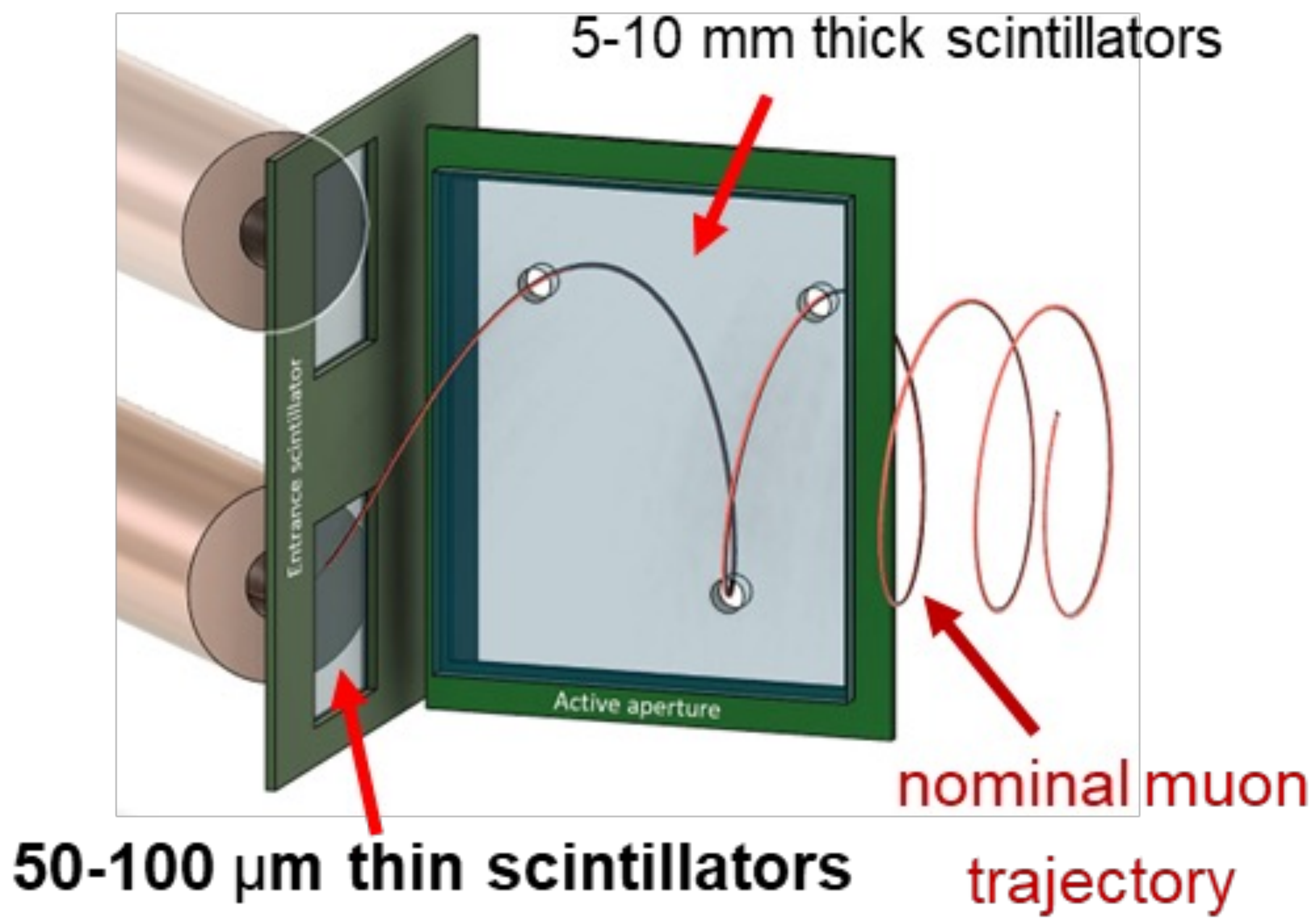
Fast trigger for kicker coils

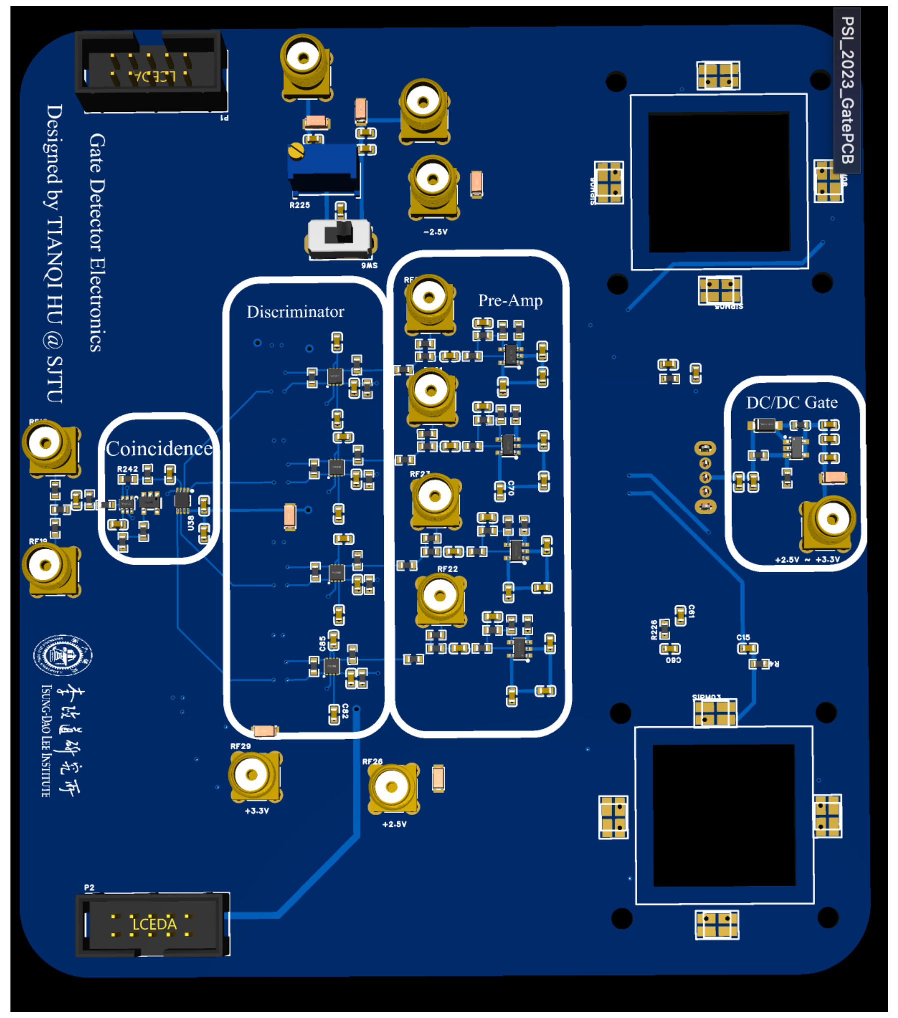


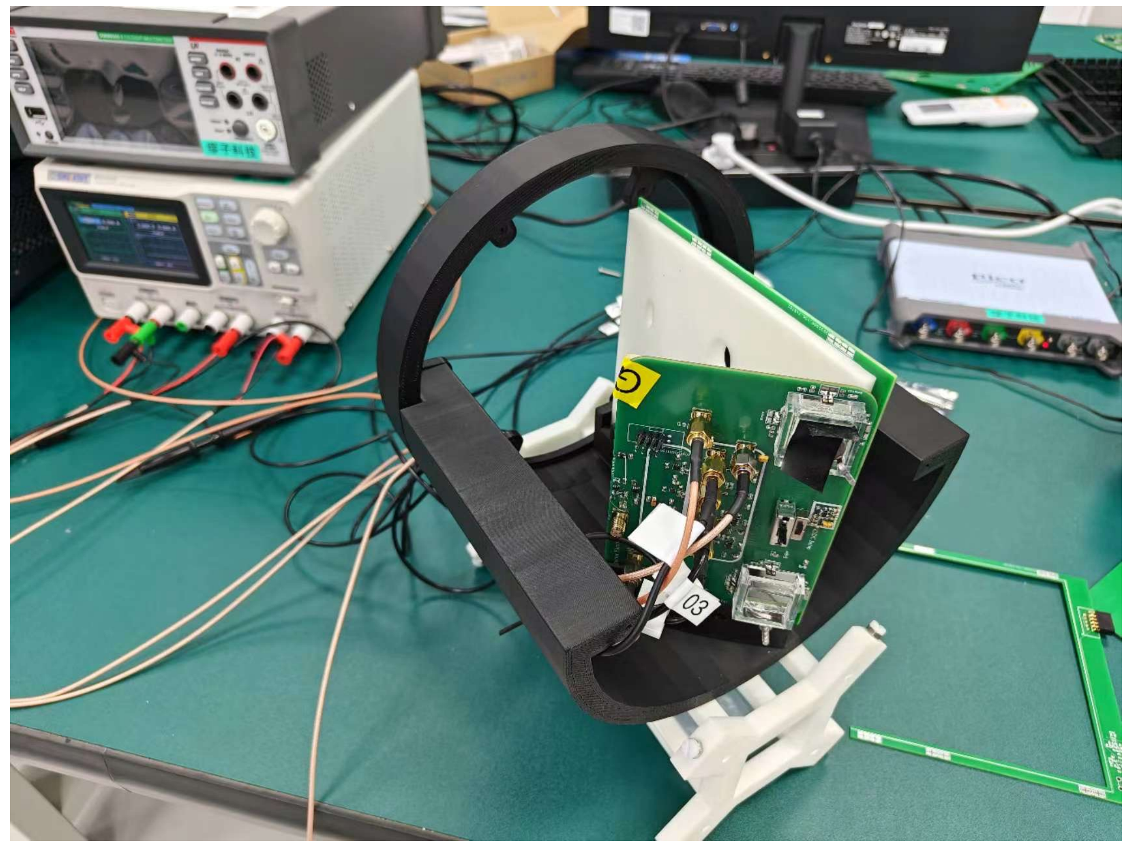


Fast electronics design to satisfy timing requirements



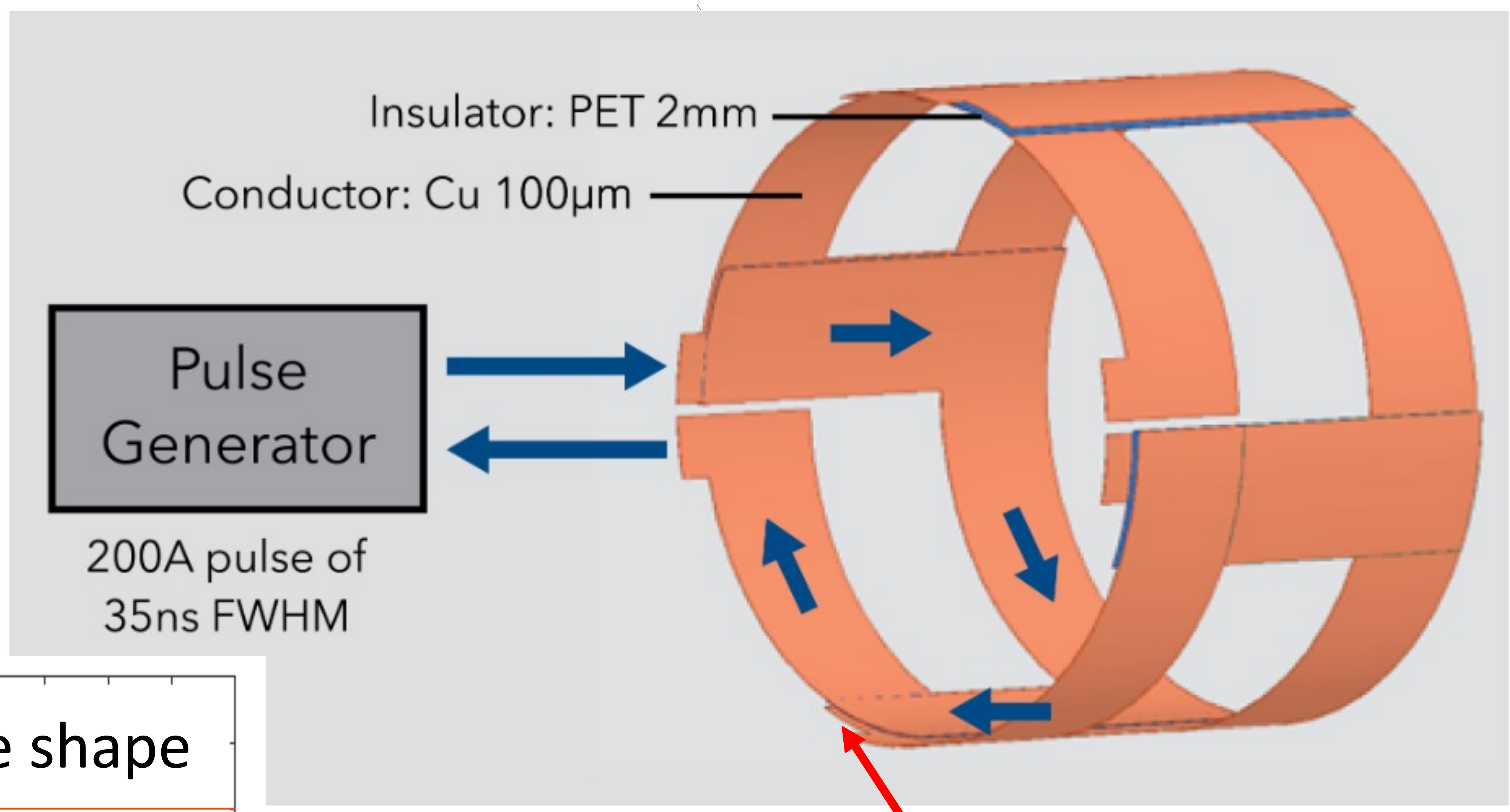


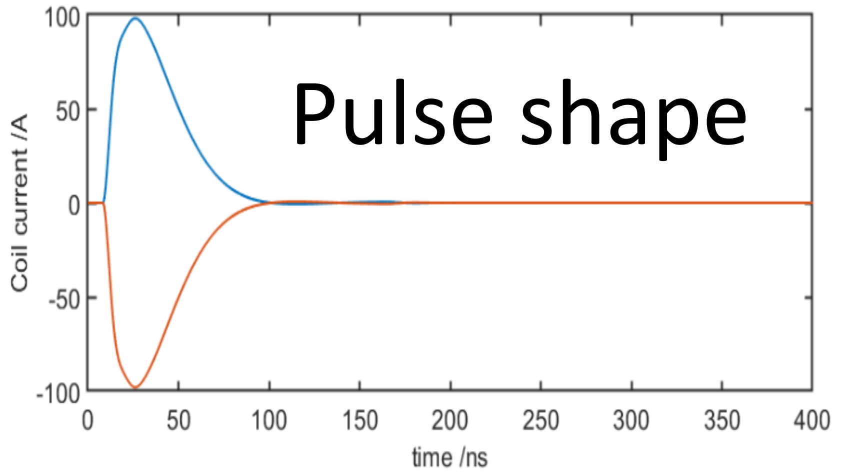


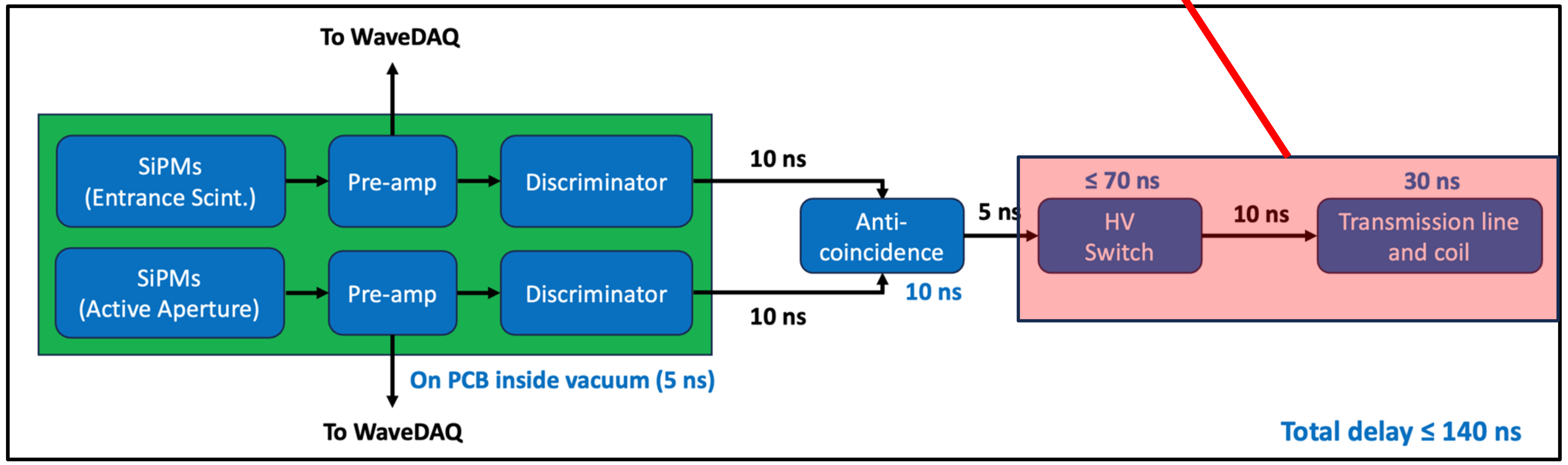


Entrance detector wrapping up for beam test in this October

Storage Pulse Kicker

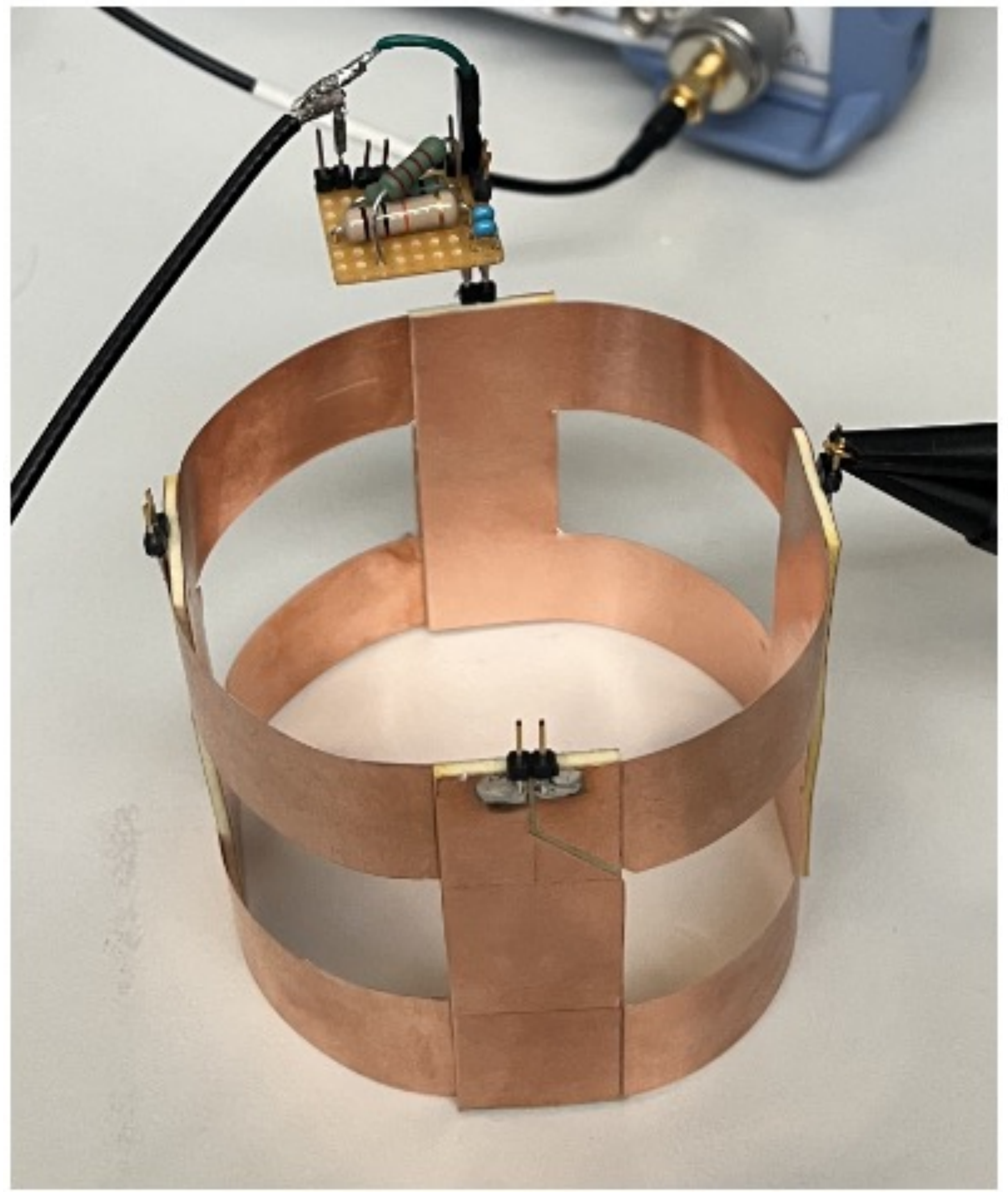


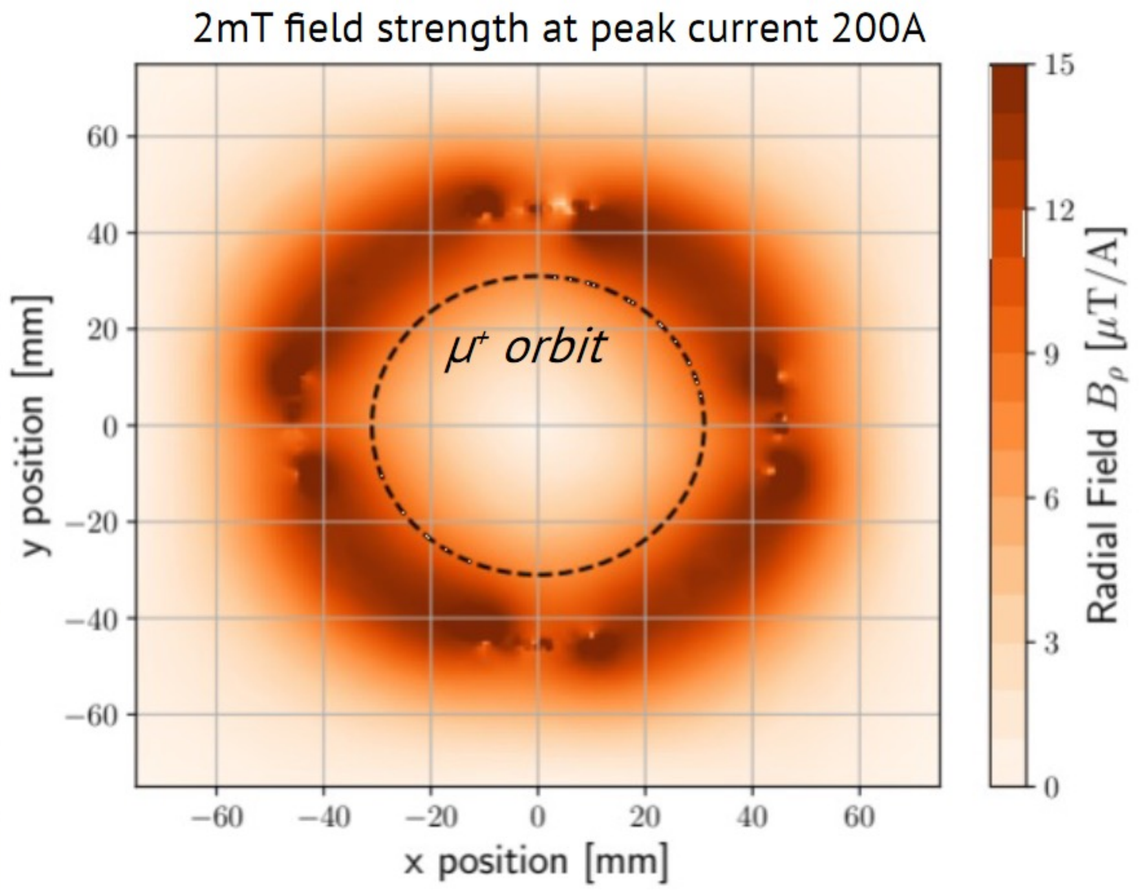




Short trigger delay necessitates internal latency of pulse generator to < *60 ns*

First prototype

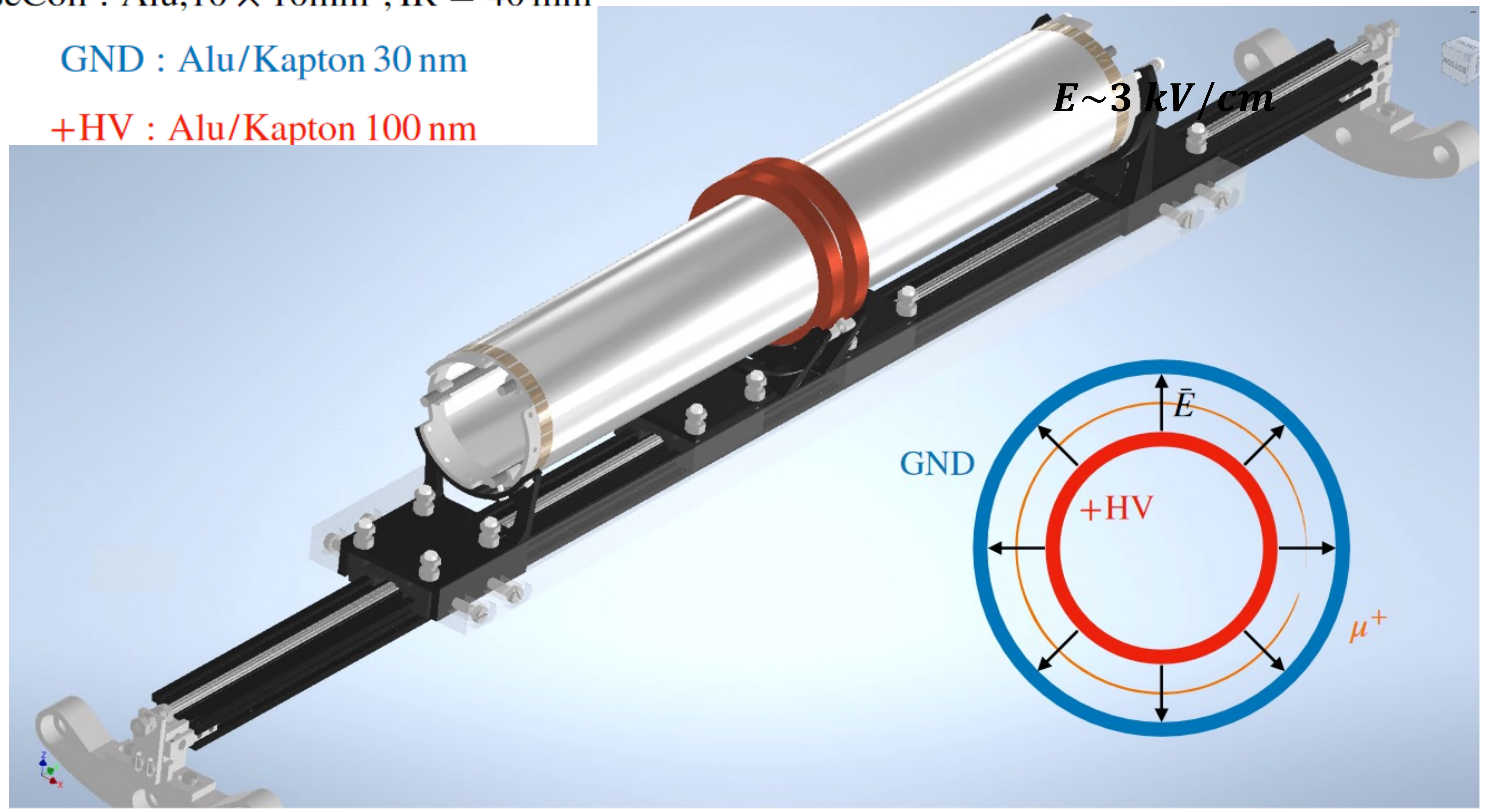


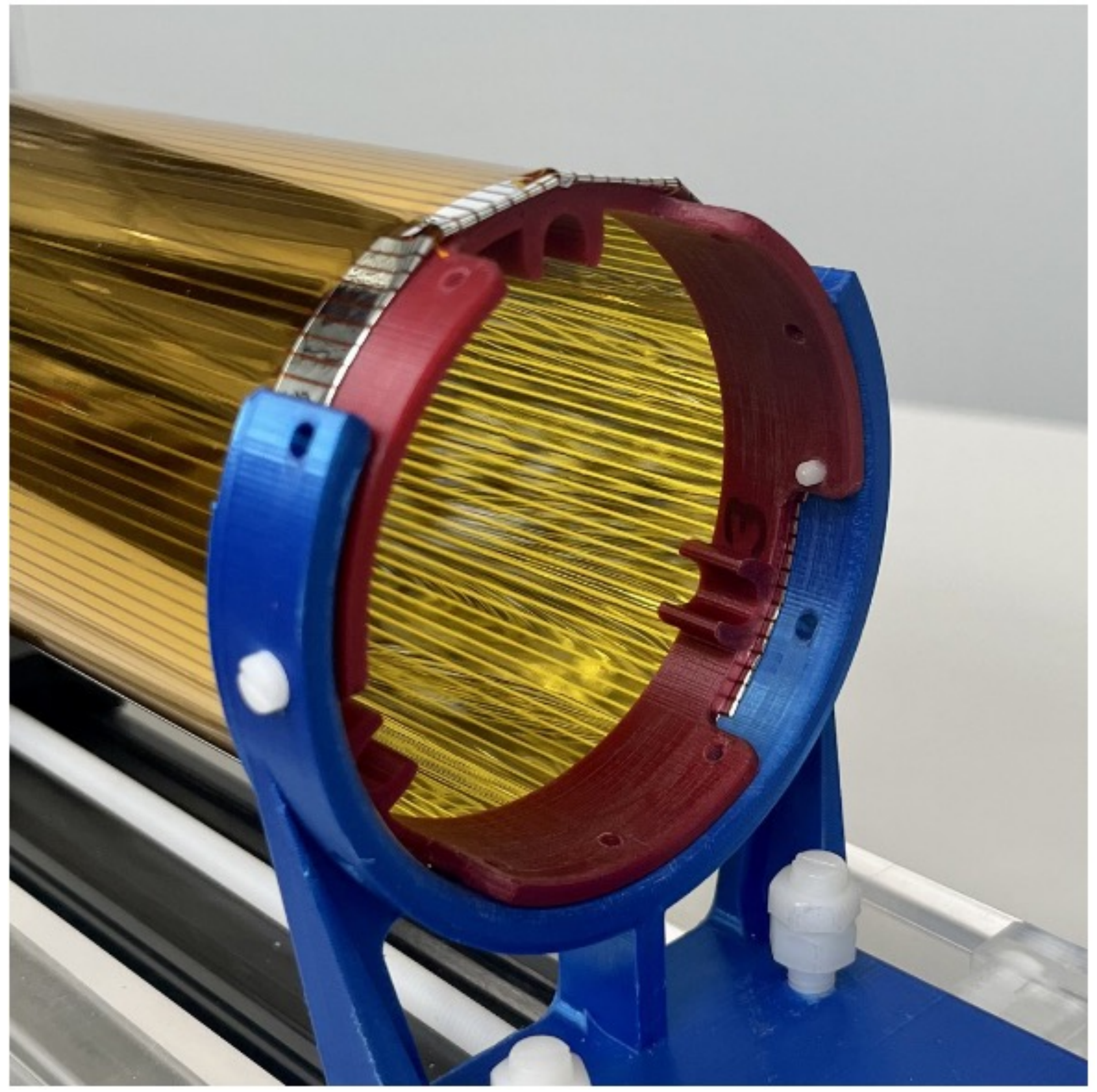


- Coil quadrants generating pulsed longitudinal kick to store muons
- Technical requirements:
  - large amplitude
  - rapid triggering of short-duration pulsed magnetic field, with strong tail suppression

Frozen-spin Electrodes

Radial electric field applied by two concentric electrodes enclosing muon orbit





Current solution:

- 25 μm Kapton films
- Strip-segmented ~30 nm Al coating
- 2.2 mm pitch

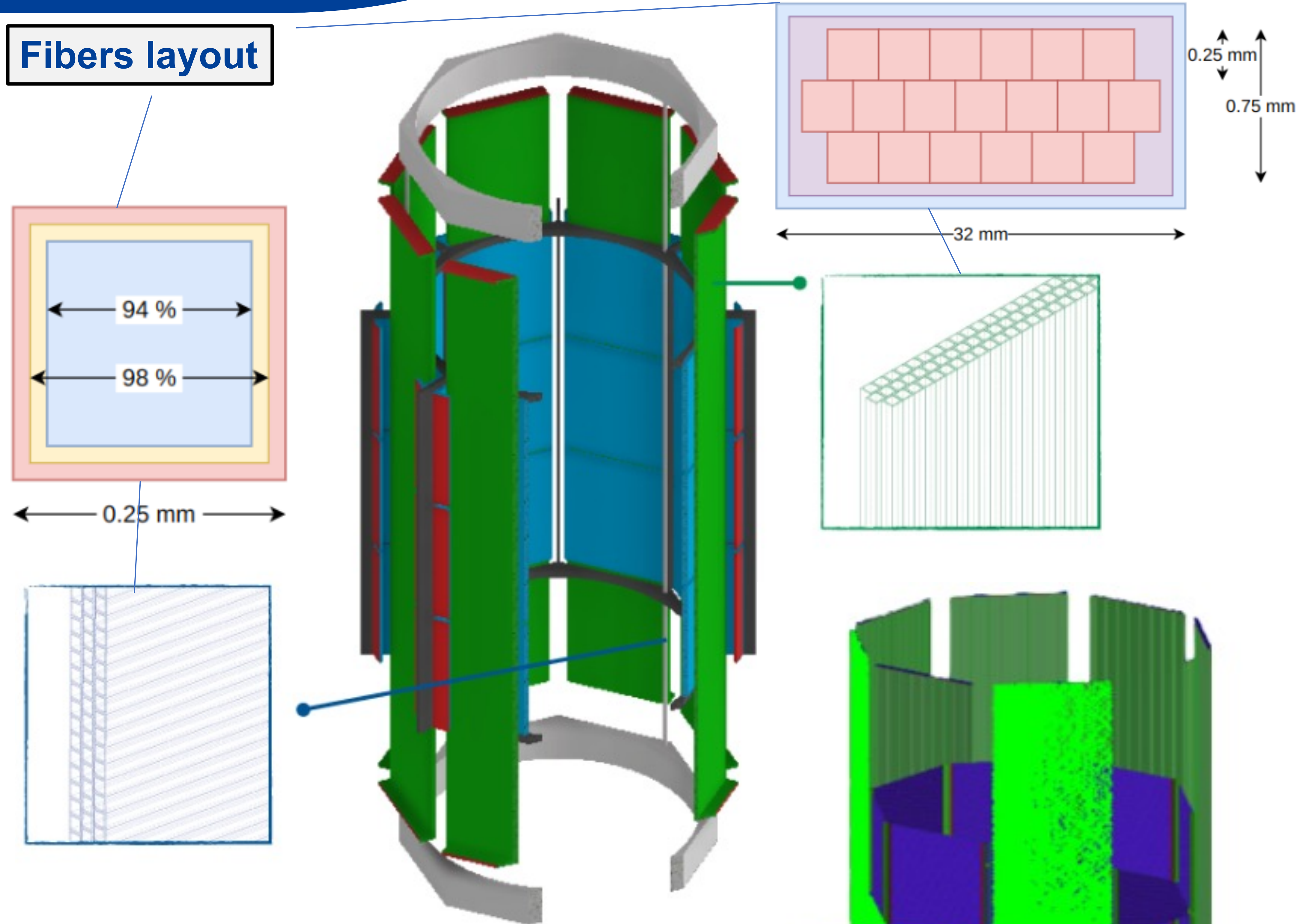
Technical requirements:

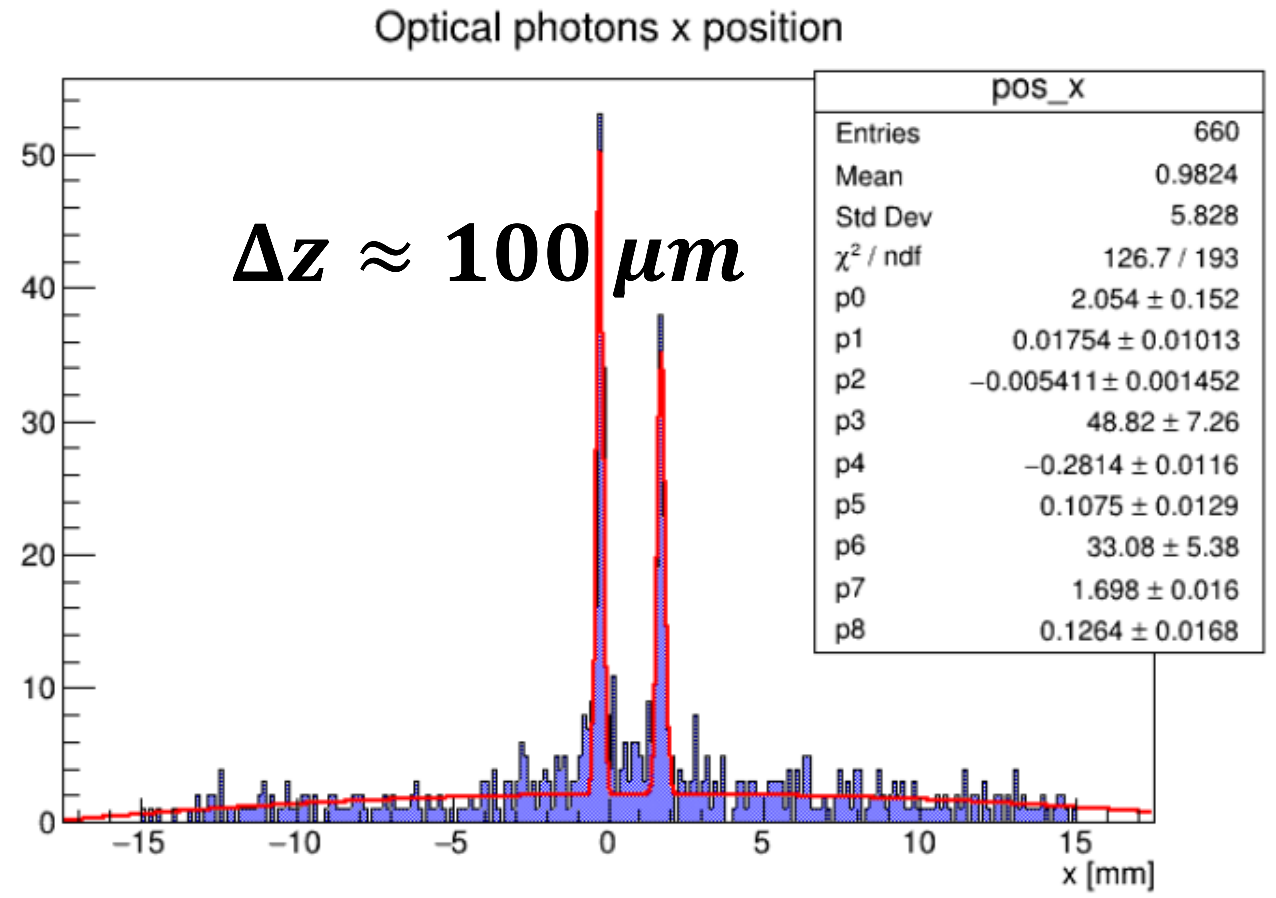
- Precise alignment with muon storage plane
- Heat dissipation
- Minimal multiple scattering for positrons
- Suppress Eddy current

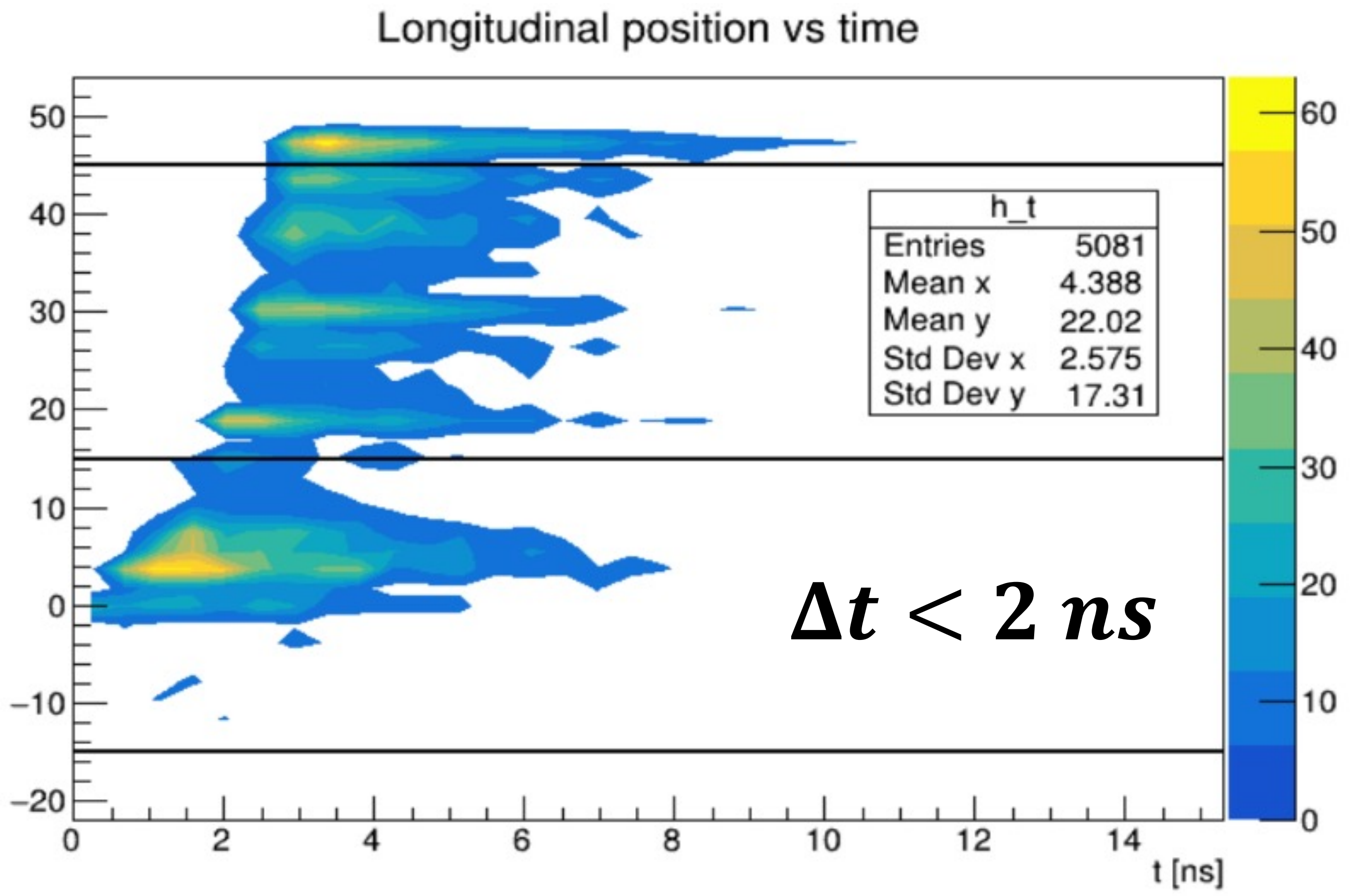
Strip-segmented Alu-Kapton film approach **suppresses Eddy current damping**, without compromising **electric field uniformity**.

Positron detectors for EDM Signal

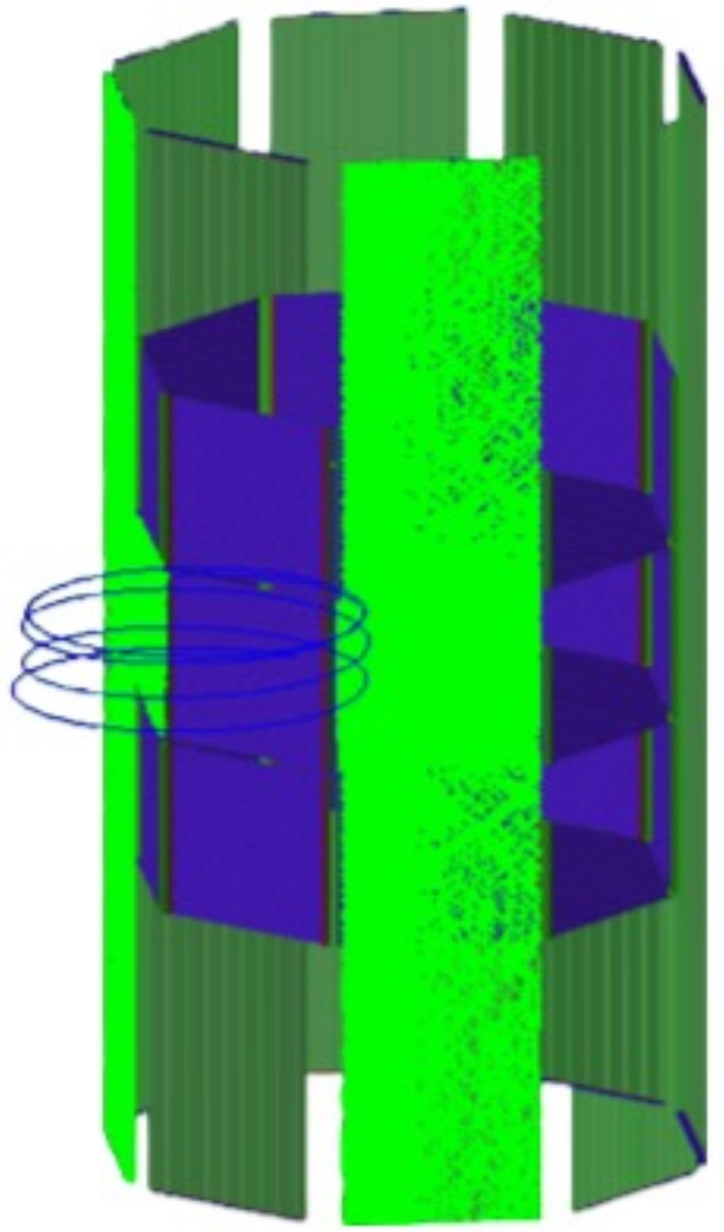
- Double barrel SciFi tracker
- Measures longitudinal asymmetry of positron
- Bundles of fibers with good timing and position resolutions
  - transverse and longitudinal fibers







- Photon time and position (longitudinal info on internal barrel)
- Large number of readout channel a challenge
- Considering other possible geometries



Potential systematic effects

- Systematics: all effects that lead to the real or apparent precession of the spin mimicking EDM signal
- BNL/FNAL EDM searches provided very good guidance:
  - Misalignment in fields and detectors
  - Variation in detection efficiency
  - New type of systematics inclusively for frozen-spin approach
- Derive specifications of all technical designs of the experiment
  - Careful analysis of systematics using toyMC and Geant4 simulations
- A recent study can be found at arXiv:2311.10508

Annual beam tests at PSI

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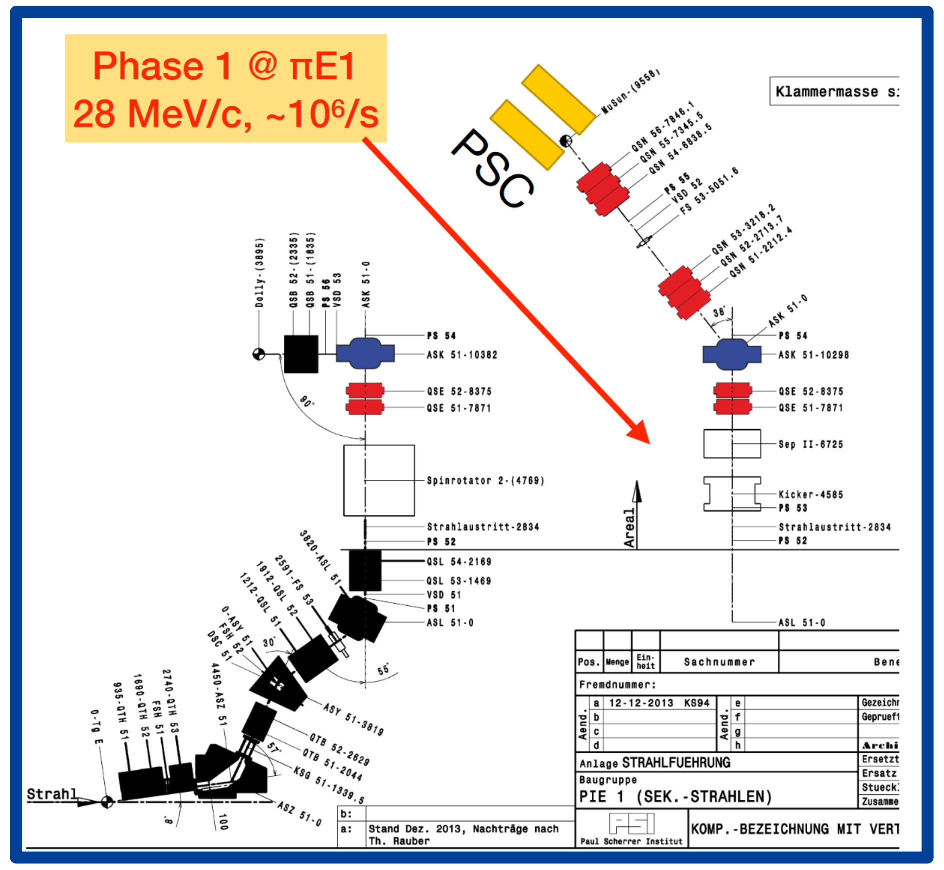
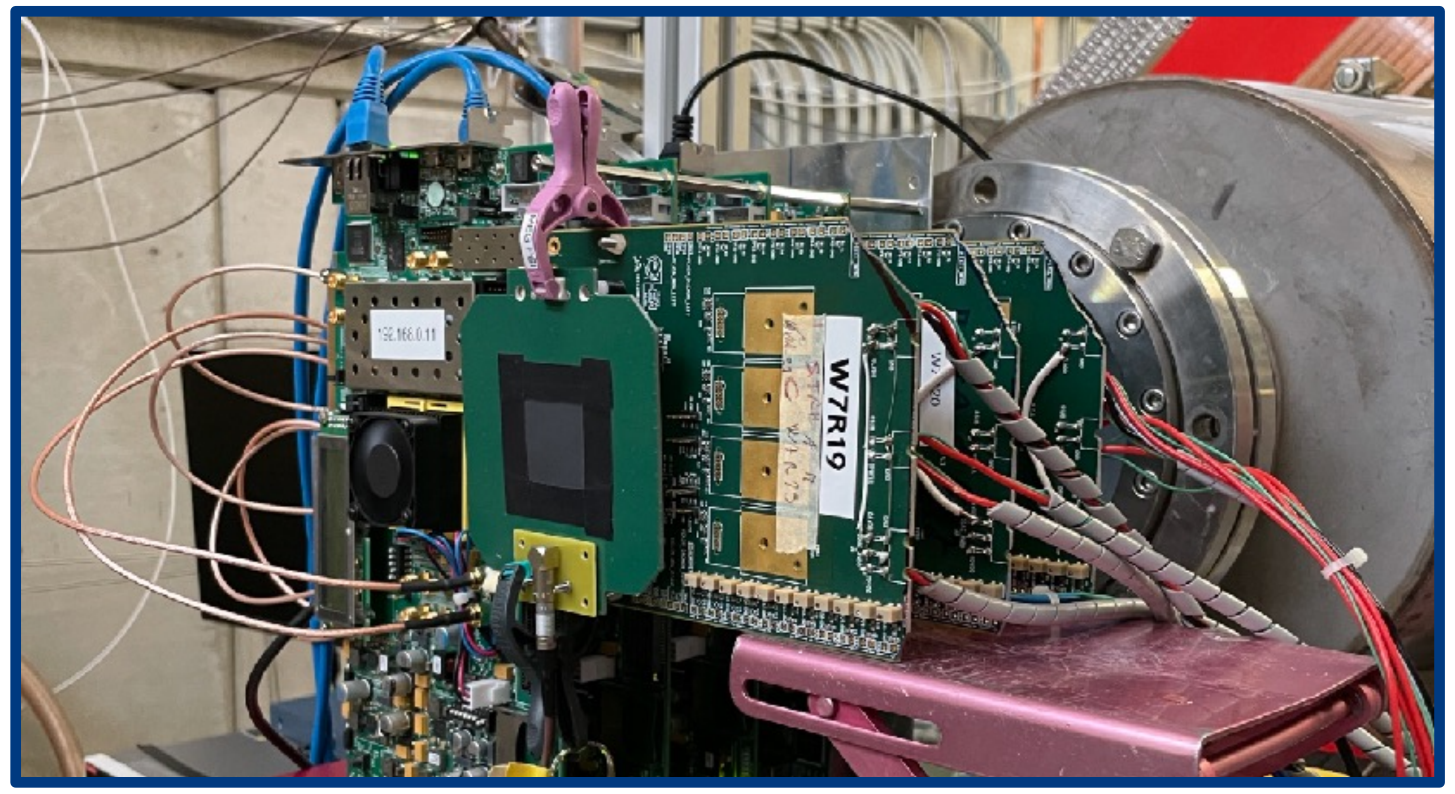
2019



Characterisation of potential beam lines

2020

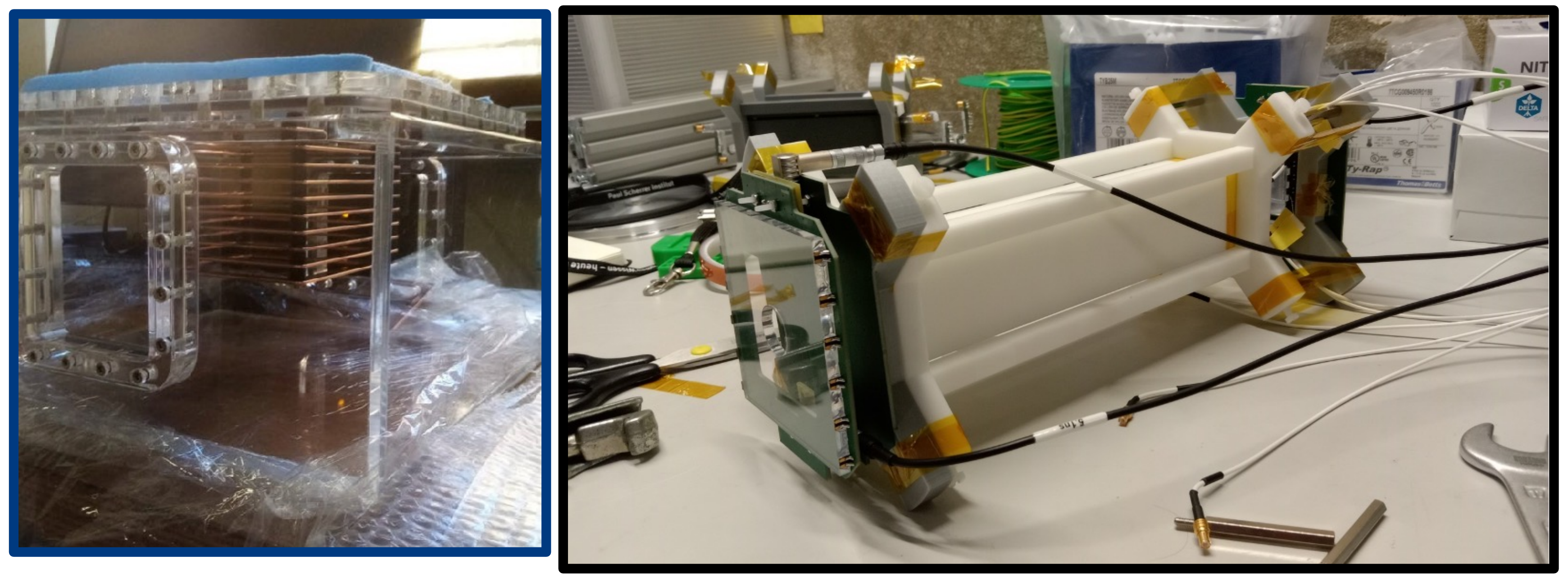


Study multiple scattering of e⁺ at low momenta

2021

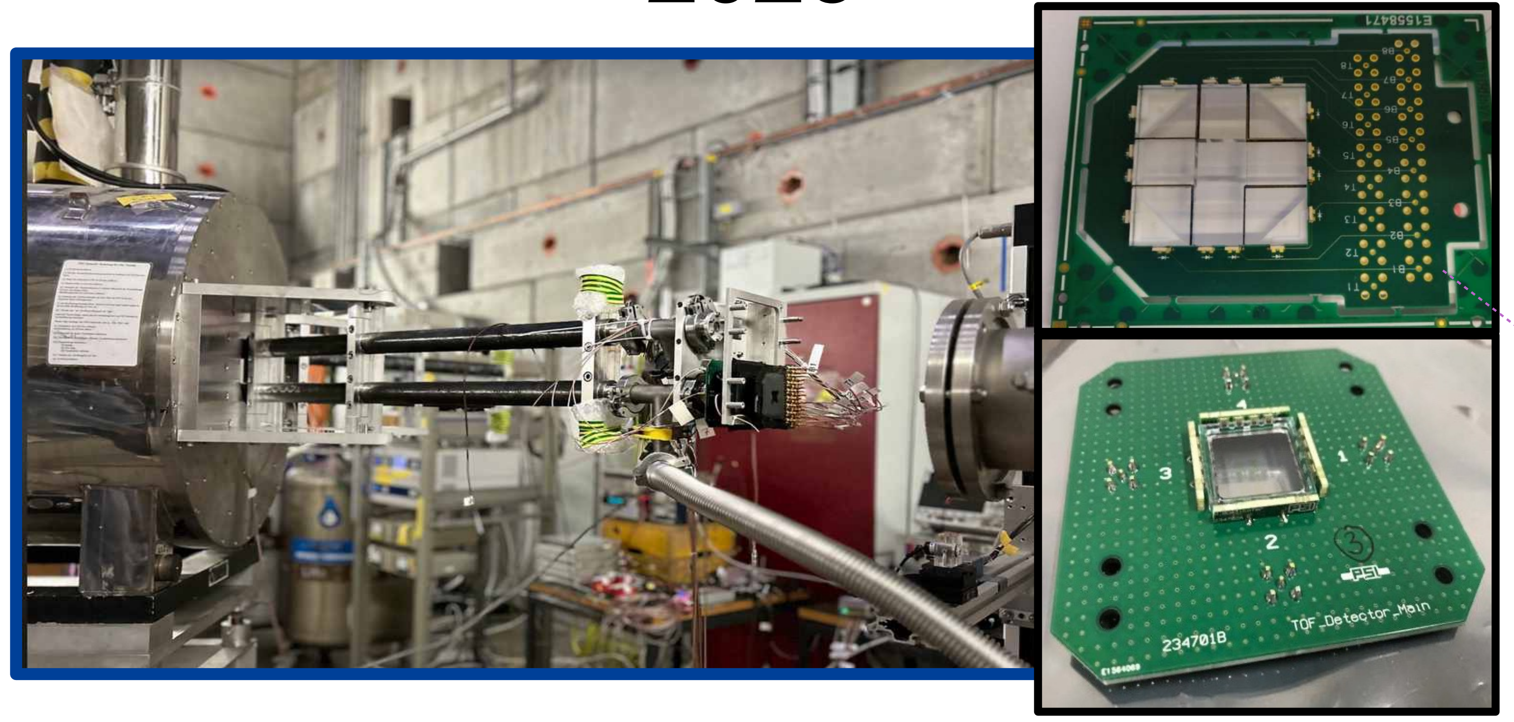
Characterization of potential electrode material with e⁺ and μ^+

2022



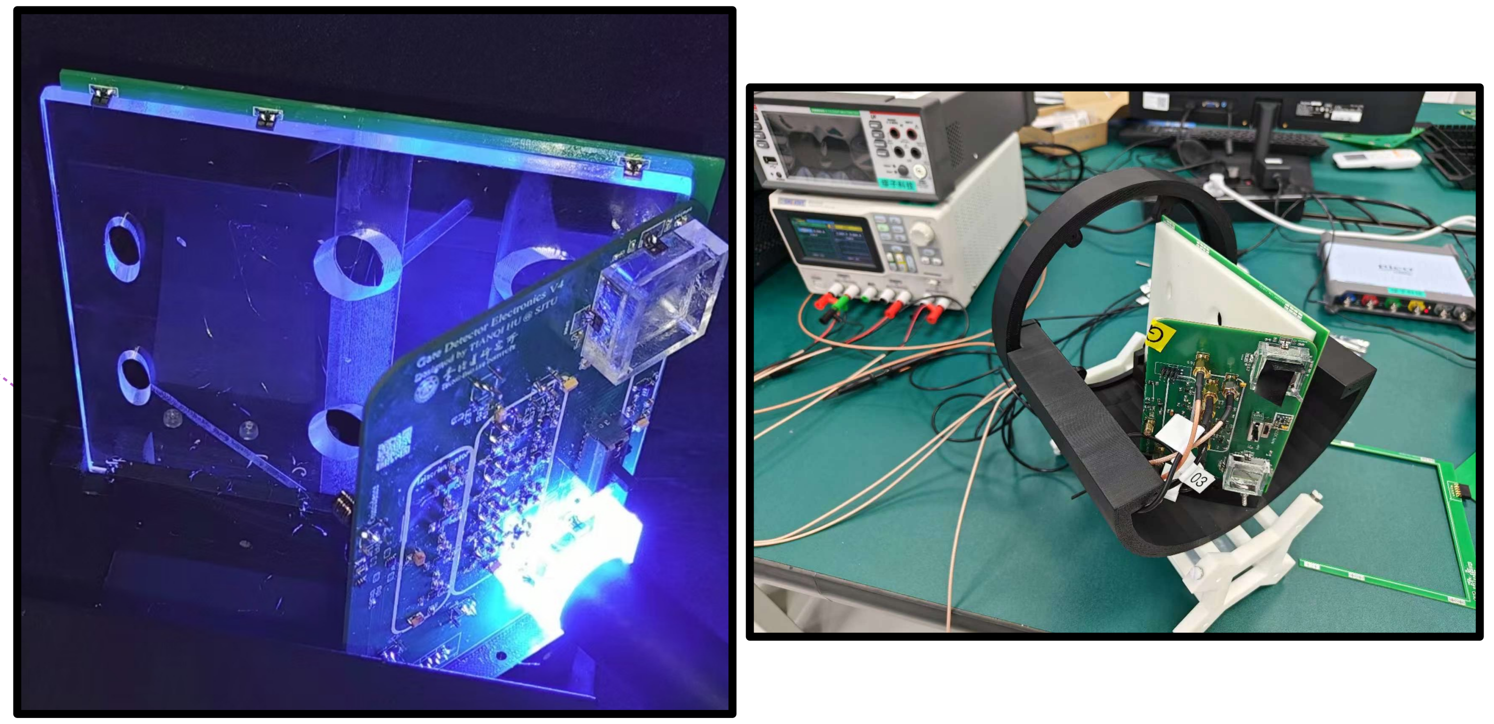
Performance test of prototype entrance detector and TPC tracker

2023



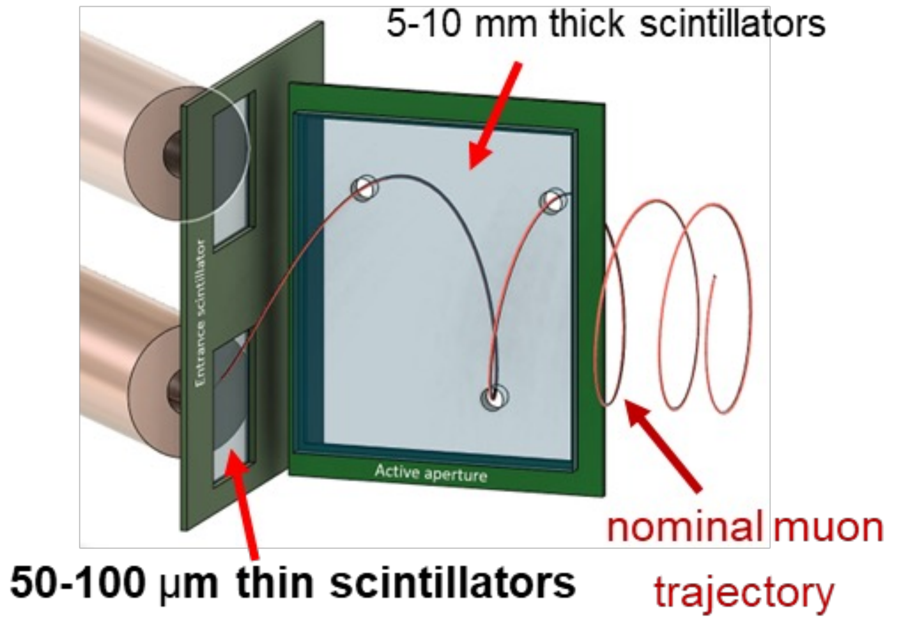
Aligning muon beam with center axis of injection channel

2024

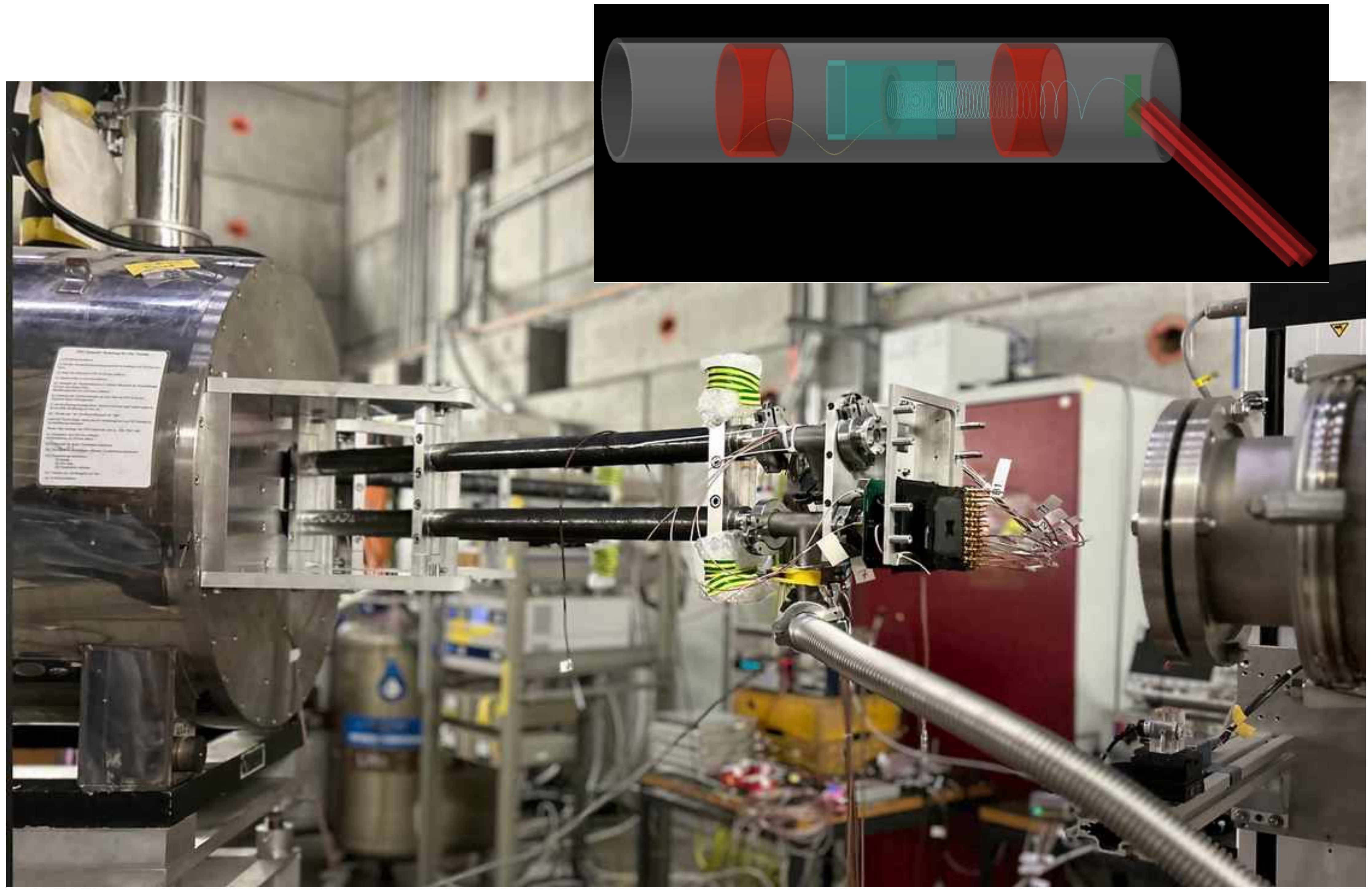


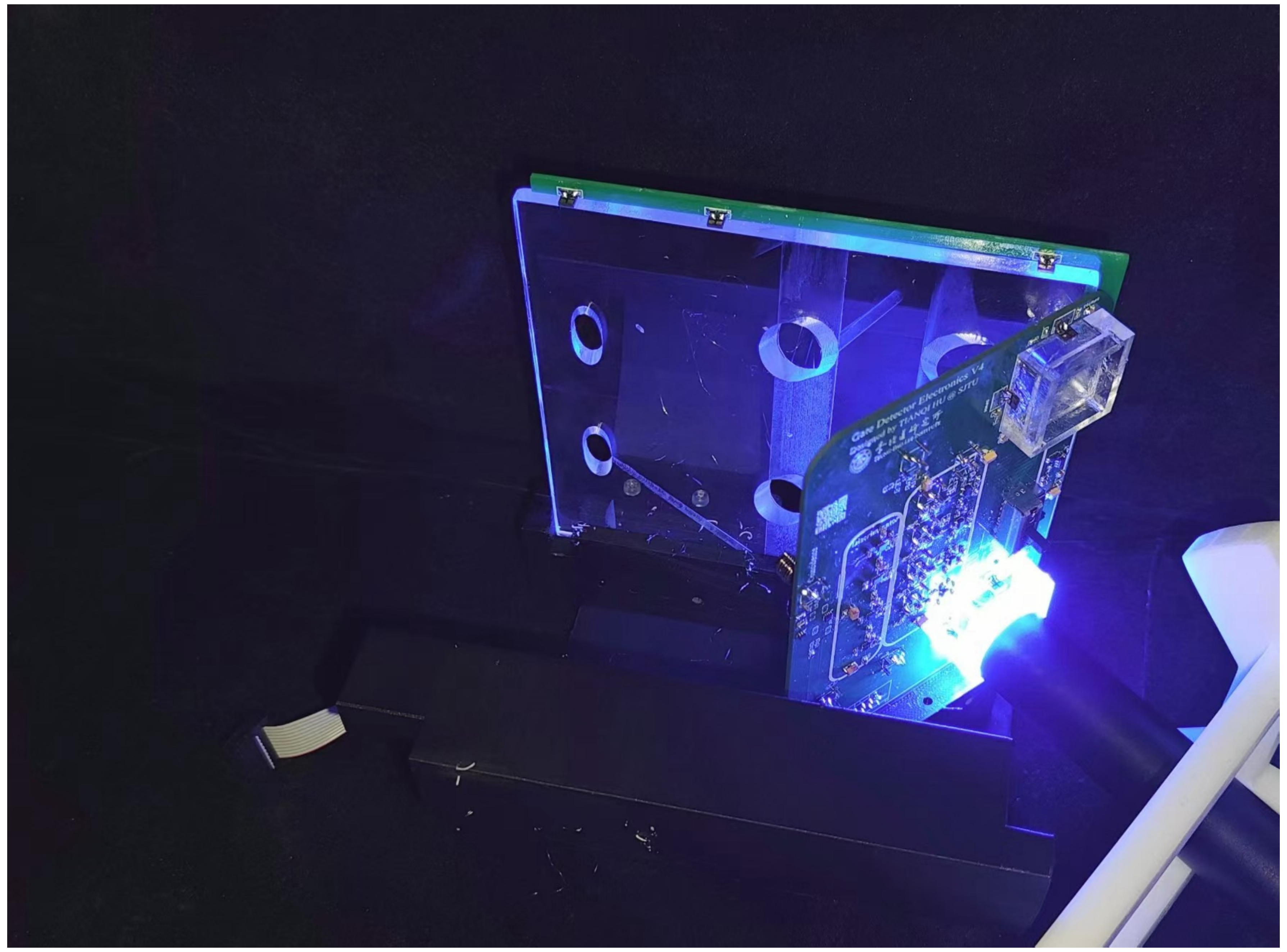
Positron detection efficiency, muon entrance detector

Beam time @ PSI in Oct/Nov 2024

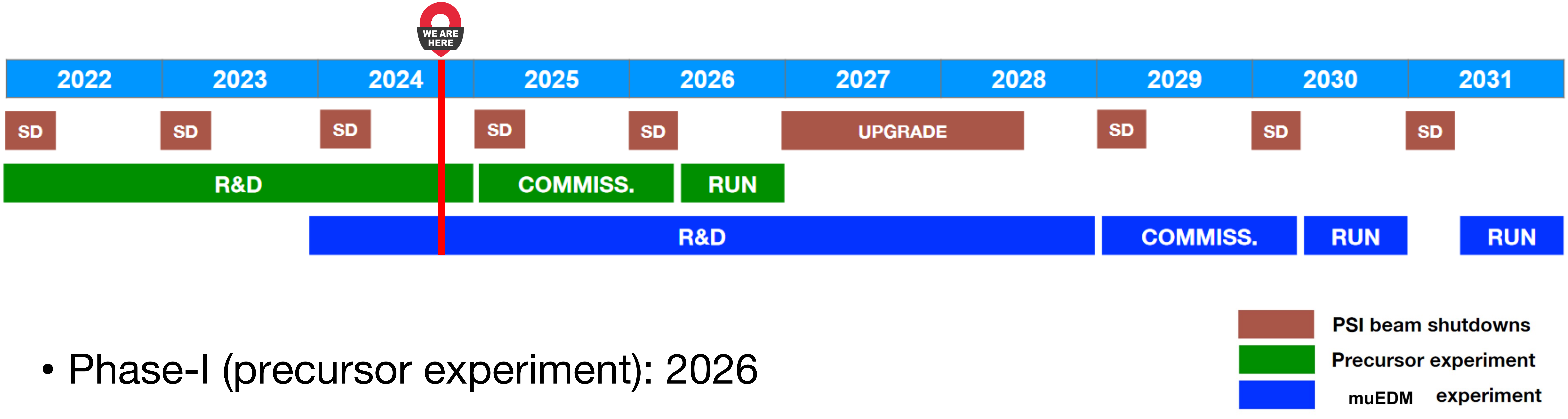


- Demonstrate successful spiral injection of particles into the solenoid.
- Measure reproducibility of the initial phase for both clockwise (CW) and counterclockwise (CCW) injections.
- Test performance of the muon entrance detector within the solenoid for stability and accuracy.





muEDM timeline



- Phase-I (precursor experiment): 2026
  - Frozen-spin and off-axis spiral injection demonstrator
  - Competitive muon EDM measurement
- Phase-II: 2030s
  - Possibilities of incorporating novel muon beam cooling technology

Summary and outlook

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- The muEDM experiment at PSI is designed to probe the muon's electric dipole moment (EDM) with a target sensitivity of 10^{-23} e cm
  - Utilizes a frozen-spin approach specifically designed for precise EDM measurements
  - Capable of testing a wide range of beyond Standard Model (BSM) physics scenarios.
- R&D for the Phase I of the experiment is progressing well.
  - Annual beam tests have been conducted since 2019 to evaluate key experimental components.
- We may have a better picture of the muon g-2 puzzle and new LFV results in the next 5 years
  - Results from muon EDM searches will provide complementary insights into muon sector BSM physics.