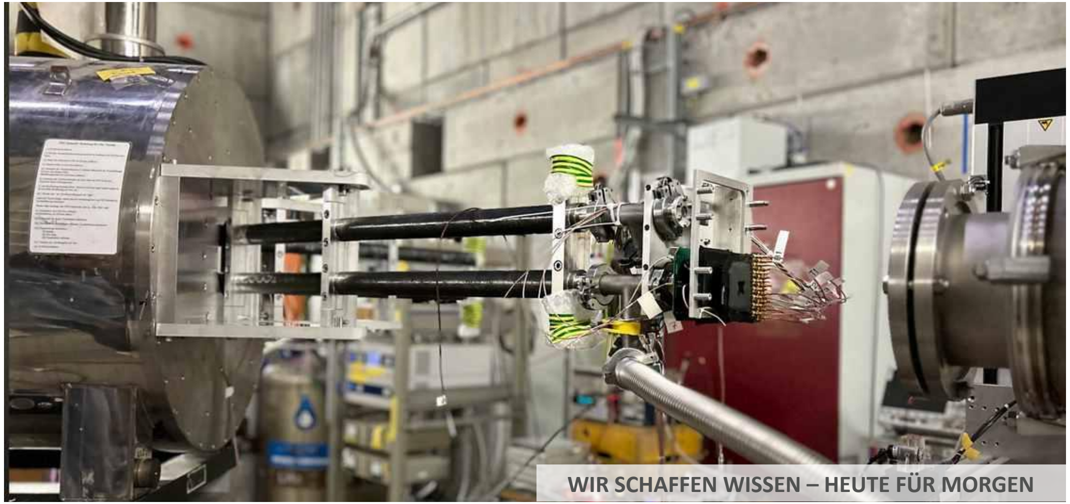
PAUL SCHERRER INSTITUT
PSI



Diego Alejandro Sanz-Becerra - on behalf of the muonEDM collaboration :: ECT* workshop on EDMs

Toward an improved measurement of the muon EDM

Project funded by

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

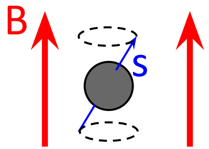
Swiss Confederation

Federal Department of Economic Affairs,
Education and Research EAER
State Secretariat for Education,
Research and Innovation SERI

FNSNF
FONDS NATIONAL SUISSE
SCHWEIZERISCHER NATIONALFONDS
FONDO NAZIONALE SVIZZERO
SWISS NATIONAL SCIENCE FOUNDATION
This work is financed by the SNSF
under grant № 204118.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 884104 (PSI-FELLOW-III-3i)

THE BASICS



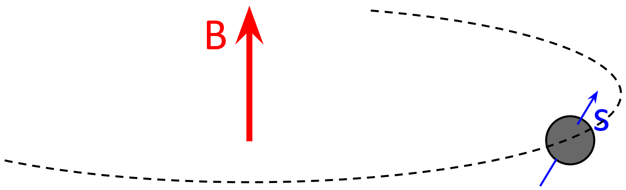
$$\vec{\omega}_0 = -\frac{q\,a}{m}\left(\left(1+\frac{1}{\gamma\,a}\right)\vec{B} - \frac{\gamma}{\gamma+1}\left(\vec{B}\cdot\vec{\beta}\right)\vec{\beta} - \left(1+\frac{1}{a\,(1+\gamma)}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right)$$

Larmor precession

$$\hat{H} = -\vec{\mu}\cdot\vec{B} - \vec{d}\cdot\vec{E}$$

$$\vec{\mu} = g\,\frac{q}{2\,m_\mu}\,\vec{s} \qquad \vec{d} = \eta\,\frac{q}{2\,m_\mu\,c}\,\vec{s}$$

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



Cyclotron frequency

MDM

$$\vec{\omega}_a = \vec{\omega}_0 - \vec{\omega}_c = \frac{q\,a}{m}\left(\vec{B} - \frac{\gamma}{\gamma+1}\left(\vec{B}\cdot\vec{\beta}\right)\vec{\beta} - \left(1 + \frac{1}{a\,(1-\gamma^2)}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right)$$

Larmor ($\vec{\omega}_0$) Cyclotron ($\vec{\omega}_c$)

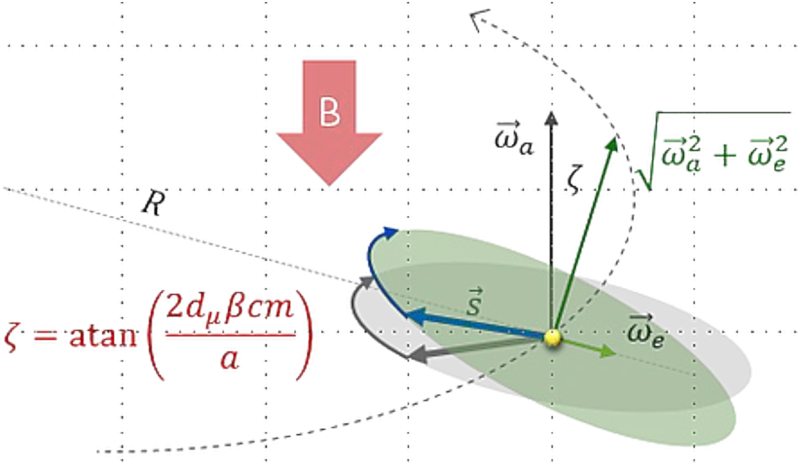
- This precession is only due to the magnetic dipole moment
- What if it has an EDM?

MDM And EDM

$$\vec{\omega} = \vec{\omega}_a + \vec{\omega}_e = \frac{q\,a}{m}\left(\vec{B} - \frac{\gamma}{\gamma+1}\left(\vec{B}\cdot\vec{\beta}\right)\vec{\beta} - \left(1+\frac{1}{a\left(1-\gamma^2\right)}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right)$$

$$+\frac{q\,\eta}{2\,m}\left(\frac{\vec{E}}{c} - \frac{\gamma\,c}{\gamma+1}\left(\vec{E}\cdot\vec{\beta}\right)\vec{\beta} + \vec{\beta}\times\vec{B}\right)$$

$$\vec{B}\perp\vec{\beta}\perp\vec{E}$$



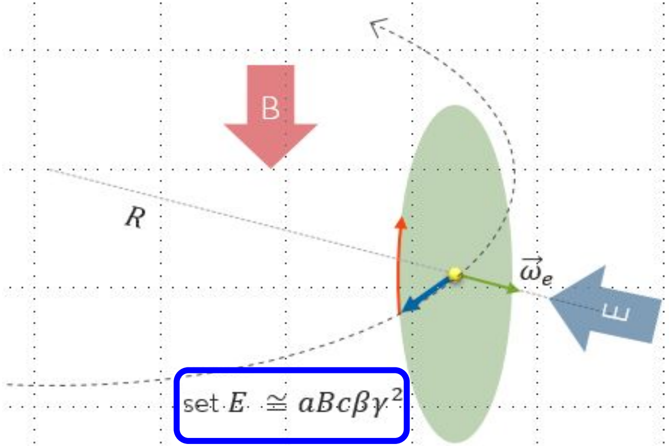
The Frozen-Spin Technique

$$\vec{\omega} = \vec{\omega}_a + \vec{\omega}_e = \frac{q\,a}{m}\left(\vec{B} - \frac{\gamma}{\gamma+1}\left(\vec{B}\cdot\vec{\beta}\right)\vec{\beta} - \left(1 + \frac{1}{a\left(1-\gamma^2\right)}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right)$$

$$+ \frac{q\,\eta}{2\,m}\left(\frac{\vec{E}}{c} - \frac{\gamma\,c}{\gamma+1}\left(\vec{E}\cdot\vec{\beta}\right)\vec{\beta} + \vec{\beta}\times\vec{B}\right)$$

$\vec{B} \perp \vec{\beta} \perp \vec{E}$

$E \simeq a\,B\,c\,\beta\,\gamma^2$



PAUL SCHERRER INSTITUT PSI

The Frozen-Spin Technique

$$\vec{\omega}_{FS} = \frac{q\,\eta}{2\,m}\left(\frac{\vec{E}}{c} + \vec{\beta} \times \vec{B}\right)$$

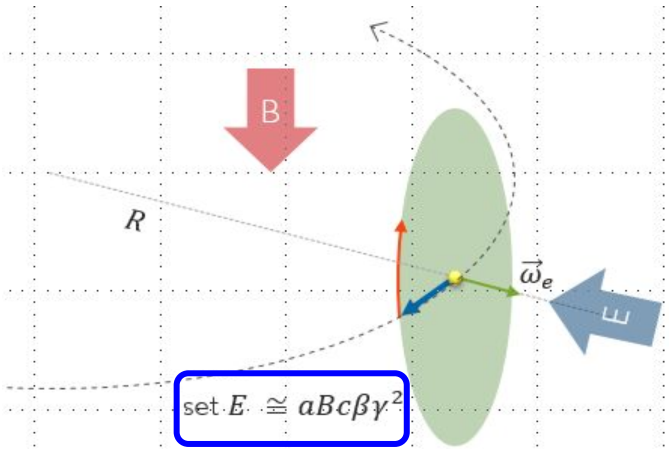
Muon’s rest frame:

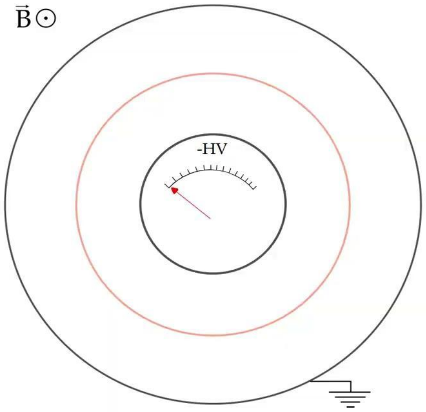
Lorentz boosted B field

$$\vec{E}'_B = \gamma\, c\, \vec{\beta} \times \vec{B}$$

$$\vec{B} \perp \vec{\beta} \perp \vec{E}$$

$$E \simeq a\, B\, c\, \beta\, \gamma^2$$





For the experiment:

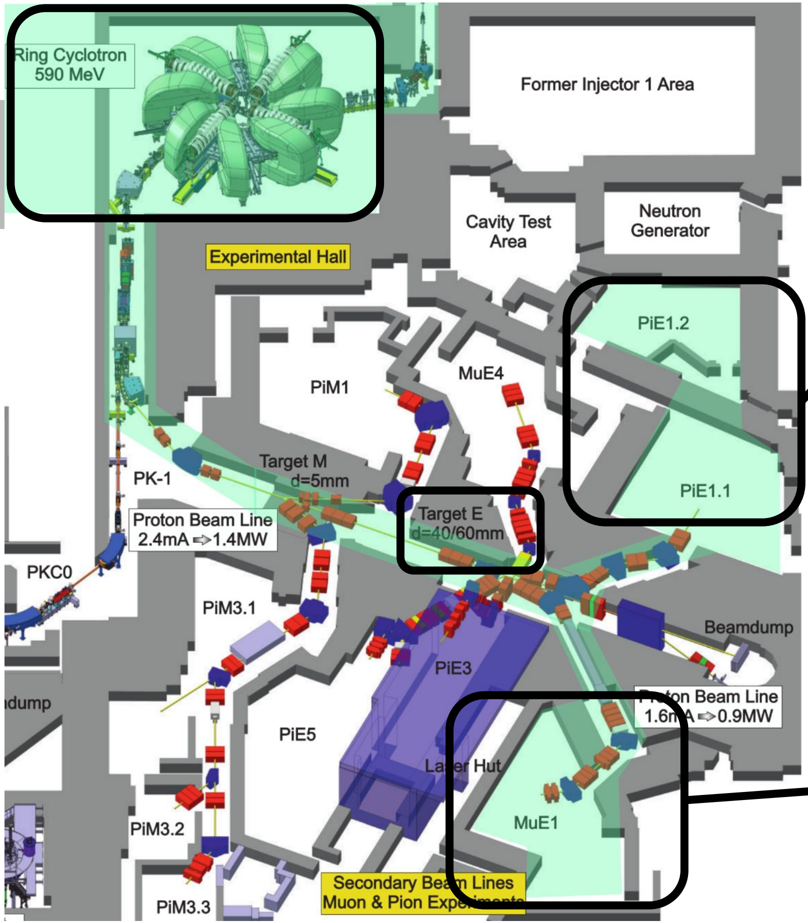
- B = 3 T
- p: O(100 MeV/c)
- E: O(1 MV/m)
- E_B’: O(1 GV/m)

PAUL SCHERRER INSTITUT

THE EXPERIMENT

PAUL SCHERRER INSTITUT

The Experiment - The Muons



Phase 1:

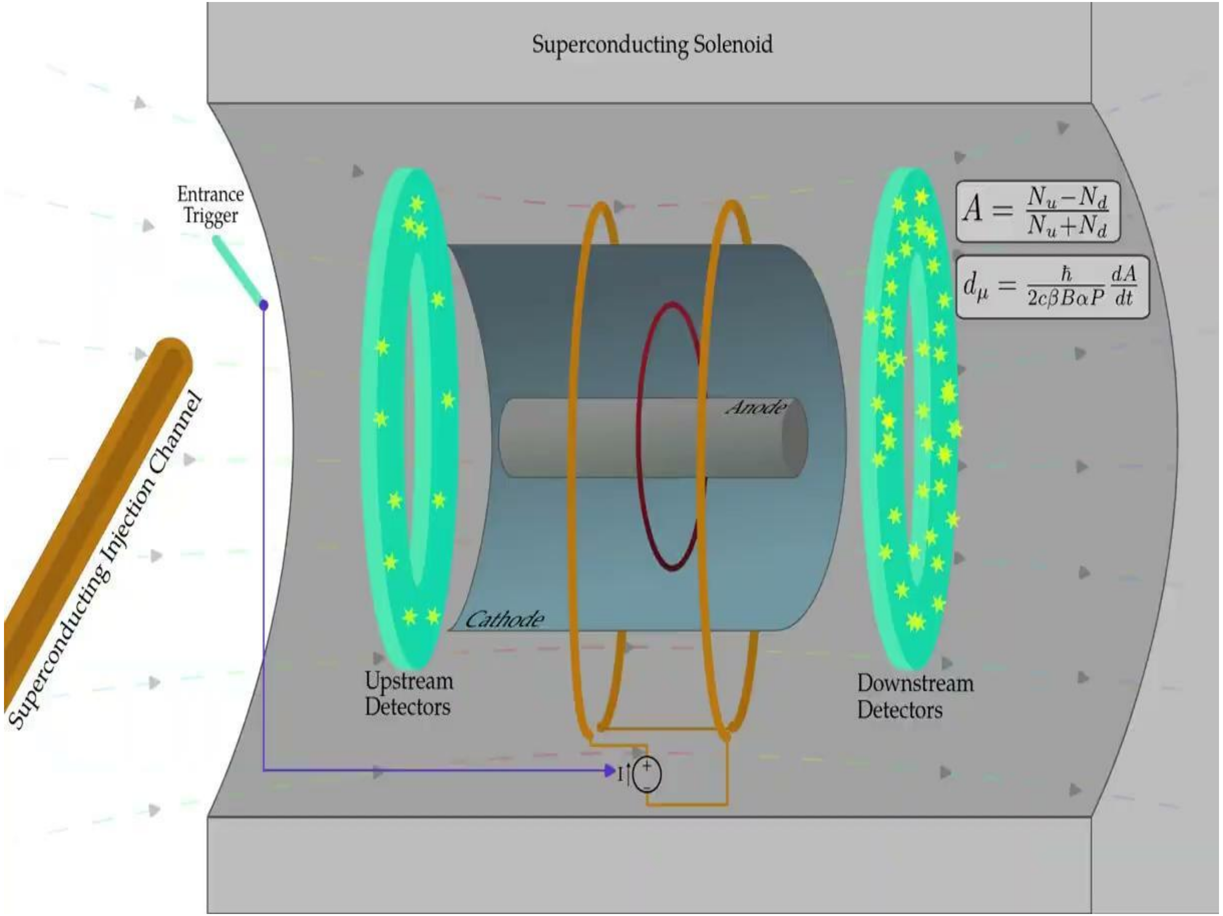
- Negative helicity (95%)
- p=28 MeV/c
- Flux: O(10^6 μ^+/s)
- Sensitivity/year < 3×10^{-21} e · cm

Phase 2:

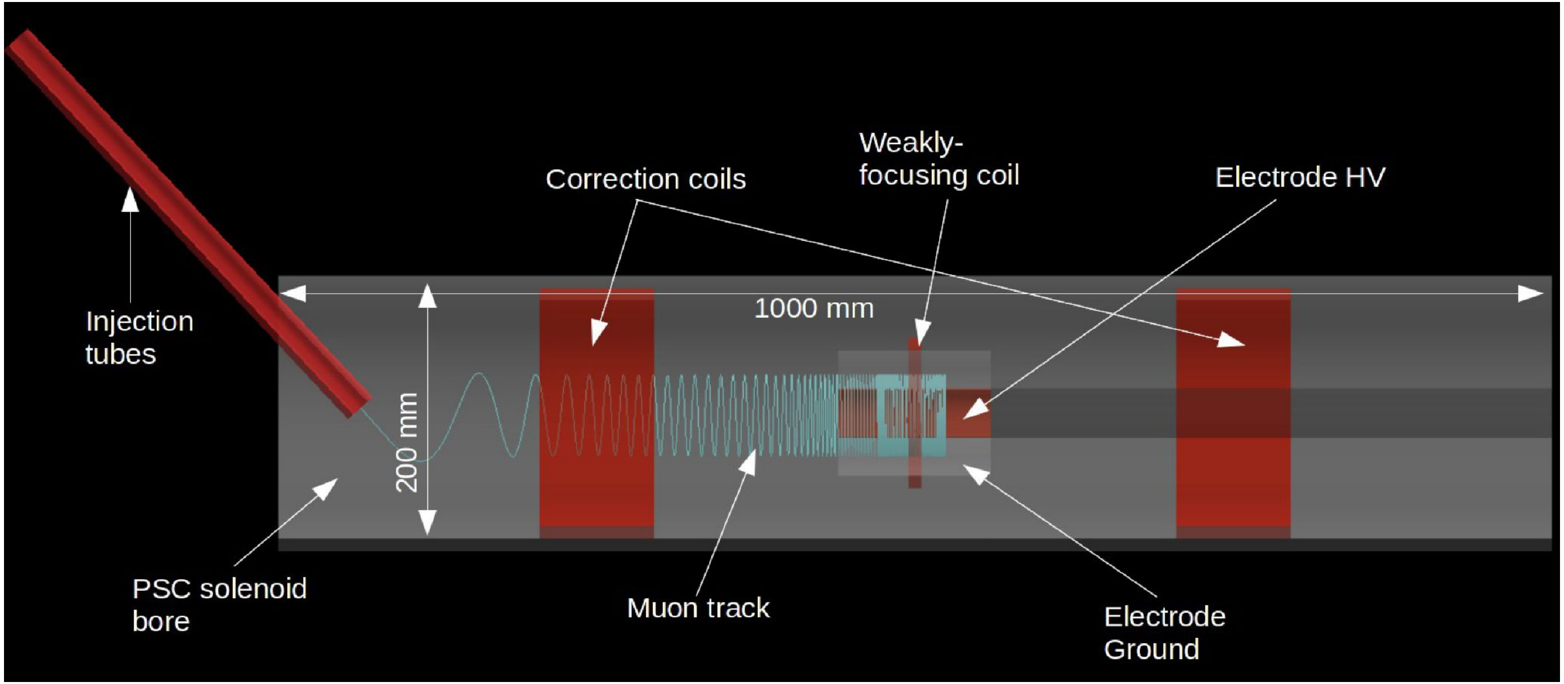
- Positive helicity (95%)
- p=125 MeV/c
- Flux: O(10^8 μ^+/s)
- Sensitivity/year < 6×10^{-23} e · cm

PAUL SCHERRER INSTITUT

The Experiment

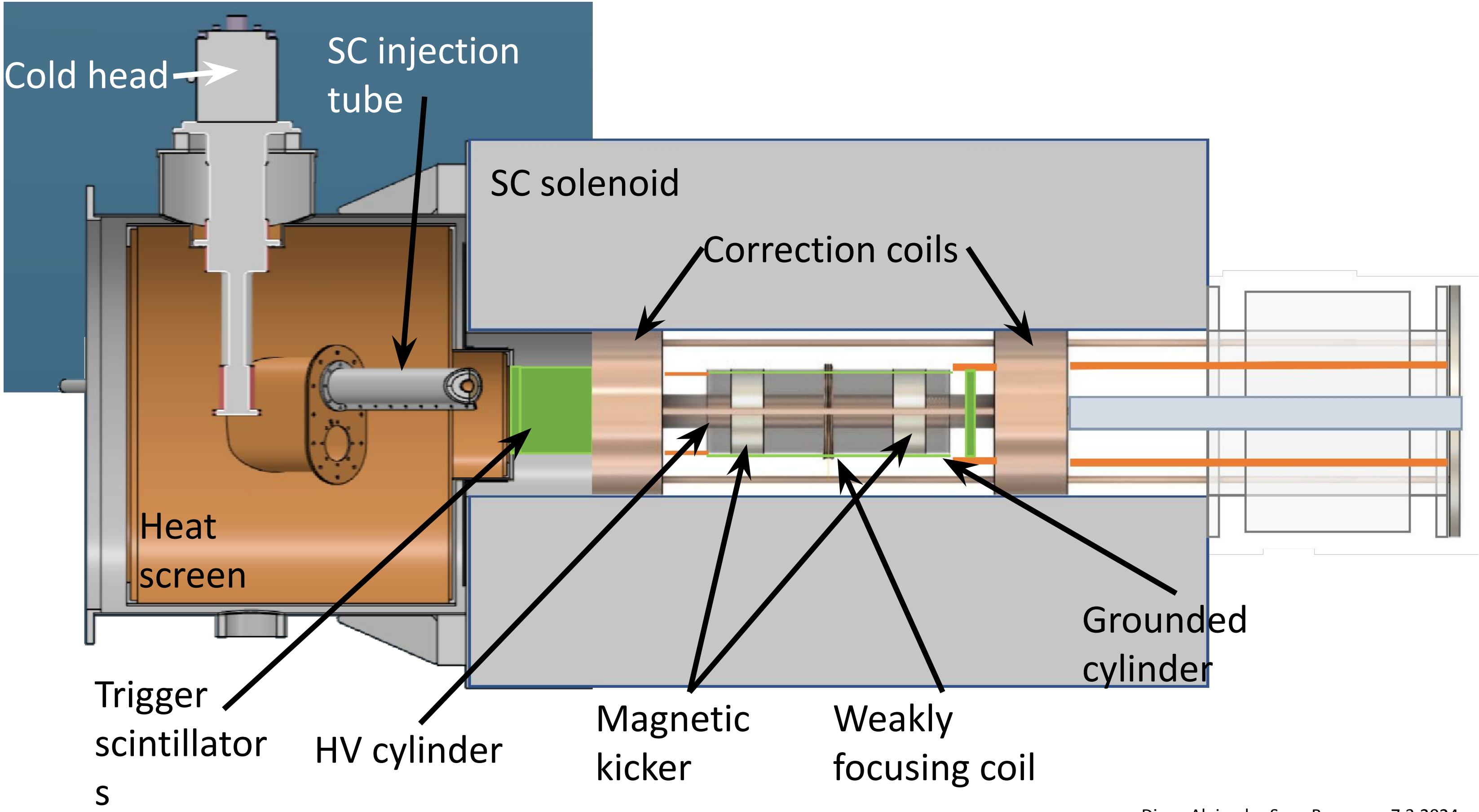


The Experiment - Storage Parameters

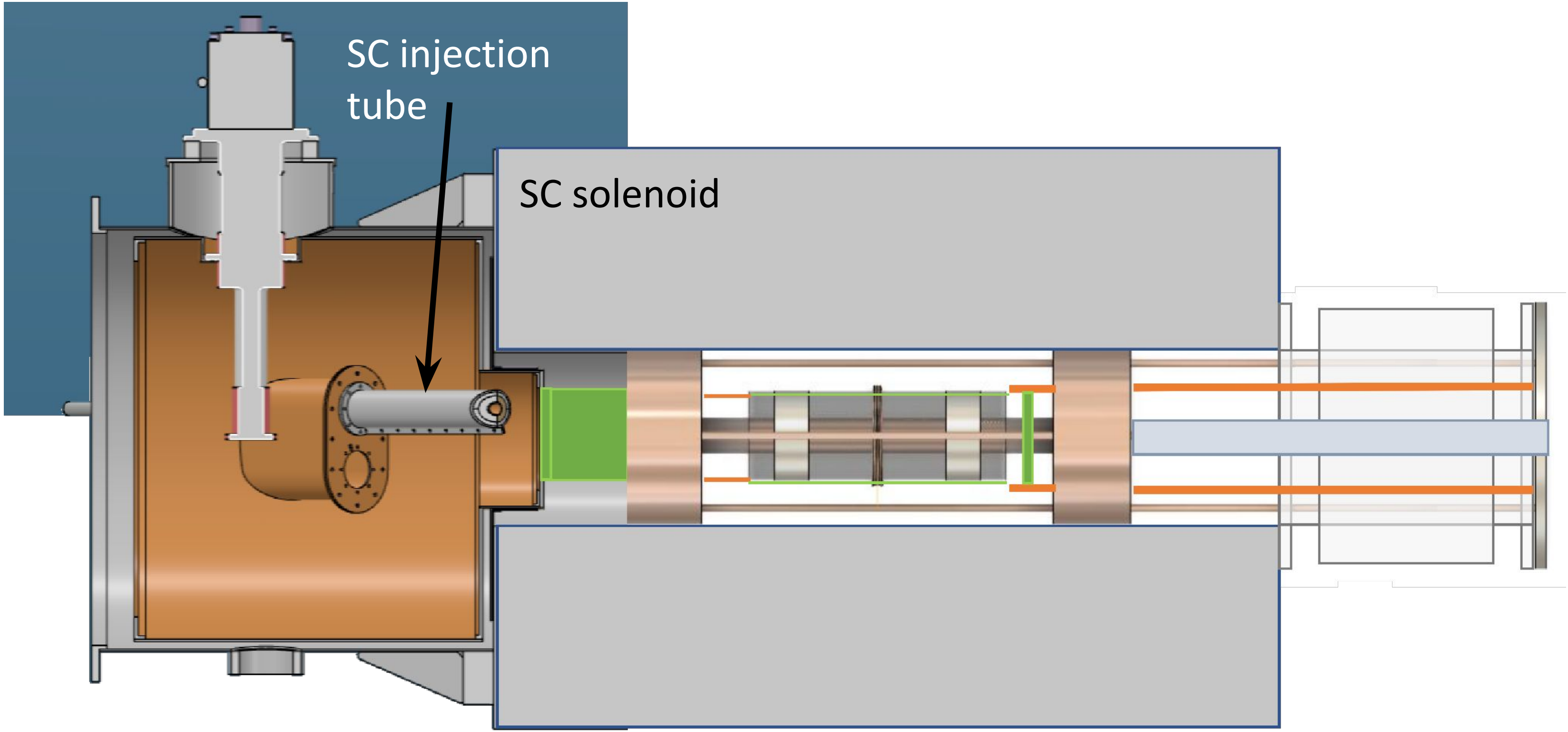


- Using G4beamline and surrogate models, we optimized the storage efficiency of muons up to ~0.4 %.

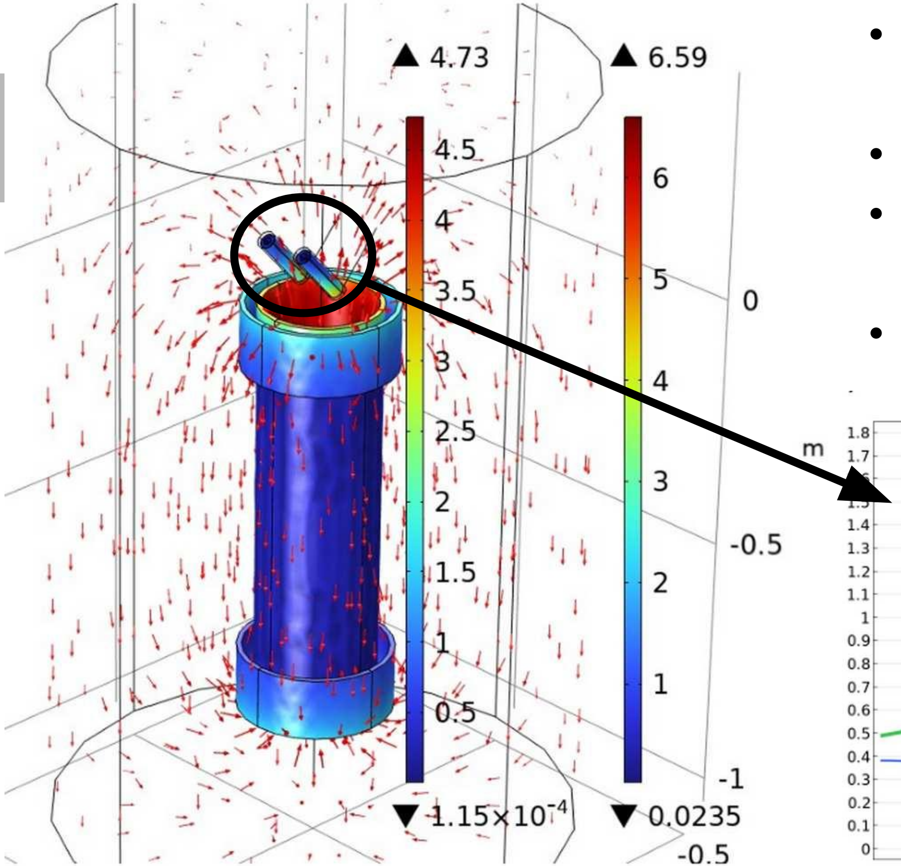
The Experiment - Parts



Injection Channels

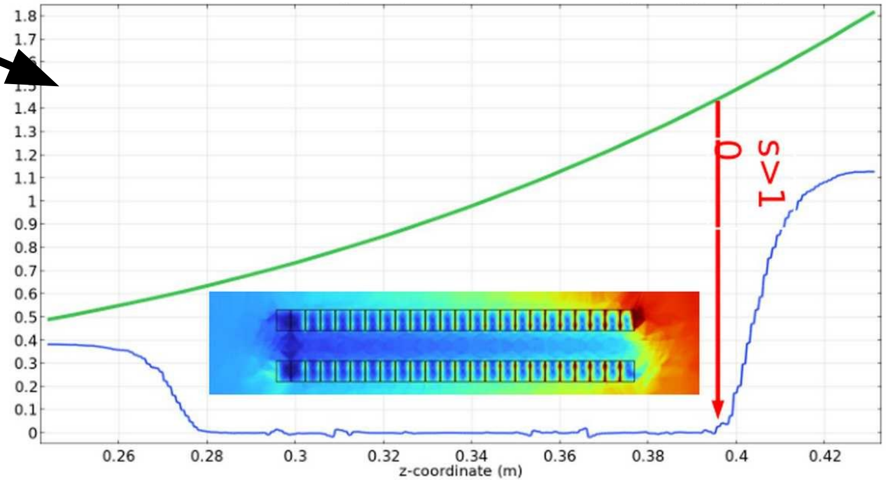


Injection Channels - High Fields

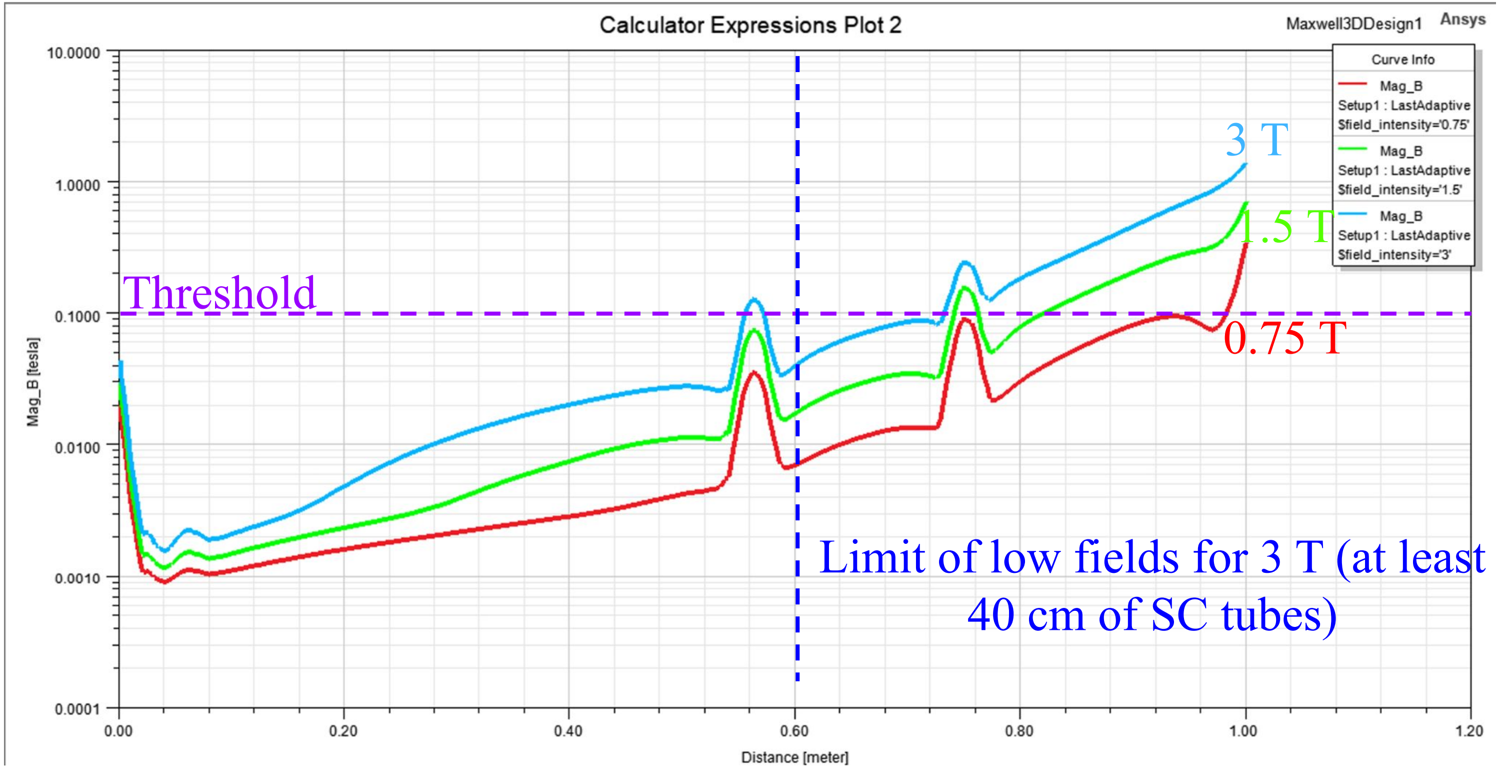


- Shield muons during the transport to the magnet's bore (B ≳ 0.8 T) with SC materials.
- SC channels inside cryostat.
- Simulating different concepts and SC materials.
- Expected prototype tests this year.

Unshielded and shielded magnetic field intensity (T)

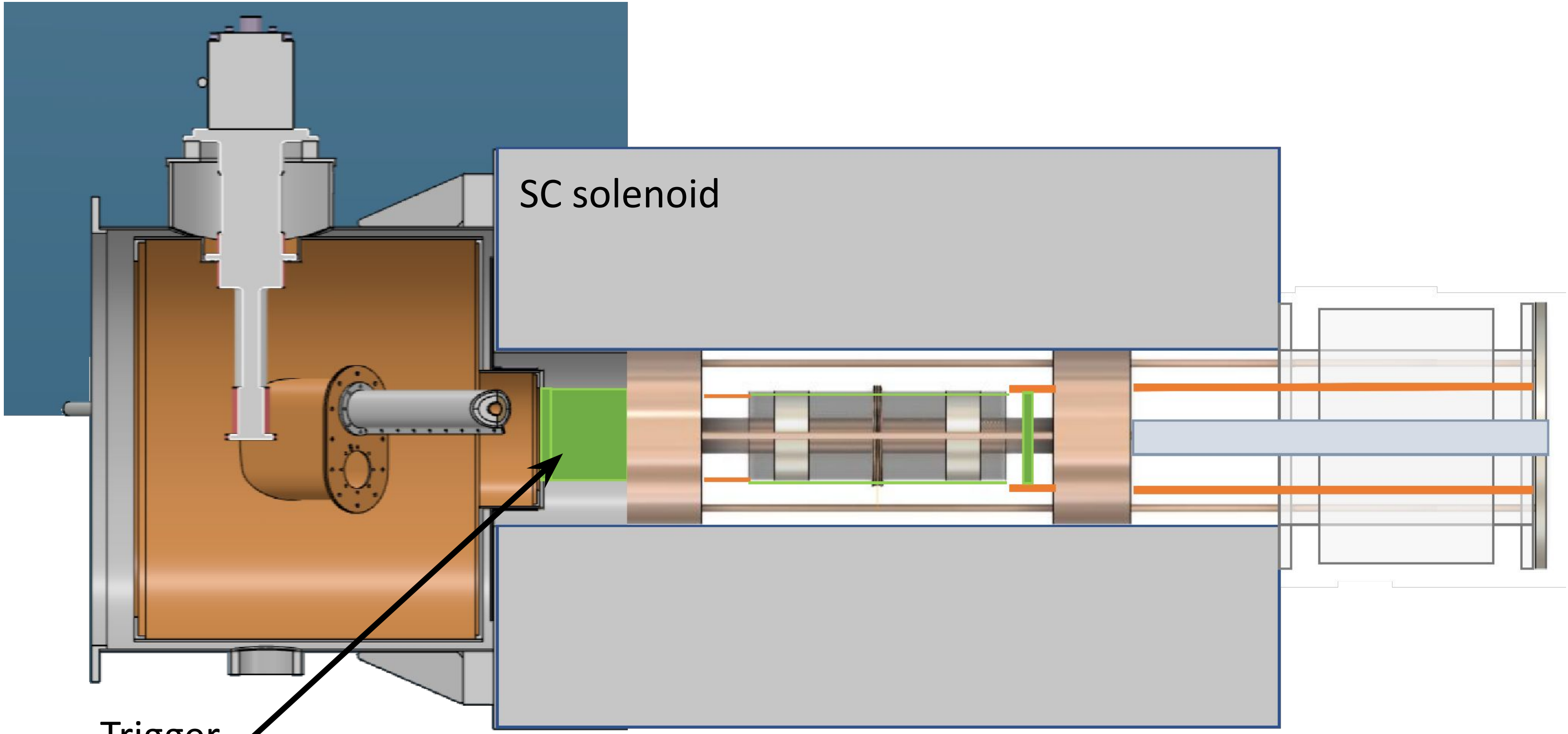


Injection Channels - Low Fields

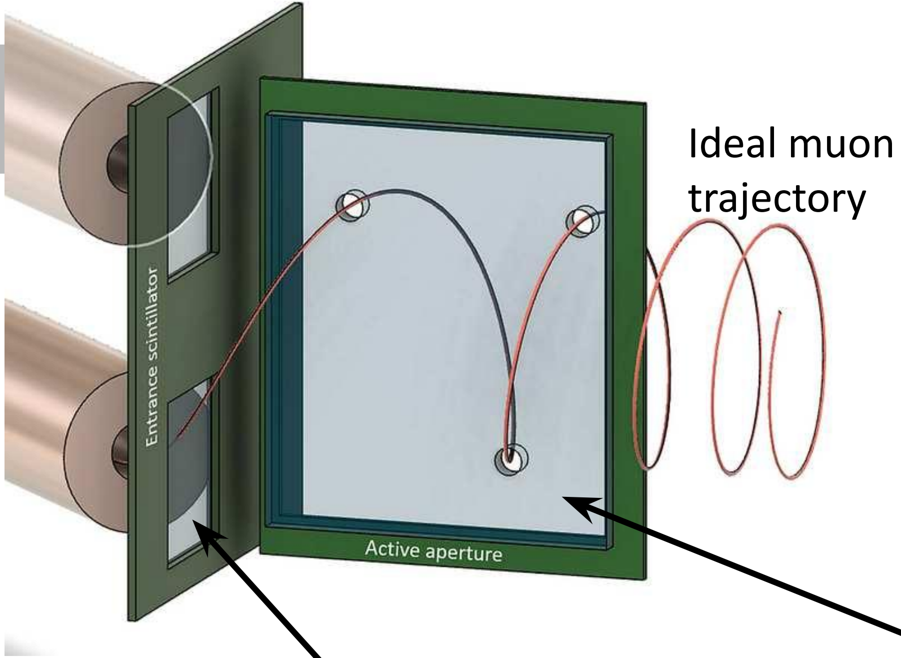


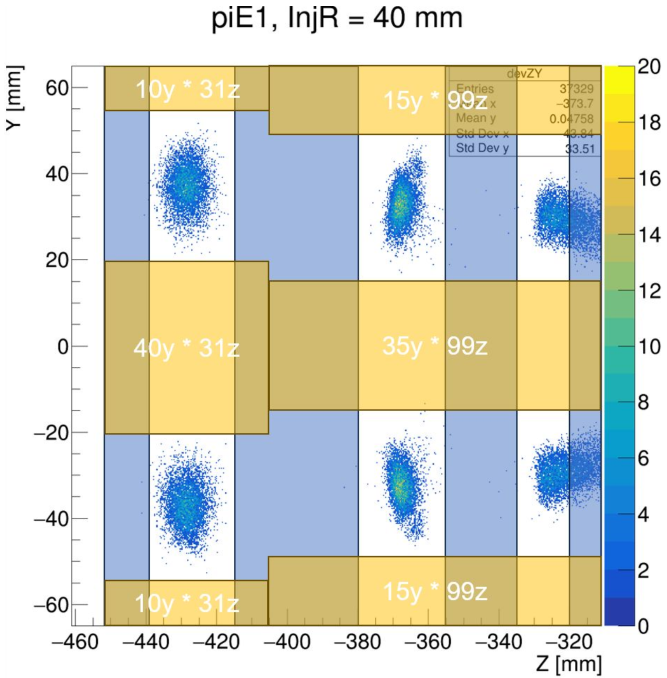
- Use magnetic steel to prolong the SC tubes outside cryostat to the beamline window.
- Shield the injected muons to below ~100 mT.

Trigger Scintillators



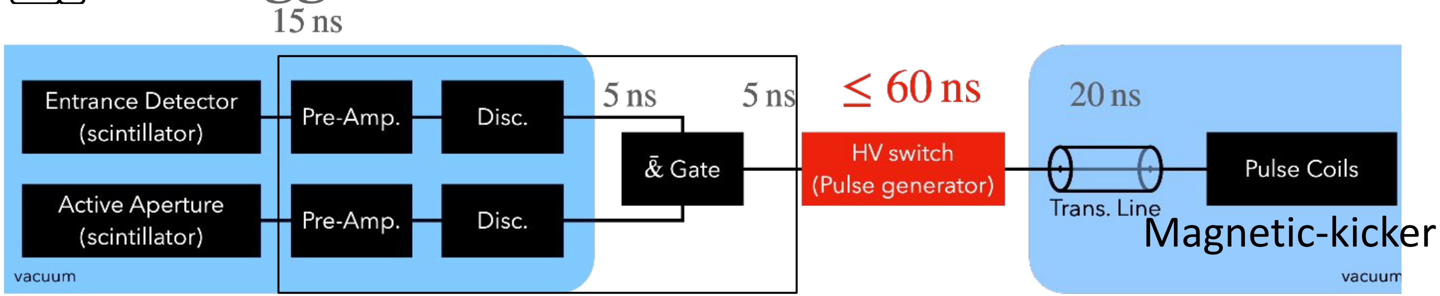
Trigger Scintillators - R&D



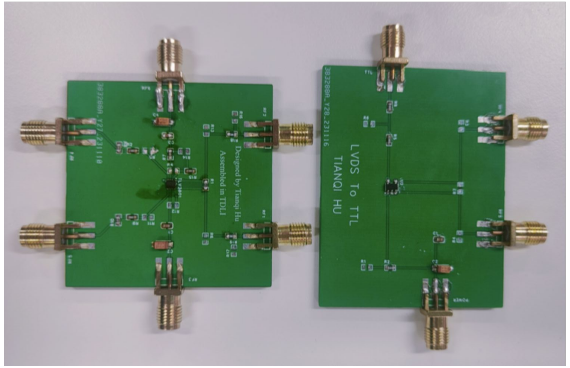


- Thin entrance detector in anti-coincidence with veto-detectors
- Meshed array of scintillator strips determine the trajectory of the storable-muons

Trigger Scintillators - Fast Electronics R&D

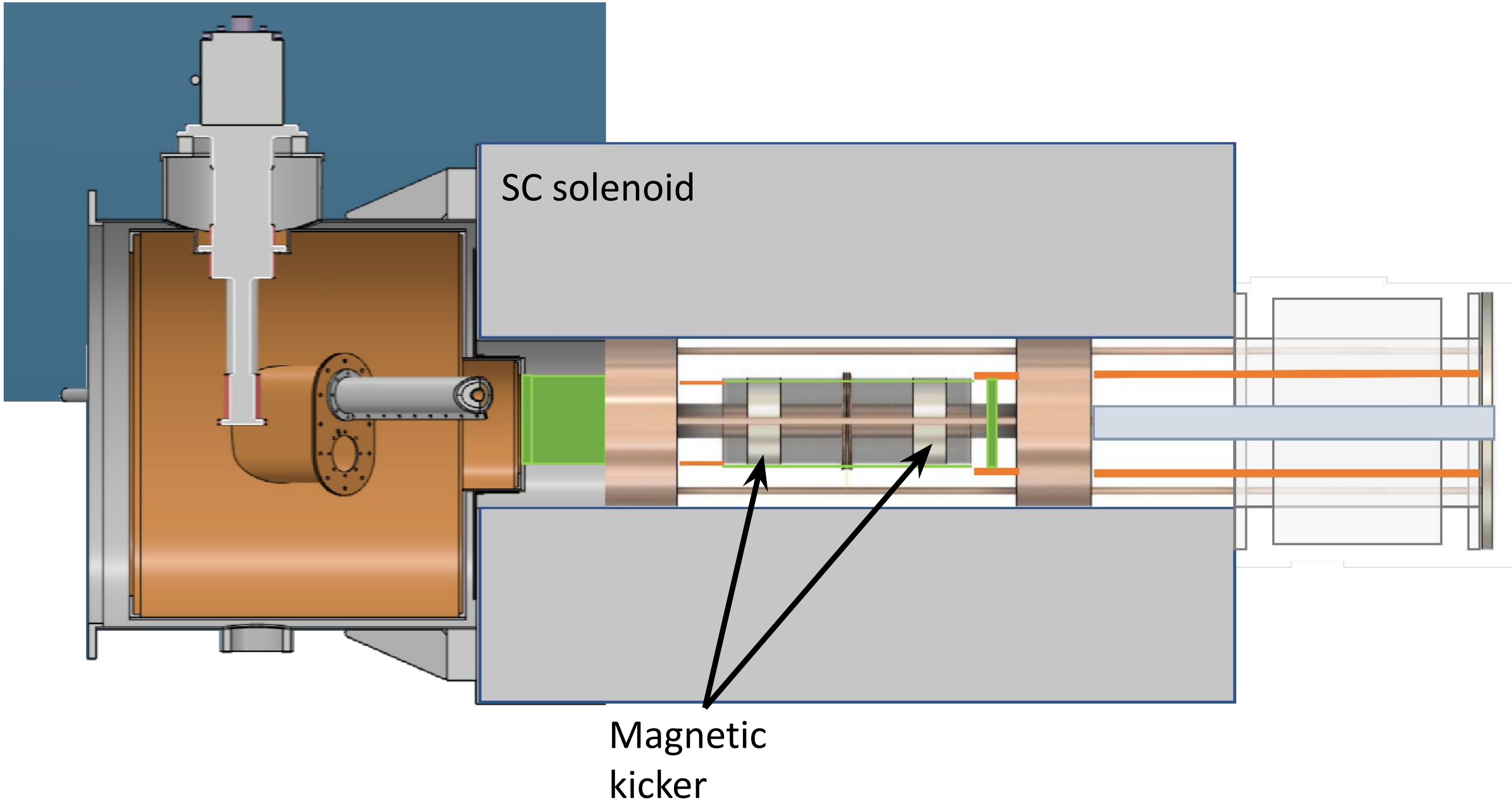


- The trigger signal has to reach the Magnetic kicker within O(100 ns)

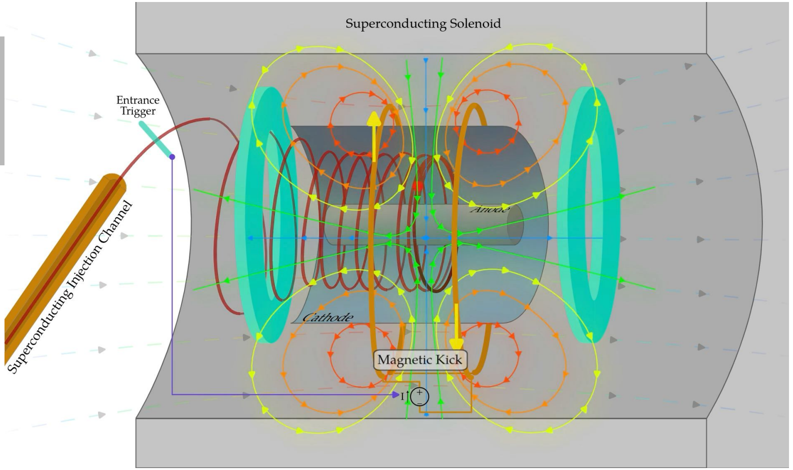


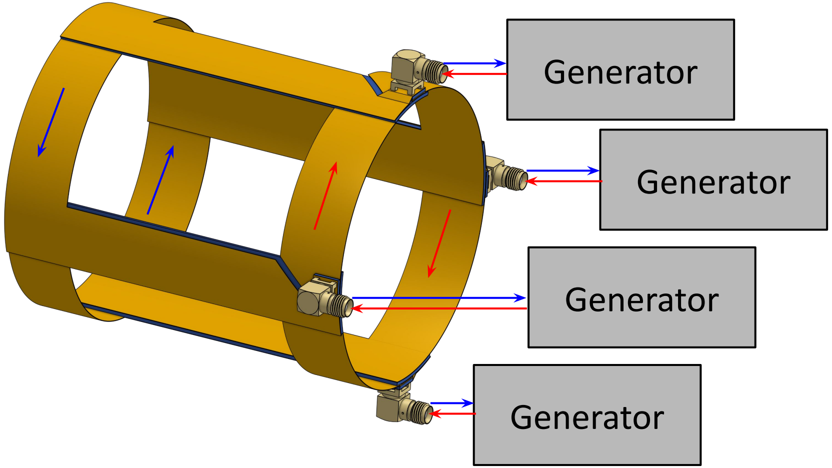
- Custom electronics with 3 ns discriminator and 2 ns pre-amplifiers and splitter.

Trigger Scintillators

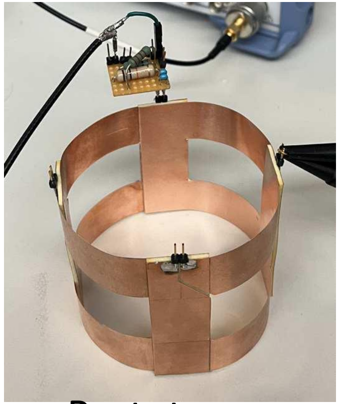


Magnetic Kicker R&D





- Magnetic kick generated by Anti-Helmholtz coils.
- Segmented into quadrants to reduce inductance:
  - Lower driving voltage.
  - Faster pulse.

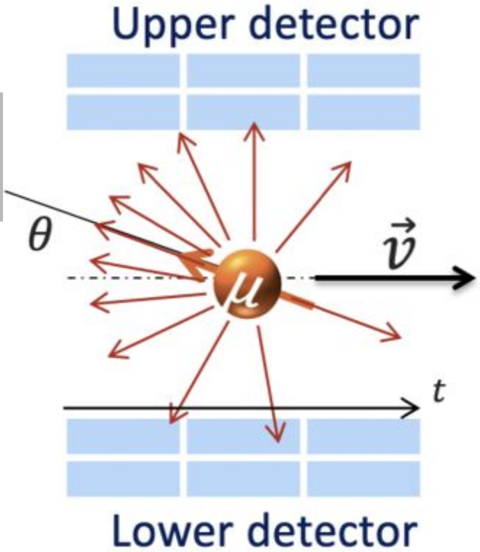


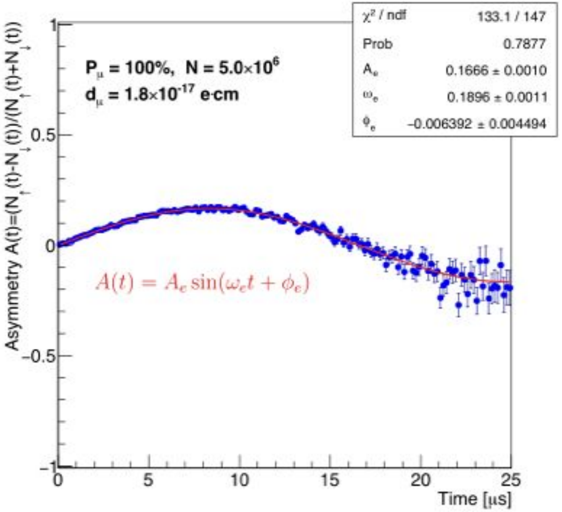
Prototype

PAUL SCHERRER INSTITUT

THE MEASUREMENTS

The Measurements - The Signal





$$A = \frac{N_u - N_d}{N_u + N_d}$$

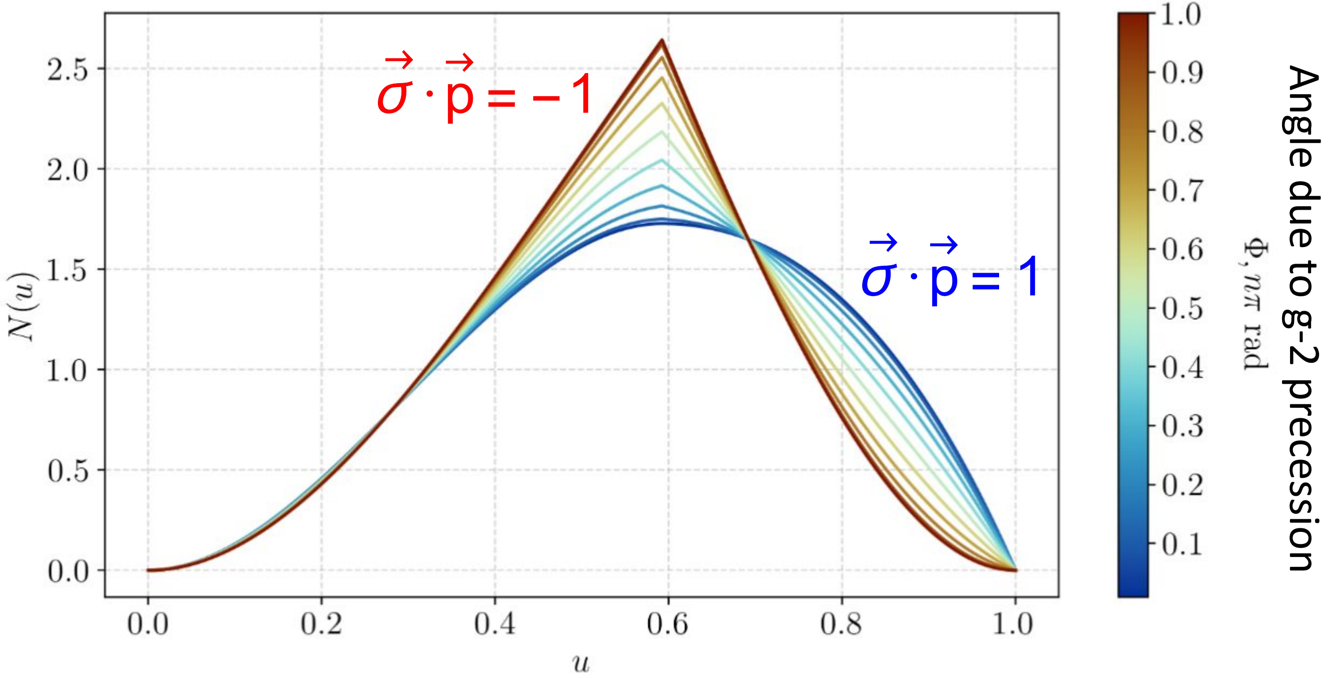
$$\dot{A}(\Psi_0, t) = \frac{\partial A}{\partial \Psi} \frac{\partial \Psi}{\partial t}\bigg|_{\Psi_0} = \alpha(\Psi_0)\, \dot{\Psi}(t)$$

$$\sigma_{d_\mu} = \frac{\hbar}{2\, c\, \beta\, B\, \alpha\, P} \frac{1}{\gamma\, \tau\, \sqrt{N}}$$

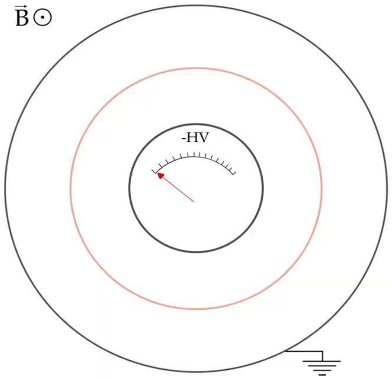
- P: Initial polarization
- E_B': cβBγ (Boosted B)
- N: Detected positrons
- τ: Muon life-time
- α: Analysis parameter

- Asymmetry precession due to EDM is too slow.
- The change of asymmetry with respect to time is relevant.
- The sensitivity is optimized by maximizing α√N: (Figure-of-merit)

The Measurements - Freezing The Spin

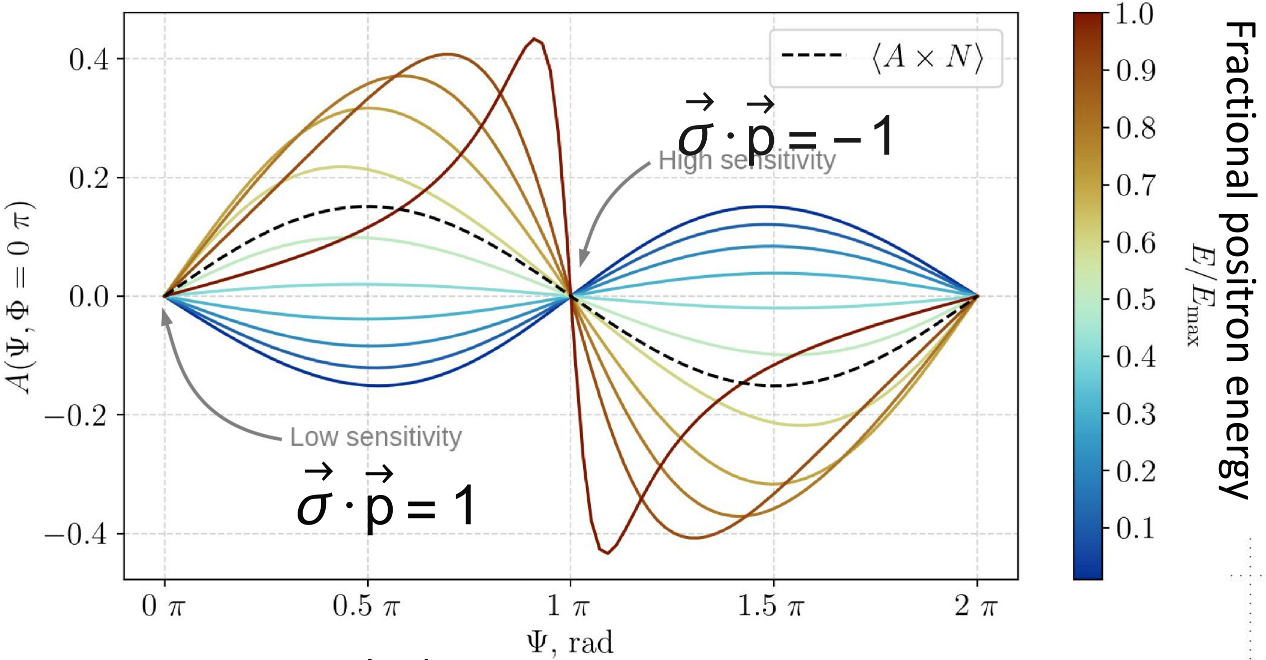


Fractional positron energy E/E_{max}



- Counts oscillate between the red curve and the blue curve.
- Counts above a threshold would give the g-2 oscillation signal.
- Increase the electric field until the g-2 oscillations “freeze”

The Measurements - Measuring The EDM



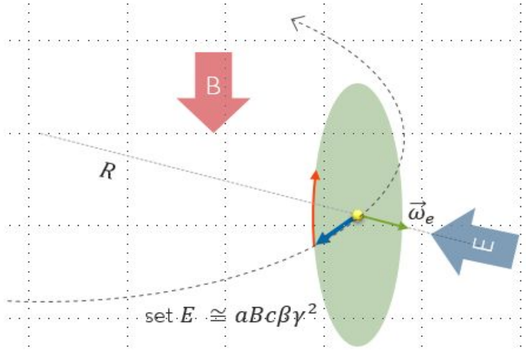
Angle due to EDM precession

$$\dot{A}(\Psi_0, t) = \frac{\partial A}{\partial \Psi}\frac{\partial \Psi}{\partial t}\Big|_{\Psi_0} = \alpha(\Psi_0)\,\dot{\Psi}(t)$$

Working point

EDM precession

$$d_\mu = \frac{\hbar}{2\,c\,\beta\,\alpha\,P}\dot{A}$$



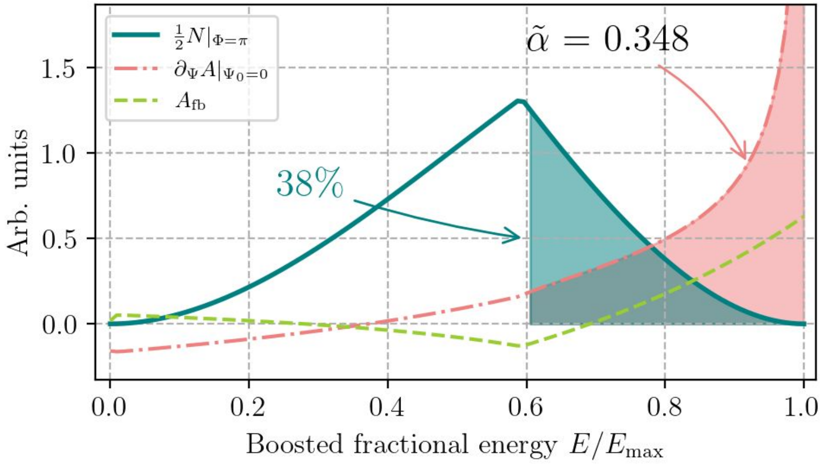
- Low sensitivity working point: Negative helicity.
- High sensitivity working point: Positive helicity.
  - The configuration for phase 1.

The Measurements - Sensitivity

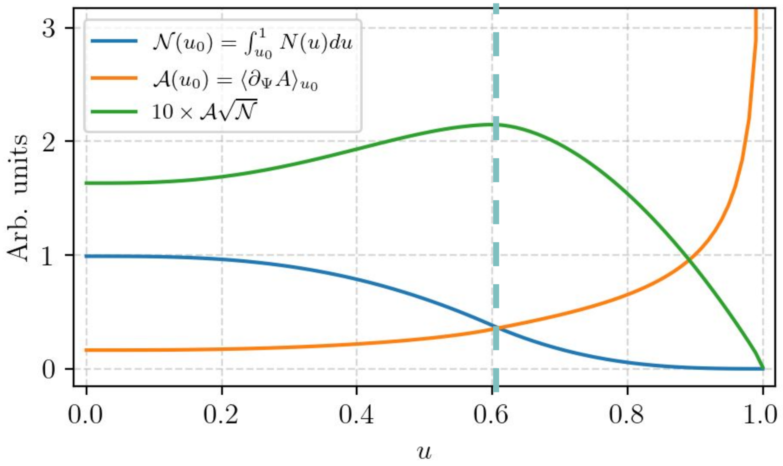
We studied three methods with different complexity:

1. Simple: Use all measured events. $d_\mu = \frac{\hbar}{2\,c\,\beta\,\alpha\,P}\dot{A}$

2. T-Method: Count events only over a threshold that maximizes the FoM. $d_\mu = \frac{\hbar}{2\,c\,\beta\,\tilde{\alpha}\,P}\dot{A}_{Th}$

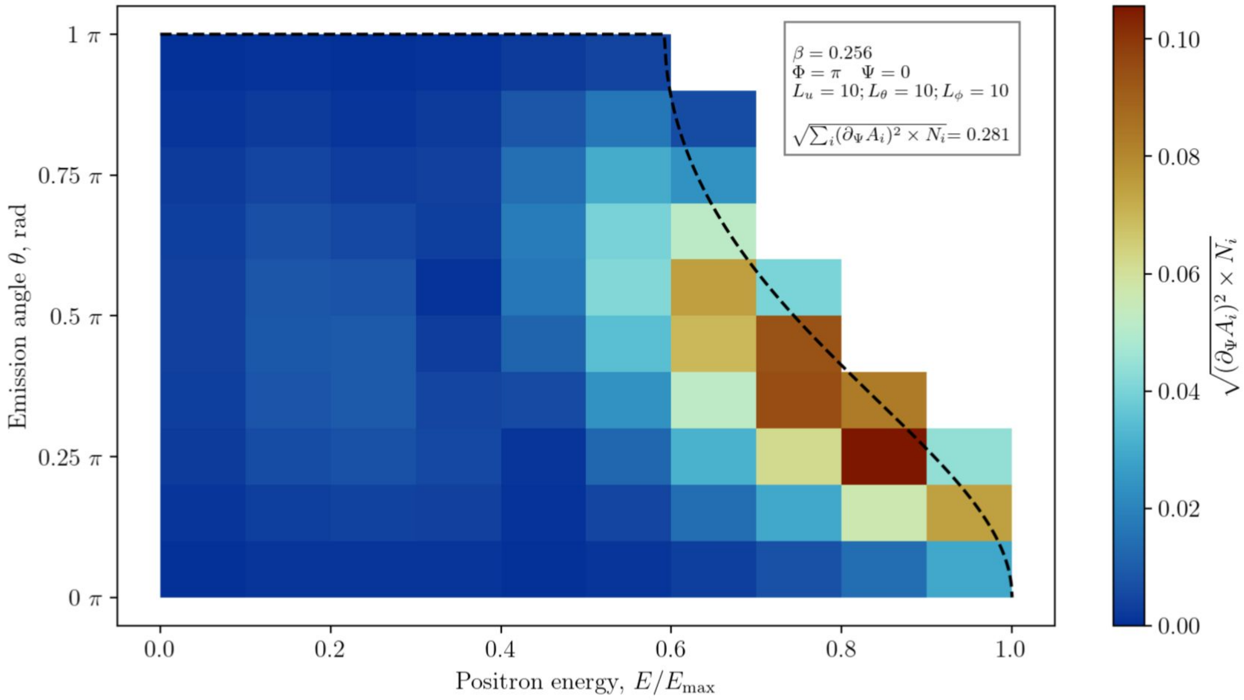


Threshold



The Measurements - Sensitivity

3. W-Method: Weight the measured events for each voxel in energy and direction.



$$W_i = \alpha_i \sqrt{N_i}$$

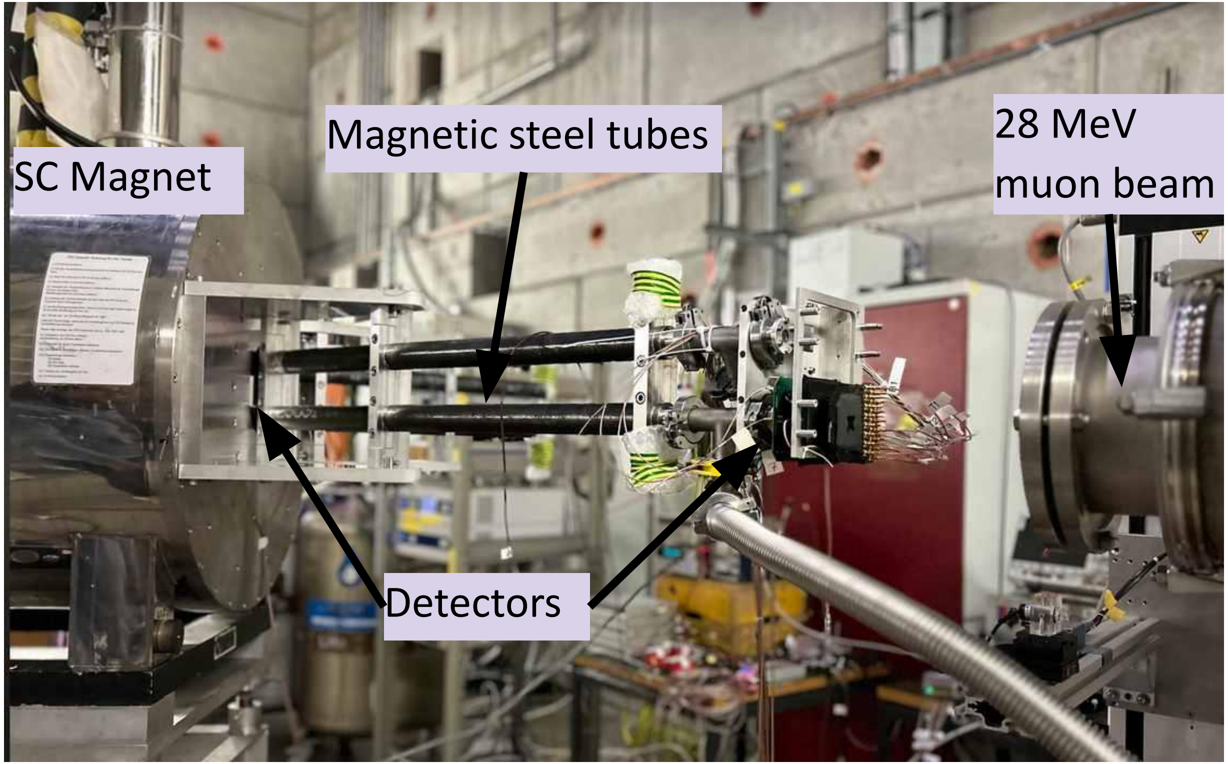
$$W = \sqrt{\sum_i W_i^2} = \sqrt{\sum_i \alpha_i^2 N_i}$$

$$d_\mu = \frac{\hbar}{2 c \beta B P} \frac{\sum_i \frac{\dot{A}_i}{\alpha_i} W_i^2}{\sum_i W_i^2}$$

The Measurements - Sensitivity

Method	Phase I	Phase II
	FoM	FoM
Simple	0.17	0.17
T-method	0.22	0.18
W-method (20x20x20bins)	0.29	0.28

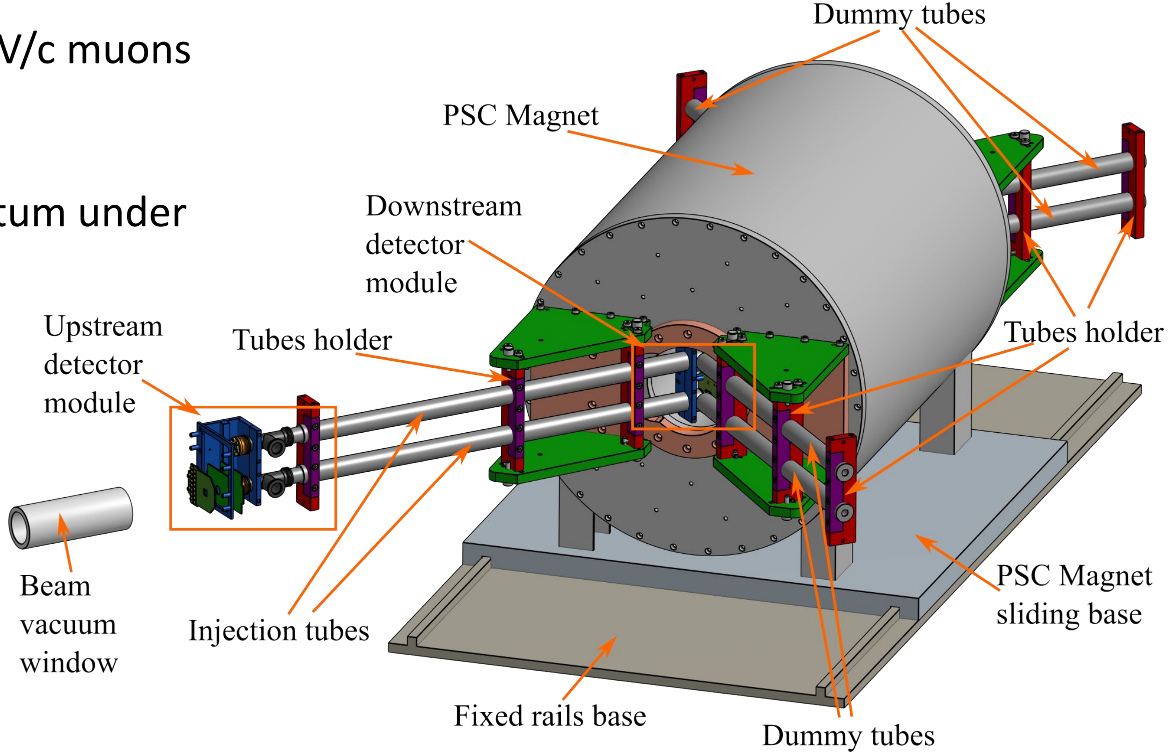
- The T-method is considered good enough for phase 1, but not for phase 2.
- The W-method is considered for phase 2.
  - Strong requirements for the detectors (momentum resolution, and good tracking)



LATEST PROGRESS

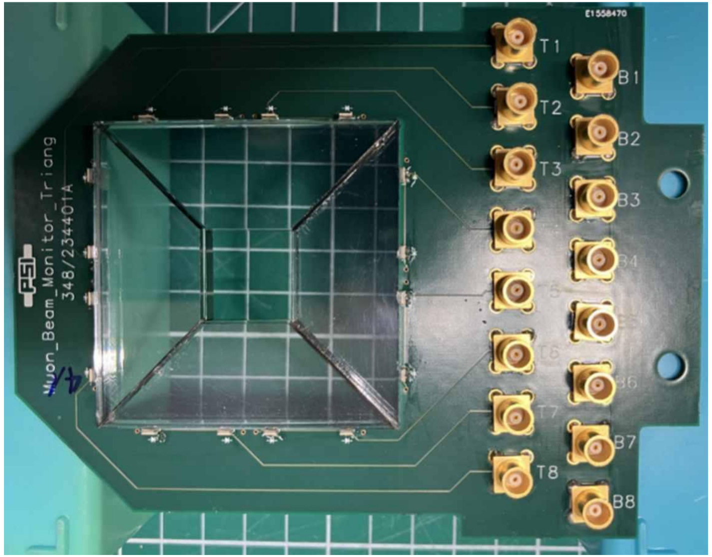
Latest Progress - Test Beam 2023

- Test Beam-Monitor detector.
- Test Entrance detectors.
- Test the injection of 28 MeV/c muons at low B fields.
- Test control of the momentum under external changes.
  - Systematic effect

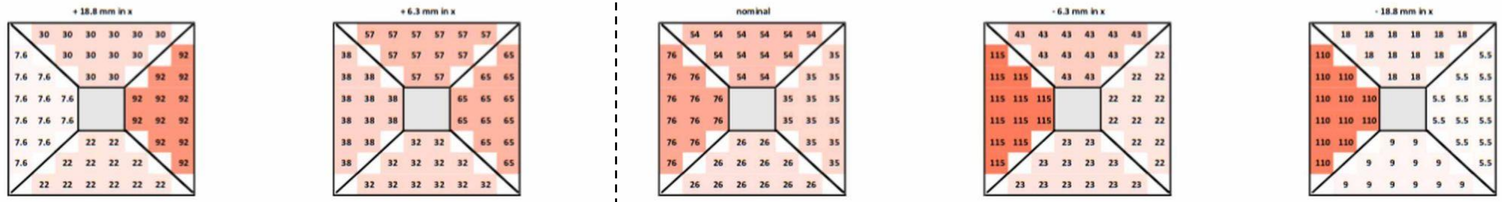


Latest Progress - Beam-Monitor

- Objective:
  - Align the beam with the injection channel.
  - Monitor the stability of the beam (e.g. during change of B-field direction).
- Tests:
  - Performance of different detector geometries.
  - Stability under external changes (e.g. position)
  - Sensitivity to beam displacement.

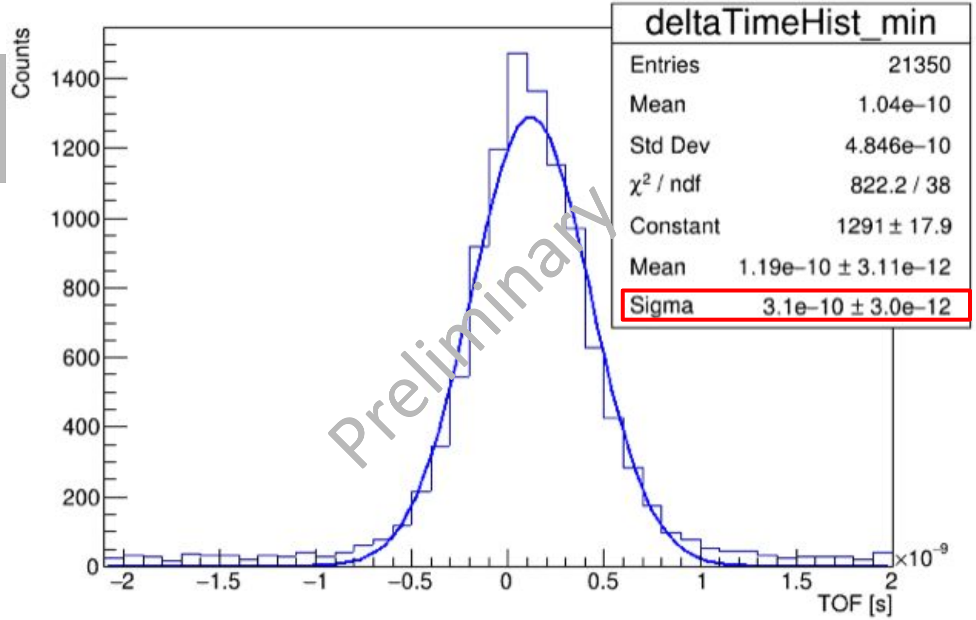


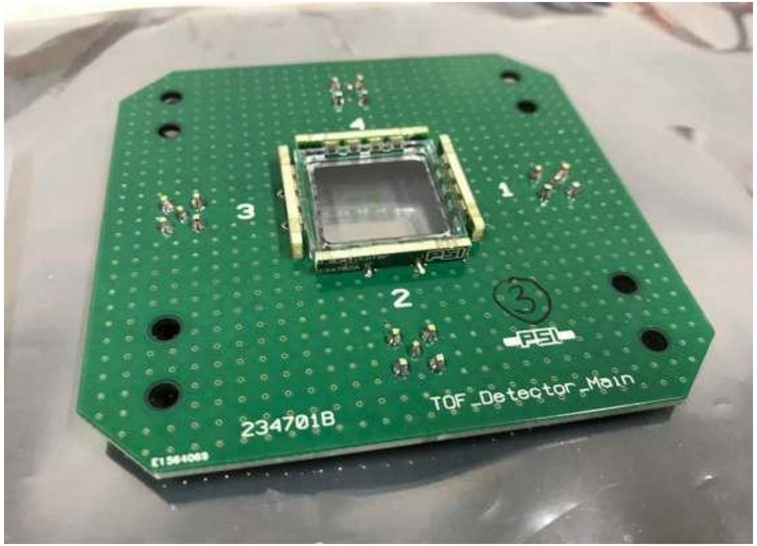
Horizontal displacement



Displaced beam position

Latest Progress - Entrance Detector





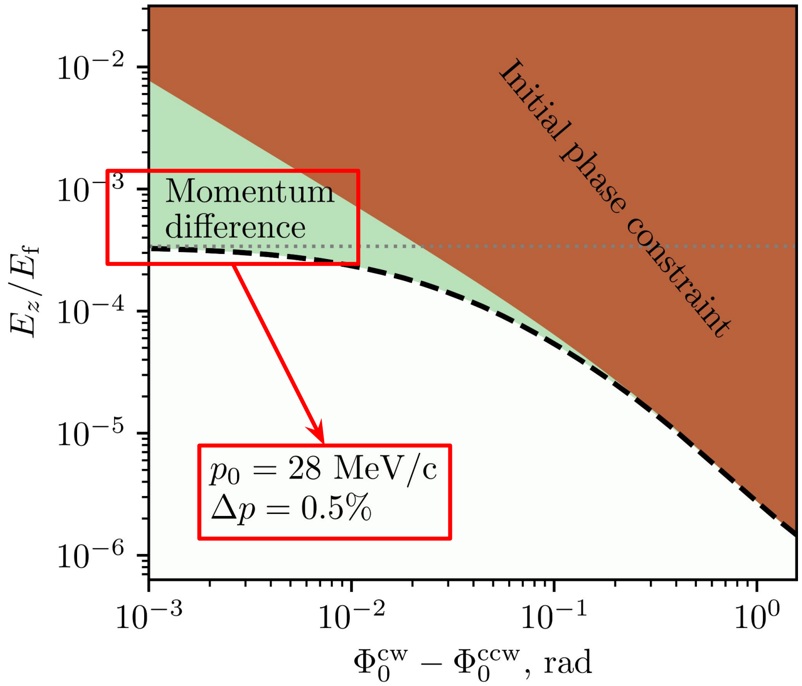
- Benchmarked different scintillators for future use as trigger for the magnetic kick.
- Obtained timing resolution on individual muons of ~300 ps.

Detectors Tests - Injection And Systematic Study

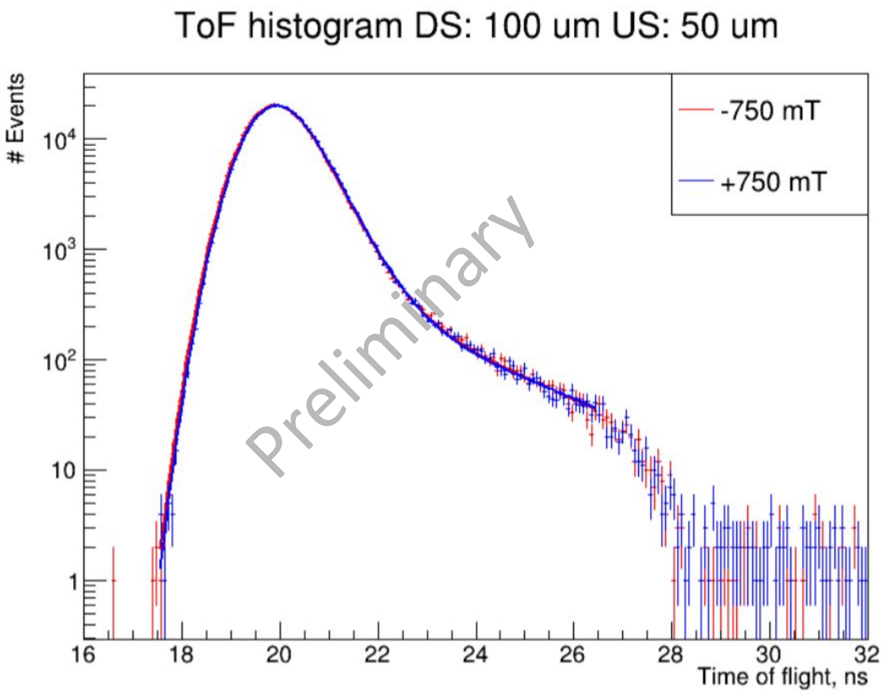
- False EDM-like precession (Ω∝βxE) due to non-zero longitudinal electric field (E_z):

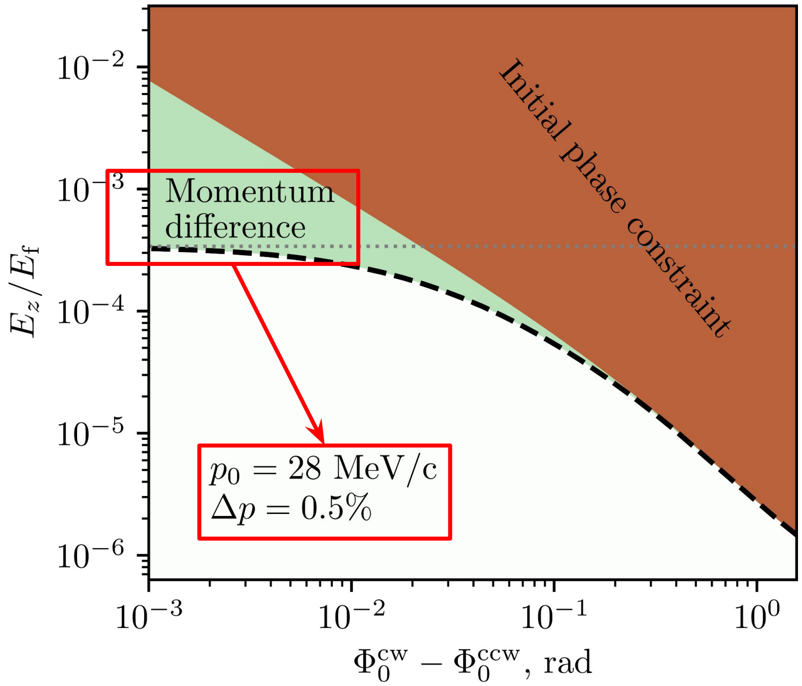
$$\Omega_\rho^{E_z} = -\frac{e}{mc}\left(a - \frac{1}{\gamma^2 - 1}\right)\beta_\theta E_z,$$

- One of the criteria to cancel the false signal:
  - Momentum distribution for clockwise (CW)and anticlockwise (CCW) injection should be "equal".
  - CW and CCW injections achieved by inverting the B field.



Detectors Tests - Injection And Systematic Study



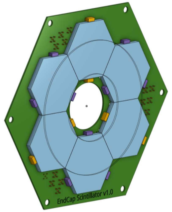


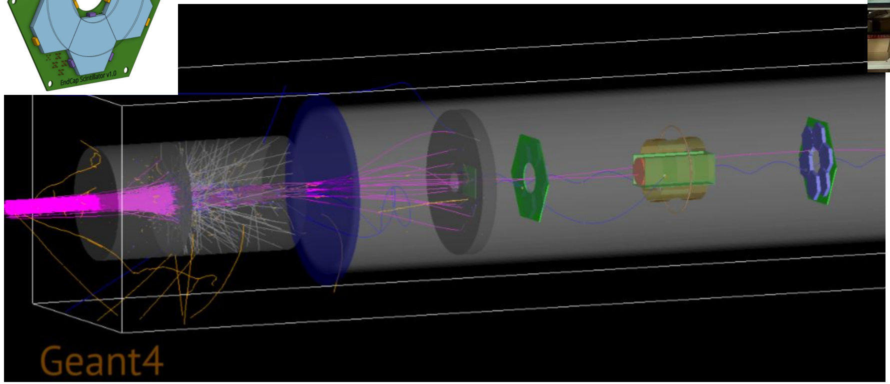
- Agreement of the ToF spectra for positive/negative B field configurations within 0.2%.
- Momentum control better than 0.5%: Necessary condition to avoid false signal from $E_z \neq 0$

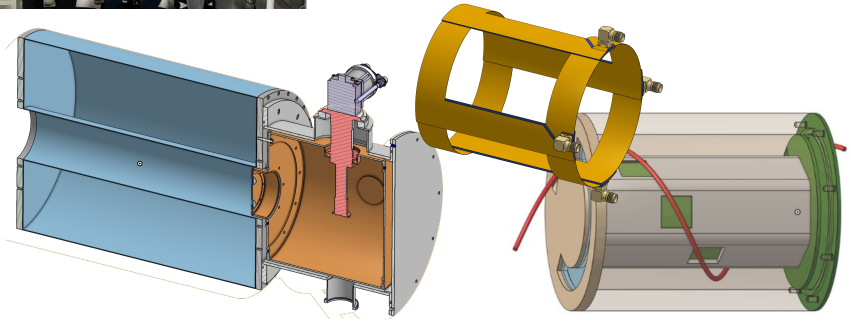
STATUS AND OUTLOOK

Outlook

- Study possible effects of magnetic kick on the positron detection.
- Characterize muons trajectory.
- Test cryogenics and SC tubes.
- Precise mapping of the magnet’s B field.
- Stop muons in orbit with magnetic kicker.



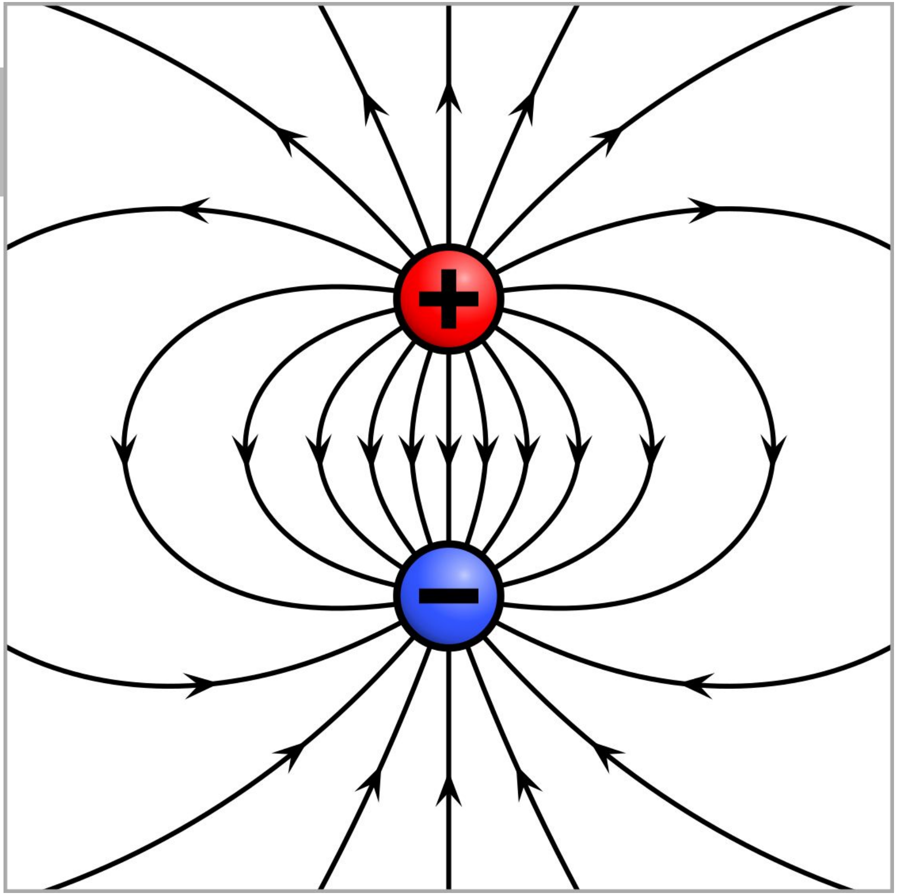


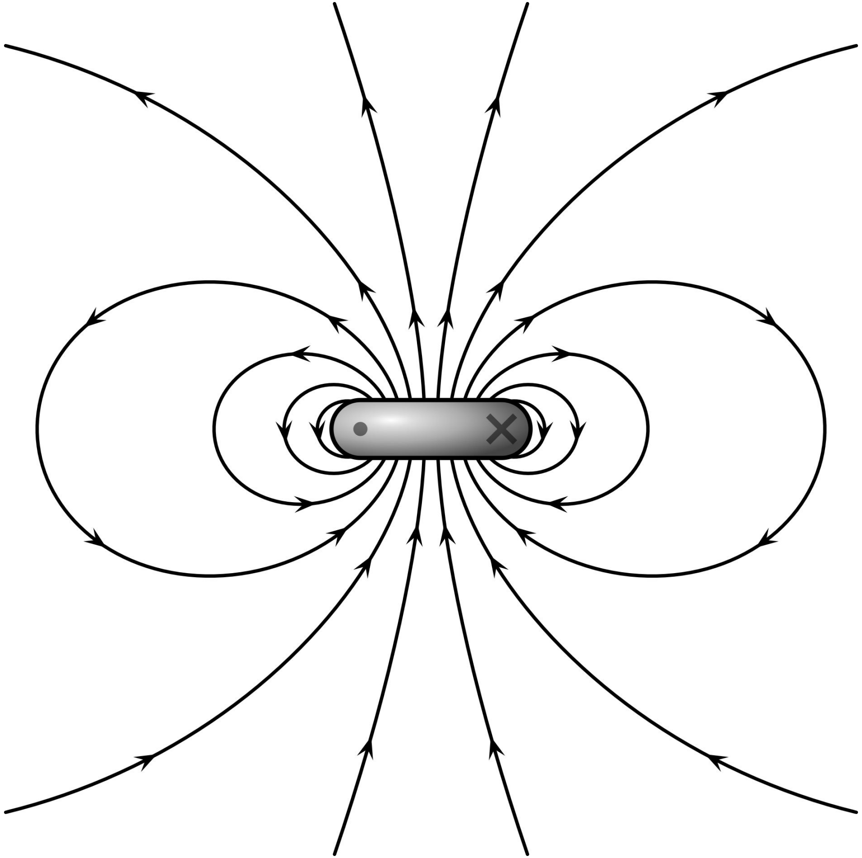


Backup

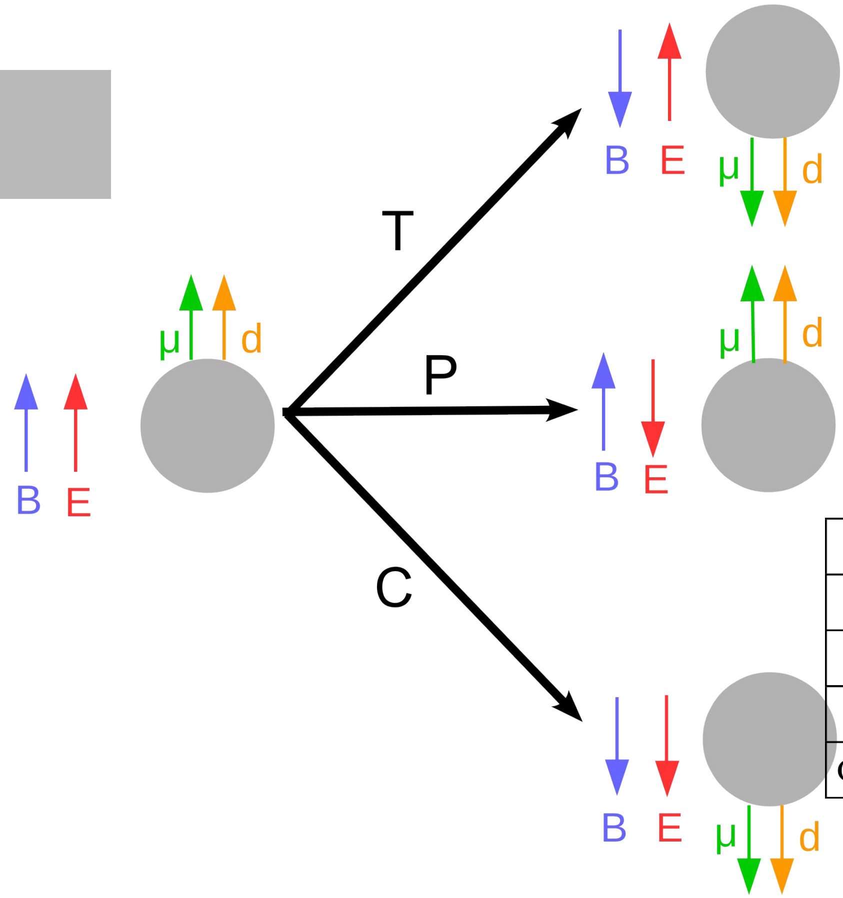
PAUL SCHERRER INSTITUT

MDM And EDM





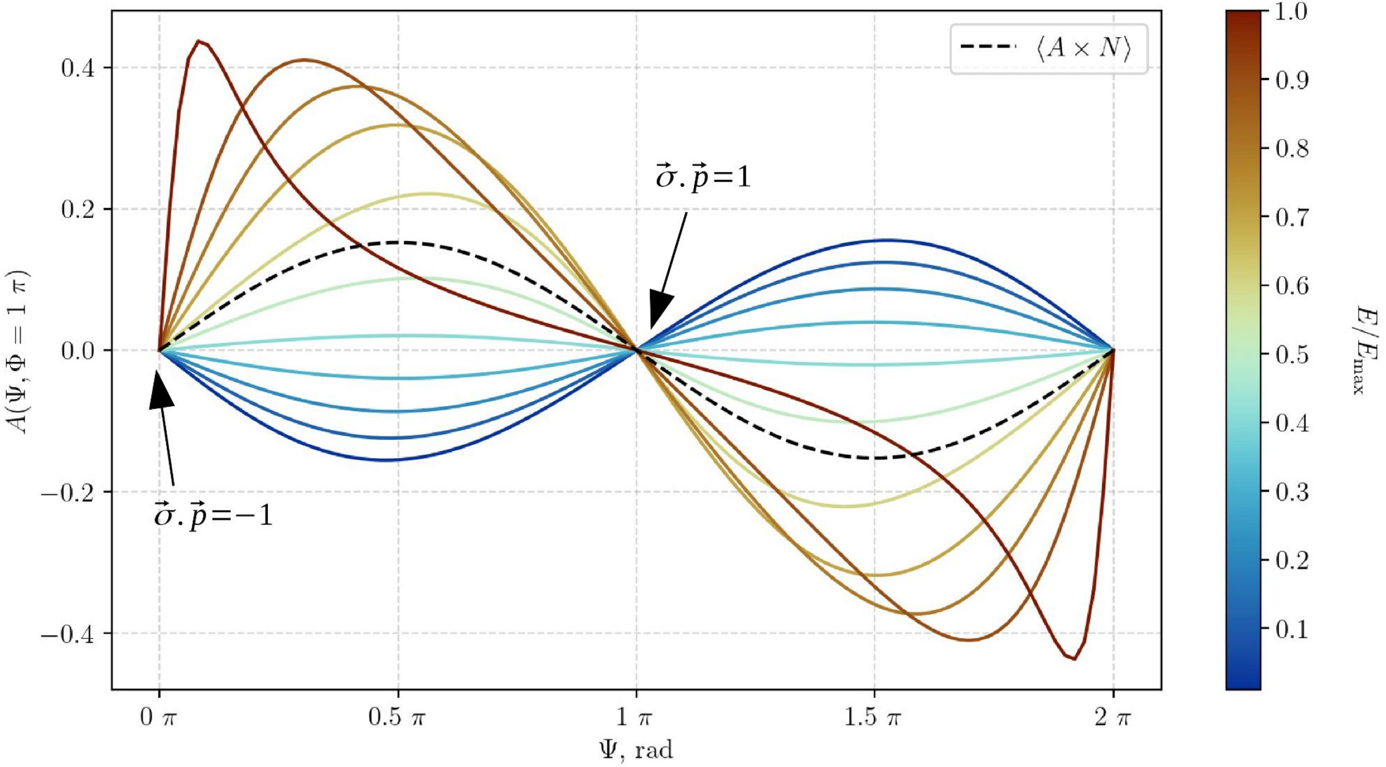
MDM And EDM



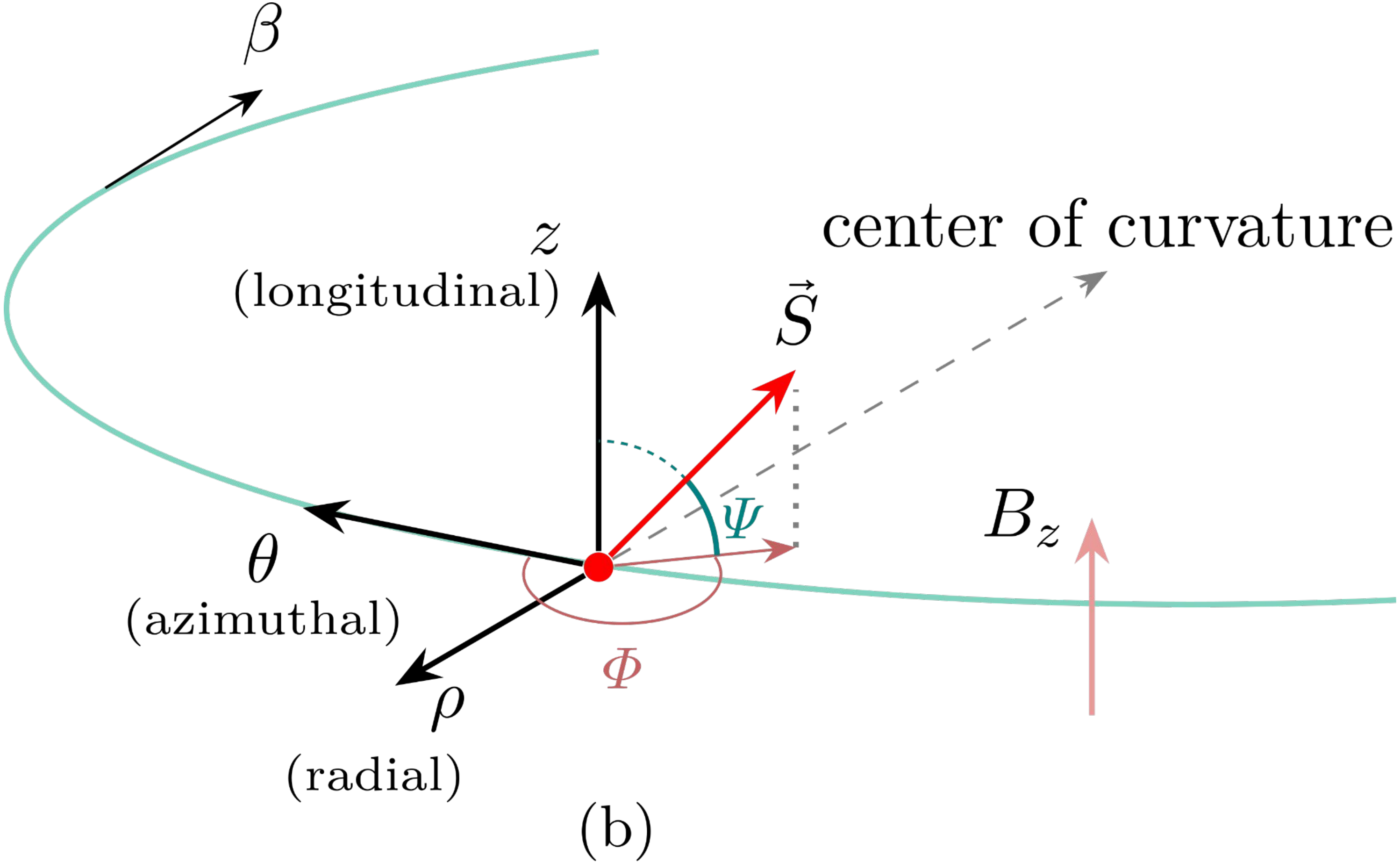
$$\hat{H} = -\vec{\mu} \cdot \vec{B} - \vec{d} \cdot \vec{E}$$

$$\vec{\mu} = g \frac{q}{2\ m_{\mu}} \vec{s} \qquad \vec{d} = \eta \frac{q}{2\ m_{\mu}\ c} \vec{s}$$

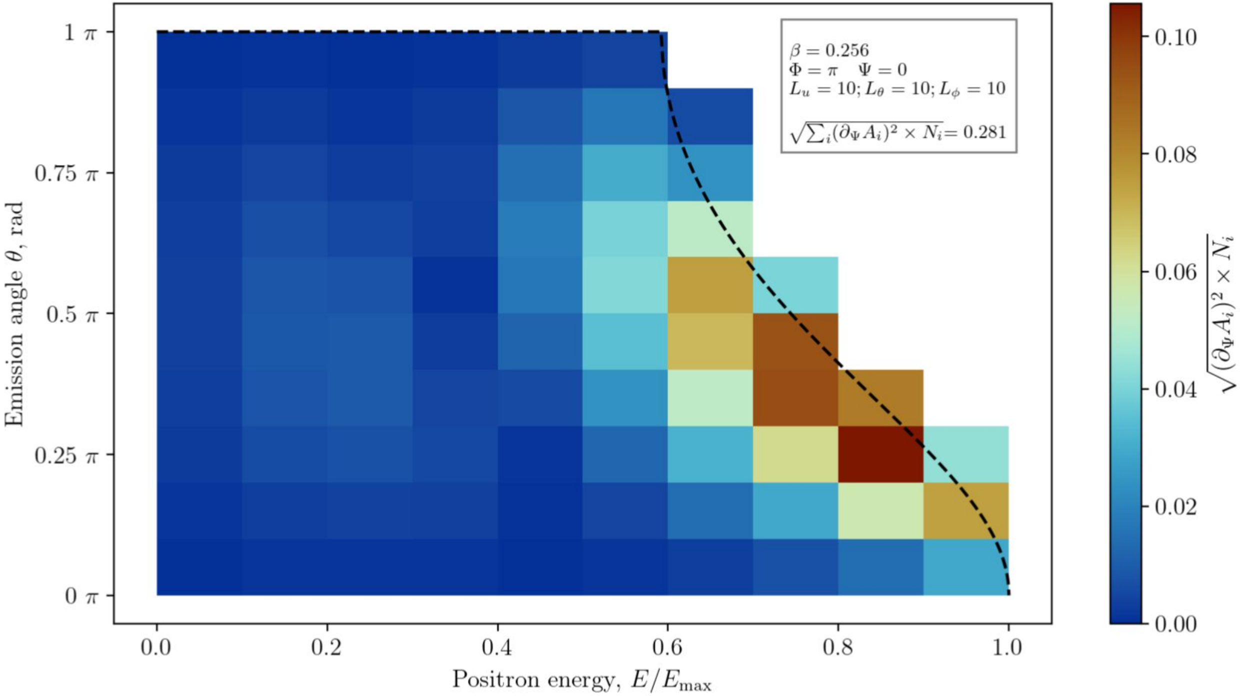
	μ	d	$\mathbf{s}$	$\mathbf{E}$	$\mathbf{B}$	$-d\ \mathbf{s} \cdot \mathbf{E}$	$-\mu\ \mathbf{s} \cdot \mathbf{B}$
parity	$+$	$+$	$+$	-	$+$	$(++-) = -$	$(+++) =$
time	$+$	$+$	-	$+$	-	$(+-+) = -$	$(+--) =$
charge	-	-	$+$	-	-	$(-+-) = +$	$(-+-) =$
charge & parity	-	-	$+$	$+$	-	$(-++) = -$	$(-+-) =$


$\langle A \times N \rangle$
$\vec{\sigma}.\vec{p}=1$
$\vec{\sigma}.\vec{p}=-1$
0.4
0.2
0.0
−0.2
−0.4
$A(\Psi, \Phi = 1\ \pi)$
0 π
0.5 π
1 π
1.5 π
2 π
Ψ, rad
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
$E/E_{\max}$

PAUL SCHERRER INSTITUT



Minimize The Uncertainty - Sensitivity

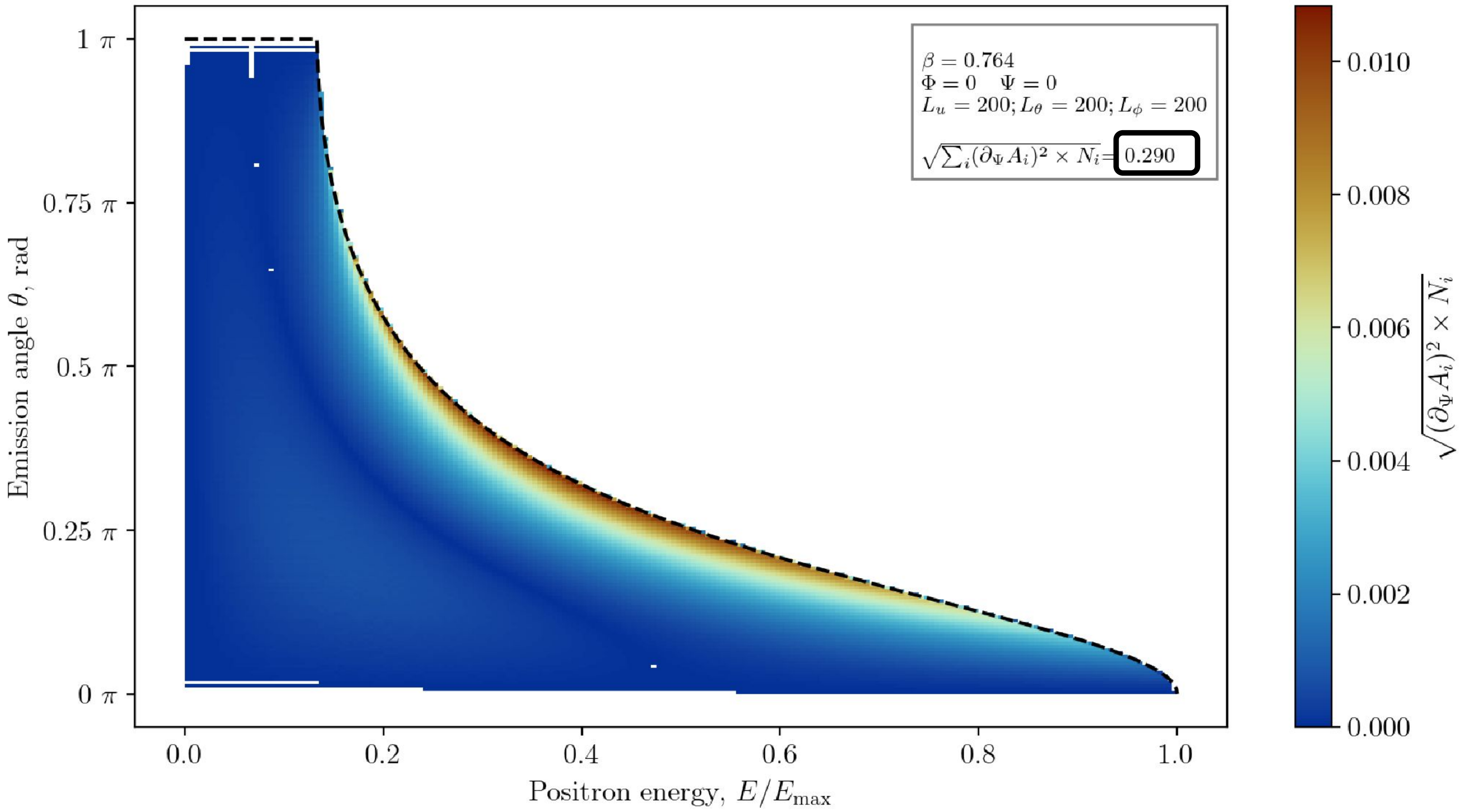


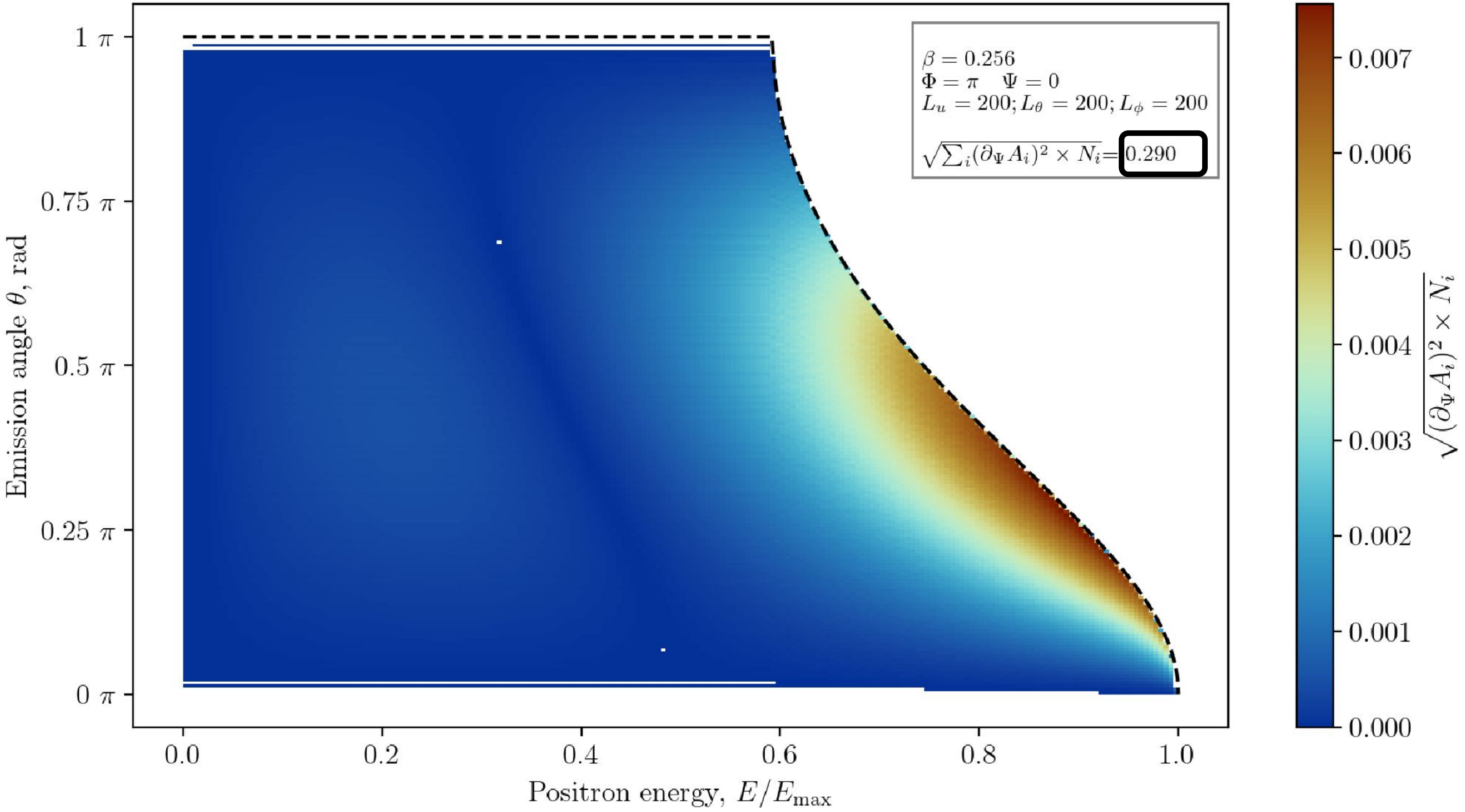
$$W_i = \alpha_i \sqrt{N_i}$$

$$W = \sqrt{\sum_i W_i^2} = \sqrt{\sum_i \alpha_i^2 N_i}$$

$$d_\mu = \frac{\hbar}{2 c \beta B P} \frac{\sum_i \frac{\dot{A}_i}{\alpha_i} W_i^2}{\sum_i W_i^2}$$

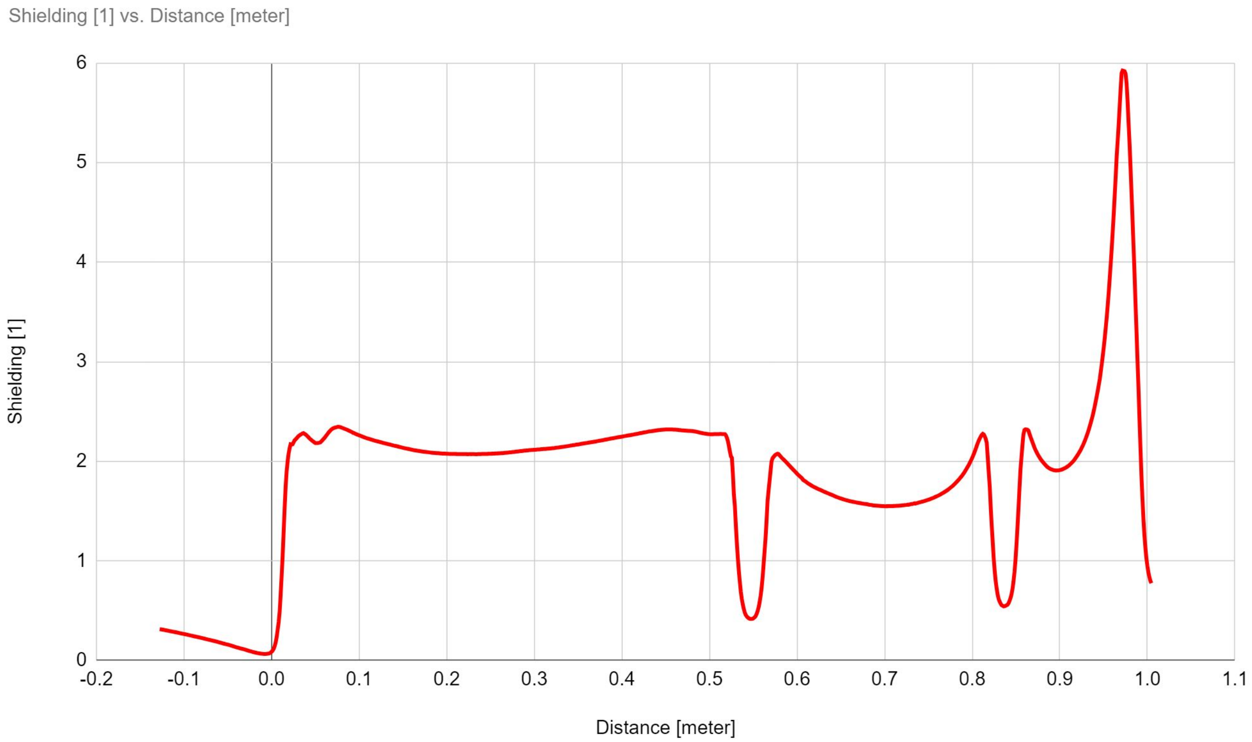
- Binning in energy and direction.
- The W-method is preferred, which imposes strong requirements for tracking and momentum discrimination of the detectors.


$\beta = 0.764$
$\Phi = 0 \quad \Psi = 0$
$L_u = 200; L_\theta = 200; L_\phi = 200$
$\sqrt{\sum_i (\partial_\Psi A_i)^2 \times N_i}$ = 0.290
Emission angle θ, rad
1 π
0.75 π
0.5 π
0.25 π
0 π
0.0
0.2
0.4
0.6
0.8
1.0
Positron energy, $E/E_{\max}$
0.010
0.008
0.006
0.004
0.002
0.000
$\sqrt{(\partial_\Psi A_i)^2 \times N_i}$



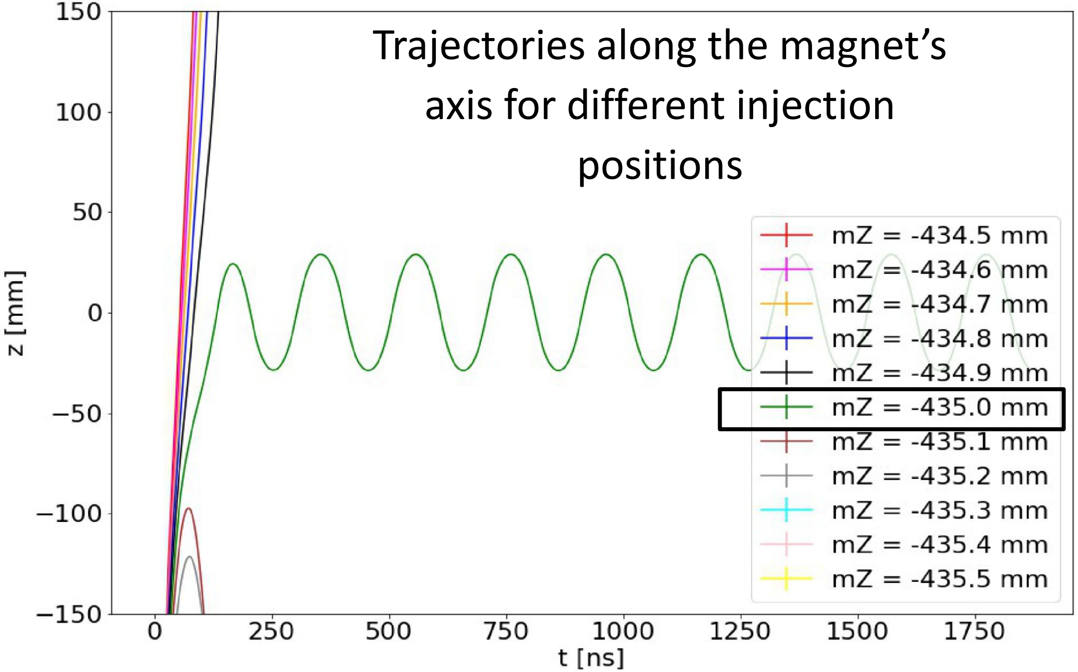
$\beta = 0.256$
$\Phi = \pi \quad \Psi = 0$
$L_u = 200; L_\theta = 200; L_\phi = 200$
$\sqrt{\sum_i (\partial_\Psi A_i)^2 \times N_i}$= 0.290
1 π
0.75 π
0.5 π
0.25 π
0 π
Emission angle θ, rad
0.0
0.2
0.4
0.6
0.8
1.0
Positron energy, E/E_{max}
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0.000
$\sqrt{(\partial_\Psi A_i)^2 \times N_i}$

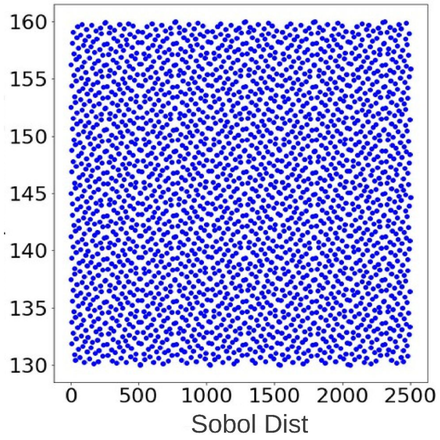
Field Intensity - Estimated Shielding Factor



- Operate magnet at a field high enough without saturating the injection tubes
- Shield the injected muons to below ~100 mT

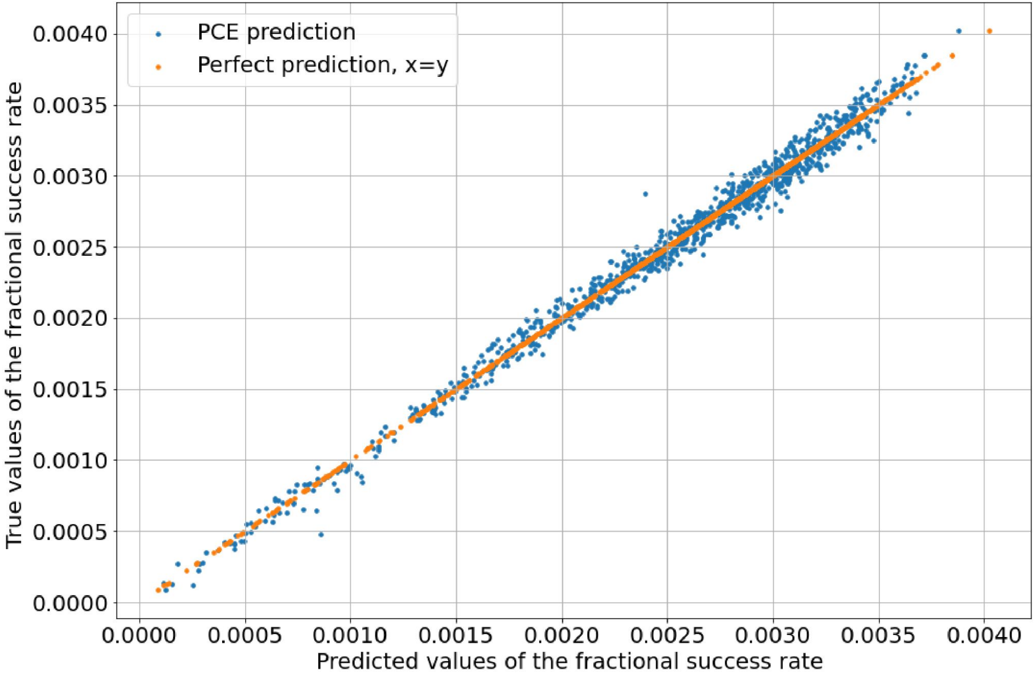
Optimize The Experiment - Numerical Methods





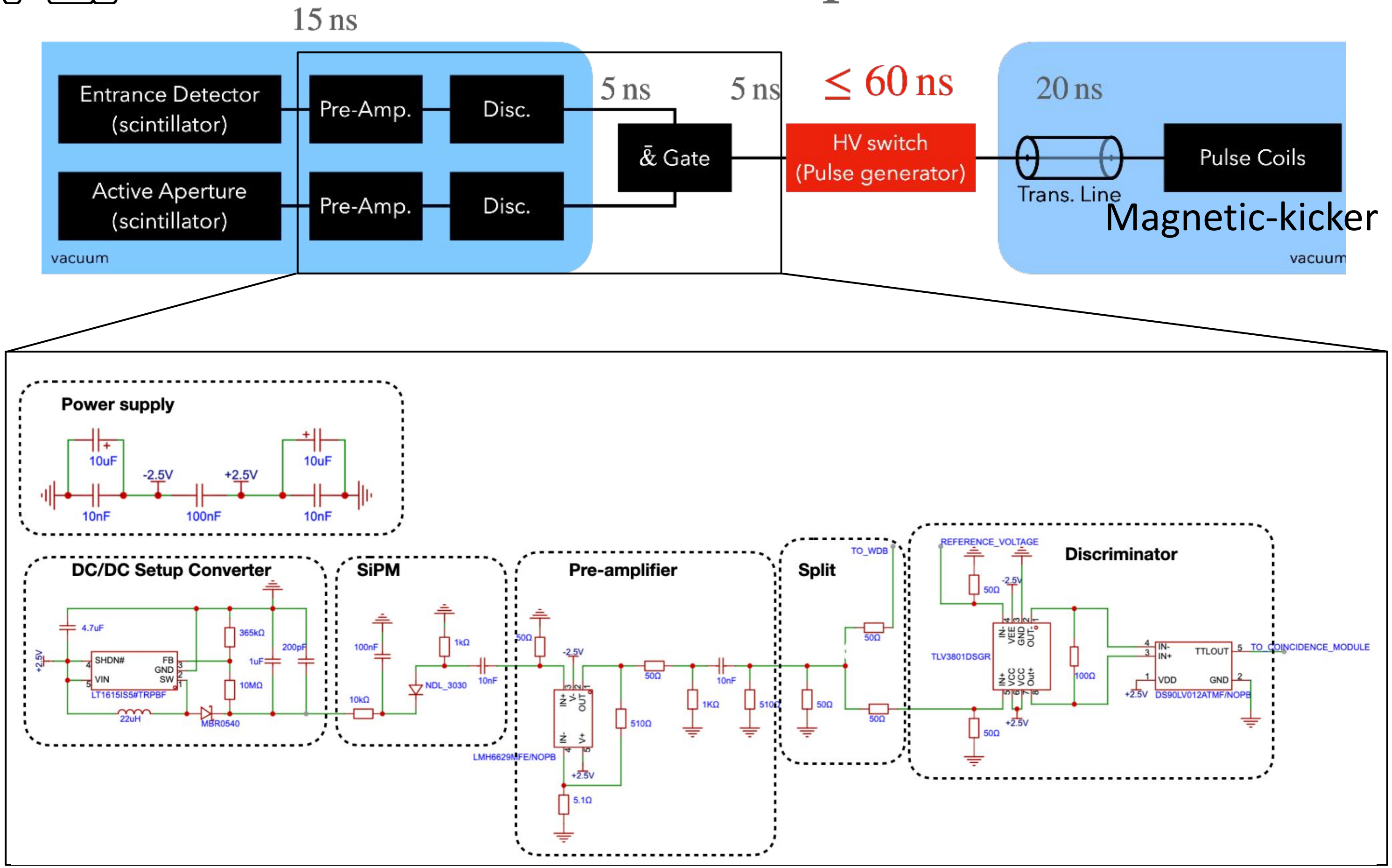
- Highly restrictive parameter space for successful injection of muons.
- Need for efficient methods to sample the parameter space and generate estimations.

Optimize The Experiment - Preliminary Result

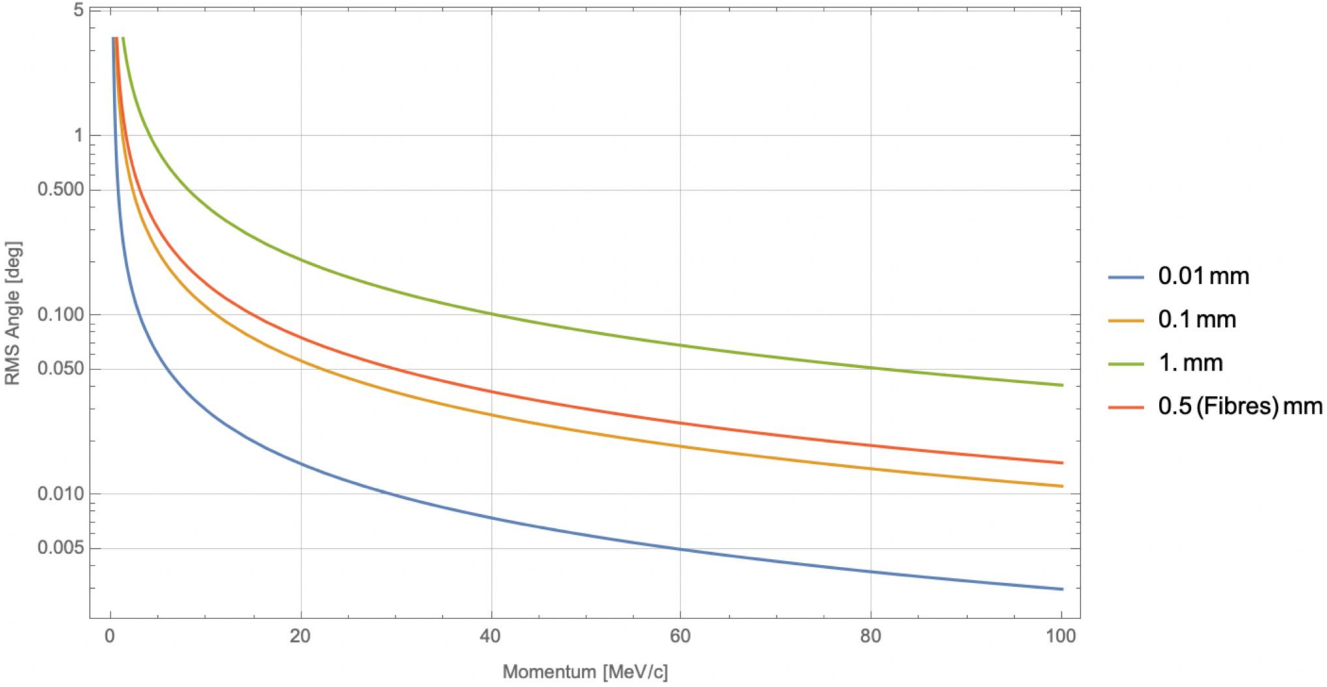


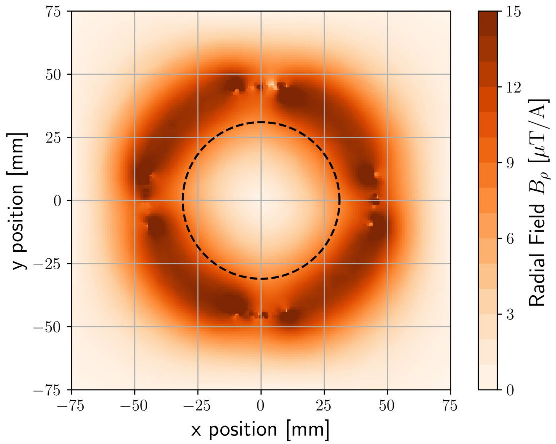
- 6^{th} degree polynomial-chaos-expansion surrogate model performs well for predicting the efficiency.
- Using optimization based in Genetic-Algorithm, found experiment parameters for storing 0.4 % of the injected muons (0.47% with G4beamline)

Fast Electronics Development



PAUL SCHERRER INSTITUT



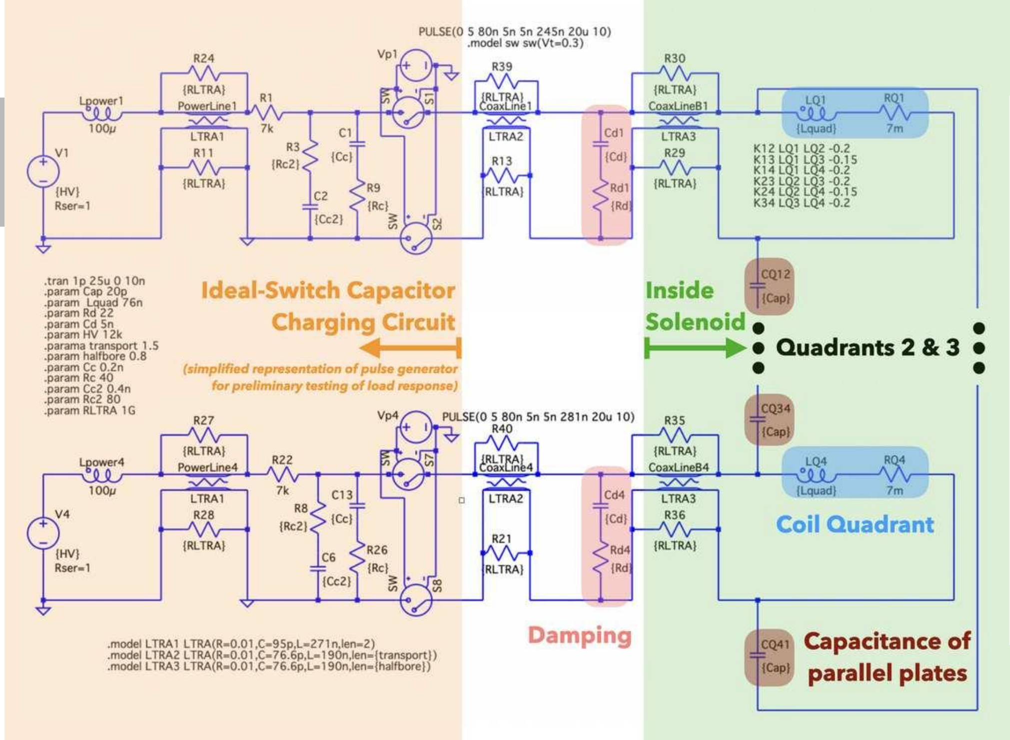


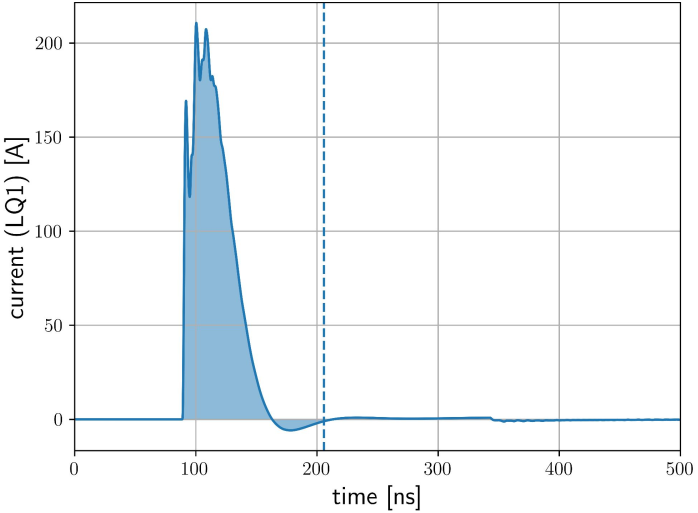
$$\frac{dp_\phi}{dz} = -\frac{e\rho}{2}\frac{dB}{dz}$$

$$\dot{\vec{p}}(t) = \frac{e}{\gamma m}\vec{p} \times \vec{B}_{\text{pulse}}(t)$$

$$\implies \dot{p}_z(t) = \frac{e}{\gamma m} p_\phi \vec{B}_{\text{pulse}}(t) \cdot \hat{\rho}$$

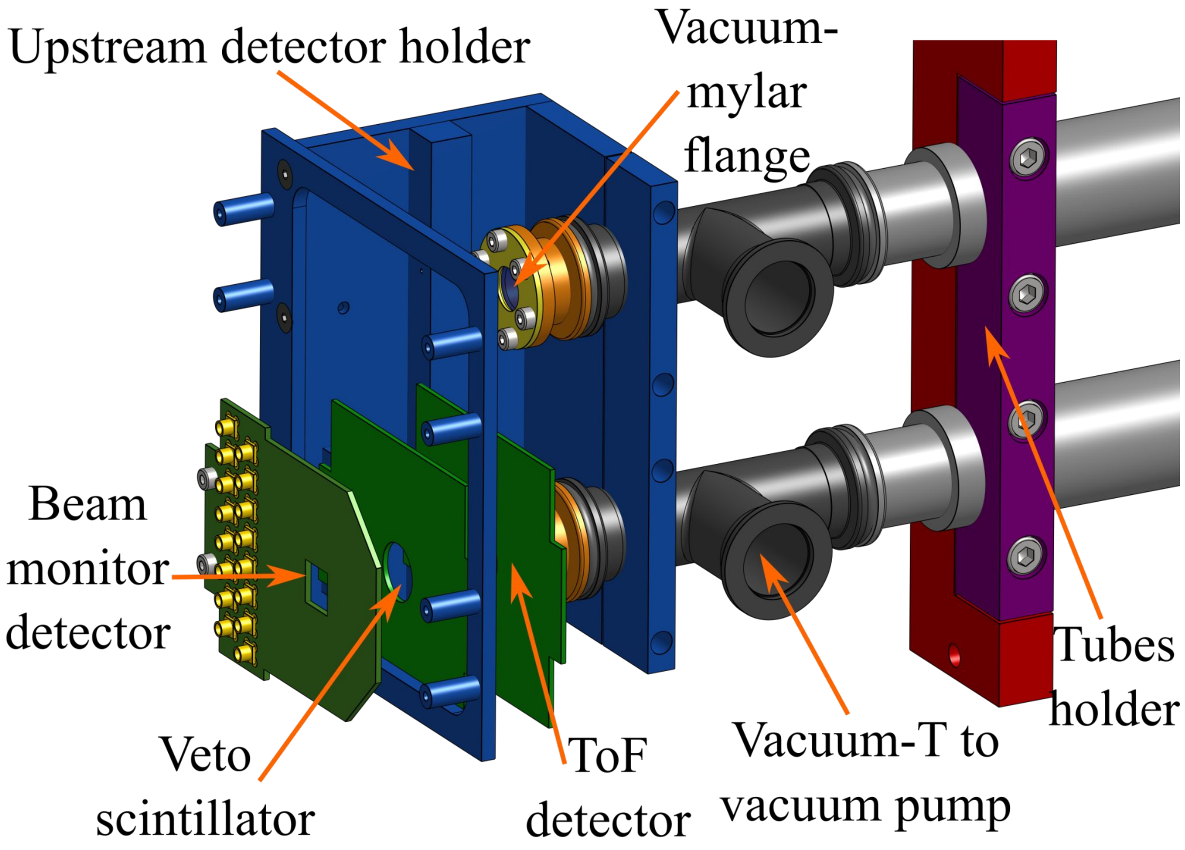
Magnetic Kicker R&D



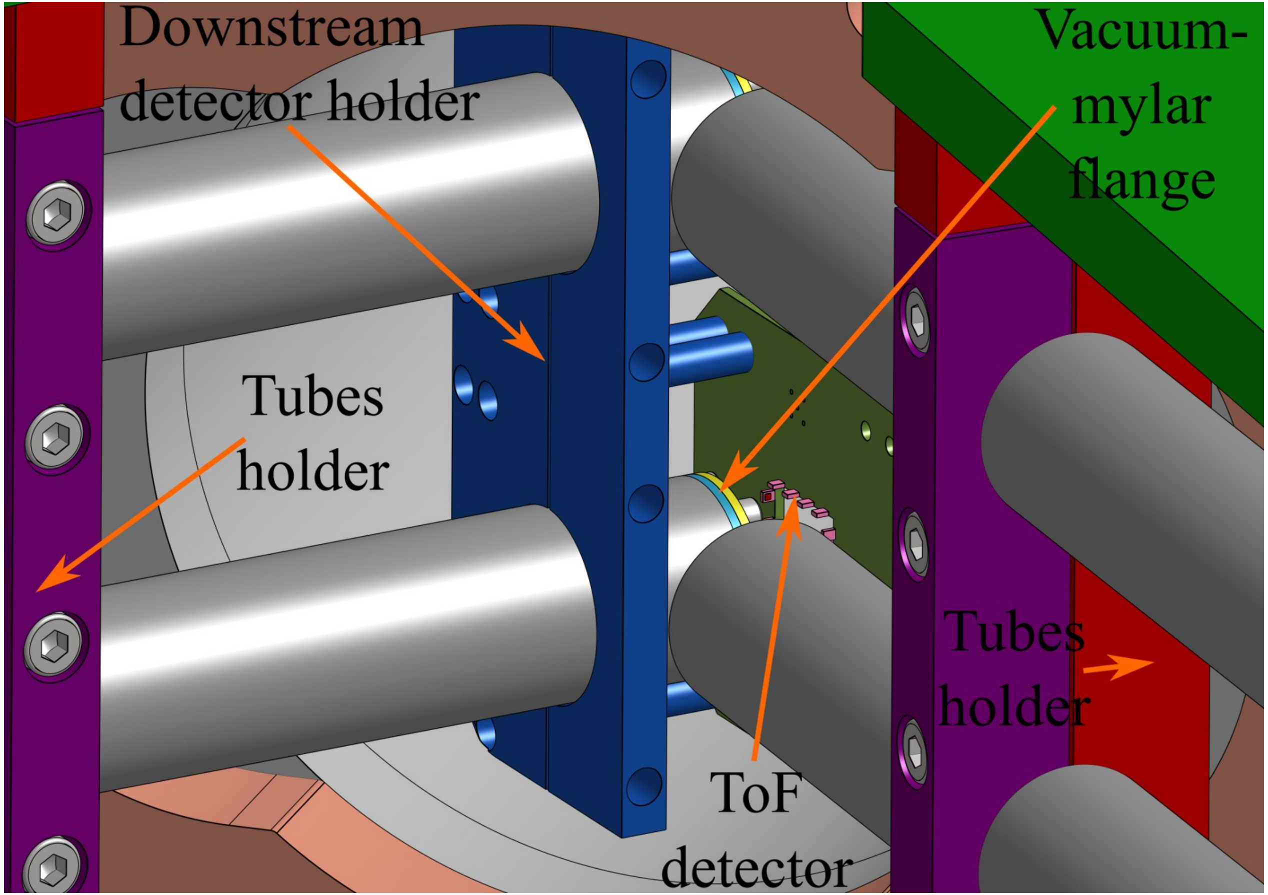


- 200 A - 35 ns FWHM pulse.
- Prototype under development for testing in summer.

Latest Progress - Test Beam 2023



Latest Progress - Test Beam 2023



Status And Outlook

- Study possible effects of magnetic kick on the positron detection.
- Stop 200 MeV/c pions inside 3 T field.
  - Uniform distribution of positrons from muons at rest.
  - Hexagonal-tiling scintillating detectors before and after the stopping target.