Implementation of the frozen-spin technique for the search for a muon EDM

– New Frontiers in Lepton Flavor (Pisa, May 2023) –

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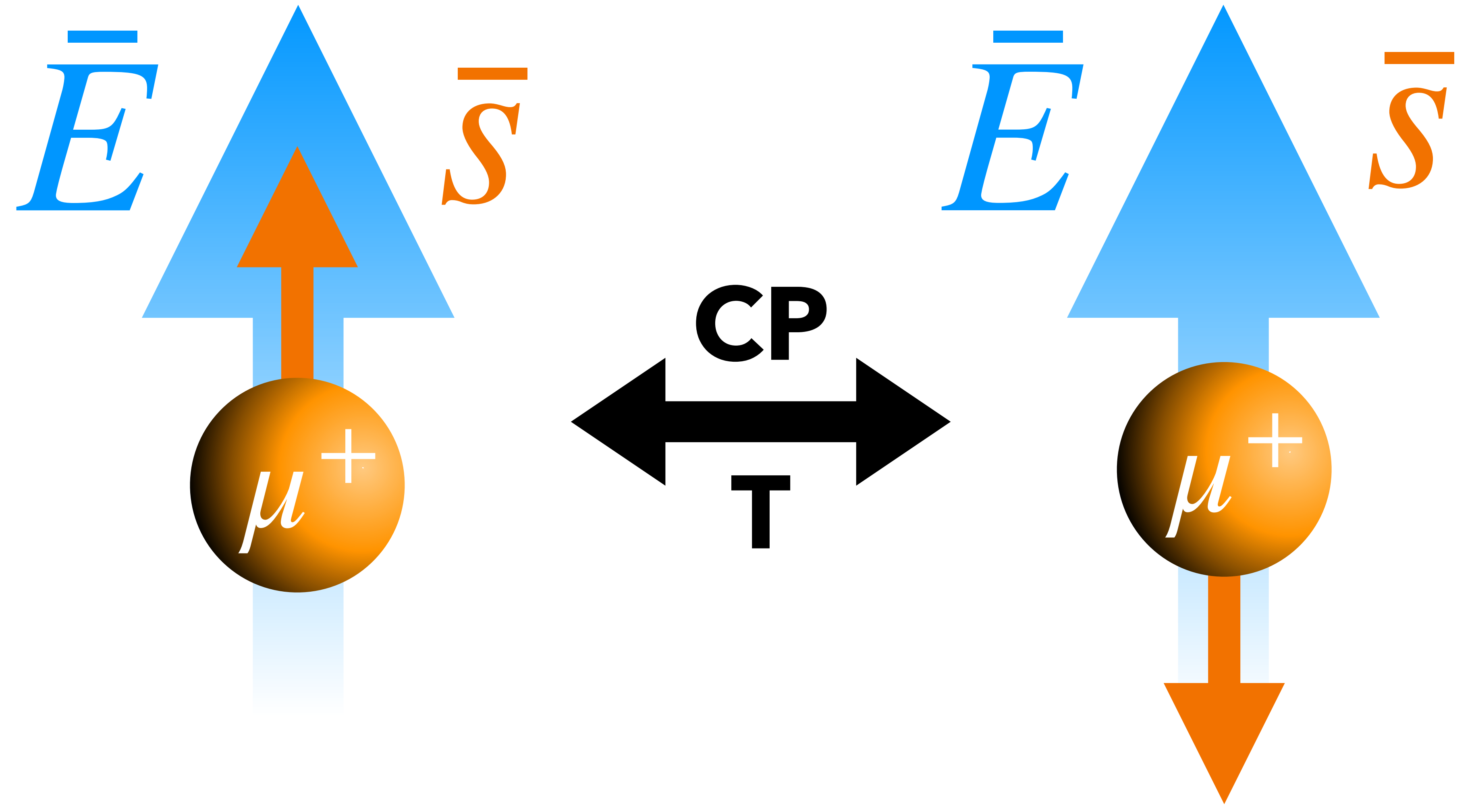
muEDM Experiment @ PSI

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



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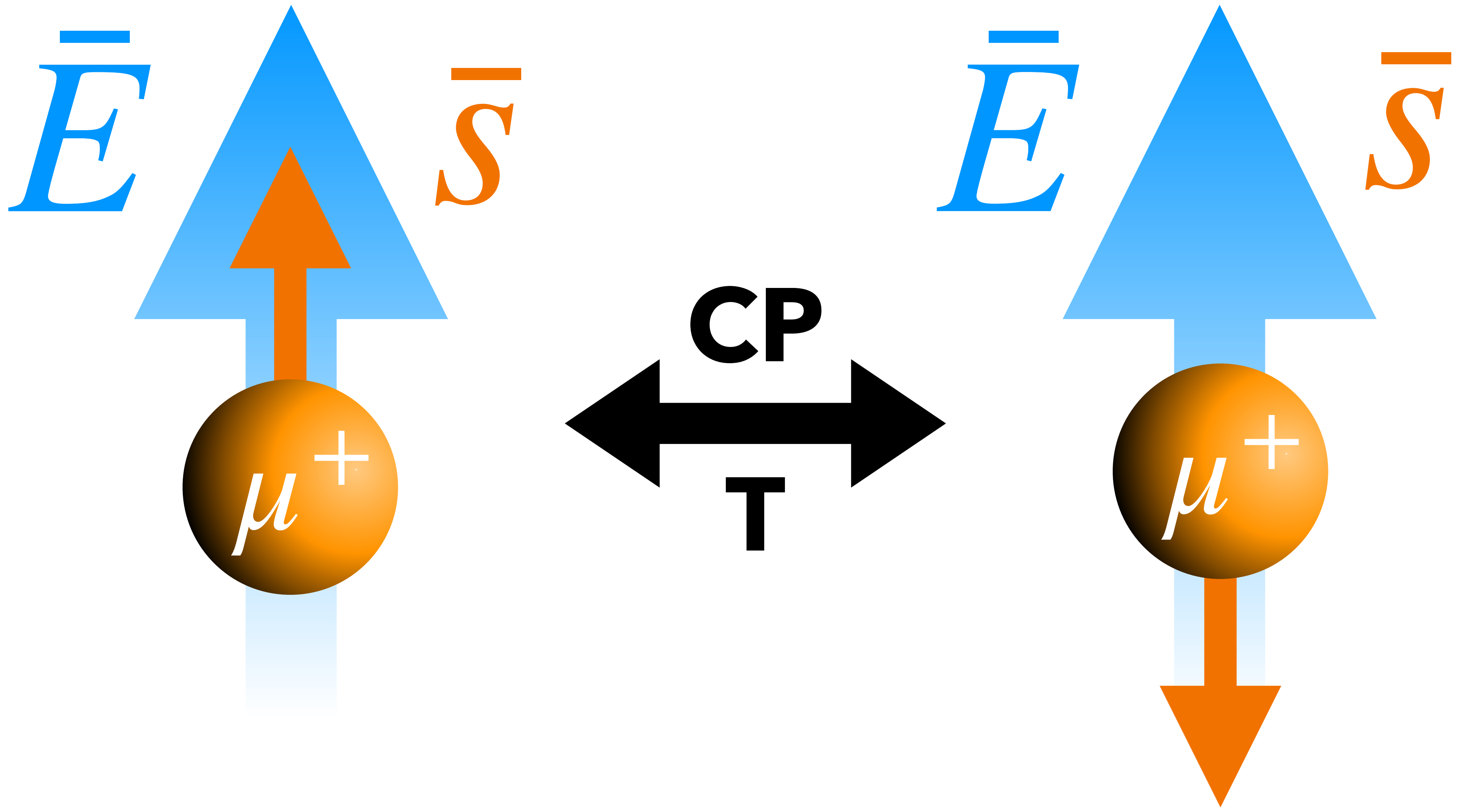

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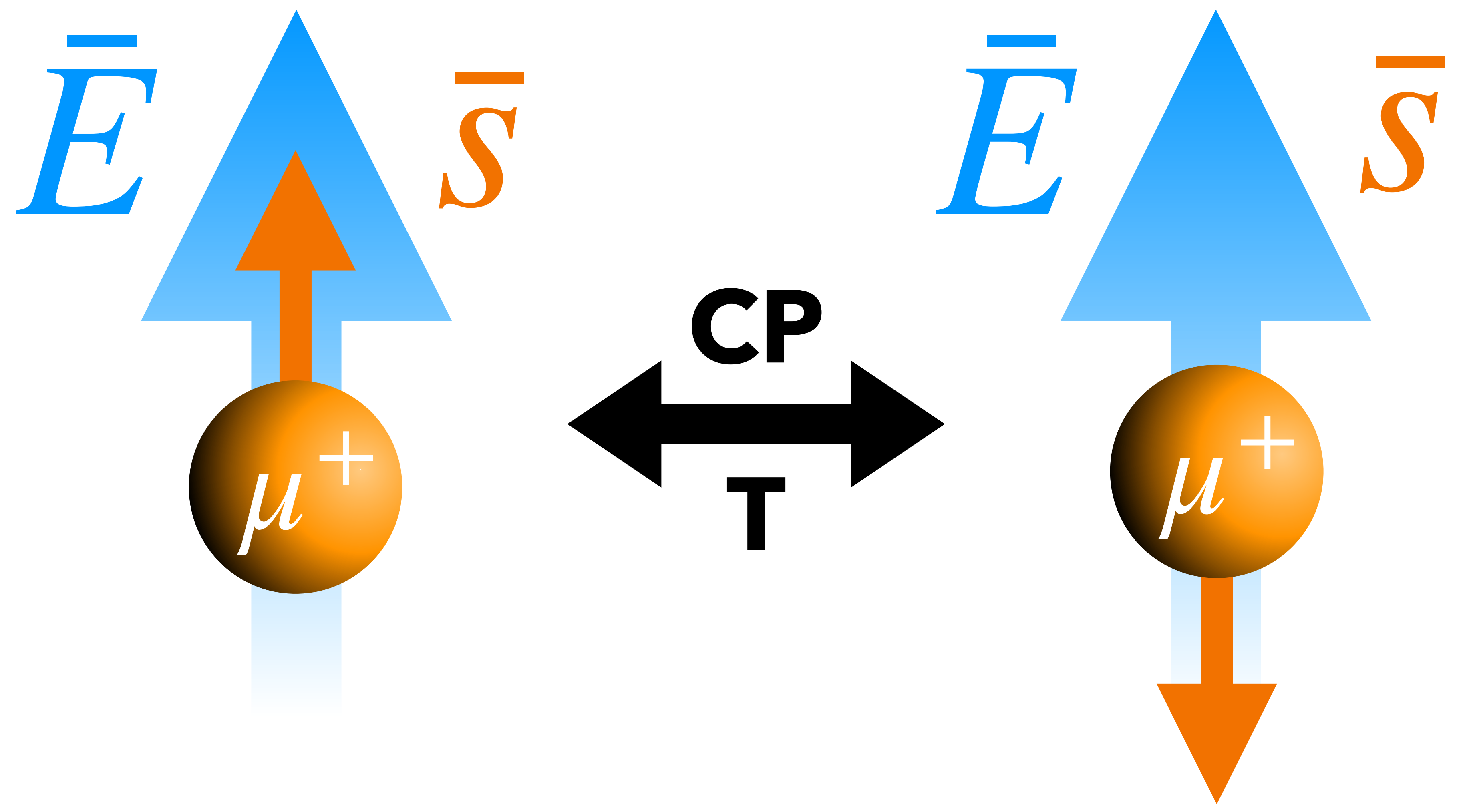

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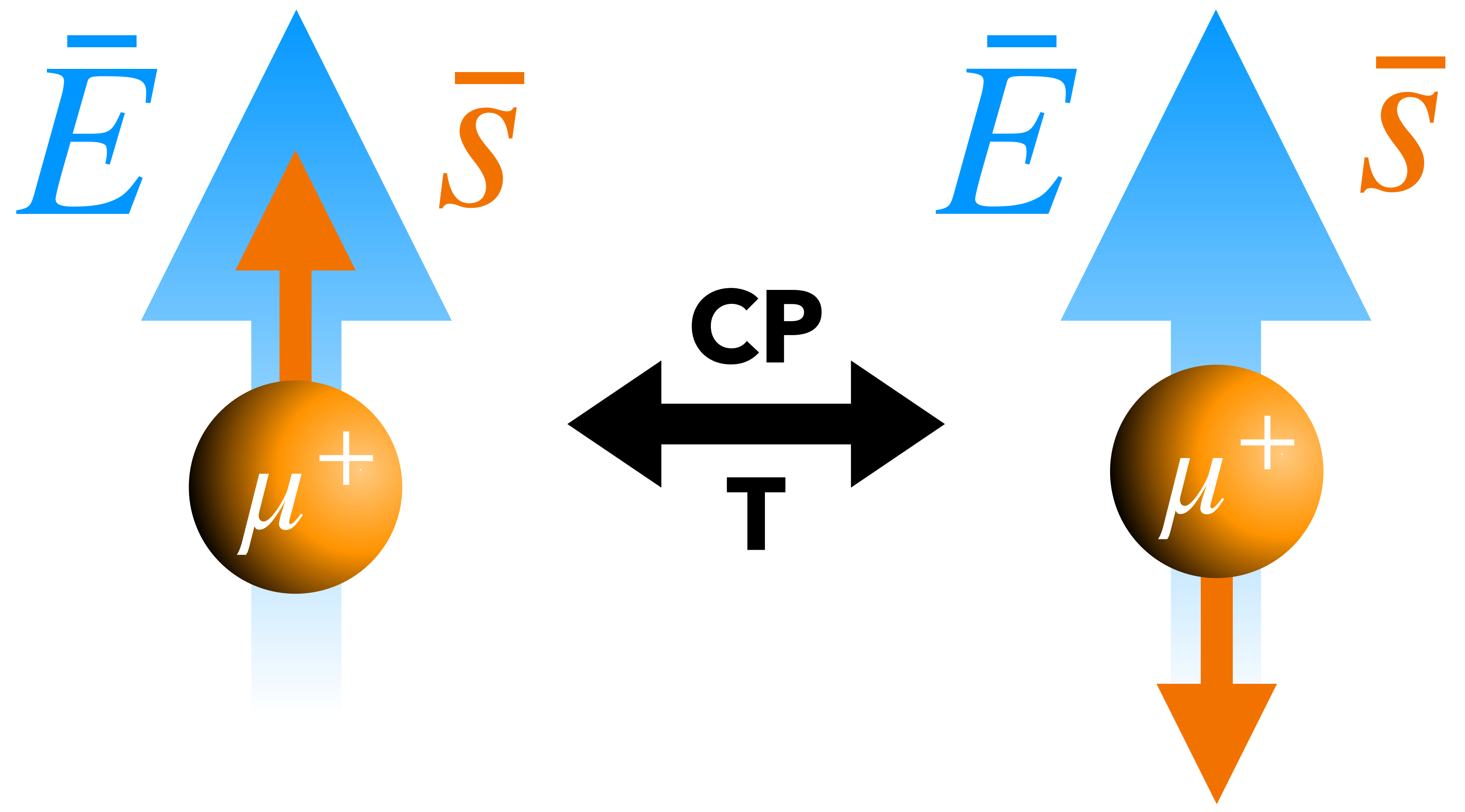

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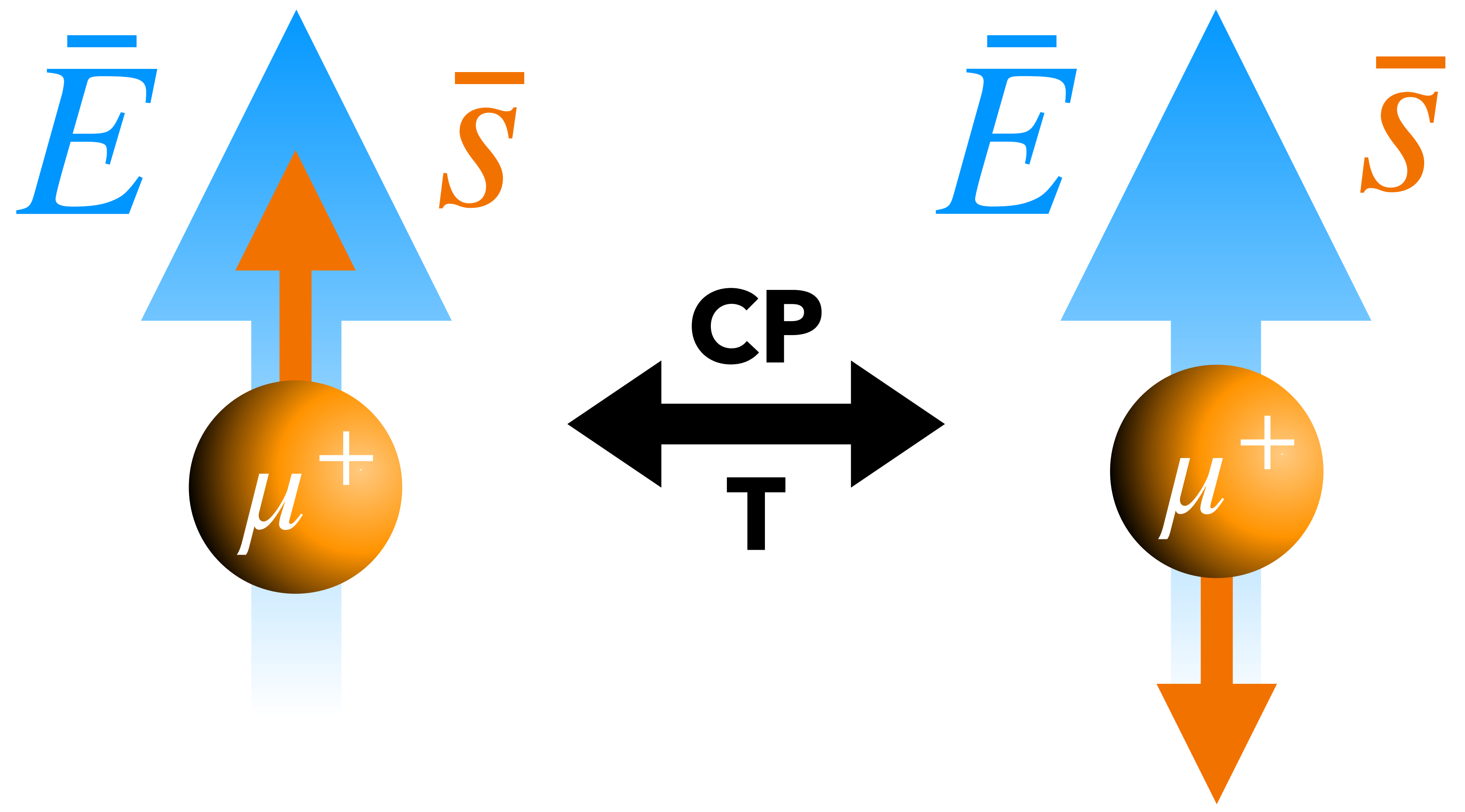

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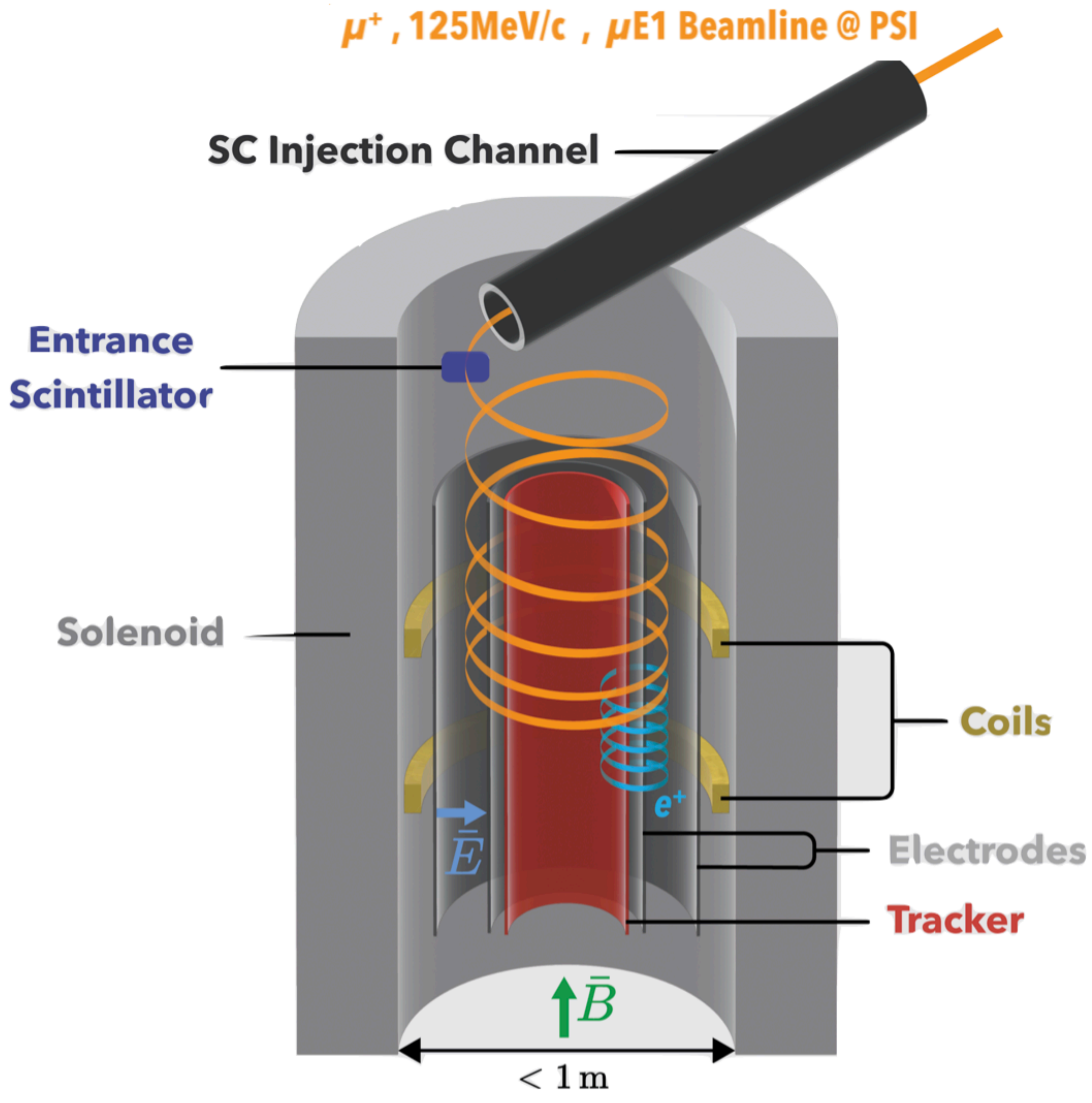

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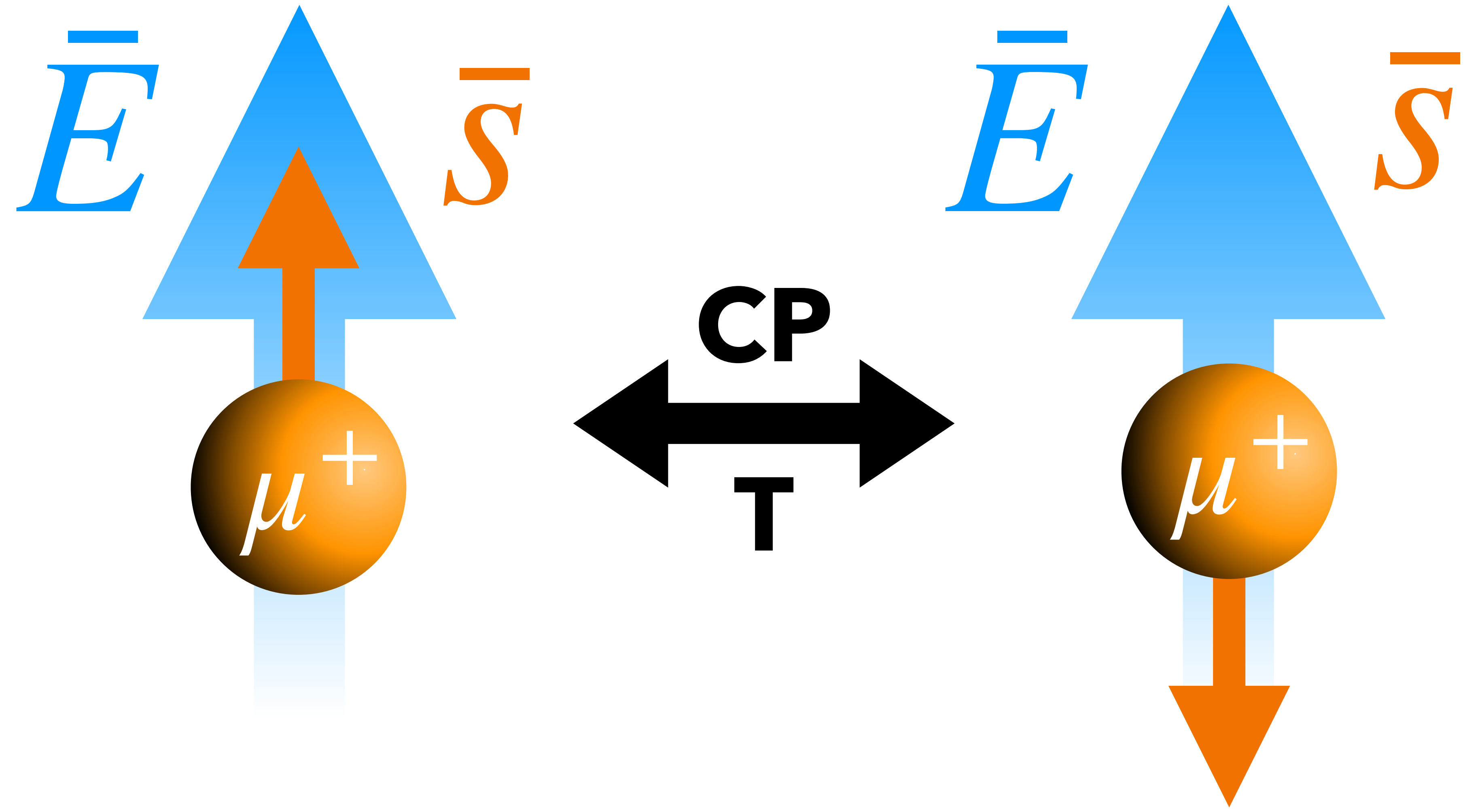

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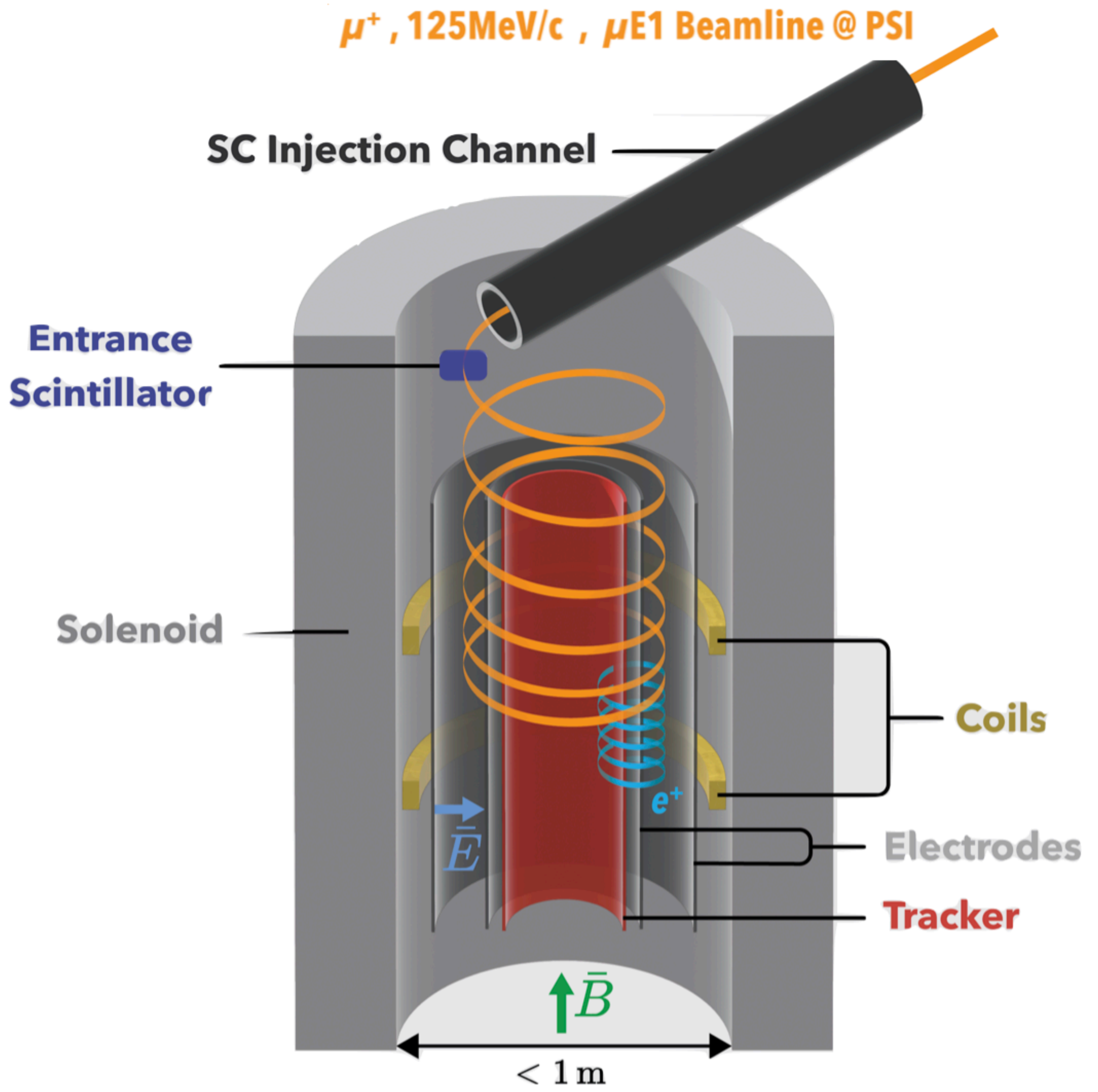


Final muEDM Experiment Sensitivity

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

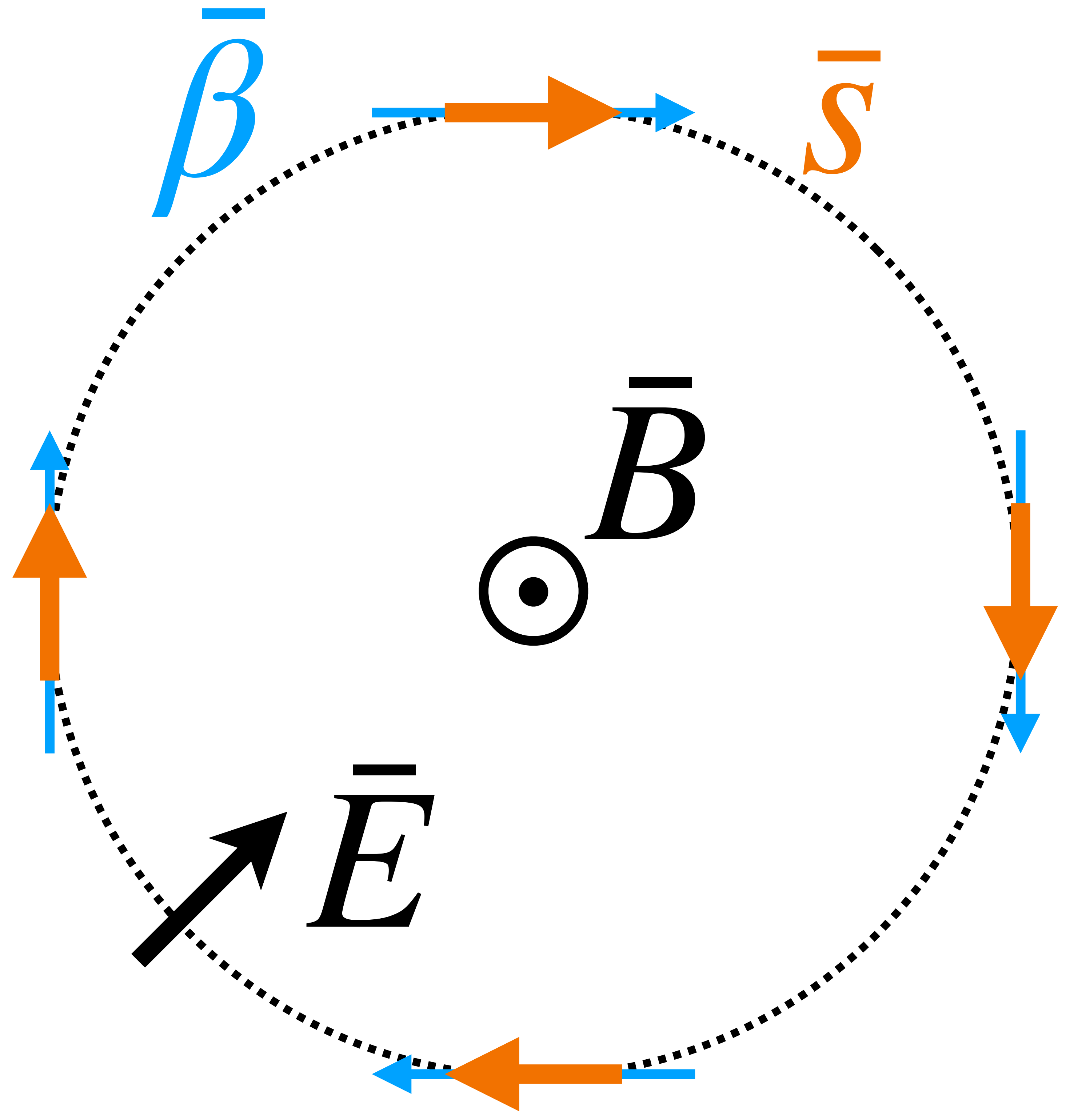
$$\sigma(d_\mu) = \frac{a\hbar\gamma}{2P_0E_f\sqrt{N}\tau_\mu A} \sim 6\times 10^{-23} e\,.\,\mathrm{cm}$$

(with $N = 200$ days)

Frozen Spin Technique

Goal: Configure E, B fields such that spin follows velocity vector and EDM is the only inherent source of spin precession.

$$\frac{d\bar{\beta}}{dt} = \bar{\Omega}_c \times \bar{\beta} \qquad \frac{d\bar{s}}{dt} = \bar{\Omega}_0 \times \bar{s}$$



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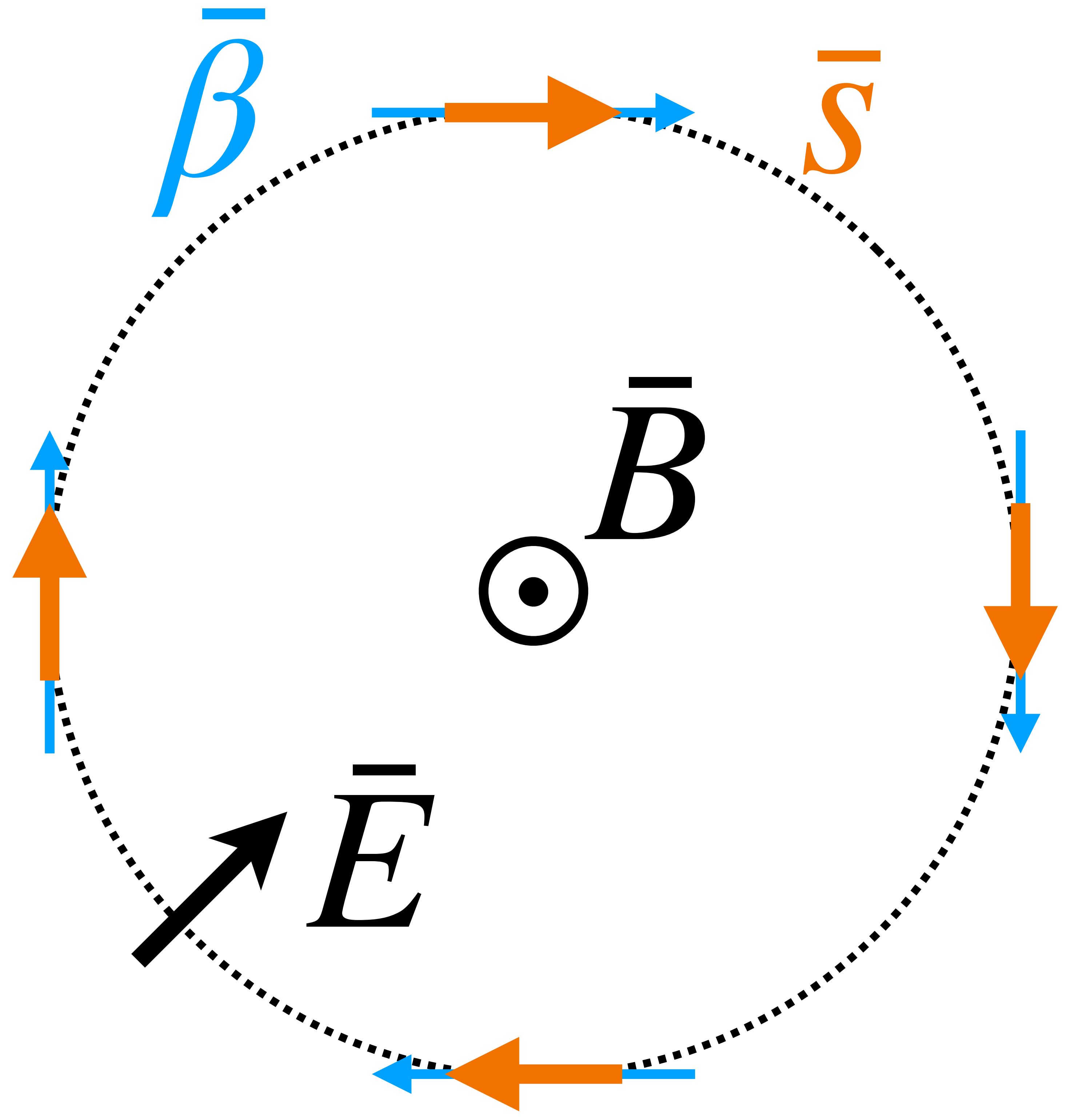
$$\bar{\Omega} = \bar{\Omega}_0 - \bar{\Omega}_c = \frac{aq}{m}\left(\bar{B} - \frac{\gamma}{\gamma+1}(\bar{\beta}\cdot\bar{B})\bar{\beta} - \left(1 + \frac{1}{a(1-\gamma^2)}\right)\frac{\bar{\beta}\times\bar{E}}{c}\right) + \frac{\eta q}{2m}\left(\bar{\beta}\times\bar{B} + \frac{\bar{E}}{c} - \frac{\gamma/c}{\gamma+1}(\bar{\beta}\cdot\bar{E})\bar{\beta}\right)$$



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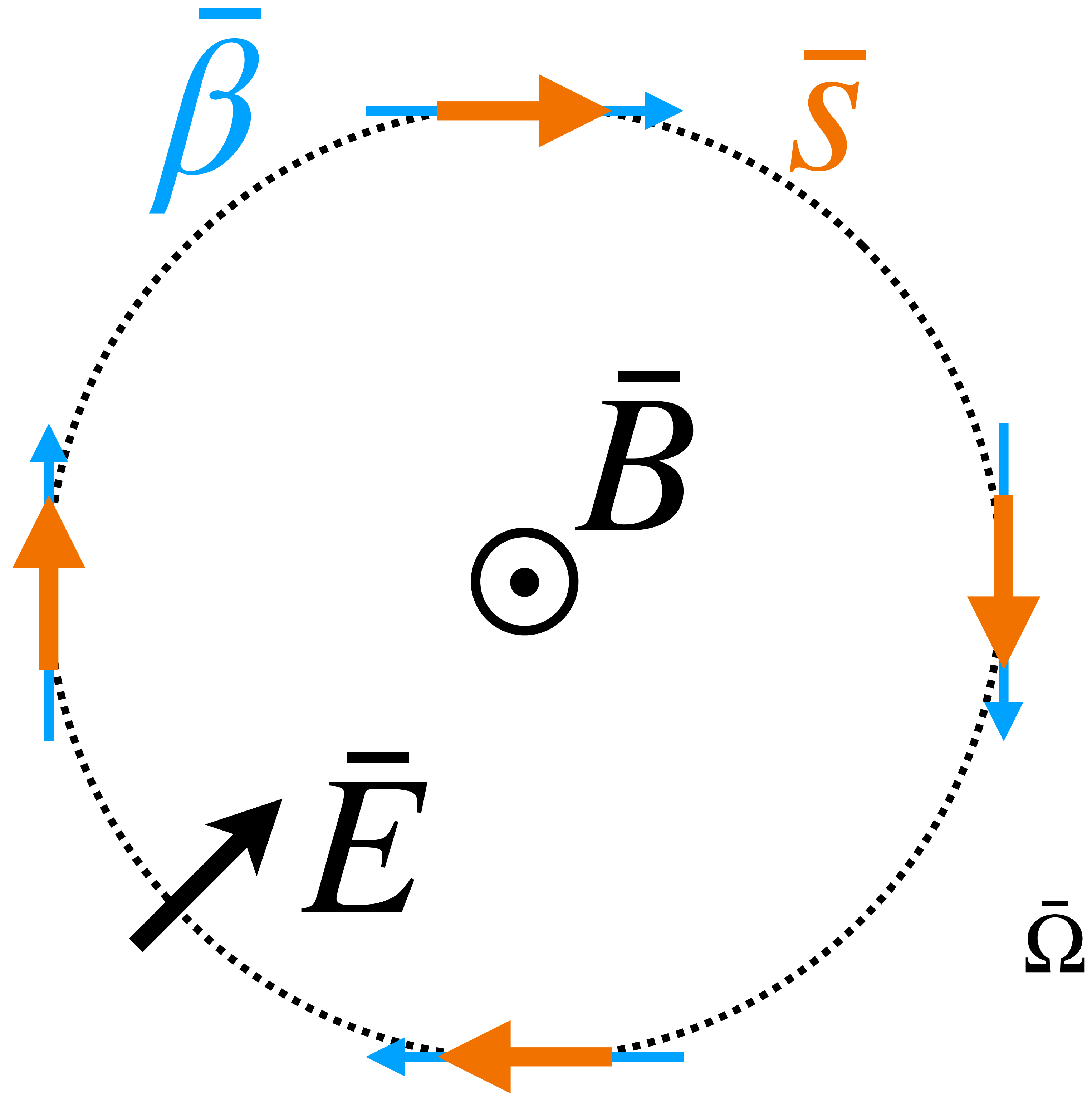
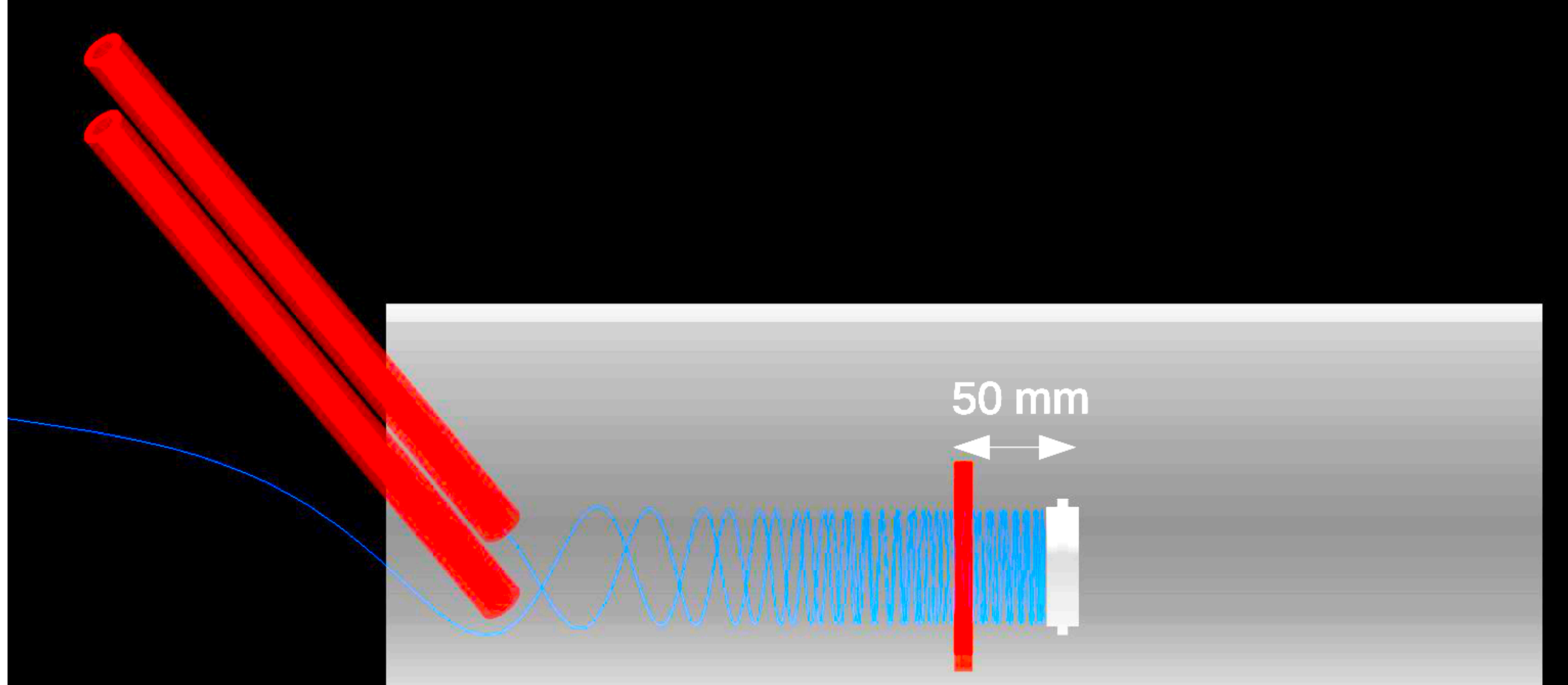


$$\text{Frozen Spin Condition}: \; E_f \overset{a<<1}{\approx} aB\beta c\gamma^2$$

$$\bar{\Omega} = \frac{\eta q}{2m}\left(\bar{\beta}\times\bar{B} - \frac{\bar{E}}{c}\right) \quad \text{for} \quad |\bar{E}| = E_f \; , \quad \bar{\beta}\cdot\bar{E} = \bar{\beta}\cdot\bar{B} = \bar{E}\cdot\bar{B} = 0$$

Magnetic Kick Specifications

- **Objective:** achieve stable circular orbit by kicking longitudinal momentum into the transverse plane when muon enters weakly focusing storage region.
- **Challenge:** the muon transit time to the storage region is ~100ns after a trigger is generated at the entrance detector.
- **Technical Problem:** High amplitude, short duration pulsed magnetic field must be rapidly triggered, with strong tail suppression.



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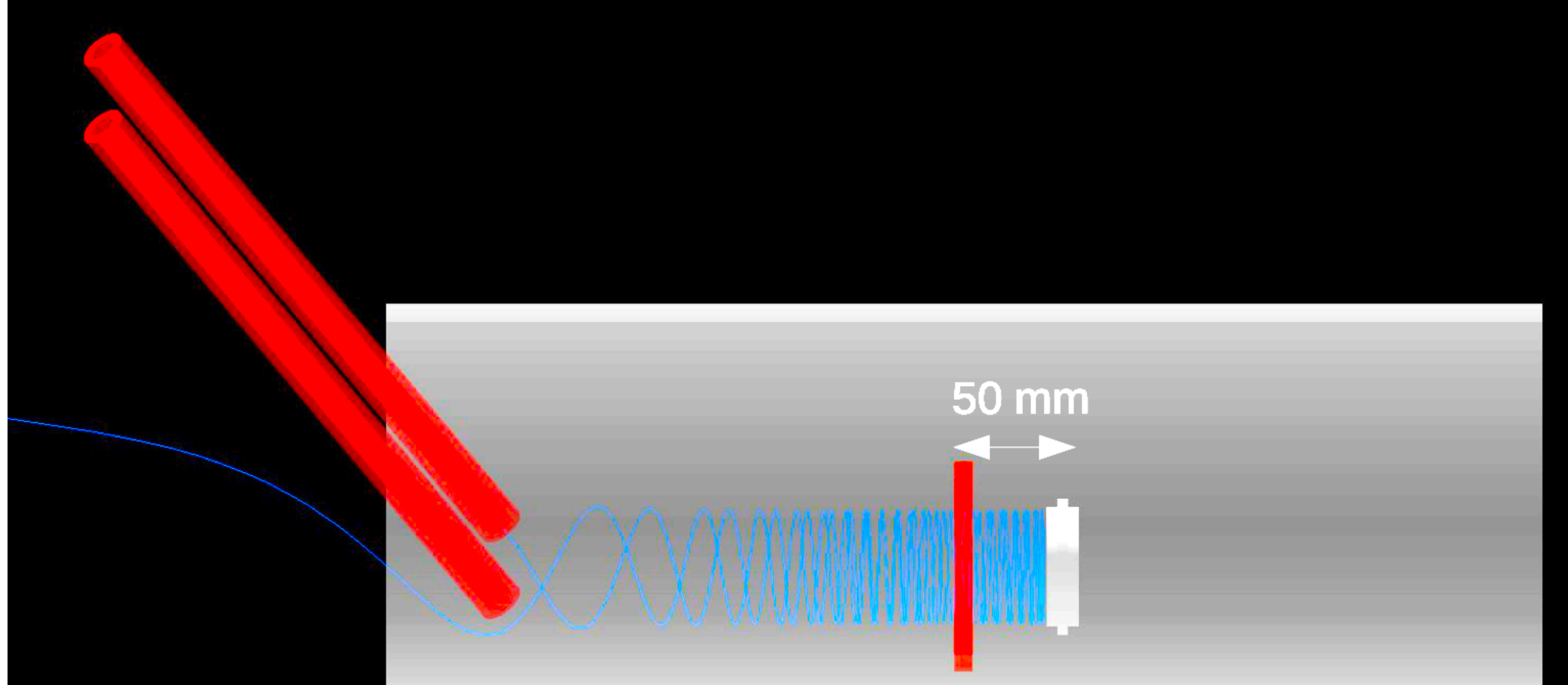

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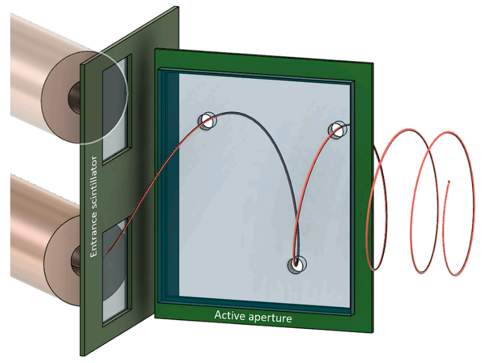
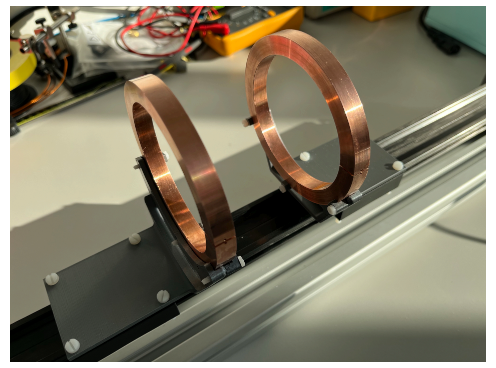


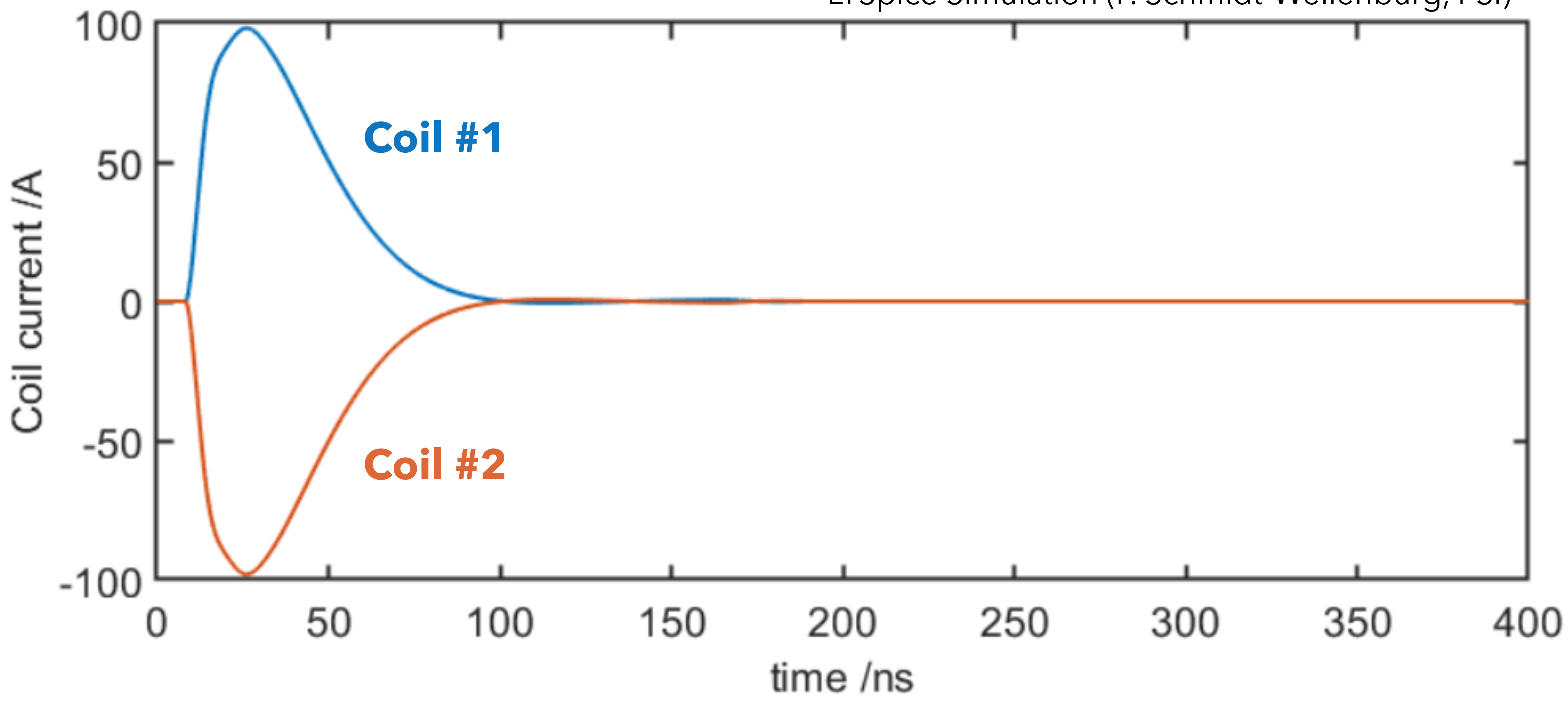
Assuming time of 100ns for PSC magnet, the delays in the lines constrain the HV switching of the pulse generator to be <60ns.



Current Pulse Specifications

- Delay between trigger input and pulse output $\Delta t_d < 60\,\mathrm{ns}$
- Pulse FWHM $\sim 40\,\mathrm{ns}$
- Peak current $\sim 170\,\mathrm{A}$
- Eddy current damping by electrodes, need safety factor in peak current of at least a factor ~1.5
- Suppression of current oscillations in tail to $< 1A$ (corresponding to radial magnetic field $< 5\,\mu\mathrm{T}$)

LTSpice Simulation (P. Schmidt-Wellenburg, PSI)



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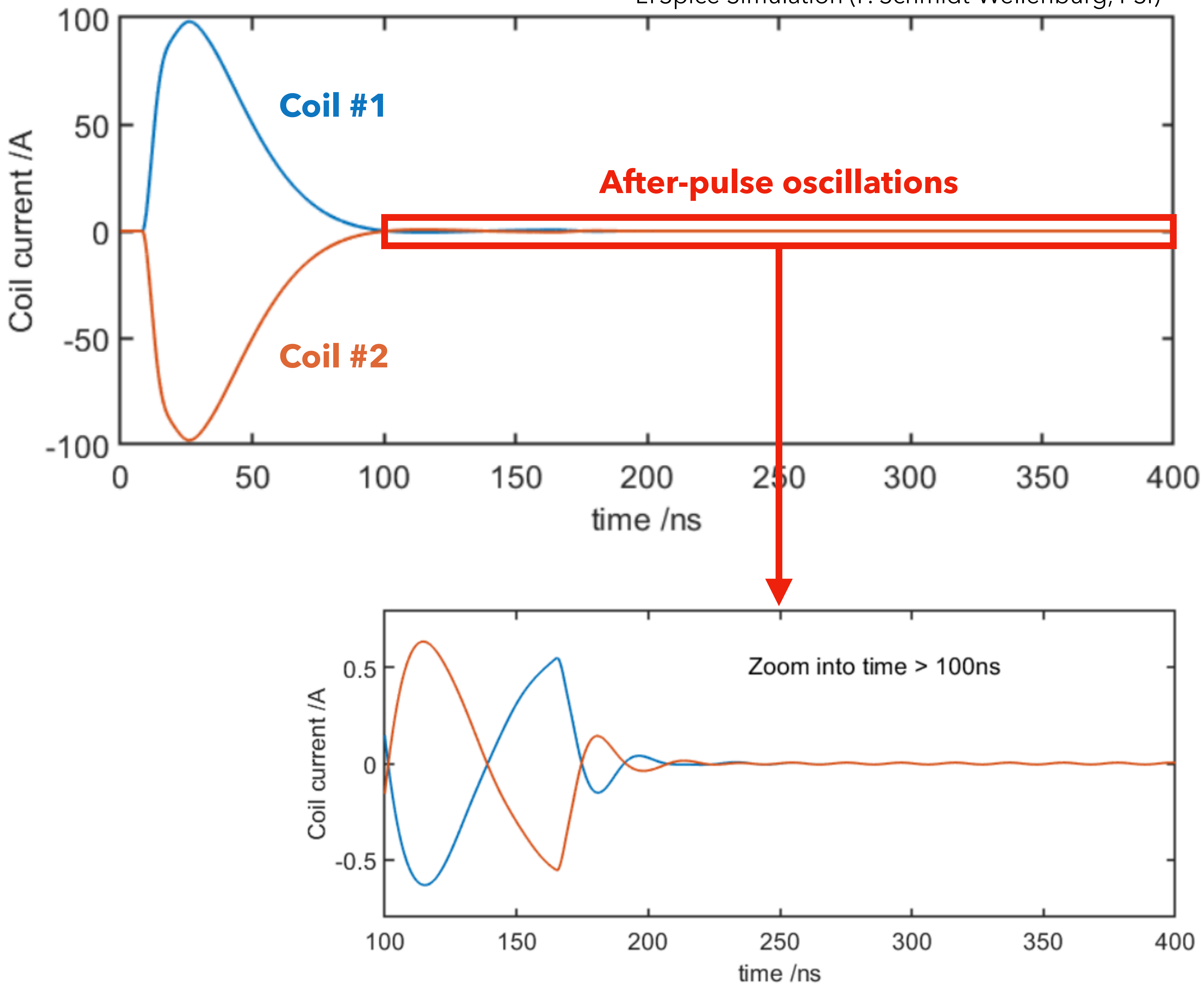

Pulse Coils

- Need low inductance to drive high-frequency, high-current pulse and minimise residual oscillations.
- Self inductance of each coil:
  - Measured: $L = 121 \pm 1\,\mathrm{nH}$
  - Wire Loop Approximation: $L = 129\,\mathrm{nH}$
  - Ansys FEM: $L = 139\,\mathrm{nH}$
- Optimisation of coil geometry to be informed by simulation studies of muon injection.

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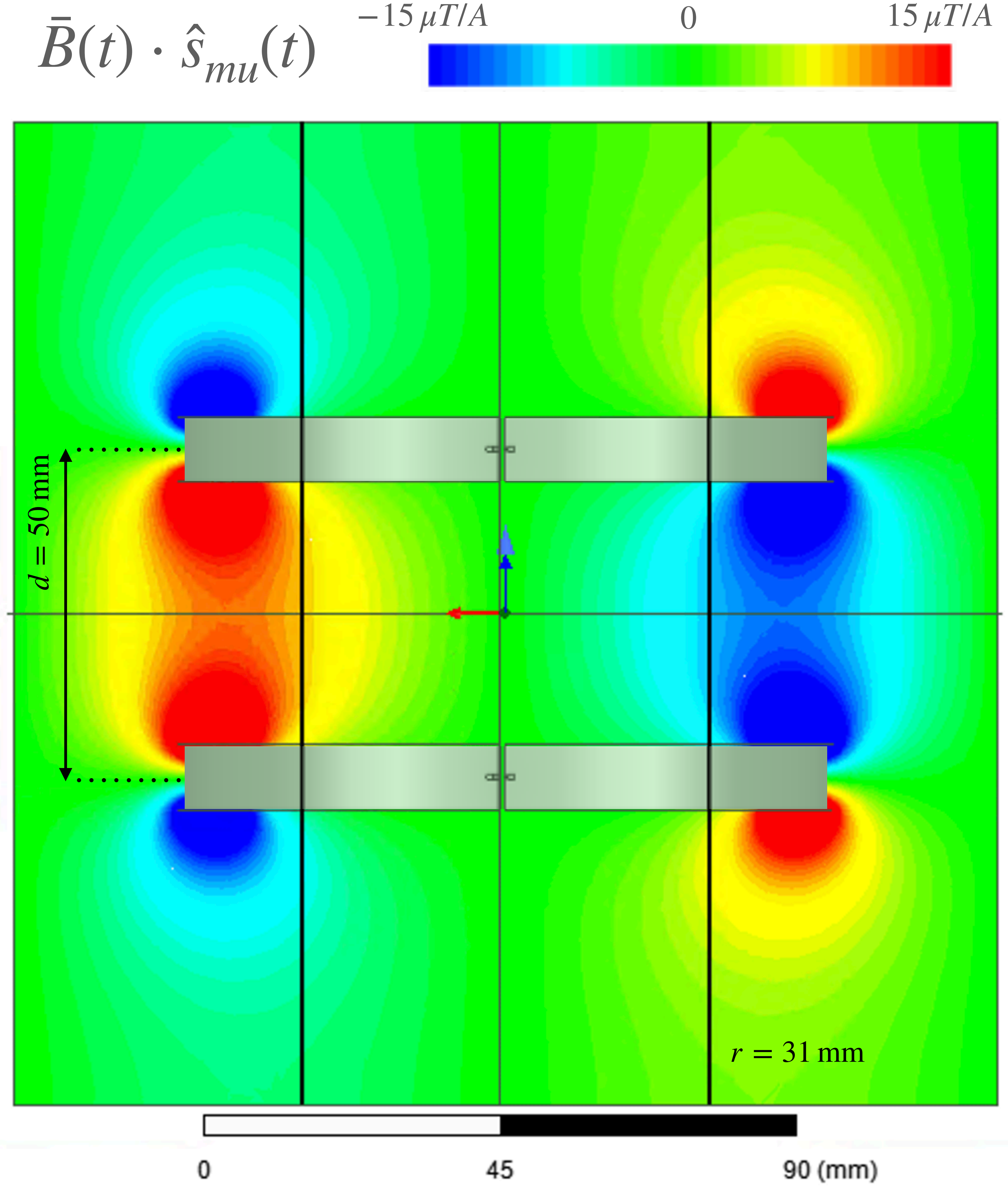

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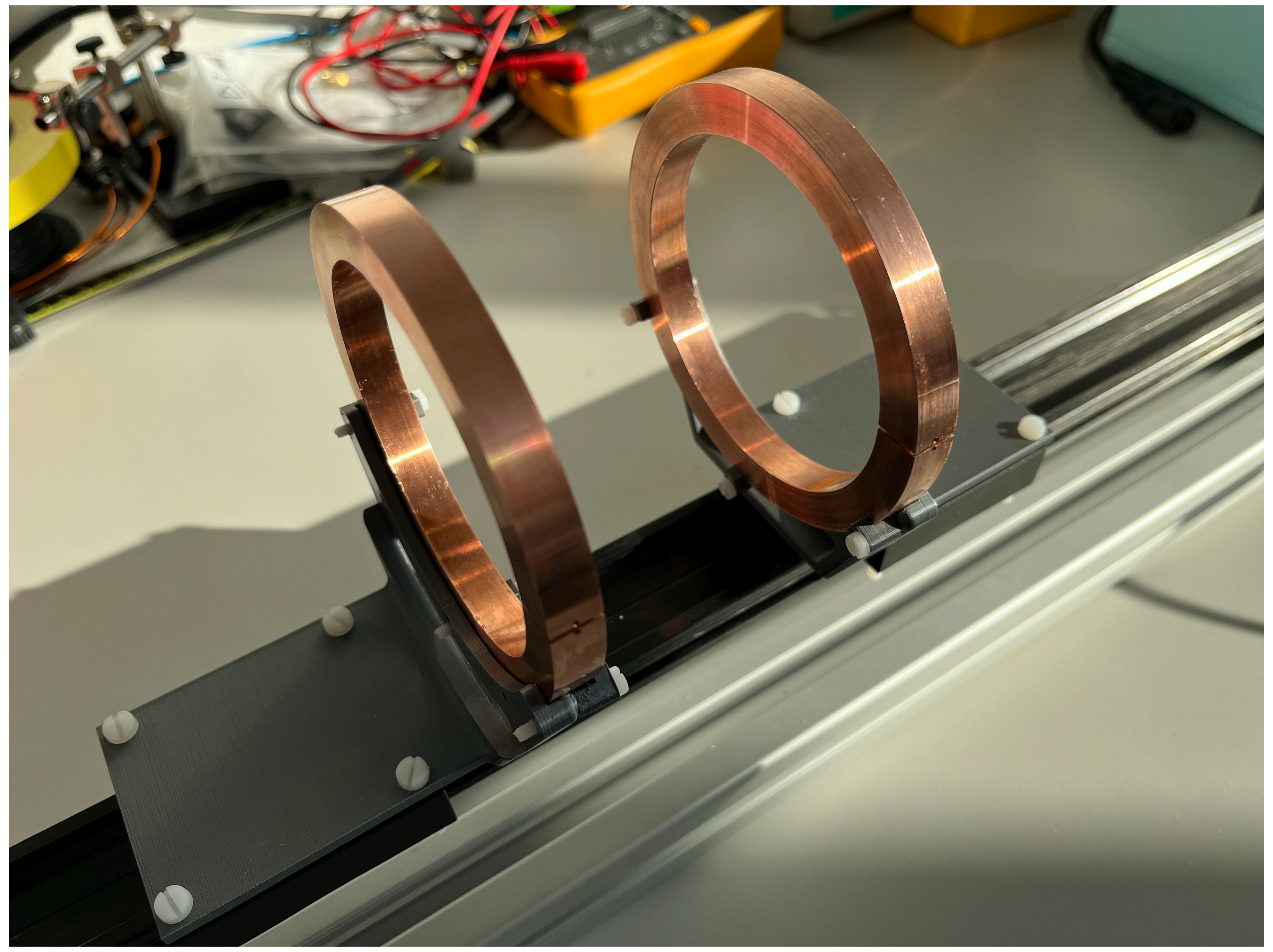

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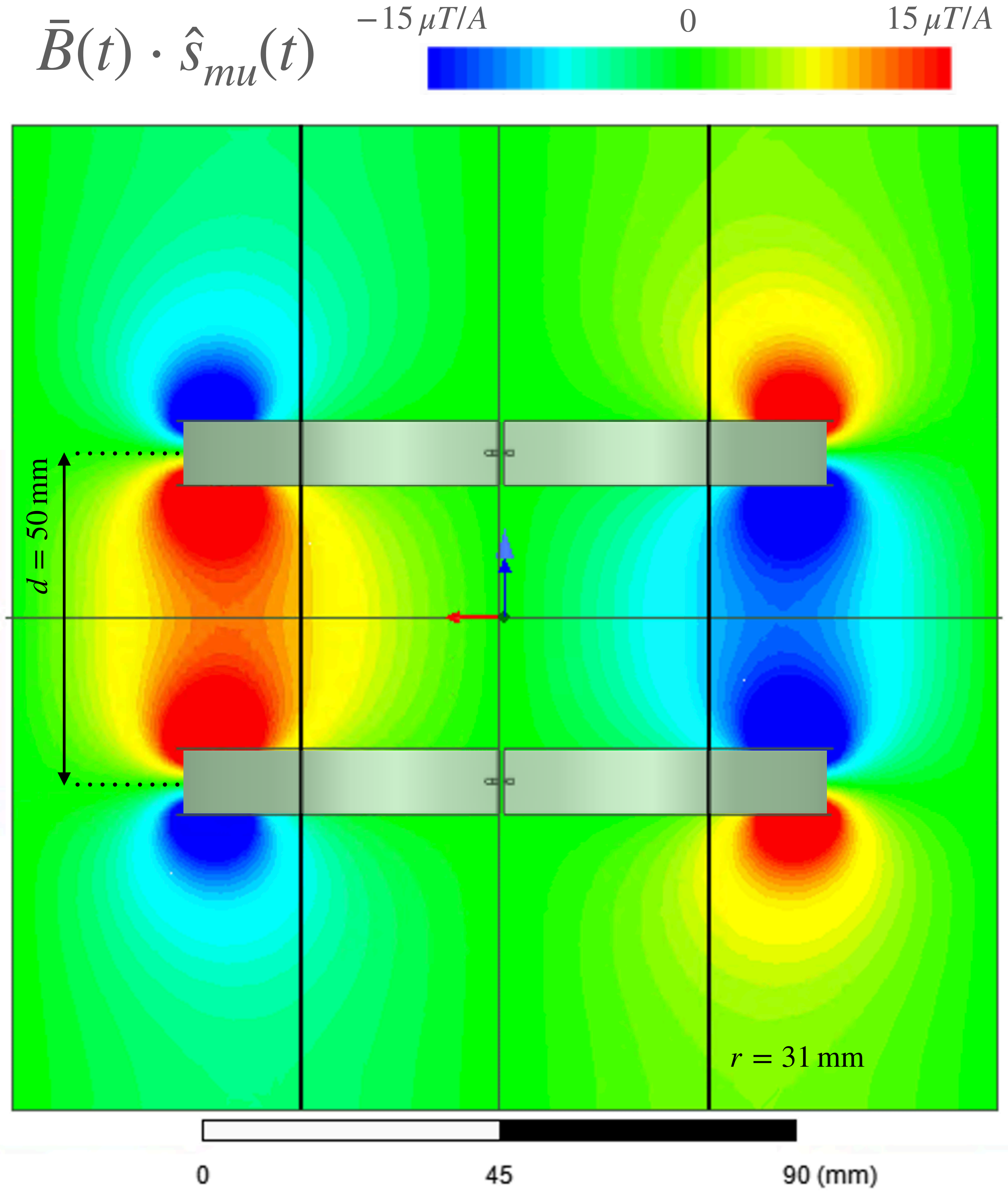

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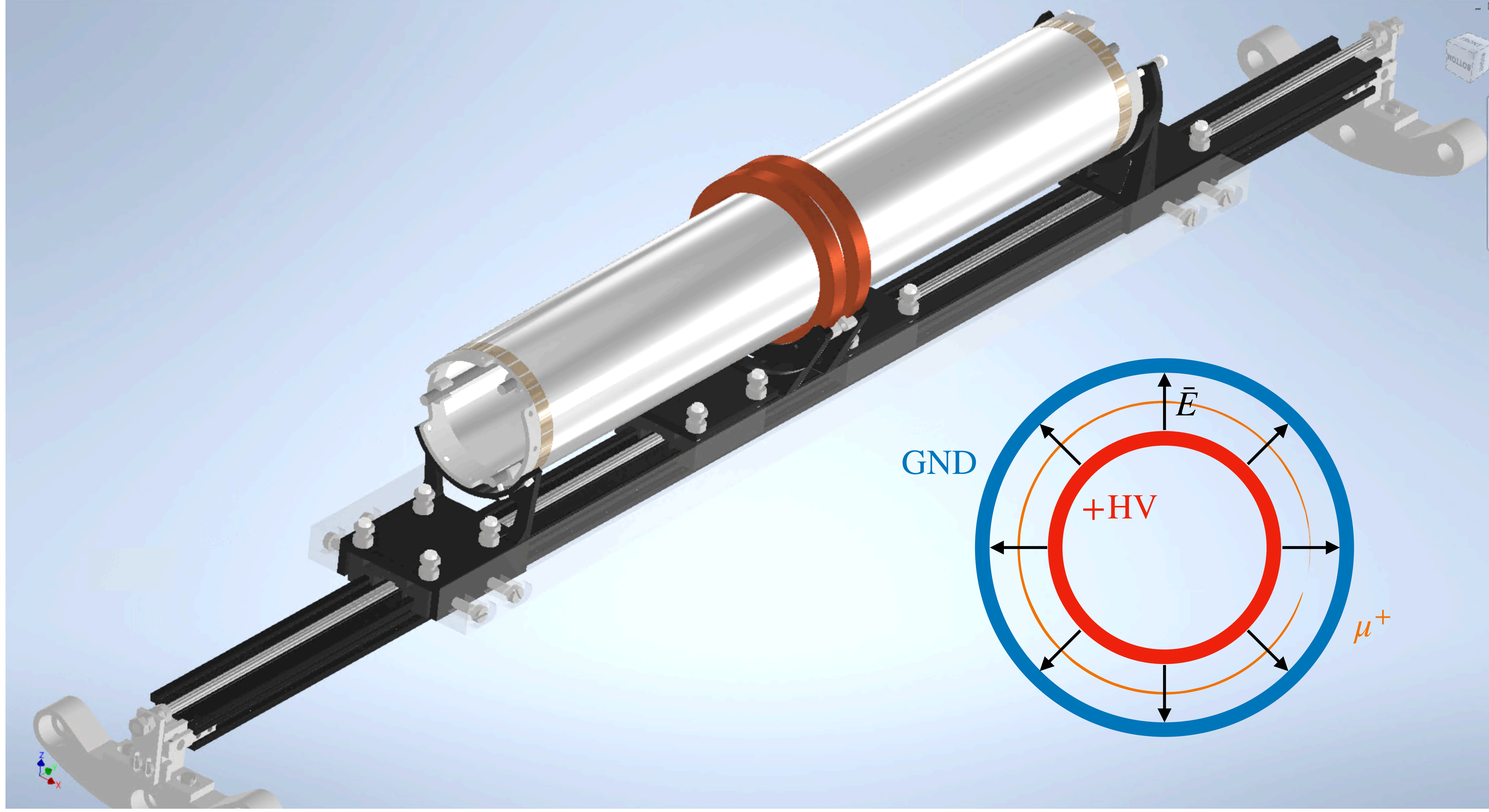
Thin Foil Electrodes

Requirements

- Precise alignment (systematic effects)
  - *Material robust as thin foil*
- Eddy currents
  - *Low electrical conductivity*
  - *Weak thermal expansion*
  - *High thermal conductivity*
- Material budget
  - *Weak multiple scattering of positrons*



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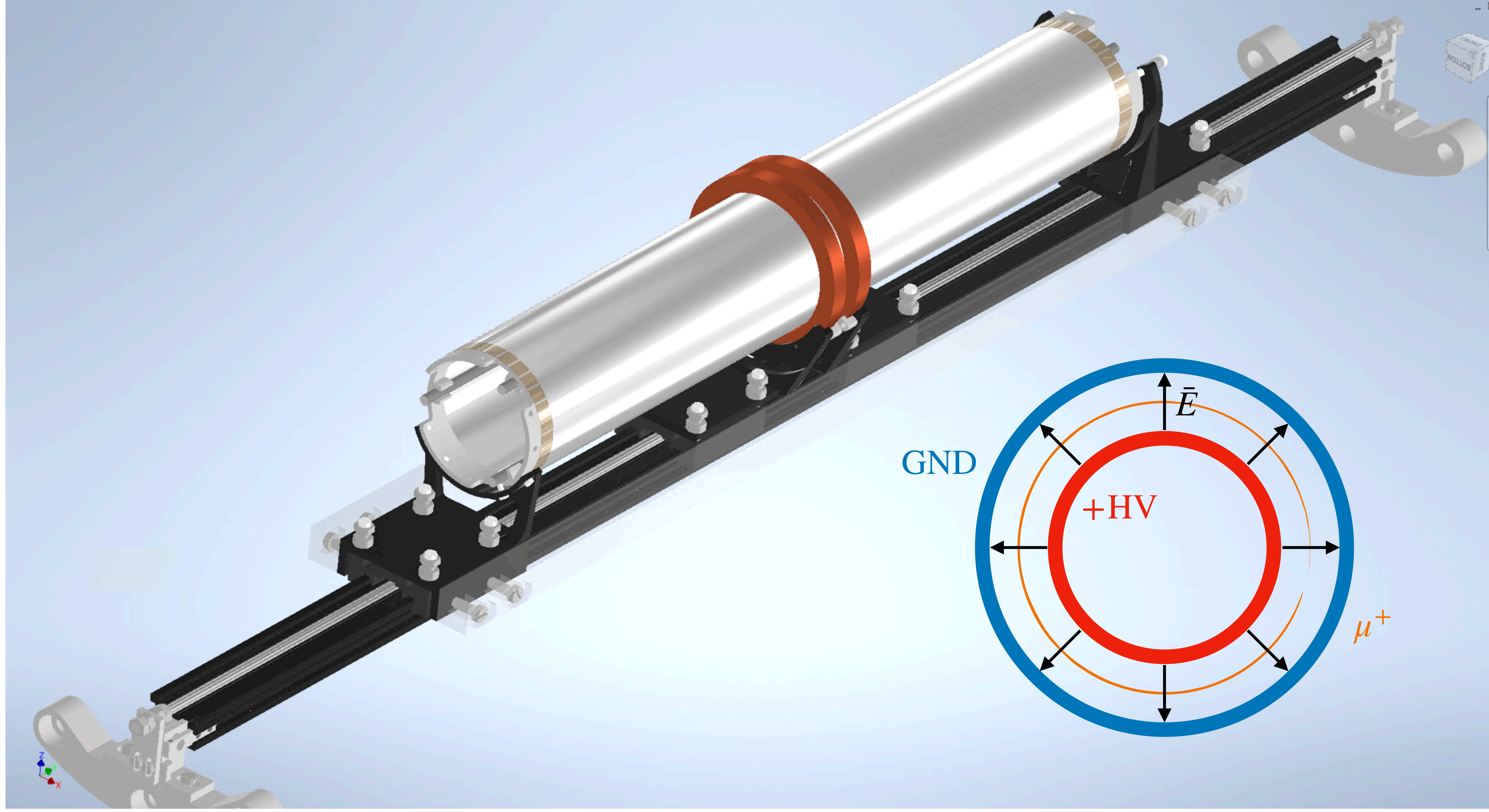

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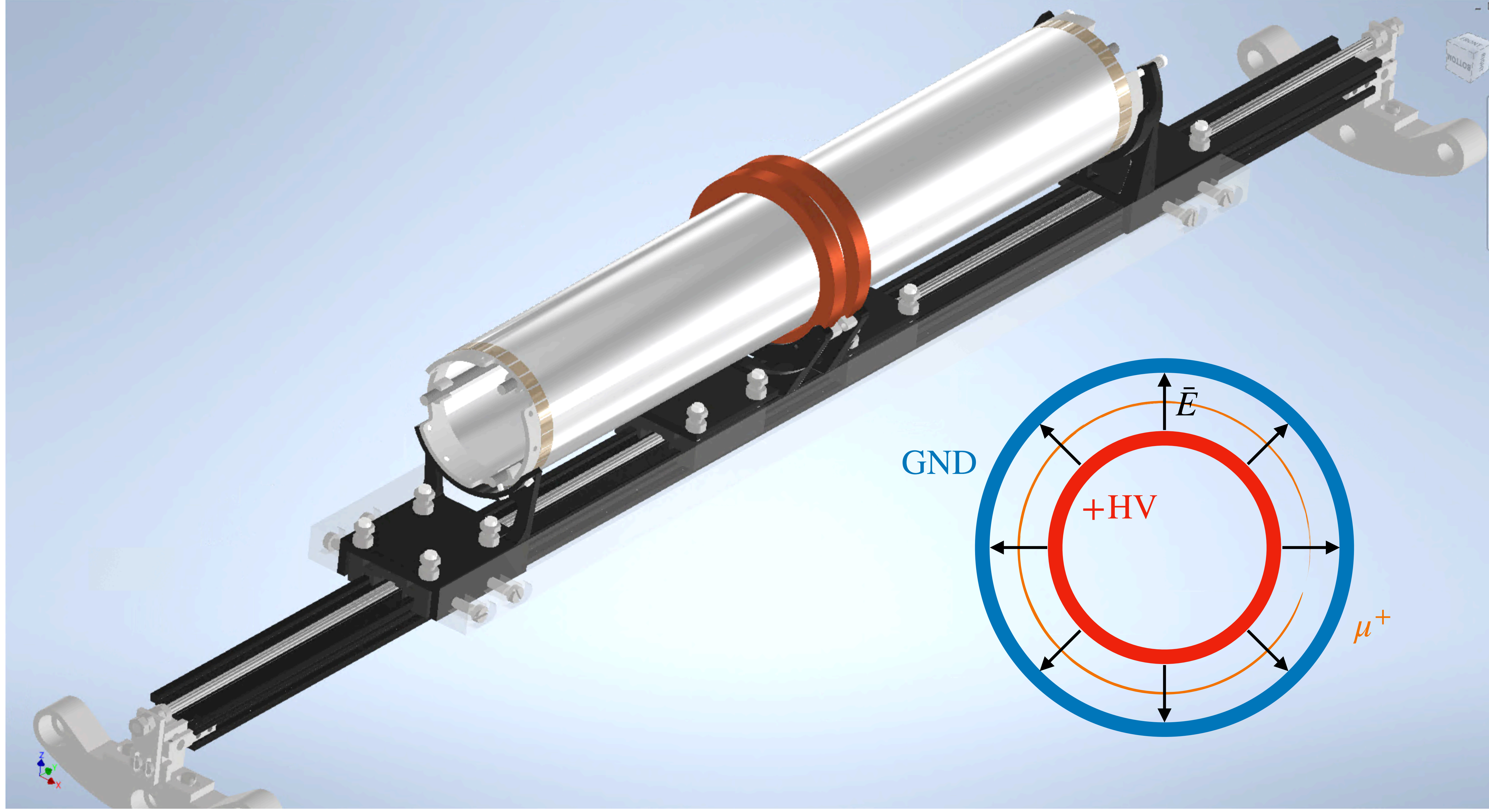
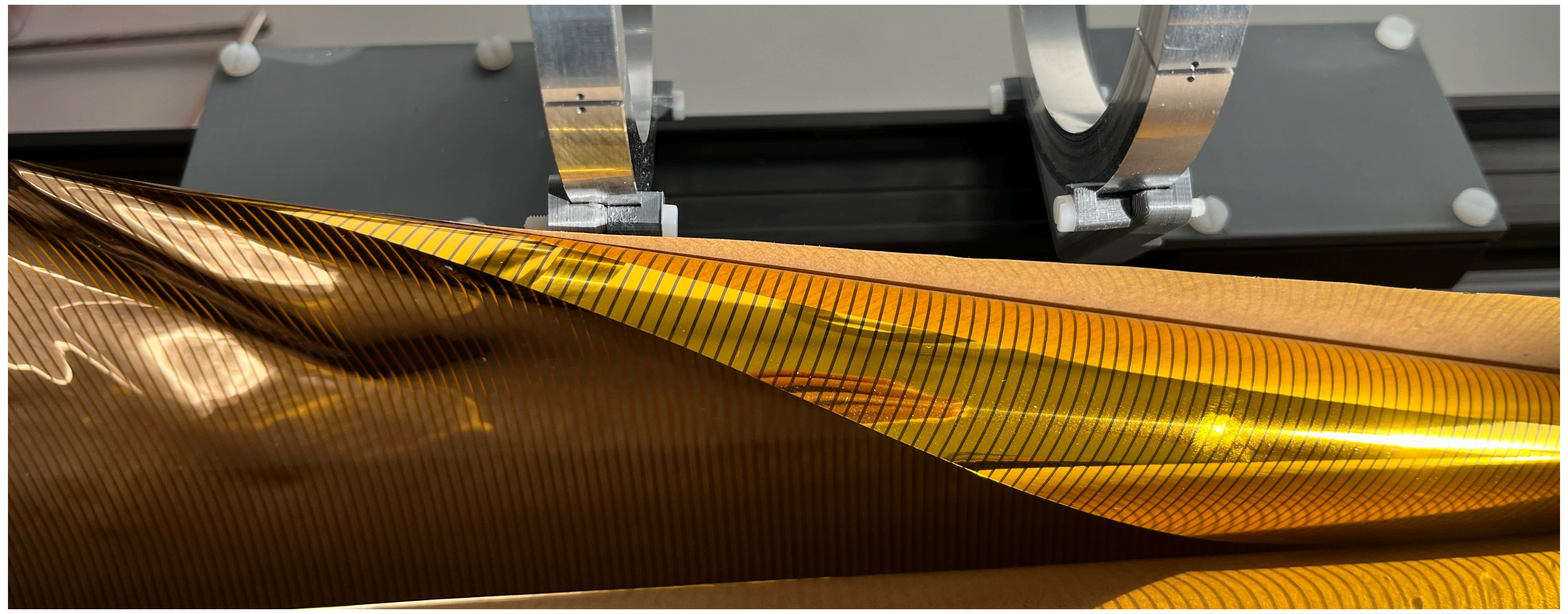
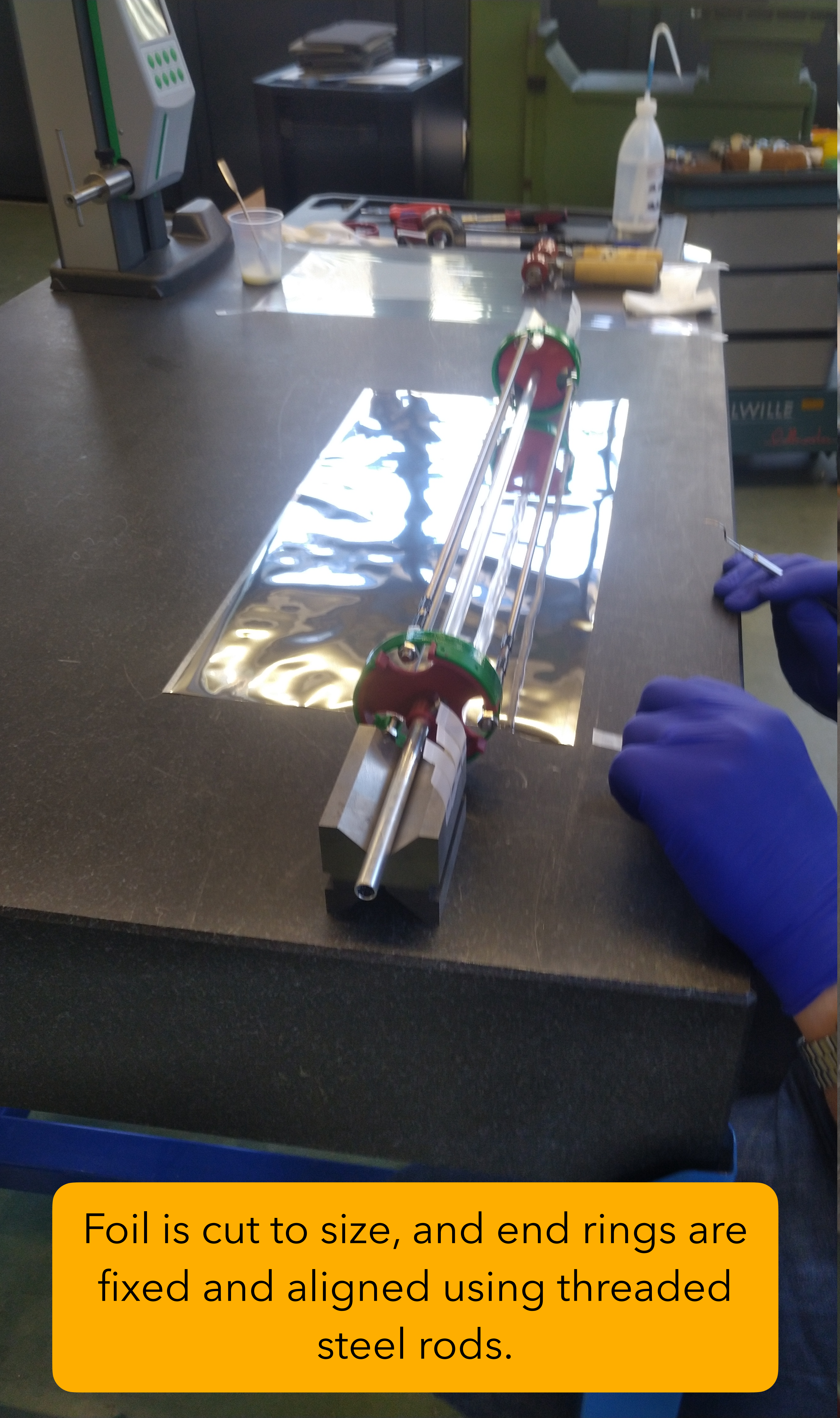
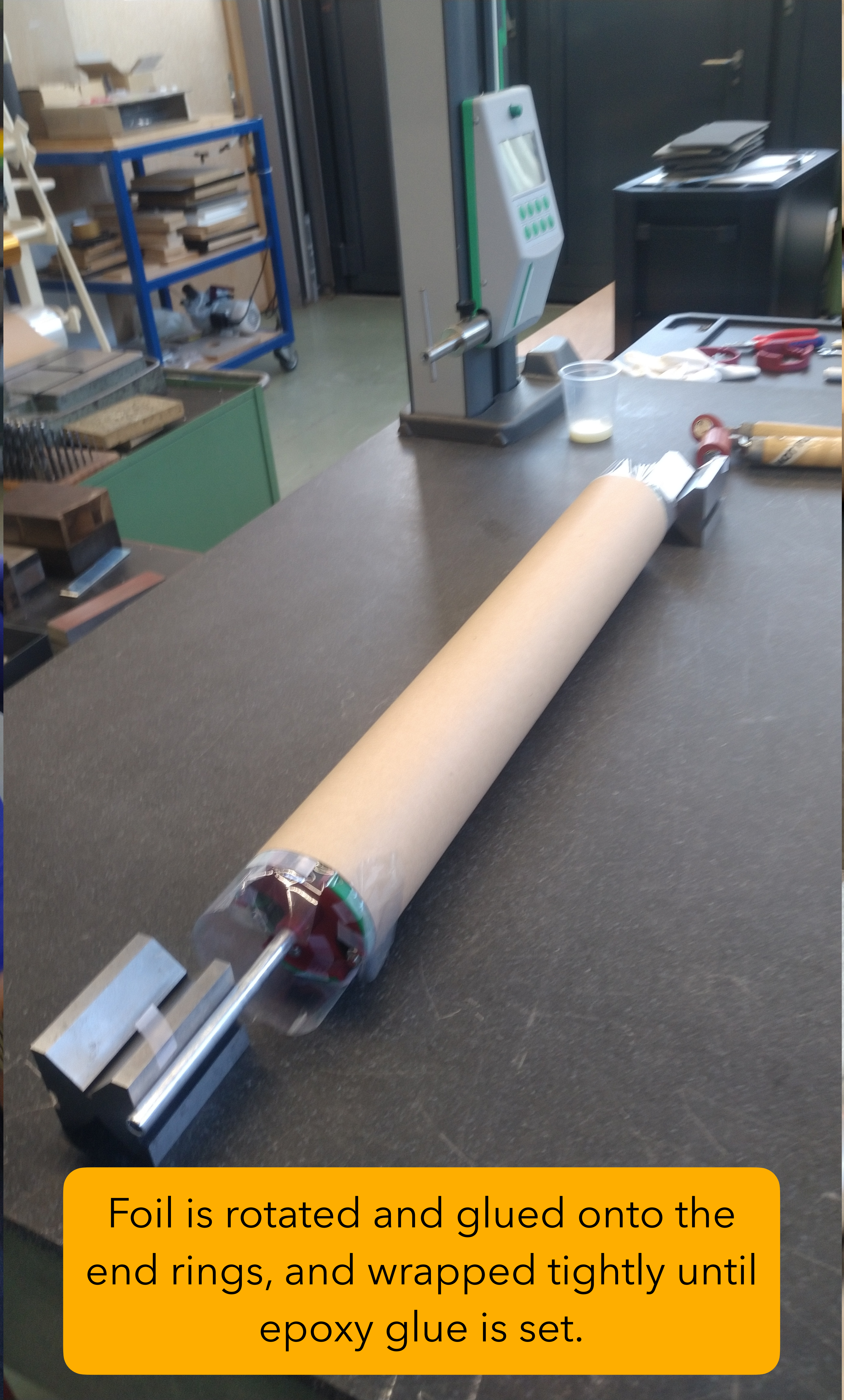




New prototypes under development using aluminised Kapton with 2mm stripes (2.2mm pitch) to suppress radial eddy currents.

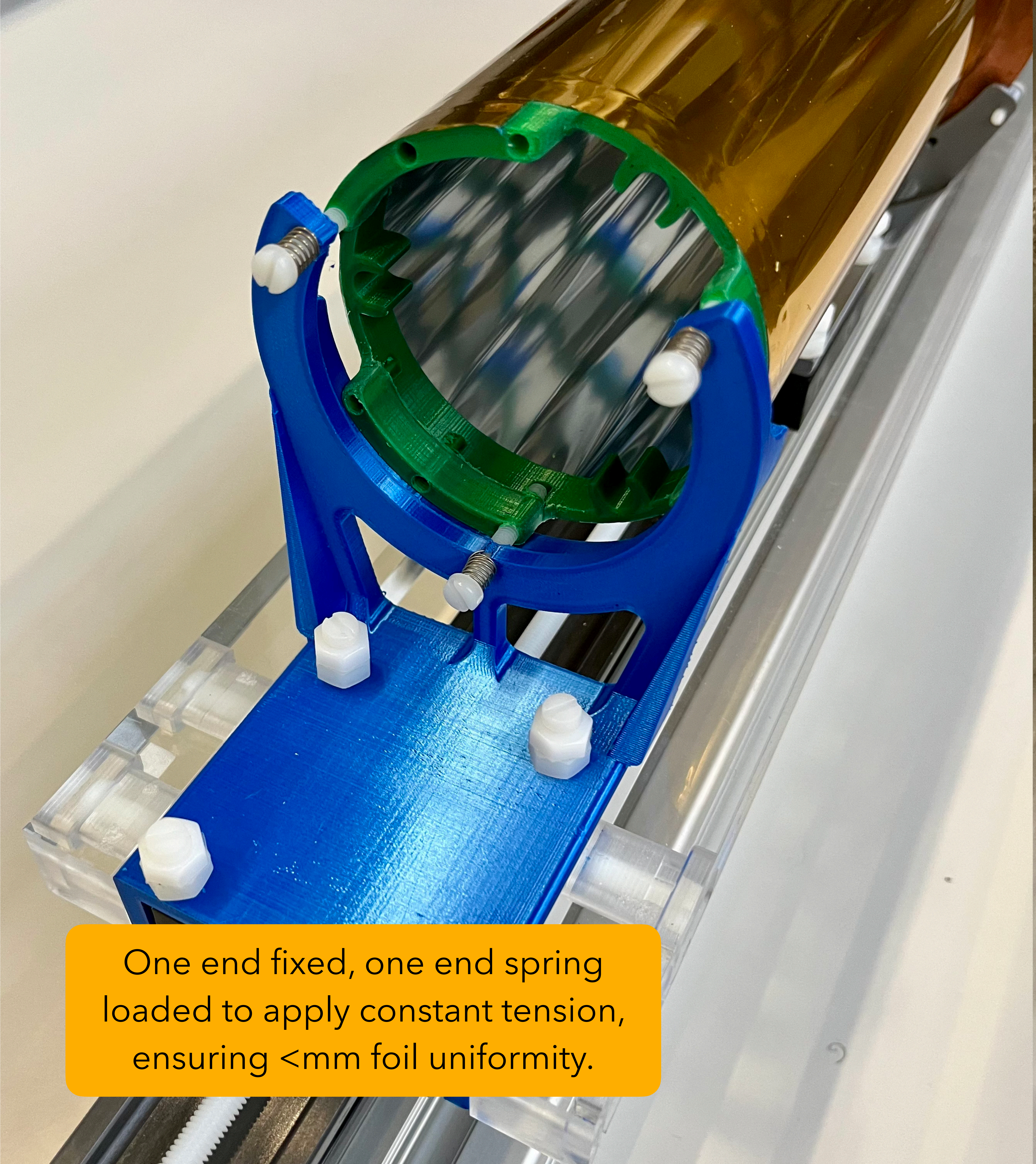


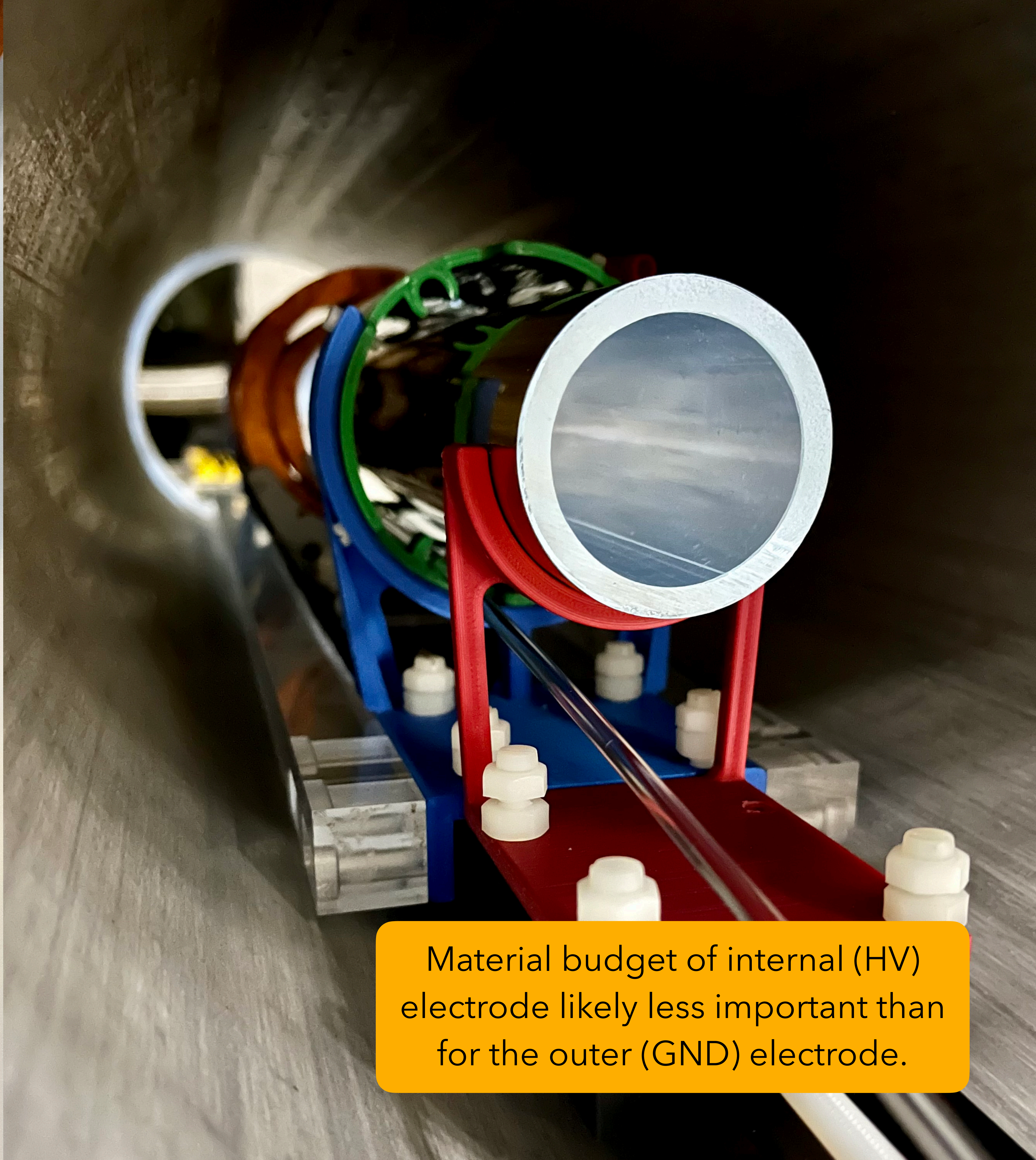
Foil is cut to size, and end rings are fixed and aligned using threaded steel rods.



Foil is rotated and glued onto the end rings, and wrapped tightly until epoxy glue is set.

Structurally fixed cylinder, ready to mount onto electrode supports.


One end fixed, one end spring
loaded to apply constant tension,
ensuring <mm foil uniformity.

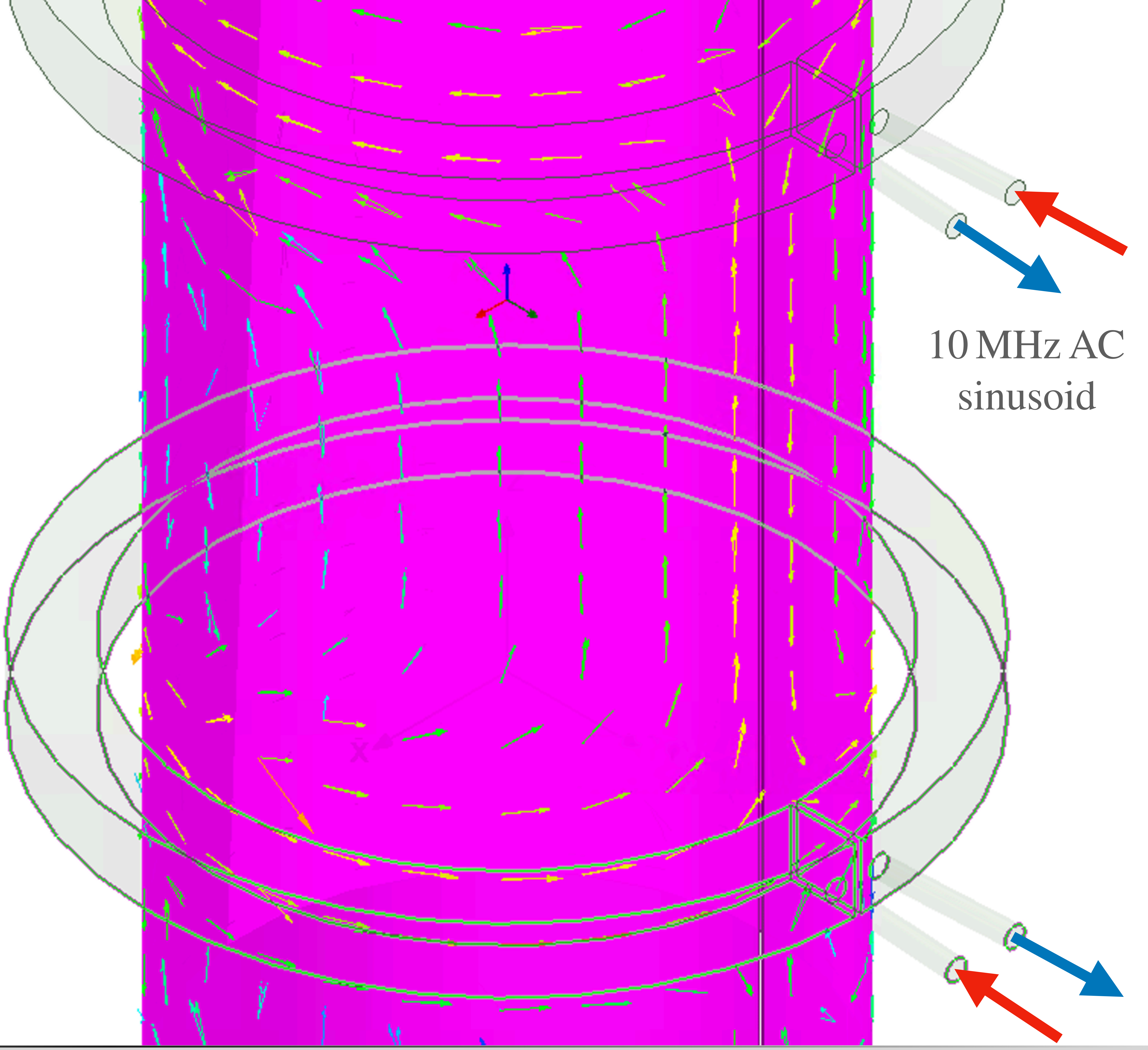

Material budget of internal (HV)
electrode likely less important than
for the outer (GND) electrode.

Eddy Currents & Magnetic Field Damping

- $\sim 10\,\text{MHz}$ primary frequency component
- Skin depth in aluminium:

$$\delta = \sqrt{\frac{2}{\omega\sigma\mu}} \quad , \quad \delta_{Alu}(\omega = 10\,\text{MHz}) = 65\mu\text{m}$$

- By Lenz's Law, eddy currents are induced such that they oppose the change in the original magnetic field.
- The magnetic field seen by the muon will be suppressed.



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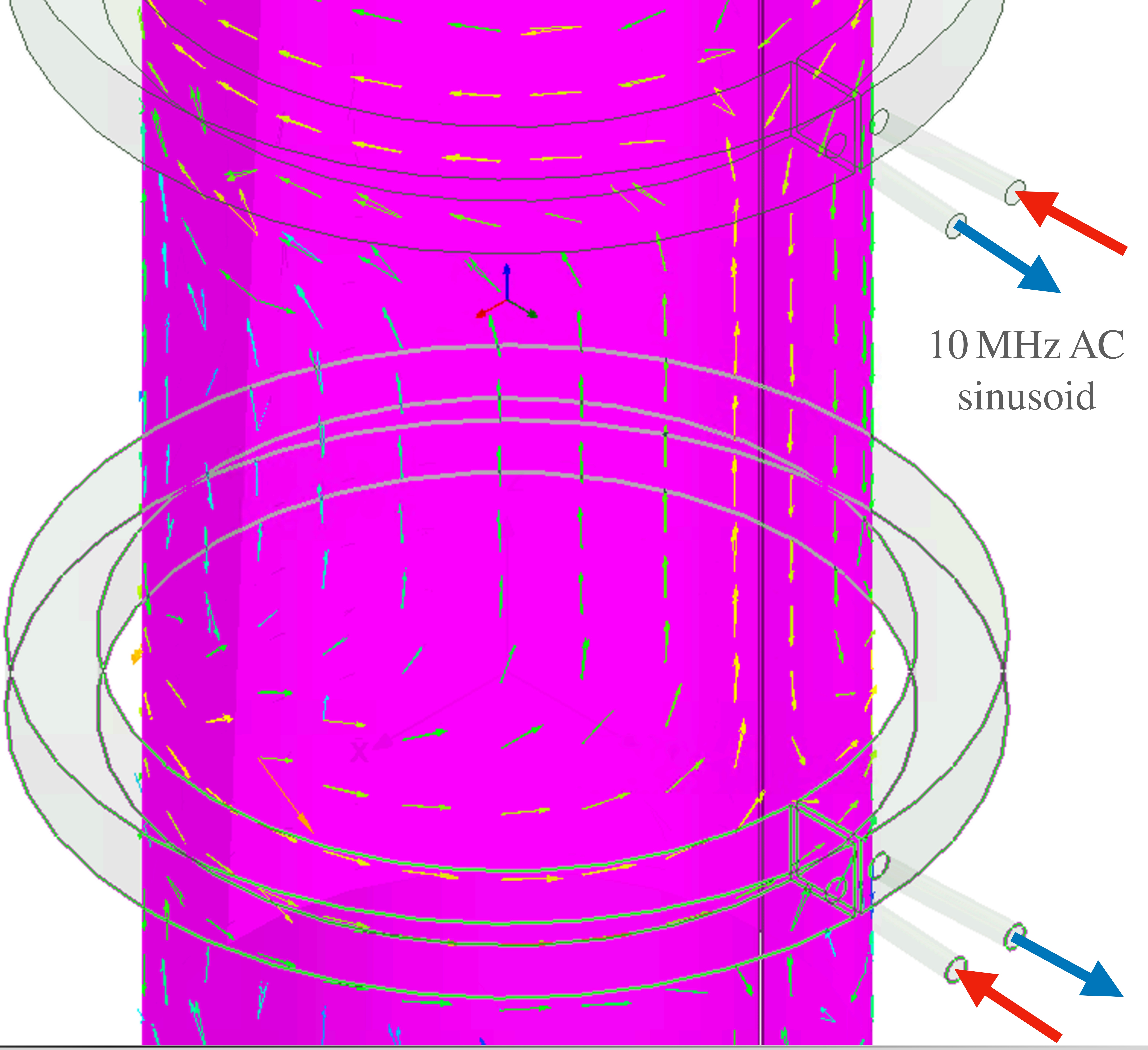
- To achieve the field strength necessary to trap the muons in the storage region, we must:
  - Increase current
  - Optimise electrode geometry & material



Radial Magnetic Field Measurements

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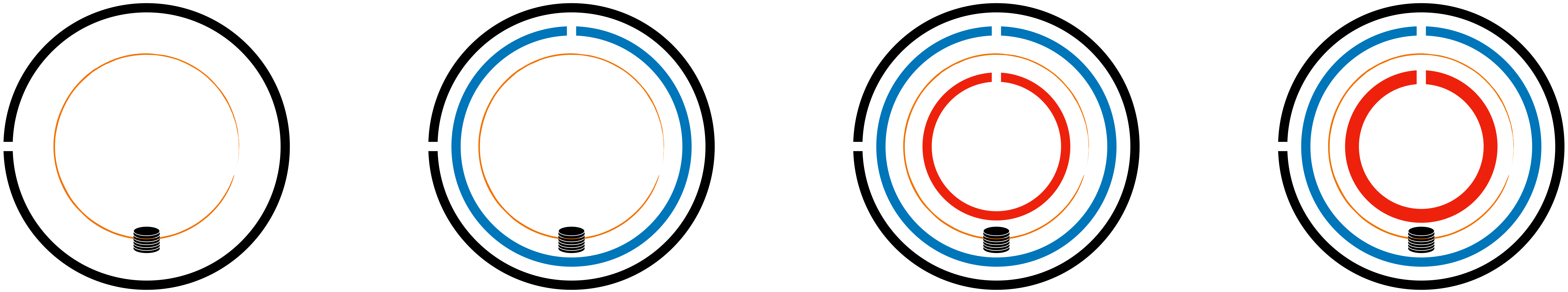
- Different components added to observe effect, due to induction of eddy currents.



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Field Reference B_{coil}

Damping Factor, $D = \dfrac{B}{B_{\mathrm{coil}}}$

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$D = 0.54 \pm 0.04$

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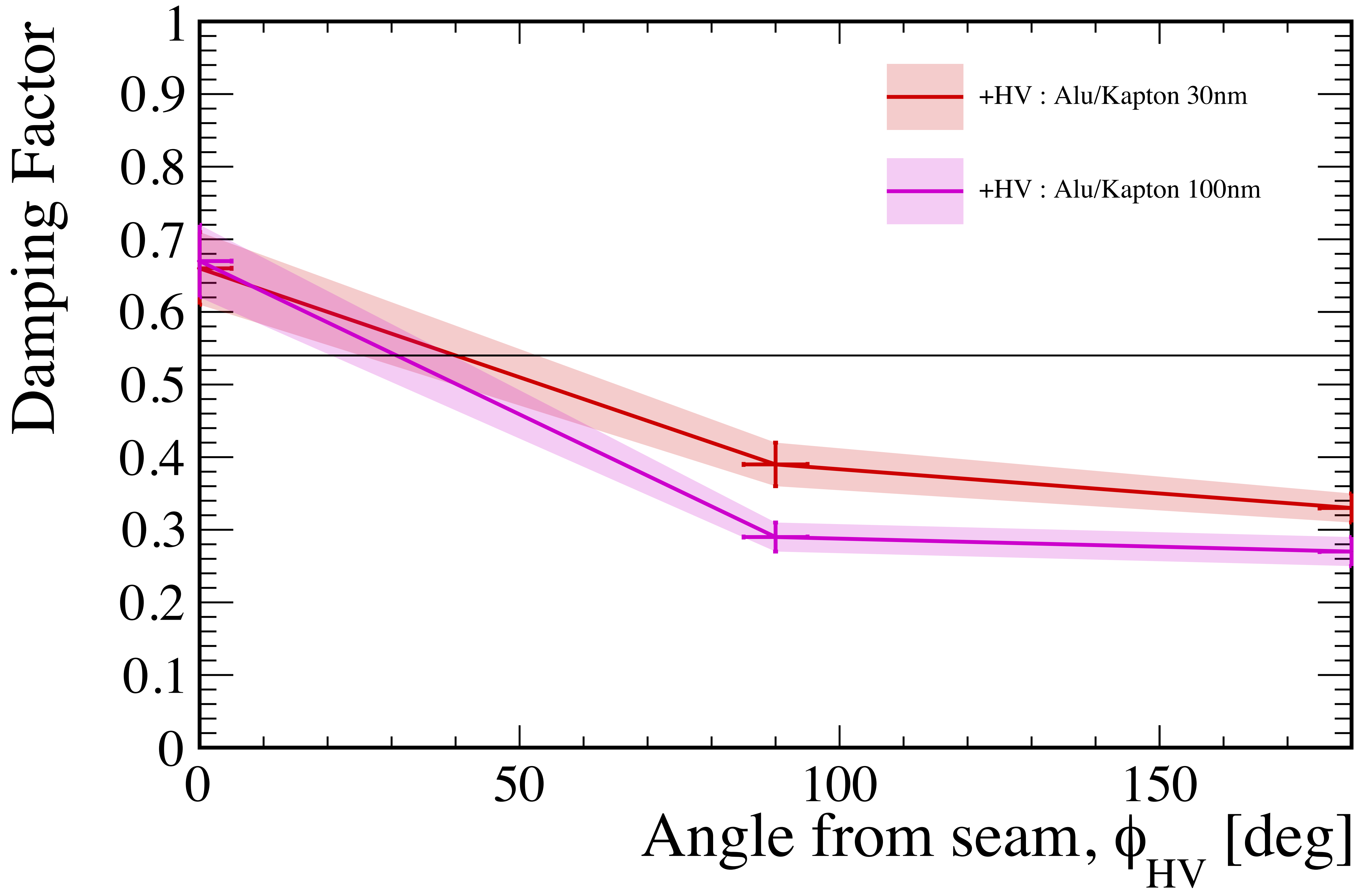

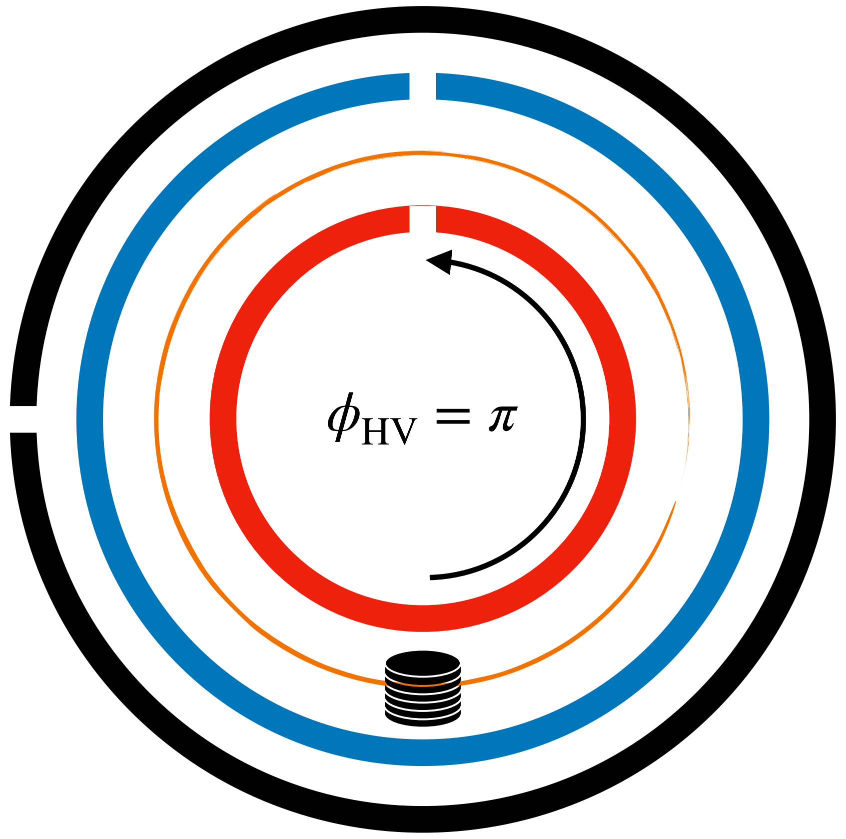

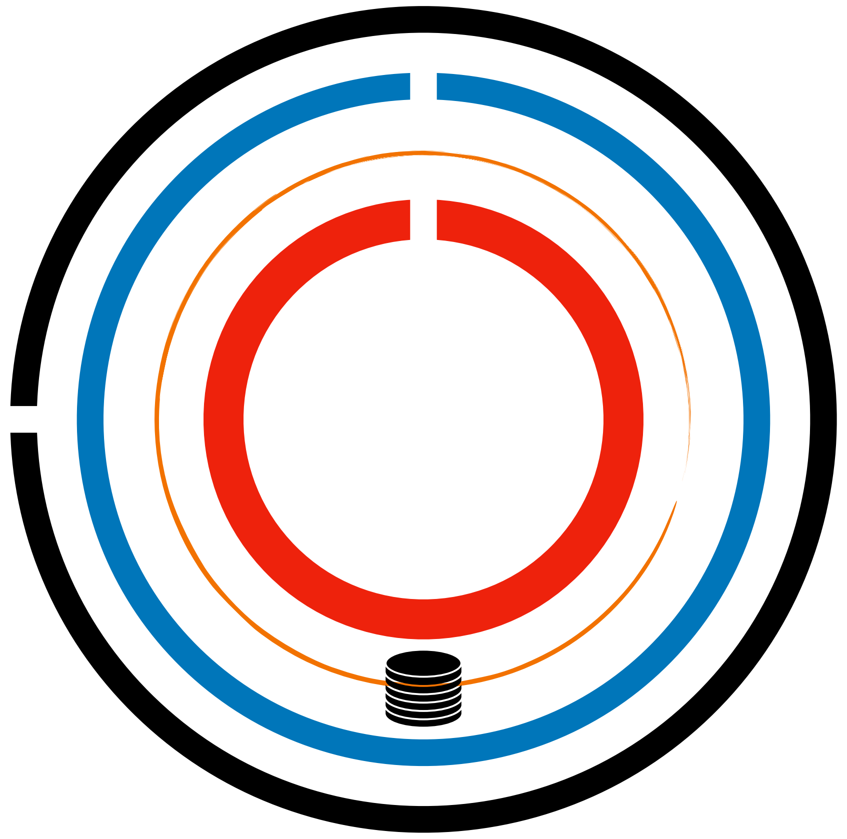

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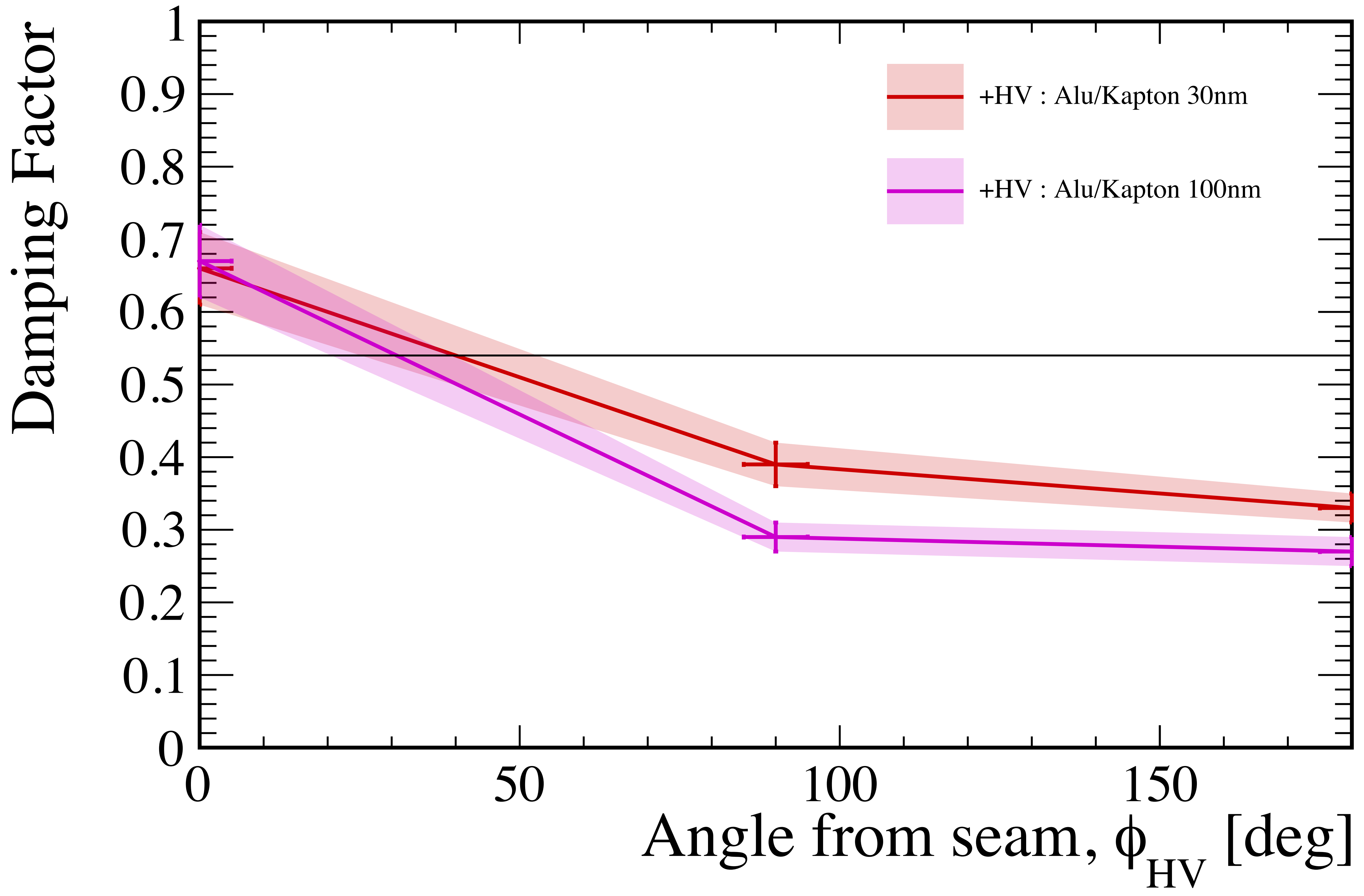

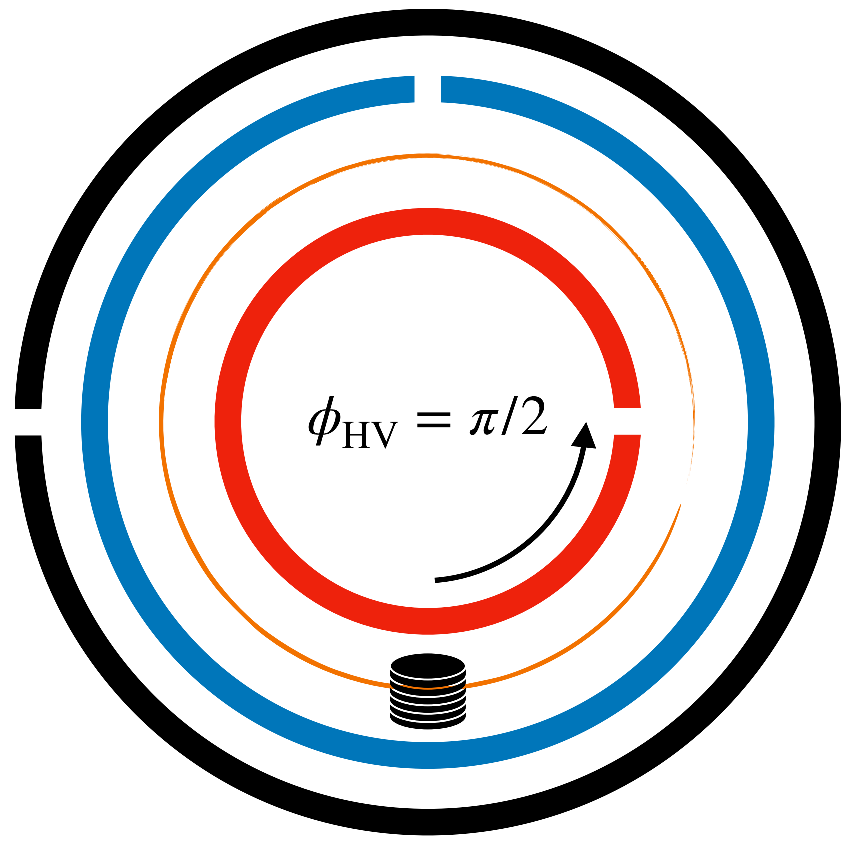

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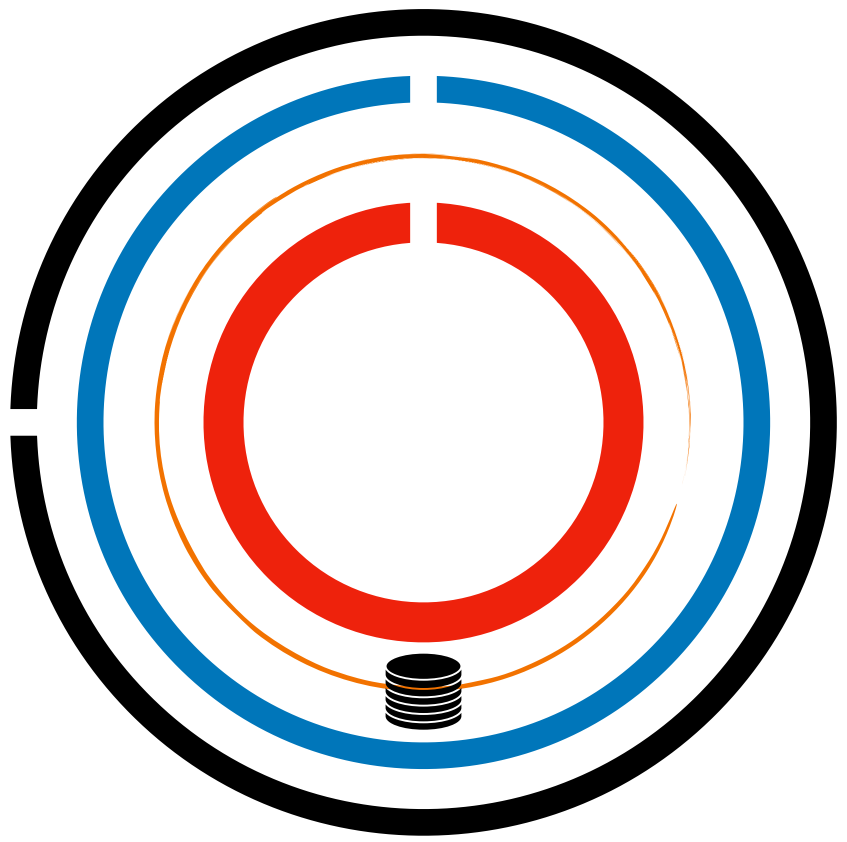

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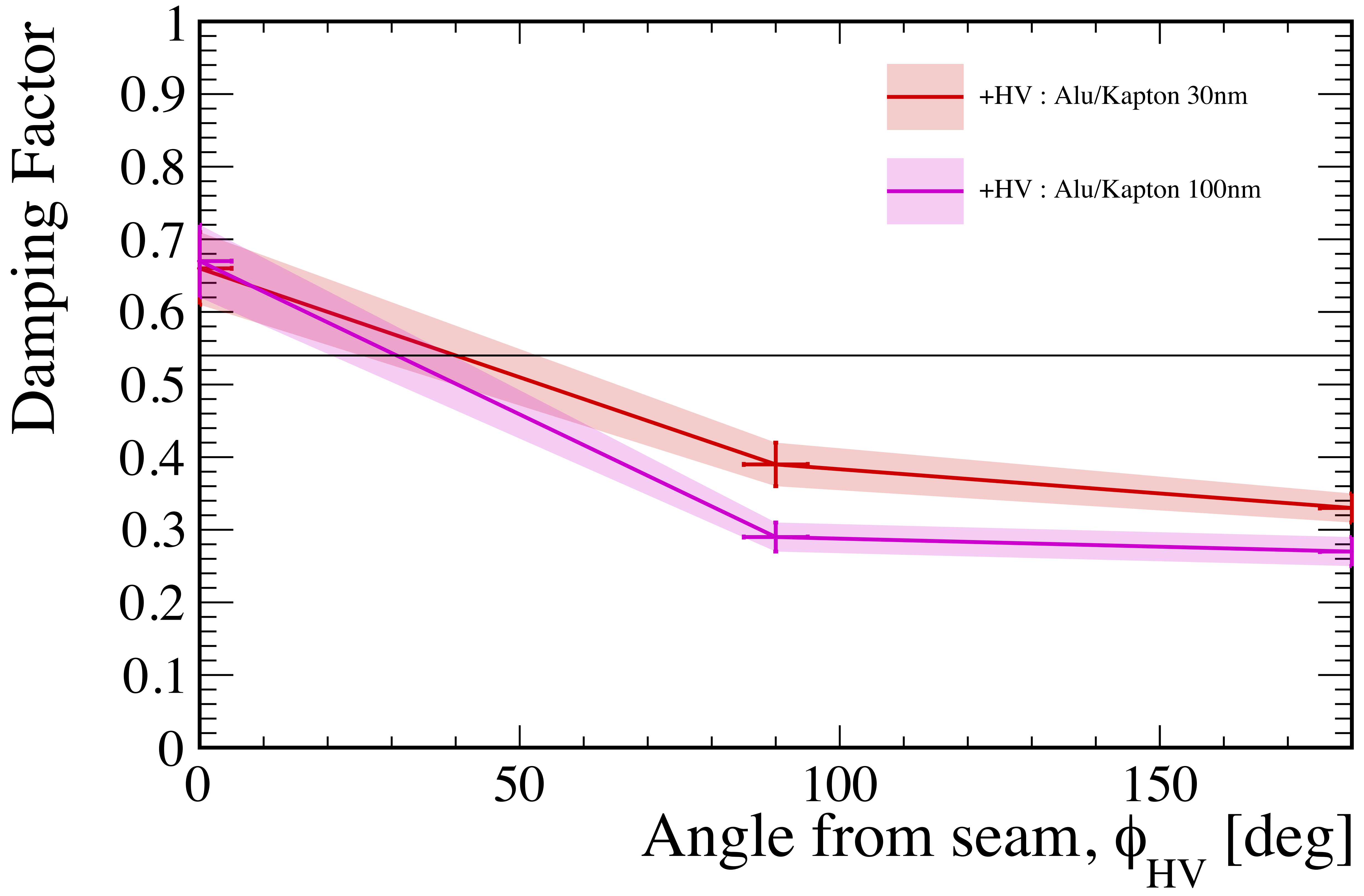
GND : Alu/Kapton 30 nm

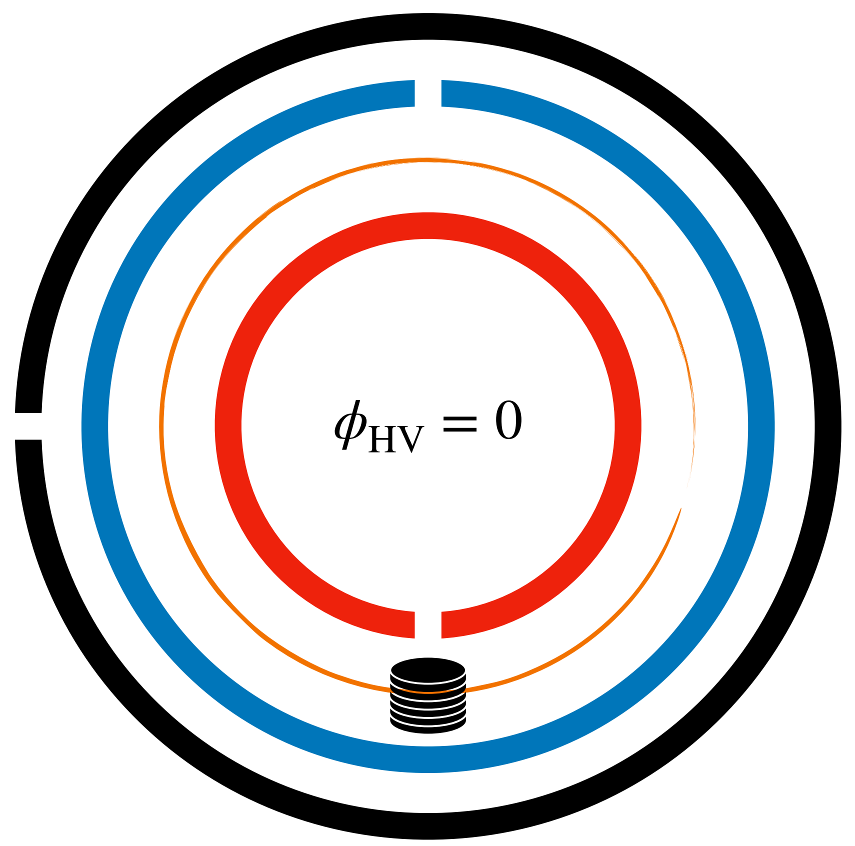
+HV : Alu/Kapton 100 nm

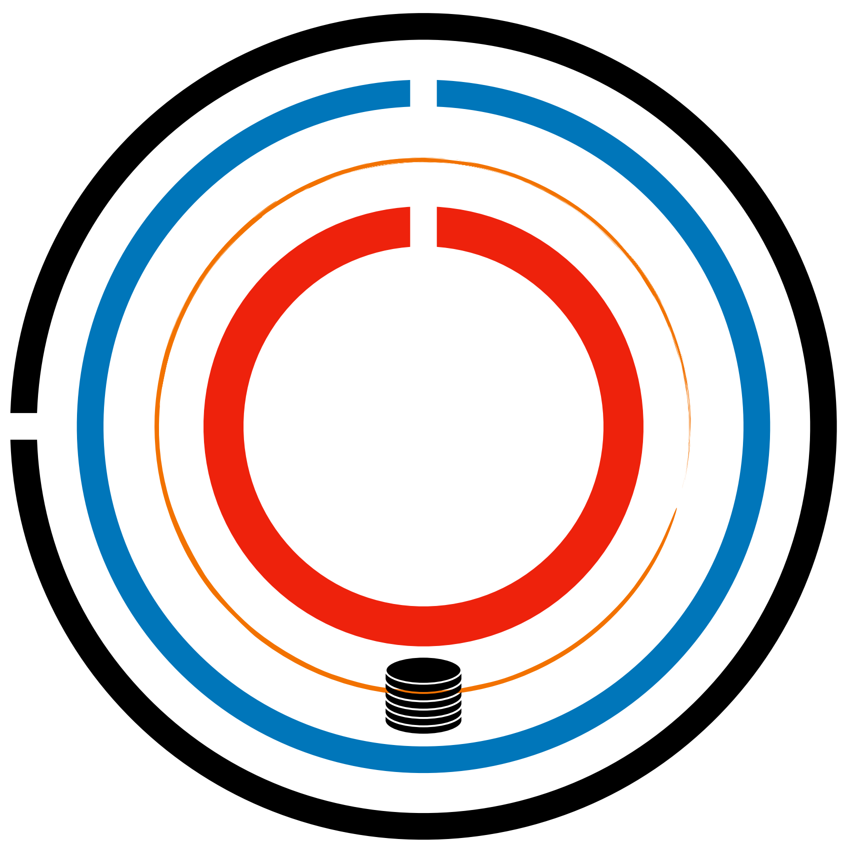
$D(\phi_{HV} = \pi) = 0.27 \pm 0.02$

Radial Magnetic Field Measurements

- Measured using a pickup coil (⛁) at radius $30.0 \pm 0.5\,\mathrm{mm}$, close to the muon orbit radius.
- Different components added to observe effect, due to induction of eddy currents.







$\mathrm{PulseCoil: Alu, 10 \times 10mm^2, IR = 40\,mm}$

GND : Alu/Kapton 30 nm

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$D(\phi_{HV} = \pi) = 0.33 \pm 0.02$

$\mathrm{PulseCoil: Alu, 10 \times 10mm^2, IR = 40\,mm}$

GND : Alu/Kapton 30 nm

+HV : Alu/Kapton 100 nm

$D(\phi_{HV} = \pi) = 0.27 \pm 0.02$

Summary

- The frozen-spin technique cancels the spin precession due to the anomalous magnetic moment (g-2), using a radial E field, leaving the EDM as the only inherent source of precession.
- The muon must be trapped in a compact stable orbit at the centre of a solenoid and the E fields precisely aligned.
- First prototypes of pulse coils and electrodes have been constructed for exploring feasible design concepts and verifying key parameters.
- Uniformity of thin foil electrode in first prototype gives encouragement that the alignment requirements (for reducing systematic effects) can be realised.
- Magnetic field damping has been estimated, informing a safety factor for the peak current of the pulse generator.
- Alternative geometries and foil types are now under investigation.

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