Search for the muon Electric Dipole Moment at the PSI

SPS Joint Annual Meeting 2023, Basel

Anastasia Doinaki

on behalf of the muEDM collaboration

05/09/2023

PAUL SCHERRER INSTITUT

Project funded by

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Swiss Confederation

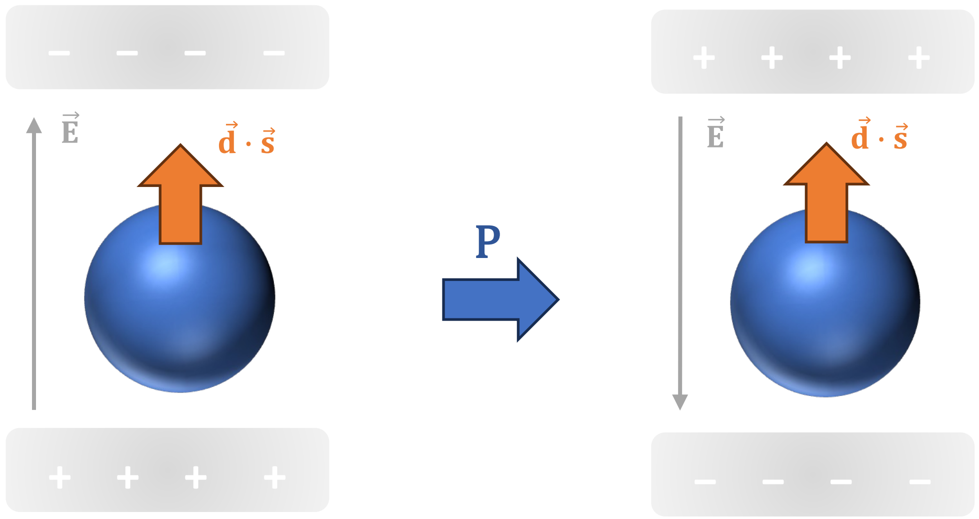
Federal Department of Economic Affairs,
Education and Research EAER
State Secretariat for Education,
Research and Innovation SERI

EDM and CP-violation

The Hamiltonian expressing the intaction of the particle's spin with the electric ($\vec{E}$) and magnetic ($\vec{B}$) field:

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

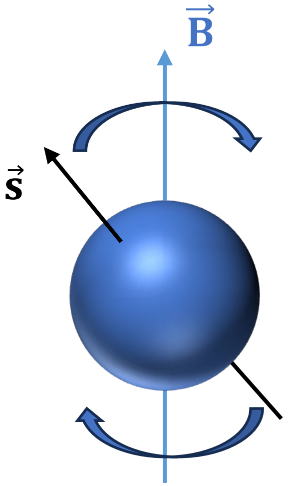
where $\vec{\mu} = \frac{ge}{2m_{\mu}c}\vec{s}$, the magnetic dipole moment and $\vec{d} = \frac{\eta e}{2m_{\mu}c}\vec{s}$, the electric dipole moment.



A non-zero particle EDM violates Parity (P) inversion symmetry, and assuming CPT invariance, violates also CP-symmetry.

Spin motion of the muons in electric and magnetic fields

The spin of a static muon in the presence of a magnetic field will precess about the $\vec{B}$:



$$\frac{d\vec{s}}{dt} = \vec{\mu}\times\vec{B} = \vec{\omega}_L\times\vec{s}\,,$$

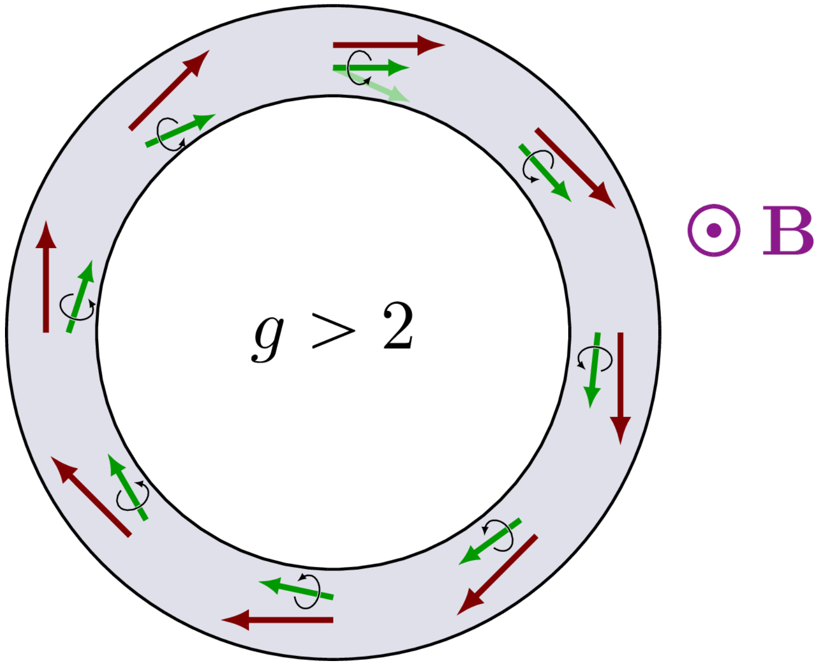
$\vec{\mu} = \frac{ge}{2m_\mu c}\vec{s}$ magnetic dipole moment

$\vec{\omega}_L = \frac{-2\mu\vec{B}}{\hbar}$ Larmor precession frequency

Likewise, a possible muon EDM, $\vec{d} = \frac{\eta e}{2m_\mu c}\vec{s}$ would result in a spin precession , $\vec{\omega}_d = \frac{-2d\vec{E}}{\hbar}$ in the presence of an $\vec{E}$.

Spin motion of the muons in a storage ring

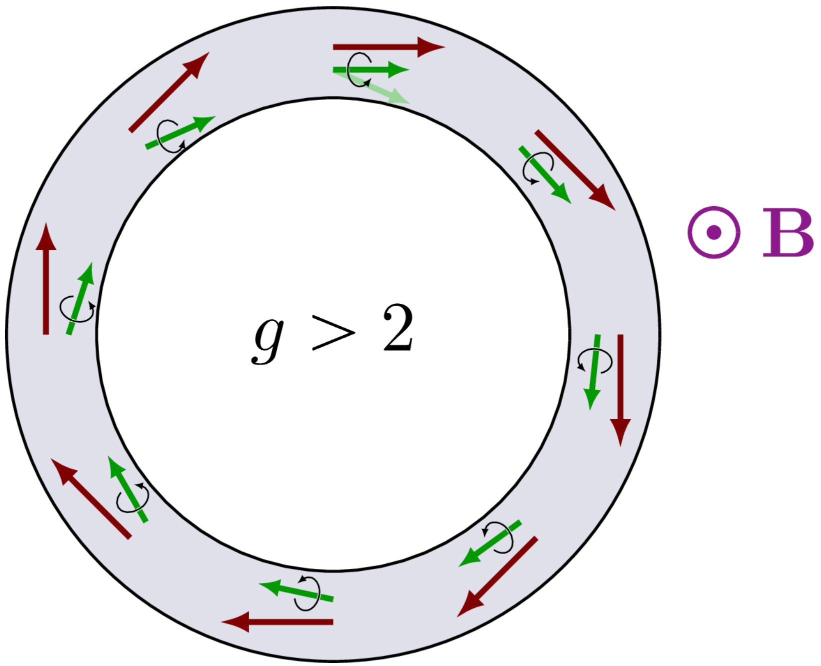
For a muon, with a magnetic dipole moment $\vec{\mu} = \frac{ge}{2m_\mu c}\vec{s}$, in a storage ring in the precense of a $\vec{B}$ field, and an $\vec{E}$ field steering the beam:



If g>2, spin rotates faster than momentum due to anomalous magnetic moment $a = \frac{g-2}{2}$.

Spin motion of the muons in a storage ring

For a muon in a storage ring in the precense of a $\vec{B}$ field, and an $\vec{E}$ field steering the beam:



Spin dynamics: $\frac{d\vec{s}}{dt} = \vec{\omega}_0 \times \vec{s}$, where $\vec{\omega}_0 = -\frac{e}{m\gamma}\left\{(1+\gamma a)\vec{B} - \frac{a\gamma^2}{(\gamma+1)}(\vec{\beta}\cdot\vec{B})\vec{\beta} - \gamma\left(a + \frac{1}{\gamma+1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right\}$ the Thomas precession frequency.

Acceleration: $\frac{d\vec{\beta}}{dt} = \vec{\omega}_c \times \vec{s}$, where $\vec{\omega}_c = -\frac{e}{m\gamma}\left(\vec{B} - \frac{\gamma^2}{\gamma^2-1}\frac{\vec{\beta}\times\vec{E}}{c}\right)$ the cyclotron frequency.

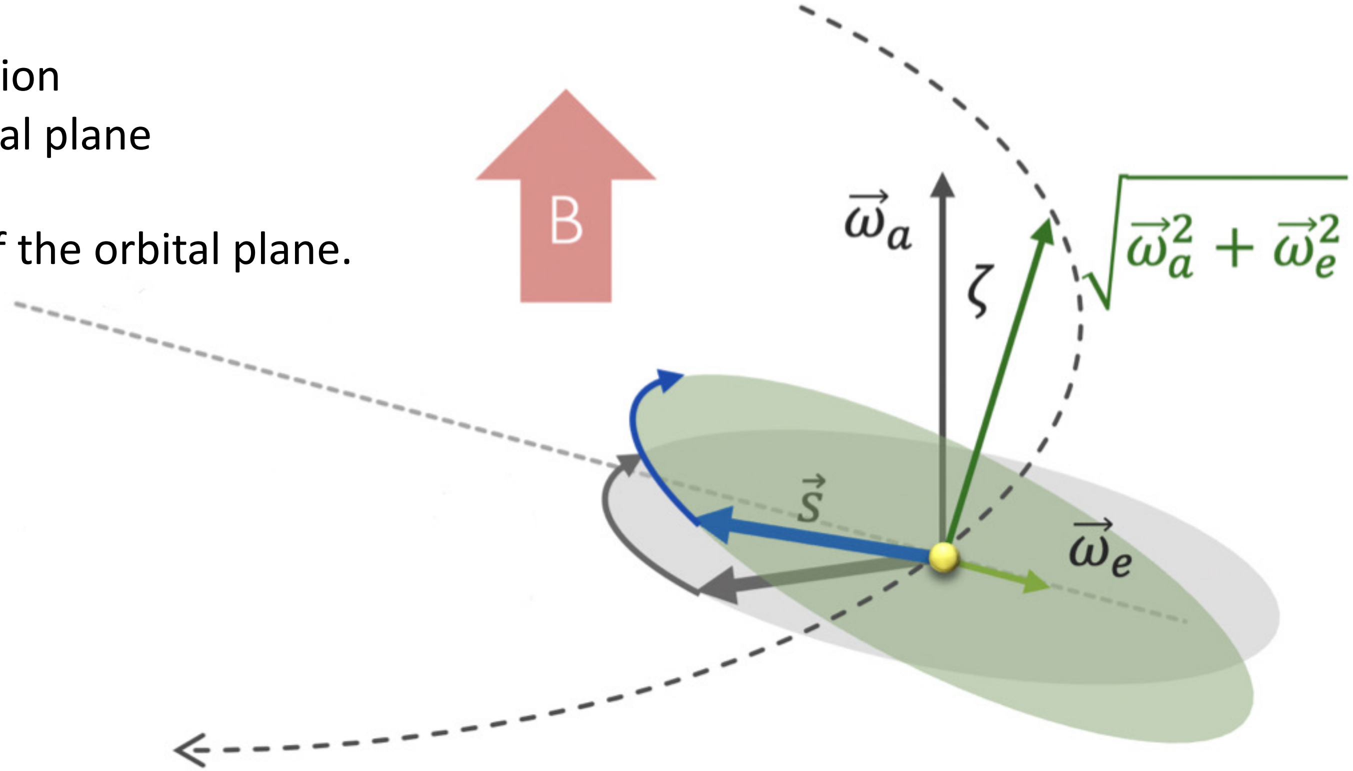
Muon spin precession in $\vec{E}$ and $\vec{B}$ field in the presence of an EDM

The muon spin precession in a storage ring with an $\vec{E}$ and $\vec{B}$ field, perpendicular to each other and to the muon momentum is:

$$\vec{\omega} = -\frac{e}{m}\Big\{\underbrace{a\vec{B} + \left(\frac{1}{1-\gamma^2} - a\right)\frac{\vec{\beta}\times\vec{E}}{c}}_{\vec{\omega}_a = \vec{\omega}_0 - \vec{\omega}_c} + \underbrace{\frac{\eta}{2}\left(\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B}\right)}_{\vec{\omega}_e}\Big\},$$

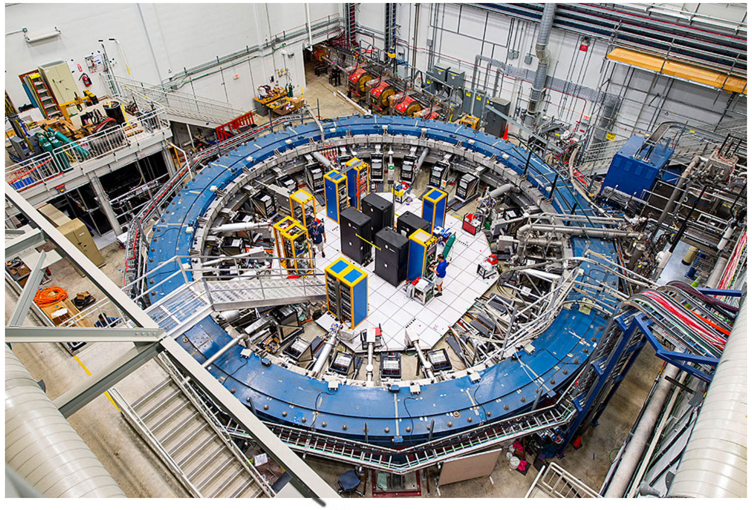
$\vec{\omega}_a$: spin precession in the orbital plane, g-2 precession
$\vec{\omega}_e$: spin precession due to an EDM, out of the orbital plane

A non-zero EDM results in a **tilted precession** out of the orbital plane.



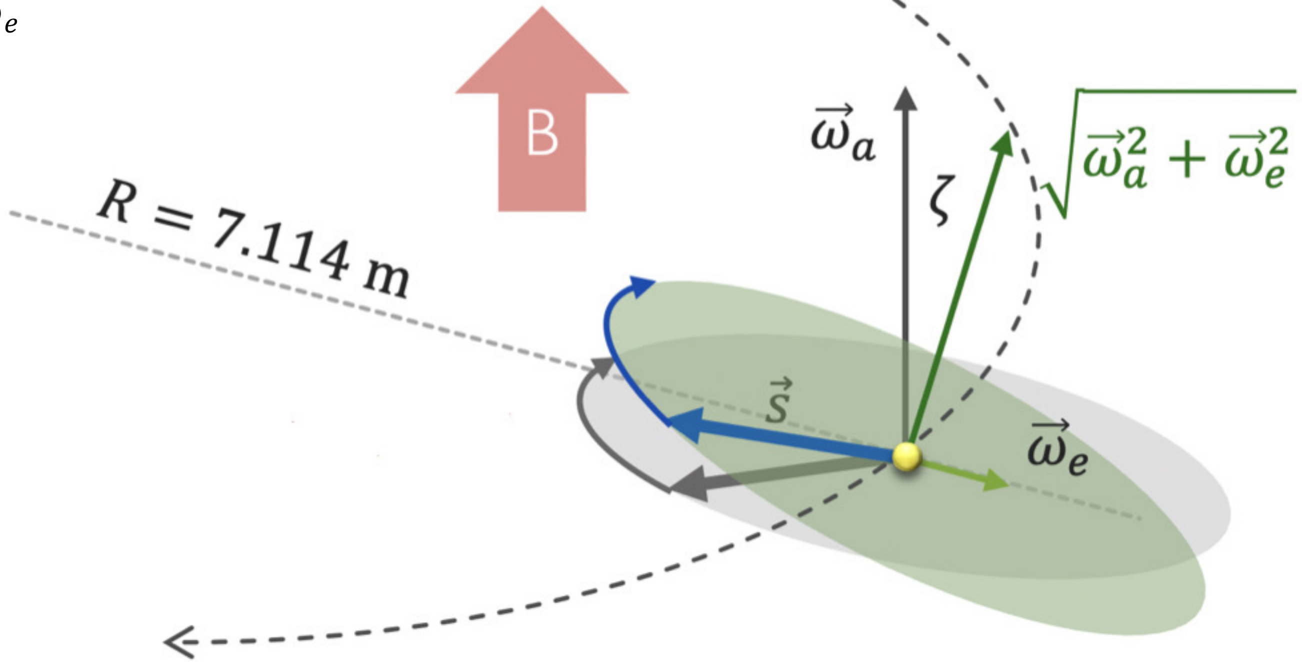
Muon spin precession in $\vec{E}$ and $\vec{B}$ field, g-2 experiment

At the g-2 storage ring experiment E821 at BNL used a "magic momentum" of $\vec{p}_{magic}$~3.1GeV/c, such that it cancels:



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

There is a vertical oscillation with a frequency $\vec{\omega}_e$ and an amplitude proportional to the muon EDM.



Sensitivity : $d\mu < 1.8\times10^{-19} e\cdot cm$

The frozen-spin technique

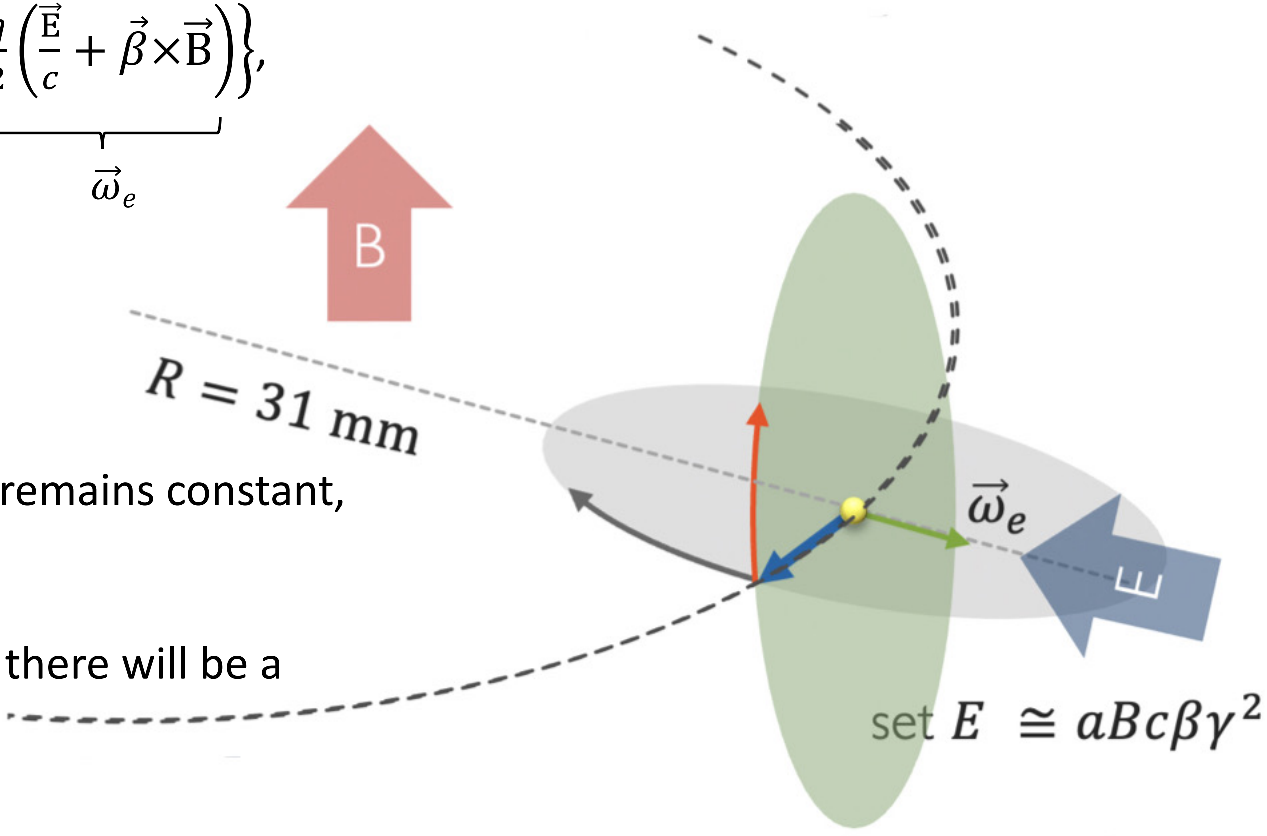
Based on the frozen-spin technique we are choosing a radial electric field such that to cancel the precession due to the anomalous moment:

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

This radial electric field is $E_f \approx aBc\beta\gamma^2$.

The relative angle between the momentum and the spin remains constant, "frozen", if $\eta = 0$ (no EDM).

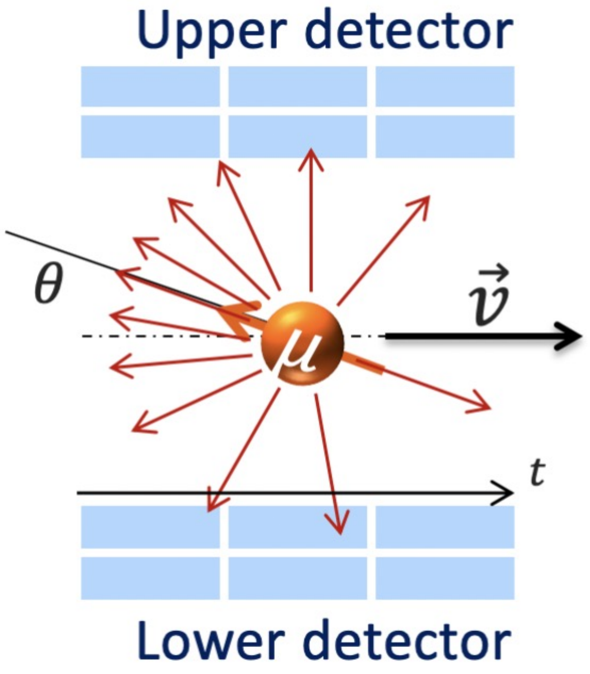
In the presence of a muon EDM the spin will precess and there will be a longitudinal build-up of the polarization.

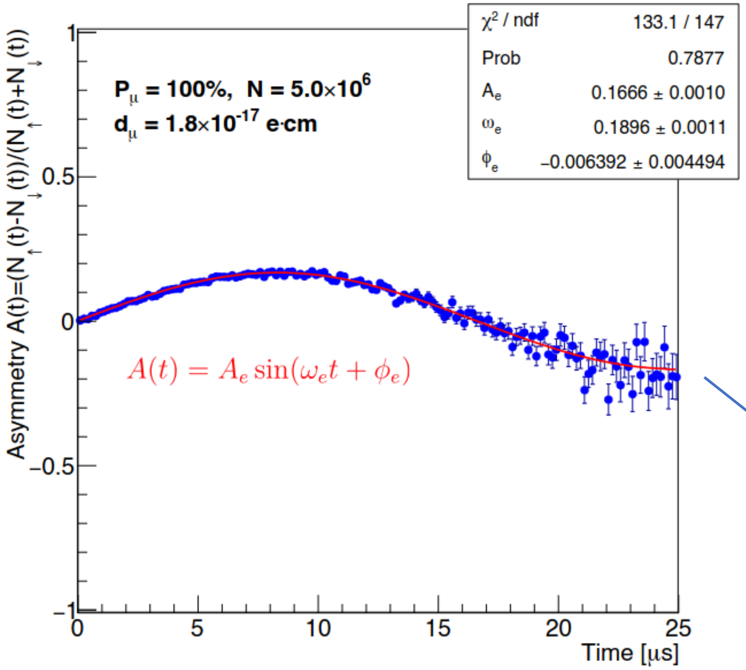


The muEDM experimental base

Measuring the increasing positron decay asymmetry, A(t), as a function of time.

- ❑ A(t)=0 ➡ spin parallel to the momentum ➡ muon EDM=0
- ❑ A(t)≠0 ➡ vertical precession out of the orbital plane* ➡ muon EDM ≠ 0





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

compute statistical sensitivity from A(t) slope

*For other effects that lead to false EDM signals:

- ➢ *C.Dutsov session, "Systematic effects in the search for the muon EDM using the frozen–spin method"*

The muEDM statistical sensitivity

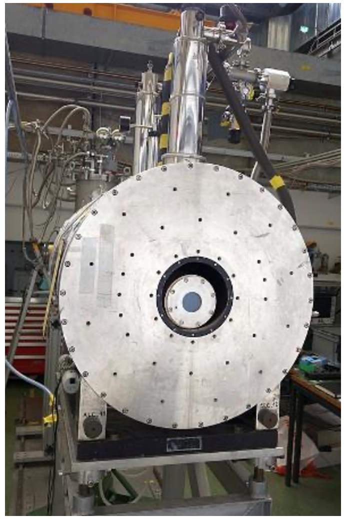
The frozen-spin technique profits from the build-up of the phase $\vec{\omega}_e t$ to achieve a high statistical sensitivity.

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

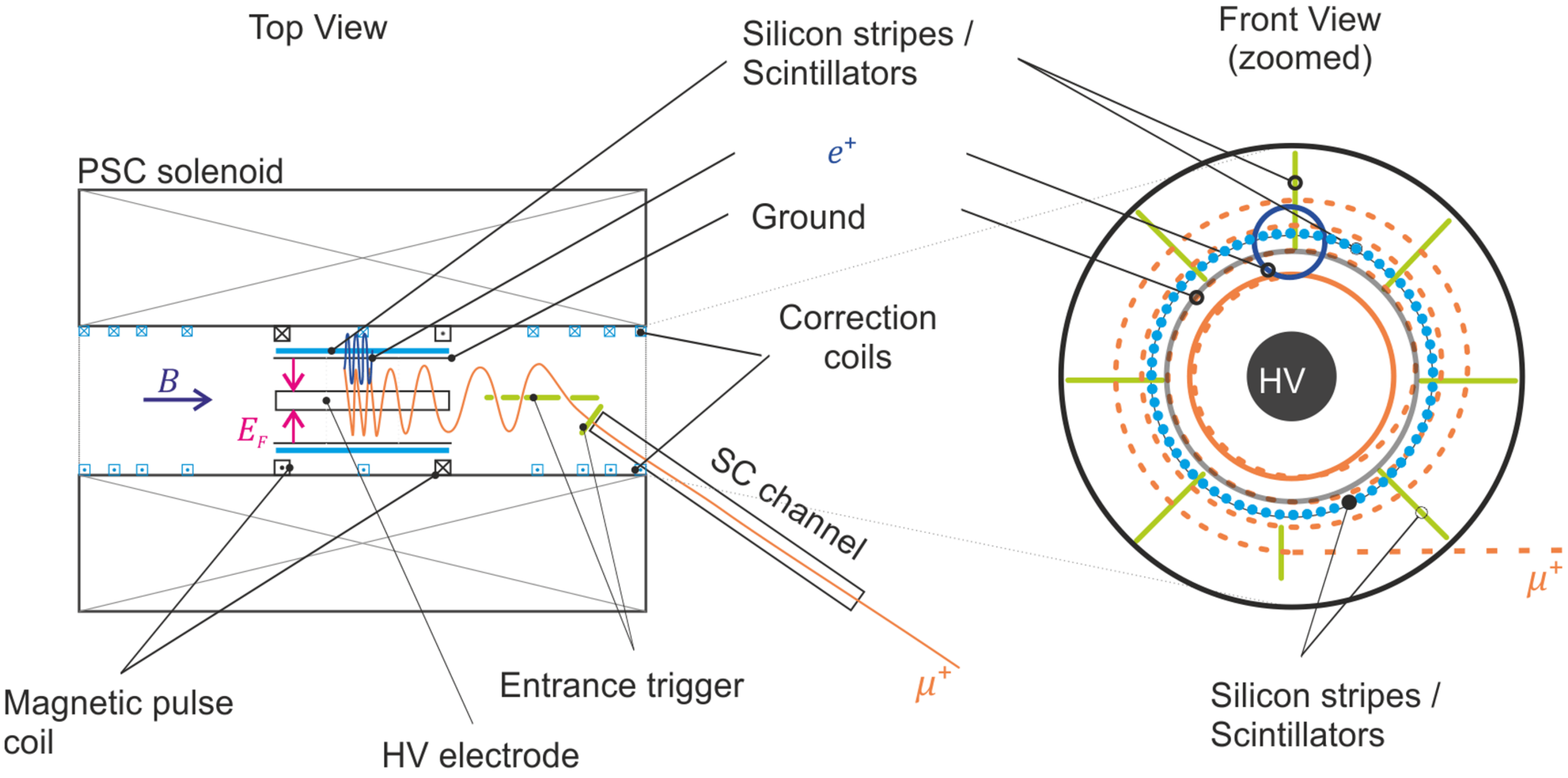
The muEDM experiment is split into two phases, Phase 1 and 2.

Phase	1	2
Muon momentum (MeV/c)	28	125
Muon flux density (μ^+/s)	4×10^6	1.2×10^8
Sensitivity in a year (e·cm)	$<3\times10^{-21}$	$<6\times10^{-23}$

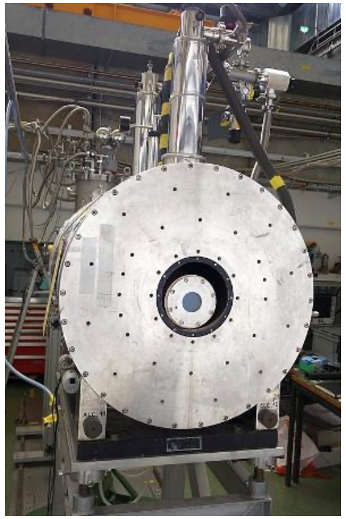
Breakdown of the muEDM experiment, Phase 1



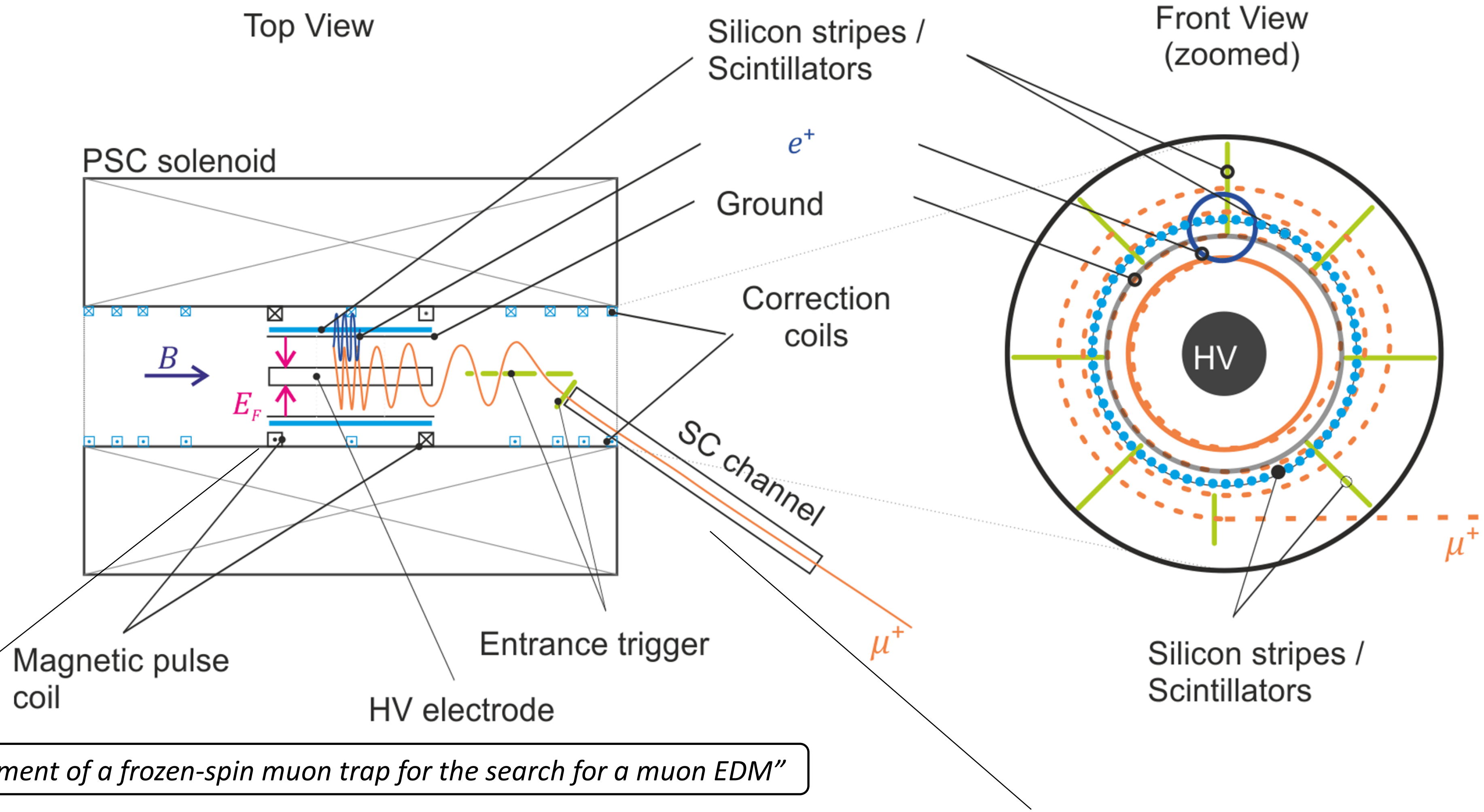
3 T storage solenoid
Bore Diam. 200 mm
Length 1000 mm



Breakdown of the muEDM experiment, Phase 1



3 T storage solenoid
Bore Diam. 200 mm
Length 1000 mm



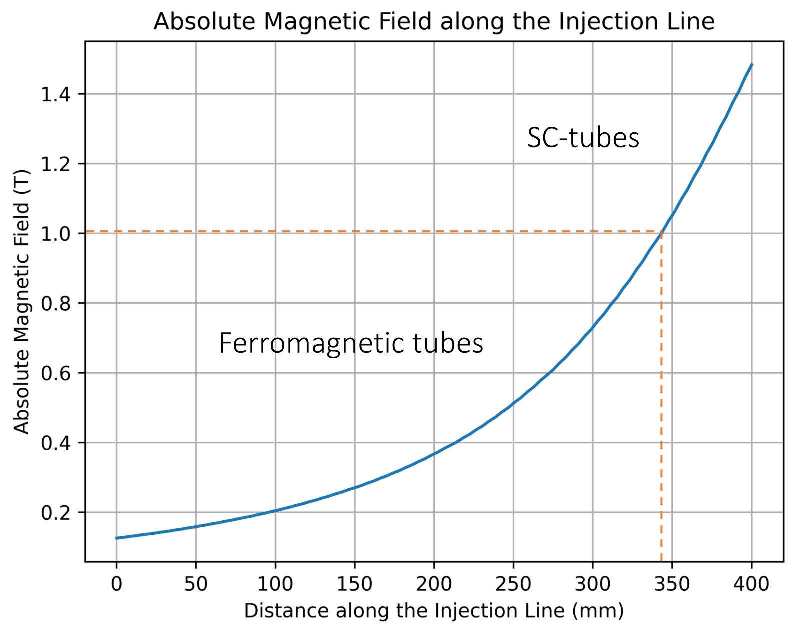
T.Hume session, “Development of a frozen-spin muon trap for the search for a muon EDM”

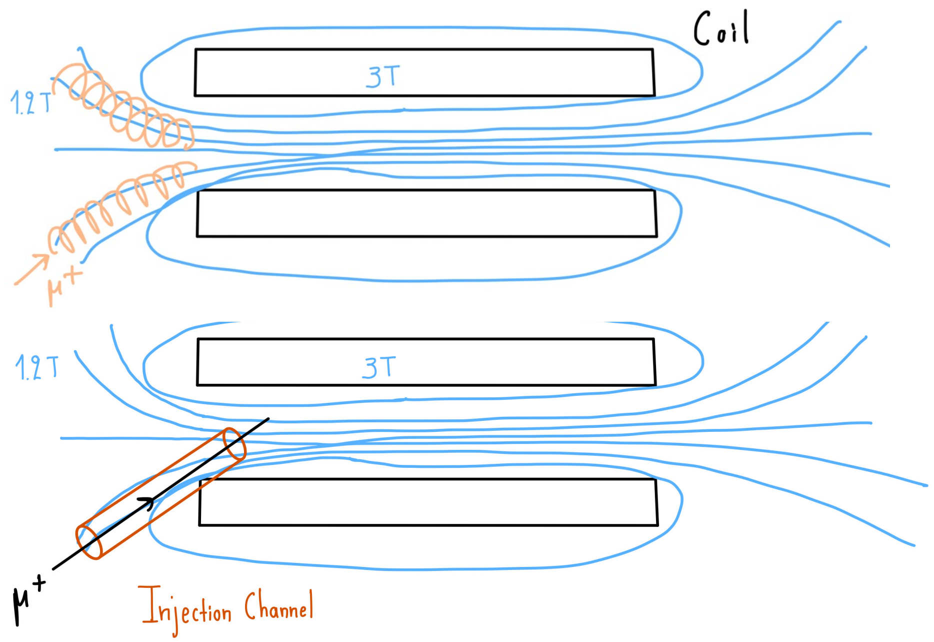
R.Chakraborty session, “Optimization of muon EDM experimental setup using simulations”

The injection channel

The muons encounter various magnetic field strengths as they are approaching the bore of the magnet.

On the right, we see the absolute magnetic field that the muons encounter along the injection line towards the magnet.





These varying field strength introduce challenges for the muon transportation:

- ➢ Muons transported from a low-field (fringe field<1T) to a high-field region (solenoid~3T) , muons will spiral in and back out (Magnetic Mirror Effect).

Magnetically shielded channel

We develop a magnetically shielded channel to protect the muons from external field variations, and it consist of:

- Thick ferromagnetic tubes, for the low magnetic fringe field region (<1T)
- Superconducting (SC) shielded tubes, for the high field region (1-1.4T)

Develop and test three SC-shielded prototypes:

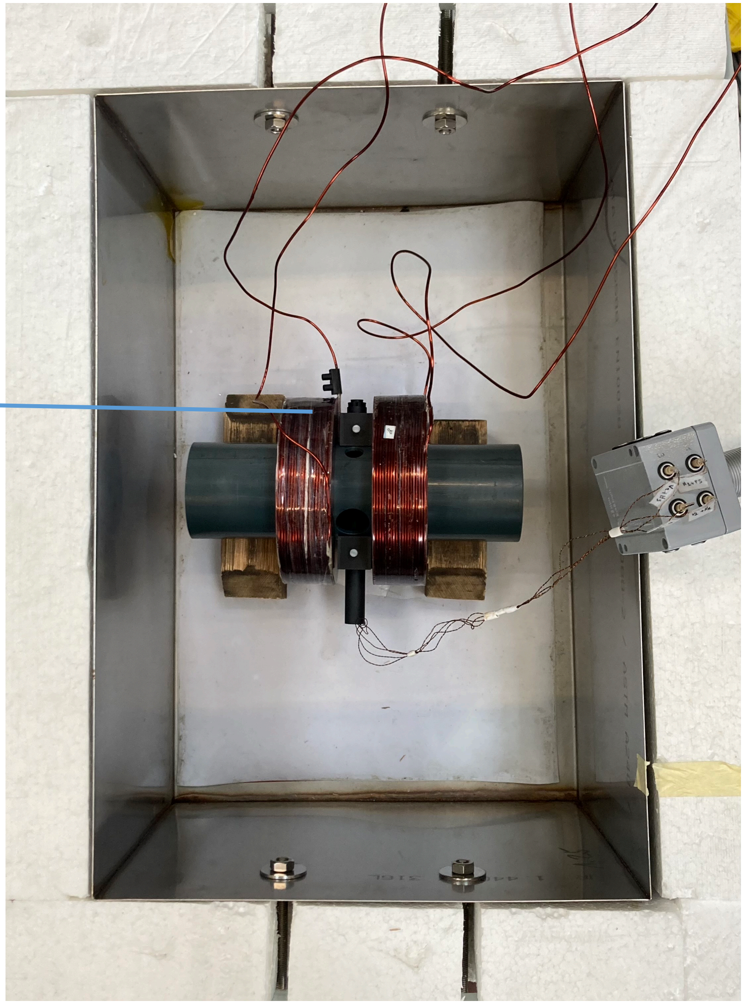
Prototype I: High-Temperature Superconducting (HTS) Tape, helically coiled around a copper tube

Prototype II: Copper tubes wrapped with Nb-Ti/Nb/Cu SC-Sheets

Prototype III: Combination of a Bi-2223 cast tube possibly reinforced with superconducting "ribbons"

Testing SC-shielded prototypes

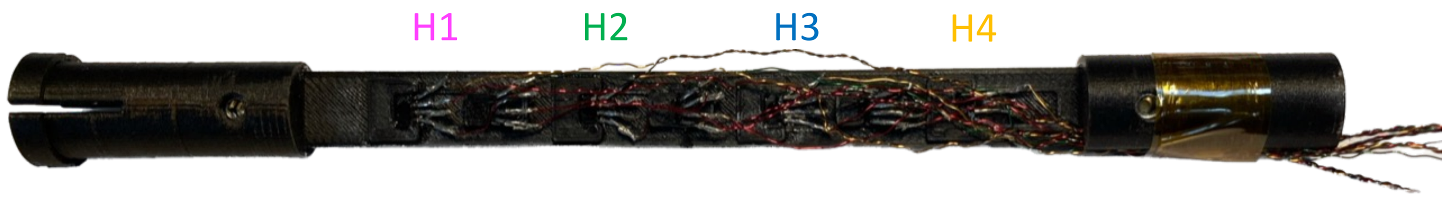
Testing the superconductive properties of a Bi-2223 tube, with a Helmholtz coil pair of 100 mT, in a 77K cryogenic bath.

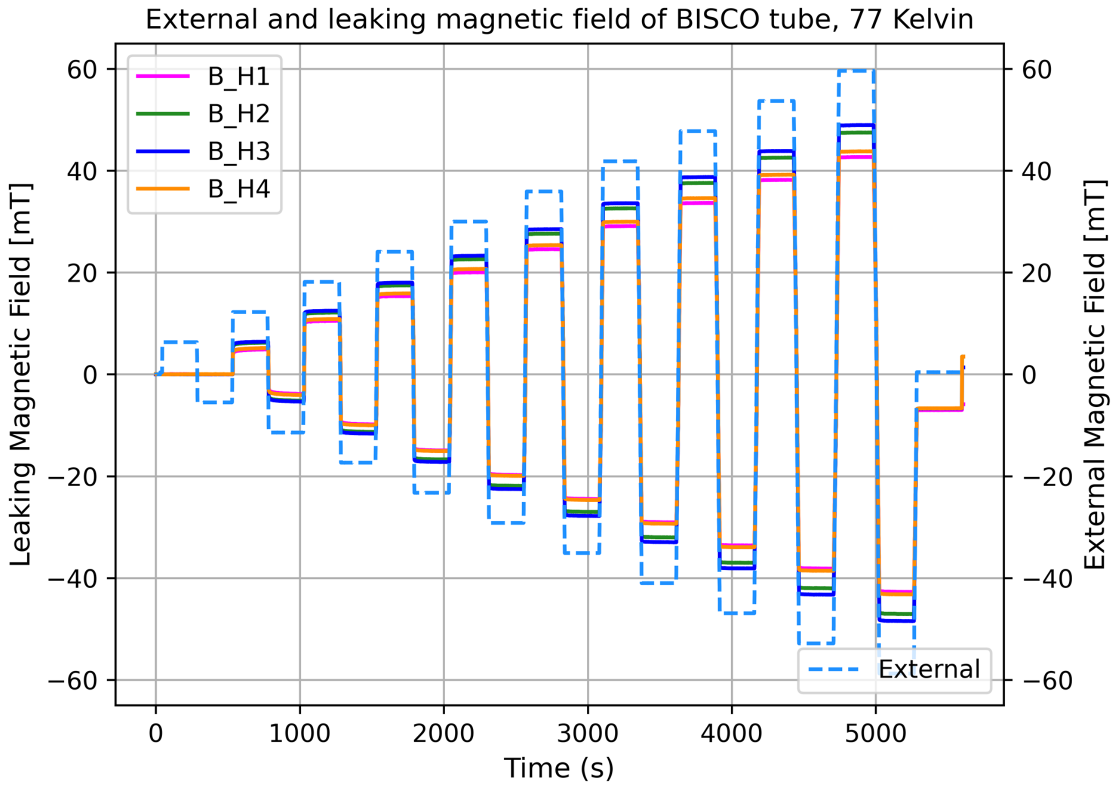


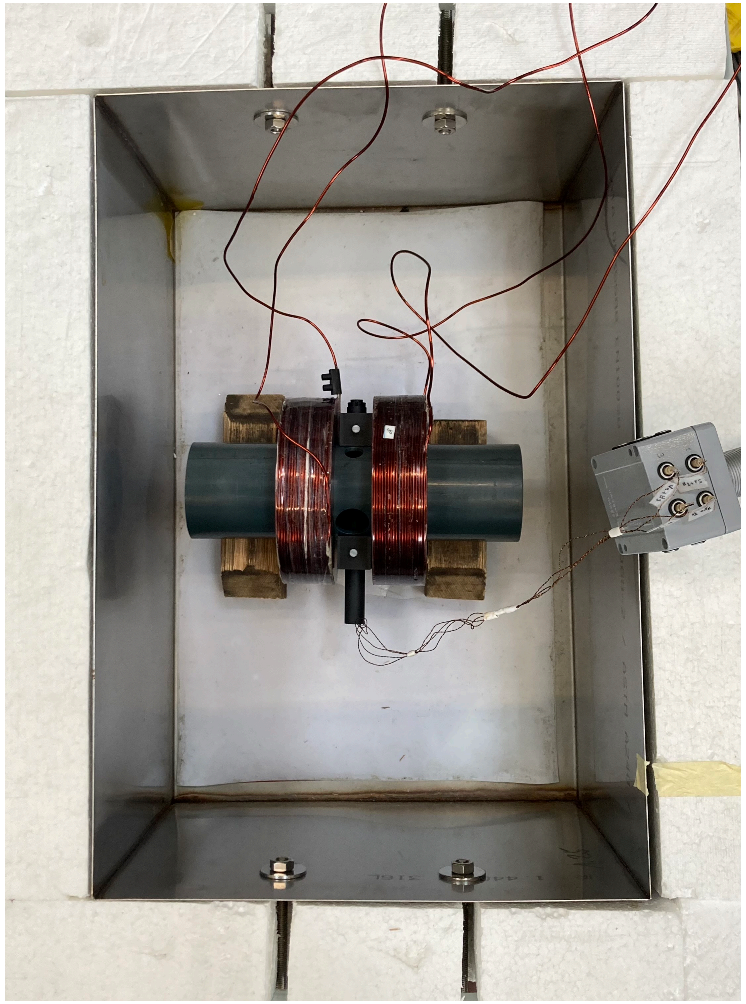
Bi-2223 tubes (BiPbSrCaCuO)
Critical Temperature 105-110 K
ID : 15mm
OD: 18.5mm
L: 200mm
Wall Thickness: 1.6-1.8 mm

Testing SC-shielded prototypes

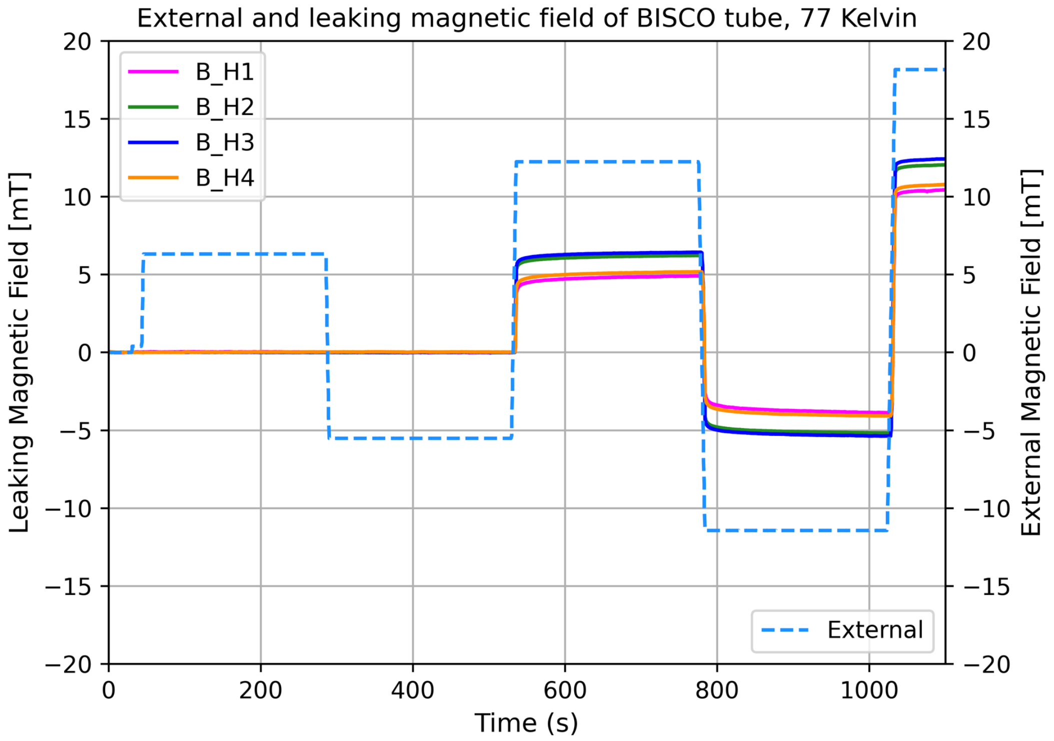
Testing the superconductive properties of a Bi-2223 tube, with a Helmholtz coil pair of 100 mT, in a 77K cryogenic bath.

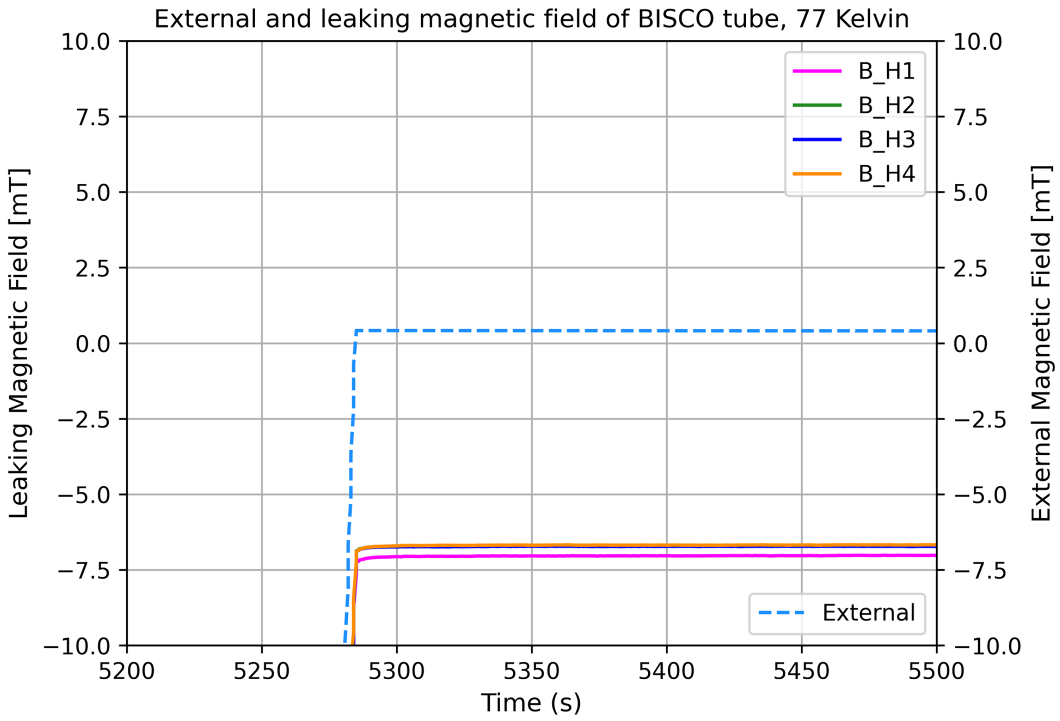






Testing SC-shielded prototypes, signs of superconductivity





- ✓ Full shielding of at least 6 mT external magnetic field
- ✓ Hysteresis effect

Conclusions and Outlook

- A dedicated experiment to search for the muon EDM is setup at PSI.
- The muEDM is based on a novel technique, called frozen-spin technique.
- The first experimental phase will test the frozen-spin technique, and after optimizations, will lead to the second phase with high sensitivity of $d\mu < 6\times10^{-23} e\cdot cm$.
- A magnetically shielded channel is needed for the injection of muons from the exit of the beamline to a 3T storage solenoid.
- Underway development and testing of SC-shielded prototypes as part of the injection channel.

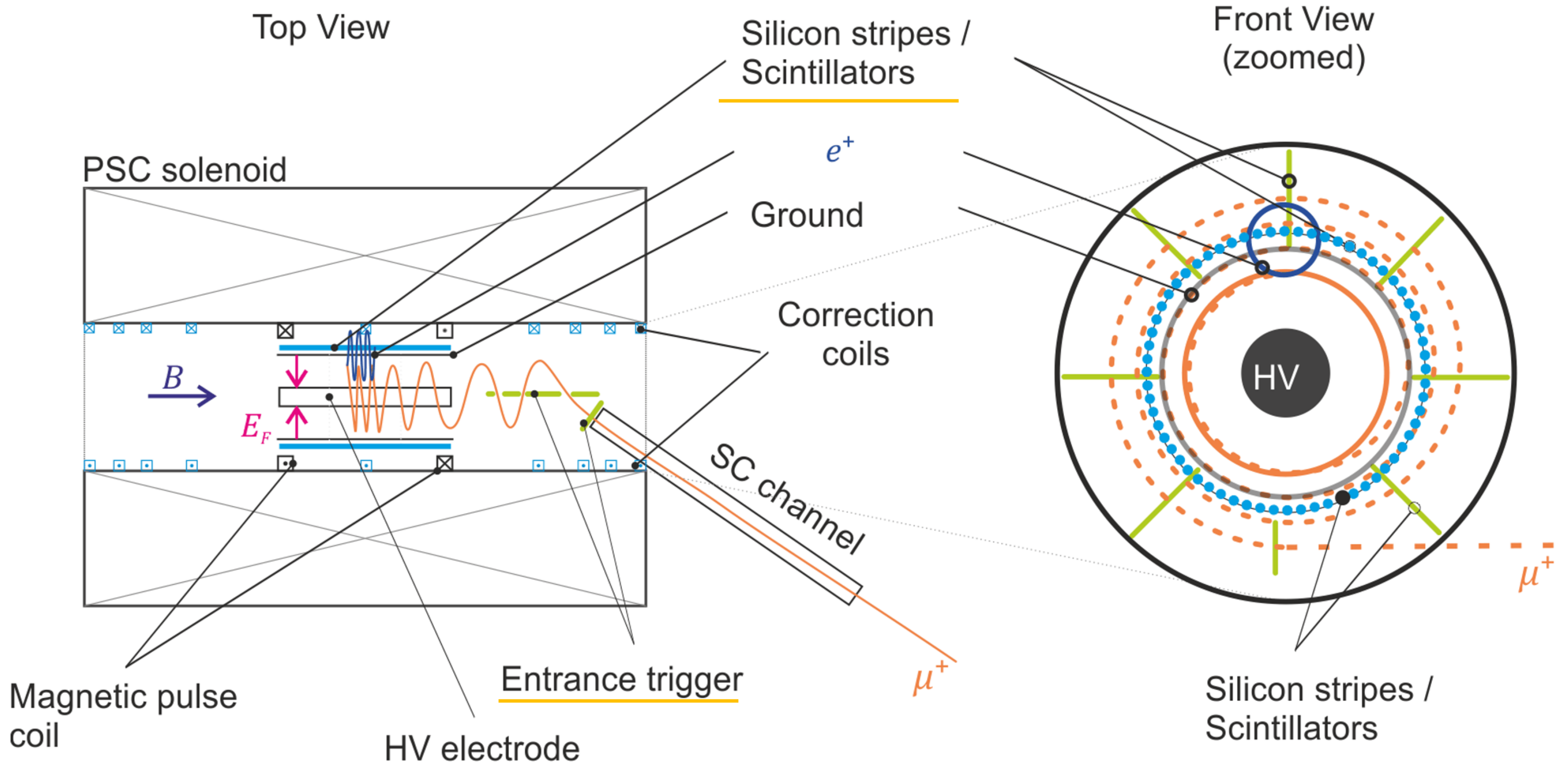
on behalf of the muEDM collaboration

Thank you for your attention!

PAUL SCHERRER INSTITUT

Backup Slides

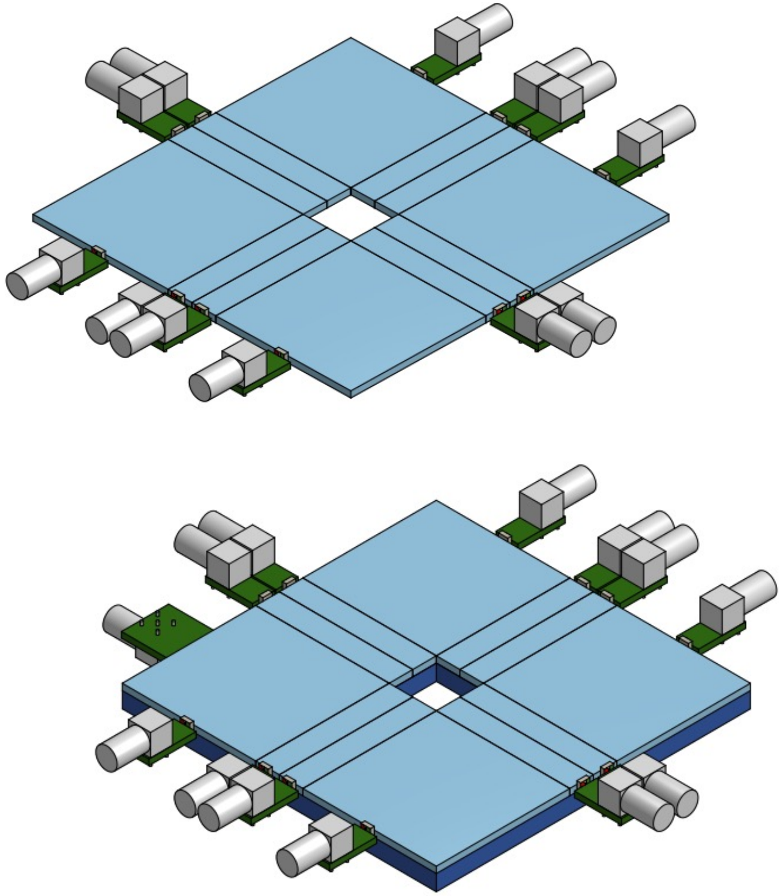
Breakdown of the muEDM experiment, the detectors



Muon entrance monitor

<u>Purpose</u>: Focus muon beam onto opening of injection channel

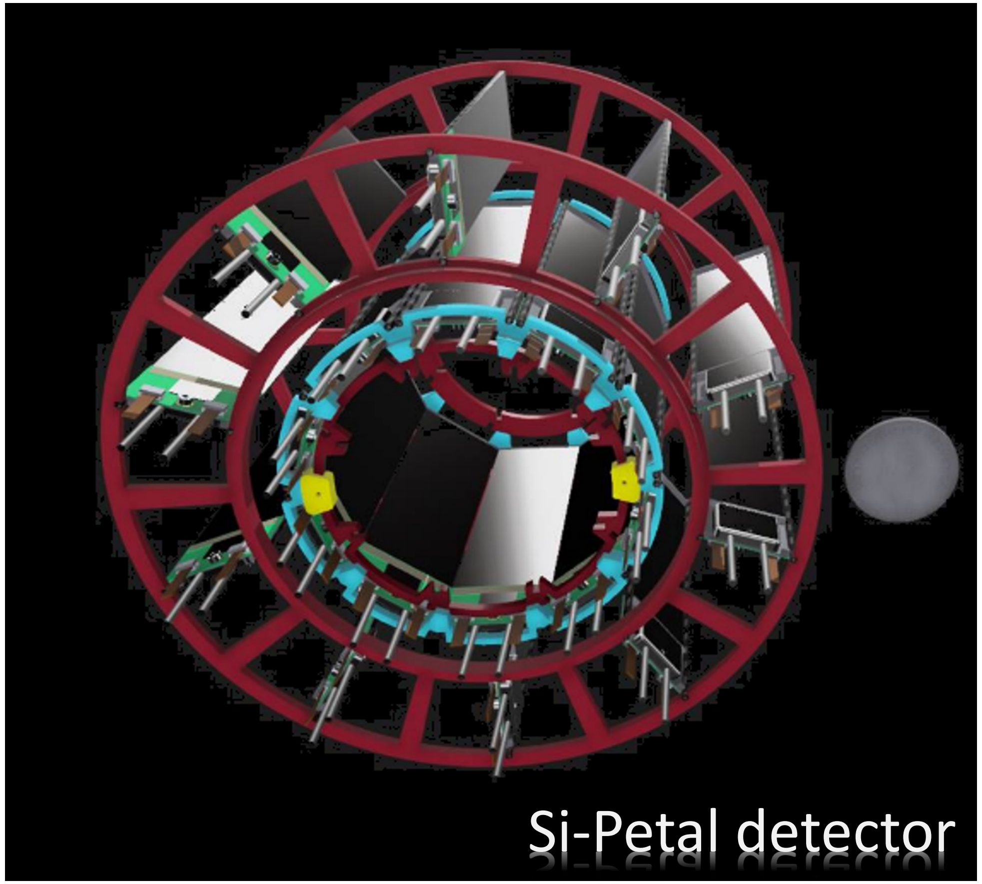
- ✓ Scintillator tiles coupled to SiPMs
- ✓ Hole in center to let muon beam pass
- ✓ Front tile thickness 1-2 mm to stop surface muons
- ✓ A thicker (up to ~5 mm) scintillator layer could be added to better discriminate muons and positrons



Silicon strip detector

Silicon strip detector for g-2 detection.

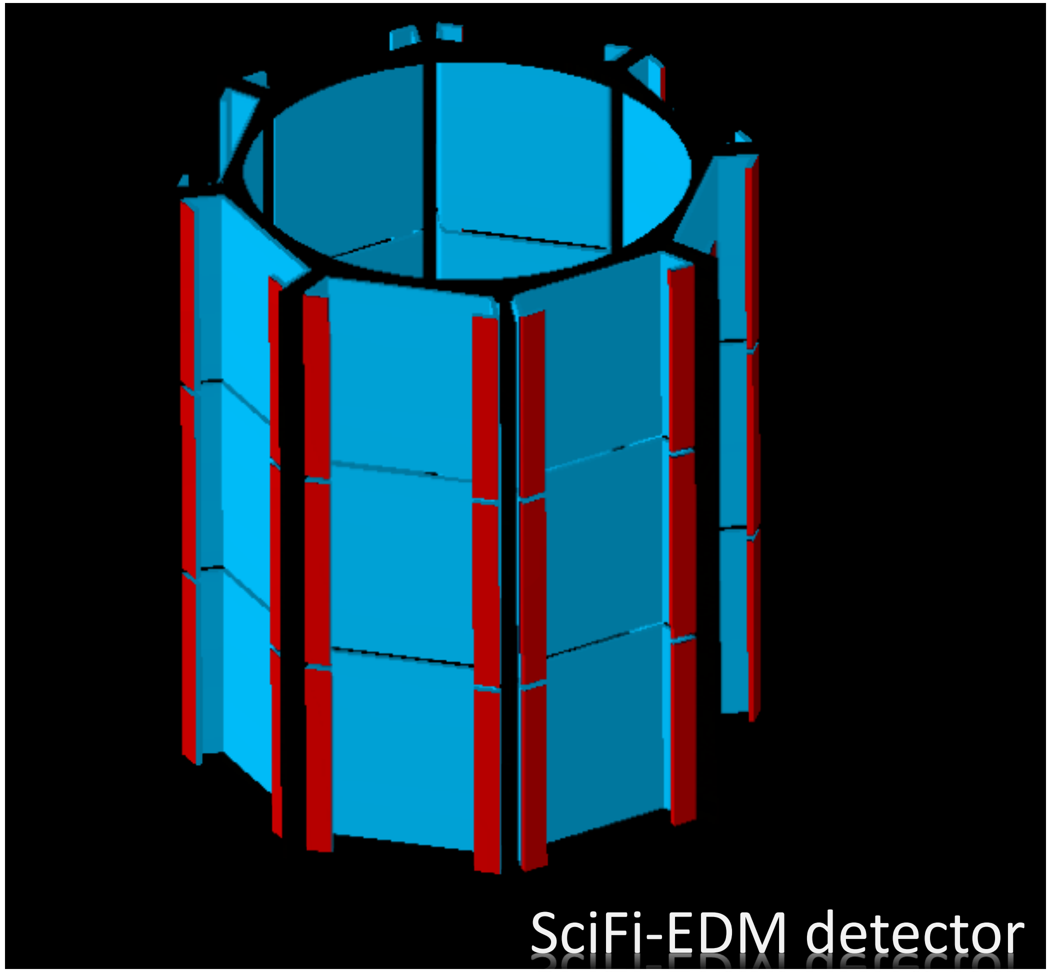
- ✓ Reconstruction of transverse positron momentum ($\Delta p \approx 5\mathrm{MeV/c}$)
- ✓ Timing $\Delta t \approx 2\mathrm{ns}$
- ✓ Spatial resolution $\approx 0.1\mathrm{mm}$ (lateral)



Scintillating fiber detector

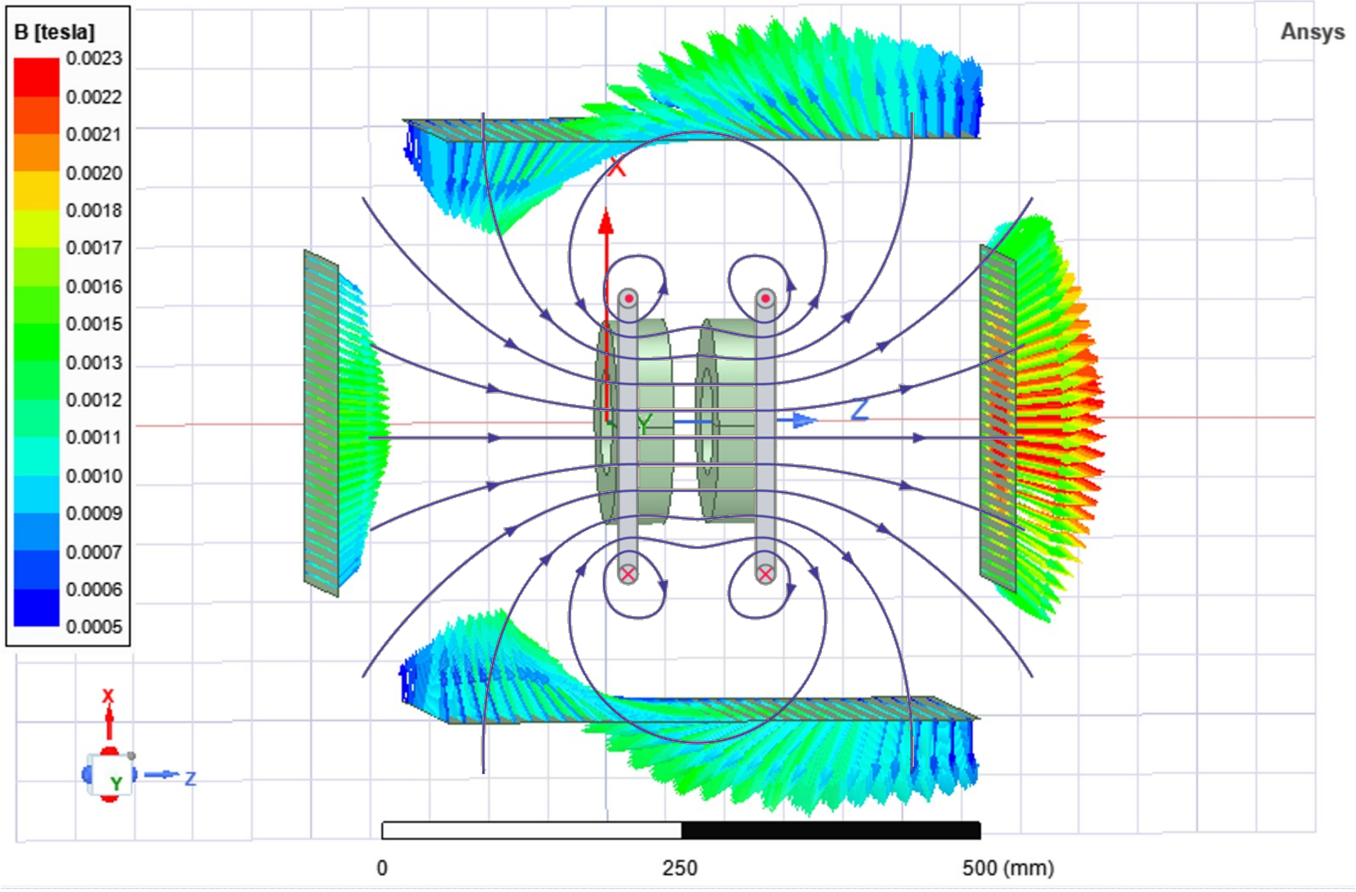
Scintillating fiber detector for EDM asymmetry measurement and timing.

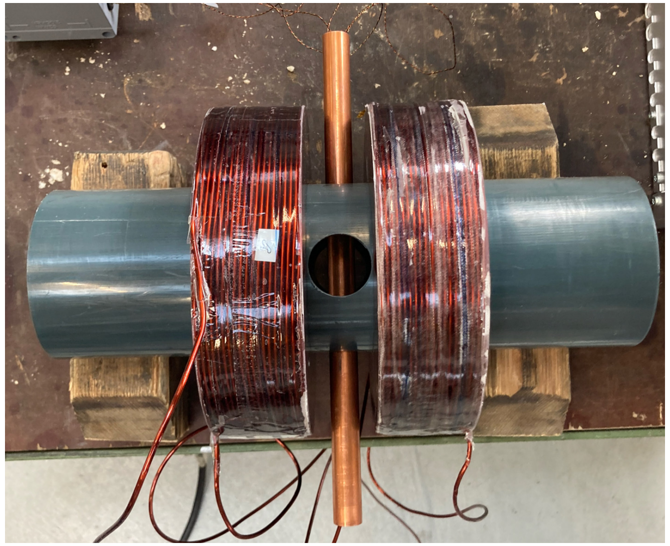
- ✓ Horizontal fiber ribbons with $250\mu\text{m}$ pitch and $100\mu\text{m}$ resolution
- ✓ Timing resolution $< 2\text{ns}$
- ✓ Reconstruction of longitudinal momentum

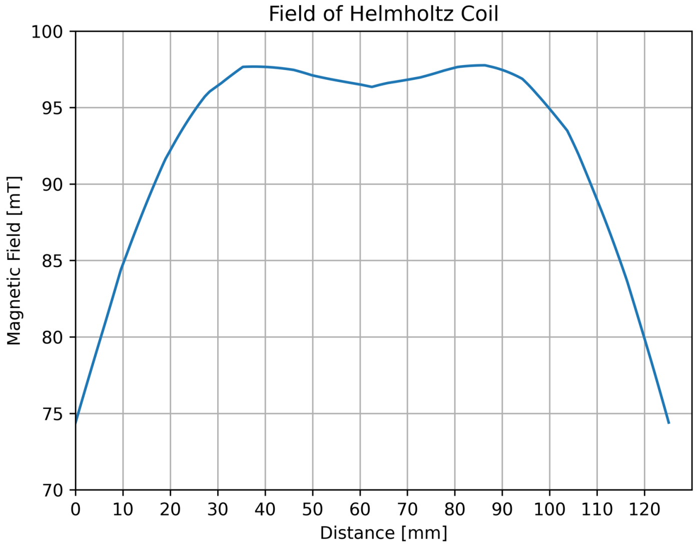


Magnetic field simulation of the Helmholtz coil pair

Designed and constructed a Helmholtz coil; 100 mT at the center of the coil when inducing a current of I=20 Amps while the coils are connected in series.



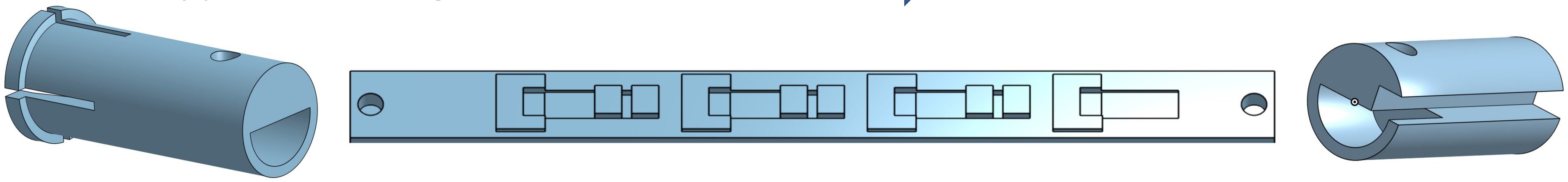


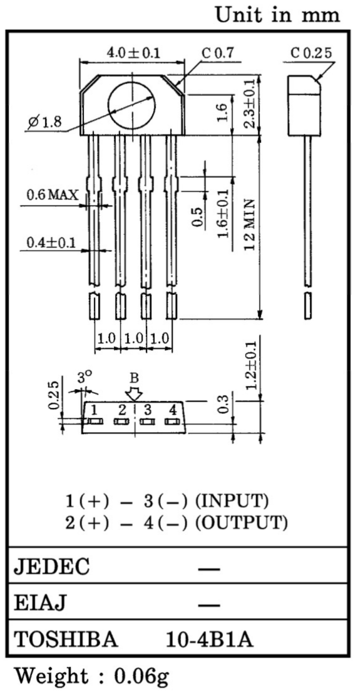


Hall sensor support system

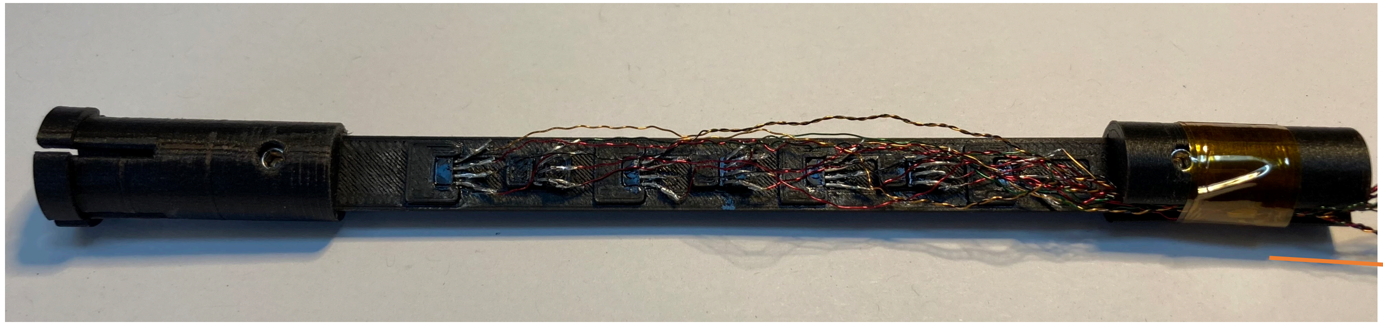
In order measure the magnetic field inside the SC-shielded tube; 3D designed and printed a Hall Sensor Support system that fulfilled the following requirements:

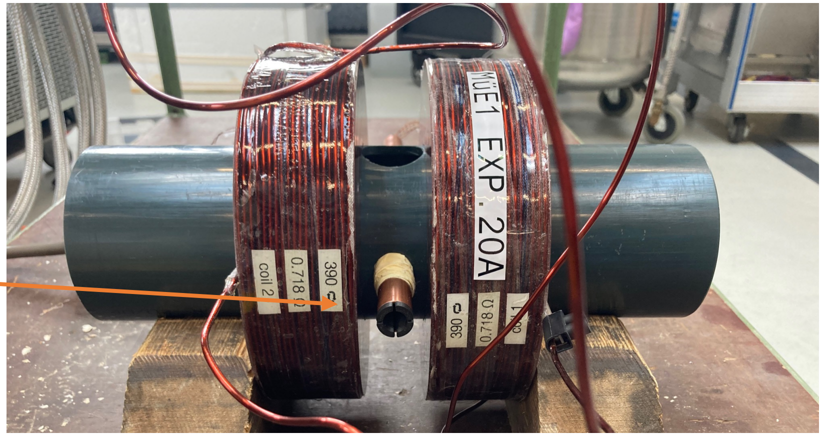
- ✓ Cryogenic-proof material, Onyx.
- ✓ The support remaining fixed inside the SC-tube → 7 sensor slots (4 horizontal, 3 vertical).



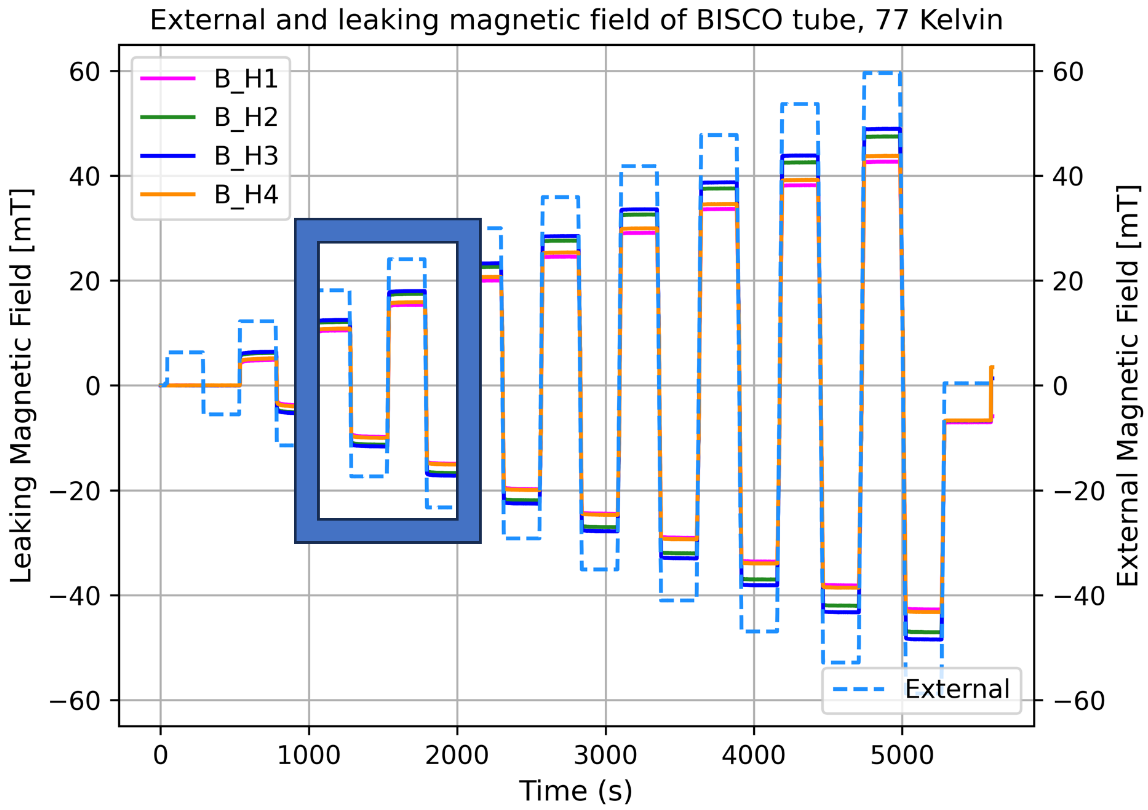


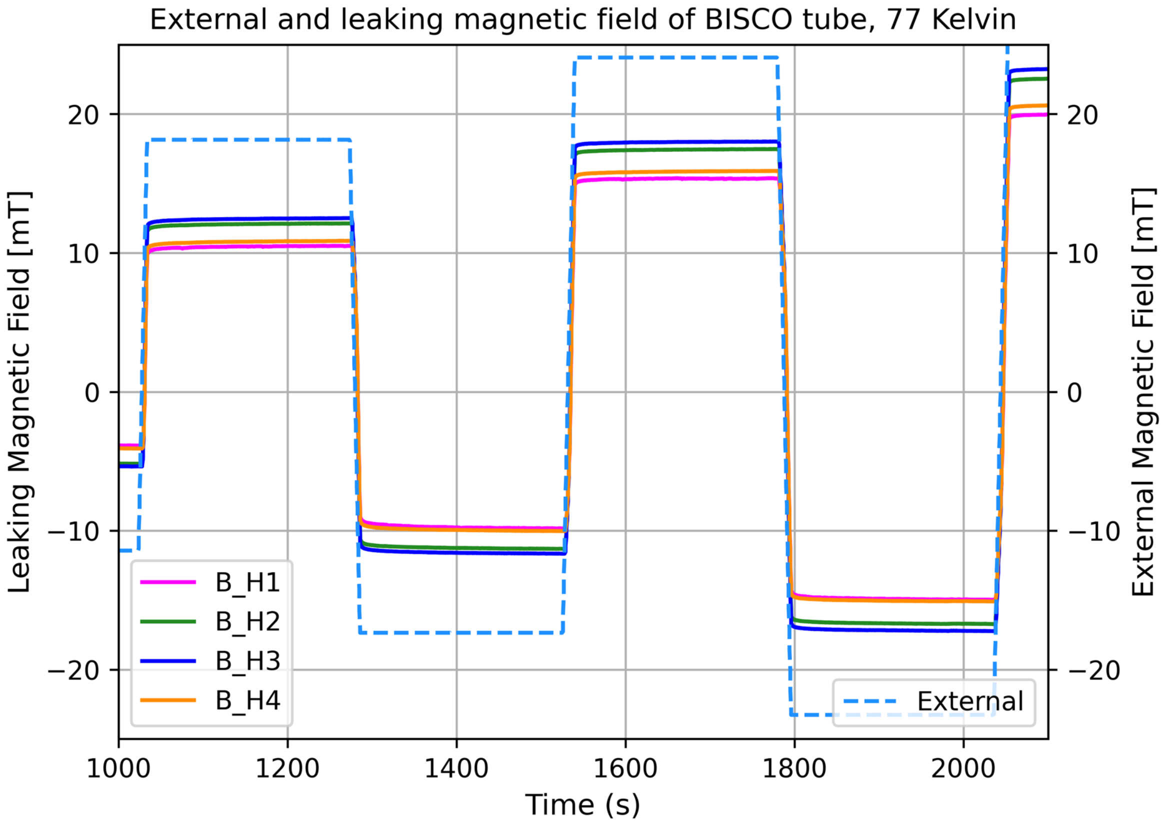
- ➢ Glued and soldered seven Toshiba THS119 Hall sensors on the support system.



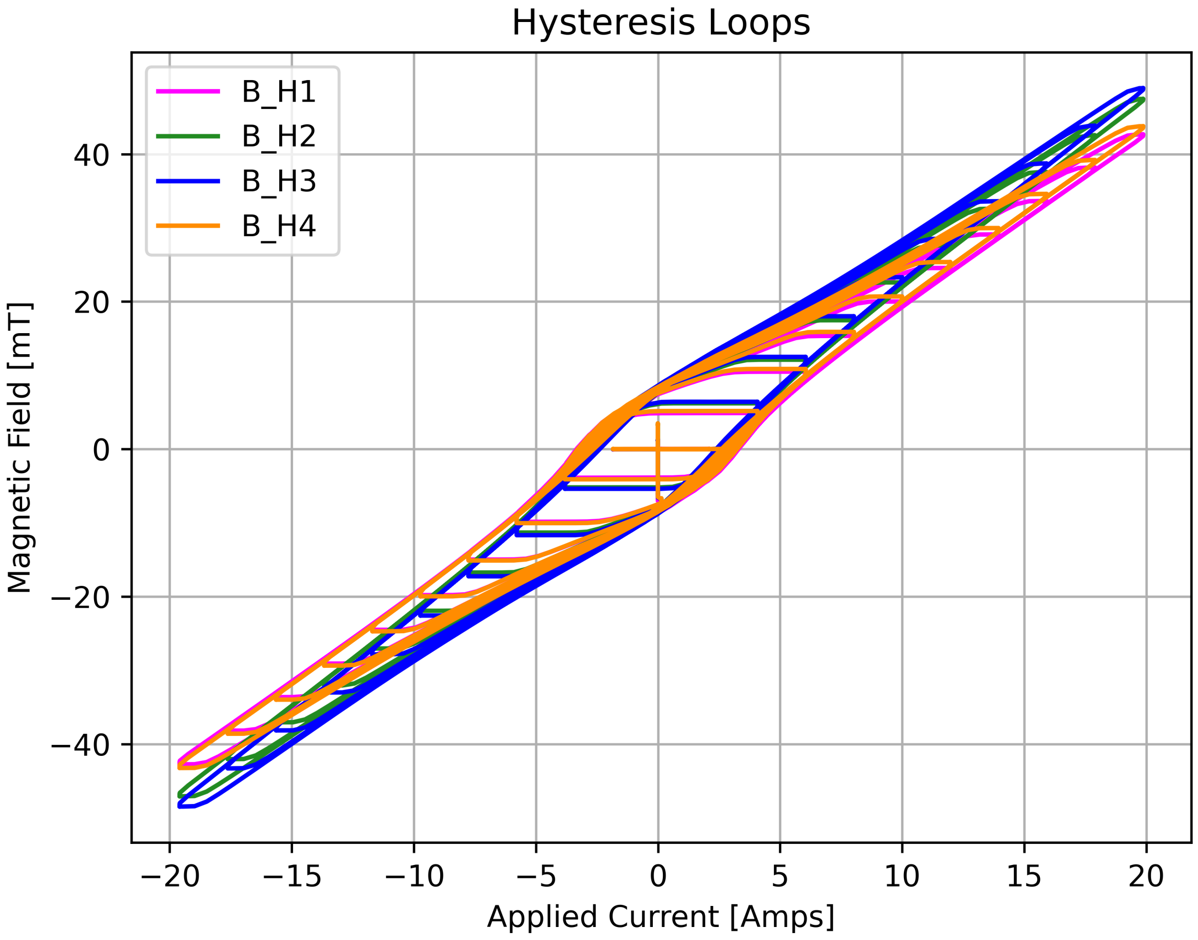


Signs of superconductivity, BISCO tube

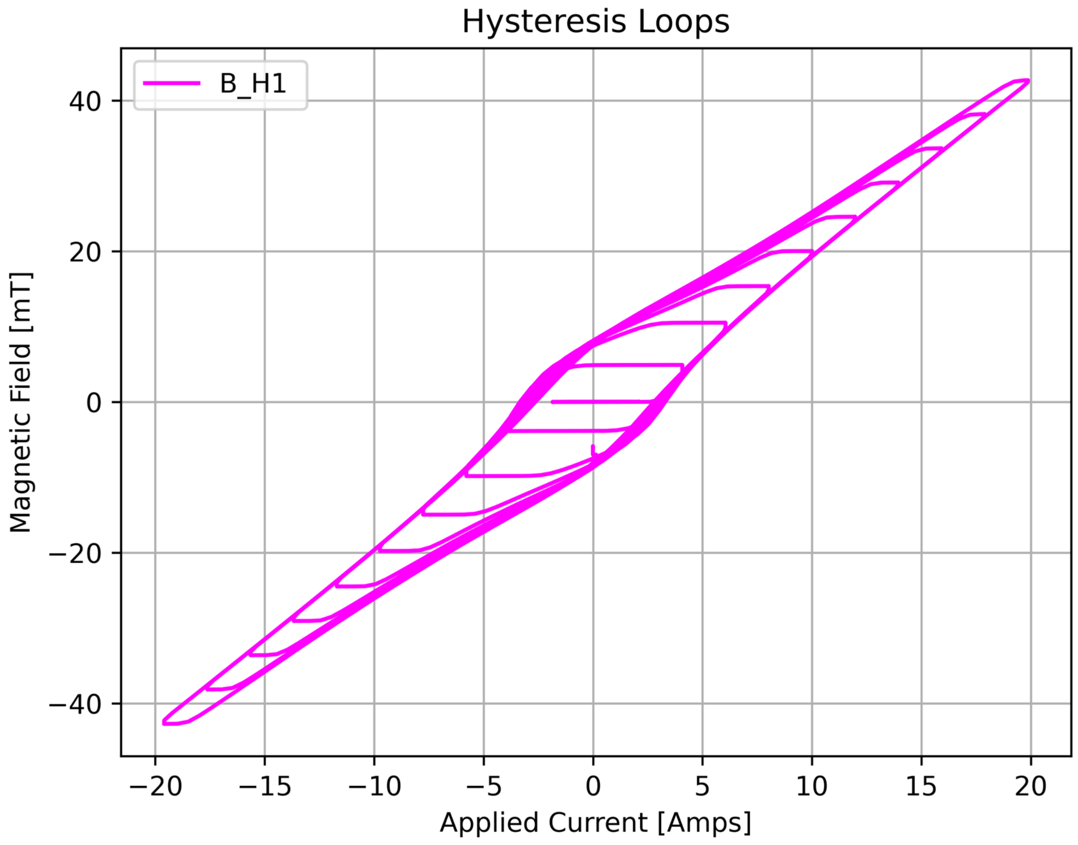


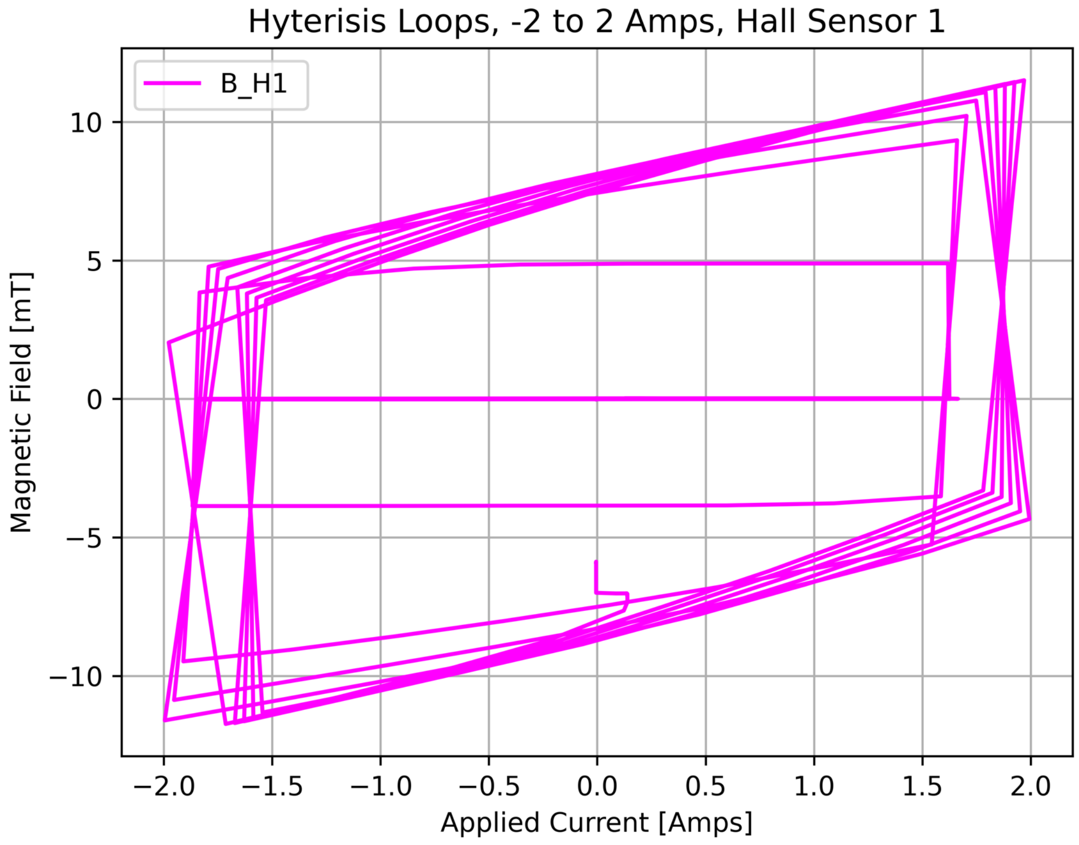


Signs of superconductivity, Hysteresis Loops, BISCO tube



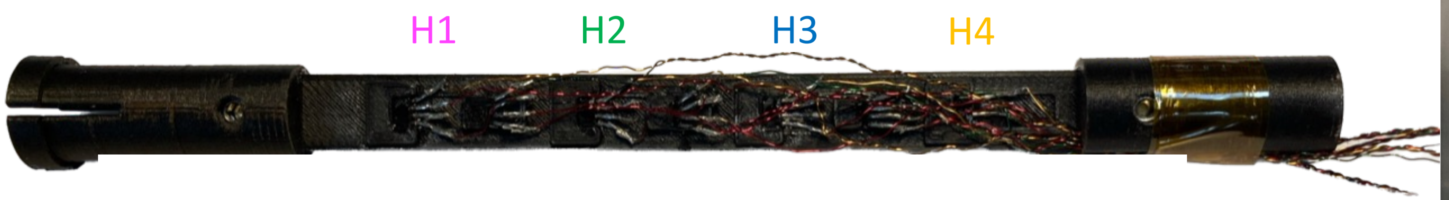
Hysteresis Loops, H1 sensor, BISCO tube

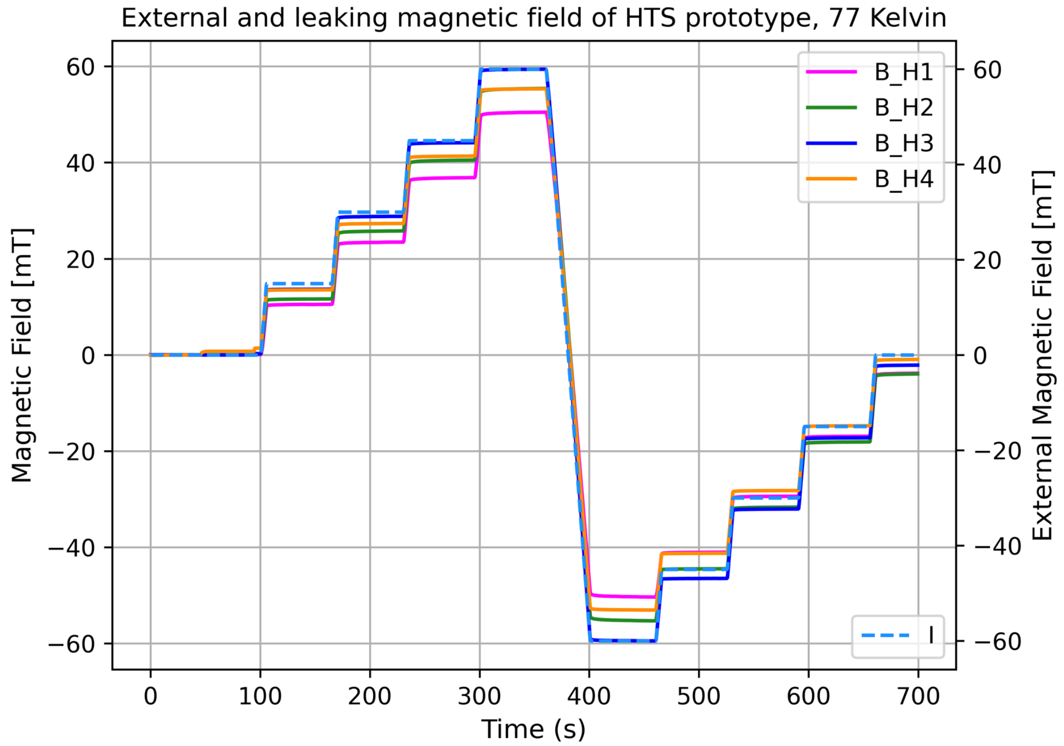


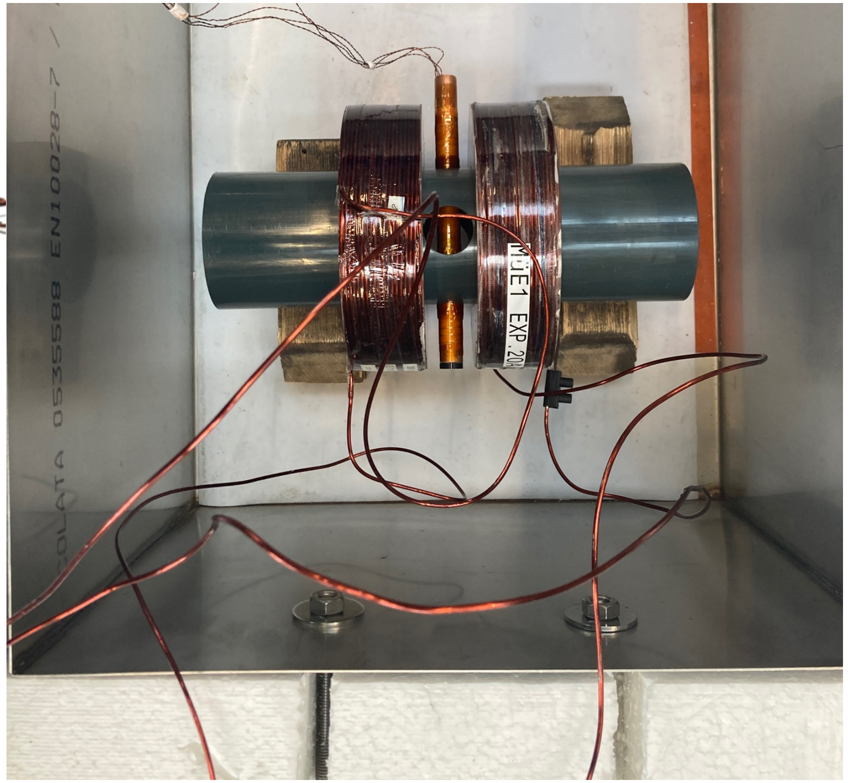


Testing SC-shielded prototypes, HTS prototype

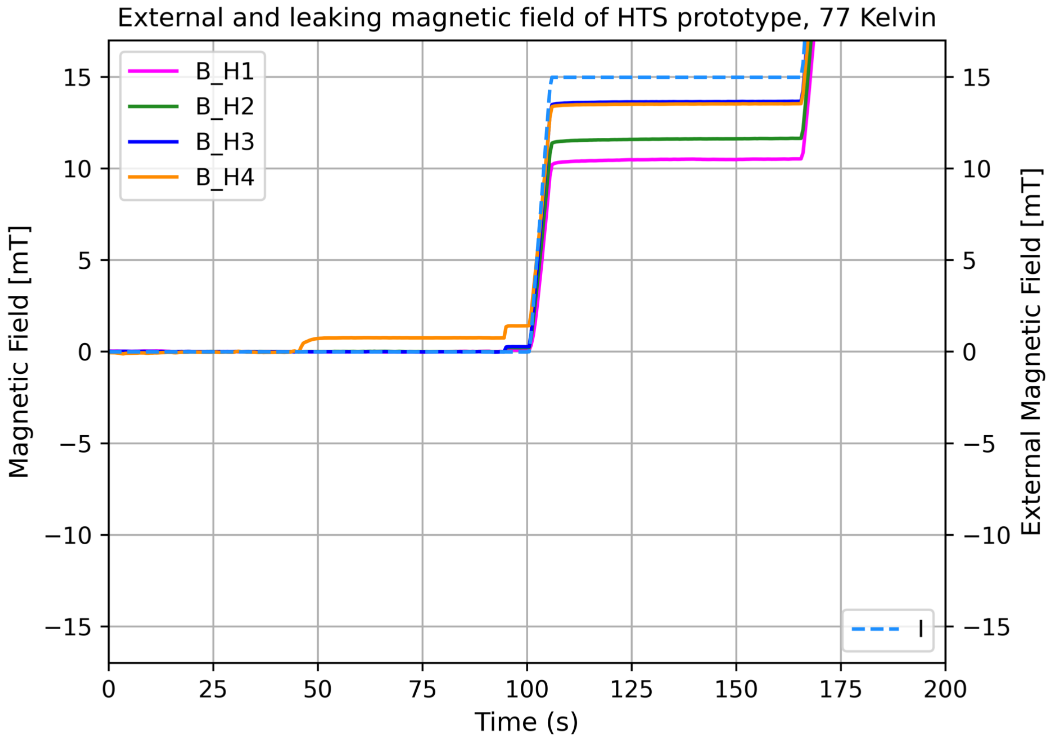
Testing the superconductive properties of an HTS prototype, with a Helmholtz coil pair of 100 mT, in a 77K cryogenic bath.

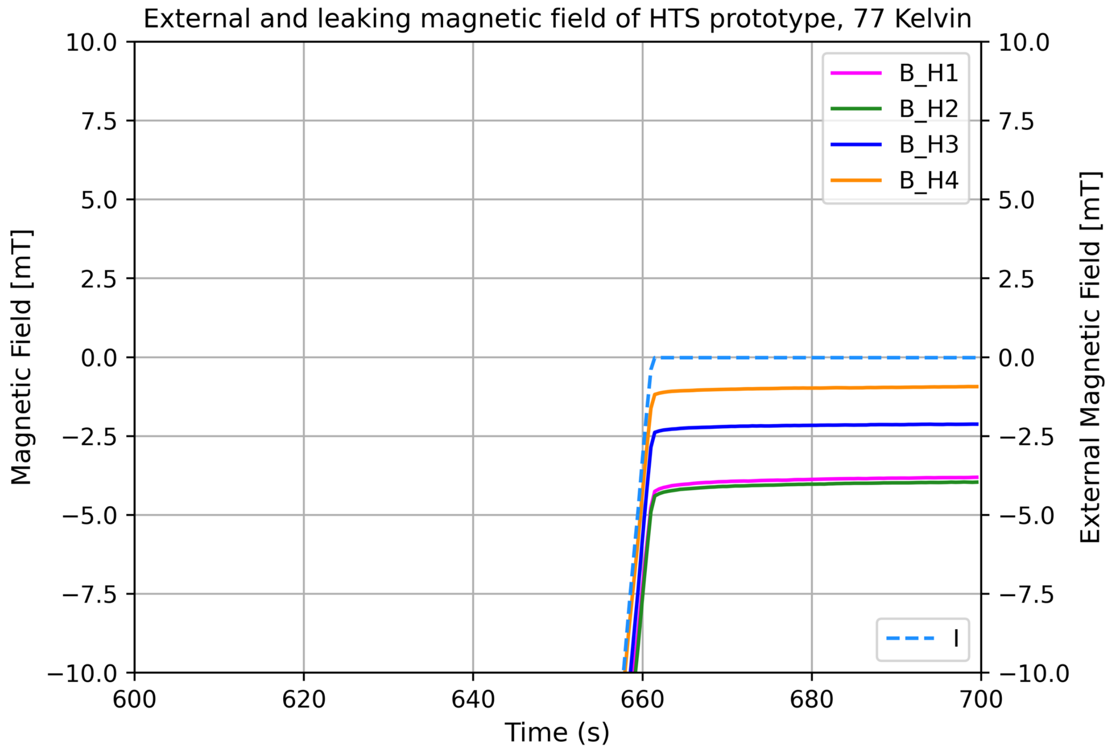






Testing SC-shielded prototypes, signs of superconductivity, HTS prototype





Signs of superconductivity, Hysteresis Loops, HTS prototype