Superconducting shield for the injection channel of the muEDM experiment at PSI

Journal Article

Author(s):
Doinaki, Anastasia; Calzolaio, Ciro; Chakraborty, Ritwika; Duda, Michal; Dutsov, Chavdar; Giovannozzi, Massimo; Hume, Timothy; Michielsen, Katia; Morvaj, Ljiljana; Papa, Angela; Schmidt-Wellenburg, Philipp; Stäger, David; Vitali, Bastiano

Publication date:
2023-10

Permanent link:
https://doi.org/10.3929/ethz-b-000641860

Originally published in:
Journal of Instrumentation 18(10), https://doi.org/10.1088/1748-0221/18/10/C10011

Published by IOP Publishing for Sissa Medialab
Received: *August 8, 2023*
Accepted: *September 6, 2023*
Published: *October 18, 2023*

New Frontiers in Lepton Flavor
Pisa, Italy
15–17 May 2023

Superconducting shield for the injection channel of the muEDM experiment at PSI

Anastasia Doinaki,[a,b,*] Ciro Calzolaio,[a] Ritwika Chakraborty,[a] Michal Duda,[a] Chavdar Dutsov,[a] Massimo Giovannozzi,[c] Timothy Hume,[a,b] Katia Michielsen,[a,b] Ljiljana Morvaj,[a] Angela Papa,[a,d,e] Philipp Schmidt-Wellenburg,[a] David Stäger[a,b] and Bastiano Vitali[d,f] on behalf of the muEDM collaboration

[a]*Paul Scherrer Institut (PSI), 5232 Villigen, Switzerland*
[b]*Eidgenössische Technische Hochschule Zürich (ETH Zürich), 8092 Zurich, Switzerland*
[c]*CERN Beams Department, 1211 Meyrin, Switzerland*
[d]*Istituto Nazionale di Fisica Nucleare (INFN) Sezione di Pisa, 56127 Pisa, Italy*
[e]*Dipartimento di Fisica dell'Università di Pisa, 56127 Pisa, Italy*
[f]*Dipartimento di Fisica dell'Università di Roma "La Sapienza", 00185 Roma, Italy*

E-mail: anastasia.doinaki@psi.ch

Abstract: At the Paul Scherrer Institute (PSI), we are setting up an experiment to search for the electric dipole moment (EDM) of the muon using the frozen-spin technique. The discovery of a muon EDM would indicate violation of charge conjugation parity symmetry (CP-violation) and lepton flavor universality, beyond the Standard Model. The experiment aims to achieve a sensitivity of $\sigma(d_\mu) \leq 6 \times 10^{-23}\,\mathrm{e} \cdot \mathrm{cm}$.

This study is taking place during the first phase of the experiment and it focuses on the off-axis injection of muons into a 3 T storage solenoid. Muons need to be transported from the exit of the PSI beamline, a low magnetic-field region, into the strong magnetic-field of the solenoid. For this purpose, two magnetically shielded channels are being developed. In the direct vicinity of the injection helix inside the solenoid bore, we will use superconducting (SC) shielding to avoid any hysteresis effect, while farther away in the fringe field we will use iron tubes. Three prototypes of SC injection tubes will be produced: the first will use a commercial high temperature superconducting (HTS) tape wrapped around a hollow copper tube, the second will utilize several Nb-Ti/Nb/Cu sheets obtained from CERN, wrapped and mechanically clamped around another hollow copper tube, while the third will consist of a commercial cast Bi-2223 superconducting tube coiled with HTS tape. To evaluate the effectiveness of the different SC-shields, we will measure their shielding factors and determine the muon injection efficiency from the beamline into the solenoid.

Keywords: Instrumentation for particle accelerators and storage rings - low energy (linear accelerators, cyclotrons, electrostatic accelerators); Low-energy ion storage

*Corresponding author.

https://doi.org/10.1088/1748-0221/18/10/C10011

2023 JINST 18 C10011

Contents

1 Introduction

A non-zero EDM of a fundamental particle indicates CP-violation [1]. Thus, the discovery of a muon EDM would be a signal indicating physics beyond the Standard Model. The most recent investigation of a muon EDM was conducted at the $g - 2$ storage ring of the Brookhaven National Laboratory. This set an upper limit of $\sigma(d_\mu) \leq 1.8 \times 10^{-19}$ e · cm (95% CL) [2] on the muon EDM searches.

A dedicated search for the muon EDM is conducted at PSI using the frozen spin technique [3], for the first time. The muEDM experiment is split into two phases. During the first phase, where this research takes place, the feasibility of the frozen-spin technique will be tested and a search for the muon EDM will be conducted with a sensitivity of $\sigma(d_\mu) \leq 3 \times 10^{-21}$ e · cm. Following, after optimizations the second phase aims to achieve a sensitivity surpassing $\sigma(d_\mu) \leq 6 \times 10^{-23}$ e · cm.

2 The injection channel

Muons with a momentum of 28 MeV/c, need to pass from the exit of the beamline, a low magnetic-field region, into a 3 T storage solenoid, high magnetic-field region. The muons will encounter a changing magnetic field as they approach the bore of the magnet. Figure 1 shows the absolute magnetic field strengths along the injection channel. These varying magnetic field strengths make the muons susceptible to the magnetic mirror effect [4], and most muons will spiral in and back out of the solenoid. To mitigate this effect and ensure efficient muon injection, magnetic shielding will be employed.

Two magnetically shielded injection channels will be developed, one injecting muons clockwise and the other one counterclockwise. Possible systematic effects are characterized by comparing the injection performance of both channels. In particular, it will be essential to maximize the transmission of muons through the channel while preserving their polarization, to maintain an overall high sensitivity.

2023 JINST 18 C10011

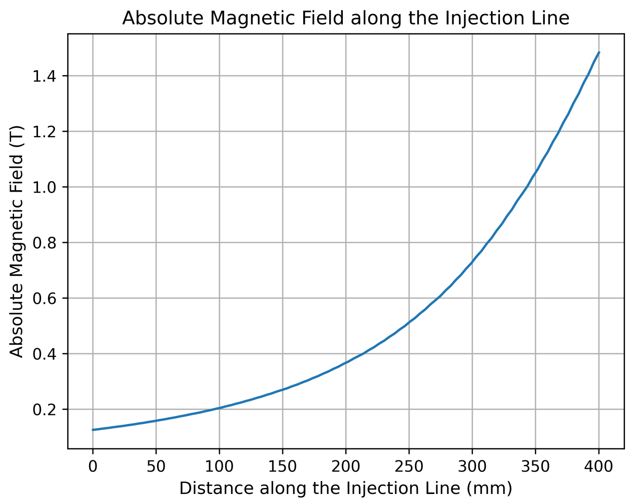

Figure 1. The absolute magnetic field that the muons encounter along the injection channel.

2.1 The injection tube prototypes

To ensure a magnetically shielded injection in the fringe field region, below 1 T, iron tubes will be employed. However, when it comes to higher magnetic field strengths, iron tube shielding becomes inadequate as it allows magnetic field leakage and is susceptible to hysteresis effect [5]. To address this, SC-materials will be employed in the high field region ranging from 1 to 3 T. The SC-materials will be directly connected to a cryocooler, ensuring that they remain below their critical temperature, T_c, and thus superconducting.

As part of the injection channel, three SC-prototype tubes are currently being developed and tested. The first prototype utilizes High Temperature Superconducting (HTS) tape,[1] with a high T_c of 93 K, helically wounded around hollow copper tubes. The second prototype consists of Nb-Ti/Nb/Cu SC-sheets [6], with a T_c of 9.2 K, clamped around hollow copper tubes. These SC-sheets are no longer produced and we have borrowed them from CERN. Lastly, the third prototype will be a combination of a commercial SC-tube Bi-2223,[2] with an inner diameter of 15 mm, and a T_c between 105–110 K, reinforced with SC-tape. This way we will utilize both the isotropic induced currents, in the Bi-2223 tube, and the persistent currents along the coiling direction of the SC-tape.

Once the SC-prototypes are developed, the next step is to test them and identify the most efficient configuration with the highest shielding factor. Various parameters, including the length and diameter of the injection tubes, as well as the number of layers and orientation of the shielding, will be studied and optimized.

2.2 SC-prototype testing

A precursor experiment is designed to evaluate the superconducting prototypes, incorporating a Helmholtz coil pair with a magnetic field strength of 100 mT and a liquid nitrogen (LN_2) bath maintained at 77 K. The SC-prototype, under study, will be placed between the two coils and the whole system will be submerged into the cryogenic bath, as shown in figure 2.

[1] 2G HTS wire, S-Innovations, 2011–2020.
[2] CAN-superconductors, 2023.

2023 JINST 18 C10011

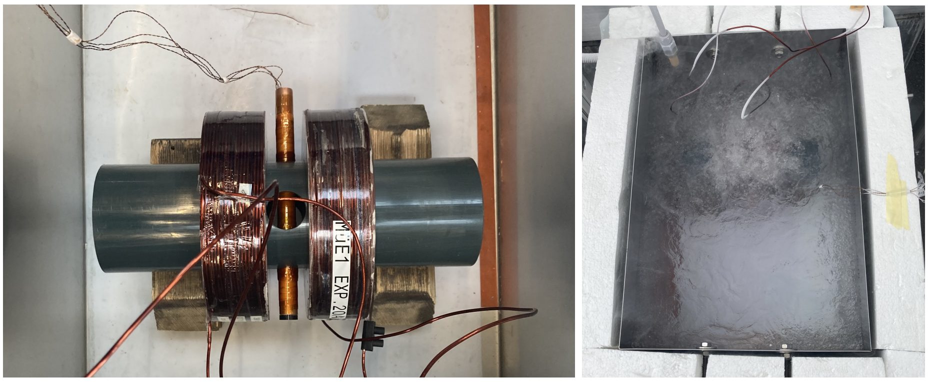

Figure 2. On the *left*, the experimental set up; Helmholtz coil pair and a SC-prototype placed between the two coils. On the *right*, the experimental set up submerged in the LN_2 bath.

Initial measurements were performed on a prototype with an HTS tape, helically wounded around a hollow copper tube with an inner diameter of 15 mm. Measurements of the magnetic field inside the prototype were conducted using four Hall Sensors,[3] positioned on four horizontal slots with a separation of 24 mm between them on a support system. This setup enables the characterization of the field as a function of the position. The measurements were taken at 77 K, with and without superconducting shielding, as illustrated in figure 3.

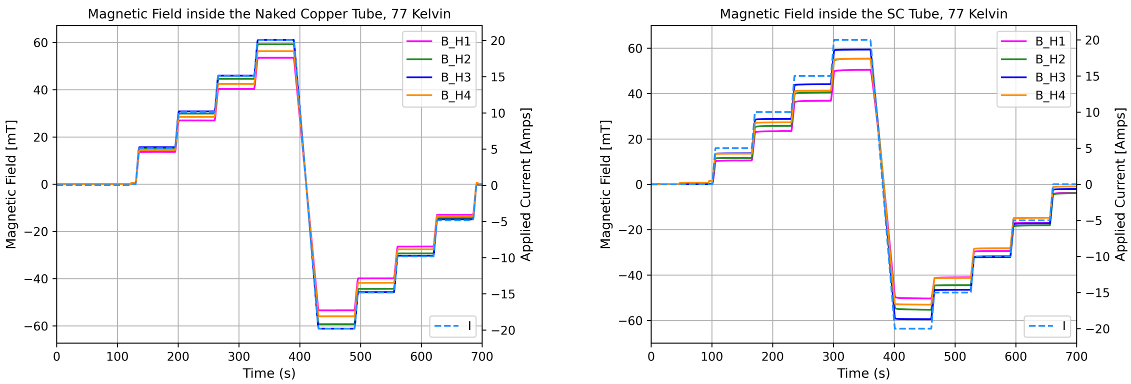

Figure 3. The leaking magnetic field inside a “naked” (without SC-shielding) copper tube, *left*, and a SC-tube, *right*, under a magnetic field of 100 mT at 77 K for the four Hall Sensor positions.

Comparing the plots in figure 3, we notice that the plateaus of the SC-shielded tube are curved with respect to the sharp plateaus of the tube without the SC-shielding. This indicates the presence of persistent currents flowing in the SC-shielded tube, counteracting the external magnetic field, and thus shows signs of superconductivity. After completing the measurement cycle, the current returns to 0 A, but there is still remaining magnetic field inside the SC-tube. This indicates the presence of hysteresis effect [5], where persistent currents are still flowing inside the superconductor even when the magnetic field is removed. In future tests with better SC-tubes, a more dominant presence of persistent currents and hysteresis is expected as well as lower leaking magnetic flux densities.

[3]THS119 Hall Sensors, TOSHIBA Electronic Devises & Storage Corporation, 2023.

2023 JINST 18 C10011

3 Outlook

At PSI we are setting up a novel experiment to search for the muon EDM. The successful injection of the muons into the 3 T storage solenoid is crucial for the experiment. Three prototypes of the injection channel are currently developed and tested, studying different superconducting shielding configurations. All prototypes will be tested with respect to their shielding factor and thus to their muon injection efficiency. An experiment is already set up including a 100 mT Helmholtz coil pair and a LN_2 cryogenic bath. Tests conducted on an HTS prototype showed signs of superconductivity.

Acknowledgments

The author extends gratitude to all the muEDM collaborators for their support throughout this project. This project is funded by the Swiss State Secretariat for Education, Research and Innovation (SERI) under grant No. MB22.00040 and Swiss National Science Fund under grant No. 204118.

References

[1] G. Lüders, *On the equivalence of invariance under time reversal and under particle-antiparticle conjugation for relativistic field theories*, *Dan. Mat. Fys. Medd.* **28** (1954) 1.

[2] Muon $g-2$ collaboration, *Final Report of the Muon E821 Anomalous Magnetic Moment Measurement at BNL*, *Phys. Rev. D* **73** (2006) 072003 [hep-ex/0602035].

[3] A. Adelmann et al., *Search for a muon EDM using the frozen-spin technique*, arXiv:2102.08838.

[4] R.J. Allen, *A Demonstration of the Magnetic Mirror Effect*, *Am. J. Phys.* **30** (1962) 867.

[5] H.W.F. Sung and C. Rudowicz, *Physics behind the magnetic hysteresis loop—a survey of misconceptions in magnetism literature*, *J. Magn. Magn. Mater.* **260** (2003) 250.

[6] D. Barna et al., *NbTi/Nb/Cu multilayer shield for the superconducting shield (SuShi) septum*, *IEEE Trans. Appl. Supercond.* **29** (2018) 4900108 [arXiv:1809.04330].

2023 JINST 18 C10011