Superconducting shielding with Pb and Nb tubes for momentum sensitive measurements of neutral antimatter

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ABSTRACT: In this paper we report on measurements and simulations of superconducting tubes in the presence of inhomogeneous externally applied magnetic fields in a cryogenic environment. The shielding effect is studied for two different tube materials, Pb and Nb, employing Hall sensors in a tabletop experiment. The measured internal and external fields of the tubes agree with the theory of the Meissner-Ochsenfeld effect [1], field trapping of type 2 superconductors, phase transitions and tube geometries. The obtained measurements are compared to a finite element simulation. Next, the simulation model is applied to estimate the shielding effect in the vicinity of a cryogenic Penning trap experiment. The controlled suppression of external magnetic fields is important for future precision experiments in atomic and antimatter physics in cryogenic environments.

KEYWORDS: Superconductive detection materials; Superconductive detectors (bolometers, tunnel junctions etc)

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1 Superconductive shielding

In this paper, the effects of an externally applied magnetic field on superconductor (SC) tubes are studied. The SC tubes are investigated experimentally and via simulations on their property of shielding external magnetic fields. Shielding magnetic fields with SC have been studied for SC Pb cans in [2] and investigated for the application of SC linear accelerators as a Nb can in [3–5] and for bulk and thin layers of Pb, Cu and In in [6]. High-Tc SC shields have been studied in [7] and for the application of SQUID sensors in [8]. NbTi SC magnetic shields and their soldering joints to build various geometries have been studied in [9]. A Meissner shield was further proposed for the ALICE detector in [10].

In the present work, SC tubes made from bulk Pb and Nb at different geometrical aspect ratios of 1.2, 4.4 and 5.1 were studied at 300 K and 4.2 K. The SC field trapping during the phase transitions was investigated along with the Meissner-Ochsenfeld shielding effect at 4.2 K. The magnetic field was provided by a SmCo permanent magnet, which could be oriented along the radial and axial positions relative to the SC tubes.

Theoretically, superconductive shielding is described by the Meissner-Ochsenfeld effect. Here certain solid-state materials are approximated as an ideal SC that behaves as a diamagnet with relative permeability $\mu_r = 0$, reflecting all applied magnetic fields. For an area surrounded by a SC the condition of a quantization of the flux, described in [1], is

$$ n \frac{h}{q} = \mu_0 A_L^2 \oint j_s dr + \phi. $$

(1.1)
For this equation the solutions are a null field or the channeling of the field lines parallel to the SC. Field lines with a perpendicular component to the SC wall are canceled by formation of a counter circular current. Those fields are exponentially suppressed and described by the London equation applied to Ampere’s law [11] as

$$\lambda_L = \sqrt{\frac{m}{\mu_0 n q^2}}$$

(1.2)

with the mass of the charge carriers $m$ and the number density $n$. In the studied case of a SC tube geometry with a wall thickness $D \gg \lambda_L$, the contribution

$$\mu_0 \lambda_L^2 \int j_s dr$$

(1.3)

becomes negligible and results in a flux

$$n = \frac{\hbar}{q} \sim \phi$$

(1.4)

with

$$|q| = 2e,$$

(1.5)

as discussed in BCS-theory [12]. Experiments have confirmed the relation

$$\phi = \phi_0 n = \frac{\hbar}{2|e| n}.$$  

(1.6)

in [13]. The magnetic field lines cannot permeate through the present SC geometries, as indicated in figure 5a. Thus depending on the strength of the magnetic field and the diameter of the superconducting tube, the field lines can be displaced out of the open tube ends. A magnetic field that is already present during the process of cooldown can be repelled from the superconducting body or trapped depending on material properties and field conditions.

## 2 Field trapping

In non-ideal type 1, as well as in type 2 SC, field trapping may occur. During the process of cooldown in the temperature vicinity of the superconducting phase transition, flux lines can get pinned to normal conducting (NC) impurities [14] or grain boundaries [15]. This process of flux pinning [14] occurs normally only in the Shubnikov phase [16] $H_{c1} < H < H_{c2}$, where the critical current flows within a depth necessary to reduce the field inside the SC to $H_{c1}$. At field strengths $H_{c1} < H < H_p$, below a penetration field $H_p$, fluxlines will not penetrate through the Bean-Livingston barrier, which is caused by the attraction of the Abrikosov vortices to their ‘mirror images’ near the surface. For a plain type 2 SC with ideal homogeneous surfaces, $H_p$ can be assumed as the thermodynamic critical field $H_c$ as

$$H_p \approx H_c \approx \frac{kH_{c1}}{\ln(\kappa)} \approx \sqrt{H_{c1}H_{c2}}$$

(2.1)

with $\kappa = \frac{\lambda}{\xi}$ [17]. Here $\lambda$ is the penetration depth and $\xi$ is the coherence length. For the typical values of Nb $H_{c1} \approx 130 \text{ mT}$ and $H_{c2} \approx 280 \text{ mT}$ this would result in $H_p \approx 190 \text{ mT}$. The number of pinned flux lines can be reduced by applying a temperature gradient $\Delta T$ to the SC during cooldown. This
can cause an effect of driving the field out of the bulk material through the not-yet superconducting part [18]. Further in practice, field trapping can also be reduced by special preparations such as annealing the superconductor and surface polishing [19].

In the case of a SC tube geometry, most field trapping is expected in the longitudinal direction parallel to the z-axis of the tube.

3 Experimental setup

The following experimental setup was used to study the behavior of SC tubes in externally applied magnetic fields. Two different length SC tubes made of Pb (99.95%) and Nb (300 R.R.R.) respectively were studied in the presence of various external magnetic fields. A permanent magnet mounted on a manipulator allowed us to apply the fields from different positions, orientations and field strengths. The employed SmCo permanent magnet consisted of a cylinder of dimensions $r = 5\text{ mm}$ and $l = 20\text{ mm}$ and exhibited an axial magnetic field strength of 40 mT at a distance of 10 mm at 300 K. Two magnetic Hall sensors, one mounted at the center position inside the SC tubes and one adjacent to the permanent magnet, measured the inner magnetic field strengths $B_i$ and outer $B_o$. A temperature range of 300 K down to 4.2 K was investigated. The Hall sensors were made from an AlGaAs/GaAs chip (MagCam CHS-6 [20]) and could be operated at room temperature and at a LHe environment. Figure 1, left side, depicts the liquid helium bath cryostat with a viewport, showing the Pb-tube at boiling helium temperature and atmospheric pressure. The sensor chip was fabricated with six Hall sensors of various sensitivities. The sensor with the highest sensitivity range was used (see figure 1 right picture). The sensor chips were Al wirebonded and glued to a PCB board (ENEPIG on FR4). The Hall sensors were mounted (G10 structures) with tilts of 45° in the three Cartesian angles relative to the SC tube to determine the present radial and axial magnetic field components. As the electron population in the conducting band of the sensor depletes at cryogenic temperatures within seconds the sensors were activated (conducting band repopulated) with light at 890 nm (LED TSHF5210, 70 mA) over a duration of 1 min which guaranteed a stable measurement time of several hours. The readout was performed with two multimeters (Keithley 2000) connected to a LabView program. The constant Hall current to the sensors was provided via two source-meters (Keithley 2410) at 0.2 mA. The temperature of the SC tube was monitored during the entire measurement (TVO 205 sensor connected to a Keithley 2000). To set the temperature of the tubes, two resistive heaters were attached to the outside of the SC ($R = 10\Omega$ and 100\Omega).

Due to the fact that the offset and the sensitivity of the Hall sensors are temperature dependent [20] and the exact field strength of the permanent magnet was modeled from [21], all values of the magnetic fields are obtained with only relative precision. Here, we deduce the measured magnetic flux of the Hall sensors to be about a factor of 3.4 weaker at liquid helium temperatures than at room temperature, which is considered in the results.

4 Results

In the following the behaviour of SC tubes of various aspect ratios are discussed for materials of Pb and Nb. For each measurement the magnetic field flux density is plotted versus the relative magnet-tube distance. The data is compared to a finite element simulation of the SC described in section 5 for the different tube geometries. In a first measurement, the magnet-tube distance is
Figure 1. Experimental setup build up at the Cryogenic Laboratory at CERN. Left side: picture of the LHe bath cryostat with a viewport showing one of the Pb tubes and the adjacent magnet holder. Right side: picture of the outer Hall sensor and LED mounted on a PCB board. The SmCo magnet is seen in dark gray mounted next to the PCB. The magnetic field produced by coiled cables is below $10^{-8}$ mT. The lower picture shows the Hall sensor and the Chip inside the long lead tube.

varied in the on-axis direction with $h_1$ the distance measured from the magnet to the tube middle position $L/2$ of length $L$. In a second measurement, the off-axis dependence of the magnet distance was recorded. Here $h_2$ is the distance to the tube middle position $L/2$ and the movement direction of the magnet has a fixed off-axis displacement in comparison to the tube axis of $47\,\text{mm}$. In a third measurement, the radial distance magnet-tube $r$ is varied with the magnet initially positioned at the middle of the tube. The three sets of measurements are plotted for each tube geometry in figure 2a, e for Pb and in figure 3a, e for Nb. The magnet was moved in steps of $10\,\text{mm}$ for the axial and $3\,\text{mm}$ for the radial measurements but a continuous data readout was taken. To avoid errors from vibrations, each data point was taken after at least 10 seconds of waiting time. The size of the steps was measured with a ruler and by using several marks on the aperture.

The results of the on-axis measurement are plotted in figure 2b, f for Pb and in figure 3b, f for Nb. Here the magnet was initially at an axial position of $h_1 = 220\,\text{mm}$ and $r = 0\,\text{mm}$. Figure 2c, g and figure 3c, g show the results from the off-axis measurements. From an initial position of $h_2 = 220\,\text{mm}$ and $r = 47\,\text{mm}$, the magnet was moved parallel to the tube axis. The radial measurement is plotted in figure 2d, h for Pb and figure 3d, h for Nb starting at an initial magnet position in the tube middle and at a radius of $r = 47\,\text{mm}$. The magnet was then moved closer to the tube. Once the magnet reached the closest of $h_{1\text{min}} = 5\,\text{mm}$, $r_{\text{min}} = 7\,\text{mm}$ constraint by the magnet mount and the outer tube diameter, the magnet was again moved to the initial position using the same step sizes.
The used Hall sensors were not calibrated to a null-field at 300 K and 4 K and exhibited a
temperature dependent sensitivity and offset.

Due to this, all data are expressed in relative values. To compare the individual measurements,
an offset was added in each plot to bring the initial data points of 300 K and 4.2 K closer to each
other. This was performed for both the outer and inner sensor data. An offset was added to the
simulation graph to have a common starting value with the data points of the inner sensor. The error
on all measurements depended on the distance from the sensor to the magnet and even more on the
angle of the field lines of the magnet and the reflected field penetrating the Hall sensors. In the case
of the axial measurements on short tubes, the Gaussian $\frac{1}{\Sigma}$ error ranges from ±8 µT for distances of
~ 100 mm to ±3 mT for the closest distance. Thus, for the plots the following notations were made:

- Black squares: measurements at 300 K.
- Red triangles: measurements at 4.2 K.
- Blue star: simulation at 4.2 K
- Green circle: second recording at 4.2 K for the on-axis measurement for the short Pb tube.
- Full symbols: data recorded by the Hall sensor inside the tube.
- Empty symbols: data recorded by the outer Hall sensor mounted on the magnet holder.
- $h_1$: distance of the magnet from the tube middle (L/2) with the cylinder axis of the magnet
  and the tube aligned.
- $h_2$: distance of the magnet from the tube middle (L/2) with the cylinder axis of the magnet
  parallel to the tube axis with a radial distance of $r = 47$ mm.
- $r$: distance of the magnets surface (10 mm diameter) to the center of the tube axis.

4.1 Long lead tube

Figure 2a) depicts the measurement for the case of a Pb tube of length $L = 200$ mm and diameter
$D = 45$ mm. The inner sensor measured no change of the magnetic field during the movements at a
temperature of 4.2 K. The tube created a diamagnetic field that increased the field measured by the
outer sensor. This can be seen both axially (in figure 2b, c) and radially (in figure 2d). Further, at a
distance below $h_1 = 100$ mm, the magnet induced a field at 4.2 K in the Pb tube that can be seen in
figure 2b at 105 mm and in c during the movement. This hysteresis is typical for type 2 SC. In the
Shubnikov phase [16] flux lines can enter the superconductor, get caught by pinning centers [14]
and thus do not exit the superconductor when the magnet gets moved away. From the figures a
shielding effect can be observed at 4.2 K. Here all measurements of the inner sensor stay below a
field change of 0.05 mT compared to a change of 0.3 mT for the equivalent 300 K measurement.
The shielding effect is also seen in the simulation To explain the strong hysteresis in figure 2b, c,
one must know that the long lead tube measurement was performed in another way than the other
three measurements. As it was originally planned to display the recordings at six different magnet
positions only the measurement points on these known positions could be taken. This also means
Figure 2. Measured relative magnetic field changes inside and outside of Pb tubes of two different lengths. The empty symbols depict the outer Hall sensor and the solid symbols the inner Hall sensor. Black squares: magnetic field at 300 K. Red triangles: magnetic field at 4.2 K. The blue solid stars indicate the simulated field at 4.2 K at the position of the inner sensor. The blue vertical line indicates the top end of the tube. In figure 2a, e the tube geometry and the three measurement sets are sketched: in figure 2b, f the magnet was moved relative to the tubes in the on-axis direction; in figure 2c, g in the off-axis direction and in figure 2d, h in the radial direction. An offset was added to the relative values in each measurement and in the simulation to compare the values at the same starting points $h_1 = h_2 = 220$ mm and $r = 47$ mm.

that the magnet was moved to different positions in a certain order which explains why in figure 2b the magnet passed the position $h_1 = 105$ mm two times and was able to build up a hysteresis in between. This also implies the hysteresis effect in figure 2c. Here the magnet was moved to different positions closer to the tube as well in between the two measurement points at $h_2 = 5$ mm.

4.2 Short lead tube

Figure 2e displays the measurement on a Pb tube with dimension of $L = 55$ mm and $D = 45$ mm. Here, in figure 2f the inner sensor observed an increase in the magnetic field at 300 K and also in
the SC phase at 4.2 K. This is caused by two factors: the magnetic field leaking into the tube as seen in figure 5b and the diamagnetic field built up by the SC to shield against the B-field of the magnet. In figure 2f the measurement at 4.2 K was performed twice to verify the observed hysteresis effect. It can be seen that the second on-axis measurement (run 2) starts at the same field as the end of run 1. Due to the limited number of pinning centres in the tube, the hysteresis in run 2 is smaller than in run 1. The simulation reproduces the increase in field for smaller distances, however shows a factor two higher value for the closest point. This is most likely due to high sensitivity to unintended movements in radial direction, which manifest a larger error at close distances. Compared to the measurement at 300 K, the shielding effect is still visible but not as strong as in the case of the longer Pb tube. The measured higher field values in figure 2f, h are because in the short lead tube, the magnet could be moved 75 mm closer in $h_1$ to the inner Hall sensor. Thus at $h_1 = 105$ mm the inner sensor at 300 K shows about 0.2 mT difference in figure 2f compared to the long lead tube in figure 2b.

Figure 2g pictures the off-axial measurement. Here at 300 K a clear change of the direction of the magnetic field is visible as the inner sensor recorded the magnetic south and north part of the vector field. When the tube is in the SC phase, the inner sensor observed a field increase in the same direction on both end positions of the tube when the magnet passed by. Leakage of the field at the ends of the tubes were recorded, with the primary magnet’s field being mostly blocked by the SC.

For the measurement the inner sensor had a small axial displacement of order of mm from the tube center position. Together with the tilt of the sensor chip of $45^\circ$ and the magnetic pattern of the SmCo this led to the observed asymmetry of the heights of the two maxima at $h_2 = -25$ mm and $h_2 = 50$ mm in the 4.2 K curve. Further, the local minima is not at $h_2 = 0$ mm but at a distance of $h_2 \sim 10$ mm. Similarly, the measurement at 300 K showed the turnover point in the field shifted in $h_2$ by the same amount. Similar to the inner sensor at 4.2 K, the outer sensor measured a stronger field at the ends of the tube compared to in the middle position. The outer sensor also recorded a hysteresis between the movement closer and away from the tube.

In figure 2h the radial measurement shows a slight field change in the SC-phase. Because of the small aspect ratio of the tube, the magnetic field leaked into the open ends. As expected, the outer sensor saw an increase in the magnetic field close to the tube with also a small hysteresis effect visible. At 300 K, the slight hysteresis of the inner sensor most likely derives from a small inaccuracy of $r$. 

### 4.3 Long niobium tube

Figure 3a depicts the used Nb tube with dimensions $L = 179$ mm and $D = 35$ mm. For the on-axis measurement with the tube in the SC-phase, seen in figure 3b, the inner sensor recorded an almost complete shielding against the magnet compared to the measurement at 300 K. Plotted in the same graph, the outer sensor measured an increase in the field strength with smaller $h_1$ as a result of the diamagnetic field from the SC.

Figure 3c shows the off-axial measurement. At 300 K, the inner sensor measured the direction change of the magnetic field, similarly to figure 2c, g. For this measurement the inner sensor was mounted intentionally 20 mm closer to the top of the tube to yield more sensitivity to the shielding effect. At 4.2 K the inner sensor recorded no changes in the field strength for various distances. Thus, with the tube in the SC-phase, the magnetic field is shielded completely. The accompanying
Figure 3. Measured magnetic field inside and outside of Nb tubes of two different lengths. The empty symbols depict the outer Hall sensor and the solid symbols the inner Hall sensor. Black squares: magnetic field at 300 K. Red triangles: magnetic field at 4.2 K. The blue solid stars indicate the simulated field at 4.2 K at the position of the inner sensor. The blue vertical line indicates the top end of the tube. As sketched in the figure 3a, e the magnet was moved relative to the tubes: figure 3b, f shows on-axis direction; figure 3c, g shows off-axis direction and figure 3d, h indicates the radial direction. An offset was added to the relative values in each measurement and in the simulation to compare the values at the same starting points at \( h_1 = h_2 = 220 \text{ mm} \) and \( r = 47 \text{ mm} \).

The increase of the magnetic field alongside the tube is recorded by the outer sensor. Due to the tube diameter of \( D = 35 \text{ mm} \), the \( r \) position of the outer sensor was 10 mm further away from the magnet compared to the Pb tubes. Therefore, the measured diamagnetic field on the tube edges was recorded to be smaller for Nb.

Figure 3d shows that the tube also shields the radial influence of the field completely. The changes of the closest point to the tube in the opposite direction of the inner sensor at 300 K and at 4.2 K are caused by the magnet slightly touching the tube and therefore changing its angle. As
mentioned before the sensor has shown to be very sensitive to the angle of the magnetic field. Further, in this measurements no definite signs of a hysteresis loop could be found.

### 4.4 Short niobium tube

Figure 3e sketches the used Nb tube with dimensions of $L = 55$ mm and $D = 45$ mm. As described for the case of the short Pb tube for figure 2e, only a partially shielding effect was observed.

In figure 3f a residual shielding effect is visible in the SC-phase. For a large range of $h_1$ the simulation reproduced the measured values. The closest point of the inner sensor at 4.2 K at $h_1 = 30$ mm deviates about 3 mT from the simulated point. We attribute this to the aforementioned sensor’s high sensitivity to unintended movements in radial direction, which manifest a larger error at close distances. At the same time, the outer sensor at 4.2 K and $h_1 = 30$ mm is also out of order. We would expect the value to be higher than the point at $h_1 = 45$ mm, given the magnet in the correct position. Figure 3g shows a very similar graph as in figure 2g for Pb. For the case of Nb, at 4.2 K, the outer sensor measured a less pronounced diamagnetic field on the edges of the tube and a small hysteresis, which is due to the fact that Nb is a type 2 SC. In figure 3h the measurement of the radial movement of the magnet is plotted. Because of the small aspect ratio of the tube, the field could leak inside. The outer sensor also recorded a rising diamagnetic field with closer distances.

### 4.5 Field trapping

In the following section, the process of field trapping is studied in more detail. During cooldown the magnet was initially positioned at the side of the tube at $h_2 = 0$ and at the radial distance $r = 32$ mm. After reaching the SC-phase, the magnet was brought to the far distance of $h_2 = 220$ mm. After reaching the NC-phase again the magnet was brought back to the initial position. In the long Pb tube, figure 4a, the inner Hall sensor recorded a change of the magnetic field despite being in the SC-phase. This is explained as the flux lines in the Shubnikov phase [16] leaked into the tube.

For the long Nb tube, figure 4b, the plot on the left side of the blue line indicates the trapped field when the magnet was at the close-by position $h_2 = 0$ mm and $r = 27$ mm at the time when the tube became a SC. While the tube remained in its SC-phase, the magnet was moved to the farthest possible distance of $h_2 = 220$ mm and $r = 47$ mm. At the blue line sufficient helium has boiled away for the tube to become a NC. As expected, the trapped field then disappeared. At a temperature of 11.5 K, the red line indicates when the magnet was brought back to the close-by position of $h_2 = 0$ mm and $r = 27$ mm.

The height difference between the left side of the blue line and the area between blue and red line (trapped field disappearing) of this measurement shows that 92.5% of the field was trapped both due to the present geometry and material. Applying a temperature gradient of approximately 3 K over a tube length of $L = 179$ mm using two heaters (10 Ω and 100 Ω) did not significantly change the value of the trapped field.

### 5 Simulations

To show the shielding effect and the behavior of the magnetic field lines, several simulations were performed with COMSOL 5.2 with various tube geometries and are shown in figure 5a. As COMSOL does not implement a relative permeability of 0, a permeability of $\mu_r = 10^{-16}$ was used throughout this paper to calculate the magnetic fields close to the superconductor.
(a) Inner tube diameter $D$: 45 mm.  
Tube length $L$: 200 mm.

(b) Inner tube diameter $D$: 35 mm.  
Tube length $L$: 179 mm.

Figure 4. a) Pb tube. The left dashed line indicates the transition of NC- to SC-phase. In between the solid lines the magnet was moved. The right dashed line indicates the transition from the SC- back to the NC-phase. b) Nb tube. The solid (blue) line shows the phase transition at $\sim$ 9 K. The solid line (red) shows the point, where the magnet was brought to same position as during the cooldown process.

Figure 5a depicts the case where the tube is in a Meissner phase without a field being present during the transition. Here, all field lines are shaped around the tube and can only enter through the open endings, where they are forced back out by the diamagnetism of the SC.

In figure 5b a tube with an aspect ratio of 1.1 was used as in the experiment. The line graphs show that the center of the tube has a much higher field compared to the center of figure 5a. Figure 5a and figure 5b indicate that the field lines of the magnet intrude from both sides into the tube. To show the field trapping effect of the tube geometry, two sketches, figure 5c and figure 5d were calculated. The plots show that the fields present during phase transition are pushed out of the SC and depending on their former position resided inside or outside the tube. The field lines that are moved inside of the tube are flux quantized [1] and repel each other and the tube body. Therefore they exist only in configurations of straight parallel lines. The line graphs indicate that the field stays constant when the field lines are trapped and parallel, in accordance with [1, 18]. In the case of the small aspect ratio tube from figure 5d the field lines were not sufficiently pressed together to be parallel, so the field strength does not stay constant over the tube length.

In the case of the high aspect ratio Nb tube of 4.44, the parallel field lines exhibit a negligible radial field gradient, (figure 6)

6 Magnetic shielding at the AEGIS experiment

In this section, the application of a Meissner-Ochsenfeld tube as a shield of residual magnetic field from a Penning trap magnet and environmental stray fields is discussed.

In the AEGIS experiment at the antiproton decelerator (AD) facility at CERN, an interferometer is proposed to measure the acceleration of antihydrogen ($\bar{H}$) due to Earth’s gravity [22]. The scheme of using matter wave interferometry to resolve $g$ of $\bar{H}$ has been proposed also as a suitable method in [25–27]. Amongst them, a promising design constitutes the Talbot-Lau interferometer (TLIF)
(a) Inner tube diameter: 45 mm. Tube length: 200 mm.
(b) Inner tube diameter: 45 mm. Tube length: 55 mm.
(c) Inner tube diameter: 45 mm. Tube length: 200 mm.
(d) Inner tube diameter: 45 mm. Tube length: 55 mm.

Figure 5. a), b) Simulations of SC tubes that express shielding of the inner part of the tube against the axial magnetic field. c), d) Sketch of SC tubes guiding a field trapped by the tube geometry through the SC. Red dashed lines show the dependencies for the NC-phase and the blue lines for the SC-phase.
first described by [28]. A TLIF operates by measuring the phase change that occurs when splitting and recombining atomic wave functions, typically using three periodic gratings, and can reach sensitivities of relative position changes on the order of the de Broglie wavelength of the examined particles [29]. Using a TLIF the phase shift induced by gravity has been measured for neutron beams by rotating the IF grating plane to control the influencing effect of g during the measurement [30]. In a similar scheme, the axially emitted fraction of $\bar{H}$ could be allowed to traverse a TLIF attached to the downstream opening of the Penning trap.

For such a setup in AEgIS, the antiatoms are proposed to be produced from resonant-charge-exchange of its constituents antiprotons and positrons [23] resulting in Rydberg states of $n \sim 30$ [22]. The total angular momentum $J$ of the $\bar{H}$ are then randomly projected on to the magnetic field axis of the Penning trap to a broad distribution of about $-30 < m_f < 30$. However, a magnetic field gradient of 1 µT/cm acting on a $\bar{H}$ in the $m_J = 30$ state during its passage through the TLIF can mimic the effect of gravity due to the Zeeman force $F_b = \nabla B \mu_B m_J$. To have complete knowledge of magnetic fields, or suppress them, to such accuracies poses a critical challenge to AEgIS and similar experiments, which are proposed to be carried out at cryogenic temperatures. Considering the geometrical constrain of the AEgIS apparatus [32], a SC tube of material Nb with length of 2 m and 0.2 m diameter could be placed within the apparatus in the cryogenic bore hole approximately 0.31 m away from the 5 T coil of the Penning trap. For this experimental configuration a simulation was performed with the results shown in figure 6a. At the proposed SC position in the setup and with the assist of the installed correction coils, the magnetic fields strength around the SC tube can then be kept under $H_{c1}$ 130 mT of Nb [32–34] with the calculated value of the residual field of 116 mT on axis at R=0. A SC tube then attenuates the field by a factor of 5.6 to 20.5 mT. According to the simulation from figure 6c a radial gradient of 5.6 mT/R at the SC tube entrance at R=0.1 m causes an acceleration due to the Zeeman force in vertical direction of $a = F_b/m_{\bar{H}} = 9538$ m/s$^2$. However, 40 cm inside the SC tube the acceleration due to the magnetic field gradient would have decreased to $9.08 \times 10^{-4}$ m/s$^2$ for the same $m_J = 30$ state. In the center of the 2 m tube, the residual field is 5.4 mT, which would be reduced the field to below $3.6 \times 10^{-7}$ mT.

To further suppress the magnetic fields inside the SC tube, a Nb iris of 80 mm can be electro-welded [35] onto the front open end of the SC tube without blocking the $\bar{H}$ beam emitted from the Penning trap. This would enhance the performance of the SC tube by approximately a factor of 100 (as pictured in figure 6a). In this case, the tube could be mounted even closer, e.g. 30 cm distance to the 5 T magnet and the field would further decrease from 124 mT at the beginning of the tube by a factor of 13.5 to 9.2 mT. Additionally, the field of 5.4 mT in the center of the tube would be suppressed to under $2.4 \times 10^{-9}$ mT as shown in figure 6b.

In figure 6c the radial gradient of a tube with 8 cm iris and a tube without iris is compared. Assuming complete field freezing at the phase transition, only the constant Earth’s magnetic field of $\sim 50$ µT is considered in the simulation. Hence, a Meissner shield can greatly assist in a measurement of the gravitational acceleration g of $\bar{H}$.

7 Conclusion

In this manuscript, the SC shielding effect of Pb and Nb tubes for tube aspect ratios of 1.2, 4.4 and 5.1 was studied. Nb tubes exhibit a significantly better performance in shielding. This is most
likely explained due to higher impurities in the Pb material and the more pronounced presence of a Shubnikov phase [16]. This effect was also visible in the presence of a hysteresis in the lead tube measurements. To achieve high shielding, according to the simulations and the results, the SC tube should be made of a high RRR Nb ($RRR \geq 300$) rather than Pb and exhibit a large aspect ratio as this creates a larger area of low field. Here an aspect ratio of $> 5$ is found to be sufficient to suppress external present magnetic fields by a factor of at least $2 \times 10^7$ or with an 8 cm iris by a factor of at least $2 \times 10^9$.

Further, to reduce field trapping by impurities and grain boundaries, a resistive heater could be mounted on one end of the SC with the other end brought into thermal contact with liquid helium. As the power to the heater is gradually lowered, the tube is transferred adiabatically into Meissner phase. When $\Delta T$ is sufficiently large, the field trapped by impurities is predicted to be significantly reduced [18]. Furthermore, the tube should be annealed to increase the size of the grains and therefore reduce the number of grain boundaries.

The trapped field caused by the tube geometry can not be moved out. However, the trapped field will be free of a radial gradient, as seen in figure 5c. The presented results are particularly
interesting for any experiment faced with the challenge of carrying out momentum measurements sensitive to the Earth’s gravitation acceleration on atoms.

Acknowledgments

We would like to thank the Cryolab at CERN for their support and Torsten Koettig, Michael Eisterer as well as Sarah Aull for their much appreciated advice.

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