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The very large n2EDM magnetically shielded room with an exceptional performance for fundamental physics measurements

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I. INTRODUCTION

Magnetic shielding is used when the absolute magnetic field strength at a measurement site must be lower than the Earth’s magnetic field or when Earth’s or ambient magnetic field fluctuations would limit the measurement accuracy.

A common parameter to describe the performance of shields is the shielding factor. It is defined as the ratio of the magnetic flux density \( B \) measured at the center of the shield and the magnetic flux density without shield at the same position.

There are two classes of magnetic shields at room temperature, active and passive, which can be used either individually or in combination.

Passive magnetic shields are built from high-permeability materials which have a high 'conductivity' for magnetic fields. A shell of such material guides the external magnetic field around an inner volume, thus reducing the static magnetic field as well as magnetic field variations in that volume.

The shielding effect of a passive shield of one layer is proportional to the layer thickness. For two separated layers the shielding effect is the product of the shielding factors of the single shells if the distance in between is large enough. Using multiple shield layers hence reduces the required amount of the expensive high-permeability material necessary to achieve the same shielding factor, but increases the volume of the shield walls.

The field guiding effect of high-permeability materials is the dominating shielding effect only for magnetic disturbances with frequencies below about 1 Hz. For these low frequencies the shielding factor approaches a constant value, the quasi-static shielding factor, measured here with an exci-
tation field oscillating at a frequency of $f_{\text{ex}} = 0.01 \text{ Hz}$. The strong increase of the shielding factor above 1 Hz is caused by the electrical conductivity of the shielding layer and can be further increased by an additional ‘eddy-current’ layer. This is usually made of copper or copper-coated aluminum with a thickness of 5 - 12 mm.

For magnetic field disturbances above 1 kHz the shielding factor is dominated by the radio-frequency (RF) shielding properties of the shield, which would be perfect for an electrically-closed conducting surface, but in practice is limited by the size and design of the largest openings. If the openings are designed as electrically conducting pipes in the RF-shield, the shielding effect can be maintained for larger frequencies if the length to diameter ratio is appropriately chosen. For most magnetic shields the incorporated eddy-current shield is designed to simultaneously act as RF shield.

A static active shield uses a constant current in an arrangement of coils to create a magnetic field which compensates the surrounding field in the volume of interest. An dynamic active shield is a coil arrangement additionally equipped with one or more reference magnetic-field sensors and a feedback control system that adjusts the current source driving the coils to compensate the detected magnetic-field variations, see e.g. Refs.3–6. The passive shield described in this article will be finally surrounded by an active magnetic shielding installation to further enhance the shielding performance for frequencies below 5 Hz.

A common passive shielding material is permalloy, which is a nickel-iron alloy with a nickel content above 75%. Various brand names with slightly different material compositions and properties exist. The high permeability is obtained by a special annealing process in a reductive atmosphere at temperatures above ~$1050 \text{ °C}$. Another relevant manufacturing factor is the necessary careful handling of the material after annealing. Mechanical stress on the material, for example during bending, reduces the permeability. Large shields have to be assembled from flat sheets and edge pieces bent before annealing.

The first magnetic shields large enough for humans, used to measure the magnetic field of the heart or brain, were built in the 1960s.7–10. Such large shields with two or more magnetic shielding layers and door access, called magnetically shielded rooms (MSR), are nowadays commercially available from different companies.

Initially, the driving force for installation of large MSRs with more than two layers were precise measurements of bio-magnetic fields in humans. For many years the MSR with the highest shielding factor was ‘BMSR-2’ at the Physikalisch-Technische Bundesanstalt, Berlin, Germany, with originally seven, now eight, magnetic shielding layers, having at 0.01 Hz a shielding factor of 75,00014, and 300,000 after the recent upgrade with an additional layer which reduced the available shielded volume.15

Large multilayer shields were pioneered also in fundamental physics measurements already in the 1980s, e.g. Refs.16–20. One of the first large MSRs dedicated to physics experiments was built at Oak Ridge National Laboratory,21 followed by one at Technical University Munich.22,23

The MSR described in this work serves the n2EDM experiment, aiming at an improved measurement of the neutron electric dipole moment (nEDM).24 The key requirement for n2EDM, besides a high shielding factor, is the ability to generate a very uniform magnetic field in the central 1 m$^3$ volume of the MSR.25 The MSR design has to meet those requirements while complying with mechanical boundary conditions such as shield geometry, size, weight, number and size of openings and accessibility. Factors that affect the field uniformity are the magnetization state of the shielding metal, the homogeneity of a desired field produced by an internal coil system necessary for the nEDM experiment, and disturbances caused by the openings. Since those effects drop off with distance, MSRs with a large inner volume facilitate a good magnetic field uniformity, while MSRs with a smaller inner volume make it easier to achieve large shielding factors. The design presented here is a compromise between these two factors, which optimizes the overall performance of our experiment. In this publication we demonstrate that the realized design achieves both a high shielding factor and a low and homogeneous enough magnetic field, which results from low disturbances of field uniformity due to the MSR’s magnetization state.

II. DESIGN GUIDELINES

The design of the MSR was driven by the performance needed to reach the sensitivity goals of the n2EDM experiment and by the restrictions imposed by the apparatus to be installed inside the MSR.24 Further constraints were set by the spatial dimensions of the installation area within the experimental hall.

The number and the dimensions of the openings were given by the components of the apparatus. Two very large openings with a diameter of 220 mm are required for the installation of the ultracold neutron guides. As a design principle all openings are symmetrically mirrored on opposite MSR walls, which helps to suppress first-order gradients.

The doors must provide a minimum 2 m × 2 m access for the inner chamber to allow for equipment installation, the largest one being the vacuum tank.

The key specified design performance criteria were: 1) a quasi-static magnetic shielding factor at 0.01 Hz of 70’000, and 2) a remanent magnetic field in the central 1 m$^3$ below 500 pT with a field gradient lower than 300 pT/m.

III. CONSTRUCTION OF THE MSR

The MSR was engineered, designed and constructed by VAC, Germany, in an iterative process with input from the nEDM collaboration. The high permeability materials used in all shielding layers were produced via smelting from the original ores in the furnaces of the VAC Hanau facility.

The MSR design consists of an outer and an inner chamber, and an intermediate space as shown in Fig. 1. The inner chamber is centrally placed and separated from the outer chamber...
FIG. 1. Vertical cut showing the positioning and dimensions of the inner and outer chambers with shielding layers, with MUMETALL® layers indicated in blue, ULTRA VAC® layer in green, and aluminum layer in red, as listed in Tab. I. All dimensions are in mm.

horizontally by a distance of approximately 45 cm in all directions from the outer wall, with a vertical offset of 14 cm towards the floor. The intermediate space between the chambers shown in Fig. 2 provides an area which is RF shielded, and magnetically shielded with a quasi-static shielding factor of about 65. It is accessible for persons and can be used for additional experimental equipment as well as sensitive signal electronics that are too magnetic to be located next to the central n2EDM apparatus. The outside dimensions of the MSR are 5.2 m × 5.2 m horizontally, and 4.8 m vertically. The inner chamber is almost perfectly cubic with a side length of 2.92 m, thus featuring 25 m³ of internal volume for the installation of the experimental apparatus.

Many openings in all six walls of the MSR provide access to and allow operation of the n2EDM apparatus on the inside. The two neutron guides require the largest openings with 220 mm diameter, with their centers separated by 550 mm. The diagram in Fig. 2 illustrates this arrangement. Identical openings on opposite sides of the chamber will be used for two pumping lines. Furthermore, nine large openings are symmetrically placed on the roof and the floor (Fig. 3), which will be used for e.g. laser paths, optical fibers, cables and sensor tubing. A few openings are only either in the inner or outer chamber. The total number of openings amounts to 87, planned with contingency:

- 4 with inner diameter (ID) = 220 mm,
- 4 with ID = 160 mm,
- 43 with ID = 110 mm (21 only in outer chamber),
- 2 with ID = 80 mm,
- 26 with ID = 60 mm (8 only in inner chamber),
- 8 with ID = 55 mm.

Apart from the openings which are in one chamber only, all openings are coaxially passing through the inner and outer chamber walls. Figure 3 provides a sense of the arrangement of the openings in the floor of the MSR.

The assembled MSR, installed in experimental area South of the ultracold neutron (UCN) source at the Paul Scherrer Institute (PSI), is shown in Fig. 4 from the side of the entrance door and in Fig. 5 from the rear. It is placed on an aluminum frame positioned on four 1364 mm high granite pillars with 1 m × 1 m base, all placed on top of its own concrete foundation, vibrationally isolated from the surrounding concrete floor of the experimental hall.

The MSR consists of seven shielding layers (Tab. I), with one aluminum layer acting as eddy-current and RF shield. Of the six soft magnetic layers, the five outer ones are made of MUMETALL® (Ni 77%, Cu 4.5%, Mo 3.3%, Fe balance), a soft magnetic NiFe alloy with a Z-shaped hysteresis curve and correspondingly high maximum permeability. MUMETALL® is a standard alloy for magnetic shielding. However, the alloy ULTRA VAC® 816 (Ni 81%, Mo 6%, Fe balance) employed for the innermost layer was applied.
This novel NiFe alloy has a round-loop-shaped hysteresis curve due to its composition. In this alloy, remagnetization processes take place mainly via reversible domain wall motions. This material is characterized by a high initial permeability even at saturation levels of magnetic field strength \( H < 0.1 \, \text{A/m} \) in the shielding layer, and by a lower maximum permeability compared to MUMETALL®. Due to the round-loop-shaped hysteresis curve, the remanence of ULTRAVAC®816 with a residual magnetic flux density \( B_r = 0.2 \text{–} 0.3 \, \text{T} \) is less than half that of MUMETALL® (\( B_r = 0.45 \text{–} 0.55 \, \text{T} \)). This hysteresis shape allows for an optimal demagnetization of the innermost layer to achieve minimum residual fields. All walls were manufactured using the VAC proprietary panel technique.

All additionally materials used in the MSR construction were previously checked for magnetic contaminations with different specifications. The most stringent restrictions applied to materials in the inner chamber, i.e. allowing for a maximum 200 pT signal at 50 mm distance, when scanned in the BMSR-2 magnetic testing facility at PTB Berlin. Expanded polystyrene placed between the individual layers serves as thermal insulation.

Figure 6 shows a photograph of the open MSR with the doors visible on the sides. Information about the dimensions can be found in Fig. 3. All doors are larger than the door openings. The overlap is necessary to reduce the magnetic re-
The shielding factor was measured using excitation coils on the outside edges of all outermost walls of the MSR (see Fig. 5). The coil constants $K_{ex}$ of those coils were calibrated with an additional external coil system, which had been mounted on a large frame before the installation of the MSR. The distance of these coils to the later position of the MSR walls was approximately 1.5 m. The excitation coils produced a sinusoidal signal $B_{ex} = K_{ex} I_{ex} \sin(2\pi f_{ex} t)$ with 2 µT peak-to-peak amplitude at the MSR center position. A QuSpin® magnetometer recorded the excitation signal inside the inner chamber. The sensor was installed in the center of the chamber, inside a small calibration coil that generated a sinusoidal reference signal $B_{ref} = K_{ref} I_{ref} \sin(2\pi f_{ref} t)$ with the reference frequency $f_{ref}$ well separated from the excitation frequency $f_{ex}$. The coil constant $K_{ref}$ of the reference coil was independently measured and agrees to better than 1% with the calculated value. During data taking the magnetometer signal as well as the monitor signals for the two currents in the coils $I_{ex}$ and $I_{ref}$ were recorded by a multichannel ADC which was synchronized with the function generator that supplied the $f_{ex}$ and $f_{ref}$ signals. The duration of the times series recorded by the ADC for each test frequency was programmed such that it contained an exact integer multiple of the oscillation periods of $f_{ex}$ and $f_{ref}$. This simplified the data analysis since each oscillation signal was guaranteed to contribute only to a single frequency bin in the Fast Fourier Transformation (FFT) spectrum of the time series. This method minimizes the influence of external disturbances on the final result because noise in frequency bins other than the ones centered at $f_{ex}$ and $f_{ref}$ is disregarded. The applied FFT algorithm extracted the root-mean-square amplitudes of the signals at the relevant frequencies. Those were the amplitude of the current in the excitation coil $I_{ex}^{RMS}$, the amplitude of the current in the reference coil $I_{ref}^{RMS}$, the magnetometer signal at the excitation frequency $B_{ex}^{RMS}$, and the magnetometer signal at the reference frequency $B_{ref}^{RMS}$. Comparing the measured reference signal to the expected amplitude gave us an in-place correction factor $C_{cal}$ for the calibration of the magnetometer:

$$C_{cal} = \frac{R_{ref}^{RMS}}{K_{ref} I_{ref}^{RMS}}$$  \hspace{1cm} (1)

The shielding factor $F_S$ results in a similar way from comparing the measured amplitude at the excitation frequency to the value calculated from the coil constant and current:

$$F_S = \frac{K_{ex} R_{ex}^{RMS}}{B_{ex}^{RMS} C_{cal} = \frac{K_{ex} I_{ex}^{RMS} R_{ex}^{RMS}}{K_{ref} I_{ref}^{RMS}}}$$  \hspace{1cm} (2)

The measurement method makes the result independent of the magnetometer calibration and depends only on amplitude measurements and coil-constants which were independently cross-checked. The measurement was performed for the three spatial directions in almost the same way. Only the density of excitation frequencies $f_{ex}$ was increased for the $x$ and $z$ direction in order to investigate the noise above 5 Hz.

The measured frequency-dependent shielding factor is shown in Fig. 7. At frequencies above 5 Hz the shielding factor is so large that the sensor reaches its noise limit. Additionally, the measurement above 5 Hz shows interference from the PSI magnetic environment which lead to fluctuating results, with a minimum shielding factor of $10^8$. The specified performance is surpassed at all measured frequencies.

The quasi-static shielding factor at 0.01 Hz, which is most important for the n2EDM experiment, is $\sim$100,000 in all spatial directions, namely 101,300±500 in $x$-direction, 101,000±1000 in $y$-direction, and 94,900±1400 in $z$-direction.

Figure 7 also shows that for frequencies between 0.03 and 5 Hz the shielding factor in the $y$-direction is consistently larger than in the other directions. This behavior is expected since the eddy current induced by a magnetic disturbance in the $y$-direction is not crossing the door contacts which are, in terms of electric conductivity, the weakest link in the eddy current shield. A comparison of the performance in the $x$- and $y$-directions shows that the $y$-direction is by far the most important.
FIG. 7. Dependence of the magnetic shielding factor on frequency measured with a sinusoidal 2 μT peak-to-peak signal for the 3 spatial dimensions as defined in Fig. 4. The black line shows the specified minimum required shielding factor for the depicted frequency range. The gray shaded area shows the region where due to the shield the excitation signal is reduced to the level of the sensor noise.

y-directions thus gives an estimate on the losses caused by the imperfect magnetic and electric contacts of the doors.

FIG. 8. Histogram of all measurements of the quasi-static shielding factor at 0.01 Hz in the three spatial directions.

A histogram of the individual shielding factor measurements at 0.01 Hz is shown in Fig. 8. The quasi-static shielding factor in the x-direction is slightly smaller than in the other directions. This is caused by the smaller distance and the offset between the inner and outer chamber in the vertical direction. The spread is likely due to a combination of the statistical uncertainty of the measurement and the changing magnetic environments over the course of the measurements which also causes a small change of the shield response.

V. EQUILIBRATION OF MSR LAYERS

In order to minimize the remanent field in the inner chamber, all MSR walls need to be demagnetized\textsuperscript{31}, or more precisely ‘equilibrated’\textsuperscript{32} to achieve the energetically most favorable state. This process is also sometimes colloquially referred to as ‘degaussing’. Therefore, four coils per spatial direction are installed with cables along every edge of every wall of layer 1 to 6 individually, as sketched in Fig. 9, similar to what is shown in Fig. 2 of Ref.\textsuperscript{32}, thus allowing the driving of a magnetic flux independently in the three spatial dimensions. Such an arrangement was first used in Ref.\textsuperscript{32} for the ‘ZUSE’ chamber at PTB Berlin and was also used in Ref.\textsuperscript{33}. Here, layer 6 has additional coils distributed over the width of the walls and the door to further improve the equilibration procedure for the innermost layer\textsuperscript{34}.

V. REMANENT MAGNETIC FIELD

A. Measurement procedure

For this investigation the magnetic field in the inner chamber was measured with a low-noise Bartington MAG03 three-axis fluxgate\textsuperscript{35} located in a plexiglas tube installed between opposite openings in the MSR walls. Position scans were
recorded by sliding the fluxgate along the axes of this tube using a pushrod. The rod has pin holes every 100 mm that were used to reproducibly fix the position along the tube as well as the rotation of the fluxgate around the axis of the tube. The front part of this setup is depicted in Fig. 10. The accessible measurement positions range from -60 cm to +140 cm relative to the center of the chamber. At 140 cm the fluxgate sensors are as close as 7 cm to the ULTRAVAC® surface of the innermost shielding layer.

A typical measurement consisted of integrating the sensor signals for 3 s and then rotating the fluxgate by 90 degrees. This procedure was repeated until all four orientations (0, 90, 180, 270 degrees) of the fluxgate were recorded before proceeding to the next position along the tube. The rotation allowed the compensation of the sensor offsets in the two transverse directions since the contribution of the local magnetic field to the sensor reading must invert when the sensors are rotated by 180 degrees.

When scanning in the vertical direction, the tube could be installed from the outside so that the MSR doors did not have to be opened between measurements and the equilibration procedure did not have to be repeated. This means the magnetic configuration of the MSR was unchanged except for possible relaxation processes in the wall material. All other measurements were performed after an equilibration of all shield layers.

### B. Results

In order to assess the repeatability of the magnetic field measurements we repeated one vertical scan after four days. Figure 11 compares the offset-corrected measurements from both scans. The root mean square of the differences between the two measurements are 21 pT and 24 pT for the x- and y-directions, respectively. The total deviation is close to the expected statistical uncertainty but shows also a small systematic component, especially in $B_x$, where the mean difference between all points of the scans amounts to 18 pT. Combining these two deviations, we conservatively estimate the total measurement error to be 30 pT which is reflected by the error bars shown in Fig. 12, 13 and 14.

All measured values for $B_x$ and $B_y$ taken during vertical scans in different positions are shown in Fig. 12 and show the results after a single equilibration procedure. Figure 13 shows the $B_z$ field component, which was measured in a horizontal scan after equilibration performed on different days since the doors had to be opened in order to install the tube for the fluxgate.

The largest deviation from ideal behavior was found in a horizontal scan along the y-direction. The corresponding measurements of $B_x$ are shown in Fig. 14. Here the mechanical scan range was increased to reach from wall to wall. The measurements show the expected effect that repeating an equilibration leads to the strongest magnetic field uncertainties close to the wall and especially close to the door.

Already with a non-optimized equilibration procedure we find a large volume, ranging from -76 cm to 76 cm in x and y, and -60 cm to 140 cm in z, in which all measured field values for $B_x$, $B_y$, and $B_z$ are below 150 pT, originally specified to be below 500 pT. Positions at lower x, y, and z values could not be measured with the described setup. The gradients in the central 1 m$^3$ were significantly smaller than originally specified (300 pT/m, see Section II). In this volume the gradients...
are within the statistical uncertainty of the fluxgate sensors used, which is estimated to correspond to 60 pT/m at 1σ confidence level.

The remanent magnetic field measurements along the three spatial directions are summarized in Fig. 15 relative to their distance from the center of the inner chamber. This distance is computed relative to a plane through the center and perpendicular to the scan direction. Hence, all measured points in the central 1 m³ volume are at a distance <50 cm. The ULTRAVAC® material of the layer 6 wall is at a distance of 146.5 cm. One can see that all 1σ confidence intervals in the central 8 m³ (positions <100 cm) are below 100 pT. For the z-component of the magnetic field, which is most important for n2EDM, also the maximum deviation is below 100 pT in the central 8 m³. Only when approaching the wall, the remanent field values slowly increase to approximately 500 pT at a distance of about 4 cm from the ULTRAVAC®.

VII. SUMMARY

We constructed a unique magnetically shielded room with excellent performance, providing 25 m³ of usable shielded volume for the n2EDM apparatus, which will search for the neutron electric dipole moment with a baseline sensitivity of $10^{-27}$ cm. This MSR provides the largest ultra-low magnetic field environment in the world despite the numerous openings allowing for access and throughgoing connections.

The excellent magnetic performance is achieved using five MUMETALL® layers, one ULTRAVAC® layer, and one aluminum layer. A quasi-static shielding factor at 0.01 Hz of $\sim 100,000$ was measured in all three spatial directions. The shielding factor rapidly raises with frequency and already reaches $10^8$ for frequencies above 3 Hz.

After applying the equilibration procedure the MSR provides an exceptionally low magnetic field environment across a large volume. As the other two magnetic field components, in particular the most important field component $B_z$ (vertical) shows remanent magnetic field values below 100 pT in the central 8 m³.
FIG. 15. Summary of all measured scans of the three field components $B_x$, $B_y$, and $B_z$ performed after equilibration of the MSR. The magnitude of the magnetic field components is shown as a function of distance to a central plane perpendicular to the scan direction. All points in the central cubic meter thus fall into the region with distance smaller than 50 cm. The black lines gives the mean values with the 1σ uncertainties displayed as the shaded area.

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IX. DATA AVAILABILITY

The datasets generated and/or analyzed during the current study are not publicly available but are available from the corresponding authors on reasonable request.

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excitation coils

$z = 50\text{cm}$

$z = 0$

$z = -50\text{cm}$
alignment holes

pushrod

guiding tube

translation degree of freedom

rotation degree of freedom

field sensors in the fluxgate
incorrect offset

$B_z (\text{pT})$

$z = -27.5 \text{ cm}$

$z = 27.5 \text{ cm}$

$z = 0$

position of the wall

horizontal position along $x$ (cm)
Distance from central plane (cm)

$B_x (\text{pT})$

$B_y (\text{pT})$

$B_z (\text{pT})$

Measurements towards door

Wall

1σ confidence interval

Mean