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# DESIGN OF A SPIN ROTATOR FOR THE ISIS SUPER-MUSR BEAMLINE

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*Abstract*

The spin rotators (SR) are DC electromagnetic devices that produce a homogeneous magnetic field to rotate the spin of the muons in flight, which is counterbalanced by a matched perpendicular electric field to avoid the bending of the muon beam trajectory. Two identical SR will be used in the new Super-MuSR beamline to rotate the muon spin by up to 34º per device relative to the beam direction, enabling higher transverse field muon measurements and other experiments not currently possible in the present ISIS MuSR beamline. The fundamental electromagnetic (EM) design of the SR is presented in this paper, both for the magnet and the high voltage vessel. The optimization of the electric and magnetic fields shape and strength is presented including fundamental hand calculations, 2D/3D models and particle tracking simulations. The high voltage feedthroughs and the electrode insulating supports were thoroughly designed to reduce the breakdown probability. A sensitivity study was also developed to estimate the manufacturing tolerances, but it is not presented in this paper.

## DESIGN PARAMETERS

The MuSR muon beamline in ISIS is being upgraded to maximise the counting rate advantage afforded by the flux now available from the already upgraded primary beamline, giving a 15 to 20-fold improvement compared to the present instrument. The increased flux allows the problem of the muon pulse width to be mitigated by slicing the ends off each pulse to increase the timing resolution 6 to 10-fold, still giving a higher count rate than before.

The new Super-MuSR beamline consists of two identical SR, 2 quadrupole triplets, one pulse slicer and a highly segmented detector array of about 700 elements. A beamline optics model was developed to define the parameters required for each of the components [1]. The output of the model was the spot size and the intensity of the expected beam, and it also provided the final position and other requirements for the beamline devices.

A collaboration with PSI was signed to share their expertise in the manufacturing of SRs. The electromagnetic design of the Super-MuSR SR used some of the ideas and techniques used by PSI in their Sep41v design [2], while the high voltage (HV) feedthroughs were designed from scratch in a collaboration with Essex X-Ray [3], to allow the use of standard connectors and to be easier to maintain. The details of that design cannot be published to protect the intellectual property contributed by Essex X-Ray.

The main technical requirements and constraints for the design of the SR are shown in Table 1 (where GFR stands for “good field region”). The operating voltage was limited to reduce the challenge and cost of the HV design.

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Table 1: Technical Requirements and Constraints

| Parameter | Value | Units |
|---|---|---|
| Muon momentum | 28.63 | MeV/c |
| Spin rotation angle (on vertical plane) | 34 | deg. |
| Maximum structure length | 1910 | mm |
| Max. structure width (horizontal) | 1050 | mm |
| Max. structure height (vertical) | 1400 | mm |
| Operating/conditioning voltage (±) | ~190/215 | kV |
| Maximum breakdown rate | 10 | 1/h |
| Horizontal aperture | 200 | mm |
| Vertical aperture | 140 | mm |
| GFR horizontal dimension | 175 | mm |
| GFR vertical dimension | 133 | mm |
| Electric and magnetic fields homogeneity in GFR | < ±2.5 | % |

### *Analytical calculations*

The spin rotation of muons is based on a physical effect called Larmor precession [4], which requires a magnetic field. The muon trajectory bending in the B field can be compensated by a matching perpendicular E field. Equalling the integrated transverse electric and magnetic Lorentz forces on the ideal on-axis particle, a first order condition emerges to achieve a trajectory at the exit that is parallel to the entrance (Eq. (1)), where $v$ is the speed of the muons.

$$vB_{int} = E_{int} \tag{1}$$

The total rotation of the magnetic moment (spin) depends on the time the muon is inside the magnetic field, for which relativistic effects have to be considered. Additionally, the magnetic field that the muon experiences in its reference frame has to be adjusted due to the particle’s movement and the E field included to compensate the B field bending strength (see the relativistic transformations for the E and B fields in [5]). The required integrated magnetic flux density ($B_{int}$) to achieve a desired spin rotation ($\theta$) inside a matching E field can be expressed in the compact form shown in Eq. (2), where $\mathcal{R}$ is the magnetic rigidity, $\gamma$ is the relativistic Lorentz factor and $g$ is the muon g-factor. Therefore, the required integrated magnetic flux density $B_{int}$ to rotate the spin of the muons by 34º is 58.6457 mT.m.

$$B_{int} = \frac{2\theta\mathcal{R}\gamma}{g} \tag{2}$$

An integrated transverse E field $E_{int}$ = 4.5982 MV (i.e. transverse voltage) is required to compensate $B_{int}$. The electric field between the electrodes for the desired voltage and vertical aperture will be around 2.714 MV/m. Given that $E_{int} = E_0 * L_{eff}$, the effective length ($L_{eff}$) of the electric field

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should be around 1.69 m, which will require an electrode length slightly smaller depending on the end effects and the proximity to ground (studied in FEM models).

The component of the electric force perpendicular to the trajectory (bending) depends on the actual followed trajectory, unlike for the magnetic force. Therefore, the optimization in FEM models should minimize the heterogeneous effects of the electric and magnetic fields on the actual particle's path (Fig. 1), which can be considered a second order condition to achieve an exit trajectory that is parallel and not biased vs. the entrance trajectory.

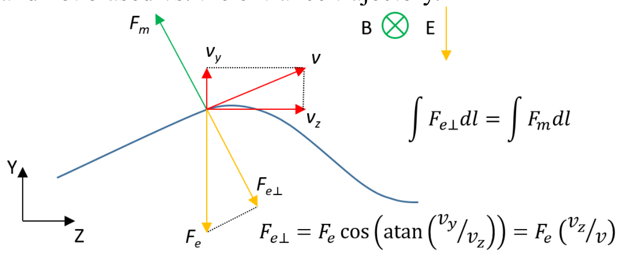


Figure 1: E and B forces on a 2D trajectory.

### *Initial geometry and dimensions*

The SR has to be dimensioned starting from the inside parts outwards. The final dimensioning was done by FEM simulations, but the shape and initial dimensions had to be defined manually by hand estimations and calculations.

The rough idea is a vacuum vessel with electrodes to be surrounded by a magnet (not in vacuum). The spin rotation defined on the vertical plane parallel to the beam direction (Table 1) requires a magnetic field parallel to the horizontal plane to produce the desired effect (Fig. 2). Therefore, the compensating electric field has to be vertical, with two electrodes charged at opposite voltages (grounded virtual mid-plane) to ease the HV engineering.

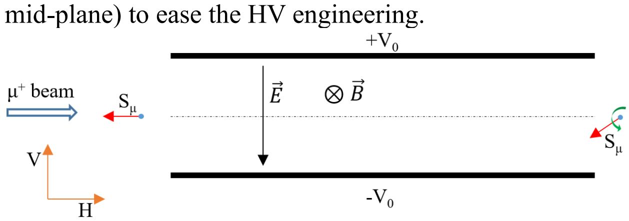


Figure 2: Sketch of the electrodes and muon spin change.

The electrode width was defined according to the required E field homogeneity, and the electrodes were surrounded by a cylindrical vessel which was roughly dimensioned analytically (see Fig. 3).

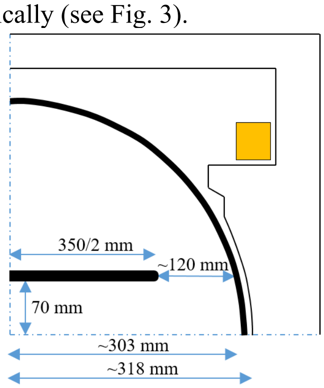


Figure 3: Estimated shape for 1/4$^{th}$ SR cross section.

The magnet was designed with a standard H shaped yoke with a big aperture compared to the yoke length, and the total required magnetic strength was very small. The distance between the magnet poles was estimated according to the vessel dimensions and the required gap, and their shape was made circular with shims to better adapt to the vessel and to improve the field quality. Using the 1.69 m estimated effective length for the E field, the magnet needs to produce 34.7 mT of averaged field in the good field region (GFR), which can be obtained with about 8800 A.turn and a relatively small cross section coil.

The long electrodes are supported inside the vessel by 2 ceramic insulators each (distance optimized to reduce the sag), and connected to the high voltage by 2 receptacles designed for standard R30 connectors and C2236 HV cable [6]. The insulators are based on a modified design from PSI that is still under R&D testing, while the feedthroughs are a new design to avoid using oil as an insulator, which should ease assembly and future maintenance. Both parts were independently designed from the main SR, as their presence does not affect the electric field between the electrodes.

## ELECTROMAGNETIC SIMULATIONS

### *2D models*

The sketch shown in Fig. 3 was modelled and optimized in FEM to estimate the dimensions of the cross section for both the HV vessel and the magnet. The homogeneity of the GFR was evaluated in an ellipse centred on the aperture axis, as the beam is not cylindrical at this position.

The electrodes were shaped to reduce the E field on the edges while controlling the field quality and the weight. Figure 4 shows a COMSOL Multiphysics [7] electrostatic 2D model of the HV vessel (1/4$^{th}$ symmetry). The peak field is below 6 MV/m @ 215 kV, and the 2D field homogeneity is +0.2/-0.96%.

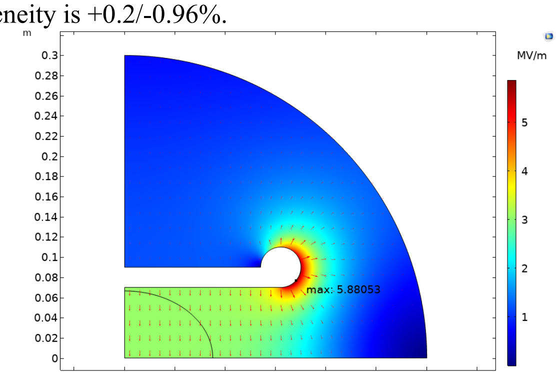


Figure 4: 2D E field distribution in the HV vessel.

The magnet yoke was dimensioned to maximize the field quality and strength for a given total coil current. The yoke thickness was defined to avoid saturation and to mechanically support the magnet, while still not exceeding the maximum structure width. The 2D magnetostatic FEM model returned a field homogeneity of ±0.18% after optimization. The insulating supports were redesigned starting from PSI's design, to try to better shield the triple joints and reduce the breakdown probability (Fig. 5). The ceramic

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to metal brazing is challenging, as the insulators need to support the electrode weight with no clamping on the ceramic, to reduce the field enhancement at the triple joint.

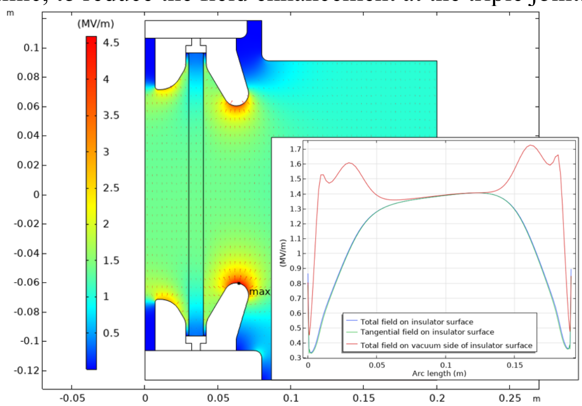

Figure 5: Axi-symmetric FEM model of the insulators.

### *3D models*

The initial guess for the 3D magnet geometry was a single long dipole magnet to achieve the required integrated field. However, a reduction of the B field at the middle of the SR [8] would make the muons oscillate around the central path, better compensating the different fringe field lengths from E and B and also reducing the total oscillation range (or path excursion) to make a better use of the GFR. Hence, 2 equal magnets were designed (Fig. 6), and their distance to the mid-plane and the position of the magnetic plates (field clamps) were used to tune the shape of the B field to match the E field effects. 9885.4 A.turn were required in the coils to achieve the required integrated field with XC06 steel [9], which corresponded to 154.46 A of current in 8x8 turn coils. The B field homogeneity measured on line integrals was +0.3/-0.4%, and the maximum remanent field was estimated to be only 0.13% of the peak aperture field, though bipolar power supplies to demagnetize the yoke might still be needed.

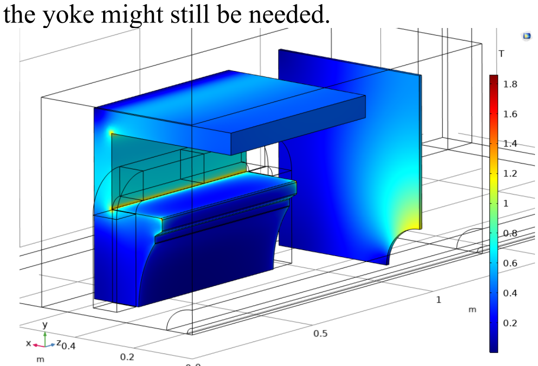

Figure 6: B field in the yoke (1/8$^{th}$ symmetry).

The electrodes in the HV vessel were extended as much as possible (1.6 m) to reduce the voltage requirements, and their edges were optimized and rounded in 3D to keep the local surface fields below 8 MV/m (Fig. 7). The total required voltage in the electrodes was ±192.94 kV to achieve the required transverse voltage, and its 3D homogeneity in the aperture was +0.5/-1.9%. The mutual capacitance matrix including the feedthroughs and insulators was $C_{11}=C_{22}=112.1$ pF and $C_{12}=C_{21}=35.1$ pF.

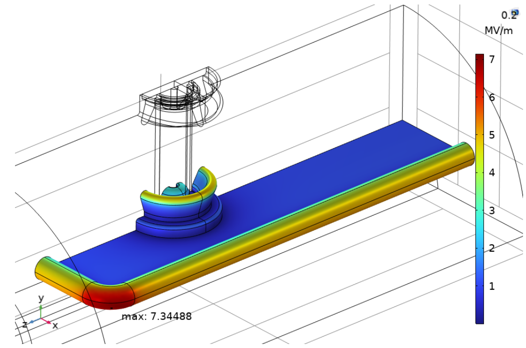

Figure 7: Electrode shape and E field (1/8$^{th}$ symmetry).

### *Particle tracking*

The SR field shape optimization required using both 3D E and B fields in the same model to track the muons through the aperture, which required unfolding the symmetrical fields in a full 3D model of the GFR. The E and B field shapes were optimized in a manual iterative process where the magnet poles, lengths, relative positions and the end field clamps locations were tuned until the path excursion (Fig. 8) was symmetric about Z=0 and minimized in peak amplitude (about ±1.1 mm achieved). Note the double oscillation of the ideal muon around the GFR due to the middle gap in the magnetic force. The force graphs in Fig. 8 also represent the fields shape on the muon's trajectory, so for the magnetic force graph the peaks correspond to 40.37 mT and the valley to 28.5 mT. For the electric force, the flat top corresponds to 2.755 MV/m.

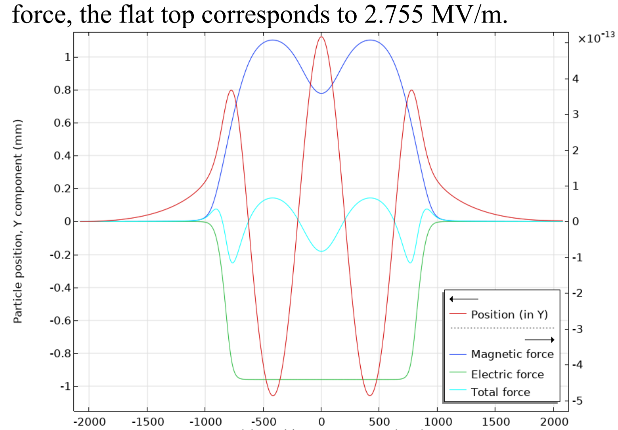

Figure 8: E & B forces and particle's path excursion.

## CONCLUSION

The EM design presented for the Super-MuSR spin rotators predicts a reliable design and is expected to cause a minimal disruption to the muon beam. The electrostatic vessel and the electrodes, insulators and receptacles inside it were designed to reduce the breakdown probability, although an injection of He-Ne gas is being considered to reduce it further during operation. The magnet was designed to shape the B fields so they minimized the muon path excursion for a flat shaped E field.

The mechanical design for the whole SR is now in a quite advanced state. The manufacturing of the HV receptacles is finished and the manufacturing tests for the insulators (mainly brazing) are ongoing.

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