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MECHANICAL DESIGN OF A SPIN ROTATOR FOR THE ISIS SUPER MUSR BEAMLINE

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Abstract

The Super MuSR spin rotators (SR) are electromagnetic (EM) devices with a horizontal dipolar magnetic field to rotate the muon spin by 34° and a perpendicular electric field that operates at +/-192 kV. The electromagnetic (EM) design was already presented elsewhere. The mechanical design is now complete, and the manufacturing of components has started, both of which are discussed here.

The stainless steel vessel is 598 mm in diameter, 1.8 m long and has several ports along it. Most notably the large feedthrough port with a 15 mm inner radius to reduce the electrical fields. Mirror polished electrodes are mounted on ceramic insulators, optimised to shield the triple points from the high electric fields. The insulator mechanical design, manufacture & testing will also be discussed here. A high voltage test rig has been developed in parallel to test critical aspects such as the high voltage feedthrough, insulator design, vessel manufacture and surface finish requirements, before testing and assembling the main vessel. The magnet yoke is H-shaped with traditional racetrack coils. It was designed to be assembled around the vacuum vessel with kinematic feet for adjustment and alignment.

MECHANICAL DESIGN

The mechanical design is based on the electromagnetic design [1] which details the requirements of the components required to achieve a vertical electric field and a perpendicular magnetic field.

The electric field is produced by high voltage feedthroughs, connected to electrodes that are mounted on insulators inside a vacuum chamber. The magnetic field is produced by two dipole magnets in series with field clamps to shape the field and essentially compensate the electric field (Fig. 1). The high voltage feedthrough was designed with Essex X-ray [2]. The design has been covered in the images to protect the intellectual property of Essex X-ray.

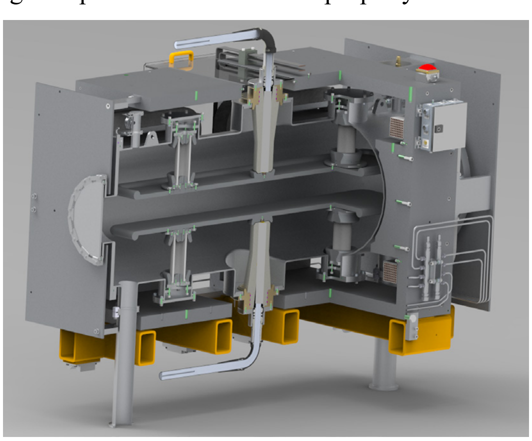

Figure 1: SR assembly cut section.

Vacuum Vessel

The SR vacuum vessel operates at 1e-7 mbar and consists of a cylindrical tube with end flanges at both ends, two vacuum ports, four insulator mounting ports, two central feedthrough ports and two KF40 ports (Fig. 2). The vessel has two welded lifting lugs on top to facilitate lifting.

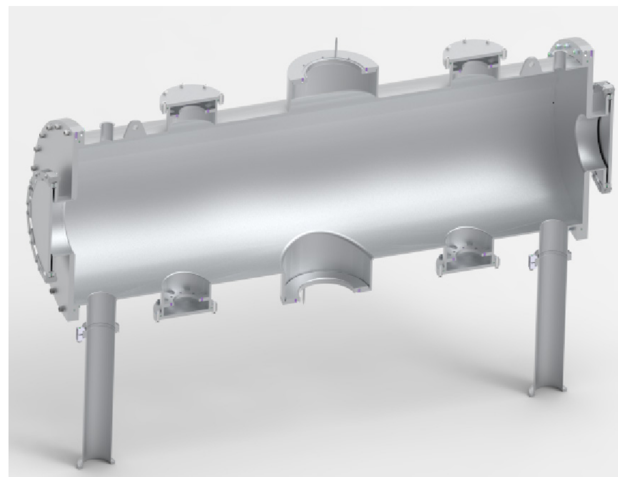

Figure 2: Vacuum vessel cut section.

The vacuum vessel material is Stainless Steel 316L rather than 304L, to minimise the permeability which could interfere with the magnetic field. An Aluminium vessel was considered, but the required increase in wall thickness to cope with the vacuum pressure would result in either making the external magnet aperture larger or reducing the clearance between the vessel and magnet which is nominally 9 mm.

The inner diameter is 598 mm; a wall thickness of 8 mm was chosen due to availability of standard plate thicknesses. It was not possible to use a stock tube for this application because the standard gauge thickness was too thin. Therefore, a plate was rolled and welded along the seam. The position of the seam was chosen to be at the top to have the least impact on the permeability, which was expected to increase slightly along the weld line.

The maximum electric field at the vessel inner walls is only around 2 MV/m [1]. Therefore, it was decided to only specify a surface finish of 1.6 Ra on the inside of the vessel. This was partially due to cost and manufacturing complexity, but also mainly due to the fact that a better surface finish should not be required to avoid electrical breakdowns, as fields are significantly lower than the selected design limit of 8 MV/m.

However, the internal port radii are critical to avoiding electrical breakdowns. The central ports internal radii are

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15 mm, and the insulator ports are 5 mm. Early in the design, it was thought about "pulling out" the ports, however, due to the diameter of the ports (300 & 159 mm) and the wall thickness (8 mm), this was not feasible. The chosen solution was to machine saddles that were welded into the main vessel body, followed by a hand blended finish over the internal weld [3].

Magnet

The magnet consists of two yoke assemblies with two coils on each assembly mounting over the pole tips and end plates to limit the fringe fields extension (Fig. 3).

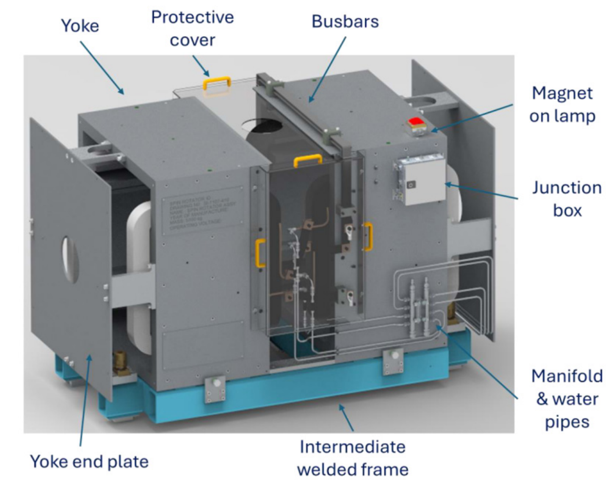

Figure 3: Labelled magnet assembly.

The coil has 8 x 8 turns of 9 x 9 mm conductor with a central cooling channel. Busbar tabs and Klixon block connections are brazed to the tails. The cross section of the busbar selected is 4 x 40 mm which is connected electrically in series and the current is 154.4 A. The ends of the conductor are machined down to an 8 mm diameter that can be connected via a Swagelok fitting, rather than brazing on a pipe connection. Each winding will be wrapped with one half-lapped insulating layer to insulate turns, and two half-lapped layers around the coil assembly once wound into its final shape.

The outer yoke is made of 60 mm machined plates fixed and dowelled together, made from XC06 steel [4]. The pole tips are circular to fit around the vacuum vessel and have a profile tolerance of 0.4 mm once assembled (Fig. 4).

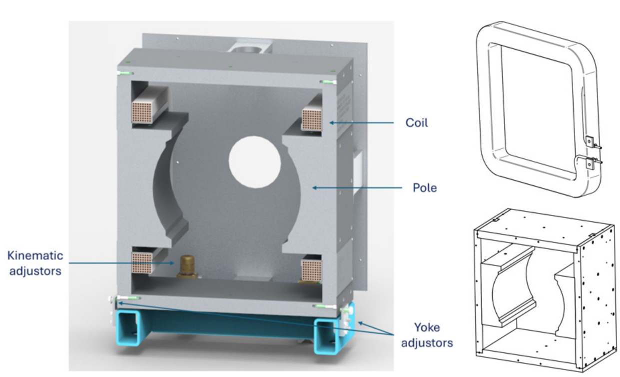

Figure 4: Magnet yoke and coil

The yoke end plates are 10 mm and will be manufactured from TG-S04 Pure Iron since XC06 steel is not available in this thickness. They are mounted with non-magnetic support brackets to not influence the field.

A stainless steel manifold will be used with inline ceramic water breaks designed for demineralised water.

A polycarbonate cover has been designed to limit access to live parts and protect the internals of the equipment between the magnet yokes.

The magnet yokes sit on a welded base frame that has kinematic feet for alignment and adjustment.

Electrode and Insulators

The dimensions of the electrode are 1600 x 350 x 20 mm, with a 40 mm diameter lip running around the entire edge. The electrode material selected was Aluminium. Other materials such as Stainless Steel and Titanium were considered but decided against them due to their increased weight and cost in comparison. The calculated deflection of an Aluminium vs Stainless Steel electrode was comparable, 18 and 20 µm respectively [5]. After consulting with the Paul Scherrer Institute (PSI), they agreed an Aluminium electrode would be suitable.

The maximum electric field on the electrode corners is 7.47 MV/m [1]. Therefore, it was decided to specify a mirror polish finish (0.2 Ra) on the electrode. First, the bulk of the material will be roughed out before stress relieving for a period of time, followed by a ball nose machining operation to achieve a 0.4 Ra finish, then hand polishing to achieve the final 0.2 Ra specification. A flatness of 0.2 mm has been specified on the electrode surface with rotational adjustment available via the spherical flanges connected to the electrode (Fig. 5). Push and pull screws in the insulator ports control the height and separation of the electrodes for final alignment.

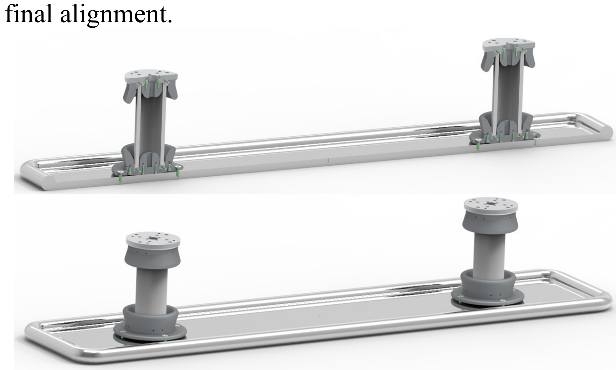

Figure 5: Electrode and insulators.

For the insulators, Alumina with a purity of >99 % was chosen. Alumina is isostatically pressed in a mould to achieve the green state, then sintered via a firing process and machined or grinded to its final tolerances. The process has many challenges to account for. For example, the first test insulators had a shrinkage issue at one end due to the demoulding process and the grinding process took a long time which added manufacturing complexities. Initially, the idea was to use a solid ceramic insulator. However, it was decided to move towards a hollow shape because there were concerns over the shielding of the triple points and

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gaps. As a result, a corona shield was added on the inside of the diameter to shield in the internal hollow wall. PSI have also moved towards this solution in recent years.

A brazed solution was proposed for the insulator design, but this proved to be challenging to manufacture. The conclusion was that the optimised EM design did not align itself with the preferred brazing techniques of ceramics to metals. The EM design required a face to face joint on the end of the ceramic, whereas, for brazing it is better to clamp on the diameter and use the difference in thermal expansion as an advantage whilst it is cooling, meaning the outer metal collar contracts faster than the inner ceramic. In the face to face design, it was desirable to minimise the surface area contact due to the clamping force required and there was a concern that the difference in thermal expansion could result in voids forming. One proposed solution from multiple companies suggested to metallise the ceramic and braze on a thin titanium layer that could then be welded to the main flange. This was a complicated multi-stage process which was risky for ISIS but also the manufacturer, not only from a technical point of view but also cost.

After many iterations, it was decided that a mechanical clamping design would be taken forward instead of the brazed option (Fig. 6). This design requires tight fitting parts and well machined ceramics, however, after engaging with manufacturers this seemed achievable and much more cost effective. The clamped design relies on the friction between the outer ceramic lip and the clamping ring screwed together.

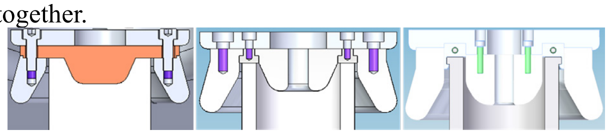

Figure 6: (a) Brazed – solid, (b) Brazed – hollow, (c) Clamped – hollow, outer lip.

The loading conditions are in tension at the top and compression at the bottom. In compression, ceramics are strong, therefore, load tests have been proposed to confirm the ceramic strength in tension.

The insulator has inner and outer corona shields to protect the triple point. This is particularly important because any inception point at the base of the ceramic could lead to breakdowns tracking along length of the insulator.

HIGH VOLTAGE TEST VESSEL

It was decided to create a high voltage test vessel that represented the SR setup to confirm that key critical design features, such as the insulator design, feedthrough and surface finish, were suitable before assembling the entire SR. The vessel (Fig. 7) is mounted on a frame to allow the vacuum pump mounting underneath and to be able to work at a practical height.

Prior to testing, all internal components will be ultrasonically cleaned and assembled inside a cleanroom tent. During testing, the voltage will be raised slowly whilst monitoring the current, x-ray emission and pressure. Once confidence in the vessel is achieved, the main SR vessel will be conditioned in a similar manner in mid-late 2025.

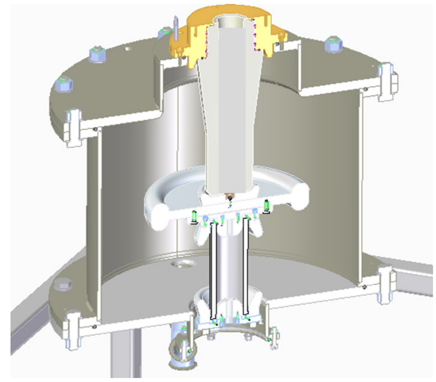

Figure 7: High voltage test vessel assembly.

ASSEMBLY AND TESTING

All internal components in the vessel will be ultrasonically cleaned and assembled in a cleanroom environment. The electrodes will be aligned relative to the vessel, then the vessel aligned to the magnet assembly, which can then be aligned in the beamline to the beam position to satisfy the physics requirements.

During operation the SR will function at +/-192 kV to achieve the required spin rotation angle but during conditioning they will be tested up to +/-215 kV, which is approximately 10 % higher. In addition, the device is operating near the best practice design limit of 8 MV/m therefore this is expected to be challenging. At ISIS, similar devices have been conditioned up to +/-140 kV but never up to these voltages before.

In the instrument area, space is limited, therefore, both spin rotators will be fully assembled in a pre-build area offline and the electrodes conditioned at high voltage. The SR will be lowered onto the base frame that has rails on top that interface with the kinematic feet of the SR during installation. The pre-alignment will reduce the work required in the space constrained area and hopefully minimise the time that the muon instrument is down during the upgrade. Finally, the services will be connected and tested (e.g. water, high voltage, electrical, vacuum) before being signed off as fully operational.

CONCLUSION

The main aspects of the mechanical design have been presented, including the vacuum vessel, magnet, electrode, insulator, high voltage test vessel, assembly and testing. The design is currently in manufacture with high voltage testing planned for both the high voltage test vessel and whole spin rotator assembly. After alignment, assembly and commissioning in the pre-build area in 2026, the SR's will be installed with the rest of the beamline during the Super MuSR project in 2027 at ISIS Neutron and Muon Source.

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