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MAGNETIC FIELD MEASUREMENTS AND SHIELDING AT THE UKRI-STFC DARESBURY LABORATORY SRF VERTICAL TEST FACILITY

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Abstract

A novel vertical test facility has been developed, commissioned, and entered steady-state operations at the UKRI-STFC Daresbury Laboratory. The cryostat is designed to test 3 jacketed superconducting RF cavities in a horizontal configuration in a single cool-down run at 2 K. A 2-year program is currently underway to test ESS high-beta cavities. Upon completion of this program, the facility will undertake a testing program for PIP-II HB650 cavities. In the current configuration, a solution combining passive and active magnetic shielding has been validated for the ESS requirement of field attenuation to the level of <1 µT, although continuous field measurements are not provided. This paper reports the implementation of passive and active shielding, along with simulation and experimental measurements thereof.

INTRODUCTION

UKRI-STFC Daresbury Laboratory (DL) houses a Vertical Test Facility (VTF) located in the Superconducting Radio Frequency (SuRF) Laboratory. This facility is used for testing and qualifying the performance of jacketed SRF niobium cavities at 2 K for users before their final installation into cryomodules and subsequent integration into particle accelerators.

For cavity testing, the SuRF lab is equipped with two cavity support inserts (CSIs) which can mount 3 jacketed SuRF cavities each, allowing Daresbury to test three cavities per run. The dressed cavities are loaded into the top, middle and bottom cradle positions as shown in Fig. 1b). The facility is enabled by a closed cycle warm compression Air Liquide Helial ML[1] cryoplant that provides cold helium gas at 50 K for cooling the cryostat's thermal shield and liquid helium at 4 K for cooling the cavities and CSI. The liquid produced is stored in a 3000 L liquid helium dewar. The spent (boil-off) helium is recovered at 300 K, dried, purified, and then stored in a clean gas buffer tank or reliquefied/cooled depending on the state of the cryoplant. Once liquid transfer into the cryostat is complete, a set of 2 K pumps pump the vapour pressure above the helium liquid down to 30 mbar which provides the operating temperature of 2 K where RF testing and qualification of the SRF cavities take place. The dressed cavities are also actively pumped throughout except when being transferred from the CSI stand to the VTF bunker. Further detail is given in Ref. [1].

Currently, the SuRF lab is undertaking cavity testing for the European Spallation Source (ESS) to be built in Lund, Sweden. The ESS cavity testing specification requires that the ambient magnetic field present in the test environment does not exceed 1 µT. The main sources of field within the lab are the Earth's ambient field, steel rebar in concrete used to provide radiation shielding and, stray field from pumps and other miscellaneous equipment located in the vicinity. In order to meet the magnetic hygiene requirements of the ESS project, the VTF employs both passive magnetic shielding (Mu-Metal[2]) and active magnetic shielding (tuneable coils). The current system was validated in 2017 to meet the ESS requirement of <1 µT during the VTF's commissioning although it does not have the capability for magnetic field measurements during cavity testing.

EXISTING SHIELDING

The magnetic shielding of the VTF comprises both passive magnetic shielding and active magnetic shielding, in order to meet the magnetic hygiene requirements of <1 µT for the ESS project.

Passive Shielding (Mu-metal Shield)

The VTF's passive shield is a Mu-metal cylinder with an open lid at the top and 3 side ports as shown in Fig. 1a). The open lid allows the CSI to be lowered and removed from the cryostat with ease at the start and end of each test cycle. The cryostat is housed in the Mu-metal shield with the largest access for residual magnetic field being located at the top of the Mu-metal shield where the lid is open.

Active Shielding (Top and Bottom Coils)

The VTF's active magnetic shielding consists of 2 coils, one located just above the lid of the cryostat and the other located on the floor of the cryostat bunker as shown in Fig. 1b). The two coils are made of tri-rated cable with 2.5 mm^2 cross sections. However, the number of turns in the coils are not identical with the top coil being made up of 10 turns and the bottom coil comprised of 20 turns.

MAGNETIC FIELD SIMULATIONS

Simulations of a simplified version of the proposed magnetic shield were performed in OPERA[3] using a background field strength and direction set according to a Hall probe survey conducted at the site before installation. The shield was modelled as an open-topped can of height 3.5 m and outer diameter 2.2 m, using the material BH curve for Mu-metal supplied with OPERA (a potential source of er-

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ror as Mu-metal BH curves are highly variable). Simulations investigated the effects of the thickness of the Mu-metal shield as well as the effect of position and current in a coil near the shield top. No bottom coil was included and was not seen as necessary by the simulation.

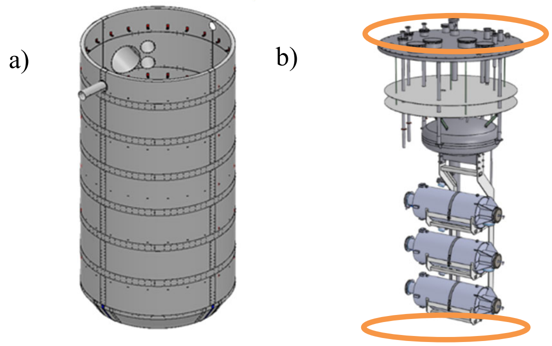

Figure 1: a) CAD of passive Mu-metal shielding on VTF cryostat with a height of 3.5 m and outer diameter of 2.2 m b) CAD of CSI with illustration of active coils.

The simulations as shown in Fig. 2 predicted that, as expected, the field inside the cryostat is decreased by increasing the thickness of the Mu-metal however the effect was small for thicknesses above 1.5 mm. A significant jump in performance was observed between 1 mm and 1.5 mm thick shielding. Simulations also predicted that the field would monotonically increase as a function of height, with the lowest field being present at the base of the shield. From measurements this is now known to be a false result as the field in the real shield reaches a minimum and then measurably increases near the bottom, likely a result of small gaps at the feet of the shield, and magnetic steel present in the concrete surroundings which was not present during the site field survey causing local saturation of the Mu-metal.

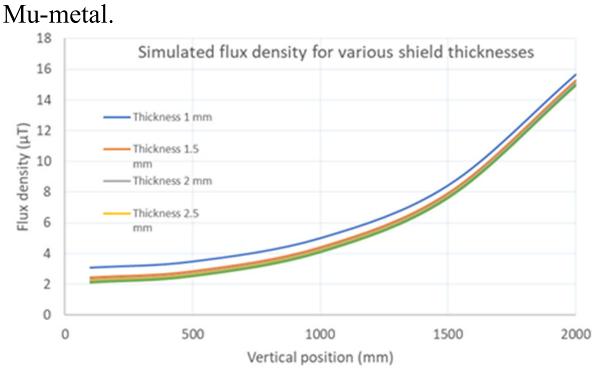

Figure 2: Predicted central flux density as a function of height for different shield thicknesses. Height 0 is floor level.

The simulations accurately predicted that the target field of 1 µT would not be achievable purely by a single layer passive shield with an open top, with the best achievable result at the shield base being 2 µT. A series of adapted simulations included a lip at the top to decrease the diameter of the opening and an active coil to repel flux from entering the shield top. These simulations predicted that a field below 1 µT at a wide range of positions would be achievable with a top coil but that using a top coil alone would require approximately 240 ampere turns to achieve the optimal result, a discrepancy from the measured reality discussed below that highlights the difficulties of using finite element modelling to accurately predict the behaviour of large but thin structures. A bottom coil was also included in the final design to give greater control.

MAGNETIC FIELD MEASUREMENTS

2017 Facility Commissioning Measurements

In 2017, UKRI-STFC Daresbury began commissioning of its vertical test facility (VTF). The compliance of the VTF's magnetic hygiene was validated using fluxgates to measure the magnetic field in the top, middle, and bottom cradle positions under a range of top and bottom coil current configurations. The addition of the active coils reduces the magnetic field in the VTF to <1 µT. The results of the nominal coil configuration (top coil = 6 A) are presented in Fig. 3.

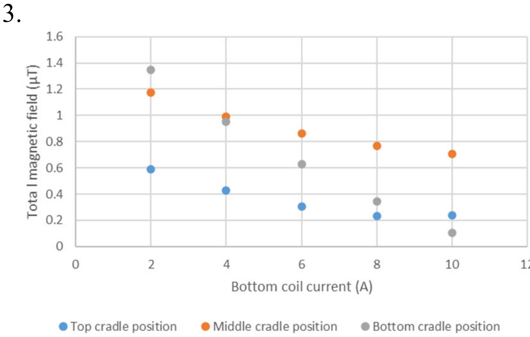

Figure 3: Magnetic field measurement with Top coil at 6 A.

2021 VTF Magnetic Field Measurements

A second set of magnetic field measurements were made in 2021 to revalidate the bottom coil after a repair. The magnetic field measurements were performed at room temperature under atmospheric pressure using three three-axis (transverse, vertical, and longitudinal) CryoMag[4] magnetic fluxgates with a full directional measurement range of ± 70 µT (Fig. 4). These fluxgates with an ADC of 14 bits can measure a minimum magnetic field of 8 nT. The dominant uncertainty of these measurements is that of the calibration scaling factor thus all other uncertainties can be neglected. This scaling factor uncertainty is no more than ± 0.5 %. These fluxgates are capable of operating in cryogenic conditions (2 K) and under vacuum and are different from the fluxgates used in the 2017 commissioning measurements. The fluxgate and its drive electronics are housed separately. The fluxgates were strapped onto the middle of the cavity frame for each cavity position to be tested using Kapton tape and black cable straps as shown in Fig. 5. This mounting provided a simple, swift, and secure way of mounting and dismounting the CryoMag fluxgates onto the cradle positions for our test. The fluxgates' cryogenic cables (Be-Cu ribbon) were then routed out the top of the CSI lid where the drive electronic were housed. A DecaPSU unit was used to activate the fluxgate and produce a ± 10V analogue output signal. This power supply unit can power and produce output signals for up to 10 magnetic field fluxgates.

[4] bartington.com

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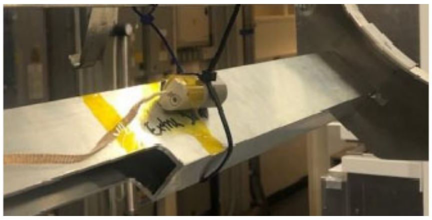

Figure 4: CryoMag fluxgate strapped onto middle cradle position. Diameter: 20mm and length 50mm.

The DecaPSU output signals were read into a 14-bit NI[5] ADC and LabVIEW[5] script on a PC, which converted the voltage measured into a magnetic field measurement in µT. The voltage to µT scaling factor used is 143 mV/µT.

A first set of measurements were taken using 3 CryoMag fluxgates to quantify the attenuation in the VTF's magnetic field as a result of its passive magnetic shielding. The results are presented in Table 1.

Table 1: Magnetic Field Measurement on CSI Stand and Within Passive Shield Taken in 2021

	Total magnetic field on CSI stand (µT)	Total magnetic field in passive shielding (µT)
Top	33.03	1.223
Middle	33.28	1.194
Bottom	33.14	1.855

Table 1 shows a significant reduction of 96% in the local magnetic field, from an average of 33 µT on the CSI stand to an average of 1.44 µT within the passive Mu-metal shield.

For the active shielding measurements, these were made by varying the current in the top and bottom coil independently. Both coils started at 0 A with the current in the top coil kept constant until the current in the bottom coil had been swept from 0 A to 10 A. The current in the top coil was then increased by 1 A. The process was repeated until the top coil reached 10 A and the final measurement of top and bottom coil = 10 A was made. The results of measured magnetic field for the VTF's nominal coil configuration (top coil = 6 A, bottom coil = 7 A) are presented in Fig. 5. The results show that at top = 6 A, with a current >4 A in the bottom coil, the field in the VTF in all cradle positions is <1 µT with minima for each cradle position achieved between 6 A and 8 A in the bottom coil. A significant improvement was also observed in the field measured in the middle cradle between 2017 (0.861 µT) and 2021 (0.457 µT) at the nominal bottom current of 6 A. It is suspected from this improvement that not all of the turns on the originally installed bottom coil were connected correctly.

[5] ni.com

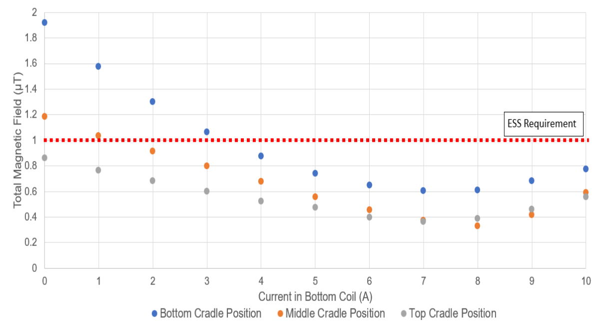

Figure 5: Total field measurements when top coil = 6 A.

SUMMARY

STFC DL's Vertical Test Facility is still within ESS cavity testing magnetic field requirement of <1 µT, with a comfortable margin of safety of 39%. Under the normal coil operating configuration (top coil = 6 A and bottom coil = 7 A). The measured magnetic field under nominal coil configuration in each cradle position is - Top = 0.365 µT, middle = 0.375 µT and bottom = 0.607 µT. The performance of the Mu-Metal passive magnetic shield also has not deteriorated significantly since commissioning. A reduction of 96% in the magnetic field from stand to the bunker is still observed and with the active coils on, the field drops further to below 1 µT in a range of coil configurations.

FUTURE PLANS

After completion of the ESS testing program, the VTF will be used to test and qualify the HB650 cavities for the Proton Improvement Plan II (PIP-II) at Fermi National Accelerator Laboratory (FNAL). The PIP-II project has a more stringent magnetic hygiene requirement of <0.5 µT thus Daresbury's VTF will need to be re-validated to evidence it does meet this new requirement.

To meet this new requirement the UKRI-STFC DL plans to install an additional coil in the middle of the cryostat, a number of CryoMag fluxgates on the CSI, a DecaPSU into the control rack and a passive shield degaussing system. The goal of these additions is to equip DL with the ability to monitor and tune the magnetic field within its VTF during 2 K cavity testing, demagnetise the existing passive shield and improve the magnetic hygiene in the VTF such that it meets PIP-II's requirement with a suitable margin of safety.

REFERENCES

[1] May, A. J., *et al.* "Commissioning and cryogenic performance of the UKRI STFC Daresbury Vertical Test Facility for jacketed SRF cavities", *IOP Conference Series: Materials Science and Engineering*, vol. 1240, no. 1. IOP Publishing, 2022.