MAGNETIC FIELD MANAGEMENT IN LCLS-II 1.3 GHZ CRYOMODULES*

S. K. Chandrasekaran†, A. Grassellino, C. Grimm, G. Wu, Fermilab, Batavia, Illinois, USA

Abstract

The ambient magnetic field at the SRF cavity surface of the LCLS-II 1.3 GHz cryomodules is specified to be less than 0.5 μT (5 mG). Multiple methods were designed to lower the magnetic fields inside the prototype cryomodule. The resulting ambient magnetic field components in this cryomodule just prior to its first cool down was <0.15 μT (1.5 mG), as measured using fluxgates inside and outside the cavity helium vessels.

INTRODUCTION

Trapped magnetic fields on the RF surface of a SRF cavity can limit the quality factors (Q) achieved, due to increased RF surface resistance. The LCLS-II 1.3 GHz cryomodule specifications [1] therefore require the ambient magnetic fields to be less than 0.5 μT (5 mG), to obtain a Q of 2.7x10^{10} at 16 MV/m. The methodologies used to meet this specification include a 2-layer passive magnetic shield, an active longitudinal compensation scheme, and a strict magnetic field control program. The effectiveness of these methods are evaluated in the two prototype cryomodules (pCM), one at Fermi National Accelerator Laboratory (Fermilab) and one at Thomas Jefferson National Accelerator Facility (JLab). The Fermilab pCM is fully assembled and currently installed at the Fermilab Cryomodule Test Stand 1 (CMTS1). The JLab pCM is currently being assembled, and the results from this prototype shall be presented by JLab colleagues in a later publication.

MAGNETIC INSTRUMENTATION

The two pCMs are populated with 13 Bartington® Instruments Mag-F fluxgates each [2, 3]. Of the eight cavities in the pCM, four are instrumented with 2 fluxgates each inside the helium vessels, attached to the outer surface of the cavity, as illustrated in Figure 1. The first fluxgate is placed perpendicular to the cavity axis, in a vertical plane perpendicular to the cavity axis, and close to the bottom equator. The second fluxgate is placed at 45° to the cavity axis, in a vertical plane parallel containing the cavity axis.

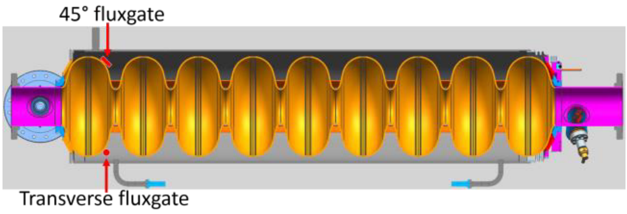

Figure 1: The two fluxgate locations within the cavity helium vessel. These fluxgates are mounted on the outside surface of the cavities.

An additional 5 fluxgates are placed external to the cavity helium vessels, between the two layers magnetic shields, parallel to the cavity axis and close to the vertical plane containing the cavity axis. The locations of these 5 fluxgates in the pCM are illustrated in Fig. 2.

The fluxgates inside the helium vessel have three functions: (1) to monitor the magnetic fields during assembly of the cryomodule and qualify the magnetic control program, (2) to quantify magnetic flux expulsion of the cavities during cool down, and (3) to monitor magnetic field generated by thermoelectric currents at the superconducting critical temperature of the niobium cavity at 9.2 K.

MAGNETIC SHIELDING

The magnetic shielding design for these cryomodules was optimized computationally [4] to reduce the ambient magnetic field at the cavity to less than 0.5 μT (5 mG). This shield scheme assumes a low carbon steel vacuum vessel is used for the cryomodules. These calculations assumed a relative permeability (μ_r) of 12,000 for the magnetic shielding material. The shields were designed to envelope the outside surface of the helium vessels of the cavities, but also had to accommodate several components attached to the cavities, including the fundamental power coupler, the cavity support bearing brackets, the end lever tuner to cavity attachment arms, beam tubes, etc. A 3-dimensional CAD model of the resulting magnetic shield used in the pCM is illustrated in Figure 3.

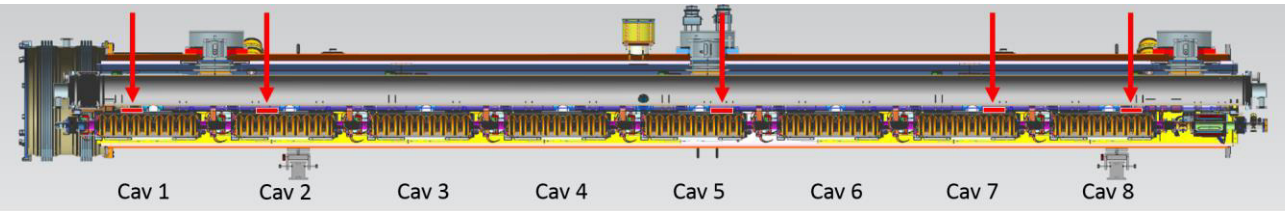

Figure 2: The locations of the five fluxgates external to the cavity helium vessels.

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† saravan@fnal.gov

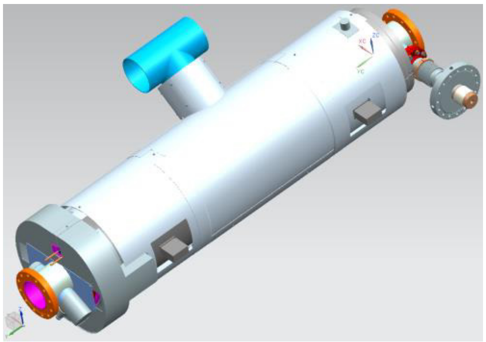

Figure 3: A 3-dimensional CAD illustration of a pCM magnetic shield around a 1.3 GHz cavity.

Shield Inspection

The majority of pCM shields were manufactured using Cryoperm 10, and a subset were manufactured using Amumetal 4K. The shields for the pCMs were manufactured by two vendors in USA. Magnetic shield sets from each shipment from the vendors were quality checked magnetically and physically. The magnetic checks involved measurement of the attenuation factors of the main body shields, without the tuner and coupler side end caps, in the earth's magnetic field. The measurement location was chosen based on the local magnetic field, and had to have a longitudinal component of about 15 µT (150 mG) to represent the longitudinal component at the SLAC National Accelerator Laboratory (SLAC) tunnel [5]. A shield, without its end caps, during such a measurement is pictured in Figure 4.

The measured magnetic field along the axis of the shield set is illustrated in Figure 5, along with the background magnetic field (i.e. without the shields). The shields had to meet a specification [6] of $\mu_r \geq 10{,}000$. The calculated magnetic field for the attenuation measurement set up is also illustrated in Figure 5, for a relative magnetic permeability of 10,000. Despite variations between vendors and shipments, the shields sets were deemed to meet this specification, and the estimated μ_r was greater than 40,000.

Physical checks of the magnetic shields were performed by assembling a magnetic shield set on a spare LCLS-II type cavity.

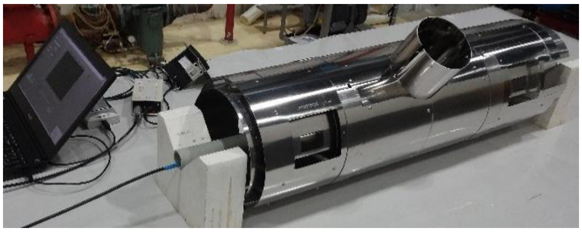

Figure 4: The on-axis magnetic field attenuation measurement of a shield set, without end caps.

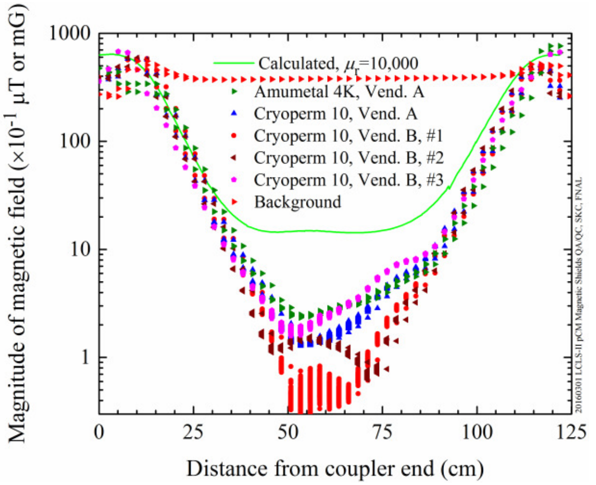

Figure 5: The attenuated magnetic field, as measured along the axis of the 2-layer magnetic shields, without end caps. Also illustrated are the background magnetic field without the shield, and the calculated magnetic field for $\mu_r = 10{,}000$.

MAGNETIC CONTROL PROGRAM

A strict magnetic control program was implemented to reduce sources of magnetic fields within the CM. This includes selection of non-magnetic (e.g. titanium) or low permeability (e.g. 316 series stainless steel) materials for components in close proximity to the cavities, a residual magnetic field check for components made from stainless steels and their demagnetization as needed, demagnetization of the low carbon steel vacuum vessels [3, 7, 8], and demagnetization of the fully assembled cryomodule [3, 9].

All components in close proximity to the cavities, including fasteners, beam line bellows, beam line spool pieces, gate valves, beam position monitors, tuners, bearing blocks, invar rod and clamps, etc., are inspected for residual magnetic field. Fasteners are typically required to have a residual magnetic field less than 0.5 µT (5 mG) at 6 mm (0.25″) from its surface. The remaining hardware are required to have residual field less than 0.5 µT (5 mG) at the distance of the hardware piece from the cavity. These specifications mean that some components can have a relatively high residual magnetic field at the beam, yet satisfy the 0.5 µT (5 mG) at cavity requirement. Hardware that are close to the beam but away from the cavity, are therefore inspected to have a residual field less than 50 µT (500 mG) at the beam. This would be the field that the beam is exposed to in the magnetically unshielded drift tube sections of the accelerator due to the earth's magnetic field.

Vacuum Vessel Magnetic Control

The LCLS-II vacuum vessels are manufactured from ASTM A516 Grade 60 low carbon steel. These vessels have a high, non-uniform, residual magnetic field at the cavity locations due to manufacturing processes. The residual magnetic field of the vacuum vessel was measured along three lines, containing the lower equators of the cavities, the beamline, and the upper equators of the cavities, respectively.

Figure 6: Helmholtz coils on the exterior surface of the LCLS-II pCM vacuum vessel [3, 9].

The pCM vacuum vessel, after receipt at Fermilab, had average fields greater than 50 μT (500 mG) at the cavity location. In addition, the fields were varying in magnitude and would have resulted in greater fields within the magnetic shields. These varying magnitudes cannot be cancelled by the active cancellation, described next, either. The vessel was therefore demagnetized [3, 8], using Helmholtz coils wound on the outer surface of the vessel as pictured in Figure 6, similar to that proposed in [7]. Subsequently, the average magnetic field at the cavity locations within the vacuum vessel was less than 5 μT (50 mG). The field distribution within the vessel, before and after demagnetization, is illustrated in Figure 7.

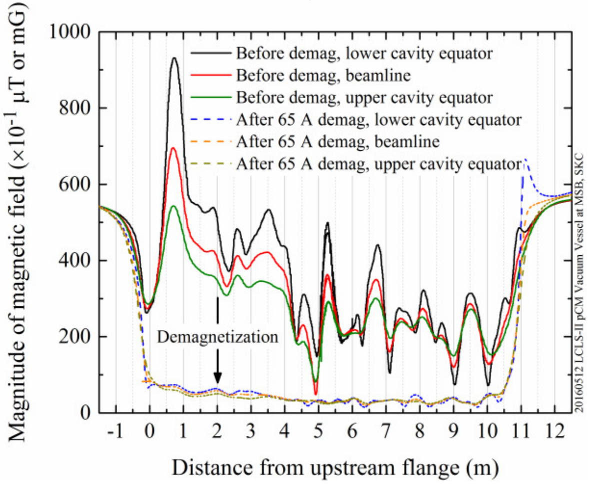

Figure 7: Measured magnetic fields before (solid lines) and after (dashed lines) demagnetization of the pCM vacuum vessel [3, 8].

Demagnetization of Fully Assembled CM

The magnetic fields in the pCM were monitored periodically during assembly and installation at CMTS1, using the 13 fluxgates. Increased magnetic fields were detected by these fluxgates during assembly, up to 4.6 μT (46 mG), as illustrated in Figure 8. Demagnetizing the assembled pCM successfully lowered the fields to <0.23 μT (2.3 mG) [2, 3, 9]. Although not required, the pCM was demagnetized again at CMTS1 [3, 12] to confirm that demagnetization of the cryomodule at test stand would not affect any other systems. The field components before cool down of the pCM, as measured by the 13 fluxgates, were <0.15 μT (1.5 mG).

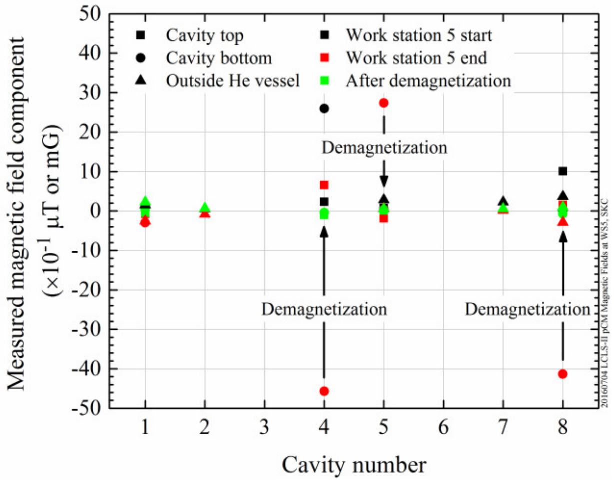

Figure 8: The magnetic fields measured by the 13 fluxgates in the pCM during assembly, and after a successful demagnetization [2, 3].

Longitudinal Field Active Cancellation

A long, narrow, hollow ferromagnetic cylinder will inherently have lower magnetic attenuation in the axial direction than in the transvers direction [7, 10, 11]. The Helmholtz coils on the outside of the vessel are used as active cancellation coils. They are used and tuned as needed on the prototype cryomodule.

CONCLUSION

The magnetic field components measured by the 13 fluxgates in the Fermilab prototype cryomodule was <0.15 μT (1.5 mG) before first cool down. These are the lowest recorded magnetic fields in an assembled cryomodule. This validated the designs and methodologies used to meet the LCLS-II ambient magnetic field specification of <0.5 μT (5 mG). The need for and methodology for demagnetizing a fully assembled cryomodule was demonstrated for the first time.

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