MEASUREMENT OF A SUPERCONDUCTING SOLENOID WITH APPLICATIONS TO LOW-BETA SRF CRYOMODULES*

S.H. Kim#, M.P. Kelly, Z.A. Conway, P.N. Ostroumov, ANL, Argonne, IL 60439, USA
E.E. Burkhardt, Cryomagnetics, Inc., Oak Ridge, TN 37830, USA

Abstract

Proton and heavy-ion linacs with superconducting cavities require compact lattices to suppress emittance growth in the low-velocity region. For beam focusing superconducting solenoids are superior in this regard to normal conducting quadrupoles. A superconducting solenoid with integral x-y steering coils has been fabricated for the Project-X Injector Experiment (PXIE) half-wave resonator cryomodule. It is capable of generating 6 T solenoidal fields and dipole steering fields of 30 T·mm field integrals in both of transverse directions. We experimentally investigated issues for practical use of this solenoid in cryomodules including: 1) the superposition of dipole steering fields on solenoidal fields, 2) the magnetic axis of the solenoid with respect to the mechanical references in cryogenic temperatures, and 3) the residual magnetic field generated by the solenoid on the superconducting RF cavity surfaces even after degaussing; a 72 MHz quarter wave resonator was used for this experiment. In this paper, we present details of experimental setup and results.

INTRODUCTION

Proton and ion linacs require a compact focusing lattice in the low-velocity region to minimize the required real-estate and to minimize emittance growth and corresponding beam loss [1]. Superconducting solenoids are superior in this regard to normal conducting quadrupoles. To reduce the real-estate requirements further dipole steering coils are integrated with solenoids [2]. This superconducting solenoid with dipole steering coils is to be installed in a cryomodule with superconducting RF cavities so the following questions regarding beam and cavity performance need to be verified: 1) Are the dipole fields linearly superposed with the solenoid fields? 2) Is the solenoid aligned to the beam in the cryomodule? 3) Are the residual magnetic fields generated by the solenoids small enough not to degrade the cavity Q-factor?

We studied these issues with a superconducting solenoid prototype fabricated for the Project-X Injector Experiment (PXIE) Half-Wave Resonator (HWR) cryomodule [3]. This solenoid generates 6 T solenoidal fields and each pair of the dipole steering coils integrated with the solenoid produces up to 30 T·mm integrated deflecting fields. In this paper, we will briefly introduce the solenoid used in these experiments and present the dipole field measurements with and without the solenoidal field to discuss field superposition. Then, we will present magnetic axis measurements relative to the mechanical axis and discuss accuracy of this measurement method. Another alignment issue, the alignment of the solenoid to the beam axis in the cryomodule, is not discussed in this paper [4]. Next, measurements of the residual magnetic fields generated by the solenoid on the surface of a 72 MHz superconducting Quarter-Wave Resonator (QWR) will be presented with a discussion of the degaussing employed to reduce the residual magnetic fields on the cavity surface. Finally, a summary of these experimental results will conclude this paper.

FIELD PROFILES AND SUPERPOSITION

The solenoid contains two bucking coils at either end. The bucking coils are wired in series with the main solenoid to produce an opposing field polarity relative to the solenoidal field. There are no iron return yokes or magnetic shields surrounding the solenoid. The bucking coils minimize the axial fringe fields and stray fields on the cavity surfaces. The measured axial field profile is shown in Fig. 1. The measured solenoid field in the high field region is in good agreement with the design values; this ensures that the focal length will be the same as the designed value. The fringe fields are slightly higher than the design but are still small enough for the residual magnetic fields around the cavity wall to be successfully reduced by degaussing as will be discussed later in this paper.

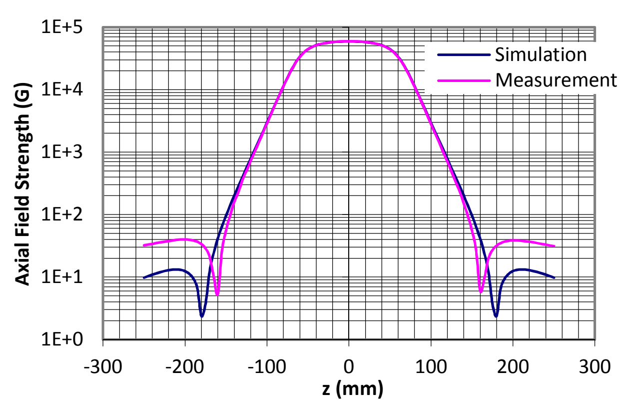

Figure 1: Axial field profiles on the axis. z is the longitudinal position which is 0 in the middle of the solenoid. Note that the magnetic field drops at z = ±160 mm in the measured data and at z = ±180 mm in the simulated response correspond to a polarity change in the axial field.

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# shkim121@anl.gov

Each dipole steering coil is composed of two racetrack shaped coils located outside of the solenoid coil; one is oriented vertically and the other is oriented horizontally. The dipole fields are measured on the z-axis of the solenoid bore with and without the solenoid field on. When the solenoid is energized to 6 T, the dipole field is 5~7% higher than when the solenoid is off, Fig. 2. With no current the solenoid coil, which is composed of multi-filamentary NbTi strands twisted within a copper matrix, is supposed to partly shield the dipole fields. However, the operating solenoid field of 6 T is high enough relative to the lower critical field of NbTi such that the dipole fields will be stable in actual operation. In the measurements presented here, the solenoid was turned on and off at each data point shown in Fig. 2. Notice that the measured field is axially symmetric with respect to the middle of the solenoid so the dipole coil is mechanically stable against Lorentz forces produced by the solenoid.

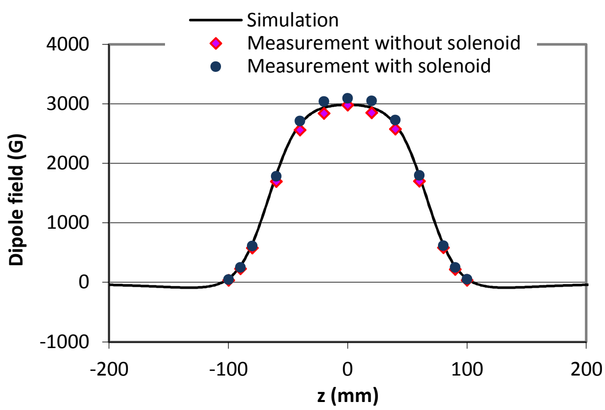

Figure 2: Dipole field profiles of simulation and measurement with and without solenoid fields.

MAGNETIC AXIS OF SOLENOID

The magnetic axis, here defined as the center of the solenoidal equipotential lines, is derived from an angular scan of the radial magnetic field using a hall probe. We measured the radial component of the magnetic field at two longitudinal positions, z = ±64 mm. These locations satisfy the following conditions; 1) the radial field is linear and 2) the radial field strength is large enough relative to the axial field component which reduces measurement errors arising from the misalignment of the probe. Because of the linearity this field sinusoidally oscillates with the azimuthal angle if the magnetic center has an offset from the mechanical center of the solenoid bore which is the center of probe rotation. The relationship between the magnetic field parameters and geometries is given by:

$$\Delta B/B_0 = d/R, \qquad (1)$$

where ΔB is the field amplitude, B_0 is the field offset of the measured magnetic fields, d is the offset of the magnetic center from the mechanical center, and R is the radius of the angular scan.

The measurement results are shown in Fig. 3, the measured offsets are 0.32 mm at z = -64 mm and 0.27 mm at z = +64 mm where R = 16 mm. The phase of each cosine curve corresponds to the angular offset of the magnetic center relative to the x-axis of the solenoid; so the magnetic center is located 145 degrees (z = -64 mm) and 115 degree (z = 64 mm) from the x-axis of the solenoid. Uncertainty in the longitudinal position of the measurements is the source of the field-offset difference between two curves in Fig. 3.

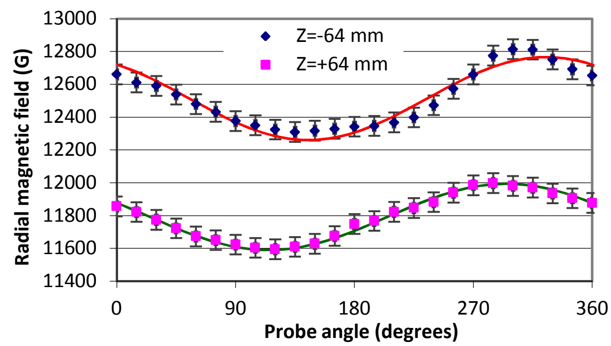

Figure 3: Angular scan of radial magnetic field to find the magnetic axis with respect to the mechanical axis (probe angle is 0 on the x-axis of the solenoid) measured at two different longitudinal positions.

Errors in these measurements are given by these factors: 1) uncertainty of the probe position in the radial and longitudinal directions, 2) misalignment of the hall probe, 3) contribution of the second or higher order of d/R because eq. (1) is derived with the first order approximation of d/R, 4) instrument errors of the probes and the gauss-meter, and 5) wobbling of the rotating rod on which the probes are attached during the angular scan. The factors from the first to the fourth totally give a fractional error of 5% in the result of d, which is negligible because typical transverse alignment tolerance of this solenoid is 0.25 mm. However, the last factor, which originates from the gap between the rotating rod and the rotation guide as shown in Fig. 4, gives uncertainty in the offset by the same amount of the gap distance which is ±70 μm after correction by thermal contraction. Multiple scans per angle would reduce this error statistically. It is measured once per angle in this study.

RESIDUAL MAGNETIC FIELDS

The solenoid test with the QWR is done to observe any residual magnetic field which is possibly generated by materials around the cavity, such as the helium jacket and the solenoid housing, magnetized after solenoid operation. To minimize the residual magnetic field, we degaussed the solenoid with a temporally sinusoidal current profile whose envelope is exponentially decayed with a decay time of 5 times the sinusoidal oscillation period and it finished when the field amplitude of the last degaussing cycle was 7 G in the middle of the solenoid.

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We installed the solenoid with the cavity in a cryostat as shown in Fig. 5 and measured magnetic fields during and after solenoid degaussing at two representative locations: one on the axis where the solenoid field is a maximum and the other on the cavity wall, which is the higher position in Fig. 5, where the RF magnetic field is a maximum when we use the PXIE HWR.

On the cavity wall, the magnetic field measured during the degaussing behaved like a hysteresis curve which is supposed to be dominated by the NbTi in the solenoid coil [5] and it came to the center of the hysteresis curve after degaussing was finished; therefore, there is no residual magnetic field after degaussing at that position except for leakage of the earth's magnetic fields, which cannot be degaussed by the solenoid, no matter what was magnetized during solenoid operation. On the other hand, the probe installed on the axis is too coarse to measure the residual magnetic field by accuracy of tens of mG because it is for measuring high level fields; note that the maximum field is 75 G on the axis whereas it is 55 mG on the cavity wall. The residual field on the axis was measured again after warming up scanning the low field probe and it was found that there were ~100 mG residual fields around the solenoid and the source of these fields was inside the solenoid housing; other than that, there are no significant residual field more than 10 mG except for leakage of earth's magnetic fields. For accurate measurements, we set the solenoid alone inside a good magnetic shield. The measurement results are shown in Fig. 6. Even though there still remain the residual magnetic fields inside the solenoid, the degaussing worked successfully so that the residual field at the position of the cavity surface is 2~3 mG.

SUMMARY

With the PXIE solenoid, we experimentally verified that 1) the dipole field of the steering coil is well superposed to the solenoid field and this coil is mechanically stable on solenoid operation, 2) the magnetic axis can be found with accuracy of less than 100 µm by scanning hall probes, 3) residual fields generated by the solenoid can be reduced to a few mG at the cavity surface by degaussing the solenoid.

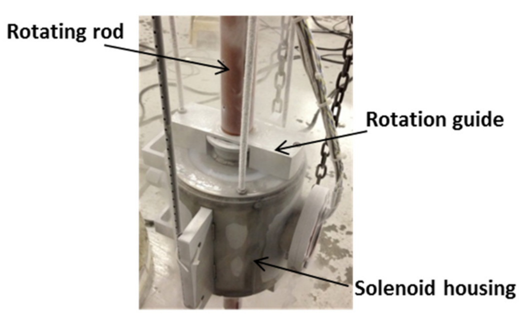

Figure 4: Setup for angular scan of the radial magnetic field. Hall probes are attached on the rotating rod which is composed of bakelite while the rotation guide is composed of aluminium and the solenoid housing is composed of stainless steel.

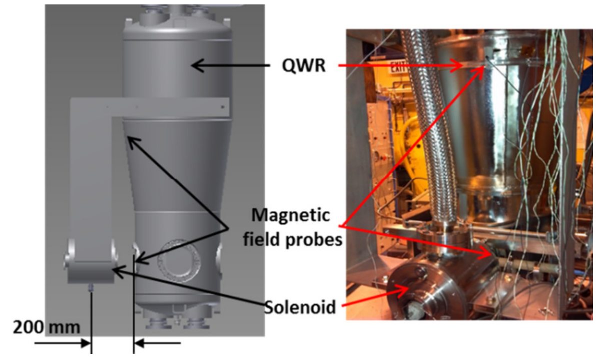

Figure 5: Magnetic field measurement setup in the cryostat. The QWR is hung on the cryostat lid. Each probe measures the magnetic field normal direction to the cavity wall; higher position on the cavity wall: low field probe (Bardington Fluxgate Magnetometer, Mag-01), lower position on the axis: high field probe (Lakeshore Hall Probe, HMCT-3160).

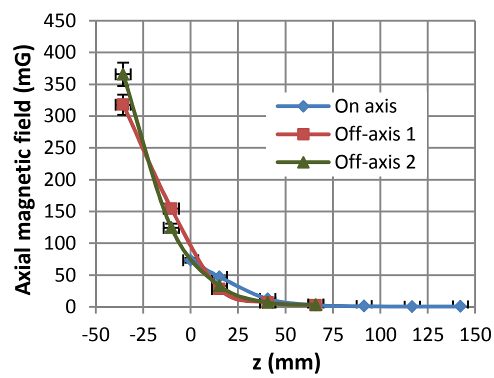

Figure 6: Axial scans of the residual magnetic field generated by magnetized materials in the solenoid. It is measured with the solenoid alone. The solenoid flange is placed at z=0 and the cavity flange will be placed at z=75 mm. The radial position of the "off-axis" scan is r=56 mm where the measured residual magnetic field is maximum.

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