Design and Performance of Focusing Lenses for Installation into Superconducting Cryomodules of a Proton Linac

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***Abstract*—The high energy sections of the Fermilab HINS R&D proton linac will utilize superconducting spoke resonator (SSR) RF cavities. These will be assembled into cryomodules with strong solenoid focusing lenses closely interleaved with the cavities. A design for lenses has been made for the lower (SS1) and higher (SS2) energy ranges of the SSR-section. Prototype lenses for both SS1 and SS2 sections have been built and the SS1 has been tested. Shielding is needed to reduce the solenoid fringe field on the cavity wall below the 10 μT level, and a preliminary design was built and tested with the SS1 prototype lens. We discuss the design requirements and challenges, and the results from quench testing and magnetic measurements of the SS1 prototype lens.**

***Index Terms*— Superconducting, Solenoid, Cryomodule, Accelerator Magnet, Magnetic Shielding**

I. INTRODUCTION

ONE of the problems associated with acceleration of high intensity ion beams in RF linacs is the development of a low loss beam transport line. Within this task, building a high quality transport line in the low energy section is considered to be one of the critical issues. A proton (or H^-) accelerator which uses superconducting spoke resonator (SSR) cavities is now in development at Fermilab [1]. It was shown, for the front end of this superconducting linac, that superconducting solenoid-based focusing lenses can provide the required focusing while leaving some space for diagnostic equipment. Moreover, attempts to use quadrupole triplets for the same purpose proved unsuccessful. A program to develop and test front end SSR acceleration and superconducting solenoid focusing technologies in an R&D proton linac (HINS) has been ongoing at Fermilab for several years [2].

The HINS solenoid focusing lens design challenges have previously been discussed in detail [3], [4]. The solenoids are subject to constraints imposed by the accelerator lattice design, as well as the requirements for installing and operating in the cryomodule environment in close proximity to SSR cavities. The lattice defines the lens focusing length, which in turn defines the solenoid strength. For solenoid focusing, the strength of the lens is defined by the expression $FS_l = \int_{-\infty}^{+\infty} B^2 dz$; as the beam energy grows, the lens strength also must increase. The short focal length of ~0.5 m in the HINS linac requires a focusing strength FS_l = 1.8 T^2-m for the lowest energy section from 2.5 to 10 MeV (which utilizes room temperature cross-bar H, or CH, cavities) [4]. The SSR cryomodules operate at higher energies, with the first section (SS1) accelerating beam from 10 to 30 MeV, and the second (SS2) from 30 to 60 MeV. The SS1 solenoids must provide a focusing strength of FS_l = 3.0 T^2-m in SS1, and FS_l = 5.0 T^2-m in SS2. The flange-to-flange length in which to produce the field integrals is limited, and the 30 mm beam tube aperture affects the peak field that can be achieved with a given (NbTi) superconducting strand. The solenoids will operate at 4.6 K or higher temperature with intense beams and unknown beam heating; thus the designs allow 25 % current margin between the operating point and the maximum quench current. Tolerances on alignment precision during installation and cool down are challenging, at the level of ±0.15 mm, and steering dipoles to center the beam are required; space constraints require these to be embedded within the solenoid. The required field integral is relatively weak, $BL_s = \int_{-\infty}^{+\infty} B dz$ = 0.5 T-cm for the SS1 section.

II. SSR SOLENOID LENS DESIGN

The solenoid lens design [6] is strongly driven by close proximity to SSR cavities within the cryomodule. The allowed magnetic field level on the walls of SSR cavities was specified [5] to be $<10^{-5}$ T; this is at a distance only 225 mm from the center of the SS1 solenoid, where the peak operating field is about 6.6 T. The rapid reduction in field at the solenoid ends is effectively achieved by optimizing the use of bucking coils and a low carbon steel flux return to reach the few $\cdot 10^{-4}$ T level. Further reduction to reach $<10^{-5}$ T requires the use of a specially designed cryogenic magnetic shield, which must accommodate penetrations for the solenoid support post, helium lines, instrumentation and current leads, beam tube, and alignment target support beams. A method for conducting optical survey of the alignment target positions for each solenoid within the cryomodule must be possible after installation, and following cool down, with up to nine solenoids and cavities envisioned inside each cryomodule. Two orthogonal weak steering dipoles were incorporated within the solenoid using thin single-layer superconducting coils, thus keeping the solenoid aperture as small as practical, and optimizing the coil angles for the best possible dipole field

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quality. Fig. 1 shows the design concept for the SS1 solenoid-based focusing lens.

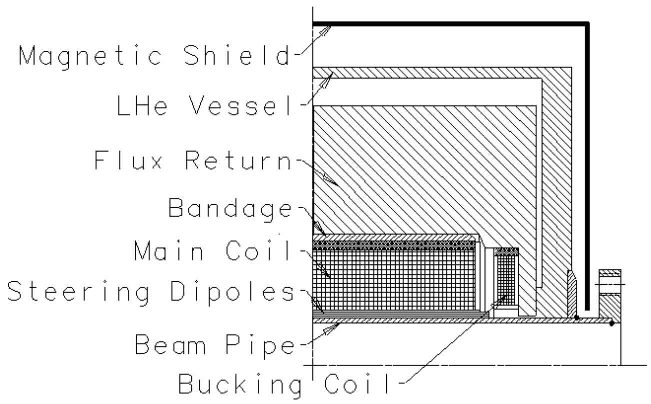

Fig. 1. Design concept of a solenoid-based focusing lens for the SSR cryomodule.

Most of these design challenges and solutions are common to the SS1 and SS2 sections. The increased focusing strength needed for SS2 is achieved by increasing the solenoid coil length (aperture, coil peak field, and margin being equal). Quench protection of these magnets has been extensively modeled [7]-[8], and the stored energy in the SS2 solenoid is such that the superconductor is at risk to high temperatures and voltages without taking special care. A prototype design for the SS2 is similar to that of the SS1, but the longer main coil is split into two coils separated by an insulating wall [9]. This requires an extra pair of leads, but allows more options for powering, quench detection, and protection. A prototype SS2 lens has been built, and a performance test is planned to occur soon.

III. SS1 Solenoid Development

The SS1 lens has advanced through several iterations of design, prototype fabrication, and testing. The first constructed prototype, SS1_SOL_01, did not include dipole coils. Test results at 4.2 K confirmed the predicted maximum 220 A quench current in the solenoid main coil, although with slow training to a somewhat erratic (~20 A variation) plateau. Magnetic measurements also agreed very well with the as-built predictions for field strength in all regions from the peak to the fringe field area [10]. Also as expected, the magnet was self-protecting and survived numerous quench events without energy extraction.

A second lens, SS1_SOL_02d, with the first dipole coils embedded within the solenoid, was built and tested [11]. In this case, inventory of the best quality superconductor strand was found to be insufficient for production of the expected number of SS1 lenses; therefore some changes to the design were introduced to compensate for the use of lower grade strand with less regular insulated dimensions. The ~5 % loss from strand performance and packing factor was compensated by changing geometric parameters of the solenoid main coil (MC). Also, the two bucking coils (BC) were placed at different radial and axial distances from the solenoid (varying each by 0.5 mm) to check sensitivity of the fringe field to BC placement.

The test of SS1_SOL_02d took place at higher temperature, 4.43 K, following changes to the test stand that increased the helium pressure (using refrigeration plant supply and return, rather than portable dewar supplies). Consequently, a calculated correction to the NbTi strand critical surface was applied to the quench predictions for both solenoid and dipoles [12]. The solenoid reached a stable quench plateau in the MC at the expected 200 A current in 8 quenches; yet during later testing two spontaneous quenches below 190 A were experienced, one while ramping and one at constant current. Magnetic field measurements again showed excellent (1 % at the peak) agreement with predictions: only a slight disagreement was visible at the BC locations, but the as-built model suggests that these can be explained by small variation of the actual BC positions from those in the model. Furthermore, the fringe field in the region of a cavity wall agrees with the calculated level of a few Gauss at the operating current. Since the flux return can saturate in some regions at higher currents, the current dependence of the fringe field was studied and found to match the Opera2D prediction very well, as shown in Fig. 2.

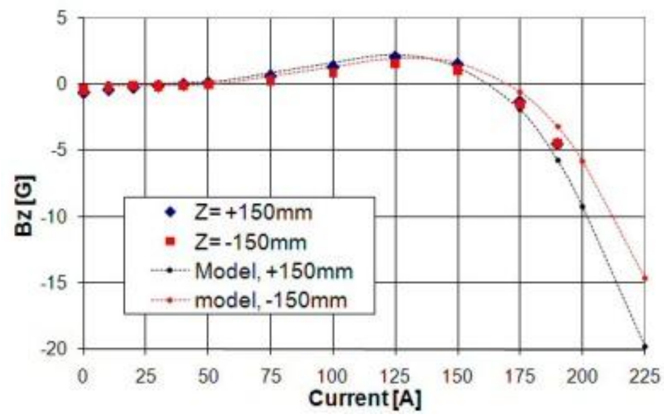

Fig. 2. Model and data axial field strength versus current for SS1_SOL_02d fringe field.

The dipole coils performed as expected, quenching just above 40 A with the solenoid operating at 190 A, and reaching the required 0.5 T-cm integral strength with plenty of margin at 23.5 A. An additional study of the dipole field quality was also made by performing warm integral magnetic field harmonics measurements, with each coil separately powered at ±0.25 A. This was successfully done before the dipole package was assembled into the lens, to validate the 3D model prediction of dipole field errors for these single-layer coils. A tangential coil probe of radius 1.22 cm was used, and the resulting map of field errors was in good quantitative agreement with the model. The maximum deviation from a uniform dipole was at the outer (probe) radius, measured to be about 12-15 % from the central strength.

After this test, it was realized that the loss of margin due to operating temperature has a significant impact. After the re-design, the SS1_SOL_02d current margin at 4.2 K was 19 % (not the desired 25 %), and this declines to 9 % considering a 4.6 K operating temperature expected in the beam line. Therefore another iteration was made that resulted in the SS1_SOL_03d coil geometry, in which the MC was basically lengthened to increase the focusing strength [13]. During this iteration, the magnetic shield design was also considered and performance of a prototype shield was modeled. This magnet also met its quench and magnetic performance expectations for both the solenoid and correctors; however, after reaching a quench plateau it also showed quite erratic and low quench currents [14]. It was realized that during fabrication inadequate pre-load had been applied to the ends, which could allow some motion of the bucking coils and cause them to quench. A method to fix this problem was devised, and a re-test of the repaired cold mass was completed [15]. The end pre-load was accomplished by inserting a shim (the maximum achievable, 0.36 mm) under the end flange, and further tightening the axial bolts. One training quench was seen before a stable plateau of a dozen quenches was made, with no degradation or retraining after a thermal cycle, to show convincingly that this problem was fixed. Fig. 3 plots the quench history of the original and modified solenoid, made over 5 thermal cycles (TC) from room temperature to 4.4 K. As a result of this mechanical change, the fringe magnetic field at 180 A was reduced by 5 G, to less than 1 G in the region of SSR - a clear improvement from the unshimmed case.

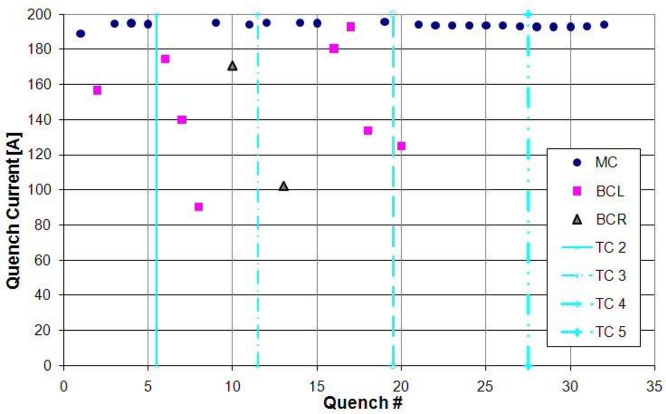

Fig. 3. Quench history for SS1_SOL_03d. End pre-load was increased following thermal cycle 3.

IV. Magnetic Shielding Test

The effectiveness of a magnetic shield can vary significantly from expectations, due to uncertainties in the shield material properties caused by handling during assembly, or temperature. An opportunity to experimentally measure this arose, due to availability of both a working lens, SS1_SOL_02d, and a Test Cryostat being prepared for use in testing of SSR cavities [16]. The prototype magnetic shield design [13] was fabricated from Cryoperm10® and annealed by the manufacturer, Amuneal. The shield was assembled around the solenoid lens, with an array of cryogenic Hall probes, commercially available from Cryomagnetics, Inc., mounted in a plane at the location of the SSR cavity wall, 225 mm from the solenoid center.

This assembly was installed in the Test Cryostat, which was mounted and supplied with cryogenic services via transfer lines in the Fermilab Magnet Test Facility (MTF). The measurement system used AC excitation of the solenoid and the Hall probes, with low noise electronics and a lock-in amplifier technique. In the test [17], the radial and azimuthal field components were measured at two points each along the vertical and horizontal axis orthogonal to the beam tube in the SSR plane, as a function of the solenoid current. The data show a measurement system resolution below 10^{-6} T. A detailed 3D model of the solenoid and shield was made, with all the actual shield penetrations and features. The agreement of measurements with the model prediction, shown in Fig. 4, is remarkably good. This gives us great confidence in the reliability of model predictions and material performance.

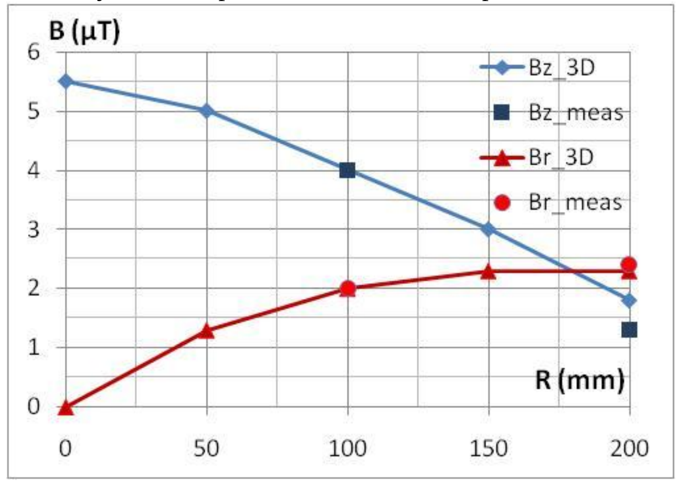

Fig. 6. Measured longitudinal and radial components of the fringe magnetic field at the location of RF cavity wall compared with those predicted by modeling.

V. Alignment Issues

Placing the focusing lens in a cryomodule requires accurate knowledge of the magnetic axis, and an understanding of how that axis moves from the installed position during cool down to operating temperature. The magnetic axis can be found with respect to fiducial targets using a moving or vibrating stretched wire technique [18] and survey. Due to complexity of the lens which consists of three separate solenoid coils, and the inevitable uncertainties in lens fabrication, the wire technique measures some weighted average of the coil centers. Furthermore, it is not yet completely clear how the magnetic axis found this way relates to the behavior of charged particles moving through the lens. Studies of the lens optical properties based upon particle tracking and simulation of the wire techniques [19] suggest these axes may differ at the level of 100 μm. An alternative approach using Hall probes to find the coil magnetic centers may yield complementary information to the wire technique, and is presently under study at Fermilab [20]. Laser-based optical techniques are being developed at Fermilab [21] that can track transverse displacements through cryostat windows at the 30 μm level, and angular displacements to 100 μrad, in a 9 m long cryomodule.

VI. Conclusion

The first stage of beam transport channel development for a high power proton linac front end at Fermilab has been completed with the successful testing of pre-production focusing lenses that meet the beam line and cryomodule requirements. The next stage of R&D includes integration of these elements in a prototype cryomodule and testing the system with beam. The development of a prototype cryomodule containing several SSR cavities and solenoid-based focusing lenses is in progress. All aspects of the cryomodule assembly and performance will be investigated using this test unit. Future work will include adjusting the lens design to work at 2 K, which will result in saving some precious real estate in the cryomodule, and incorporating beam position monitors inside each lens, which facilitates solving the beam transport problem.

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