HINS Linac Front End Focusing System R&D

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***Abstract*—This report summarizes current status of an R&D program to develop a focusing system for the front end of a superconducting RF linac. Superconducting solenoids will be used as focusing lenses in the low energy accelerating sections of the front end. The development of focusing lenses for the first accelerating section is in the production stage, and lens certification activities are in preparation at FNAL. The report contains information about the focusing lens design and performance, including solenoid, dipole corrector, and power leads, and about cryogenic system design and performance. It also describes the lens magnetic axis position measurement technique and discusses scope of an acceptance/certification process.**

***Index Terms* — linac, solenoid, focusing, dipole, magnet, alignment, cryostat**

I. INTRODUCTION

As part of the High Intensity Neutrino Source (HINS) program, an R&D is ongoing at Fermilab to build a high power H^- RF linac [1]. Currently, the efforts are concentrated on development of accelerating and transport elements of the front end of the linac. To mitigate the problem of halo formation (e.g. see [2]), it was found attractive to use superconducting solenoids as focusing lenses in the low energy part of the “front end” [3] illustrated in Fig. 1. This low energy part is further divided into sections which are identified by the type of RF structure used for acceleration.

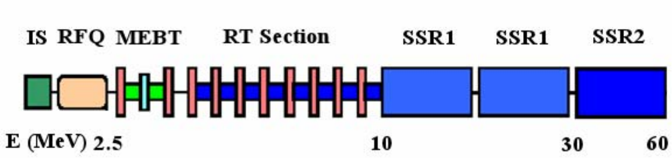

Fig. 1. HINS front end layout schematic.

Initial acceleration and focusing are achieved with an RFQ section. This is followed by a medium energy beam transport (MEBT) section where beam bunches are structured, and a room temperature (RT) section, that utilizes Cross-bar H-type (CH) cavities interleaved with solenoid lenses mounted in individual cryostats. Above 10 MeV, an alternating sequence of several stronger solenoid lenses and superconducting spoke resonators (SSR) will be assembled into long cryostats. Employing focusing solenoids in the low energy transport channels for reduction of the beam emittance growth rate seems useful up to the energy ~100 MeV. At higher energies, alternating gradient focusing with quadrupoles can be effectively used without significant beam quality degradation [3]. The development of superconducting quadrupole magnets for this purpose has begun at Fermilab with the design, fabrication, and test of a superferric quadrupole suitable for installation in an ILC-style cryomodule [4].

At present, the maximum energy of the HINS linac front end is fixed at the level ~60 MeV. With increasing energy, focusing strength requirements in the available space become more challenging and therefore three separate solenoid designs are needed for the CH, SSR1, and SSR2 sections [5]. Two styles of solenoids are required in each section: those with embedded steering coils for horizontal and vertical orbit correction are designated as Type-2 solenoids, and those without this feature are designated as Type-1. A total of 45 focusing lenses will be built for the linac (including spares).

The solenoid lens development effort has progressed for designs in each of the three sections. Solenoids for the CH-section are most advanced: having evolved from early designs and model magnets through prototyping and pre-production R&D stages, they are now into production and assembly into cryostats. Successful tests have been carried out at all of these stages [6].

The design of the SSR1 solenoid has benefited from the CH solenoid experience [7]. The first prototype Type-1 SSR1 solenoid has been built and successfully tested [8], and fabrication of the first Type-2 SSR1 solenoid is in progress.

A preliminary design for the SSR2 solenoid exists, but is still evolving due to challenges posed by quench protection in the case of a bucking coils quench.

II. CH SECTION FOCUSING SOLENOID DESIGN

Because of the relatively high H^- beam current (~40 mA) and low particle velocity in the front end part of the accelerator, required focusing strength of the lenses must be quite high. Since it is proportional to $(\int B^2 dl) / U$, where U is kinetic energy of particles in the beam, squared magnetic field integral must grow with the energy of the particles. Focusing period in the transport channel must be quite short (~ 0.5 m) to keep the beam diameter small; as a result, magnetic field in

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the solenoid must be on the level of several Tesla, which can only be obtained in superconducting systems. On the other hand, the magnetic field inside adjacent cavities must be small to prevent the appearance of additional multipacting zones. Since accelerating cavities in the CH section are ~0.25 m long, design of the CH solenoids became quite a challenge. Basic requirements for the focusing lens include 20 mm warm bore diameter, integrated focusing strength of ~ 1.8 T^2-m, and effective length less than 0.1 m (normalized to the maximum magnetic field). In accordance with results of beam dynamics study [9], steering dipoles must have an integrated strength of ~0.25 T-cm to be able to compensate for uncertainties in the focusing solenoid positioning of ~0.3 mm.

As an additional complication, steering coils need to be placed inside some of the solenoids which results in increased solenoid diameter. Also, anticipated coil heating from beam losses in the high intensity linac, requires creating a design with reasonably large operating margin.

A design study has been conducted to prove the very possibility of building a proper focusing lens: it was found that this task is solvable if a high quality superconducting strand is used, accompanied with high-density winding [10]. An additional strand R&D has been conducted to find an appropriate strand. Several types of strand developed for the SSC project and obtained by LBNL have proved to meet our needs; many more were not good enough. As part of this strand R&D study, three test solenoids were built to evaluate superconducting strands, develop the manufacturing technology, validate the design concept, and find approach to solving quench protection issues. These test solenoids each consisted of a single solenoid coil wound with round, rectangular, or flattened NbTi strand. The coils were epoxy impregnated and collared to apply pre-stress; each coil was assembled into a soft iron yoke. Test results confirmed the mechanical, quench, and magnetic model predictions [10, 11].

Based on the test coil fabrication experience, strand choice was made and prototyping activities started. At this stage, bucking and steering coils were introduced and the solenoid assembly technology (including coil winding and longitudinal pre-stress application) was developed and tested with one prototype Type-1 and one Type-2 device. These CH-section focusing solenoid designs were then finalized; the final design geometry for the CH Type-2 solenoid is shown in Fig. 2.

Several features of the focusing solenoid design required special attention. First, the introduction of bucking coils significantly changed the distribution of magnetic forces inside the solenoid. Due to high repulsive forces (~40 kN) between the main and the bucking coils, a sound mechanical solution was needed to keep the assembly from exploding. The soft steel magnetic flux return provides part of the solution, but is not able do the job on its own; the additional end support needed was provided by stainless steel compression flanges welded to the stretched LHe vessel pipe, also made of stainless steel. While testing the first prototype, quench training was very slow. Thorough mechanical analysis was made to understand stress and deformation at different stages of the solenoid fabrication, assembly, cool down, and excitation [12]. It was found that the way the solenoid was assembled resulted in partial separation of the bucking coil from the side flange during cool down and subsequently allowed movement of the coil during excitation. Introduction of a small gap in the flux return and screws to apply additional axial pre-stress helped to resolve the problem.

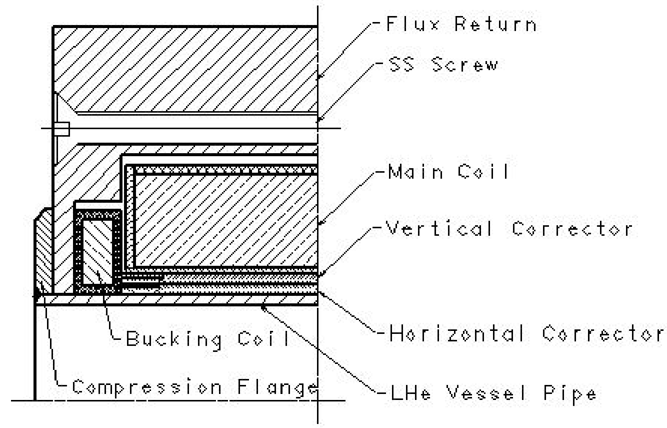

Fig. 2. Focusing solenoid with embedded dipole correctors.

The second important issue to be analyzed was quench protection. To analyze this problem, a thermal model and software tool were developed [13, 14]. It was shown that the main coil was self-protected against quenches because of rather fast normal zone propagation through the volume of the epoxy-impregnated coil. Appearance of a normal zone in one of the bucking coils resulted in much higher temperature rise because the full energy in the system is deposited in a relatively small volume. The models confirmed that the temperature rise in the bucking coils is not dangerous. It was also possible to choose an optimal dump resistance in the quench protection system to reduce the energy deposition in the solenoid and minimize voltage to ground during quench.

Having mechanical and quench protection issues resolved, a pre-production series of four focusing solenoids were built and tested. At this stage of the R&D, we tried to finalize the design, optimize fabrication tooling and procedures, and get some understanding of how predictable and reproducible the solenoid parameters are.

III. CH Focusing Solenoid Performance

Two pre-production focusing solenoids of each type were built and tested with similar test plans using the existing Test Stand 3 at the Fermilab Magnet Test Facility (MTF). In this paper we show results for the solenoid HINS_CH_SOL_04d (with dipole correctors), which are representative of all the solenoids. The test program and results are summarized in [6].

The test plans explored quench and magnetic performance of each solenoid, starting with quench training in which a dump resistor was utilized for energy extraction. After reaching a quench current plateau close to the predicted maximum, quenches with no dump resistor tested the solenoid survival. Current ramp rates were kept low; nevertheless, the quench current ramp rate dependence was explored for several solenoids up to the rate of 8 A/s. A dipole coil performance test determined the maximum steering corrector current with the Type-2 solenoid field set above the nominal operating value. Finally, there were solenoid and correction dipole magnetic field measurements to systematically explore the field strength versus position, to assess effectiveness of bucking coils, measure the field integrals, and compare the results with predictions of the "as-built" magnetic model.

The expected quench current was 233 A. Training started from 160 A and it took 24 ramps to reach the plateau at the level of ~235 A, with 200 A reached at the tenth cycle (Fig. 3). The solenoid did not require re-training after a thermal cycle. The solenoid survived after a bucking coil quench with deactivated dump resistor. At high current, one can clearly see the ramp rate dependence of the quench current. With the current of 200 A in the solenoid, there were no quenches in the correctors excited to 275 A, the power supply limit.

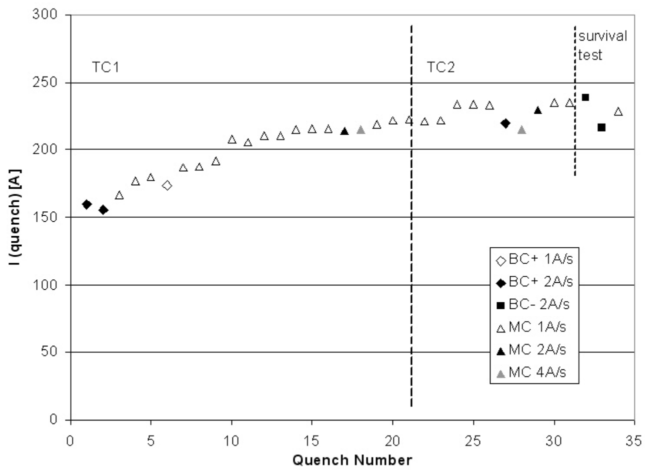

Fig. 3: Training history for HINS_CH_SOL_04d solenoid.

Comparison of the expected and observed magnetic field distribution on the solenoid axis at 200 A is shown in Fig. 4.

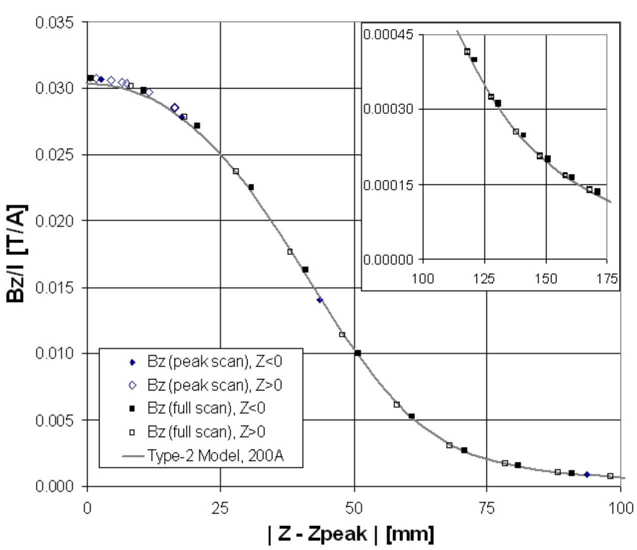

Fig. 4. Comparison of measured and predicted axial field transfer function profiles for bucked main coil at 200A in the central and fringe regions.

The data points from both sides of the magnet are overlaid here, and the profile is quite symmetric. The calculated field integral $\int B^2 dz$ from these data at 200A is 2.5 T^2-m, versus the predicted value of 2.4 T^2-m. The required value of 1.8 T^2-m can be achieved at 170 A.

The expected and measured magnetic field in the fringe field region (outside the solenoid) are also very close. At the nominal current of 170 A, the magnetic field in the area of the accelerating cavity (~150 mm from the solenoid center) is ~0.03 T for the Type 2 solenoids; for the Type 1 systems it is ~0.01 T. Additional shielding is needed if the accelerating cavity test shows that this field is too high.

The magnetic field integral $\int Bdz$ at 200 A for the horizontal corrector is 0.37 T-cm; for the vertical corrector it is 0.41 T-cm. So, the required integrated strength of 0.25 T-cm is achieved at ~ 130 A.

IV. CH Section Lens Production and Certification

The pre-production solenoid fabrication and testing experience gave us enough confidence to allow building these systems by an outside vendor. An order has been placed with Cryogenics, Inc. for production of 23 cold masses, each consisting of a solenoid encapsulated in a liquid Helium (LHe) vessel. Two cold masses have been fabricated and successfully tested so far at the vendor's site. Preparations for verification tests at FNAL (for a fraction of the production solenoids) are ongoing. Fabrication of all the cold masses will be completed in 2008.

Assembled and tested cold masses are to be placed in cryo-vessels at FNAL to form completed focusing lenses. Description of the cryostat design can be found in [15]. These cryostats will be connected in series mechanically and in parallel cryogenically using a header – a pipe that contains LHe and LN2 supply and return lines. In the production of Type-1 lenses, one pair of HTS current leads will be used; Type-2 lenses will use three pairs of vapor-cooled leads.

Assembled lenses are to be certified at FNAL using a dedicated test stand in MTF. An extensive study of the first prototype cryostatted lens is ongoing [16]. Besides testing the lens performance, a certification procedure must be developed as a result of this study. Especially important is to find the solenoid magnetic axis position relative to fiducials located on the body of the cryostat. The accuracy of this measurement must be better than the required level of the solenoid alignment tolerance of ~0.3 mm. The relative position of the magnetic axis will change depending on the system state, and therefore must be known for: a) the warm lens without vacuum (case during the lens installation in the beam line), b) after pumping out the cryo-vessel, c) after cooling down, and d) versus current in the solenoid.

The method to make magnetic axis position measurements relies upon the single stretched wire (SSW) technique and laser survey of the wire and fiducial positions. First results with the prototype cryostat [16] show ~0.5 mm vertical shift of the axis after cooling down, in agreement with expectations. Pumping out and energizing the system also result in small shifts, ~0.1 mm, of the magnetic axis position. The level of reproducibility of these behaviors is also important, and will be determined as part of the prototype certification testing. Thus, one of the main and final goals of CH solenoid R&D is to ensure that this requirement is met, and make corresponding changes in the design of the cryostat if necessary.

V. SSR section Lens Design and Test

Sections of the front end that use superconducting (spoke) cavities [17] also require focusing solenoids. In this case, cold masses can be placed in a cryostat used by the cavities.

There are two superconducting accelerating sections that differ in the cavity design and in the required focusing strength of the lenses. For both sections, it is essential to have the magnetic field on the walls of the superconducting cavities at a very low level. This level is defined by an increased surface resistance of the superconducting material in magnetic field, which results in lower quality factor and increased input power requirement. For the spoke cavities used in the SSR sections, the field on the walls must not exceed ~10 μT if the cavity is cooled to 4.2 K [18]. Other requirements for the system are: 30 mm cold bore diameter, integrated focusing strength of ~ 3 T^2-m, and effective length less than 0.15 m (normalized to the maximum magnetic field). Each steering dipole must have an integrated strength higher than 0.5 T-cm.

From the experience of building and testing CH section lenses, it was clear that a refined design is needed to meet the fringe field requirement. Some help comes from the fact that there is no need for individual cryostats, so the solenoid coil inner diameters can be made smaller. However, a new design approach was needed to make the correctors "slim" to reduce the inner diameter of the solenoid. A special new winding technique was developed to fabricate correctors using 0.3-mm NbTi strand; as a result, the narrow dipole coils made it possible having the same geometry for both solenoid types. The rest of the design is quite similar to that of the CH solenoids [10]. With quench current of ~220 A, the required focusing strength is reached at 174 A (current margin ~25%). Quench protection analysis made for this system showed that, as for CH solenoids, this design is self-protected [19]. A prototype Type-1 focusing solenoid for the SS1 section has been fabricated and tested. The solenoid quench performance and magnetic field distribution are close to the expected [8].

The expected fringe magnetic field in the area where cavity walls are situated is ~10^{-4} T. Although this field is much smaller than for the CH solenoids, we still need an additional shield to bring it to the desired level. Using a 1-mm shield made from a material with μ = 50000 drops the fringe field to the level of ~3 μT. However, taking into account the number and size of holes needed in the shielding, it will be not a simple task to make proper shielding design.

Although cold mass testing of the SSR section solenoids is quite similar to that of the CH section, certification of the solenoids for installation into the cryostat will be a difficult task. The problem, as for many similar systems (e.g. see [20]), is that the lenses are installed in a long cryostat (in a clean environment in the presence of cavities) which is then brought under vacuum and cooled to cryogenic temperature. One needs to know movement of the magnetic axis during different stages of the assembly to position the solenoid. Drift of the axis must be reliably monitored to ensure proper beam transport properties over the life of the linac. Although this problem is not a new one and some solutions can be found, specifics of the design will require a lot of work to implement a known solution or to find a new one. Modeling to better define the installation position requirements is ongoing, but they are thought to be comparable to the CH section.

This part of the solenoid lens R&D is still in the initial stage; we plan to build a prototype cryostat to address the issue. At the moment, a cryostat for testing spoke cavities is being used to start collecting data on the magnetic shielding issue and to compile a set of requirements for the test cryostat.

Design of the SS2 section focusing solenoid is similar to that of the SS1 solenoid. Fabricating and testing it will be quite straightforward. One problem exists though – this solenoid will have quite high stored energy, and the protection method that worked for the CH and SS1 solenoids is not going to work for the SS2 solenoid. Some effort must be spent here to find an optimal method of quench protection.

VI. Conclusion

A focusing solenoid R&D program is ongoing at FNAL to build a solenoid-based transport system for the front end of the HINS linac under construction at FNAL. The solenoid design and fabrication technology parts of the R&D are close to completion and the first CH series of lenses are in production. A shift is now being made towards development of adequate procedures for testing and certification of the focusing lenses.

References

[1] G. W. Foster, J. A. MacLachlan, "A Multi-Mission 8GeV Injector Linac as a Fermilab Booster Replacement", *Proceedings of LINAC 2002*, pp. 826 – 830, 2002.

[2] Dong-o Jeon, et al., "Halo Formation and its Mitigation in the SNS Linac", *Proceedings of LINAC 2002*, pp. 121 – 123, 2002.

[3] P. Ostroumov, "Physics Design of the 8-GeV H-minus Linac", *New Journal of Physics*, vol. 8 p. 281, 2006.

[4] V. S. Kashikhin, et al., Test Results of a Superconducting Quadrupole Model Designed for Linear Accelerator Applications", *IEEE Trans. Appl. Supercon.*, vol. 19, submitted for publication.

[5] P. N. Ostroumov, et al., "Front end design of a multi-GeV H-minus linac," *Proceedings of PAC-05*, pp. 3286-3288, 2006.

[6] M. Tartaglia, et al., "Test Results for HINS Focusing Solenoids at Fermilab," *IEEE Trans. Appl. Supercon.*, vol. 19, submitted for publication.

[7] G. Davis, et al., "HINS Linac SS-1 Section Prototype Focusing Solenoid Design", FNAL TD note TD-08-010, March 2008.

[8] G. Davis, et al., "HINS_SS1_SOL_01 Fabrication Summary and Test Results", FNAL TD note TD-08-012, April 2008.

[9] P. Ostroumov, B. Mustapha, V. Aseev, (ANL), Private communication.

[10] G. Davis, et al., "Designing Focusing Solenoids for Superconducting RF Accelerators," *IEEE Trans. Appl. Supercon..,* vol 17, June 2007, pp.1221-1224

[11] R. Carcagno, et al., "Superconducting Solenoid Magnet Test Results," *IEEE Trans. Appl. Supercon..,* vol 17, pp.1213-1216, June 2007

[12] B. Wands, "A Finite Element Simulation of the Winding, Cool down, and Energizing of the Focusing Solenoid for the CH Section of the HINS Linac", FNAL TD note TD-06-043, August 2006.

[13] S. Obraztsov, I. Terechkine, "A Tool for Modeling Quench Propagation and Related Protection Issues", FNAL TD note TD-06-063, Dec. 2006.

[14] I. Terechkine, "CH Section Focusing Solenoid Quench Analysis", FNAL TD note TD-06-067, 2006.

[15] T. Page, et al, "High Intensity Neutrino Source Superconducting Solenoid Cryostat Design", in *Advances in Cryogenic Engineering* 53A, edited by J. G. Weisend II, AIP, New York, 2008, pp. 341-348.

[16] T. Page, et al., "HINS Superconducting Lens and Cryostat Performance", *IEEE Trans. Appl. Supercon.*, vol. 19, submitted for publication.

[17] T. Nicol, et al, "High Intensity Neutrino Source Superconducting Spoke Resonator and Test Cryostat Design and Status", *IEEE Trans. Appl. Supercon.*, vol. 19, submitted for publication.

[18] T. Khabiboulline, I. Terechkine, "Superconducting Cavity Magnetic Field Requirements", FNAL TD note TD-08-006, 2008.

[19] V. Veretennikov, I. Terechkine, "Normal Zone Propagation in Superconducting Focusing Solenoid and Related Quench Protection Issues", *IEEE Trans. Appl. Supercon..,* vol. 18, pp.1325-1328, June 2008

[20] G. Stanford, et al, "Engineering and Cryogenic Testing of the ISAC-II Medium Beta Cryomodule", LINAC 2004, Proceedings, pp. 630 – 632.