FERMILAB-CONF-08-405-TD

FOCUSING SOLENOIDS FOR THE HINS LINAC FRONT END*

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Abstract

The low energy part of a linac for the High Intensity Neutrino Source (HINS) project at Fermilab will use superconducting solenoids as beam focusing elements (lenses). While the lenses for the conventional DTL-type accelerating section of the front end require individual cryostats, in the superconducting accelerating sections solenoids will be installed inside RF cryomodules. Some of the lenses in the conventional and in the superconducting sections are equipped with horizontal and vertical steering dipoles. Lenses for the DTL section are in the stage of production with certification activities ongoing at Fermilab. For the superconducting sections of the linac, a prototype lens has been built and tested. Each lens will be installed in the transport channel of the accelerator so that its magnetic axis is on the beamline. Corresponding technique has been developed at Fermilab and is used during the certification process.

This report summarizes design features, parameters, and test results of the focusing lenses.

INTRODUCTION

As part of the High Intensity Neutrino Source (HINS) program at Fermilab, building a high power H⁻ RF linac is under consideration [1]. At the moment, main R&D efforts are concentrated on development of accelerating and transport elements of the front end of the linac. To reduce beam losses by mitigating the beam halo formation in the low energy part of the "front end" (e.g. see [2]), superconducting solenoids will be used as focusing lenses [3]. There are three sections of the "front end" where the lenses are employed, which are identified by the type of 325 MHz RF structure used for acceleration. The first section uses low-beta room temperature Crossbar H-type (CH) structures [4]; in this section, each focusing lens is in its own cryostat. For higher energies, superconducting spoke resonators [5] are used with several of them in one cryostat; focusing lenses in these sections are mounted in the same cryostats. There exist two types of superconducting spoke resonators in the linac: SS1 and SS2; focusing lenses for these sections differ in strength.

One of the major requirements for focusing lenses in the superconducting sections of the linac is low fringe field. According to [6], to limit the power loss in walls of accelerating cavities, it is desirable to keep the magnetic field on the walls below 10 μT.

*Work supported by the U.S. Department of Energy under contract No. DE-AC02-07CH11359.
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In each section of the linac, two styles of lenses are required: with and without embedded steering dipoles for horizontal and vertical correction of beam position.

A total of ~45 focusing lenses will be built for the linac (including spares). Solenoids for the CH section are in the production stage, solenoids for the SS1 section are being prototyped, and design work is ongoing for the SS2 system. This report will summarize the status of the focusing solenoid development.

CH SECTION FOCUSING SOLENOID

Focusing length of a solenoid-based focusing lens is given by the following expression:

$$F = \frac{8mU}{q \cdot \int_{-\infty}^{+\infty} B^2 dz},$$

where U is the kinetic energy of the particles in the beam of mass m and charge q . For high intensity ion beams, it is essential to have the focusing period small; this requires high magnetic field, which only can be generated by superconducting systems. Basic requirements for the focusing lens include 20 mm warm bore diameter, the squared magnetic field integral $\int B^2 dz$ of ~1.8 T^2-m, with an effective length less than 0.1 m (normalized to the maximum magnetic field). Steering dipoles must have an integrated strength of ~0.25 T-cm to be able to compensate for uncertainties in the solenoid magnetic axis positioning of ~0.3 mm. Due to lack of space in the beamline, the dipoles must be placed inside of some of solenoids. To solve the fringe field problem, each solenoid is made of a main coil and two bucking coils with the direction of magnetic field opposite to that of the main coil. Design of the solenoid is described in [7] and [8]. Several prototypes of the focusing solenoid were tested before serial production started. Magnetic field distribution of a solenoid with embedded steering coils in the central and the fringe area is shown in Fig. 1. Here the measured field is compared with a model prediction and the data points from both sides of the magnet are overlaid. The squared field integral 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 measured magnetic field in the fringe field region (outside the solenoid) is also very close to the expected. At the nominal current of 170 A, for the solenoids with the embedded steering coils, the magnetic field in the area of the accelerating cavity (~150 mm from the solenoid center) is ~0.03 T; it is ~0.01 T for the solenoids without the steering coils. Additional shielding is needed if the accelerating cavity test shows that this field is too high.

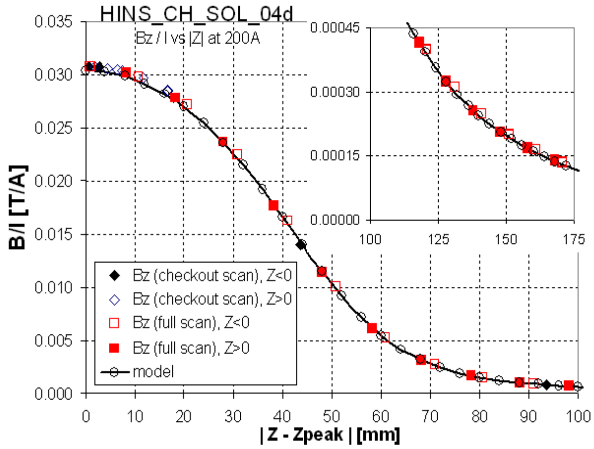

Figure 1: Comparison of measured and predicted axial magnetic field transfer function profiles for CH section solenoid at 200A in the central and fringe regions.

Each steering dipole was made by placing a one-layer winding on the surface of a cylinder made of G-10. NbTi 0.8 mm strand was used for both the horizontal and vertical dipole. The steering dipole assembly is placed inside the main coil with the horizontal dipole inside the vertical one; the total radial thickness of the assembly was ~4.8 mm. The magnetic field integral $\int Bdz$ = 0.37 T-cm was measured at 200 A for the horizontal corrector; for the vertical corrector it is 0.41 T-cm. The required integrated strength of 0.25 T-cm is achieved at ~130 A.

Assembled and tested cold masses are to be placed in cryo-vessels at FNAL to form completed focusing lenses (see Fig. 2).

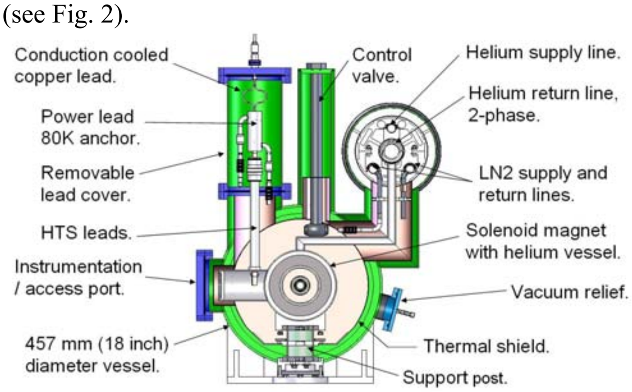

Figure 2: Cross section through CH solenoid cryostat

Description of the cryostat design can be found in [9]. All 19 cryostats in the beamline will be connected in series mechanically and in parallel cryogenically using a header – a pipe that contains LHe and LN2 supply and return lines. The first cryostat has been assembled with the prototype solenoid and tested to show good performance [10].

One of the most important aspects of using the solenoid-based focusing lenses is their alignment in the transport channel. During certification process at FNAL, it was found that positions of the geometric axis and the magnetic axis of a solenoid can differ by ~0.5 mm. Alignment of the lenses in the linac must be done to place the magnetic axis within ~0.25 mm of the beamline. To ensure this accuracy of alignment, the Single Stretched Wire (SSW) system is used to find the magnetic axis position relative to external fiducials. This measurement is made at different stages: warm solenoid at atmospheric pressure and after pumping out the air, the solenoid cooled to 4.2 K without any current, and finally, powered solenoid at different current levels. Several cycles of these measurements were made with the first prototype lens to understand reproducibility of the magnetic axis positioning. Preliminary results show that reproducibility of the alignment is on the order of ±100 μm.

SS SECTION FOCUSING SOLENOIDS

There are two superconducting accelerating sections in the front end: SS1 and SS2. Main requirements for the SS1 section focusing solenoids 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 was 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 could be made smaller. Nevertheless, a new steering coil design was needed to make the assembly "slim" to allow further reduction of the inner diameter of the solenoid. A new coil winding technique was developed that employed 0.3-mm NbTi strand. The reduced radial thickness of the steering dipole assembly was ~2.5 mm including the thickness of the main coil barrel; this made it possible to have identical solenoid geometry for both styles of the solenoid: with and without steering coils. Main design features of the SS-1 focusing solenoid are described in [11]. A prototype lens has been built and tested. Fig. 3 shows a comparison of the measured and predicted fringe field for the solenoid without steering coils [12].

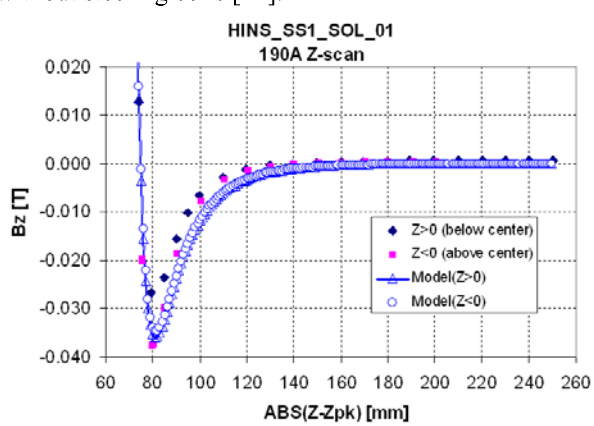

Figure 3: Predicted and measured axial magnetic field in the fringe region at 190A for SS1 prototype solenoid

Expected magnetic field on the walls of the spoke cavities is ~20 μT, and additional shielding will be needed to bring it to the level below the recommended 10 μT.

Alignment issues for the lenses in the superconducting sections of the linac are more demanding than they are in the CH section. They are installed in a common cryostat with the accelerating cavities, and special techniques and procedures must be developed to align the lenses and follow the drift of the magnetic axis in time. An approach to solving this problem has been developed (e.g. see [13]), but specifics of the design will require a lot of work to implement a known solution or to find a new one. This part of the solenoid lens R&D is in the initial stage; a prototype cryostat is to be built to address the issue.

Design of the SS2 section focusing solenoid is similar to that of the SS1 solenoid except it is much stronger: the required squared field integral for this solenoid is 5 T^2-m. As a result, this solenoid stores more energy, and quench protection solution becomes more complicated in comparison with the SS1 and CH systems, which can absorb all the stored energy safely.

SOLENOID QUENCH PROTECTION

Quenches in the superconducting magnets are inevitable. Quench training is part of testing performed on each assembled lens. Because each focusing solenoid contains a main coil and two bucking coils, which are much smaller and connected in series with the main coil, quenching in the bucking coils can result in an unacceptable temperature rise. Protection of focusing solenoids was the subject of several studies (e.g., see [14], [15], and [16]). A proper protection scheme should prevent the temperature and voltage to ground in the coils from going too high: $T_{max} < 300$ K, $V_{max} < 300$ V. Reliability of the protection dictates choosing a simple solution from many possible ones. CH and SS1 focusing solenoids appear to be self-protected; this means that if the energy stored in the system is fully dissipated by the quenching coil, the temperature and the voltage are still below the allowed limits in any part of the coil. Nevertheless, to reduce heat dissipation within LHe bath, we use an external dump resistor, which, if chosen correctly, helps to lower the voltage and temperature. For solenoids of the SS2 section, using a dump alone does not solve the problem, and additional measures must be taken to prevent coil overheating and to lower the voltage. A solution to this problem is still to be found and tested.

SUMMARY

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 efforts within the R&D are close to completion and the first CH series of lenses is in production. A shift is now being made towards development of adequate procedures for testing and installation of the focusing lenses.

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