SOLENOID-BASED FOCUSING IN A PROTON LINAC *

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Abstract

Development of solenoid-based focusing lenses for the transport channel of an R&D linac front end at FNAL (HINS linac) is in its final stage. Superconducting lenses for the room temperature RF section of the linac are assembled into individual cryostats and certified using a dedicated test stand. During this certification process, the optical axis of each lens relative to the cryogenic vessel is found in the warm and cold state. Lenses for the superconducting RF sections are ready for production, and development of a cryomodule (which contains multiple superconducting lenses and RF cavities) is in progress. Studies have been conducted to measure fringe magnetic field of a lens in the cryomodule, to investigate a laser-based method of alignment, and to evaluate the extent of beam quality degradation due to imperfections in lens construction and alignment. This report presents some results of these studies.

INTRODUCTION

Building a high quality transport line in the low energy section of a high intensity RF linac is recognized as one of critical issues. For an H^- RF linac front end in development at FNAL, which employs superconducting spoke-type cavities, it was found that solenoid-based lenses can provide the needed focusing [1], [2]. Axially symmetric focusing results in saving some longitudinal space, which is highly desired for beam line diagnostic equipment.

Several types of superconducting solenoid-based lenses were developed to meet the requirements of different sections in the linac. During early stages, the main efforts were directed towards building systems with satisfactory magnetic performance, reliable quench protection, and simple steering coil design. Prototypes of focusing lenses for each section of the linac were built and tested [3], [4], and the main R&D efforts shifted towards issues related to using the solenoid-based focusing lenses in a cryomodule: magnetic shielding of superconducting RF cavities, lens production and certification, assembly and alignment in the cryomodules.

FOCUSING LENS DESIGN

The low energy beam line sections of the superconducting RF (SRF) linac described in [1], known as HINS linac, require three types of solenoid-based focusing lenses that differ in focusing and steering coil strength. The focusing length of a solenoid-based lens depends on the energy of the charged particles and on the focusing strength of the lens: $FS_l = \int_{-\infty}^{+\infty} B^2 dz$. Lenses in cryomodules of the first SRF section (SSR1) of the HINS linac require FS_l = 3.0 T^2·m. These lenses have a flange-to-flange length of 260 mm, a 30 mm bore diameter, and 25% current margin for better cryo-stability.

Placed inside each lens are two dipole corrector windings that provide horizontal and vertical beam steering. The bending strength is defined by the field integral $BS_s = \int_{-\infty}^{+\infty} B dz$; for the dipole coils of the SSR1 lens, the bending strength reaches $8 \cdot 10^{-3}$ T·m at I = 40 A; the current is limited at this level by quenching in the magnetic field of the lens.

The fringe magnetic field of lenses installed in cryomodules must be quite low: the allowed level of magnetic field on walls of a superconducting spoke resonator (SSR) RF cavity of the linac was specified to not exceed 10 µT [5]. The solenoid-based focusing lens design employs bucking coils and flux clamps to quickly reduce the magnetic field outside the lens. In combination with the beam pipe, the clamps also provide the mechanical constraint for high repulsive forces in the lenses.

The bucking coils and flux clamp significantly reduce the field outside the lens: with a peak central field of 6 T, the stray field at the location of cavity walls (225 mm from the central plain of the lens) is just several Gauss. Nevertheless, to reach the required 10^{-5} T level, additional magnetic shielding must be employed. This additional magnetic shield was fabricated of Cryoperm10®, which has good magnetic properties at cryogenic temperatures. The shield was then assembled with the prototype lens, and its effectiveness was tested in a test cryostat.

MAGNETIC FIELD MEASUREMENTS IN THE TEST CRYOSTAT

A number of things may affect the magnetic shield performance, such as uncertainties in the material properties, the shield temperature, and material handling procedures during assembly. Furthermore, the shield must have penetrations for helium lines, support post, and alignment structures. Therefore a shield effectiveness verification test was planned and executed.

The shielded prototype focusing lens was installed in a test cryostat, which was connected to a liquid helium supply line at the Fermilab Magnet Test Facility (MTF). The cryostat [6] was equipped with six power leads to power the focusing lens and with its own mu-metal magnetic shield to reduce the background DC magnetic field to ~1 µT. Low level magnetic field measurements were made using an array of commercially available Hall probes certified for use at low temperature.

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Eight Hall probes were mounted on a 2-mm thick copper plate used as a heat sink. The plate was connected to LN_2 shield of the cryostat by two copper braid straps with total copper cross-section of ~50 mm^2. As measured by a sensor installed on the plate, the plate temperature did not exceed 100 K. To fully characterize the fringe field, the probes were oriented to measure both longitudinal and radial field components at the plane of a cavity wall. Each Hall probe was coupled with a small test coil able to generate a relatively strong field (~5 G) that was used to check integrity of the Hall probe wiring and calibrate probe responses and system noise levels at different stages of the test. Based on the sensitivity of the probes (~40 mV/T), expected voltage signal at the 10 µT field level was about 0.4 µV. To reduce inevitable noise, the measurements relied upon AC excitation of the Hall probes accompanied by using sinusoidal current in the lens and lock-in amplifier readout [7].

Fig. 1 shows typical dependence of the axial and radial magnetic field components measured by the Hall probes in the test cryostat. At the nominal current (180 A), at the location of superconducting RF cavity walls, the absolute value of the fringe field is ~5 µT. This value is in a good agreement with what magnetic modelling predicted.

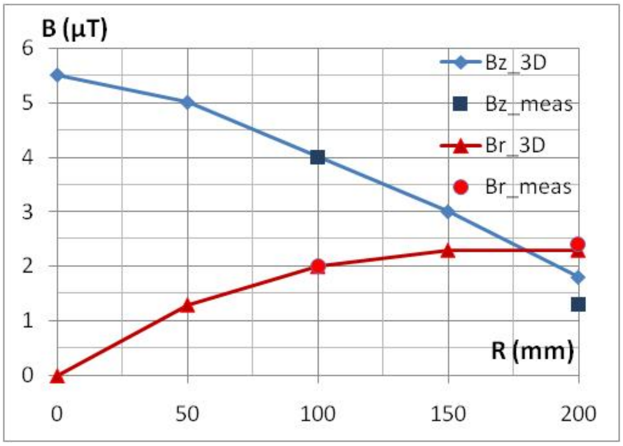

Figure 1: Measured longitudinal and radial components of the fringe magnetic field at the location of RF cavity wall compared with that predicted by modelling.

IMPACT OF DEFECTS IN LENS ASSEMBLY AND PLACEMENT

While considering solenoid-based focusing for a front end of a high current proton (or H$^-$) linac, one needs to keep in mind imperfectness of its optical properties. First, even a precisely fabricated and installed lens has spherical aberrations that can result in beam quality deterioration (e.g., see [8]). Second, position of the optical axis of an ideal lens relative to its LHe vessel is never precisely known; it can be found by several techniques based on magnetic measurements, but with limited accuracy. This position, and also the position of the LHe vessel relative to a cryomodule where the lens is installed, changes as the cryomodule is pumped out, cooled down, and the lens is powered. Finally, some positioning defects exist within each lens.

A case study was made for a 2.5 MeV proton beam which showed that, for the linac front end in development at FNAL, spherical aberration in the lenses does not result in significant emittance growth [9]. A similar conclusion was reached in a tracking study of solenoid-based beam focusing [10], [11]. In [10], the action of spherical aberrations was studied by modeling propagation of 2.5 MeV beam through the lens of MEBT channel of the HINS linac. It was found that if the beam diameter inside the lens is smaller than ~15 mm, its emittance practically does not change.

The impact of defects in lens assembly and placement on the proton beam quality was studied in [11], where tracking was made for the beam with 8 mm radius and 0.4 π mm-mrad initial emittance. It was found that if the lens is shifted in the transverse direction, the emittance grows by 0.1 π mm-mrad for each 1 mm of the shift. Tilt of the lens, even if it is relatively large (e.g. 5 mrad), does not result in emittance deterioration, although it does set the beam off axis. In both cases, correctors must be used to steer the beam towards the center of the next lens to avoid further emittance growth.

Because each lens is made of one main coil and two bucking coils, defects in assembly can also result in beam deflection and emittance growth. For example, bucking coils in the lens can be shifted relative to the axis of the main coil. As the study in [11] shows, the action of this defect is equivalent to some tilt of the lens (no significant emittance growth was found), and can be corrected by steering.

OPTICAL AXIS AND ALIGNMENT

Because beam emittance can grow if the beam passes a solenoid-based focusing lens off-center, lenses must be properly aligned when installed in a cryomodule. The level of acceptable misalignment established for the HINS linac is 0.3 mm lateral shift and 5 mrad tilt.

As existing experience of using solenoid-based lenses in beam transport channels have shown (e.g. see [12]), the optical axis of the lens does not always coincide with its geometric axis; so one needs to find a way to establish a reliable reference line that is as close as possible to the optical axis. This reference can be used later to position each lens on the projected beam line.

The term “optical axis” means in our case that a charged particle entering the focusing element along this line also exits the lens along the same line. The most direct way of finding the “optical axis” is by passing charged particles through the lens and monitoring their trajectories; this method is not always convenient or even possible to use. Often the problem can be mitigated by positioning lenses based on their magnetic axis. In [13] the magnetic axis of a solenoid-based lens was found using a stretched wire techniques (moving wire and vibrating wire). Studies conducted on the production series of focusing lenses for the MEBT section of the HINS linac came to a preliminary conclusion that magnetic axis found by this method is within ~0.4 mm from the axis of the cryostat beam pipe, and within ~0.1 mm from the "optical" axis of the lens. Reproducibility of the "warm" and "cold" magnetic axis position found during several thermal cycles is ~25 µm.

In a cryomodule with accelerating RF cavities and focusing lenses, elements of the transport channel experience thermal contraction; because it is not always reproducible, a means to verify lens positions is needed. In many cases, this verification is made by using BPM-type monitors with a reference line defined by stretched wire. Lately, some attempts were made to use laser-based means for alignment of transport elements in accelerators. This approach can result in significant simplification of the in-situ alignment verification procedure. Analysis of uncertainties for a prototype laser-based system in [14] shows that position measurements with ~20 µm absolute accuracy can be achieved. An optical system that uses the Poisson line reference can be a promising approach [15]. A proof-of-principle long baseline experiment is in preparation at FNAL.

A prototype cryomodule containing three cavities and four focusing lenses is in the design stage at FNAL. In this cryomodule, SRF cavities and solenoid-based focusing lenses developed, built, and tested for the HINS linac front end will be used. Among other things, the experience of building the prototype cryostat will help to verify the chosen approach to alignment of the elements of the beam transport channel.

To ensure proper alignment of all optical elements in a cryomodule of the linac, the following assembly steps are envisioned:

1. Using the vibratring wire technique, magnetic axis of each focusing lens will be found (a "certification" cryostat equipped with optical windows and a stretched wire interface must be built for this purpose). Position of the magnetic axis will be referenced to fiducials attached to each lens. The procedure will be repeated for the next stages: a) warm, no vacuum; b) warm, vacuum; c) cold, no current.
2. Correspondence will be established between the "cold, no current" magnetic axis position and the "warm, no vacuum" fiducial position.
3. Focusing lenses will be installed in the cryomodule in accordance with the found relation.
4. A laser-base alignment system will be used to establish the starting point for in-situ alignment verification protocol.

CONCLUSION

The initial stage of a high-power proton linac front end development at FNAL is completed by testing individual elements of a beam transport channel: superconducting RF cavities and solenoid-based focusing lenses. The next stage of this R&D includes integration of these elements in a prototype cryomodule and testing the system with beam. First steps made towards this goal show that using solenoid-based focusing lenses in a cryomodule of a linac front end with spoke cavities seems feasible; how many beam transport elements can be placed in one cryomodule is still to understand.

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