Solenoid-Based Focusing Lens for the Low-Beta Section of a Superconducting Proton Linac

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Abstract—A superconducting solenoid-based focusing lens was designed and built for use in the SSR1 cryomodule of PXIE test facility at FNAL. As the cryomodule contains superconducting spoke-type cavities, one of main goals during design stage was minimization of magnetic field on walls of the cavities. The design also attempted minimization of the uncertainty of the magnetic axis position in the lens. This report describes main features of the design and summarizes results of performance tests and magnetic axis position measurements.

Index Terms—Accelerator magnets, focusing lenses, magnet alignment, proton linac front end cryomodules, superconducting magnets.

I. INTRODUCTION

To reduce beam loss in a high power superconducting linear RF accelerator of ions, or linac, focusing period in the low-energy part of its beam line, or front end, must be sufficiently short. As a result, magnetic focusing elements, or focusing lenses, in the front end must be positioned inside cryomodules - vacuum vessels where cryogenic environment for superconducting accelerating RF cavities is created. In the SSR1 cryomodule of PXIE test facility at FNAL [1], each focusing lens is placed between two superconducting spoke-type resonators (SSR). Focusing period in the cryomodule is 1.2 m, and gaps in the string of the SSR1 cavities available for insertion of four focusing lenses are ~380 mm long.

Major source of heat influx in cryomodules of linacs is RF power loss in superconducting cavities, which is strongly affected by magnetic field trapped in superconducting walls of the cavities during cooling down. It is commonly recognized that the acceptable level of the magnetic field on walls of accelerating cavities during cooling down must be sufficiently small, usually measured in micro-Tesla, or even less if high quality factor of the cavities is in pursuit [2]. As the magnetic field inside focusing lenses in proton linacs often exceeds 5 T, magnetic shielding must be used to protect the cavities. Magnetic shielding can be built around cavities [3] or focusing lenses [4]; both ways were used and proved efficient, but expensive. Diamagnetism of superconducting niobium, the material the cavities are made of, can be naturally employed [5]; an obstacle on this way is cavity quenching - thermal instability in the cavity wall that causes abrupt dissipation of electro-magnetic energy stored in the cavity.

During quenching, affected part of cavity surface warms up above the superconductivity threshold, forming a normally-conducting opening in the superconducting wall. Magnetic field penetrates inside the cavity through this opening and remains trapped in the cavity wall after it becomes superconducting again. The amount of the magnetic flux trapped in the wall of a quenching cavity depends on the level of magnetic field inside cryomodule and on the size of normally conducting zone that develops during quenching. The trapped flux increases surface resistance of Niobium and, hence, the power loss; corresponding cavity performance degradation is manifested by reduced quality factor. Quench can happen occasionally in each cavity of any linac, and the frequency of quenches cannot be neglected, unfortunately. So, practical approach to design of cryomodules shall suggest measures that help to keep degradation of cavity performance after quenching under control. As the magnetic field of focusing elements inside cryomodules is substantially non-uniform, the requirement for the fringe magnetic field expressed as a single number can be very misleading and difficult to meet. Instead, an integrated criterion can be considered that reflects the reduction of cavity quality factor, which is also an integrated quantity.

While the level of magnetic field in a cryomodule affects the cooling power required for the operations, precision of positioning of the lenses directly affects beam trajectory and profile. Poor alignment can immediately result in unacceptably high beam loss. While a cryomodule is assembled, all elements of beam optics are mounted on an optical bench at room temperature and normal pressure, but they are used in the high vacuum and at cryogenic temperature. Deformation of the vacuum vessel and thermal contraction of elements inside cryomodules, compares well with the installation precision specified by beam trajectory requirements [6]. As geometric features of focusing lenses are usually used during installation of the lenses in the beamline, even if this installation is ideal, the question remains where the magnetic axis is located relative to the geometric features of each lens. While designing a focusing lens for the PXIE SSR1 cryomodule, an attempt was made to limit deviation of the magnetic axis from the geometric one. Position of the magnetic axis in the prototype of the SSR1 focusing lens was measured at different stages of fabrication and assembly to understand the effectiveness of this attempt.

This paper summarizes our efforts to design and certify the
focusing lens for the PXIE SSR1 cryomodule.

II. MAIN REQUIREMENTS

A set of requirements for a focusing lens of the SSR1 cryomodule of PXIE test stand was developed during multistep iterative process that included beam tracing, design of superconducting RF cavities, design of the cryomodule itself, and magnetic and mechanical design of focusing elements. The beam tracing efforts provided requirements for the strength of the lenses in terms of the squared magnetic elements. The beam tracing efforts provided requirements for its size, and magnetic and mechanical design of focusing of superconducting RF cavities, design of the cryomodule cavities in the cryomodule. This step is described in more details below.

A. Effect of Trapped Magnetic Field

Superconducting cavities in linear RF accelerators are made of pure Niobium. In 325 MHz spoke-type cavities used in cryomodules of PXIE test facility, thickness of walls is 3 mm. The cavities are cooled down to ~2 K, which is well below the transition point for Nb, so the Meissner effect prevents magnetic field generated inside the cryomodule after cooling down from penetrating into walls of the cavities. When quench occurs in one of the cavities, the energy stored in the electro-magnetic field is released on the RF surface around the starting point. Corresponding temperature rise results in propagation of this energy along the surface and through the thickness of the cavity wall. As a result, part of the cavity wall becomes normally conducting, thus allowing the external magnetic field to penetrate inside the cavity. The size of the normally conducting opening grows fast assisted by the energy deposition in the new-born normally conducting layer on the RF surface. After all the energy stored in the cavity is dissipated, two relatively slow processes – heat diffusion and cooling of the outer surface by liquid Helium – compete to define the maximum size of the opening. This size also depends on the location of the spot where the quench starts. This dependence is expressed in terms of a location factor $A_H$, which is a function of the local surface current or local energy density, which is equivalent:

$$A_H = \frac{\mu_0 H^2 \cdot V}{2W_0}.$$  

(1)

It this expression $H$ is the RF magnetic field at the point of the quench, $W_0$ is the total energy stored in the cavity, and $V$ is the volume of the cavity. So, the dimensionless $A_H$ factor is the ratio of the local energy density at the point of quench to the average one. At locations where this factor is high, higher RF surface currents exist, and hence higher energy deposition rate is expected at quench, which affects the size of the opening. Dynamic modeling of this process was conducted in [7]. Simple empirical formula can be used to evaluate the maximum radius of the normally conducting opening in the SSR1 cavity wall depending on the energy stored in the cavity and the location of the quench:

$$R_m = 25.5 + \frac{9.8}{A_H} + 0.8 W_0$$  

(2)

Fig. 1 shows how the radius of the normally-conducting opening in the wall of the SSR1 cavity depends on the initial energy in the cavity for $A_H = 2.6$, which is at the point of the highest RF field on the outer surface of the cavity. Another curve in the plot shows the time when this maximum radius is achieved. The energy initially stored in the cavity totally dissipates in the first several milliseconds of the process.

Knowing the size of a “warm hole” in the superconducting wall of a cavity makes it straightforward to evaluate the effect of a trapped magnetic flux for any magnetic system activated inside a cryomodule after cooling down. Trapped flux that reduces the unloaded quality factor $Q_0$ to the level $Q_f = \eta Q_0$ can be found using the next expression [8]:

$$\Phi_{tr} = \frac{2 \mu_0 \Phi_0 R_s}{\eta Q_0} \cdot \frac{V}{\xi_0} \cdot \frac{1 - \eta}{\eta}.$$  

(3)

In this expression $\mu_0 = 4\pi \cdot 10^{-7}$ H/m is the permeability of empty space, $\Phi_0 = 2 \cdot 10^{-15}$ Wb is the magnetic flux quant, $\xi_0 = 3.9 \cdot 10^{-8}$ m is the coherence length in Niobium, $f$ is the frequency of the cavity, and $R_s$ is the surface resistance of Niobium at this frequency.

Acceptable level of cavity degradation, which is defined by the factor $\eta$, must be negotiated based on the number of cavities and available cooling power and RF input power in a particular cryomodule. In the case of the SSR1 cryomodule, this factor can be made as low as $\eta = 0.5$ [8]. Making this choice results in the next expression for the acceptable trapped flux:

$$\Phi_{tr} A_H < 6.7 \cdot 10^{-6} \text{ Wb.}$$  

(4)

At the point where the magnetic field on the outer surface of the cavity is the highest, $A_H = 2.6$ and $\Phi_{tr} \approx 2.6 \cdot 10^{-6}$ Wb.
Knowing this “allowed” trapped flux level, the maximum size of the normally-conducting opening during quench, and the geometry of superconducting cavities inside a cryomodule, magnetic design of focusing lenses can be finalized. Additional restrictions must be taken into account though.

B. Geometry and Assembly Restrictions

Insertion gap of 380 mm between the superconducting cavities in the cryomodule accommodates the lens, beam position monitors, and bellows that permit adjustment of the lens position within certain limits at the time when it is installed in the beam line. This leaves only ~170 mm for the lens and a liquid Helium vessel used to cool it down to 2K.

Another restriction comes for the maximum transverse size of the lens; to relax requirements specific to the high pressure vessel environment, it should be less than ~150 mm.

Each lens is assembled in two steps. First the winding is made to results in a cold mass assembly. After this cold mass is tested for performance, liquid helium vessel is added by welding. The welding steps usually result in some deformation of geometry of welded objects, so one should expect undesirable and random deviation of the position of the magnetic axis relative to the geometric features of the lens after welding. To mitigate uncertainty of the magnetic axis position, the next measures were taken:
- Bobbins of the lenses were fabricated paying proper attention to the relative positioning accuracy;
- Lens flanges and welding preps were designed having in mind reduction of post-welding deformation.

III. PROTOTYPE LENS FABRICATION AND TESTING

The use of the integrated requirement for the fringe magnetic field described above has allowed finding a satisfactory design of the lens [9] without employing passive shielding made with the use of ferromagnetic materials. This magnetic design was verified by making trapped flux analysis. To make sure that all spatial restrictions are addressed, the mechanical design of the lens was incorporated in the solid model of the cryomodule and needed corrections were made before the final version of the concept design was accepted. The design was finalized at Cryomagnetics, Inc., where a prototype of the lens’s cold mass was fabricated and tested. Fig. 2 shows main design features of the lens.

The lens consists of a main solenoid-type coil, two bucking coils located concentrically at the ends of the main coil and separated by a gap, and four windings generating transverse magnetic field. These windings, located in the radial gap between the main coil and the bucking coils, will function as a combination of two dipoles steering the beam in X and Y transverse directions and a skew quadrupole. Mechanical features of the bobbin are machined to ensure precise location of the coils. The outer sleeve, which is made of a seamless pipe, can be slid onto the bobbin and welded during the final assembly step to form a liquid Helium vessel.

The lens was tested in several steps. First, the cold mass was tested at the fabrication site at 4.2 K: performance test was conducted, and position of the magnetic axis was found using a rotating Hall probe technique. Second the cold mass performance test was conducted at Fermilab at 2 K, and position of the magnetic axis was found using a vibrating wire technique. Finally, the lens was assembled by adding the liquid Helium vessel by welding, position of the magnetic axis after welding was found using a vibrating wire technique, and a performance test of the assembled lens was conducted. Main results of the tests are summarized below.

A. Performance tests

Round, 54-filament, 0.4 mm diameter NbTi strand by Oxford Wire&Cable Inc. was used in the magnet. Knowing critical current of the strand and winding data, performance of the lens could be evaluated; corresponding quench current diagram is shown in Fig. 3 for two temperatures used for the lens testing at Fermilab: 4.58 K and 2.15 K.

The magnet was tested at 4.2 K in a liquid Helium bath at Cryomagnetics, Inc. and at the Vertical Test Stand at the Magnet Test Facility at Fermilab. With the expected maximum current of 68 A at 4.58 K (see Fig. 3), 67.9 A quench current was measured at FNAL. At 2.15 K, the quench current of 91.7 A was measured, which also agrees well with the prediction.
As the fringe field is one of the main concerns for the lens, the field in the lens was measured at 4.2 K at Cryomagnetics, Inc.; results of the measurements are compared in Fig. 4 with what modeling predicts for the final geometry. Flux trapping modeling shows that condition (4) is satisfied for the prototype magnet.

![Graph](image)

**Fig. 4.** Predicted and measured axial magnetic field in the lens

B. Position of Magnetic Axis

Position of the magnetic axis in the cold mass was measured at Cryomagnetics, Inc. at 4.2 K using rotating Hall probe. The measurements showed that the translational shift of the magnetic axis relative to the geometric one is ~0.12 mm and the angular shift of the axis is ~0.8 mrad. Both values are within the range specified by corresponding requirements.

At Fermilab, position of the magnetic axis was measured at room temperature using the vibrating wire technique [10]. Because of different temperatures, direct comparison of the measurements at Fermilab and at Cryomagnetics provides little useful information. It has a lot of sense though to compare the impact of the welding on the axis shift. So, the two measurements were made before and after adding a liquid Helium vessel to the assembly by welding at Fermilab. The measurement made before the welding showed that the magnetic axis had the translational shift relative to the geometric axis ~0.1 mm and the angular one ~0.7 mrad. The measurement made after welding resulted in the 0.15 mm translational and 0.3 mrad angular shifts. Both sets of the shift values are within specification, although the direction of the translational shift has changed by ~90°.

IV. CONCLUSION

A prototype of a focusing lens for use in the SSR1 cryomodule of PXIE test facility at FNAL has been designed, fabricated and tested. The lens meets the requirements set by demands of beam optics, degradation of superconducting cavity performance after quenching is within allowable level, and the size of the lens is comparable with the available insertion space in the cryomodule. Relative position of the magnetic and geometric axes was measured at room temperature and at 4.2 K. Drift of the magnetic axis after final welding step was also measured and found satisfactorily small.

A set of four focusing lenses to be installed in the SSR1 cryomodule is in production stage at Cryomagnetics, Inc.

REFERENCES