

SOLENOID FOCUSING LENSES FOR THE R&D PROTON LINAC AT FERMILAB *

M. A. Tartaglia[#], J. DiMarco, Y. Huang, D. F. Orris, T. M. Page, R. Rabehl, I. Terechkin, J. C. Tompkins, T. Wokas, Fermi National Accelerator Laboratory, Batavia, IL 60510, U.S.A.

Abstract

An R&D proton linac is under construction at FNAL and it will use solenoid lenses in the beam transport line. Because the needed focusing field is on the level of 6 Tesla, superconducting systems are used. In the low energy part of the linac, which uses room temperature accelerating structures, the lenses are placed in stand-alone cryostats. Production of the lenses and cryostats for the low energy section is under way. In the superconducting accelerating sections, the lenses are mounted inside RF cryomodules. Although focusing solenoids for the high energy sections have been designed and prototypes tested, R&D is still ongoing to address magnetic shielding and alignment issues. This report summarizes the performance of lenses for the low-energy part of the linac and presents the status of ongoing R&D.

INTRODUCTION

An R&D proton linac has been under development at Fermilab for several years. Superconducting solenoids are used for focusing in the first three sections of the linac, which are segregated by the range of beam energy and the type of RF accelerating structure used in each range [1]. The low energy section uses room temperature Crossbar H (CH) copper cavities that are interleaved with the CH-section solenoids, which are assembled into cryostats. The higher energy sections will utilize Superconducting Spoke Resonator (SSR) cavities that will be interleaved with superconducting solenoids mounted in the same long cryomodule. Three solenoid designs are needed to achieve adequate focusing strength with increasing energy in the CH, SSR-1 and SSR-2 sections of the linac.

Design constraints for the solenoids start with achieving adequate integrated field strength in the allowed space (specified by the lattice design); a philosophy of maintaining a fairly large operating current margin (~25%) was adopted in anticipation of unknown heat loads from beam losses or cryogenic conditions. Proximity to RF cavities imposes severe constraints upon the allowed magnetic field a short distance from the end of each solenoid. Therefore the designs incorporate field-cancelling "bucking coils" at both ends of a main coil to reduce the field to a few Gauss within a few centimeters of the end; further reduction to 0.1 Gauss in SSR sections will require the use of magnetic shielding. Each section contains two types of solenoids: without, or with dipole coils to allow horizontal and vertical beam steering corrections.

Numerous challenges were imposed by these constraints, including: finding sufficiently good NbTi superconductor strand, achieving consistently high

packing factor in the coil windings, optimizing the geometry of coils for end field cancellation and allowing sufficient radial space to accommodate steering coils, as well as a warm bore tube in the CH section; maintaining sufficient pre-load on the bucking coils to prevent motion during cool down and controlling large axial forces during excitation. The weak steering dipole coils are nested between the main coil and beam tube, and must operate in the main solenoid field. Proximity to the beam tube implies field quality may be an issue, while the small radial space available for the dipole windings leaves little freedom to optimize the geometry. Measuring the field quality of the weak dipole correctors (warm) is a challenge, as is confirming the effectiveness of magnetic shielding. In addition to mechanical and magnetic design issues, careful study of the quench development and protection scheme also were needed: many turns of strand in the main coil result in large inductance and stored energy that can result in a damagingly large temperature or voltage rise during a quench, especially in the case of a bucking coil quench. The final challenge is for solenoid lenses to be assembled into cryogenic vessels with magnetic axis fiducialized to high precision and good reproducibility for subsequent installation into the beam line. In general, the design issues become more challenging with the progression from CH to SSR-2. We will discuss the R&D, status and plans for focusing solenoids in each section.

CH SECTION

A complete R&D cycle was made beginning with model main coil magnets to test feasibility of manufacturing and performance of the basic design [2]. These were followed by fabrication and testing of two prototype and four pre-production CH lenses that validated mechanical, quench, and magnetic performance of the bucked main coil designs of lenses, and developed the design and methods for incorporating steering dipoles. Tests of the solenoid quench behavior and measurements of magnetic field properties were made for all R&D models, and these compared favorably to predictions from as-built model calculations [3]. A prototype CH cryostat lens was built and thoroughly tested [4], including an alignment study carried out over several thermal cycles. Assembly of the CH lenses into individual cryostats at Fermilab has begun, with testing and alignment of the first four production cryostatted lenses expected to begin soon. Some modification to the cryostat design is being considered for future CH assemblies to incorporate a beam position monitor (BPM) into the warm bore.

An industrial vendor (Cryomagnetics, Inc.) was selected in late 2007 for the production and testing of 23

solenoids for the CH section. As of May 2009 twelve production solenoids, 6 with and 6 without steering dipoles, have been delivered. Half of those were re-tested in liquid helium at Fermilab as a cross check to validate vendor's data.

All 12 of the production solenoids have met the electrical, quench, and magnetic performance requirements, with small variance in the performance parameters. The tests were performed by the vendor after final welding into a stainless steel helium vessel. After a 500 V to ground hipot test in liquid Helium at 4.2 K, solenoid quench training was conducted until reaching the expected maximum current level. Steering correctors were also ramped to 250 A, while in the solenoid field at the nominal operating current of 180 A. Hall probe measurements of the solenoid and dipole magnetic field shapes along the solenoid axis were made at 180 A for the solenoid, and 200 A for the dipoles. The solenoid fringe field levels, 150 mm from the solenoid center, were of particular interest. The peak solenoid transfer function was also taken with a stair-step profile up and down, to check hysteresis and magnetization effects.

Each solenoid is inspected upon receipt at Fermilab. This includes the same basic electric checks, including a warm hipot in air, as performed by the vendor. Mechanical dimensions are checked and the helium vessel is leak tested. A subset is selected for cold testing at the Fermilab Magnet Test Facility (MTF). MTF cold tests repeat the vendor qualification tests and measurements. To date, six production CH solenoids have been re-tested at MTF.

Quench Performance Summary

Production magnet training has proven to be much faster than was found for the pre-production models, which showed very gradual training curves [4]. Typically the vendor has reached the expected maximum quench current in 6 quenches or less, and the first quench was above the nominal operating current for 10 of the 12 solenoids tested. Retraining at MTF has been similarly fast – all reaching the maximum current in three quenches or less. We attribute this better performance to different epoxy impregnation procedures: the vendor uses a vacuum-pressure technique, while only vacuum is used at Fermilab. Quench currents at the vendor (at 4.2 K) and MTF (4.4 K) are in agreement after taking into account the temperature-dependence of NbTi critical surface.

Magnetic Performance Summary

The standard deviation of the solenoid peak field at operating current is very small, less than 0.4 %. The peak transfer function measured at MTF is systematically 1% lower than measured by the Vendor, which is probably the accuracy to which the solenoid current is known. The field profiles, and consequently the field-squared integrals are nearly identical. We found that superconductor magnetization results in a 60 Gauss remnant field at the center after a ramp up to high current and down again. The stair-step up/down center field

measurements are consistent with this effect. The soft iron flux return shows very slight saturation at high current, and the iron magnetization is negligible compared to the superconductor. The measured fringe field levels are all at or slightly below the expected level. Similarly, peak strengths and transverse field profiles of the steering dipoles are all very similar.

Cryostatted Lenses

Focusing lenses without dipole coils will use a pair of HTS leads, while those with dipoles will use six vapor-cooled leads. Fifteen pairs of 300 A HTS leads were procured from industry last year. The upper copper section of the leads, designed at Fermilab, is conduction cooled with a liquid nitrogen heat exchanger at the HTS joint. Several prototypes were tested and the final design is now in production. Plans are to test all copper/HTS subassemblies before installation; three pairs have been successfully tested at MTF, and will be used to build the first Type-1 cryostats.

A prototype CH cryostat was assembled in May 2008 using the first prototype solenoid, in order to test the cryogenic interface and quench protection systems, make studies of the cryostat performance and solenoid alignment, and to provide feedback for the production cryostat and system designs. The prototype made it possible to investigate the important issue of quench development and propagation in the superconducting (SC) leads [5]. In testing individual cold masses, the leads are typically protected separately from the magnet using special voltage taps, but these were not envisioned for use in the production cryostat devices. Total SC lead lengths are approximately 30 cm of 0.6 or 0.8 mm round strand in liquid helium, and quench propagation and voltage development are expected to be slow. It was possible to induce quenches in either lead by lowering the vapor-cooled lead flow to heat either SC lead after a ramp to the desired current. Thus, it was possible to map out the quench development time and voltage for both SC leads, as a function of the magnet current. We found that induced SC lead quenches would not propagate at low current, at or below 80 A, where the SC lead voltages each remained stable at about 6 mV. At 85 A and above, the SC lead quenches propagated to the solenoid in which resistive voltage rapidly developed and was detected. The SC lead voltages and quench propagation times were measured over a range of operating currents up to just below the solenoid quench point with no lead damage. Thus, we concluded that no special measures are needed for SC lead protection in the CH cryostat assemblies.

Alignment studies of the prototype cryostat have been made over repeated thermal cycles using a Single Stretched Wire (SSW) system combined with laser tracker survey of wire and magnet fiducials [4]. Preliminary results suggest the warm magnetic axis position is reproducible at the level of $\pm 50 \mu\text{m}$, and the overall warm to cold repeatability is about the same level. Solenoid alignment studies are continuing with the goal to assess the performance of a vibrating stretched wire system,

which may deliver greater accuracy (because solenoid aperture limits the wire transverse motion), and usefulness over the longer baseline needed for the SSR sections. In addition to solenoid axis determination, the SSW system will be able to measure precisely the steering dipole field angles and field integrals in production lens assemblies under operating conditions.

SSR SECTIONS

Focusing Solenoids

The SSR-1 section solenoid design [6] is similar to the CH solenoid: not needing space for a warm bore tube, it has smaller aperture, and to provide the required focusing strength it is longer with more inductance. The main design challenges were to keep the fringe field as low as possible, introduce a thin radial layer of steering dipoles with good field quality, and keep adequate current margin. Fabrication and testing of prototype solenoids was successfully completed, with quench and magnetic performance closely matching predicted behavior [7],[8]. However, because the expected operating temperature in the R&D linac will be higher than expected, the prototypes provide less operating margin than planned. Therefore a revised design [9] with increased margin will result in building and testing a pre-production SSR-1 solenoid this summer, and production will follow thereafter.

The SSR-2 section solenoid design [10] follows from the SSR-1 design, but the requirement of increased strength leads to a longer and more inductive main coil. In this case quench protection becomes a concern due to large voltage development. This was handled by splitting the main coil into two halves to allow greater flexibility in the electrical connections. In particular, this allows setting the main coil center at ground potential, which reduces the potential to ground by a factor two at the quench location.

Magnetic Shielding

Establishing the magnetic shield effectiveness is the next major milestone for SSR solenoid R&D. A magnetic shield was designed [9] and fabricated by Amuneal, Inc.; the shield accommodates beams extending from the helium vessel that will be needed for alignment, and has other necessary penetrations. The SSR-1 prototype focusing solenoid with correctors was welded into a helium vessel and its shield assembled. It is now mounted in a magnetically shielded test cryostat where an array of Hall probes is arranged to measure the radial and axial field strengths at the plane where an SSR cavity will reside next to the solenoid; we expect to complete these measurements this summer.

Solenoid Alignment

Installation and alignment of the SSR section solenoids into cryomodules will be challenging, especially given the expected tight tolerances now envisioned of about 0.2 mm on the installed magnetic axis positions at cold temperature. Each production solenoid must undergo a magnetic axis fiducialization process, so a test cryostat and procedure to locate solenoid centers will be needed.

CONCLUSION

Production and testing are well under way for CH section lenses. The superconducting solenoids reach their predicted quench current with short training, and magnetic properties are in good agreement with expectations. The first production cryostat lens assemblies will soon be completed, tested, and alignment measured. Some design modifications are under consideration to incorporate beam position monitors within the cryostats, in order to save space along the beamline.

R&D continues on solenoids for the SSR sections. Refinements have been made for the SSR-1 design and a pre-production model is being built, and a prototype SSR-2 magnet design will be built and tested over the next few months. A study is in preparation and should yield results in the coming months on the effectiveness of magnetic shielding for solenoids adjacent to superconducting RF cavities. A system is being evaluated for solenoid axis alignment in the SSR cryomodules, and plans are being made to build a dedicated test cryostat to study solenoid installation, alignment, stability and reproducibility.

REFERENCES

- [1] I. Terechkine, *et al.*, "Focusing Solenoids for the HINS Linac Front End," FERMILAB-CONF-08-405-TD, Presented at LINAC'08, September 2008.
- [2] R. Carcagno, *et al.*, "Superconducting Solenoid Magnet Test Results," *IEEE Trans. Appl. Supercond.*, Vol. 17, pp.1213-1216, June 2006.
- [3] M. Tartaglia, *et al.*, "Test Results for HINS Focusing Solenoids at Fermilab," FERMILAB-CONF-08-324-TD, Presented at ASC'08, August 2008.
- [4] T. M. Page, *et al.*, "HINS Superconducting Lens and Cryostat Performance," FERMILAB-CONF-08-266-TD, Presented at ASC'08, August 2008.
- [5] D. Orris, *et al.*, "Superconducting Strand Quench Development Tests," TD-09-012, FNAL, April 2009.
- [6] G. Davis, *et al.*, "Prototype Focusing Solenoids for SS-1 Section of HINS Linac," TD-08-010, FNAL, March 2008.
- [7] G. Davis, *et al.*, "HINS_SS1_SOL_01: Fabrication Summary and Test Results," TD-08-012, FNAL, April 2008.
- [8] G. Chlachidze, *et al.*, "HINS_SS1_SOL_02d Fabrication and Test Results," TD-09-001, FNAL, February 2009.
- [9] G. Davis, *et al.*, "Pre-Production Solenoid for SS1 Section of HINS Linac," TD-09-010, FNAL, March 2009.
- [10] G. Davis, *et al.*, "HINS Linac SS2 Section Prototype Focusing Lens Design," TD-09-003, FNAL, January 2009.