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उच्च तीव्र प्रोटॉन त्वरकों हेतु चालन शीतित अति-चालक चुंबक का बहु-भौतिक अभिकल्पन, विकास एवं कार्य-निष्पादन

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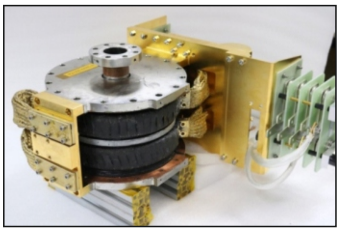

ऊष्मा अभिगम एवं शीत डायोड के साथ प्रसाधित चुंबक समाहार

सारांश

उच्च तीव्रता रैखिक प्रोटॉन त्वरकों को मध्यम और उच्च ऊर्जा व्यवस्था में अति-चालक त्वरण संरचनाओं के कार्यान्वयन की आवश्यकता होती है ताकि एकल-स्पोक अनुनादकों और दीर्घवृत्ताकार गुहिकाओं के संयोजन का उपयोग किया जा सके जो उच्च ऊर्जा के लिए प्रोटॉन कणपुंज के कुशल त्वरण को समर्थ बनाता है। लिनॉक के मध्यम ऊर्जा खंड में दो प्रकार के अतिचालक एकल स्पोक अनुनादक (एसएसआर) रेडियो आवृत्ति गुहिकाएँ (एसएसआर1 और एसएसआर2) होती हैं, जो उच्च-क्षेत्र सोलनॉइड फ़ोकसिंग लेंस के साथ अंतरित होती हैं [1]। त्वरक नियंत्रण प्रभाग, भापअ केंद्र में अति-चालक सोलनॉइड का एक एकीकृत बहु-भौतिकी अभिकल्पन विकसित किया गया है, जो एसएसआर 1 और एसएसआर 2 क्रायोमॉड्यूल अभिकल्पनों दोनों का ध्यान केंद्रित करते हुए आवश्यकताओं की पूरा करता है। उच्च ऊर्जा त्वरकों हेतु मध्यम ऊर्जा क्रायोमॉड्यूल्स के लिए पारंपरिक अभिकल्पित एससीआरएफ गुहिकाओं के समान अति-चालक सोलेनोइड्स के लिए संवहन-शीतित तापन-पात्र शीतित अभिकल्पन अपनाते हैं। वर्तमान अभिकल्पन चुंबक एवं गुहिका शीतलन को काफी हद तक वियुग्मन करके क्रायोमॉड्यूल प्रचालन हेतु एक अद्वितीय और तकनीकी रूप से बेहतर समाधान का अन्वेषण करता है। लिनॉक कणपुंज-रेखा में चुंबक के एकीकरण के बाद समान अभिकल्पन आवश्यकताओं [2,3] के साथ अंतरराष्ट्रीय सहयोग कार्यक्रमों के अंतर्गत क्रायोमॉड्यूल प्रचालन में प्रायोगिक रूप से विश्वसनीयता स्थापित की जाएगी।

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Multi-physics Design, Development and Performance of Conduction Cooled Superconducting Magnets for High Intensity Proton Accelerators

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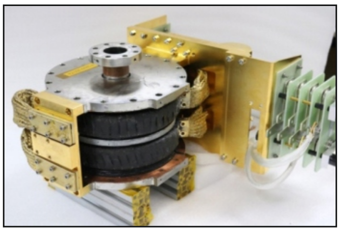

Dressed magnet assembly with heat sinks and cold diodes

ABSTRACT

High Intensity Linear proton accelerators necessitate implementation of superconducting accelerating structures at the medium and high energy regime to utilize combination of single-spoke resonators and elliptic cavities enabling proficient acceleration of proton beam to higher energies. The medium energy section of the linac contains two types of superconducting Single Spoke Resonator (SSR) radio frequency cavities (SSR1 and SSR2), interspersed with high-field solenoid focusing lenses [1]. A unified Multi-physics design of the superconducting solenoid has been developed at the Accelerator Control Division, BARC, satisfying the focusing requirements of both the SSR1 and SSR2 cryomodule designs. Conventional designs for medium energy cryomodules for high energy accelerators adopt convection-cooled bath cooled design for superconducting solenoids similar to that of the SCRF cavities. The present design explores a unique and technically superior solution for the cryomodule operation by decoupling the magnet and cavity cooling to a large extent. Reliability in cryomodule operations shall be experimentally established after integration of magnets in the Linac beamline under International collaboration programs with similar design requirements [2,3].

KEYWORDS: *Single spoke resonator, Cryomodule operation, Linac beamline*

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Introduction

Functional requirement of the SSR focusing lens envisages a primary focusing solenoidal field along with horizontal and vertical correction fields for the beam centroid. Furthermore, it is imperative to minimize the fringe magnetic field at the cavity surface to prevent field dependent escalation in the cavity surface resistance. To meet these requirements, the magnet assembly has been designed to consist of one main coil, two active shielding coils and four steering coils. The design has been optimized to maximize the strength of the focusing field in the aperture, limiting the peak fields on the superconductor surface and minimizing the fringe magnetic field at the cavity surface, all within the specific spatial and electrical constraints. Fig.1. shows the cross-section of the focusing lens assembly inside the cryomodule.

Electromagnetic Design

The arrangement of elements in the SSR cryomodules has been meticulously selected to minimize optics perturbations at the cryomodule-to-cryomodule transitions. Aperture limitations in the superconducting (SC) cavities constrain the SSR1 and SSR2 modules, setting the apertures at 30 mm and 40 mm, respectively [3]. Notably, the SSR1 and SSR2 cavities lack axial symmetry, causing the compensation of their quadrupole components challenging across the entire beam velocity range. The quadrupole field strength is proportional to the strength of axially symmetric cavity defocusing. The cavity quadrupole and skew-quadrupole fields exert a minor yet discernible impact on beam dynamics, compensatory measures become necessary. Hence, it is imperative that the SSR1 and SSR2 cryomodule are equipped with skew-quadrupole correction coils positioned within the focusing solenoids. The creation of the skew-quadrupole field will entail an intentional imbalance in the currents of independently powered x and y dipole correctors. Functional requirements for focusing lenses in the SSR cryomodule are summarized in Table1.

The necessity for fringe field requirements arise from the operational context of the lenses housed within the cryomodule alongside adjacent superconducting Spoke cavities made of pure Niobium (Nb). In the event of a quench occurring in one of the cavities, the energy stored in the electro-

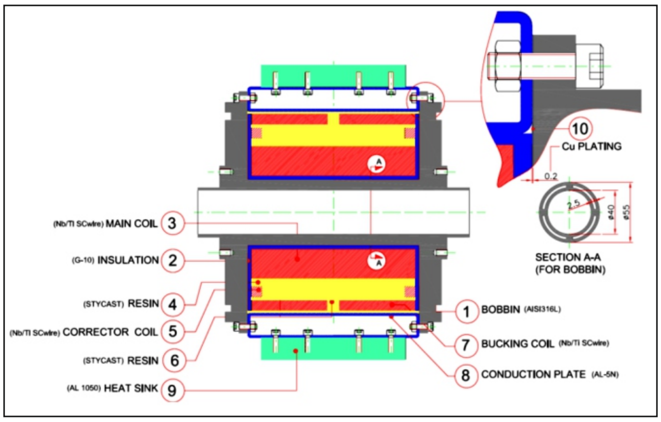

Fig.1: Cross-section of the proposed conduction cooled SSR lens in the cryomodule.

Table 1: Design Specifications.

Sr. No.	Parameters	Values
1.	Focusing strength $\int B_z^2\, dl$	4.5 T^2m
2.	Nominal current	< 100 A
3.	Bmax at cavity Surface	<10 G
4.	Bending strength	5mT.m
5.	Effective length of solenoid (FWHM)	≤ 150 mm
6.	Maximum current in the dipole correctors	< 50 A

magnetic field is discharged onto the RF surface surrounding the point of initiation [4]. This elevated temperature causes a portion of the cavity wall to transition into a normally conducting state, thereby allowing the external magnetic field to penetrate inside the cavity.

Fig.2 shows the magnetic field (Bmod) plot with only main coil powering configuration & with Main coil and Bucking coils powering configuration. It shows the level of reduction in the fringe field at the cavity location, thereby justifying the need for an active bucking coil.

Tolerance studies on bucking coil dimensions

The electromagnetic analysis of the SSR Focusing lens indicated the critical requirement for precise tolerances concerning the dimension and positioning of the bucking coil relative to the main coil. Any positional inaccuracy of the bucking coil can significantly impact the fringe magnetic field on the cavity surface [1].

The analysis results shown in Fig.3. Indicates the anticipated level of accuracy necessary in the bucking coil dimensions, estimated to be in the order of 0.5 mm. This precision is crucial to optimize the fringe field level at the maximum energy deposition surface on the cavity. These studies were utilized to specify the manufacturing tolerances for the bucking coil during coil winding. Bucking coil inside and outside diameter were varied for a fixed dimension of main coil and effect on the Peak field on the cavity surface as well as surface integral was seen at the cavity location of maximum energy deposition.

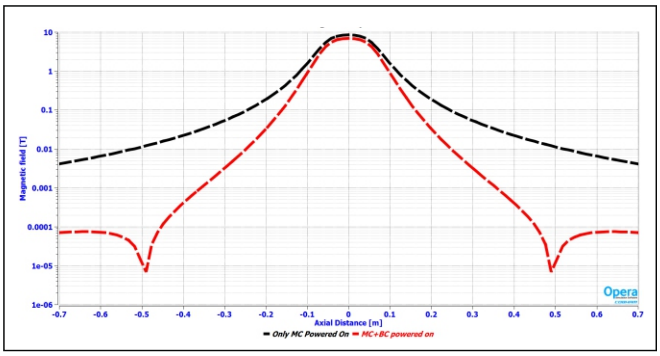

Fig.2: Bmod field profile of the SSR2 Focusing lens.

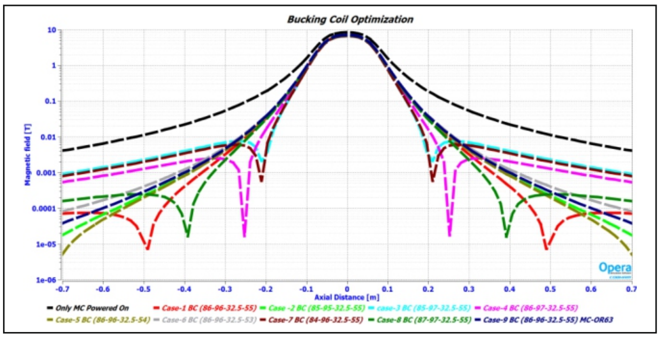

Fig.3: Effect on Fringe Field level for different configuration of Bucking Coil Design.

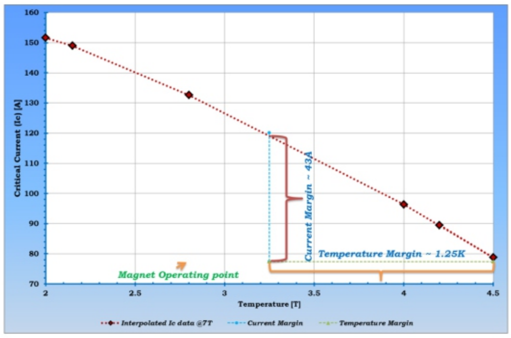

Fig.4: Design Margin for the SSR magnet.

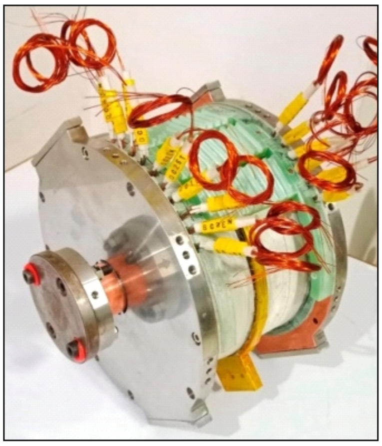

Fig.5: Bare SSR magnet assembly.

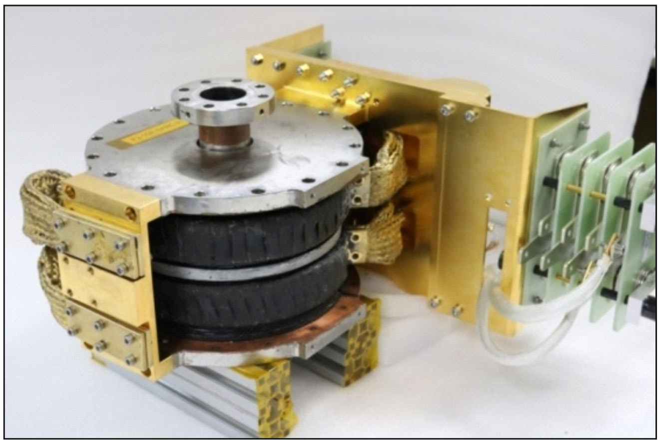

Fig.6: Dressed magnet assembly with heat sinks and cold diodes.

Operating Region and design margins

The SSR focusing lens design parameters are chosen in the way so as to operate with sufficient safety margin that is well below the Quench limit. Nominal operating current for the magnet is 75 A with a peak field level of 7.135 T on wire strand shown with yellow marker in the graph. Steady state operating temperature of the magnet inside cryomodule is ~3.2K. Fig.4. Shows the current margin and temperature margin of the designed lens.

Development of the Magnet assemblies

Maintaining tight tolerances during the winding of the coil is imperative due to the high sensitivity associated with the dimension of bucking coil. Moreover, variations in the fringe field level from magnet to magnet might occur based on the dimensions achieved during winding. Manufacturing of the magnet assemblies were carried out with tight tolerance during winding. Additional positional tolerances were specified on the coil former and coil spacers used during manufacturing. Fig.5-6 shows the photograph of the developed magnet assemblies.

Results

Developed magnet assemblies were tested in a cryocooler based test stand developed indigenously at Accelerator control Division, BARC. Axial field mapping and detailed thermal tests were carried out during cryogenic testing of the magnet assemblies. Quench data was acquired

Fig.7: Magnet assembly integrated with indigenous cryo-cooler based magnet test stand.

Fig.8: Croystat housing the conduction cooled magnet assembly during cryogenics tests & the measured magnetic field in the aperture @ 43.5A.

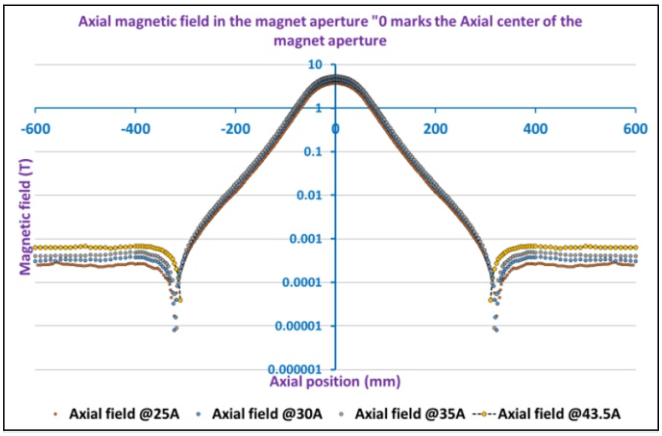

Fig.9: Measured axial field profile of the magnet assembly.

using with voltage tap data acquisition and thermal sensors data. Fig.7-8 shows the magnet assemblies integrated with the test stand during cryogenic testing of magnets.

Axial field mapping and detailed thermal tests were carried out during cryogenic testing of the magnet assembly. Passive quench protection cold diodes were used during testing of the magnet in the test stand. Fig.9. shows the measured axial field map.

Conclusion

Conduction-cooled superconducting solenoid consisting of the main coil, the bucking coils and the corrector coils has been designed for a medium beta cryomodule for a high intensity proton accelerator. Four magnet assemblies were constructed and successfully tested in indigenously developed Vertical and horizontal magnet test stands. The measurement results, enhanced insight into the thermal analysis, leading to improvement in the thermal design, thereby enhancing the efficiency of conduction cooling inside the cryomodule. Electromagnetic parameters have been experimentally assessed and validated with the design estimates in terms of integral focusing strength, fringe fields present on the cavity surface, and evaluating the nominal operating currents. The upcoming stages of testing are expected to encompass comprehensive quench characterization and ramp rate dependence studies. These tests are crucial as they help testing the magnets under simulated machine operation cycle and contribute significantly to the thermal design validation.

References

[1] Electromagnetic design and performance of conduction cooled superconducting magnet for spoke resonator cryomodule for Proton Improvement Plan (PIP)-II, Elsevier, Superconductivity 11 (2024) , Kumud Singh , Janvin Itteera , Mahima , Vikas Tiwari , Himanshu Bisht , Sanjay Malhotra ,R.R. Singh , Rajesh Jalan , Sanjay Howal , Rajesh Chimurkar.

[2] The PIP-II Reference Design Report V1.00 June 2015, The PIP-II Collaboration

[3] The PIP-II Conceptual Design Report V0.00 March 1, 2017 M.Ball, A.Burov, B. Chase, A.Chakravarty, A.Chen, S.Dixon J.Edelen, A.Grassellino, D.Johnson, S.Holmes, S.Kazakov, A.Klebaner, I.Kourbanis, A.Leveling, O.Melnychuk, D.Neuffer, T.Nicol, J.Ostiguy, R.Pasquinelli, D.Passarelli, L.Ristori, W.Pellico, J.Patrick,L. Prost, I. Rakhno, A. Saini, W.Schappert, A.Shemyakin, J.Steimel, V.Scarpine, A.Vivoli, A. Warner, V.Yakovlev.

[4] "SSR1 Cavity Quenching in the Presence of Magnetic Field,"T. Khabiboulline,D.Sergatskov, and I. Terechkine, FNAL TD note TD-12-007, June 2012.

[5] T. Khabiboulline, T. Nicol, and I. T erechkine, " Acceptable Level of Magnetic Field on the Surface of a Superconducting RF Cavity," FNAL TD note TD-12-008, June 2012.