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Superferric quadrupoles for FAIR Super FRS energy buncher

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ABSTRACT

The quadrupole magnets for FAIR Super FRS energy buncher have large usable aperture, high magnetic pole-tip field and high gradient field quality. The iron-dominated magnets with superconducting coils have to be used in this application. The NbTi coil, laminated iron, and support structure of about 22 tons is immersed in liquid helium. The 4.5 K helium chamber is completely covered with a thermal shield cooled by helium at 50–80 K on its outer and inner surface. The helium chamber and thermal shield is enclosed in a vacuum shell.

The paper presents design details of the long quadrupole. Coupled thermal, magnetic and structural analysis was carried out to design the magnet iron, magnet coil, helium vessel and support links and ensure the required gradient field quality is achieved. The paper also presents the design of support links and outer vacuum chamber.

1. Introduction

The energy buncher at the low energy beam line of Superconducting Fragment Separator (Super-FRS) in the Facility for Antiproton and Ion Research (FAIR) at GSI, Germany [1] is a valuable and attractive experimental device for use as a magnetic spectrometer for particle identification after secondary reactions. The dipole, quadrupole and sextupole magnets forming the energy buncher have to accept fragment beams which can be transported in a large cylindrical volume. The quadrupole magnets have large usable aperture of ±0.3 m horizontally and ±0.25 m vertically, high magnetic pole-tip flux densities of 5.2 T/m, gradient field quality $\Delta G/G$ of $\pm 8 \times 10^{-4}$ with a pole tip field of up to 1.8 T. The design of these magnets is quite complex as they have short length, large aperture and have to achieve the high magnetic field quality. These specifications require the use of iron-dominated magnets where the magnetic field is formed by shaped iron poles using superconducting coils. Similar type of magnets have also been used at the A1900 in-flight fragment separator at MSU, USA [2–4] and BigRIPS fragment separator at RIKEN, Japan [5], RIA at TRIUMF, Canada [6]. All of these facilities work at much lower beam energies and hence the magnets are much smaller compared to those of the Super-FRS. India has a proposal to supply components, viz., beam line magnets, detector, power supplies, etc. for building this accelerator facility.

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2. Quadrupole magnets

The quadrupole magnets in the energy buncher section of the Super-FRS have to generate high magnetic field in its usable aperture. Two types of quadrupoles are required to be used in the energy buncher. The long quadrupoles have an effective length of 1.2 m and short quadrupoles have an effective length of 0.8 m. The short quadrupoles have a large operating range of magnetic field gradient from a minimum gradient of 0.05 T/m to a maximum gradient of 4.7 T/m. The corresponding figures for the long quadrupole are 0.1 T/m and 5.2 T/m respectively. The quadrupole magnets have large usable aperture of ±0.3 m horizontally and ±0.25 m vertically, high magnetic pole-tip flux density of 5.2 T/m, gradient field quality $\Delta G/G$ of $\pm 8 \times 10^{-4}$ with a pole tip field of up to 1.8 T. These magnets are required for handling beams with a maximum beam rigidity of 7 T-m. In order to cater to different users and to reduce the time required to change the beam species, it is desired that the magnets have energisation time of about 120 s.

3. Two dimensional design

3.1. Physics design

A 2D design of the quadrupole magnet was first carried in order to determine the approximate size and shape of the magnet. Preliminary calculations using computer code POISSON [7] show that an NI value of 250,000 in the coils around each pole is needed for producing a field of gradient of 5.2 T/m when the pole radius

Table 1
Comparison between superferric and room temperature magnet.

Superferric magnet	Normal room temperature magnet
High current density, small coil size, small magnet size	No helium cooling, no supply lines and associated paraphernalia
Non-resistive, low operational cost	No complicated cryostat, but high operational cost
No water cooling needed	No quench detection and protection system
Very high field and field gradients	Maximum field is below 2 T

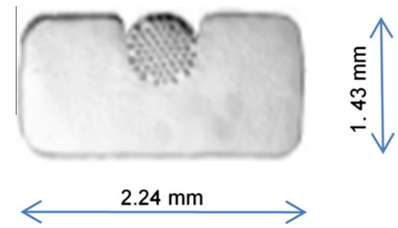

Fig. 1. NbTi conductor cross section.

is 0.35 m. The required field gradients can be reached both by normal room temperature magnets as well as superconducting magnets. If we use copper conductor of size 8 mm × 8 mm with a hole of 4 mm diameter for water cooling, the conductors can carry a current of 300 A. The number of turns comes out to be about 830. The coil cross section will be about 270 mm × 270 mm. To accommodate this coil, the length of the pole stem has to be about the same as the half-aperture of the magnet. As a result the magnet yoke will have large cross-section. Moreover, the coil cross-section will be about 10% of the iron cross-section. So the cost of copper will be about the same as that of iron. A feasible alternative is to adopt superferric magnet technology. In a superferric magnet, the coil size is very small and the iron volume is large. The field is iron dominated, although the coil is superconducting. Superferric magnets have the combined advantage of a very compact coil and low operating cost. Table 1 compares the salient features of the two types of magnets.

The analysis showed that a superconducting magnet having NbTi superconductor with 2.24 mm × 1.43 mm cross section (Fig. 1) and an operating current of about 300 A can be used for this magnet. The coil with a cross section of 2700 mm^2 having 830 turns will be required to produce the same NI. The NbTi conductor embedded in a copper substrate was selected for giving high Cu/SC ratio to ensure cryogenic stability of the coil. Specification of the superconducting wire is given in Table 2.

The quadrupole magnets are DC magnets, but need frequent change in field level from experiment to experiment. Quick changes in the field levels are needed for increasing the beam time. A ramp rate of 120 s has been thought to be optimum for this changeover. Laminated iron core will be utilised for minimising the eddy loss, which occur due to fast change of operating current. The large volume of iron and the superconducting coil will be maintained at liquid helium temperature.

3.2. Structural design

The magnet iron and coil are immersed in liquid helium inside the liquid helium chamber. An iron chamber cannot be used as it will change the magnetic field profile. Also, iron does not have sufficient ductility, when it is cooled down to 4.5 K. Stainless steel of type SS 304 has ferrite content in the weld zone, so a fully austenite grade of stainless steel, SS 316, has to be used.

The magnet is assembled at room temperature. But, it has to be operated at a temperature of about 4.5 K. Iron contract by about 2.3 mm for a metre and stainless steel contracts by about 3 mm in a metre. The contraction of iron and magnet energisation changes the pole profile of the magnet.

It was evaluated that in order to keep the magnet quality within acceptable limits, the deviation of iron has to be below 50 μm. It is observed that the iron deformed by 0.8 mm with the applied loads. This required re-evaluation of the iron profile at room temperature. The required pole face geometry at room temperature was evaluated in an iterative process by successively correcting the pole face geometry for deviations and the error at 4.5 K was reduced to 10 μm (Fig. 2). During cooldown of the magnet from room temperature to 4.5 K, stainless steel contract more than iron and applies an external force on the iron. ANSYS [8] was used to evaluate the stresses. It was observed that after cooldown and energisation, the iron is subjected to a maximum stress of 38 MPa (Fig. 3).

Table 2
Conductor specifications.

Superconducting material	NbTi
Conductor size	1.17 mm × 1.93 mm
Conductor size with insulation	1.43 mm × 2.24 mm
Filament diameter	50–105 μm
No. of strands in wire	55
Diameter of core wire	0.63 mm
Twist pitch on filaments	13 mm
Ratio of Cu and non Cu in wire	1.3
Ratio of Cu and non Cu	14
Operating temperature T_{op}	4.2 K
Critical current Ic_1 at 4.2 K and 4 T	560 A
Critical current Ic_2 at 4.2 K and 2 T	774 A
Critical current Ic_3 (calculated) at 4.2 K and 1.6 T	813 A
Operating current I_{op}	300 A
Current density	133 A/mm^2
Critical temperature T_{cs}	7 K
Temperature margin T_{cs}–T_{op}	2.8 K

4. Three dimensional design

4.1. Physics design

Based on the approximate mechanical layout and 2D design, the 3D design of the magnet was performed using the MagNet [9] from M/s Infolytica and OPERA [10]. The 3D analysis showed that NI of 290,000 A turns was required to achieve the same magnetic field. The racetrack type coils (Fig. 4) having an overall inner dimension 1189 mm × 597 mm and cross sectional of about 43 mm × 95 mm was used. Because of the short length and wide aperture of the magnet, an elaborate process of end chamfering had to be carried on the pole profile obtained by 2D analysis on 3D geometry of the 1/16th model with end shaping is shown in Fig. 5. The required field quality was finally achieved (Fig. 6) [11,12].

The superconductor would be wound on a SS 316 bobbin and potted with resin to fill the voids in order to provide strength to coil and prevent conductor movement. Resisting conductor movement in the coil is very important in a superconducting coil. The assembly of coils and bobbin is mounted on the iron around the pole tip using a fixture of SS 316 [13].

Due to the very high value of required pole tip field, the pole ends were completely saturated. Majority of higher order harmonics were because to 12 (6th harmonic) and 20-pole (10th harmonic) components without any chamfering. At around 550 mm from centre and at 300 mm radius, contribution of 12-pole component was almost 500 gauss with respect to main harmonic of about 0.042 though at centre it was 9.5 gauss with respect to main har-