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MAGNETIC PARAMETERS OF A NB$_3$SN SUPERCONDUCTING MAGNET FOR A 56 GHz ECR ION SOURCE*

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Abstract

Third generation Electron Cyclotron Resonance (ECR) ion sources operate at microwave frequencies between 20 and 30 GHz and employ NbTi superconducting magnets with a conductor peak field of 6-7 T. A significant gain in performance can be achieved by replacing NbTi with Nb$_3$Sn, allowing solenoids and sextupole coils to reach a field of 15 T in the windings. In this paper we describe the design of a Nb$_3$Sn superconducting magnet for a fourth generation ECR source operating at a microwave frequency of 56 GHz. The magnet design features a configuration with an internal sextupole magnet surrounded by three solenoids. A finite element magnetic model has been used to investigate conductor peak fields and the operational margins. Results of the numerical analysis are presented and discussed.

INTRODUCTION

Electron Cyclotron Resonance (ECR) ion sources are an essential component of heavy-ion driver accelerators [1]. In order to confine the plasma and provide a closed surface where the rf power can heat the electrons, the magnet system has to generate a field consisting of closed iso-surfaces obtained by the combination of sextupole and solenoid fields, respectively for radial and axial containment. While third generation sources use NbTi superconducting coils and operate at microwave frequencies between 20 and 30 GHz, with conductor peak fields in the 6-7 T range, future sources (fourth generation) will need to use different superconducting materials, such as Nb$_3$Sn, in order to reach the required magnetic confinement and operate at microwave frequencies beyond 50 GHz [2].

A preliminary design study of a Nb$_3$Sn magnet system designed to operate at 56 GHz with conductor peak field at the 15 T level was described in [3]. The magnet lay-out was based on the design of the existing 28 GHz ECR source VENUS (Versatile ECR ion source for Nuclear Science) [4], a NbTi magnet system composed of three solenoids surrounding a sextupole magnet (sextupole-in-solenoid design). The study focused on a Nb$_3$Sn version of the VENUS design, called VENUS56, and a second design using wider sextupole coils, called VENUS56w. The results of the analysis demonstrated that both of the Nb$_3$Sn designs meet the magnetic requirements of a 56 GHz source, but the larger amount of conductor used in VENUS56w is essential to increase operating margins and reduce stresses to acceptable levels for Nb$_3$Sn coils.

In this paper, we present an optimization of the Nb$_3$Sn sextupole coil cross-sections using state-of-the-art superconducting cables used in high field magnets for particle accelerators. Two sextupole configurations, implementing respectively 2-layer or 4-layer coils, are analyzed and compared in term of current margin, temperature margin, and quench protection systems.

MAGNET DESIGN

Sextupole Coils

In order to satisfy the 56 GHz ECR requirements, the sextupole magnet has to provide a 200 mm warm bore and generate a field of 4.2 T at a diameter of 140 mm [3]. The magnet cross-section, depicted in Fig. 1, features cos(3θ)-type coils wound with a 15.350 mm wide Rutherford cable composed by 35 strands (see Table 1). The same cable design is currently used by the LARP program to develop high field quadrupoles for future LHC luminosity upgrades [5]. In each layer, the angular position of the pole turn, corresponding to approximately 20° from the magnet mid-plane, was chosen to minimize the first allowed field harmonic (b_9).

Two different magnet cross-sections were considered. The first lay-out (2-layer design) features two layers with respectively 23 and 26 turns (see the inner double-layer of Fig. 1). In order to increase the operational margin with respect to maximum current capability of Nb$_3$Sn, a second cross-section (4-layer design), with two additional layers placed around the double-layer of the previous design, was analyzed (see entire lay-out of Fig. 1). The two outermost layers contain respectively 30 and 33 turn. The radial dimensions of each layer are provided in Table 2.

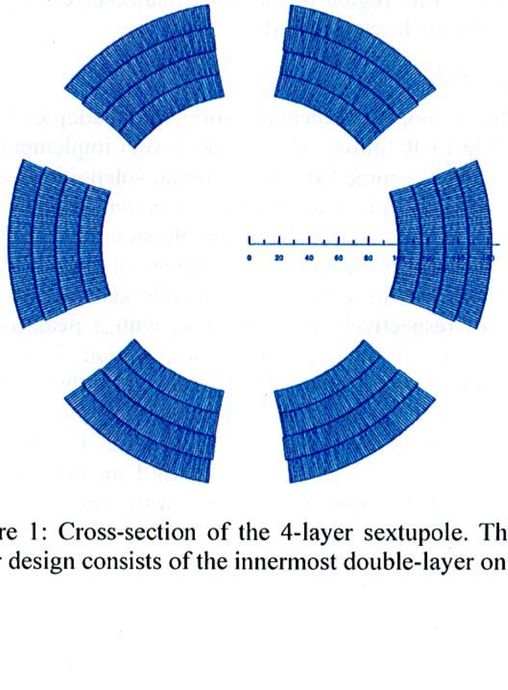

Figure 1: Cross-section of the 4-layer sextupole. The 2-layer design consists of the innermost double-layer only.

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Table 1: Conductor and cable parameters.

Parameters	**Unit**	
Strand diameter	mm	0.8
Non Cu area	%	54
No. strands		35
Cable width (bare)	mm	15.150
Cable thickness (bare)	mm	1.437
Keystone angle	deg	0.750
Insulation thickness	mm	0.100

Table 2: Radial dimensions in mm (r1/r2) of sextupole coils, solenoids, and iron.

	Sext.	**Inj.**	**Middle**	**Extr.**	**Iron**
2-layer	100/131	163/215	163/213	163/215	220/318
4-layer	100/162	194/253	194/244	194/253	258/357

In the end region each layer is subdivided in two blocks of conductors separated by end-spacers (see Fig. 2). The number of turns per block and the relative axial position of the end spacers were optimized to reduce the peak field in the end region. The total coil length is 1.3 m with a straight section 1 m long.

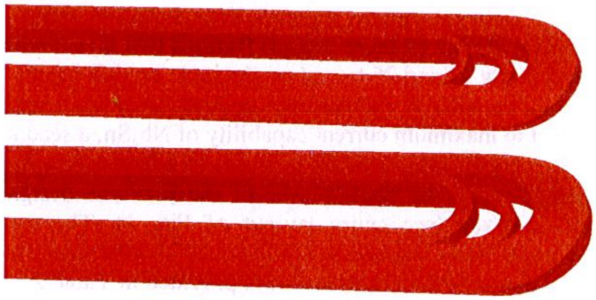

Figure 2: End region of the inner double-layer (top) and outer double layer (bottom).

Solenoids

The sextupole-in-solenoid configuration adopted for the 56 GHz ECR follows closely the design implemented in the VENUS source [3]. Two external solenoids (see Fig. 3), called the *injection* and the *extraction* solenoids, are located at each end of the sextupole straight section and provide closure of the field surfaces at the ends. The injection and the extraction solenoids generate an axial field of respectively 8 T and 5 T, with a peak-to-peak distance of 0.5 m. Over the central region, in order to maintain the 4.2 T iso-surface produced by the sextupole magnet, the solenoid field generated by the external solenoids must be minimized to the 1-2 T field level. This is accomplished through a third *middle* solenoid, powered with opposite current with respect to the injection and extraction solenoids. The radial dimensions of the solenoids are given in Table 2.

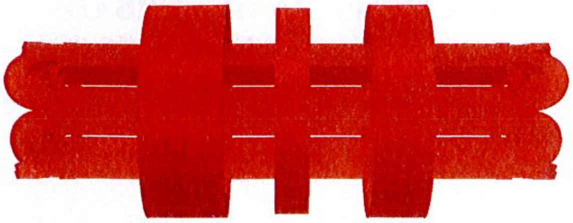

Figure 3: Injection (left), middle (center), and extraction (right) solenoids surrounding the 4-layer sextupole.

MAGNETIC ANALYSIS

Finite Element Model

The magnet parameters were calculated with two finite element models (see Fig. 4) implemented in the commercial code TOSCA by VECTOR FIELD.

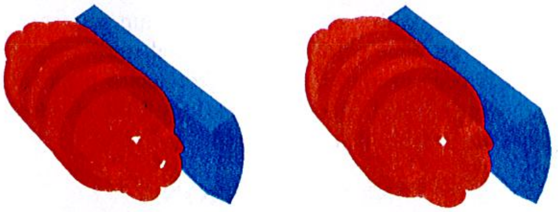

Figure 4: Finite element models of the 2-layer (left) and 4-layer (right) sextupole magnets.

The sextupole coils were modelled by creating each individual turn with the "constant perimeter" conductor option, for a total of 297 conductors in the 2-layer design and 675 conductors in the 4-layer design. The solenoids were modelled as single blocks. The iron yoke was simulated as an external shell placed around the solenoids over the entire magnet length.

From a finite element model point of view, the computation of the field produced by a sextupole magnet, oriented as shown in Fig. 1, can be obtained with a 30° model (from 0° to +30°), imposing parallel magnetic field conditions on the 30° plane and perpendicular magnetic field conditions on the horizontal plane. In the case of the ECR magnet, the presence of a superimposed solenoid field along the z axis (parallel to the horizontal plane) requires the use of a 60° model (from -30° to +30°), with parallel magnetic field conditions imposed on all the outer surfaces.

Computation Results

A total current of 13.2 kA and 8.2 kA per turn was needed in the sextupole respectively for the 2-layer and 4-layer design in order to generate a field of 4.2 T at $r = 70$ mm.

The numerical results show that the iron produces a negligible effect (less than 1%) on the sextupole field, and an increase of 7% in the solenoid field. The current densities of the solenoids were therefore adjusted to meet the requirements of the axial field in the four cases (2-layer and 4-layer designs, with and without iron), as shown in Fig. 5.

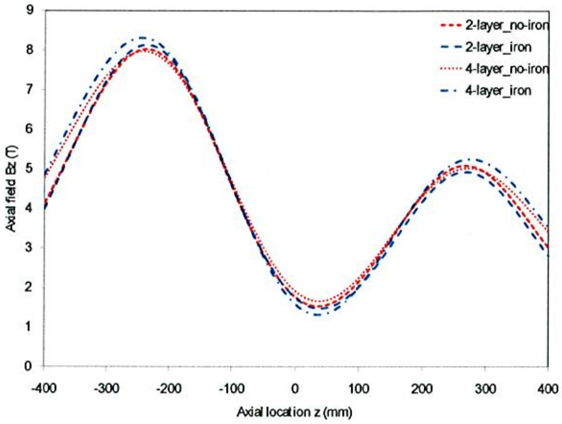

Figure 5: Axial field (T) produced by the solenoid along the magnet axis in the two designs, with and without iron.

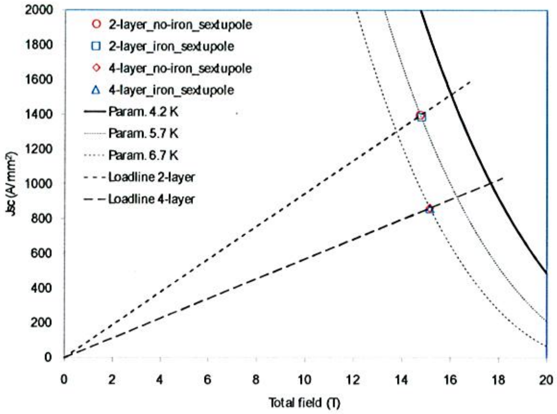

Figure 6: Critical current density in the superconductor (A/mm^2) vs. total magnetic field (T): operational conditions (markers), magnet load-lines (straight dashed line) and critical current parameterization curves.

Figure 6 shows the operational conditions of the two designs in terms of current densities in the superconductor as a function of the conductor peak fields, and compares them with the expected limits of the Nb_3Sn superconductor. Since the solenoids feature conductor peak fields at least 9% lower than the ones computed in the sextupole coils, only the latter are plotted in the graph. The markers indicate the operational conditions of the two sextupole designs, both with and without iron: the 2-layer (4-layer) design reaches the conductor peak field of 14.8 T (15.1 T) on the layer 2 (layer 3) pole turn, at the center of the injection solenoid.

The two dashed lines indicate the magnet load-lines, i.e. the dependence of the conductor peak field on the current densities, assuming that all the magnets are powered in series. The solid line represents a parameterization curve based on critical current measurements performed at 4.2 K on short-samples of strands used in the LBNL high field magnet program [6]. The intersection of the magnet load-lines and the 4.2 K parameterization curve provides the expected current density limits at 4.2 K. The 2-layer design reaches the nominal conditions at a current density of 1400 A/mm^2, which corresponds to 92% of the expected current limits based on short-sample measurements. The 4-layer design, with more than twice the number of turns, operates at 860 A/mm^2, about 86% of the current limits.

The temperature margin is determined by extrapolating the 4.2 K curve to higher temperatures and estimating the critical temperature in the operational conditions. The 4-layer design operates with a temperature margin of 2.5 K, compared to the 1.5 K of the 2-layer design.

QUENCH PROTECTION

Preliminary quench computations have been performed in order to evaluate the peak temperature reached in the windings after a spontaneous quench with different quench heater designs. At operating conditions, the 2-layer and the 4-layer magnets have respectively a stored energy of 2.9 MJ and 5.5 MJ. The QuenchPro program [7] was used to estimate the maximum temperature (hot spot temperature) under the conservative assumption that the entire magnet stored energy is dissipated in the sextupole. If the coils have full quench heater coverage, the hot spot temperature reaches 390 K (260 K) in the 2-layer (4-layer) design. If the coverage is reduced to 75%, the hot spot temperature becomes 430 K (2-layer design) and 280 K (4-layer design). Experience with accelerator magnets suggests that peak temperatures should be kept below 300 K. Under the assumptions described above, this requirement is met only by the 4-layer design.

CONCLUSIONS

We presented the design parameters of two magnet systems proposed for a ECR source designed to operate at 56 GHz. The designs feature respectively a 2-layer and a 4-layer sextupole magnet surrounded by three solenoids, with conductor peak field at the 15 T level. The results of the analysis show that the 2-layer design, although more attractive in term of overall cost and size, operates with lower current and temperature margin than the 4-layer design. In addition, the use of a 4-layer sextupole reduces the hot spot temperature and, as shown in [3], brings the coil stresses to acceptable levels.

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