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Nb_3Sn superconducting magnets for electron cyclotron resonance ion sources[a)]

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Electron cyclotron resonance (ECR) ion sources are an essential component of heavy-ion accelerators. Over the past few decades advances in magnet technology and an improved understanding of the ECR ion source plasma physics have led to remarkable performance improvements of ECR ion sources. Currently third generation high field superconducting ECR ion sources operating at frequencies around 28 GHz are the state of the art ion injectors and several devices are either under commissioning or under design around the world. At the same time, the demand for increased intensities of highly charged heavy ions continues to grow, which makes the development of even higher performance ECR ion sources a necessity. To extend ECR ion sources to frequencies well above 28 GHz, new magnet technology will be needed in order to operate at higher field and force levels. The superconducting magnet program at LBNL has been developing high field superconducting magnets for particle accelerators based on Nb_3Sn superconducting technology for several years. At the moment, Nb_3Sn is the only practical conductor capable of operating at the 15 T field level in the relevant configurations. Recent design studies have been focused on the possibility of using Nb_3Sn in the next generation of ECR ion sources. In the past, LBNL has worked on the VENUS ECR, a 28 GHz source with solenoids and a sextupole made with NbTi operating at fields of 6–7 T. VENUS has now been operating since 2004. We present in this paper the design of a Nb_3Sn ECR ion source optimized to operate at an rf frequency of 56 GHz with conductor peak fields of 13–15 T. Because of the brittleness and strain sensitivity of Nb_3Sn, particular care is required in the design of the magnet support structure, which must be capable of providing support to the coils without overstressing the conductor. In this paper, we present the main features of the support structure, featuring an external aluminum shell pretensioned with water-pressurized bladders, and we analyze the expected coil stresses with a two-dimensional finite element mechanical model. © *2010 American Institute of Physics.* [doi:10.1063/1.3259234]

I. INTRODUCTION

Third generation electron cyclotron resonance (ECR) ion sources, designed to operate at rf frequencies in the 20–30 GHz range, require full superconducting magnet systems capable of generating high-field isosurfaces to confine the plasma. Currently, three superconducting third generation ECR sources, VENUS,[1] SECRAL,[2] and SUSI (Ref. 3) are in operation and others are under development.[4–8] These sources implement coils made of NbTi, with conductor fields of 6–7 T.

As current facilities continue to upgrade to higher power target capabilities, significantly higher beam intensities will be required. As a result, the ECR systems will have to operate at field levels beyond the capability of NbTi. Fourth generation sources, built with state-of-the-art Nb_3Sn superconductor and advanced structure designs, open the possibility of 15 T coil fields and rf frequencies above 50 GHz.[9]

Nb_3Sn is a superconductor that can generate fields in the 10–20 T range. Wires fabricated with the rod-restack-processed, currently used in high-field magnet development for high energy colliders, can carry current densities in the superconductor up to 3000 A/mm^2 at 12 T and 4.2 K.[10] Unlike NbTi, which is ductile and can withstand high compressive force, Nb_3Sn is brittle and strain sensitive. As a result, the current carrying capability of Nb_3Sn coils is affected by mechanical stresses in the windings. The actual behavior depends on several factors, such as the wire design and the fabrication process. However, reversible degradation is generally observed above 150 MPa with severe and permanent degradation occurring above 200 MPa.

In addition to high stresses, electromagnetic forces can cause local motion of the conductor leading to frictional energy dissipation and premature transitions (quenches) to the normal resistive state. In a Nb_3Sn ECR source, where complex electromagnetic force distributions arise from the combination of the sextupole and solenoid fields, it is therefore mandatory to carefully analyze the strain in the supercon-

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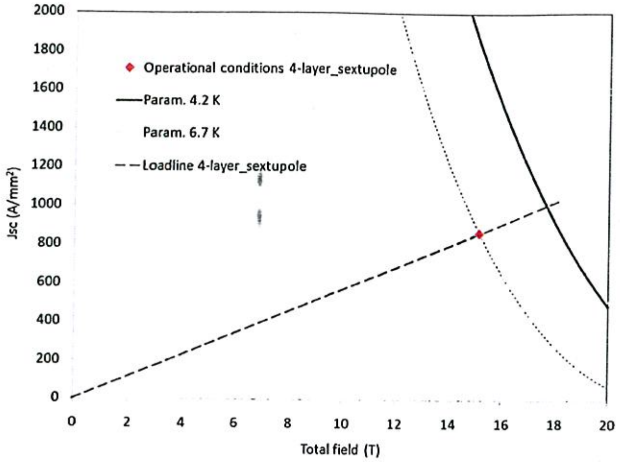

FIG. 1. (Color online) Critical current density in the superconductor (A/mm^2) vs total magnetic field (t): operational conditions (marker), magnet load lines (straight dashed line), and critical current parameterization curves (curved lines).

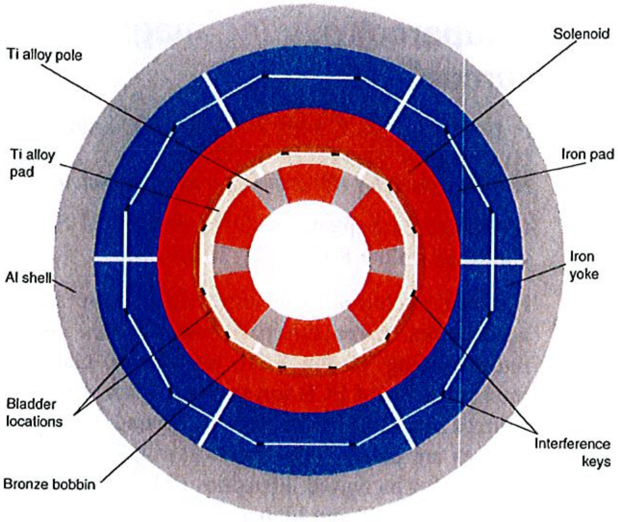

FIG. 2. (Color online) Magnet cross section.

ductor, and devise a support structure capable of minimizing the stress and motions in the coils from assembly to cool down and excitation.

In Ref. 11, we provided an overview of the main features of a fourth generation ECR ion source magnet structure operating at an rf frequency of 56 GHz and a conductor peak field of 15 T. A detailed study of the field in the plasma chamber and coils under operational condition was provided in.[12,13] In this paper we focus on the design of the support structure, which features an external aluminum shell pretensioned with water-pressurized bladders. After a brief summary of the magnet parameters, we will describe the main components of the structure, the loading procedures and the expected coil stresses during magnet assembly and operations.

II. MAGNET PARAMETERS

The magnet design that we propose for the fourth generation ion source adopts the sextupole-in-solenoid concept used in most of the third generation sources, with the same plasma chamber dimensions as the VENUS source. In order to satisfy the 56 GHz ECR requirements, the sextupole magnet has to generate a field of 4.2 T at a diameter of 140 mm, at the same time providing a 200 mm clear aperture. Two external solenoids, located at the injection and the extraction of the chamber and generating an axial field of, respectively, 8 T and 5 T, provide closure of the field surfaces at the ends. Over the central region, the axial field is minimized to 1–2 T through a third middle solenoid. The sextupole magnet features two double-layer $\cos(3\theta)$-type coils wound with a 15.35 mm wide Rutherford cable. The same cable is currently used for large aperture quadrupole models for the Large Hadron Collider luminosity upgrades.[14] In each of the four coil layers, composed, respectively, by 23, 26, 30, and 33 turns, the angular position of the pole turn corresponding to 20° from the magnet midplane was chosen to optimize the field quality.

Peak fields and superconductor current densities expected in the sextupole coils, where the highest fields of the magnet system are reached, are plotted in Fig. 1, together with Nb_3Sn critical curves at different temperatures. At a rf frequency of 56 GHz, the conductor peak field is 15.1 T and the current density in the superconductor is 860 A/mm^2, corresponding to a cable current of 8.2 kA. In these conditions, the sextupole coils will operate with a temperature margin of 2.5 K and at 86% of their limits (fraction of short sample). This level of short sample has been consistently reached in recent Nb_3Sn quadrupole magnets.[15]

III. SUPPORT STRUCTURE DESIGN

The support structure proposed for the fourth generation ECR ion source is based on an external aluminum shell. Shell-based support structures have been developed by the LBNL superconducting magnet program to cope with the needs of high-field Nb_3Sn magnets.[16] Because of large em forces acting on a brittle superconducting material, these magnets require a precise control of the coil preload in order to minimize conductor motions and coil strain during excitation. This is usually achieved by precompressing the windings so that the cables stay in contact with the winding poles and no gaps develop during the current ramp-up. A cross section of the proposed support structure is depicted in Fig. 2. The sextupole coils wound around titanium alloy poles are surrounded by bolted titanium alloy pads. Interference keys lock the sextupole coils and the titanium alloy pads inside a

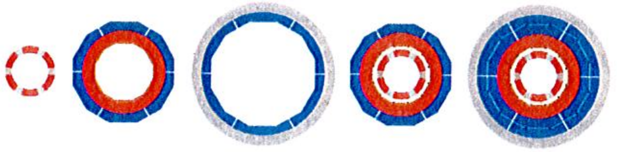

FIG. 3. (Color online) Assembly and loading procedure. From left to right: sextupole-pad subassembly, solenoid-pad subassembly, yoke-shell subassembly, loading of sextupole-pad subassembly inside solenoid-pad subassembly, and loading of coil subassemblies inside shell-yoke subassembly.

In the solenoid center region the model predicts that after cooldown, the shrinkage of the aluminum shell determines an increase of coil compression up to −159 MPa, despite part of the force is intercepted by the solenoid. During excitation, the peak stress reduces to −86 MPa (Fig. 5, left). In the "end region," the compressive force generated by the shell is partially intercepted by the bronze rings, and the coil maximum stress is −138 MPa. During excitation, the combined effect of solenoid and sextupole field creates an asymmetric stress distribution with a maximum stress of −175 MPa (Fig. 5, right). All the other components of the structure operate at a stress level below the yield point. In particular, the Ti pads experience a peak stress of 250 (500) MPa at 293 (4.2) K.

V. CONCLUSIONS

We described the design of a Nb_3Sn superconducting magnet system for a fourth generation ECR ion source operating at 56 GHz with a conductor peak field of 15.1 T. The support structure, based on an external aluminum shell, is assembled and preloaded in 5 steps with water pressurized bladders. According to a 2D analysis, after cooldown the structure provide enough preload to maintain the sextupole turns in contact with the poles during excitation, with maximum coil stress of −175 MPa. As a next step, a full three-dimensional analysis needs to be performed to confirm the 2D calculations and further optimize the mechanical structure.

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