OPTIMIZATION OF THE NEW SC MAGNETIC STRUCTURE DESIGN WITH A HYBRID MAGNET*

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Abstract

In the development of the next generation Electron Cyclotron Resonance Ion Source, so far either a set of full NbTi or Nb_3Sn magnets has been proposed to construct the magnet system. However, the single set of NbTi magnets may not be the optimum in terms of the field strength and configuration. An optimization of the new SC magnetic structure [1] with a hybrid magnet (NbTi and Nb_3Sn) is being investigated. With the hybrid magnet and other minor changes the optimized new magnetic system is capable of producing field maxima of 9.0 T on axis and 4.1 T at the plasma wall, which are about 30 and 5 percent higher than the new SC magnetic structure to be built with a set of full NbTi magnets. In addition, the axial length of the optimized magnetic structure has been slightly shrunk resulting in a less bulky system. This new magnetic field profile is high enough for operation frequency up to 56 GHz. The design features and the preliminary stress analysis of the optimized new SC magnetic structure will be presented and discussed.

INTRODUCTION

The significant performance enhancement of Electron Cyclotron Resonance Ion Source (ECRIS) in the last decade has demonstrated that operating with higher-field and higher-frequency remain to be the most effective and straightforward path to further improve the ECRIS performance [2-4]. To meet the increasing ion beam demands from the accelerators worldwide under construction or design, the next generation ECRISs of much higher-field and higher operating-frequency have been proposed to be built with either a set of full Nb_3Sn or a set of full NbTi magnets. As a continuation of the classical magnet structure, a set of full Nb_3Sn magnets would yield field maxima of 8.0 T on axis and 4.0 T at the plasma chamber walls [5]. The newly proposed magnetic structure (MK-I) would produce 7.0 T and 3.9 T with a set of full NbTi magnets, and 12.0 T and 6.0 T with a set of full Nb_3Sn magnets, respectively [1]. However, there are many uncertainties of the Nb_3Sn magnet to be used in ECRIS and which need thoroughly addressed before an ECRIS of Nb_3Sn can become a reality. On the other hand, the NbTi magnet has been fully proven its reliability in the present generation ECRISs, but the configuration of maximum fields of 7.0 T and 3.9 T may not be very satisfactory to support operations up to 56 GHz. Development has demonstrated that higher magnetic fields is the needed basis for a next generation ECRIS to achieve higher performance [6]. Therefore building an ECRIS with a set of full NbTi magnet may not be the best option in the near future and an exploration of any possible optimizations on the magnet system would greatly benefit the development.

A HYBRID MAGNET WITH THE NEW MAGNTIC STRUCTURE

Fabrication of a Nb_3Sn solenoid coil nowadays is a pretty straightforward process. In reference to the case of a set of full NbTi magnets (NbTi-I) with the MK-I magnet structure [1], the hybrid magnet (Hybrid-I) described here is such a set of magnets that injection solenoid is fabricated of Nb_3Sn wires but keep the rest coils of NbTi wires, as indicated in Fig. 1.

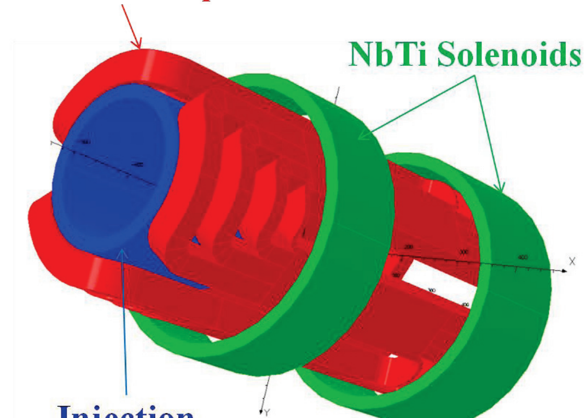

Figure 1: The hybrid magnet in the MK-I magnet structure in which the injection solenoid is made of Nb_3Sn wires and the rest of NbTi wires.

Other Optimizations

Since the Nb_3Sn wires can carry higher currents than the NbTi wires, thus the following optimizations are also exercised:

- Thinning the solenoid coil by keeping the outer diameter constant but increasing inner diameter by 24 mm so that there will be more space for inserting more injection components;

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- Shortening the extraction side of the sextupole magnet by 60 mm that results in an 800 mm long magnet, instead of the previous length of 860 mm;
- Replacing the intended EAS NbTi (F54) wires with the Supercon NbTi (56S53) wires of slightly higher critical currents in the sextupole magnet to obtain field increase of a few percent along the larger radius of the hexagonal plasma chamber.

Table 1 below lists the variations and comparisons of the mechanical dimensions and the system stored energy between the Hybrid-I and the NbTi-I. With these modifications, the Nb_3Sn injection solenoid and the NbTi sextupole excited respectively at 82% and 88% of its critical currents at 4.2 K as indicated in Fig. 2, the field maxima on the coils are 10.9 T at the inner surface of the injection solenoid and 8.15 T at the sextupole coil. These excitations of less than 90% of its critical currents should be achievable with careful coil winding and clamping as have demonstrated in SECRAL and other sources. Under these excitations, the Hybrid-I produces a peak field of 9.0 T on axis and a radial field of 4.1 T at the plasma chamber walls. These fields are about 30% and 5% higher in comparison to the 7.0 T and 3.9 T in the NbTi-I, as shown in Fig. 3 and Fig. 4. This field configuration of 9.0 T and 4.1 T should satisfactorily support operations with microwaves of frequency up to 56 GHz, based on the present design criteria.

Table 1: Magnet System Variations

	Hybrid-I	NbTi-I
Total Magnet Length (mm)	800	860
ID (mm) of the Injection Solenoid (OD = 240 mm)	200	176
Peak Axial Field/Radial Field at Chamber Walls (T)	9.0/4.1	7.0/3.9
Axial Peak Field Distance (mm)	612	644
System Stored Energy (MJ)	1.4	0.9

The 24 mm enlargement in the injection solenoid ID will increase the diameter of the injection snout accordingly which allows more space for wave guide insertions, easier wave mode conversion and oven ports. With more wave guides available it is easier to launch multiple-frequency plasma heating of various combinations of 14 to 56 GHz to explore any further performance enhancement other than two-frequency plasma heating [7]. More injection space will also allow easier wave conversions to investigate the wave-mode effects on plasma heating and source performance [8]. In addition, more oven ports would provide a better flexibility of solid-ion beams for daily operations with the accelerators. A shorter magnet length will lead to a less bulky source that would benefit the ion beam extraction, transport, vacuum pumping and somewhat lower cost, as the higher-field SC ECRIS becomes larger and bulkier.

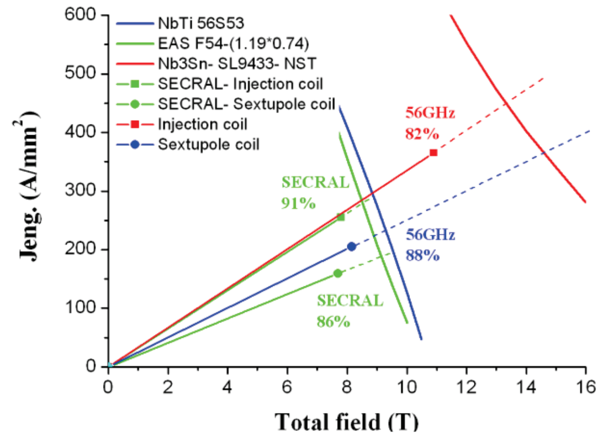

Figure 2: Magnet coil current loading at 4.2 K and comparison between the Hybrid-I and SECRAL.

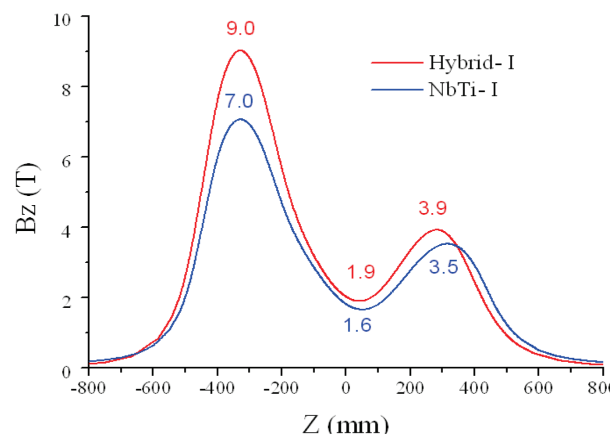

Figure 3: The Hybrid-I produces about 30% higher axial field (red line) and slightly shorter distance between the field peaks in comparison to the NbTi-I (blue line).

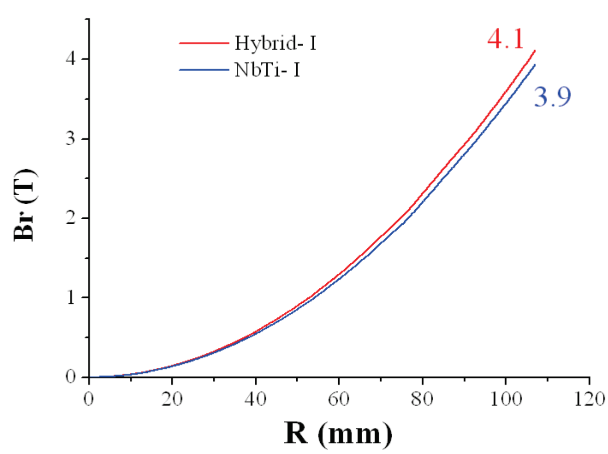

Figure 4: With the Supercon 56S53 wires the Hybrid-I produces slightly higher radial field (red line) than the NbTi-I with EAS F54 wires (blue line) at the plasma chamber walls.

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PRELIMINARY STRESS ANALYSIS

A full 3D ANSYS model has been developed for the stress analysis to verify the feasibility of the Hybrid-I design. In this preliminary analysis, the controlled pre-stress to the coils is omitted but real material properties were applied to the coils cooled down to 4.2 K. Fig. 5 shows the applied constraints assuming infinite rigid the cold iron segments. With the magnet coils were excited at the maximum design currents flowing at the same direction, the stress distribution has shown a maximum stress of 108 MPa at the inner surface of the injection solenoid, as shown in Fig. 6. The peak field at this location is of only 10.1 T computed by the ANSYS model but TOSCA calculations showing a field of 10.9 T. This field strength discrepancy could well be due to the mesh size of the ANSYS code is relatively coarse in comparison to TOSCA. In the future analyses, the e.m. forces should be imported from the 3D TOSCA model for better accuracy and consistency [5].

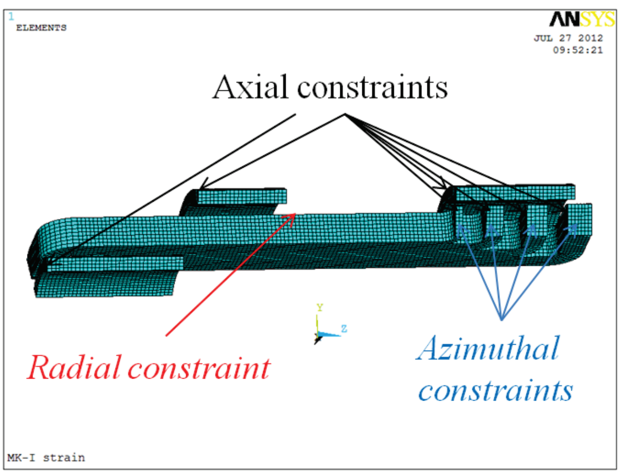

Figure 5: Constraints applied to the preliminary stress analysis in one sixth of the Hybrid-I model at 4.2 K. The same azimuthal constraints were applied to the other end of the sextupole but not graphically indicated in this figure.

Under the above stated excitations, all the e.m forces exert on the coils are both radially and axially outward, which is the characteristic of the MK-I and the non-classical magnetic structures. Fig. 7 indicates the likely maximum deformation could be of about 0.18 mm that occurs mostly in the axial direction at the inner side of the Nb_3Sn injection solenoid where there is a peak radial field from the sextupole magnet that has 3-fold of symmetry. So cares should be taken to well secure the injection solenoid to minimize the potential of quenching. The rest deformations at other places are pretty minimal, most of them in the orders of a few hundredths of one mm and that should be taken care by the cold iron segments without great difficulties.

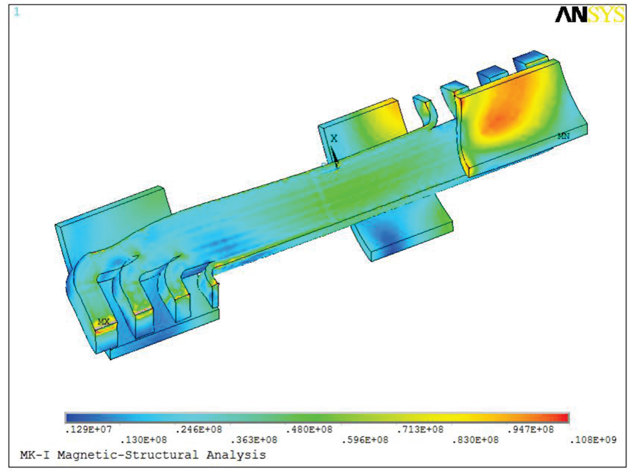

Figure 6: Stress distribution of the Hybrid-I with the applied constraints indicated in Fig. 5. In this preliminary analysis the maximum stress is of 108 MPa occurring at the inner surface of the Nb_3Sn injection solenoid which is within the stress limit.

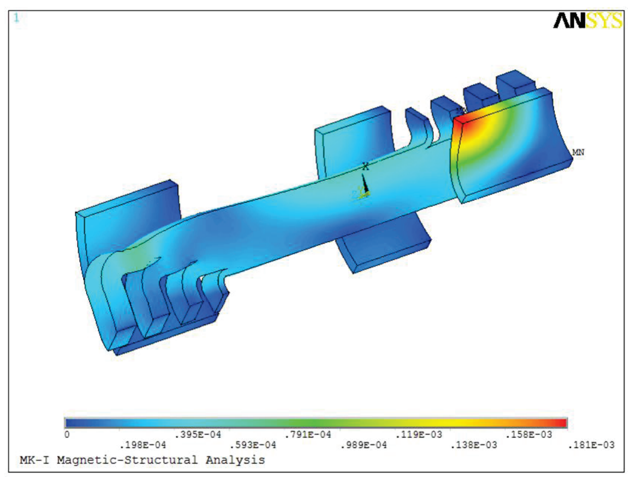

Figure 7: Distribution of the likely deformation of the Hybrid-I with the applied constraints indicated in Fig. 5. The maximum deformation occurs mostly in the axial direction at the inner side of the Nb_3Sn injection solenoid.

DISCUSSIONS

The studied optimizations have lead to a substantial axial field increase at the injection, more space for injection insertions and a less bulky magnet system that would accordingly result in a smaller cryostat. All of these features are very preferable for the next generation ECRISs. Without pre-stressing and at 4.2 K, the preliminarily analyzed peak stress of 108 MPa at the Nb_3Sn injection solenoid and about 80 MPa at the NbTi sextupole coil, which are well within the yield stress limits even taking into account that there is about 8% field underestimate by the ANSYS model. Though further stress analyses with controlled preload need performed in

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the near future, this study has established a base to start designing the detailed system clamping and supports, given that the one-body-wound NbTi sextupole can be fabricated.

The explored optimizations have shown that the Hybrid-I in many aspects is superior to the NbTi-I. Thus if a set of full Nb_3Sn magnets with the MK-I structure is not feasible in the near future, the Hybrid-I could well be a good option for the next generation ECRIS.

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