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Development of a new superconducting ECRIS for operations up to 18 GHz at LBNL[a)]

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A new superconducting Electron Cyclotron Resonance Ion Source (ECRIS) is under development at LBNL to harness the winding techniques of a closed-loop sextupole coil for the next generation ECRIS and to enhance the capability of the 88-inch cyclotron facility. The proposed ECRIS will use a superconducting closed-loop sextupole coil to produce the radial field and a substantial portion of the axial field. The field strengths of the injection, central and extraction regions are adjusted by a three solenoids outside the closed-loop sextupole coil. In addition to maintaining the typical ECRIS magnetic field configuration, this new source will also be able to produce a dustpan-like minimum-B field to explore possible ECRIS performance enhancement. The dustpan-like minimum-B field configuration has about the same strengths for the maximum axial field at the injection region and the maximum radial pole fields at the plasma chamber walls but it can be substantially lower at the extraction region. The dustpan-like minimum-B will have a field maximum $B_{max} \geq 2.6$ T for operations up to 18 GHz with a ratio of $B_{max}/B_{res} \geq 4$ and higher ratios for lower frequencies. The field maxima of this new source can reach over 3 T both at the injection and the plasma chamber walls which could also support operation at 28 GHz. The source will be built of cryogen-free with the magnets directly cooled by cryo-coolers to simplify the cryostat structure. The source design features will be presented and discussed.

I. INTRODUCTION

A next generation of higher-field and higher- frequency ECRIS is needed to satisfactorily meet the increasing demands worldwide. Since the NbTi magnets have essentially reached their limits, higher-critical-current Nb_3Sn wires have to be used to construct the source magnet system to produce magnetic field strength up to ~ 10 Tesla. There are substantial issues that need to be addressed before an ECRIS magnet structure can be built. The brittleness and poor ductility of the Nb_3Sn wires and the difficulties in clamping the much stronger em interaction forces are challenging. One possible scheme is to fabricate a closed-loop sextupole coil and combine it with a few solenoids to build the source magnet system. This may have many advantages over the existing magnet structures.[1,2] However, the fabrication of a closed-loop sextupole coil is the most critical step to realize the promising new magnet structure.

As a stepping-stone for the development of the next generation ECRIS, the development of harnessing the winding techniques by prototyping a closed-loop sextupole coil with NbTi wires is ongoing at the 88-Inch Cyclotron, LBNL. If successful, the prototyped NbTi closed-loop sextupole will be used to build a new superconducting 18 GHz ECRIS for the production of the very highly-charged heavy-ion beams to enhance the capability of the 88-Inch Cyclotron for nuclear science research, and the chip testing at the Berkeley Accelerator Space Effects Facility.

The empirical design criteria of magnetic fields for an ECRIS are B_{inj} ~ 4, B_{ext} ~ B_{rad} ~ 2 and B_{mid} ~ 0.5-0.8 of the cold electron resonance heating field B_{res}. Such a magnetic configuration has worked fairly well so far for ECRISs, but question of whether other substantially different field configurations will work as well or better has not been investigated. The exploration of higher radial field was carried out over a very limited range of magnetic fields for an ECRIS optimized with B_{ext} ~ B_{rad} ~ 2 of B_{res} in which the ECR heating volume decreased as B_{rad} increased.[3] In addition to the capability of reproducing the typical magnetic field configuration, the dynamic field strengths of this new 18 GHz ECRIS are capable of generating a magnetic field configuration with B_{inj} and B_{rad} up to ~ 4 B_{res} and B_{ext} to ~3.5 B_{res}. This new magnetic field configuration will be used to explore possible source performance improvements with higher radial and extraction magnetic fields, especially for the production of the very highly-charged heavy-ion which needs long confinement time that can be enhanced with the magnetic fields of higher mirror ratios.

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II. THE CLOSED-LOOP SEXTUPOLE COIL

Figure 1 shows the closed-loop sextupole coil to be prototyped. It has combined six ~340 mm long Ioffe bars as one coil through continuous winding (closed-loop) and connecting all the end-turn consecutively so that the current flows through each end-turn in the same azimuthal direction. Such a coil end-turn configuration produces substantial axial magnetic fields at both end regions, in addition to the radial field. In contrast, the existing sextupole magnets of SC ECRISs consist of six race-track coils with the end-turn current flowing in alternatively opposite direction leading to zero axial field contribution. This closed-loop sextupole is a hexagonal-shaped coil of length of 520 mm with the Ioffe bars of rectangular cross-section of 90x40 mm^2. To get a better conductor filling, rectangular NbTi (Cu/Sc = 1.35) wires of 1.91x1.23 mm^2 manufactured by Oxford Scientific Instrument will be used to wind the prototype coil. Figure 2 shows the maximum field strengths and profiles of the prototyped coil calculated by TOSCA.

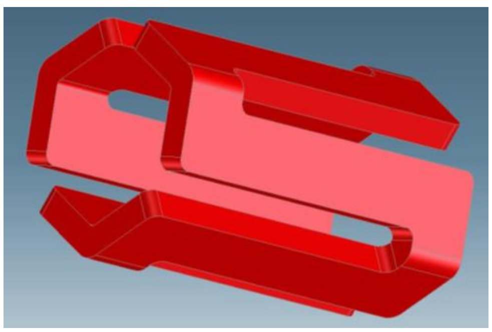

FIG. 1. A 3D view of the closed-loop sextupole coil to be prototyped with rectangular NbTi wires.

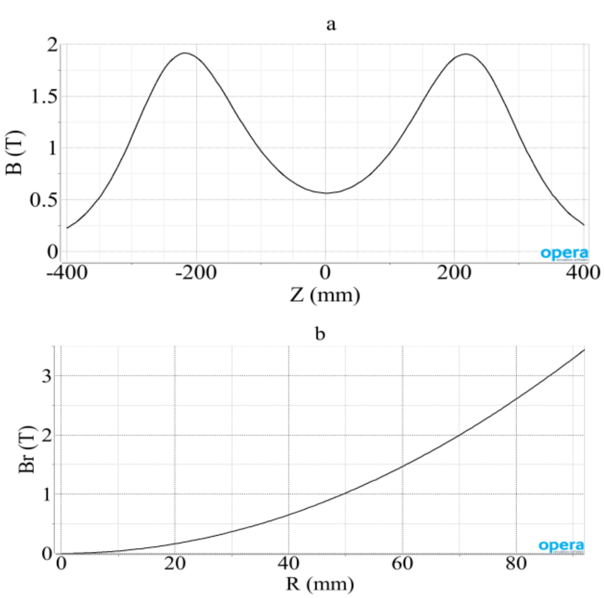

FIG. 2. TOSCA calculations have shown the maximum field profiles of the prototyped closed-loop sextupole coil can reach 1.9 T on axis (a) and up to 3.3 T in the radial poles (b) at a hexagonal plasma chamber wall of major inner radius of 92 mm in the closed-loop coil symmetric plane (z = 0).

III. THE NEW STRUCTURED 18 GHZ ECRIS

With the closed-loop sextupole coil prototyped, a superconducting magnet structure can be constructed by adding three solenoids to build an 18 GHz ECRIS named as "MARS" (Mixed Axial and Radial field System). The radial field and a good portion of the axial field is contributed by the closed-loop coil. The main goal of this new 18 GHz ECRIS is to produce the very highly-charged heavy-ion for the 88-Inch cyclotron to enhance its capability. Figure 3 shows the overall layout of the MARS magnet system in which all the solenoids are located outside the sextupole coil so that the cryostat can be built with a straight-through hexagonal mandrel for simplicity.[1] Like SECRAL, the MARS magnet coils will be enclosed by six cold iron segments (blue colored in Fig. 3) with an aluminum sleeve for field concentrating, pre-stressing and magnet coil clamping.[4]

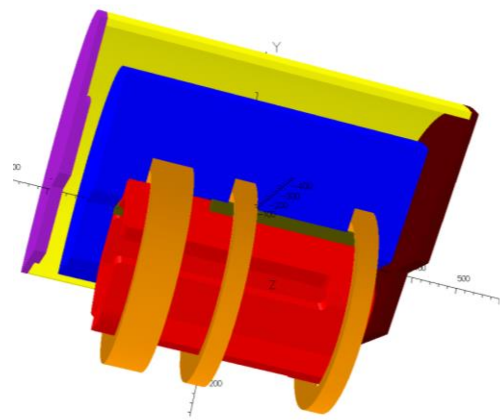

FIG. 3. Illustration layout of the MARS magnet system. The closed-loop sextupole coil is in red and the solenoids are in brown-yellow colors. The rest are the cold mass iron (blue) and the warm iron yoke.

To maximize the magnetic field strength along the sextupole at the chamber inner surface, MARS will be built with a hexagonal plasma chamber of major diameter of 184 mm and minor diameter of 160 mm. Figure 4 shows the calculated axial (a.) and radial (b.) field profiles at maximum and lower excitations. The peak field distance between the injection and extraction is slightly over 400 mm. This leads to a plasma chamber volume of about 9 liters, about the same as VENUS, one of the best ECRISs worldwide.[5] With a more dynamic field range, MARS will be able to generate not only the typical 18 GHz field configuration but also a dustpan-like field configuration in which the radial B_{rad} and extraction B_{ext} will reach up to 3-4 times of B_{res} at 18 GHz for possible longer plasma confinement. Table I lists a few key designed parameters, computed by TOSCA, of the MARS magnet system. Although MARS' magnet system is designed for operation at 18 GHz, it can also be excited to operate at 28 GHz if desired, though the field configuration may not be optimal. If equipped with a cylindrical plasma chamber of ID of 150 mm, MARS could produce essentially the same field configurations as those in VENUS for operations at 18 and 28 GHz.

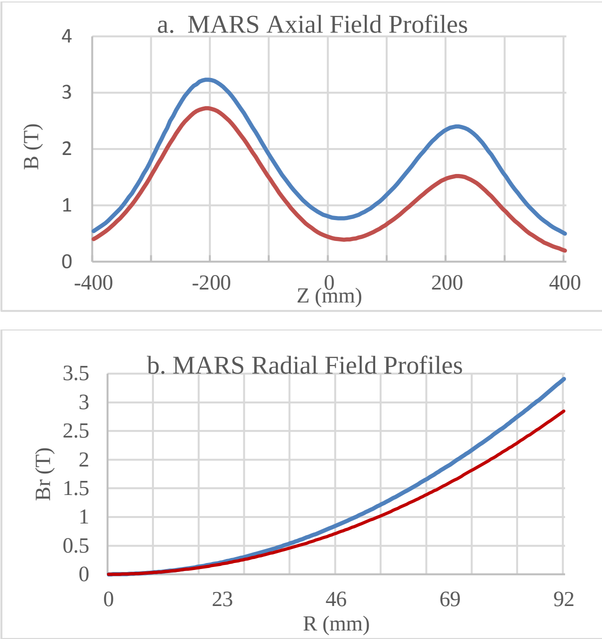

FIG. 4. The MARS' field profiles calculated by TOSCA. Blue color lines indicate the maximum axial (a.) field strength reaching ~ 3.3 T while the radial (b.) field could also reach up to 3.3 T at a hexagonal plasma chamber wall of major inner radius of 92 mm in the closed-loop coil symmetric plane (z = 0). The brown color lines indicate the designed fields for operations at 18 GHz.

Table I. A few calculated key parameters of MARS

Operations (GHz)	18+14	Possible 28+18
Max. B on conductor (T)	6.8	8.3
Maximum Stored E (kJ)	224	370
Force on 1 Ioffe bar (kN)	302	407
Max. Force on 1 end (kN)	208	313
Loading @4.2 K (%)	74	91

IV. SOURCE CRYOSTAT

For easier operations, MARS is to be built of cryogen-free (a dry-magnet system) through direct conduction cooling by three 1.5 W GM coolers. The cryostat structure of a dry-magnet SC ECRIS is simpler and slightly less bulky. If cooling power is sufficient, the dry-magnets can possibly operate below LHe temperature which would yield a slightly higher operation temperature margin that is very favorable for the ECRIS superconducting magnets typically operating at high loadings. Also, a dry-magnet ECRIS is suitable for installation on a HV platform without the costly and complex LHe piping and consumption.

MARS could produce substantially higher radial fields, though its total maximum stored energy is about half of that of VENUS and SECRAL. The magnet coil quench protections are to be located outside the cryostat so that most of the stored energy could be bled to the external diodes when a quench occurs. The goal is to bleed over 90% of the stored energy through external resistivity matching so that the recovery time of the magnet system will be around two to three hours, essentially the same as the LHe bathed ECRISs. Even with substantial iron in the cold mass, the size of the designed MARS cryostat is 820 mm in length and about 950 mm in diameter, thanks to the closed-loop sextupole coil and cryogen-free structure.

V. DISCUSSIONS AND CONCLUSIONS

Development of prototyping a promising new magnet structure for the next generation ECRIS and exploration of a new superconducting 18 GHz ECRIS (MARS) has been described. If successfully developed, the closed-loop sextupole coil could become the main component of the magnet structure for the future SC ECRISs.

Once constructed, MARS will be a test bench for exploring further source improvement with higher mirror fields for the production of the very highly-charged heavy-ion beams. In the present ECRISs with $B_{rad} \sim B_{ext} \sim 2 B_{res}$, the production of the very highly-charged heavy-ion always tend to run B_{ext} as high as possible. However, B_{rad} limits the increase of B_{ext} because increasing B_{ext} intensifies the plasma loss (plasma burning) at the weakest magnetic field regions located on the chamber walls and reduces the extracted beam intensities. Substantial hot electron losses in a very small area on the wall can easily damage or destroy the plasma chamber, which results in poor source long-term reliability. A much higher $B_{rad} > B_{ext}$ could be a good remedy that eliminates the damage to the plasma chamber walls and increases the mirror ratios of the off axis field lines. Attempts to increase B_{rad} in ECRISs optimized with $B_{rad} \sim B_{ext} \sim 2 B_{res}$ so far have resulted in lower source performance, which may be in part due to the reduction of the ECR heating volume. In MARS' dustpan-like magnetic field configuration, the optimized VENUS' ECR heating volume and maximum fields are maintained within the radius of 75 mm, while the increase of B_{rad} is realized by extending the inner radius from 75 to 92 mm. This differs from the existing magnet structures in exploring the potential merits of having a substantially higher B_{rad} at the ECRIS plasma chamber walls.

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