DESIGN, CONSTRUCTION AND COMMISSIONING OF THE SUSI ECR*

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Abstract

An electron cyclotron resonance ion source (ECRIS) was constructed at the NSCL/MSU to replace the existing SC-ECRIS. This ECRIS operates at 18+14.5 GHz microwave frequencies and it is planned an upgrade to 24-28 GHz in the second phase of commissioning. A superconducting hexapole coil system produces the radial magnetic field; the axial trapping is produced with six superconducting solenoids enclosed in an iron yoke to allow tuning the distance between the plasma electrode and resonant zone in the plasma. We report the details of the design, construction and initial commissioning results of this new ECIS.

INTRODUCTION

The National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University operates two cyclotrons in coupled mode in order to produce radioactive ion beams by projectile fragmentation [1]. The primary beam energy is up to 200 MeV/u, and since October 2000 many different primary beams were accelerated between 16O and 238U. The primary ions are produced by two ECR ion sources, one superconducting (SC-ECR) built in the early 90's [2], and the other (ARTEMIS) with room temperature magnets [3] built from a design based on the AECR-U at LBNL [4].

Since commissioning the coupled cyclotrons, the experience gained showed us that the emittance of these ion sources poorly matches the acceptance (about 75 π mm mrad) of the cyclotrons. In order to achieve good transmission from the ion sources to the inflector of the K500 cyclotron, the ion beam has to be collimated strongly, loosing a large fraction of the extracted ion beam from the ion sources. Besides the improvement of the injection beamline focusing elements and bending magnets, a planned upgrade of the existing ECR ion sources extraction systems and further studies to improve the transport efficiency of the injection beamline, the other approach is to build an ECR ion source, which is more flexible than the existing ones in order to better match the emittance of the source with the acceptance of the accelerators. Because the coupled cyclotrons require intense medium charged ions, the emphasis is shifted from the production of very high charge states to medium charge states, but the increased intensities make the effect of the space charge more important than in the previous stand-alone operation mode. Thus, the new ECR ion source with the associated focusing and analyzing system has to be capable of handling total extracted currents of several mA.

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After studying several technical options, we decided that we would design and build the Superconducting Source for Ions (SuSI) capable of operating at 18+14.5 GHz, using fully superconducting magnets.

DESIGN PARAMETERS OF SUSI

According to the currently accepted semi-empirical design criteria [5], an ECRIS should have a magnetic confinement characterized by the following field values: an axial magnetic trap with $B_{inj} \approx 4\ B_{ECR}$ at the injection side, $B_{ext} \approx 2\ B_{ECR}$ at the extraction side, with a minimum magnetic field $B_{min} \approx 0.8\ B_{ECR}$. The radial confinement magnetic field value at the plasma chamber walls should be $B_{rad} \approx 2B_{ECR}$. The extraction magnetic field is also correlated to the radial field through the relationship: $B_{ext} \approx 0.9\ B_{rad}$. The resonant magnetic field value can be obtained from the following equation:

$$\omega_e = \frac{qB_{ECR}}{m} = \omega_{rf}$$

where q is the charge of the electron, m is the mass of the electron, B_{ECR} is the resonant magnetic field value, ω_e is the gyro frequency of the electron and ω_{rf} is the microwave frequency used to heat the electrons in the plasma.

In order to reach these magnetic field values for 18 GHz microwave frequency (B_{ECR} = 0.64 T) and a plasma chamber of 100 mm diameter, it is difficult to use room temperature solenoids and permanent magnet hexapole. It is more convenient to construct a fully superconducting magnet system. This has the advantage of a tunable radial magnetic field, lower electric power consumption for the axial solenoids and no risk of demagnetization of the permanent magnets used in a room temperature hexapole system for the radial confinement. With a superconducting solenoid magnet there is no need for an iron plug in the injection side, leaving more room for different devices necessary to produce metallic beams, for multiple waveguides, bias disk and good vacuum pumping. Considering the existing 2 kW liquid helium (LHe) plant at NSCL, it is not necessary to use cryocoolers and high-T_c superconductor current leads to minimize the LHe consumption, simplifying the design and lowering the initial capital investment.

THE FLEXIBLE MAGNETIC FIELD CONCEPT

The Nakagawa group in RIKEN reported [6] that the extracted beam intensity for a specific ion type depends on the position of the plasma electrode relative to the plasma. In fact, it seems that each charge state of a

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particular ion has an optimum plasma electrode position. Furthermore, as reported by the Koivisto group in Jyväskylä [7] the beam emittance is also influenced by the plasma electrode position. In order to mach the plasma meniscus with the extraction electrode system at a fixed extraction voltage, it is important to have an adjustable puller electrode. It is very difficult to design a plasma electrode system remotely movable inside the plasma chamber. In the SuSI design we adopted a different approach. Because the plasma and the resonant zone location inside the plasma chamber is determined by the magnetic field structure, the other way to change the relative position of the plasma electrode from the plasma is to keep the plasma electrode fixed and move the axial magnetic field. This can be accomplished with two solenoids at each end of the ion source, INJ_1 and INJ_2 at the injection end, EXT_1 and EXT_2 at the extraction end. In order to have the magnetic field minimum easily adjustable, there is a third pair of solenoids between the injection and extraction ends, running electric currents in the opposite direction: MID_1 and MID_2. Each combination of INJ_i, MID_j and EXT_k (i, j, k =1, 2) is capable of producing the required magnetic field profile for optimum operation at 18 GHz.

The advantage of the above solenoid configuration relies in a great flexibility of shaping the axial magnetic field profile. By tuning the current values in the solenoids, a multitude of field configurations can be easily obtained. It is possible, for example to produce a flat-field magnetic configuration necessary for the volume-ECR type ion source [8]. The distance between the magnetic field maxima is variable in the range of 340 to 460 mm; the length of the resonant zone for 18 GHz can be varied between 102 and 154 mm and the whole axial magnetic field profile can be shifted with fixed distance between the two magnetic maxima, equivalent with a plasma electrode movement of about 50 mm.

THE CONVENTIONAL PARTS

Another important finding which influenced our design is the dependence of the ECR ion source output on the bias disc position [9]. It is believed that the length of the plasma chamber is changed by moving the bias disc and by this the coupling between the microwave and the plasma is tuned for better matching. The whole injection hardware is movable without breaking the vacuum, with a stepper motor driven bellows-based mechanism, providing possibility to tune the plasma chamber length. The bias disc is movable also, relative to the traveling flange of the injection hardware, providing maximum flexibility to tune its position relative to the plasma chamber end wall and the axial magnetic field maximum on the injection side.

Because the interest in the production of intense medium charge state ions for the Coupled Cyclotron Facility operation at NSCL, SuSI is designed with a smaller plasma chamber than the other existing superconducting ECR ion sources. The plasma chamber has a 100.8 mm diameter, with a 5 mm wall thickness; the material is aluminum, in order to provide good secondary electron yields. The plasma chamber has two parts and it is water-cooled by three independent helicoidal passages machined on the wall of the inner cylinder. The cooling is capable to remove a total of 4 kW heat injected by the 18 and 14.5 GHz microwave generators. The high voltage insulation was tested to hold voltages above 40 kV. The main ceramic insulator between the plasma chamber and beamline is rated over 60 kV, allowing to keep the ion source at +30 kV and bias the beamline at –30 kV in order to increase the velocity of the extracted ions, decreasing in this way the negative effect of the space charge on the beam emittance. The gas inlet valves are stepper motor driven precision needle valves, with stabilized temperature in order to assure a constant gas flow.

The extraction system is an accel-decel three-electrode configuration similar to the Gyro-SERSE design [10]. In order to match the plasma meniscus with the extraction electrode system at a fixed extraction voltage, it is important to have an adjustable puller electrode. The moving mechanism allows adjusting the extraction gap, without breaking the vacuum. The details of the conventional ion source parts and following ion beam line are given in [11] and [12].

FABRICATION OF THE SUPERCONDUCTING COILS

All of the superconducting coils, both solenoids and sextupoles, were wound from 1 mm x 2 mm NbTi rectangular wire with a Cu/SC ratio of three. The coils were wound using Stycast 2850FT black epoxy using catalyst 11, which requires heat to fully cure. Interlayer insulation included 0.08 mm fiberglass cloth. All coils were wound on forms and then removed before installing into the magnet assembly structure. Single coil tests were done on the coils to give confidence in the quality and to help reduce coil training later when assembled as a magnet. All solenoids are 80 mm wide and have an inside diameter of 300 mm. Of the six solenoid coils needed, the two solenoids at the injection end are larger, these being 460 mm outside diameter before banding and having 2628 turns. The middle and extraction solenoids are 400 mm outer diameter before banding and have 1626 turns. All solenoid coils were wound and cured in an oven, followed by banding with ten layers of 1 mm 3 mm rectangular aluminum wire bonded with Stycast as a construction aid only. Two small solenoids and one large solenoid were tested individually beyond their 400 A operational design current with no training. The small solenoids were taken to 445 A, and the large solenoid was taken to 485 A without quenching.

The hexapole coils are 743 mm long; their turns are far away from the field of the solenoids, to minimize the forces acting on this part of the hexapole coils. One hexapole coil occupies 60º in the azimuthal direction; the cross-section of each side of the coil and that of the pole occupy 20º in azimuth. These coils were wound around a

3-piece core, the central portion being a steel pole piece to enhance the field and the ends being aluminum. This set matches the thermal displacement of the 66 cm long coil to the core. After curing, the coil leads were configured for installation and G-10 end shoes were potted on to give good surfaces for axial restraint. Because coil forces are significantly different when the whole sextupole is assembled only coil quality and information on current at peak field in the coil could be obtained from single coil tests. The operating current for the coils at 18 GHz is 400 A. For the possibility of 28 GHz operation 600 A is required. The first coil tested was trained to 663 A corresponding to a calculated peak field in the coil of 6.3 T where testing was stopped. The remaining tests were stopped at 700–720 A. The last coil tested was taken to 770 A where training reached a plateau.

MAGNET ASSEMBLY

The procedure used to build the magnet system was similar to the Versatile ECR for Nuclear Science (VENUS) ECRIS built in LBNL [13], except for the solenoid bobbin and sextupole radial constraint cylinder being one piece. The VENUS source had the solenoids wound directly on the bobbin and a separate cylinder placed around the banded sextupole. They were both machined to fit closely before inserting the sextupole assembly into the solenoid bobbin. For SuSI we wound the solenoids on forms instead of directly on the bobbin. This allowed the use of one cylinder around the banded sextupole, its wall thickness being sufficient to support the sextupole radial forces. The solenoid coils were stacked around the aluminum solenoid bobbin separated by plates. The SuSI sextupole uses stainless steel bladders between the coils that are inflated after insertion, similar to the VENUS source.

Sextupole Coil Preassembly

The sextupole coils were assembled around the helium vessel bore with welded end flanges. Stainless steel bladders insulated both sides with 0.05 mm Kapton were placed between the coils azimuthally. The end shoes at one end of each coil rest directly against the vessel bore flange. G-10 ground plane insulation was wrapped around the vessel bore to match the space between it and the inner radii of the coils. The coils were clamped radially to the bore with aluminum ring clamps that were tightened at the ends of each coil core. This assembly was then wrapped with 0.5 mm G-10 insulation on the outer diameter between the ring clamps in the area to be banded. This assembly was placed on a fixture in a lathe and the central region banded with 0.4 mm thick 3 mm wide stainless steel rectangular wire wrapped at a helical pitch of 5 mm to clamp the coils to the helium vessel bore. The ends of the banding were secured with a clamp affixed to the ends of one of the coil's core pieces. This then allowed removal of the ring clamps. The coils could not be banded over the area where the coil lead starts into the coil as it sticks outside of that cylindrical surface on one end. This area was therefore left unbanded at both ends. The sextupole assembly prepared for the insertion in the solenoid bobbin bore is shown in Figure 1.

Figure 1. The banded hexapole coil assembly ready for insertion in the solenoid bobbin bore.

Solenoid Coil Assembly

The solenoid coils were stacked on the solenoid bobbin with 0.1 mm Kapton film for ground plane insulation. Two-piece annular plates with machined channels for the coil leads were fitted to grooves in the solenoid bobbin separating the solenoids. The solenoids have a close slip-fit at assembly. The radial loads are carried by the coil structure. In operation they buck against the separator plates and each other under axial loads. A large collar, annularly keyed to the solenoid bobbin, is placed at the end of the last solenoid assembled. Each solenoid coil has a retainer band on each side to assure the aluminum banding does not become loose and spiral off. These bands also double as rotational restraint devices to help keep shearing loads off the coil leads which are in the machined channels of the separator plates. They are pinned to a bar attached to the ends of the solenoid bobbin to complete this structure.

Sextupole Assembly Into the Solenoid Bobbin

The banded sextupole assembly was made to fit tightly into the solenoid bobbin before bladder inflation. This was done through matching the size of the banded sextupole to the inside dimension of the solenoid bobbin to create a size-on-size fit. The solenoid bobbin was then heated to a temperature of 100 °C, the thermal expansion giving the clearance necessary to insert the banded sextupole assembly. The annular end-bladders were then placed and the bladder inflation equipment attached. The magnet system was then heated to 50 °C, the temperature needed to keep the indium alloy fluid. The bladders were next inflated with the indium alloy under pressure to fix them radially within the solenoid bobbin and axially against the ends of the helium vessel bore. A pressure of 10.4 MPa for the azimuthal bladders and 2.6 MPa for the end bladders was used. The indium solidifies after cooling, locking the coils in place. The space left after bladder inflation was not potted with epoxy unlike the VENUS source. The sextupole coil leads are connected in series to a set of G-10 insulated bus rings attached at one end of the solenoid bobbin. A G-10 structure routes the sextupole magnet leads and solenoid coil leads to the current leads. The details of the magnet system testing in a vertical test Dewar were described in a separate publication [14]. The maximum total stored energy in the magnet system was calculated using the inductance matrix and it is the largest (350 kJ) in the case when the distance between the axial maxima is the smallest. The estimated heat load mainly due to the conventional current leads is 5 W, which will result in a 7-liter/h LHe consumption.

MAPPING THE MAGNET SYSTEM

In order to align the magnetic axis of the hexapole system with the geometrical axis of the plasma chamber, we adopted the following procedure. A magnet mapper was constructed consisting three radial transverse Hall probes and a 3-axis Hall probe, placed on a moving mechanism, showed in Figure 2.

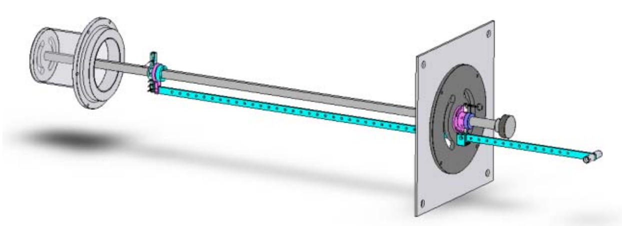

Figure 2. Magnet mapper device

The rotation axis of the mapper coincides with the geometrical axis of the plasma chamber. The mapper can be positioned at six positions corresponding to the 6 poles of the sextupole. The longitudinal position of the probes can be varied in 25.4 mm increments. After the cryostat was installed in the magnet yoke, the cryostat links were adjusted till the longitudinal magnetic field profiles measured with the radial Hall probes coincided at all 6 angles. The result of this field mapping at r=56.2 mm radius is shown on Figure 3, together with the theoretically calculated profile using the AMPERE code [15]. The central field bump is due to the iron insert in the hexapole coil post. There is a very good agreement between the calculated and measured field values.

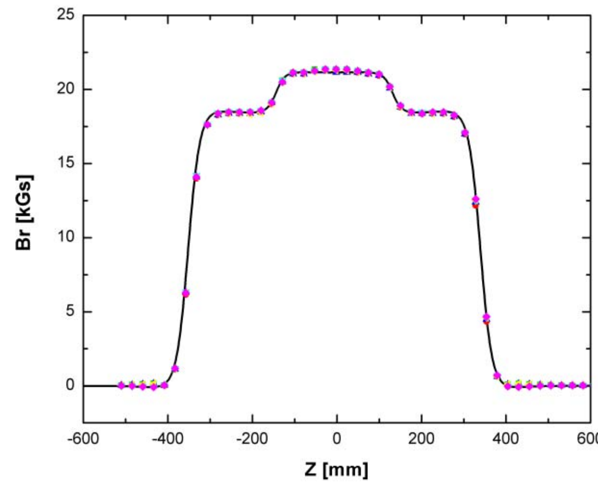

Figure 3. Radial magnetic field measured parallel with the plasma chamber axis at r=56.2 mm radius. Solid line – calculated; colored dots – measured values at 0, 60, 120, 180, 240 and 300 degrees.

Figure 4 shows the measured and calculated magnetic field values for all 6 individually powered solenoid coils at 100 and 300 Amp excitation. The axial magnetic field was measured at r=55.9 mm radius.

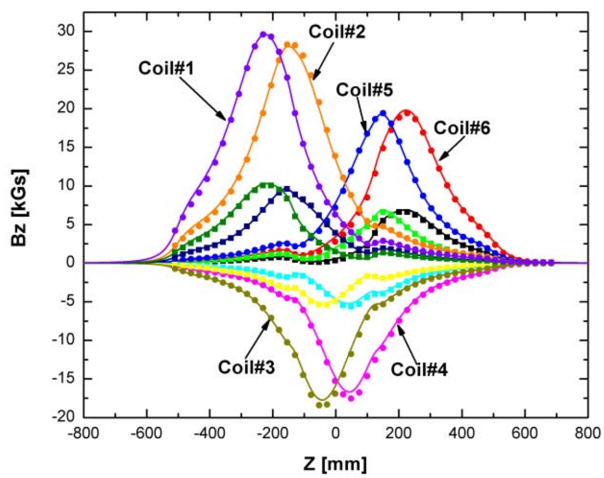

Figure 4. Axial magnetic field profiles of the individual coils excited with 100 and 300 A currents. The field values were measured at r=55.9 mm radius and 0 degrees. Solid lines – calculated, dots – measured.

Figure 5 shows the calculated and measured full axial magnetic field profile in four different configurations: field values optimized for 24 GHz microwave operation and maximum distance between the axial maxima, field values optimized for 18 GHz operation and maximum, minimum and intermediate distance between the axial maxima. The currents in the INJ_1, INJ_2, MID_1, MID_2, EXT_1 and EXT_2 solenoids are also listed in the caption of the figure.

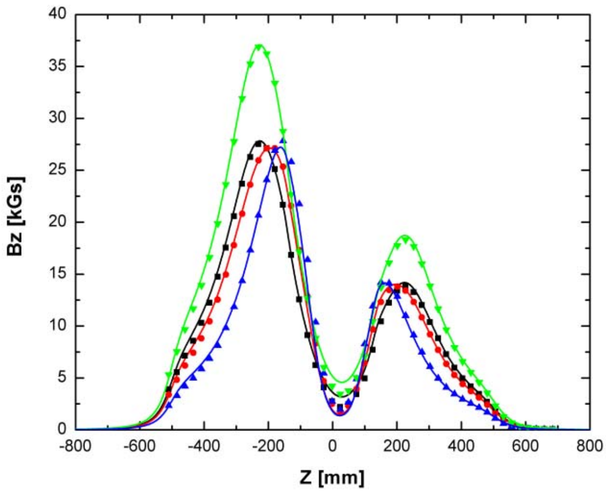

Figure 5. Axial magnetic field profiles at r=55.9 mm radius. Solid lines – calculated, dots – measured. Green – 24 GHz (390, 0, -66, -66, 0, 280 A); black – 18 GHz (290, 0, -50, -50, 0, 210 A); red – 18 GHz (175, 175, -130, -130, 135, 135 A); blue – 18 GHz (0, 390, -220, -220, 320, 0 A)

FIRST COMMISSIONING RESULTS

The first plasma was ignited with the 14.5 GHz microwave generator. The purpose of that test was to check the magnetic confinement, microwave hardware and vacuum system. The base pressure in the injection and extraction boxes is $3x10^{-9}$ and $6x10^{-9}$ torr, respectively. After completion of the high voltage personal safety system and assembly of the test beamline, the first analyzed ion beam was obtained on June 8, 2007. The strong outgassing observed in the initial stage of the commissioning is a normal behavior observed at each ECR ion source built previously by us. Figure 6 shows a charge state distribution measured after the 90° analyzing magnet in a biased Faraday cup.

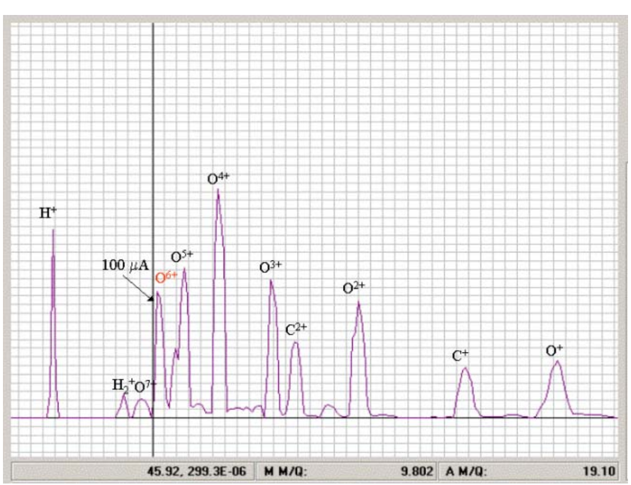

Figure 6. Oxygen charge state distribution. The 18 GHz microwave power was 150 W, 15 kV extraction voltage.

At a modest 150 W of 18 GHz microwave power and 15 kV extraction voltage we were already able to measure over 100 emA of O^{6+} ion current.

Some unexpected magnet quenches prevented us to continue the normal commissioning of SuSI. The nature and origin of these magnet quenches are presently under investigation.

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