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Development of the 3rd Generation ECR Ion Source

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Abstract

The LBNL 3rd Generation ECR ion source has progressed from a concept to the fabrication of a full scale prototype superconducting magnet structure. This new ECR ion source will combine the recent ECR ion source techniques that significantly enhance the production of high charge state ions. The design includes a plasma chamber made from aluminum to provide additional cold electrons, three separate microwave feeds to allow multiple-frequency plasma heating (at 10, 14 and 18 GHz or at 6, 10 and 14 GHz) and very high magnetic mirror fields. The design calls for mirror fields of 4 T at injection and 3 T at extraction and for a radial field strength at the wall of 2.4 T. The prototype superconducting magnet structure which consists of three solenoid coils and six race track coils with iron poles forming the sextupole has been tested in a vertical dewar. After training, the sextupole magnet reached 105% of its design current with the solenoids off. With the solenoids operating at approximately 70% of their full design field, the sextuple coils operated at 95% of the design value which corresponds to a sextupole field strength at the plasma wall of more than 2.1 T.

I. INTRODUCTION

The 3rd Generation ECR source[1] at LBNL is designed to boost the performance of the 88-Inch Cyclotron by providing more intense high charge state heavy-ion beams and to continue working at the cutting edge of ECR (Electron Cyclotron Resonance) ion source technology. Recent results with two-frequency heating, high mirror ratios and enhanced supplies of cold electrons indicate that significant advances in ECR technology are possible.[2-6] To incorporate these ideas into a new 3rd Generation ECR source presents significant technical challenges, but improving ion source performance continues to be a cost effective method to better heavy-ion accelerator performance. ECR ion sources play a critical role in nuclear physics by providing high charge state ions for cyclotrons, linacs, and synchrotrons. For example, the relativistic heavy-ion program at CERN relies on an ECR ion source to produce high charge state lead beams. The next generation of ECR sources with increased high charge state intensities and improved pulsing capabilities might be utilized to improve the luminosity of relativistic heavy ion colliders such as RHIC at Brookhaven National Lab.

At LBNL the 88-Inch Cyclotron can accelerate elements up to mass 160 with sufficient energy and intensity for nuclear structure experiments such as those now utilizing Gammasphere.[7] With the 3rd Generation ECR ion source to increase the usable mass range up to uranium, new scientific opportunities can be provided to the nuclear science research programs. For example, using very heavy ion beams to produce compound nuclei far from stability and study them with state of the art gamma-ray detectors such as Gammasphere or proposed detectors such as the Gamma Ray Energy Tracking Array (GRETA). Another research area which could benefit from higher intensities is the study of the nuclear and chemical properties of heavy elements using a the Berkeley Gas-filled Separator now under construction. The optimum production of these low cross section reactions will require high intensity beams at about 7 MeV/nucleon from the cyclotron for elements with masses between 30 and 70.

II. MAGNET DESIGN

The design of the 3rd Generation ECR including the magnet assembly and iron yoke is illustrated in Fig 1. In Table I, the geometry and field strengths of magnet structure are given. These fields are considerably greater than those of earlier superconducting ECR ion sources and early in the initial design study, it became clear that most critical technology centered on the design, fabrication and performance of the superconducting coils. The acquisition of surplus superconducting wires from SSC made it feasible to build a prototype magnet as an R&D project. Therefore it was decided to build and test a prototype magnet. The project is a collaborative effort with Nuclear Science Division and the Supercon group in the Accelerator and Fusion Research Division.

Calculations using the three dimensional code, TOSCA, were used to design the superconducting magnet structure and evaluate designs to support the coils against the inter–coil forces. One of the unique features of this magnet design is the use of iron poles in the superconducting sextupole structure which increase the maximum sextupole field by 15% and decrease the axial field in the center region. A cross section view on one of the sextupole coils with the iron pole tip is shown in Fig. 2. The 80 cm long poles which are a permanent part of each coil, have 35 cm of iron in the center and non-magnetic stainless steel ends as indicated in Fig 1. The magnetic interaction between the sextupole coils and solenoid coils results in very large forces, particularly at the sextupole ends. Forces on the conductor were calculated for design fields with the sextupole overall current density of 200 A/sq. mm. The total radial forces on the coil ends alternate outward and inward due to the interaction with the solenoid fields and at the injection end are 37.5 kN and 25.0 kN, respectively. The end of the sextupole was extended 15 cm in axial direction away from the stronger injection mirror coil to reduce the forces. The forces on the ends of the sextupole coils at the extraction end are 32.4 kN outward and 16.5 kN inward.

All of the superconducting magnets were wound at Wang NMR, Inc. using 48 Km of surplus superconducting wire from the SSC project. The sextupole has 0.8 mm diameter NbTi wire insulated with 0.05 mm Kapton tape. Each coil was wound and vacuum impregnated using tooling that results in a precise I.D., O.D., and an azimuthal arc of 60 degrees. The ends of pole pieces were shaped to facilitate layer winding of the 1677 turns. The six coils were assembled on a 200 mm o.d. bobbin with appropriate ground plane insulation. The assembled and insulated coils were then wrapped with 3 mm of stainless steel wire to provide radial support.

III. MAGNET TESTS

The prototype coil assembly consisting of the sextupole and three solenoid coils along with the quench protection circuitry was mounted on a vertical fixture so that it could be tested in a 20 inch ID helium dewar. The coils were powered by four 250 A 10V power supplies which were manually controlled. The voltage across each was monitored by a AstroMed dash 10 multichannel recorder.

Initially each solenoid coil and the sextupole was individually trained to determine its inherent performance and then the magnets were tested in a combined mode. The training results are summarized in Table 2. After more than 40 quenches, the sextupole trained up to 154 amps which is 104% of its design current. This corresponds to a maximum radial field at r=80 mm (approximate inner radius of the magnet warm bore) of 2.7 T and at r=75 mm (design radius for the plasma wall) of 2.38 T. Solenoid 1 (at the injection end) went to 64 amps or 71% of its design field in a relatively small number of quenches but did not train to higher fields. Solenoid 2 (at the extraction end) trained to 85 amps which was 103% of design current and solenoid 3 (at the mid plane) trained to 87 amps, 145% of its design value.

The main focus of the combined tests with all coils powered was to study the interaction of the solenoid field on the sextupole. Since solenoid 1 did not reach its design value in the individual tests it was set to a lower value for these tests. In the combined, tests solenoids 1 and 2 were set to 50 and 66 amps, respectively which produces peak mirror fields at injection and extraction of about 2.3 T and solenoid 3 was set to 42 amps which is roughly 70% of the design value and corresponds to the average percentage of the design values used for solenoids 1 and 2. With the solenoids in operation, the sextupole initially quenched at 60 amps, but then trained up to 139 amps which is 95% of its design value. This corresponds to a sextupole field strength of at the radius of the plasma wall of 2.16 Tesla.

On the basis of the test results we believe that the training behavior of the sextupole is due to movement of individual coils caused by the Lorentz forces. The most probable explanation is that the thermal contraction of the sextupole coils was sufficiently large to reduce the prestress on the coils when they were cooled the liquid helium temperature. The coils were dry wound, then vacuum epoxy impregnated before being assembled on a steel bore tube. Heavy aluminum clamping rings were used to clamp the end coils where there are large radial forces. In the center sections the coils were wrapped with stainless steel wire and glass epoxy. After cooling the center sections may have been poorly constrained in the azimuthal direction due to thermal contraction and this made macroscopic movements of the coils possible. A 1" cube of the superconducting wire epoxy assembly from a spare sextuple coil was used to measure the thermal contraction from 293° K to 77° K. In the direction parallel to the wire strands the contraction was .28%, in the direction normal to the interlayer glass (azimuthally on coil assembly) the contraction was .674% and in the direction normal to the wire strands and parallel to the interlayer fiber glass the contraction was .491%.[8] The comparable numbers for copper and aluminum are .274% and .395%, respectively. This indicates that particularly in the azimuthal direction there may have been insufficient stress to restrain the coils. More detailed finite element calculations are underway and a concept for providing greater prestress is being developed. We plan to disassemble the prototype magnet and test a new technique for prestressing the sextupole sufficiently so that the magnet can reach its design field with minimal training. This may require increasing the ID of the sextupole coils, in which case a new set of solenoid coils will be fabricated to replace the prototype coils.

IV. ECR COMPONENTS

Shown in Fig. 1 is an elevation view of the ECR source. The helium supply dewar which is designed to sit vertically above the source is not shown. The plasma chamber walls, injection and extraction plate will be made from aluminum to provide a source of cold electrons for the plasma. This technique has been developed and tested on the LBNL AECR. In addition to the favorable secondary emission properties of the aluminum wall which come from the formation of Al_2O_3 on the surface, the aluminum is very resistant to plasma etching. This reduces contamination in the plasma of ions from the wall and the etching of the extraction electrode. The plate shown on the injection end of the plasma chamber will be biased to act as a bias probe. Water cooling of all surfaces in contact with the plasma is also planned to minimize the temperature effects caused by plasma and microwave heating at high power. The relatively large plasma chamber diameter, 15 cm, provides sufficient space to bring in 3 or more off-axis microwave feeds as well as ovens for the production of ions from solid feeds. Up to 10 kW of microwave power at frequencies of 6, 10 and 14 GHz or 10, 14 and 18 GHz are being considered. Recent experience with the AECR-U shows that with sufficient magnetic confinement it is possible to operate ECR sources at high power density and low pressures[6] and since the volume of the 3rd Generation ECR is about a factor 10 larger than the AECR-U it may require 10 kW to reach optimum performance. Pumping will be provided by a turbo pump at the injection end through holes in the injection plate designed to reflect the microwave power. Detailed mechanical design of the cryostat, plasma chamber and other components will begin in fall of 1997 with initial tests are expected in about 1 year.

ACKNOWLEDGMENTS

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[8] K. Chow, LBNL Engineering Note, SCMAG-599

Table I. Design characteristics of the prototype superconducting magnet structure.

I.D. of plasma chamber	15 cm
Mirror field on axis	4T, 3T
Mirror-mirror spacing	50 cm
Central field (variable)	0 to 1.0 T
Max. radial field, plasma wall	2.4 T
Min. field, plasma wall	2.0 T

Table II. Summary of coil tests.

	Sext.	Sol-1	Sol-2	Sol-3
Design current (A)	146	89.6	82.5	59.8
Individual tests				
Max. current (A)	152	64	85	87
Percent of design	104%	71%	103%	145%
Combined tests				
Current (A)	139	50	66	42
Percent of design	95%	56%	80%	70%

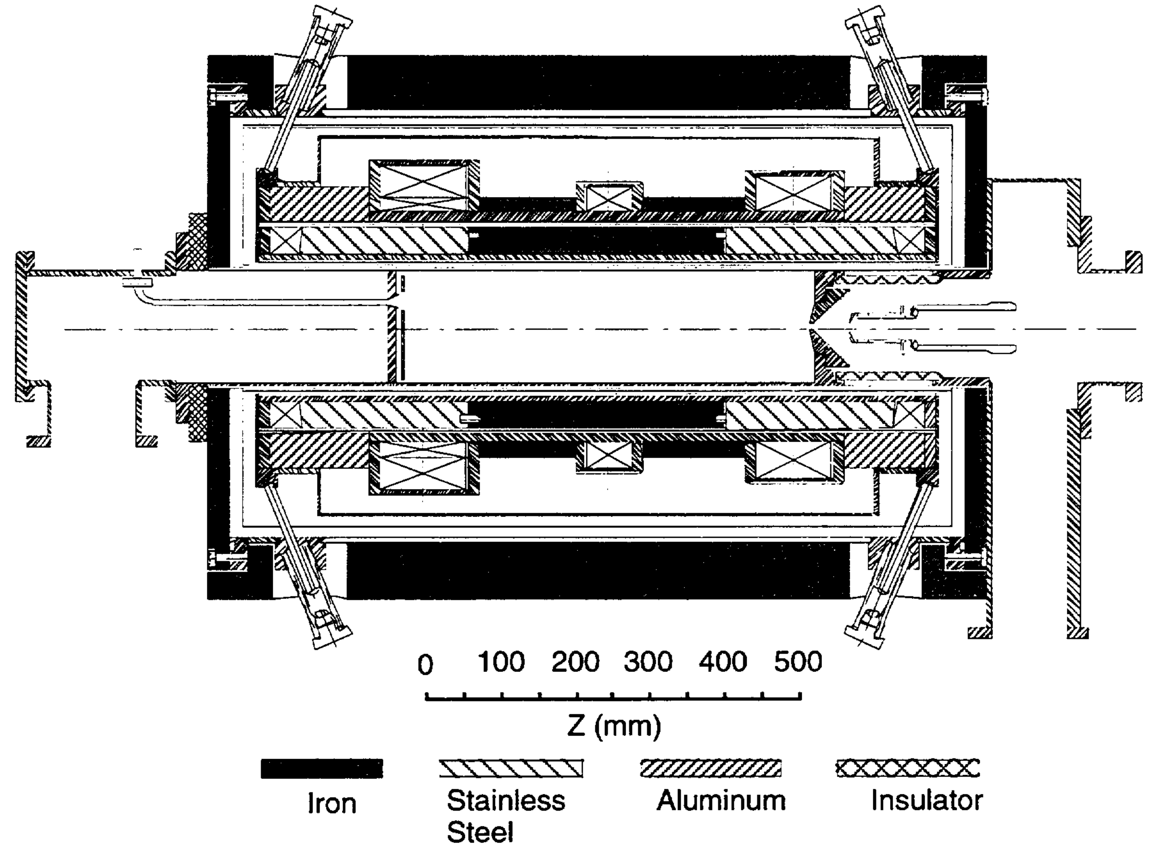

Fig. 1 An elevation view of the 3rd Generation ECR source including the iron yoke, coils and plasma chamber.

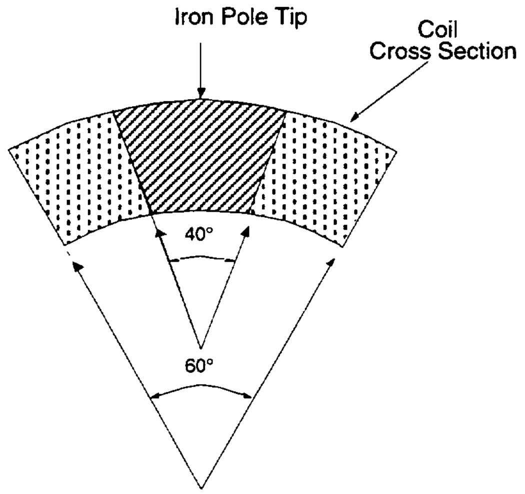

Fig. 2 shows the cross section of the one sextupole coil with the iron pole tip.