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Production of High Charge State Ions with the Advanced Electron Cyclotron Resonance Ion Source at LBNL

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ABSTRACT

Production of high charge state ions with the Advanced Electron Cyclotron Resonance ion source (AECR) at Lawrence Berkeley National Laboratory (LBNL) has been significantly improved by application of various new techniques. Heating the plasma simultaneously with microwaves of two frequencies (10 and 14 GHz) has increased the production of very high charge state heavy ions. The two-frequency technique provides extra electron cyclotron resonance heating zone as compared to the single-frequency heating and improves the heating of the plasma electrons. Aluminum oxide on the plasma chamber surface improves the production of cold electrons at the chamber surfaces and increases the performance of the AECR. Fully stripped argon ions, ≥ 5 enA, were produced and directly identified by the source charge state analyzing system. High charge state ion beams of bismuth and uranium, such as $^{209}Bi^{51+}$ and $^{238}U^{53+}$, were produced by the source and accelerated by the 88-Inch Cyclotron to energies above 6 MeV/nucleon for the first time.

To further increase the production of high charge state ions to support the nuclear science research programs at the 88-Inch Cyclotron, an upgrade is taking place to increase the AECR magnetic field strengths and mirror ratios to improve the plasma confinement. Conceptual design is underway for a 3rd Generation ECR that uses superconducting magnets to reach higher magnetic field strengths and higher mirror ratios, high secondary emission chamber walls to increase the yield of cold electrons at the chamber surfaces and microwaves of multiple frequencies to improve plasma heating.

I. INTRODUCTION

Since the LBL ECR ion source began operation with the 88-Inch Cyclotron in 1985,[1] ECR source development has played an important role in providing new capabilities for the cyclotron and new scientific opportunities for nuclear science research. Source development has focused on increasing the production of high charge state ions and producing a wide range of beams using solid feeds. One measure of the successful production with solids is that all 30 elements from hydrogen to zinc along with 10 heavier elements have been ionized in the ECR sources and accelerated by the cyclotron. The Advanced ECR ion source was completed in 1990 and it operates at 14 GHz and substantially high magnetic field than its 6.4 GHz predecessor.[2,3] Since it began operation it has served the dual roles of providing higher charge state beams for experiments requiring higher beam energies and as a development source.[4,5] Two developments with the AECR source described below have resulted in significant performance gains. These are two-frequency heating and the addition of an aluminum oxide from an aluminum liner to the plasma chamber or an all aluminum plasma chamber. Two additional aspects of ECR developments at LBNL are also described below. First, a project to upgrade the AECR source by increasing the magnetic confinement and installing an all aluminum chamber is underway. Second, a 3rd Generation ECR ion source utilizing superconducting coils to provide very high axial and radial magnetic fields along with multiple-frequency heating is being designed.

II. TWO-FREQUENCY HEATING

In an ECR source, the electrons are heated in a thin zone at the ECR surface as they spiral back and forth between the magnetic mirrors. If microwave power at a single frequency is used then only one egg shaped ECR heating zone will exist. If two significantly different frequencies that match the minimum B-field are used, two well separate ECR surfaces in the ECR plasma can be produced . Electrons will then be heated at both surfaces and that could lead to a higher population of the energetic electrons and enhanced production of high charge state ions. A higher number of closed ECR shells could be produced if microwaves at several frequencies are simultaneously injected.

Although some ECR sources use a second microwave frequency to drive an injector stage, the plasma in the main stage where the highly charged ions are produced is typically heated by single microwave frequency. Tests with the AECR indicate that using two well separated microwave frequencies can enhance the high charge state performance. This is in contrast to an earlier test done in Grenoble using two slightly different frequencies to simultaneously heat an ECR plasma which did not indicate any advantage in using two frequencies.[6]

The AECR source was modified for these tests so that both 10 and 14 GHz microwaves could simultaneously be injected into the plasma chamber. A second waveguide was coupled to the plasma chamber so that the 10 GHz microwave could be launched with the electric field vector at 90° with respective to the 14 GHz microwave brought in by another waveguide. Very little power was coupled from one wave guide to the other through the plasma chamber. To eliminate microwave interactions, isolators were installed between the AECR and the klystrons. The magnetic field shape of the AECR source was adjusted to provide a closed ECR resonance surface at 10 GHz in addition to the one at 14 GHz. Schematically shown in Figure 1 are the ECR surfaces used to produce uranium ions and it clearly indicates that the ECR surface at 10 GHz is well separated from and nested inside the one at 14 GHz.

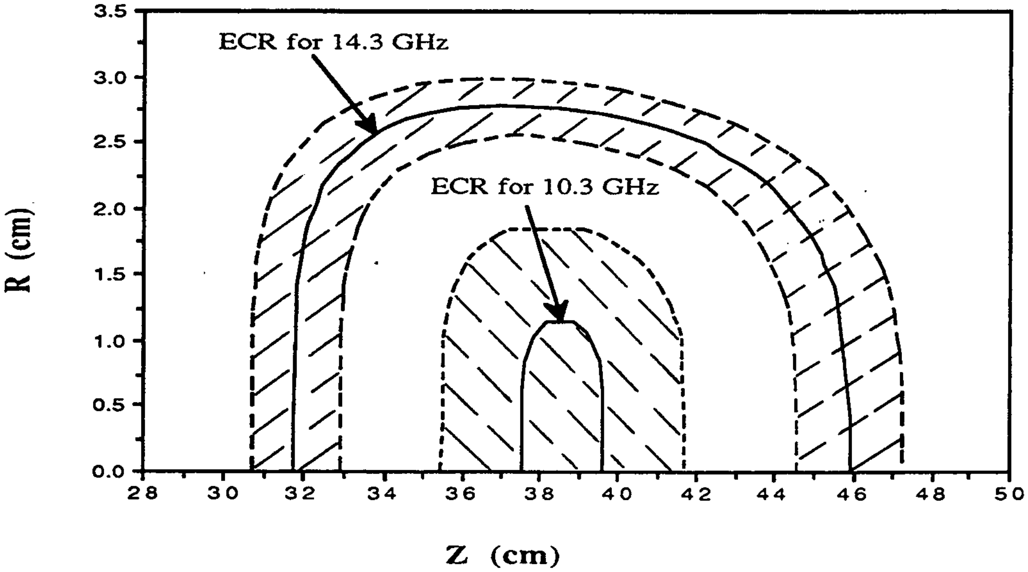

Fig. 1. Calculated heating zones (hatched regions), assuming the electrons have 2 keV energy along the field lines, for 10.3 and 14.3 GHz in the AECR source with the magnetic field configured for the best performance on uranium. It indicates that there are two well separate heating zones in the AECR plasma.

The plasma chamber was coated with Al_2O_3 about one month before this test.[7] With this two-frequency heating the AECR plasma was more quiescent than single-frequency heating. The short-term and the long-term plasma stability were both improved and more total microwave power could be launched into the plasma. The AECR could be operated with reduced gas input which indirectly indicates operating at lower neutral pressures since the mechanical pumping speed is the same. The production of the very high charge state ions is greatly enhanced. Fully stripped Ar ions, at least 5 enA ($\geq 1 \times 10^9$ pps), were directly identified by the AECR charge state analyzing system for the first time. With the same source conditions as compared to the case of single-frequency heating, such as gas, vapor inputs and total microwave power, the peak charge state for bismuth shifted from 32+ to 33+ and up to a factor of 2 increase on the intensity for charge states from 36+ to 40+. With 15% more microwave power, the two-frequency heating shifted the peak charge state for uranium from 33+ to 36+ and increased the intensity by a factor of 2 to 4 for charge states from 35+ to 39+. Increases up to an order of magnitude for the very high charge state of bismuth and uranium ions were achieved. High charge state bismuth ions up to 51+ and uranium ions up 53+ were produced by the AECR source and the 88-Inch Cyclotron accelerated these very heavy ions to an energy surpasses the Coulomb barrier for the first time. After acceleration to an energy above 6 MeV/nucleon, the extracted beam intensities for Bi^{51+} and $^{238}U^{53+}$ were a few to tens of epA ($\geq 1 \times 10^6$ pps).[5]

III. TESTS WITH AN ALUMINUM CHAMBER SURFACE

The basic physics of an electron cyclotron resonance (ECR) ion source involves coupling microwave energy to plasma electrons confined by a magnetic bottle which then produce singly or multiply charged ions by electron impact ionization. The neutrals and ions are mainly stepwise ionized by electron impact ionization and the ionization process provides the primary electrons to compensate the escaped electrons to maintain a dynamic equilibrium plasma in which the plasma loss is electrically neutral. Early experiments on ECR sources demonstrated that adding extra electrons to the ECR plasma with a microwave-driven first stage or by using electrons emitted from the plasma chamber walls coated with materials of high secondary electron emission can substantially enhance the production of high charge state ions.[8,9] Since the AECR source was built, we have explored various techniques to provide more electrons for the plasma. The early methods used, such as coating the plasma chamber walls with SiO_2 or Al_2O_3 and using an electron gun to axially injecting electrons to the plasma, substantially enhanced the performance of the AECR source.[3,7,10]

Enhanced production of high charge state ions due to the aluminum oxide wall coating has been demonstrated in various ECR sources.[7,11,12] Empirically speaking, a good chamber surface should have high secondary electron emission, long lifetime in against plasma etching and low material sticking coefficients to minimize the surface memory. Aluminum oxide not only has high secondary emission but it is also very resistant to plasma etching. The aluminum oxide coating, done by running an aluminum plasma, did not entirely cover all the chamber copper surfaces in the AECR source and only had about one month lifetime. The relatively short lifetime poses problems for use with the cyclotron so an all aluminum plasma chamber was built. Tests with the aluminum plasma chamber in the AECR source were delayed due to insufficient cooling. As short term alternative a 0.38 mm thick aluminum liner was installed in the copper plasma chamber. The initial tests with this aluminum liner and two-frequency heating were very promising. An increase of up to 60% in beam intensity of the high charge state ions was achieved as shown in Table I. With this technique the AECR source has produced 210 eμA of O^{7+}, 238 eμA of Ar^{11+}, 4.7 eμA of Ar^{16+}, 33 eμA of Bi^{28+} and 14 eμA of Bi^{34+}. Unfortunately one segment of the aluminum liner melted during source tuning. After the melted segment of aluminum liner was removed, gold ions were tuned and 22.5 eμA of Au^{26+}, 10.3 eμA of Au^{30+} and 1.0 eμA of Au^{34+} were produced. Very recently, the all aluminum chamber was installed with improved thermal cooling and run with microwave power limited to 1.2 kW which is 60% of the maximum input. Under these conditions, tests with gold showed an increase up to a factor of 5 for high charge state gold ions compared to earlier tests with a partial aluminum liner. As shown in Table I, 41.7 eμA of Au^{24+}, 34 eμA of Au^{26+}, 14.3 eμA of Au^{30+}, 3.5 eμA of Au^{34+} and 1.3 eμA of Au^{36+} were produced with the all aluminum chamber. Although the tests will continue, these results have shown aluminum walls in the plasma chamber enhance the production of high charge state ions.

Table I

Preliminary Results of the AECR Source with An Aluminum Chamber Surface

Q	I (eμA) a	Q	I (eμA) b
$^{16}O^{6+}$	**510**	$^{197}Au^{24+}$	**41.7**
$^{16}O^{7+}$	**210**	$^{197}Au^{26+}$	**34**
$^{40}Ar^{11+}$	**238**	$^{197}Au^{29+}$	**20**
$^{40}Ar^{12+}$	**158**	$^{197}Au^{30+}$	**14.3**
$^{40}Ar^{13+}$	**84**	$^{197}Au^{31+}$	**10**
$^{40}Ar^{14+}$	**47.5**	$^{197}Au^{32+}$	**6.6**
$^{40}Ar^{16+}$	**4.7**	$^{197}Au^{34+}$	**3.5**
$^{209}Bi^{28+}$	**33**	$^{197}Au^{35+}$	**2.4**
$^{209}Bi^{31+}$	**26**	$^{197}Au^{36+}$	**1.3**
$^{209}Bi^{34+}$	**14**	$^{197}Au^{38+}$	**0.4**
$^{209}Bi^{36+}$	**6.6**		

Note: **a** -- With an aluminum liner and two-frequency heating.
b -- With an aluminum chamber and two-frequency heating.

All ion beams are extracted at 10 or 15 kV extraction voltage and through an 8 mm aperture. Currents are measured with the Faraday cup biased at 150 V to suppress the secondary electrons.

IV. AECR UPGRADE

The maximum axial field strengths of the AECR source are 1.0 Tesla at the injection region and 0.7 Tesla at the extraction region respectively. Because slots are used between NdFeB sextupole bars to provide pumping and radial oven access, the maximum radial field strength is only 0.64 Tesla at the plasma chamber walls.[2] The maximum values of the axial and the radial fields of the AECR source are lower than some of the ECR sources operating at 14 GHz. However techniques such as aluminum walls and two-frequency heating provides performance comparable or better than other higher field 14 GHz sources. Further improvement appears possible by increasing the strength of its magnets to improve the plasma confinement.

An upgrade of the AECR is underway to modify its magnetic structure and raise both its peak magnetic field strengths and the mirror ratios. Shown in Figure 2 is a schematic view of the expected axial field profile. The existing solenoid magnets will be replaced by new ones with larger conductors and the maximum current density will increase from 740 A/cm^2 to 950 A/cm^2. The thickness of the iron return yoke will be doubled (from 3 cm to 6 cm) and iron plugs will be used to concentrate the magnetic flux inside the plasma chamber. With these modifications and at the same total dc magnet power of 75 kW as the existing configuration, the peak field strengths at the injection and the extraction regions will increase about 70%. The central field strength will remain the same which produces mirror ratios of 4.1 at injection and 3.0 at extraction. The new plasma chamber will be made from aluminum to increase the yield of secondary electrons. The wall thickness will be reduced and a new sextupole magnet constructed with stronger NdFeB permanent magnets to increase the radial magnetic field at the wall from 0.64 to 1.0 Tesla. Plasma in this upgraded AECR source will be heated by microwaves of 10 and 14 GHz.

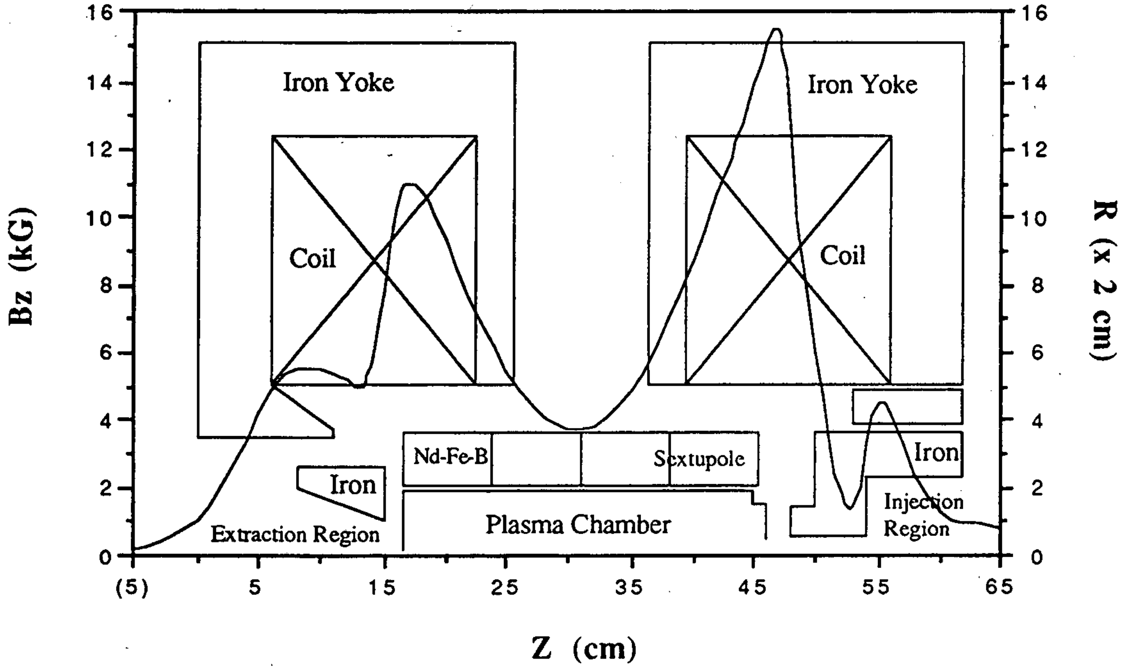

Fig. 2. The conceptual design of the upgraded AECR source with the axial magnetic field profile superimposed. At dc power of 75 kW and with iron plugs to concentrate the field flux, the maximum peak field strengths on axis will reach 1.5 and 1.1 Tesla at the injection and extraction region, respectively. In addition, a set of new NdFeB permanent sextupole magnet will increase the maximum radial field strength at the wall to 1 Tesla.

V. THE 3RD GENERATION ECR SOURCE

ECR source development, especially in the last few years, indicates that further enhancement on the production of high charge state ions by ECR sources is possible with higher field strengths and higher magnetic mirror ratios,[13] chamber surface with high secondary emission materials and heating the plasma with multiple frequency microwave power.

Although with the high charge state ions produced by the AECR using two frequency heating the 88-Inch Cyclotron has accelerated bismuth and uranium to energies of 6 - 7 MeV/nucleon, the extracted intensities of the order of 10^6 to 10^7 particles per second were too low for most of the nuclear experiments. Therefore a new 3rd Generation ECR source is being designed with the goal of producing the high charge states and intensities needed for nuclear physics experiments above the Coulomb barrier for heavy elements such as bismuth and uranium. The solenoid and sextupole magnets of this new source will be made from superconductor to achieve higher magnetic field strengths and high mirror ratios. Shown in Table II are some main parameters of the ECR source with mirror ratios of 15 at injection and 10 at extraction. A thick iron yoke and iron plugs are used to enclose the solenoid magnets to concentrate the magnetic flux inside the plasma chamber and reduce the stray field outside the source. Besides the highest field strength ever designed for an ECR source, a novel feature under consideration for this source is to use iron poles and a thin return yoke to boost the maximum sextupole field strength at the chamber walls as schematically shown in Figure 3. Preliminary calculations have shown that the maximum sextupole field strength at the chamber surface can be increased by about 20% with the iron booster even if it is saturated at a high magnetic field environment. The plasma chamber will be made from aluminum or better materials to yield more secondary electrons. The minimum-B field geometry in this source will be able simultaneously to provide closed ECR surfaces for 10, 14 and 18 GHz or higher for heating the plasma with multiple frequencies.

The 3rd Generation ECR source will have great flexibility in both on the axial and radial magnetic field strengths which should not only provide peak performance but the opportunity to explore the effects of the axial and magnetic field strength and configuration on the production of high charge state ions.

Table II. Parameters of the 3rd Generation ECR Source

$B_{\text{on axis}}$	
$B_{\text{injection}}$	≤ 4.5 T
$B_{\text{extraction}}$	≤ 3.2 T
B_{min}	0.3 T (variable)
B_r at wall	≤ 2.5 T
Plasma chamber dia.	160 mm
Main coil separation	500 mm

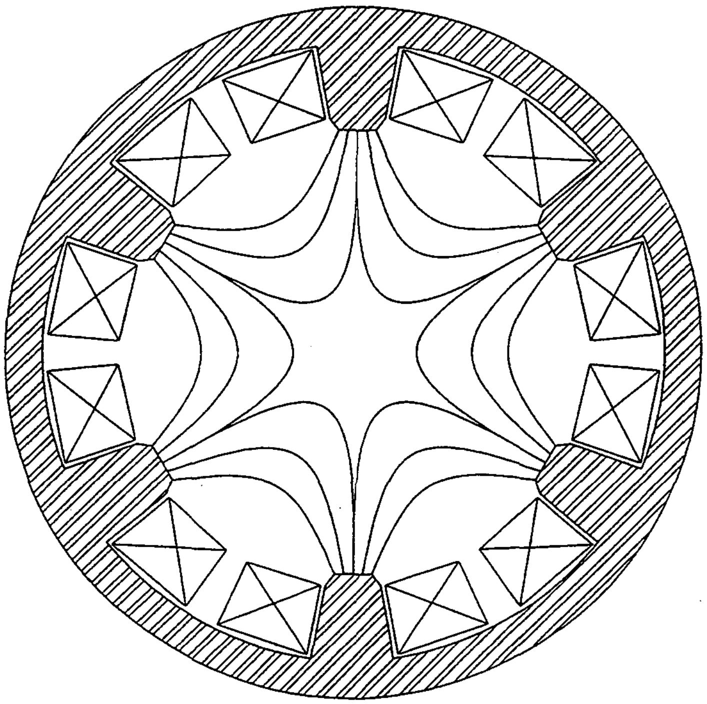

Fig. 3. A schematic cross-section view of the superconducting sextupole magnet of the 3rd generation ECR source with iron poles and a thin return yoke (hatched area) to boost the maximum radial field strength.

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