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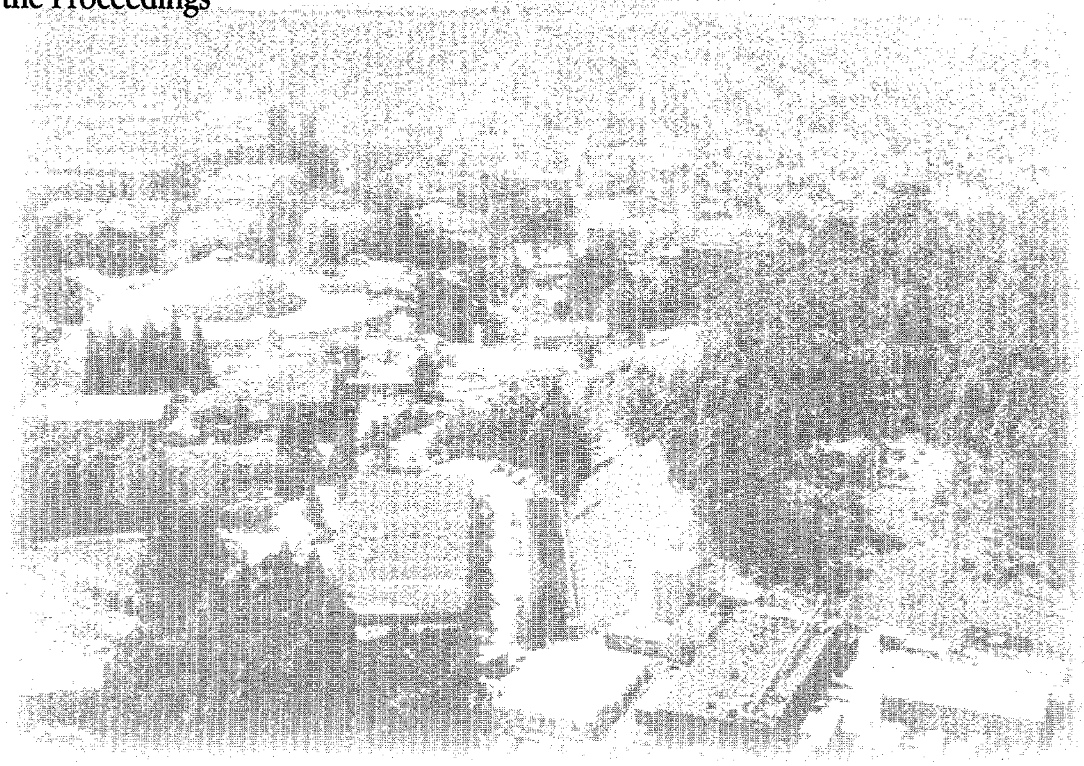

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Performance of the Upgraded LBNL AECR Ion Source

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Abstract

The LBNL AECR ion source has been upgraded in July 1996 by increasing its magnetic fields to improve its plasma confinement and thereby enhance the source performance. After a few months of tailoring the magnetic field configuration to match the two-frequency plasma heating (14 and 10 GHz), the upgraded AECR ion source (AECR-U) with its higher magnetic fields and higher magnetic mirror ratios has demonstrated significantly enhanced performance. For heavy ions at intensity of about 1 eμA, the charge state was shifted from 42+ to 48+ for uranium and from 41+ to 46+ for bismuth. An order of magnitude enhancement for fully stripped argon ions ($I \geq 60$ enA) also has been achieved. Hydrogen-like krypton ions at intensity of about 10^5 pps were extracted from the source and confirmed by measuring its characteristic x-ray with a SiLi crystal detector. High charge state heavy ion beams of xenon-136 and uranium-238 produced with the AECR-U ion source were accelerated by the 88-Inch Cyclotron. Despite poor transmission for the highly charged heavy ions due to vacuum losses in the cyclotron, 11 MeV/nucleon $^{136}Xe^{41+}$ at $1x10^7$ pps, 13 MeV/nucleon $^{136}Xe^{46+}$ at a few hundred pps, and 7 MeV/nucleon $^{238}U^{55+}$ at $3x10^4$ pps and 8 MeV/nucleon $^{238}U^{60+}$ at a few pps were confirmed with a crystal energy detector after extraction from the cyclotron. The total energy of 1.935 GeV of the extracted $^{238}U^{60+}$ ions is the highest energy ever produced by the 88-Inch Cyclotron. Detailed optimization of the AECR Upgrade will be presented in this paper.

Introduction

Although the LBNL AECR ion source had lower magnetic fields than other 14 GHz ECR sources such as Caprice-14 GHz and ECR4, it produced record beams for many high charge state heavy-ion beams.[1,2] Two factors which contributed to its performance were the use of two-frequency heating[2] and aluminum oxide coatings on the plasma chamber walls.[1] In recent years, several groups have reported improved performance as a result of using stronger magnetic fields which provide better plasma confinement.[3-6] We therefore decided to upgrade the AECR source by increasing both its radial and axial magnetic fields.[7]

With the ion beams provided by the AECR source prior to its upgrade, the 88-Inch Cyclotron could already produce a wide range of beams and intensities. For nuclear structure experiments which require about 1 particle nA at about 5 MeV/nucleon, the heaviest usable mass was about 160.[8] The goal of the upgrade was to increase the mass range of heaviest beams and to increase the intensities of lighter beams thereby providing new research opportunities at the cyclotron.

Source Upgrade

While the overall design of the AECR-U is similar to its predecessor, there are some significant differences. Shown in Figure 1 is an elevation view of the current configuration of the AECR-U source. The source axial length was shortened 20 cm by eliminating the space set aside in the earlier design for a microwave-driven first stage. The iron yokes are thicker which adds 5 cm to their outer diameter. Each magnet consists of 9 double-layer pancakes made from larger hollow core copper conductor of diameter of 7.94 mm. These 9 pancakes are divided into 3 subgroups and each subgroup is driven by a pair of 300A/33V dc power supplies to provide a maximum current of 600 Amps. Iron plugs are used in both the injection and extraction regions to shape the magnetic field flux in the plasma chamber. The maximum axial peak magnetic fields increase from 1.0 to 1.7 Tesla at injection and from 0.7 to 1.1 Tesla at extraction with no increase in ac power. While the center field remains at about 0.4 Tesla, the maximum mirror ratios increase from 2.4 to 4.3 at the injection side and from 1.8 to 2.8 at the extraction aperture.

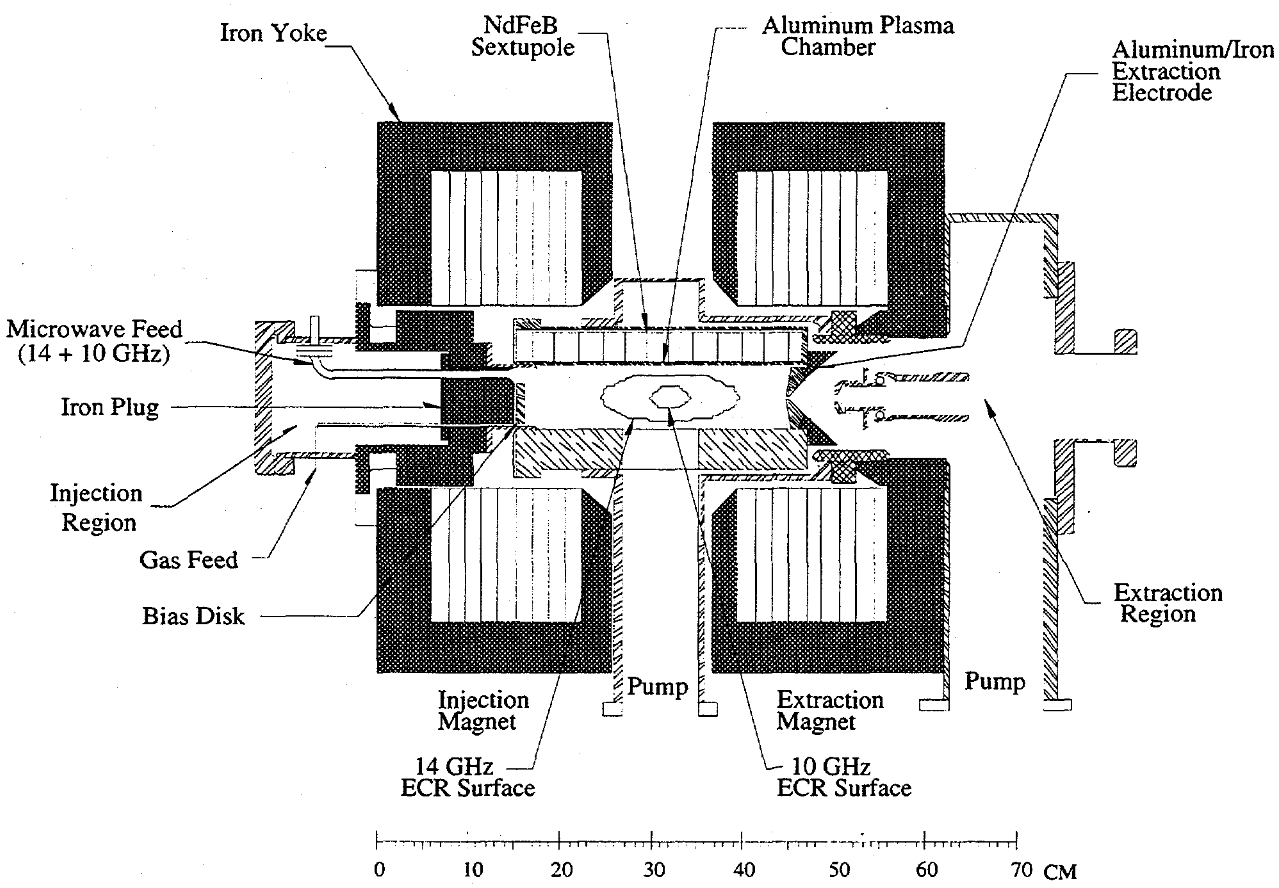

Fig. 1. An elevation view of the LBNL AECR-U ion source.

The new plasma chamber is made from aluminum to increase the yield of secondary cold electrons and eliminate the copper contamination. Radial pumping and oven access are maintained. The inner diameter of the plasma chamber has been increased from 7.0 cm to 7.6 cm. Because the thermal conductivity of aluminum is a factor of 2 poorer than copper and the plasma heating is very localized, the wall thickness between the sextupole magnets and the chamber inner surface, which was 2 mm in the initial design, was increased to 3 mm to diffuse local plasma heating. Cooling loops are installed in both the injection and extraction end plates to provide sufficient cooling at the two locations.

A new set of NdFeB permanent sextupole magnet with a nominal magnetic remanence Br of 1.3 Tesla was installed to raise the maximum radial field strength. To provide sufficient cooling, the permanent sextupole magnet bars are enclosed in 0.25 mm thick watertight stainless steel cans and the canned magnets are directly cooled with three set of cooling channels in which the water enters one magnet bar slot and returns through an adjacent one. The combination of the can enclosures, increased chamber wall thickness and magnet assembly errors reduced the maximum sextupole strength somewhat. The measured maximum sextupole field strength at the chamber inner surface is 0.85 Tesla, up from 0.62 Tesla in the old sextupole.

The AECR-U source is still driven by two-frequency heating (14 and 10 GHz) and the microwaves are launched off axis with the rectangular wave guides terminated at the injection bias plate. There angle between the 14 and 10 GHz wave guides is 30° instead of the 90° in the previous configuration.[2]

Source Performance

Testing of the AECR-U began at the end of July 96 after completion of its mechanical assembly. As expected, the increase in magnetic fields and mirror ratios did not immediately result in better source performance. Maximum performance for an ECR source requires a careful matching between the magnetic field configuration and the microwaves.[9] In the early tests, the AECR–U performance was similar to its predecessor. A series of modifications to the iron yoke and iron plugs at injection and extraction were made during the first few months to improve the coupling of the microwaves at 14 and 10 GHz to the plasma. These modifications are described in more detail in the next section.

The overall performance of the AECR-U is summarized in Table I. The primary focus of the testing was on the performance at very high charge state since those are most important for the research programs at the cyclotron. Higher intensities of moderate charge states are less important since space charge effects in the cyclotron injection system reduce the transmission efficiency for beams above a few hundred eμA. The peak charge state of the heavy elements such as xenon, bismuth and uranium were shifted higher. For uranium the peak charge state shifted from the 36+ to 42+. The production of a usable current of the uranium with more than half the electrons removed (1.1 eμA of $^{238}U^{48+}$) represents a milestone in ECR ion source development. Figure 2 shows a comparison of the best performances for uranium before and after the upgrade. It indicates an increase in intensity of about a factor of 2 for charge state 32+ to 39+ and significantly greater percentage increases from 42+ to 48+. Figure 3 shows the 1 eμA level for xenon-136 increased four charge states, from 32+ to 36+. The production of 21 eμA of Ar^{16+}, 1.35 eμA of Ar^{17+} and at least 60 enA of Ar^{18+} represents, as Figure 4 shows, an enhancement by a factor of 4.5 on Ar^{16+}, a factor of 8.4 on Ar^{17+} and more than an order of magnitude for the fully stripped argon ions, respectively. While the peak of the oxygen charge state distribution remained at O^{6+}, higher intensities of O^{7+} (more than 300 eμA) were produced and for the best charge state distributions the ratio of O^{7+} to O^{6+} increased from 40% to 67%.

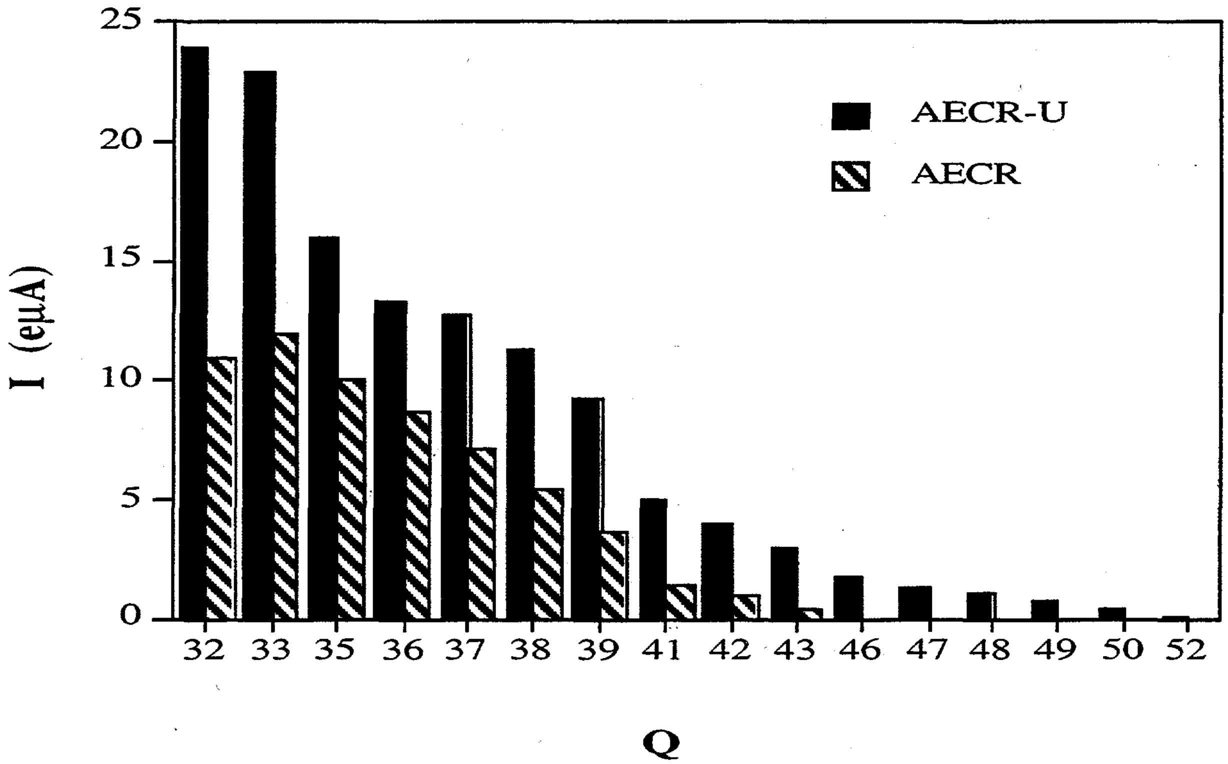

Fig. 2. A comparison of the best high charge state uranium-238 ion beams before (indicated by AECR) and after the AECR source upgrade (AECR-U). Beside enhancement on the lower charge states, at 1 eμA level, the charge state was shifted 6 charge states higher from 42+ to 48+.

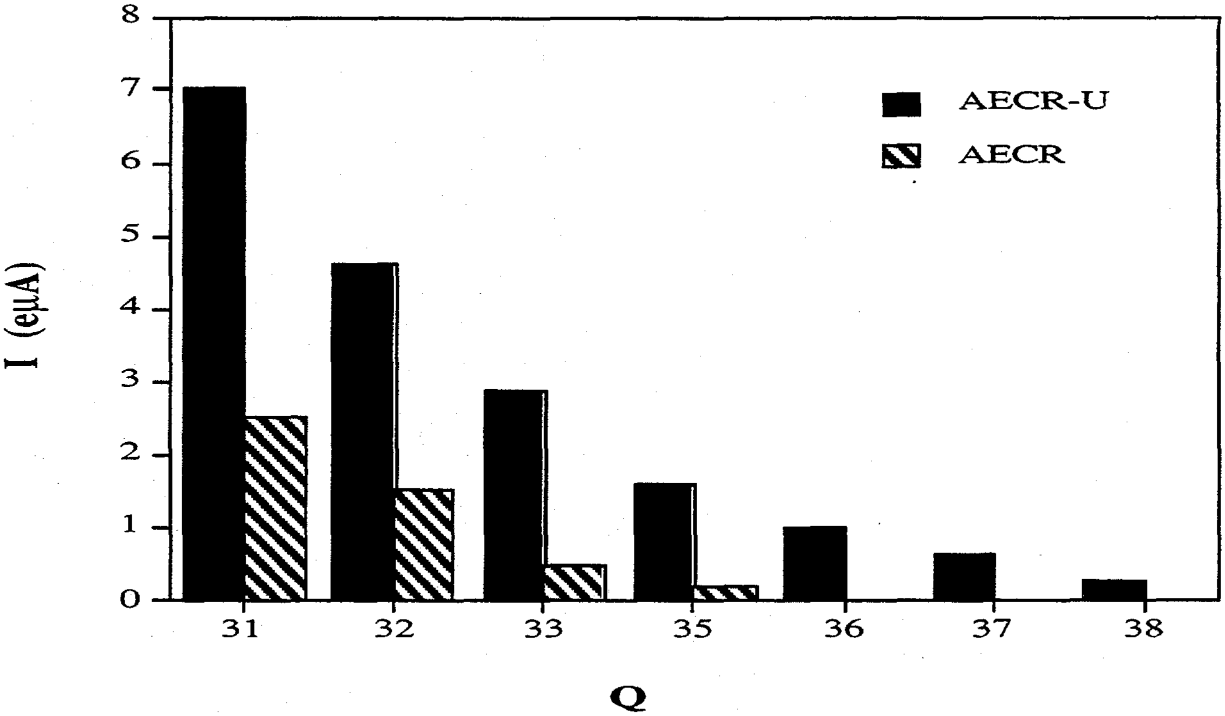

Fig. 3. A comparison of the best high charge state xenon-136 ion beams before (indicated by AECR) and after the AECR source upgrade (AECR-U). Beside a factor of 3 to 5 improvement on xenon charge state 31+ to 35+, at 1 eμA level, the charge state was shifted 4 charge state higher from 32+ to 36+.

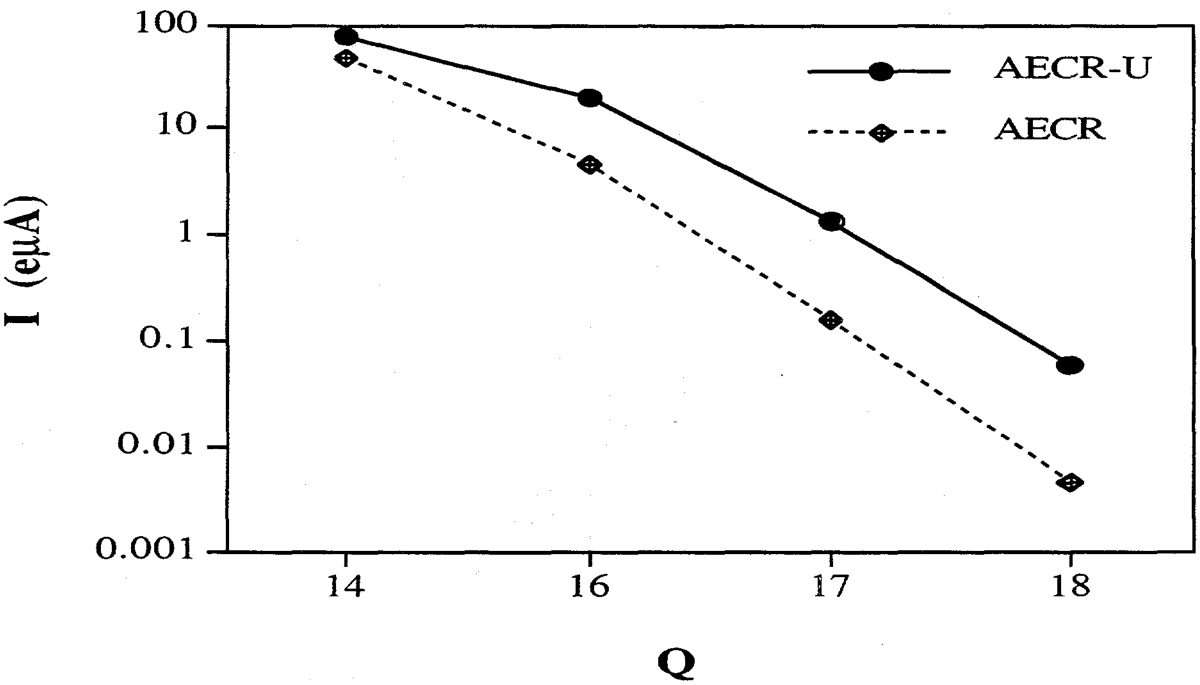

Fig. 4. A comparison of the best high charge state argon ion beams before (indicated by AECR) and after the AECR source upgrade (AECR-U). The 60 enA of Ar^{18+} from the AECR-U represents more than an order of magnitude enhancement on the fully stripped argon ions.

As indicated in Table I, intense high charge state boron ion beams (100 eμA of $^{11}B^{4+}$ and 45 eμA of $^{11}B^{5+}$) were also produced with the AECR-U. Earlier attempts at LBNL to produce high charge state boron ion beams by running boron oxide or boron trifluoride resulted in relatively low intensities because of negative gas mixing. Tests with pure boron injected by a high temperature oven failed due to the chemical reactivity of boron at high temperature. During the AECR-U source development, a new technique using a mixture of 15% diborane (B_2H_6) in helium produced record intensities of fully stripped boron ions. Although diborane must be handled carefully because of safety concerns, it appears to be the best way to produce intense high charge state boron beams in an ECR.

We decided to look at the limits of high charge state production in ECR sources with the AECR-U. These limits may be useful in exploring the physics of ECR plasmas and the very high charge state low intensity beams may be useful for some nuclear and atomic physics experiments. The cyclotron was used to identify and measure the extremely low intensity beams. A silicon detector measured the energy of ion beams extracted from the cyclotron and provided positive identification of the ion species and charge state. It also provided a rough estimate of the ion intensity from the source. Table II lists the extracted intensity and energy of some high charge state heavy ions accelerated by the 88-Inch Cyclotron. The vacuum losses in the cyclotron due to charge exchange increase rapidly with charge state and transmission drops accordingly. Despite this, high charge state ions up to xenon 46+ and uranium 60+ were accelerated and detected. The extracted beam intensities from the cyclotron were $1x10^7$ pps of xenon 41+, a few hundreds pps of xenon 46+, $3x10^4$ pps of $^{238}U^{55+}$ and a few pps of $^{238}U^{60+}$. Uranium 60+ ions is the highest charge state ion beam ever injected into the cyclotron and its total energy of 1.935 GeV is the highest beam energy ever produced by the 88-Inch Cyclotron.

A second technique used to identify the highly charged ions was the detection of the characteristic x-rays produced when a low energy, high charge state ions from the AECR-U were stopped on a copper target. A SiLi crystal with an efficiency of 10^{-5} was used to measure the x-rays. Shown in Figure 5 is the k x-ray spectrum of the hydrogen-like krypton ions. The x-ray intensity were measured at a few counts per second. This indicates a few x 10^5 pps of Kr^{35+} ions were being extracted from the AECR-U source. The production of hydrogen-like krypton at about 10^5 to 10^6 pps by the AECR-U shows that ECR sources capable of producing beams previously only attainable with the EBIS. ECR ion sources can now produce higher currents than EBIS for fully stripped intermediate heavy ions up to calcium. They also appear to have an advantage for heavier elements for the production of intensities 10^6 pps or above as demonstrated by the U^{55+} beams from the AECR-U.

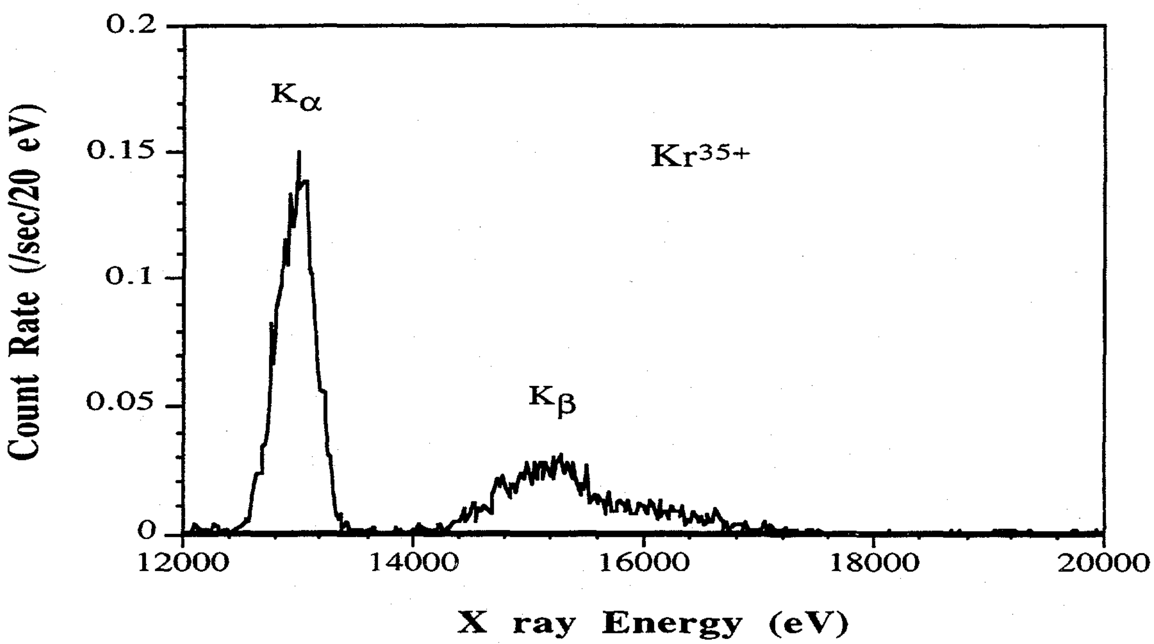

Fig. 5. Observed K x-ray spectrum of the Kr^{35+} ions with an estimated intensity of a few x 10^5 pps extracted from the AECR-U ion source.

Observations And Discussions

As mentioned previously, the first results with the AECR-U were not significantly different from the final performance of the previous configuration. To improve the performance several modifications to the iron used to shape the magnetic field geometry were made. First a piece of iron was incorporated into the aluminum extraction electrode, as indicated in Figure 1, which slightly extends the effective length of the sextupole magnet. This was necessary since the sextupole magnet, due to space constraints, does not extend far enough beyond extraction to eliminate the end effects. Near extraction the sextupole fields combine with the solenoid field create 3 weak magnetic field spots ("magnetic holes") which are off axis and close to the chamber surface. Even though the field strengths of these 3 magnetic holes are higher than the ECR field at 14 GHz,[3] the plasma tends to escape through those holes rather than through the extraction aperture where the field strength is higher. Addition of the iron in the extraction electrode eliminated the magnetic holes. Prior to adding the iron, the total extracted currents were typically in the range of 0.5 to 0.8 emA when the source was tuned for high charge state heavy ions. After the iron plug was inserted into the aluminum extraction electrode, the total extracted currents from the source were almost doubled, its tuning improved and the intensities of the high charge state heavy ions increased about 50%. This improvement clearly indicates the importance of eliminating off axis magnetic holes in ECR magnetic field configuration.

A second modification to the iron configuration was made by removing some of the iron on the inner radius of the injection magnet iron yoke next to the plasma tank. This slightly decreased the mirror ratio, lowered the gradients at the ECR zone and provided better matching between the plasma and the 10 and 14 GHz microwave power. The last modification to the iron configuration was the addition of an small iron plug on axis in the injection region. Previously, the injection iron plug had a 1.0 cm hole on axis to accommodate the addition of an oven. While this small iron plug only effects the axial field in close proximity to itself, it improved the high charge state performance of the source.

Microwave matching is crucial to the production of high charge state ions.[10,11] In the previous AECR source, the 14 GHz microwave were launched using a tapered transition between an off-axis rectangular waveguide and an on-axis circular waveguide at the injection region. That transition provided good coupling to the hot electrons in the plasma based on its outstanding performance.[1,2] In contrast, the 14 GHz microwave coupling in the AECR-U uses a relatively simple off-axis rectangular waveguide which ends abruptly at the location of the bias plate. The off-axis coupling in this case appears to provide good coupling to the hot electrons as evidenced by the source performance. During the commissioning phase, we tested an on-axis feed similar to that used in the earlier design. To our surprise, this on-axis coupling produced very little O^{7+} and it was very difficult to produce more than 10 eμA of O^{6+}. The total extracted current was low and oxygen charge state distribution from this test peaked at O^{2+}! This test clearly demonstrates that microwave matching to an ECR plasma is crucial to the production of high charge state ions and that simply increasing the magnetic fields does not automatically improve the source performance. Unfortunately, coupling of microwaves into an over moded ECR plasma chamber is still too complex to analyze and must be done empirically.

Plasma current in the AECR-U ion source can flow radially to the plasma chamber walls or axially to the extraction end depending upon the plasma conditions. During the AECR-U source development, plasma current flow measurements were carried out by using two current meters. One was connected between the injection end plate and the chamber wall and the other between the extraction end plate and the chamber wall. In the tests, the axial magnetic fields were about 1.5 Tesla at the injection side and 0.9 Tesla at the extraction electrode which is the typical field configuration in the AECR-U for the production of high charge state ions. When the source was in an outgassing stage with a neutral pressure of mid 10^{-6} Torr in the plasma chamber, a positive current of a few milliamps were measured flowing from the plasma chamber walls to the extraction electrode indicating a net positive radial loss in the plasma. There was essentially no net current flowing between the injection end and the chamber wall, probably as a result of higher magnetic field at injection. In the outgassing stage with positive radial losses or running at higher gas flow to create a positive radial loss, a negative bias on the extraction electrode with a few tens of volts increased the extracted currents of O^{6+} or O^{7+} by a factor of 2 to 3. When the neutral pressure in the plasma chamber decreased to about a few x 10^{-7} Torr, which is the normal pressure for the AECR-U for high charge state operation, a positive current of a few emA flowing from the extraction electrode to the chamber walls was observed. Under these conditions, any biasing, either positive or negative, on the extraction electrode decreased the output of the high charge state ions. This change in the current flow from radial to axial at lower neutral pressures was also observed in the Caprice source at Grenoble.[12] Although negative biasing the extraction electrode does not help the output of the high charge state ion when there is a positive axial current flow, it could improve the performance of the ECR after glow mode operation. As the measurement in the Caprice source indicates, the positive current flow changes from axial to radial when the microwave are turned off since the loss of plasma confinement results in more ions than electrons diffusing to the chamber walls. So negatively biasing the extraction electrode when the microwave is turned off could provide a guiding electric field to increase the ion axial loss. By varying the strength of this guiding electric field, one might be able to manipulate not only the peak intensity but also the width of the after glow pulse to match the injection requirements of the pulsed accelerators, such as synchrotrons.

The performance of the AECR-U could still be improved if a third microwave frequency is added to drive the plasma. In the production of the intense ion beams or the very high charge state ions, the AECR-U was running at the maximum microwave power of 2.1 kW available from the 14 and 10 GHz klystrons while the plasma remained stable. This indicates more microwave power at a third frequency could be injected into the plasma to further enhance its performance. Heating the AECR-U with three frequencies is planned to take place in the near future.

The performance LBNL AECR-U source demonstrates ECR source performance can be improved by increasing magnetic field strengths and magnetic mirror ratios. This provides additional support for the idea that building sources with high magnetic fields may yet lead to further gains.

Acknowledgment

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Table I. AECR-U Test Results

ION	$^{11}B^{a}$	^{16}O	^{20}Ne	^{34}S	$^{35}Cl^{b}$	^{40}Ar	^{40}Ca	^{59}Co	^{86}Kr	ION	^{136}Xe	^{197}Au	^{209}Bi	^{238}U
4+	100									**30+**	10.2	35.5		
5+	45									**31+**	7	33.4	29.3	24.5
6+		570	260							**32+**	4.6	30	29.3	24
7+		306	274							**33+**	2.9	*	27	23
8+		~75	320							**34+**	*	22.5	24.1	20
9+			110							**35+**	1.6	18.5	*	16
10+			~20							**36+**	1	13.5	16	13.3
11+				71.5		270	225			**37+**	0.6	*	11.9	12.7
12+				56		192	175	125		**38+**	0.25	9.2	9.4	11.3
13+				35		120	125	116		**39+**		*	*	9.3
14+				18	8	77	83	97		**40+**		4.8	5.2	*
15+				2.6	*	*	*	*		**41+**		3.2	4.4	5
16+				0.1	0.4	21	25.6	58		**42+**		*	*	4
17+					0.01	1.35	*	63	116	**43+**		2	3	3.1
18+						0.06	3.1	24	100	**44+**		1.5	2.2	*
19+							0.25	20	79	**45+**		*	*	*
20+								13.1	63	**46+**		1	1.2	1.8
21+								*	50	**47+**		0.5	0.9	1.4
22+								*	40	**48+**			0.6	1.1
23+								0.8	29	**49+**			0.25	0.8
24+									22.6	**50+**			0.15	0.5
25+									19.4	**52+**				0.1
26+									18	**54+**				0.04
27+									*	**55+**				0.02
28+									2.3					
29+									0.4					

a: Mixture gases of B_2H_6 (15%) in helium were used. b: Tuned on the source contamination.
*: Mixed ion species.
Ions were extracted at voltage of 10 to 16 kV through an 8 mm aperture with beam defining slits opening from 4x4 to 20x20 mm. Currents were measured at eμA with the Faraday cup biased at 150 V to suppress the secondary electrons.

Table II. High Charge State Heavy Ions Accelerated by the 88-Inch Cyclotron.

Q	E/n (MeV)	E (MeV)	I extracted (epA)
$^{136}Xe^{41+}$	10.98	1493	73
$^{136}Xe^{43+}$	11.89	1617	17
$^{136}Xe^{45+}$	13.01	1770	0.5
$^{136}Xe^{46+}$	13.60	1849	$4x10^2$ pps
$^{238}U^{55+}$	6.84	1627	$3x10^4$ pps
$^{238}U^{59+}$	7.86	1871	28 pps
$^{238}U^{60+}$	8.13	1935	2.5 pps

Note; Particle detector were used to identify the high charge state ions.