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Nuclear Science Division

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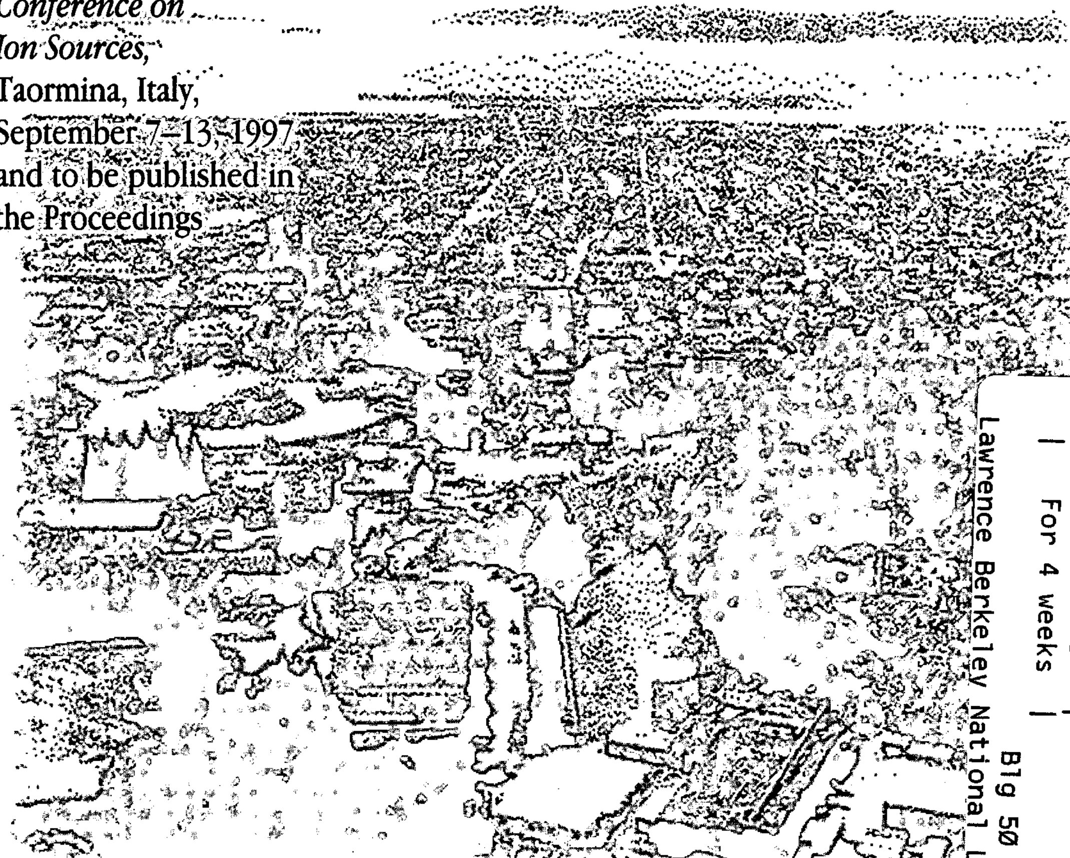

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Production of highly charged ion beams from ECR ion sources

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Electron Cyclotron Resonance (ECR) ion source development has progressed with multiple-frequency plasma heating, higher mirror magnetic fields and better technique to provide extra cold electrons. Such techniques greatly enhance the production of highly charged ions from ECR ion sources. So far at cw mode operation, up to 300 eμA of O^{7+} and 1.15 emA of O^{6+}, more than 100 eμA of intermediate heavy ions for charge states up to Ar^{13+}, Ca^{13+}, Fe^{13+}, Co^{14+} and Kr^{18+}, and tens of eμA of heavy ions with charge states to Kr^{26+}, Xe^{28+}, Au^{35+}, Bi^{34+} and U^{34+} have been produced from ECR ion sources. At an intensity of at least 1 eμA, the maximum charge state available for the heavy ions are Xe^{36+}, Au^{46+}, Bi^{47+} and U^{48+}. An order of magnitude enhancement for fully stripped argon ions ($I \geq 60$ enA) also has been achieved. This article will review the ECR ion source progress and discuss key requirement for ECR ion sources to produce the highly charged ion beams.

I. INTRODUCTION

ECR ion sources (ECRIS) are now widely used in heavy ion accelerators and atomic physics research worldwide and are finding applications to industry ion implantation.[1] Application in accelerators often requires ion beams not only with high charge states but also high intensities. Presently there are mainly two type ion sources, Electron Beam ion sources including Electron Beam ion trap (EBIS and EBIT) and ECRIS, which can produce highly charged ions of all natural elements with ratios of charge state Q to atomic number Z greater than half.[2,3] EBIS applications are limited due to their low beam intensities of the order of a few to tens of epA and pulsed mode of operation. Although the maximum charge states of the very heavy ions produced by ECRIS are less than those from EBIS, ECRIS outperform EBIS in the application to accelerators with capability of producing "intense highly charged" ion beams with cw intensities of a few to hundreds of eμA. In application to synchrotrons, ECRIS beam intensities can be enhanced by a factor of 2-5 by pulsing as compared to cw operation. In the past years with new techniques, such as multiple-frequency plasma heating, better surface coating to provide extra cold electrons and higher magnetic mirror fields, ECRIS performance on ion charge state and beam intensity both have been greatly enhanced. Fig. 1 shows the present cw mode performance of high charge state ECRIS at various intensity levels as a function of atomic number.[4-6] With the higher mirror field superconducting ECRIS, such as the Catania's SERSE and LBNL's 3rd Generation ECR,[7,8] coming into operation in the near future, the production of highly charged ion beams from ECRIS should be further enhanced.

This article will review the recent ECRIS progress achieved with the above mentioned techniques and discuss qualitatively the relations of these techniques to the key requirement for the production of the highly charged ion beams.

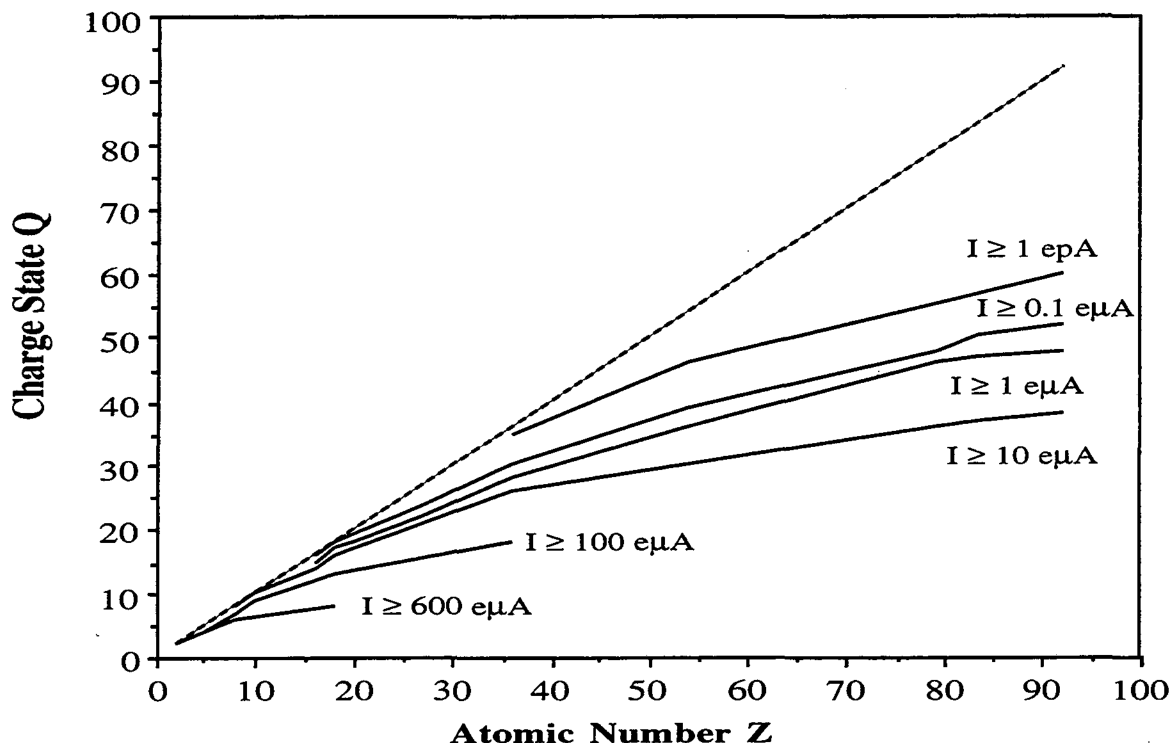

FIG. 1. Present cw performance of ECRIS at various intensity levels as a function of atomic number up to uranium.

II. ECR ION SOURCE PROGRESSES WITH NEW TECHNIQUES

The current methods to maximize the performance of high charge state ECRIS include multiple-frequency plasma heating, aluminum oxide surface coating to provide extra cold electrons into the plasma, and improved plasma confinement with higher magnetic mirror fields.

A. Multiple-frequency Plasma Heating

Microwaves of various frequencies can be simultaneously launched into and absorbed by a high charge state ECR plasma. The minimum-B magnetic field configuration in an ECR ion source can provide many closed and nested ECR heating surfaces, as graphically shown in Fig. 2, if the incoming microwave frequencies match the electron cyclotron frequencies. If two or more significantly different frequencies are used, two or more well separated and nested ECR surfaces will exist in the ECR plasma. With the multiple ECR surfaces, electrons can be heated four times or more for one pass from one mirror end to the other while the electrons are heated only twice in the case of single-frequency heating. Multiple-frequency heating can couple more microwave power with better efficiency into the plasma and it leads to a higher density of the hot electrons, essential to the production of highly charged ions.

Two-frequency plasma heating has been tested with the LBNL AECR and AECR-U, an upgraded version of the LBNL AECR which is discussed in more detail in section II. C. These tests have shown that plasma stability improves and more total microwave power can be launched into the plasma.[5,9] With the improved plasma stability, the source can operate at lower neutral

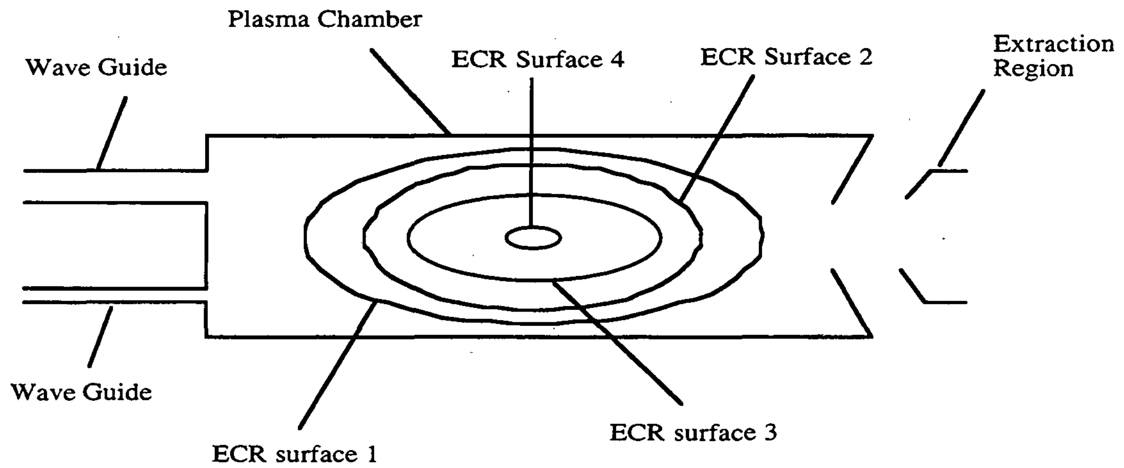

FIG. 2. Schematic view of 4 nested ECR surfaces in a high charge state ECR ion source for 4 well separated frequency waves.

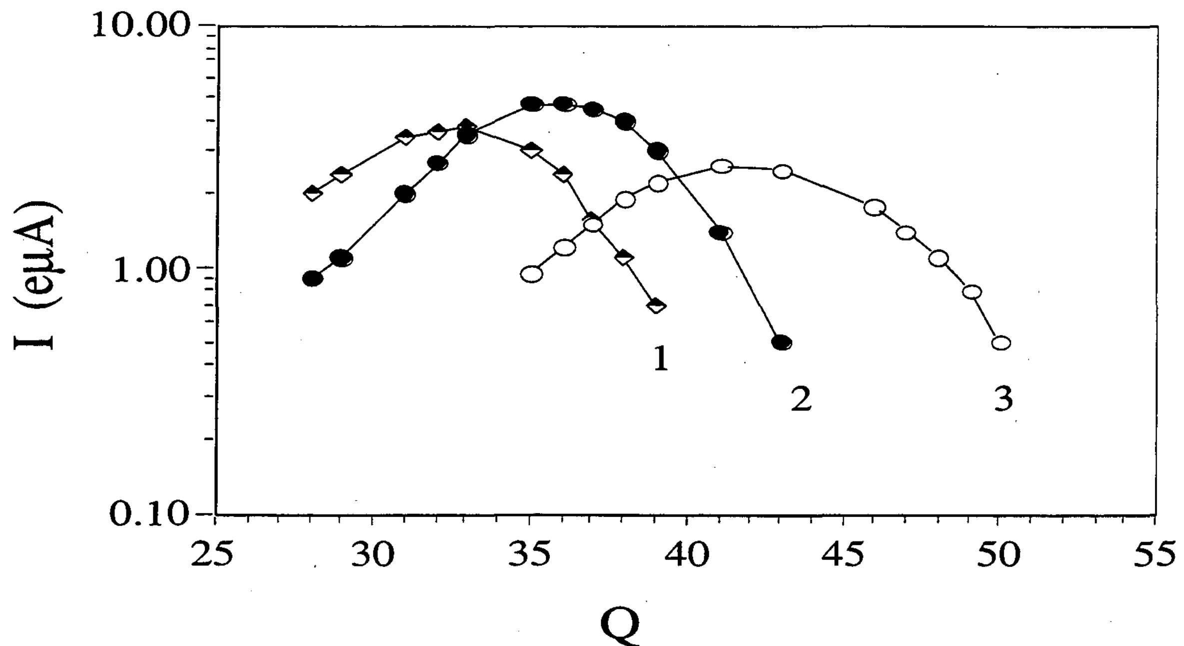

FIG. 3. Optimized charge state distributions for uranium produced with the LBNL AECR and AECR-U ion sources. Curve 1 indicates the case of single-frequency (14 GHz, total μ-wave power = 1.54 kW, reference pressure = 2×10^{-7} Torr) heating and Curve 2 is the case of two-frequency (14+10 GHz, total μ-wave power = 1.77 kW, reference pressure = 1×10^{-7} Torr) heating, both in the AECR. Curve 3 shows the higher charge state uranium ion beams produced by the AECR-U with higher magnetic mirror fields and at higher microwave power (14+10 GHz, total μ-wave power = 2.1 kW, reference pressure = 4.6×10^{-8} Torr) .

input which indicates a lower neutral operating pressure since the mechanical pumping speed is fixed. The lower neutral pressure and higher microwave power lead to a higher "temperature" plasma with increased density of hot electrons.[10] Operation with higher microwave power and lower neutral pressure made possible by the two-frequency plasma heating significantly enhanced the production of highly charged ions. Fig. 3 shows the optimized uranium charge state distributions produced with the AECR and AECR-U ion sources with two-frequency plasma heating (Curve 2 and Curve 3) in comparison to the case of single-frequency heating (Curve 1) in the AECR ion source. Besides a shift in the peak charge state from 33+ (Curve 1) to 36+ (Curve 2), there is also great enhancements for the higher charge state ions from 35+ to 43+.

B. Aluminum oxide coating

ECR plasma needs additional sources of cold electrons, besides the primary electrons come from ionization process, to enhance the production of high charge state ions. Microwave-driven first stages,[11] an electron gun,[12] bias probes,[13] plasma cathodes[14] and plasma chamber surface coatings with high yield of secondary electrons, such as SiO_2, ThO_2 and Al_2O_3, have been explored to provide the extra cold electrons to ECR plasmas.[15-17] With these extra cold electrons, ECRIS can run at lower neutral pressure and higher microwave power that are essential to the production of highly charged ions. Besides a maximum secondary electron coefficient of 9, Al_2O_3 is very resistant to plasma etching and has relatively low material memory. Plasma potential measurements have shown that Al_2O_3 coating reduces the average plasma potential and it is almost independent of microwave power.[18] A lower plasma potential reduces the ion sputtering and improves plasma stability.[19] Even though its secondary electron coefficient is not the highest, all of the desirable characteristics make Al_2O_3 the best surface coating for high charge state ECRIS to date. Although an aluminum plasma chamber was used in one of the minimafios ECRIS in the early 80s, the effects of Al_2O_3 coating were not noticed until recent years.[20] Various ECRIS, such as the Riken ECR-18GHz, Grenoble CAPRICE-14GHz, IMP ECR-II and LBNL AECR (14GHz), have shown substantially enhanced production of highest charge state ions with an Al_2O_3 chamber surface coating.[4,18,21,22]

C. Higher Magnetic Mirror Fields

A number of ECRIS with operating frequencies up to 30 GHz were designed and built in the late 80s and early 90s as guided by the "frequency scaling law".[16,23] The typical magnetic fields in these sources were designed with maximum mirror ratios of 2 to 3. Development of the Grenoble CAPRICE-10GHz and NSCL SCECR@6GHz have demonstrated that the nominal magnetic mirror field with a maximum mirror ratio of 3 is not optimum.[24,25] Significant improvement on source performance is possible with higher magnetic mirror fields. A higher magnetic mirror field improves the plasma confinement and thereby leads to an enhanced production of highly charged ions. Newly built or upgraded ECRIS with higher magnetic mirror fields, such as the Grenoble Caprice-14GHz,[4] Ganil ECR4 (14 GHz),[26] Texas AM&M ECR (6.4 GHz),[27] Louvain-La-Neuve ECR (6.4 GHz),[28] Riken ECR-18GHz[6] and LBNL AECR-U (14+10 GHz),[5] all have demonstrated improved production of highly charged ions.

Among these higher magnetic mirror field ECRIS, the LBNL AECR-U, which combines all the techniques mentioned above, has produced many record high charge state ion beams. The LBNL AECR, predecessor of the AECR-U, had relatively low overall magnetic fields but also produced many intense highly charged ion beams with the applications of two-frequency plasma heating and Al_2O_3 coating.[9] The LBNL AECR was upgraded (LBNL AECR-U) in 1996 by increasing

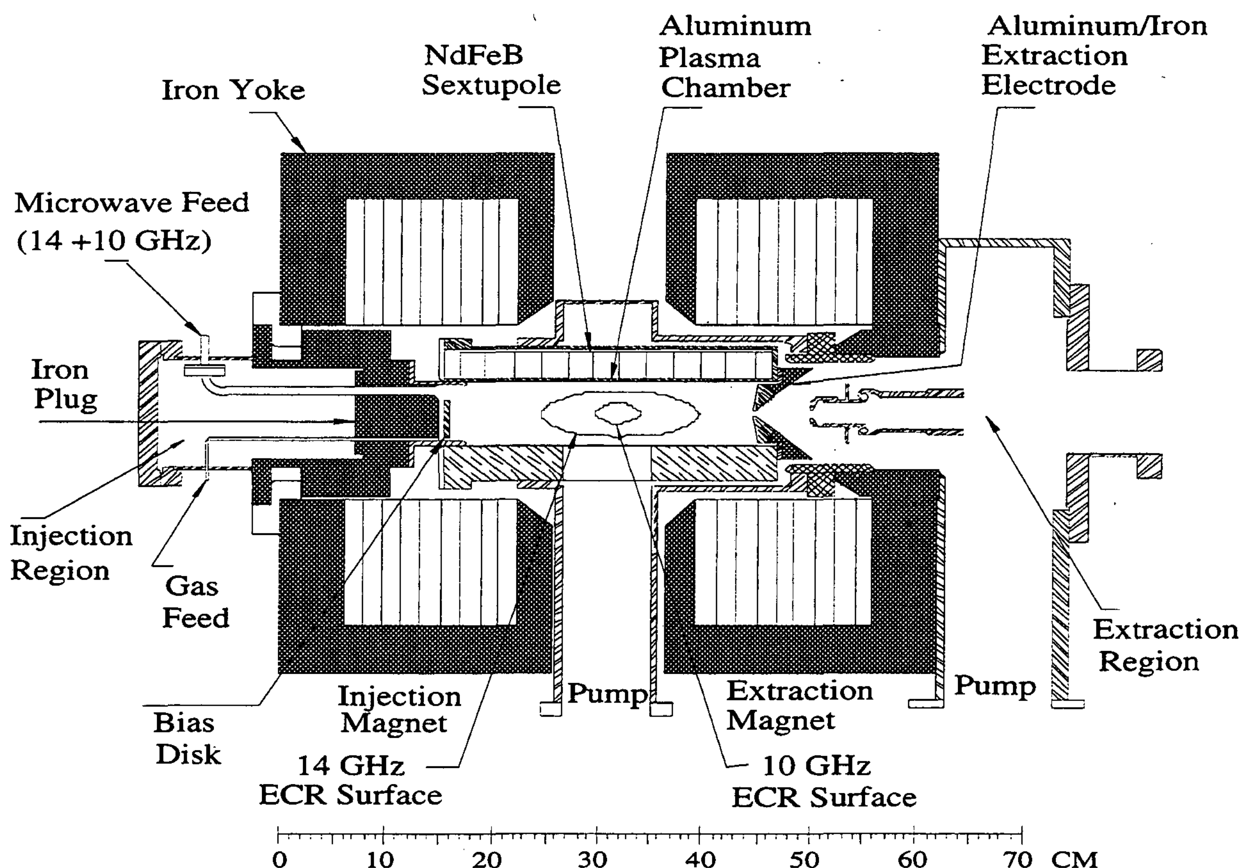

FIG: 4. An elevation view of the LBNL AECR-U ion source.

the magnetic fields to further enhance the source performance. Shown in Fig. 4 is an elevation view of the AECR-U ion source. With the modified solenoid magnets and at no increase in ac power, the maximum axial fields of AECR-U increased from 1.0 to 1.7 Tesla at the injection side and from 0.7 to 1.1 Tesla at the extraction region. While the center field remains at about 0.4 Tesla, the mirror ratios increased from 2.4 to 4.2 at the injection side and from 1.8 to 2.8 at the extraction region.[29] A new set of NdFeB permanent sextupole magnets raised the maximum radial field from 0.62 to 0.85 Tesla at the inner surface of the plasma chamber, which was made from aluminum. After the magnetic field configuration was optimized to match the two-frequency plasma heating (14+10 GHz), the AECR-U demonstrated significantly enhanced production of highly charged ions. It further shifted the peak charge state of uranium from 36+ up to 41+ with greatly enhanced production of highly charged ions as indicated by Curves 3 in Fig. 3. Table 1 lists the present performance of this ion source for a few typical elements. So far up to 300 eμA of O^{7+}, more than 100 eμA of intermediate heavy ions for charge states up to Ar^{13+}, Ca^{13+}, Co^{13+} and Kr^{18+}, and tens of eμA of heavy ions with charge states to Kr^{26+}, Xe^{28+}, Au^{35+}, Bi^{34+} and U^{34+} were produced from the AECR-U. At an intensity of about 1 eμA, the charge states for the heavy ions increase up to Xe^{36+}, Au^{46+}, Bi^{47+} and U^{48+}. The production of 1 eμA of the heaviest natural element with more than half its electrons removed represents a milestone in ECRIS development. Besides the improvement on the heavy ions, an order of magnitude enhancement for

Table 1. Performance of the LBNL AECR-U ion source

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

Note: 99% enriched isotopes of ^{86}Kr and ^{136}Xe were used.
Currents are in eμA. *: Mixed ion species.

fully stripped argon ions (I ≥ 60 enA) also has been achieved. Hydrogen-like krypton ions at intensity of about epA were first time produced from an ECR ion source.

In the production of the high charge state ion beams or intense intermediate charge state ion beams, the source runs best at the maximum available microwave power of 2.1 kW from both of the 14 and 10 GHz klystrons (1.5 kW and 0.6 kW, respectively) and the plasma remains stable. Such operation conditions indicate that further source enhancement is still possible with higher microwave input power, i.e., using either two higher output klystrons or three-frequency plasma heating.

Higher charge state heavy ion beams at low intensities produced with the AECR-U have been accelerated and extracted from the 88-Inch Cyclotron at LBNL. Despite the heavy vacuum losses in the cyclotron due to charge exchange that increases rapidly with charge state, the extracted beam intensities from the cyclotron were 1×10^7 pps of xenon 41+, a few hundred pps of xenon 46+, 3×10^4 pps of $^{238}U^{55+}$ and a few pps of $^{238}U^{60+}$. Uranium 60+ ion beam and its total energy of 1.935 GeV are the highest charge state ion beam and the highest beam energy ever produced by the 88-Inch Cyclotron.

III. KEY REQUIREMENT FOR THE PRODUCTION OF INTENSE HIGHLY CHARGED ION BEAMS

It is the author's point view, a high density of hot electrons is the key for the production of the highly charged ions with an ECR ion source because of the ionization cross section decreases dramatically with increasing charge states. The question is how to produce a high density of hot electrons in an ECR plasma?

In cw ECR plasmas, ions and electrons are kept in a dynamic equilibrium by ambipolar diffusion that maintains the neutrality of outgoing plasma. That is, the average ion confinement time τ_i is linked to the average electron confinement time $<\tau_e>$ that depends on the whole electron population. Although ECRIS have been developing for more than two decades, the detailed physics processes are not fully understood in large part due to the difficulty of making unambiguous measurements of the important plasma parameters. There is evidence indicating the electrons in ECR plasmas are not in a Maxwellian distribution but with two electron populations.[30] The so called "cold" electrons have energies up to hundreds of eV and with confinement times of a few tens to hundred microseconds.[31] These cold electrons do not directly contribute to the ionization of the highly charged ions but can produce low charge state ions and contribute to the average ion confinement. The other group electrons are the "hot" electrons with energies up to hundreds of keV which are magnetic confined with confinement times in the range of milliseconds.[31] Given such a division of electrons in an ECR plasma, the average electron confinement time $<\tau_e>$ can be approximated as;

$$<\tau_e> \approx (1 + \frac{n_{eh}}{n_{ec}})\tau_{ec} \qquad (1)$$

where n_{ec} and n_{eh} are the cold and hot electron density, and τ_{ec} is the average cold electron lifetime. τ_{ec} may not vary very much since by definition that a cold electron, in its lifetime, will either leak out of the plasma or become a hot electron. Equation (1) indicates that a higher ratio of hot electrons to cold electrons could increase the average electron confinement and thereby the average ion confinement time τ_i.

The ionization rate of ion of charge state q is expressed as,

$$\alpha = n_{ef}\sigma_q v \qquad (2)$$

where n_{ef} is the effective electron density denoting those energetic electrons with energies at least equal to the ionization potential of the ion charge state q, σ_q and v are the ionization cross section

and the electron velocity. The ionization cross section decreases dramatically with increasing charge states as the ionization potentials become higher and higher. Following the work of Müller *et al*,[32] the ionization cross-section σ_q is

$$\sigma_q = \frac{1.4\mathrm{x}10^{-13}}{P_q E_e} \ln\frac{E_e}{P_q}\ \mathrm{cm}^2 \qquad (3)$$

where E_e and P_q are the electron energy and the ionization potential of the ion charge state q. So Equation (2) can be written as;

$$\alpha \propto \frac{n_{ef}}{P_q\sqrt{E_e}} \ln\frac{E_e}{P_q} \qquad (4)$$

Equation (4) indicates that, at a given electron density, electrons with energies of a few tens to hundreds of keV are needed to maximize the ionization rate of ion of charge state q with ionization potentials of a few to tens of keV. For example, mono energetic electrons at 31 keV produce the highest rate for Ar^{18+} (ionization potential IP = 4.26 keV) ions, 55 keV for Xe^{46+} (IP = 7.5 keV), 29 keV for U^{60+} (IP = 3.95 keV) and 124 keV for Kr^{35+} (IP = 16.8 keV). In the case of a maxwellian electron distribution, higher electron temperature than the mono-energy E_e is required to reach a maximized ionization rate. Equation (2) shows that a higher density of the energetic electron reduces the ionization time for ions of charge state q. Stepwise ionization by electron impact is the dominant ionization process in an ECR plasma for the production of highly charged ions. So a higher density of hot electrons will successively reduce the ionization times of ions of intermediate and high charge states in an ECR plasma and that should lead to an enhanced production of highly charged ions.

IV. DISCUSSION OF MICROWAVE POWER EFFECT IN SELECTED EXPERIMENTS

Measurements on the Grenoble ECRIS indicate that the maximum electron energy can reach hundreds of keV even at low microwave power of 100 W in a high charge state ECR ion source typically operates at neutral pressures of 10^{-6} to 10^{-7} Torr in the ionization chamber.[10] Increasing the microwave power input at a given neutral pressure does not increase the maximum electron energy or hot electron "temperature" but does slowly increase the density of the hot electrons because of the confinement decreases.[10,31] Shown in Fig. 5 are the pinhole plasma chamber wall bremsstrahlung x-ray spectra taken at the beam analysis magnet along the axis of the LBNL AECR-U. The energy and intensity of the bremsstrahlung x-ray are roughly proportional to the electron energy flow ($n_e E_e/\tau$) of the hot electrons that escaped from the plasma. The plasma was a mixture of argon and oxygen and was generically tuned on Ar^{16+}. Source operating parameters were held constant except the input microwave power with single-frequency (14 GHz) and two-frequency plasma heating (14+10 GHz) were varied. The x-ray intensity is essentially linear with input microwave power. The Grenoble measurements demonstrated that the density of the hot electrons increases, but slower than a linear rate with microwave power.[31] The maximum electron energy can easily reach 600 keV or higher even at microwave power of 200 W and there is essentially no change in the slopes of the spectra for microwave power from 200 W up to about 2

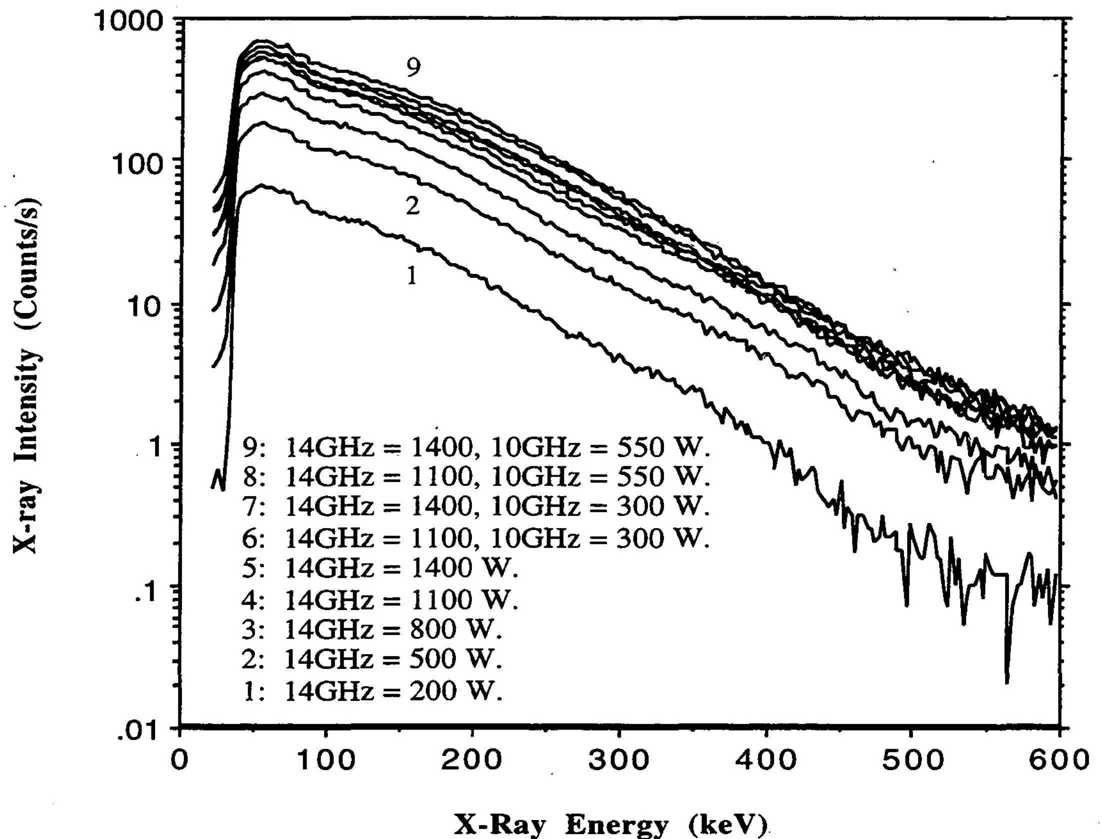

FIG. 5. Plasma chamber wall bremsstrahlung x-ray spectra of a plasma of argon and oxygen in the LBNL AECR-U at various microwave power levels with single and two-frequency plasma heating.

kW. A maximum electron energy of hundreds of keV, may not be as high energy for the maximized ionization of fully stripped uranium, but it is well above the ionization potential. Shown in Fig. 6 are the Ar^{16+} output intensities and source net total extracted currents (I_{net}) at various microwave power levels with single and two-frequency plasma heating. The output of Ar^{16+} ions increases rapidly with microwave power levels especially in the case of two-frequency plasma heating. In the case of single-frequency plasma heating, the output of Ar^{16+} ions increased a factor of 23 at power of 1.4 kW as compared to the case of 200 W and a factor of 4 as compared to the case of 500 W, respectively. In the case of two-frequency plasma heating, the increase on the Ar^{16+} is a factor of 58 at total power of 1.95 kW against the single-frequency heating of 200 W and a factor of 10 against the case single-frequency heating of 500 W, respectively. At about the same microwave power of 1.4 kW, two-frequency heating increased the Ar^{16+} output by a factor of 1.5 indicating that two-frequency heating can more effectively couple the microwave power into the plasma than the case of single-frequency plasma heating.

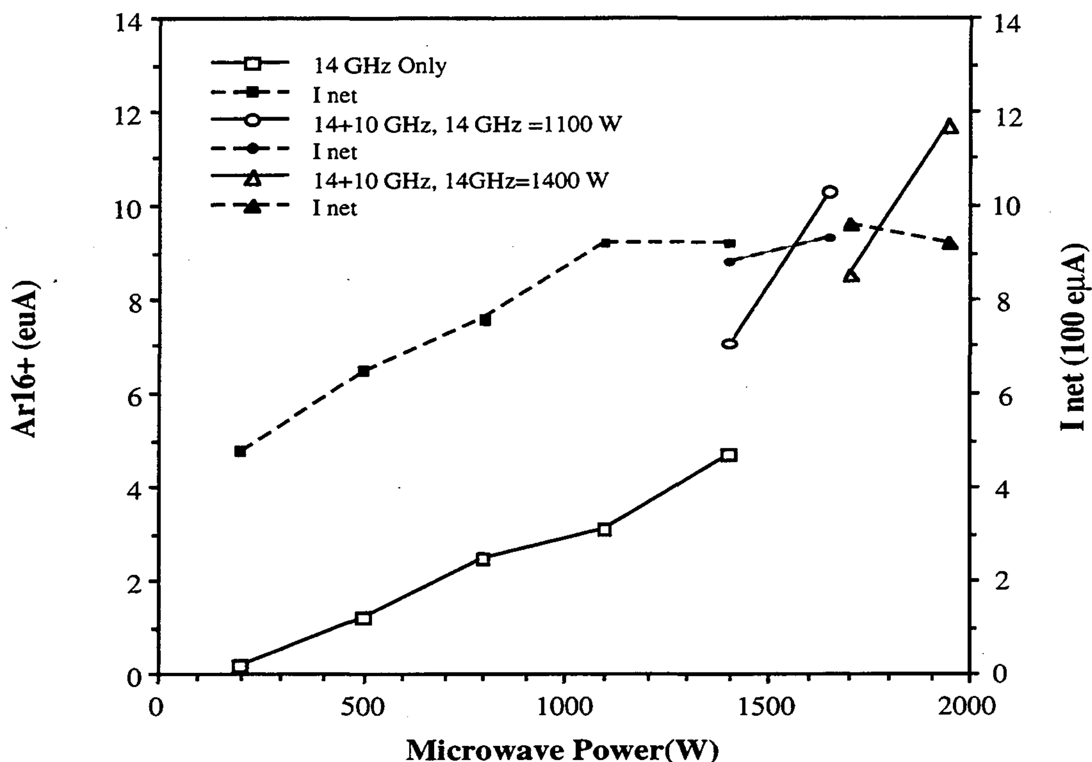

FIG. 6. Measured Ar^{16+} intensities and source net total extracted currents (I_{net}) at various microwave power levels with single and two-frequency plasma heating in the AECR-U ion source. Higher microwave indicates a higher density of the hot electrons.

The dramatic enhancement of the Ar^{16+} ions with microwave power inputs indicates an increase in the $n_e\tau_i$ product. If the ratio of hot electrons to the cold electrons is small in which τ_i may not vary much as indicated by Equation (1), then the enhanced Ar^{16+} output is likely due to a higher density of hot electrons at higher microwave power than at low power. Scaled with the Grenoble measurements, there could be a factor of 2 to 3 increase on the hot electron density at microwave power of about 2 kW as compared to the case of 200 W. The total net extracted ionic electric currents (I_{net}) increased only a factor of 2, from 0.48 emA at 200 W to a maximum of 0.96 emA at total microwave power of 1.7 kW of two-frequency plasma heating, and it saturated above power of 1.1 kW. This ion electrical current increase could well be mainly due to the charge state distribution shifted to higher charge state ions that carry more charges than the lower charge state ions, while the total number extracted ions may not increase much at all as indicated by the measurements in a Riken ECR ion source.[33] The measurement of the bremsstrahlung x-ray in this study is very incomplete because of the electrons with energy of a few keV which significantly contribute to the production of the Ar^{16+} ions were not measured. A systematic investigation is needed to thoroughly study the whole electron density distribution versus energy and its

relationship to the microwave power. Nevertheless, the non-linear output of the Ar^{16+} ions versus the microwave power in this study has indirectly shown a correlation between a higher density of the hot electrons and the production of intense highly charged ions in an ECR ion source.

Grenoble measurements also indicate the hot electron "temperature" depends strongly on the neutral pressure; a lower neutral pressure results in a higher hot electron "temperature" at the same microwave power.[10] This is physically sound because of a lower neutral pressure results in fewer collisions between the electrons and ions and neutral atoms. Therefore high microwave power and low neutral pressure are the two necessities to achieve a high density and hotter electrons in an ECR plasma.

The maximum useful microwave power that can be launched into the ECR plasma to increase the output of the highly charged ions depends on the plasma stability. The techniques used in recent ECRIS development all seem to improve ECR plasma stability. 1). Besides providing the needed additional cold electrons to improve the ECR plasma stability,[34] other properties of aluminum oxide coating, such as resistance to plasma etching and lower plasma potential, all improves plasma stability. 2). By nature a higher magnetic mirror field will improve the plasma confinement by sustaining a higher power density. 3). The ECR heating occurs at multiple heating surfaces can result spread energy distribution that can improve the plasma stability besides more efficiently coupling the microwave power into the plasma.

With the improved plasma stability, ECRIS can operate at lower neutral pressures. Low operating neutral pressure reduces the charge exchange between the highly charged ions and neutrals. Charge exchange can become the limiting factor in the production of the highly charged ions since the charge exchange cross section increases rapidly with ion charge states.[35] Unlike most other ECRIS, the AECR-U, its predecessor and a similar version of the AECR-U at Argonne National Laboratory which is under commissioning,[36] have radial pumping through its plasma chamber. This comes at the price of lower sextupole magnetic field strength and requires careful engineering. But the radial pumping provides better control of the neutral background and is, in the author's point of view, a significant contribution factor in the production of record high charge state ion beams from the AECR-U.

All of the aspects discussed in this section appear to contribute to optimizing ECRIS performance. Other aspects such as improving ion beam extraction and transport efficiencies can also substantially contribute to the production of intense highly charged ion beams. While a thorough investigation is needed to study the detailed relations of the techniques to a high density hot electrons, it is clear that producing higher charge state and more intense ion beams are possible with the higher magnetic mirror field superconducting ECRIS as evidenced by recent ECRIS progress.

With enhanced production of highly charged ion beams, ECRIS will play an important role in providing improved luminosity for the relativistic heavy ion colliders such as RHIC at Brookhaven National Lab as demonstrated at CERN.[37]

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