STATE OF THE ART OF ECR ION SOURCES

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Abstract

Electron Cyclotron Resonance (ECR) ion source which produces highly-charged ions is used in heavy ion accelerators worldwide. Applications also found in atomic physics research and industry ion implantation. ECR ion source performance continues to improve, especially in the last few years with new techniques, such as multiple-frequency plasma heating and better methods to provide extra cold electrons, combined with higher magnetic mirror fields. So far more than 1 emA of multiply-charged ions such as He^{2+} and O^{6+}, and 30 eμA of Au^{32+}, 1.1 eμA of $^{238}U^{48+}$, and epA currents of very high charge states such as $^{86}Kr^{35+}$ and $^{238}U^{60+}$ have been produced.

1 INTRODUCTION

Significant progress has been achieved since the first high charge state ECR ion source was developed more than two decades ago and it has become the choice of ion source for heavy ion accelerators worldwide [1,2]. Over the past years, ECR ion source development has evolved into two directions: production of higher charge states, more intense ion beams for accelerators; and compact ECR ion source with moderate performance for the production of radioactive ion beams and industry ion implantation. Figure 1 shows the present cw mode performance of high charge state ECR ion sources at various intensity levels as a function of atomic number [3,4].

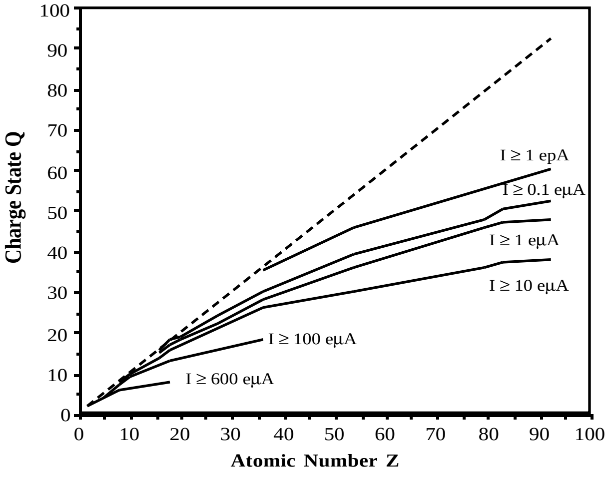

Figure: 1 Present ECR ion source performance at various intensity levels as a function of atomic number up to uranium.

ECR ion sources have been used to produce intense pulsed sulfur and lead ion beams for the heavy ion injector at CERN [5]. The present ECR ion source cw performance improved by pulsing (current ECR pulsed beam intensity is a factor of 2 to 3 or higher than its cw output [6]) or the next generation ECR ion sources with increased high charge state ion intensities could provide improved luminosity for the relativistic heavy ion colliders such as RHIC at Brookhaven National Lab.

This paper is not intended as a broad survey of ECR ion sources, instead it will review the progress made in the last few years that has significantly enhanced the performance of high charge state ECR ion sources.

2 ECR BASICS

In an ECR ion source microwave power is coupled by Electron Cyclotron Resonance Heating into a plasma confined in a minimum-B field magnetic bottle to produce ions. As the electrons spiral back and forth between the magnetic mirrors they are heated in a thin zone at an egg shaped ECR surface where the microwave frequency ω_f matches the electron cyclotron frequency ω_c;

$$\omega_f = \omega_c = \frac{eB}{m_e}$$

where e, m_e are the electron charge and mass, and B is the local magnetic field.

The primary source of cold electrons in an ECR ion source is the stepwise ionization of atoms and ions. Ions and electrons are kept in a dynamic equilibrium by ambipolar diffusion which maintains the neutrality of outgoing plasma. That is, the longer average electron confinement is the longer average ion confinement. There are two electron populations in a high charge state ECR ion source, cold and hot electrons due to the ECR heating [6]. The hot electrons have energies from about ten to a few hundred keV and confinement times in the range of milliseconds. The dominant electrons are the cold electrons which have energies up to a few hundred eV and confinement times in the range of hundred microseconds. These cold electrons are not magnetically confined and tend to escape more rapidly from the plasma than the ions because of their much higher mobility. The average electron confinement time $<\tau_e>$ in an ECR ion source can be expressed as;

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

where n_{ec}, and n_{eh} are the cold and hot electron densities, and τ_{ec} is the cold electron average confinement time.

This equation indicates that either a higher ratio of hot electrons to cold electrons or a longer cold electron confinement time τ_{ec} will increase the average electron confinement and thereby the average ion confinement time τ_i. High hot electron density and long ion confinement are very essential to ECR ion sources for the production of high charge state ions, especially those ions with ionization potentials of tens of keV in which the ionization cross sections are very small. To produce the high charge state ions, ECR plasma always tends to run as high microwave power as possible if the plasma remains stable and low neutral pressure to reduce the charge exchange.

3 ECR ION SOURCE PROGRESS

The current methods to maximize the performance of high charge state ECR ion sources 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.

3.1 Multiple-frequency Plasma Heating

The minimum-B field configuration in a high charge state ECR ion source can provide many closed and nested ECR heating surfaces, as graphically shown in Fig. 2, for incoming microwaves with various frequencies. Typically a single microwave frequency is used in an ECR ion source to produce only one egg-shaped ECR heating zone. The electrons are heated twice when they travel from one mirror point to the other. If two or more significantly different frequencies that match the minimum B-field are used, two or more well separate and nested ECR surfaces will exist in the ECR plasma. The lower frequency waves can propagate through the ECR plasma because a high charge state ECR ion source typically runs with an underdense plasma. With the multiple ECR surfaces, electrons can be heated four times or more for one pass from one end to the other and this will lead to a higher density of the hot electrons and enhanced production of high charge state ions.

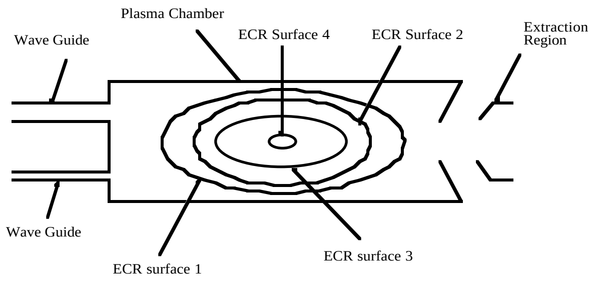

Figure: 2 Schematic view of the a few nested ECR surfaces in a high charge state ECR ion source.

Tests with two-frequency plasma heating on the LBNL AECR ion source [7] have shown that plasma was more quiescent than single-frequency heating [8]. The short-term and the long-term plasma stability were both improved and more total microwave power could be launched into the plasma. With the improved plasma stability, the source can run at lower neutral inputs which indicates a lower neutral pressure since the mechanical pumping are the same. The lower neutral pressure and higher microwave power result in higher hot electron density. Tests were done to compare two-frequency heating to single frequency heating with the same gas and vapor inputs and the same total microwave power. The two-frequency heating shifted the peak charge state of bismuth slightly and enhanced the high charge state ions by a factor of 2 for charge states 36+ to 40+ [8]. The intensity increase and slight peak charge state shift indicate the difference between single frequency and two-frequency heating. With 15% more microwave power than the case of single-frequency heating, 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+ and produced greater enhancements for the higher charge states as indicated by Curve 1 and Curve 2 in Fig. 3.

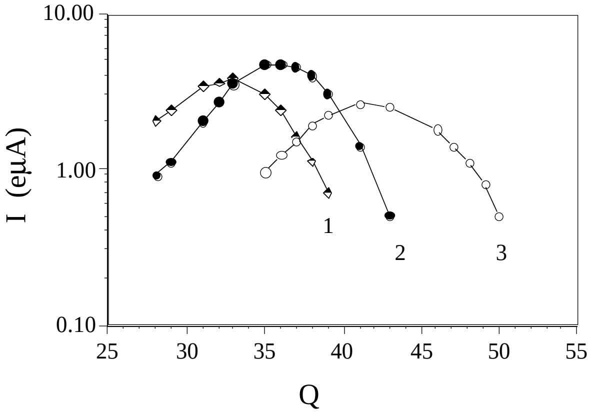

Figure: 3 Charge state distributions for uranium produced with the LBNL AECR and AECR-U ion source. Curve 1 indicates the case of single-frequency (14 GHz, at power of 1.54 kW) heating and Curve 2 is the case of two-frequency (14+10 GHz, at total power of 1.77 kW) heating. Curve 3 shows the higher charge state uranium ion beams produced with the AECR-U at higher microwave power (14+10 GHz, at total power of 2.1 kW).

3.2 Effects of the Extra Cold Electrons

Besides the cold electrons from ionization process, ECR plasma needs additional cold electrons to enhance the production of high charge state ions. With these extra cold electrons, the high charge state ECR ion sources can run at lower neutral pressure and higher microwave power which are essential to the production of high charge state ions.

Various active methods, such as a microwave-driven first stage [9], an electron gun [10], a bias probe [11] and a plasma cathode [12], have been used to provide the extra cold electrons to ECR plasmas. The electrons injected by these active methods are mainly along the magnetic field lines. Except the bias probe, they are more complex and costly than plasma chamber surface coatings. In ECR ion sources the plasma chamber surface is parallel to the axis therefore a large portion of the secondary electrons emitted from the surface are perpendicular to the axis. Enhanced source performance by plasma chamber surface coatings with high yield of secondary electrons, such as SiO_2, ThO_2 and Al_2O_3, have been experimentally observed [13-15]. The improved source performance demonstrated that chamber surface coating is an excellent method to provide the additional electrons needed by an ECR plasma. Empirically speaking, a good surface coating for an ECR ion source should have:

1. High secondary electron emission.
2. Resistance to plasma etching.
3. Low material memory.

Although the secondary electron emission of Al_2O_3 (δ_{max} = 9) is not the highest, it is very resistant to plasma etching and has relatively low material memory. Plasma potential measurements have shown that Al_2O_3 coating yields the lowest average plasma potential and it is almost independent of microwave power [16]. A lower plasma potential reduces the ion sputtering and improves plasma stability [17]. All of these desirable characteristics make Al_2O_3 the best surface coating for high charge state ECR ion sources. With an Al_2O_3 chamber surface coating, various ECR ion sources have shown that the ECR plasma can run at lower neutral pressure and substantially enhanced the production of highest charge state ions [3,4,18]. Listed in Table 1 are the performance of a few ECR ion sources with Al_2O_3 coating.

Table 1. Performance of a few ECR ion sources with aluminum oxide coating

ION	LBNL AECR-U 14+10 GHz	Grenoble CAPRICE 14 GHz	RIKEN ECR-18 18 GHz
O^{6+}	570	760	500
O^{7+}	306	100	130
Ar^{14+}	77	15	25
Ar^{16+}	21	1	5
Kr^{18+}	100	55	
Kr^{25+}	19.4	2	
Xe^{28+}	21	10	
Xe^{31+}	7		
U^{36+}	13.3	1.4	
U^{39+}	9.3	0.17	
U^{48+}	1.1		

Currents are in eμA.

3.3 Higher Magnetic Mirror Fields

Based on the so called “frequency scaling law” proposed in 1987 [13], a number of ECR ion sources were designed and built to operate at frequencies of 14, 18 and up to 30 GHz [19]. The designed magnetic fields of these sources were typically with maximum mirror ratios of 2 to 3. The significantly improved performance of these higher frequency ECR ion sources, as compared to the lower frequency sources with lower magnetic fields, indicates an increase in the $n_e\tau_i$.

Recent ECR ion source development demonstrated that the nominal magnetic mirror field with a maximum mirror ratio of 3 is not yet optimized for the current operating frequencies [20,21]. Significant improvement is still possible with higher magnetic mirror fields [22,23].

In an ECR ion source the plasma pressure w_{pl} can be loosely related to the magnetic field as;

$$w_{pl} = K\,(n_{ec}T_{ec} + n_{eh}T_{eh}) \propto B^x \qquad (1 \le x \le 2)$$

where K is the Boltzmann constant, T_{ec} and T_{eh} are the cold and hot electron temperatures, respectively. A higher magnetic mirror field will surely improve the plasma confinement. It can sustain a higher plasma pressure with either a higher total electron density or a higher density of the hot electrons when the source operates at lower neutral inputs. Naturally the higher magnetic mirror field should lead to an enhanced ECR ion source performance.

4 PERFORMANCE OF THE LBNL AECR-U ION SOURCE

Although its overall magnetic fields of the LBNL AECR were about 50% lower than other 14 GHz ECR ion sources, it had produced outstanding high charge state ion beams with the applications of two-frequency plasma heating and Al_2O_3 coating [8,16]. This ion source was recently upgraded (LBNL AECR-U) by increasing its magnetic fields. Shown in Fig. 4 is an elevation view of the AECR-U ion source. The maximum axial peak fields of AECR-U increased from 1.0 to 1.7 Tesla at the injection side and from 0.7 to 1.0 Tesla at the extraction region. With 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 3.0 at the extraction region [3]. A new set of NdFeB permanent sextupole magnet raised the maximum radial field from 0.62 to 0.85 Tesla at the inner surface of the plasma chamber 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 performance compared to its predecessor. When tuned to produce the very 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 the 14 and 10 GHz klystrons (1.5 kW and 0.6 kW, respectively). The optimum operation neutral pressure is also lower. Table 2 lists the present performance of this ion source for a few typical elements. So far, 30 eμA of Au^{32+}, 18.5 eμA of Au^{35+} were produced. For heavy ions at intensity of about 1 eμA, the charge state shifted from 42+ to 48+ for uranium-238 (see Fig. 3). The production of about 1 eμA of the heaviest natural element with more than half its electrons removed represents a milestone in ECR ion source development. Besides the improvement on the heavy ions, 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 epA were first time produced from an ECR ion source. High charge state heavy ion beams of xenon-136 up to 46+ and uranium-238 up to 60+ were produced from the AECR-U source and were accelerated and extracted by the 88-Inch Cyclotron. U^{60+} was accelerated to a record energy of 1.94 GeV at the cyclotron. The greatly improved performance of the AECR-U for the high charge state ions demonstrates the effect of higher magnetic mirror fields.

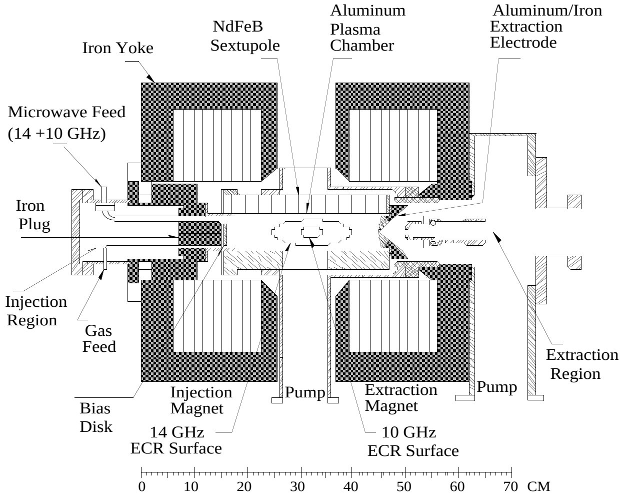

Figure: 4 An elevation view of the LBNL AECR-U ion source.

The AECR-U ion source and a similar version of this source under commissioning [24] at ANL are currently the only ECR ion sources that combine multiple-frequency plasma heating, aluminum oxide coating with a bias probe and higher magnetic mirror fields. The AECR-U has produced record intensities of high charge state ions. Unlike other high field ECR ion sources, the AECR-U has radial pumping through six radial slots, which also provide oven access. In the author's point of view this also contributes significantly to the source performance. The radial pumping results in better vacuum control inside the plasma chamber. A lower neutral density in a high charge state ECR ion source is critical for the production of high charge state ions as the charge exchange cross sections increase faster than the square of the charge state [25].

Table 2. Performance of the LBNL AECR-U ion source

Q	O	Ar	Ca	Kr	**Q**	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: Enriched isotopes of Kr and Xe were used.
Current are in eμA. *: Mixed ion species.

5 FUTURE ECR ION SOURCES

Recent ECR ion source development demonstrated the further enhanced performance on high charge state ions remains possible with higher magnetic mirror fields. However the maximum field strengths reached by conventional magnets of practical size and power consumption is about 2 Tesla while superconducting magnets can achieve higher magnetic mirror fields. Previous superconducting ECR ion sources built demonstrated the feasibility of higher mirror fields with superconducting magnets [19,26,27]. New superconducting ECR ion sources with magnetic fields up to 4 Tesla and maximum mirror of 10 are under construction and commissioning [28,29]. Shown in Table 3 are the design parameters for the new superconducting ECR ion sources, the Catania SERSE and the LBNL 3rd Generation ECR ion source. These higher magnetic mirror fields combines with multiple-frequency heating and better techniques to provide the extra cold electrons, should further greatly enhance the ECR ion source performance.

Table 3. Design parameters of the new superconducting ECR ion sources

	LBNL 3rd ECR source	CATANIA SERSE
Mirror field on axis (T)	4, 3	2.7, 1.5
Central field (T)	0 to 1.0	0.4 to 0.5
Typical radial field on I.D. of plasma chamber (T)	2.4	1.4
Mirror-mirror spacing (cm)	50	50
I.D. of plasma chamber (cm)	15	13
Proposed operating frequency (GHz)	10+14+18 or 6+10+14 ?	14 to 30 or ?

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