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IMPROVEMENTS ON THE LBL AECR SOURCE

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Abstract

Performance of the LBL AECR source was improved by simultaneously heating the plasma with microwaves of 10 and 14 GHz (two-frequency heating). Plasma stability was improved and the ion charge state distribution shifted to higher charge state. Production of high charge state ions was increased a factor of 2 to 5 or higher for the very heavy ions such as bismuth and uranium, as compared to the case of single-frequency (14 GHz) heating. Fully stripped argon ions at intensity I ≥ 5 enA were directly identified by the AECR charge state analyzing system for the first time. High charge state ion beams of bismuth and uranium produced by the source were injected into the 88-Inch Cyclotron. After acceleration to energies greater than 6 MeV/nucleon, the extracted beam intensities were 1×10^6 pps or higher for $Bi^{50+,51+}$ and $^{238}U^{52+,53+}$. Tests in the AECR source have also shown Al_2O_3 coating is an effective coating and a better method than the electron gun for providing cold electrons to the ECR plasma.

The AECR source will be upgraded to raise its magnetic field strengths to obtain better plasma confinement and enhanced production of high charge state heavy ions.

Introduction

The LBL ECR and the AECR both provide a great variety of ion beams for the 88-Inch Cyclotron to support the nuclear and atomic research programs. In addition to the research programs, development on ECR sources remains a high priority. Study and understanding of the physics mechanisms involved in ECR plasma are important for the improvement of ECR source performance and the future source development. Also the scientific programs at this facility, such as Gammasphere and the search for the superheavy elements, will benefit from heavy-ions with higher charge states and higher intensities especially for the elements of mass greater than 100. So our ECR source development has been focused on enhancing the production of high charge state ions of heavy elements with the AECR source.

Effects of Two-Frequency Heating

In an ECR source electron cyclotron resonance heating couples microwave power into the plasma electrons. This occurs when the microwave frequency w_f matches the cyclotron frequency $w_c \approx eB/m_e$ of the electrons. In high charge state ECR sources with one frequency, the geometry of the minimum B-field results in a closed, approximately ellipsoidal ECR surface. The electrons are heated in a thin resonance zone at the surface as they spiral back and forth between the magnetic mirrors. When two frequencies are used it is possible to produce two concentric surfaces whose physical separation depends on the frequency difference and the strength and gradient of the magnetic field. If the two frequencies are significantly different, the ECR surfaces will be well separated and electron heating at both surfaces could lead to a higher density of the energetic electrons.

The LBL AECR is designed to operate at 14 GHz.[1,2] The plasma is heated with microwaves of a single-frequency but the magnetic field shape can be adjusted so that the closed ECR resonance surfaces at both 10 and 14 GHz coexist. The source was recently modified so that both 10 and 14 GHz microwaves could simultaneously be injected into the main chamber. A second waveguide (WR90) was coupled to the plasma chamber so that the 10 GHz microwave could be launched with the electric field vector at 90° with respect to the 14 GHz microwave brought in by a WR62 waveguide. To eliminate microwave interactions extra isolators were installed between the AECR and each of the klystrons which independently provide power to the source. Very little power was coupled from one wave guide to the other through the plasma chamber. For example when 1.5 kW of microwave power of 14 GHz was launched into the AECR, less than 0.5 W power was measured coming back through the 10 GHz waveguide. In order to provide the ECR surface at 10 GHz, the magnetic field at the center was lowered by 10% compared to the normal field configuration for 14 GHz only. With this two-frequency heating the AECR plasma was more quiescent than with 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 optimum gas and oven

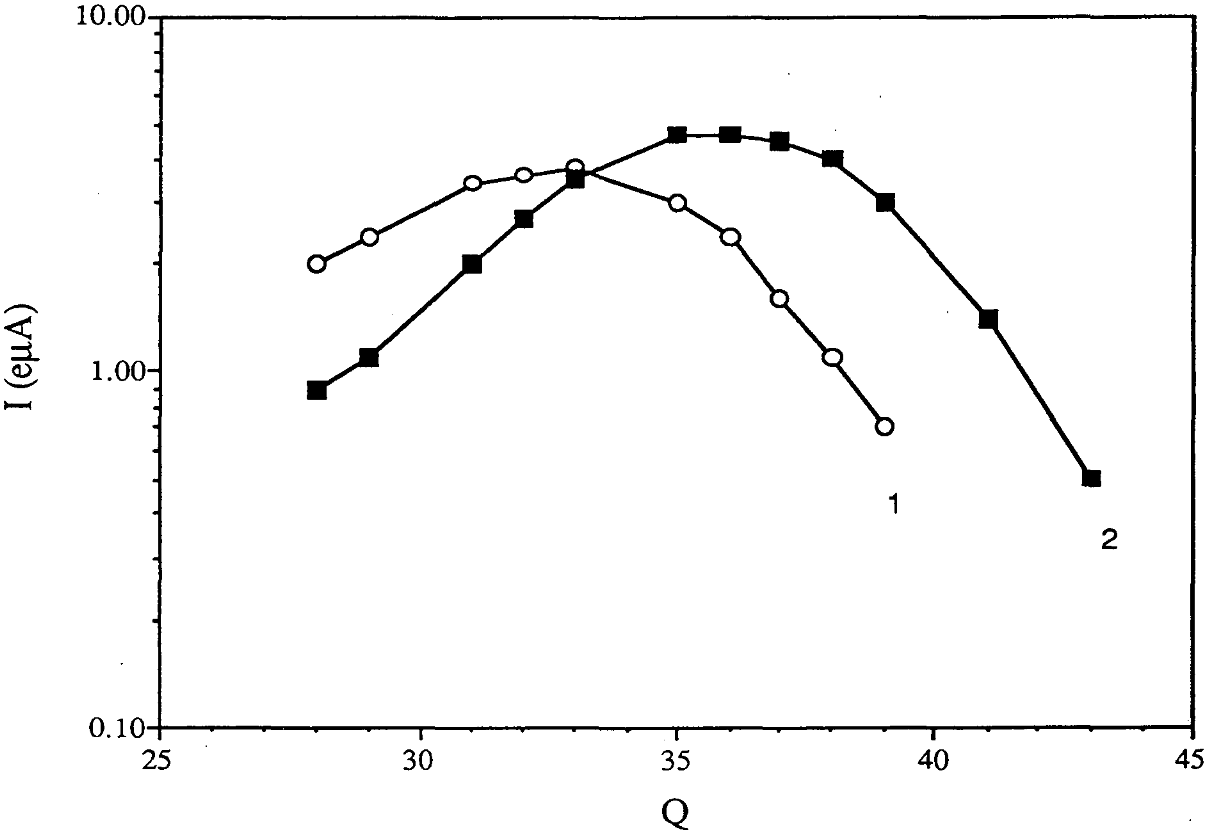

Fig. 1 Charge state distributions for ^{238}U produced with the AECR source are shown for two cases. Curve 1 indicates the best distribution obtained with single-frequency (14 GHz, at power of 1540 W) heating. Curve 2 shows the distribution obtained with two-frequency (14 + 10 GHz, at a total power of 1770 W with 1480 W of 14 GHz and 290 W of 10 GHz) heating. The peak charge state shifts from 33+ in curve 1 to 36+ in curve 2.

	SF + e Gun	SF + Al Coating		TF (14 + 10 GHz)	
Q	**Bi**	**Bi**	**U**	**Bi**	**U**
25	3.8	8.7			
27	5.5	16.6			
28	6.0	19.5			
29	5.7	20.0			
31	4.5	15.7			
32	3.5	12.8	3.6		11
33	2.6	8.4	3.8	12.1	12
34	1.5	6.0	&	10.2	&
36	0.7	2.5	2.4	6.5	8.7
37	0.4	2.2	1.6	5.0	7.1
38	0.2	1.3	1.2	3.2	5.4
39			0.7	&	3.7
40		0.5		1.8	&
41		0.25		1.1	1.5
42				&	1.0
43				&	0.5
44				0.24	
46				0.08	

Table I Comparison of the bismuth and uranium results produced with three different methods as indicated.

Note: **SF**: Single-frequency heating. **TF**: Two-frequency heating. &: Mixed ion species. All ion beams are extracted at 10 kV extraction voltage and through an 8 mm aperture. Currents are in eμA and measured with the Faraday cup biased at 150 V to suppress the secondary electrons.

vapor input levels are reduced by roughly 30% to 50% while the total extracted currents remain essentially the same as with single-frequency heating. Figure 1 shows the best charge state distributions of ^{238}U obtained with single-frequency and two-frequency heating from the AECR source. With about 15% more microwave power compared to the optimum single-frequency heating, two-frequency heating shifted the peak charge state from 33+ to 36+ and increased the intensity by a factor of 2 to 4 higher for charge states from 35+ to 39+. With the same source conditions, such as gas, vapor inputs and total microwave power, the peak charge state for bismuth shifted from 32+ to 33+ and the improvement on intensity was up to a factor of 2 for charge states from 36+ to 40+. While for producing the same high charge state bismuth ions as single-frequency heating at 14 GHz, 30% less two-frequency microwave power was required. High charge state bismuth and uranium ions produced with two-frequency heating and with single-frequency heating are compared in Table I. It clearly shows the greatest improvement is for the highly charged bismuth and uranium ions and increases up to an order of magnitude for the very high charge states were achieved. Improvements also observed on lighter elements. Fully stripped Ar ions, at least 5 enA (≥1x10^9 pps), were produced and directly identified by the AECR charge state analyzing system for the first time.

The improved performance of the AECR source with two-frequency heating makes it possible for the 88-Inch Cyclotron to accelerate the very heavy ions such as bismuth and uranium to an energy above the Coulomb barrier -- 5 MeV/n. The extracted beam intensities were 1x10^6 pps or higher for Bi$^{50+,51+}$ and ^{238}U$^{52+,53+}$.

The details of ECR heating are quite complex;[3] however it is interesting to consider the implications of two-frequency heating in the simplest model where collective effects are ignored and we only consider a single particle model in an underdense plasma. In this model the microwave power is coupled to the electrons as they traverse the ECR resonance zone. Experimental probes have shown that outside the ECR zone the density of hot electrons decreases rapidly.[4] If we assume that the hot electrons are localized to the immediate vicinity of the ECR zones then the presence of a second zone could lead to an increase in the hot electron density at the center. From the calculation of the magnetic field we know that the optimum results were produced with a small (~ 2 cm in length) 10 GHz ECR zone surrounded by a larger (~14 cm in length) 14 GHz ECR zone as indicated in Figure 2. Although the size of the two heating regions are not exactly known, approximating heating zone boundaries with phase differences of $\emptyset = \pm \pi/2$ could give us a hint for what happens inside the AECR plasma. Following Jongen's argument [5] and assuming an electron is in phase with the microwave right on the ECR surface, one would see that a phase difference will occur when it travels away from the ECR surface due to the non-zero magnetic field gradient. The assumption of a constant parallel velocity $v_{//}$ to the magnetic field line gives

$$\emptyset = \frac{1}{2}\frac{\partial B}{\partial s}\frac{e}{m_e}\frac{s^2}{v_{//}}$$

where $v_{//}t = s$ is the distance along the field line, $\frac{\partial B}{\partial s}$ is the magnetic field gradient and $\frac{e}{m_e}$ is the ratio of charge to mass of the electron. By letting $\emptyset = \pm \pi/2$ one will be able to approximate a heating region of half width and this region is proportional to $\sqrt{v_{//}}$, i.e., cold electrons will result in a narrower heating zone than the energetic electrons. Thus a heating zone defined for the energetic electrons covers the heating zones for the colder electrons. The temperature of the hot electrons in the AECR source is a few tens of keV,[6] so it is reasonable to assume a hot electron can have a few keV energy along the magnetic field line. Shown in Figure 2 are two approximated heating zones, assuming the electrons have a longitudinal energy of 2 keV, for 10.3 and 14.3 GHz microwaves for the AECR source with the field configuration which produced the best uranium performance. This field configuration provides a small ECR surface of about 2 cm long on axis at 10 GHz and the distance between the two ECR surfaces is 6 cm. It indicates that the heating zones for these two frequencies are well separated which means the heating in the AECR source is more distributed. If the frequency spacing is small, then there may not be a separate heating zone but a thickening of the first heating zone, and the effect of the second frequency may exist but not be significant enough to be identified. Those electrons with large mirror ratios will oscillate between the mirrors and cross both ECR zones in each reflection. Electrons with low mirror ratios on the other hand will oscillate only close to the bottom of the mirror and only be heated by the 10 GHz microwaves. It is reasonable to expect that the presence of this second (10 GHz) zone would lead to enhanced density of magnetically trapped hot electrons. This in turn would improve the confinement of high charge state ions by increasing the plasma potential dip [8] assumed to be responsible for the long confinement times measured in high charge state ECR sources.

The production of highly charged ions in an ECR source requires high microwave power to increase the plasma density [7] and low neutral pressures to reduce the charge exchange between ions and neutrals. Plasma instabilities generally limit the amount of microwave power that can be injected into the plasma for the production of highly charged ions. The localized plasma heating which occurs in a narrow region at the ECR surface may contribute to the ECR plasma instabilities.[9] Experimentally, this distributed two-frequency heating reduces the plasma instabilities. A stable plasma could increase the average lifetimes of both the electrons and ions. As long as the plasma is stable, more microwave power can be injected and the neutral pressure can be reduced. Therefore improved production of very highly charged ions and increased ionization efficiency may be due to improved plasma stability achieved with two-frequency heating.

These tests also showed that, with the same total microwave power, two-frequency heating produces better results than single-frequency heating and that for the same output of the high charge state ions it takes less total microwave power if the plasma is heated with two frequencies. This indicates that even if the plasma heating in an ECR is stochastic, source performance can be improved by heating the plasma with two widely spaced microwave frequencies. The addition of a very high and off-resonance frequency might give even better ECR performance.[10]

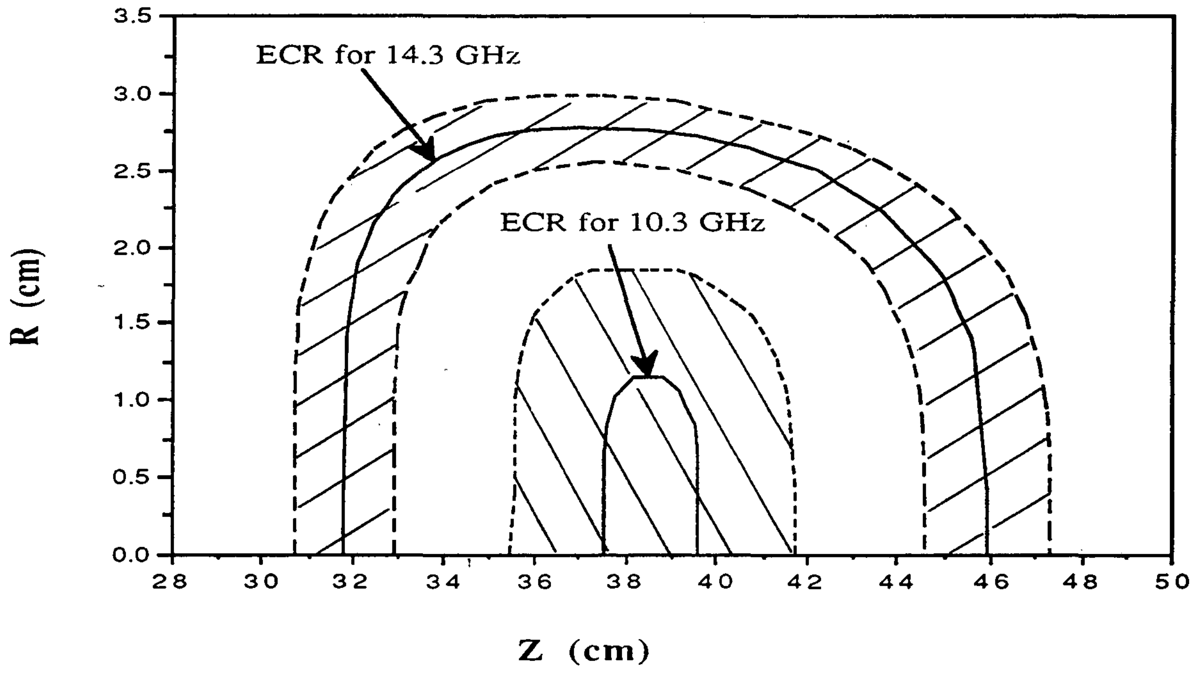

Fig. 2 Approximated heating zones (hatched regions), by assuming the electrons have 2 keV energy along the field lines, for 10.3 and 14.3 GHz in the AECR source with the magnetic field configuration for the best performance on uranium. It indicates that there are two well separate heating zones in the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

Two-frequency heating has been previously explored by other groups. The ELMO facility was used to study the heating of high-B plasmas in a simple mirror machine. In this test the second frequency heating was off-resonance, but generated strong coupling.[10] More recently, Geller et al reported tests using microwave power at 10 GHz and additional power with variable frequency f_V between 9.6 and 11 GHz.[1] They reported that the optimum source performance was independent of f_V and when the sum of the powers was equal to the single frequency power no enhancement was observed. The most obvious difference between this Grenoble work and the work reported here is that the frequency difference was much larger in our tests. This results in a larger physical separation between the ECR zones that may be significant. Further experiments are needed to identify the critical factors for successful two-frequency heating.

Two-frequency heating using 10 and 14 GHz in the AECR provides significantly better performance and indicates that still higher performance with multiple-frequency heating may be possible. Among the open questions is what is the optimum spacing between frequencies. Klystrons are typically used to provide the microwave power for ECR sources and generally their bandwidths are relatively narrow, which may not be optimum for multiple-frequency heating, as indicated by the Grenoble results.[1] Therefore the option of several klystrons, each operating at different frequencies, would be a straight-forward method to provide multiple-frequency heating. Another approach might be to use lower power solid state amplifiers to provide multiple frequencies. While multiple-frequency heating would increase the complexity and cost of an ECR source, it could provide significant performance gains.

Effects of Aluminum Coating in the AECR Source

Although the current understanding of the mechanisms involved is incomplete, it is experimentally demonstrated that an ECR plasma needs extra electrons, beside the primary electrons coming from the ionization process, to enhance the production of high charge state ions.[11] These extra electrons can be actively provided by a microwave-driven first stage, electron gun, biased disk, or they can be passively provided by chamber surface coatings with high secondary electron emission such as silicon oxide, thorium and aluminum oxide.[1,12-15] The active methods, such as a microwave-driven first stage and an electron gun, inject the extra electrons into the plasma mainly along the axis so the electrons have mostly longitudinal velocity. Also the employment of these methods is more complex and costly than using the surface coatings. In an ECR source the chamber wall surface is parallel to the axis therefor a large portion of the secondary electrons emitted from the surface are mainly perpendicular to the axis. Thus the electrons emitted from the surface can have a higher ratio of the transverse velocity to its longitudinal velocity and a higher probability of being trapped in the plasma compared to the electrons injected by the active methods. Therefore the surface coating could be a more efficient method to provide the extra electrons to an ECR plasma and results in even better performance. Empirically speaking, a good surface coating for an ECR source should have the following characteristics:

1. High secondary electron emission.
2. Long lifetime, i.e., coating should resist plasma etching.
3. Low material sticking coefficients to minimize the surface memory.

Although the secondary electron emission of Al_2O_3 is not the highest, it is a good coating for an ECR source because it is strong against plasma etching. With such an Al_2O_3 aluminum coating and a biased probe the AECR runs in a mode that does not require gas mixing for optimum performance of the intermediate and higher charge state ions for noble gases up to xenon. For bismuth a smaller amount of mixing gas helps. In general, the aluminum coating allows the AECR to operate at lower neutral pressures and produces a strong enhancement of the highest charge state intensities, especially for the heavier elements. The enhancement produced by the aluminum coating in comparison to electron injection and gas mixing is indicated in Table I. For bismuth the oxygen mixing level was about 20% lower than the case of no coating but electron injection was used.

Plasma potential measurements were carried out with the aluminum oxide coating at the same running conditions for an oxygen plasma as the previous measurements.[16] As shown in Figure 3, the plasma potential with the aluminum oxide coating is a factor two to three lower than the case of no electron injection and is up to a factor of 2 lower than the case of external electron injection under the indicated running conditions. The plasma potential with the aluminum coating is essentially independent of microwave power within the measurement error in contrast to the other cases. The independence of plasma potential with microwave power may indicate that as the microwave power increases, more secondary electrons are emitted from the walls to compensate for the increasing number of electrons that escape the plasma. With a plasma potential in the order of tens of volts in an ECR plasma, the energy of the multiply charged ions can be a few hundred eV when they arrive at the chamber wall. These energetic ions can sputter the chamber surface materials and the sputtered off materials can interfere with the production of high charge state ions as an uncontrolled material feed which can contribute to the plasma instability and beam contamination. Therefore the production of high charge state ions can surely benefit from a lower plasma potential which results in a more stable plasma.[8] Experiments have shown that with gas mixing, external electron injection or wall coating, the ECR plasma is more quiescent and better source performance can be obtained. Plasma potential measurements indicate that under any of these conditions, the plasma potentials are lower than when none is present. The aluminum coating results in the lowest the plasma potential and the best source performance among the compared cases.

The preliminary tests have shown the lifetime of the aluminum coating in the AECR source is at least one month or longer. A very low level of aluminum beam contamination was observed, a few enA compared to as much as 10 eμA of copper without coating. The memory of various materials by the aluminum coating does not seem to be in any way worse than the copper walls, so the material sticking coefficient of aluminum coating is not a serious issue for daily source operation. As a result of the improved performance by the aluminum coating, it has replaced the electron gun on the AECR source.

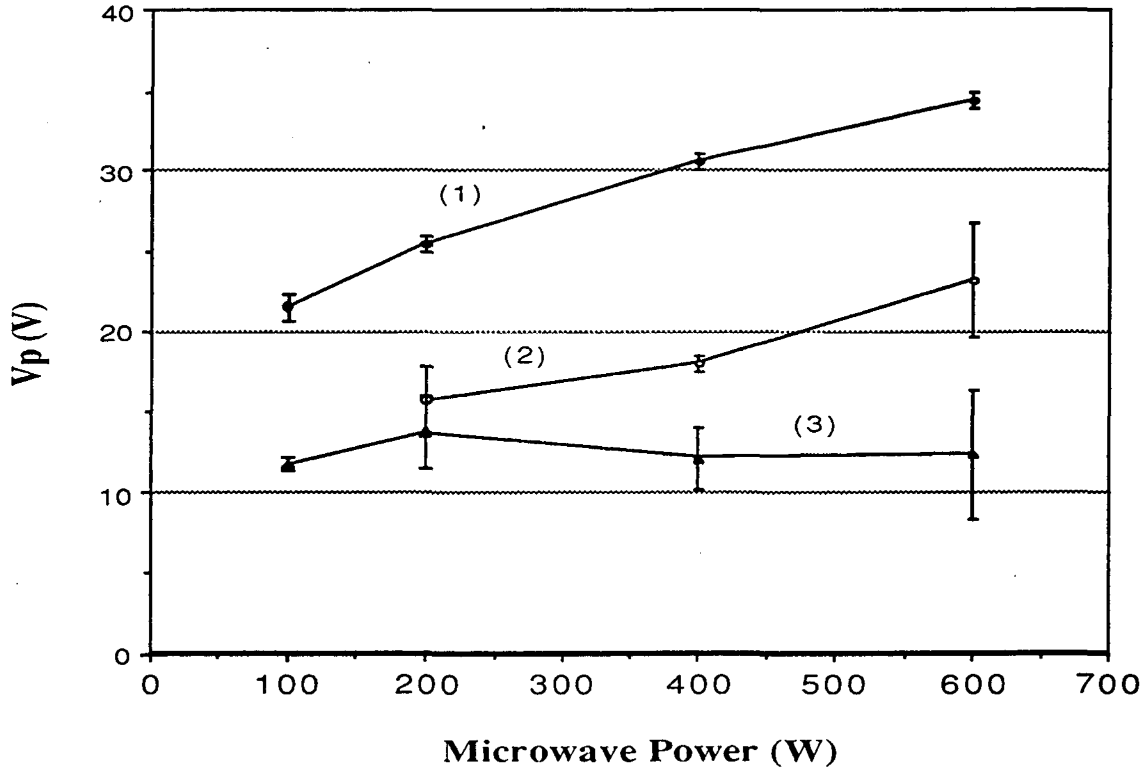

Fig. 3 Plasma potentials of oxygen at the same gas flow (pressure P = 1.6×10^{-6} Torr) for three cases at various microwave power levels. Curve (1) indicates the case of no electron injection and without a coating and curve (2) shows the case with external electron injection by an electron gun. Curve (3) indicates the potential with an aluminum oxide coating which is essentially independent of microwave power and is a factor of almost 2 to 3 lower than cases of (1) and (2).

AECR Upgrade

Although the performance of the AECR source has been improved steadily,[11,17] higher intensities of high and intermediate charge state ions, especially for elements with mass greater than 100, are of great importance for the scientific programs at 88-Inch Cyclotron, such as Gammasphere and complex fragmentation. An upgrade is underway on the AECR source to modify its magnetic field structure and raise its peak magnetic field strengths as well as the maximum mirror ratios to improve the plasma confinement.

Shown in Figure 4 is a schematic view of the expected axial field profile. The existing solenoid pancakes made from 0.25 inch hollow copper conductor will be replaced by new and larger ones of 0.313 inch, and the maximum current density will increase from 740 A/cm^2 to 950 A/cm^2. The injection magnet will be shortened to the same length as that of the extraction region since there is no need to reserve field and space for a microwave-driven first stage. The thickness of the iron return yoke will be doubled (from 3 cm to 6 cm) and iron plugs will be used at both the injection and extraction regions to concentrate the field flux inside the plasma chamber. With these modifications and at the same total dc magnet power consumption of 75 kW as the existing configuration, the peak field strengths at the injection and the extraction regions will increase about 70% while the central field strength remains the same, thus the mirror ratios will be increased accordingly, i.e., from 2.4 to 4.1 at the injection side and from 1.8 to 3.0 at the extraction region. The new plasma chamber will be made from aluminum to increase the yield of secondary electrons and eliminate the copper contamination. The inner diameter of the plasma chamber will increase from 7.0 cm to 7.7 cm. With a new sextupole magnet constructed from NdFeB permanent magnets the maximum radial field strength at the wall will reach 1.0 Tesla. Radial oven access will be reserved and off axis wave feed will be tested to investigate the feasibility of axial oven access for

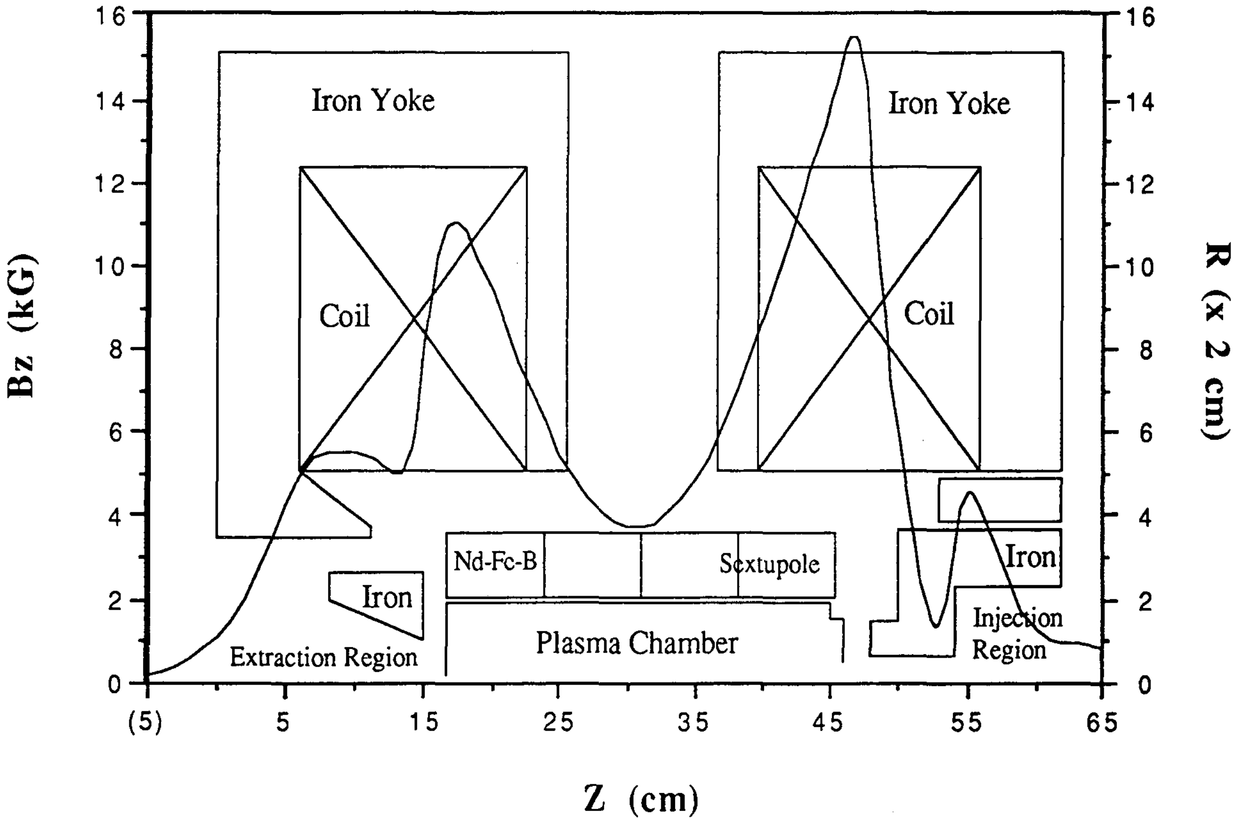

Fig. 4 The conceptual design of the upgraded AECR source. At dc power of 75 kW and with iron plugs to concentrate the field flux, the maximum peak field strengths on axis will reach 1.5 and 1.1 Tesla at the injection and extraction region respectively. In addition, a set of new NdFeB permanent sextupole magnet will increase the maximum radial field strength at the wall to 1 Tesla.

better efficiency. Plasma in this upgraded AECR source will be heated by microwaves of 10 and 14 GHz or multiple-frequency.

A collaboration between the Berkeley and ATLAS ECR groups will result in a second upgraded AECR source being built at Argonne National Laboratory.[18]

Acknowledgment

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