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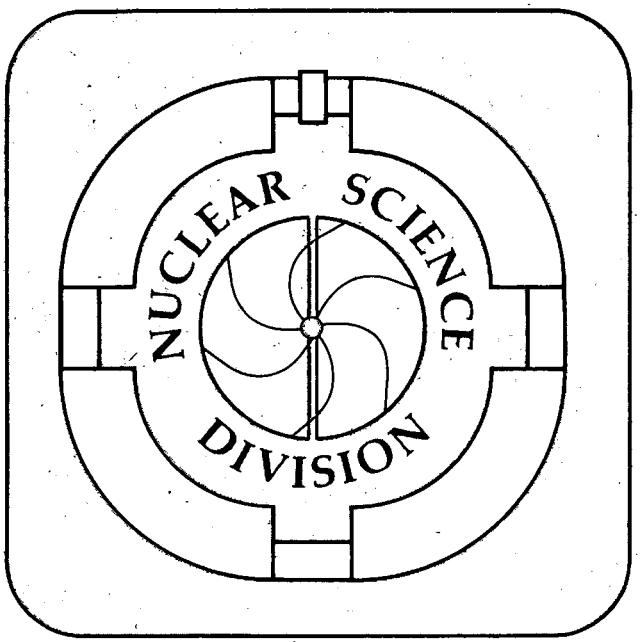

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Plasma potentials and performance of the advanced electron cyclotron resonance ion source

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The mean plasma potential was measured on the LBL Advanced Electron Cyclotron Resonance (AECR) ion source for a variety of conditions. The mean potentials for plasmas of oxygen, argon and argon mixed with oxygen in the AECR were determined. These plasma potentials are positive with respect to the plasma chamber wall and are on the order of tens of volts. Electrons injected into the plasma by an electron gun or from an aluminum oxide wall coating with a very high secondary electron emission reduce the plasma potential as does gas mixing. A lower plasma potential in the AECR source coincides with enhanced production of high charged state ions indicating longer ion confinement times. The effect of the extra electrons from external injection or wall coatings is to lower the average plasma potential and to increase the $n_e\tau_i$ of the ECR plasma. With sufficient extra electrons the need for gas mixing can be eliminated or reduced to a lower level, so the source can operate at lower neutral pressures. A reduction of the neutral pressure decreases charge exchange between ions and neutrals and enhances the production of high charge state ions. An aluminum oxide coating results in the lowest plasma potential among the three methods discussed and the best source performance.

I. INTRODUCTION

Electron Cyclotron Resonance ion sources are used for a variety of applications both for the production of singly charged ions and for multiply charged ions. The focus of this paper is on the characteristics of ECR sources used for the production of highly charged ions that are typically used with heavy-ion accelerators or atomic physics experiments. During the last two decades steady progress has been made on ECR sources in terms of performance and theory. Frequently, progress has been made first experimentally with theoretical insight following. In this paper we report the development of a technique to measure the plasma potential in high charge state ECR sources and the use of this technique to study some experimentally known methods for enhancing source performance.

ECR ion sources produce multiply charged ions in a plasma in which the ions and electrons remain in dynamic equilibrium to maintain the neutrality of outgoing plasma, that is, the plasma loss rate is equal to and determined by the production rate. The primary source of cold electrons in these devices is the stepwise ionization of atoms and ions. However, the extra electrons such as secondary electron emission from the walls,[1,2] electron gun,[3] or biased probe[4] can be used to modify the electron balance. The cold electrons, which are not magnetically confined, tend to escape more rapidly from the plasma than the ions because of their much higher mobility. As a result a positive plasma potential builds up to retard the escape of electrons and to accelerate the escape of the ions from the plasma to maintain equilibrium.[5] This process is very similar to the ambipolar diffusion effect in a lowly ionized plasma. Thus in an ECR source the average ion confinement time in the plasma is linked to the net loss of the electrons by the average plasma potential. There are many parameters involved in the ECR plasma, so the plasma potential should be a function of the related parameters

$$V_p = f(n_e, n_i, n_0, T_e, T_i, m_i, B, \Omega_w)$$

where n_e, n_i, and n_0 are the electron, ion and neutral density distributions, T_e and T_i the electron and ion temperature, m_i the ion mass, B the source magnetic field and Ω_w the plasma chamber configuration and wall condition. Some of these parameters may depend on the others. The product of $n_e\tau_i$ plays a dominant role in determining the charge state distribution for ECR plasmas.

Enhanced production of high charge state ions as a result of wall coatings has been experimentally observed for a variety of coating including silicon,[2] thorium[1] and aluminum oxide.[6] The coatings are typically done by evaporating the coating material into a plasma with a mixing gas such as oxygen. For silicon the resulting coating is probably the SiO_2 which has a maximum secondary electron emission coefficient of 4. All of these materials have high secondary emission coefficients and can serve as a source of cold electrons for the plasma.

It was discovered during operation of ECR sources that the production of high charge state ions can be substantially enhanced by adding a light support or mixing gas to the ECR plasma.[1,7] Normally about 80% mixing gas is used and it can be up to 95% or higher for very heavy elements. A high ratio of mixing gas increases the neutral pressure inside the ECR plasma and may also limit the production of higher charge states or the maximum intensity of the heavier ions. Plausible explanations for the gas mixing effect have been proposed, including an elastic collision cooling and an evaporative cooling mechanism.[8,9,10] Whether one of these mechanisms or some other is responsible for the effect in ECR sources remains open to debate. As described below there appears to be a link between the injection of electrons and gas mixing.

The LBL AECR, shown in Fig. 1, was built in 1990 as a second ECR source for the 88-Inch Cyclotron.[11] As expected, it provides higher charge states and more intense heavy-ion beams in comparison to the older source. The addition of a second source also provides more operational flexibility and allows source development to continue. It is designed to operate at 14 GHz based on the frequency scaling proposed by Geller et al.[12] The discovery of the "silicon-effect,"[2] a coating effect, prompted the idea of adding extra electrons to the plasma to enhance the AECR source performance. In May 1990, the development of an electron gun, which axially injects the electrons into the plasma, enhanced the performance of the AECR by a factor of two to three over its performance with a silicon coating.[3] In these operating modes gas mixing is still beneficial but at a much lower percentage with no electron injection. For optimum results, electron beams of 10 to 30 mA at energies from 50 to 200 eV are injected into the plasma. Larger currents are required for heavier ions. The enhancement of source performance by external electron injection has been reported by other ECR workers using biased probes, electron gun or biased plasma cathode.[4,6,13]

An investigation was carried out on the LBL AECR to measure how these extra electrons affect the ECR plasma potentials. In this paper, the preliminary studies are presented.

II. PLASMA POTENTIALS IN THE AECR

Because of the large number of hot electrons in the ECR plasma, deep insertion of any probe to the plasma will either melt the probe or dramatically reduces the number of hot electrons. Thus a direct measurement of plasma potentials in ECR sources by using a Langmuir probe is not possible. However the plasma potential can be determined by carefully measuring the energy of ions extracted from a source. If there is a uniform potential difference between the plasma and the chamber wall (i.e., a plasma potential), then total energy of the ions extracted will be equal to the charge state multiplied by the sum of the plasma potential and the source bias potential. We used the 90° analyzing system on the AECR to measure the total energy of the ions as a function of applied bias voltage. The value of the plasma potential was then extracted from these measurements.

The relationship between the magnetic field required to bend an ion beam can be written as

$$B_{90}^2 = \frac{Km_i}{Q}(V_s+V_p)$$

where K is a constant, Q the ion charge state, V_s the source bias potential and V_p the mean plasma potential. V_p can be determined if B_{90}, V_s, K, and $\frac{m_i}{Q}$ are known.

For maximum resolution, all the measurements were done with narrow slits, 1 mm opening, at the object and image points of the 90° bending magnet. Meters with 0.01% accuracy (a Keithley 191 digital multimeter and a GMW DTM-141D Digital Teslameter) were used to measure the source bias voltage V_s and the bending magnetic field B_{90}. For all of the measurements the source magnetic field was kept constant and not optimized for individual charge states. Oxygen and argon gases were used in the measurements. The source bias voltage was varied and the corresponding bending magnetic field B_{90} was measured. V_p was evaluated by plotting the square of the bending magnetic field B_{90} versus the source bias potentials V_s and fitting the data with a least square fit to determine the offset that is equal to the mean plasma potential. V_p was then measured as a function of gas flow and microwave power for oxygen and argon.

Figure 2 shows a set of data and the least square fits for oxygen beams of charge from 4+ to 7+ as a function of source bias potentials at a constant gas flow and microwave power. It shows that all the ions of different charge have escaped from a same plasma potential. This potential is positive with respect to the plasma chamber wall which is at the source bias potential V_S. In Fig. 3 the plasma potentials of an oxygen plasma at various microwave power levels for two different gas flows are shown along with one case with external electron injection. Without external electron injection, higher gas flow shows a slightly higher plasma potential. Injecting a 17 mA electron beam at 200 eV into the source reduces the plasma potentials about 10 V. A similar reduction in the plasma potential has been reported when electrons are injected into cusp ion sources.[14] In all three cases shown in Fig. 3, the plasma potential increases with the microwave power. Figure 4 shows the plasma potentials for an argon plasma are slightly higher than for an oxygen plasma at about the same gas input. This may be a mass effect since the average mobility of argon ions is lower than oxygen ions. Thus a higher plasma potential is required to push the argon ions out of the plasma to maintain the equilibrium. On this basis, the addition of a lighter gas to the plasma should lower plasma potential. In Fig. 5, the plasma potentials of an argon mixed with oxygen at a ratio of 1 to 1 are lower than those for a pure argon feed supporting the above model.

The measured plasma potential dependence on microwave power, neutral gas flow and electron injection is very similar to an ambipolar diffusion. First, as the microwave power increases, the plasma potential rises. In ECR sources, the plasma density generally increases with microwave power[15] and so do the electron and ion density gradients because the plasma is confined in a cavity of fixed dimensions. A higher density gradient would tend to enhance the escape of the electrons and ions, but the difference in mobility between the electrons and ions results in a higher plasma potential. Second, injecting electrons at constant microwave power reduces the plasma potential. Since injecting cold electrons reduces the net rate at which electrons are lost, this should reduce the plasma potential. Third, increasing the neutral density (gas flow) within the ECR source operation conditions generally increases the plasma density, so the plasma potential should increase. Fourth, heavier elements produce higher plasma potentials. This may be due to the decreased mobility of the higher mass ions, which would then require a higher potential to balance the electron losses. Finally, light mixing gases reduce the potential and such reduction is consistent with the ambipolar diffusion since it would increase the average ion mobility.

The plasma potential in the AECR is on the order of a 10 to 40 volts. This is much lower than the potentials measured in the large test device Constance-B[16] which were in the range of 90 to 200 V. A positive potential increases the loss of ions at the edge of the plasma. However, to produce high charge state ions such as O^{7+} or Ar^{16+} in an ECR plasma requires that the ion be confined on the order of tens of milliseconds.[17] Transit times for ions even at a low energy of 1 eV are much shorter than that. In a model with a flat plasma potential across the chamber with a steep gradient in the sheath near the wall, it is difficult to understand how such long confinement times can be generated. On the other hand, if the plasma potential has a small well in the middle, this could provide the required confinement. A shallow potential well (possibly a few volts deep) resulting from two populations of electrons with different temperatures in a mirror field has been proposed.[5] The high charge state ions would be confined in this potential well thereby accounting for the production of very high charge states in ECR sources. The reported afterglow effect also suggests the existence of such plasma potential well.[4,18]

The measurements discussed above show that the average plasma potential can be reduced by either the injection of electrons with an electron gun or by gas mixing. Both of these techniques

increase the $n_e\tau_i$ product as evidenced by a shift of the charge state distribution to higher charges. This shift of the charge state distribution may indicate that both the injection of electrons and gas mixing increase the depth of the potential well in ECR plasma.

Tests with the AECR source indicate that electron injection can replace gas mixing at least for relatively light elements such as oxygen and nitrogen. For these light elements, the AECR source with optimized electron injection generally produces better results than gas mixing without electron injection, and no further gain is achieved with gas mixing. With electrons added 90 eμA of Ar^{11+} was produced without gas mixing.[19] However for argon, better results were achieved when electron injection was combined with a modest amount of oxygen gas mixing (141 eμA of Ar^{11+}). At least qualitatively, it appears that the effects of gas mixing and electron injection are closely linked. The fact that for heavy elements gas mixing still helps even with the electron injection may indicate a better method of injecting electrons into the AECR needs to be developed. Biased probe has been tested in the AECR source and the results were 30 to 40% lower than the case of electrons injected by a gun. In the AECR the electron gun is located on axis at the peak of the injection mirror field. The injected electrons have mainly longitudinal energy and very little transverse energy which makes the probability for magnetically trapping these electrons in the plasma is very low.

III. ALUMINUM COATING IN THE AECR SOURCE

A competing technique for adding electrons to an ECR plasma is to use a wall coating with a high secondary emission coefficient. This technique was exploited by using SiO_2 on the walls of the LBL ECR to boost its performance.[2] While this method also produced good results with the AECR, it was found to have a relatively short lifetime of about 24 hours. Therefore we decided to test aluminum coatings in the AECR which significantly enhanced the performance of the RIKEN ECR.[6] The RIKEN group reported that after coating their source with Al_2O_3 gas mixing was no longer required for optimum production of high charge state argon. Aluminum oxide has two potential advantages over SiO_2. First it has a secondary emission coefficient of about 9 compared to 4 for SiO_2. Second it is a very tough coating and should resist plasma etching better.

To produce the Al_2O_3 wall coating on the copper plasma chamber of the AECR we coated the walls with an aluminum film by using a high temperature oven to evaporate the aluminum. The film was then exposed to air so that the oxide could grow. In addition the copper extraction plate of the AECR was replaced by an aluminum extraction plate. With the aluminum coating and a biased probe the AECR runs in a mode that does not require gas mixing for optimum performance for noble gases up to xenon. For ^{209}Bi 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. Table I illustrates the enhancement produced by the aluminum coating in comparison to electron injection and gas mixing. For bismuth the oxygen mixing level was about 20% lower than the case of no coatings but electron injection were used.

Plasma potential measurements were carried out with the aluminum oxide coating in the AECR source at the same running conditions for an oxygen plasma as the previous measurements. Figure 6 shows the plasma potentials measured with aluminum oxide coating in comparison to the plasma potentials measured without a coating. 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 aluminum 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, the secondary electrons emitted from the walls compensate for the increasing number of electrons that escape the plasma. The preliminary tests have shown the lifetime of the aluminum oxide coating in the AECR source is at least one month or longer. The aluminum oxide coating is a highly effective alternative to an electron gun to provide electrons to an ECR plasma.. The results with an aluminum oxide coating also show that gas mixing is not necessary for the production of high charge state ions at least for noble gases up to xenon. The enhancement in the production of high charge state heavy ions is up to a factor of three to four with an aluminum oxide coating and a biased probe, compared with electrons injected by an electron gun.

IV. DISCUSSION

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 measurement indicate that under any of these conditions, the plasma potentials are lower than when none is present. With a plasma potential in the order of tens of volts, the energy of the multiply charged ions in an ECR source can be of a few hundred eV when they arrive at the chamber wall . These energetic ions can sputter the chamber surface and this sputtering process may contribute to the plasma instability. In addition to the possibility that there is a deeper potential well when the mean plasma potential is lower, the ECR source performance may also benefit from lower sputtering rates.

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Table I

Preliminary Results of AECR Source with Aluminum Coating and Comparison with External Electron Injection and Gas Mixing

	Ne (eμA)		Ar (eμA)		Kr (eμA)		Xe (eμA)		Bi (eμA)	
Q	Ext	Int	Ext	Int	Ext	Int	Ext	Int	Ext	Am
6	121	181								
7	90	138								
8	86	122								
9	7.5	18.5								
11			141	161						
12			78	110						
13			34	53						
14			17	24						
15			&	~10	44	85				
16			1.4	2.5	&	&				
17					48	100				
18					45	94				
19					36	77.5	24.5	33		
20					23	57.5	27	40		
21					13	40.5	28.5	44		
22					10	27	29.5	48		
23					6.8	18.5	29.5	55		
24					4	11	30	64		
25					2.2	5.5	&	68	3.8	8.7
26					1.0	3.0	&	56	&	&
27					&	&	12	37.5	5.5	16.6
28					.25	.6	6.8	21	6	19.5
29							&	&	5.7	20
30							2.5	5.0	&	&
31							1.0	1.5	4.5	15.7
32								.5	3.5	12.8
33								.15	2.6	8.4
34									1.5	6.0
36									.7	2.5
37									.4	1.4
38									.2	.75

Note: Ext -- External electron injection and gas mixing.
Int -- Aluminum oxide coating and no feeding of support gases.
Am -- Aluminum oxide coating and low level of support gas.
& --- Mixed ion species.

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

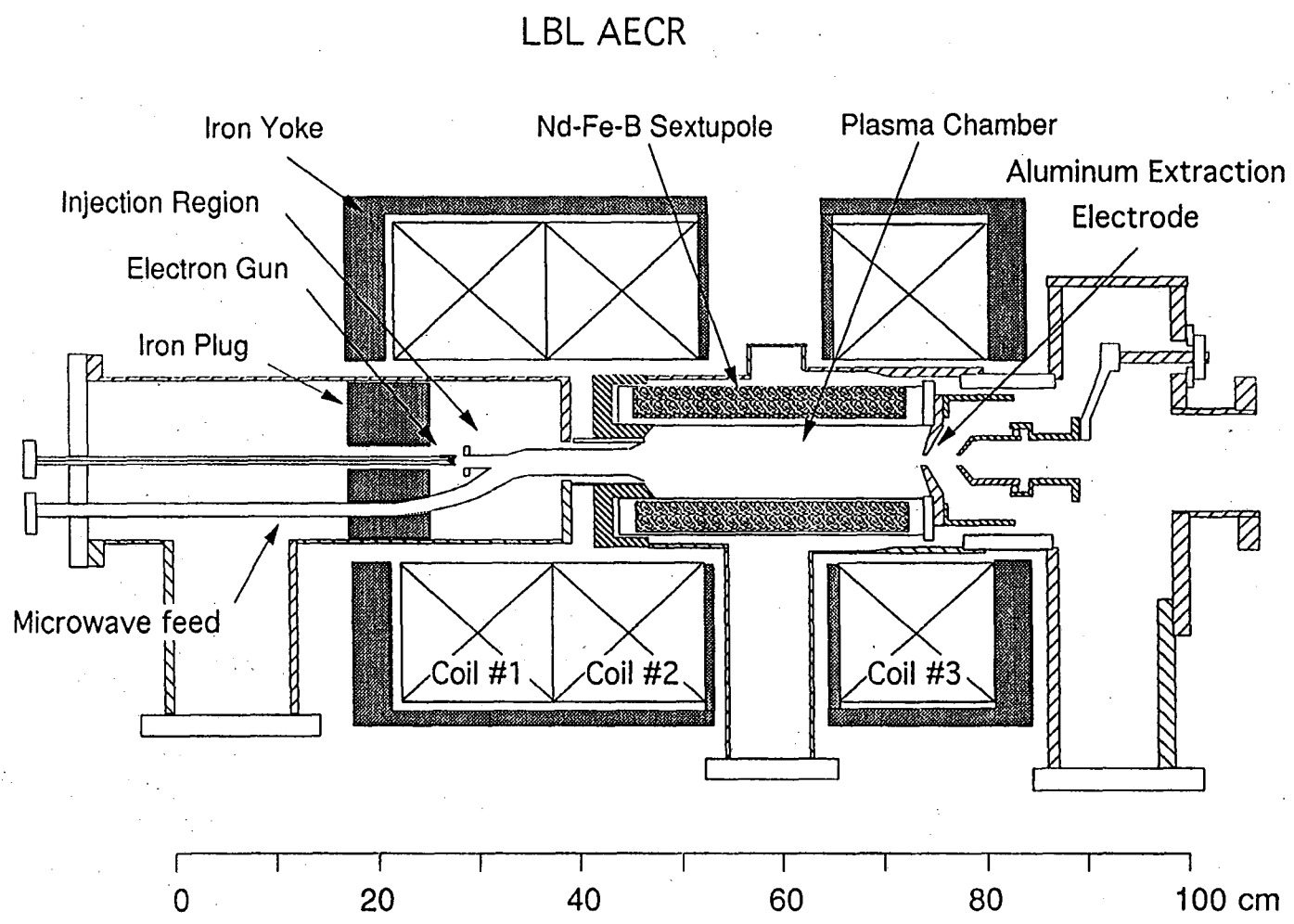

Fig. 1. Schematic drawing of the AECR. The axial magnetic field is produced by copper coils in an iron yoke. The iron plug on the injection side was added to increase the axial magnetic field. Electrons from a LaB_6 filament flow along the axial magnetic field lines into the plasma chamber.

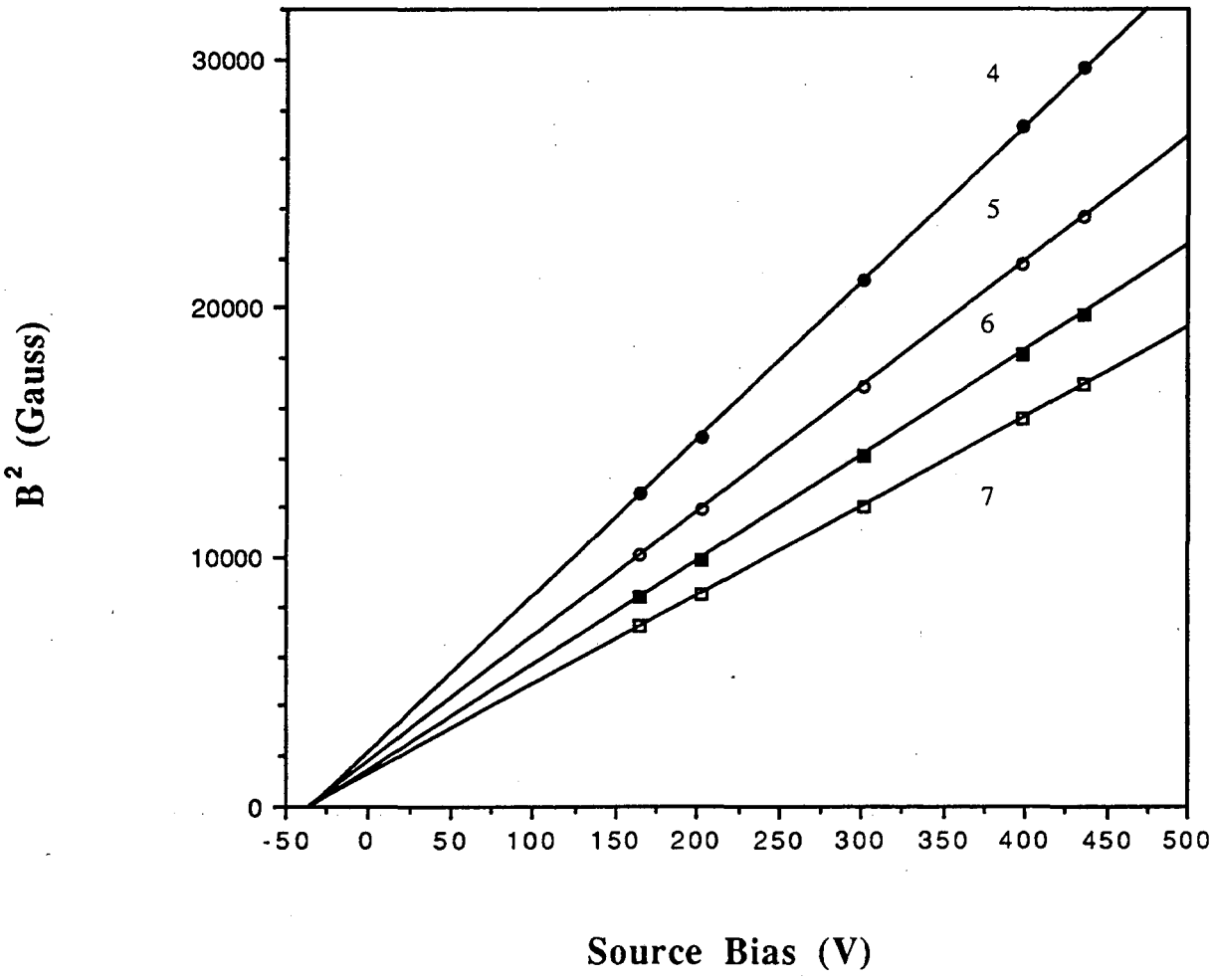

Fig. 2. Measurement data for oxygen beams with charge states from 4+ to 7+. The least square fit lines all have a same intercept that corresponds to the plasma potential. The AECR source conditions were kept constant except for the source bias which was varied. Pure oxygen gas was fed to the plasma chamber at pressure of 1.6×10^{-6} Torr and at microwave power of 600 W.

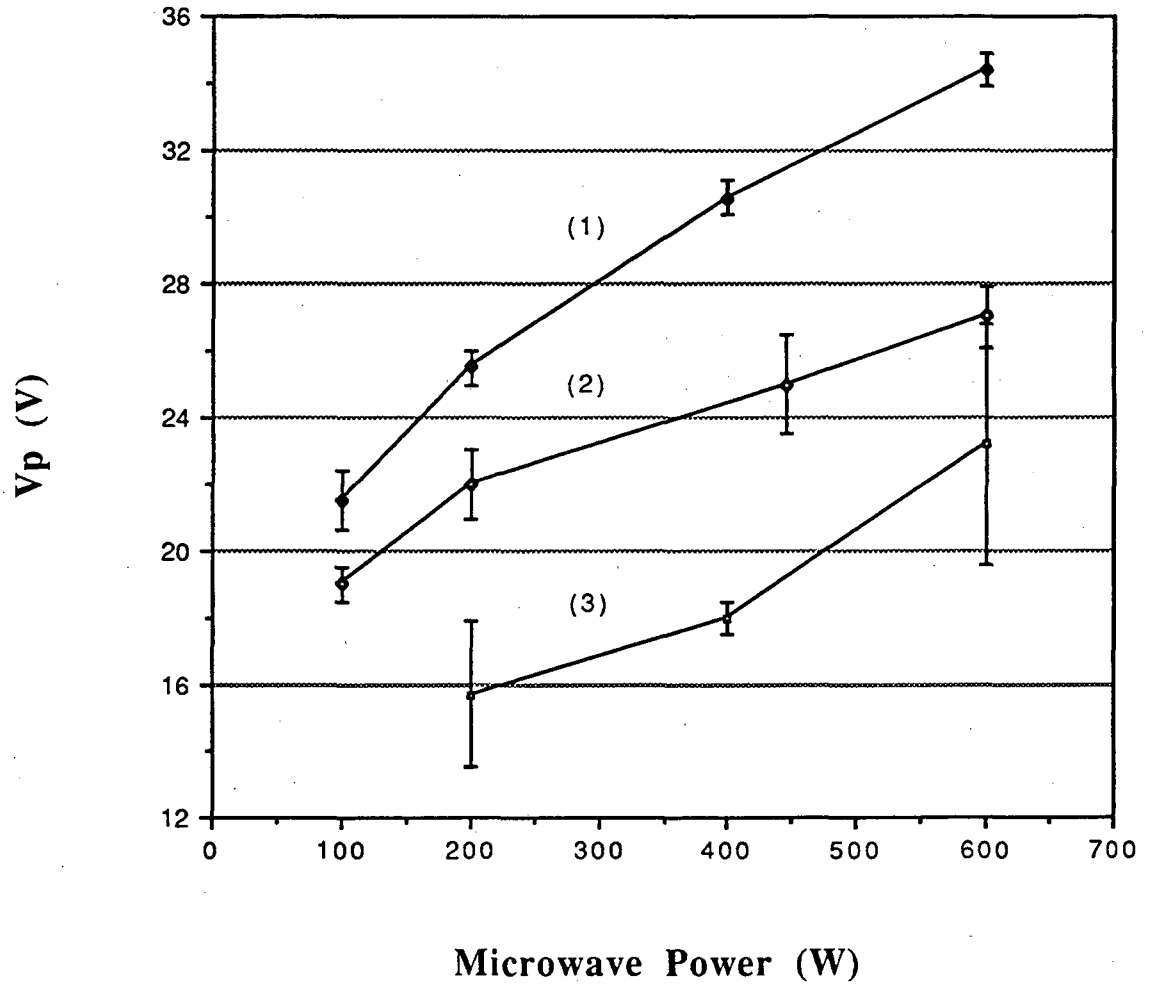

Fig. 3. The upper two curves (1) and (2) show the plasma potential of oxygen as a function of microwave power for two different pressures (P1 = 1.6×10^{-6} Torr and P2 = 1.0×10^{-6} Torr) without external electron injection. The lower curve (3) shows that the externally injected electrons reduce the plasma potential to a substantial level. In this case, 17 mA electrons with 200 eV energy are injected into the plasma and the pressure is the same as the case indicated by curve (1). Higher microwave power results in higher plasma potential in all three cases.

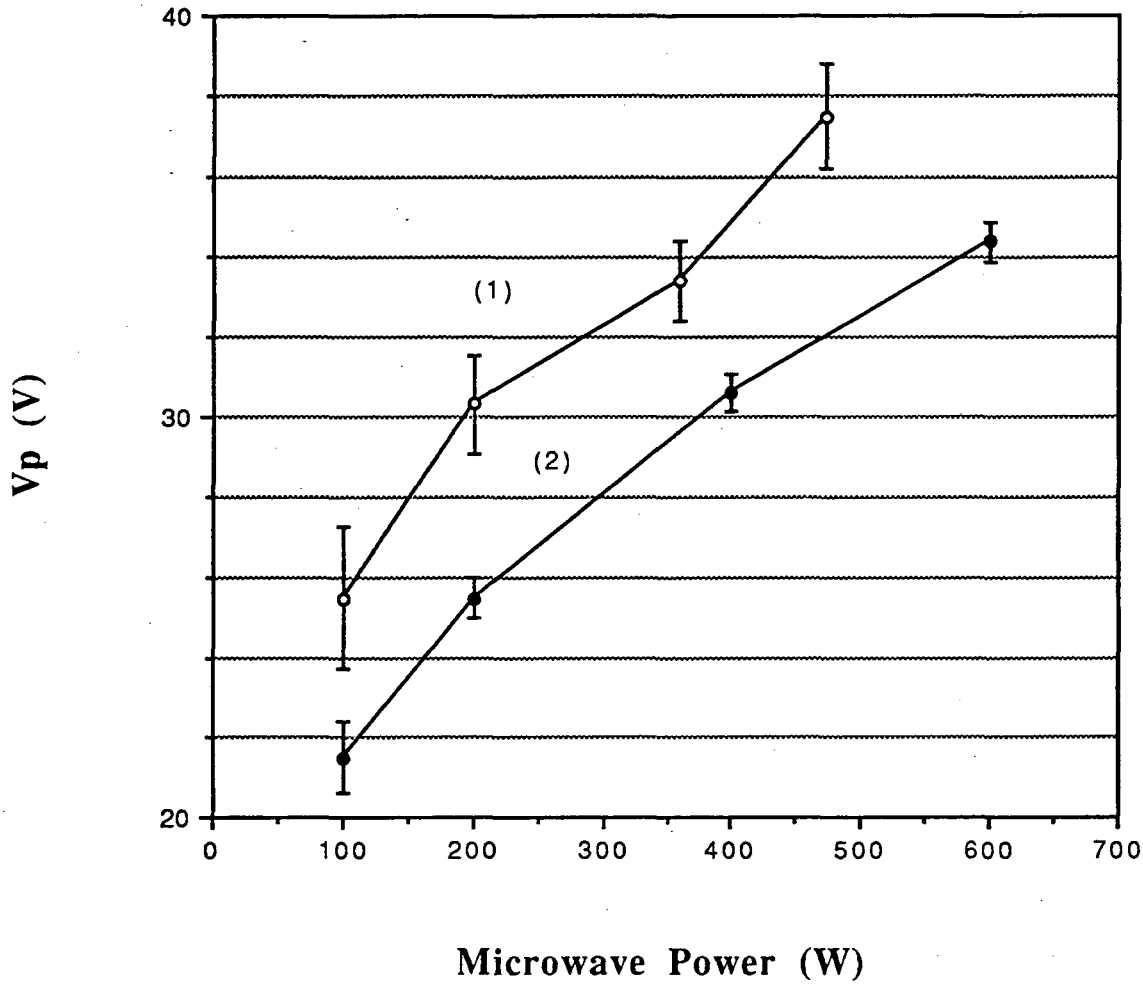

Figure 4. Plasma potentials of a pure argon (curve (1)) and a pure oxygen (curve (2)) at about the same gas flow (pressure of 1.6×10^{-6} Torr) as a function of microwave power in the AECR. Argon which is heavier results in a higher plasma potential compared to the oxygen.

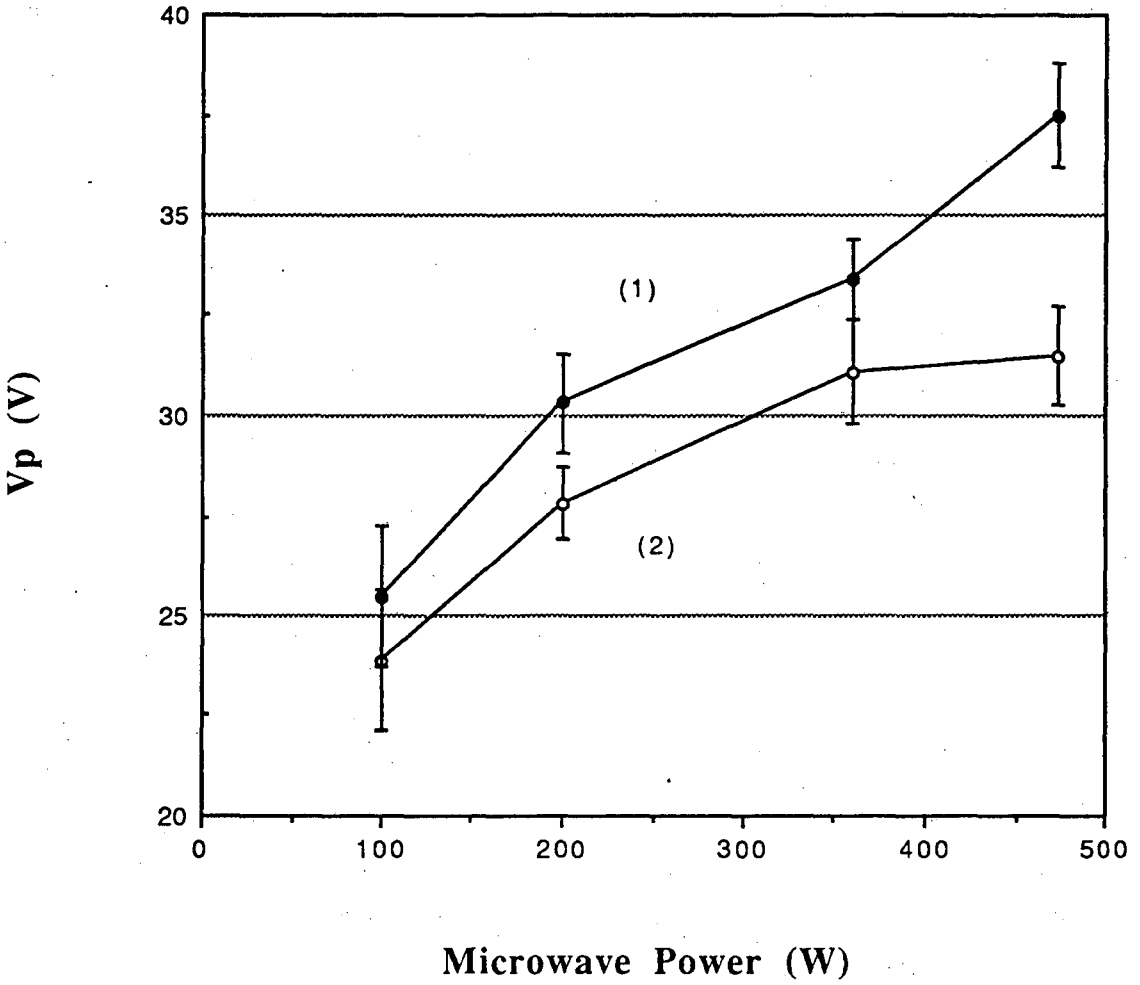

Fig. 5. Plasma potentials with a pure argon (curve (1)) and with an argon mixed with oxygen of ratio 1 to 1 (curve (2)) at about the same gas flow rate (pressure P = 1.6×10^{-6} Torr) as a function of microwave power in the AECR. Gas mixing slightly lowers the plasma potential.

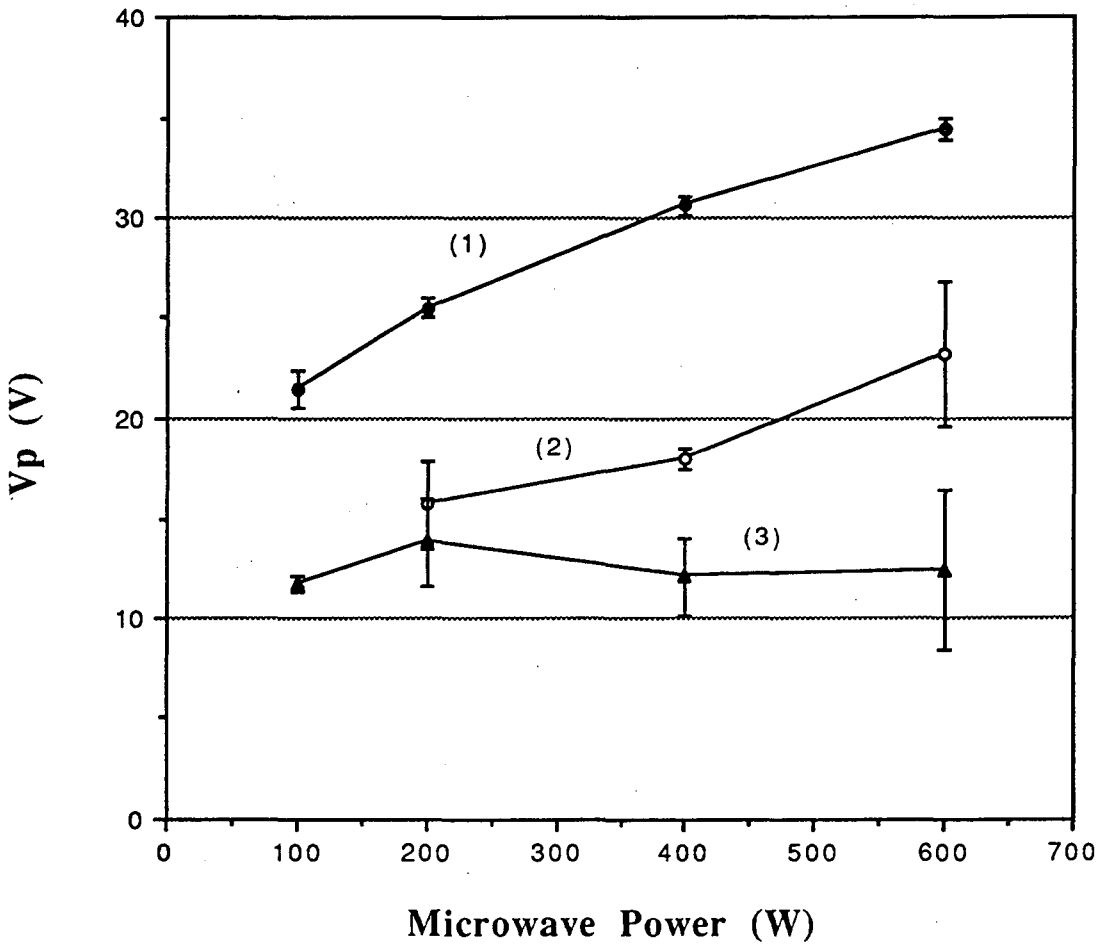

Figure 6. Plasma potentials of oxygen at the same gas flow (pressure P = 1.6×10^{-6} Torr) for three cases. Curve (3) indicates the potential with an aluminum oxide coating at various microwave power levels. This potential is a factor of two to three lower than the cases indicated by curves (1) and (2) which are shown in Figure 3 as curves (1) and (3). Within the measurement error, this plasma potential is essentially independent of microwave power.

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