Lawrence Berkeley National Laboratory
Recent Work

Title
Recent Developments on ECR Sources at LBL

Permalink
https://escholarship.org/uc/item/9m63z76z

Authors
Xie, Z.Q.
Lyneis, C.M.

Publication Date
1993-05-05

Recent Developments on ECR Sources at LBL

Z. Q. Xie and C. M. Lyneis

Nuclear Science Division, Lawrence Berkeley Laboratory
University of California, Berkeley, California 94720, USA

May 5, 1993

RECENT DEVELOPMENTS ON ECR SOURCES AT LBL

Z. Q. Xie and C.M. Lyneis

Nuclear Science Division, Lawrence Berkeley Laboratory,
1 Cyclotron Road, Berkeley, California, 94720, USA

After a number of refinements, the stability and ease of tuning of the LBL AECR ion source are greatly improved. Several nuclear science experiments have now used cyclotron ion beams injected by the AECR ion source and have taken advantage of its good short and long term stability and high performance. Refinements include installation of a dc filament power supply for the electron gun, improved gas flow control and temperature stabilization of parts of the microwave transmission network.

Measurements of the mean plasma potential and plasma potential difference were made on the AECR and the LBL ECR sources. The absolute mean potentials of plasmas of oxygen, argon and argon mixed with oxygen in the AECR have been determined. These plasma potentials are positive with respect to the plasma wall and are on the order of a few tens of volts for microwave power up to 600 W and normal operating gas flow. Electrons injected by an electron gun into the AECR plasma reduce the plasma potentials. Beam energy spreads of oxygen, argon and argon mixed with oxygen have also been measured. Measurement of the plasma potential difference between the first and the second stage of the LBL ECR ion source shows that the plasma potential in the first stage is higher than the second stage. Such plasma potential differences range from about 10 to 200 volts depending on the microwave power and density of neutral atoms. With these potential differences, typically of 10 to 40 V at the LBL ECR running conditions, most of the 1+ ions produced by the first stage are probably not be confined by the second stage plasma. Thus it appears that the main function of a microwave-driven first stage is to provide electrons to the second stage plasma, as is done with an electron gun in the AECR source.

I. INTRODUCTION

Two ECR sources, the LBL ECR and the AECR (Advanced ECR) are used to produce ion beams for the 88-Inch Cyclotron. The LBL ECR which was first operated in 1984 operates at 6.4 GHz and provides many of the beams in support of the nuclear physics program.[1] The AECR which operates at 14 GHz began test operation in 1990.[2,3] It is currently used to provide beams with higher charge state or greater intensities than can be produced by the LBL ECR. With two ECR sources and one cyclotron, it is possible to support the cyclotron research program and continue to enhance the ECR source capabilities. Recent AECR development has focused on improving its operating characteristics, especially its short and long term stability which is crucial for operating with the cyclotron. In addition, the two sources have also been used to measure the plasma potentials, the effect of electron injection on source performance, and the role of microwave driven first stages in ECR performance.

II. IMPROVEMENTS ON THE AECR

Testing the AECR began in 1990. After an electron gun was added to inject electrons axially into the plasma chamber, it produced high charge state beams from nitrogen, oxygen, argon, krypton, xenon, and bismuth.[3,4] Although its peak performance was excellent, good long-term stability

needed for regular operation with the cyclotron was missing. Since then, we have made a number of modifications to improve its stability and ease of operation.

During tests on the source, we found significant variations in the current from the gun filament power supply. The supply was a simple isolated step-down transformer and changes in the electrical contact between the electron gun filament and the filament holder resulted in temperature variations which caused substantial fluctuations in the injected electron currents. The supply was replaced by a dc current regulated supply and this stabilized the injected electron currents.

The AECR frequently operates at 1.0 to 1.5 kW of microwave power. At these power levels the temperature of the wave guide can go up to almost 150 °C. This temperature also depends on the ambient temperature which varies substantially between day and night at the source. The variation of the wave guide temperature resulted in a 5% variation of the microwave power fed to the source. Water cooling channel was then added to the wave guide to minimize the temperature variation. This refinement stabilized the microwave power to the source. Water cooling was also added to the transition section between the wave guide and the plasma chamber.

During a gas consumption measurement on the AECR source, we found that the gas flow was very sensitive to the ambient temperature. The gas flow can vary up to a factor of 2 for 2 °C change on the gas valves (Balzer UDV 035). Water cooled jackets were added on to these valves to stabilize the temperature on the gas valves.

After the above mentioned modifications, the source long-term stability improved substantially. The source tuning is less critical and its output from the source is more reproducible. Its recovery versus time after the source is opened to air for a short period of time ($\leq$ 0.5 hour) is shown in Figure 1 for O^{7+}. It takes about 5 to 6 hours, counting from the time of starting pumping, to recover to a moderate output of O^{7+} (~ 60 to 70 eμA, about half of its best output).

The AECR source is now used with the cyclotron in cases when its higher performance is required. So far, it has produced high intensity or high charge state ion beams of nitrogen, oxygen, krypton and tin to the cyclotron.

Injecting electrons into the AECR seems to eliminate the need for gas mixing at least for gaseous elements up to argon. This is consistent with the results reported by the RIKEN group that after coating their source with Al_2O_3 gas mixing was not necessary.[5] They attributed this to the high secondary emission coefficient of Al_2O_3 which supplies electrons to the plasma. In Figure 2, the performance of the AECR with pure argon feed and electron injection is illustrated. Approximately 90 μA of Ar^{11+} was produced.

III. PLASMA POTENTIALS IN THE AECR

ECR ion sources are plasma devices for producing multiply-charged ions and operate in a dynamic equilibrium state. The plasma loss rate is equal to and determined by the production rate. The ion confinement in such device is believed to be dominated by the ambipolar diffusion. The cold electrons escape more rapidly 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 push the ions out of the plasma in order to maintain the equilibrium.[6] There are many parameters involved in the ECR plasma, so this plasma potential should be a function of the related parameters

$$V_{plasma} = f (N_e, N_i, N_0, T_e, T_i, M_i, B, \Omega_w) \tag{1}$$

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.

Ions are globally extracted in an ECR source, and if there is a plasma potential inside the plasma chamber, then ions with different charge state have to escape from the same plasma potential. The energy that the ions gain from the plasma and the extraction process should be proportional to its charge state. We used the 90° analyzing system on the AECR to measure the total energy of the ions as a function of applied bias voltage. From these measurements the value of the plasma potential was extracted.

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

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

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, $\frac{M_i}{Q}$ are known.

For maximum resolution, all the measurements were done with a set of narrow slits, 1 mm opening, at the object and image of the 90° bending magnet. Meters of 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}. The source magnetic field was kept constant and without optimization of any charge state ions, but simply varying the microwave power and gas flow. Oxygen and argon gases were used in the measurements. The source was biased at different potentials (≤ 1000 V) to determine the corresponding bending magnetic fields B_{90}. 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 off set which is equal to the mean plasma potential.

Figure 3 shows a set of data and the fittings for oxygen beams of charge from 4+ to 7+ versus various source bias potentials V_s at a constant gas flow and microwave power. It clearly shows that all the ions of different charge have escaped from a same plasma potential. This potential is higher than the plasma chamber wall which is at the source bias potential V_s. Shown in Figure 4 are the plasma potentials of an oxygen plasma at various microwave power levels for two different gas flows and one case with electron injection. Without electron injection, the case with higher gas flow shows a slightly higher plasma potential. It may be that the higher gas flows produce higher density plasmas with a larger fraction of cold electrons. Then as the cold electrons escape, they generate an enhanced plasma potential. When electrons of current ~ 17 mA and energy of 200 eV are injected into the source, the plasma potentials are reduced by ~10 V compared to the case of no electron injection. This is in agreement with the observation of plasma potential reduction by electron injection in cusp ion sources.[7] Shown in Figure 5 are the plasma potentials for an argon plasma with a pure argon feed and argon mixed with oxygen at a ratio of 1 to 1. Comparison of the pure argon feed and pure oxygen feed at about the same gas flow indicated in Figure 4 shows that the plasma potentials of argon plasma are slightly higher than the oxygen plasma. This could be a mass effect because of the average mobility of argon is lower than oxygen. Thus a higher plasma potential is required to push the argon ions out the plasma and maintain the equilibrium. Based on such analysis, then if there is a lighter gas present in the plasma, one would expect a lower plasma potential. The plasma potentials of argon mixed with oxygen at various microwave power levels, as indicated in Figure 5, support such speculation.

Figure 6 and 7 show the energy spreads for the oxygen and argon ion beams for the cases indicated in Figure 4 and 5 respectively. At no electron injection, they are generally in the order of 5 to 10 eVxQ depending on the microwave power and gas flow. Such energy spreads are in agreement with the previous reported measurements.[8,9,10] When electrons are injected into the plasma, the energy spread is a factor of two higher as indicated in Figure 6.

IV. PLASMA POTENTIAL DIFFERENCES IN THE LBL ECR

It was recognized early in the development of ECR sources that the addition of a microwave driven first stage, improved the production of high charge state ions.[11] A typical first stage operates at less than 100 W of microwave power and pressure on the order of 10^{-3} to 10^{-4} Torr. The plasma produced in the first stage is not magnetically confined in the axial direction. The empirical explanation of such improvement is that the microwave driven first stage produces a cold plasma of singly charged ions. The plasma diffuses into the second stage and singly-charged ions then are ionized to higher charge states.[11] The second stage has a minimum B field configuration for better plasma confinement and stability. It operates at much higher microwave power (up to 2 kW) and much lower pressure (10^{-6} to 10^{-7} Torr). With such large differences on operating conditions it would not be surprising if there was a plasma potential difference between plasmas in the first and the second stage.

The 90° analyzing system can be used to search for a difference in the plasma potentials of the first and second stage in a manner similar to that described above to measure plasma potentials. Rewriting Eq. (2) gives

$$\Delta V_p = \frac{Q}{KM_i} \Delta(B_{90}{}^2) \tag{3}$$

where ΔV_p is the plasma potential difference.

Measurements of plasma potentials were carried on the LBL ECR source which has two stages driven by two separate klystrons. The first stage operates at 8.6 GHz and has a ceramic tube inside it to concentrate the gas for a stable discharge. The second stage operates at 6.4 GHz.[1] Separate microwave power control allows each stage to be operated independently. Narrow slits with 1 mm opening again were used at the object and image of the bending magnet. Source was biased at 6 kV for better resolution. The measurements were done with oxygen. The O^{1+} ions produced in the first stage and the second stage were easily resolved as shown in Figure 8. The source magnetic field was kept constant for all these measurement tests with microwave power. This allowed operation of both stages at the same time or first stage only to assure the identification of the oxygen 1+ ions produced in the first stage. Measurements were carried out at different microwave power levels and various gas inputs.

Figure 9 shows the plasma potential in the first stage is higher than the second stage plasma potential. At a fixed gas flow, this potential difference increases as first stage microwave power is increased. Figure 10 indicates, at a fixed microwave power level, the plasma potential difference is approximately inversely proportional to the gas flow.

$$\Delta V_p \sim \frac{1}{N_0} \tag{4}$$

The result seems to contradict the plasma potential measurements on the AECR with different gas flows. There higher gas flow gave slightly higher plasma potentials.

V. DISCUSSION

The measurements of the plasma potentials in the AECR show the following systematics:

1) Plasma potential is positive with respect to the chamber wall and is in the order of a few tens of volts depending on the running conditions;
2) Higher microwave power increases the plasma potential as well as energy spread.

At constant microwave power
1) Injected electrons reduce the plasma potential;
2) Higher density results in higher plasma potential;
3) Heavier element plasma has a higher potential;
4) Light support gases reduce the plasma potential;
5) Lower plasma potentials come with higher energy spreads.

The plasma potential in the AECR is between 10 and 40 V and is smaller than the potentials measured in the large test device Constance-B.[12] Such positive potential increase 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 10 milliseconds.[13] Transit times for ions even at temperature of 1 eV are much shorter than that. If a flat plasma potential with sharp drops at the sheath is proposed, it is difficult to account for the production of high charge state ions. If the plasma potential has a small dip in the middle, this could provide the required confinement. A shallow potential dip (possibly a few volts) resulting from two populations of electrons with different temperatures in a mirror field has been proposed.[6] The reported afterglow effect also suggests the existence of such plasma potential dip.[14,15] The high charge state ions are mainly produced inside this dip while the low charge state ions which do not require very long ionization time can be produced inside and outside this dip. With such potential configuration, one would see larger energy spread for low-charge state ions than for intermediate charge state ions since the low charge state ions could pick up quite different potential energies depending on where they are ionized. Measurement of argon beam energy spreads for various charge state, as shown in the Figure 11, and earlier reported measurements have shown the abnormally high energy spread for the lowly ionized argon ions.[10]

These energy spreads increase slightly at higher microwave power level. This may be a result of increased plasma instability which heats the ions. In the case of electron injection, the injected electrons have an energy of 200 eV and the source was biased at only a few hundred volts. Therefore, many of the injected electrons could get into the extraction gap, through the extraction hole, before they are reflected. This might distort the extraction potential distribution in the gap and this will result in an increase of the measured energy spread. There may be other mechanisms by which the injected electrons increase the beam energy spread.

The plasma potential difference between the first stage and the second stage of the LBL ECR source is inversely proportional to the neutral density and opposite to the plasma potential dependence on the AECR source. The dramatically different operating conditions, in the first stage and the second stage, may be responsible. There are a number of differences including pressures, magnetic field shapes and electron temperatures which may account for the differences in the plasma potential.

There are now several pieces of evidence that the function of a microwave-driven first stage in two stage ECR sources is to supply cold electrons to the second stage. Tests on the LBL ECR showed the first stage could be turned off after coating the plasma chamber walls with SiO_2.[2,16] The SiO_2 coating provides electrons to the plasma because of its high secondary emission coefficient. The AECR peak performance is obtained by the injection of electrons with an electron gun.[4] Similar

effects have been reported using Al_2O_3 coatings, negatively biased first stage[5] and biased probes to increase the supply of electrons.[13] The existence of a plasma potential difference between the first and second stage of the LBL ECR seems to indicate that the 1+ ions from the first stage are not confined by the second stage. Also the transit time is short compared to the time required for subsequent ionization. Finally, we made current flow measurements on the LBL ECR between the first and second stage. The direction of the current between the two stages depends on microwave power and the neutral pressure in the first stage. However, when the source is tuned to produce high charge state ions, the net current shows that the first stage is providing .5 to .8 mA more electrons than ions to the second stage.

VI. CONCLUSION

After a number of modifications, the AECR operating characteristic are much improved. Most of the improvement came from better control of external parameters such as gas flow, electron gun filament current, and microwave coupling network. The plasma potential of the AECR is positive and ranges between 10 and 40 V. This positive potential and the production of high charge state ions support the model with a small potential dip in the center to provide ion confinement. The function of a microwave-driven first stage is to provide cold electrons to the second stage to enhance the production of high charge state ions. Microwave-driven first stages, especially those driven by a separate klystron, can be replaced by external or internal electron sources with lower costs and greater simplicity.

ACKNOWLEDGMENT

References;

1. C. M. Lyneis, Proceedings of the 6th International Workshop on ECR Ion Source, Berkeley, CA, USA, 1986, p. 51.
2. C.M. Lyneis, J. Phys. (Paris) Colloq. 50, Cl 689 (1989)
3. C. M. Lyneis, Zuqi Xie, D. J. Clark, R.S. Lam and S. A. Lundgren, Proceedings of the 10th International Workshop on ECR Ion Sources, Oak Ridge, ORNL CONF-9011136, 1990, p. 47.
4. Zuqi Xie, C.M.Lyneis, R.S. Lam, and S.A. Lundgren, Rev. Sci. Instrum. 62, 775 (1991).
5. T. Nakagawa, T. Kageyama, M. Kase, A. Goto and Y. Yano, Proceedings of the XIII International Conference on Cyclotrons and their applications, Vancouver, Canada, 1992, p 365.
6. C. C. Petty, D. L. Goodman, D. K. Smith and D. L. Smatlak, J. Phys. (Paris) Colloq. 50, Cl 783 (1989)
7. K.N. Leung, C.A. Hauck, W.B. Kunkel, and S.R. Walther, Rev. Sci. Instrum. 61, 1110 (1990)
8. F. W. Meyer, Proceedings of the 7th International Workshop on ECR Ion Sources, Julich, Germany, 1986, p. 11.
9. H. Kohler, M. Frank, B. A. Huber and K. Wiesemann, Proceedings of the 7th International Workshop on ECR Ion Sources, Julich, Germany, 1986, p. 215.
10. T.A. Antaya, J. Phys. (Paris) Colloq. 50, Cl 707 (1989).
11. R. Geller, IEEE Trans. NS-26, No. 2, 2120 (1979)

12. C. C. Petty, Ph. D. Thesis, MIT (1989)
13. Y. Jongen, Universite Catholique de Louvain, Laboratoire du Cyclotron Report LC-8001 (1981).
14. G. Melin et al, Proceedings of the 10th International Workshop on ECR Ion Sources, Oak Ridge, ORNL CONF-9011136, 1990, p. 1.
15. P. Sortais, Rev. Sci. Instrum. **64**, 2801, (1991).
16. C.M. Lyneis, Proceedings of the International Conference on ECR Ion Sources and their applications, East Lansing, NSCL Report #MSUCP-47, 1987, p. 42.
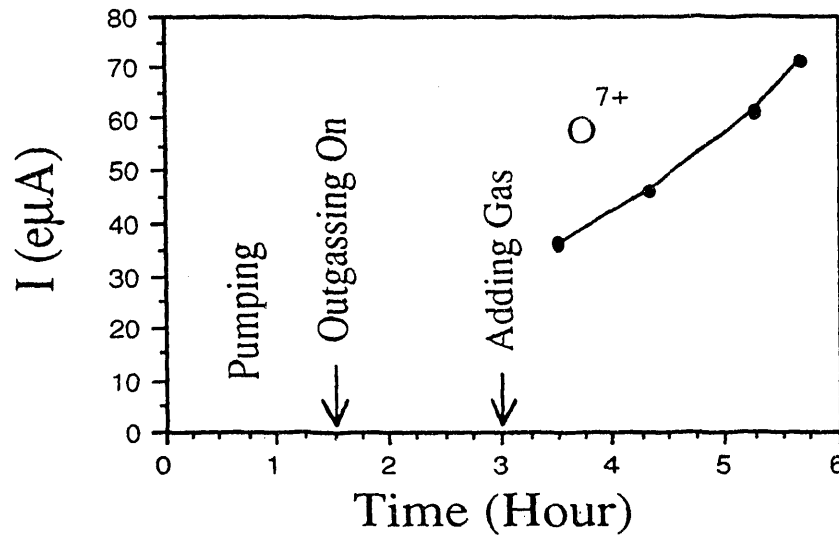
Fig. 1. Typical recovery of the O^{7+} output from the AECR source after the source was opened to air for a short time. The electron gun was used in this operation.
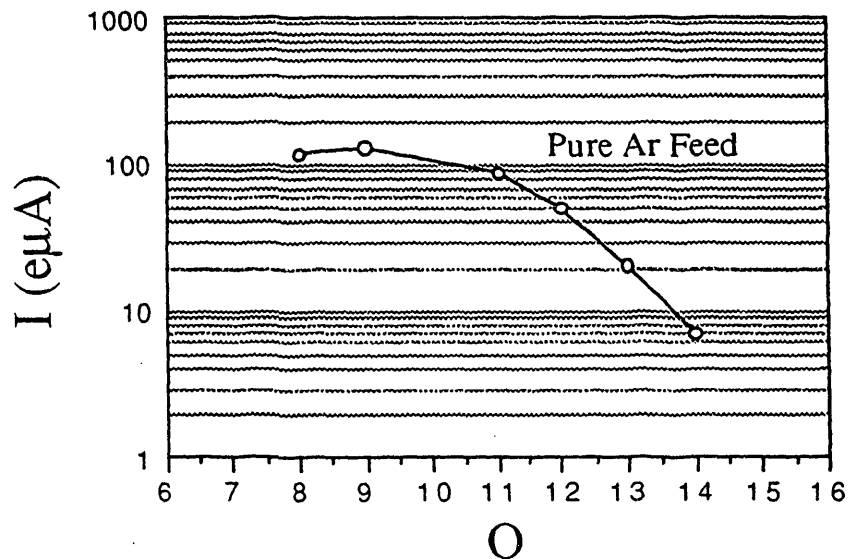
Fig. 2. With sufficient injected electrons, the AECR source can run on pure argon feed and maintain a moderate output for the high charge state Ar ion beams. Source was optimized for Ar^{11+} and the oxygen background is about 10 to 20 eμA for intermediate charge state oxygen beams.
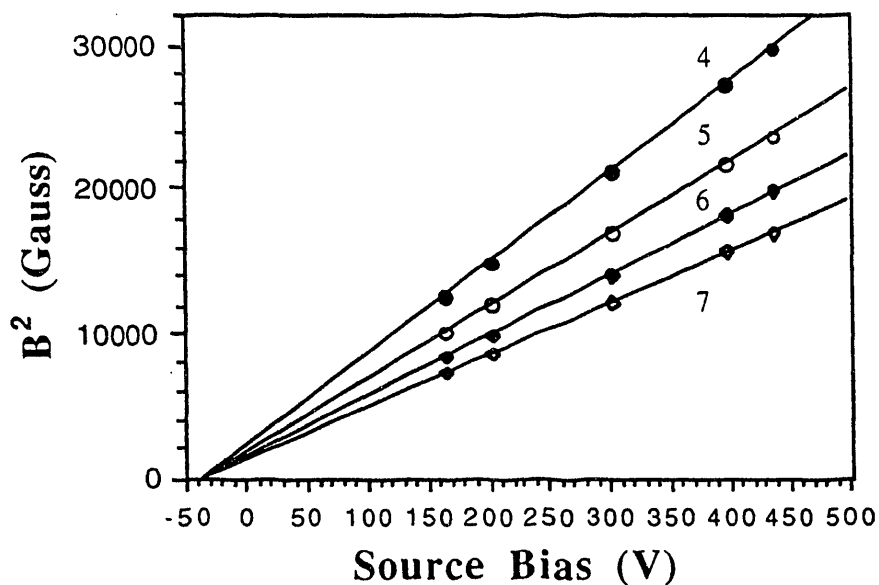
Fig. 3. Measurement data for oxygen beams with charge states from 4+ to 7+. The least square fit lines all have a same intercept which corresponds to the plasma potential. The AECR source conditions were kept constant except for the source bias which was varied. Pure oxygen gas was fed to the plasma chamber at pressure of 1.6×10^{-6} Torr and at microwave power of 600 W.
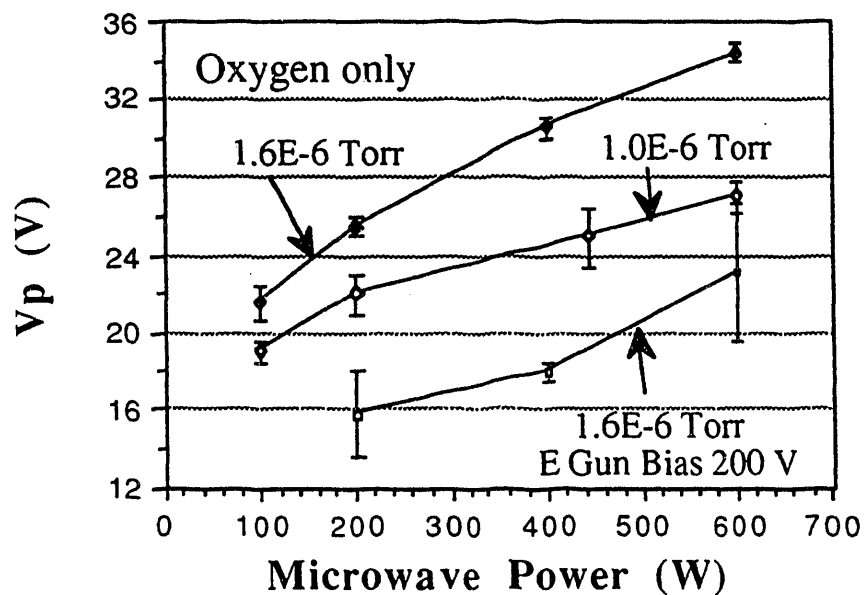

Fig. 4. The upper two curves show the plasma potential as a function of microwave power for two different pressures without electron injection. The lower curve shows that injecting electrons reduces the plasma potential.
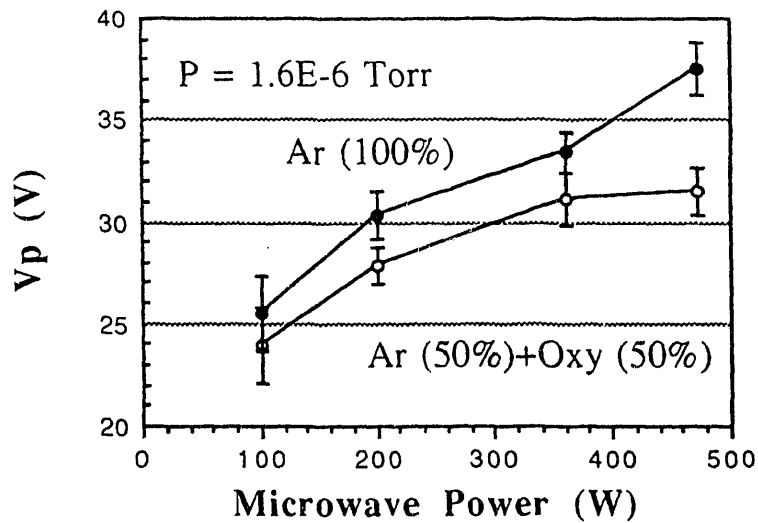
Fig. 5. Plasma potentials with a pure argon and with an argon mixed with oxygen as a function of microwave power in the AECR. Gas mixing lowers the plasma potential.
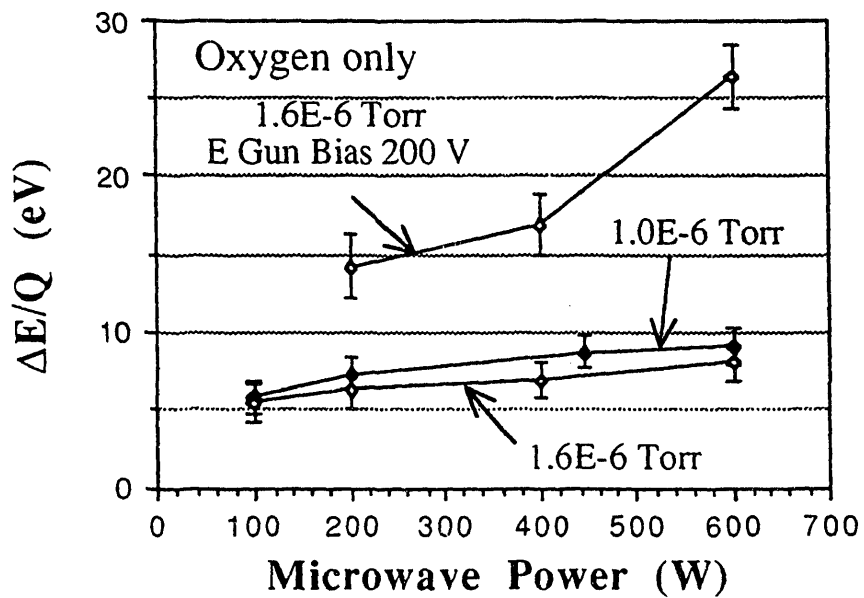
Fig. 6. Average energy spreads on oxygen ions of charge state from 4+ to 6+ for the cases indicated in Fig. 4. It shows that the case with lower plasma potential has the higher energy spreads.
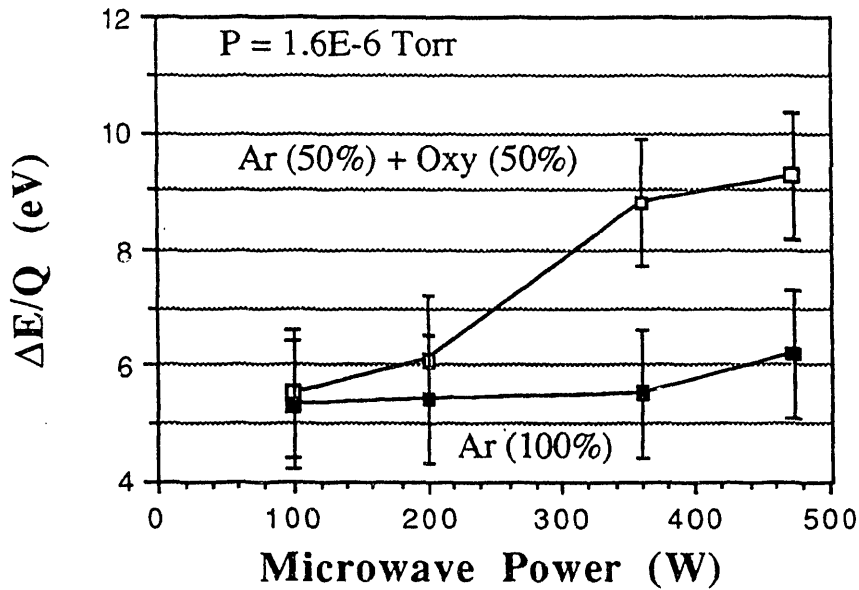
Fig. 7. Average energy spreads on argon ions of charge 6+ to 9+ and 11+ for the cases indicated in Fig. 5. The case with gas mixing, which results in lower plasma potential, has higher energy spreads than the case of pure argon feed.
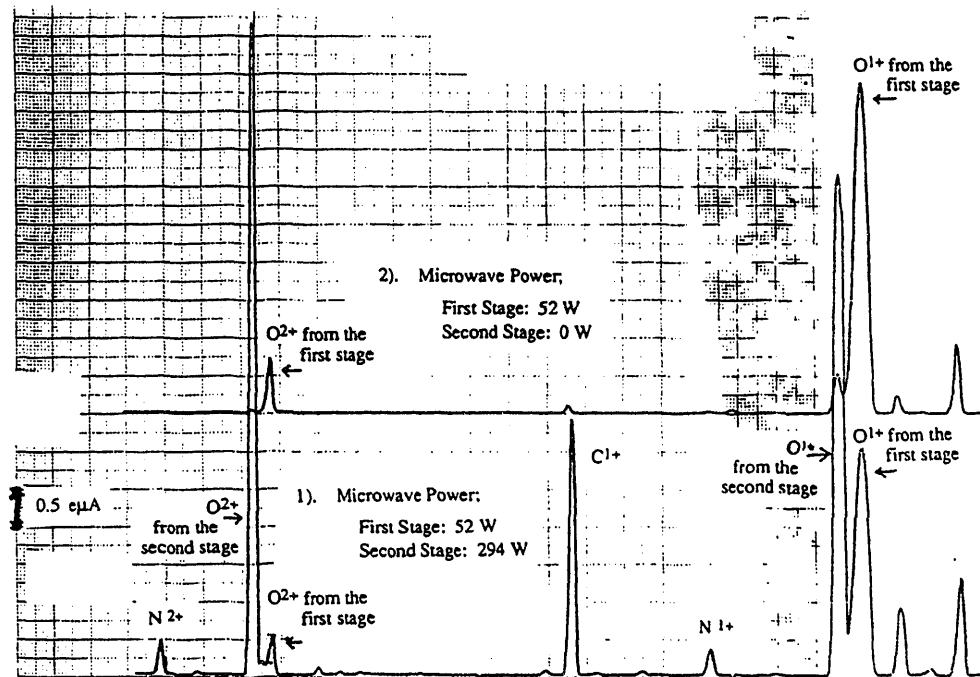

Fig. 8. With the narrow slits, the O^{1+} and O^{2+} ions produced in the first stage and the second stage are well separated as shown. In the lower spectrum, both stage are powered at a normal level of 52 and 294 W respectively while in the upper spectrum, only the first stage is powered with 52 W. Gas flow for this case was about a factor of 2 lower than normal running condition.
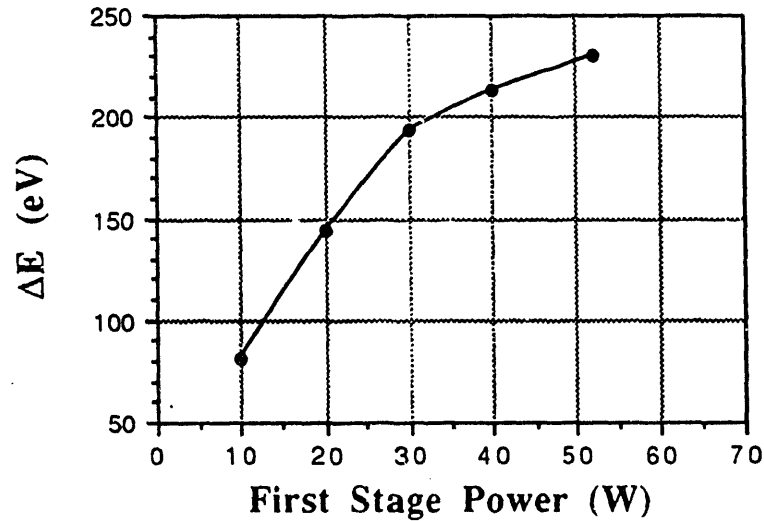
Fig. 9. Plasma potential differences between the first stage and the second stage of the LBL ECR source at a constant gas flow as a function of microwave power in the first stage. The microwave power level in the second stage was 298 W, which is a typical operating level.
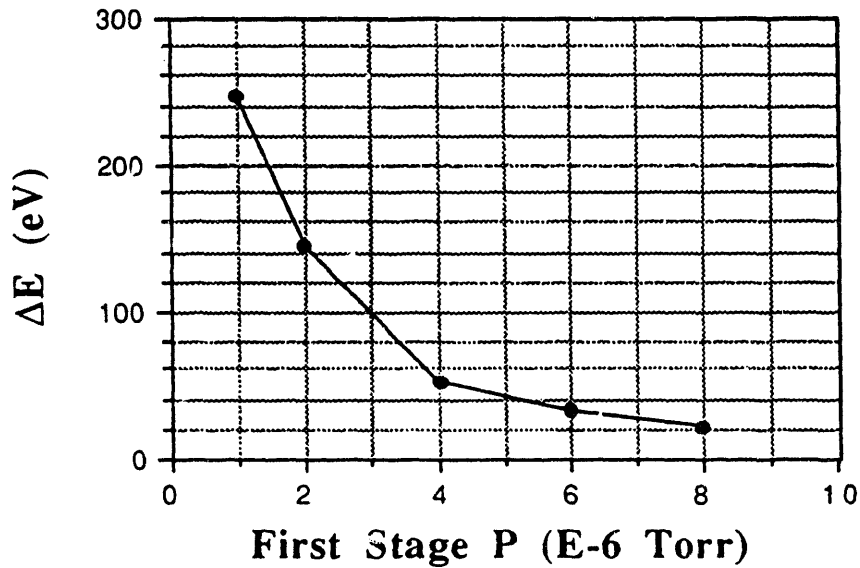

Fig. 10. Plasma potential differences between the first stage and the second stage on the LBL ECR source at a constant microwave power level but with various gas flows to the first stage. Microwave power of 52 W and 70 W were launched into the first stage and the second stage respectively. This potential difference is approximately inversely proportional to the neutral pressure. The pressures indicated on the abscissa are the reference readouts, not the actual pressure inside the first stage.
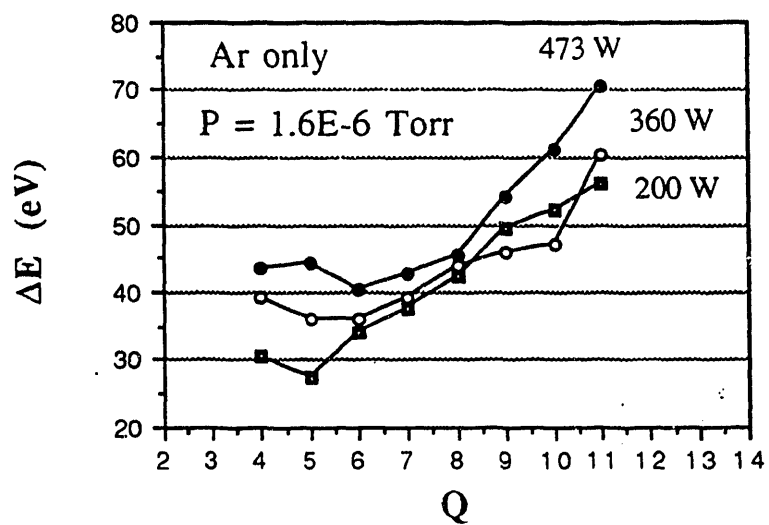
Fig. 11. The energy spread as a function of charge state for argon ions (pure argon feed) for the case shown in Fig. 5.