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ABSTRACT

An electron gun for the Advanced ECR source has been developed to increase the production of high charge state ions. The AECR source, which operates at 14 GHz, is being developed for the 88-Inch Cyclotron at Lawrence Berkeley Laboratory. The electron gun injects 10 to 150 eV electrons into the plasma chamber of the AECR. With the electron gun the AECR has produced at 10 kV extraction voltage 131 eμA of O^{7+}, 13 eμA of O^{8+}, 17 eμA of Ar^{14+}, 2.2 eμA of Kr^{25+}, 1 eμA of Xe^{31+}, and 0.2 eμA of Bi^{38+}. The AECR was also tested as a single stage source with a coating of SiO_2 on the plasma chamber walls. This significantly improved its performance compared to no coating, but direct injection of electrons with the electron gun produced the best results.

INTRODUCTION

In recent years the development of Electron Cyclotron Resonance ion sources for the production of multiply-charged ions has centered on higher frequencies.[1] Frequency scaling in ECR sources was first predicted and then demonstrated by Geller et al.[2] This was a key factor in the design of a new ECR source for the 88-Inch Cyclotron. The Advanced ECR (AECR) operates at 14 GHz compared to 6.4 GHz for the LBL ECR which has been in regular operation with the cyclotron for 5 years. In May 1990, the development of an electron gun, which injects cold electrons directly into the plasma, significantly enhanced the performance of the AECR. The development of the electron gun not only increased the source performance, but also should lead to considerable simplification and cost reduction in future ECR sources. In this paper we describe the design of the AECR and compare its initial performance for two distinct operating modes. First, we tested it as a single stage source using a SiO_2 coating to enhance its performance. Second, we tested it with an electron gun installed in place of a conventional microwave-driven ECR first stage.

The discovery of the "silicon-effect"[3] prompted the idea of adding electrons to the plasma to enhance ECR performance. We found that the LBL ECR operated with better stability, at lower neutral pressure, and with higher charge state production after coating the plasma chamber walls with SiO_2. This is done by producing a plasma in the source from a mixture of SiH_4 and O_2 gases. The proposed explanation for this phenomenon was that the SiO_2 coating enhanced the production of cold electrons at the plasma chamber walls due to its high secondary electron emission.[3] These secondary electrons serve as an additional source of cold electrons to replace those heated by ECR heating. In a conventional ECR source the primary sources of cold electrons are stepwise ionization of atoms and ions, and plasma injected from a microwave-driven first stage. Experiments with the LBL ECR showed that with a sufficient SiO_2 coating in the plasma chamber, the best performance could be obtained with the first stage off. This indicated that the secondary electrons produced on the plasma chamber walls can replace the cold electrons normally supplied by the first stage. Tests with the AECR showed that excellent high charge state performance could be obtained without a first stage by using SiO_2 on the plasma chamber walls. However, optimum performance with the coating lasted only about one day. Therefore we have developed an electron gun which takes the place of a conventional first stage and eliminates the need for a special wall coating to supply electrons.

I. DESCRIPTION OF THE AECR

Figure 1 illustrates the design of the AECR. A single 14 GHz 2.5 kW klystron supplies microwave power to the source. We chose 14 GHz because commercial klystron amplifier systems are available at this frequency. Each of the magnet coils shown in Fig. 1 is a vacuum epoxy-impregnated assembly consisting of 12 pancakes. Each pancake has two 20 turn layers of 6.5 mm hollow-core copper wire. Each of the nine 300 A, 33 V magnet power supplies drives 4 pancakes. This makes it easy to vary the axial magnetic field. An iron yoke around the coils increases the axial field at each end while the iron plates between coils 2 and 3 reduce the axial field in the center to achieve the required mirror ratio. A recently added iron plug increases the injection peak field to more than 1 Tesla as shown in Fig. 2 for the case with the electron gun. The significant asymmetry in the mirror fields enhances the production of high charge state ions in the AECR. The sextupole field is produced by a Nd-Fe-B multipole designed to give sufficient field at the plasma chamber walls and still allow for radial pumping, access for ovens, and the direct insertion of refractory materials for the production of beams from solids.[4] Pumping for the plasma chamber and extraction region is provided by a 240 l/s and a 500 l/s turbomolecular pumps, respectively.

The electron gun installed in the AECR source is made from lanthanum hexaboride (LaB_6) because of its better electron emission, longer lifetime and lower evaporation compared to the tungsten material.[5] The design of the electron gun is shown in Fig. 3 and its location in the AECR is indicated in Fig. 1. The planar LaB_6 cathode has an electron emission area $A = 0.58\ cm^2$ and is held by a carbon chuck and a carbon pusher which also provide the electrical connection to the cathode. The two concentric conductors of the gun are water cooled. At the present an AC power supply heats the electron gun. The heating current ranges from 280 to 350 A at voltages of 2 ~ 3 V. At cathode temperatures from 1250 to 1350 ^0C and gun DC bias voltage from 10 to 200 V, electron currents (when plasma is on) from a few mA to about 200 mA are obtained.

II. PERFORMANCE OF THE AECR

The performance of the AECR for two distinct modes is discussed below. First as a single stage source with SiO_2 on the plasma chamber walls (AECR-SiO_2) and second with the electron gun installed (AECR-Egun). In Table I, we list the currents for various high charge state ions produced with the AECR for the two operating modes. Currents are also listed for the 6.4 GHz LBL ECR.

We applied SiO_2 to the plasma chamber walls after testing the AECR as a single stage source without a wall coating. The source performance was much improved, just as the source performance of the LBL ECR was improved earlier by adding SiO_2. As shown in Table I, the intensities for high charge state ions extracted from the AECR-SiO_2 at 14 GHz are significantly higher than from the LBL ECR at 6.4 GHz also tested with SiO_2. This is as expected from frequency scaling arguments. Other characteristics of the AECR-SiO_2 were that the optimum microwave power and total extracted current were about 1 kW and 1 mA, respectively. Higher total extracted currents could be achieved by increasing the neutral pressure, but this depressed the production of high charge state ions. During the test tunings using SiO_2, we observed that the source peak performance only lasted 5 to 10 hours for each deposition of SiO_2. Afterwards the source performance dropped to ~50% of its peak performance and continued to decay with time. In order to keep the source running at peak performance, SiO_2 had to be frequently coated onto the plasma chamber walls.

With the addition of the electron gun to the AECR, significantly more intense high charge state ion beams can be extracted. As shown in Table I, the maximum ion currents of the AECR-Egun are two to three times those from the AECR-SiO_2. As illustrated in Fig. 4, the main effect appears to be an increase in the extracted intensity, while the shape of the charge state distribution is almost unchanged. The best results to date were obtained with electron currents between 20 and 100 mA at bias voltages between 50 and 150 V. With the electron gun, the optimum microwave power and total extracted currents were typically 2 kW and 2 to 3 mA, respectively. Figure 2 shows that with the electron gun the optimum extraction mirror ratio for O^{7+} was 1.78 for AECR-Egun vs 1.64 for the AECR-SiO_2.

The lifetime of the first LaB_6 cathode was about 600 hours. Though the lifetime is long compared with other type materials, longer cathode lifetime is desirable. The lifetime can probably be extended by using higher density LaB_6, optimizing the cathode shape and stopping ion sputtering. During the operations of the electron gun with the AECR source, it has been observed that the cathode heating current could vary up to 10 to 20% of its set value because of the electric connection between the carbon chuck and the LaB_6 cathode changing under high temperature conditions. These heating current changes result in variations of the electron emission current. Since the gun DC bias voltage is about 100 V, the 60 Hz AC potential variation also affects the electron current stability. The stability of the electron gun can be improved by using a regulated DC power supply to heat the cathode so the gun heating current can be stabilized. A stable electron gun would help the long term stability of the AECR source. Operation with a DC power supply to heat the gun will be carried out in the near future.

III. DISCUSSION

In terms of ECR source performance, the injection of cold electrons with a gun not only takes the place of a SiO_2 coating, but also enhances the performance. It is difficult to interpret the mechanism by which injection of cold electrons into the ECR plasma improves high charge state ion performance, since we have not measured crucial plasma parameters such as plasma density, plasma potential, electron temperature, and ion confinement time. It appears that injecting electrons increases the plasma density in the AECR since the total extracted current increases by about 2.5 as does the optimum microwave power. The success of the AECR-Egun is consistent with the explanation that the "silicon-effect" is due to enhanced production of cold electrons at the plasma chamber walls. Leung et al[6] have shown that the injection of additional cold electrons into an H^- cusp source increased the plasma density and decreased the plasma potential. Both of these effects would improve ECR source performance.

In the case of the AECR-Egun the electrons are injected on axis. This may increase the electron density on axis and improve ion radial confinement. It could also affect the extraction of ions since the injected electrons have relatively large longitudinal velocities and are therefore not magnetically confined in the mirror field. An experiment done on the AECR seems to support this idea. The copper extraction end plate was replaced with an iron end plate which strongly enhanced the mirror field at extraction. When the AECR was run in this configuration without injecting electrons almost no current could be extracted (I_{ex} = ~0.2 mA with 1.6 eμA of O^{6+}). After turning on the electron gun with a slightly higher mirror field, the total extracted current increased to about 1 mA (with 115 eμA of O^{6+}), although the source performance was not as good as it is with a copper extraction plate. Figure 2 also shows that with the electron gun, the optimum mirror field at extraction is higher. This indicates that ions can be extracted in a higher mirror field when electrons are injected into the source.

We also tested the AECR using both a SiO_2 coating and the electron gun, to see if the effects were additive. After coating the plasma chamber walls, the best performance was obtained with no injected electrons. After a day of operation, which presumably partially removed the coating, the performance was improved slightly by injecting a small electron current at 10 to 20 eV; the observed performance was about 10 to 20% better than the case of SiO_2 coating alone for the high charge state oxygen and krypton ions. The over all characteristics of SiO_2 coating with the electron gun are very much like the case of SiO_2 coating alone.

IV. CONCLUSION

The initial performance of the AECR with the electron gun is very encouraging. It demonstrates that the addition of cold electrons to an ECR source plasma improves the output of high charge state ions. Further tests and the measurement of the plasma parameters are needed to develop a better understanding of the mechanisms involved. From a practical point of view, it may be desirable to retrofit some existing ECR sources with electron guns and design new ECR sources to take advantage of the simplification offered by their use.

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Table I Representative ion currents in eμA from the AECR source at 14 GHz with SiO_2, with the electron gun, and from the LBL ECR at 6.4 GHz. The intensities quoted are for natural feed material except for those followed by an asterisk in which case isotopically enriched gases were used. All measurements reported were done with an 8 mm extraction aperture at 10 kV. Typical operating pressures in the ECR plasma chambers were about $3x10^{-7}$ Torr.

ION	LBL AECR with SiO_2	LBL AECR with E. Gun	LBL ECR with SiO_2
O^{6+}	170	475	90
O^{7+}	51	131	20
O^{8+}	~6	~13	~0.95
Ar^{11+}	44.5	141	18
Ar^{12+}	22.6	78	13
Ar^{13+}	9.8	34	7
Ar^{14+}	4	17	1.4
Ar^{16+}	0.28	1.4	0.03
Kr^{18+}	22.6*	45*	
Kr^{19+}	19.1*	36*	2
Kr^{20+}	14.4*	23*	0.9
Kr^{22+}	6.7*	10*	0.1
Kr^{23+}	4.4*	6.8*	
Kr^{25+}	1.2*	2.2*	
Kr^{28+}	0.16*	0.25*	
Xe^{24+}	13*	30*	2
Xe^{27+}	5.5*	12*	0.3
Xe^{28+}	2.7*	6.8*	
Xe^{31+}		1*	
Bi^{28+}		6	2.5
Bi^{29+}		5.7	1.6
Bi^{31+}		4.5	0.56
Bi^{32+}		3.5	0.26
Bi^{33+}		2.6	0.1
Bi^{34+}		1.5	0.05
Bi^{36+}		0.7	
Bi^{37+}		0.4	
Bi^{38+}		0.2	

* Isotopically enriched gas used.

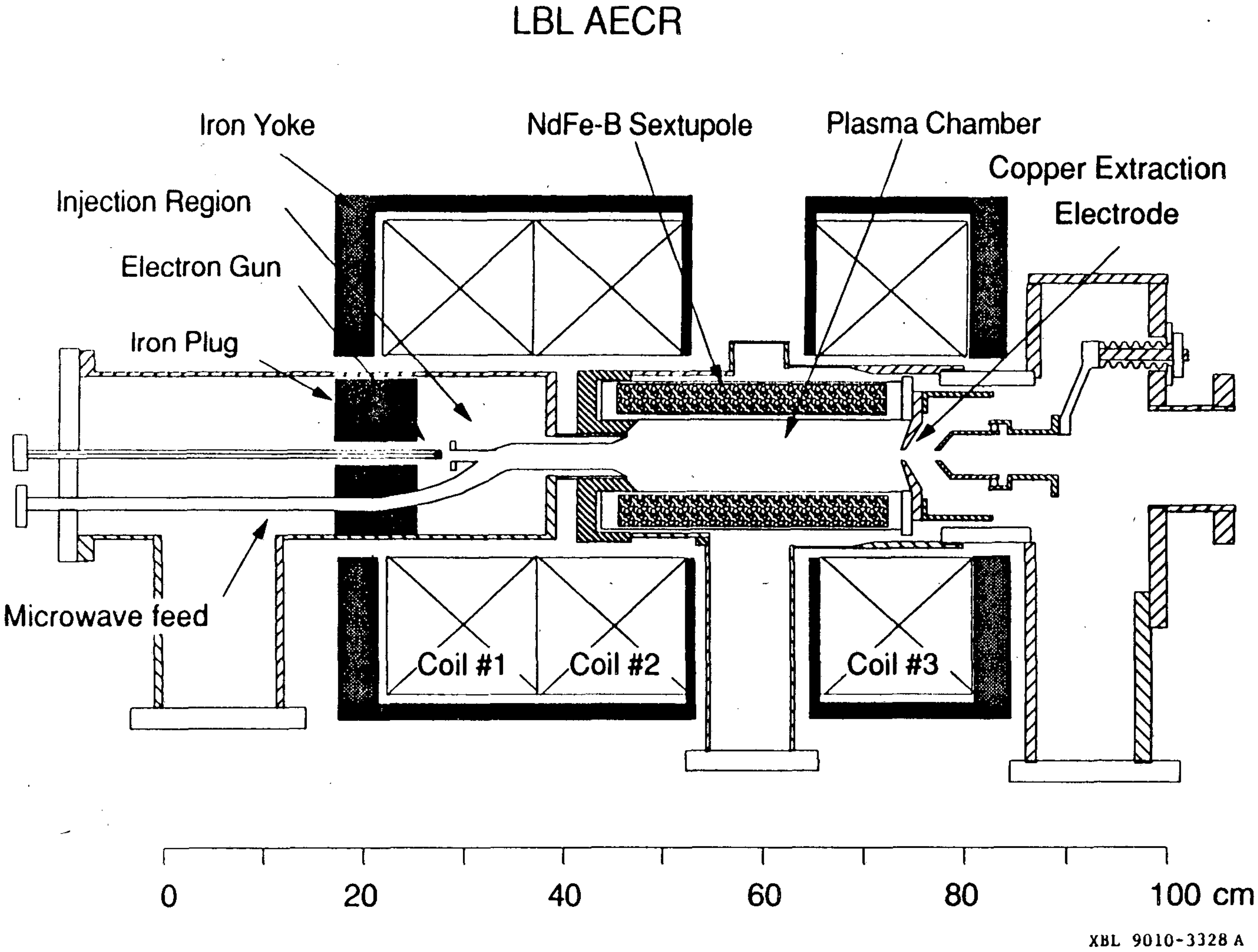
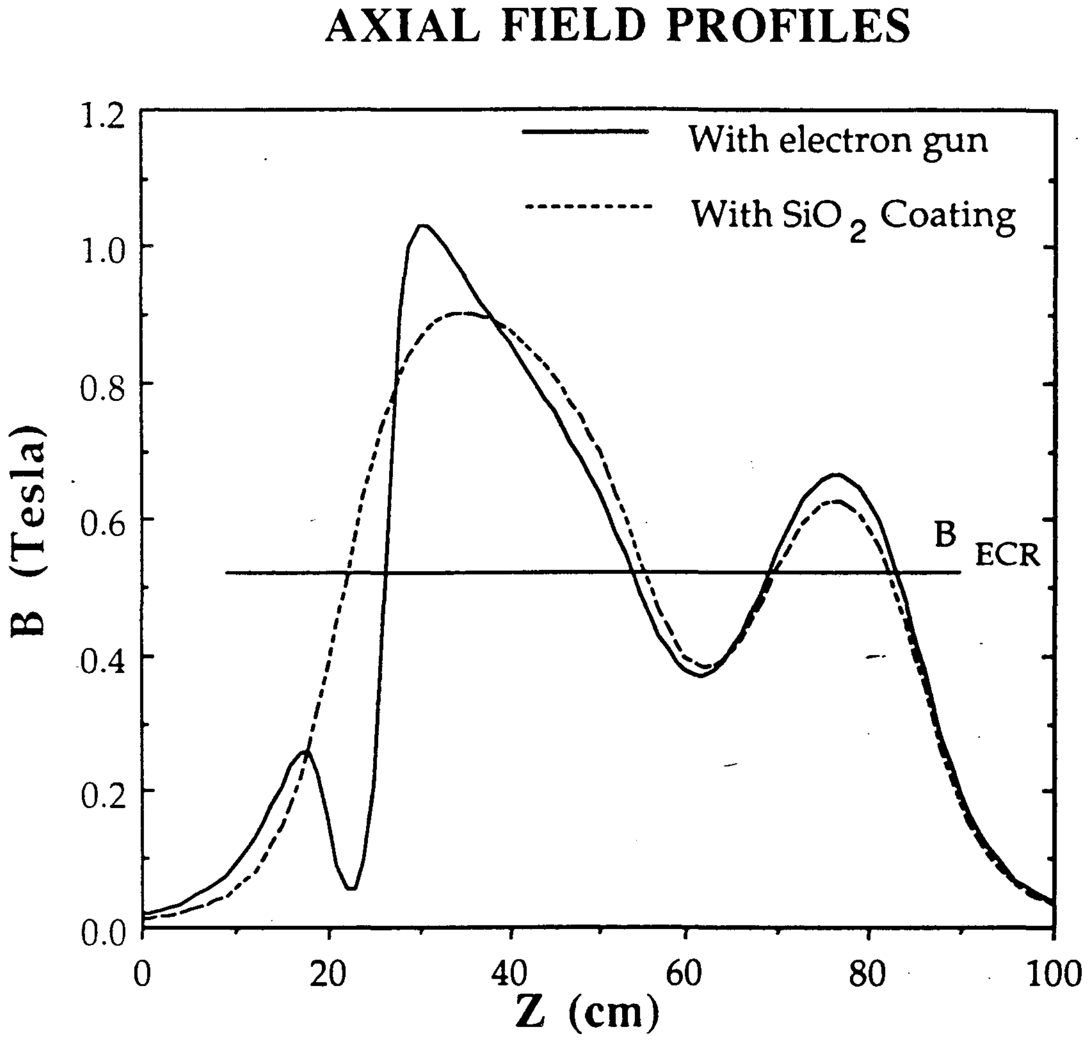
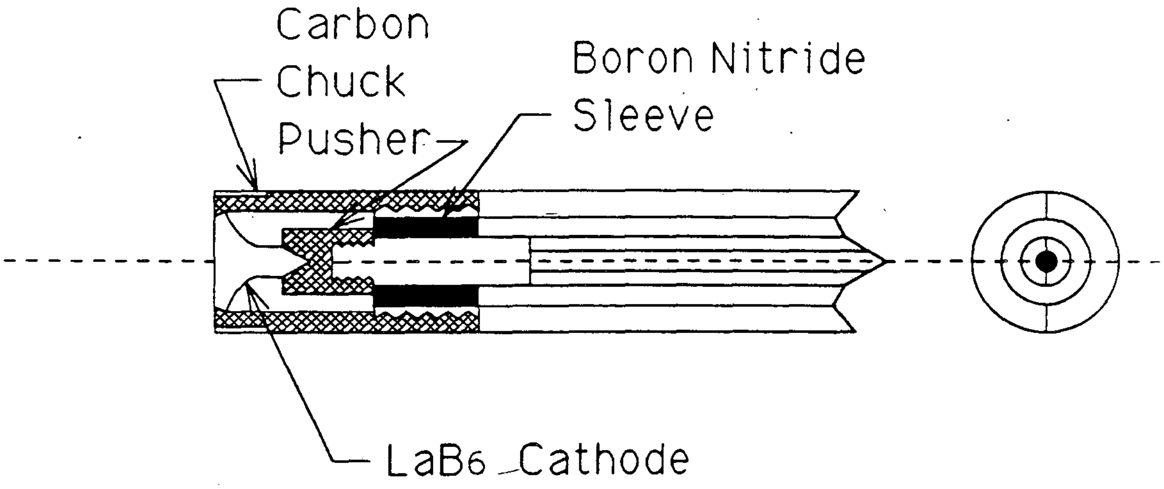


Fig. 1. Schematic drawing of the AECR. The axial magnetic field is produced by copper coils in an iron yoke. The iron plug on the injection side was added to increase the axial magnetic field. Electrons from a LaB_6 filament flow along the axial magnetic field lines into the plasma chamber.



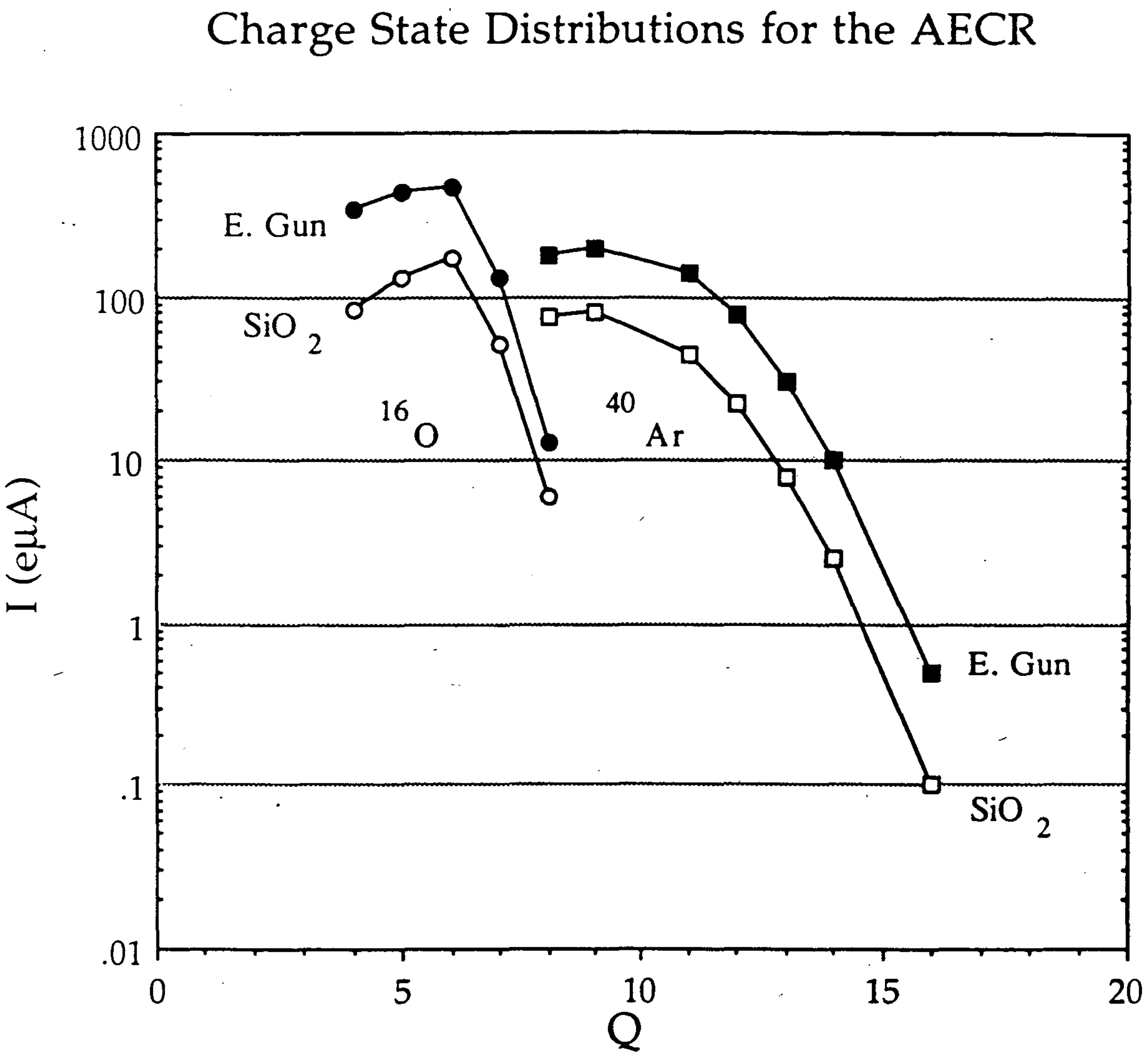
XBL 9010-3329

Fig. 2. Two axial magnetic field profiles are shown for the AECR. In both cases the fields were optimized for maximum O^{7+} beams. The dotted line shows the profile for operation as a single stage source with SiO_2 on the plasma chamber walls. The solid line shows the profile for operation with the electron gun. The iron plug, which was added after the SiO_2 test, enhances the injection mirror field.



XBL 9010-3330

Fig. 3. Schematic drawing of the electron gun developed for the AECR. A carbon chuck and a carbon pusher not only hold the LaB_6 cathode, but also provide electrical connection to it. The cathode has an electron emission area of 0.58 cm^2. Water is provided to the center conductor and the outer annulus to cool the electron gun.



XBL 9010-3331

Fig. 4. Charge state distributions for oxygen and argon produced with the AECR for two cases: first, with SiO_2 on the plasma chamber walls and second, with the electron gun. For oxygen and argon the source was tuned to maximize O^{7+} and Ar^{11+}, respectively. Operating pressures in the ECR plasma chamber for these tunes were about $3x10^{-7}$ Torr.

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