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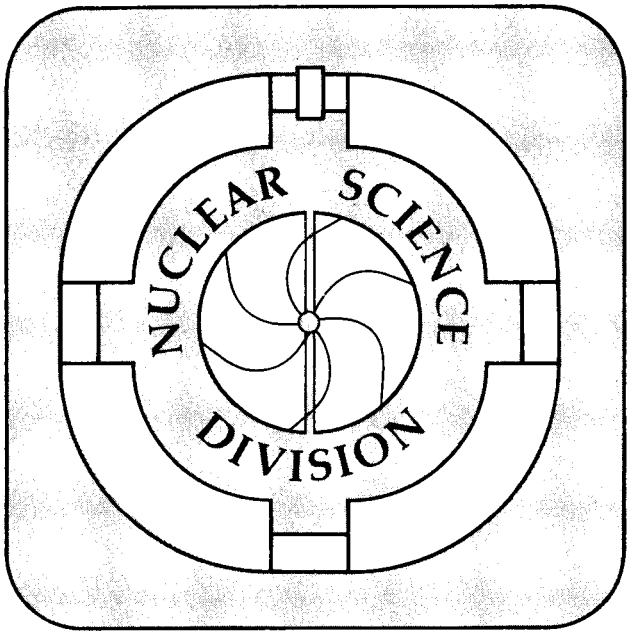

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PRELIMINARY PERFORMANCE OF THE LBL AECR

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The AECR source, which operates at 14 GHz, is being developed for the 88-Inch Cyclotron at Lawrence Berkeley Laboratory. The AECR has been under source development since December 1989, when the mechanical construction was completed. The first AECR beams were injected into the cyclotron in June of 1990 and since then a variety of ion species from the AECR have been accelerated. The cyclotron recently accelerated $^{209}Bi^{38+}$ to 954 MeV. An electron gun, which injects 10 to 150 eV electrons into the plasma chamber of the AECR, has been developed to increase the production of high charge state ions. 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

ECR ion source development has been the main ingredient in the upgrading of the 88-Inch Cyclotron's performance. The LBL ECR source, which began test operation in January 1984 and regular operation with the cyclotron in January 1985 is a reliable and flexible ion source. A new Advanced ECR (AECR) source for the 88-Inch Cyclotron is now undergoing tests. Milestones for the AECR project are listed in Table I. This new source operates at 14.5 GHz compared to 6.4 GHz for the LBL ECR. The impetus for building the AECR was the demonstration of frequency scaling by Geller's group in Grenoble — the group which built the first high charge state ECR source in 1974. They showed with a 16.6 GHz ECR that both higher intensities and higher charge states could be produced by operating at higher frequency [1]. These results are reflected in the initial performance of the AECR.

Table I. AECR Project Milestones

Dec 88	Construction began.
Dec 89	High charge state ions produced and magnetically analyzed.
Jan 90	High performance single stage operation (Silicon effect).
May 90	Electron gun installed.
Jul 90	AECR beams accelerated in the cyclotron.
Jul 90	Extraction of metallic ions from the AECR.

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 RF-driven ECR first stage.

The discovery of the "silicon-effect" [2] 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 walls due to its high secondary electron emission [2]. 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 an RF-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 performance of high charge state ions could be obtained without a first stage by using SiO_2 on the 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 RF 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 wall and still allow for radial pumping, access for ovens, and the direct insertion of refractory materials for the production of beams from solids [3]. 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 other materials [4]. The design of the electron gun is shown in Fig. 3 and its location in the AECR source is indicated in Fig. 1. The planer 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 II, we list the currents for some high charge state ions produced with the AECR for the two operating modes. Currents are also listed for the 6.4 GHz LBL ECR. In Table III, the to date performance of the AECR is listed.

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 II, 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 with SiO_2 were that the optimum RF 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 II, 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 RF 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 heating 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. PERFORMANCE OF THE 88-INCH CYCLOTRON WITH THE AECR

Figure 5 shows the beam transport lines from the AECR and the LBL ECR to the 88-Inch Cyclotron. The sections of the beamline between the source analyzing magnets and the axial injection are commonly powered, which not only reduces the cost but also simplifies the control system. The completion of the AECR source means that ion beams can be injected into the cyclotron from either of the sources. With the higher charge state ion beams produced by the AECR, the performance of the 88-Inch Cyclotron has been greatly enhanced. Now the energies of the ion beam accelerated from the 88-Inch Cyclotron can reach up to 1 GeV. Table IV shows the ion beams injected from the AECR and accelerated by the 88-Inch Cyclotron. The AECR source will be in a fully operational mode with the 88-Inch Cyclotron in the near future.

IV. 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 RF 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 have shown that the injection of additional cold electrons into an H^- cusp source increased the plasma density and decreased the plasma potential [5]. 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 due to the space charge force of the injected electrons. 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. Thus the injected electrons can pull more ions into the extraction region to form a more intense beam. 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. Figure 6 shows the magnetic axial field profiles with the iron extraction end plate. The magnetic fields at the extraction region not only are higher but also have higher field gradients. When the AECR was run in this configuration for tuning on O^{6+}, 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 filed, 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 of a few mA 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.

V. 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 II 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.

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.

Table III Representative ion currents in eμA from the AECR source at 14 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.

ION CS	^{4}He	^{15}N # *	^{16}O	^{18}O # *	^{20}Ne	^{28}Si	^{40}Ar	^{40}Ca	ION CS	^{86}Kr *	^{136}Xe *	^{209}Bi
1+	2000								**15+**	44		
2+	1120								**16+**	&		
3+									**17+**	48		
4+		94	375						**18+**	45	20	
5+		123	442	40					**19+**	36	24.5	
6+		41	475	81	121				**20+**	23	27	
7+		5	131	32	90				**21+**	13	28.5	
8+			~13	5.5	86	~50	210		**22+**	10	29.5	
9+					7.5	35	231		**23+**	6.8	29.5	
10+						~22	&		**24+**	~4	30	3.1
11+						5.6	141	47	**25+**	2.2	&	3.8
12+						~2.5	78	34	**26+**	~1	&	&
13+						.037	34	21.8	**27+**	&	12	5.5
14+							17	10.3	**28+**	0.25	6.8	6
15+							&	&	**29+**		&	5.7
16+							1.4	0.83	**30+**		~2.5	&
17+								&	**31+**		1	4.5
18+								0.02	**32+**			3.5
									33+			2.6
									34+			1.5
									35+			&
									36+			0.7
									37+			0.4
									38+			0.2

Tunings were done without the electron gun.

* Isotopically enriched gas used.

& Mixed with other ion species.

Table IV AECR Beams Accelerated by the 88-Inch Cyclotron.

Ion	C.S.	E (MeV)	BS (nA)
^{16}O	6	160	6200
^{16}O	8	520	200
^{20}Ne	10	650	90
^{40}Ar	14	686	320
^{40}Ar	16	896	30
^{86}Kr	23	861	60
^{86}Kr	25	1017	8
^{136}Xe	29	865	30
^{136}Xe	30	926	20
^{136}Xe	31	990	8
^{136}Xe	32	1054	3
^{209}Bi	35	809	1.4
^{209}Bi	36	856	1.1
^{209}Bi	37	904	0.3
^{209}Bi	38	954	0.1

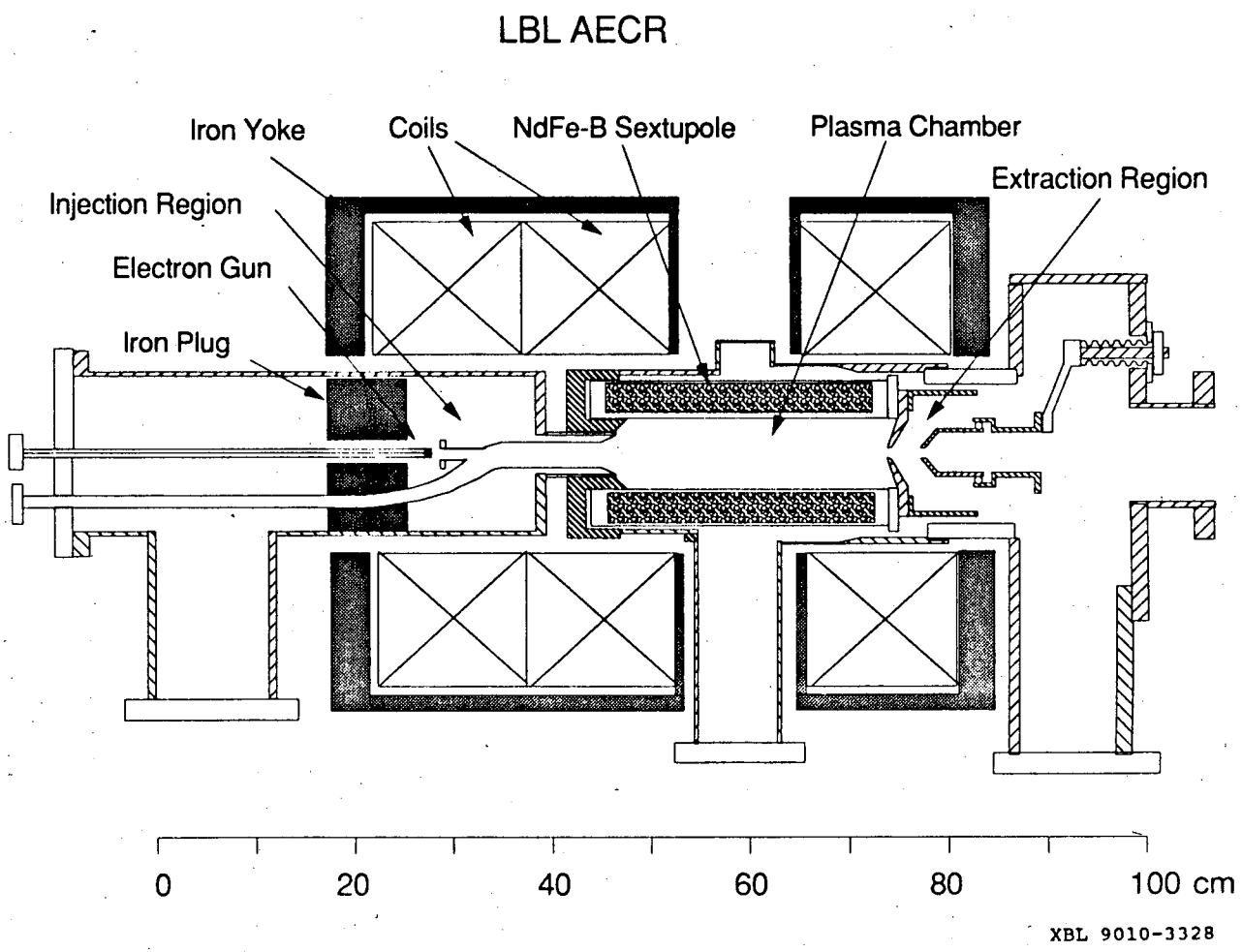

Fig. 1. Schematic drawing of the AECR. The axial magnetic field is produced by copper coils in an iron yoke. The iron plug on the injection side was added to increase the axial magnetic field. Electrons from a LaB_6 filament flow along the axial magnetic field lines into the plasma chamber.

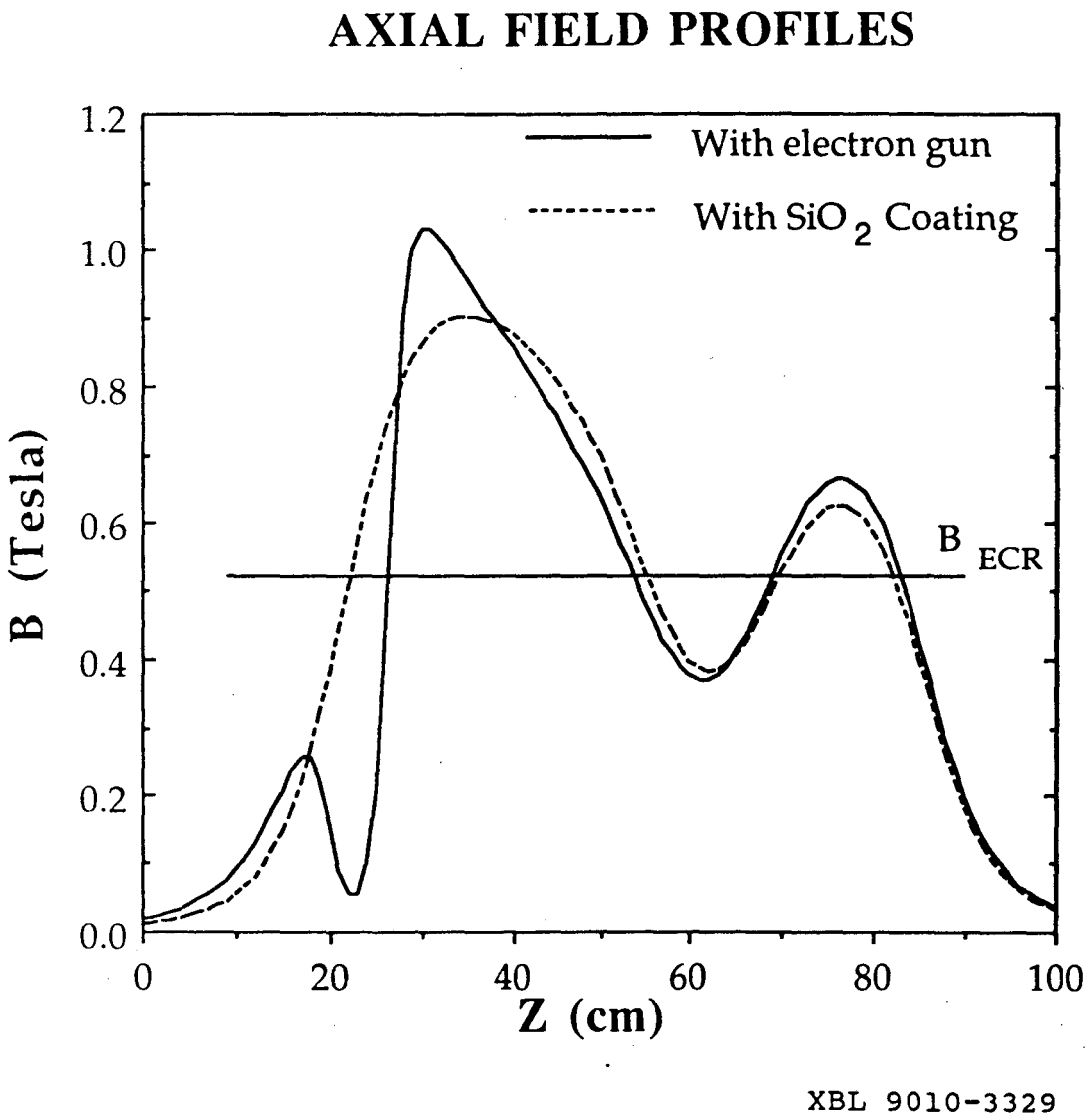

Fig. 2. Two axial magnetic field profiles are shown for the AECR. In both cases the fields were optimized for maximum O^{7+} beams. The dotted line shows the profile for operation as a single stage source with SiO_2 on the plasma chamber walls. The solid line shows the profile for operation with the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

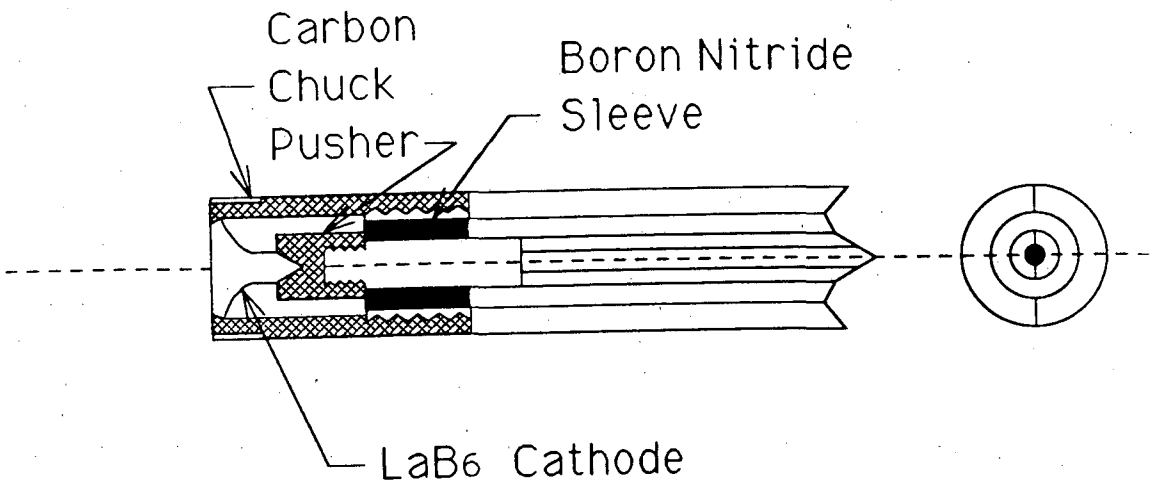

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Fig. 3. Schematic drawing of the electron gun developed for the AECR. A carbon chuck and a carbon pusher not only hold the LaB_6 cathode, but also provide electrical connection to it. The cathode has an electron emission area of 0.58 cm^2. Water is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

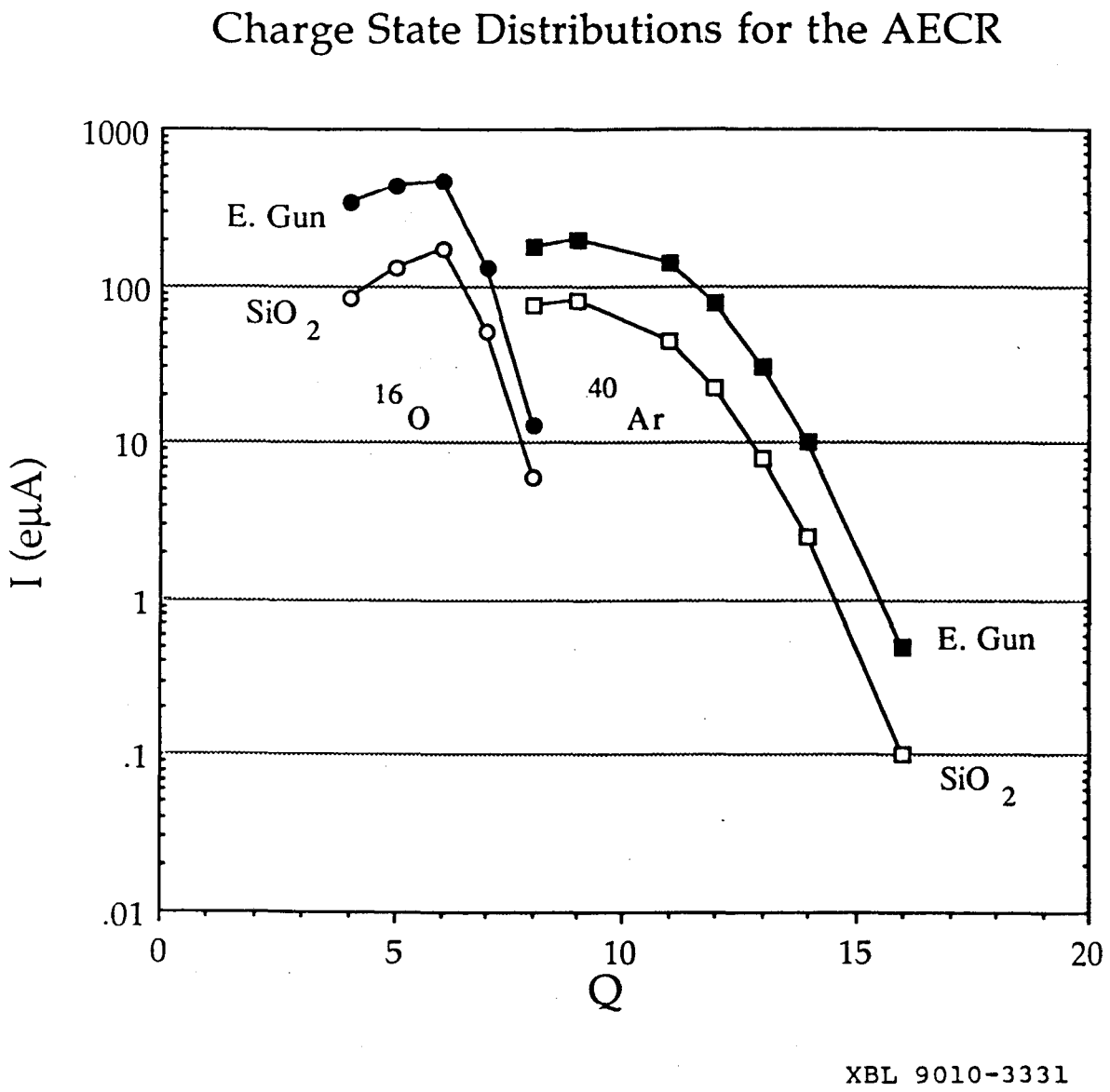

Fig. 4. Charge state distributions for oxygen and argon produced with the AECR for two cases: first, with SiO_2 on the plasma chamber wall and second, with the electron gun. For oxygen and argon the source was tuned to maximize O^{7+} and Ar^{11+}, respectively.

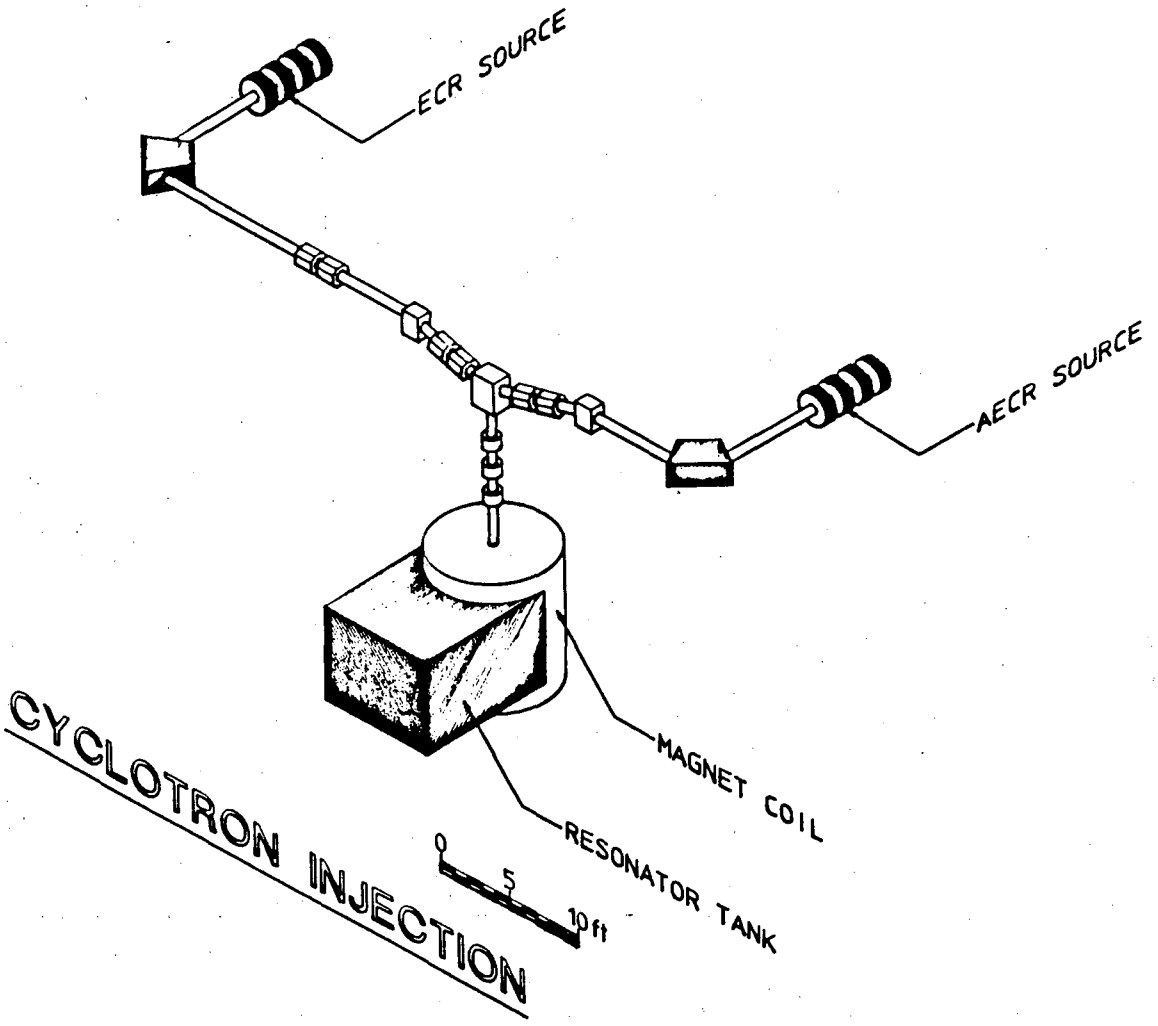

Fig. 5. Schematic view of the beam transport lines among the 88-Inch Cyclotron, the AECR and the LBL ECR sources. These two ion sources can alternately inject ion beams to the cyclotron and atomic physics research facility.

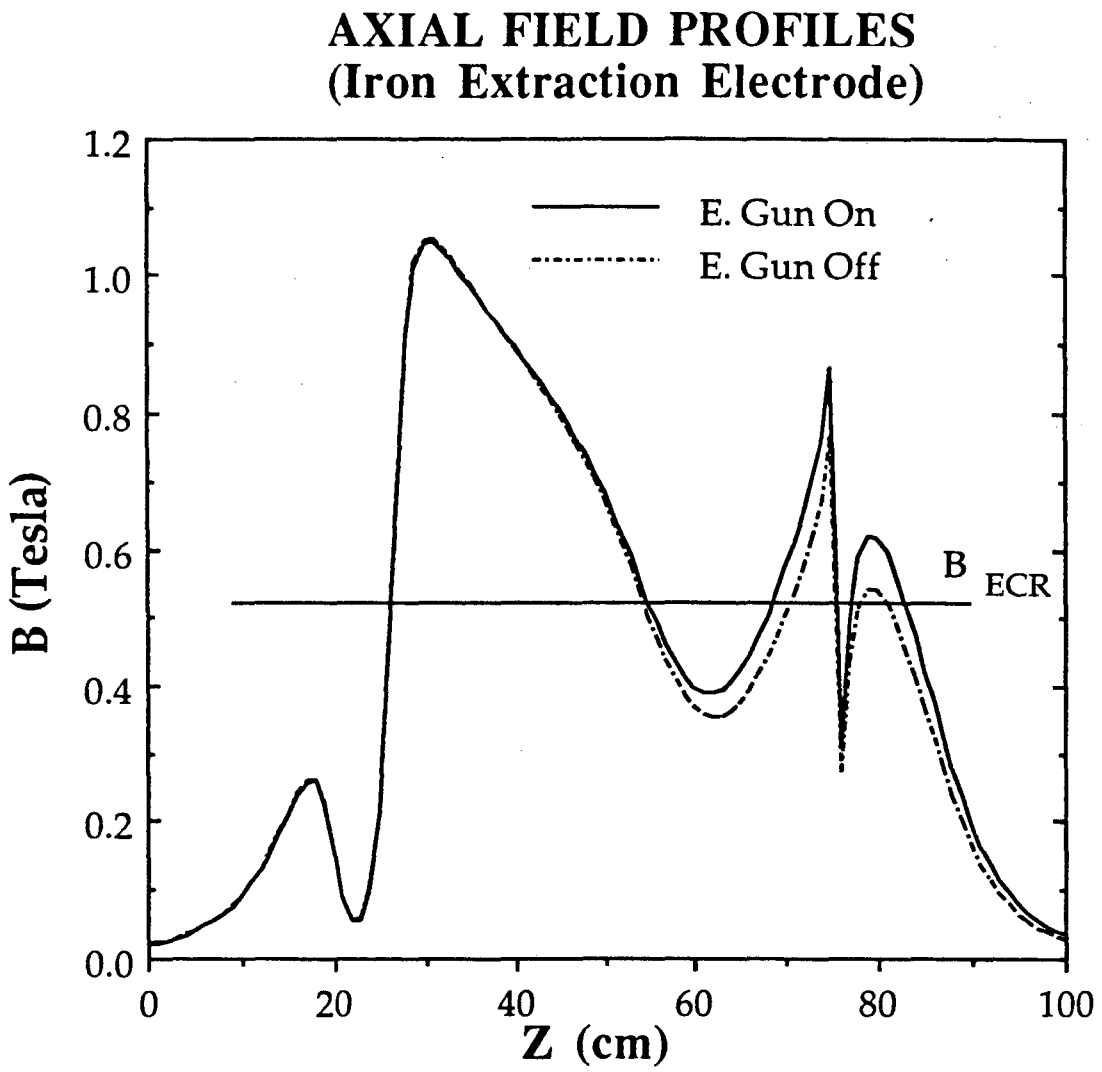

Fig. 6. Two axial magnetic field profiles for the AECR with an iron extraction end plate. Fields were optimized for O^{6+} beams. The dotted line shows the case with the electron gun off and 1.6 eμA of O^{6+} was produced. The solid line shows the case with the electron gun on and 115 eμA of O^{6+} was obtained though at a slightly higher mirror field. The mirror ratios are R = 2.17 for the case with the electron off and R = 2.24 for the case with the electron gun on.

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