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RECENT DEVELOPMENTS OF THE LBL ECR ION SOURCE

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INTRODUCTION

The performance of the LBL ECR has improved significantly since January 85 when the last ECR Ion Source Workshop was held in Berkeley. The 88-Inch Cyclotron began regular operation with the ECR source just prior to the Workshop. Since then about 80% of the cyclotron operating schedule has been with the ECR source. The light-ion filament source is used only for runs two or more shifts in length using proton, ^{3}He, or alpha beams. Occasionally the polarized ion source is used. The heavy-ion PIG sources are no longer used. The operating experience with the Cyclotron+ECR has been highly successful in terms of reliability, stability, production of high charge state currents, and in the range of ions which can be produced. For example, a 32.5 MeV/u $^{16}O^{8+}$ beam was developed and successfully used for a nuclear structure experiment. The 60 nA beam available from the cyclotron was more intense than the experiment could use. A 1.08 GeV $^{36}Ar^{18+}$ beam was used to test the response of various scintillator materials to intermediate energy heavy ions. A more detailed discussion of the operating characteristics of the 88-Inch Cyclotron+ECR has been published elsewhere.[1] Three aspects of the LBL ECR source development are discussed below. First, the installation of a new first stage cavity has resulted in improved source performance. Second, a number of metal ion beams have been developed and are used regularly for nuclear science experiments with the cyclotron. Third, the source performance has been compared to charge state distribution (CSD) calculations using a computer code developed by Jongen.[2]

DISCUSSION

The main components of the LBL ECR are shown in Fig. 1. Its design and construction have been described in detail elsewhere.[3,4] It is a compact source using copper coils to produce the axial magnetic field and an open $SmCo_5$ sextupole magnet to produce the radial magnetic field. The first stage uses a 1 kW 9.2 GHz klystron and the second stage uses a 3 kW 6.4 GHz klystron. Typically the first stage operates at 100 to 200 W of RF power and the second stage at 200 to 1000 W depending on ion species. Pumping for the source is provided by three 6" diffusion pumps. Two distinguishing features of the LBL ECR are the relatively low second stage RF frequency and high pumping speed in the plasma chamber due to radial pumping design.

The performance of the LBL ECR is summarized in Tables1 and 2. All results are given for an extraction voltage of 10 kV and 12 mm analyzer slit widths except for xenon where 6 mm slits were used to improve the resolution. The currents represent the best results taken from many tests. Larger currents can be attained at higher extraction voltage. For example, the current for Ar^{8+} increased from 106 μA at 10 kV to 140 μA at 14 kV. This is due at least in part to a decrease in

the transverse emittance at high voltage. The ^{84}Kr currents were produced using natural krypton so if mono-isotopic krypton were used the currents would be about twice as large. Similarly ^{129}Xe currents would increase a factor of 4 if mono-isotopic xenon were used.

To a large extent the ion beams developed have been dictated by the needs of the cyclotron users. For elements such as nitrogen, oxygen, and argon that have been frequently used, the values in the tables are well optimized. Other beams such as fluorine, sulfur, and titanium have been infrequently used and performance will probably improve with further development. Gas mixing using either oxygen or nitrogen was used to enhance the high charge state performance for all ions heavier than oxygen. In general oxygen appears to work better than nitrogen as a mixing gas, but because of possibility of oxide formation some of the metal ion beams are run with nitrogen. As discussed below the modifications made to the first stage resulted in significantly better performance. Ion beams of carbon, fluorine, silicon, and sulfur are produced by using gases CH_4, CHF_3, SiH_4, and $S0_2$; respectively. To reduce contamination problems in the first stage, these gases are introduced directly into the second stage with oxygen being used as a support gas in the first stage. The iodine beam was developed to explore the source's performance with very heavy ions. The highest charge state observed was I^{30+} with an intensity of 9 enA. Because iodine is mono-isotopic, the identification of very high charge states is much easier than for multiple isotope elements such as xenon.

New First Stage

The installation of a new first stage resulted in a significant improvement in the performance of the LBL ECR. The O^{7+} current increased from 4 to 14 μA and Ar^{14+} from 0.13 to 1.4 μA.[5] The new first stage made tuning the source easier and more reproducible and it improved the long term stability. The design of the new first stage shown in Fig. 2 differs from the old one in two main respects. First, the 9.2 GHz RF power is now injected into the first stage microwave cavity where the axial magnetic field exceeds B_{ECR}. This allows the microwaves to propagate to the ECR resonance zone without first crossing the upper hybrid mode resonance. Presumably, much of the hysterisis and instabilities observed in the old first stage were caused by reflection or wave conversion at the upper hybrid resonance. Second, a 12 mm id alumina tube containing the plasma is mounted coaxially in the new first stage microwave chamber. This reduces the gas conductance in the first stage decreasing the neutral gas flow required to maintain as sufficient pressure (~ 10^{-3} Torr) at the first stage ECR zone. As a result, the gas usage has been reduced and the operating pressure in the second stage is lower. To further improve the first stage operation two iron plates have been added to the first stage structure as shown in Fig. 1 to enhance the axial magnetic field in the first stage and to move B_{ECR} a few centimeters closer to the gas feed.

After the installation of the new first stage a comparison of operating parameters and performance was made with the old configuration using oxygen. Oxygen has been used frequently and the source performance with it is well quantified. The optimum oxygen flow into the first stage decreased 50%, the first stage pressure decreased from ~$1.2x10^{-5}$ to $0.6x10^{-5}$ Torr (measured

outside the small cavity), and the pressure in the plasma chamber (measured outside the sextupole) decreased from $6x10^{-7}$ to $3x10^{-7}$ Torr. While the flow of neutral gas into the second stage was decreased by 50%, the plasma flow was essentially unchanged. After the new first stage was installed, O^{7+} and N^{6+} currents were no longer improved by adding helium as a mixing gas to the first stage. The new first stage produces a very stable quiescent plasma, that allows the second stage to be tuned to low pressure and high RF power levels before the plasma becomes unstable. Tuning in this direction increases the electron temperature in the plasma.

Oven Development

A variety of metallic ion beams can now be produced from the LBL ECR using a simple resistance heated oven. The oven (Fig. 3) is inserted radially into the second second stage so that vaporized metal atoms stream through the ECR plasma and are ionized by electron impact. Typically with oven operation, the plasma is maintained by running either oxygen or nitrogen as a support gas in the first stage. This is similar to the use of a mixing gas when operating the source with gases heavier than oxygen. The amount of metal in the plasma is adjusted by varying the oven temperature. A proportional temperature controller is used to keep the oven temperature constant. The beam stability with the oven is quite remarkable. A number of cyclotron runs lasting several days have used the metal ion beams from the ECR source. During some of these runs no adjustment of the ECR source or oven was required. This is quite important from the point of view of operations, since the cyclotron is run by a single operator per shift and no one is available to make frequent source adjustments during the night.

For calcium the measured usage was found to be in good agreement with the mass flow rate calculated using the conductance of the oven nozzle and the vapor pressure of calcium at the operating temperature. Typical operating conditions to produce 10 μA Ca^{11+} beam from the ECR are an oven temperature of 507 °C which corresponds to a calcium vapor pressure of $1x10^{-3}$ Torr and a calcium usage rate of 2.1 mg/h. Similar results were obtained with magnesium using oven temperatures corresponding to Mg vapor pressure of 1 to 3 $x10^{-3}$ Torr.

For many nuclear physics experiments only very low intensity beams are necessary. An experiment to study the cross sections for fission using $^{48}Ca^{11+}$ beams from 200 to 400 MeV on ^{197}Au and ^{208}Pb was recently completed at the 88-Inch Cyclotron. The oven was operated at 476 °C and was loaded with a piece of enriched calcium (54% ^{48}Ca). In 68 hours of operation only 10 mg of the enriched calcium were consumed, which corresponds to 0.15 mg/h. During the run the $^{48}Ca^{11+}$ beam from the ECR was .6 μA and the beam extracted from the cyclotron was typically 25 nA depending somewhat on energy and cyclotron tuning.

A slightly different technique was used to produce potassium beams from the ECR source.[6] The oven was loaded with a mixture of KCl and Ca and heated to 450 °C. Inside the oven chamber the calcium reacts with the KCl forming $CaCl_2$ and potassium vapor. This technique avoided the problems associated with handling potassium metal, reduced the chlorine beam, and made a very stable, easily controlled potassium ion beam in the ECR. The ratio of potassium to chlorine in the plasma was about 40 to 1. This method should work equally well with all of the alkali metals. A

stable titanium beam was produced using TiF_4 in the oven at 100°C to produce a molecular vapor of TiF_4 which dissociates in the plasma. The maximum intensity of the titanium is limited by increase in neutral pressure caused by the accompanying fluorine atoms. However, this technique circumvented the problems of building an oven capable of 1500 °C, as would be required to produce a sufficient vapor pressure of titanium from the metal.

Comparison with CSD model

Jongen's computer code for calculating CSD for ECR sources, BALANC[2], which he revised in May 1984 has been used to calculate CSD for the LBL ECR source. In this version of the code the neutral pressure **p**, plasma density $\mathbf{n_e}$, ion confinement time $\mathbf{t_i}$, electron temperature $\mathbf{E_e}$, ion temperature $\mathbf{T_i}$, neutral gas temperature $\mathbf{T_o}$, and plasma potential $\mathbf{V_p}$ are all treated as input parameters. The code has been modified so that the electron impact ionization cross sections previously calculated using the formula proposed by Müller and Salzborn[7] (MS) can be now be calculated using the Lotz formula[8]. Some of the parameters such as neutral density and ion temperature can be set approximately on the basis of experimental measurement. The CSD depends strongly on the product of the plasma density and the ion confinement time . Unfortunately, neither of these quantities can be calculated or measured with sufficient accuracy, so they must be treated as fitted parameters. The CSD also depends on the electron temperature, especially for high charge states. In spite of the incomplete knowledge of necessary input parameters, fitting experimental CSD's with the code provides a useful context for understanding the operating regimes of ECR sources.

In Fig. 4 an oxygen CSD for the LBL ECR tuned for maximum O^{7+} is compared with computed CSD using Jongen's code with two formulas for the electron impact ionization cross sections. The Lotz formula is generally thought to be the best general model for electron impact ionization[9], while the MS formula was fit empirically to the experimental argon cross sections[7]. The details of the CSD depend strongly on the electron impact cross sections and for oxygen the MS and Lotz cross sections differ by as much as a factor of 2. As illustrated in Fig. 4 the CSD calculated using the Lotz cross sections fits the experimental CSD for oxygen better than does CSD calculated using MS cross sections. This is also true for nitrogen. However, using MS cross sections seems to produce a better fit for the argon CSD measured on the LBL ECR, in agreement with earlier observations.[10] Actually, this is not surprising since the coefficients used in the Lotz cross sections for nitrogen and oxygen are fitted to experimental data, while those for argon are extrapolated. On the other hand the MS formula was developed by fitting the experimental cross sections for argon. Using either Lotz or Müller Salzborn formulas becomes more problematical for higher Z elements such as xenon.[11]

In Fig. 5 the calculated CSD for ^{18}O with neutral densities corresponding to pressures in the plasma chamber of 4×10^{-7}, 8×10^{-7}, and 16×10^{-7} Torr are compared with a measured CSD. This calculation shows that decreasing the neutral density from 16×10^{-7} to 8×10^{-7} Torr increases the $^{18}O^{8+}$ current 50%. This shows how strongly the neutral density, via charge exchange, affects the

output of O^{7+} and O^{8+} from the LBL ECR.

Additional evidence on the critical role played by the neutral pressure in the second stage comes from the contamination effects we observe after running the ECR with the oven to produce metal ion beams. The CSD for oxygen is strongly depressed immediately after a metal ion run. Several magnesium runs have shown this effect. Although little or no magnesium can be detected in the CSD, the effect on source performance can last a few days of continuous operation. The mechanism seems to be that magnesium coated on the walls of the plasma chamber adsorbs gas molecules which are then slowly desorbed by plasma bombardment, thereby raising the neutral density. The best cleaning technique is to run the source continuously with an oxygen plasma. Gradually, the second stage neutral pressure drops and the maximum performance returns.

Conclusion

The LBL ECR has continued to evolve and improve since it began regular operation in January 85. The impact on the operation and experimental program has been extremely positive with a wide variety of new beams made available. During the next year new beams such as vanadium, iron, copper, and chlorine will be developed.

Acknowledgment

The 88-Inch cyclotron has benefited greatly from the pioneering work in the field of ECR ion sources at Grenoble[12], Louvain-la-Neuve[13], and Karlsruhe[14]. The open sharing of ideas within the ECR ion source community makes continuing rapid progress possible.

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TABLE 1
Currents for the LBL ECR: Hydrogen through Silicon

CS	^{1}H	^{3}He	^{12}C	^{14}N	^{16}O	^{19}F	^{20}Ne	^{24}Mg	^{28}Si
1+	300	300	27	82	118				
2+		200	37	117	143	43	51	32	20
3+			*	106	152	55	63	34	33
4+			31	110	*	53	78	28	69
5+			6.5	93	96	37	58	44	72
6+				19	82	17	45	34	47
7+					14	11	21	18	30
8+					0.95	1	11	8	17
9+						0.05	1.1	6.3	7
10+							0.04	2.2	2.7
11+								0.1	0.5
12+									0.2

TABLE 2
Currents for the LBL ECR: Sulfur through Xenon

CS	^{32}S	^{39}K	^{40}Ar	^{40}Ca	^{48}Ti	^{84}Kr	^{127}I	^{129}Xe
3+	10	4	38	23				
4+	*	4.5	82	24				
5+	20	5	*	*				
6+	*	8.5	60	37		9		
7+	63	11	66	38	2.4	12		
8+	*	18	106	36	*	22		
9+	36	37	72	31	12	25		4.1
10+	*	22	*	*	10	22	4.2	4.7
11+	5	12	18	22	8	19	4.9	5.1
12+	*	2.4	13	11	*	*	5.7	5.2
13+	.4		5	3.2	1	21	7.5	5.2
14+	*		1.4	1.1		*	8.5	5
15+	.001		*	*		16	11	4.3
16+			0.03	0.03		8	*	4.6
17+						7	12	4.3
18+						*	15	4.4
19+						2	15	4.8
20+						0.9	14	4.8
21+						*	*	4
22+						0.1	11	3.5
23+							10	3.1
24+							8.3	2.7
25+							5.6	2
26+							2.1	1.1
27+							0.83	0.34
28+							0.2	
29+							0.05	
30+							0.009	

All currents in eμA measured at 10 kV extraction voltage.
* Indicates not measured because a mixture of two ions with identical charge to mass ratios were present.
Natural isotopic abundance source feeds were used except for ^{3}He and $^{22}Ne^{10+}$

FIRST STAGE CAVITY

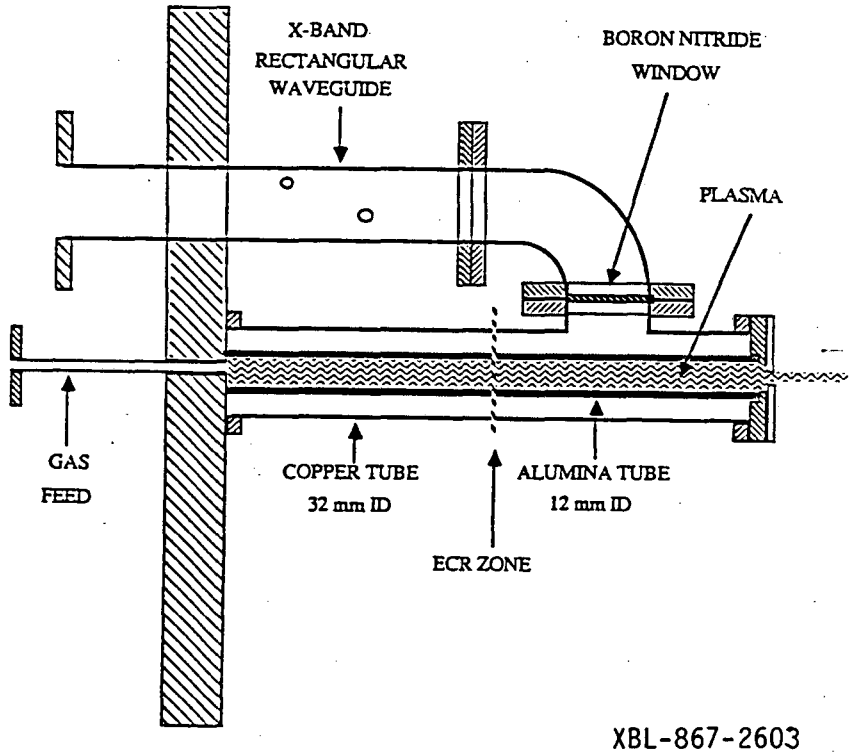

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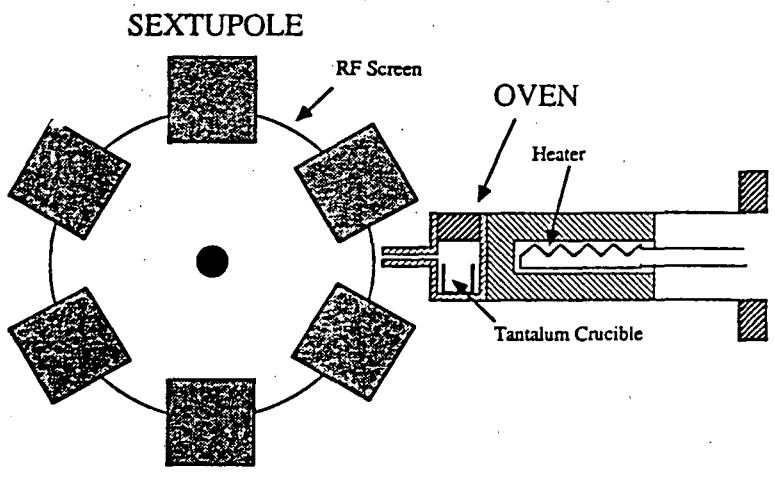
Fig. 2. The details of the new first stage are illustrated. The ceramic tube reduces gas consumption by decreasing gas conductance. The X-band waveguide has pump out holes so the pressure remains low enough that no plasma discharge occurs in it.

LBL ECR



XBL-867-2604

Fig. 3. A cross section view showing the radial position of the oven with respect to the sextupole structure. The source material is loaded into the tantalum crucible, which inhibits liquid film flow. The oven temperature is monitored and controlled using a type K thermocouple and a commercial proportional temperature controller.

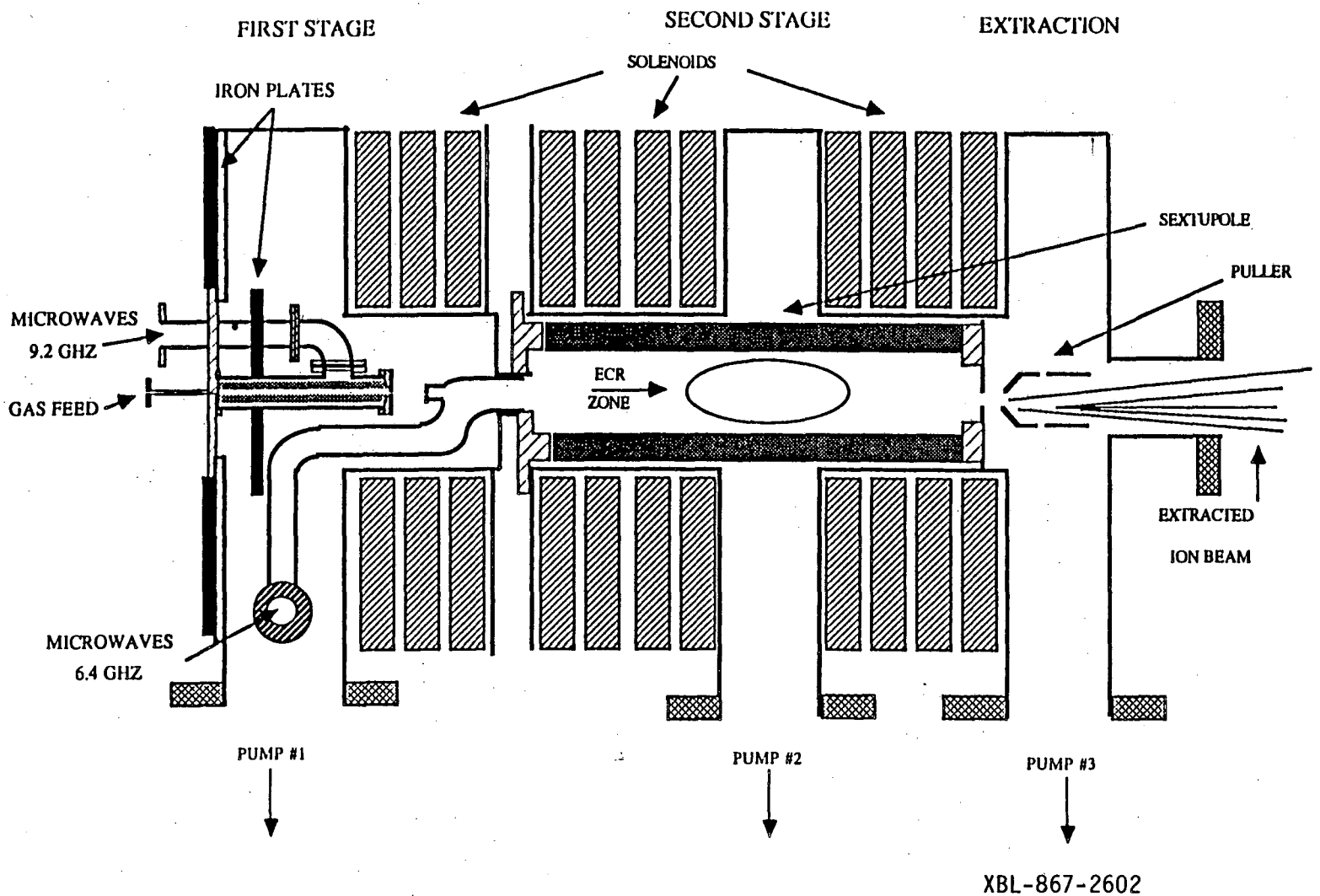


Fig. 1. Schematic drawing showing the main features of the LBL ECR. A new first stage and two iron plates to increase the magnetic field in the first stage were added during 1985.

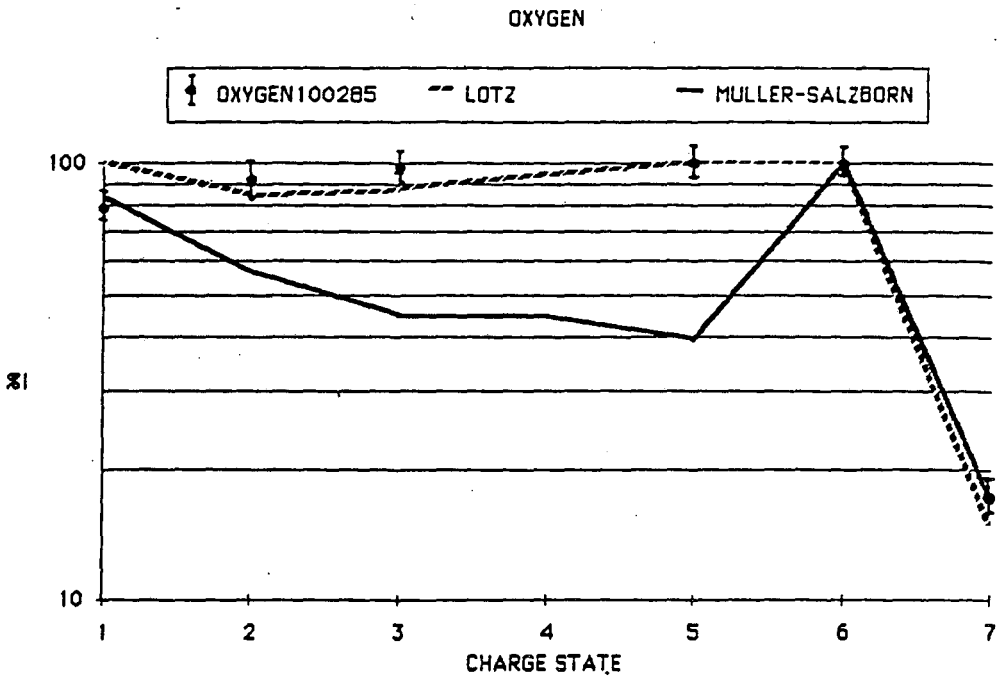


Fig. 4. Comparison of the measured charge state distribution (CSD) of oxygen with calculated CSD using Jongen's code with Lotz cross sections and Muller Salzborn cross sections. Parameters for Lotz are $p = 8\times10^{-7}$ Torr, $n_e = 3\times10^{11}$ cm^{-3}, $E_e = 2000$ eV, $T_i = 5$eV, $T_o = 3000$ °K, and $V_p = 0$ V.
Parameters for Müller Salzborn are the same except $E_e = 1000$ ev.

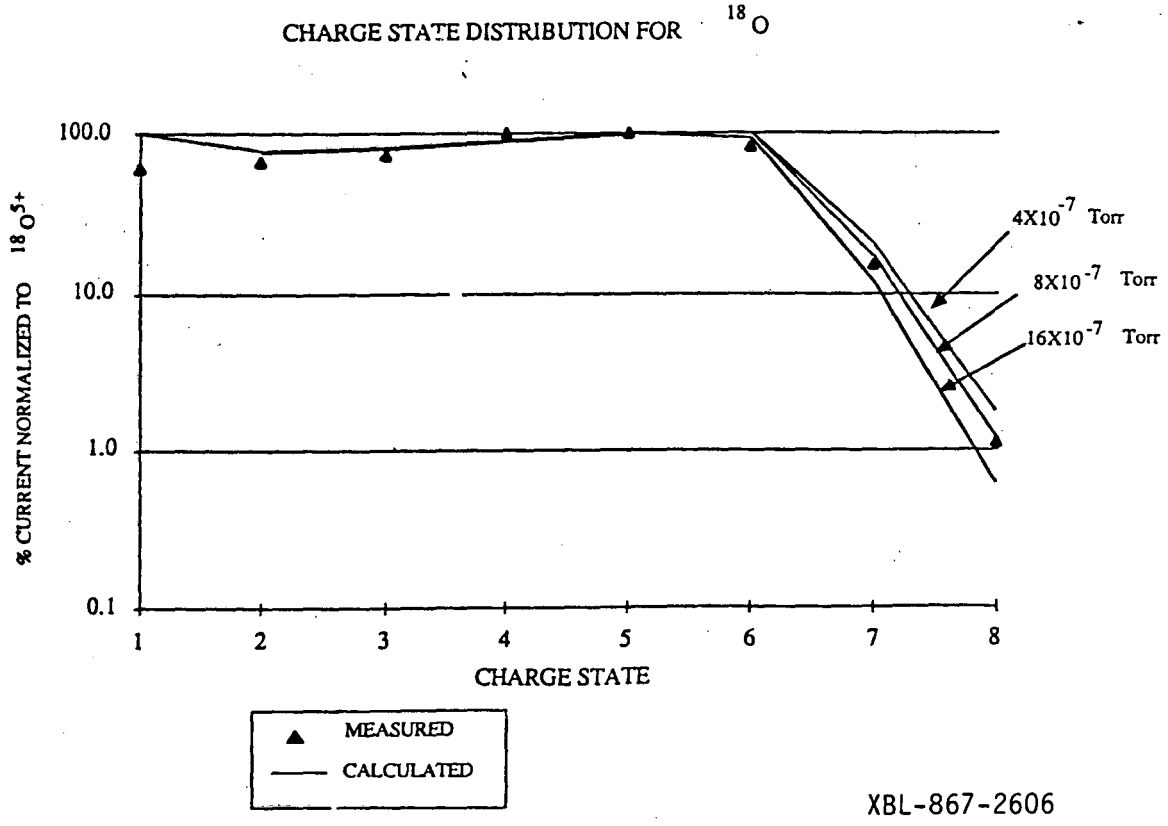


Fig. 5 Comparison of the measured CSD for ^{18}O from the LBL ECR with calculated CSD using Jongen's code and neutral pressures of 4×10^{-7}, 8×10^{-7}, and 16×10^{-7} Torr. Other parameters were $n_e = 3\times10^{11}$ cm^{-3}, $E_e = 2000$ eV, $T_i = 5$eV, $T_o = 3000$ °K, and $V_p = 0$ V.

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