OPERATIONAL PERFORMANCE OF THE LBL 88-INCH CYCLOTRON WITH AN ECR SOURCE*

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Summary

The 88-Inch Cyclotron began regular operation with the ECR (Electron Cyclotron Resonance) source in January 1985. 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, deuteron, ^{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 range of ions which can be produced.

The performance of the Cyclotron+ ECR has steadily improved since regular operation began. The improvement is a result of better source performance, better stability and tuning of the injection line, and better cyclotron tuning. Development of the ECR source has resulted in improved high charge state performance and a greater variety of ion species. The LBL ECR now produces 14 μA of O^{7+}, 1 μA of O^{8+}, 72 μA of Ar^{9+}, 1.4 μA of Ar^{14+}, 5 μA of I^{25+}, and .009 μA of I^{30+}. Metal ions from Mg, K, and Ca are produced in the ECR using an oven to inject vapor into the plasma chamber. Operation with the oven is quite stable and frequently requires no adjustment during runs lasting several days. Beams of F, Si, S, and Ti have been produced using various compounds as gases or solids with the oven. The overall transmission from source analyzing magnet to cyclotron external beam is typically 2 to 10% with a maximum of 17%. As a result of the improved source performance and transmission a wide variety of new beams can be produced. For example, a 32.5 MeV/u $^{16}O^{8+}$ beam and $^{48}Ca^{11+}$ beams with energy from 200 to 350 MeV have been used for nuclear physics experiments. A 1.08 GeV $^{36}Ar^{18+}$ beam was used to test the response of various scintillator materials to intermediate energy heavy ions.

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Introduction

The LBL ECR source, injection beam line, and cyclotron center region have performed reliably since coming into regular operation in January 1985. The cyclotron is operated on 24 hours per day, 5 days per week, 46 weeks per year. All of the heavy-ion operation, which accounts for 80% of the operating time, is done using the ECR source. The remaining 20% of the time is used for light-ion operation with the filament source for protons, deuterons, ^{3}He, and alphas, or with the polarized ion source. Proton, deuteron, ^{3}He, and alpha beams can be run with the ECR source, but generally the filament source is used to free the ECR source for development or atomic physics applications. The improved performance of the cyclotron with the ECR source has resulted in more demand for beam time. Many new beams have been developed which has enabled the physicists to do experiments previously impossible at the 88-Inch Cyclotron.

The 88-Inch Cyclotron+ECR serves diverse users who need a wide range of beams, energies, and intensities. Nuclear chemistry experiments frequently require several eμA beams of ^{16}O, ^{18}O, ^{20}Ne, or ^{22}Ne at ~6 MeV/u. The group studying rapidly rotating nuclei generally use intensities of ~20 enA at an energies ~4.5 MeV/u with beams such as ^{34}S, ^{40}Ar, ^{40}Ca, and ^{48}Ti. Groups studying heavy-ion reaction mechanisms and complex fragmentation of highly excited nuclei use 3 to 30 enA intensities of beams such as 32.5 MeV/u ^{16}O, 19 MeV/u ^{40}Ar,and 8 MeV/u ^{48}Ca. Industrial users simulate the effect of cosmic rays on computer chips (single event upsets) by using beams from nitrogen to xenon at energies ~3.5 MeV/u and intensities ~10^5 p/s. One technique frequently used is to run a mixture of gases in the ECR source so that beams of $^{15}N^{3+}$, $^{20}Ne^{4+}$,and $^{40}Ar^{8+}$ (m/q=5) can be selected in the cyclotron simply by making a small change in cyclotron frequency. This way, the computer chips can be bombarded with a range of linear energy transfer (LET) particles without time consuming energy changes. The highest energy beams such as $^{36}Ar^{18+}$ at 1.08 GeV have been used to test scintillator materials response to intermediate energy heavy ions.[1] This technique is also useful for measuring very high charge states produced by the ECR source that are too low in intensity to be detected with the ECR analyzing system. $^{36}Ar^{18+}$, $^{40}Ca^{20+}$, and $^{84}Kr^{28+}$ are examples of charge states from the ECR detected this way.

TABLE 1
Optimized beams from the 88-Inch Cyclotron+ECR

Ion	Cyclotron Energy (MeV)	H	Source Current (eμA)	Cyclotron Ext. Current (eμA)	Trans-mission (%)
$^{14}N^{5+}$	180	1	60	7	11
$^{18}O^{5+}$	117	1	60	10	17
$^{16}O^{6+}$	315	1	40	3	7
$^{16}O^{7+}$	429	1	10	0.2	2
$^{22}Ne^{6+}$	151	1	40	7	17
$^{24}Mg^{7+}$	192	1	20	1.5	7
$^{28}Si^{6+}$	180	1	60	3	5
$^{40}Ar^{12+}$	504	1	6	0.2	3
$^{16}O^{2+}$	20	3	69	2	3
$^{40}Ar^{9+}$	180	3	30	3	10
$^{86}Kr^{14+}$	301	3	2.5	0.08	3
$^{129}Xe^{21+}$	451	3	.8	0.02	3
$^{16}O^{2+}$	20	5	67	0.15	0.2

H is the cyclotron harmonic.

System Description, Operation, and Performance

The horizontal and vertical sections of the beam transport system from the 90 degree analyzing magnet to the center of the cyclotron are described in more detail in paper in this conference.[2] Magnetic rather than electrostatic bending and focusing elements were chosen because of better space charge neutralization for high intensity beams, fewer vacuum penetrations, and better long term reliability. Beam diagnostics along the injection beam line consist mainly of fixed four jaw collimators with beams readouts before each set of lenses where the beam is large. Beam current can be read on Faraday cups before and after the analyzing magnet and at the top of the axial injection line. Beam at the bottom of the axial injection line can be read on the mirror electrode in the midplane of the cyclotron and then on the cyclotron beam probe at small radius. The vacuum system uses cryo-pumps and turbo-pumps and all metal seals. The typical beam line pressure is $< 5 \times 10^{-8}$ Torr which is sufficiently low so that beam loss due to charge exchange with neutrals is negligible. To minimize beam steering due to the stray field of the cyclotron, nickel plated magnetic steel beam pipes were used where possible and magnetic shielding was added to stainless steel components such as bellows. A gridded two gap sine wave buncher installed 2.1 m above the cyclotron midplane provides a factor of 3 to 5 transmission gain over an unbunched beam. A gridded electrostatic mirror is used to bend the beam through 90 degrees into the midplane.

The currents of the focusing and bending elements are now predicted by a computer program based on a combination of calculations and beam line tuning experience. The predictions are sufficiently accurate so that the operator only needs to do some fine tuning to maximize the beam. Some examples of beams from the Cyclotron+ECR are listed in Table 1. The transmission from the Faraday cup after the analyzing magnet to extracted beam from the cyclotron varies from a few percent up to as much as 17% depending on the cyclotron main field, vacuum in the cyclotron tank, ion species, and whether first or third harmonic number is used. A recent test showed that beams can also be accelerated in fifth harmonic, but the transmission is only about .2%. Usually the source is operated at 10 kV which gives good beam centering for the maximum dee voltage of 50 kV.

The ECR Source

Figure 1 illustrates the basic design features of the LBL ECR. Details of its design, construction, and development are published elsewhere.[3-5] Two distinguishing features of the LBL ECR are the relatively low second stage frequency and high pumping speed in the plasma chamber. The first stage uses a 1 kW 9.2 GHz klystron (typical power 100 W) and the second stage uses a 3 kW 6.4 GHz klystron (typical power 400 W). The first stage operates on the uphill gradient of the axial magnetic field as shown in Fig. 2. The radial magnetic field is produced by a $SmCo_5$ sextupole with slots which allow radial pumping. The axial magnetic field is produced by tape wound edge cooled copper coils each powered by an individual supply for maximum flexibility in magnetic field configuration. Typical magnet power is 30 kW.

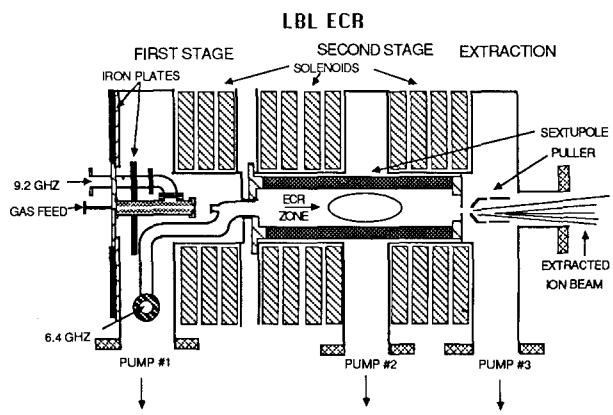

Fig. 1 Schematic drawing showing the main features of the LBL ECR. A new first stage and two iron plates to increase the magnetic field in the first stage were added during 1985.

The performance of the LBL ECR is summarized in Tables 2 and 3. 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 obtained 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 in part to a decrease in the transverse emittance at high voltage. The ^{84}Kr and ^{129}Xe currents were produced using natural krypton and xenon, respectively, so higher currents could be obtained with mono-isotopic gases. To a large extent the ion beam development has 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 the performance will probably improve with further development.

Several different techniques have been used to produce beams from the LBL ECR and these techniques are summarized in Table 4. Elements that exist in gaseous form are most easily used in the ECR source. A flexible gas manifold system, which allows up to three gases to be used simultaneously, has been installed on the LBL ECR. The gases can be injected into either the first or second stage of the source. The best proton and alpha beams are produced by feeding gas directly into the second stage and turning off the first stage. For all elements heavier than oxygen, gas mixing is used to enhance the high charge state performance of the source. Although it remains a point of discussion why, all ECR sources seem to benefit from gas mixing. In all cases adding a light mixing gas enhances the high charge states of the heavier gas. The presence of heavy ions in the plasma also acts to depress the charge state performance of light ions. For example, a very small percentage of xenon in the plasma decreases O^{7+} currents by as much a factor of 10. Prior to the installation of a new first stage, which is described in more detail elsewhere,[6] the high charge states of oxygen and nitrogen could be enhanced by the addition of helium. After the installation of the new first stage, the high charge state performance was considerably better for oxygen and nitrogen and mixing helium no longer improved it. In general oxygen works better as a mixing gas in the LBL ECR than nitrogen. One possible reason is that the first stage performance is better with oxygen than nitrogen. A charge state distribution for oxygen measured on the LBL ECR is shown in Fig. 3. For this measurement the source was tuned to maximize O^{7+}.

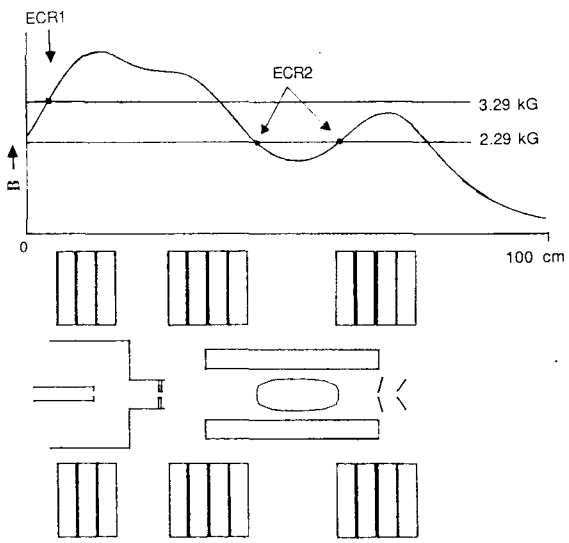

Fig. 2 Axial magnetic field distribution and schematic view of the LBL ECR showing the location of the solenoid coils, sextupole, extraction, and ECR zone. ECR1 is the location of the ECR zone in the first stage, ECR2 shows the locations of the zone on axis in the second stage.

Beams from elements such as carbon, sulfur and silicon can be produced using gaseous compounds such as CH_4, SO_2, and SiH_4, respectively. In general to take advantage of gas mixing effects, compounds with lighter atoms bonded to the desired element are chosen. For the LBL ECR geometry injecting the compound gases into the second stage and the mixing gas into the first stage produces the most consistent results. The pressure in the first stage cavity is relatively high (~3 $x10^{-4}$ Torr) and using compounds in it may result in plating the walls which can affect first stage performance. Also, since operation with the cyclotron frequently requires several different beams in a week and only a few hours is allowed for beam changes, contamination of the first stage would cause operational problems. An additional advantage to injecting the gaseous compounds into the second stage comes from the reduced gas flows required. Typically the first stage requires about 15 std cc/hr of gas, while the second stage requires at least an order of magnitude lower flow. Particularly when a corrosive gas is used, it is a significant advantage for pump lifetime to minimize the gas throughput. Other advantages to injecting compounds into the second stage are easier source tuning and better long term stability. To avoid handling problems associated with fluorine gas, Freon 23 (CHF_3) is injected into the second stage.

A variety of metallic ion beams can now be produced from the LBL ECR using a simple resistance heated oven shown in Fig 4. The oven 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

TABLE 2

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

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 $^{22}Ne^{10+}$.

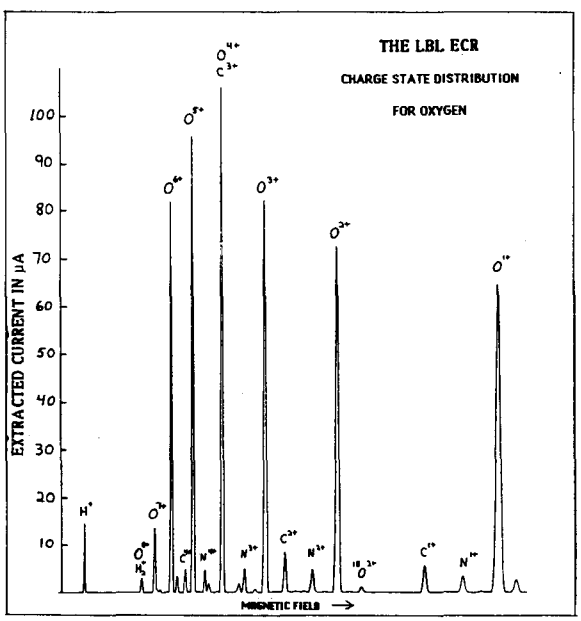

Fig. 3 Charge state distribution for oxygen measured on the LBL ECR. The plot was produced on an x-y recorder by slowly sweeping the analyzing magnet.

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. To produce a 10 eμA Ca^{11+} beam

TABLE 3

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 $^{22}Ne^{10+}$

from the ECR requires 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.

In Fig. 5 the charge state distribution (CSD) for iodine and bismuth are plotted. Both bismuth and iodine are mono-isotopic which makes the measurement of the CSD easier than using multi-isotope elements such as xenon. ^{209}Bi was chosen to explore the performance of the LBL ECR source for very heavy elements because it is mono-isotopic and its vapor pressure temperature characteristics are appropriate for the oven. The source produced .56 eμA of Bi^{31+} and .055 eμA of Bi^{34+}.

TABLE 4

Techniques Used to Produce Beams from the LBL ECR

Beam	Starting Material	Method*	Mix Gas#
Protons	H_2 gas	2	none
Alphas	He gas	2	none
Carbon	CO_2 or CH_4 gas	2	O_2
Nitrogen	N_2 gas	1	none
Oxygen	O_2 gas	1	none
Fluorine	CHF_3 gas	2	oxygen
Neon	Ne gas	1	He or O_2
Magnesium	Mg metal	400 °C	O_2 or N_2
Aluminum	Al_2O_3 rod	In plasma	O_2
Silicon	SiH_4 gas	2	O_2
Sulfur	SO_2 gas	2	O_2
Potassium	KCl & Ca	450 °C	O_2
Argon	Ar gas	1	O_2
Calcium	Ca metal	500 °C	O_2 or N_2
Titanium	TiF_4 powder	100 °C	O_2
Krypton	Kr gas	1	O_2
Niobium	Solid rod	In plasma	O_2
Iodine	I crystals	25 °C	O_2
Xenon	Xe gas	1	O_2
Bismuth	Bi metal	525 °C	O_2

* Indicates whether the primary gas was injected into the first or second stage, if the oven was used what the temperature was, or if a solid was inserted into the edge of the plasma.

Mix Gas Indicates if a mixing gas was used. In all cases listed the mixing gas was injected into the first stage.

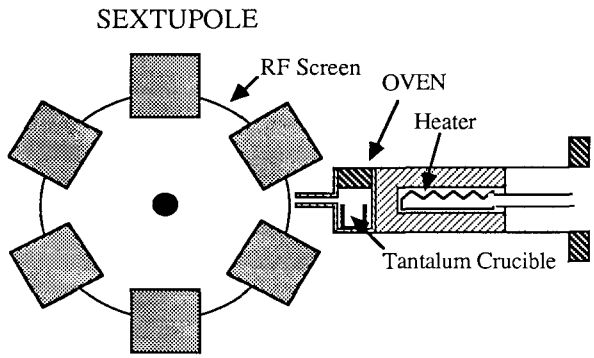

Fig. 4. A cross section view showing the radial position of the oven with respect to the sextupole structure. The source material is loaded into the tantalum crucible, which inhibits liquid film flow. The oven temperature is monitored and controlled using a type K thermocouple and a commercial proportional temperature controller.

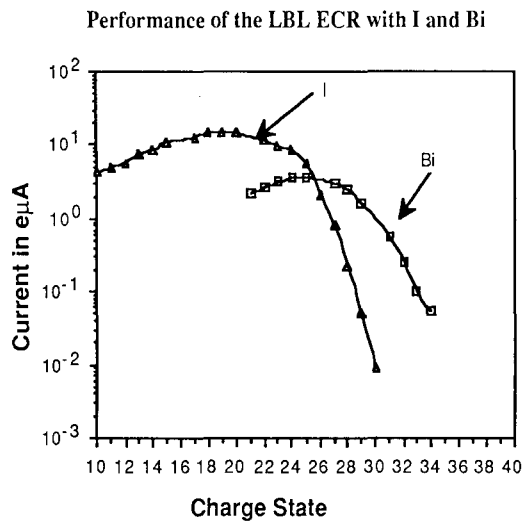

Fig. 5 Performance of the LBL ECR with ^{127}I and ^{209}Bi. The best iodine beams were produced from iodine adsorbed on the walls after the oven was removed. The bismuth beams were produced by running the oven at 526 °C.

These charge states would be quite useful for the high K superconducting cyclotrons at MSU, Milan, and Texas A&MU as well as the upgraded heavy-ion linac at ANL.

A slightly different technique was used to produce potassium beams from the ECR source.[7] 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 the 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.

Another technique used to produce beams from solids is to insert a rod into the edge of the plasma.[8] This technique has been used in the LBL ECR to produce Al, Fe, Ti, and Nb beams, which have been used for test purposes and atomic physics measurements, but not for operation with the cyclotron. The solid rods are inserted radially into the second stage plasma until they are heated to sufficient temperature by the hot electrons in the plasma to produce the required metal vapor pressure. The heating rate is a function of plasma density, axial magnetic field strength, and RF power. With careful tuning it is possible to produce stable beams for a several hour periods. In order to use this method for operating with the cyclotron, a feedback control system operating either the rod's position or RF power level needs to be developed.

Operation of the LBL ECR with solids for the cyclotron involves some compromises. Usually after solids are used there is a short term degradation in the high charge state performance of the source. The degree of degradation and the length of the recovery time depends on the type and amount of material injected into the source. Two mechanisms appear to cause the degradation. First, if a high mass solid has been run it can provide a background of heavy ions in the plasma via recirculation with the walls. These heavy ions then act as negative gas mixing depressing the lighter ion CSD. Second, contamination of the walls reduces the plasma stability making it impossible to operate the source with the parameters used when it is clean. The most effective method for cleaning the source after a metallic ion run seems to be to run it with oxygen in a mode producing a large total current. To minimize operating problem with metals, we keep the metal vapor density in the plasma as low as possible consistent with producing sufficient beam intensity for the experiment. Also, when possible we schedule a non-critical run such as O^{5+} or light ions after the metal ion run to give the source time to recover.

Conclusion

The success of the Cyclotron+ECR source has increased the demand for cyclotron beam time and therefore reduced the time available for source development and other applications such as atomic physics. It would be advantageous to build a second ECR source at the 88-Inch Cyclotron in order to continue the development in areas such as metal ion beams and high charge state performance. One possibility being investigated is to build a compact ECR source using a 14 GHz klystron, copper coils, an iron return yoke, and a neodymium-iron sextupole. The success of the MINIMAFIOS-16GHz ECR source in Grenoble indicates that such a small high frequency ECR source has great potential.[9]

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