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PROGRESS ON THE LBL ECR HEAVY ION SOURCE*

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Summary

The LBL ECR ion source, which began test operation in January 1984, has already produced a variety of high charge state heavy ion beams of sufficient intensity for cyclotron operation, although actual use must wait for completion of the beam transport system. The source has produced 40 μA of O^{6+}, 2 μA of O^{7+}, 40 μA of Ar^{8+}, and 0.20 μA of Ar^{12+}. The source development has centered on optimizing source performance with modifications and parameter tuning. Future plans include construction of an $SmCo_5$ octupole structure, and testing of solid feed techniques. The construction of the beam transport line and calculations on center region geometry for heavy ion axial injection into the 88-Inch Cyclotron are also underway.

Introduction

The heavy-ion capabilities of the 88-Inch Cyclotron at LBL will be significantly upgraded in late 1984 when the Electron Cyclotron Resonance (ECR) ion source now being tested becomes operational. The upgraded accelerator system will be capable of higher energy heavy-ion beams and improved operational efficiency, compared to current operation using internal heavy-ion PIG sources. The maximum energy available from the cyclotron for ions between oxygen and argon will increase by a factor of 2 to 3, respectively .[1,2] The improvement in operating efficiency will be just as significant since the ECR source can be operated continuously without the frequent source changes necessitated by the short lifetime of heavy-ion PIG sources. In January 1984, 10 months after fabrication began, the ECR source and beam analysis system were operated for the first time. Since that time rapid improvement in the performance of the ECR source has been made. The present performance is already more than sufficient for injection into the 88-Inch Cyclotron, but this must wait for the completion of the beam transport system. The horizontal beam line is expected to be completed in June 1984 and the new axial injection line is scheduled for installation in the fall. Physics operation of the ECR source injecting beam into the cyclotron should begin in December 1984.

Source Design

The LBL ECR source is designed for reliable operation, convenient maintenance, low operating costs, flexibility, and a reasonably short construction time. The main design features are illustrated in Fig. 1 and summarized in Table I. It is a compact source similar in size to MINIMAFIOS[3] using room temperature solenoid coils and a $SmCo_5$ sextupole structure.

The solenoid field is produced by 11 edge cooled tape wound copper coils each individually powered by 250 A power supplies. The tape wound coils have a high packing fraction (75% including the edge cooling) and therefore allow the amount of copper to be high and the power requirements to be modest. Since not all coils are needed to produce the required solenoid field strength, the field configuration can be readily modified by adjusting the currents in the individual coils. In typical operation only 30 kW of magnet power is required. The sextupole field is produced by $SmCo_5$ bars supported in an open copper fixture which allows for radial pumping between the bars. A unique feature is that the easy axes of the $SmCo_5$ bars are oriented azimuthally, which allows the escaping plasma to flow out between the bars ending on the side walls of the bars rather than on the walls facing the plasma.

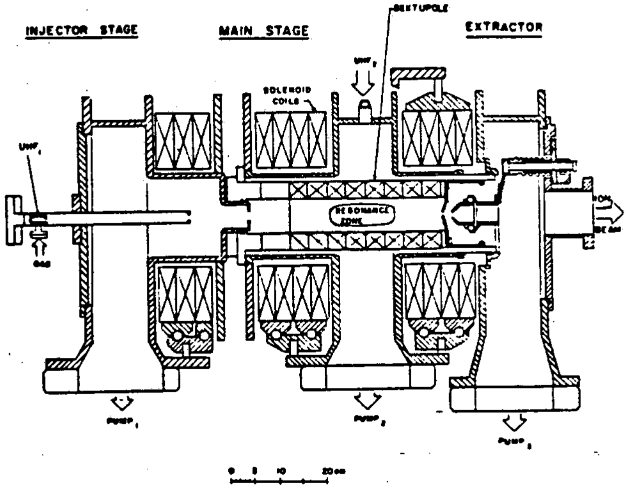

Fig. 1. An elevation view of the LBL ECR source.

Table I
LBL ECR Source Parameters

	Maximum	Typical
Magnetic Field		
On Axis	.42T	.35 T
Mirror Ratio	1.3-2.0	1.6
Sextupole at Wall		.27 T
Magnet Power	110 kW	30 kW
Microwave Power		
Injector 9.2 GHz	1.0 kW	.150 kW
Main Stage 6.4 GHz	3.0 kW	.150 kW
Vacuum		
3 6" Diffusion Pumps		
Injector Pressure		2×10^{-5} torr
Main Stage		6×10^{-7} torr
Extraction		1×10^{-7} torr
Extraction Geometry		
Plasma Electrode Hole		8 mm diam
Puller Hole		10 mm diam
Gap	10-35 mm	28 mm

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Microwave power is fed into the main stage by a waveguide, that enters the chamber radially and ends between two bars of the sextupole. In order to contain the microwave power in the region of the plasma a copper screen cylinder was formed around the sextupole. Before the screen was added measurements on the source indicated that the microwave power was only weakly coupled to the plasma, apparently because the microwaves were flowing out between the bars of the sextupole.

The present injector is basically a simple circular waveguide which is excited in the TE_{11} mode. There is an 8 mm diameter aperture at the end which reduces the gas conductance. Gas and microwaves are introduced through ports in the tube as shown in Fig. 1. The location of the ECR zone in the first stage can be moved by adjusting the currents in the first 3 solenoid coils.

The basic design features of the extraction system and the Glaser lens follow those used in ECREVIS at Louvain-la-neuve.[4] The details of the extractor geometry are given in Table I. The puller can be negatively biased to operate the extractor in an accel-decel mode. Additionally the axial position of the extractor can be easily varied without stopping source operation. The beam analysis system, which is shown in Fig. 3 consists of a Glaser lens, two sets of manually adjustable slits, and a double focusing 90 degree analyzing magnet with a bending radius of .40 m. The Glaser lens refocuses the diverging beam from the source onto the first set of slits. The 90 degree magnet coupled with the second set of slits allows a single charge state to be selected. The horizontal aperture of the slits must be closed down to 4 mm in order to attain a mass resolution of 1%. The extraction system and beam analysis system are quite efficient. The sum of the currents for all charge states collected at the Faraday cup just behind the second set of slits is typically at least 50% of the total source current indicating excellent efficiency in the beam analysis system.

Table II
Ion Currents from the LBL ECR source in μA

	^{14}N	^{16}O	^{20}Ne	^{40}Ar	^{84}Kr
1^+	43.	28.			
2^+	47.	75.	24.		
3^+	47.	80.	28.	28.	
4^+	42.	72.	35.	27.	
5^+	21.	58.	11.	34.	
6^+	1.5	38.	15.	36.	5.0
7^+	*	2.0	3.6	33.	2.6
8^+		*	.65	42.	1.8
9^+			.006	13.	2.4
10^+				3.0	2.4
11^+				1.2	2.4
12^+				.28	*
13^+					1.5
15^+					1.1
17^+					.07
19^+					.07

* Indicates not measured because a mixture of two ions with indentical charge to mass ratios were present.

Performance of the Source

The performance of the LBL ECR source is summarized in Table II. Although these results are preliminary representing only two and one half months of testing, they clearly show that the source is performing quite well and has already met its design goals for argon up to Ar^{12+}. Only the oxygen and argon beams have been extensively tuned. It should be noted that the results given in Table II are taken from a number of different measurements on the LBL ECR source and therefore do not represent a single typical charge state distribution. The results for argon achieved with this source at 6.4 GHz are comparable with those of MINIMAFIOS achieved at 10 GHz indicating there may not be a significant advantage in increasing the operating frequencies of ECR sources.

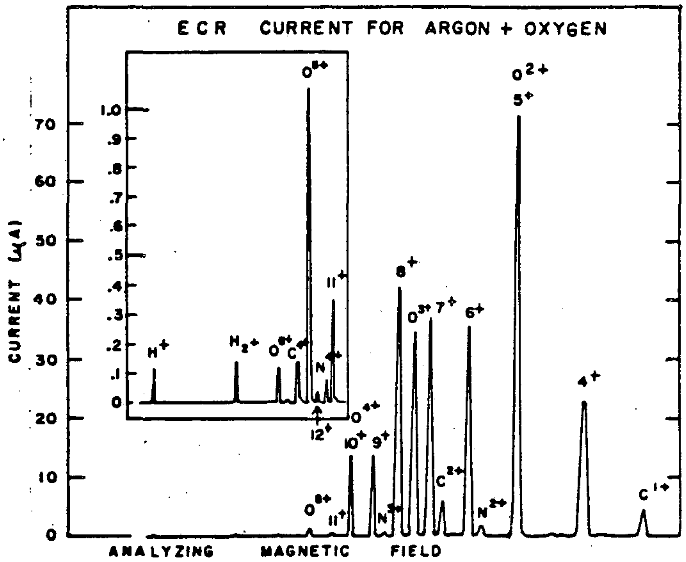

Fig. 2. Charge state spectrum for argon mixed with oxygen.

In Fig. 2 a typical spectrum obtained for argon is shown. The source was tuned to maximize the amount of Ar^{8+}. To obtain the best charge state distribution in this source we have found it necessary to mix a second lighter gas. This effect has also been observed in other ECR sources.[5] The spectrum in Fig. 2 was optimized by adding oxygen to the argon fed into the injector. Helium, nitrogen, and oxygen were each mixed with argon to see which was most effective in improving the charge state distribution of argon. The results indicate that oxygen is most effective, nitrogen slightly less effective, and helium least effective but still an improvement over no gas mixing. Although the mechanism by which the gas mixing shifts the charge state distribution is not yet clearly understood, the effect was systematically observed with a variety of gases. Just as a light gas increases the charge state distribution of a heavy gas, introduction of a heavy gas suppresses the charge state distribution of a light gas. This was very evident when a small amount of xenon was added to oxygen which strongly depressed the oxygen charge state distribution.

The flexibility of the LBL ECR source has proved to be very beneficial in optimizing the source performance. Tests on the source show that to obtain maximum intensities for different charge states of the same ion species several parameters must be adjusted. A typical example is the difference in parameters for Ar^{8+} and for Ar^{11+}. The settings for Ar^{11+} require higher magnetic field at extraction, more microwave power in the main stage, and a reduced flow of argon gas into the injector. These same tendencies have also been observed with other ions. For a given ion charge state there is an optimum microwave power level in the main stage. The dependence of ion current versus microwave power is a slowly varying function with a maximum at relatively low power levels. For example, the optimum power for Ar^{8+} is about 150 W.

One difficulty encountered is that the injector runs at a constant plasma density and cannot be easily adjusted by varying gas flow or microwave power. The flow of plasma can be adjusted by moving the location of the ECR zone in the first stage, but this does not vary the flow rate in a simple monotonic way. To solve this problem a mechanical "throttle" has been installed which can attenuate the plasma flow by intercepting a portion of it. Preliminary tests indicate this makes source tuning easier.

Future Source Development

In addition to exploration and optimization of the LBL ECR source performance in its current configuration, three areas of further source development are beginning. First, the orientation of the easy axis of the sextupole will be changed from azimuthal to radial to explore what effect this has on the ECR source's performance. Changing the orientation affects both the radial mirror ratio and the location where the escaping plasma strikes the sextupole bars[2] . Second, the first tests using solid feed material in the LBL ECR source will be done. Initially, solid material such as Al_2O_3 will be inserted radially into the main stage utilizing the plasma to vaporize the solid material. Third, a prototype octupole structure is being constructed to test whether the octupole has some advantage over the sextupole. Comparison of the charge state distribution from the LBL ECR source with model calculations indicates that the production of high charge states is limited by the average electron energy.[6] One of the loss mechanisms for energetic electrons is the drift of the electron orbits due to magnetic gradients or, equivalently, curvature of the magnetic flux lines. Calculations indicate that near the axis of a magnetic mirror field produced by superimposing a solenoidal axial field with an octupole field the flux line curvature is much lower than when a sextupole field is used. This is a result of the cubic dependence on radius of the octupole field versus the quadratic dependence of the sextupole field. The most direct method to study this question is to experimentally test an octupole configuration on the LBL ECR source. The prototype octupole will utilize the same $SmCo_5$ bars that were used in the sextupole, plus 2 spares. The additional two bars reduce the pumping conductance in the main stage, so if the octupole proves to be superior, a new octupole with optimal geometry will be fabricated.

Beam Transport System

The horizontal and vertical sections of the beam transport system from the 90 degree analyzing magnet to the center of the cyclotron are shown in Figs. 3 and 4 . Magnetic rather than electrostatic focusing and bending elements were chosen because of better space charge neutralization for high intensity beams, fewer vacuum penetrations, and better long term reliability. Magnetic steering coils are used at each lens. The beam diagnostics consists mostly of fixed four jaw collimators with beam readouts before each set of lenses, where the beam is the largest. Tuning of the upstream focusing and steering system will be used to minimize the beam loss on each collimator. A movable 4 jaw collimator and Faraday cup are provided near the top of the vertical line. Beam at the bottom of the vertical line will be read on the mirror electrode in the midplane of the cyclotron and then on a cyclotron beam probe at small radius. The vacuum system uses cryo-pumps and turbo-pumps and all metal seals on the vacuum penetrations. The average pressure in the beam line must be 10^{-7} torr to keep charge exchange losses to a few percent. Beam pipe and boxes are constructed out of magnetic steel 5 mm thick to reduce the 0.5-1.0 mT cyclotron leakage field to .05 mT required for beam transport.

The optics elements and beam profiles are shown in Fig. 5 . The emittance of ECR sources is assumed to be 200 π mm-mrad, un-normalized. The energy spread from these sources has been shown to be very low, less than 5 eV, or .05% at 10 kV so dispersion cancellation in the bends is not provided. The horizontal section of the beam line uses two magnetic quadrupole doublets with large aperture (15 cm diameter). The large aperture with few lenses was chosen in preference to small aperture and more lenses because of simplicity and because the lens coil power is low even at 15 cm aperture due to the low acceleration voltages of 5-15 kV. In the vertical line, magnetic solenoid (Glaser) lenses are chosen because quadrupoles will not work due to the rotation introduced by the cyclotron field which leaks up the axis. Two lenses are placed above the cyclotron yoke and one is built into the bottom of the .20 m diameter hole in the yoke. The bottom lens will focus the beam into the start of the "hole lens" of the cyclotron field, which will place the second minimum at the midplane[2] for high energy beams. The AXIN

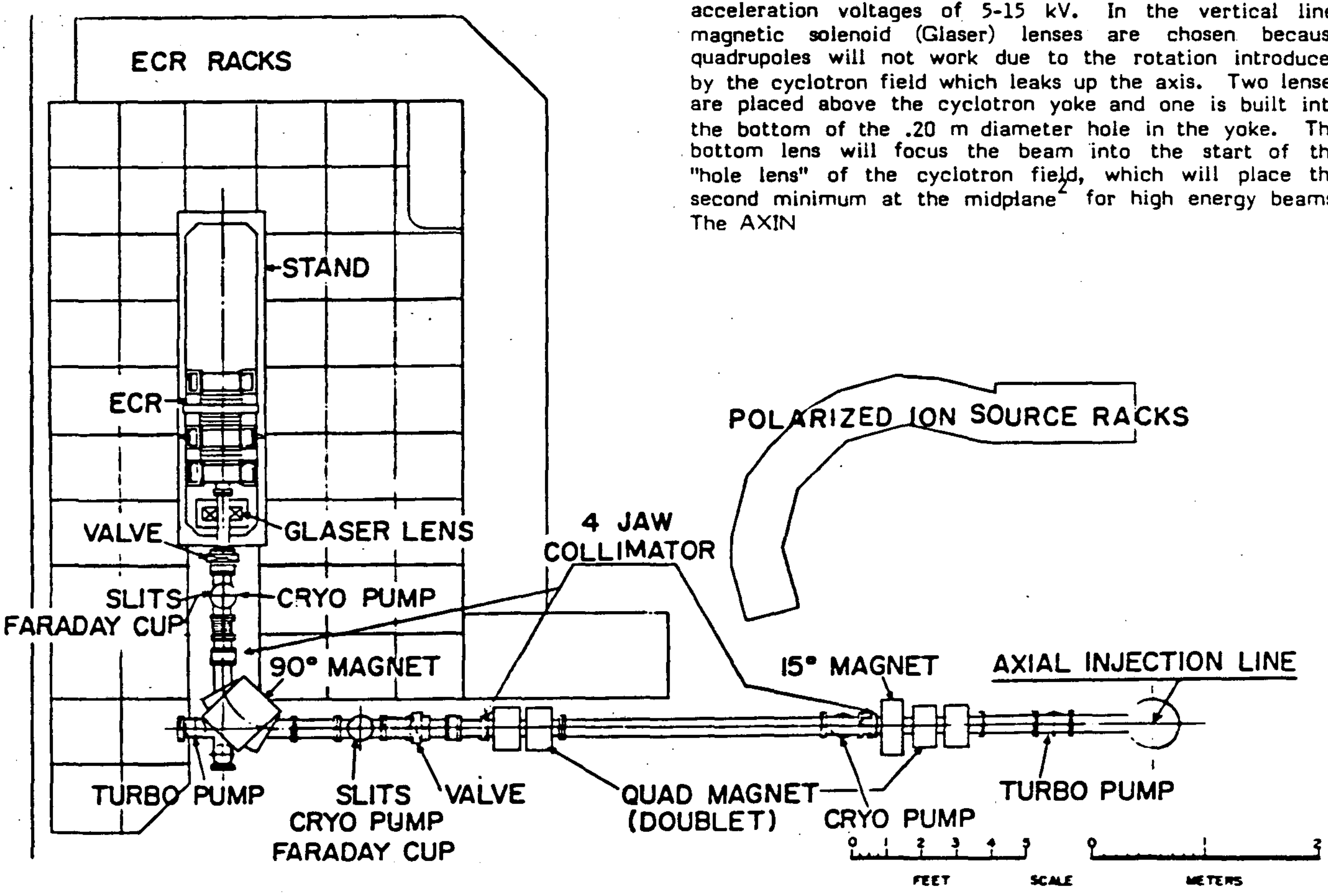

Fig. 3. Plan view of the ECR source and horizontal beam line on the vault roof of the 88-Inch Cyclotron.

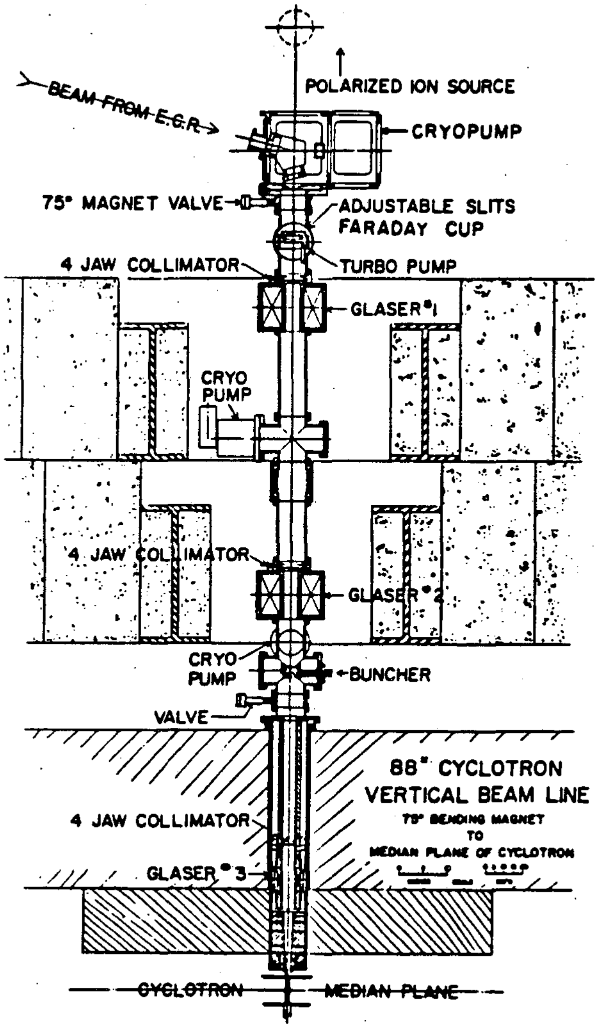

Fig. 4. Elevation view showing the design of the axial injection beam line to be used for injecting heavy ions from the ECR source and polarized ions from the Polarized Ion Source.

computer program was used to track beams through the solenoid lenses and hole lens.[7] In the lower part of the line, thicker walls of magnetic iron beam pipe are used to shield the beam from the cyclotron leakage field, and from asymmetries in this field due to steel structure in the concrete shielding blocks. The POISSON computer program was used to design the solenoid lenses and magnetic shielding.

The center region will use an electrostatic gridded mirror, as the present system does, to bend the beam through 90 degrees into the midplane. Inserts in the dee and dummy dee will provide narrow gaps for acceleration on the first turn. Typical dee voltage on the 180 degree dee will be 50 kV for an injection voltage of 10 kV.

Acknowledgements

The rapid progress that has been made on the LBL ECR is the result of the efforts of a group of dedicated and skilled people. We gratefully acknowledge the contributions of the mechanical and electrical engineering groups and the Bldg. 88 shops, as well as the support from other shops within Lawrence Berkeley Laboratory.

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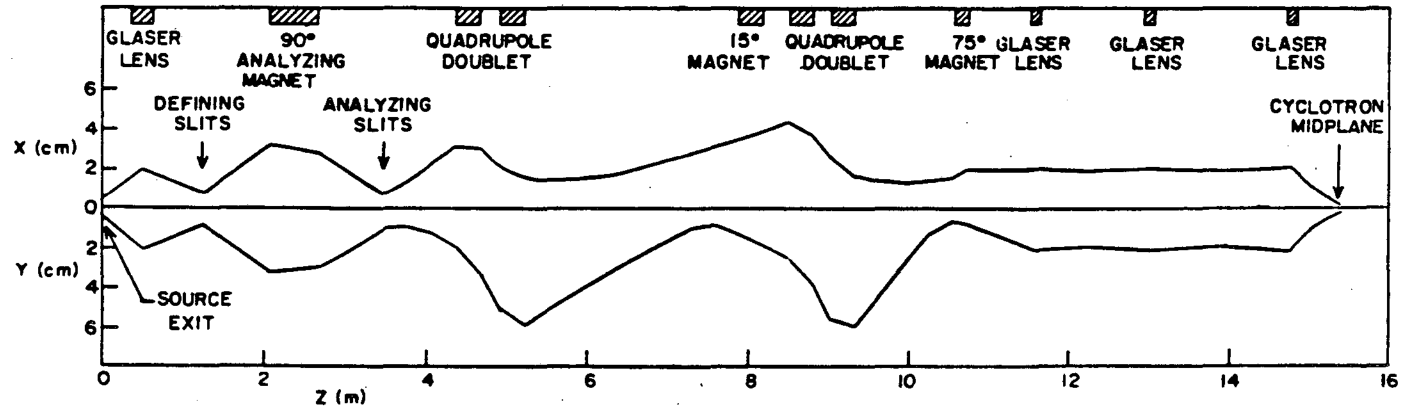

Fig. 5. Beam profiles from exit of the ECR source to the cyclotron midplane.

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