

FIRST OPERATION OF THE LBL ECR ION SOURCE WITH THE 88-INCH CYCLOTRON*

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Abstract

The LBL ECR ion source and new injection system are now in regular operation with the 88-Inch Cyclotron supplying stable, reliable heavy ion beams for both nuclear physics and applied research. The ions accelerated to date cover the mass range from nitrogen to xenon, and the energy range of 3 to 27 MeV/nucleon. Overall transmission of up to 14% from source to external cyclotron beam has been obtained. A beam from solid material, magnesium, has been used successfully for an experimental run. The emittance has been measured, at 10 kV accelerating voltage, for a variety of ions and has been found to vary from 100π mm mrad for the low charge states to 20π mm mrad for high charge states, for about 50% of the beam.

Introduction

The LBL ECR ion source began test operation in January 1984. A new axial injection line, which has improved beam optics and a much better vacuum than the old axial beam line, was completed in September 1984. Injection tests into the 88-Inch Cyclotron began in October, and regular operation with the cyclotron started in January 1985. Previous publications have described the design of the source and injection system and the initial source performance [1], [2]. This paper describes the first operational experience and recent developments of the source and injection system.

Summary of System Operation and Performance

The ECR source, injection beam line and cyclotron center region have performed reliably since coming into regular operation in January 1985. Sixty percent of the cyclotron operating time since January has been with the ECR source. The nuclear physics groups have already become enthusiastic users of the new ECR beams. Operation of the ECR source and injection beam line requires about 100 kW of power. In some cases, the ECR source allows a higher charge state to be accelerated than did the internal PIG source. This results in a lower main cyclotron field and a net power savings. The long term stability over several days has been good, requiring only an occasional adjustment of the source.

A list of beams which have been accelerated through the cyclotron is shown in Table 1. The cyclotron external beam current includes total current on a beam stop and horizontal collimator, and beam on target is 5-50% of the total current listed, depending on transport collimation. The energies range from 3.5 MeV/nucleon ⁸⁶Kr and ¹²⁹Xe up to 27 MeV/nucleon ¹⁶⁰. All use first harmonic mode except for ⁴⁰Ar⁹⁺, ⁸⁶Kr¹⁴⁺ and ¹²⁹Xe²¹⁺ beams, which use third harmonic. The overall transmissions range up to 14%. It appears that most low and medium energy

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Table 1. Accelerated Beams

Ion	Cyclotron Energy (MeV)	Source Current (eμA)	Cyclotron External Beam (eμA)	Transmission (%)
¹⁴ N ⁴⁺	135	80	6	8
¹⁴ N ⁵⁺	180	63	9	14
¹⁶ O ⁵⁺	135	46	4	9
¹⁶ O ⁶⁺	315	15	1.1	7
¹⁶ O ⁷⁺	429	8	.2	3
¹⁸ O ⁴⁺	117	87	5.5	6
²⁰ Ne ⁶⁺	160	23	2	9
²⁰ Ne ⁷⁺	340	8	.15	2
²² Ne ⁵⁺	157	29	3	10
²⁴ Mg ⁷⁺	192	20	2	10
²⁸ Si ⁶⁺	180	30	2	7
³² S ⁹⁺	350	20	1.2	6
⁴⁰ Ar ⁹⁺	175	50	2.4	5
⁴⁰ Ar ¹²⁺	504	6	.3	5
⁸⁶ Kr ¹⁴⁺	301	2.5	.1	4
¹²⁹ Xe ²¹⁺	451	.8	.03	4

beams will lie in the 10-14% range after careful tuning. At high energies, such as 429 MeV ¹⁶O⁷⁺, transmission goes down to 3%. It is also low at the high energy end of the third harmonic mode at 5-6 MeV/nucleon. This is partly due to small orbit clearances and reduced axial focusing in the central region. More study is planned in this area. The injection is normally at 10 kV and dee voltage is about 50 kV. Increasing injection voltage can increase transmission for some beams, because of emittance reduction, space charge effect reduction, and better center region clearance. The bunching factor, ratio of external cyclotron beams with buncher on and off, is typically 3-6, which is lower than the theoretical value of 8. This is partly due to space charge effects near the midplane [7].

The ECR Source

The testing and development of the source, which began test operation in January 1984, is still continuing although the source is now largely dedicated to providing beam for the cyclotron. In its original configuration the second stage radial magnetic field was produced by a sextupole with an effective inner diameter of 80 mm. In June 1984 an octupole was installed to test the effect of using a higher multipole. The inner diameter of the octupole was 94 mm. The source performance was significantly improved by this change [3]. In November, with the collaboration of the NSCL group at Michigan State University, a new large sextupole with the same inner

diameter as the octupole was installed to determine whether the improvement was due to the increased chamber volume or the change of multipole. The performance of the source with the large sextupole was comparable to the performance with the octupole. It appears that the increased volume in the second stage allows for more efficient coupling of the RF power to the plasma, thereby raising the average electron temperature. This effect may be more significant in the LBL ECR because the operating frequency in the second stage is 6.4 GHz compared to 8.5 GHz [4] and 10 GHz [5] in other ECR ion sources. Since regular operation of the ECR source with the cyclotron began in January 1985 we have not had time to continue the multipole tests and have been operating the source with the large sextupole.

The installation in April 85 of the new first stage resulted in a dramatic improvement in the performance of the LBL ECR. The O^{7+} current increased from 4 to 8 μA and Ar^{14+} from 130 to 730 nA. The new first stage made tuning the source easier and more reproducible and it improved the long term stability. The source recently ran for 4 days producing 50 μA of Ar^{9+} with no adjustment.

In Table 2 the performance of the LBL ECR source is summarized. All results are given for 12 mm analyzer slit widths and an extraction voltage of 10 kV except in cases such as $^{180}O^{8+}$ where narrower analyzer 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 higher voltage. Currents for fully stripped oxygen and neon were measured using ^{18}O and ^{22}Ne , respectively.

With respect to operation of the source, the elements in Table 2 fall into three classes. First, elements available in gaseous form present no particular problems. Generally, they are injected into the first stage with an appropriate mixing gas. The second class are elements which occur as solids, but are available as gaseous compounds such as silicon and sulfur. The silicon beam was produced by injecting silane gas directly into the second stage of the source with oxygen used to maintain the first stage plasma. This method gave much better results than injecting silane and oxygen into the first stage where the silicon appeared to deposit on the walls of the first stage. Similarly, the sulfur beam was produced by injecting SO_2 directly into the second stage while oxygen was supplied to the first stage. No problems with source contamination were observed after the silicon run. After the sulfur was run for 3 days, small ion currents of sulfur were observed for a few days, but the contamination problem was not as severe as in cases where SO_2 was injected into the first stage [6].

The third class of elements are the metals. Some, such as aluminum, were run by direct insertion into the plasma [2]. Others such as magnesium and calcium, used an oven. The open structure of the LBL ECR multipole allows for easy radial insertion of solids into the plasma and it also allows for ovens to be used for injecting metal vapor beams. Stable beams of magnesium and calcium were produced with ovens for periods of 24 hours. After running the magnesium beam for 48 hours, the performance with oxygen and argon was degraded. The mechanism for this is not clear since the vacuum in the source remained good and no magnesium was observed in the charge state distributions. Good source

Table 2.
Ion Currents of the LBL ECR source

	N	O	Ne	Mg	Al	Si
1 ⁺	73.	74.				
2 ⁺	96.	87.	51.	32.	18.	20.
3 ⁺	104.	85.	63.	34.	40.	33.
4 ⁺	76.	79.	78.	28.	60.	69.
5 ⁺	64.	89.	58.	44.	43.	72.
6 ⁺	7.	82.	45.	34.	36.	47.
7 ⁺	*	8.	15.	18.	22.	30.
8 ⁺		.37	4.2	6.	10.	17.
9 ⁺			.15	2.4	*	7.0
10 ⁺			.005		*	2.7
11 ⁺					.065	0.5
12 ⁺						0.2
13 ⁺						.005

	S	Ar	Ca	Kr	Xe
3 ⁺	10.	38.	23.		
4 ⁺	*	40.	24.		
5 ⁺	20.	*	*		
6 ⁺	*	54.	37.	8	
7 ⁺	63.	66.	38.	7.8	
8 ⁺	*	106.	36.	14.	
9 ⁺	36.	72.	31.	18.	.7
10 ⁺	*	*	*	20.	.7
11 ⁺	5.0	18.	18.	20.	.66
12 ⁺	*	11.	11.	12.	.8
13 ⁺	.40	3.3	1.6	15.	.94
14 ⁺	*	.73	0.2	10.	1.1
15 ⁺	.001			6.8	1.1
16 ⁺				4.2	1.4
17 ⁺				2.8	1.6
18 ⁺				1.5	2.0
19 ⁺				0.6	2.0
20 ⁺					2.2
21 ⁺					2.3
23 ⁺					1.8

All currents in μA at 10 kV extraction voltage. Feed materials had natural isotopic abundances. *Indicates a mixture of two ions with identical charge to mass ratios were present.

performance was recovered by disassembling the second stage and mechanically cleaning the sextupole and extraction plate. It appears that the oven was producing an excess amount of magnesium vapor. The tests with a calcium oven did not result in a severe contamination problem.

Radial Emittance Measurements

The emittance from the ECR source was measured by a motor driven scanning Faraday cup with electrostatic secondary electron suppression. The cup measures the beam passing through a slit 1.6 mm wide and 13 cm high. The cup was placed 2 meters downstream from the analyzing slit after the 90° analyzing magnet. Simple emittance measurements have been made by using the analyzing slit to define the beam size at a waist and the scan cup to measure the divergence profile. These measurements have proven to be useful in optimizing source emittance and understanding beam transport.

An example of scan cup measurements is shown in Fig. 1. For this data the source was tuned on 16O^{7+} , with helium mixed to improve the high charge state currents of oxygen. For scans of charge states 1-6, only the analyzing magnet and focusing Glaser lens were readjusted for each charge state. The analyzing slit width was set at its standard value of 12 mm full width. This figure shows that each charge state typically has a center small divergence core and high divergence tails. The tails may be due to a high energy tail in the source plasma, a distortion in the extraction meniscus due to multipole induced non-uniformities, or extraction geometry. A high energy tail of only 1-10 eV would produce the tails observed. A multipole effect would be expected to be reduced by a change from the sextupole used here to an octupole.

The emittance values of the beam inside the central core, within the full width at half maximum, are $20\text{--}110\pi$ mm mrad for high to low charge states. They fall in the range reported for the Micromafios ECR source at the 50% beam level [8]. More recently the emittance of the Micromafios O^{6+} beam was measured as 30π mm mrad for 75% of the beam [9], which is close to the value from Fig. 1 for the beam core. The wide range of emittance values reported in [8] and [9] may be due to inclusion of various fractions of beam tails. The divergence of the central core of the beam implies an upper limit of energy spread of only .1 -5 eV for high to low charge states.

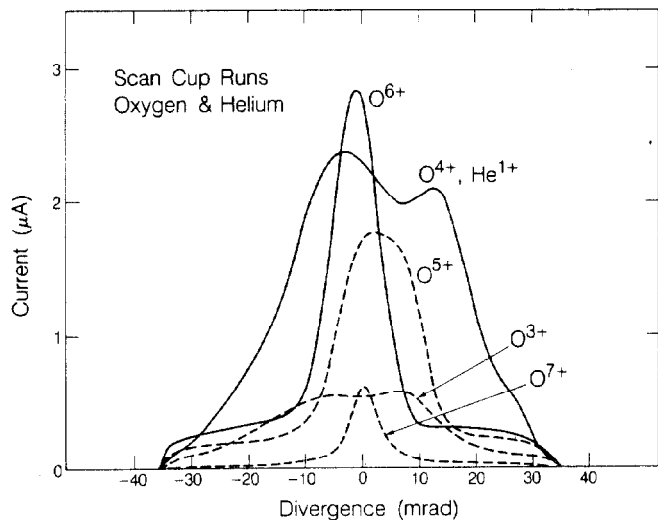


Fig. 1. Beam current profiles across beam pipe, taken with scan cup, at 10 kv accelerating voltage. The beam intensities are: 1+ $16\mu\text{A}$, 2+ $19\mu\text{A}$, 3+ $27\mu\text{A}$, 4+ $108\mu\text{A}$, 5+ $46\mu\text{A}$, 6+ $56\mu\text{A}$, 7+ $7\mu\text{A}$.

Future Developments

We plan to develop feed systems for a wider range of solid materials. Also, following the results reported by Geller on the large increase of Ne^{10+} intensity with an increase in rf frequency from 10 to 16 GHz [10], we plan a test of increased frequency for the second stage from 6.4 to 9.2 GHz, using the present first stage klystron supply.

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References

- [1] D. J. Clark, Y. Jongen, and C. M. Lyneis, "Progress on the LBL ECR Heavy Ion Source", Proceedings of the Tenth Int'l Conf. on Cyclotrons and their Applications, pp. 133-136, East Lansing, MI (1984).
- [2] C. M. Lyneis, "Performance of the LBL ECR Ion Source", Proceedings of the 8th Conference on the Application of Accelerators in Research and Industry, Denton, Texas (1984), to be published in Nuclear Instruments and Methods; and LBL Report 18501.
- [3] Y. Jongen and C. M. Lyneis, "Experimental Results from an E.C.R. Source Using an Octupole", Proceedings of the International Conference on the Physics of Highly Ionized Atoms, Oxford, England (1984) (in press).
- [4] Y. Jongen and G. Ryckewaert, "Initial Operation of E.C.R. Ion Sources with Cyclone", IEEE Trans. Nucl. Sci., NS-30, pp. 2685-2689, August 1983.
- [5] R. Geller, B. Jacquot and C. Jacquot, "ECR Sources for Single and Multiply Charged Ion Production", Proc. Int'l Ion Engineering Congress - ISIAE '83 and IPAT '83, pp. 187-198, Kyoto (1983).
- [6] Yves Jongen, private communication.
- [7] R. Baartman, private communication.
- [8] N. Chan Tung, S. Dousson, R. Geller, B. Jacquot and M. Lieuvain, "Some Radial Emittance Measurements of the Multiply Charged Heavy Ion Source Micromafios", Nucl. Instr. and Meth. 174, 1/2, pp. 151-150 (1980).
- [9] P. Spadtke, K. D. Leible and B. H. Wolf, "Emittance of the ECR-Source with a Simple Extraction-System", Proceedings of the Workshop on the Sixth International ECR Ion Source, pp. 103-106, Lawrence Berkeley Laboratory, Berkeley (1985), PUB-5143.
- [10] F. Bourg, J. Debernardi, R. Geller, B. Jacquot, R. Pauthenet, M. Pontonnier and P. Sortait, "The Micromafios Status 1985", Proceedings of the Workshop on the Sixth International ECR Ion Source, Lawrence Berkeley Laboratory, pp. 1-27, Berkeley (1985), PUB-5143.

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