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Author
Lyneis, CM.

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Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

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PERFORMANCE OF THE LBL ECR ION SOURCE

C.M. Lyneis

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Performance of the LBL ECR Ion Source.[*]

C. M. LYNEIS,
Nuclear Science Division, Lawrence Berkeley Laboratory,
University of California, Berkeley, California 94720, USA

Abstract

The LBL Electron Cyclotron Resonance (ECR) ion source in test operation since January 1984 has produced a wide variety of high charge state ion beams suitable for injection into the 88-Inch Cyclotron. Two recent developments have dramatically improved the capability of the ECR source. The first development was the production of metallic ions. The intensities of aluminum ions produced were 36, 22, 10, and .065 eμA for charge states 6, 7, 8, and 11, respectively. Calcium ion intensities were 36, 31, 4.6, and 0.20 eμA for charge states 8, 9, 12, and 14, respectively. The second development was the replacement of the sextupole magnet used in of all other high charge state ECR sources with an octupole structure. This modification resulted in a dramatic improvement in the intensities of the high charge state beams and a significant upward shift in the charge state distribution (C.S.D.). The ECR-octupole or "OCTIGUN" has produced 89, 52, 9, and 2.5 eμA of $Ar^{8,9,11,12+}$ and 21, 10, and 0.34 eμA of $Kr^{10,14,18+}$, respectively. For the high charge states of argon and krypton the improvement gained by using the octupole is typically a factor of 5 to 10.

1. Introduction

The LBL ECR ion source began test operation in January 1984 and is scheduled to begin injection tests into the 88-Inch Cyclotron in October.(1-3) The source has already produced a wide variety of ion beams with sufficient intensities to be used in the cyclotron for both nuclear physics and applied research. In June, the new horizontal beam line was connected to the old axial injection line and beams of Ar^{8+} and Ar^{11+} from the source were injected into the cyclotron and extracted at energies of 175 Mev and 330 Mev, respectively. The new axial injection line, which will have a much better vacuum than the old axial beam line and improved beam optics, will be installed in October. The transmission of the new system from the source to external cyclotron beam is expected to be between 5 and 10%.

The test period has been used to explore and improve the source's performance, test methods for producing beams of metallic ions, and most recently to test a new octupole magnet structure in the second stage. Because of the great success of the octupole test, the LBL ECR has been named the OCTIGUN (OCTupole Ion GUN).

Three aspects of the development of the OCTIGUN will be discussed below. First the basic design of the source will be reviewed. Second, the performance to date will be summarized. Third, we will discuss in more detail some specifics of the source such as the comparison of its performance with the sextupole and with the octupole, experimental aspects of metallic ion production, and the effect of gas mixing on the source.

2. Source Design

The LBL ECR source was designed for reliable operation, convenient maintenance, low operating costs, flexibility, and a 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 MICROMAFIOS.(4) Eleven tape-wound copper coils are used to produce the axial magnetic field. Since not all the coils are needed to produce the required field strength, the axial magnetic field configuration can be readily modified by adjusting the currents in the individual coils. The octupole field is produced by $SmCo_5$ bars supported in an open copper fixture which allows for radial pumping between the bars.

The present injector is a simple circular waveguide in which RF power from the 9.2 GHz klystron propagtes 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 amount of plasma produced by the first stage is typically adjusted by changing the magnetic field distribution in the injector, but this does not vary the plasma flow in a simple monotonic way.

The basic design features of the extraction system follow those used in ECREVIS.(5) 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. The beam analysis system consists of a short solenoidal (Glaser) lens, two sets of manually adjustable slits, and a double focusing 90 degree analyzing magnet with a bending radius of 0.40 m. The Glaser lens refocuses the diverging beam from the source onto the first set of slits. The analyzing magnet coupled with the second set of slits allows a single charge state to be selected. With the horizontal aperture of the slits set at 4 mm a mass resolution of 1% is obtained.

3. Performance of the Source

The performance of the source for some common gases is summarized in Table II. For these measurements the source extraction voltage was 10 kV The beam was measured on a Faraday cup after the analyzing magnet with the horizontal slits set to 1 cm width. The source has been extensively tested with argon and oxygen. As will be discussed in more detail below, the introduction of the octupole resulted in both an increase in the extracted current for intermediate charge state ions such as Ar^{8+} and a shift of the C.S.D. to higher charges The most dramatic improvement was for krypton where a factor of 5 to 10 increase in currents was found. For all of the gases listed, adding a lighter mixing gas to the plasma was found to improve the C.S.D. just as it did on the first compact ECR source, MINIMAFIOS.(6) Helium was used as a mixing gas for nitrogen, oxygen, and neon. Similarly, oxygen was used as a mixing gas for argon and krypton. Systematically, the introduction of a lighter mixing gas enhances the C.S.D., while the introduction of a heavier mixing gas depresses the C.S.D.. It seems that introducing a lighter gas into the plasma increases the ion confinement time of the heavier ions.

In Table III the source performance for metallic ions is summarized. These tests were done on the ECR source prior to the installation of the octupole. The OCTIGUN has not yet been used to produce metallic ions. The results are preliminary since only two weeks of testing was done. Further development of metallic ions is planned for the near future since many of the nuclear physics experiments will require beams of metallic ions.

Metallic ions were produced both by inserting solid feed material directly into the main stage plasma chamber and by directing vapor from a small oven into the same region. Aluminum, calcium and titanium beams were produced by inserting a solid material radially between the sextupole bars midway between the main stage magnetic coils. This is similar to the technique developed earlier by Geller, except that in MINIMAFIOS the solid material is inserted between the injector and main stage.(7) For all the metallic ion tests oxygen was used as a support gas. After the source was adjusted for maximum high charge state production, the current from the source tended to drift with time. This is due to the regenerative nature of using the plasma to heat the solid material and using the solid material to supply neutral atoms to the plasma. To operate the source on a routine basis with this type of injection it may be necessary to build in a feedback loop using the RF power to keep the plasma density constant.

To avoid the problems inherent in using direct plasma heating to produce metallic ions, a small resistance heated calcium oven was built. The metal vapor from the oven was directed radially into the plasma chamber at the same point that the rod had been inserted. The currents produced for calcium with this method were slightly lower than those produced by direct insertion, but the operating stability was remarkably improved. The source produced between 18 and 20 e A of Ca^{9+} over a 12 hour period without any adjustment.

4. Discussion

The OCTIGUN is the first ECR source to use an octupole rather than a sextupole to produce the radial confinement of the plasma. The motivation for using an octupole on the LBL ECR came from calculations done by Jongen.(8,9) He suggested that the reason the C.S.D. for the large source ECREVIS(10) is shifted to higher charges compared to the C.S.D. for small sources such as MINIMAFIOS(11), Pre-Isis II(12), and the LBL ECR is due to higher average electron temperatures in ECREVIS. In Jongen's model, the average electron temperature is limited by the azimuthal drift of energetic electrons into regions where confinement is impossible. The loss rate is proportional to the radial gradient of the magnetic field, or equivalently to the curvature of the field lines. The curvature of the field lines decreases with increasing size of the source, which would explain the higher electron temperatures in ECREVIS. Calculations indicate that the flux line curvature is much lower with an octupole than when a sextupole is used. This is a result of the cubic dependence on radius of the octupole field versus the quadratic dependence of the sextupole field.

A prototype octupole structure was built using six $SmCo_5$ magnets plus two spares from the orginal sextupole. The advantage of this approach was that a rapid and inexpensive test of the octupole could be made. The main disadvantage is that adding two additional magnets required a substantial reduction in the spacing between the bars, which is used for radial pumping, insertion of solid feed material, and for the injection of microwave power into the second stage. The RF feed into the main stage was modified so that the RF could be injected on axis to eliminated problems encountered with coupling to the plasma through the narrow gap between the bars. A new octupole structure is being constructed which will use smaller bars of $SmCo_5$ and provide larger spacing between bars.

In Table IV the best performance of the OCTIGUN is compared to that for the ECR with the sextupole for argon and krypton. This table represents a summary of many different tests and it points out the superiority of the OCTIGUN over its predecessor for ions such as argon and krypton. On the other hand, the performance of the OCTIGUN for lighter ions such as oxygen is only slightly better the ECR with the sextupole. In Fig. 2 the C.S.D. for the OCTIGUN is compared to the C.S.D. for the source operated with the sextupole. This shows that using the octupole in place of the sextupole has increased the extracted current for intermediate charge states and shifted the C.S.D. upward. Two C.S.D.'s for the OCTIGUN are shown in Fig. 2. In the first, the source was adjusted to maximize the extracted Ar^{8+} current, and in the second, the source was adjusted to maximize Ar^{12+}. This clearly demonstrates the strong dependence of the C.S.D. on source tuning. Shifting the C.S.D. upward in the OCTIGUN is done mainly by decreasing the flow of argon and increasing the flow of oxygen into the first stage. Usually some adjustment of the solenoid field and main stage RF power is also necessary.

It is still an open question whether the improved performance of the OCTIGUN is due to increased electron temperature, increased ion confinement time, or greater plasma density. The X-ray intensity close to the source axis increased significantly when the octupole was installed, which is consistant with higher electron temperatures. An attempt to determine the average electron temperature by fitting the experimental C.S.D.'s to a theoretical model developed by Jongen(13) proved inconclusive, since at present there are too many free parameters. It may be that with further refinement this method could lead to an unambiguous conclusion about the role of the octupole in improving ECR source performance.

5. Conclusion

The performance of the LBL ECR has greatly improved during the first eight months of testing and development. Future development will emphasize injecting the beam into the cyclotron, producing ions from solid materials, making the source easier to operate, and testing a new octupole structure with improved conductance for better vacuum.

6. 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. The author is grateful to Y. Jongen for his many contributions and for the enthusiasm he brought to the project during his sabbatical at LBL, to J. Cerny and R. Stokstad for initiating the project, and to D. Clark for many helpful discussions and the design of the beam transport system. The author also wishes to acknowledge the contributions of the Bldg. 88 mechanical and electrical engineering groups and shops, as well as the support from other shops within Lawrence Berkeley Laboratory.

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Fig. 1. An elevation view of the OCTIGUN ECR ion source.

Fig. 2. The C.S.D. for argon from the LBL ECR for three cases. The triangles show the C.S.D. for the OCTIGUN tuned for maximum Ar^{8+}, the solid dots for the OCTIGUN tuned for maximum Ar^{12+}, and the open circles for the ECR source with the sextupole tuned for maximum Ar^{12+}.

Table I

LBL ECR Source Parameters

	Maximum	Typical
Magnetic Field		
On Axis	.42 T	.35 T
Mirror Ratio	1.3-2.0	1.9
Octupole at Wall		.38 T
Magnet Power	110 kW	30 kW
Microwave Power		
Injector 9.2 GHz	1.0 kW	200 W
Main Stage 6.4 GHz	3.0 kW	220 W
Vacuum		
3 6" Diffusion Pumps		
Injector Pressure		2×10^{-5} torr
Main Stage		6×10^{-7} torr
Extraction		1×10^{-7} torr
Extractor		
Plasma Electrode Hole		8 mm diam
Puller Hole		10 mm diam
Gap	10-35 mm	23 mm
Source Voltage	20 kV	10 kV
Puller Voltage	-5 kV	-2 kV

Table II

Ion Currents of the LBL ECR source

	^{14}N	^{16}O	^{20}Ne	^{40}Ar	^{84}Kr
1^+	43.	48.			
2^+	47.	75.	24.		
3^+	47.	80.	34.	28.	
4^+	42.	72.	48.	27.	
5^+	21.	79.	*	34.	
6^+	1.5	51.	45.	48.	8.0
7^+	*	4.3	5.0	59.	*
8^+		*	3.8	89.	14.
9^+			.06	52.	18.
10^+				*	20.
11^+				9.2	20.
12^+				2.5	18.
13^+				.38	12.
14^+				.036	10.
15^+					4.4
17^+					.48
19^+					.34

All currents in eμA at 10 kV extraction voltage.

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

Table III

Intensities for metallic ions from the LBL ECR

Ion	Current eμA	Ion	Current eμA
$^{27}Al^{6+}$	36.	$^{40}Ca^{8+}$	36.
$^{27}Al^{7+}$	22.	$^{40}Ca^{9+}$	31.
$^{27}Al^{8+}$	10.	$^{40}Ca^{11+}$	11.
$^{27}Al^{11+}$	0.065	$^{40}Ca^{12+}$	4.6
		$^{40}Ca^{13+}$	1.2
		$^{40}Ca^{14+}$	0.2

Table IV

Comparison of the performances of the LBL ECR with the octupole and the sextupole

Ion	Octupole (eμA)	Sextupole (eμA)
$^{40}Ar^{8+}$	89.	42.
$^{40}Ar^{9+}$	52.	13.
$^{40}Ar^{11+}$	9.2	1.2
$^{40}Ar^{12+}$	2.5	0.28
$^{40}Ar^{13+}$	0.38	0.013
$^{84}Kr^{8+}$	14.	1.1
$^{84}Kr^{9+}$	19.	1.3
$^{84}Kr^{10+}$	20.	1.4
$^{84}Kr^{11+}$	20.	2.2
$^{84}Kr^{13+}$	12.	2.5
$^{84}Kr^{15+}$	4.4	1.2

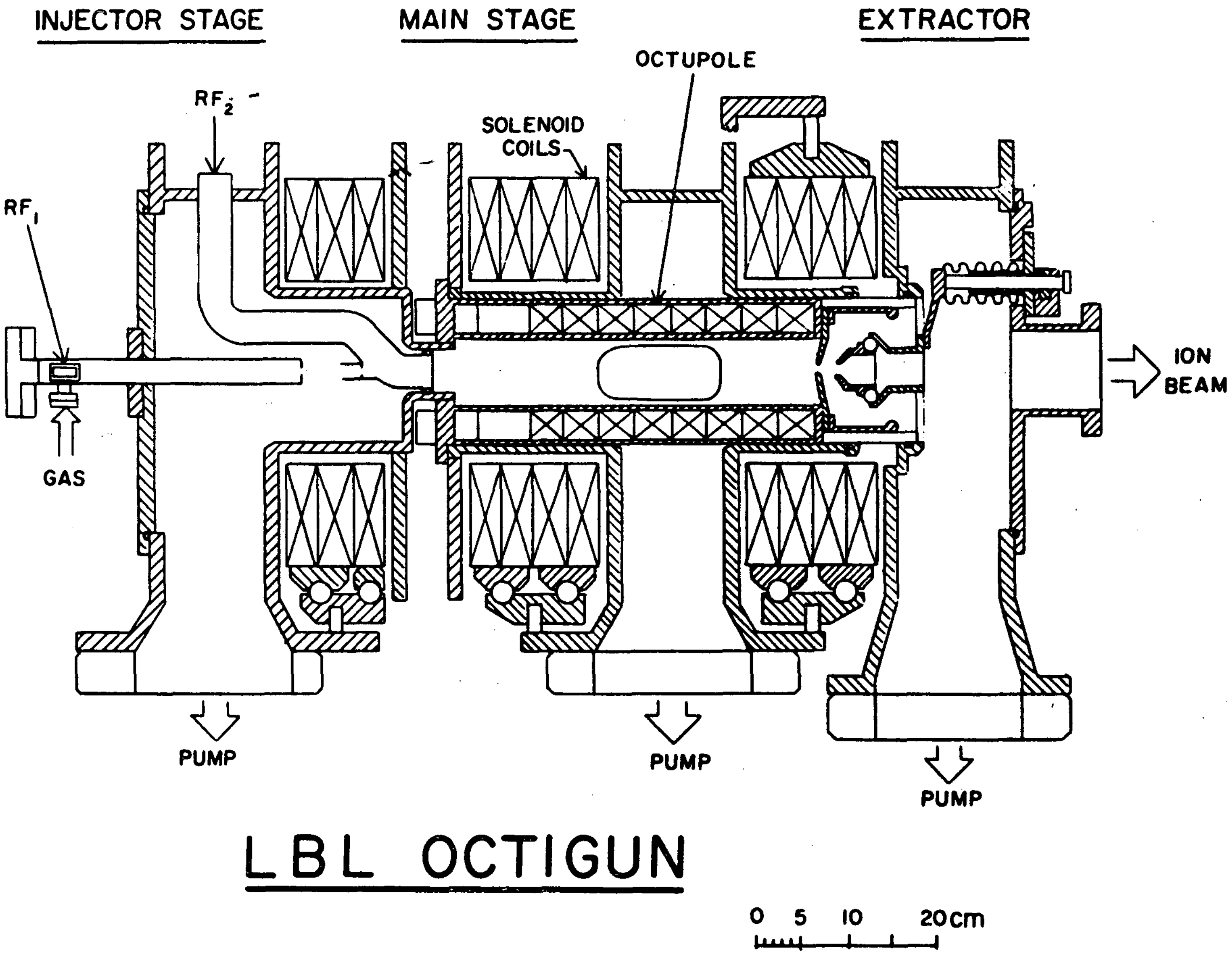

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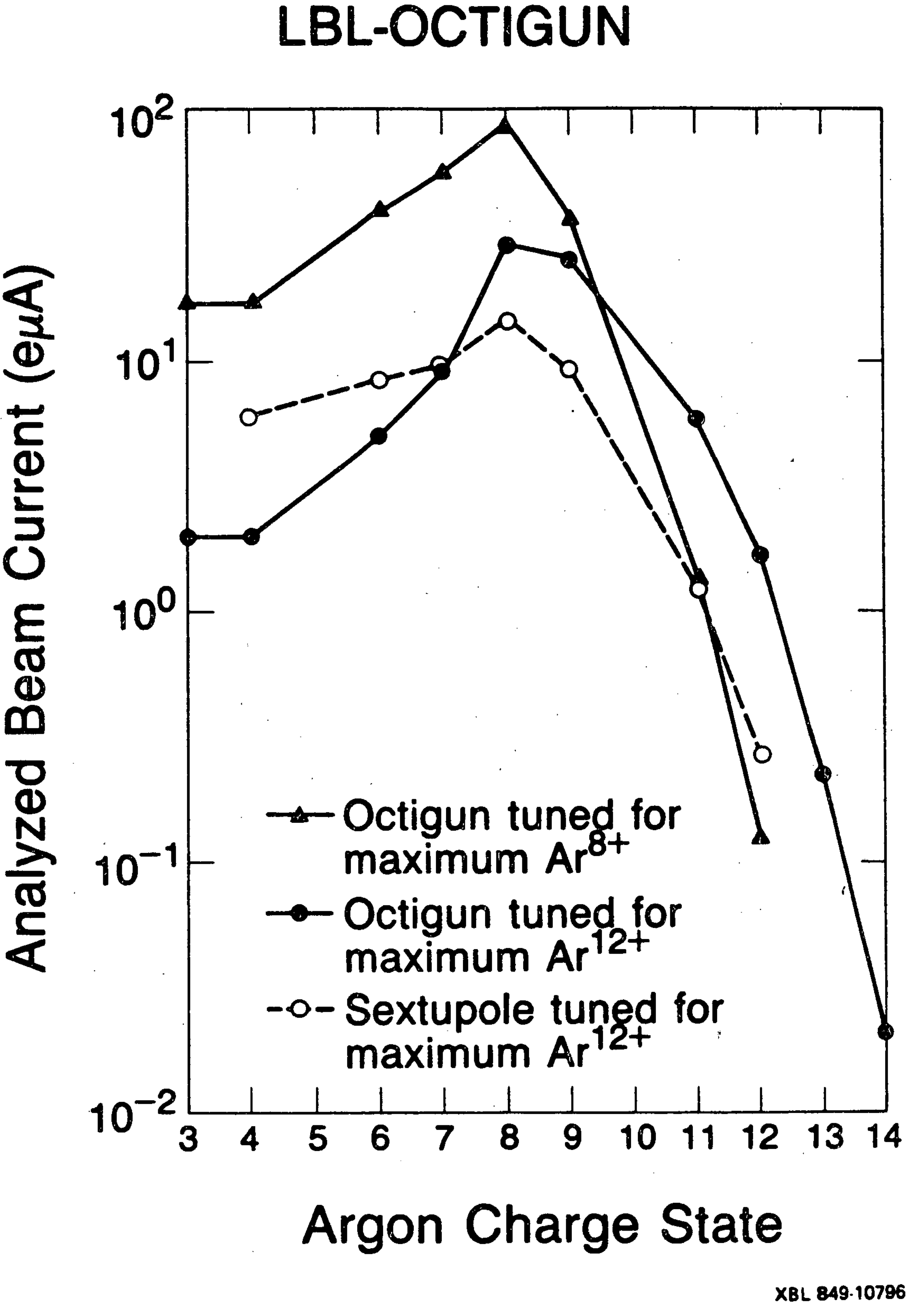
Fig. 1. An elevation view of the LBL ECR source.



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