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AN ECR HEAVY ION SOURCE FOR THE LBL 88-INCH CYCLOTRON*

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Summary

An Electron Cyclotron Resonance (ECR) heavy-ion source is under construction at the LBL 88-Inch Cyclotron. This source will produce very high charge state heavy ions, such as O^{8+} and Ar^{12+}, which will increase cyclotron energies by a factor of 2-4, up to A = 80. It is a two-stage source using room temperature coils, a permanent magnet sextupole, and a 6-9 GHz microwave system. Design features include adjustable first to second stage plasma coupling, a variable second stage mirror ratio, high conductance radial pumping of the second stage, and a beam diagnostic system. A remotely movable extraction electrode will optimize extraction efficiency. The project includes construction of a transport line and improvements to the cyclotron axial injection system. The construction period is expected to be two years.

Introduction

To increase significantly the heavy-ion beam energies of the 88-Inch Cyclotron, a project to construct an Electron Cyclotron Resonance (ECR) ion source is under way. The ECR ion source will be capable of stripping heavy ions to higher charge states than can currently be achieved using the internal heavy-ion PIG source. The maximum energy of a heavy-ion beam from the cyclotron increases as the ion charge state squared, so the ECR ion source is a cost-effective method for improving the cyclotron's performance. In June 1982 the decision to construct an ECR ion source was made after careful evaluation of the results of the EBIS R and D program at LBL[1] and of ECR ion sources developed in Europe. Basically the high duty factor, high intensity beams from the ECR source are better matched to the nuclear physics experiments using the cyclotron than the somewhat lower intensity, lower duty factor, higher charge state beams from EBIS. The successful development of compact room-temperature ECR sources in Grenoble by Geller and his associates in the past several years[2] led us to adopt the general features of his design for our source. The energy and mass range of the ECR source injecting the 88-Inch Cyclotron is shown in Fig. 1. Details on the nuclear science justification are given in the proposal.[3]

The ECR Source

Figure 2 illustrates the main design features of the LBL ECR source. The design is intended for developmental and operational flexibility. Separate turbopumps will be used on each stage. The injector stage of the LBL ECR source is still under design. The solenoid coils can provide an axial magnetic field of up to 0.42 T. The injector vacuum chamber is relatively large so it can accommodate a number of possible sources. One possibility would be to use a Lisitano coil to produce an overdense plasma in the injector.[4] In the future metallic ion beams will be required from the ECR, so enough room has been left in the injector to allow the installation of a metal ion source.

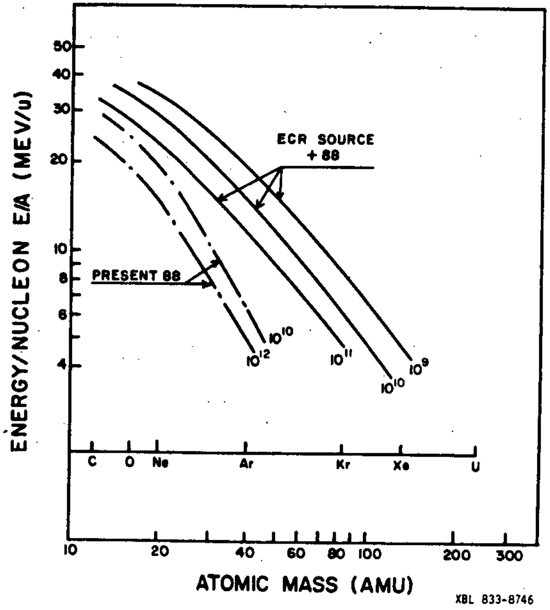

Fig. 1. Energy per nucleon vs mass number for 88-Inch Cyclotron. Cyclotron external beam intensity (particles/s) is shown for each contour line. Lower curves show performance with present internal PIG source. Upper curves give estimate for injection with ECR source, assuming a transmission of 4% from source to external beam.

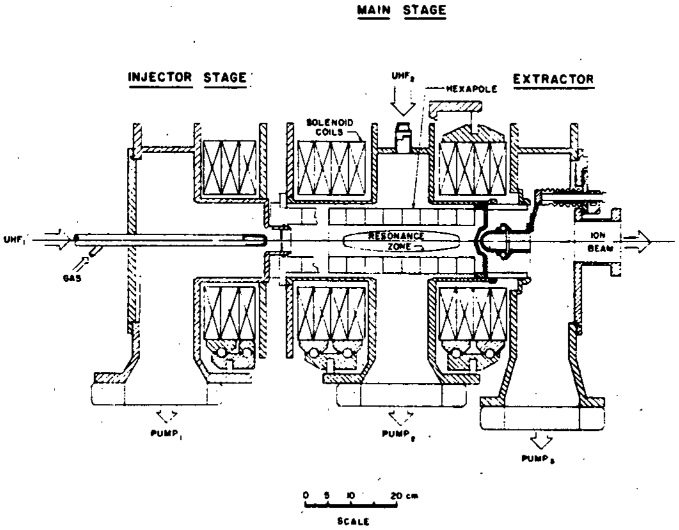

Fig. 2. An elevation view of the LBL ECR source.

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The extractor can be moved along the axis to maximize the current from the ECR source. The extractor will be operated in an accel-decel mode. The injector and mainstage will operate at a positive potential between 5 and 20 kV. The first extraction element will operate at a negative potential between 0 and -5 kV, and the second element will operate at ground potential. The combination of variable extractor position and variable accel-decel voltage will be used to optimize beam intensity and emittance.

The axial field, summarized in Table 1, is produced by two sets of four coils in the mainstage and one set of three coils in the injector. The coils are tape-wound copper pancakes with water jackets between the coils for cooling. The shape of the axial field can be tuned by adjusting the currents to each coil.

The sextupole magnet is designed with an open configuration to allow for radial pumping of the mainstage.[5] The design of the sextupoles represents a compromise between the desire to have a strong, ideal sextupole field out to large radius and the need for sufficient pumping conductance between the sextupole members. To optimize the design of the sextupole, calculations were done based on the multipole expansion for rare earth cobalt magnets suggested by Halbach.[6] The dimensions and field strengths of the sextupole are summarized in Table 1.

Table 1
LBL ECR Source Parameters

Axial Magnetic Field	
Mirror Ratio	1.3-2.0
Max B on axis	0.42 T
Sextupole Dimensions	
Inner radius (r)	4 cm
Element height (h)	3 cm
Element width (d)	2.8 cm
Length	33 cm
Sextupole Magnetic Field	
Maximum B_{MAG} ($\theta = 0^\circ$)	0.41 T
Maximum B_{MAG} ($\theta = 30^\circ$)	0.28 T
$B_{remanent}$ $SmCo_5$	0.94 T
Microwave Power	
Mainstage	3.3 KW at 6.4 GHz
Injector	1.0 KW at 9.2 GHz

A second design feature of the sextupole is that the easy axis or magnetization axis of the rare earth cobalt magnets is oriented azimuthally rather than radially as in other ECRs,[7] as shown in Fig. 3b. With this azimuthal orientation the flux lines flow out between the elements rather than ending on the interior walls of the sextupole. The escaping plasma follows the flux lines so the plasma will leak out between the pole pieces. This has two potential advantages. First, since the plasma will not strike the interior wall there should be less outgassing in the center region of the source where charge exchange with neutral atoms should be avoided. Second, it allows the insertion of a probe into the region where the plasma is escaping to produce ions from solid materials.

The results of calculations, similar to those made by Jongen,[8] to compare the characteristics of the mirror field produced by the azimuthal and radial orientation are illustrated in Figs. 3a-3d. Only flux lines with mirror ratios of 1.4 or greater are plotted. The calculations are done with an axial mirror ratio of 1.5 and maximum axial fields of 0.25 T and 0.40 T, corresponding to operating frequencies of 6.4 and 10.4 GHz, respectively. Figure 3a and 3b illustrate that the number of flux lines at 6.4 GHz are similar for the two orientations. Figures 3c and 3d illustrate that at the higher frequency where the axial field is stronger the flux lines are better contained by the field produced by the radial orientation. This difference is due to the non-ideal sextupole field near the inner radius of the sextupole magnet. With the radial orientation, flux lines end on the pole faces where B_{mag} is larger than between the pole pieces, where the flux lines go with tangential orientation of the sextupole elements.

Present plans are to use a 6.4 GHz 3.3 kW klystron in the mainstage of the source. A 9.2 GHz 1 kW klystron already on hand will be used during the early testing stages and may later be used in the injector stage. The choice of 6.4 GHz is based mainly on the availability of a commercial klystron and power supply package. During the testing phase of the LBL ECR the source performance at 6.4 and 9.2 GHz can be compared at least up to the 1 kW power limit of the 9.2 GHz source. Driving the mainstage of the ECR at two distinct frequencies simultaneously is also possible. This would mean there would be two nested resonance surfaces and the electrons could adsorb energy as they passed through each zone.

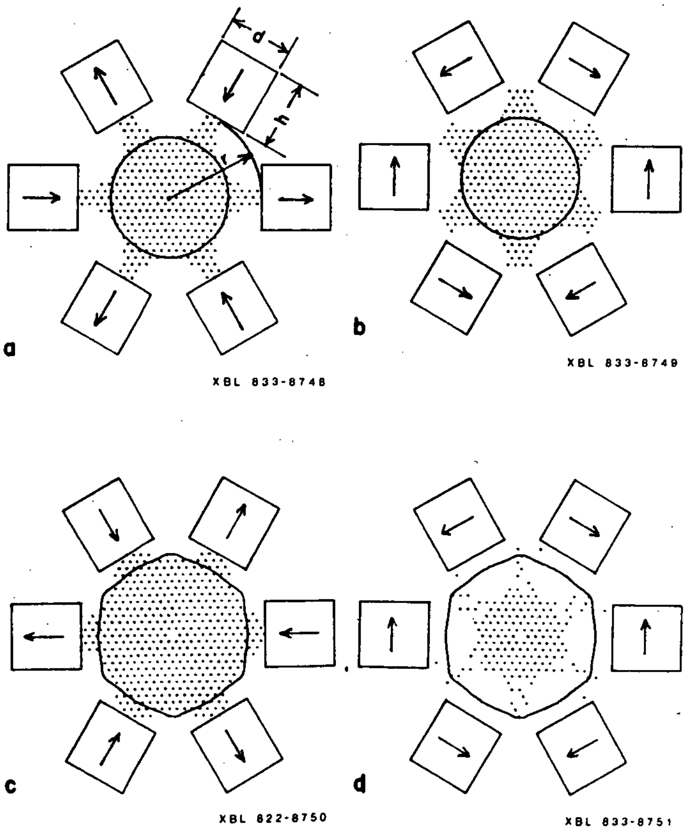

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Fig. 3 Plots of "good" flux lines at the symmetry plane of the mainstage of the ECR source. The mirror ratio of the axial magnetic field is 1.5 in all four cases of this figure. In 3a and 3b the axial field maxima are 0.25 T and in 3c and 3d they are 0.40 T corresponding to operating frequencies of 6.4 GHz and 10.4 GHz, respectively. The sextupole strength is the same in all four cases of the figure. The only difference in sextupole field is that in 3a and 3c the magnetization is oriented radially and in 3b and 3d it is oriented azimuthally.

Axial Injection System

The ECR source will be placed on top of the cyclotron roof shielding, near the polarized ion source. A new 9-meter long beam line will transport the beam to join the 5-meter long vertical axial injection transport line used by the polarized ion source. This vertical line will be upgraded to obtain better vacuum and to provide optimum matching of the ECR source beam to cyclotron acceptance. The beam line vacuum system will be designed for 1×10^{-7} torr to keep the charge exchange losses below 5% for a cross section of 10^{-14} cm^2.

The principal focusing elements planned for the beam line are magnetic quadrupoles. An analyzing magnet will be used after the ECR source to provide a mass resolution of 1/200, to separate isotopes as heavy as xenon. The present electrostatic mirror appears to be satisfactory for bending the beam into the midplane.

Present transport line studies are centered on the lower part of the vertical injection line, where the beam enters the axial cyclotron magnetic field. This area presents an unusual type of beam optics,[9,10] where the beam is strongly focused by the half-solenoid "hole lens" of the cyclotron field. Beam particles are given a rotational velocity component v_θ, which is proportional to their radial displacement r, according to the conservation of canonical angular momentum: $v_\theta = qB_Zr/2m$. This can lead to increase in emittance areas in 2-dimensional transverse projections.

Beam tracking studies have been done in the hole lens region using the computer code AXIN (courtesy of G. Bellomo, Michigan State University and University of Milan, and G. Ryckewaert, University of Louvain). To understand the characteristics of a typical ECR source phase space entering the hole lens, we simulated the magnetic field rise by a simple linear rise, Fig. 4a, with a maximum value the same as for the highest cyclotron field level. The emittance area in a 2-dimensional projection, Fig. 4b, shows periodic size changes with a wavelength $\lambda_Z = 2\pi(B\rho)/B_Z$ where $B\rho$ is the beam rigidity. We wish to place one of the minima at the median plane to avoid emittance increase in the beam injected into the cyclotron. Figure 4c shows the increase in maximum transverse divergence as the beam enters the hole lens, caused by the transfer of longitudinal to transverse energy. The beam envelope undergoes periodic oscillations in the hole field, as shown in Fig. 4d. This is due to particles having helical trajectories passing through the axis. The minimum at the median plane is a good match to acceptance requirements of the cyclotron center region.

Acknowledgements

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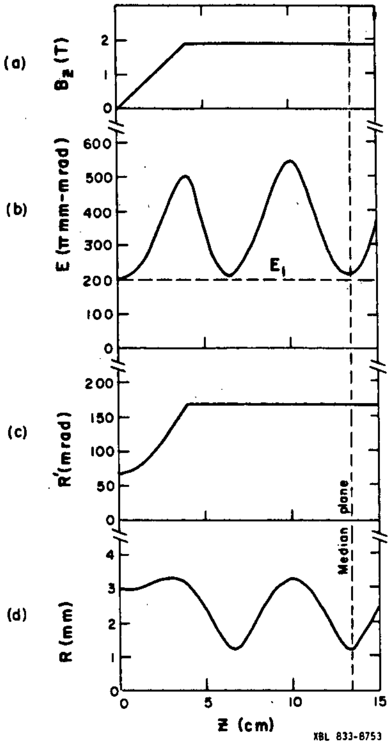

Fig. 4. Beam tracking calculations for a beam with Q/A = 0.5, E/A = 5 keV/u and unnormalized emittance = 200 π mm mrad. An initial waist is assumed at beginning of the magnetic field rise.
(a) Simplified hole lens field.
(b) The beam emittance πE.
(c) The maximum transverse divergence R'.
(d) The beam envelope R.

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