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ABSTRACT

The 88-Inch Cyclotron produces a wide range of ions for basic and applied research. The 6.4 GHz ECR source has completely replaced the PIG source, giving higher charge states and higher cyclotron energies. The ECR source has produced ions of 34 elements, of which 28 have been accelerated in the cyclotron, using gases, and low and high temperature ovens. A higher frequency 14.5 GHz advanced ECR is now under construction. It will further increase the charge states and energies available. A conceptual design has been done for a superconducting ECR driven by a gyrotron at 28 GHz.

1. THE CYCLOTRON

1.1 Operations

The cyclotron produces light, heavy and polarized ions for research in nuclear science, biomedicine and radiation effects in solid state electronic components. The ion sources used are the ECR source for heavy and light ions, the polarized ion source for protons and deuterons and the original filament source for light ions. The energy vs. mass curves for the ECR and PIG sources are shown in Fig. 1. The range of ions available from the ECR source has continued to expand, as shown in Table 1. The PIG source has not been used since the ECR source came into regular operation in January 1985. The cyclotron operating efficiency has improved, since no source changes are needed.

The experimental program calls for a wide range of beam masses, energies and intensities. These include a few μA of ions up to mass 40 at 6-8 MeV/u, a few nA of O^{8+} and Ne^{9+} at 25-30 MeV/u, and very low intensities of beams of A=15-130 at 4 MeV/u.

During periods when the ECR source is not needed for the cyclotron, it is available for atomic physics research. The beam is switched with a bending magnet from the cyclotron injection line to the atomic physics beam lines, where one of three target areas can be selected with a another magnet.[1]

1.2 Tuning Techniques

1.2.1 Fast particle changes. For research in radiation effects on electronic components and for counter calibrations, rapid switching of ion type over a wide range at constant energy/nucleon is required.[2] This is accomplished by providing a mixture of gases, or "cocktail", at the ECR source. Several gases can be mixed in one bottle and others are available with a 5 valve manifold. Choosing charge/mass = 1/5, beams at 4 MeV/u can be switched in a few minutes between ions such as N, Ne, Ar, Cu (from ECR walls), Kr and Xe. The beams are separated in the cyclotron by their small difference in charge/mass.

1.2.2 Fast energy changes. Another useful technique is rapid energy variation by charge state change. Keeping the cyclotron K constant, the settings for the transport line to the experiment can remain unchanged, while scaling the injection voltage with charge state leaves the injection line settings constant. This system was used with a run on Cu^{15+}, Cu^{17+} and Cu^{19+} at 8-13 MeV/u.

1.2.3 Fast intensity changes. A beam attenuator has been installed on the injection line.[3] It consists of 6 meshes with various transmissions, mounted on air cylinders with bellows. Any combination can be inserted in the beam line in a few seconds to vary the attenuation from a factor of 2 to 10^9. This is a very useful feature for doing beam optics without changing the emittance, and for quickly obtaining very low intensity beams.

2. THE PRESENT ECR SOURCE

2.1 Description.

The LBL ECR source has been described in a recent paper[4] and in its references. It is shown is Fig. 2. It has two stages, with an independent microwave feed to each stage. The first stage operates at 8.6 GHz and the second stage at 6.4 GHz. There is vacuum pumping on the second stage. It has been well optimized, and its high charge state performance is comparable with sources operating at higher frequency.[5] The beam intensities are shown in the contour plot of Fig. 3. Mixing gases and forms of source feed are shown in Table 1.

2.2 Ovens

Two ovens are used for the feed of vapor from solid materials into the ECR source.[6] They are located outside the plasma, so their vapor feed rates depend only on their temperatures and not on plasma conditions. This is an advantage over wire or rod feed. At the 1 eμA level at the source, the charge states from the oven beams are similar to those from gases in the same mass range, indicating that the oven feed systems have been well optimized. This is illustrated in Fig. 4. The oven beams have good long term stability. In the low temperature oven, operating up to 700 deg. C, beams of 9 elements have been produced, as shown in Table 1.

2.3 The High Temperature Oven

The new high temperature oven is now in full operation. It has a resistance-heated tantalum crucible, operating up to 2000 deg. C. It has been used for the 10 elements listed in Table 1. Some elements, such as Ni, form alloys with Ta, so an Al_2O_3 liner is used. For uranium beams, the compound URe_2 is used to prevent liquid U migration. The material usage rate is about 1 mg/hr for high charge state operation, and 5-10 mg/hr for medium charge state running. To explore the upper mass region of the cyclotron for Coulomb barrier energies $^{159}Tb^{30+}$ was accelerated to 5 MeV/u, giving 5 enA external beam. The maximum mass region was tested by accelerating $^{238}U^{28+}$ and $^{238}U^{30+}$ to 2 MeV/u, with external beam intensities of about 1 enA. A charge exchange loss of a factor of 30-40 was observed during acceleration, due to the high cross-section of this very heavy, low energy beam. Vacuum improvement in the cyclotron will reduce this loss.

3. THE ADVANCED ECR (AECR)

The present focus in developing new capabilities at the cyclotron is the construction of a new Advanced Electron Cyclotron Resonance (AECR) source.[4] This source will take advantage of the frequency scaling which has been demonstrated by Geller's group at Grenoble.[7] According to this observed scaling, the intensity and charge states from an ECR source increase significantly with microwave frequency. So by increasing the frequency from 6.4 GHz in the present source to 14.5 GHz in the AECR, we expect to increase the intensity of charge states presently available, and to obtain higher charge states (higher cyclotron energy) for the same intensities. The source is shown in Fig. 5. Initially the source will operate with a single stage driven by a 2.5 kW klystron at 14.5 Ghz. The magnetic field is produced by hollow core water-cooled copper pancake coils. Each of the three main coil groups are divided into 3 sections, to be fed with separate power supplies, providing control over the field profile. The sextupole will be constructed from Nd-Fe-B giving a magnetic field at the chamber wall of .6 T. It has radial slots for pumping which will also be useful for inserting ovens and rods for solid material feed. The source has a 7 cm chamber diameter. It will be pumped by turbo-pumps, including one on the first stage. Construction of this source is now underway. Testing of the AECR with its analyzing magnet is expected in late 1989. In 1990 a microwave transmitter for an independent first stage, an oven for solid feed, and a transport line to connect the source with the present injection system will be installed.

4. THE GYROTRON ECR (GECR)

A project further in the future is an even higher frequency ECR source, the GECR, driven by a gyrotron at a frequency of 28 GHz.[8] This increase in frequency by a factor of 2 above the AECR is expected to give a further increase in intensity and charge state distribution. This project is made feasible by the development by Varian Associates of a 28 GHz laboratory scale gyrotron with power up to 15 kW. To produce the 1-2 T magnetic fields necessary for this frequency, superconducting solenoid and sextupole coils are necessary. The design criteria are:

a) the source diameter should be greater than twice the microwave wavelength (2x1 cm = 2 cm).

b) the coil system should should be large enough to keep the peak current density in the superconductor comfortably below the short sample limit of Nb-Ti wire.

c) the volume should be small enough to allow the microwave supply to provide enough power density (8 W/cm^3).

A conceptual design for this source has been developed. The plasma chamber is 7 cm diameter and 30 cm long, giving a volume of about 1 litre, requiring a power of around 8 kW. Four superconducting solenoid coils form the mirror field. Both superconducting solenoid and sextupole coils operate below the short sample limit, with the sextupole coming closer to the limit at 80%.

5. ACKNOWLEDGMENTS

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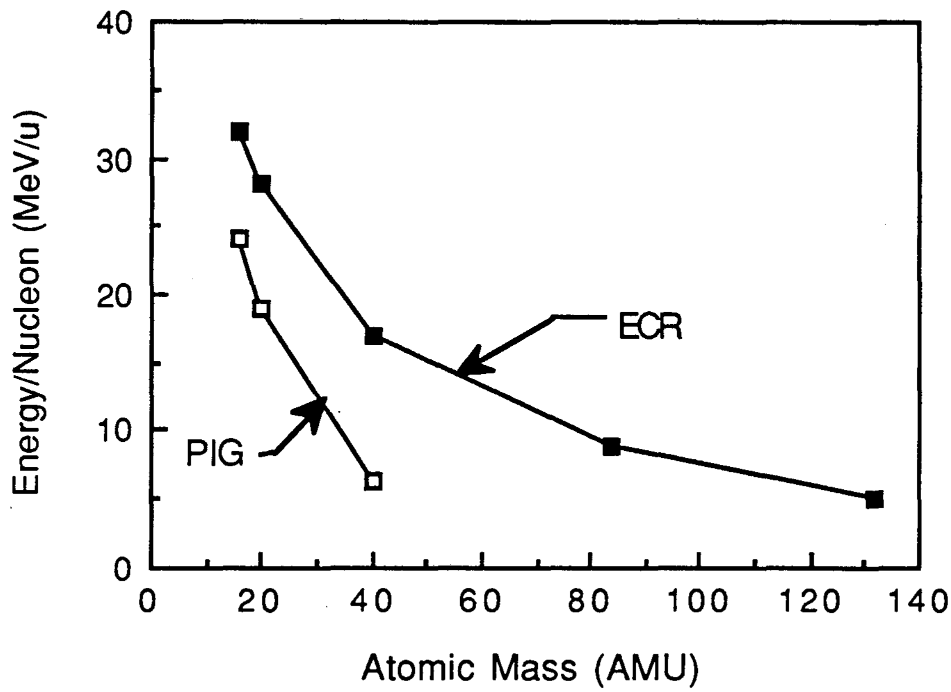
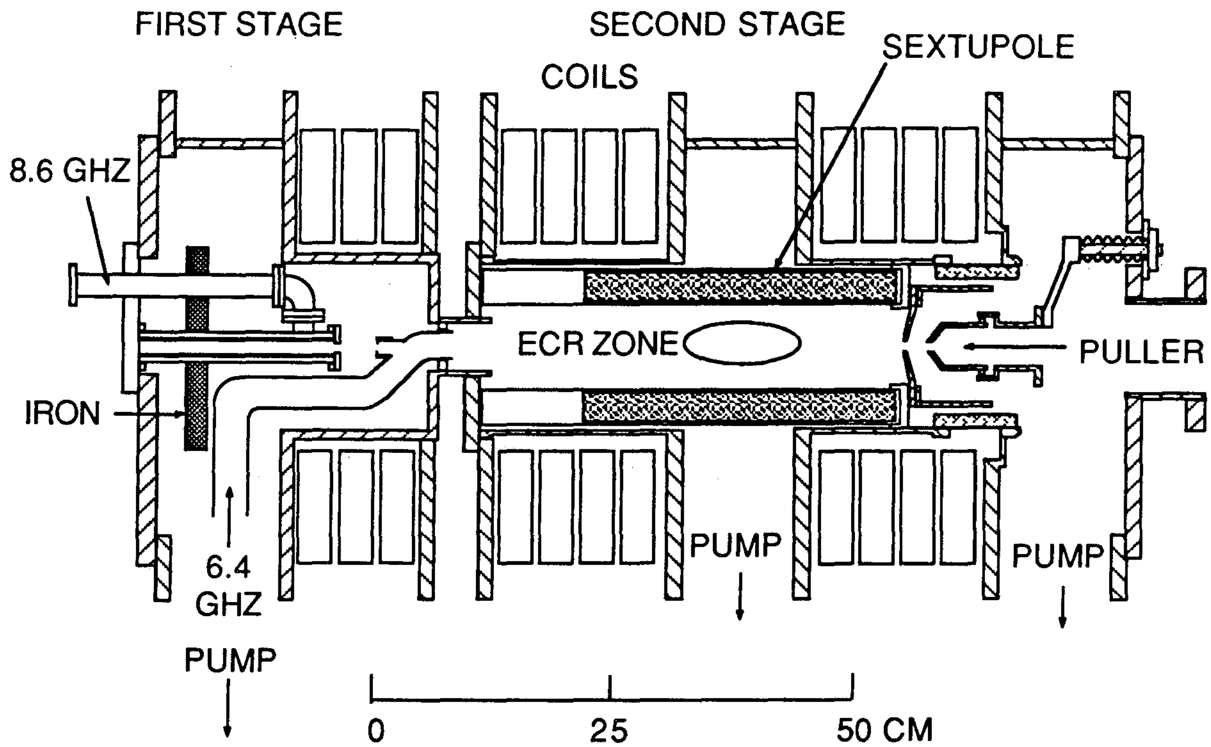
Table 1. Ions Produced by the ECR Source

Z	Ion	Feed	Stage	Mixing Gas	Mixing Stage	Cycl. Accel.
1	H	H_2	2			x
2	He	He	2			x
3	Li	Li	2L	He	2	x
6	C	CH_4	2	He	2	x
7	N	N_2	1			x
8	O	O_2	1			x
9	F	CHF_3	2	O_2	1	x
10	Ne	Ne	1	He or O_2	1	x
11	Na	NaCl+Ca	2L	N_2	1	
12	Mg	Mg	2L	O_2	1	x
13	Al	Al	2H	O_2	1	x
14	Si	SiH_4	2	O_2	1	x
15	P	P	2L	N_2	1	x
16	S	SO_2	2	O_2	1	x
17	Cl	CCl_4	2	O_2	1	x
18	Ar	Ar	1	O_2	1	x
19	K	KCl+Ca	2L	O_2	1	x
20	Ca	Ca	2L	O_2	1	x
21	Sc	Sc	2H	O_2	1	x
22	Ti	TiF_4	2L	O_2	1	x
24	Cr	Cr	2H	O_2	1	x
26	Fe	Fe	2H	O_2	1	
28	Ni	Ni	2H	O_2	1	x
29	Cu	Cu	2H	O_2	1	x
36	Kr	Kr	1	O_2	1	x
41	Nb	Nb rod	2	O_2	1	
47	Ag	Ag	2H	O_2	1	x
53	I	I	2L	O_2	1	
54	Xe	Xe	1	O_2	1	x
57	La	La	2H	O_2	1	x
65	Tb	Tb	2H	O_2	1	x
83	Bi	Bi	2L	O_2	1	
90	Th	Th foil	2	O_2	1	
92	U	URe_2	2H	O_2	1	x

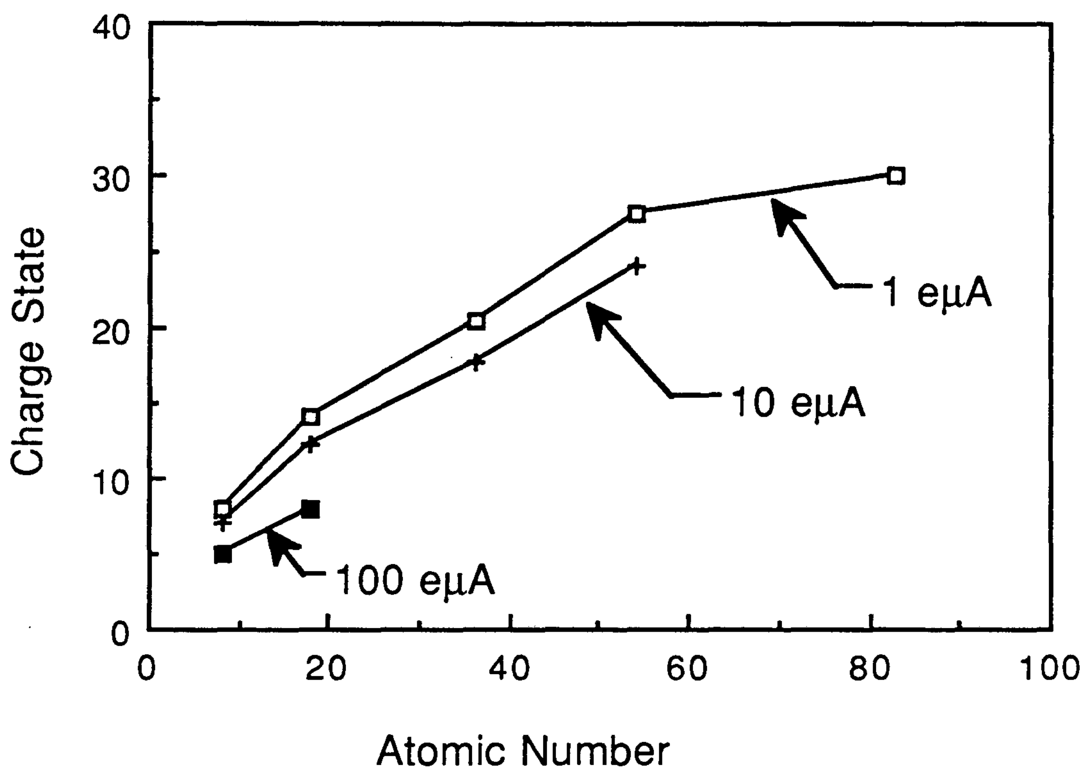
Notes:
1. In the "Stage" column, 2L indicates use of low temperature oven and 2H indicates use of high temperature oven.
2. "Cycl. Accel." indicates ion was accelerated through the cyclotron to give external beam.



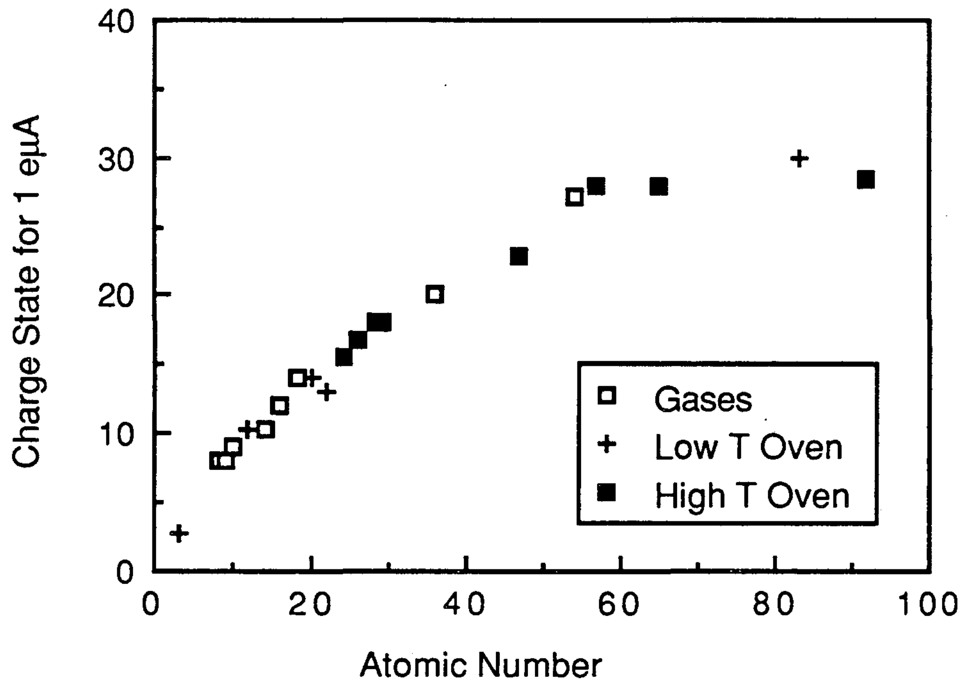
1. Energy vs. mass using PIG and ECR sources, with 10^{10} particles/sec cyclotron external beam.



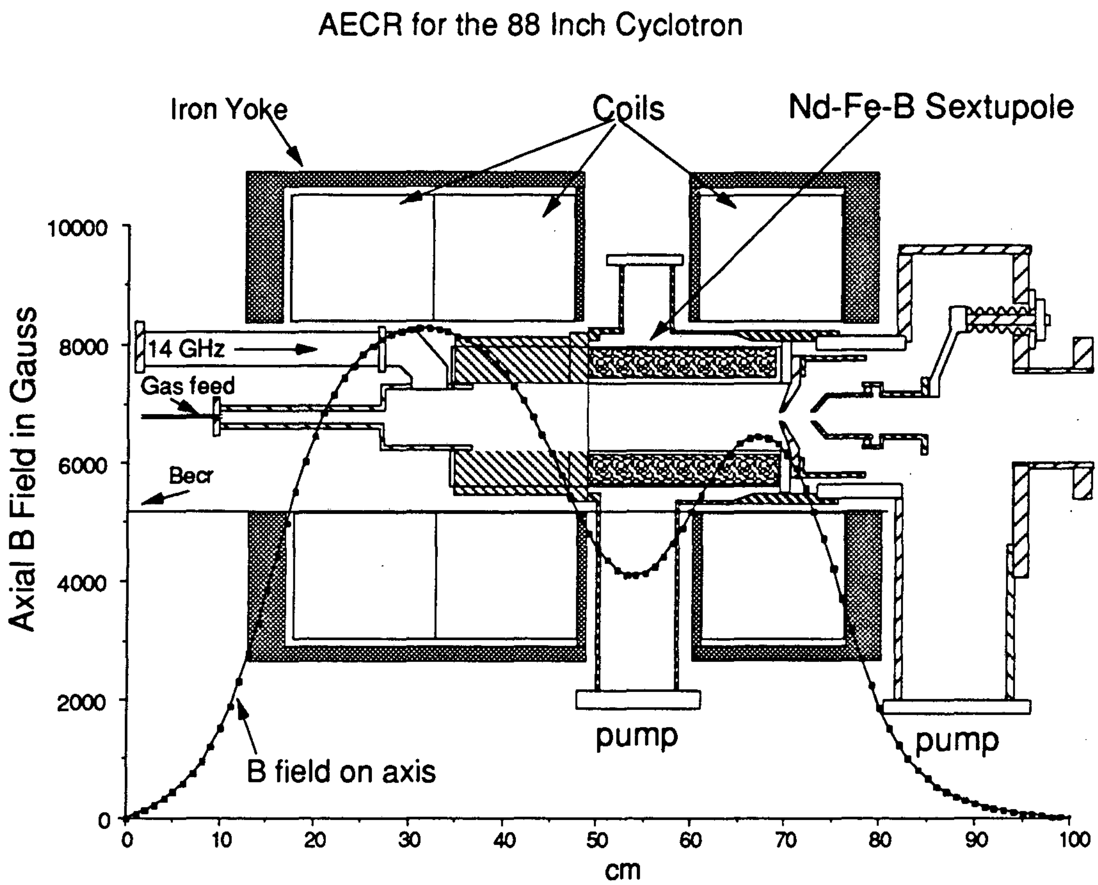
2. Vertical section of present ECR source.



3. Charge states for indicated beam intensities from ECR source.



4. Charge states for 1 eμA intensity from the ECR source for gas and solid material feed.



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5. Elevation section of AECR source.

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