STATUS OF ECR SOURCE TECHNOLOGY

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Introduction

ECR (Electron Cyclotron Resonance) ion sources are now in widespread use for the production of high quality multiply charged ion beams for accelerators and atomic physics experiments, and industrial applications are being explored. In the last decade ECR sources have evolved from a single large, power consuming, complex prototype (SUPERMAFIOS)[1] into a variety of compact, simple, reliable, efficient, high performance sources of high charge state ions. Eight laboratories have one or more ECR sources in regular operation with cyclotrons. At least seven other ECR sources are under development or in the planning stage for use with cyclotrons. An ECR source supplied an O^{6+} beam to the CERN SPS accelerator where it was stripped to O^{8+} and accelerated to 200 GeV/u.[2] A project is underway at Argonne to couple an ECR source to a superconducting heavy-ion linac.[3] Four ECR sources are in dedicated use for atomic physics and three of the ECR sources coupled to cyclotrons are also used for low energy atomic physics research. Polarized ion sources are being developed, which employ ECR discharges to ionize the beams. A very high efficiency ECR ion source is being developed for the purification of medical radioisotopes.[4]

Several general characteristics of ECR sources explain their widespread acceptance. For use with cyclotrons which require CW multiply charged ion beams, the ECR source has many advantages over heavy-ion PIG sources. Most important is the ability to produce higher charge states at useful intensities for nuclear physics experiments. Since the maximum energy set by the bending limit of a cyclotron scales with the square of the charge state, the installation of ECR sources on cyclotrons has provided an economical path to raise the energy. For example, at Berkeley the maximum energy of the 88-Inch Cyclotron was doubled for oxygen and quadrupled for heavier beams such as argon. Another characteristic of ECR sources is that the discharge is produced without cathodes, so that only the source material injected into an ECR source is consumed. As a result, ECR sources can be operated continuously for periods of weeks without interruption. Techniques have been developed in the last few years, which allow these sources to produce beams from solid materials. The beam emittance from ECR sources is in the range of 50 to 200 π mm-mrad at 10 kV which matches the acceptance of cyclotrons and RFQ's well. Maintenance required on ECR sources is also minimal, consisting mainly of occasional repair of vacuum equipment and electrical support equipment. Finally, ECR ion sources are quite robust, which makes them suitable for day to day operation with an accelerator.

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Basic Principles

The basic figure of merit for an ECR ion source plasma is $n_e\tau_i$ where n_e is the plasma density and τ_i is the ion confinement time. The equilibrium charge state distribution (CSD) in an ECR ion source is determined by the balance between the ion production rate (proportional to n_e) and the ion loss rate (proportional to τ_i). Although the basic concepts involved in ECR ion sources are straight forward, the theoretical understanding of their operation is not yet sufficient to predict scaling laws. An accurate model requires the detailed understanding of a variety of atomic and plasma physics processes. The atomic physics processes include electron impact ionization, ion-ion charge exchange, ion-neutral charge exchange, electron-electron scattering, electron capture by ions, and electron-ion scattering. The plasma physics processes include magnetic confinement, stochastic heating of electrons by ECRH, plasma potentials, microinstabilities, and wave propagation in plasmas. Most of the uncertainty lies in τ_i, which has not been measured directly and cannot as yet be calculated from first principles.

Although a variety of ECR sources have been built and are now in operation, those producing intense high charge state beams all have a number of features in common. Figure 1 shows a schematic drawing of the LBL ECR which illustrates these features. The plasma in the second stage is confined magnetically in a minimum B field configuration. The minimum B field has axial mirror field produced by solenoid coils and a multipole field produced by either a sextupole or octupole magnet. In the second stage, microwaves in the multimode cavity heat the plasma electrons as they cross the closed ECR surface defined by

$$\omega_{RF}=eB_{ECR}/m$$

where ω_{RF} is the RF frequency, e is the electron charge, m is the electron mass and B_{ECR} is the resonant magnetic field. The hot electrons strip the ions by sequential electron impact ionization. The typical operating pressure in the second stage is $\sim 1\times10^{-6}$ Torr. In the first stage a cold dense plasma is produced at an ECR zone where the neutral pressure is about 1×10^{-3} Torr. This plasma flows into the second stage due to the density gradient. An aperture between first and second stage defines the plasma flow as well as the flow of neutrals into the second stage. In the LBL ECR the first stage ECR zone occurs on an uphill gradient of the axial magnetic field. Many other ECR source use a mirror field in the first stage. Extraction of the ions is done with accel-decel geometry with the source biased at a positive potential and the puller biased at a negative potential.

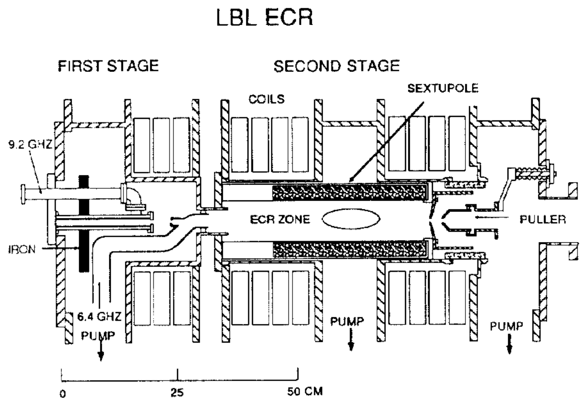

Fig. 1. Elevation view of the LBL ECR in its present configuration. The open sextupole structure allows radial pumping in the second stage.

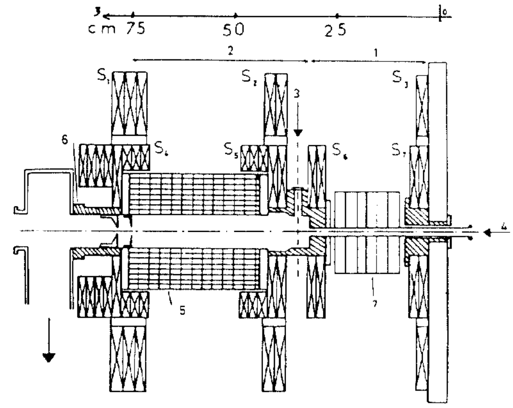

Fig. 2. Schematic drawing of the new MINIMAFIOS-16GHz ECR source. S1 through S7 are solenoids, 1 is the first stage, 2 the second stage, 3 the RF feed, 4 gas injection, 5 hexapole, 6 extraction, and 7 heat radiator. The only pump used is in the extration region.

Present ECR Sources

In Table 1, the worldwide development and application of ECR sources is summarized. Included in the table are status, second stage chamber dimensions, RF frequencies, special aspects, and the application of each ECR source. The variety of sizes and frequencies used in the various sources reflects both a search for scaling laws and to some extent practical considerations of cost, fabrication facilities, and space requirements in the laboratories. More complete descriptions of the historical development of ECR sources can be found elsewhere.[2,5,6]

Although theory cannot yet give scaling laws, it is possible to draw some conclusions about scaling by considering the performance of the sources in the table. First, it is necessary for the second stage chamber to be a multimode cavity. A simple measure of this is to calculate the ratio of second stage diameter to RF wavelength (D/λ). As long as $D/\lambda \geq 2$, increasing the chamber size does not result in a gain in charge state performance, but as D/λ becomes significantly less than 2 high charge state performance falls rapidly. There is some evidence that source tuning becomes less critical when D/λ is made considerably greater than 2.

Measurements at 16 and 18 GHz by Geller et al [8] demonstrate that high charge state performance of ECR sources increases as the RF frequency is increased above 10 GHz. All high charge state ECR sources operate at plasma densities in the second stage below the critical plasma density given by

$$n_{crit} = 1.24 \times 10^{-8} f^2$$

in cm^{-3} where f is the microwave frequency in Hz. Geller has argued that increasing the RF frequency should therefore increase the plasma density and $n_e\tau_i$.[2,7] The results of tests in the last two years at Grenoble using MINIMAFIOS-16GHz show significant performance gains as a result of increasing the operating frequency to 16 GHz. The design of MINIMAFIOS-16GHz shown in Fig. 2 is similar to the earlier source MINIMAFIOS-10GHz. However, there are several important differences including the suppression of pumping in the second stage, a high field sextupole, and additional solenoid coils. In Figs. 3 and 4 the performance for neon and argon of MINIMAFIOS-16GHz (pulsed at a duty factor $\leq$ 0.5) is compared with the CW performances of MINIMAFIOS at 10 GHz and the LBL ECR at 6.4 GHz. These figures demonstrate the significant improvement in source performance for high charge states attained at 16 GHz. Although not shown in Fig. 3, the 16 GHz source has produced 10 enA of Ar^{17+} and 1 enA of Ar^{18+} for atomic physics research.[8] For both neon and argon the largest percentage gains are in the highest charge states showing that the effect is due not only to increased density, but also to increased $n_e\tau_i$. These figures also show somewhat paradoxically, that for high charge states the differences between 6.4 GHz and 10 GHz are not very significant. Of course, there are several design differences between the LBL ECR and MINIMAFIOS-10GHz. These include higher pumping speed in the second chamber and independent RF feeds in the LBL ECR, which may compensate for its lower frequency. The performances of a number of ECR sources including MINIMAFIOS-10GHz, ECREVIS, OCTOPUS, the ORNL-ECR, the LBL-ECR, and RT-ECR are more remarkable for their similarity, than differences. The performance of the large superconducting ECR source ISIS, which operates at 14 GHz lies above that of the 6 to 10 GHz sources and below that of MINIMAFIOS-16GHz. Measurements on ISIS indicate that more RF power would improve performance. The large size of ISIS means the 3.5 kW of RF may not provide a sufficient power density to operate at the maximum plasma density allowed at 14 GHz.[9,10]

Recently, a new mode of ECR source operation has been reported using the compact 10 GHz ECR source CAPRICE.[11] This new mode (2B-mode) occurs when the second stage axial field of CAPRICE is raised to twice B_{ECR}. This produces a subharmonic resonance surface where ω_{RF} equals $0.5\omega_{ce}$, the electron cyclotron frequency. Because the sextupole field in this source was only .4T (the design value for normal 10 GHz operation), the subharmonic surface was not closed. A new sextupole with .8T is under construction to rectify this. When the source was operated in this 2B-mode, the classical ECR zone was also present. This was achieved by increasing the mirror ratio of CAPRICE. The currents produced in the 2B-mode were 3 to 4 times as great as those produced in the classical mode indicating an increase in the plasma density. The CSD was largely unchanged, however, which indicates that $n_e\tau_i$ was not increased. Another indication of the increased plasma density in the 2B-mode is an increase in the optimum RF power to ~500 W from ~200 W in the classical mode. Operating in this mode CAPRICE produces more intense beams of intermediate charge states such as O^{6+} and Ar^{8+} than any other ECR operating at 10 GHz or less.

The performance of the LBL ECR for a wide range of ions is summarized in Tables 2 and 3. The currents listed for gases are representative of the performance levels of a number of ECR sources now in use with accelerators or for atomic physics such as OCTOPUS, RT-ECR, MINIMAFIOS-10GHz, the ORNL-ECR, and ISIS. There is a much wider spread in the results for beams

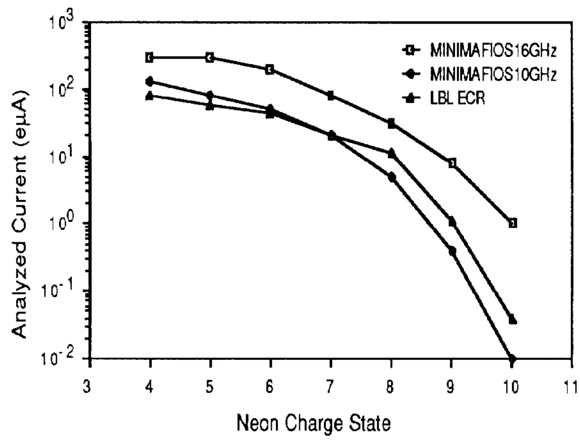

Fig. 3 Comparison of the extracted neon ion currents in eμA for MINIMAFIOS-16GHz, MINIMAFIOS-10GHz, and the LBL ECR.

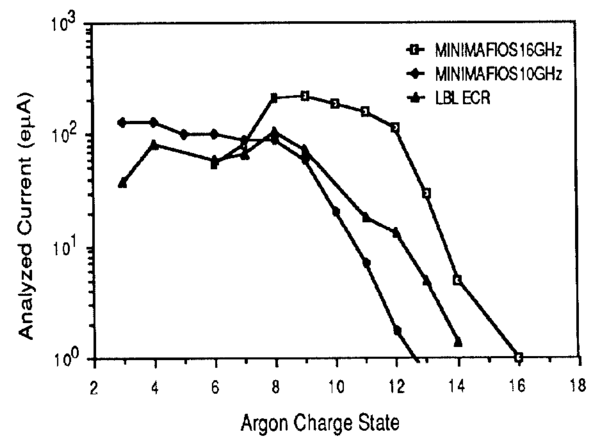

Fig. 4. Comparison of the extracted argon ion currents in eμA for MINIMAFIOS-16GHz, MINIMAFIOS-10GHz, and the LBL ECR.

from solids. As discussed below, special techniques are required for solid feeds. The currents represent the best results taken from many tests on the LBL ECR in which the source was readjusted to optimize some of the individual charge states. For all elements heavier than oxygen, gas mixing was used to enhance the high charge states. Gas mixing is now a standard technique for all ECR sources although details vary from source to source. The techniques used on the LBL ECR are described in more detail elsewhere.[12]

ECR Ion Source Beams From Solids

The development of techniques which allow the production of high charge state ions from solid materials has also been of great importance. Since a very high percentage of the elements more massive than Ar are solids at room temperature, the ability to use solid materials as source feeds is vital for ion sources used with heavy-ion accelerators. The two main methods are direct insertion of solids into the plasma and use of ovens to vaporize solids. In some respects these two methods are complimentary. Direct insertion works well with high temperature materials such as iron, nickel, niobium, tantalum and tungsten. The oven works well with low temperature materials such as lithium, magnesium, calcium, and bismuth.

Direct insertion has been studied in detail in Grenoble with the CAPRICE source for a wide variety of materials ranging from aluminum to gold.[11] In CAPRICE, a solid rod is positioned close to the ECR surface where it is vaporized by hot electrons in the plasma. The plasma is maintained by adding a support gas such as oxygen or nitrogen. To maintain a stable plasma the rod's position is automatically controlled with a feedback loop. In a one week run using tantalum in CAPRICE, the average consumption was approximately 1 mg/hr.[2] Direct insertion has been used in the ORNL-ECR to produce iron, nickel, and chromium beams and in the LBL-ECR to produce niobium beams for atomic physics. Even without feedback, the stable beams can be produced for periods of several hours.[13]

A variety of metallic ion beams have been produced from the LBL ECR using a simple resistance heated oven. Because the oven temperature is controlled externally it makes stable operation and efficient usage possible. The oven is inserted radially into the second stage so that vaporized metal atoms stream through the ECR plasma and are ionized by electron impact. Typically with oven operation, the plasma is maintained by running either oxygen or nitrogen as a support gas in the first stage. This is similar to the use of a mixing gas when operating the source with gases heavier than oxygen. The amount of metal in the plasma is adjusted by varying the oven temperature. A proportional temperature controller is used to keep the oven temperature constant. The beam stability with the oven is quite remarkable. A number of cyclotron runs lasting several days have used the metal ion beams from the ECR source. During some of these runs no adjustment of the ECR source or oven was required. When using rare isotopes such as ^{48}Ca, the usage can be minimized by lowering the operating temperature so that only the required intensity is produced. In this way a 68 hour cyclotron run with ^{48}Ca consumed only .15 mg/h of an enriched sample of calcium (25% ^{48}Ca). ^{209}Bi was chosen to explore the performance of the LBL ECR source for very heavy elements because it is mono-isotopic and its vapor pressure temperature characteristics are appropriate for the oven. As listed in Table 3, the source produced .56 eμA of Bi^{31+} and .05 eμA of Bi^{34+}. Other materials, such as low temperature compounds can also be used in the oven.[12]

Future of ECR sources

The successful coupling of ECR sources to cyclotrons, a synchrotron, and soon to a heavy-ion linac make it clear that continued development of ECR source technology is essential. This is a relatively young technology. ECR source performance has steadily progressed and further improvements are to be expected. These improvements may come in an incremental way as a result of refinements in extraction geometry, first stage performance, source vacuum, or other areas. They could come in a more dramatic fashion, if higher frequency RF sources such as gyrotrons can be successfully used to drive ECR sources. Since the power density should increase with the plasma density, as the source frequency increases the size should decrease. Comparison of the performances of small and large sources give no clear indication that $n_e\tau_i$ scales with source size, although RF wavelength sets a minimum plasma chamber size. This is consistent with the trend to higher frequencies and smaller sources.

Acknowledgement

The author received many helpful responses to a request for current information about status of projects from the ECR community. Discussions with Dr. T.A. Antaya and Dr. F.W. Meyer were very useful in completing this paper.

TABLE 1
ECR ION SOURCES

Country / Laboratory / Source	Status	L (cm)	D (cm)	F (GHz)	Comments	Application
France						
Grenoble-CEN						
SUPERMAFIOS	Dism.	100	35	16,8	3 MW used.	Test
MICROMAFIOS	Dism.	30	7	10	Compact, copper coils,SmCo	Test
MINIMAFIOS	Operat.	30	7	10	Now at KVI, SARA,GANIL	Test, A.P.& Cyc.
"	"	"	"	"	and CERN-SPS	Synchrotron
MINIMAFIOS-16GHz	Test	30	7	16.6	Pulsed source	Test
CAPRICE	Test	13.5	8	10	Iron yoke, very compact	Test
MINIMAFIOS-18 GHz	Test	30	7	18	Highest frequency ECR	Test,Synchrotron
Germany						
KFZ-Karlsruhe						
p-HISKA	Dism.	28	7	14.5,7.5	Compact,SmCo Sextupole	Test&Cyc
HISKA	Standby	70	10	14, 7.5	s.c. Solenoids,SmCo Sextupole	Cyclotron
LISKA	Operat.	25	7	7.5	Lithium ECR	Cyclotron
High Efficiency ECR	Operat.	20	5	6.4	Isotope separation	Test
KFA-Jülich						
Pre-ISIS I	Dism.	25	5	2.5	Small, low frequency, single stage	Test
Pre-ISIS II	Operat.	25	5	5	Two stage	Test & Cyc.
ISIS	Operat.	70	20	14.3,14.3	Large s.c, high freq	Cyc
Giessen						
Pre-ISIS II	Operat.	25	5	5	Two stage	Atomic Physics
Belgium						
Louvain-la-Neuve						
ECREVETTE	Dism.	40	12	14.7,8.5	1st superconducting ECR	Test & Cyc.
ECREVIS	Dism.	120	32	14.7, 8.5	Large superconducting ECR	Cyc, A.P.
OCTOPUS	Operat.	70	18	14.3,8.5	Iron yoke, open octupole	Cyc & A.P.
U.S.A.						
Oak Ridge National Lab						
ONRL-ECR	Operat.	40	8.5	10.6	Compact,SmCo	Atomic Physics
Lawrence Berkeley Lab						
LBL-ECR	Operat.	33	9.	9.2, 6.4	Open SmCo sextupole	Cyc. & A.P
NSCL-MSU						
RT-ECR	Operat.	50	14	6.4,6.4	Iron yoke, 1st stage, sextupole	Cyclotron
CP-ECR	Constr.	24	11	6.4	Low cost, moderate charge states	
Argonne National Lab						
PIIECR	Constr.	53	10	10	On high voltage platform	Linac
Texas A&M University						
ECR	Design			14,6.4		Cyclotron
Japan						
RIKEN						
ECR1	Operat.	100	8	9,2.5	Overdense experiments	Test
ECR2	Operat.	30	8	2.5,2.5	Whistler mode heating	Test
ECR	Design	52	10	10		Cyclotron
Sweden/Finland						
The Svedberg Lab. (Uppsala)						
ECR	Design					Cyclotron

Dism.= Dismantled, A.P. = Atomic Physics, Cyc. = Cyclotron, s.c. = superconducting

TABLE 2

Currents for the LBL ECR: Hydrogen through Silicon

CS	^{1}H	^{3}He	^{12}C	^{14}N	^{16}O	^{19}F	^{20}Ne	^{24}Mg	^{28}Si
1+	300	300	27	82	118				
2+		200	37	117	143	43	51	32	20
3+			*	106	152	55	63	34	33
4+			31	110	*	53	78	28	69
5+			6.5	93	96	37	58	44	72
6+				19	82	17	45	34	47
7+					14	11	21	18	30
8+					0.95	1	11	8	17
9+						0.05	1.1	6.3	7
10+							0.04	2.2	2.7
11+								0.1	0.5
12+									0.2

All currents in eμA measured at 10 kV extraction voltage.
* Indicates not measured because a mixture of two ions with identical charge to mass ratios were present.
Natural isotopic abundance source feeds were used except for ^{3}He and $^{22}Ne^{10+}$

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13. F.W. Meyer, private communication.

TABLE 3

Currents for the LBL ECR: Sulfur through Xenon

CS	^{32}S	^{39}K	^{40}Ar	^{40}Ca	^{48}Ti	^{84}Kr	^{127}I	^{129}Xe	^{209}Bi
3+	10	4	38	23					
4+	*	4.5	82	24					
5+	20	5	*	*					
6+	*	8.5	60	37		9			
7+	63	11	66	38	2.4	12			
8+	*	18	106	36	*	22			
9+	36	37	72	31	12	25		4.1	
10+	*	22	*	*	10	22	4.2	4.7	
11+	5	12	18	22	8	19	4.9	5.1	
12+	*	2.4	13	11	*	*	5.7	5.2	
13+	.4		5	3.2	1	21	7.5	5.2	
14+	*		1.4	1.1		*	8.5	5	
15+	.001		*	*		16	11	4.3	
16+			0.03	0.03		8	*	4.6	
17+						7	12	4.3	
18+						*	15	4.4	
19+						2	15	4.8	
20+						0.9	14	4.8	
21+						*	*	4	2.2
22+						0.1	11	3.5	2.6
23+							10	3.1	3.1
24+							8.3	2.7	3.7
25+							5.6	2	3.6
26+							2.1	1.1	*
27+							0.83	0.34	3
28+							0.2		2.5
29+							0.05		1.6
30+							0.009		*
31+									0.56
32+									0.26
33+									0.1
34+									0.05

All currents in eμA measured at 10 kV extraction voltage.
* Indicates not measured because a mixture of two ions with identical charge to mass ratios were present.
Natural isotopic abundance source feeds were used.