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ABSTRACT

ECR ion sources have become the most frequently used heavy-ion source for cyclotrons. They are also being used with heavy-ion linacs, synchrotrons, and radioactive beam accelerators. Although almost 20 years have gone by since the first high charge state ions were extracted from an ECR source, the efforts to improve their performance and simplify their construction and operation seem to be expanding. Recent developments include new high frequency sources, electron injection, and superconducting magnet ECR sources. This paper surveys the application of ECR sources to accelerators, discusses recent innovations and the results of experimental studies, reviews current thinking on how they operate, and looks at potential directions for future improvement.

1. INTRODUCTION

The number of Electron Cyclotron Resonance (ECR) ion sources used for the production of high charge state ions continues to expand with more than 40 now in operation. The majority of the sources have been built for use with accelerators with the remainder being utilized for atomic physics research. The desirable characteristics of ECR sources for accelerator applications include high charge state production, high intensity, stability, wide range of ion species, reliability, longevity, and ease of operation. This has made them the source of choice for heavy-ion cyclotrons. ECR sources are also now used with heavy-ion linacs, synchrotrons, storage rings, and in a radioactive beam accelerator. Table 1 summarizes the ECR sources being used at accelerators and illustrates that they have found application in many laboratories and different countries. Much of the incentive and effort to develop better ECR sources has come from the accelerator community. The Grenoble group, which developed the first high charge state ECR source in 1974[1] and remains very active in source development, is an exception in that it is not directly associated with an accelerator facility. However, they have supplied ECR sources to many accelerators as evidenced by the number of their sources listed in Table 1 (Minimafios, Neo-Mafios, and CAPRICE).

2. ECR SOURCE DESIGN AND PERFORMANCE

Even though it has been 18 years since the first source produced high charge states, ECR source development remains very active. The development continues in spite of or perhaps because source design and performance has not yet been reduced to a known set of scaling laws. In Section 3 we discuss some aspects of ECR physics, but in this section we describe the present state of the art and summarize present performance standards.

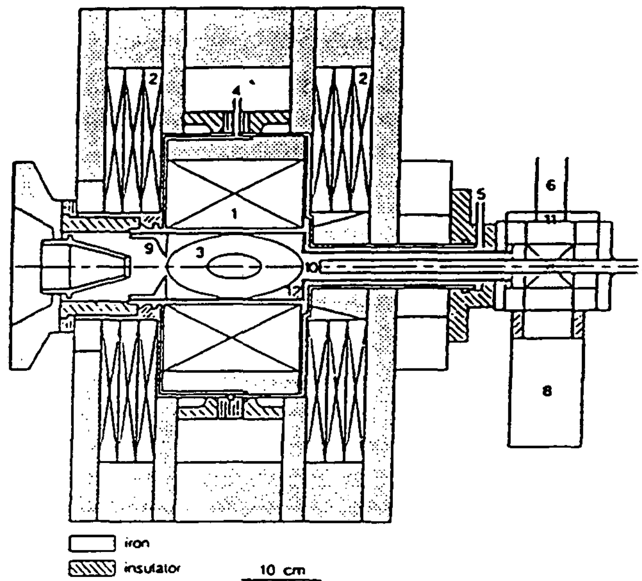

Fig. 1. Elevation view of the CAPRICE-2ω_{ce} source. (1) shows the sextupole magnet. (2) shows the solenoid magnets. (3) shows a inner elipse where the ECR resonance condition is met. On the outer elipse the magnetic field is twice as great. (6) shows RF waveguide which feeds into a transition section. (10) shows the end of the coaxial coupling.

Figure 1 illustrates the main features of the CAPRICE source from Grenoble.[2] The 10 GHz version of this source called CAPRICE-2ω_{ce} produces very large currents of intermediate charge state ions such as O^{6+}, Ar^{11+}, and Kr^{17+}. It is compact in size with a plasma chamber 16 cm long and 6.6 cm in diameter, simple in design, and has excellent stability. Three features make this source different from other 10 GHz sources. First, it operates with a very high axial mirror field of about 1 T. Second, the radial field is also very strong with a value at the wall of 0.8 T, more than twice that need to maintain a closed ECR zone at 10 GHz. Third, the microwave power is coupled into the plasma

Table 1

Applications of high charge state ECR sources with accelerators. OP indicates the source is operational with the accelerator. TE indicates the source is being tested. PR indicates the project is in the proposal stage.

Lab Name	Country	Status	Source Name,Type or Comments
	Cyclotrons		
Louvain-la-Neuve	Belgium	OP	OCTOPUS (8.5 GHz)
Lanzhou	China	OP	CAPRICE (10GHz)
Jyväskyla	Finland	OP	Derived from RT-ECR at MSU(6.4GHz)
Ganil	France	OP	ECR3, ECR4 (14 GHz)
SARA	France	OP	Minimafios, CAPRICE
Jülich	Germany	OP	ISIS, (14 GHz) superconducting
Karlsruhe	Germany	OP	LISKA, lithium source
VECC	India	TE	Derived from CP-ECR at MSU
Catania	Italy	PR	Plans for superconducting ECR
RIKEN	Japan	OP	RIKEN ECRIS (10GHz)
INS	Japan	OP	SF-ECR (10 GHz)
JAERI,Takaski	Japan	OP	OCTOPUS
NAC	S. Africa	TE	Minimafios (10GHz)
Uppsala	Sweden	OP	Derived from RT-ECR at MSU
PSI	Switzerland		To operate in 1993
LBL	USA	OP	LBL-ECR (6.4 GHz), AECR (14 GHz)
MSU	USA	OP	CP-ECR,RT-ECR, SC-ECR
Texas A&M	USA	OP	6.4 GHz
Dubna	Russia	TE	
	Heavy-ion Linacs		
GSI	Germany	OP	CAPRICE
Argonne	USA	OP	PI-ECR (10 GHz)
Legnaro	Italy	TE	Alice(14 GHz)
RIKEN	Japan	OP	Neomafios (8GHz)
	Synchrotrons		
NIRS-HIMAC	Japan		Medical Acc., NIRS-ECR(10GHz)
GSI	Germany	OP	CAPRICE (14GHz)
CERN	Switzerland	OP	Minimafios (14 GHz)
	Storage Rings		
Uppsala	Sweden	OP	Derived from RT-ECR at MSU(6.4GHz)
INS-TARN2	Japan		
GSI	Germany	OP	CAPRICE
	Radioactive Beam		
TRIUMPH	Canada	TE	TISOL, Isotope Separator
ISN, Grenoble	France	PR	ERIC, Reactor to Cyclotron
Louvain-la-Neuve	Belgium	OP	6.4 GHz

launch the RF from a rectangular or circular waveguide. Pumping is provided by a small turbomolecular pump in the injection region. A 14 GHz version of CAPRICE has recently been installed at GSI. Another 14 GHz source called ECR4 has been built at GANIL,[3] which differs in engineering design, but follows the general features of CAPRICE.

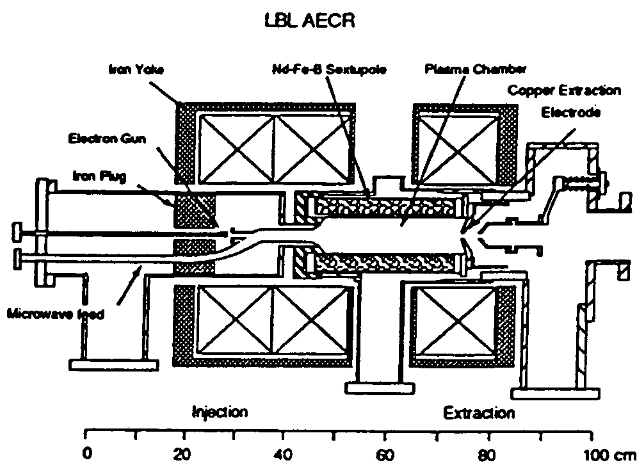

Fig. 2. Elevation view of the LBL AECR. This Nd-Fe-B sextupole has radial slots for pumping the plasma chamber. RF power is fed by a transition from rectangular to round waveguide.

Figure 2 illustrates the design of the AECR built at Berkeley.[4] This source operates at 14 GHz and differs in design from CAPRICE in several features. The plasma chamber is 30 cm in length and 7 cm in diameter. In place of an RF driven first stage, the AECR has an electron gun which can inject up to 100 ma of electrons into the plasma chamber. It also has 6 radial slots in the plasma chamber to provide pumping to the second stage. This also allows solid materials to be injected from ovens located radially. The main drawback is that the sextupole strength at the wall is only 0.6 T because the radial slots limit the achievable field. The peak performance of this source is high, but it has proved difficult to maintain the performance for the long periods required for operation with the cyclotron.

The SC-ECR built at Michigan State University is the newest ECR to use superconducting coils to produce the magnetic field.[5] The only other superconducting ECR source still in operation is ISIS at Jülich.[6] The plasma chamber of the SC-ECR is relatively large with a length of 45 cm and a diameter of 15 cm, which is characteristic of superconducting sources. The superconducting coils are designed to reach fields sufficient for the source to operate up to 35 GHz. The sextupole magnet can be adjusted independently, which allows the detailed study of how radial field strength affects source performance. The source has been operated at 6.4 GHz and performs better than the MSU RT-ECR. Extensive testing at 14 GHz is planned for the near future.[7]

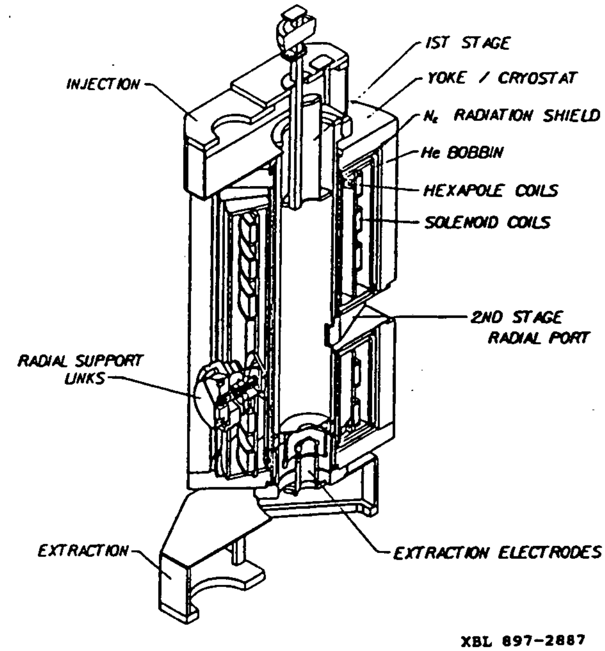

Fig. 3. Cutaway view of the MUS SC-ECR. This source operates in the vertical position. An iron yoke strengthens and confines the magnetic field produced by superconducting coils.

In Tables 2a and 2b, the current performance of ECR sources is summarized for elements as light as oxygen and heavy as uranium. These tables are not meant to be all inclusive since the field of ECR sources is so large and diverse and data was selected from published results only. It does illustrate how ECR sources perform for various ions at frequency from 6 to 18 GHz and in two modes: (CW) continuous operating and (AG) a pulse mode using the plasma after glow. For lighter elements we have quoted the performance for gases only, while the very heavy elements are by necessity produced from solids. The performance of ECR sources with metal ions and the techniques for their production was recently reviewed[14] and will not be repeated here. If we compare the values in the tables to those produced a decade earlier it is clear how much progress has been made. For example, O^{6+} is up from 15 to 800 eμA, Ar^{12+} is up from 0.3 to 80 eμA, and instead of 0.1 eμA of Kr^{16+} 1.0 eμA of Kr^{26+} can now be produced.

Table 2a

Representative beams for various ECR sources for oxygen to krypton . CW indicates continuous power. All currents in eµA.

ION	6.4 GHz (CW)	10 GHz (CW)	14 GHz (CW)	18 GHz (CW)
O^{6+}	82[8]	385[2]	475[10]	800[12]
O^{7+}	20[9]	45[2]	131[10]	180[12]
Ar^{8+}	106[8]	500[2]	500[11]	
Ar^{9+}	72[8]	260[2]	300[11]	
Ar^{11+}	18[8]	60[2]	141[10]	130[13]
Ar^{12+}	13[8]	32[2]	78[10]	80[13]
Ar^{13+}	5[8]	11[2]	34[10]	45[13]
Ar^{14+}	1.4[8]	4[2]	17[10]	20[12]
Ar^{16+}			1.4[10]	1.4[13]
Kr^{13+}	21[8]		115[11]	
Kr^{15+}	16[8]		90[11]	
Kr^{17+}	7[8]	42[2]	50[11]	
Kr^{19+}	2[8]		36[10]	
Kr^{21+}		7[2]	13[10]	
Kr^{23+}		1.9[2]	6.8[10]	
Kr^{24+}		1[2]	4[10]	
Kr^{25+}			2.2[10]	
Kr^{26+}			1[10]	

Table 2b

Representative beams for various ECR sources for xenon to uranium. CW indicates continuous power. AG indicates the RF power is pulsed and the current is measured during a short pulse produced in the plasma afterglow. All currents in eµA.

ION	6.4 GHz (CW)	10 GHz (CW)	14 GHz (CW)	14 GHz (A. G.)	18 GHz (A. G.)
Xe^{22+}	3[8]	34[2]	30[11]		
Xe^{25+}	2[8]	25[2]	17[11]		
Xe^{27+}		8.4[2]	12[10]		
Xe^{29+}		1.9[2]	3[11]		
Xe^{31+}			1[10]		
Pb^{25+}		16[2]	30[11]	70[3]	
Pb^{27+}		10.5[2]	25[11]	90[3]	
Pb^{31+}		2.2[2]	8[11]	75[3]	
Pb^{32+}		1.1[2]		55[3]	
Bi^{23+}	3.1[8]				
Bi^{25+}	3.6[8]		3.8[10]		80[13]
Bi^{27+}	3[8]		5.5[10]		85[13]
Bi^{29+}	1.6[8]		5.7[10]		90[13]
Bi^{31+}			4.5[10]		85[13]
Bi^{34+}			1.5[10]		30[13]
Bi^{36+}					15[13]
U^{21+}		28[2]			
U^{23+}		21[2]	22[11]		
U^{25+}		14[2]	18[11]		
U^{27+}		8[2]	10[11]		
U^{29+}		3.5[2]			
U^{31+}		1[2]			

Some general characteristics of ECR source performance can be observed in the tables. First the intensity for high charge state ions improves as the source frequency is increased. The results for Minimafios-18GHz are particularly impressive.[12, 13] However, as discussed below, frequency is only one of many factors which determine source performance and at a given frequency there is a wide range of source performance. Second, even though uranium has 92 electrons and xenon only 54, the intensities of U^{29+} and U^{31+} are not higher than those for Xe^{29+} and Xe^{31+}. While this is in part due to the increased difficulty in producing uranium beams since it is a solid, it also indicates the maximum charge state attainable increases very slowly with increasing atomic number for very heavy elements.

3. ECR Physics and Source Design

The basic concepts for high charge state production in ECR sources are relatively straight forward. Electrons are heated by microwave power on a surface defined by the ECR resonance condition

$$\omega_{RF} = eB/m_e \qquad \text{Eq (1)}$$

where B is the magnitude of the magnetic field, e the electron charge and m_e the mass of the electron. The ionization is produced largely by stepwise electron impact ionization and the degree of ionization is determined by $n_e\tau_i$, where n_e is the density of hot electrons and τ_i is the ion confinement time. Computer codes based on these concepts have been developed which incorporate the cross sections for ionization, charge exchange and other atomic physics processes involved.[15,16] These models usually require that the plasma density, neutral density, confinement time, and electron temperatures be specified. With a reasonable set of parameters these codes can reproduce measured charge state distributions. From these models it is clear that for high charge states the sources should run at low neutral pressures, high plasma densities, with sufficiently high electron temperatures, and long ion confinement times.

The challenge in understanding, predicting, or improving ECR performance comes from the tenuous connection between the set of internal variables discussed above and the external variables of ECR sources. The external variables available in the design stage include size, shape and strength of the magnetic field, microwave frequency and power, microwave coupling, plasma chamber dimensions, and pumping. Once the source is built the adjustable variables are axial magnetic field, gas flow, and microwave power. During the last decade many ideas to improve the source performance have been proposed and tried. To increase τ_i some sources were made large. This was not successful and the trend is to small compact sources such as CAPRICE. To reduce the neutral pressure increased pumping to the plasma chamber has been used. While this may help when producing low density high charge state plasmas, it conflicts with the need to increase the radial magnetic field described below.

To increase the plasma density, sources have been built to operate at higher frequencies. The idea is that the ECR sources must operate below the critical density and since it scales as f^2, higher densities should be achieved at higher frequencies.[17] In order to increase frequency, the ECR resonance condition given by Eq. 1 requires the magnetic field must also be increased proportionally. While increasing the frequency has resulted in improved performance as shown in Table 2a and 2b, the improved performance is not as great as would be expected if the plasma density was increasing as f^2.[13] Another approach has been to increase the magnetic field of both the sextupole and axial mirrors as with the CAPRICE source. This was based on a prediction of improved microwave to coupling.[2] This approach has produced very good performance as shown in Tables 2a and 2b for the 10 GHz Caprice source. Tests with the MSU SC-ECR, on which the radial field strength can be independently adjusted, also indicated that increasing the radial field strength enhanced high charge state production.[7] So it appears that both higher frequency and stronger magnetic fields improve performance although the connection to internal variables remains unclear. The fact that the plasma density increases more slowly than f^2 indicates some other mechanism may be limiting it. This indicates there is still the possibility for much better performance if this limitation can be overcome.[13]

One external variable which has been largely overlooked, is the coupling of microwave power into the plasma. This is a complex question since most ECR sources operate in multimode configuration. That is the microwave modes of the plasma chamber are spaced close together and depending on their loaded Q (Q_L) several modes may be excited at one time. In addition, the dielectric constant for the plasma depends on the density so the cavity modes are shifted in frequency roughly as

$$\omega^2 = \omega_o^2 + \omega_p^2 \qquad \text{Eq (2)}$$

where ω_o is the mode frequency in vacuum and ω_p is the plasma frequency given by

$$\omega_p^2 = 4\pi e^2 n_e/m_e \qquad \text{Eq (3)}$$

The typical loaded Q's for ECR plasma chambers are also not known. While the cavity Q_o can be estimated for any single mode, it is difficult to measure or calculate the plasma loading. Measurements in Grenoble indicated that in a stainless steel cavity only 20% of the microwave power was coupled into the plasma.[18] While the question is complex, there is considerable evidence that microwave cavity modes play an important role in the coupling to the plasma. Much of the tuning done with ECR sources involves making small changes in the magnetic field and microwave power. Small changes in magnetic field can result in large changes in high charge state production, total extracted current, and bremsstrahlung radiation from the source. Other evidence includes instabilities where the plasma jumps back and forth between two states, suggesting the microwave field in the chamber shifts between two modes. Finally, a hysteresis is sometimes observed when a source is carefully tuned to peak at high output and then jumps back to a very different state. To recover it is sometimes necessary to reset the source parameters and work the output back up.

Table 3

Calculated frequencies in GHz for all modes in vacuum between 9.5 and 10.5 GHz for a cylindrical cavity 16.28 cm in length and 6.6 cm in diameter.

Mode	Frequency	Mode	Frequency
TE 3.1.8	9.55394	TE 2.2.3	10.0888
TE 1.1.10	9.59107	TM 1.2.0	10.1513
TM 3.1.3	9.63604	TM 1.2.1	10.1930
TE 5.1.3	9.68456	TE 0.2.1	10.1930
TM 2.1.6	9.71339	TE 2.1.10	10.2185
TE 2.2.1	9.74641	TM 2.1.7	10.2657
TM 0.1.10	9.84895	TE 3.1.9	10.2815
TE 2.2.2	9.87620	TM 3.1.5	10.3167
TM 3.1.4	9.93960	TM 1.2.2	10.3172
TM 1.1.9	9.97518	TE 0,2,2	10.3172
TE 0.1.9	9.97518	TE 5.1.5	10.3621
TE 5.1.4	9.98665	TE 2.2.4	10.3791
TE 4.1.7	10.0400	TE 1.1.11	10.4793
TE 1.2.7	10.0556		

If we accept for the moment this picture of cavity modes, then can techniques be developed to determine which modes couple efficiently to the plasma at the ECR surface and then control those modes? For a simple cylindrical cavity it is easy to calculate the distribution of modes without plasma. In Table 3 a set of modes are listed for a CAPRICE size cavity operating at 10 GHz. The average mode spacing is 37 MHz not counting mode degeneracies. The half power points for cavity modes are given by

$$\Delta f/f = 1/Q_L \qquad \text{Eq (4)}$$

Substituting the average mode spacing into this equation gives Q_L of 270. So if the cavity modes have Q's significantly higher that this they will not necessarily overlap, while if the Q's are lower then there would be a significant overlap. It remains to be experimentally or theoretically determined what the typical Q's are for ECR sources. To determine if a cavity mode will couple well to the plasma, calculations could be made to evaluate the coupling of the RF electric fields to the transverse energy of the electrons. By integrating this over the ECR surface the relative coupling strength could be determined. These calculations could indicate whether it is advantageous to excite TE or TM type modes. Some modes will couple only weakly to the electrons because their electric field patterns don't overlap the ECR surface strongly. Techniques to experimentally control the modes include using coupling schemes which preferentially excite one type of mode, selectively loading unfavorable modes, using adjustable coupling, or even dynamically tunable cavities. The coaxial coupling developed for CAPRICE has an adjustable tuning short in the waveguide to coaxial transition section, which may allow some mode control.[19] Some of these techniques have been used for low charge state ECR sources for commercial applications. In these sources, they adjust both the cavity frequency and the coupling strength and report significant improvements in the transfer of microwave energy to the plasma.[20]

4. Special Techniques

There are several special techniques which have been developed recently to boost ECR source performance. Surface coatings with high secondary emission coefficients such as SiO_2, Mb, Ca and Th have been applied to the walls of ECR plasma chambers.[17,21] Very recently Al_2O_3 has also been shown to be very effective in enhancing high charge state production.[22] Direct injection of electrons into the plasma chamber was developed with the LBL AECR and it can result in an increase of 2 or more in extracted intensities.[4] A similar technique using a bias disk to intercept plasma and feed electrons back in has also proved effective.[23,24] The optimum bias voltages and currents for the disks are similar in magnitude to those for the electron gun. Short intense pulses suitable for synchrotrons have been developed by utilizing the beams extracted during the plasma afterglow.[3,13] Some data is given in Table 2b for afterglow currents and it appears that for heavier elements this can produce much higher intensities than continuous operation. The typical pulse lengths are on the order of 1 ms.

5. Conclusion

As we have indicated, the field of ECR sources continues to grow and diversify. New applications such as radioactive beam accelerators are appearing. With ECR sources now operating in 14 countries, the effort has truly become international. It is difficult to predict where the next major step will come from. It could come from higher frequencies, stronger magnetic fields, better coupling systems, or specialized techniques. However there are ample indications that there is still room for better performance from ECR sources.

6. Acknowledgment

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7. References

1) Geller, R., " Electron Cyclotron Resonance Multiply Charged Ion Sources," IEEE Trans. Nucl. Sci. NS-23, 904 (1976):
2) Jaquot, B. and Pontonnier, M, "The New CAPRICE source-Magnetic Structures and Performances," in **Proceedings of the 10th International Workshop on ECR Ion Sources** (Oakridge National Laboratory, Knoxville, 1990) pp. 133-155.
3) Sortais, P., "Pulsed ECR Ion Source Using The Afterglow Mode," Rev. Sci. Instrum. **63** (4), 2801 (1992).
4) Xie, Z., Lyneis, C.M., Lam, R.S., and Lundgren, S.A., "Enhanced ECR Ion Source Performance With An Electron Gun," Rev. Sci. Instrum. **62**, 775 (1991).
5) Antaya, T.A., "A Review of Studies For a Variable Frequency Superconducting ECR Ion Source at MSU," J. Phys. (Paris) Colloq **50**, cl 707 (1989).
6) Beuscher, H., "Status of the ISIS-ECR-Source and its Operation at the Cyclotron," in **Proceedings of the International Conference on ECR Ion Sources and their Applications** (NSCL Report#MSUCP-47, East Lansing, 1987) pp. 33-41.
7) Antaya, T.A. (Private Communication).
8) Lyneis, C.M., "Operating Experience with the LBL ECR Source and their Applications," in **Proceedings of the International Conference on ECR Ion Sources and their Applications** (NSCL Report #MSUCP-47, East Lansing, 1987) pp. 42-56.
9) Lyneis, C.M., "High Performance Single Stage Operation of the LBL ECR and the Design of an Advanced ECR Ion Source," J. Phys. (Paris) Colloq. **50**, cl 689 (1989).
10) Lyneis, C.M., Xie, Zuqi, Clark, D.J., Lam, R.S., Lundgren, S.A., "Preliminary Performance of the LBL AECR," in **Proceedings of the Workshop on the 10th International ECR Ion Sources** (Oakridge National Laboratory, Knoxville, 1990) pp. 47-62.
11) Sortais, P. Attal, Bisch, M., Bourgarel, M.P., Cornen, P.M., Leherissier, J.Y., Rataud, G. Schmiechen, "Results of the New "ECR 4" 14.5 GHz ECRIS, at GANIL," in **Proceedings of the Workshop on the 10th International ECR Ion Sources** (Oakridge National Laboratory, Knoxville, 1990) pp. 36-46.

12) Barue, C., et al, "Hot Electron studies in the minimafios ECR Ion Source," Rev. Sci. Instrum. **63** (4), 2801 (1992).
13) Melin, G., Hitz, C., Barue, C., Bourg, F., Briand, P., Delaunay, M., Geller, R., Girad, A., Jaquot, B., Ludwig, P., Pontonnier, M., "Electron Cyclotron Resonance Sources of Multicharged Ions: State of the Art, Recent Developments and Prospects," in **Proceedings of EPAC 92**, Berlin (1992) (To be published).
14) Geller, R., Ludwig, P. and Melin, G., "Metal Ion Production in ECRIS," Rev. Sci. Instrum. **63**, 2795 (1992).
15) Jongen, Y., "E.C.R. Electron Acceleration," **in Proceedings of the Workshop on the sixth International ECR Ion Source** (Lawrence Berkeley Laboratory, Berkeley, 1985) pp. 238-255.
16) West, H.I. Jr., "Calculation of Ion Charge-State Distribution in ECR Ion Source," **(UCRL-53391, LLNL**, 1982).
17) Geller, R., et al, "The Grenoble ECRIS Status 1987 and Proposals for ECRIS Scalings," in **Proceedings of the International Conference on ECR Ion Sources and their Applications** (NSCL Report#MSUCP-47, East Lansing, 1987) pp. 1-32.
18) Melin, G., et al, "Some Particular Aspects of the Physics of ECR sources for Multicharged Ions," Rev. Sci. Instrum. **61**, 236 (1990).
19) Delaunay, M., Jacquot, B. and Pontonnier, M., "Exploration axiale du plasma RCE d'une source d'ions multicharges CAPRICE," Nucl. Instru. and Math. **A305**, 223 (1991).
20) Asmussen, J., Hopwood, J. and Size, F.C., "A 915 MHz/2.45 GHz ECR Plasma Source for Large Area Ion Beam and Plasma Processing, "Rev. Sci Instrum. **61** (1), 250 (1990) and Amussen, J. (private communication).
21) Lyneis, C.M., "Operation Experience with the LBL ECR Source," in **Proceedings of the International Conference on ECR Ion Sources and their Applications** (NSCL Report#MSUCP-47, East Lansing, 1987) pp. 42-56.
22) Nakagawa, T., "Effect on Coating on the Plasma Chamber Wall in RIKEN Electron Cyclotron Resonance Ion Source," Japanese Journal of Applied Physics Vol **30**, 930 (1991).
23) Melin, G., et al., "Recent Developments and Future projects on ECR Ion Sources at Grenoble" in **Proceedings of the 10th International Workshop on ECR Ion Sources** (Oakridge National Laboratory, Knoxville, 1990) pp. 1-15.
24) Gammino, S., Sijbring, J. and Drentje, A.G., "Experiment with a Biased Disk at the K.V.I. ECRIS," Rev. Sci. Instrum. **63** (4), 2872 (1992).

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