

ECR ION SOURCES FOR ACCELERATORS

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ECR ion sources have proven to be ideal providers of multi-charge-state ions for many cyclotrons in the world, as well as for some accelerators besides cyclotrons. The ECR ion source injecting the Super Proton Synchrotron (SPS) at CERN is a notable example of the latter case. Some ECR sources are capable of fully stripping species as heavy as argon and providing ion beams of some of the heaviest species with charge-to-mass ratios up to 1/4, while other ECR sources are designed to produce 100 mA proton beams for accelerator injection. The properties of ECR ion sources, the methods used to produce both intense and high-charge-state ion beams of many stable and radioactive species, and the methods and problems associated with optimizing these sources to match with widely varying requirements will be discussed.

1 Introduction

Electron cyclotron resonance (ECR) ion sources are reliable and versatile producers of highly charged as well as intense beams of positive ions of many different species. At present there are roughly 33 ECR ion sources serving research cyclotrons at 22 facilities around the world [1]. These same type sources can also match well with heavy-ion linear accelerators and synchrotrons, while new designs can produce intense beams of singly charged ions suitable either for direct injection into linacs or for conversion into negative ion beams to be injected into tandem accelerators.

The development of ECR ion sources began with the work of Richard Geller, and his text book gives a definitive description of their operating principles [2]. In an ECR ion source, an electrically neutral plasma consisting of ions and electrons is excited by microwaves. A strong magnetic field is produced throughout the volume of the plasma chamber by an arrangement of current-carrying coils, steel and/or permanent magnets, surrounding the chamber. Most of the interaction of the microwaves with the electrons in the plasma is in those regions of the source where the frequency of rotation of the electrons about the magnetic field lines equals the microwave frequency. For a cold electron, a region of ECR occurs when

$$B(\text{Tesla}) = f(\text{GHz}) / 28$$

where B is the magnetic field and f is the microwave frequency. Here B is designated B_{ecr} . This resonance broadens as the electron temperature increases because of both Doppler shifting of the microwave frequency and relativistic-mass gain for the electrons. Both neutrals and ions experience ionizing collisions with the hot electrons. If the containment of the plasma by the magnetic field is sufficient, a given species can experience successive ionizing collisions. By applying a positive bias of several kilovolts to the plasma chamber, ions are extracted along magnetic field lines through an aperture towards a grounded or negatively-biased puller.

ECR ion sources for accelerator injection can

conveniently be separated into two groups: simple low-confinement sources for the production of singly charged ions, and high-confinement sources for the production of multi-charged ions. For the former only an axial magnetic field is supplied, but for the latter a more complex field arrangement is necessary. This is typically a superposition of an axial mirror field, i.e. one with a central minimum, and a multipolar field, usually a hexapole, whose zero coincides with the axis of the source. In this arrangement, known as a minimum-B field geometry, the field increases along any line directed away from the center of the source allowing a roughly ellipsoidal surface inside the source where the field is equal to B_{ecr} . In either a high-confinement or low-confinement source, ions are extracted along the axis. Microwave power is usually injected from the end opposite to extraction, so this is referred to as the injection end of the source. Low-confinement sources will first be discussed while the rest of this report will be concerned with high-confinement ECR ion sources.

2 Low-confinement Sources

There has been recent interest in using low-confinement ECR ion sources for reliable, low-maintenance, high-intensity sources of singly charged ions. In response to this interest much development work was done on small, low-frequency sources at Chalk River Laboratories [3]. In these sources microwave power of 2.45 GHz frequency is injected into a plasma chamber where it creates a low-temperature, high-density plasma. Gas flow is about 2 scc/m ($3\mu\text{g/s}$) for hydrogen. In one mode the axial magnetic field reaches B_{ecr} (875 gauss) near the microwave window inside the plasma chamber, but in another mode the field everywhere is slightly below the ECR field. Since it is unclear if the interaction is entirely through the ECR mechanism, these type sources are sometimes referred to as microwave discharge ion sources. Since the wavelength of 2.45 GHz microwaves is close to the dimensions of the plasma chamber, the wave must be carefully matched with a tapered or stepped waveguide and with a three-stub tuner between the transmitter and the source.

With a 2.5 mm diameter extraction aperture and a 50 kV potential between the source and the puller, Ref. [3] reports 95

mA of hydrogen atoms with a proton fraction in excess of 85%. With 75 kV extraction voltage, a similarly designed source at Los Alamos Laboratories has produced 110 mA of protons [4]. The Los Alamos program and similar programs at other laboratories [5,6,7] aim to inject high currents of protons and deuterons into RFQ and linac combinations producing intense beams at 0.5 to 1.0 GeV for spallation neutron-source applications [8].

These sources also have been shown to produce copious quantities of singly charged, light to heavy ions—9.5 mA He⁺, 6.2 mA O⁺ and 1.8 mA Xe⁺ at 20 kV extraction voltages [9]. By running these beams through a charge-exchange canal, negative ions were produced at the 10 to several hundred μ A level for injection into the tandem accelerator at Chalk River and further accelerated by the superconducting cyclotron [9]. An ion source of this type is being tested for the EXCYT program at Catania for the production of a beam of radioactive negative ions for tandem injection [10]. The attractive features of this type of ECR source for radioactive ion production are its high efficiency and its lack of internal electrodes needing to be periodically replaced.

3 General Features of High-confinement Sources

The requirement of accelerators for highly charged, heavy ions is often met with a high-confinement ECR ion source. To reach the electron temperatures required for the production of highly charged ions, confinement of energetic electrons is necessary. The minimum-B geometry provides this along with being compatible with extraction of the ions along the source axis. As a necessary condition, the magnetic field must be somewhat higher than B_{ecr} near the walls so that microwave energy cannot be absorbed by the plasma too close to any wall material. This will result in an excessive heat load which can melt or evaporate the wall. The plasma chamber is cylindrical to match the symmetry of this field geometry.

The source gas pressure is typically about 10^{-6} torr. Higher gas pressure results in more total extracted current and higher amounts of the lower charge states, and lower gas pressure decreases the neutral background resulting in more high-charge-state production. For better matching to reasonable source dimensions and to increase the plasma density, the microwave frequency is at least 5.0 GHz with 6.4 GHz, 10 GHz, or 14.5 GHz, the standard, available bands for satellite communication transmitters, being common. 18 GHz is available as well and beginning to be used. The 18 GHz ECR ion source at RIKEN will soon be used for accelerator injection [11].

In general, the higher performing sources have used higher frequencies, in line with early prediction and demonstrations [12], but lower-frequency sources have moved into the performance range of high-frequency sources as their magnetic fields have been increased. ECR ion

sources for accelerators range from compact ones that use only permanent magnets to produce their fields to large volume ones that are constructed using superconducting coils exclusively. There is still no wide agreement on the best way to build an ECR ion source, and there is a wide variety to source design and construction. Some of this variety arises from differing requirements of space, electrical power, or available money, and some is due to the desire to try different solutions and in this way contribute to determining the important parameters for ultimate performance. Table 1 lists some newly operating sources and some recently upgraded sources along with their construction parameters.

4 Strategies for Enhancement

The operation of an ECR ion source is not as simple as suggested before by the description of a minimum-B field in a plasma chamber. Needless to say, new strategies for enhancing the output are always being tried, and some have been quite successful. Gas mixing [25], with helium or oxygen admixtures of greater than 50%, has long been used to increase the output of ECR ion sources, particularly high-charge states, and it adds only minor complications to accelerator injection. Also, all of these sources achieve their optimum performance with some sort of "first stage" or electron injection and/or the use of aluminum walls or special wall coatings. In one case, the use of two microwave frequencies has proven effective.

4.1 First Stages and Electron Injection

One of the paths that ECR ion source development has followed is the revision of the concept of a first stage. In the early sources a division of the volume into stages was effective in producing higher charge-state distributions. The second stage from which the ions are extracted is as described above, minimum-B geometry and low gas pressure, while the first stage, also microwave driven, is higher pressure with an open ECR surface cutting through the first-stage volume. The first stage is located on the injection end, on-axis with the second. The plasma, consisting of singly-charged ions and electrons flows into the second stage, but it has been unclear whether the ions or the electrons cause the beneficial effect.

The substitution of an electron gun on the AEER [26], or negatively biased disks in MINIMAFIOS sources at Grenoble [27] and KVI [28] for a first stage and the negative biasing of the first stage in the RIKEN 10 GHz ECRIS [29] demonstrated that electron injection would cause the "first stage" effect. This is understandable since the hot electrons are most likely lost from the plasma along the axis of the source. Replacing these electrons lowers the positive potential of the plasma to the walls thus helping to prevent ion loss. The biased disk is the simplest and the most common strategy to enhance performance. It is placed on-axis just inside the source on the injection end. For the SCEER at NSCL the bias ranges from

Table 1 : Construction parameters of some newly operating or upgraded ECR ion sources.

	freq (GHz)	d X l (cmXcm)	wall-fields inj/extr/rad(T)	hexapole	axial	wall mat.
LNS SERSE [13]	10, 14.5, 18	13 X 52	2.7/1.5/1.4	SC	SC	SS
LBL AECR-U [14]	14.5, 10	7.6 X 28	1.7/1.1/.85	NdBF _e	RT	Al
RIKEN 18 [15]	18	8 X 28	1.4/1.4/1.3	NdBF _e	RT	Al
CAPRICE 1.2T [16]	14.5	6.6 X 16	1.4/1.4/1.2	NdBF _e	RT	Al
GANIL ECR4M	14.5	6.6 X 17	1.25/1.05/1.25	NdBF _e	RT	-
JINR DECRIS-14-2 [18]	14.5	6.4 X 22	1.2/.85/1.1	NdBF _e	RT	-
TAMU HIGH B [19,20]	6.4	13.2 X 59	1.15/.58/.48	NdBF _e	RT	Al
LOUVAIN [21]	6	10.5 X 28	.98/.38/.71	NdBF _e	RT	Al
SUPERNANOGAN [22]	14.5	4.4 X 15	1.1/.9/1.0	NdBF _e	NdBF _e	-
HIRFL ECR2 [23]	10	6.4 X 17	1.0/.8/.75	NdBF _e	RT	Al
KVI ECR3 [24]	14.5	6.8 X 21	1.3/.95/.93	NdBF _e	RT	SS

SC = superconducting, RT = room temperature, NdBF_e = neodymium-boron-iron permanent magnets

-200 V to -1000V [30], for the high B source at Texas A&M the bias can be -30 V to -90 V [31], while for the RIKEN 10 GHz source the bias is about -200 V [32]. The current drawn from the plasma by this bias is typically 1-2 mA. Figure 1 illustrates the increase in high-charge-state output as bias is applied to a small aluminum disk in the Texas A&M High-B source.

4.2 Aluminum Walls

Enhancement of the high-charge-state output by depositing a layer of oxide on the plasma chamber walls had been practiced for some time, and this led to experiments on the AECR with aluminum wall coatings [33]. Aluminum was evaporated into the source with an oven. After cycling the source up to air to oxidize the aluminum, and back to vacuum, the performance for high-charge states improved dramatically. Electron injection with the electron gun became ineffective, indicating that the capacity of the plasma for extra electrons was saturated by the secondaries arising from the walls. The CAPRICE ECR ion source demonstrated a respectable improvement when the stainless steel tube that formed the wall of the plasma chamber was replaced by an aluminum one [16]. As shown in Table 1, aluminum is now being used as a wall material in many sources to capitalize upon this effect.

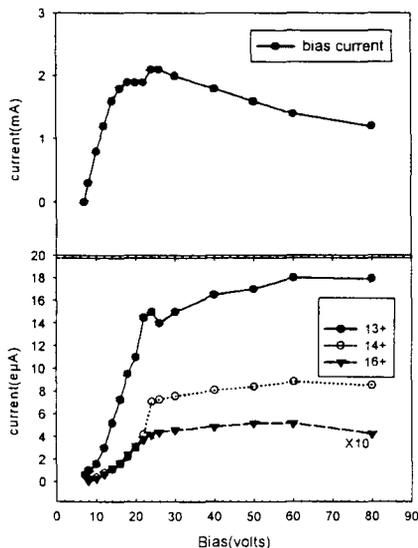
4.3 High Magnetic Fields

Initially minimum-B geometries of ECR ion sources typically had maximum fields only about 30% higher than the fields required for ECR. The field maxima were significantly increased over this with the CAPRICE source to the point where the fields near the walls were over twice B_{ecr} . This required more coil power and a stronger, more difficult to construct hexapole, but the performance improved each time the field was raised [34].

When the mirror fields on the SCECR were raised from the fields that were used on the RTECR, the performance improved dramatically [35]. The source operates at 6.4 GHz, but at that time its performance was exceeding most 14 GHz sources. The hexapole mirror field was about twice B_{ecr} while the axial maxima were over 2.5 B_{ecr} at extraction and 5 B_{ecr} at injection. An upgrade project at Texas A&M, which aimed at duplicating the fields of the SCECR in this mode with the original room-temperature coils of the Texas source, with extra steel, and with a new hexapole constructed of Nd-Fe-B, resulted in the same improvement in performance [19].

4.4 Two Frequencies

The concept of having two microwave inputs of differing frequencies was first successfully implemented on the LBL


 Figure 1. Intensities of argon beams and I_{bias} and V_{bias} .

AECR ion source [36]. The source works well with a 14 GHz transmitter alone, but the charge-state distribution shifts substantially higher when power from a 10 GHz transmitter is added. After tuning the field shape for the best performance, the central minimum is only slightly below 0.35 T, so the 10 GHz ECR surface is located near the center of the source. Figure 2 indicates the improvements in high-charge-state production of the AECR ion source through its various upgrades, in attempts to incorporate several of these strategies into its construction [14,26,33,36].

5 Source Comparisons and Future Sources

As Table I shows, the designs of many ECRIS vary widely. The purposes that they serve makes it difficult to compare one source with another. Many of the substances put into these sources are contaminating, which can have deleterious effects more often than beneficial ones. Other sources may need some optimization to reach their potential, but are in continuous use and thus harder to change. But some general comparisons must be made in order to point out the paths for improvement. The highest performing source at this time is the AECR-U at LBL [14], but recently it has been closely rivaled in performance by the 18 GHz source at RIKEN [37] and by SERSE at Catania [38]. The interesting fact to note is that, despite the many differences between these three ECR ion sources, they all produce about 20 eµA of $^{40}\text{Ar}^{16+}$.

The major direction that ECR ion source development will take in the near future will be towards higher fields and multiple frequencies [39]. The SERSE ECR ion source is intended to be used with multiple frequencies, 10 GHz, 14.5 GHz and 18 GHz [38], and a new source using superconducting coils and steel to obtain even higher fields

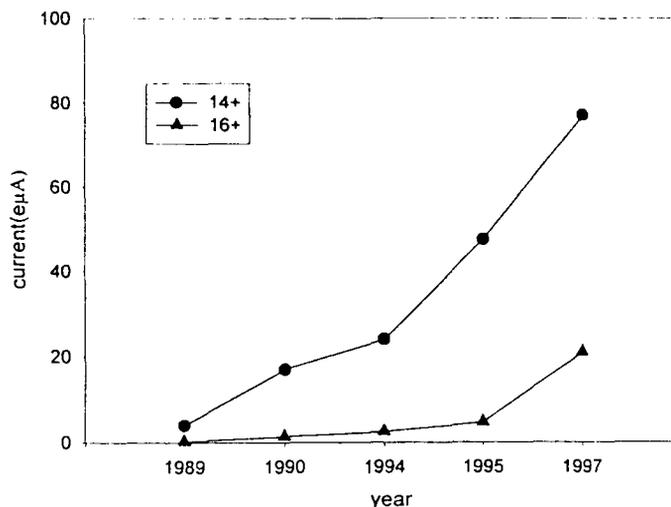


Figure 2. LBL AECR upgrades—argon charge states.

is being developed at LBL [39]. The LBL 3rd Generation Source will have mirror fields of 4 T at injection, 3T at extraction, and 2.4 T radial on the wall. Plans for the construction of a high-field, multiple-frequency ECR ion source at RIKEN are now being formulated, as well [40].

On the other hand, the specialization of high-confinement ECR ion sources for radioactive beam production has been approached from the standpoint that such sources must be radiation resistant or at least cheap and easily replaceable, they must be efficient, and perhaps the tens of milliseconds of confinement time for the very highest charge-states must be sacrificed for the short-lived isotopes (see Ref. [17], for example).

6 Beams from Solids

The disadvantages of feeding rods of material into the ECR surface for evaporation and the inconveniences of large bulky ovens for material evaporation have been overcome in recent years by several new methods for introducing solids into the plasma of an ECR ion source.

6.1 Miniature Ovens

A miniature, low-powered oven, capable of reaching 1100 °C, was developed at Grenoble and used in the CAPRICE ion source [41]. Since then, similar designs have been adapted to many ECR ion sources, including a miniature oven at NSCL capable of reaching 1400 °C [42]. The consumption rate is low, 0.03 mg/hr for a 58 Fe sample used for an experimental run with the cyclotron at NSCL [43], and the sample can be completely evaporated, making this an extremely efficient method for introducing rare isotopes into a source.

6.2 Sputtering

One of the most convenient and cleanest methods for the introduction of solids is the sputtering technique first developed at Argonne [44]. In this method, a sample of metal is introduced radially into the source on a high voltage lead. The sample is positioned just inside the wall of the source, but not close to the ECR surface, and biased negatively with respect to the plasma chamber. A light support gas, usually oxygen or helium, is used to produce a plasma, and ions from the plasma are drawn to the sample. The bias needed ranges from a few hundred volts to a few thousand volts depending on the material of the sample. Beams of Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Nb, Mo, Pd, Ag, Cd, Ta, Au, and U have been reported with this method [21,31,43] and several more should be possible. At Louvain-la-Neuve, radioactive ^{18}F was adsorbed into a copper substrate and sputtered into a source with the copper to produce ^{18}F ion beams [21].

A disadvantage to the sputtering technique is that the erosion of the material is uneven, so for small samples it is inefficient. This is a drawback when using rare isotopes. An advantage to the technique is that several sputter targets can be mounted on separate high-voltage leads, inserted into the ion source together, and run separately simply by applying voltage to the sputter target of choice [31].

6.3 MIVOC

The so-called MIVOC method has been developed at the University of Jyväskylä where vapors of liquid compounds of metals are introduced into an ECR ion source [45]. With metallocene compounds, beams of Mg, Cr, Fe, Ni, Ru, and Os can be produced, while with hexacarbonyls, beams of Cr, Co, Mo, and W can be produced. This technique is suitable for producing intense, stable beams of mid-charge-state ions, but the carbon from these compounds contaminates the source for high-charge-state production, so the source is lined with a removable aluminum foil. Most of the metallocenes used are classified as harmful but easily handled, though magnesocene is spontaneously flammable in air. The hexacarbonyls are toxic.

6.4 SF_6 Plasma

A method of eroding a metal target with a ion source plasma initiated with SF_6 gas has been developed at the Japan Atomic Energy Research Institute [46]. An annulus of sample material is placed on the extraction electrode surrounding the extraction aperture. The erosion is caused by a chemical reaction between the fluorine and the metal, and SF_6 , being chemically stable, was found to be more satisfactory than other fluorine compounds. Using the refractory metals, beams of Nb, Mo, Ta, and W could be produced and using boron nitride beams of boron could be

produced.

7 Emittance and Injection into Cyclotrons and Linacs

From considering the deflection of parts of a beam by off-axis components of a magnetic field, the maximum divergence of a beam extracted from an axially symmetric, magnetic field is predicted to be

$$x' = \frac{1}{2} qBr/p$$

where r is the radius of the extraction aperture, (typically 6-8 mm), q is the charge of the ions, B is the magnetic field at the extraction aperture, and p is the momentum gain of the extracted ions. However, for high-charge states, it has been observed that the emittance of individual beams decreases with charge [47, 48], as if the higher charge states were originating from an area less of radius less than r . In a recent measurement at Argonne National Laboratories, emittances of beams from the new ANL ECR ion source, which is a copy of the LBL AECR-U, were only 10%-20% of the emittances expected of beam extracted from a 1.0 T field, and the emittances decreased with charge-state [49].

It has also been observed that space charge plays a significant role in the transport of the high-charge-state beams from an ECR ion source. In Ref. [50] it was demonstrated that there is little or no space-charge compensation for the initial extracted beam, and thus it is imperative that the beam be strongly focused magnetically in as short a distance as possible after extraction. In this way, the different charge states are separated, and blow-up due to space-charge is kept to a minimum.

The intensity of the extracted beam can scale as $V^{3/2}$ where V is the voltage between the puller and the extraction aperture, and since the absolute emittance of the beam scales with $V^{-1/2}$, it is desirable to extract at high voltages. Typical voltages are 10-15 kV, although matching to cyclotrons sometimes requires a wider range. Voltages up to 40 kV are required by the KVI superconducting cyclotron AGOR, and the KVI ECR3 has been insulated to hold this between source and puller [24]. The matching to the K500 cyclotron at NSCL has been changed so that voltages up to 30 kV are required, to take advantage of the scaling with voltage, and the SCECR has been insulated accordingly [51]. At Argonne National Laboratory, the two ECR ion sources are mounted on separate high-voltage platforms, the AECR-U on a 275 kV platform, for preacceleration of heavy ion beams before injection into the ATLAS superconducting linac [49].

8 Afterglow or Pulsed Mode and Injection into Synchrotrons

The pulsed modes of ECR ion sources were first studied at Grenoble [12] where it was suggested that their performance

could be optimized for synchrotron injection in this manner. When the microwave input power is switched off, the current extracted from the source persists for a few milliseconds after the cut-off. The total extracted current does not change immediately, but the charge-state distribution does. The source can be tuned so that high charge-states that are extracted during this afterglow period are multiplied by large factors. Experiments on this afterglow pulse have since been performed at GANIL [48], GSI [52] and CERN [53]. A CAPRICE ECR ion source is now used along with the PIG injected, low-energy Wideroe section at GSI for injection into the synchrotron [54], and an ECR4 source from GANIL is used at CERN for acceleration of lead ions by the Super Proton Synchrotron [55].

9 Conclusions

High-confinement ECR ion sources are now critical to the best performance of heavy ion cyclotrons, and they are important to other accelerators as well. They continue to improve. Recent landmarks could be cited as the production of 1.0 emA of $^{16}\text{O}^{6+}$ by ECR4M at GANIL [17], a few pps of $^{238}\text{U}^{60+}$ accelerated through the LBL 88" cyclotron using AEER-U [14], and 2.9×10^8 $^{208}\text{Pb}^{82+}$ ions in four pulses accelerated to 157 GEV/u by the CERN SPS from an initial pulsed beam of $^{208}\text{Pb}^{27+}$ produced by an ECR4 [55]. Low-confinement ECR ions will develop productive alliances with accelerators as well, and both types will improve to meet even higher demands of present accelerators and of future colliders and drivers.

References

- [1] Cyclotron data table from the *Proceedings of the 14th International Conference on Cyclotrons and Their Applications*, Cape Town, South Africa (1995).
- [2] R. Geller, *Electron Cyclotron Resonance Ion Sources and ECR Plasmas*, IOP Publishing (1996).
- [3] T. Taylor and J. Mouris, *Nucl. Instrum. Meth.* **A336**, 1 (1993).
- [4] J. Sherman *et al.*, *Rev. Sci. Instrum.* **69**, 1003 (1998).
- [5] R. Gobin *et al.*, *Rev. Sci. Instrum.* **69**, 1009 (1998).
- [6] S. Kosta, S.K. Jain, and P.R. Hannurkar, *Proceedings of the 13th International Workshop on ECR Ion Sources*, College Station, Texas, 111 (1997).
- [7] Y.S. Hwang *et al.*, *Rev. Sci. Instrum.* **69**, 1015 (1998).
- [8] J. Sherman *et al.*, *Rev. Sci. Instrum.* **67**, 1296 (1996).
- [9] J.S.C. Wills *et al.*, *Rev. Sci. Instrum.* **67**, 1227 (1996).
- [10] S. Gammino *et al.*, *Rev. Sci. Instrum.* **69**, 747 (1998).
- [11] T. Nakagawa, these proceedings.
- [12] F. Bourg *et al.*, *Workshop on the Sixth International ECR Ion Source*, Berkeley, Calif., 1 (1985).
- [13] G. Ciavola *et al.*, *Proceedings of the 12th International Workshop on ECR Ion Sources*, Tokyo, INS-J-182, 131 (1995).
- [14] Z.-Q. Xie and C.M. Lyneis, *Proceedings of the 13th International Workshop on ECR Ion Sources*, College Station, Texas, 16 (1997).
- [15] T. Nakagawa *et al.*, *Proceedings of the 13th International Workshop on ECR Ion Sources*, College Station, Texas, 10 (1997).
- [16] D. Hitz *et al.*, *Proceedings of the 12th International Workshop on ECR Ion Sources*, Tokyo, INS-J-182, 126 (1995).
- [17] R. Leroy *et al.*, *Proceedings of the 12th International Workshop on ECR Ion Sources*, Tokyo, INS-J-182, 57 (1995).
- [18] A. Efremov *et al.*, *Rev. Sci. Instrum.* **69**, 662 (1998).
- [19] D.P. May *et al.*, *Proceedings of the 13th International Workshop on ECR Ion Sources*, College Station, Texas, 43 (1997).
- [20] D.P. May, *Rev. Sci. Instrum.* **69**, 688 (1998).
- [21] C. Barue, *et al.*, *Proceedings of the 13th International Workshop on ECR Ion Sources*, College Station, Texas, 38 (1997).
- [22] P. Sortais *et al.*, *Rev. Sci. Instrum.* **69**, 656 (1998).
- [23] H.W. Zhao *et al.*, *Proceedings of the 13th International Workshop on ECR Ion Sources*, College Station, Texas, 34 (1997).
- [24] A.G. Drentje, H.R. Kremers, and J. Sijbring, *Proceedings of the 12th International Workshop on ECR Ion Sources*, Tokyo, INS-J-182, 148 (1995).
- [25] A.G. Drentje, *Proceedings of the 11th International Workshop on ECR Ion Sources*, Groningen, KVI-Report 996, 155 (1993).

- [26] Z.-Q. Xie *et al.*, *Rev. Sci. Instrum.* **62**, 775 (1991). (1993).
- [27] G. Melin *et al.*, *Proceedings of the 10th International Workshop on ECR Ion Sources*, Knoxville, Tenn., ORNL Report CONF-9011136, 1 (1990).
- [28] S. Gammino, J. Sijbring, and A.G. Drentje, *Rev. Sci. Instrum.* **63**, 2872 (1992).
- [29] G. Ciavola *et al.*, *Proceedings of the 12th International Workshop on ECR Ion Sources*, Tokyo, INS-J-182, 156 (1995).
- [30] T. Nakagawa *et al.*, *Proceedings of the 13th International Conference on Cyclotrons and their Applications*, Vancouver, 365 (1992).
- [31] D.P. May, *Rev. Sci. Instrum.* **69**, 688 (1998).
- [32] T. Nakagawa *et al.*, *Proceedings of the 13th International Conference on Cyclotrons and their Applications*, Vancouver, B.C., 365 (1992).
- [33] Z.-Q. Xie and C.M. Lyneis, *Rev. Sci. Instrum.* **65**, 2947 (1994).
- [34] D. Hitz, *Proceedings of the 12th International Workshop on ECR Ion Sources*, Tokyo, INS-J-182, 161 (1995).
- [35] T. Antaya and S. Gammino, "The SCECR 6.4 GHz High B Mode and Frequency Scaling in ECR Ion Sources", NSCL Report No. MSUCP-71 (1993).
- [36] Z.-Q. Xie and C.M. Lyneis, *Rev. Sci. Instrum.* **66**, 4218 (1995).
- [37] T. Nakagawa, these proceedings.
- [38] S. Gammino, these proceedings.
- [39] C.M. Lyneis, Z.Q. Xie, and C.E. Taylor, *Rev. Sci. Instrum.* **69**, 682 (1998).
- [40] T. Nakagawa, private communication.
- [41] D.Hitz, G. Melin, M. Pontonnier, T.K. Nguyen, *Proceedings of the 11th International Workshop on ECR Ion Sources*, Groningen, KVI Report 996, 91 (1993).
- [42] R. Harkewicz, *Rev. Sci. Instrum.*, **67**, 2176 (1996).
- [43] R. Harkewicz and D. Cole, *Proceedings of the 13th International Workshop on ECR Ion Sources*, College Station, Texas, 92 (1997).
- [44] R. Harkewicz *et al.*, "Ion Plasma Sputtering as a Method for Introducing Solid Materials into an ECR Ion Source," ANL Report No. PHY-7894-HI-94.
- [45] H. Koivisto, J. Arje, and M. Nurmi, *Rev. Sci. Instrum.* **69**, 785 (1998).
- [46] Y. Saitoh, K. Ohkoshi, and W. Yokata, *Rev. Sci. Instrum.* **69**, 703 (1998).
- [47] K.A. Harrison and T.A. Antaya, *Rev. Sci. Instrum.* **65**, 1138 (1994).
- [48] P. Sortais *et al.*, *Proceedings of the 10th International Workshop on ECR Ion Sources*, Knoxville, Tenn., ORNL Report No. CONF-9011136, 35 (1990).
- [49] M. Schlapp *et al.*, *Rev. Sci. Instrum.* **69**, 631 (1998).
- [50] Z.-Q. Xie and T.A. Antaya, *Rev. Sci. Instrum.* **61**, 793 (1990).
- [51] "K500xK1200, a Coupled Cyclotron Facility at the National Superconducting Cyclotron Laboratory," NSCL Report No. MSUCL-939 (1994).
- [52] H. Schulte *et al.*, *Proceedings of the 11th International Workshop on ECR Ion Sources*, Groningen, KVI-Report 996, 120 (1995).
- [53] K. Langbein, *Proceedings of the 12th International Workshop on ECR Ion Sources*, Tokyo, INS-J-182, 198 (1995).
- [54] K. Tinschert *et al.*, *Rev. Sci. Instrum.* **69**, 709 (1998).
- [55] M.P. Bourgarel *et al.*, *Proceedings of the 12th International Workshop on ECR Ion Sources*, Tokyo, INS-J-182, 193 (1995).