**AN ADVANCED ECR ION SOURCE WITH A LARGE UNIFORMLY DISTRIBUTED
ECR PLASMA VOLUME FOR MULTIPLY CHARGED ION BEAM GENERATION**

G. D. Alton

Oak Ridge National Laboratory,* P. O. Box 2008, Oak Ridge, Tennessee 37831-6368

and

D. N. Smithe

Mission Research Corporation, 8560 Cinderbed Road, Suite 700, Newington, Virginia

22122

RECEIVED

SEP 23 1994

OSTI

ABSTRACT

A new ECR ion source geometry has been conceived which uses a minimum-B magnetic mirror geometry consisting of a multi-cusp, magnetic field, to assist in confining the plasma radially, a flat central field for tuning to the ECR resonant condition, and specially tailored mirror fields in the end zones for confining the plasma in the axial direction. The magnetic field, designed to achieve an axially symmetric plasma "volume" with constant mod-B, extends over the length of the central field region. This design, which strongly contrasts with "surface" ECR zones characteristic of conventional ECR ion sources, results in dramatic increases in the adsorption of RF power, thereby increasing the electron temperature and "hot" electron population within the ionization volume of the source. The ECR zone is concentrated symmetrically around the axis of symmetry and along the length of the plasma volume rather than in thin surface layers

*Managed by Martin Marietta Energy Systems, Inc., under contract No. DE-AC05-84OR21400 with the U.S. Department of Energy.

The submitted manuscript has been authored by a contractor of the U.S. Government under contract No. DE-AC05-84OR21400. Accordingly, the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for U.S. Government purposes.

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, make any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

located off-axis as is the case in conventional ECR ion sources. The creation of a "volume" rather than a "surface" ECR zone and its distribution relative to the optical axis where the ions of interest are extracted is commensurate with the generation of higher beam intensities, higher charge states and a higher degree of ionization. The new ECR ion source concept has been computationally designed through the use of magnet design codes, plasma-dispersion sources, and particle-in-cell (PIC) codes. A summary of the design attributes of the source is given in this report.

1. Introduction

Ion sources based on the Electron Cyclotron Resonance (ECR) principle have played major roles in the advancement of our knowledge of atomic and nuclear physics and in many areas of applied science since their inception.^{1,2} Since the final energy on an ion beam is directly proportional to the charge on the ion during acceleration, a premium is placed on ion sources which are capable of generating very high charge state ion beams for use at accelerator-based research facilities. Heavy-ion cyclotrons, linear accelerators, synchrotrons, and new generation heavy ion colliders now under construction, such as the relativistic heavy-ion collider (RHIC) at the Brookhaven National Laboratory and the large hadron collider (LHC) which has been proposed for construction at CERN, would benefit immensely from the advent of advanced ECR ion sources with charge states and intensities superior to sources presently available; the source described in this article offers this distinct possibility with many applications in atomic and applied physics research, as well. Although the source described in this proposal is specifically designed for multiply charged ion beam generation, the principles employed in the new ECR ion source are also equally suitable for low-charge-state applications.

In the ECR ion source concept described in this report, the ECR zone is large and uniformly distributed along and about the axis of symmetry of the source, thus enabling the heating of electrons over a much larger volume than is possible in conventional ECR ion sources. The magnetic field design permits independent control of the ECR "tune" magnetic field and the radial and axial magnetic fields used to confine the plasma; this configuration differs from designs used in conventional sources where these fields are coupled. The separation of the "tune" and confinement magnetic fields enables the use of low-frequency, ECR power sources; the location and increased physical size of the ECR zone over those in conventional sources is commensurate with the generation of higher beam intensities, higher charge states, and a higher degree of ionization within the ionization volume of the source. Figure 1 schematically illustrates the locations and relative sizes of the ECR zones in a conventional "surface" ECR ion source and in the "volume" ECR ion source. For more details of the design attributes of the new source concept, the reader is referred to the initial publication.³ For detailed descriptions of sources which reflect the present state of conventional ECR ion source technology, reference is made to the proceedings of recent workshops on this source type (see, e.g., Refs. 4-6) and the ECRIS status report published in these proceedings.⁷

2. ECR plasma heating

The energy source for plasma generation and maintenance in the ECR ion source is electron cyclotron resonance (ECR) heating of the plasma electrons. The energy (electron temperature), energy distribution (temperature distribution), and electron number density and ion lifetime τ_i in the plasma, are fundamental properties which govern the performance of the ion source in terms of degree of ionization and multiple ionization capabilities of the source. The typical multiply-charged ECR ion source consists of two stages, which serve as independent cavities for plasma generation. The

second-stage is an oversized multi-mode wave guide which serves as the primary plasma generation and confinement cavity. Magnetic mirror coils are situated at the inlet and ion-extraction ends of the multi-mode wave guide to confine the plasma in the axial direction. Multicusp, magnetic fields are usually used to assist in containing the plasma in the radial direction. A high-frequency cavity is positioned on the inlet side of the source and high-frequency power of several gigahertz is used to produce a plasma from the gaseous feed material that is metered into the source. A plasma generated in the first stage flows into the second stage, which is the primary plasma region, where multiply-charged ions are created. The operating pressure in the first stage of the source is $>10^{-5}$ Torr. After generation, the plasma drifts down the axial magnetic field gradient into the second-stage wave guide region of the source pressure $\leq 10^{-6}$ Torr until the electrons traverse a plane in the wave guide where they may be resonantly excited by the high-frequency electromagnetic field provided that a component of the $\vec{E}$ field lies perpendicular to the magnetic field direction.

In conventional ECR ion sources, the ECR zones are fluted, ellipsoidal-shaped "surfaces" rather than "volumes" due to the superposition of the radially varying multipoles and the continually varying solenoidal field, which usually has a parabolic axial profile in the plasma region between the mirror coils; the ECR surface surrounds the axis of symmetry of the source as illustrated in Fig. 1. The physical region or surface over which the ECR condition is met is referred to as the ECR zone. As noted in Fig. 1, the points of intersection of the ECR surface with the optic axis occur in conventional ECR ion sources in the mirror regions near the end of the cylindrical plasma column. Electrons passing through the ECR surface, which are coincidentally in phase with the electric field, are accelerated by the transfer of electromagnetic energy perpendicular to the direction of the magnetic field; electrons arriving out of phase with the electric field undergo deceleration. On subsequent passes through the ECR zone,

the electrons gain a net energy and are said to be stochastically heated. Thus, the physical size of the ECR zone in relationship to the total ionization volume of the source is important because only free electrons which find themselves within the ECR zone can be accelerated. Since the "hot" electrons can only be excited in the surface which lies, in general, above the axis of symmetry, multiply charged ions must be, primarily, created off axis. The ions, therefore, must find their way to the ion extraction aperture, located on the axis of symmetry, through diffusion, scattering, and along field lines which intersect the optical axis. Ions arriving at the outlet end of the source diffuse through an aperture into the extraction field region of the source, where they are extracted by acceleration through a few kV potential difference.

Long electron containment times τ_e are fundamentally important for the production of high-charge-state ions; this is generally achieved by increasing the magnetic fields which serve to confine the "hot electrons." Ion-ion collision recombination processes tend to lower the charge state distribution at higher operating pressures and, therefore, low pressures ($\leq 10^{-6}$ Torr) are used in the second or primary stage of the source. At high pressures, the electron temperatures are lowered, as well [8]. Ions diffuse along the axial field gradient and flow from stage to stage until they are extracted. Ionization occurs principally by single electron removal with contributions from multiple electron removal and inner shell vacancy creation, which may result in Auger electron ejection. Single electron loss processes are believed to dominate so that multiple collisions are necessary to produce highly charged ions. Thus, it is necessary to make the product $n_e \tau_i$ as large as possible where n_e is the electron density and τ_i is the containment time of the ions. The containment time for ions τ_i is related to the efficiency of the axial and radial magnetic fields for confining the electrons in the plasma.

The most efficient and effective means for heating the plasma is by injecting right-hand circularly polarized (RHCP) waves along the direction of the magnetic field of angular frequency ω_{rf} . The electric field vector for the RHCP wave rotates clockwise in time as viewed along the direction of $\vec{B}$ and has a resonance at the electron cyclotron frequency ω_c or

$$\omega_{rf} = \omega_c = Be/m_e. \quad (1)$$

In Eq. 1, m_e and e , respectively, are the mass and charge of the electron and B the magnetic field strength at the resonant condition. The direction of rotation of the plane of polarization for the RHCP wave is the same as the direction of gyration of the electrons. The electromagnetic wave loses its energy by continuously accelerating electrons and is, therefore, attenuated. The LHCP waves do not have a resonance with the electrons because they rotate in the opposite sense to the direction of electron gyration. For details of the propagation of various types of RF waves in plasma media, see, e.g., Ref. 9.

Power can be coupled into the plasma until the plasma density n_e reaches the critical value n_c , at which time the plasma ω_p , excitation ω_{rf} , and electron cyclotron frequencies ω_c are equal, i.e., $\omega_{rf} = \omega_p = \omega_c$ where $\omega_c = Be/m_e$.

The plasma frequency ω_p is related to the critical plasma density n_c through the following expression:

$$\omega_p = \left(\frac{n_c e^2}{\epsilon_0 m_e} \right)^{1/2} \quad (2)$$

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

thus, $n_c \propto \omega_p^2$.

In Eq. 2, ϵ_0 is the permittivity of free space.

According to Eq. 2, the maximum plasma density that can be achieved with a particular ω_{rf} under ECR conditions is limited by the plasma frequency ω_p at the critical density n_c which, in turn, is related to the magnetic field strength B through ω_c . For this case, the critical density n_c scales as ω_{rf}^2 and, consequently, B^2 ; therefore, to increase the critical density requires increases in both the microwave frequency and magnetic field strength.

3. Perceived limitations of traditional ECR ion source designs

Considerable progress has been made in ECR ion source technology in recent years, as evidenced in Refs. 4-7; however, the source has not reached its full potential, particularly for multiply charged ion generation, due, in part, to traditional magnetic-field geometries used to confine the plasma. Improvements in performance, in terms of high-charge-state yields and intensities, can, no doubt, be realized by optimizing the magnetic field configurations which confine the plasma effectively, and by increasing the physical sizes of the ECR or "hot" zones in relation to the total size of the ionization volume.

The energy source for ionization is ECR microwave energy, transferred to electrons through resonant absorption processes. In typical ECR ion sources, this absorption occurs along a thin ellipsoidal surface located above the axis of symmetry of the source (see Fig. 1, e.g.). Because of the thinness of the ECR resonant surface, the actual microwave absorbing volume of the ECR plasma is quite small in comparison to the total volume of the ion source plasma. In addition, most of this surface surrounds the

axis of symmetry of the source, such that diffusive processes are required for energetic electrons to reach the optical axis, where the ions are extracted. During such diffusive processes, electron energy is degraded through collisions and ionizations with neutrals and ions at large radii.

In conventional sources, the ECR zones are usually thin annular, ellipsoidal-shaped surfaces which surround the optical axis of the source; the microwave power can only be coupled to the plasma in these zones, which occupy a small percentage of the plasma volume; therefore, the absorptivity of the plasma is governed by the size of the region of ECR plasma. Furthermore, if the ECR zones are small in relation to the total volume, the probability for further coherent acceleration of electrons is substantially reduced because of the low probability of the initially accelerated electrons which leave the ECR zone returning to the zone in phase with the electrostatic field for further acceleration. Electrons can only gain energy in these surfaces and cannot be further heated in the nonresonant or "unheated" zones of the source; they lose their energy or thermalize during collisions with the electrons, atoms, and ions within the resonant and nonresonant plasma volume. The lack of ability to heat electrons in the bulk of the plasma creates an "unheated" zone where the average charge state and degree of ionization are lower. High-charge-state particles ionized in the interior of the source must necessarily pass through extended regions of "unheated" plasma before extraction. Wall recombination, resonant, and to a lesser extent, nonresonant charge-exchange collisions between ions and neutral atoms, reduce the degree of ionization and high-charge-state population of the source.

ECR sources are claimed to perform better in terms of charge state distribution whenever the excitation frequency is increased.¹⁰ Higher frequency power supplies require higher magnetic fields to maintain the same position of the ECR zone relative to

the optic axis of the source. Therefore, the improved performance is most likely attributable to the increased confinement times for electrons τ_e and ions τ_i which result whenever the B "mirror" fields and multicusp fields used to confine the plasma in the respective axial and radial directions are increased rather than associated with any fundamental attribute of the excitation frequency. Thus, the microwave radiation only serves to accelerate the electrons, which, in turn, ionize atoms or molecules in the plasma through collisional processes. However, the choice of higher frequency power sources permits generation of higher critical densities (see, e.g., Eq. 2) and effectively increases the Doppler width of the ECR resonance³ (see also Section 5.1) which, in turn, increases the physical size of the ECR zone in conventional ECR sources.

4. Design studies for the ECR "volume" ion source

4.1 Computer codes

The primary computer codes employed in these studies were the POISSON group of codes [11] used to model the static magnetic fields, and the two-dimensional particle-in-cell (PIC) code [12], used to model the ion source plasma, including the ambipolar electric fields and microwave interactions with the plasma electrons under ECR conditions. The PIC code used in the simulation studies is a two-dimensional, finite-difference, time-domain code for simulating plasma physics processes which involve interactions between charged particles under the influence of electromagnetic fields. The code solves, in a self-consistent way, the time-dependent forms of Maxwell's equations to obtain the electromagnetic fields; the complete Lorentz force equations are then solved to determine relativistic particle trajectories through these fields which are used to provide charged-particle and current-density distribution parameters for use as input for Maxwell's equations. Although the code is two-dimensional, it can simulate

three-dimensional geometries by taking advantage of any coordinate invariance in the problem, or, in some cases, approximating three-dimensional electromagnetic fields by two-dimensional analytical expressions. Numerous modeling runs were performed for several magnetic field geometries to determine a single prototype design. The physical dimensions of the ECR source were 20 cm in length and 6 cm in diameter. A wide range of plasma densities were initially considered; however, because of the ease of simulation, a low-density plasma with a baseline density near $n_e = 5 \times 10^{10}/\text{cm}^3$ was used for all simulations. The strength of the resonant magnetic field determines the maximum density of plasma which can be excited under normal ECR conditions by a given RF power source (see e.g., Eq. 2). The baseline magnetic field used during the simulation for the "tune" solenoidal field was near $B_0 = 0.3 \text{ T}$.

4.2 Baseline parameters

The vacuum cutoff frequency for the baseline cavity dimensions in the radial direction was 3 GHz (TE₁₁₁ mode). The corresponding plasma frequency for the baseline density is $f_p = \omega_p/2\pi = 2 \text{ GHz}$. The ECR frequency is around $f_c = eB_0/2\pi m_e = 8 \text{ GHz}$. Because f_c is greater than either the cutoff frequency or the plasma frequency f_p , both of these conditions are favorable for coupling of the microwave power to the plasma at the ECR condition. In general, it is necessary for f_c to be greater than the plasma frequency f_p because this condition guarantees that the microwave power will not be reflected as it enters the plasma and because the plasma will absorb the microwave power at f_c . In actuality, the absorption of waves by the plasma is dependent on the angle of propagation of the microwaves within the plasma (see e.g., discussions held in Refs. 9 and 13).

5. The magnetic field design

The magnetic field plasma confinement geometry considered in this study is that of a cylindrical multicusp radial magnetic field with tailored mirror magnetic fields in the end zones of the source. The magnetic field geometry consists of abrupt highly tailored mirror fields designed to produce a region of uniform (flat) magnetic field between the mirror regions, rather than the usual parabolic field configuration used in traditional ion sources. The multicusp magnetic field is used to provide the inward curvature necessary for plasma stability in the radial direction; by increasing the number of cusps, the uniform magnetic field volume in the regions between the coils can be increased.

The ideal magnetic field for confining the plasma can be expressed in terms of the appropriate forms of Maxwell's equations for a constant solenoidal magnetic field B_z along the z direction surrounded by multicusp magnetic field in the r direction with N cusps of order m and radial and azimuthal coordinates r and ϕ , respectively. The appropriate set of Maxwell's equations for the interior (central) magnetic field configuration is

$$\begin{aligned}\nabla \cdot \vec{B} &= 0, \quad \nabla \times \vec{B} = 0, \\ B_z &\equiv m_e \omega_c / e, \\ B_r &= B_a \left(\frac{r}{r_a} \right)^m \cos(m+1)\phi, \\ B_\phi &= -B_a \left(\frac{r}{r_a} \right)^m \sin(m+1)\phi,\end{aligned}\tag{3}$$

where $m \equiv \frac{1}{2}N - 1$, $B_z = \text{constant}$, B_a is the magnetic field at $r = r_a$ and r_a is the radial coordinate from the axis of symmetry to the cusp field pole tip. The radial and axial

distributions used in these simulations are shown in Fig. 2. An r^6 field variation was used in the azimuthal magnetic field to model an $N = 14$ cusp field.

5.1 The radial multicusp magnetic field

For magnetic-hydro-dynamic (MHD) stability to interchange modes, it is necessary that any cylindrical mirror device possess field components in the plane perpendicular to the axis of the device such that the field lines must curve inward toward the plasma. The simplest field is a traditional cusp, and can be produced with either four current carrying wires aligned parallel to the axis of the device or with four rows of permanent magnets. However, this configuration has an "on-axis" but limited uniform magnetic field in the radial direction because of the rapid variation of field strength as one moves radially outward from the center of the device and the consequent reduction in plasma volume which can be tuned to the ECR condition. In general, if N is the number of wires or rows of permanent magnets (i.e., the number of cusps), then the radial distribution is proportional to the magnetic field strength $r^{N/2-1}$ (Eq. 3) where r is the radial distance from the center of the device to the pole tip of the cusp. Figure 3 displays the fractional volume of the plasma F_v which contains a uniform field to within a specified tolerance σ versus the number of cusps or coils N as determined from the $r^{N/2-1}$ behavior, $F_v = \sigma^{4/N-2}$. A rough estimate of the tolerance of the field may be taken as the Doppler width of the resonance, which is basically

$$\sigma = \frac{\delta B}{B} \approx k_{||} \rho_e, \quad (4)$$

where $k_{||}$ is a typical wave number of the RF power, and ρ_e is the electron gyroradius. Since the Doppler width of the resonance increases with the frequency of the power source, then the width of the ECR zone increases correspondingly. This phenomenon

may partially explain why conventional ECR sources appear to perform better when the RF frequency is increased. For electrons at 10 eV in a 0.1-Tesla field and an ECR wave length near 5 cm, the tolerance is near $\sigma \approx 1\%$. From Fig. 3, it can be seen that for tolerances near 1%, the increase in resonant volume is fairly linear from 4 to 16 cusps, but beyond 16 cusps, the increase in volume with number of cusps begins to decrease (actually, the inflection point for 1% tolerance is nearer 12 cusps). Therefore, there is little gain in terms of increase in the central volume field beyond 16 cusps.

Illustration of the electron orbit projections in the central field region of the plasma chamber for $N = 6$ and $N = 12$ cusps are shown, respectively, in Figs. 4 and 5, as determined from PIC simulations with a uniform axial field and a multicusp radial field derived from finite thickness wires. The PIC simulations were run for times long enough for electrons to transverse ~20 cm in the z direction. The electrons were assumed to have energies of 1000 eV in order to see their gyro-orbits. The results of these simulations clearly show that the number of electrons confined to orbits in the uniform field region of the source increases with an increase in the number of cusps N .

5.2 The axial magnetic field

The primary difficulty with the mirror fields used to confine electrons in the axial direction in conventional ECR ion sources is that the field varies between the mirror regions of the source parabolically with position in the z direction. In order to create a long, "on-axis", ECR zone, a much flatter axial profile is needed which can be produced by either an electromagnetic solenoid or annular permanent magnets equipped with mirror coils in the end zones. Although other methods were evaluated for effecting a flat central field between abrupt "mirror" fields in the end zones of the source, the method of using a combination of mirror, trim coils, and ferromagnetic shunts was found to be more

practical; this arrangement yielded flatter fields near the mirror regions of the plasma volume. The trim coil is driven in an opposite direction to that of the main and mirror coils; to maintain the same effective mirror ratio, the current in each mirror coil must be increased by an amount equivalent to the current in the trim coil. The field from the trim coil tends to cancel the mirror coil field toward the center of the device. If the current in the trim coil is adjusted properly, the result is a very flat uniform field inside of the trim and mirror coils. Figure 6 illustrates the coil design. The trim coils are located on either end just inside the mirror coils. Figure 7 contrasts the axial magnetic field distributions for the ECR3/CAPRICE^{14,15} and NEOMAFIOS¹⁶ ion sources with that of the new ECR ion source concept.

6. Simulation studies of ECR plasma heating

The plasma ions were assumed to be infinitely massive, a good approximation for the time scales used in the simulations. The plasma was allowed to equilibrate, and then the microwave power source was introduced into the cavity via a coaxial wave guide penetrating through one end of the plasma chamber. Two heating scenarios were simulated: 1) source heating in a conventional ECR, and 2) plasma heating in the new ECR concept.

The simulations were initially populated with cold electrons (1 eV thermal distribution) of density $n_e = 5 \times 10^{10} \text{ cm}^{-3}$ and hot electrons (100 eV thermal distribution) of density $n_e = 5 \times 10^8 \text{ cm}^{-3}$. The hot electrons were added because they provide information on the partition of ECR absorption between hot and cold electrons. The unconfined hot electrons leave the plasma volume and help set up the ambipolar field. The hot electrons also have large gyro-radii, making it easier to observe their behavior in the output. Figure 8 displays typical hot electron orbits in the device for a time period

corresponding to roughly one full cycle from end-cell to end-cell. Note that some electrons are not well confined, and strike the device wall on their first cycle. Most orbits, however, show the classical trajectory reversal in the mirror fields, including the decreasing gyro-radius and decreasing orbit pitch as the mirror bounce-point is approached.

The effect of increasing the field multiplicity on the physical size of their respective ECR zones for $N = 6$ and $N = 22$ multipole fields is illustrated in Fig. 9, which displays, respectively, magnetic field versus radial position (lower portion), and the velocity of the electrons as a function of radial position (upper portion). The transition from heated to nonheated regions of the plasma at the ECR condition is very apparent. The lower order multipole field ($N = 6$, hexapole) results in a smaller volume of hot electrons which extends over the length of the ionization volume in the source concept described in this paper.

Comparisons of electron heating of the "hot" electron population in the conventional and new ECR ion source designs are compared in Fig. 10. The RF frequency for these cases was set at ~ 10 GHz. The microwave power is turned on after $t=45$ ns, to allow the unconfined electrons to leave the plasma. The duration of the simulation extended 45 ns past the start time of the microwave power or roughly 400 rf periods. This time duration is somewhat longer than the typical end-cell-to-end-cell transit time of fast electrons. The initial rapid decrease in the fast electron population is due to electrons in unconfined orbits leaving the plasma. These electrons establish the ambipolar electric field which further slows electron loss. The relative increase in heating for the indicated time period is ~ 7 times higher for the new ECR ion source design than for the conventional ECR ion source.

One fundamental feature of heating the central plasma rather than the mirror region is that the ECR tends to deliver more energy to the perpendicular components of velocity than in the former case, rather than uniformly mixed between perpendicular and parallel components. The magnetic field scenario used in the central region to create a large, uniformly distributed ECR zone is ideally suited for the use of RHCP microwave radiation. The scale of the radial velocity is markedly larger, indicating better acceleration in the perpendicular than in the parallel direction as anticipated. The net result of this effect is that ECR traps accelerated electrons so that their mirror points are at the position where they are being heated. Thus, heating the bulk plasma tends to trap electrons at the minimum of the minimum-B configuration which is "on-axis", whereas heating in the mirror field regions tends to trap particles higher up in the minimum-B well or "off-axis". Thus, in some sense, bulk heating can do a better job of trapping accelerated electrons.

7. Conceptual ECR ion source design

The advanced design features considered in this document allow for heating of a large fraction of the total volume of the ECR ion source. A schematical representation of a room-temperature "volume" type ECR source is shown in Fig. 11. A superconducting version of the source is also under design consideration, which will reduce the power required for operation. A high-order multicusp field design for confining the plasma in the radial direction is the key to providing a larger resonant volume at a constant ECR magnetic field. However, a high order multicusp field may not be prerequisite for improved performance. An $N=6$ (hexapole) radial field source with a flat axial magnetic field also will be effective for generating multiply charged ions. The tune magnetic field is effected by adjusting the central solenoidal field.

8. Discussion

The ECR concept is designed to establish a large, "on-axis" ECR zone, allowing ECR power to be coupled all along the axis, thus eliminating "unheated" zones and possible microwave power saturation effects. By varying the multiplicity of the radial cusp magnetic field, the size of the ECR zone can be varied. These features of the source result in significantly greater interaction of the ECR microwaves with the plasma electrons, both in terms of total power absorptivity and in a more uniform spatial distribution of the absorptivity. The more uniform distribution of the ECR power and the greater proportion of hot electrons, as a consequence, implies a greater degree of ionization of the plasma and higher charge states of multiply charged ions within the plasma volume. Because of the greater absorptivity of the RF waves, the electron population may reach energies that are too high for optimum ionization of tightly bound electrons. To overcome this potential handicap, should this be the case, it is proposed that the power be pulsed at variable pulse widths to allow a more optimum electron velocity distribution for creating multiply charged ions. Alternatively, the pressure in the discharge chamber can be increased at a sacrifice of less than optimum high-charge-state generation. ECR ion sources typically perform better when cold electrons are added to the plasma. This can be accomplished by either adding negatively biased disks,^{17,18} electron guns,¹⁹ or plasma cathodes.²⁰ The plasma cathode is a particularly simple and appealing solution to the problem and may need to be incorporated to supply cold electrons to the plasma.

The magnetic field and particle simulation studies have shown that the source plasma confinement geometry is sound and that the bulk plasma ECR heating scenario most likely will result in improved performance in terms of its capability of generating high-charge-state ion beams because of the excellent ECR heating of the plasma electrons.

While this study is by no means exhaustive, we clearly show that this device looks feasible from a physics perspective.

Acknowledgments

The authors express their gratitude to Ms. Jeanette McBride for typing the manuscript.

9. References

1. R. Geller, B. Jacquot, and C. Jacquot, *Plasma Phys. Controlled Nucl. Fusion Res.* (1972), Proc. Int. Conf., 4th, Madison, Wis., CN-28, G6 (1971).
2. R. Geller, *Trans. Nucl. Sci.* NS-23, No. 2, 904 (1976).
3. G. D. Alton and D. N. Smithe, *Rev. Sci. Instrum* 65, 775 (1994).
4. Proc. Int. Conf. on ECR Ion Sources and their Applications, ed. by J. Parker (NSCL Michigan State University Publisher, East Lansing, MI, 1987), MSU-CP 47, 151.
5. Proc. of the Tenth Int. Workshop on ECR Ion Sources, (Knoxville, TN, Nov. 1-2, 1990), ed. by F. W. Meyer and M. I. Kirkpatrick, CONF-9011136, 1991.
6. Proc. of the Eleventh Int. Workshop on ECR Ion Sources (Gronigen, The Netherlands, May 6-7, 1993), ed. by A. G. Drentje, KVI-Report 996 (1993).
7. G. Melin, these proceedings.
8. H. Amemiya, K. Shimizu, S. Kato, and Y. Sakamoto, *Japanese J. of Appl. Phys.* 27, 2927 (1988).
9. *Introduction to Plasma Theory*, by Dwight R. Nicholson (Wiley, 1983), chapter 7.
10. R. Geller, *IEEE Trans. Nucl. Sci.* CH2669-0, 1088 (1989).
11. "User's Guide for the POISSON/SUPERFISH Group of Codes," LA-UR-87-115 (1987).
12. "MAGIC User's Manual," MRC/WDC-R-282 (1991).

13. *Principles of Plasma Physics*, by Nicholas A. Krall and Alvin W. Trivelpiece (San Francisco Press, 1986), chapter 5.
14. B. Jacquot and M. Pontonnier, Proc. of the Tenth International Workshop on ECR Ion Sources, ORNL CONF-9011136, 133 (1990).
15. P. Bricault, P. Sortais, M. Bisch, P. Leherissier, R. Leroy, J. Y. Pacquet, and J. P. Rataud, Rev. Sci. Instrum. 63, 2494 (1992).
16. P. Sortais, J. Debernardi, R. Geller, P. Ludwig, and R. Phauthenet, Proc. of the Eighth International Workshop on ECR Ion Sources and their Applications, NSCL Report-MSUCP-47, ed. by J. Parker, December 1987, p. 334.
17. T. Nakagawa and T. Kageyama, Jpn. J. Appl. Phys. 30, L1588 (1991); T. Nakagawa, T. Kageyama, M. Kase, A. Goto, and Y. Yano, *ibid.* 31, L1129 (1992).
18. G. Melin, C. Barué, F. Bourg, P. Briand, J. Debernardi, M. Delaunay, R. Geller, A. Girard, K. S. Golovanivsky, D. Hitz, B. Jacquot, P. Ludwig, J. M. Marthonnet, T. K. Nguyen, L. Pin, M. Pontonnier, J. C. Rocco, Proc. Tenth International Workshop on ECR Ion Sources, ORNL CONF-9011136, 1 (1990).
19. Z. Q. Xie, C. M. Lyneis, R. S. Lam, and S. A. Lundgren, Rev. Sci. Instrum. 62, 775 (1991).
20. T. Nakagawa, T. Kageyama, M. Kase, A. Goto, and Y. Yano, Jpn. J. Appl. Phys. 32, L1335 (1993).

Figure Captions

- Fig. 1 ORNL-DWG 94Z-10971. Schematic drawings of a conventional ECRIS with characteristic ECR "surface" and an ECRIS with a large, uniformly distributed ECR "volume."
- Fig. 2 ORNL-DWG 93Z-11210. Magnetic field profiles used in the PIC simulation studies: a) B_z versus z at $r = 1.5$ cm; b) B_r versus z at $r = 1.5$ cm; c) B_ϕ versus r ; d) B_z versus r at $z = 0$.
- Fig. 3 ORNL-DWG 92Z-15312A. The fraction of the plasma volume F_v which can be tuned to the ECR condition within a specified tolerance as a function of the number of cusps in the radial magnetic field.
- Fig. 4 ORNL-DWG 92Z-15308A. Electron orbits in a multicusp magnetic field with $N = 6$ cusps and a superposed uniform solenoidal magnetic field along the z -axis. The solenoidal field is used to tune to the ECR condition. Note the relatively small area of constant magnetic field present in the central region of the plasma volume and the relatively low number of electrons which have stationary orbits within this region of the field. If the central region is tuned to the ECR condition, then only those electrons within this limited volume can be accelerated by the microwave power source.
- Fig. 5 ORNL-DWG 92Z-15243A. Electron orbits in a multicusp magnetic field with $N = 12$ cusps with a superposed, uniform solenoidal magnetic field along the z -axis. The solenoidal field is used to tune to the ECR condition. Note the increased area of constant magnetic field present in the central region of the plasma volume and the increase in number of electrons which have stationary orbits within this region of the field. If the central field is tuned to the ECR condition, then the number of electrons available for acceleration by the microwave power source is increased.
- Fig. 6 ORNL-DWG 93Z-11221. Solenoidal magnetic field design for the ECR ion source showing locations of the main, mirror, and trim coils. The magnetic field profile is also shown to illustrate the effect of the trim coils in providing a flat central field region. The central or main solenoid is used to tune to the ECR condition.
- Fig. 7 ORNL-DWG 94Z-10970. Axial magnetic field profiles for the conventional magnetic-field geometries ECR3/CAPRICE sources described in Refs. 14 and 15, the NEOMAFIOS ECR source described in Ref. 16, and the new ECR ion source concept with a large uniformly distributed ECR "volume."
- Fig. 8. ORNL-DWG 93Z-11211. Trajectories of "hot" electrons moving along the axial magnetic field. Note the reduction in both the gyro-radius and pitch as the electrons reach the mirror points.

- Fig. 9 ORNL-DWG 93Z-7033A. Illustration of the effect of varying the number of cusps N on the volume of central (flat) magnetic field plasma that can be tuned to the ECR condition for $N = 6$ and $N = 22$ cusps. The transition from heated to non-heated regions of the plasma is very apparent from the plots of the radial velocities of the electrons in the respective plasma confinement geometries; the lower order azimuthal field results in a much smaller field volume of resonant plasma.
- Fig. 10 ORNL-DWG 93Z-11212. Time behavior of the energies of hot electrons in conventional ECR ion sources with off-axis ECR "surface" and in the new ECR ion source concept with large uniformly distributed ECR "volume." The RF power is turned on after 45 ns. The rapid loss of energy in the first 20 ns by the hot electrons is due to single-pass losses of particles in unconfined orbits; these losses are slowed by the establishment of the ambipolar electric field.
- Fig. 11 ORNL-DWG. Schematic drawing of a prototype ECR ion source with a large, uniformly distributed ECR "volume." The axial magnetic field profile for the source is displayed in Fig. 7. The RF frequency is assumed to be 6.45 GHz.

**CONVENTIONAL ECRIS with
CHARACTERISTIC ECR "SURFACE"** **ECRIS with UNIFORMLY
DISTRIBUTED ECR "VOLUME"**

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9

CONVENTIONAL ECRIS

ECRIS with TAILORED ECR VOLUME

Figure 10

Figure 11