COMPUTATIONAL STUDIES FOR AN ADVANCED DESIGN ECR ION SOURCE

G. D. Alton, J. Dellwo, and R.F. Welton
Oak Ridge National Laboratory, * P. O. Box 2008, Oak Ridge, TN 37831-6368 USA
D. N. Smithe
Mission Research Corporation, 8560 Cinder Bed Road, Suite 700, Newington, VA 22122 USA

An innovative technique for increasing ion source intensity is described which, in principle, could lead to significant advances in ECR ion source technology for multiply charged ion beam formation. The advanced concept design uses a minimum-B magnetic mirror geometry which consists 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 to confine the plasma in the axial direction. The magnetic field is designed to achieve an axially symmetric plasma "volume" with constant mod-**B**, which extends over the length of the central field region. This design, which strongly contrasts with the ECR "surfaces" characteristic of conventional ECR ion sources, results in dramatic increases in the absorption of RF power, thereby increasing the electron temperature and "hot" electron population within the ionization volume of the source.

I. INTRODUCTION

Ion sources based on the Electron Cyclotron Resonance (ECR) principle have played indispensable roles in the advancement of our knowledge of atomic and nuclear physics and in many areas of applied science and technology. For accelerator-based research applications, the final energy of an ion beam is directly proportional to the charge on the ion during acceleration and, therefore, a premium is placed on ion sources which are capable of generating very high charge state ion beams. 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 that we describe offers this distinct possibility with many applications in atomic physics and applied research, as well.

II. PRINCIPLES OF ECR ION SOURCES

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) and energy distribution (temperature distribution) are two of the fundamental properties which govern the performance of the ion source in terms of degree of ionization and multiple ionization capabilities of the source. In ECR ion sources, electrons can only be excited whenever the magnetic field meets the ECR resonant condition:

$$\omega_{ECR} = Be/m = \omega_{rf} \qquad (1)$$

where ω_{ECR} is the electron-cyclotron resonant frequency, ω_{rf} is the resonant frequency of the microwave power source, B is the magnetic field which meets the resonance requirement, and e is the electron charge and m the mass of the electron. The physical region over which the ECR condition is met is referred to as the ECR zone. Electrons passing through the ECR zone, which are coincidentally in phase with the RF electric field, are accelerated by the transfer of electromagnetic energy to the electron 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 stochaistically heated. At low collision frequencies (low ambient pressures), some of the electrons can be excited to energies sufficiently high to remove tightly bound electrons and thereby produce multiply ionized atoms.

III. CONVENTIONAL ECR ION SOURCE DESIGNS

The "volume" ECR ion source is contrasted with that of the more conventional "surface" ECR ion sources in Fig. 1. Improvements in ECR performance can, in principle, be realized by redesigning the magnetic field configuration so that the ECR zone is a "volume" rather than a "surface," as is the case in conventional ECR ion sources. In traditional ECR sources, the electrons gain energy in the fairly thin ECR zones in or near the mirror field regions. The ECR zones in conventional sources are usually annular, ellipsoidal surfaces

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

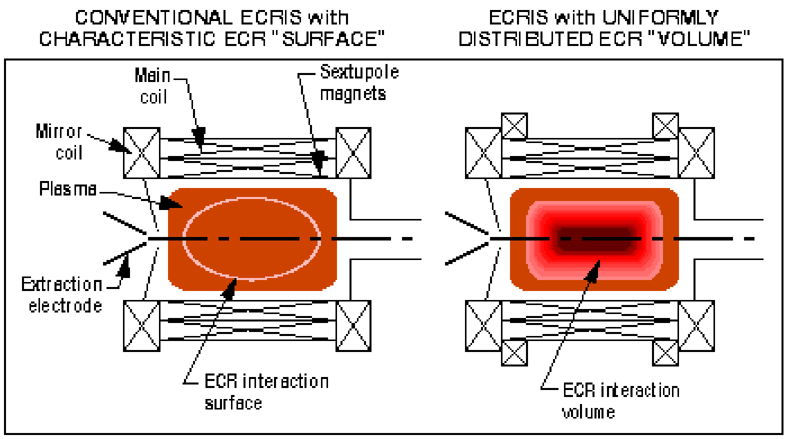

Fig. 1 Schematic drawings of a conventional ECRIS with characteristic ECR "surface" and an ECRIS with a large, uniformly distributed ECR "volume."

and, in general, lie off of the axis where ions are extracted; the microwave power can only be coupled to the plasma in these zones, which occupy a small percentage of the ionization chamber volume, leaving the remainder of the plasma chamber as "unheated" zones. In addition, the thin ECR zone in the mirror field is a relatively small fraction of the device volume, hence the absorptivity of the plasma is governed not by the size of the plasma, but by the size of the ECR region. The new ECR ion source, described below and in a previous publication,[1] overcomes this limitation. 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. 2-4).

IV. DESIGN FEATURES OF THE NEW ECR ION SOURCE

We have used magnet design codes, plasma dispersion solvers, and particle-in-cell (PIC) simulation codes to simulate the relative adsorption characteristics in a conventional ECR source and in the new ECR ion source concept described in this report. The codes were also used to design the magnetic field geometry and to track particle motion in the magnetic field. The advanced concept design uses a minimum-B magnetic mirror geometry, which consists 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 to confine the plasma in the axial direction.

The advanced ECR ion source considered in this document allows for heating of a large fraction of the total volume of the ECR ion source. The ECR volume can be varied by increasing the number of poles used for radial confinement. In all cases for $N \geq 4$, the ECR zone in the central region of the proposed ECR ion source concept is continuous and on-axis. The magnetic field is designed to achieve an axially symmetric plasma volume with constant mod-B, which extends over the length of the central field region.

V. ELECTRON HEATING CHARACTERISTICS

In order to achieve a flat field profile in the radial direction, it is necessary to use a high-order multi-cusp magnetic field. The effect of increasing the field multiplicity on the physical size of the respective ECR zones for N=6and N=22 multipole fields is illustrated in Fig. 2 which displays, respectively, magnetic field versus radial position (lower portion), and the velocity of the electrons which are resonantly excited as a function of radial position (upper portion). In Fig. 2, the transition from heated to nonheated regions of the plasma at the ECR condition is very apparent. Electron heating studies show that the ECR microwave power can be coupled more efficiently in the new ECR ion source than in conventional ECR ion sources. For the same time duration, microwave adsorption is increased by more than a factor of seven over conventional ECR sources.

VI. DISCUSSION

The ECR ion source described in this paper has a much larger volume of resonant plasma resulting in greater absorptivity of the microwave power with higher electron temperatures. By varying the multiplicity of the radial-cusp magnetic field, the size of the ECR "volume" can be varied. 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.

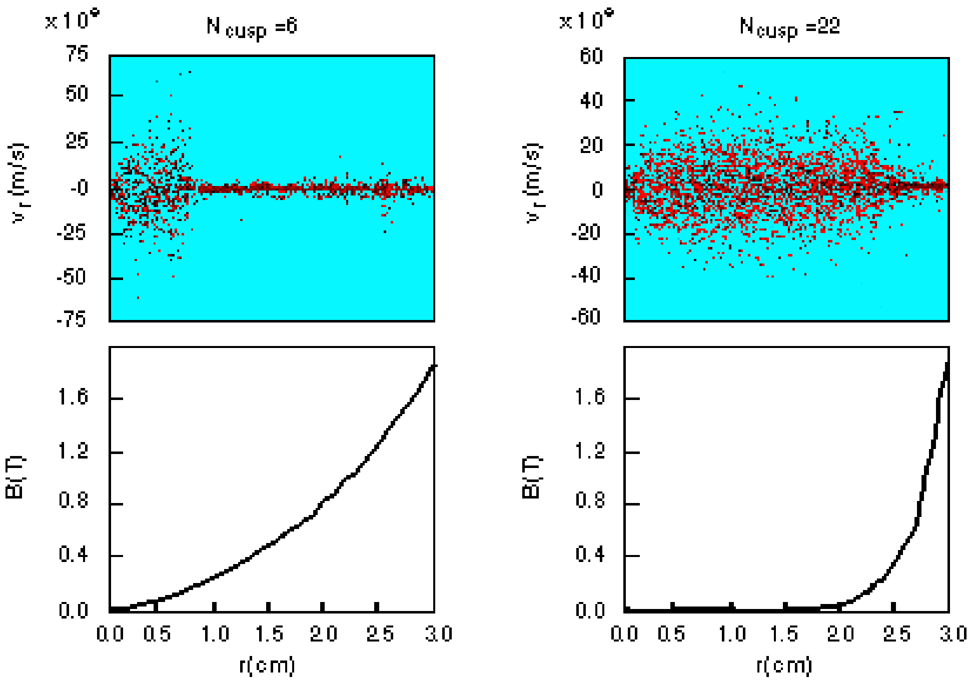

Fig. 2 Illustration of the effect of varying the number of cusps N on the volume of central (flat) magnetic field plasma that can be tuned to the ECR condition for N=6 and N=22 cusps. The transition from heated to nonheated regions of the plasma is very apparent from the plots of the radial velocities of the electrons in the respective plasma confinement geometries; the lower order azimuthal field results in a much smaller field volume of resonant plasma.

VII. REFERENCES

1. G. D. Alton and D. N. Smithe, Rev. Sci. Instrum. 65, 775 (1994).
2. 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.
3. 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).
4. 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).

VIII. ACKNOWLEDGMENTS

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