INITIAL TESTING OF THE 6 GHz, ALL-PERMANENT MAGNET, "VOLUME-TYPE" ECR ION SOURCE

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Abstract. A 6 GHz, all-permanent magnet, "volume-type" Electron Cyclotron Resonance (ECR) ion source has been initially tested at the Oak Ridge National Laboratory. The source has the following design properties: (1) an Al plasma chamber; (2) a mechanically adjustable, flat-bottomed mirror magnetic field distribution tuned to the ECR condition; *(3)* a dodecapole cusp-magnet for radial plasma confinement; (4) a Right-Hand-Circularly-Polarized (RHCP) traveling wave RF injection system, *(5)* a movable three-electrode extraction system, and (6) facility for conversion into a conventional minimum-B magnetic field "surface" source configuration. Details of the source design, magnetic field distribution, operational parameters and initial results derived from first operation of the source (e.g., charge state spectra and intensity distributions for a given charge state) are provided for argon.

INTRODUCTION

ECR ion sources are clearly the best choice of existing sources for the generation of *CW* beams of highly charged ions, and therefore, sources with enhanced charge-state distributions and intensities within a particular charge-state are at a premium for high-energy accelerator-based applications. The technology of the source has slowly but steadily advanced over the past several years principally by: improvement in plasma confinement; the use of very high frequency microwave radiation; improvement in vacuum quality [1]; supplementing their plasma discharges with cold electrons [2]; the use of wall coatings [3]; the use of *Al* plasma chambers [4]; the use of biased disks [5-6]; and the use of the gas mixing effect [7]. Recently, it has been suggested that their performances can be significantly further enhanced by increasing the physical sizes of their ECR zones in relation to the sizes of their plasma volumes (*spatial* and *frequency* domain methods) [8-10].

1. DESCRIPTION OF THE SOURCE

A compact, all-permanent magnet, single frequency ion source with a large uniformly distributed and resonant ECR plasma volume has been designed [11], fabricated and is under initial tests at the Oak Ridge National Laboratory. In contrast to conventional minimum-B ECR ion sources, this source employs a novel magnetic mirror field configuration that has an extended central flat region tuned to be in resonance with properly launched microwave radiation, a dodecapole multicusp radial field, and up to 3 kW klystron-driven RF injection system. The magnetic field configuration creates a large, on-axis ECR "volume", enabling the heating of electrons over a much larger volume that is possible in conventional ECR ion sources that are characterized by thin ECR "surfaces."

The source assembly is comprised of the following components or sub-assemblies: (1) a magnetic circuit with iron flux return yokes for axial and radial plasma confinement, specially designed to be flexible in that it can be configured for creating both flat-bottomed-B

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("volume") and conventional minimum-B ("surface") resonance conditions so that direct comparisons of the performances of the source types can be made at identical operating parameters; (2) an *Al* plasma chamber (I.D.: 54.0 mm; length: 155 mm); (3) a frequency independent, rectangular-to-circular RF injection system; (4) a remotely movable three electrode extraction system; (5) 1000 l/s turbo-molecular vacuum pumps located at each end of the source. Fig. 1 displays a schematic drawing of the source and its extraction system.

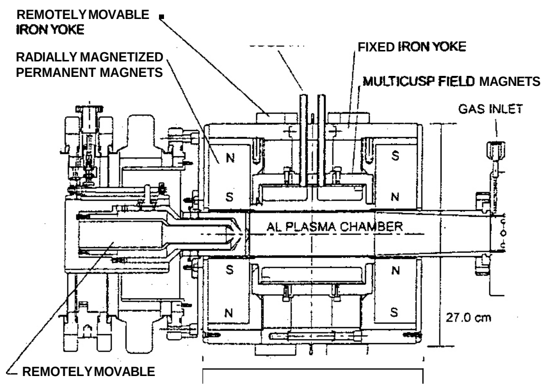


FIGURE 1. Side view of the compact, all-permanent magnet, "volume-type"ECR ion source.

2. EXPERIMENTAL SET-UP

Figure 2 schematically displays a side view of the Ion Source Test Facility (ISTF) used to evaluate the source. The components that make up the ISTF include the source, an electrostatic einzel lens, a 45 degree magnet (bending radius: ρ =0.6 m) for mass selection, Faraday cups for monitoring the beam prior and following magnetic analysis and auxiliary equipment (power supplies, vacuum pumps, electrometers, etc.) necessary for operation of the facility. The beam transport system was designed by use of GIOSP [12].

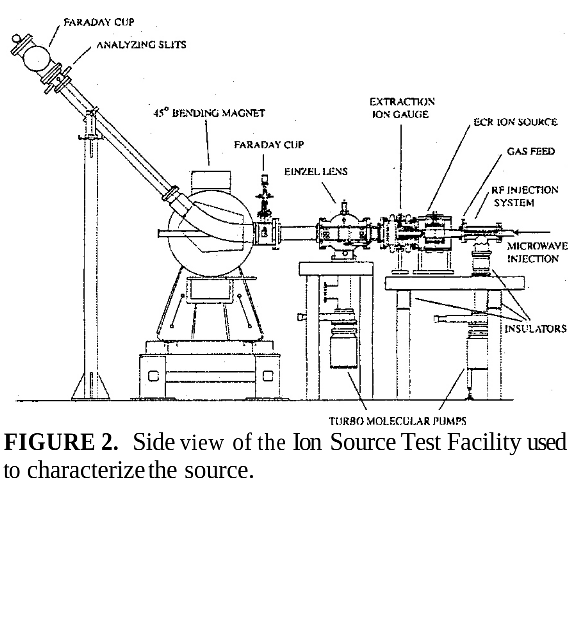


FIGURE 2. Side view of the Ion Source Test Facility used to characterize the source.

3 EXPERIMENTAL DATA

3.1 Magnetic Field Measurements

3.1.1 Axial Magnetic Field

The axial magnetic field configuration is designed to achieve an axially symmetric ECR zone with constant *B* over an extended cylindrical volume in the region between the mirrors of the source. The ECR zone is concentrated along and about the axis of symmetry, which allows microwave power to be coupled throughout the large resonant volume, thus eliminating "unheated" zones and possible microwave power saturation effects. The axial mirror field is produced by two annular 50-mm thick permanent magnets, radially magnetized in opposite directions, with inner and outer diameters, respectively, of 60 and 219 mm and separated by approximately 150 mm.

A Hall effect probe was used to measure the axial magnetic field distribution of the source when configured for "volume" operation. Computationally derived and experimentally measured axial magnetic field distributions for two different positions of the movable iron yokes are displayed in Fig. 3. The gaps were, respectively, 0.2 mm (minimum spacing between the yokes) and 5.35 mm (maximum spacing between the yokes). **As** illustrated, the experimentally measured and ANSYS [13] calculated field distributions agree reasonably well. The range of tunability of the magnetic field is seen to be approximately 4.0 x 10^{-2} T.

3.1.2 Radial Magnetic Field

Measurements were also made of the radial magnetic field in the "volume" configuration using the Hall effect probe. **As** displayed in Fig. 4, the measurements agree closely with ANSYS computational data.

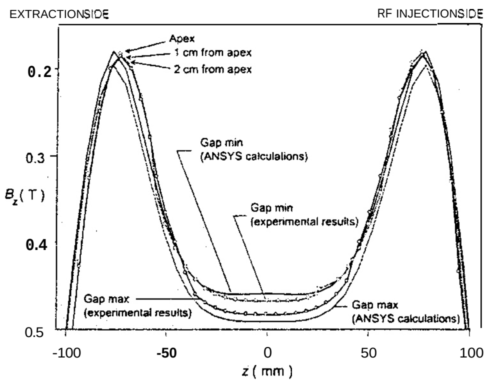


FIGURE 3. ANSYS calculations and experimental data for the axial magnetic field distribution for two different positions of the movable iron yokes (gap min = 3.0 mm and gap max = 53.5 mm).

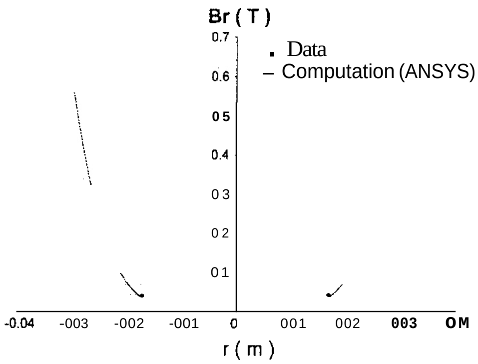
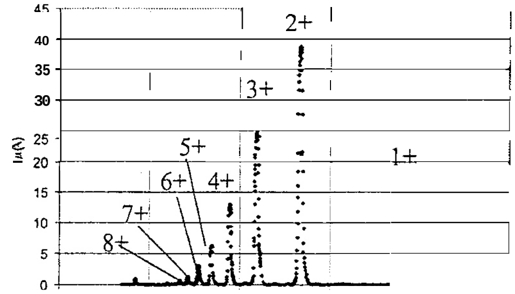
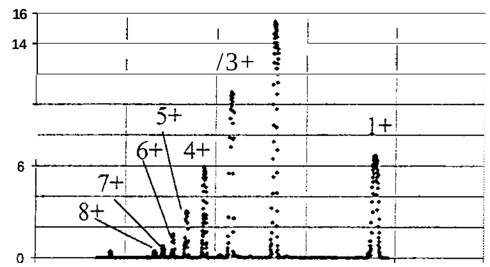


FIGURE 4. Comparison of ANSYS and experimentally measured radial magnetic field distribution.

3.2 Plasma Aperture Position

Extraction of ion beams was made with the extraction aperture set 1 cm and 2 cm behind the apex of the magnetic field at the extraction end of the source. These positions are indicated in Fig. 3. The argon charge-state distributions obtained at each position under similar operating conditions (microwave power, pressure, etc.) are respectively displayed in Figs. 5 and 6. The intensities extracted at the "1 cm position" are clearly higher than those obtained when the extraction aperture was placed at the "2 cm position". Future improvements in intensity are expected when the plasma electrode emission aperture is set on the apex of the magnetic field with the possibility of adjusting its position while operating the source..





3.3 Effect of the Parasitic Zone

At low pressure (– 2.5 x 10^{-7} Torr) only low power could be coupled into the plasma (–50 W). Fig. **7** displays the source with the axial magnetic field distribution superposed. **As** illustrated in Fig. 7, the ECR condition is met both *inside* and *outside* (referred to as the parasitic zone) the *mirror region.* In order to determine the effect of the parasitic zone, the source was run at conditions where the klystron frequency matched the "volume" ECR condition, and at conditions, where the klystron frequency did not match the "volume" ECR condition. Charge state distributions for both conditions are respectively displayed in Figs. 8 and 9.

When the klystron frequency does not match the ECR frequency condition, only the parasitic zone can absorb RF power. **As** illustrated in Fig. 9, the absorbed power under this condition is – 17% of the injected power compared to – 81% when the injected microwave frequency agrees with the resonance condition, as indicated in Fig. 8. Furthermore, the

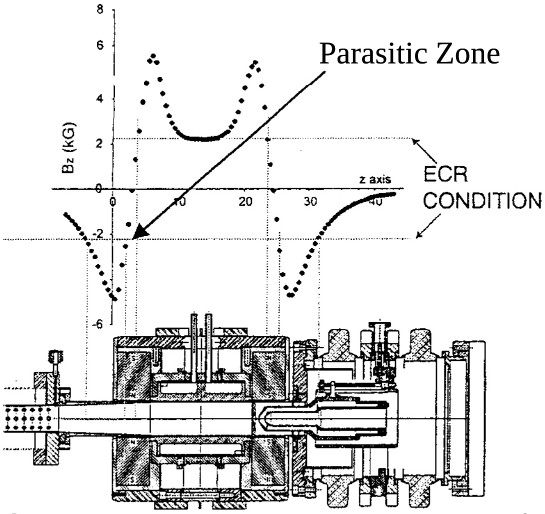


FIGURE 7. ECR ion source with the axial magnetic field distribution superposed.

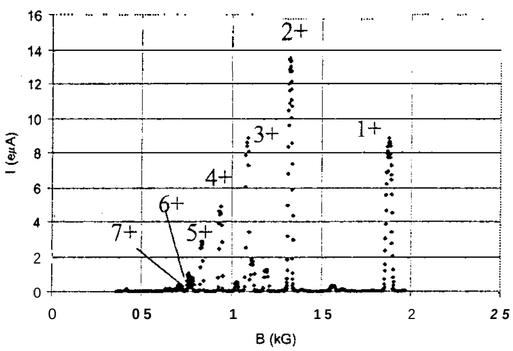


FIGURE 8. Argon charge-state distribution when the klystron frequency matches the internal ECR condition: $\omega_{klys} = \omega_{ECR} = 6.17$ GHz; $RF_{incident} = 94.3$ W; $RF_{reflected} = 17.9$ W; Total Beam Intensity: 119 μA; $P_{ext} = 4.2 \times 10^{-7}$ Torr. (P_{ext} is the pressure on the extraction side).

charge-state distribution is dramatically changed when the microwave radiation does not match the ECR condition, as illustrated in Fig. 9. The parasitic zone stochastically heats electrons and apparently does not accelerate them to energies sufficiently high to form high charge-state ions.

3.4 Optimization of the Extraction Gap

The ion extraction is effected with a two-stage, remotely positional, three-electrode extraction system (plasma, intermediate and ground electrodes), with ceramic-to-metal bonded insulators, capable of operation at potentials up to 50 kV (see Fig. 1). During testing, the source voltage was set at 20.0 kV with the extraction electrode grounded. Fig. 10 illustrates the importance of being able to adjust the extraction

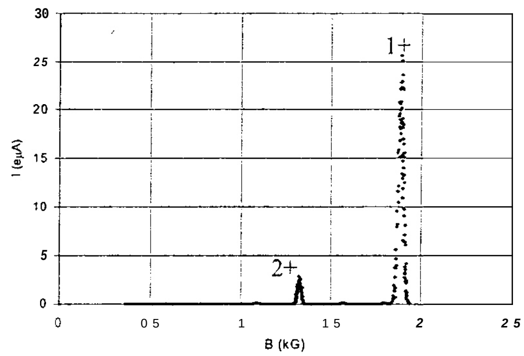


FIGURE 9. Argon charge-state distribution when the klystron frequency does not match the internal ECR condition: $\omega_{klys} = 5.9$ GHz, $\omega_{ECR} = 6.5$ GHz; $RF_{incident} = 107.3$ W; $RF_{reflected} = 88.7$ W; Total Beam Intensity = 60 μA; $P_{ext} = 6.8 \times 10^{-7}$ Torr (P_{ext} is the pressure on the extraction side).

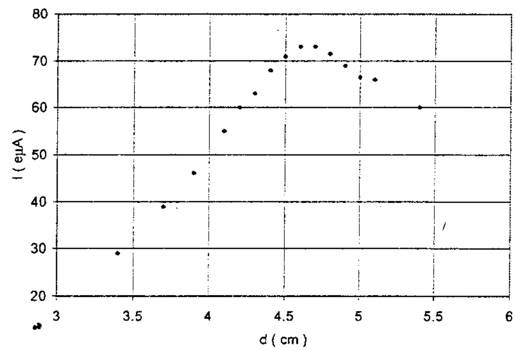


FIGURE 10. Total argon beam intensity, *I*, versus extraction gap, *d*, for the following experimental conditions: $\omega_{klys} = \omega_{ECR} = 6.17$ GHz; $RF_{incident} = 58.1$ W; $RF_{reflected} = 19.6$ W; $P_{ext} = 4.9 \times 10^{-7}$ Torr (P_{ext} is the pressure on the extraction side of the source).

electrode position in order to optimize the extracted beam intensity.

3.5 Source Performance

Fig. 11 illustrates the source performance at the highest power tested yet (–380.0 W absorbed power), at $P_{ext} = 6.0 \times 10^{-7}$ Torr.

4 DISCUSSION

Future plans call for analogous evaluation of the source performance when configured in the conventional geometry with an axial parabolic magnetic field and a radial hexapole cusp field. Comparison of the performances of the "surface" and

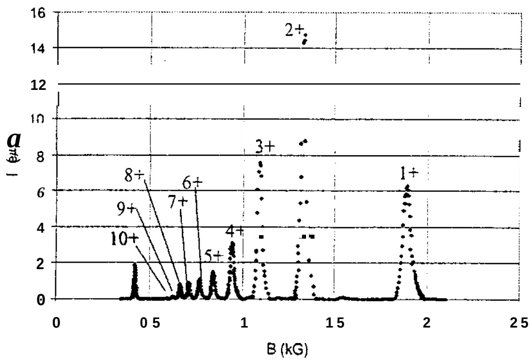


FIGURE 11. Illustration of the source performance with argon for the following experimental conditions: $RF_{absorbed}$= 380.0 W; P_{ext} = 6.0 x 10^{-7} Torr (P_{ext} is the pressure on the extraction side).

"volume" modes of operation should help to settle the question of which mode is superior. However, this question has already been answered by Heinen, et al, who compared the performances of an all permanent magnet, 6 GHz source, almost identical to the subject source, in both configurations and found the "volume" configuration performance superior to that of the conventional "surface" configuration [14].

We believe that the "volume" geometry source has a very promising future. The charge state distribution peaks at Ar^{2+} without any gas mixing with a few enA in Ar^{11+}, even under far from optimum conditions. By operating the source under optimum conditions with the aperture set at the apex of the magnetic field (theoretically a gain of ~ a factor of ~25), accounting for transmission efficiency losses (~a factor of 3 to 5), introducing a positive electrode to reflect ions that are presently lost on the injection side of the source (~ a factor of 2) and facilitating the movable extraction electrode capability, we expect to increase the intensities by 1.5 to 2 orders of magnitude or more. Future plans also call for using both klystron and TWT driven microwave power, each set at slightly different frequencies, to ignite and maintain plasmas in the source. This again should (theoretically) double the intensities of beams extracted from the source.

The "flat field" source received much attention at the ECRIS'02 in Finland [15], and is finally being recognized for its merits. Andrae and colleagues at the University of Muenster, Germany, have designed, developed and initiated testing of an all-electromagnetic version of the source that operates at 18 GHz that in initial testing, generated > 1 emA of Ar^{8+}, then a world record.

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