FUTURE PROSPECTS FOR ECR ION SOURCES WITH IMPROVED CHARGE STATE DISTRIBUTIONS

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Despite the steady advance in the technology of the ECR ion source, present art forms have not yet reached their full potential in terms of charge state and intensity within a particular charge state, in part, because of the narrow band width, single-frequency microwave radiation used to heat the plasma electrons. This article identifies fundamentally important methods which may enhance the performances of ECR ion sources through the use of: 1) a tailored magnetic field configuration (spatial domain) in combination with single-frequency microwave radiation to create a large uniformly distributed ECR "volume" or 2) the use of broadband frequency domain techniques (variable-frequency, broad-band frequency, or multiple-discrete-frequency microwave radiation), derived from standard TWT technology, to transform the resonant plasma "surfaces" of traditional ECR ion sources into resonant plasma "volumes". The creation of a large ECR plasma "volume" permits coupling of more power into the plasma, resulting in the heating of a much larger electron population to higher energies, thereby producing higher charge state ions and much higher intensities within a particular charge state than possible in present forms of the source. The ECR ion source concepts described in this article offer exciting opportunities to significantly advance the-state-of-the-art of ECR technology and as a consequence, open new opportunities in fundamental and applied research and for a variety of industrial applications.

1 Introduction

Ion sources based on the Electron Cyclotron Resonance (ECR) principle have played major roles in the advancement of science since their inception because of their capabilities for generating multiply charged ion beams.[1,2] In addition, these sources also offer a number of major advantages over more conventional hot-cathode ion sources, including the following: (1) the source has a long lifetime due to its nonfilamentary (cathode) structure, the component which limits the functional lifetime of such sources through sputter and chemical erosion processes; (2) the operational stability of the source is unaffected by chemically reactive feed materials; (3) the source operates stably over a wide dynamical pressure range which allows it to be used at low operating pressures for multiply charged ion beam generation ($\leq 1 \times 10^{-6}$ Torr) commensurate with high-energy nuclear physics research, high energy ion implantation, and low energy multiply charged ion atomic physics experiments. At higher pressures ($> 10^{-5}$ Torr) the source can be used or the generation of high-intensity, low-charge-state ion beams such as required for many applications.

The growing number and variety of fundamental, applied and industrial uses for high intensity, high charge state ion beams continues to be the driving force behind efforts to develop ECR ion sources with superior performance characteristics. Sources with these attributes could significantly impact future accelerator designs and accelerator based, heavy ion research programs by providing an extended list of multiply charged heavy ion beams with energies and intensities sufficient for fundamental and applied research. Since the energy of an ion beam increases in direct proportion to the charge on the ion during acceleration with RF or electrostatic devices and quadratically with charge during acceleration with a cyclotron, the final energy depends on the number of active acceleration components in a linear accelerator or the maximum magnetic field strength of a cyclotron. Heavy-ion cyclotron, linear accelerator, synchrotron and new generation heavy ion colliders, now under construction, such as the relativistic heavy-ion collider (RHIC) at the BNL and the large hadron collider (LHC) at CERN would all benefit by the advent of enhanced performance ECR ion sources. Because of their very high efficiencies, ECR ion sources are presently in use or under consideration for use at radioactive ion beam (RIB) facilities now under construction or being proposed for construction at several sites throughout the world including the HRIBF at ORNL[3]. For RIB applications, high efficiency sources are quintessential to the success of RIB research programs because of the low rates of producing short lived nuclei and the beam-on-target intensity requirements (typically 10^5 to 10^{12} particles/s). ECR ion sources are also strong candidates for the efficient generation of high intensity proton, neutron and He beams at light ion accelerator facilities. In addition to high energy applications, multiply charged ion beams are used in a variety of low energy, atomic physics applications in atomic physics programs at various locations around the world. This article describes two fundamentally different techniques for creating large ECR plasma "volume" sources.

2 Principles of ECR Ion Sources

The source of energy for plasma generation and maintenance in an ECR ion source is Electron Cyclotron Resonance (ECR) heating of the plasma electrons with microwave radiation. The number density of electrons, the electron energy (temperature), and energy distribution of the electron population are three of the fundamental properties which govern the performance of

ECR ion sources in terms of ion beam intensity and multiple ionization capabilities. The maximum electron temperature is affected by several processes including the ability of the plasma to adsorb microwave power, the time required to produce heated electrons, the time for thermalization of the "hot" electrons and the ability to contain (confine) the "hot" electrons.

The ECR zones in any ECR source are limited to regions of the ionization volume where the magnetic field meets the resonance condition, given by

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

where ω_{ce} is the electron-cyclotron resonant frequency, ω_{rf} is the resonant frequency of the microwave power source, e is the electron charge and m the mass of the electron. Whenever the microwave frequency is tuned to the electron-cyclotron frequency, electrons can be resonantly excited and thereby given sufficient energy to cause ionization within an evacuated volume. At low collision frequencies (low ambient pressures), some of the electrons are coherently excited and given very high energies which are capable of removing tightly bound electrons and, therefore, are responsible for producing multiply charged ions.

3 Conventional ECR Ion Sources

3.1 General Description

A schematical representation of a single frequency ECR ion source designed according to B-minimum magnetic field confinement principles is illustrated in Fig. 1. The source is comprised of a solenoidal magnetic field for confining the plasma in the axial direction, a multicusp magnetic field for confining the plasma in the radial direction, a multimode cavity which serves as the plasma confinement vessel, a single frequency wave-guide/microwave injection system for introducing microwave power into the cavity and an ion extraction electrode system for extracting ion beam current from the source. The magnetic field distributions are designed to effect a minimum in the B field (B-minimum geometry) for optimum plasma confinement. Single-frequency microwave power supplies with frequencies in the range of 2.45 to 14 GHz are typically used to generate and maintain plasmas in these sources; the band widths in these power supplies are usually quite narrow (typically, 20 MHz). The feed material of interest may be introduced in gaseous form or in solid form from ovens or other means (e.g., sputtering or solid rod plasma vaporization). Ion-neutral 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 primary stage of the source.

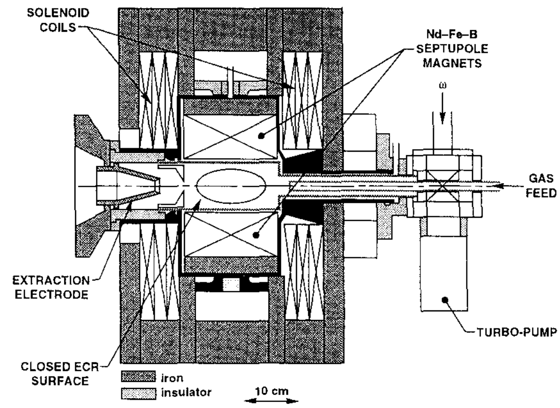

Fig. 1. Schematic drawing of a single-frequency, B-minimum magnetic field geometry ECR ion source for multiply-charged ion beam generation. (The source is patterned after the CAPRICE ECR source described in Ref. 19 and 20.)

3.2 Sizes and shapes of ECR zones

In conventional ECR ion sources, the magnetic field is a composite of the spatially varying solenoidal and multipole magnetic fields. Therefore, the ECR zones are fluted, ellipsoidal-shaped "surfaces" rather than "volumes" due to the ECR condition that occurs at very discrete positions in the magnetic field distribution where the angular frequency, given by the ECR condition (Eq. 1), is identically equal to the angular frequency of the narrow bandwidth microwave radiation. The ECR surface surrounds the axis of symmetry of the source, as illustrated in Fig. 1 and intersects the axis of symmetry at two points near the mirror regions in the cylindrical plasma column. The physical region or "surface" over which the ECR condition is met is referred to as the ECR zone.

3.3 Electron Confinement

Long electron confinement 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. The magnetic field geometry and magnetic field strength determine the confinement attributes of the ECR ion source. Confinement is usually effected with strong magnetic fields in the axial direction with solenoidal fields located at the ends of the plasma chamber and multicusp (usually sextupole) fields to confine the plasma in the radial direction which increase in magnitude from the axis of symmetry toward the walls of the plasma chamber. Thus, the magnetic field distribution has a minimum in the central region and continually varies in all directions about this point. Single electron impact ionization processes are known to be the primary mechanism for producing multiply charged ions. Thus, it is necessary to make the product $\mathbf{n}_e\tau_i$ as large as possible where $\mathbf{n_e}$ is the electron density and τ_i is the confinement time of the ions. The confinement 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 importance of confinement is clearly indicated by the fact that the charge state distributions from ECR ion sources, based on B-minimum magnetic field design principles, increase with increasing magnetic field strength for both the axial and radial directions.[4,5]

In order to confine a stable collisionless plasma, the magnetic field configuration can be designed to ensure that individual particles are contained by the external magnetic field, i.e., the lines of force never intersect the chamber walls and the drift velocities move parallel to the walls. However, a collisional plasma often acts collectively and may be unstable due to internal forces. For example, charge bunching can give rise to **E** field causing **E x B** drifts; the motion of the electrons and ions create magnetic fields as they precess about the magnetic field lines which cause gradients in the local magnetic field and as a result drift toward the chamber walls. Under these conditions, the plasma obeys the magnetohydronamic (MHD) equations. One of the important relations derived from the MHD equations is the fact that the sum of the particle pressures $\sum_i n_i kT$ and the magnetic pressure $B^2/^2\mu_0$ is a constant or

$$\sum_i n_i kT + B^2/2\mu_o = \beta \qquad (2)$$

where β is a constant, **B** is the magnetic field strength, μ_o is the permeability of free space, $\mathbf{n}_i$ is the density of particles of species i, and **T** is the temperature of the particles. From this relation, we see that for a plasma with a density gradient, the magnetic field must be low when the density is high and vice versa. The local magnetic field is reduced by the precession of charged articles about the magnetic field lines in a direction so as to cancel the external field (diamagnetic effect). Equation 2 has connotations regarding ECR ion sources in that the ECR "surfaces" necessarily are located in the high magnetic field regions where the electron density is low. Therefore, the high energy electron population is reduced as a consequence of both the equilibrium condition (Eq. 2) and the thinness of the ECR zone.

3.4 Ionization

In the ECR ion sources the principal ionization process, as established experimentally, is by sequential single electron removal through step-by-step ejection—although inner shell vacancy production followed by Auger processes and multiple electron removal through single electron impact also contribute to the formation of multiple ionized particles as well. Evidence for the sequential ionization process has been clearly demonstrated recently by Harkewicz, *et al.* in the ECR ion source at ANL.[6] The fundamental equations that denote single electron removal in such interactions can be expressed as

$$\begin{aligned} &e + A^0 \to 2e + A^+ \ , \\ &e + A^+ \to 2e + A^{+2} \ , \\ &e + A^{j+} \to 2e + A^{+(j+1)} \ . \end{aligned} \qquad (3)$$

The minimum primary electron energy required in each stage of ionization must be equal to or greater than the binding energy of the ejected electron.

The growth rate dn_i/dt of the ith multiple charged ion state subjected to bombardment with an electron density n_e can be expressed in terms of a system of differential equations of the form

$$\begin{aligned} \frac{dn_i}{dt} = {} & n_e\langle\sigma_I v\rangle_{i-1,i}\, n_{i-1} + n_n\langle\sigma_{cx} v\rangle_{i+1,i}\, n_{i+1} \\ & - n_e\langle\sigma_I v\rangle_{i,i+1}\, n_i - n_n\langle\sigma_{cx} v\rangle_{i,i-1}\, n_i - \frac{n_i}{\tau_i} \end{aligned} \qquad (4)$$

where $\langle\sigma_I v\rangle_{k,k'}$ is the average of the cross section for ionization of the k^{th} state and the velocity **v** of the electron population; n_k is the density of ions in the k^{th} state; n_n is the neutral density; $\langle\sigma_{cx} v\rangle_{k,k'}$ is the average of the cross section for charge exchange to the k^{th} state and the velocity **v** of the electron population and τ_k is the life time of the ion in the k^{th} state of density n_k

A semiempirical formula developed by Lötz reproduces experimental cross section data with good accuracy over a wide range of energies.[7] The formula, valid for electron energies T_e greater than the ionization potential I_j of the electron being ejected, is given by

$$\sigma_{i-1,i}(cm^2) \cong \frac{1}{T_e}\sum_{j=i}^{N} a_j \frac{N_j}{I_j} \ln\frac{T_e}{I_j} \ . \qquad (5)$$

The summation is made over the number of subshell electrons removed, a_j is a constant associated with a given subshell, and N is the number of equivalent electrons in a subshell.

The time $\tau_{0,\kappa}$ required to produce the k^{th} state can be approximated from the following equation:

$$\tau_{0,i} \cong \frac{e}{n_e}\sum_{i=1}^{i}\frac{1}{\langle\sigma_{i-1,i}v\rangle} \cong \frac{e}{n_e\langle\sigma_{0,i}v\rangle}\,(s) \qquad (6)$$

where n_e is the electron density, $\sigma_{\kappa,\kappa'}$ is the average of the cross section for ionization of the k^{th} state and the velocity **v** of the electron population, $\sigma_{0,\kappa}$ is the average of the effective cross section for ionizing the nuclear particles to the k^{th} state and the velocity **v** of the electron, and *e* is the electronic charge.

3.5 Electron heating

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 stochaistically 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 most efficient and effective means for heating a plasma is by injecting right-hand circularly polarized (RHCP) waves along the direction of the magnetic field. The electric field vector for the RHCP wave rotates clockwise in time as viewed along the direction of **B** and has a resonance at the electron cyclotron frequency $\omega_{ce} = \omega_{rf} = Be/m$. 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. 8.

ECR ion sources typically perform better when cold electrons are added to the plasma due to the well known fact that ECR plasma discharges are electron "starved;" i.e., the "cold" electron population is believed to be too low to optimize the performance of traditional ECR ion sources. Enhanced performances have been realized by the use of vacuum chambers, liners or wall coatings with high secondary electron yields,[9] electron guns,[10] biased disks[11-13] or plasma cathodes.[14]

4 Perceived Limitations in the Performances of ECR Ion Sources

4.1 Limited sizes of ECR zones

In conventional single frequency ECR ion sources, the shapes, physical sizes, and locations of the ECR zones are determined by the frequency and bandwidth of the microwave radiation in relation to the magnitude of the magnetic field distribution which meets the ECR condition (Eq. 1). Since conventional ECR sources utilize narrow band width, discrete frequency microwave power supplies, the ECR zones are thin ellipsoidal surfaces which surround the axis of symmetry, intersecting it at two points, as indicated in the schematic drawing of the single frequency source shown in Fig. 1. Because the ECR zone is small in relation to the physical size of the ionization chamber, it constitutes a small fraction of the ionization volume. Thus, the absorptivity of microwave radiation by the plasma is determined not by the physical size of the plasma volume but by the size of the ECR zone in the source. Electrons can only be accelerated in this zone; those which scatter from the zone have a reduced probability for returning to the zone in phase with the electromagnetic field of the microwave, and, therefore, the probability for further stochastic acceleration is reduced. Thus, traditional sources suffer due to the fact that the ECR zones are too small to provide enough electrons with energies sufficiently high to optimize the ionization rate in the plasma volume of the source.

4.2 Limiting atomic physics/wall recombination processes

The principal factors which limit high-charge-state ion production are through charge exchange, wall recombination, ion residence time in the plasma, the bombarding electron current, and the electron temperature. As a necessary consequence of the requirement of neutrality in the plasma, there is a dynamical charge balance between electron and ion loss processes. Most of the ions recombine at the radial walls of the vacuum chamber and re-enter the plasma as neutrals. Because of the thin ECR surfaces, the probability for ionizing a neutral during passage through the ECR zone and re-entry into the interior of the plasma volume is reduced. Therefore, the population of neutrals may be greater in the interior of the source than if the ECR zones were of sufficient thickness to ionize the particles during passage. If this is the case, the average charge state of the ion distribution in the plasma will be lowered through charge exchange collisions between the neutrals and multiply-charged ions. The ability to quickly ionize a large fraction of the neutral population that results from recombination of the multiply charged ions which strike the walls of the vacuum chamber effectively reduces the rate of charge exchange, and thereby, increases the residence time of an ion in a given charge state which increases the probability for subsequent and further ionization. The advantage of having a thick ECR zone between the walls of the chamber and the interior of the plasma where the multiply charged ions are extracted may be to improve reionization of neutrals returning from the walls thereby reducing charge exchange within the central plasma region of the source. If the colliding partners are positively ionized, the long range forces and relatively low energies reduce the likelihood of charge transfer in these collisions.

5 Evidence for a Volume Effect

Evidence of the importance of increasing the ECR zone was first theoretically predicted by the work described in Refs. 15 and 16; these theoretical predictions have recently been confirmed by the experiments of Xie and Lyneis.[17] In this work, the authors simultaneously used 10 GHz and 14 GHz microwave frequencies to excite the plasma in the Advanced ECR (AECR) ion source[18] which resulted in moving the charge states to higher values by 3 to 4 units for Bi and U. When operated with two frequencies, the ECR interaction surface areas are increased by ~2, and as a consequence, the absorptivity of microwave power by the plasma is also increased, making more electrons available for acceleration by the respective RF field. The outer (14 GHz) surface may serve to ionize neutrals which result during charged particle recombination at the walls of the chamber and thus, reduce the population of neutrals which would otherwise lower the charge state distribution created in the interior region of the source by the action of the 10 GHz ECR surface. The protective effect of the 14 GHz may offer the best explanation for the enhanced performance of the AECR source because of the unlikely additional stochastic acceleration of electrons that scatter from one zone into another. These experiments provide direct evidence, although incrementally, in support of the arguments made in this paper and in Refs. 15 and 16 on the advantages of the "volume" effect.

6 Methods for Increasing the Sizes of ECR Zones

Two methods are readily available for increasing the sizes of these zones. They can be increased either by tailoring the magnetic field to achieve a large, uniformly distributed ECR plasma volume[15,16] or by using the broadband microwave radiation techniques described in this paper. Both of these techniques are briefly described below.

6.1 The Spatial Domain Technique

A schematical representation of an ECR ion source concept with a large uniformly distributed plasma volume is shown in Fig. 2. The source 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, thus enabling the heating of electrons over a much larger volume than is possible in conventional ECR ion sources. The "on-axis" ECR zone allows ECR power to be coupled all along the axis, thus eliminating "unheated" zones and possible microwave power

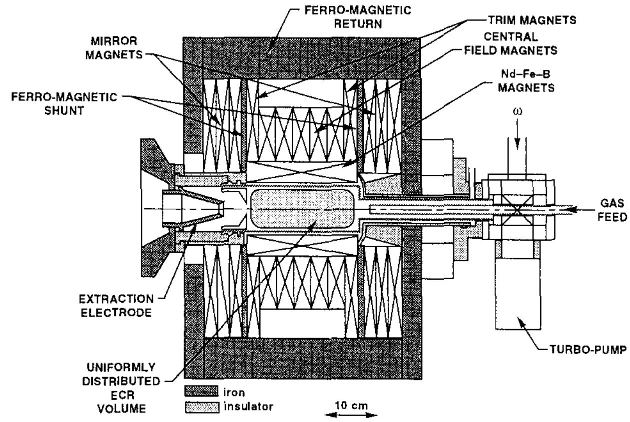

Fig. 2. Schematic drawing of the ECR ion source with large uniformly distributed ECR plasma "volume." The axial magnetic field profile for the source is shown in Fig 5. The RF frequency is assumed to be 6.45 Ghz

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.

6.1.1 Magnetic Field Design

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 $\mathbf{B}_z$ 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 $\boldsymbol{\phi}$, respectively. The appropriate set of Maxwell's equations for the interior (central) magnetic field configuration is

$$\nabla B = 0, \nabla\times B = 0, B_z \cong m_e \omega_c / e,$$

$$B_r = B_a\left(\frac{r}{r_a}\right)^m \cos(m+1)\phi, \qquad (3)$$

$$B_\phi = -B_a\left(\frac{r}{r_a}\right)^m \sin(m+1)\phi$$

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

6.1.2 The radial confinement magnetic field

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 (sextupole) radial field source with a flat axial magnetic field also will be effective for generating multiply charged ions. 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 region between the coils can be increased. 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 $\mathbf{r}^{N/2-1}$ (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 $\mathbf{F}_v$ which contains a uniform field to within a specified tolerance σ versus the number of cusps or coils **N** as determined from the $\mathbf{r}^{N/2-1}$ behavior, $\mathbf{F}_v = \sigma^{4/N-2}$. A rough estimate of the tolerance of the field may be taken as the Doppler width of the resonance, which is basically

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

where $\mathbf{k}_{\parallel}$ is a typical wave number of the RF power, and ρ_e is the electron gyroradius. 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. 4, 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 lower order multipole field (**N** = 6) sextupole results in a smaller volume of hot electrons which extends over the length of the ionization volume.

6.1.3 The axial magnetic field

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. 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. The trim coil is driven in an opposite direction to that of the main and mirror coils to cancel the mirror coil field toward the center of the device. Figure 5 contrasts the axial magnetic field distributions for the CAPRICE,[19,20] ECR3,[20] and NEOMAFIOS[21] ion sources with that of the new single frequency, "volume" ECR ion source concept.

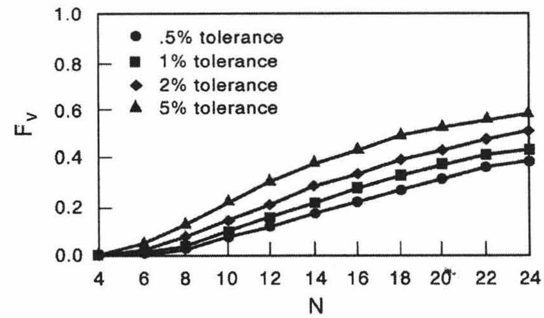

Fig. 3. The fractional plasma volume $\mathbf{F}_v$ which can be tuned to the ECR condition within a specified tolerance as a function of the number of cusps **N** in the radial magnetic field.

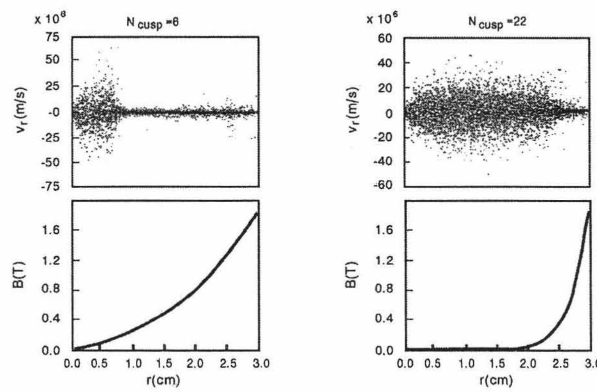

Fig. 4. Illustration of the effect of varying the number of cusps **N** on the volume of central (flat) magnetic field that can be tuned to the ECR condition for **N** = 6 cusps and **N** = 22 cusps. The transition from heated to non-heated regions of the plasma is very apparent from the plots of the 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.

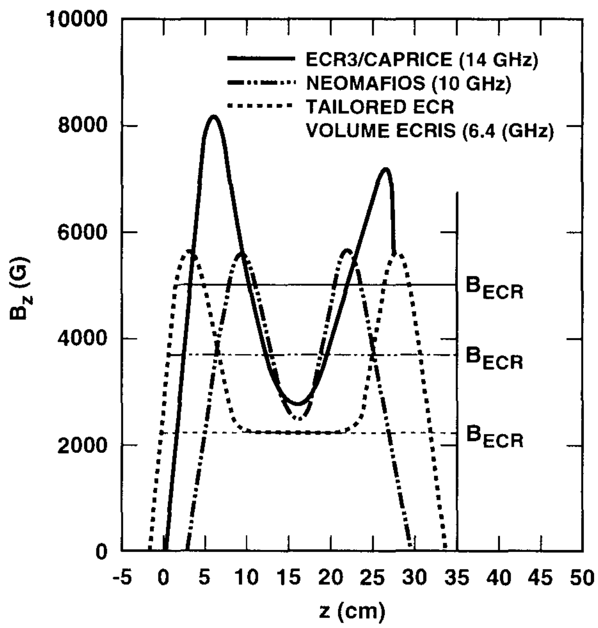

Fig. 5. Axial magnetic field profiles for the conventional magnetic geometry ECR3 source described in Ref. 20, the CAPRICE source, described in Refs. 19 and 20 and the NEOMAFIOS ECR source, described in Ref. 21.

6.1.4 *Electron heating studies*

Comparisons of electron heating of the "hot" electron population in conventional and single frequency, "volume" ECR ion source designs are compared in Fig. 6. The RF frequency for these cases was set at ~10 GHz. The microwave power is turned on after $\tau = 45$ 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. 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. The magnetic field

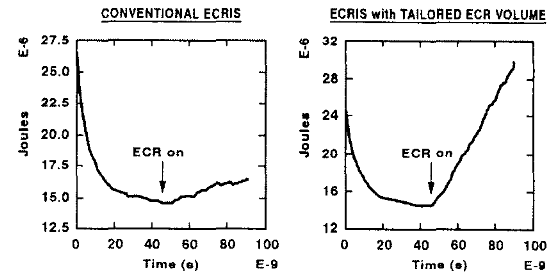

Fig. 6. ORNL-DWG 93Z-11212. Time behavior of the energies of hot electrons in a conventional ECR "surface"-type source and in the single frequency ECR ion source (Fig. 2) with a large uniformly distributed resonant plasma volume. The RF power is turned on after 45 ns. The rapid loss of energy in the first 20 ns by the hot electrons is due to single-pass losses of particles in unconfined orbits; these losses are slowed down by the establishment of the ambipolar electric 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.

6.2 *Frequency Domain Methods*

6.2.1 *Principles of Traveling Wave Tubes*

Operation of the traveling wave tube (TWT) is based on the transfer of energy between an electron beam and an RF wave; the transfer can only be efficient if the electron beam and RF wave are traveling at about the same velocity. Since the microwave travels at a velocity of about 100 times that of the electron in free space, a helical structure is used to slow the wave down so that their velocities are about the same. By directing the electron beam along the axis of the helix, the time varying electric field set-up on the helix causes the electron beam energy to vary according to the field strength. The resulting velocity modulation causes the electron beam to form bunches and as the bunches move through the helix, their sizes grow. The helix senses a time varying electric field from the electron bunches which induces an RF wave onto the helix of the same frequency as the initial RF wave, but greatly amplified. Power gains up to 70 db (10,000) can be achieved; a single tube can deliver several hundred watts of RF power.

TWTs can be used to generate variable-frequency, discrete multiple frequency or broad-band frequency power for injection through an appropriately sized wave guide for ECR ion source applications. The frequency domain techniques for increasing the resonant volumes in the ECR source concepts described below can be effected with standard traveling wave tube (TWT) technology that has been developed for military applications and more recently developed for processing materials when operated in the microwave regime.[22,23] A schematic drawing of a TWT based microwave power supply that could be used to effect increases in the resonant plasma volumes for any of the ECR concepts described in this report is shown in Fig. 7. The broadband frequency technique of choice can be effected by simply choosing the appropriate complex waveform signal generator.

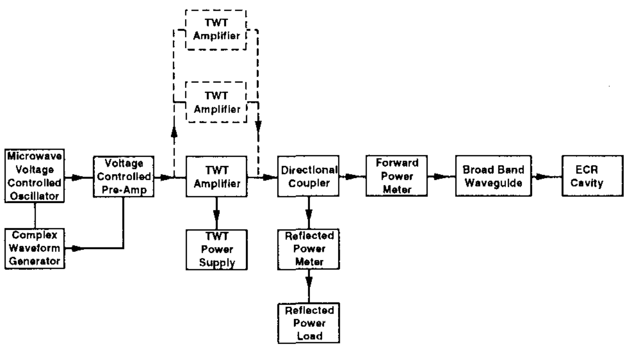

Fig. 7. Schematic diagram of a broadband, TWT based microwave power supply system for creating large resonant plasma zones in ECR ion sources with B-minimum magnetic field distributions. The complex wave form generator can be 1) a fast sweeprate, variable frequency signal generator; 2) a broadband frequency signal (noise) generator or; 3) a multiple, discrete frequency signal generator.

The ECR ion source concepts, described below, are based on the use of high power, broadband width microwave radiation to create large resonant plasma volume sources for multiply charged ion beam generation. The wave form of the signal generator for the TWT amplifier system, required for increasing the sizes of the ECR zones can either be: 1) fast scan rate, variable frequency; 2) broad-band frequency; or 3) multiple, discrete-frequency microwave radiation. In choosing the bandwidth of the TWT, care must be taken to ensure that the frequency distribution of the TWT is compatible with both the resonant frequency distribution of the confining magnetic field and the bandpass of the waveguide used to inject the microwave radiation into the source. The size of the ECR "volume" depends on the band width of the variable-frequency or broadband microwave power supply or the number of discrete frequencies introduced into the cavity, as well as the magnetic field distribution within the plasma volume. The methods for increasing the physical sizes of the ECR zones are frequency domain complements of the single-frequency, spatial domain technique described in Refs. 15 and 16. The new frequency domain ECR ion source concepts can easily be tested by simply replacing single frequency microwave radiation sources with high-power TWT based microwave power supplies in which the broadband output is generated by amplification of the outputs of selectively chosen complex waveform signal generators. The particular signal generator would replace the complex wave form generator schematically displayed in the block diagram representation of the TWT-based microwave power supply, shown in Fig. 7. This type of power supply has been successfully developed by commercial firms and applied for microwave sintering of ceramic materials and other material processing applications.[22,23] Retrofitting existing ECR ion sources can be easily accomplished by replacing the single-frequency microwave power supply with a broad-band, variable-frequency power supply and replacing the wave guide/microwave injection system with a low-loss system which will transmit all frequencies within the band width of the power supply.

6.2.2 The Variable Frequency ECR Ion Source Concept

This new ECR source concept is based on the use of variable-frequency power to generate and maintain the plasma derived from a TWT based microwave power supply. This source concept is schematically illustrated in Fig. 8. Microwave signals are generated by a voltage controlled oscillator; control voltages are used to vary the oscillator over the complete

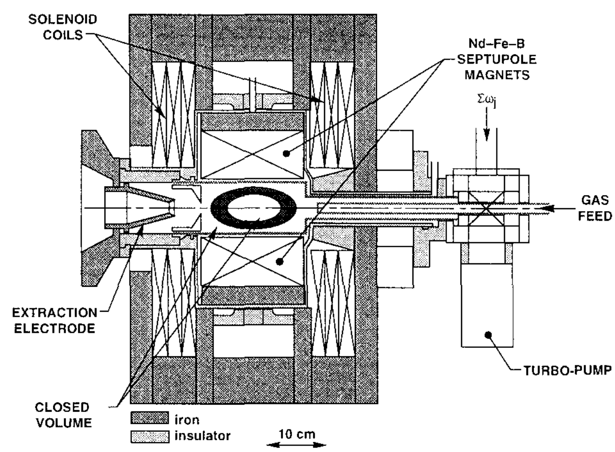

Fig. 8. Schematic illustration of an ECR ion source with a large, uniformly-distributed, ellipsoidal resonant plasma volume. The microwave power supply is assumed to be a broadband TWT based system driven with either of the following complex wave form generators: a) a variable frequency at fast sweep rate (< 1 ms) or; b) a broadband noise generator.

operating range of the power supply or a selected frequency range within the band width of the power supply; the microwave signal is passed through a preamplifier to provide equal power outputs for a given frequency. The forward power delivered by the traveling wave tube (TWT) and reflected power from the ECR cavity are sampled by the directional couplers and displayed on power meters. The TWT design can deliver power in the kW range and withstand relatively high levels of reflected power. Since the TWTs are rather expensive, the tolerance to reflected power is very important. The concepts can be effected by simply modifying the input signal to a traveling wave tube TWT amplifier system, such as illustrated in Fig. 7. In the variable-frequency scenario, the complex wave form generator is a variable frequency signal generator which is continuously swept through a selected frequency range at a sweep rate less than 1 ms. By sweeping the frequency at a sufficiently fast rate, power can be continually and more uniformly distributed over the resonant plasma volume. The ability to homogeneously distribute the power over the resonant plasma volume suggests that the stability of operation would be improved over that for a conventional source. Saturation effects are avoided since the ECR zone continually moves due to the changing frequency. However, it is not yet known whether or not this method will produce a stable discharge. It may be desirable to use two or more variable frequencies phased so that one signal is increasing while the other is decreasing so as to create a more homogeneous plasma. The frequency range is chosen to match the bandwidth of the waveguide and the resonance zone frequency distribution of the plasma confinement magnetic field. Since the sweep rate is less than the estimated confinement time τ of a low charge state particle in an ECR ion source, electrons can be accelerated to high energies during the sweep cycle. This scenario permits coupling of the total output power into the instantaneously discrete frequency whereas the total output power would be distributed among the frequency components present in multiple-discrete and broadband frequency ECR ion source concepts such as described below.

6.2.3 Broadband Frequency ECR Ion Source Concept

This scenario is also illustrated in the source concept shown in Fig. 8. This scheme, again, would incorporate TWT technology with an appropriately chosen broadband signal generator as the complex waveform generator in Fig 7. For this scenario, the power would be distributed across the band width of the frequency spectrum. The bandwidth of the frequency distribution would again be chosen to match the wave guide bandwidth and resonant frequency distribution of the magnetic field associated with the particular ECR ion source.

6.2.4 The Multiple, Discrete Frequency ECR Ion Source Concept

The ECR plasma volume also can be increased by exciting the plasma with multiple, discrete frequencies such as illustrated in Fig. 9. For this scenario, the complex wave form generator is a multiple, discrete frequency generator selected to fill the bandwidth of the wave guide. Again the set of frequencies is chosen to fit into the resonance frequency distribution of the particular ECR ion source. This technique can be easily effected by use of traveling wave tube (TWT) technology. The total power output would be distributed among the frequencies which are used. Two klystron based microwave power supplies could also be utilized, much like the system utilized at LBL,[17] to achieve a larger ECR zone within the source. However, this course of action would appear to be impractical for most situations because of the expense of microwave power supplies, wave guides and auxiliary equipment as well as complicating operation of the source. As well, there is a physical limit to the number of ports that can be practically incorporated on an ECR ion source. The expense can be reduced and the space related mechanical problems eliminated in part by use of a single, high power TWT based amplification system equipped with a multiple discrete frequency generator that fills the band width of a broadband wave guide used for injection into the source. Of course, these wave forms could be phased randomly or in some programmable way if beneficial in terms of operational stability or to enhance performance of the source.

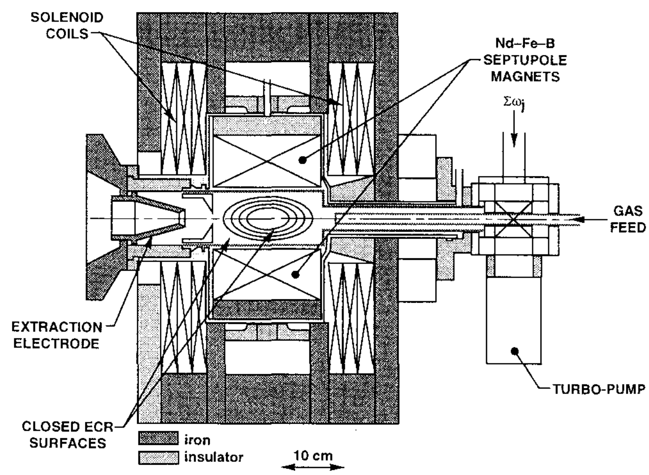

Fig. 9. Schematic illustration of an ECR ion source with multiple, ellipsoidal resonant surfaces. The microwave power supply is assumed to be a broadband TWT based system driven with multiple discrete frequencies.

7 Discussion

If successful, the ECR ion source concepts embodied in this article will significantly impact accelerator based research programs by providing higher energy ion beams for an extended number of heavy ion species with adequate intensities for heavy-ion atomic and nuclear physics research as well as for a variety of applied research and commercial applications. Creating a large ECR volume will result in significantly greater interaction of the microwave radiation with the plasma electrons, both in terms of total power absorptivity and in a more uniform spatial distribution of the absorptivity. This beneficial aspect of the presence of large ECR zone as well as the additional effect of accelerating much larger electron populations to much higher average energies are commensurate with higher charge states and higher ion beam intensities within a particular charge state. Based on the results of computational studies, presented in Ref. 15 and 16 and the recent experimental results of Ref. 17, give confidence that the bulk plasma ECR heating scenarios described in this paper will lead to enhanced performance ECR ion sources.

Acknowledgments

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