SCALING LAWS IN ELECTRON CYCLOTRON RESONANCE ION SOURCES *

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Abstract

In the last 36 years, the performance of high charge state ECRIS has improved dramatically as a result of improvements to the magnetic field confinement, increases in the microwave heating frequency and techniques to stabilize the plasma at high densities. For example, in 1980 15 eμA of O^{6+} was produced in an ECRIS[1] and now it is possible to produce as much as 4700 eμA. [2] In this paper the parameters and performance of ECRIS are reviewed and compared to empirical scaling laws to see what can be expected when fourth generation ECRIS begin to operate.

INTRODUCTION

Electron Cyclotron Resonance Ion Sources, ECRIS, are widely used to produce intense high charge state ions for accelerators used for nuclear physics and for hadron cancer therapy facilities. In nuclear physics, new heavy-ion driver accelerators are under construction and these machines require ion source production beyond the present day performance both in terms of ion charge states and ion intensities. In some ways, this parallels the efforts in the much larger field of magnetic fusion where the goal is to improve the performance beyond that of existing machines and demonstrate net power production. For many years the fusion community has used various scaling laws to both study the complex behavior of these plasma devices and to guide the design of future devices. For ECR ion sources, the search for and testing of scaling laws began with experiments in Grenoble in the 1970's, when the first high charge state ECRIS was built under Richard Geller's direction. During the last 40 years, the performance of ECRIS has progressed a great deal as illustrated with the 300 fold increase in O^{6+} currents going from 15 eμA to 4700 eμA. We now have a large number of ECRIS operating between 6.4 GHz and 28 GHz, built with a variety of shapes, sizes and operating parameters and these can be used to test existing scaling laws and perhaps uncover new ones.

Scaling laws for plasma devices can take several forms. In some cases they are used to describe the parameters of a single machine as a function of some external variable such as ECRH frequency, magnetic field confinement or RF power level. In other cases a scaling law could be used to summarize a general performance characteristic than can be applied across a wide variety of ECRIS sources. When this latter approach is applied to ECRIS, the result is often more qualitative than quantitative because there are a wide variety of source designs and only the very strong dependences will be clearly demonstrated.

Many aspects of the physics of ECR ion sources are well understood, such as the atomic physics of electron impact ionization and the magnetic confinement of plasmas and these processes can be simulated with computer codes. [3] However, the picture is not complete since these codes typically require that certain internal parameters be specified; such as the plasma density, electron energy distribution function, electron and ion confinement times and even the microwave electric field strength. Typically these parameters cannot be experimentally measured in an ECRIS plasma and so we have to rely on other methods to extrapolate ECRIS performance.

In this paper, we will review some of the scaling laws, which have been proposed over the years, and test them against to the data generated by the ECRIS now in operation. In addition we will look for new scaling laws or even rules of thumb that can help predict the performance of future ECRIS.

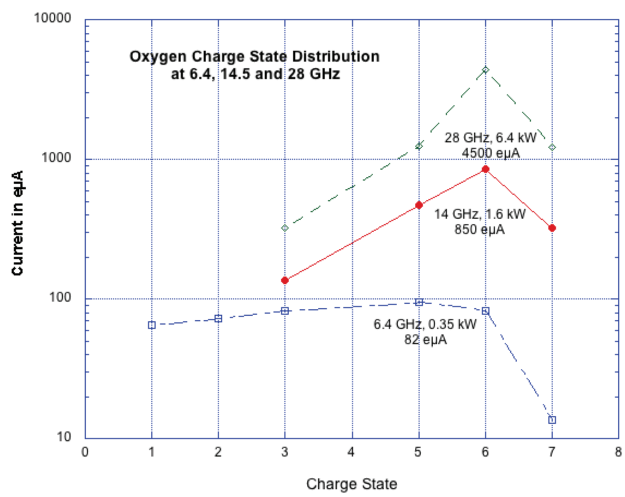

Figure 1: Oxygen charge state distributions produced on the 6.4 GHz LBL ECR, the 14 GHz AECR-U and VENUS at 28 GHz.

PHYSICS AND SCALING LAWS IN ECRIS

The physics and operation of ECRIS has been reviewed a number of times in depth. [4-6] This paper focuses on certain aspects of high charge state ECRIS, which could help in understanding the performance and scaling without an exhaustive review of the physics behind them. For the discussion that follows, it is still useful to briefly discuss the key plasma and physics mechanism in the production of high charge state ions in an ECRIS. For electrons in a magnetic field their cyclotron resonance frequency is given by

$$B_{ecr} = F_{rf}/28$$

where B_{ecr} is in Tesla and F_{rf} is in GHz.

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The plasma frequency, which arises from the oscillations between the electron and plasma densities, increases as the square root of the plasma density, ne, and the critical density defined by the density at which the plasma frequency is equal to the microwave frequency, F_{rf}, or

$$n_{crit} = 1.26 \times 10^{10} \ (F_{rf})^2 \text{ electrons/cm}^3,$$

where n_{crit} is in units of electrons/cm^3 and F_{rf} is in GHz. At the critical density, the propagation of microwaves becomes problematic. While over dense plasmas can be produced in ECR ion sources designed for 1^+ ion production, the electron temperature are only on the order 10 eV and the neutral densities are also very high and under these conditions no high charge state ions are produced. While direct measurements of the plasma density in high charge state ECRIS have not been done, modeling of ion charge state production indicate they operate at a fraction of the critical density.

Another important parameter of the a magnetically confined plasma is the ratio of the kinetic plasma pressure to the magnetic field confinement pressure, which is expressed by the dimensionless factor

$$\beta = P_{plasma}/[B^2/2\ \mu o]$$

where plasma pressure, $P_{plasma} \sim n_e k T_e$, depends on the electron temperature T_e and the plasma density n_e. For stability $\beta < 1$, and while the large fusion devices can achieve values of have $\beta \sim 1$, in high charge ECRIS β values are much lower, perhaps ~ 0.01, although the values are not well quantified because of the lack of direct measurement. [7]

One of the key aspects of high charge state ECR ion sources is the use of a minimum B magnetic field configuration consisting of a two solenoid mirrors to provide axial confinement and a superimposed multipole field, typically a sextupole, to provide radial confinement. The minimum B configuration stabilizes the outward plasma pressure described above and also reduces the electron losses. The combination of these effects results in ion and electron life times in the millisecond range compared to microsecond confinement times in simple mirror traps.

Much of the progress in the performance of ECRIS has come from increasing the magnetic confinement. Largely based on experimental results, the optimum fields have the following characteristics. The minimum B field generates closed surfaces of constant magnetic field and ideally there should be a closed surface inside the chamber with $B \geq 2\ B_{ecr}$. The injection field should be 3 B_{ecr} or more, the extraction field ~ 2 B_{ecr} and the radial field ~ 2 B_{ecr}. The large value of B_{inj} reduces the ends losses at injection and the lower value of B_{ext} increases end loss and extracted current. The optimum magnetic field strengths are summarized in Table I. [8]

While the injection, extraction and wall fields should be scaled directly with B_{ecr} or equivalently with F_{rf}, practical considerations may require limiting Bmin values below 0.75 T. Recent experiments on the 28 GHz VENUS ECRIS show that the spectral temperature of axial bremsstrahlung is depends linearly on B_{min} and that it is independent of B_{ecr} and F_{rf}.[9]. The increase in the spectral temperature with B_{min} indicates that the hot tail of the electron energy distribution function above 50 keV increases linearly with Bmin. The hot tail carries a significant proportion of the plasma energy and as it increases this causes two practical problems in superconducting ECRIS. First, bremsstrahlung generated by collisions of the hot electrons with the plasma chamber walls can penetrate into the cold mass and add an unwanted cryogenic heat load.[10] Second, the x-ray shielding requirements grow rapidly and the x-rays can also damage the high voltage insulation between the plasma chamber and magnet system. Additionally, excess energy in the hot tail may lead to turbulence, which reduces the global lifetime of the plasma and limits the production of high charge states.[11]

Table 1: Optimum Magnetic Field for ECRIS

Last Closed Bsurface	$\geq 2 * B_{ecr}$
B_{inj}	≥ 3 to 4 times B_{ecr}
B_{ext}	~ 2 B_{ecr}
B_{rad} at wall	~ B_{ext}~2 B_{ecr}
B_{min}	~ 0.4 to 0.8 B_{ecr}

Frequency Scaling

The most important scaling law, which was proposed by Geller[12] is that the current for a charge state q should scale as frequency squared,

$$I_q \propto F_{rf}^2.$$

This was based in part on the Grenoble measurements of the miniMafios sources at 10, 16 and 18 GHz and the Caprice sources at 10 and 14 GHz. Also, Geller pointed out that the since the critical density scales as frequency squared, that provides upper limit on plasma density, which scales with F_{rf}^2. [12] This simple relationship may be somewhat akin to Moore's Law in semiconductors, which was initially based on the observation that the number of transistors in an integrated circuit double approximately every two years. The semi-conductor industry was able to innovate fast enough to follow the law for a couple of decades. Similarly in the ECR community Geller's frequency scaling ideas have spurred the effort to build higher frequency, higher magnetic field ECRIS. In Fig. 1, the oxygen charge state distributions are shown for the LBL ECR at 6.4 GHz, the AECR-U at 14 GHz, and VENUS at 28 GHZ and these demonstrate how ion currents has grown with high microwave frequency sources.

Experimentally, this relationship only holds if the magnetic fields are scaled appropriately with frequency as described above in Table 1. An alternative explanation is that since B is scaled with frequency, then the scaling is actually due to the increase in magnetic field and that

$$I_q \propto B^2.$$

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With the requirement that frequency and magnetic field be scaled together, it is difficult to determine experimentally whether I_q goes as F_{rf}^2or B^2. From an ion source design point of view, it is not critical to decide, which is correct, as long as both B and F_{rf} are scaled as shown in Table 1.

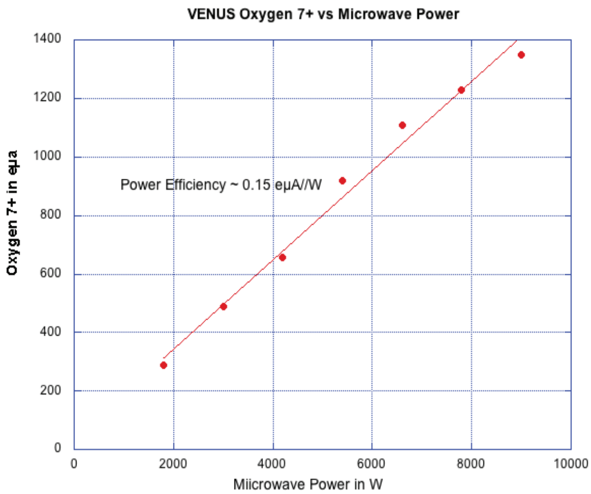

Figure 2: The linear dependence of O^{7+} current vs input microwave power measured on VENUS.

The output of a particular ion charge state depends on a number of variables including, the microwave power injected, the background pressure in the ion source or neutral pressure, presence of impurity ions in the plasma, which can improve the production of high charge states in the case of gas mixing [13] or depress the production when impurities higher mass than the desired ion. The charge state distributions have been successfully simulated when the plasma density, neutral density, electron energy distribution function and ion confinement time constant are considered variables[3]. These provide useful guidelines for understanding some aspects of ECR performance. For example the peak of the distribution depends primarily on the plasma density n_e, the ion confinement time τ_i and the electron energy distribution function, which usually approximated by a Maxwellian distribution for the electrons with a temperature T_e.

Scaling RF Power and Frequency

While the maximum ion currents produced in ECRIS roughly scale as frequency squared, the microwave power needed to produce those beams has also increased rapidly. Recent experiments with superconducting sources show that under certain conditions, the ion currents of a single ion charge state depend linearly on microwave power over a significant range of powers. [14] For example in Fig. 2, the O^{7+} ion current scales as 0.15 eµA per watt of microwave power between 1800 W and 8000 W as measured in VENUS. In this measurement, the neutral pressure was maintained at a constant value by increasing the input gas flow to adjust for the plasma pumping due to beam extraction. The charge state distribution stayed constant as did the spectral temperature. The linear behavior indicates the efficiency in converting microwave power into current remains unchanged while the power is increased a factor of 5. Other measurements on VENUS and SECRAL have shown a similar linear dependence with the power to current efficiencies for O^{6+} production between 0.7 and 1.2 eµA/watt. Since the maximum currents scale roughly as frequency squared and the current per W is linear, the power requirements for higher frequency sources should also scale as frequency squared. Scaling the VENUS source power at 10 kW and 28 GHz to a 45 GHz source would predict at least 26 kW would be needed and 40 kW would be needed at 56 GHz .[15]

As we have shown, the extracted current scales roughly as F_{rf}^2 or B^2 and this means that operation at higher frequencies and magnetic fields operation will increase the total extracted currents. This in turn will require higher source extraction voltages in order to control space charge effects. Although the beam current in an ECRIS typically does not increase as $V_{ext}^{3/2}$ when the Child-Langmuir law dominates extraction, the space charge of the beam after extraction does contribute to the transverse size of the beam and to maintain the same transverse dimensions V_{ext} should be scaled as $I_{tot}^{2/3}$. Assuming the total extracted current scales with the F_{rf}^2, then V_{ext} should be scaled as

$$V_{ext} \propto F_{rf}^{4/3}.$$

The VENUS source needs 30 kV to properly transport a total extracted current of 20 mA in high power operation and then V_{ext} should be at least 56 kV at for 45 GHz operation and 75 kV at 56 GHz. If an ECRIS at these frequencies were designed only for the production of very high charge state ions well above q_{opt}, then the total extracted currents would be somewhat less and it would require somewhat lower extraction voltage.

For the measurements shown in Fig. 2, the charge state distribution and the spectral temperature remained constant as the power was increased from 1.8 to 9 kW. This indicates that $n_e\tau$ and T_e were approximately constant. The ion current, which depends on n_e/τ, scaled linearly with power. These two conditions can only be met if n_e is proportional to $P^{1/2}$ and τ is proportional to $P^{-1/2}$. While further work is needed to understand the full implications of this, the linear nature of the process indicates that even at 10 kW of 28 GHz power, the plasma density is well below the critical density, where many nonlinearities would be evident.

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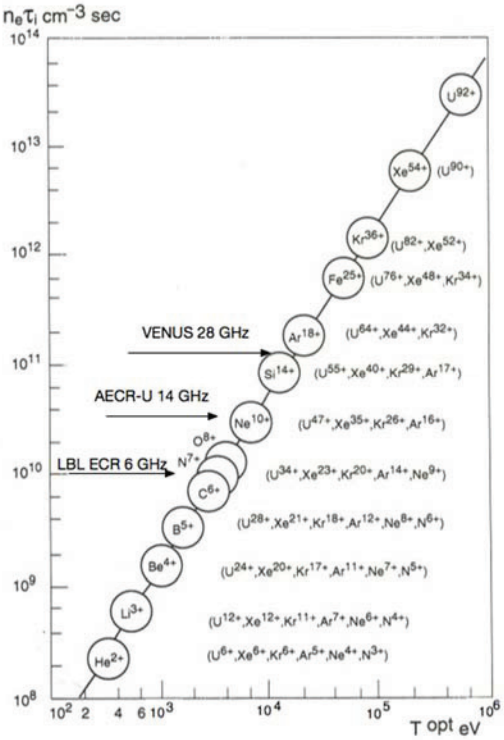

Figure 3: This illustrates the required values of $n_e\tau_i$ and optimum electron temperature to produce various ions.

The analysis of power scaling above was done for oxygen, which is a relatively light element and has relatively low ionization potentials. For example the ionization potential in oxygen going from 5 to 6^+ is only 146 eV and even 7 to 8^+ is only 836 eV. For much heavier elements such as xenon, the situation is more complex and a wide range of charge state distributions can be produced by varying the parameters of an ECRIS. Often useful intensities of ions can be utilized from the tail of the charge state distribution, well above the charge state, q_{opt}, which is defined as the ion charge state with the maximum electrical current. For example, q_{opt} for xenon in VENUS is Xe^{27+}, but Xe^{43+}, while produced at much lower intensities, is often used at the 88-Inch Cyclotron for radiation effects testing. For these ions with charge state far above q_{opt}, the scaling of intensity with frequency is stronger than F_{rf}^2 because q_{opt} increases with frequency. Figure 3 illustrates the requirements for high charge state production in terms of ($n_e\tau_i$) and electron temperature T_e. The ionization potential for going from Xe^{42+} to Xe^{43+} is 3 keV and the maximum electron impact ionization cross section K.S. Golovanivsky criterion[4] in Fig. 3 indicates that $n_e\tau_i$ in VENUS at 28 is about 10 times that for the 6.4 GHz source and this is reflected in the maximum current for very high charge states such as Ar^{16+} scaling much faster than frequency squared between the LBL ECR at 6.4 GHz and VENUS at 28 GHz.

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