# PHYSICS OF MULTIPLY CHARGED OXYGEN IN THE CONSTANCE B QUADRUPOLE MIRROR

C. Petty, D. Goodman, D. Smith, D. Smatlak

JOURNAL DE PHYSIQUE
Colloque C1, supplément au n°1, Tome 50, janvier 1989 

# PHYSICS OF MULTIPLY CHARGED OXYGEN IN THE CONSTANCE B QUADRUPOLE MIRROR

C.C. PETTY, D.L. GOODMAN, D.K. SMITH and D.L. SMATLAK

*Plasma Fusion Center, Massachusetts Institute of Technology, Cambridge, MA 02139, U.S.A.*

Detailed experimental measurements of multiply-charged ion densities, endloss currents, and temperatures have been made in a single cell quadrupole mirror. The purpose of these experiments is to determine the confinement physics of ions over a range of charge states in an ECR ion source. The parallel ion confinement times agree well with a theoretical model including Pastukhov and flow confinement for a potential dip of $\phi_i/T_i \sim 1$. The ion endloss currents were found to be up to 50% hollow. Radial transport of ions was found to be important in limiting the extraction of high charge state ions. In addition, by heating $O^{4+}$ with ion cyclotron resonance heating we were able to increase its extracted current in the plasma center by 25%.

## INTRODUCTION

Although ECR ion sources have been used for many years with great success, the physics behind their operation is not well understood. Of particular interest are the ion confinement times, which relate the ion density to the extracted ion current. We have determined the parallel ion confinement times for $O^{+}$ through $O^{6+}$ by measuring the ion densities, endloss currents, and temperatures in a quadrupole mirror for plasma parameters close to those of an actual ECR ion source. These confinement times were found to agree with a theoretical model including Pastukhov and flow confinement. In addition, experimental measurements of ion radial transport were made to determine its importance in ion confinement and extraction.

## I. THE CONSTANCE B EXPERIMENT

Constance B is a single cell quadrupole mirror in which hot electron plasmas ($\beta \sim 30\%$) are created with up to 4kW of fundamental ECRH /1/ /2/. This experiment has been extensively diagnosed over five years, accumulating a database of over 25,000 shots. The electron cyclotron resonance lies along a closed mod-$B$ surface shaped like an ellipsoid. Experimental analysis shows that the equilibrium pressure profile is approximately 50% hollow and is concentrated along a baseball seam curve. Typical operating parameters for oxygen are shown in Table 1. The extremely high temperature of the hot electrons is an indication of their excellent confinement in a quadrupole mirror.

## II. DIAGNOSTICS

Detailed experimental measurements of ion and electron densities, endloss currents, and temperatures for oxygen plasmas have been made in order to better understand the physics of ion confinement in an ECR ion source. The electron line density was measured using a microwave interferometer. By studying the decay rate of the density after turning off the ECRH, the electron

Table 1: Constance B parameters for oxygen plasmas.

| | |
|---|---|
| Hot electron density | $4.1 \times 10^{11}\mathrm{cm}^{-3}$ |
| Hot electron temperature | 450keV |
| Hot electron confinement time | 25msec |
| Cold electron density | $1.2 \times 10^{11}\mathrm{cm}^{-3}$ |
| Cold electron temperature | 90eV |
| Cold electron confinement time | 120$\mu$sec |
| Neutral pressure | $5 \times 10^{-7}$T |
| ECR power | 1kW |
| ECR frequency | 10.5GHz |

density was separated into two components: the cold electrostatically trapped electrons ($n_{ec}$) and the hot magnetically trapped electrons ($n_{eh}$). The cold electron temperature was found from the observed line ratio of $\lambda 4713\AA$ to $\lambda 4921\AA$ in helium. The hot electron temperature was determined from x-ray spectra measured with a Na(I) detector. The electron density profile was found from visible light pictures of neutral gas emission lines. Corrections were made to the brightness profile for magnetic geometry and the electron temperature profile. The electron density profile was measured in helium and argon plasmas, and found to be almost identical.

In order to determine the confined ion densities in the plasma, a vacuum ultraviolet (VUV) spectrometer was used to measure the brightness of several emission lines for each ion species. The brightness ($B_{ij}$) of an emission line is related to the ion line density by

$$B_{ij} = \frac{1}{4\pi}\left(\frac{A_{ij}}{\sum_k A_{ik}}\right)\int n_i\, n_{ec} < \sigma v >^{ex} dl, \tag{1}$$

where $A_{ij}$ is the Einstein coefficient for spontaneous emission, $n_i$ is the ion density of the ground state (or low metastable level), $n_{ec}$ is the cold electron density (the hot electrons contribute negligibly to the line brightness), and $< \sigma v >^{ex}$ is the electron impact excitation rate. The relative ion densities measured by the VUV spectrometer were scaled according to the electron density measured by the microwave interferometer,

$$\sum_i z_i n_i = n_{eh} + n_{ec}. \tag{2}$$

A significant fraction of the ions were found to be in metastable states and their contribution was included in calculating the total ion density.

A time-of-flight (TOF) analyzer /3/ was used to measure ion endloss current-densities and ion endloss temperatures. The relative particle currents were found from the heights of the analyzer output pulses. This data was then converted into particle current densities ($\Gamma_i$) by scaling it according to the ion electric current-density ($J_{\|i}$) collected by a Faraday cup located next to the TOF analyzer,

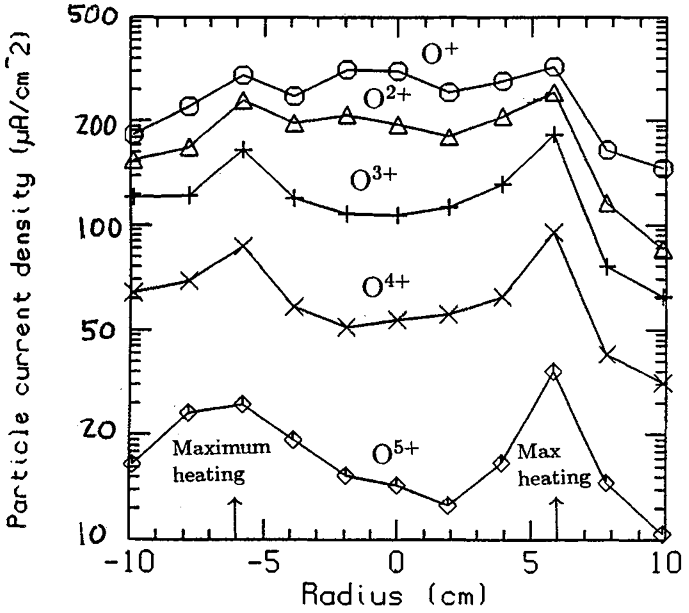
$$\sum_i q_i \Gamma_i = J_{\|i}. \tag{3}$$

One dimensional radial scans of the ion endloss were made using a pair of deflecting magnets which moved the mirror fan relative to the endloss detectors.

The energy distribution of each ion species was calculated from the rise time of its TOF analyzer pulse /3/, and its form fitted to a flow confinement model to determine the ion endloss temperature. In addition, the ion temperatures of $O^{+}$ through $O^{4+}$ were independently found from Doppler broadening of ion emission lines.

## III. EXPERIMENTAL RESULTS

The ion endloss current was found to be radially hollow, with the peak occurring at a radius where maximum electron heating occurs (see Figure 1). The degree of hollowness was not the same



for all charge states, however, with the higher charge states increasing more with radius than the lower ones. For example, the endloss current of $O^{5+}$ increases by a factor of two. Thus the amount of extracted ion current could be substantially increased by moving the extraction off axis. The endloss current of high charge states such as $O^{6+}$ were found to increase linearly with ECR power, up to the limit of 4kW.

The measured ion densities in the plasma center are shown in Figure 2. The ion densities were found to be monotonically decreasing with charge state, with higher charge states decreasing exponentially as

$$n_i \propto \exp(-0.5 z_i). \tag{4}$$

The ion densities and average ion charge state are strongly affected by the amount of ECR power. A factor of 3.4 increase in power increased the density of $O^{5+}$ by a factor of seven and increased the average ion charge state from 1.9 to 2.7.

The parallel ion confinement times were determined from the ion density and endloss particle current-density by the formula

$$\tau_{\parallel i} = \frac{n_i L_p}{\Gamma_i}, \tag{5}$$

where $L_p$ is the plasma length. A radial profile of the measured ion confinement times is shown in Figure 3 (since only the line averaged ion densities were measured, it was assumed that all charge states had the same radial profile). Two things to note are that the confinement is better in the center of the plasma, and that the confinement time increases with charge state. The latter is an indication of electrostatic trapping of the ions, which will be discussed in the next section.

Table 2 shows the average temperatures of confined ions measured from Doppler broadening of emission lines, with and without ICRH (see section V). The temperatures are an order of magnitude higher than can be explained from electron drag alone, although electron drag probably explains the slight increase in ion temperature with charge state. Most of the ion heating is anomalous, with the most likely cause being turbulent heating from the electron microinstability. Radial scans of the ion endloss temperature indicate that the ion temperature radial profile is flat. Under most plasma conditions, however, the measured ion endloss temperatures are substantially higher then

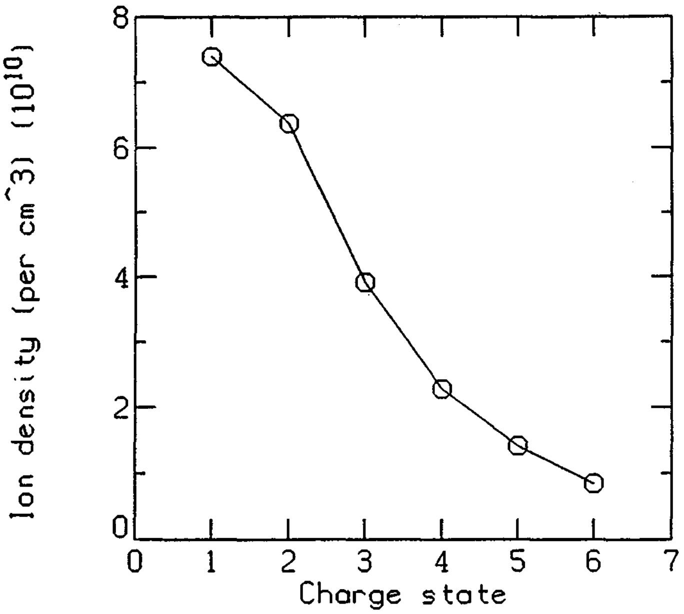



Figure 2: Measured ion densities from spectroscopy in the plasma center.

Figure 1: Measured ion endloss current-densities as a function of radius, mapped to the magnetic midplane.

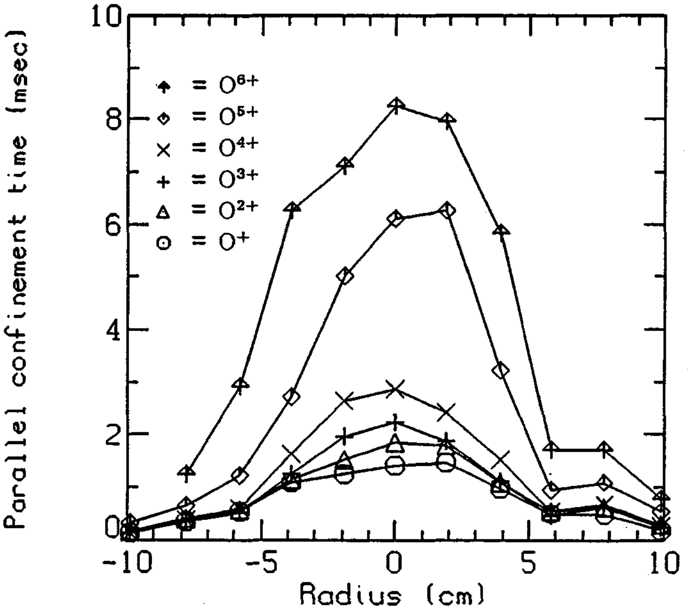



Figure 3: Measured parallel ion confinement times as a function of radius and charge state.

Table 2: Ion temperatures from Doppler broadened emission lines.

| Ion species | $T_i$ (eV) | $T_i$ (eV) with ICRH |
|---|---|---|
| $O^+$ | 17 | 39 |
| $O^{2+}$ | 18 | 100 |
| $O^{3+}$ | 22 | 344 |
| $O^{4+}$ | 23 | 609 |

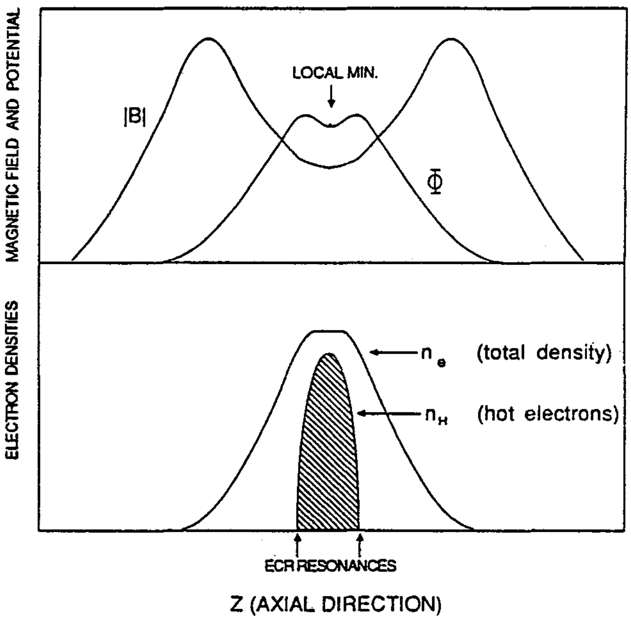



Figure 4: Model of magnetic and potential axial profiles.

the Doppler measured temperatures, with the disagreement increasing linearly with $z_i$. A possible explanation of this is given in the next section.

# IV. THEORETICAL MODELING

## A. Ion confinement

Parallel ion confinement is dependent upon the axial profiles of the magnetic field and potential. The vacuum magnetic field is well known, but there is as yet no accurate measurement of the potential profile. The potential model shown in Figure 4 is therefore proposed based on the following physical reasons:

1. If the cold electrostatically trapped electrons follow a Boltzmann distribution between the midplane and the mirror peak, with the electron density at the midplane being significantly larger, then the potential must decrease from the midplane to the mirror peak according to the relation
$$\frac{n_m}{n_0} = \exp[(\phi_m - \phi_0)/T_{ec}], \tag{6}$$
where the subscript 0 refers to the midplane value and $m$ refers to the value at the mirror peak.
2. The potential should dip in the region of the magnetically confined hot electrons. This is because the hot electrons have relatively long confinement times, forcing the electrostatic confinement of ions to neutralize them.
3. The anomalous linear rise in ion endloss temperature with charge state suggests the presence of Yushmanov-trapped ions, which are a special class of ions caught between a mirror peak and a central positive potential peak. As these ions fall down the potential hill and collide, they gain an amount of energy proportional to $z_i$. Under these conditions endloss temperatures are not an accurate measure of the confined ion temperature.

The majority of the ions are confined in the region of the potential dip. This is supported experimentally because no cold ions are observed in the endloss, as there would be if there were an ambipolar hole in the ion distribution function. The parallel ion confinement time in this region is given by the sum of the long and short mean-free-path confinement times. The long mean-free-path confinement time (collision time > bounce time) is given by the Pastukhov formula /4/ /5/,

$$\tau_p = \frac{\sqrt{\pi}}{4}\frac{1}{Z_i}\tau_c\left(\frac{q_i\phi_i}{T_i}\right)\exp\left(\frac{q_i\phi_i}{T_i}\right)G(RZ_i)\,I^{-1}\left(\frac{T_i}{q_i\phi_i}\right), \tag{7}$$

where $\phi_i$ is the potential dip,

$$Z_i = \frac{1}{2}\frac{\sum_j n_j q_j^2\lambda_{ij}}{\sum_j n_j q_j^2\lambda_{ij}(T_j/T_i)(m_i/m_j)}, \tag{8}$$

and

$$\tau_c = \left[4\pi\sum_j \frac{n_j q_i^2 q_j^2\lambda_{ij}}{m_i m_j v_i^3}\frac{T_j}{T_i}\right]^{-1} \tag{9}$$

is the ion collision time. The short mean-free-path confinement time (collision time < bounce time) is given by the flow formula,

$$\tau_f = RL_p\sqrt{\frac{\pi m_i}{2T_i}}\exp\left(\frac{q_i\phi_i}{T_i}\right). \tag{10}$$

The high collisionality regime in which ion confinement is governed by spatial diffusion,

$$\tau_{sd} = \frac{L_p^2 m_i}{\tau_c T_i}\exp\left(\frac{q_i\phi_i}{T_i}\right), \tag{11}$$

is only valid for $z_i \geq 7$ in Constance where $T_i \sim 20$eV. Ions lost out of the region of electrostatic confinement can become Yushmanov trapped, but since they are pitch angle scattered rapidly into the loss cone this does not affect the overall confinement time much except for low charge state ions.

Using the measured ion densities and temperatures, the theoretical ion confinement time parallel to the magnetic field becomes a function of only the potential dip ($\phi_i$). Figure 5 shows a least squares fit of the experimental ion confinement times to the theoretical model for the plasma center. A radial profile of the potential dip can be calculated from the measured confinement times at various radius, resulting in a potential dip which peaks on axis ($\phi_i = 15.4$V) and decreases to zero at a radius of 10cm.

## B. Ion particle balance

The ion particle balance in the plasma center has been modeled in a simple way, balancing ionization, charge exchange, and loss of confinement,

$$\frac{dn_i}{dt} = 0 = n_e n_{i-1} <\sigma v>_{i-1}^{ion} + n_0 n_{i+1} <\sigma v>_{i+1}^{cx} - n_e n_i <\sigma v>_i^{ion} - n_0 n_i <\sigma v>_i^{cx} - \frac{n_i}{\tau_i}. \quad (12)$$

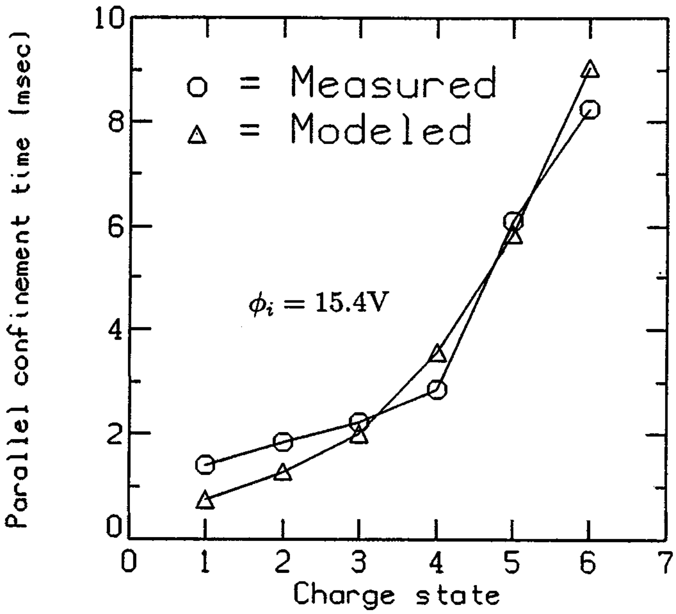



Figure 5: Experimental and theoretical ion confinement times parallel to the magnetic field for the plasma center.

Since radial transport is an important mechanism of ion loss, its effect has been included in determining the overall ion confinement time,

$$\tau_i = \left[\frac{1}{\tau_{\parallel i}} + \frac{1}{\tau_{\perp i}}\right]^{-1}. \quad (13)$$

At this time no accurate measurement of perpendicular confinement time for oxygen exists, but measurements in helium and argon show that the average perpendicular and parallel confinement times are about equal.

In solving Eqn. 12, the electron parameters were not calculated, but instead the experimentally determined values were used. Experimental values for the ion temperature and the potential dip were also used, since no accurate model exists for them as yet. The parallel ion confinement times were calculated from Eqns. 7 and 10 for each charge state. The perpendicular confinement time was assumed to be independent of charge state. All neutral gas was assumed to be atomic, and molecular processes were ignored. The predicted ion endloss current-densities from this model are shown in Figure 6 along with the experimentally measured values. Also shown are what the extracted ion currents would be if there were no radial transport. From this we concluded that radial transport can significantly degrade the performance of an ECR ion source by decreasing the overall ion confinement time with no resulting increase in the the extracted ion current for the plasma center.

# V. EFFECT OF ICRH

In general, only one ion species from an ECR ion source can be used at a time. Therefore any method of increasing the extracted current of that particular charge state would be useful. One such method is the application of ion cyclotron resonant heating (ICRH). The purpose is to heat a charge state to decrease its parallel confinement time and thus increase the amount of extracted current.

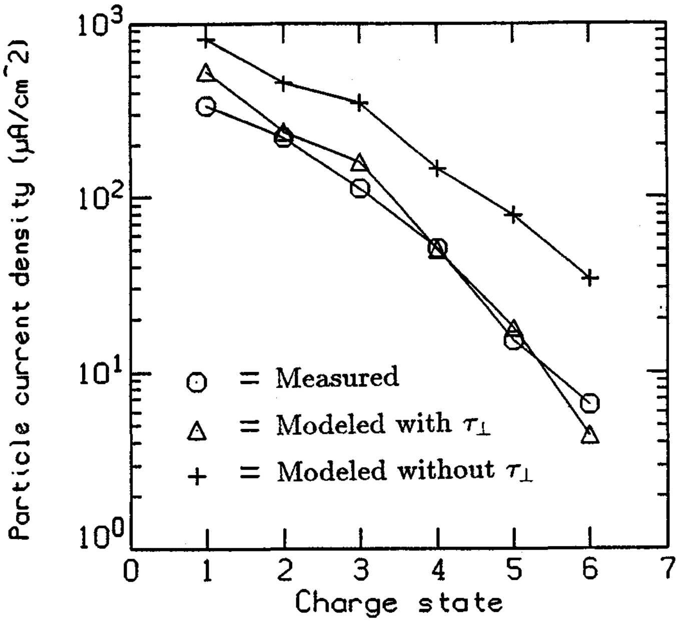



Figure 6: Experimental and modeled extracted ion particle current-densities (midplane values).

Experiments were done in oxygen plasmas using 2kW of ICRH tuned to the resonance frequency of $O^{4+}$. The amount of ion heating, seen in Table 2, was substantial. The result was that in the plasma center the amount of $O^{4+}$ extracted increased by 25%. However, the total amount of $O^{4+}$ extracted over the whole plasma cross section actually decreased. Since ICRH has been previously found to increase the amount of ion radial transport, this is believed to limit the benefit ICRH has on high charge state extraction.

## ACKNOWLEDGMENTS

This work was performed under U.S. Department of Energy Contact No. DE-AC02-78ET51013.

/1/ R.S. POST, *et. al.*, Plasma Physics and Controlled Nuclear Fusion 1984: Tenth Conference Proceedings, London, 12-19 September 1984 (IAEA, Vienna, 1984), Vol. 2.
/2/ D.L. SMATLAK, X. CHEN, B.G. LANE, S.A. HOKIN and R.S. POST, Phys. Rett. Lett. **58** (1987) 1853.
/3/ C.C. PETTY, D.K. SMITH and D.L. SMATLAK, Rev. Sci. Instrum. **59** (1988) 601.
/4/ R.H. COHEN, M.E. RENSINK, T.A. CUTLER and A.A. MIRIN, Nuclear Fusion **18** (1978) 1229.
/5/ F. NAJMABADI, R.W. CONN and R.H. COHEN, Nuclear Fusion **24** (1984) 75.