EXPERIMENTAL OBSERVATIONS AND MODEL CALCULATIONS OF
IMPURITY RADIATION IN A PLASMA GUN COMPACT TORUS EXPERIMENT*

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INTRODUCTION

Several types of radiation measurements were performed on the Beta II compact forms experiment.¹ Among these are time integrated spectra ranging in wavelength from the VUV to the UV, time resolved bolometer measurements of radiation from the x-ray to the infrared, and time and wavelength resolved measurements of certain spectral lines. It is difficult to relate any one of these measurements to plasma parameters of interest such as temperature, density, or impurity content. In this report we compare the results of these, and other measurements with two simple models of the power balance in the plasma in order to estimate the effect of carbon and oxygen impurities on plasma lifetime.

MEASUREMENTS

In Fig. 1 we show a densitometer trace of a spectrum on photographic film taken with a 1-m grazing incidence spectrograph. The spectrograph had an f/50 aperture and viewed the plasma along a chord diagonally through the center of the flux conserver where its projected area was approximately a circle of 3 cm diameter (see Fig. 2). An exposure of 20 shots was necessary to obtain a useful exposed film density. As a result of identifying the spectral lines it is apparent that the major sources of radiation are carbon and oxygen. In particular it is seen that the largest signal is seen for the CIV 1548-1550 Å resonance line. Also of interest is the relatively small Lyman alpha line at 1216 Å.

10/16/80
20 shots

Fig. 1. Densitometer trace of a spectrograph taken by superimposing 25 shots.

Fig. 2. Schematic layout of Beta II showing the location of various diagnostics.

Complementing the time integrated spectra time resolved (submicrosecond) wavelength integrated measurements of emitted power were made using a PZT-pyroelectric detector.² This detector viewed along a major diameter of the flux conserver. The detector was calibrated using the known output (10 W) of an argon ion laser (λ 5134 Å). The calibration related the detector current to the power incident on the detector. This was then related by geometrical considerations to the average emitted power in the field of view. Assuming the plasma in the entire flux conserver volume emitted at this same average level the total emitted power and energy was calculated and compared with the magnetic energy. In Fig. 3 the emitted radiation energy is plotted as a function of the magnetic energy of the configuration at the time the configuration is fully formed (80 μ s). It is apparent that essentially all the magnetic energy is being radiated away.

In Fig. 4 we show the intensity as a function of time for three carbon lines; CIII 2297 Å, CIV 1548 Å, 1550 Å, and CV 2277 Å. These measurements were made using a 0.3 M grating monochrometer with a sodium salicylate scintillator - photomultiplier combination as detector. For these conditions the CIV line rises at the time the magnetic structure first builds up in the flux conserver and radiates strongly for the entire lifetime. Also we note the close proximity of the CIII and CV lines ($\Delta\lambda = 20$ Å) and the large difference in signal strength. Since the calibration is approximately the same for these two nearby lines, the CIII intensity is much larger than the CV intensity. Assuming that the carbon density remains constant after the flux conserver is filled, these observations lead to the conclusion that CIII and CIV are emitted from the gun and that electron temperatures (T_e) in the range of 10-30 eV are maintained during the decay.

Fig. 3. Plot of radiated energy vs magnetic energy of Beta II plasma.

Fig. 4. Oscilloscope traces of the intensity of three carbon lines. The intensity and time scales are the same for all traces. The initial rise of the signals corresponds to the time the plasma and magnetic field enters the flux conserver.

Finally He-Ne laser interferometer measurements indicate that the line averaged electron density (n_e) along a major diameter is about $2 \times 10^{14} \text{ cm}^{-3}$ for the cases discussed here. Also magnetic probe and flux loop measurements indicate that the field decays on a characteristic timescale of about $150 \text{ } \mu\text{s}$.^{2,3}

POWER BALANCE MODELS

Based on our belief that the major energy loss is line radiation from carbon and oxygen ions we have developed two simple models of the power balance, including radiation losses, to try and find a model of decay which agrees with the observations. In one model, called the ionization rate equation model, the differential equations governing the evolution of the different stages of ionization of carbon and oxygen are integrated and the radiation from each stage is estimated by calculating the electron-impact excitation rate from the ground state to the first excited state. The second model, called the coronal equilibrium model, utilizes previous rate equation calculations in which the densities of excited states in different ionization stages were calculated for constant temperature and the radiation output found when coronal equilibrium has occurred, i.e., when the distribution of ionization stages becomes constant. In utilizing this model it is assumed that temperature changes occur slowly enough that the system slowly evolves through a series of coronal equilibrium. Recombination is the slowest process which determines whether coronal equilibrium occurs. For the temperatures and densities occurring here, the ions will be reasonably close to equilibrium if the temperature does not change too rapidly (eg., in less than $10 \text{ } \mu\text{s}$ timescale). Nevertheless we use both models to compare with each other and the experiment.

IONIZATION RATE EQUATION CALCULATIONS

We assume as initial conditions what we believe to be the parameters characteristic of the plasma entering the flux conserver from the gun. Values for the electron temperature, current density, deuteron density, and density of the different stages of ionization of carbon and oxygen are chosen as initial conditions, and the time evolution of these quantities are calculated using the appropriate differential equations.

The density $n_{i,z}$ of ions of species i and charge state z are calculated from the equation

$$\frac{dn_{i,z}}{dt} = -S_{i,z} n_e n_{i,z} - R_{i,z} n_e n_{i,z} + S_{i,z-1} n_e n_{i,z-1} + R_{i,z+1} n_e n_{i,z+1}$$

where $S_{i,z}$ is the ionization rate coefficient given by⁴

$$S_{i,z} = \frac{2.5 \cdot 10^{-6} Q_{i,z} (T_e)^{1/2} \exp(-E_{i,z}^{\infty}/T_e)}{E_{i,z}^{\infty} (T_e + E_{i,z}^{\infty})} \text{ cm}^3/\text{s}.$$

In this equation $E_{i,z}^{\infty}$ is the ionization potential and $Q_{i,z}$ is the number of electrons in the outer shell. In this formula and the formulas given below energy and temperature units are electron volts (eV). The recombination rate coefficient $R_{i,z}$ is the sum of radiative recombination and dielectronic recombination. The radiative rate⁵ is

$$R_{i,z}^r = 5.2 \cdot 10^{-14} z \left(\frac{E_{i,z}^{\infty}}{T_e} \right)^{1/2} \left[0.429 + 0.5 \ln \left(\frac{E_{i,z}^{\infty}}{T_e} \right) + 0.469 \left(\frac{T_e}{E_{i,z}^{\infty}} \right)^{1/3} \right] \text{ cm}^3/\text{s}.$$

For the dielectronic recombination we use an effective rate which estimates the required sum over all the relevant, quantum states⁶

$$R_{i,z}^d = 4.14 \cdot 10^{-9} Q_{i,z} \left(\frac{Z+2}{n_{v,z}} \right)^{8/3} \frac{(Z-1)^2}{T_e^{5/2}} \exp(-E_{i,z}^*/T_e) \text{ cm}^3/\text{s}$$

where $E_{i,z}^*$ is the first excitation potential of ion i,z and $n_{v,z}$ is the principle quantum number of the ion ground state.

To estimate the radiation loss from each stage of ionization we assume that the ion is formed, and usually found, in its ground state and that it is excited by electron impact. Furthermore we assume for each excitation there is a subsequent re-emission. For the excitation rate we use the Maxwellian average rate⁷

$$\epsilon_{i,z}^{mn} = 1.65 \times 10^{-5} f_{i,z}^{mn} G_{i,z} \frac{\exp(-E_{i,z}^{mn}/T_e)}{E_{i,z}^{mn}/T_e} \text{ cm}^3/\text{s}$$

In the excitation rate $f_{i,z}^{mn}$ is the absorption oscillator strength for the transition between states m and n , $G_{i,z}$ is the Maxwellian averaged Gaunt factor, and $E_{i,z}^{mn}$ is the energy difference between the two states. Because transitions between nearby energy levels have the highest rate, it appears likely that of the transitions from the ground state those to the first excited state are more likely than transitions to more highly excited states. In addition collisionally induced transitions between excited states are more likely than radiative transitions. For these reasons we consider only transitions between the ground state and the first excited state as controlling the radiative power output. For the power density emitted from each stage of ionization we take

$$p_{i,z}^{01} = \xi E_{i,z}^{01} \epsilon_{i,z}^{01} n_e n_{i,z} \text{ ergs/cm}^3/\text{s}$$

whereby 01 we mean that we use parameters characteristic of the ground state "0", and the first excited state "1". The factor ξ accounts for radiation emitted by other resonance lines and excited state. We take $\xi = 2$ in the work reported here. No attempt is made to account for photo-absorption.

The energy lost by radiation and gained by Ohmic heating is accounted for by use of a simplified zero dimensional power balance equation,

$$\frac{3}{2} n \frac{dT_e}{dt} = \eta_{||} j^2 - \sum_{i,z} P_{i,z}^{01},$$

in which we use either Spitzer-Harm resistivity ($\eta_{||} = 0.57 \cdot 10^{-14} \Omega \ln T_e^{-3/2}$) or a phenomenological anomalous resistivity ($\eta = 5 \times 10^{-15} \Omega$) which was chosen to give the observed 150 μ s decay time. The current density is initially started at some value, typically 0.4 kA/cm^2 , and allowed to freely decay by Ohmic dissipation.

$$\frac{dj}{dt} = -\frac{j}{\tau}$$

where the decay time τ is the longest decay time associated with the Bessel function model for the spheromak magnetic configuration

$$\tau = \frac{4\pi}{n_{||} c^2} \frac{1}{\left[\left(\frac{3.83}{R_s} \right)^2 + \left(\frac{\pi}{L_z} \right)^2 \right]},$$

R_s and L_z are the separatrix radius (37.5 cm) and length (40 cm), respectively. In this formulation we have neglected any collisional coupling to the ions.

The equations are then integrated forward in time assuming initial conditions for each of the variables. Since the model has no spatial variations in it, we are implicitly assuming average quantities which are felt to be typical of regions of the plasma where the energy gain and loss are most important.

DISCUSSION OF RATE EQUATION RESULTS

In Fig. 5 we show the results of a calculation in which we assumed a deuterium density of $5 \times 10^{13} \text{ cm}^{-3}$, a carbon density of $8 \times 10^{13} \text{ cm}^{-3}$ and an oxygen density of $5 \times 10^{12} \text{ cm}^{-3}$. In addition both the carbon and oxygen densities are assumed at time zero to be 50% in the second stage of ionization (CIII, OIII, $Z = 2$) and 50% in the third stage of ionization ($Z = 3$). These fractions give an electron density of $2.6 \times 10^{14} \text{ cm}^{-3}$ at $t = 0$. Furthermore we take an initial electron temperature of 10 eV and a current density of 0.4 kA/cm^2 . The integration is performed using a fourth-order Runge-Kutta technique in steps of $0.2 \text{ } \mu\text{s}$ for a total time of $80 \text{ } \mu\text{s}$. In this case we see that the temperature remains between 7.5 and 12 eV while the Z_{eff} ranges from 2.2 to 2.3. During the $80 \text{ } \mu\text{s}$ of the calculation the current is seen to decay almost linearly. We then define a computational decay time as

$$\tau_c = \frac{J(0)}{J(0) - J(80)} 80 \text{ } \mu\text{s} .$$

For the case shown in Fig. 5 the decay time is $160 \text{ } \mu\text{s}$. Note that if we use an average temperature of 10 eV, Z_{eff} of 2.25 and $n_e = 2.6 \times 10^{14} \text{ cm}^{-3}$ the exponential decay time is only slightly longer, $216 \text{ } \mu\text{s}$. The radiation output from this "representative" unit volume of plasma is at the rate of 0.8 to 1.6 kW/cm^3 . If the entire plasma volume (175 liters) radiated this energy density the total energy radiated would be 18.1 kJ. The intensities of the CIII and CIV resonance lines are shown in the bottom panel of Fig. 5 in relative units. Here we see that for these conditions the CIII line is approximately an order of magnitude more intense than the CIV line. In the next panel up we see that the electron density (which in this model only changes by ionization and recombination) changes very little ($\sim 10\%$) while the fraction of CIV ions remains approximately at its initial value of 50%.

Fig. 5. Time dependence of various quantities computed from the rate equation model.

In conclusion this particular case agrees with the experimental current decay rates quite well. Intuitively one feels that the current decay rates are of a global character, i.e., the decaying current at one location affects the current elsewhere, so it is probably most reasonable to match current decay rates in the model with experimental flux and field decay rates. On the other hand it is not clear how to relate the radiation output calculations to the experiment, since the radiation output is sensitive to local conditions of temperature and density. At best one can hope for a rough agreement for both total radiation and line intensity ratios. If the spatially averaged emission rate is a third the rate calculated here, the total energy radiated would be 6 kJ which agrees very well with the experiment. Because of the wide separation of wavelengths of the observed CIV lines (1540 Å) and the CIII line (2297 Å) it was not possible to obtain a useful relative calibration at these two wavelengths. Nevertheless the temporal behavior of the lines in the calculation is qualitatively similar to that seen in the experiment. In addition at the calculated 10 eV temperatures, very little CV emission is predicted. Because the CV line at 2277 Å is near the CIII line the instrument sensitivity is probably not changed in this interval. Since the observed CV emission is very much less than the observed CIII emission, there is agreement between the calculation and experiment on this point as well.

A variety of calculations with other starting conditions have also been performed. In Fig. 6 we show calculational decay times as a function of carbon density for two different deuterium densities. All other conditions are the same as in Fig. 5. We see that there is a very steep radiation barrier below which there is very little change in decay time. If there is a large carbon density, a substantial reduction may be necessary before a large increase is observable in the decay time. Additional calculations were done

Fig. 6. Calculational decay times as a function of carbon density n_C for two values of deuterium density from the rate equation model.

with the carbon content fixed and the oxygen density varied. Similar behavior to the carbon variation is seen for these calculations in Fig. 7. To check whether the initial temperature was an important factor, the calculations were repeated with the initial temperature increased from 10 eV to 40 eV. These results are shown in Figs. 8 and 9. The effect of temperature is to increase the density at which the precipitous drop in decay times occurs. The saturation of decay times at large impurity levels is seen to be the same as for low initial temperatures.

Since the resistivity involves Z_{eff} one expects that if the plasma emerging from the gun has a higher initial charge state than we have assumed the heating and decay rates would be different. To observe this effect we assumed the initial carbon and oxygen had 50% of the ions triply ionized (CIV and OIV) and 50% with a charge of four (CV and OV). The decay times, for otherwise the same conditions as Fig. 6, are shown in Fig. 10. Again we see the saturation in decay times at large carbon densities. In this case, however, the decay times are shorter since the Z_{eff} remains large due to the inability of CV to recombine significantly on the shot timescale. Since the experimental decay times agree well with the calculations with no CV or OV it seems reasonable to assume the gun is not emitting these ions.

Finally, the question of anomalous resistivity must be addressed. Since the current density is high there might be streaming or drift instabilities present which produce a high level of electrostatic turbulence which enhances the effective electron collision frequency. First, without discussing which microinstabilities are likely to be important, let us assume a constant value of resistivity which gives the approximate observed decay time of 150 μs ($\eta \approx 5 \times 10^{-15}$ s). If there is no mechanism to turn the instability off, strong heating will result below some critical value of impurity density.

Fig. 7. Calculational decay times as a function of oxygen, density n_{oxy} for two values of deuterium density from the rate equation model.

Fig. 8. Calculational decay times as a function of carbon density for two values of the initial electron temperature and a deuterium density of $1.5 \times 10^{14} \text{ cm}^{-3}$.

Fig. 9. Calculational decay times as a function of oxygen density for two values of the initial electron temperature and a deuterium density of $1.5 \times 10^{14} \text{ cm}^{-3}$.

Fig. 10. Calculational decay times as a function of carbon density for the same conditions as in Fig. 6 except that the initial carbon and oxygen are 50% CIV and OIV and 50% CV and OV.

This is illustrated in Fig. 11 where we show the electron temperature at 40 μ s for a variety of carbon impurity densities. In reality, one expects some temperature dependent switch. For example with the ion-acoustic instability when $T_e \gg T_i$ if the drift speed drops below the ion acoustic speed $[(kT_e/M_i)^{1/2}]$ the instability turns off. For our current densities and $n = 2 \times 10^{14} \text{ cm}^{-3}$ the switching temperature would be $T_s = 160 A \text{ eV}$, where A is the atomic mass number of the ions. This temperature is sufficiently high that intense CV emission should have been observed at some time during the experiment if the impurity level were low. On the other hand if the impurity level were sufficiently high the temperature would equilibrate at about 8 eV for a wide range of carbon densities. At these temperatures and densities $T_e = T_i$ and the ion-acoustic instability would not be excited. It seems that for our conditions with the current parallel to the magnetic field, the ion-acoustic instability is the most likely microinstability to contribute to anomalous resistivity. Comparing 2-D computer simulations and analytic theory in which non-linear stabilization occurs via ion tail formation Krall and Davidson⁸ predict the resulting resistivity will be in the range $0.06 \omega_{pe}^{-1} < \eta < 0.6 \omega_{pe}^{-1}$. For a density of $2 \times 10^{14} \text{ cm}^{-3}$ this gives $7.5 \cdot 10^{-14} < \eta < 7.5 \cdot 10^{-13} \text{ s}$, the lower limit of which is approximately an order of magnitude too large to give the decay times observed. For these reasons it does not appear that the ion-acoustic instability is likely to be active here.

CORONAL EQUILIBRIUM CALCULATIONS

The second approach used to model the radiative power loss from Beta II makes use of the corona equilibrium calculation of Post, et. al.⁹. In

Fig. 11. Electron temperature at 40 μs for a plasma with anomalous resistivity of $\rho = 5 \times 10^{-15} \text{ s}$, other conditions the same as Fig. 6.

coronal equilibrium the rate of ionization is balanced by the rate of recombination for each ionization stage of each species, resulting in constant ionization fractions. If the densities do not change the radiation rate can be calculated for a given temperature. Post, et al. used the rate equations for the change of density of the different ionization stages along with the excitation equations for various radiation emitting transitions and allowed the system to evolve in time at constant temperature to coronal equilibrium. Doing this for a range of temperatures, they were able to find polynomial expressions for the radiation per particle for different elements as a function of temperature. Assuming then that enough time is available to reach coronal equilibrium and that the temperature varies slowly enough that a new coronal equilibrium is quickly established as the temperature changes, we may use their formulas to estimate the radiation loss.

In this case the equations used are the power balance equations for electrons and ions

$$\frac{3}{2} n \frac{\partial T_e}{\partial t} = n_{II} j^2 - p_r - n(T_e - T_i) f_{ei} - p_t ,$$

$$\frac{3}{2} n \frac{\partial T_i}{\partial t} = n(T_e - T_i) f_{ei} .$$

Here f_{ei} is the collision frequency for energy equilibration between electrons and ions and p_r is the radiation loss term for each summed over the impurity ion species i ;

$$p_r = \sum_i n_e n_i 10^{L_i} ,$$

$$L_i = \sum_{j=0}^5 A_j [\log_{10}(T_e/1000)]^j ,$$

The coefficients A_j are from the tables of Post, et al, and as before T_e is in eV. Polynomial expressions are also given by Post, et al.⁹ for the average charge state $\langle Z \rangle$ and the mean square charge state $\langle Z^2 \rangle$,

$$\langle Z \rangle = \sum_{j=0}^5 \left(B_{j,c} \frac{n_c}{n_d} + B_{j,oxy} \frac{n_{oxy}}{n_d} \right) [1.05(T_e/1000)]^j$$

$$\langle Z^2 \rangle = \sum_{j=0}^5 \left(C_{j,c} \frac{n_c}{n_d} + C_{j,oxy} \frac{n_{oxy}}{n_d} \right) [\log_{10}(T_e/1000)]^j.$$

In these expressions n_c , n_{oxy} , and n_d are the density of carbon, oxygen and deuterium ions respectively, and the B and C coefficients are taken from the tables of Post, et al. The electron density and the effective charge, Z_{eff} , used in the resistivity are computed from these quantities in the following way:

$$n_e = n_d(1 + \langle Z \rangle),$$

$$Z_{eff} = \frac{1 + \langle Z^2 \rangle}{1 + \langle Z \rangle}.$$

The decay of the plasma current is treated in an identical fashion to the rate equation method. Finally other power losses beside radiation, have been included. For the Beta II parameters discussed here the only significant additional classical loss process is electron thermal conduction along the magnetic field lines from the flux conserver region to the gun during the formation phase when field lines are open. This of course is only important prior to the completion of reconnection, which we take to be the first 30 μ s. During this time we take the power density due to electron thermal conduction to be

$$p_t = \frac{1.9 \cdot 10^{21} T_e^{3/2}}{\ln \Lambda \lambda^2} \frac{\text{eV}}{\text{cm}^3 \cdot \text{s}}$$

where $\ln A$ is the Coulomb logarithm, T_e is expressed in eV and the length ℓ is taken to be 30 cm, 100 cm or in finite. At times later than 30 μ s it is assumed that the field lines have closed and this loss is eliminated.

DISCUSSION OF CORONA EQUILIBRIUM RESULTS

In Fig. 12 we show the output for a case in which the initial conditions were: $T_e = T_i = 40$ eV, $n_d = 1.5 \times 10^{14} \text{ cm}^{-2}$, $n_c = 0.6 n_d$, $n_{\text{oxy}} = 0.1 n_d$, and $j = 0.4 \text{ kA/cm}^2$. The time dependence for the first 100 μ s of these and other quantities are shown in Fig. 12. In the top panel of this display we have drawn an average magnetic field, the details of which are not important for this study except to note that $j = kB$ where $k = (0.4/3.5) \text{ kA/kG-cm}^2$. Again we see an almost linear decay of j for an appreciable period of time. Using currents at $t = 0$ and $t = 100 \mu$ s the linear decay time as previously defined is 385 μ s for this case. More interesting for our present understanding is the temporal behavior of the radiation output (P-RAD) and the Ohmic heating power (P-OHMIC) both of which are displayed in units of eV/ μ s/particle. We see at early times the power radiated is about twice the Ohmic heating power. As a result the plasma cools, further increasing the radiation loss until the temperature drops significantly increasing the Ohmic dissipation until power balance is achieved which for this level of impurities occurs at a temperature of about 8 eV. A schematic view of the power flow and temperature variation is shown in Fig. 13. Point A in the diagram corresponds to $t = t_0 = 0$. As time progresses the temperature drops increasing the resistivity, causing the system to evolve to point B at $t = t_1$, where $P\text{-RAD} = P\text{-OHMIC}$. Because the temperature has dropped the electron density also drops, due to recombination, so that at succeeding times the radiative power at a given temperature

Fig. 12. Time dependence of various quantities computed from the corona equilibrium model.

Fig. 13. Corona equilibrium radiative power and Ohmic heating power as a function of temperature.

decreases. In addition because of Ohmic dissipation the current decreases and new equilibria are found where $P\text{-OHMIC} = P\text{-RAD}$. Since the radiative power is such a steep function of temperature at low temperature, the power balance is maintained at a relatively constant temperature during the decay.¹⁴

In a similar fashion to the rate equation calculations we have determined the field and current decay rates as a function of carbon and oxygen concentrations. In Fig. 14 we plot the decay times as a function of the oxygen density for an initially 10 eV plasma with $n_d = 0.5 \times 10^{14} \text{ cm}^{-3}$, $n_c = 0.1 n_d$, and $j = 0.4 \text{ kA/cm}^2$. Again we see a rapid drop in decay time as the oxygen density passes a critical value. We see a qualitative similarity between this curve and Fig. 7, although in the latter case the drop is not nearly so rapid and the decay rate at large impurity levels is about half the value in Fig. 14.

A greater degree of similarity, between the two models is obtained for the situation where the carbon density is varied. This is shown in Fig. 15 where we have plotted three cases; $\ell = \infty$, 100 cm, and 30 cm, corresponding to different amounts of thermal conduction losses as noted previously. For the case with no conduction losses ($\ell = \infty$) we find that the sharp drop in decay times is at about $n_c/n_d = 1.4$. By inspection of Fig. 6 we see that the critical density is the same for both models. At larger impurity levels the corona equilibrium model again gives longer decay times than the rate equation model by a factor of 1.5 to 2. Finally we see that parallel conduction losses are only important at impurity levels below the critical value.

Fig. 14. Calculational decay times as a function of oxygen density from the corona equilibrium model.

Fig. 15. Calculational decay times as a function of carbon density from the corona equilibrium model for three different values of electron temperature parallel gradient scale lengths.

CONCLUSIONS

Experimentally it is observed that for a wide variety of conditions the current decay time is approximately 150 μ s. Using both a corona equilibrium model and a simplified rate equation model we have observed a critical impurity density above which there is very little change in the decay time and which has approximately the right magnitude to agree with the experiment. Because of this observation, as well as the large amounts of emitted radiation observed, it seems reasonable to assume that the experiment is operating below the radiation barrier. For an electron density of about $2 \times 10^{14} \text{ cm}^{-3}$, and predominately carbon impurities, it appears that the ratio of carbon to deuterium ions is greater than approximately 2 to 5 depending on the exact value of the deuterium density. The location of the radiation barrier can be estimated from the corona equilibrium model for a given impurity species by equating the maximum of the power radiation curve to the Ohmic heating power at the temperature characteristic of the peak (e.g., 7 eV for carbon).

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