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NEUTRAL BEAM HEATING IN TFTR

BY

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Charge Exchange Recombination Spectroscopy Measurements in the Extreme Ultraviolet Region of Central Carbon Concentrations During High Power Neutral Beam Heating in TFTR

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ABSTRACT

The carbon concentration in the central region of TFTR discharges with high power neutral beam heating has been measured by charge-exchange recombination spectroscopy (CXRS) of the C^{+5} $n=3-4$ transition in the extreme ultraviolet region. The carbon concentrations were deduced from absolute measurements of the line brightness using a calculation of the beam attenuation and the appropriate cascade-corrected line excitation rates. As a result of the high ion temperatures (20-30 keV) in most of the discharges, the contribution of beam halo neutrals to the line brightness was significant and therefore had to be included in the modeling of the data. Carbon concentrations have been measured in discharges with $I_p=1.0-1.6$ MA and beam power in the range 2.6-30 MW, including a number of supershots. The results are in good agreement with carbon concentrations deduced from the visible bremsstrahlung Z_{eff} and metallic impurity concentrations measured by x-ray pulse-height analysis, demonstrating the reliability of the atomic rates used in the beam attenuation and line excitation calculations. Carbon is the dominant impurity species in these discharges; the oxygen concentration measured via CXRS in a high beam power case was 0.0006 of n_e , compared to 0.04 for carbon. Trends with I_p and beam power in the carbon concentration and the inferred deuteron concentration are presented. The carbon concentration is independent of I_p and decreases from 0.13 at 2.6 MW beam power to 0.04 at 30 MW, while the deuteron concentration increases from 0.25 to 0.75 over the same range of beam power. These changes are primarily the result of beam particle fueling, as the carbon density did not vary significantly with beam power. The time evolutions of the carbon and deuteron concentrations during two high power beam pulses, one which exhibited a carbon bloom (a sudden influx of carbon due to local heating of the limiter) and one which did not, are compared. In both types of discharge, the carbon concentration decreases early in the beam pulse as a result of beam particle fueling, and the carbon density rises slowly during the beam pulse until the start of the bloom. The electron density rise during the bloom is primarily due to the increase in the carbon density.

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1. Introduction

Carbon is the primary limiter and wall armor material in the current generation of large tokamaks, TFTR [1,2], JET [3], JT-60 [4], and DIII-D. As a result, it is the dominant plasma impurity in most operating regimes of these tokamaks and is usually the major contributor to Z_{eff} and the radiated power. Thus, accurate measurements of the carbon concentration play a crucial role in evaluating plasma performance in these devices.

In previous work on TFTR [1,2], the carbon concentration was inferred from Z_{eff} derived from visible bremsstrahlung measurements. This was done by subtracting from Z_{eff} the metallic impurity contribution measured by ultraviolet spectroscopy or x-ray pulse-height analysis (PHA) and allotting the remainder to carbon, oxygen, and deuterons according to a measured carbon to oxygen density ratio which was obtained by impurity transport code modeling of brightness of ultraviolet lines emitted by C^{+5} and O^{+7} (for details, see ref. 1). Because the spectrometer line-of-sight did not view across a neutral beam, these lines were primarily excited by electron impact and modeling them provided a measurement of the impurity influx in the plasma periphery. Assuming similar transport of the fully ionized carbon and oxygen ions, the transport code was used to deduce the carbon to oxygen density ratio in the plasma core. This ratio was found to be insensitive to uncertainties in plasma parameters (n_e , T_e , impurity transport coefficients, etc.) and atomic rates used in the code and could, therefore, be used with confidence. However, this technique provides an indirect measurement of the carbon concentration in the core region of the discharge. Because knowledge of the core carbon concentration is important, it is desirable to make a direct measurement independent of the visible bremsstrahlung Z_{eff} . For this reason, we have measured the core carbon concentration in a variety of TFTR discharges with high-power neutral beam heating using charge exchange recombination spectroscopy (CXRS) [5] of the $n=3-4$ transition of C^{+5} , which occurs in the extreme ultraviolet (EUV) region of the spectrum at 521 Å.

The initial results of this study are presented in this paper. Carbon concentrations from CXRS are compared with values deduced from the visible bremsstrahlung Z_{eff} and x-ray PHA measurements of metallic impurity concentrations and are found to be in good agreement, demonstrating the reliability of the atomic rates used in the beam attenuation and line excitation calculations. We discuss a problematic aspect of making CXRS measurements of C^{+6} in high ion temperature discharges: the significant contribution to the line brightnesses of beam halo neutrals produced by charge exchange of the beam atoms with plasma deuterons.

The discharges studied here had plasma currents in the range 1.0-1.6 MA and beam power in the range 2.6-30 MW, with most of the discharges having beam power in the 15-30 MW range. These plasmas were produced by beam injection into low electron density target plasmas formed using a minimum amount of deuterium (prefill only) in a vacuum vessel with a well-conditioned limiter. The discharges with nearly balanced beam injection at higher power

were supershots [6]. Previous studies of carbon behavior in TFTR concentrated on discharges with ohmic heating only and lower power beam heating (up to 15 MW) [1,2]. In this paper we document the central carbon concentration at high beam power as a function of beam power and plasma current and as a function of time during the beam pulse. Such documentation may help to elucidate the role of carbon impurities in supershots.

2. TFTR parameters and spectrometer viewing geometry

The CXR-excited lines were observed using SPRED [7], a multichannel spectrograph which covers the 100-1100 Å region. A 450 g/mm grating, which yields a spectral resolution of 2.0 Å (line FWHM), was used. Detector integration times were in the 0.017-0.1 s range. SPRED has been radiometrically calibrated [8] using synchrotron radiation from the National Bureau of Standards SURF II electron storage ring. The accuracy of the calibration is estimated to be $\pm 30\%$. At the beginning of the period of TFTR operation discussed here, this calibration was compared at several wavelengths with calibration points obtained using the branching ratio technique and data from a visible spectrometer viewing the same region of the plasma as SPRED; good agreement was found. As shown in figure 1, SPRED views the plasma with a radial line-of-sight lying in the plasma midplane.

Figure 1 also shows the arrangement of the heating beams on TFTR. There are four injectors: injectors 1 and 2 fire in the counter direction relative to the usual direction of the plasma current and injectors 4 and 5 fire in the co-direction. Each injector has three ion sources sharing a common neutralization gas cell and produces three independent beams, designated a, b, and c. As seen in figure 1, the spectrometer line-of-sight intersects the beams from the counter injectors 1 and 2, but not those from the co-injectors, which are on the opposite side of the torus. The tangency radii of the beams from injectors 1 and 2 and the radii at which these beams intersect the spectrometer line-of-sight are listed in Table I. Each beam has a width of approximately 0.2 m and a height of 0.6 m in the region of intersection with the spectrometer line of sight. The discharges had a major radius of 2.45 m and a minor radius of 0.79 m. It is clear from figure 1 and Table I that the injector 1 and 2 beams span almost the entire plasma diameter along the spectrometer line-of-sight. In general, several or all of the beams from injectors 1 and 2 were fired simultaneously; the CXR-excited line emission was, therefore, not well localized radially. However, due to the longer path length to reach the region of intersection with the spectrometer line-of-sight, the contribution from all three injector 2 beams to the total brightness of a CXR-excited line was 10% or less of that from one of the injector 1 beams. For this study, the only discharges chosen were those in which at least one of the beams 1a or 1b was on. Discharges with beam 1c only were not used. Also, discharges with high power beam heating usually have Shafranov shifts in the range 0.1-0.2 m [9], placing the plasma axis close to the radius at which beam 1a intersects the spectrometer line-of-sight. Thus, in the discharges studied here, the CXR-excited lines are primarily emitted from the core

region of the discharge ($r/a < 0.5$).

All of the data presented here are from a group of 40 deuterium plasmas with deuterium beam injection of 0.5-1.0 sec duration into the plasma current flat top period of the discharge. As previously mentioned, the beam power was in the 2.6-30 MW range and the plasma current was in the 1.0-1.6 MA range. The discharges were limited on the small major radius side by a graphite toroidal belt limiter. The target plasmas for beam injection were prefill-only with a well-conditioned limiter. The role of limiter conditioning in producing supershots is discussed by Ulrickson *et al.* [10]. Additional information on discharges with high power beam heating during this period of TFTR operation is given by Bell *et al.* [9]. With the exception of a few shots at low total beam power, the beams were operated at 90-110 keV energy and 2-3 MW injected power per source. (The exceptions were 4 shots at low beam power, where the beams were operated at 80 keV and 1.4 MW per source.) The distribution of power among the primary, half, and one-third beam energy components, was 0.7:0.2:0.1. The beam injection was balanced or close to balanced in all but a few of the shots. The important exceptions are the two shots at the lowest beam power, 2.6 MW, which had counter injection only. These shots are included to make a comparison with the carbon content of the plasma before beam injection.

3. Modeling of CXRS data

CXRS on tokamaks has been discussed extensively in the literature [11]; here we summarize briefly the concepts relevant to the present experiment. The CXR reaction used to measure the C^{+6} concentration is

where the carbon ion is left in a state denoted by principal quantum number n and orbital angular momentum quantum number ℓ . There is an analogous reaction for oxygen. The state $n\ell$ is usually an excited state, and the captured electron cascades down to the ground state via a series of radiative decays.

The population of the excited states depends on n and ℓ in the following way [12]. For carbon, the capture of the electron occurs primarily into levels with $n=n_{\max}$ equal to 4 and 5, and, for oxygen the most probable levels for capture are those with $n_{\max}=5-6$. The lines used in the present work, C^{+5} 521 Å and O^{+7} 293 Å, are due to $n=3-4$ transitions and, therefore, originate from levels at or below $n_{\max}$. At the energies of the TFTR heating beams, the most probable ℓ for capture is $\ell_{\max}=(n_{\max}-1)$.

The captured electron decays according to the selection rule for electric dipole radiation: $\Delta\ell=\pm 1$. Thus, the decay process tends to populate the states with $\ell=n-1$ in preference to those with lower values of ℓ , and, as a result, the $\Delta n=1$ transitions are the most intense. However, the line intensities can be changed by various ℓ -mixing processes which cause transitions between states of different ℓ and the same n [5]. These processes are ion-ion collisions, the motional Stark effect, and the Zeeman effect. The effect of these processes is to shift the distribution of

population for a given n to lower values of l , decreasing the intensities of the $\Delta n=1$ transitions and increasing the intensities of the $\Delta n>1$ transitions. If the mixing processes for the levels within a given n are rapid compared to the radiative decay rates for transitions originating at these levels, the population of the l levels within that n approaches a statistical distribution. Because the radiative decay rates decrease with increasing n and the mixing rates increase, this situation is reached for an $n=n_{\text{crit}}$, above which it is reasonable to assume a statistical population distribution among the l levels for a given n . Values of n_{crit} in C^{+5} have been estimated for collisional mixing and the motional Stark effect using expressions given by Fonck *et al.* [5,13] assuming the following parameters, which are typical of the central region of TFTR discharges with high-power beam heating: $T_e=20$ keV, $Z_{\text{eff}}=3$, and $n_e=5 \times 10^{19} \text{ m}^{-3}$. These results are summarized in Table II and demonstrate that $n_{\text{crit}}=5$ is a reasonable value for C^{+5} in TFTR. Note that the two values of n_{crit} given for collisional mixing, $n_{\text{crit}}=4$ obtained using the criterion of Pengally and Seaton [14] extrapolated to fusion plasma parameters [5] and $n_{\text{crit}}=7$ from the criterion of Sampson [15], bracket $n_{\text{crit}}=5$. (A detailed discussion of these criteria for the onset of collisional mixing is given in references 5 and 13.) Because T_e , n_e , and Z_{eff} vary logarithmically in these expressions, $n_{\text{crit}}=5$ applies to a wide range of these parameters in TFTR and was used in the work discussed here.

The brightness B of a line excited by CXR with beam neutrals is given by [5]

$$B = 1/4\pi \sum_{j=1}^3 \langle \sigma v \rangle_j \int n_z n_j ds \quad (1)$$

In this expression, the index j refers to the beam component with energy E_1/j (E_1 being the primary energy of the beam), $\langle \sigma v \rangle_j$ is the excitation rate coefficient for the observed line evaluated at the energy of the j th beam component, n_z is the impurity ion density, and n_j is the particle density of the j th beam component. The integration path is the spectrometer line of sight. If significant, a contribution from thermal neutrals such as halo neutrals could also be included in equation 1. To emphasize the importance of the contribution of halo neutrals to the line brightness in the present work, halo neutrals will be treated as a separate line excitation mechanism in section 5.

The excitation rate coefficient $\langle \sigma v \rangle_j$ is the product of the cascade-corrected CXR cross section and the velocity of the j th beam component. The cascade-corrected cross sections used here are those of Fonck *et al.* [5], obtained using radiative branching ratios for hydrogen-like ions and assuming a statistical distribution of the population among the l levels for $n \geq n_{\text{crit}}$ and no mixing for $n < n_{\text{crit}}$. The CXR cross sections used to calculate the cascade-corrected cross sections are from Shipsey, Green, and Browne [16,17] for energies less than 30 keV/u, Olson [5] at 40 keV/u, and Ryufuku and Watanabe [18,19] at 50 keV/u and higher energies. For transitions originating from upper levels with $n \leq n_{\text{max}}$, such as those observed here, these cross sections are in good agreement with line excitation cross sections measured at 2-12 keV/u

by Ciric *et al.* [20].

As seen from equation 1, the beam particle density must be known to deduce the impurity density from the measured brightnesses of a CXR-excited line. The density of beam particles at each of the three energies is calculated using a beam attenuation code which includes the processes of charge exchange and ionization of beam atoms due to collisions with electrons, deuterons, and impurity ions. Also included are the processes of excitation of the beam atoms due to collisions with ions and electrons, which are important [21] because the electron loss cross sections for beam atoms in excited states are large. At the energies of the TFTR heating beams, including excitation processes in the beam attenuation calculation typically results in a 20% reduction in the beam particle densities at the intersection of the injector 1 beams and the spectrometer line of sight compared to values obtained not including excitations; these processes are therefore significant and must be included in the calculation. Measured T_e and n_e profiles are used in the modeling; the beam attenuation is insensitive to the density profile shape and the magnitude of T_e . The ionic composition of the plasma is assumed to be deuterons and carbon with concentrations corresponding to $Z_{eff}=3$, a value typical of TFTR discharges with high power beam heating. The Z_{eff} profile is assumed to be flat, in agreement with measurements of Z_{eff} profiles in beam-heated and ohmic TFTR discharges [22]. In a typical case, varying Z_{eff} from 1 to 6 at constant n_e changes the beam particle densities by only 5%, so the deduced impurity concentrations are not sensitive to the value of Z_{eff} assumed in the beam attenuation calculation. The weak dependence on Z_{eff} in this energy region is due to the nearly linear dependence of the electron loss cross section for the beam atoms on the charge of the target ion and to the small contribution of electron impact ionization.

Equation 1 is evaluated for all of the beams in the spectrometer line of sight, and the results are summed to yield a total predicted line brightness assuming a given impurity concentration. The same impurity concentration is assumed for all the beams. Because the beams cross the spectrometer line of sight at different major radii, this is equivalent to assuming an impurity concentration that is constant with major radius, which is consistent with the observed flat Z_{eff} profiles.

To conclude this discussion, it is interesting to compare the merits of lines in the visible and EUV regions of the spectrum for absolute measurements of low-Z impurity concentrations. The cross sections for populating the lower-lying levels (up to $n=5-6$ in carbon and oxygen) which produce the EUV lines are better known than for the higher n levels which produce the visible lines. At low energies, excited beam atoms can cause significant excitation of visible lines, while this effect is negligible for the EUV lines [23]. The EUV lines are also brighter than the visible lines, but this advantage is usually offset by the greater efficiency of optical systems in the visible region. In a reactor environment, the visible region does have the clear advantage that fiber optics may be used to transmit the light to a remotely located spectrometer, eliminating the difficulties of shielding EUV spectrometers against radiation.

4. Example of Data and Analysis

As an example of the data and analysis, we consider data from a supershot at 1.6 MA plasma current, 5.1 T toroidal field, and 30 MW total beam power. The beam energy was 110 keV. This shot produced a high neutron flux (4×10^{16} neutrons/s) and exhibited exceptional energy confinement [9]. All of the neutral beams were fired from 3.5 s to 4.5 s from the start of the discharge, raising $\bar{n}_e$ from $1.1 \times 10^{19} \text{ m}^{-3}$ in the target plasma to $4.0 \times 10^{19} \text{ m}^{-3}$ at 4.0 s. After 4.0 s, $\bar{n}_e$ rose rapidly to $5.1 \times 10^{19} \text{ m}^{-3}$ at 4.3 s and dropped thereafter. The density rise was accompanied by a drop in the stored energy and the neutron flux and by a rise in the influx of carbon from the limiter. This phenomenon, termed the "carbon bloom," is often seen in TFTR discharges with beam power above 20 MW. The following discussion refers to the period of the beam pulse prior to the onset of the bloom; the time evolution of the carbon concentration during a bloom is discussed in section 7.

Figure 2 shows the spectrum in the 100-600 Å region during the first 0.1 s of the beam pulse and, for comparison, during the 0.1 s period just preceding the start of the pulse. The prominent CXR-excited lines are labeled with the principal quantum numbers of the transition; also labeled are several lines emitted by lower charge states of carbon, C^{+3} and C^{+2} , which are emitted from the plasma edge and are primarily excited by electron impact. Figure 2 shows many of the observed $\Delta n=1$ and $\Delta n>1$ lines of carbon and oxygen; several other observed $\Delta n>1$ lines too weak to be discernable on the scale of figure 2 are not labeled. Analysis of the relative intensities of these lines can provide information on the accuracy of the cross sections and on the degree of l-mixing present; this subject will be discussed in a separate paper. It is clear from figure 2 that, while the intensities of all the lines increase at the start of the beam pulse, the intensities of the CXR-excited lines increase much more than those of the electron-impact excited lines. This characteristic behavior of the CXR-excited lines is seen clearly in figure 3, which compares the time evolutions of the C^{+5} 521 Å and C^{+3} 312 Å lines. The intensity of the CXR-excited C^{+5} 521 Å line increases by a factor of 60 at the beginning of the beam pulse and then continues to rise only gradually for the remainder of the beam pulse. In contrast, the intensity of the electron-impact excited C^{+3} line rises slowly for the first 0.5 s of the beam pulse and then doubles starting at 4.0 s when the carbon bloom starts. Measurements with higher time resolution show that the initial rise in the intensities of the CXR-excited lines occurs in a time shorter than 0.017 s, the duration of the shortest detector integration period used, and is coincident with the start of the beam pulse.

The O^{+7} 293 Å line shown in figure 2 is quite weak compared to the corresponding $n=3-4$ line in C^{+5} at 521 Å. Since the spectrometer sensitivity is over three times greater at 293 Å than it is at 521 Å, this indicates that the oxygen concentration is much smaller than the carbon concentration. This is substantiated by modeling the brightnesses of these lines as described in section 3 to obtain carbon and oxygen concentrations 4.0 s into the discharge; the carbon concentration was 0.06 of $\bar{n}_e$ and the oxygen concentration was 0.0009. Thus, the oxygen

content of this discharge was negligible. The oxygen content of the other discharges discussed in this paper was also negligible. As a check on the accuracy of the CXRS measurement, the carbon concentration was compared with a value deduced from the visible bremsstrahlung (VB) Z_{eff} by subtracting the metallic impurity contribution and allotting the remainder to carbon and deuterons. The VB Z_{eff} was 2.64 and the metallic impurity (iron, nickel and chromium) contribution to Z_{eff} measured by x-ray PHA was 0.59, yielding a carbon concentration of 0.035. The CXRS value of the carbon concentration is in poor agreement with the VB value. As will be shown in the following section, the cause of this discrepancy is that halo neutrals make a significant contribution to the total line brightness.

5. The Contribution of Beam Halo Neutrals to the Line Brightness

A similar analysis of the C^{+5} 521 Å line was carried out for the group of 40 shots described in section 2. A comparison of the CXR carbon concentrations and the values deduced from the VB Z_{eff} is shown in figure 4a. The CXR measurement tends to yield larger values than the VB measurement, particularly in shots with the lowest values of the VB carbon concentration; these shots were those with the highest beam power and density. Agreement at the highest values of the carbon concentration is good. Because the same line was used throughout, this lack of agreement cannot be due to errors in the spectrometer calibration, and, since the beam energy varied little in this group of shots, it is not caused by inaccurate excitation rates.

The cause of this discrepancy is significant excitation of the CXR-excited lines by halo neutrals produced by charge exchange of beam neutrals with plasma deuterons. In previous measurements [5,24] of low-Z impurity concentrations in tokamak plasmas with ion temperatures of several keV or less, halo neutrals were estimated to make a negligible (10-20%) contribution to the total signal and were, therefore, ignored. This was a result of the fact that, although the halo neutral density can be comparable to the beam neutral density, the velocity of the halo neutrals at low ion temperatures is small, and, hence, $\langle\sigma v\rangle_{\text{halo}}$ is small. This is not true in TFTR discharges with high power beam heating, which often have ion temperatures in the 20-30 keV range. For C^{+5} 521 Å, $\langle\sigma v\rangle$ with 1-mbndg included as described above is $1.9 \times 10^{-7} \text{ cm}^3/\text{s}$ at an energy of 10 keV/u, $2.5 \times 10^{-7} \text{ cm}^3/\text{s}$ at 25 keV/u, and $1.4 \times 10^{-7} \text{ cm}^3/\text{s}$ at 50 keV/u [5]. Thus, $\langle\sigma v\rangle$ at the mean energy of the halo neutrals is comparable to the values at the energies of the three beam components, and it is clear that halo neutrals must be included in modeling the data.

The halo neutral densities were calculated using NUT [25], a three-dimensional neutral transport code. An expression similar to one of the terms in equation 1 was used to evaluate the line brightness due to halo neutrals. In the example discharge, the brightness due to halo neutrals was 62% of the brightness due to excitation directly from the beam. Applying this correction results in a carbon concentration of 0.04 and an oxygen concentration of 0.0006. The corrected carbon concentration is in good agreement with the VB value of 0.035. Similar

corrections were applied to the CXR carbon concentrations shown in figure 4a and the results, shown in figure 4b, agree with the VB values within the scatter of the data points. The two points at highest carbon concentration were little changed by including the contribution of halo neutrals to the brightness. These were very low power beam heating cases (2.6 MW) with ion temperatures less than 6 keV on axis; thus, $\langle \sigma v \rangle$ for these shots is small. Also, because the carbon concentration in these discharges was high (see section 6), the deuteron density, and therefore the halo neutral density, was low. As a result of these effects, the contribution of halo neutrals to the line brightness was negligible (less than 5% of the beam excitation) for these two shots. The good agreement between the CXR and VB values of the carbon concentration for these two points indicates that both the spectrometer calibration and the atomic rates in the beam attenuation and line brightness calculations are reliable.

To emphasize the importance of contribution of halo neutrals to the line brightness, we mention that the contributions to the beam-excited line brightness of the full, half, and third energy components of the beam were 59%, 27%, and 14%, respectively. Thus, the halo contribution of 62% is comparable to the contribution from the full energy component and is actually larger than the contributions of the lower energy components. This is because the full energy of the beam falls beyond the energy at which the cascade-corrected excitation rate peaks, and the energies of the other beam components and the halo neutrals fall near the peak of the excitation rate. This implies that halo neutrals will make a significant contribution to the brightnesses of CXR-excited lines in tokamaks which achieve ion temperatures similar to those in TFTR. In fact, if higher energy beams are used for CXRS in future tokamaks, it is possible that the halo contribution to the line excitation could be larger than the total contribution from the beam atoms.

Another potentially important contribution to the observed line brightness is electron-impact excited emission from C^{+5} ions at the plasma edge or from plume ions. Comparison of the signals before and immediately after the start of beam injection in figures 2 and 3 shows that the background electron-impact-excited signal from the plasma edge is negligible. Plume ions [5] are hydrogen-like impurity ions produced by CXR with the beam neutrals. They drift out of the beam volume along the field lines and can enter the spectrometer line of sight, where they may be excited by electron impact and contribute to the observed line intensity. The mean-free path for electron impact ionization of C^{+5} ions at $T_i=25$ keV, $T_e=10$ keV, and $n_e=5 \times 10^{19} \text{ m}^{-3}$ is approximately 80 m [26]. Thus, plume ions can make several transits around the torus before being ionized, filling the plasma volume. As shown in figure 1, TFTR has a large number of beams, making this a potentially serious problem. An estimate of this effect was made using data from two similar discharges, one with 6 counter beams, all of which are in the spectrometer line of sight, and the other with 6 co-beams, none of which are in the spectrometer line of sight. The C^{+5} 521 Å line brightness in the shot with co-injection was only 10% of that in the shot with counter injection. The line brightness observed with

co-injection is due to emission from plume ions and C^{+5} ions at the plasma edge excited by electron impact and charge exchange with cold thermal neutrals. Thus, assuming that the plume ion distribution is approximately uniform around the torus, the contribution of electron-impact excited emission from plume ions to the observed line brightness with counter injection is estimated to be in the range 10-20% for the discharges discussed here and can, therefore, be neglected.

6. Trends in Carbon and Deuteron Concentrations with Beam Power and Plasma Current

In this section, we use the data modeling techniques discussed previously to examine the behavior with beam power and plasma current of carbon and deuterons in the group of shots described in section 2. Many of these discharges exhibited a carbon bloom near the end of the beam pulse. The carbon concentration was measured well into the beam pulse, at least 0.4 s, but before the onset of the carbon bloom when it was present.

Figure 5 shows the carbon concentration as a function of beam power in this group of shots. The carbon concentration drops from large values of approximately 0.13 at 2.6 MW beam power to about 0.07 at 9 MW and then decreases slowly to 0.04 at 30 MW beam power. The high carbon concentration at 2.6 MW is a result of the large carbon content of the target plasma: low power beam injection causes only a small electron density rise and, therefore, does not significantly decrease the carbon concentration. This is consistent with the observation that the VB Z_{eff} is close to 6 in prefill-only discharges in TFTR. Within the scatter of the data points, no variation in the carbon concentration with plasma current is evident in figure 5. The scatter in the data points is probably due to variations in the limiter conditioning and to variations in the time evolution of the carbon concentration (see section 7 below).

It is interesting to present the same data in terms of Z_{eff} in order to facilitate a comparison with the previous results of Hill *et al.* [2] at $I_p=0.8-1.0$ MA and beam power up to 15 MW. Figure 6 shows values of Z_{eff} derived from the CXRS measurement by summing the contributions from the carbon concentrations shown in figure 5, the metallic impurity contribution measured by x-ray PHA, and a consistent deuteron concentration. Z_{eff} decreases from 5 at 2.6 MW beam power to 3-4 at 9 MW and then decreases to 2.5-3 at the highest beam power of 30 MW. The behavior of Z_{eff} with beam power and the lack of a dependence of the carbon concentration on plasma current are similar to the trends seen by Hill *et al.* [2] at lower beam power and plasma current. Also shown in figure 6 is the VB Z_{eff} : as expected from figure 4b, there is good agreement between the CXRS and VB measurements of Z_{eff} . In order to show the size of the metallic impurity contribution to Z_{eff} in these shots, the metallic impurity Z_{eff} is also plotted in figure 6. The metallic impurity contribution to Z_{eff} reaches values close to 1, but does not dominate Z_{eff} at any beam power level. At least part of the apparent rise in the metallic impurity concentration with beam power seen in figure 6 is due to increased

deposition of metallic impurities on the limiter during the period of operation spanned by these shots: in general, the discharges with higher beam power occurred later than those at low beam power. This group of shots spanned 3500 shots over five months, during which the maximum available beam power was increased. Thus, trends in the metallic impurity concentration with beam power should not be inferred from figure 6.

As a result of beam particle fueling, the electron density increases with beam power; this is seen in figure 7, a plot of $\bar{n}_e$ versus beam power for this group of shots. This raises the possibility that the decrease in the carbon concentration with beam power is caused by dilution by beam particles. Figure 8 shows the central carbon density, taken to be the product of the carbon concentration and $\bar{n}_e$, as a function of beam power. It is clear that the carbon density is constant within the scatter of the data points over a wide range of beam power, and that dilution is, therefore, the cause of the decrease in the carbon concentration with beam power seen in figure 5. In fact, the carbon densities shown in figure 8 are typical of those deduced from the VB Z_{eff} for the plasma before beam injection. Thus, it appears that the carbon source in the plasma periphery, determined by the particle influx from the limiter and particle transport in the scrapeoff region, does not change significantly with beam power. The edge T_e is observed to remain approximately constant as the beam power increases while the edge n_e rises roughly linearly with beam power [27]. Thus, the yield for sputtering of carbon from the limiter surface is not expected to change significantly as the beam power increases, but the total number of sputtered particles does increase. Measurements of core impurity transport show no significant difference between ohmic discharges and supershots [2, 28, 29]. Thus, the fraction of carbon ions produced at the plasma edge which reach the core region of the discharge is not expected to change with beam power. In order to maintain a constant carbon source in the plasma edge, the loss of carbon ions to the limiter must, therefore, increase as the edge n_e increases with beam power.

Because the carbon and metallic impurity concentrations are known and concentrations of other impurities are negligible, the deuteron concentration can be deduced. The deuteron concentration in these discharges is shown in figure 9a. The deuteron concentration rises from approximately 0.25 of $\bar{n}_e$ at 2.6 MW beam power to 0.75 at 30 MW and is greater than 0.6 for the majority of shots shown in figure 9a. The deuteron density, shown in figure 9b, rises from $0.4 \times 10^{19} \text{ m}^{-3}$ at 2.6 MW beam power to $2.5 \times 10^{19} \text{ m}^{-3}$ at 30 MW. The small deuteron concentration at low beam power is consistent with the deuteron concentration in the target plasma inferred from the VB Z_{eff} .

7. Time Evolution of Carbon and Deuteron Concentrations

In this section we examine the time evolution of the carbon and deuteron concentrations and densities during the beam pulse. In particular, we compare these quantities in two discharges with high power beam heating, one which exhibited a carbon bloom and another

which did not. Both shots were at a plasma current of 1.6 MA and were almost consecutive, so the state of limiter conditioning was similar in both cases. The discharge which bloomed had 28 MW of beam power and the one which did not had 24 MW of beam power; beam injection was from 3.5 s to 4.5 s in both shots. In TFTR supershots at high beam power, the total stored energy and neutron flux often roll over at some time later than 0.5 s into the beam pulse. The onset of a carbon bloom can cause this to happen earlier than it otherwise would, limiting the ultimate neutron flux reached. The cause of the bloom appears to be enhanced interaction of the plasma with the edges of low spots on the limiter. The bloom occurs when the limiter surface reaches a temperature of approximately 1700°C and may be due to radiation-enhanced sublimation [10, 30]. The signature of the onset of a bloom is a broadening of the electron density profile followed by a rise in $\bar{n}_e$. The influx of carbon starts after the broadening of the density profile. Figure 10 shows the time evolution of $\bar{n}_e$ in the bloom and non-bloom discharges. Early in the beam pulse, the time evolution of $\bar{n}_e$ is similar in the two cases, with the slightly higher density in the bloom discharge being the result of higher beam power. In the bloom discharge, the density profile started to broaden at 3.9 s and $\bar{n}_e$ began to rise rapidly at 4.07 s. The intensity of a routinely monitored C⁺ line started to rise at the same time, indicating an increase in the carbon influx. The radiated power measured by bolometry also started to rise at this time and ultimately saturated the detector, indicating close to 100% of the input power radiated.

Figure 11a shows the time evolution of the carbon concentration in the two discharges. In both cases, the carbon concentration drops during the early part of the beam pulse from a high value, in the range 0.065-0.08, to a lower value of approximately 0.05. This drop is due to dilution by beam particles. At 3.9 s, the carbon concentration starts to increase and by 4.15 s has reached values of 0.065-0.08, with the larger carbon concentration being seen in the bloom discharge. It is apparent from figure 11a that the time evolution of the carbon concentration up to the onset of the bloom is similar in the two cases. Thus, the time evolution of the carbon density must be similar in the bloom and non-bloom discharges up to the onset of the bloom; in the bloom discharge, there must then be a rise in the carbon density starting at the onset of the bloom. This is borne out by the time evolutions of the carbon density shown in figure 11b. The carbon density in both cases rises from $1 \times 10^{18} \text{ m}^{-3}$ at the start of the beam pulse to $2 \times 10^{18} \text{ m}^{-3}$ at 4.05 s, just before the start of the bloom. The carbon density in the bloom discharge then rises to $4.5 \times 10^{18} \text{ m}^{-3}$ at 4.35 s and starts to roll over. In the non-bloom discharge, the carbon density continues to rise gradually to $2.5 \times 10^{18} \text{ m}^{-3}$ at 4.35 s. Note that the carbon density rises gradually through the length of the beam pulse in the non-bloom case, indicating an increase in the carbon influx.

The observation of simultaneous increases in the electron density and the carbon density raises the question of whether or not the electron density rise associated with the bloom is fuelled primarily by the carbon influx. Comparing the change in the electron and carbon densities from 4.05 s to 4.25 s in figures 10 and 11b shows that approximately 85% of the

electron density rise is due to electrons from carbon atoms. Hence, it appears that the majority of the electron density rise is due to the carbon influx.

The carbon concentrations discussed above and the metallic impurity concentrations measured by x-ray PHA have been used to deduce the deuteron concentrations shown in figure 12a. In both the bloom and non-bloom discharges, the deuteron concentration rises during the first 0.2 s of beam injection, reaching values in the range 0.65-0.7. In the bloom discharge, the deuteron concentration begins to decrease at 3.85 s and by 4.15 s, it has dropped to a low value of 0.5 and remains roughly constant until the end of the beam pulse. This behavior is consistent with most of the electron density rise during the bloom being due to the carbon influx. The deuteron concentration in the non-bloom discharge gradually decreases from a peak value of 0.65 at 3.75 s to 0.55 at the end of the beam pulse. The deuteron density in both discharges is shown in figure 12b. In the bloom discharge, it rises from $0.75 \times 10^{19} \text{ m}^{-3}$ at the start of the beam pulse to $2.4 \times 10^{19} \text{ m}^{-3}$ at 3.85 s and remains constant until 4.15 s, when it rises slightly to $2.8 \times 10^{19} \text{ m}^{-3}$. In contrast, the carbon density in the non-bloom discharge increases from $0.6 \times 10^{19} \text{ m}^{-3}$ at the start of the beam pulse to $1.5 \times 10^{19} \text{ m}^{-3}$ at 3.75 s and remains approximately constant at this value until the end of the beam pulse.

8. Summary

The results of this study may be summarized as follows:

1. Extreme ultraviolet CXRS has been used to measure the central carbon concentration in TFTR discharges with high power neutral beam heating. The carbon concentrations were deduced from absolute measurements of the brightness of the $\text{C}^{+5} \text{ n}=3-4$ transition using a beam attenuation calculation and cascade-corrected line excitation rates.
2. The measured carbon concentrations are in good agreement with those derived from VB measurements of Z_{eff} provided that the contribution of halo neutrals produced by charge exchange of beam atoms with the plasma deuterons is included in the calculation of the line brightness. As a result of the high ion temperatures (20-30 keV) in many of these discharges, this effect is significant: the contribution of halo neutrals to the total line brightness can be as much as 62% of the contribution from beam neutrals. The good agreement between the CXRS and VB measurements of the carbon concentration demonstrates that the atomic rates used in the line excitation and the beam attenuation calculations are reliable.
3. Carbon concentrations have been measured in discharges with $I_p=1.0-1.6 \text{ MA}$ and beam power in the range 2.6-30 MW. The target plasmas for beam injection were low density (prefill only) with a well-conditioned limiter; many of the discharges were supershots. Carbon was the dominant impurity species in all of these discharges; the oxygen concentration measured in a

high power case was 0.0006 of n_e , compared to 0.04 for carbon.

4. Trends with I_p and beam power in the carbon concentration and the inferred deuteron concentration were examined. The carbon concentration was independent of I_p and decreased from 0.13 at 2.6 MW beam power to 0.04 at 30 MW, while the deuteron concentration increased from 0.25 to 0.75 over the same range of beam power. These changes were primarily the result of beam particle fueling, as the central carbon density did not vary significantly with beam power.

5. The time evolutions of the carbon and deuteron concentrations during two high power beam pulses, one which exhibited a carbon bloom (a sudden influx of carbon due to local heating of the limiter) and one which did not, were compared. In both types of discharge, the carbon concentration decreases early in the beam pulse as a result of beam particle fueling. The carbon density rises gradually during the beam pulse in both types of discharge until the start of the bloom. The electron density rise during the bloom is due primarily to an increase in the carbon density.

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Table I
Neutral Beam and Spectrometer Geometry

<u>Beam</u>	<u>Beam tangency radius</u>	<u>intersection radius*</u>
1a	1.74 m	2.63 m
1b	2.00	2.81
1c	2.23	2.97
2a	1.74	1.78
2b	1.99	2.02
2c	2.23	2.23

*radius at which beam and spectrometer line of sight intersect.

Table II
 n_{crit} for C^{+5} in TFTR*

Mixing process	n_{crit}
Ion-ion collisions (Pengally & Seaton [14])	4
Ion-ion collisions (Sampson [15])	7
Quadratic Stark Effect	5
Linear Stark Effect	6

*Calculated from the expressions in references 5 and 14 assuming $T_i=20$ keV, $Z_{\text{eff}}=3$, and $n_e=5 \times 10^{19} \text{ m}^{-3}$.

FIGURE CAPTIONS

- Fig. 1. Neutral beam trajectories on TFTR and spectrometer line of sight.
- Fig. 2. a. Spectrum during beam injection, showing prominent CXR-excited lines.
b. Spectrum before beam injection.
- Fig. 3. a. Time evolution of CXR-excited C^{+5} 521 Å ($n=4-3$) line.
b. Time evolution of electron-impact-excited C^{+3} 312 Å line.
- Fig. 4. a. Comparison of visible bremsstrahlung (VB) and CXRS carbon concentrations. Line excitation by halo neutrals not included in CXRS values.
b. Same comparison with line excitation by halo neutrals included in CXRS values. The good agreement between the VB and CXRS values demonstrates the importance of line excitation by halo neutrals.
- Fig. 5. Carbon concentration as a function of beam power for different plasma currents.
- Fig. 6. CXRS Z_{eff} , visible bremsstrahlung (VB) Z_{eff} , and metallic impurity contribution to Z_{eff} from x-ray PHA versus beam power.
- Fig. 7. Line-average electron density as a function of beam power.
- Fig. 8. Carbon density as a function of beam power.
- Fig. 9. a. Deuteron concentration deduced from CXRS carbon concentration versus beam power.
b. Deuteron density versus beam power.
- Fig. 10. Line-average electron density as a function of time in two discharges with high power beam heating, one with a carbon bloom and one without.
- Fig. 11. a. Carbon concentration as a function of time in bloom and non-bloom discharges.
b. Carbon density as a function of time.
- Fig. 12. a. Deuteron concentration as a function of time in bloom and non-bloom discharges.
b. Deuteron density as a function of time.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Fig. 11

Fig. 12

EXTERNAL DISTRIBUTION IN ADDITION TO UC-420

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