PPPL-3188, Preprint: May 1996, UC- 420

Measurements of tritium recycling and isotope exchange in TFTR.

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Abstract

Tritium Balmer-alpha (T_α) emission, along with H_α and D_α, is observed in the current D-T experimental campaign in TFTR. The data are a measure of the fueling of the plasma by tritium accumulated in the TFTR limiter and the spectral profile maps neutral hydrogenic velocities. T_α is relatively slow to appear in tritium neutral beam heated discharges, ($T_\alpha /(H_\alpha+D_\alpha+T_\alpha)$ = 11% after 8 tritium-only neutral beam discharges). In contrast, the T_α fraction in a sequence of six discharges fueled with tritium puffs, increased to 44%. Larger transient increases (up to 75% T_α) were observed during subsequent tritium gas puffs. Analysis of the Doppler broadened spectral profiles revealed overall agreement with the dissociation, charge exchange, sputtering and reflection velocities predicted by the neutral Monte-Carlo code DEGAS with some deficiency in the treatment of dissociation products in the 10-100 eV range.

Introduction

Hydrogenic ions, recycled from the limiter, are an important factor in the composition and reactivity of plasmas in the Tokamak Fusion Test Reactor, TFTR.[1] Deuterium-tritium operation of TFTR has provided a spec, 4417 recycling. The recycling can be observed in Balmer-alpha emission from neutral hydrogen isotopes in the inboard plasma edge region where the plasma contacts a toroidal carbon limiter. Neutral tritium has a Balmer-alpha transition, T_α, that is analogous to the H_α and D_α transitions long used in edge plasma diagnostics. The wavelengths of the H_α, D_α, T_α emission lines are separated by small isotope shifts arising from differences in the reduced mass and are at 656.28 nm, 656.104 nm, and 656.045 nm, respectively. Note that the wavelength separation between D_α and T_α is one third that between D_α and H_α and the lines are partially blended.

The first spectroscopic measurements of T_α emission from a fusion plasma were made on TFTR using a Fabry-Perot interferometer.[2] The relative fraction of the hydrogenic isotopes in the H_α, D_α, T_α spectral profile reflects the hydrogenic inventory in the surface of the limiter. This, in turn, is a function of the fueling history of prior discharges, tritium burial by codeposition and the mobility of hydrogen isotopes in graphite. Spectral resolution of the line profile gives information on processes in the edge plasma. The emission is Doppler shifted and the spectral line profile maps the velocity distribution of the neutral hydrogen isotopes. Since the edge density is insufficient to thermalize the velocity distribution, the contributions of the various reaction pathways that generate hydrogenic atoms may be identified with the different wavelength regions (velocities) in the spectral profile. Previous studies of neutral velocities have been made on TEXTOR[3,4] and DITE.[5] In this paper we will describe spectrally resolved measurements of the H_α, D_α, T_α emission on TFTR and compare the velocities to those predicted by the neutrals code DEGAS. We also compare the isotope changeover rate in the Balmer-alpha emission in a sequence of discharges with tritium neutral beam injection to a sequence with tritium gas puffs. Modeling of tritium recycling in discharges with deuterium-only neutral beam injection is reported in reference 6 and an account of tritium retention, lithium conditioning and advanced tokamak regimes on TFTR is given in reference 7 in these proceedings.

Experimental arrangement.

TFTR plasmas have a circular cross section with a plasma boundary defined by an inboard toroidal belt limiter composed of carbon composite tiles in high heat flux regions as well as graphite tiles, both supported by water cooled inconel-718 backing plates. The limiter experiences erosion, codeposition of hydrogen with carbon, and neutron flux from the DT plasmas. After exposure to many plasma discharges, each limiter sector develops a poloidally asymmetric 'footprint' or eroded area, surrounded by areas of net codeposition.[8] The rise in bulk limiter temperature remains below 50 °C during a discharge,[9] however infra-red camera measurements indicate that the surface temperature in localized hot spots increases up to 1000 °C or more depending on the discharge conditions and auxiliary heating power.[10]

Light from TFTR is collected by a telescope and transmitted via a fiber optic to a remote Fabry Perot interferometer. The telescope views a region on the TFTR inboard limiter 20 cm in diameter at the midplane. The Zeeman effect splits the H_α, D_α, T_α lines into an unshifted π component, polarized parallel to the field direction, and two σ components polarized perpendicular to the field. Previous measurements of the Zeeman splitting showed that the location of the emission region was close to the inner limiter. For the present measurements, a polarizing filter was placed in front of the telescope lens and oriented to transmit only the unshifted π component. The light was recollimated, and transmitted through a prefilter to select a 7 Å band centered at the D_α wavelength. It was then spectrally analyzed with a scanning Fabry Perot interferometer with a wavelength resolution of 0.23 Å. Alignment of the interferometer was maintained by an electronic controller locked to helium neon laser light transmitted by the interferometer between plasma discharges.[11]

Tritium Recycling.

The fraction of tritium in the hydrogenic recycling was surprisingly low in discharges fueled by tritium neutral beam injection. At low tritium concentrations the T_α line appears as a displacement or 'bulge' in the short wavelength side of D_α and the tritium fraction in the total hydrogenic emission, $T_\alpha / (H_\alpha+D_\alpha+T_\alpha)$, is revealed by subtraction of a companion deuterium discharge observed before tritium injection. In this way, T_α fractions down to 2% may be detected. In the first discharge with mixed tritium/deuterium neutral beam injection, (December 1993), the level of tritium recycling was too low to be detectable (<2%). After several deuterium/tritium neutral beam fueled discharges the T_α feature appeared and increased up to a level of 7.5%.[2] In a subsequent H-mode study[12] there were 9 sequential discharges with tritium-only neutral beam fueling intended to maximize the tritium fraction in the plasma. The injected tritium averaged 44 Ci / discharge and the T_α fraction increased by approximately 1% each discharge. The spectral profile from the penultimate discharge in the sequence is shown in figure 1. In contrast, strong tritium fueling through a gas puff produced a large T_α fraction. Figure 2 shows such a spectral profile dominated by the T_α peak, with resolved peaks due to H_α, D_α, and T_α. The isotope changeover is discussed below.

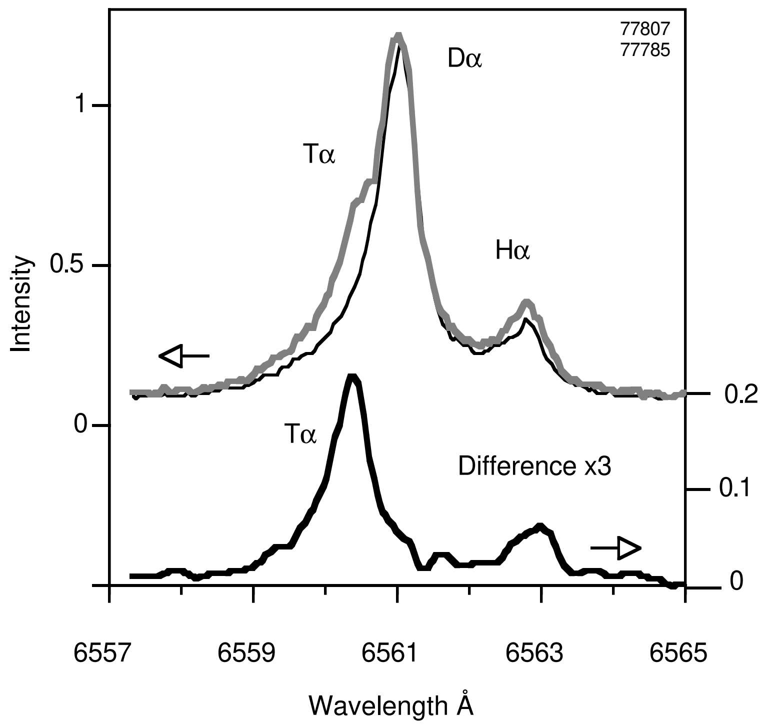

Figure 1. Tritium alpha emission is evident on the short wavelength wing of the Balmer-alpha spectral profile (thick line). A prior deuterium companion discharge (thin black line) is also shown and the difference, magnified by a factor 3 represents the T_α profile. A small increase in H_α is also evident. The T_α feature accounts for 9% of the total area.

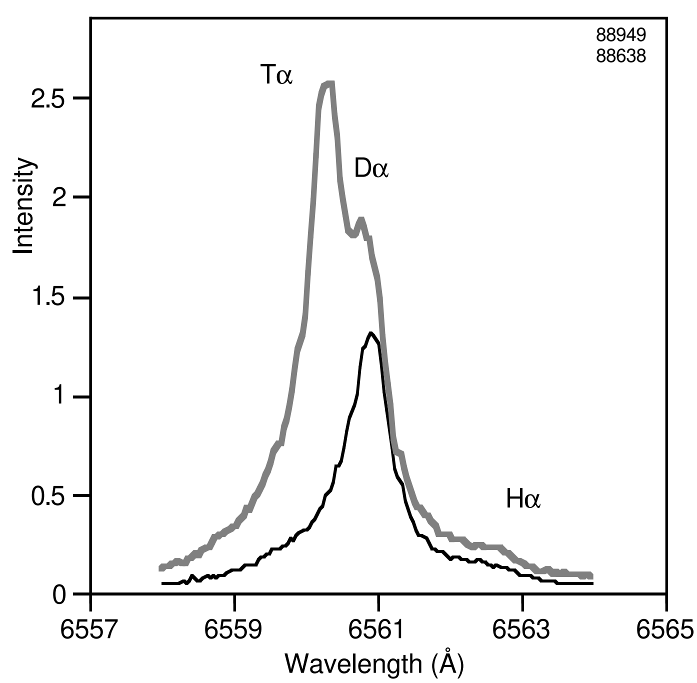

Figure 2. Spectral profiles from discharges (i) with a tritium gas puff (thick line) and (ii) a prior D companion discharge with a deuterium puff (thin line). T_α accounts for 54% of the total area of (i).

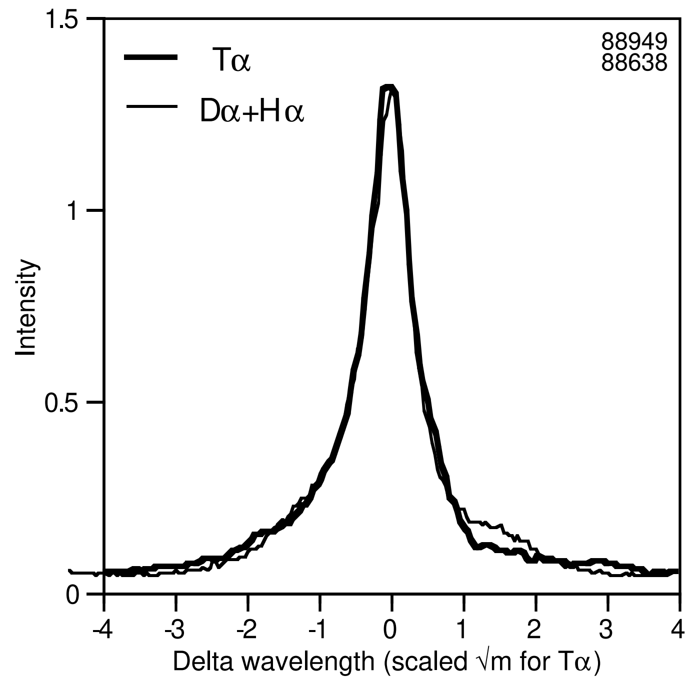

Figure 3. Superposition of T_α and $D_\alpha + H_\alpha$ spectral profiles in normalized wavelength units.

Spectral analysis.

The tritium capability of TFTR has provided an important opportunity to compare the velocity distribution of tritium and deuterium. To first order, one expects the tritium velocity to be lower by a factor $\sqrt{2/3}$ due to the mass difference, however there are other possible effects. During dissociation, the lower velocity of the tritium atoms can influence the pathways of molecular breakup. For example, Higo[13] found evidence for isotope effects originating from the different widths of the Frank-Condon region, the difference in the nuclear mass and different probabilities for curve crossing. In addition, since the tritium neutrals are moving more slowly they will experience, on average, a somewhat different plasma environment to deuterium.

The velocity distribution of neutral tritium and deuterium were compared by spectral analysis. The deuterium contribution to the blended H_α, D_α, T_α profile in Fig. 2 was subtracted in the following way. The line profile was first fit to 6 trial gaussians, 2 for each isotope, plus a first order background. The number of free parameters was reduced from 20 to 8 by using the known wavelength differences and the mass scaling factor. The results showed the relative area due to each isotope in the composite spectral profile. A companion discharge with deuterium puffing had the same plasma current, major radius, and similar RF heating power and electron density. The deuterium spectral profile (also shown in Fig. 2) was normalized to match the deuterium area derived for the DT discharge. This profile was then subtracted, yielding a profile representing the tritium-alpha line. To reveal differences in the energy distribution between tritium and deuterium, the wavelength scale was then multiplied by the mass factor, $\sqrt{3/2}$, and the tritium-alpha profile superposed on the deuterium profile observed from the companion discharge (Figure 3). Differences in the velocity distribution beyond the mass scaling factor should appear as differences in the shape of the spectral lines. It can be seen that the profiles are very similar. There is a trace of hydrogen present in the deuterium profile, otherwise isotopic differences beyond the $\sqrt{3/2}$ factor are too small to resolve. This result verifies an underlying assumption in the treatment of different hydrogen isotopes in neutral codes.

The deuterium spectral profile has been used to benchmark the atomic, molecular and surface physics used in the Monte-Carlo neutral transport code DEGAS.[14] This code tracks the 'flights' of neutral test particles in the TFTR geometry and plasma conditions as they undergo ionization, charge exchange, dissociation and surface interactions. The plasma conditions within the last closed flux surface are input from the TRANSP [15] analysis code. The temperature and density in the scrape-off region are derived from the poloidal distribution of the Balmer alpha emission. An extensive suite of atomic, molecular and surface physics data is used. Eight different pathways for molecular dissociation, each with differing product energies, are treated explicitly. The mass scaling factor is used in calculating the velocities of the different hydrogen isotopes, all the other atomic data are taken to be independent of isotopic species. When, through dissociation, excitation or charge exchange, a test particle emits a Balmer alpha photon in a volume corresponding to that observed experimentally, the particle velocity is logged and, over thousands of flights, a spectral line profile built up. This predicted profile is then compared with the observed profile.

A comparison between an observed D_α, H_α spectral profile and the predictions of DEGAS are shown in figure 4. The initial disagreement in the short wavelength line wing was narrowed considerably by the explicit addition of sputtering processes to DEGAS. Currently there is reasonable agreement between the measured and simulated spectra over a range of plasma conditions validating the treatment of charge exchange, molecular dissociation, surface reflection and sputtering in DEGAS. However a residual deficiency of neutrals in the 10-100 eV region indicates a need for further investigation of the dissociation product energies for electron temperatures in the range 100-1000 eV.

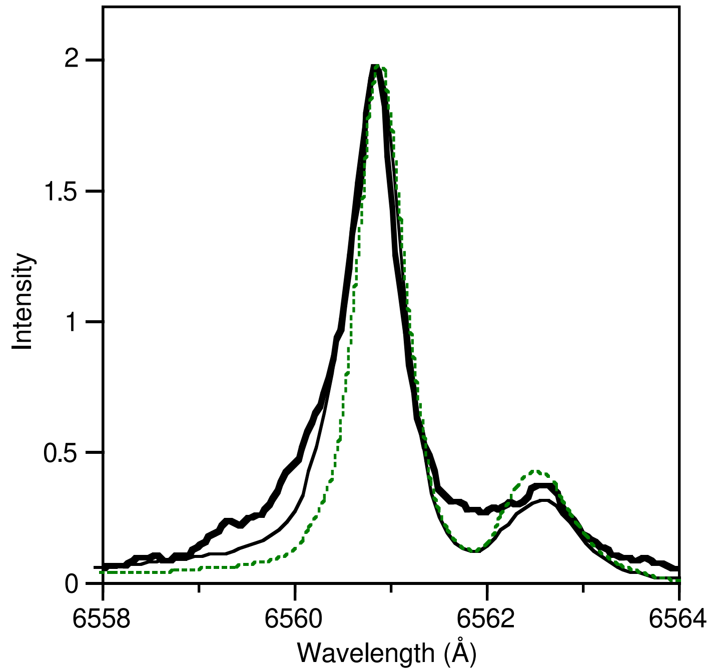

Figure 4 : Comparison of observed D_α spectral profile (thick line) with the predictions of the neutrals code DEGAS (thin line). An earlier DEGAS simulation without explicit treatment of sputtering is shown (dotted line).

Isotope changeover

Hydrogen / deuterium isotope changeover has been previously studied on TFTR[16-18] and the number of discharges required for isotope changeover found to depend on the limiter condition. Isotope changeover has also been studied on JET.[19] The release of tritium was related to a model that incorporated implantation into a thin surface layer as well as diffusion into and out of the bulk material.[20] Early in the TFTR D-T campaign there was a period of several operation days of high power deuterium and tritium neutral beam injection followed by an extended period without tritium NBI. The rate of decay of tritium was tracked by both measurements of T_α and the D-T neutrons produced by recycled tritium. The initial rate of decay fit an exponential relation with a 7.5 discharge decay constant. After an initial decrease the decay slowed markedly to a decay constant of 404 discharges.[21]

Tritium gas puffs were used to generate L-mode plasmas with a maximal fraction of tritium. Figure 5 shows the quantity of tritium injected and the corresponding rise in the tritium fraction of hydrogenic recycling on the first day of this campaign. In the first discharge with a strong tritium puff, 111 Ci were puffed into the vacuum vessel. During this puff the T_α fraction increased up to 20%. This increase was temporary - after the puff the T_α fraction

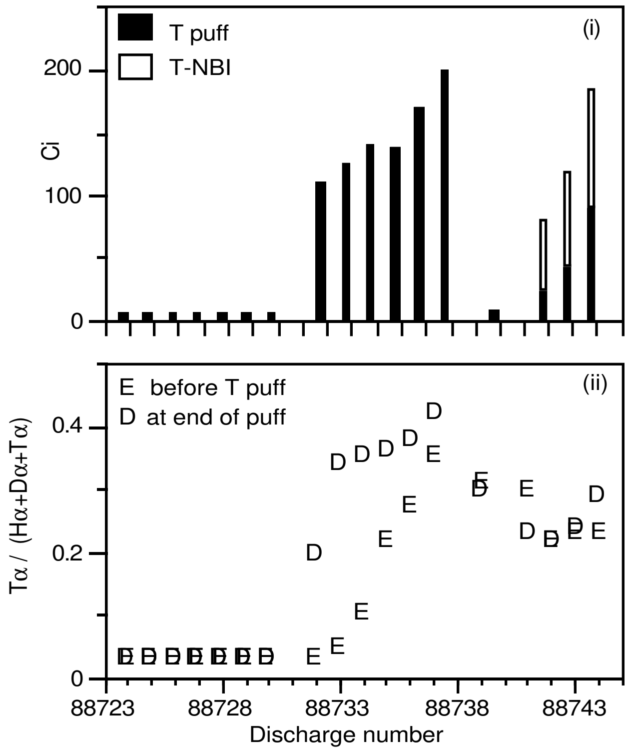

Figure 5. (i) History of tritium injection by gas puff and neutral beams and (ii) the corresponding increase in tritium fraction in hydrogenic recycling on 1st September 1995.

dropped to approximately 5%. It is likely that this initial rise was due to excitation of the incoming gas stream and not due to recycled tritium. With continued tritium puffs, the T_α fraction increased throughout the duration of the discharge. The maximum T_α fraction observed was 75% during a subsequent 460 Ci tritium puff. However, after 8 days and a total of 10,600 Ci tritium puffed, the level of T_α that persisted without a simultaneous tritium puff was approximately 50%. Although the tritium/deuterium exchange was incomplete, it did enable studies of isotope scaling in L-mode transport.[22] An account of the long term inventory of tritium injected and removed from the torus is given in reference 23.

Acknowledgments.

We thank D Ruzic and B Turkot for the sputtering data. This work was supported by the US Department of Energy Contract No. DE-AC02-76CH03073.

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