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First Measurements of Tritium Recycling in TFTR.

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Abstract

The first spectroscopic measurements of tritium Balmer-alpha ($T\alpha$) emission from a fusion plasma were made on TFTR using a Fabry-Perot interferometer. The $T\alpha$ emission line is partially blended with the $D\alpha$ line (deuterium-alpha), commonly used in edge plasma diagnostics, and the contributions of $H\alpha$, $D\alpha$, and $T\alpha$, are separated by spectral analysis. The data are a measure of the fueling of the plasma by tritium accumulated in the TFTR limiter, as well as the amount of neutral tritium generated by charge exchange of plasma ions. The $T\alpha$ line first became detectable in a high power, tritium only, neutral beam injection discharge at the level of $T\alpha/(H\alpha+D\alpha+T\alpha) = 2\%$. Subsequently this ratio has increased to as high as 7.5%. Data on the time evolution of the $T\alpha$ emission during a single discharge and over a series of tritium and deuterium discharges are presented.

I. Introduction

Magnetically confined fusion has begun to produce significant fusion power by the introduction of tritium into the plasma. Two discharges with a ratio of tritium to total beam fueling of 13% were performed in JET in 1991[1] and recently, a more extensive D-T campaign in TFTR with equal tritium(T) and deuterium (D) fueling has produced record 6.2 MW fusion power [2]. For these experiments, TFTR was operated in the supershot regime [3] that is characterized by peaked density

profiles with 1.8 MA plasma current, 5.1 T toroidal magnetic field, 2.52 m major radius and 0.87 m minor radius. The plasmas were heated by 20-23 MW of injected neutral beam power, with sources operated at 93-107 kV. Tritium fueling was accomplished by operating up to eight of the neutral beam sources in pure tritium, (with deuterium in the remainder). Recycling plays a key role in the performance of supershots. The D influx from the limiter is minimized by ohmic He conditioning discharges and Li pellet injection resulting in low target densities and improved neutral beam penetration. In D-T plasmas additional recycling issues arise due to the tritium fueling from the limiter of plasmas with nominally 100% deuterium neutral beam injection, and conversely, deuterium fueling of plasmas with 100% tritium neutral beam injection. Recycling is an important factor in core plasma composition but it is more difficult to control than the beam fueling. A related operational issue is the degree of retention of tritium in the limiter.

While tritium is at the center of attention in the TFTR D-T campaign it is difficult to observe it directly. However 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 [4-8]. 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. The T_{α} line was first observed at the dawn of the nuclear age, in 1944, at Oak Ridge National Laboratory [9] and was subsequently studied in small-scale discharges to test atomic theory [10]. It has not previously been observed in fusion plasmas. In a plasma, while some Balmer-alpha emission occurs from molecules that dissociate directly into the $n=3$ level, typically the bulk of the emission is from product atoms in the ground state that are excited by a subsequent electron collision. Additional contributions arise from the excitation of neutrals resulting from charge exchange and wall reflection of hydrogenic ions in the plasma.

Since the edge density is insufficient to thermalize the neutral velocity distribution, the emission is Doppler shifted according to the atomic velocity at the time of dissociation or charge exchange and the spectral line profile maps the velocity distribution of neutral hydrogen isotopes at the plasma edge. Observations of the H_{α} spectral line profile resulting from the dissociation of molecular hydrogen by an electron beam [11] have revealed that the velocities of the product atoms can be grouped into 'fast' (2-8eV) and 'slow' (0.2-0.6eV) components, depending on whether the dissociation channel is via a repulsive or attractive molecular state. Small isotopic differences between the H_{α} and D_{α} profile have been detected and attributed to differences in the probability of curve crossing during dissociation [12]. Data from the dissociation of CH_4 is also available [13]. In previous work, the energy distribution of the atoms in the plasma edge has been deduced from the D_{α} , H_{α} spectral line profile in DITE, [14] and measurements of the D_{α} , H_{α} line profile on TEXTOR

[15,16] have revealed evidence for emission from fast ions that were neutralized and reflected at the limiter surface.

On TFTR a modular, fiberoptic coupled spectroscopic diagnostic [17] has been used to monitor the combined D_α , H_α emission, yielding information on core recycling rates, ion and neutral particle limiter fluxes and conditions in the plasma scrapeoff layer [18,19]. Molecular emission bands at 430 nm due to CH and CD, that were observed in the Alcator C-Mod divertor [20], were not detectable on TFTR in spectra taken by a visible spectrometer. In TFTR H_α , D_α , T_α emission occurs in the inner plasma edge region where the plasma typically contacts a toroidal belt limiter that is constructed from graphite tiles. A new diagnostic system has been installed on TFTR to spectrally resolve the optical emission from all three lines.

II. Experimental Setup

Plasma emission from TFTR is collected by a telescope and transferred via a 1 mm fiberoptic cable to a remote Fabry-Perot interferometer, which analyzed the spectrum. The setup is shown in figure 1. The telescope line of sight was oriented along a major radius at bay 'R', and viewed a region on the TFTR inner limiter 20 cm in diameter at the midplane. In this location, the magnetic field strength was typically 7.6 Tesla in a direction 4° below horizontal. 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. Measurements of the Zeeman splitting were used (as in Ref. [21]) to estimate the local magnetic field and confirmed that the location of the emission region was close to the inner limiter. In the present measurements, a polarizing filter was placed in front of the telescope lens and oriented to transmit only the unshifted π component.

Fifty meters distant from the torus the light exited the fiber optic and was recollimated and input to an optical filter with 1.0 nm bandpass centered at 656.1 nm, which transmitted the H_α , D_α , T_α emission lines. The filter was calibrated with a monochromatized white light source referenced to a H calibration lamp. To resolve the individual spectral lines, the light emerging from the filter was refocused into a short optical fiber and input to a Fabry-Perot interferometer (Burleigh Model TL38). The free spectral range of the Fabry-Perot was 0.7 nm and plate reflectivity 92%, yielding a resolution of 23 pm. The hydrogen fine structure splitting of 10 pm is not resolved. The Fabry-Perot repetitively scans over the wavelength region and, for the data presented here, a 100 msec scan duration was used (20 msec is the minimum). The light was detected by a RCA R928 photomultiplier, amplified and digitized at 2 kHz. To maintain high resolution, the drift in alignment of the interferometer plates must be less than 5 nm. Since access to the interferometer was not possible during machine operations, the interferometer was housed in a chamber in which the

temperature was held constant to within 1°C. In addition, an active stabilization system was used to maintain alignment of the interferometer. An attenuated helium-neon laser beam was input to the interferometer in the same fiber optic used for the plasma light. For the period 0-7 seconds during a plasma discharge, this beam was blocked; at other times the signal from the laser signal was used in an electronic controller that maintained constant Fabry-Perot cavity separation and optimal alignment. Since the line profile is scanned in time, the line shape is sensitive to time-dependent changes in the overall emission. A beam splitter intercepted a fraction of the light entering the Fabry-Perot and reflected it via another optical fiber to a second photomultiplier with a second 1.0 nm bandpass interference filter centered at the D_α wavelength. In this way the total $H_\alpha + D_\alpha + T_\alpha$ emission from the same plasma region was recorded and could be used to normalize the line profile and remove the effect of fluctuations. A third fiberoptic (not shown) was coupled to a hydrogen lamp and positioned at the input to the Fabry Perot and used for wavelength calibration.

III. Results in deuterium plasmas

The Fabry-Perot system was first operational with deuterium plasmas in the period 10/92 - 11/92. The plasmas were fueled by deuterium neutral beam injection together with deuterium and a small amount of hydrogen recycled from the limiter. The D_α line profile was of particular significance for the planned T_α measurements since the $D_\alpha - T_\alpha$ wavelength separation is one third that of $D_\alpha - H_\alpha$ and is comparable to the Doppler width so that the T_α line is partially blended with the short wavelength wing of the D_α profile. The measured H_α , D_α spectral line profile was used to provide a prediction of the spectrum expected when tritium is introduced into TFTR [22]. A T_α line profile was simulated by manipulating the data elements in short wavelength side of the D_α profile with a spreadsheet program to construct a profile that was shifted and narrowed by an amount scaled from the reduced mass. The kinetic energies of tritium produced from dissociation and charge exchange were assumed to be the same as deuterium. There are small differences indicated in reference [15], and in the deuterium and tritium particle reflection coefficients in the database used in the DEGAS [23] neutral transport code; however the major difference in the tritium profile arises from the higher reduced mass that displaces the line center and decreases the Doppler width compared to deuterium. The calculated T_α profile was added to the H_α , D_α experimental data and plotted in the upper traces in Fig. 2.

The results indicate that the T_α line develops into a separate peak at levels of $T_\alpha / (H_\alpha + D_\alpha + T_\alpha)$ above 20% while at lower concentrations it appears as a displacement or 'bulge' in the short wavelength side of D_α . In previous work the quantitative estimates of the $H_\alpha / (H_\alpha + D_\alpha)$ ratio were obtained from a line fitting program which fit 2-4 Gaussians to the experimental profile. The program was applied to the simulated profiles to determine its accuracy in assessing the tritium level. The line profile was

fit to 6 Gaussians with some constraints related to the expected proportionality of the line widths of the different isotopes. The results showed encouraging agreement (within a few percent) between the level of tritium artificially introduced into the spectrum and that independently estimated by the line fitting program. From Fig. 2 it is also clear that the threshold of T_α detection is dependent on the level of fluctuations and noise in the D_α line wing. Prior to the D-T run the Fabry-Perot system was upgraded with a faster optical system to increase the signal to noise ratio.

IV Tritium operation

High power tritium operation commenced on 9 December 1993, after an extensive series of setup discharges using small amounts of tritium. The history of tritium neutral beam injection is shown in Fig. 3. One can see the two sets of high fusion power experiments (#73241-73274 and #73428-73460) and, in between, a cleanup campaign #(73325-73381) which removed 11 torr-l (0°C) of tritium. The solid line indicates the cumulative total tritium injected by the neutral beams, (less that recovered in the cleanup). Some of this total remains in the surface layer of the limiter and is available for recycling. The rest is pumped out of the torus, or buried by co-deposition in the limiter or other surfaces.

A series of deuterium setup discharges were performed for subsequent comparison to the tritium discharges, and the spectral line profiles observed were remarkably reproducible. In tritium operations, a search for T_α was conducted by overlaying the line profiles with those from previous deuterium shots. However, in the early tritium discharges, even though the presence of tritium in the plasma was evidenced by detection of 14 MeV neutrons, no significant changes were detected in the line profile. This was because the principal source of T_α is tritium desorption from the limiter and this was highly diluted with deuterium from previous discharges.

The first indication of T_α became apparent at the end of the first high power campaign in discharge #73273, which used tritium neutral beam injection in all 8 sources. The preceding 3 discharges were deuterium injection only, and #73272 was used as a comparison discharge. When the line profiles from #73272 and #73273 were overlaid, a small but clear difference was apparent in the short wavelength side on the line profile, similar to the spectrum previously simulated with 2% tritium concentration. A more quantitative analysis using the line fitting program showed a 2% increase in the intensity of the profile at the D_α wavelength. The clearest evidence for T_α emission was obtained by numerically subtracting the line profile for the deuterium discharge from the tritium discharge, revealing a spectral line at the T_α wavelength with an area 2% of the total. The level of T_α increased up to 7.5% in the second high power D-T campaign (#73428-73460), and we will focus our analysis on this data set.

In these discharges the plasma current was held at 1.8 MA and the toroidal magnetic field 5.1 Tesla, with 20-23 MW of neutral beam power applied in the period 3-4 seconds after discharge initiation. Fig. 4 shows an overlay of the line profiles from a tritium discharge (#73447) and an earlier deuterium comparison discharge (#73443). A clear displacement can be seen in the (#73447) line profile at the T_α wavelength. In these plots, due to the normalization of the line profile to the total $H_\alpha + D_\alpha + T_\alpha$ signal (recorded separately), the peak heights were closely matched. However, in order to reveal the smallest possible differences, an adjustment of a few % (to compensate for small differences in background emission) was applied to match the peak heights exactly. Similarly, very small adjustments were made to the relative wavelength (timing) to exactly match the position of the H_α profiles.

The T_α line may be seen most clearly in a plot of the difference between the profiles amplified by a factor 4. The difference profile was smoothed with a filter function to remove noise features beyond the instrumental spectral resolution. By integrating under the difference profile and comparing to the integral of the total, the ratio $T_\alpha / (H_\alpha + D_\alpha + T_\alpha)$ was estimated to be 5%. This is shown in the lower part of Fig. 4 together with an overlay of a T_α line profile calculated by the Monte-Carlo neutral transport code DEGAS. This code tracks the ‘flights’ of neutral test particles in the TFTR geometry with plasma conditions input from the SNAP [24] analysis code. When, through dissociation, excitation or charge exchange, a particle emits a H_α photon in a volume corresponding to the observation volume, the particle velocity is logged and, over thousands of flights, a spectral line profile built up [25]. In the present comparison, the DEGAS profile used plasma parameters from an earlier supershot discharge (#72422), and the predicted profile was convoluted with the experimental instrument function. This first comparison shows overall harmony between the observed and predicted profiles. The D-T experiments will provide a unique opportunity to study tritium edge physics. Further comparisons of the observed and predicted T_α line profile are planned and will be reported in a subsequent paper.

The threshold sensitivity for the spectroscopic detection of T_α is governed by the T_α signal level compared to the fluctuations in the short wavelength wing of the D_α line profile. Fortunately the excellent reproducibility of the D_α line shape in the discharges and the high optical efficiency (high signal level) available from the Fabry-Perot enabled a low level of tritium to be detected. Fig. 5 shows a composite of four overlay plots. Fig. 5a represents a ‘control’ experiment in which the deuterium comparison discharge #73443 is compared to an earlier deuterium discharge (#73441). It can be seen that the profiles are well matched, the calculated difference in the profiles in the area of the T_α line being remarkably low (0.02%). This pattern was observed in all deuterium/deuterium comparisons of similar discharges prior to tritium injection (see section V). Also shown in Fig. 5 (b) is the first T_α observation (#73273 compared to #73272) and, in 5(c)&(d), profiles from two

discharges after the start of tritium operation but without tritium neutral beam injection. In these cases, T_α is generated by tritium accumulated in the limiter from previous discharges.

V. Tritium time evolution

The level of recycling and hence the $H_\alpha/D_\alpha/T_\alpha$ signal was highest during neutral beam injection (NBI). Information on the time evolution of the tritium level during this time was obtained by analyzing several scans during a discharge (see Fig. 6). Discharge #73446, the first with significant tritium injection in the second high power tritium campaign, showed evidence for the beginning of tritium recycling half way through NBI. Other than this case, there was no consistent large increase or decrease of the $T_\alpha/(H_\alpha+D_\alpha+T_\alpha)$ ratio during NBI. The results also are an indication of unresolved short term fluctuations (<100 msec) in T_α and/or random errors due to noise in the measurements. The measured $T_\alpha/(H_\alpha+D_\alpha+T_\alpha)$ ratio for a discharge typically showed fluctuations in the range of $\pm 1\text{-}2\%$. Systematic errors may be estimated from the deuterium/deuterium comparisons and are less than $\pm 1\%$. Assuming the fluctuations are all due to random errors, we conservatively assign an overall uncertainty to the measurements of $\pm 2\%$.

Looking now over a longer time scale, Fig. 7 shows the history of the $T_\alpha/(H_\alpha+D_\alpha+T_\alpha)$ ratio during the experimental run day (12/16/94). The ratios from 3 or more scans are averaged for each discharge. It is clear that the level of tritium recycling reflects the recent discharge history of the machine. The $T_\alpha/(H_\alpha+D_\alpha+T_\alpha)$ ratio fluctuated close to zero in the period before significant tritium NBI. During tritium NBI the level rose to the several percent level. Interestingly, the maximum level of $T_\alpha/(H_\alpha+D_\alpha+T_\alpha)$ of 7.5% was in a deuterium NBI discharge immediately following tritium NBI. This discharge also exhibited anomalous MHD and sawteeth. Over the following remaining seven discharges of the day, the T_α level decreased relatively slowly.

The neutron diagnostics [26] have the capability of distinguishing 2.5 MeV neutrons from D-D reactions from 14 MeV neutrons from D-T, and the level of neutral tritium recycled from the wall may be correlated with the neutron data. Since the cross sections for both D-D and D-T reactions have a similar energy dependence, the tritium/deuterium density in the core of the plasma may be estimated from the ratio of D-T/D-D neutrons [27] for cases where the tritium density is small compared to deuterium (i.e. no tritium NBI). Before major tritium NBI (#73435-#73444) the neutron measurements showed the level of 14 MeV DT neutrons was less than half the 2.5 MeV DD neutrons indicating a tritium/deuterium density ratio of less than 1/2 % in the plasma core. Fig. 8 shows the latter part of the T_α data from Fig. 7, replotted on a semilog scale, together with the neutron data. The left hand scale is in percent for T_α and a simple ratio for the neutrons, the two order-of-magnitude difference being consistent with the ratio of the D-D to D-T neutron cross sections. The data from

discharges after the major tritium NBI discharges (#73453-73460) could be equally well fit with either an exponential relation with a 7.5 discharge decay constant [$F(x)=7.36 \exp(-\Delta/7.5)$; $R^2=.91$] or power law [$G(x)= 7.48\Delta^{-.47}$; $R^2=0.91$] relation where Δ is the increment in discharge number and R^2 the correlation coefficient. This decay is also mirrored in the neutron data, confirming the consistency of the two measurements. A more detailed connection is made by the TRANSP code[28], which interprets an extensive set of diagnostic data to predict the tritium influx through the last closed flux surface. The TRANSP results are in approximate harmony with the T_α and neutron data in Fig 8. In the future, the observed T_α fraction will be input data to aid the TRANSP simulations.

The long term decay of the tritium influx from the TFTR limiter was considerably slower. After the above experimental run, there was a period without tritium NBI (#73461-74430) the latter part of which included deuterium NBI discharges. In the 500 discharges following # 73910, the DT/DD neutron ratio declined from 0.35 to 0.1 and could be fit to a exponential decay with a decay constant of 451 discharges [$Y= 0.345 \exp(-\Delta/451)$; $X^2 = 0.80$]. A power law fit did not match the data. This decay pattern is similar to the earlier results. Deuterium-hydrogen exchange experiments performed previously on TFTR [29] were modeled in terms of a fast, ≈ 10 discharge, transient where recycling dilutes the surface hydrogen, followed by a much slower diffusion of bulk hydrogen to the surface of the limiter. In the preliminary tritium experiment at JET, the two tritium pulses were followed by a cleanup sequence in which the tritium levels were monitored by ionization chambers [30]. The tritium decay constant immediately following the tritium pulses in JET was 7 pulses followed by a slower decline.

In summary, T_α emission has been detected in the current D-T campaign in TFTR at levels of $T_\alpha/(H_\alpha+D_\alpha+T_\alpha)$ up to 7.5%. Although the T_α line was blended with the D_α emission, the high reproducibility of the deuterium comparison discharges and the excellent signal/noise ratio of the data enabled measurements of T_α to be made at concentrations of a few percent. No strong time dependence of the T_α emission was observed during most discharges. The T_α emission persisted in deuterium NBI fueled discharges immediately after the tritium NBI discharges, decaying at the rate of -12% /shot. The observations are consistent with estimates of the central tritium density from the neutron data and with the interpretive codes TRANSP and DEGAS. Work is in progress to study tritium edge physics by a detailed comparison of the T_α line profile to the predictions of DEGAS .

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Figure Captions

Fig. 1. Experimental Setup

Fig. 2. The lowest trace is the H_{α} , D_{α} observed spectrum in TFTR before tritium operations. The upper traces simulate the addition of 6% and 24% T_{α} respectively.

Fig. 3. History of tritium neutral beam injection. The amount injected by the neutral beams in a particular shot is shown together with the cumulative total. An arrow marks the discharge in which T_{α} first became detectable (#73273). Note the solid curve does not represent the actual inventory in the torus.

Fig. 4. Upper traces shows a comparison of the normalized line profiles from discharge #73447 (100% tritium neutral beam injection) in bold and an earlier deuterium comparison discharge before tritium injection (#73443; thin trace). A small displacement can be seen on the short wavelength side of the profile. The lower traces shows the difference between these profiles magnified by a factor four (scale on the right hand side), and (dotted) a T_{α} profile predicted by DEGAS.

Fig. 5. (a) An overlay of two deuterium discharges illustrating the excellent reproducibility of the deuterium profile; (b) the first observation of T_{α} profile (#73273) and a deuterium comparison (#73272); (c), (d) shows T_{α} in 100% deuterium neutral beam discharges (#73448; #73453) subsequent to the tritium discharge shown in Fig. 4

Fig 6. The time evolution of T_{α} during a discharge. No clear trend was apparent with the exception of #73446 (upper figure).

Fig. 7. The history of the $T_{\alpha}/(H_{\alpha}+D_{\alpha}+T_{\alpha})$ ratio during the experimental run day (12/16/94). Also shown in solid bars is the amount of tritium injected in the neutral beams (scale on the right).

Fig. 8. (x) the later part of the T_{α} data from Fig. 7 replotted on a log scale showing the T_{α} level decaying after the major tritium NBI; ($\square$) the ratio of the D-T / D-D neutrons indicative of the tritium density in the plasma core. The left hand scale represents percent $T_{\alpha}/(H_{\alpha}+D_{\alpha}+T_{\alpha})$ or a simple ratio of D-T / D-D neutrons. The right hand scale is linear and represents the quantity of tritium NBI shown by the vertical bars

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Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Neutral Beams

Fig. 6

Fig. 7

Fig. 8

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