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RF-driven Energetic Tritium Ion Tail Measurements in TFTR Using the Pellet Charge Exchange Diagnostic

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Abstract

Charge exchange interactions of ions with the ablation cloud of an injected low-Z impurity pellet can be used to measure the energy spectrum and radial profile of confined fast ions in a fusion plasma. On TFTR, we use this technique to directly measure energetic alphas from D-T reactions, tritons from D-D reactions, and RF-driven minority tail ions (e.g., H, ^{3}He, T). This paper describes the status of the Pellet Charge Exchange (PCX) diagnostic including a brief description of the measurement technique and discussion of operational experience. PCX measurements of the energy spectrum, radial density distribution, and heating deposition profile of RF-driven tritium ions during $2W_T$ heating of L-mode plasmas are presented.

I. INTRODUCTION

The Pellet Charge eXchange (PCX) uses the technique of active neutral particle analysis to measure the energy spectrum and radial distribution of confined fast ions with energies in the mega-electron volt range [1,2]. This novel diagnostic is the result of a collaboration involving General Atomics, the A.F. Ioffe Physical-Technical Institute, and the Princeton Plasma Physics Laboratory and is presently operated routinely on TFTR. Previous papers reported the first measurements of the energy distribution of energetic confined alpha particles [1], tritons [3], RF-driven energetic ^{3}He [4] and hydrogen [5], and the influence of toroidal field ripple [6] and sawtooth instabilities [7] on the behavior of the alpha energy spectra and radial distribution. This paper describes the PCX instrument and focuses on results from recent RF experiments investigating the heating of L-mode deuterium-tritium plasmas in the second harmonic tritium cyclotron frequency regime [8].

II. THE PELLET CHARGE EXCHANGE DIAGNOSTIC

An Impurity Pellet Injector (IPI) and a Neutral Particle Analyzer (NPA) are the main components of the PCX system on TFTR. A photodiode array at the top of the tokamak vacuum vessel measures the velocity and radial position of the radially injected pellet. The IPI is capable of injecting cylindrical lithium, boron, or carbon pellets of dimension 2 mm (diameter) by 3 mm to velocities of ≤ 650 m/s; the injector uses helium, hydrogen or deuterium propellant. Lithium pellets are normally used in TFTR because lithium possesses desirable wall conditioning properties [9]. Upon entering the plasma, the pellet ablates and forms a toroidally extended ablation cloud. The ablated material is ionized to successively higher charge states as it moves away from the pellet. The helium-like ionization state is expected to dominate a large toroidal region of the cloud due to the large increase in ionization potential from the helium-like to

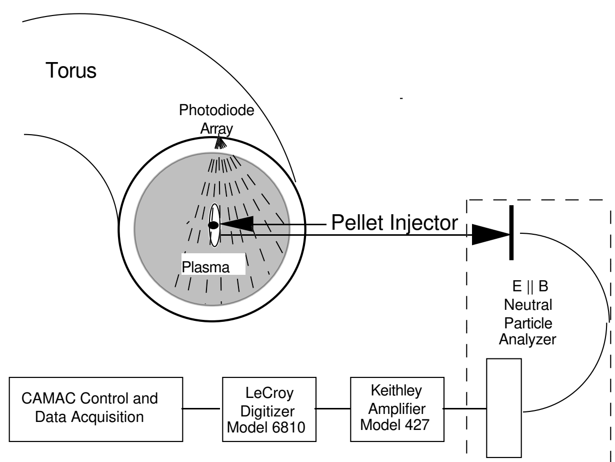

Fig. 1 Schematic of the Pellet Charge eXchange (PCX) diagnostic on TFTR.

hydrogen-like states. A small fraction of the fast ions incident on the ablation cloud is neutralized by electron capture processes. A detailed calculation of the particle-cloud interactions, which includes the helical nature of the incident particle orbits, is described in reference [10]. In the case of doubly charged fast ions, the particles are neutralized either by the double charge exchange reaction, or by two sequential single charge exchange reactions. The density of the helium-like region of the cloud should be high enough so that the neutral fraction of particles exiting the cloud approaches an equilibrium fraction F_0^∞, which is independent of the cloud density [10]. The escaping neutrals are subsequently detected by an E || B NPA with eight discrete energy channels equipped with ZnS(Ag) scintillators. In the present configuration, the NPA sight line is fixed to view the injected pellets from behind at a toroidal angle of 2.75° to the pellet trajectory. The light emission from each scintillator is measured by a photomultiplier tube and then processed by a set of amplifiers and digitizers, as shown in Fig. 1. The measured neutral signal, dn_0/dE, at each energy channel is related to the incident fast ion distribution, dn_+/dE, by the relation

$$\frac{dn0}{dE} \sim \frac{dn+}{dE} F_0^\infty(E) \qquad (1)$$

as discussed in reference [2]. Data from the NPA combined with the photodiode array provide radially resolved energy spectra and density profiles of the confined energetic particles.

The introduction of tritium in TFTR greatly increases the fusion reaction rate as well as the energy of the fusion products. Hence, the problems associated with radiation-induced background are a very serious issue for diagnostics on TFTR during D-T experiments. To reduce the radiation background, the NPA, scintillator detectors and photomultiplier tubes are housed inside a radiation shield consisting of lead and polyethylene. The polyethylene contains approximately 5% boron and acts as a neutron attenuator and moderator. The lead is used to stop the gammas. For the PCX diagnostic, the shielding factor is approximately 100 in D-T and 500 in D-D experiments [2]. These values are empirically obtained by comparing the signal response of a scintillator and photomultiplier tube outside the shield to a similar set inside the shield. In the RF-tritium experiments reported here, the D-T neutron emission reached 10^{15} s^{-1}. Hence, the radiation shield was essential for obtaining good PCX data.

Another important issue associated with the PCX diagnostic is pellet penetration. We empirically observe poorer pellet penetration at higher electron temperature. However, there is only a weak correlation between pellet penetration and electron density. These empirical observations are consistent with theory [11].Several schemes were employed to enhance the pellet penetration. One of the most effective methods is to increase the pellet velocity; in TFTR, this is accomplished by using hydrogen propellant instead of helium. When hydrogen was used, the average pellet velocity increased from 500 m/s to 600 m/s and the pellet penetration increased by 10-20 cm compared to helium propellant. Another method is to use two pellets in a stacked fashion. While the first pellet may penetrate poorly, it lowers the plasma temperature to allows the second pellet to penetrate farther. Both schemes have been successfully applied to RF discharges.

III. Measurement of Tritium Tail Ions in L-mode Plasma

In most D-T experiments on TFTR the tritium is introduced via neutral beam injection. However, in a recent campaign involving ICRF heating of a low beta, L-mode D-T plasma, the tritium was delivered to the plasma by the gas puffing technique [8]. In addition to gas puffing, the experiment also relied on tritium recycling from the vessel wall to fuel the plasma. Tritium recycling was accomplished by first conditioning the machine to remove as much of the deuterium absorbed in the limiter as possible. The limiter is then reloaded with tritium by gas puffing. This recycling scheme resulted in a high fraction (~50%) of tritium content in the gas released from the limiter. One of the primary objectives of these experiments was the demonstration of second harmonic heating of tritium in an L-mode plasma to simulate the RF startup scenario for ITER [12].

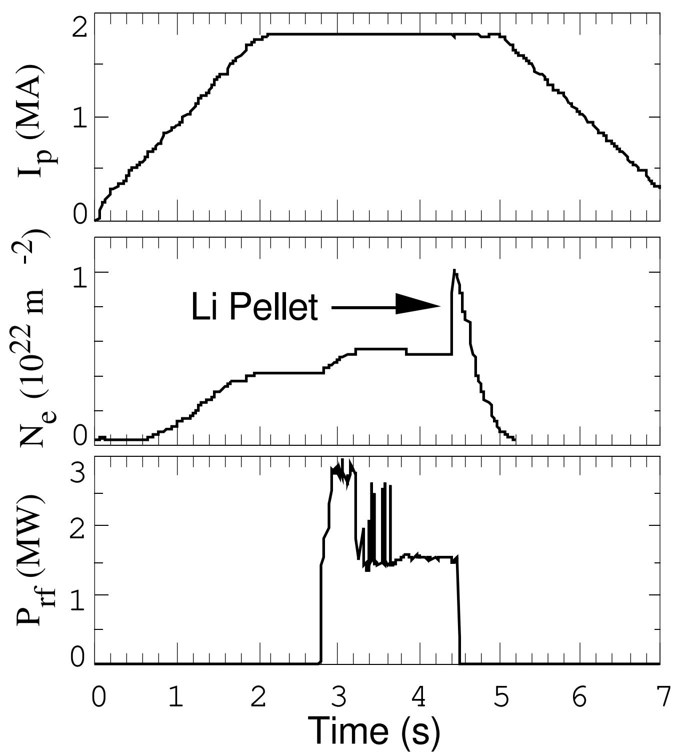

Fig. 2 Plasma waveforms during RF heating at the 2nd harmonic of the tritium cyclotron frequency.

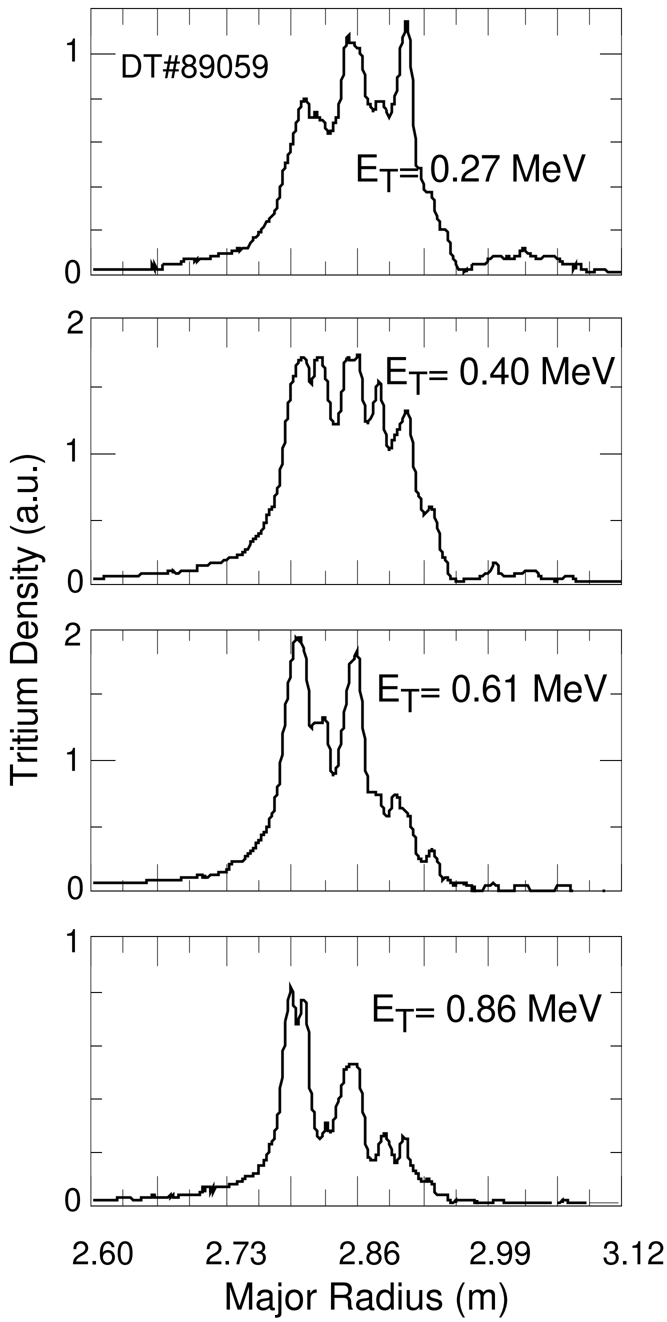

Fig. 3 Measured tritium energetic tail density at different energies.

During RF heating experiments where the antennae were tuned at the second harmonic of the tritium cyclotron frequency, the energy spectrum and radial profile of the effective temperature of the tritium tail were obtained using PCX. The plasma current, central electron density, and launched RF power of a representative discharge for these measurements are presented in Fig. 2. The basic discharge parameters were: R_{maj} = 2.63 m, a = 0.9 m, I_p = 1.8 MA and B_T = 5 T. Tritium signals for four of the eight PCX channels as a function of major radius are shown in Fig. 3. The measurement was made during the 2.8 s flattop phase of the 1.8 MA D-T discharge. The tritium content of the target plasma was about 50%. The RF heating was applied from 2.8 - 4.5 s and reached a launched power of P_{rf} = 2.75 MW, but dropped to 1.5 MW from 3.2 - 4.5 s due to a fault. The Li pellet was injected at 4.4 s near the end of the RF pulse. At the time of pellet injection, the central electron temperature and density were approximately 2.9 keV and 3.8 x 10^{19} m^{-3}, respectively. The pellet penetrated slightly beyond the magnetic axis (R_{axis} = 2.74 m).

A large increase in the signal level occurred just inside R = 2.95 m which is about 15 cm outboard of the ICRF resonance layer. The tail temperature increases as the pellet moves closer to the resonance layer as shown later in Fig. 5. The fluctuations in the PCX signals in Fig. 3 are observed on all energy channels. It is important to note that these fluctuations do not affect the energy spectrum. We believe that these fluctuations may be the result of the spatial variation in the density of the RF-driven tritium tail. We also cannot rule out the possibility that fluctuations in the ablation cloud parameters associated with charge-exchange neutralization are responsible. These fluctuations have been observed in many pellet injection experiments in tokamaks and may be due to a Rayleigh-Taylor cloud instability [13]. The PCX results to date show that the peaks in the tritium tail signals seem to occur at the same radial locations on different shots. This would seem to make cloud fluctuations, which would normally be thought to be uncorrelated shot to shot, a less likely explanation. Additional experiments under various discharge conditions using different pellet materials are needed to verify this conclusion.

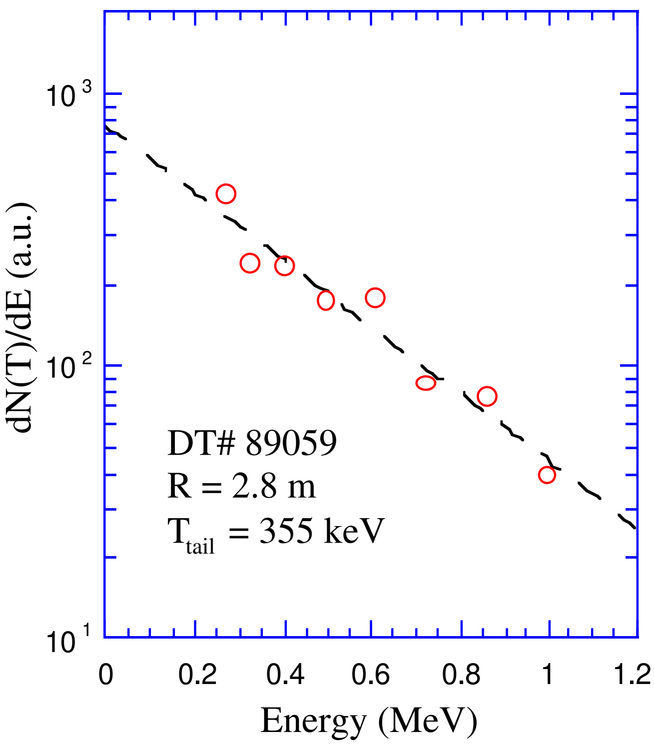

Fig. 4 Energy spectrum of the tritium tail at R = 2.8 m

The measured energy distribution function of the tritium tail near the resonance surface is shown in Fig. 4. A straight line fit to the data yields an effective tritium tail temperature of approximately 355 keV. Preliminary results indicate that the formation of the tail is quite fast; the energy spectrum of the tail is fully developed after the first 100 ms of RF heating. Furthermore, the energy confinement time in these tritium discharges is similar to that seen in D-T plasmas heated by hydrogen minority ICRF. Figure 5 illustrates the radial profile of the effective tail temperature of the discharge. The tail temperature profile exhibits a transition near R = 3.0 m where the effective temperature increases by a factor of two. Additional experiments are needed to confirm these preliminary observations. Among the effects that need to be studied in detail are the formation and evolution of the tail, density profile near the RF resonance surface, and comparison between modeling and measurements.

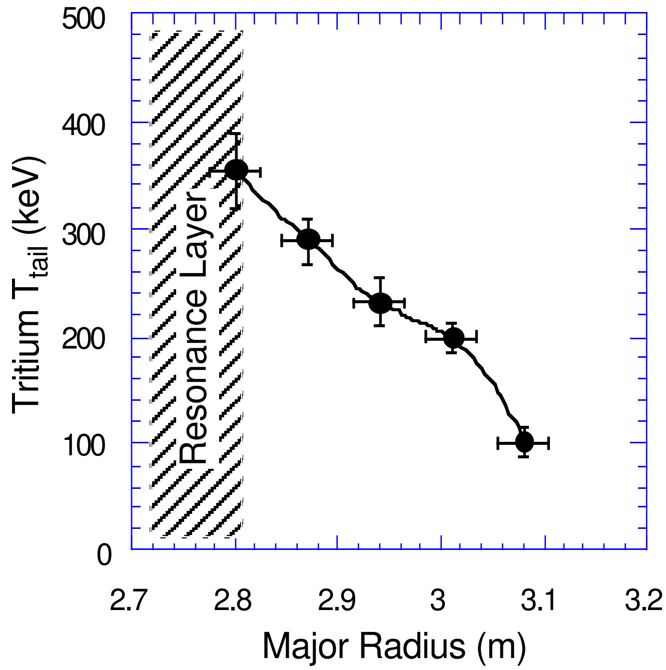

Fig. 5. Radial profile of the tritium tail temperature.

IV. Summary

The PCX diagnostic has been tested on TFTR and is routinely used to measure energetic confined alphas from D-T reactions, tritons from D-D reactions, deuterium beam ions, and RF-accelerated tritons, ^{3}He and hydrogen ions. Measurements of the radial profile and energy spectrum of the tritium tail during ICRF heating of an L-mode plasma at the second harmonic tritium cyclotron frequency were obtained. The tritium density and tail temperature radial profiles suggest that most the heating occurs within 20 cm from the resonance surface. The PCX data showing formation of an energetic tritium tail provide evidence of ion heating, and in combination with diamagnetic data showing a substantial increase in the thermal stored energy in TFTR [8], support the idea of using second harmonic ion cyclotron heating as a viable technique for heating the relatively cold, low density ITER startup plasma [12].

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