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Operation of the TFTR Pellet Charge Exchange Diagnostic in the Pulse Counting Mode during H^+ RF-Minority Heating

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Abstract

The Pellet Charge Exchange technique on TFTR has been used primarily to obtain active charge exchange measurements using a high energy (0.5 - 4.0 MeV) neutral particle analyzer (NPA) in conjunction with impurity pellet injection (Li and B) with the scintillator-photomultiplier detector system operated in the current mode. While passive measurements using pulse counting were also obtained using this instrumentation, operation in this mode was very restrictive with pulse counting rates limited to less than ~ 10 kHz in the absence of any significant neutron and gamma induced background signal. An upgrade to a specialized pulse counting capability which was developed by the Ioffe Institute was implemented which consisted of CsI(Tl) scintillators having features designed to minimize signals induced by background neutron and gamma rays and 16-channel pulse height analysis electronics on each of the eight NPA energy channels. Passive measurements of RF-driven energetic hydrogen minority ions which served to verify operation of the pulse counting mode are reported. It is shown that in the passive mode the main donors for the neutralization of H^+ ions in this energy range are C^{5+} ions. The measured effective H^+ tail temperatures range from 0.15 MeV at an RF power of 2 MW to 0.35 MeV at 6 MW.

I. INTRODUCTION

The subject matter of this paper is the study of the RF-driven H^+ minority ions in deuterium TFTR plasmas using passive neutral particle analysis in the energy range of 0.2 - 1 MeV. Similar measurements were performed earlier on JET where the efficient passive neutralization of MeV energy protons was first observed in the plasma center [1,2]. The main donors for the neutralization of the protons appeared be the hydrogen-like low Z impurity ions. In a later paper [3], a detailed analysis of the neutralization processes of MeV protons in JET was made and the cross-sections of the electron capture of H^+ ions from C^{5+} and Be^{3+} (the main donors in JET plasmas) were calculated. Similar measurements of the RF-driven H^+ minority have also been made on JT-60U [4].

The neutral particle measurements were obtained using a high energy neutral particle analyzer (NPA) developed in the Ioffe Institute [5]. The high energy NPA was used on TFTR primarily for Pellet Charge Exchange (PCX) diagnostics [6, 7] to obtain active charge exchange measurements of the energy and radial distributions of DT alpha particles in conjunction with impurity pellet injection [8] with the detector operated in the current mode. In parallel, passive measurements of H^+ RF-driven minority ions at energies up to the MeV range were also performed in the pulse counting mode. In the last stage of the TFTR experiments, the pulse counting capability was upgraded by implementing a detector system which consisted of Cs(Tl) scintillators designed to minimize the signals produced by background neutrons and gamma rays with each of the eight NPA energy channels being equipped with 16-channel pulse height electronics (ADC). The experimental data presented in this paper are the results obtained using this upgraded passive pulse counting mode.

II PHYSICAL BASIS OF THE PASSIVE CHARGE EXCHANGE DIAGNOSTIC

As was mentioned above, passive measurement of the RF-driven H^+ minority ions in the MeV energy range is based on the electron capture of H^+ ions from hydrogen-like low-Z impurity ions. The most probable donors for electron capture in TFTR plasmas are C^{5+} ions because the main low-Z impurity in TFTR was carbon. In principle, another possible donor could be the residual D^o atoms. The cross-sections for charge exchange of H^+ with D^o [9] and C^{5+} [5] are shown in Fig. 1. Figure 2 presents the charge-exchange rates of H^+ on D^o and C^{5+}. Here the density of C^{5+} in the plasma core is equal to 10^{10} cm^{-3} (estimated on the basis of spectroscopic measurements) and the upper limit of D^o density is estimated to be ~10^8 cm^{-3}. The energy range of the NPA measurements is also shown. It is clearly seen from the figure that the only possible donor in TFTR plasmas in the energy range of the interest is C^{5+}. Therefore we can conclude that the NPA detects the H^o passive signal on TFTR as a result of the reaction:

$$H^+ + C^{5+} = H^o + C^{6+}. \tag{1}$$

In this case the H^o flux produced in the plasma can be expressed as:

$$\Phi_{H^o}(E) = n_{H+} n_{C5+} f_{H+}(E)\, \sigma\, v_{H+} \quad (cm^{-3}\ s) \tag{2}$$

where n_{H+}, n_{C5+} are the densities of H^+ and C^{5+} ions in the plasma, $f_{H+}(E)$ is the local H^+ energy distribution function, σ is the cross-section of the reaction shown in Eq. (1), and v_{H+} is the H^+ velocity.

The NPA was located in the midplane with an observation line at a toroidal angle equal to 2.75° to the major radius direction. Therefore only deeply trapped ions with pitch angles in a narrow range $v_{||}/v = -0.048 \pm 10^{-3}$ were detected. The measured energy spectrum integrated over the observation sight line, L, can be expressed as:

$$dn_{H^o}/dE = \int_L \Phi_{H^o}(E,l) \exp\{-\int_L N_e(x)\, \sigma_r(E)\, dx\}\, dl \qquad (3)$$

where $N_e(x)$ is the electron density and $\sigma_r(E)$ is the sum of the cross sections for reionization of fast H^o atoms emerging from the plasma due to collisions with electrons and deuterons (including charge exchange reactions). The integral in the brackets { } represents the transparency of the plasma for the detected H^o atoms. The transparency is not very significant factor for the sub-MeV and MeV H^o atoms in TFTR and has to be taken into account only for the low energy part of the NPA energy range shown in Fig. 1 and Fig. 2.

The energy spectrum of H^+ ions can be derived from the number of counts in the n^{th} channel of the NPA, $N_n(E)$, in the following way:

$$dn_{H+}/dE \sim N_n(E)\, \{\sigma v_{H+}\, \eta(E)\, \Delta E_n/E_n\}^{-1} \qquad (4)$$

Here η (E) is the calibrated NPA detection efficiency and ΔE_n is the energy width of the n^{th} channel of the NPA. In the case of the RF-driven ions in TFTR, this yields $dn_{H+}/dE \sim f_{H+}(E)$ averaged over the RF resonance layer because the $n_{H^+}n_{C^{5+}}$ value is sensibly constant if RF resonance is located at the plasma core.

III RESULTS

The experimental data presented in this section are the results of operation in the passive pulse counting mode. Figure 3 shows the measurement scenario and Fig. 4 shows the number of H^+ counts detected by the ADC on the third NPA energy channel (E_{H+} =

0.3 MeV) during a period of 200 ms. H^+ counts here are detected in ADC channels 5 - 14 (shaded area) with the maximum in channel 11. The low amplitude pulses in channels 1 - 4 are the n, γ background and the detector noise. It is seen that the noise and background are easily distinguished from the H^+ signal which made it reasonable to use this system in the presence of high n, γ background.

Figure 5 shows the active energy spectrum of RF-driven H^+ ions for the discharge presented in Fig. 3 and the passive spectrum averaged over 200 ms during an RF power pulse in a discharge with the same parameters (#10489). Previously reported [10] active and passive spectra were shown to have the same Maxwellian shapes and very similar effective tail temperatures which provided confirmation that the proper donor (C^{5+}) was chosen to get the passive energy spectrum. These passive measurements of H^+ RF-driven minority ion temperature in deuterium plasmas were performed routinely mainly as "piggy-back" experiments during RF runs on the TFTR. Figure 6 presents the effective temperature $T(H^+)$ of the H^+ minority versus RF power, P_{RF}, for a collection of 67 discharges. The measurements were made in D(H) on-axis, RF-heated discharges for the following range of plasma parameters: I_{plasma} = (1.3 - 1.8) MA, $N_e(0)$ = (2.4 - 6.0)10^{13} cm^{-3}, $T_e(0)$ = (2.6-10) keV. It can be seen that $T_{eff}(H^+)$ increases monotonically with P_{RF} but even for P_{RF} ~ 6 MW, the values of $T_{eff}(H^+)$ do not exceed ~ 0.35 MeV.

ACKNOWLEDGMENTS

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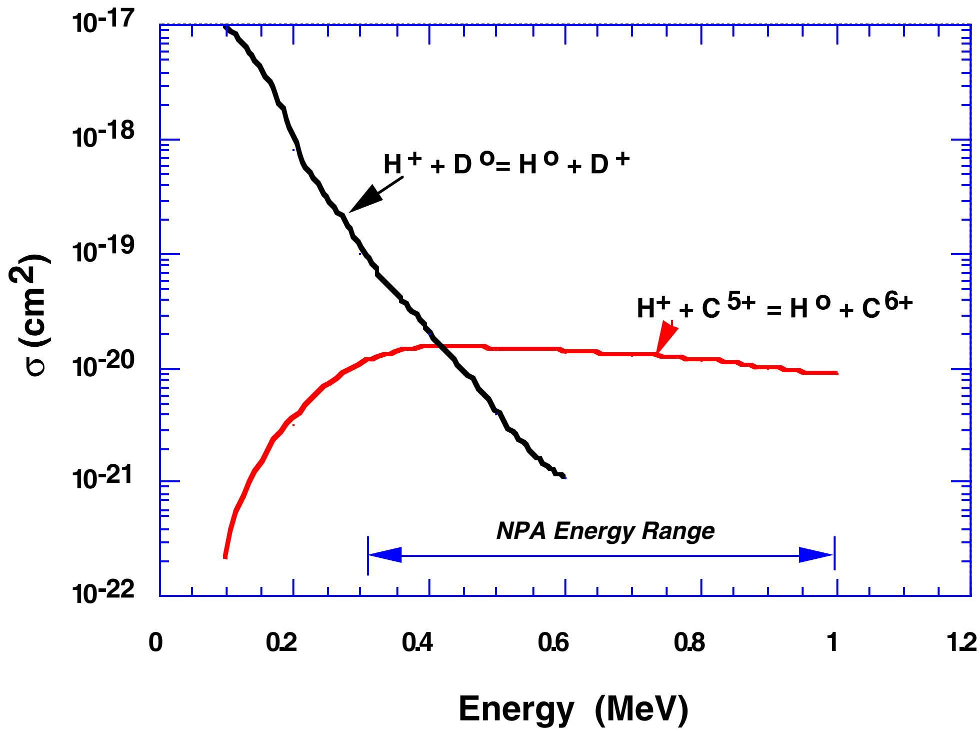

Fig. 1 Cross-sections for proton charge-exchange with D^o atoms and with C^{5+}.

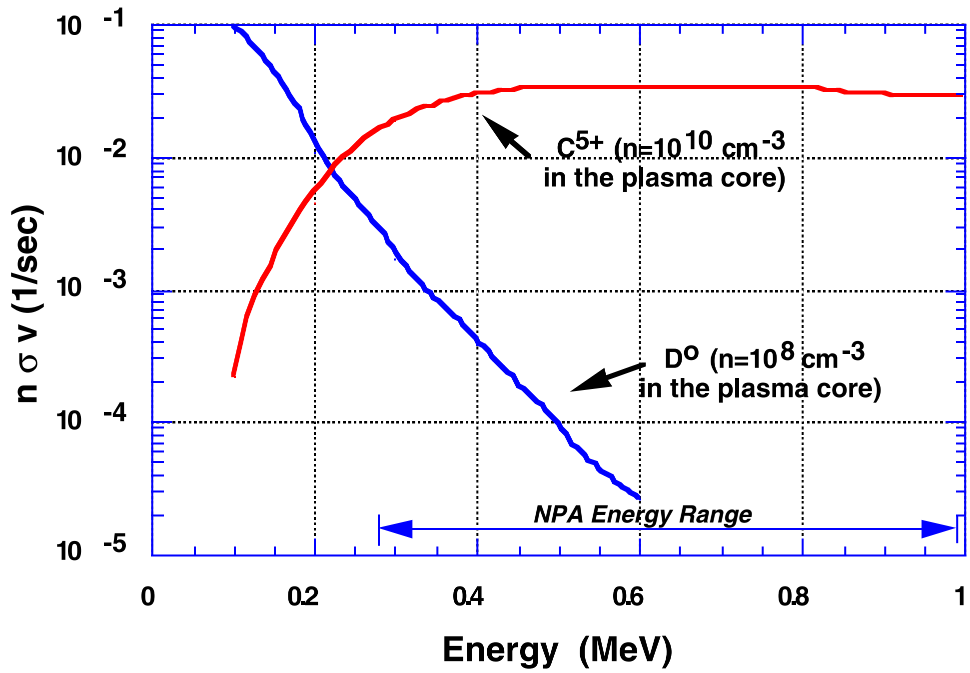

Fig. 2 Charge-exchange rates of H^+ ions with C^{5+} (n =10^{10} cm-3 in the TFTR plasma core) and with D^o (n =10^8 cm-3 in the plasma core).

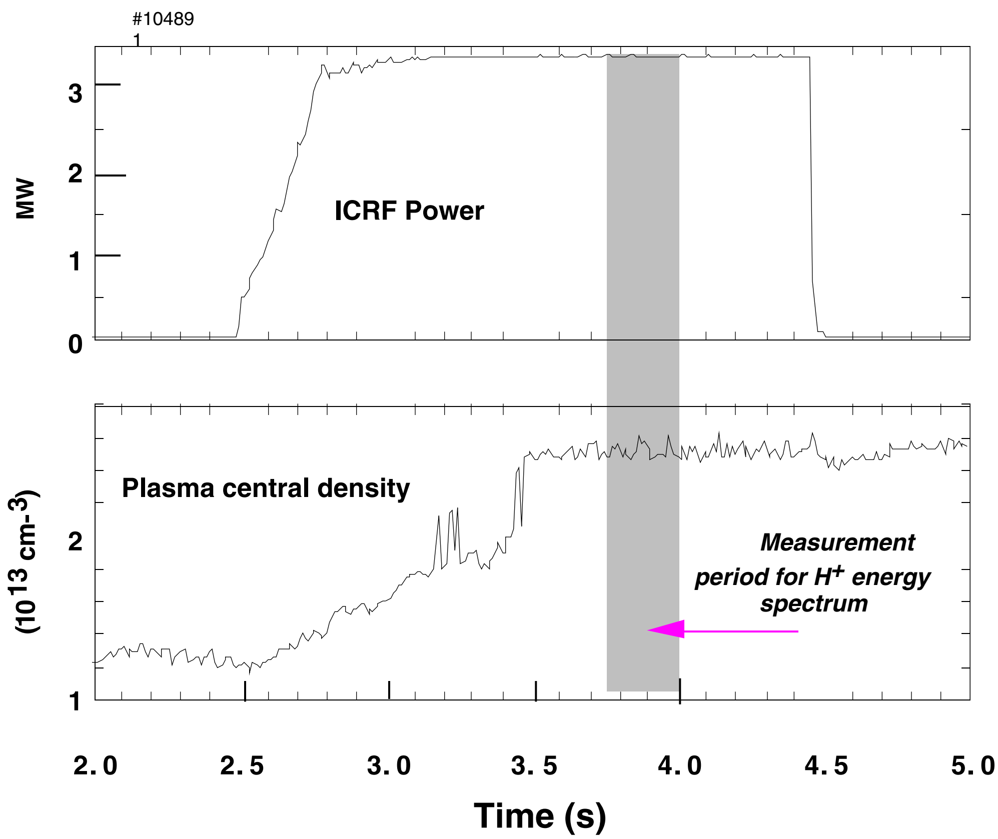

Fig. 3 Waveforms for measurement of the H^+ effective tail temperature, $T_{eff}(H^+)$.

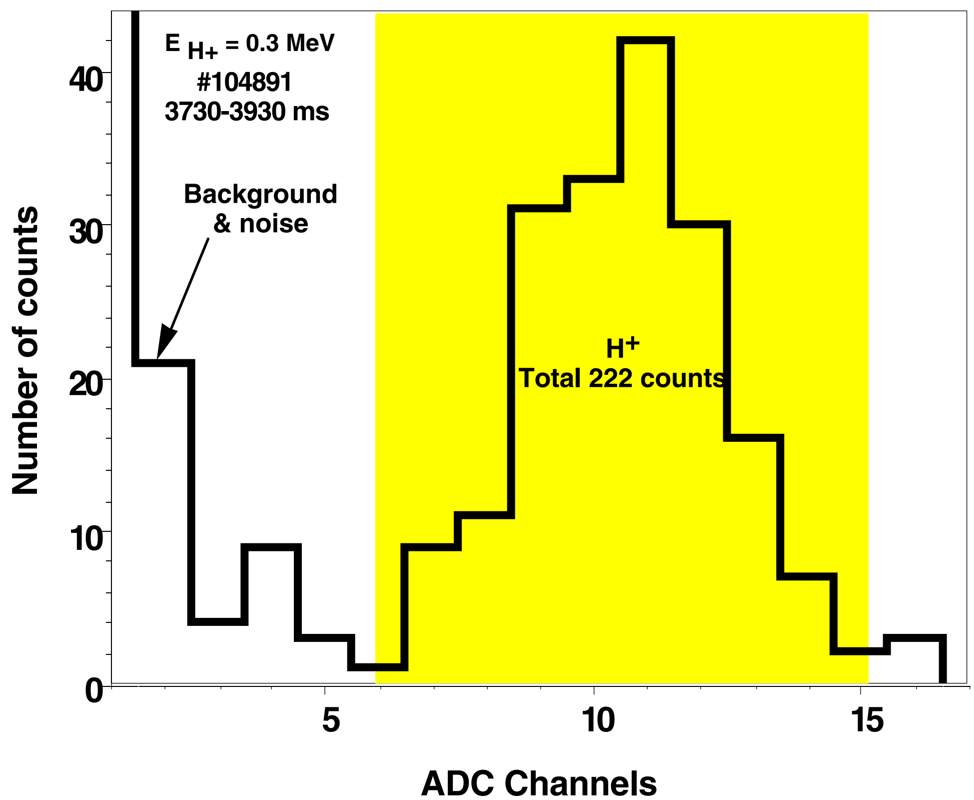

Fig. 4 Typical pulse height distribution from the ADC in the third NPA channel.

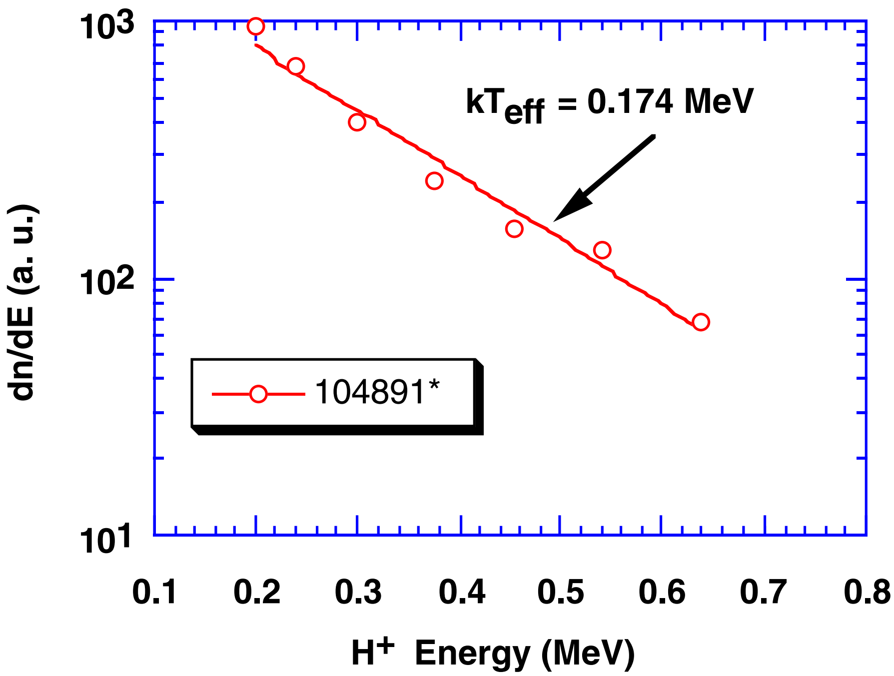

Fig. 5 RF-driven H^+ energy spectrum from passive measurements yielding T_{eff} = 0.174 MeV for P_{RF} = 3.2 MW (#104891).

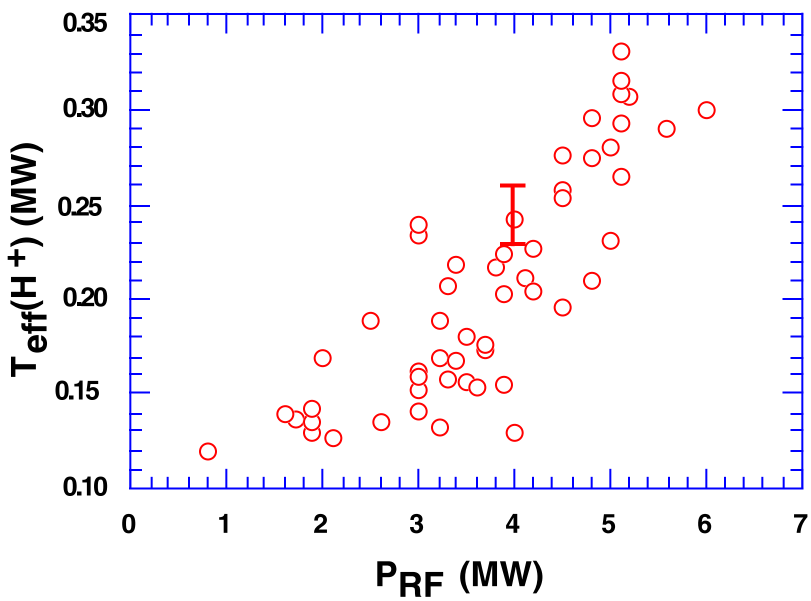

Fig. 6 H^+ effective temperatures versus RF power for D(H) on-axis ICRF heated plasma in TFTR.