Effective Temperatures, Sawtooth Mixing and Stochastic Diffusion Ripple Loss of Fast ICRF-Driven H^+ Minority Ions in TFTR

S. S. Medley, M. P. Petrov (Ioffe), R. Bell, R. V. Budny, N. N. Gorelenkov (TRINITI), A. L. Roquemore and S. J. Zweben

Princeton Plasma Physics Laboratory, P. 0. Box 451, Princeton, NJ, 08543, USA

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Effective Temperatures, Sawtooth Mixing and Stochastic Diffusion Ripple Loss of Fast ICRF-Driven H^+ Minority Ions in TFTR*

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- The Pellet Charge Exchange (PCX) diagnostic on TFTR was used primarily to obtain *active* NPA measurements using impurity pellet injection (Li and B).

- The capability for *passive* measurements was enhanced by installing an upgraded pulse counting system developed by the Ioffe Institute

- Studies of ICRF-driven H^+ minority ions in TFTR deuterium plasmas using passive H^0 flux detection in the energy range of 0.2 - 1.0 MeV are reported.

- 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 ranged from T_{eff} = 0.15-0.35 MeV for ICRF power from 2-6 MW.

- Radial redistribution of ICRF-driven H^+ ions was detected when giant sawtooth crashes occurred. The redistribution affected ions with energy below 0.7-0.8 MeV and dislaced them outboard into the stochastic ripple diffusion domain where they were lost in ~ 10 ms.

- These observations are consistent with ORBIT code simulations of H^+ stochastic ripple diffusion losses and with a sawtooth model developed previously to explain the results of DT alpha particle redistribution in TFTR due to sawteeth.

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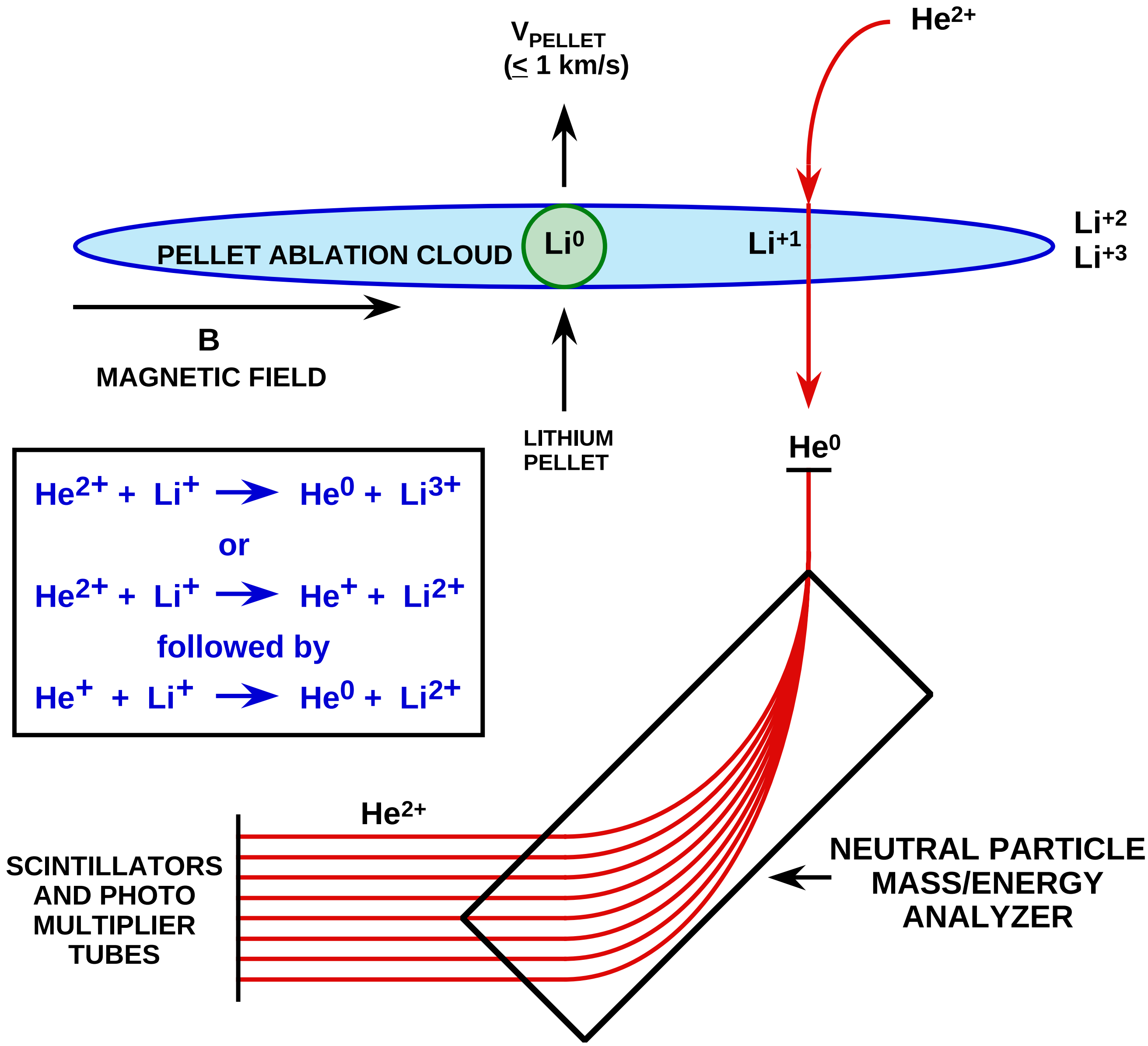
Pellet Charge Exchange Measures Alpha Energy & Radial Distribution



- dn^{2+}/dE (incident alphas) = $\dfrac{dn^{0}/dE \text{ (detected neutrals)}}{F_o^{\infty}(E)}$
- **PCX detects trapped alphas with a narrow acceptance window of ± 10^{-3} around a mean pitch angle of $v_{||}/v = -0.048$**

Physical Basis for Passive CX Measurements

- **Passive measurement of the RF-driven H^+ minority ions in the MeV energy range is based on electron capture by H^+ ions from hydrogen-like low-Z impurity ions. The most probable donor for electron capture in TFTR plasmas is C^{5+} because carbon is the main low-Z impurity:**

$$H^+ + C^{5+} = H^o + C^{6+}$$

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

$$\Phi_{Ho}(E) = n_{H^+} n_{C5^+} f_{H+}(E)\, \sigma\, v_{H+}$$

where n_{H+}, n_{C5+} are the densities of H^+ and C^{5+} ions, $f_{H+}(E)$ = local H^+energy distribution function, σ = cross-section for the above reaction, and v_{H+} = H^+ velocity.

• The measured line integral energy spectrum is given by:

$$dn_{Ho}/dE = \int_L \Phi_{Ho}(E,l) \exp\{-\int_L N_e(x)\, \sigma_r(E)\, dx\}\, dl$$

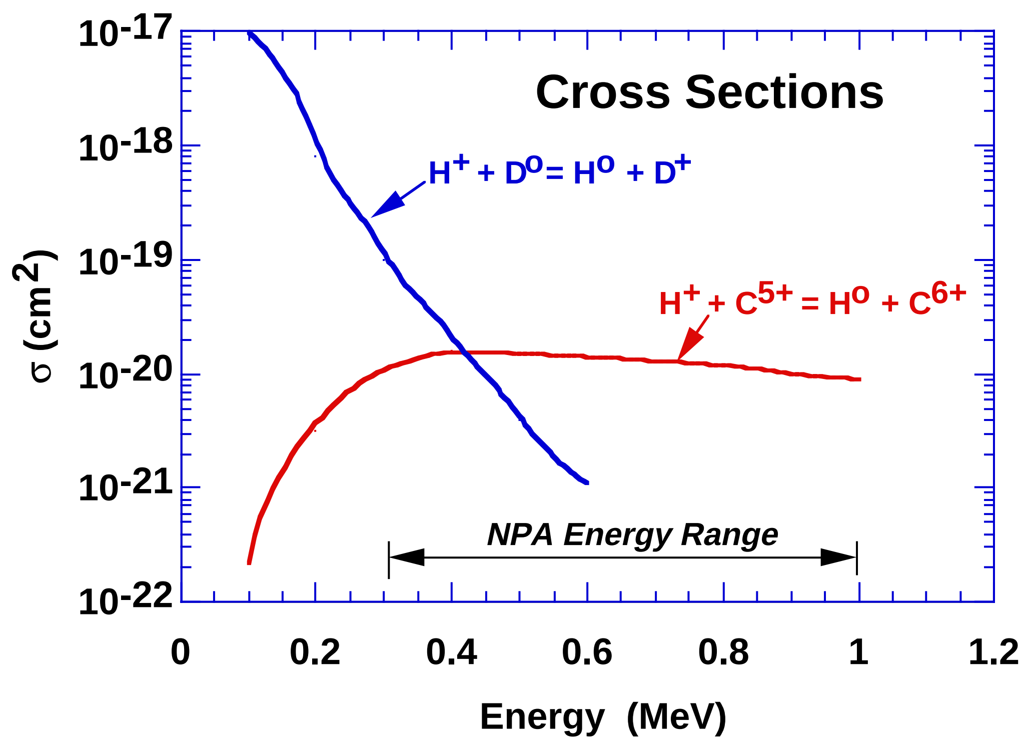
where $N_e(x)$ is the electron density and $\sigma_r(E)$ is the total cross-section for reionization of emerging H^o atoms due to collisions with electrons and deuterons.

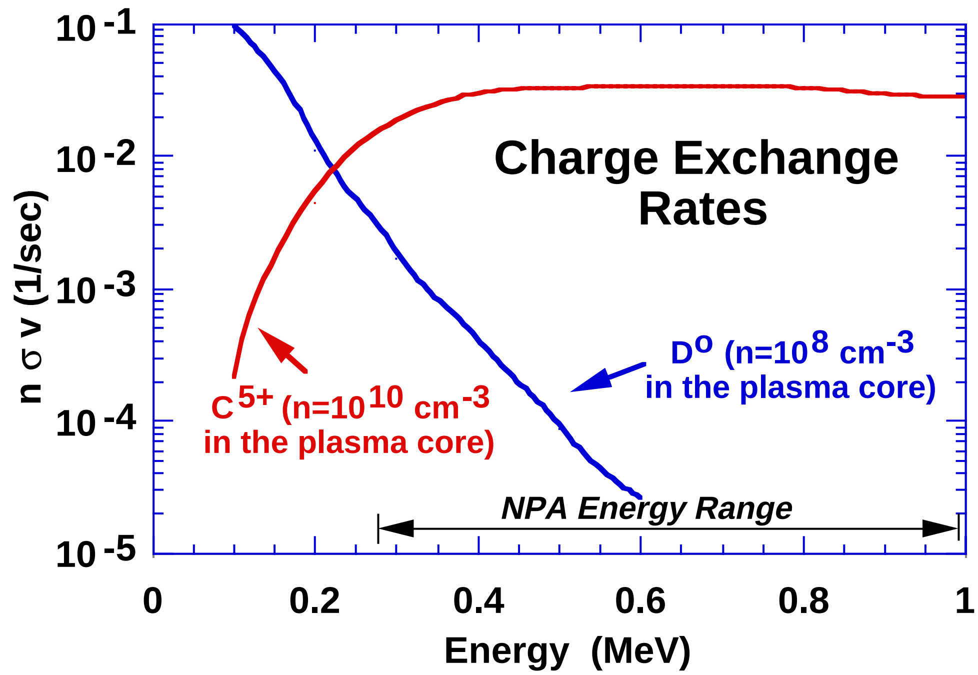
• The energy spectrum of H^+ ions can be derived from the number of counts in the n^{th} NPA channel, $N_n(E)$, as follows:

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

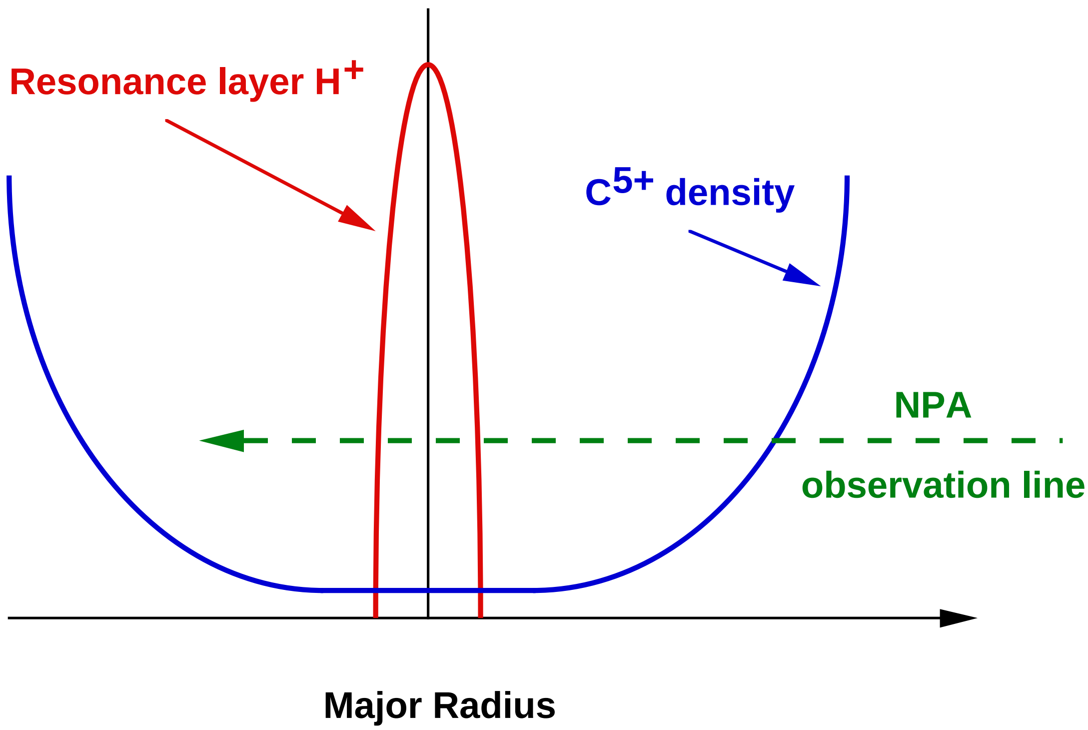
where $\eta(E)$ is the calibrated NPA efficiency. For RF-driven ions in TFTR, this yields $dn_{H^+}/dE \sim f_{H^+}(E)$ averaged over the RF resonance layer because the $n_{H^+} n_{C^{5+}}$ value is constant if RF resonance is located at the plasma core.

C^{5+} Impurity Ions are the Primary Donor for Charge Exchange of Fast H^+ Ions





Schematic Illustrating Passive H^+ Integration over the NPA Sightline



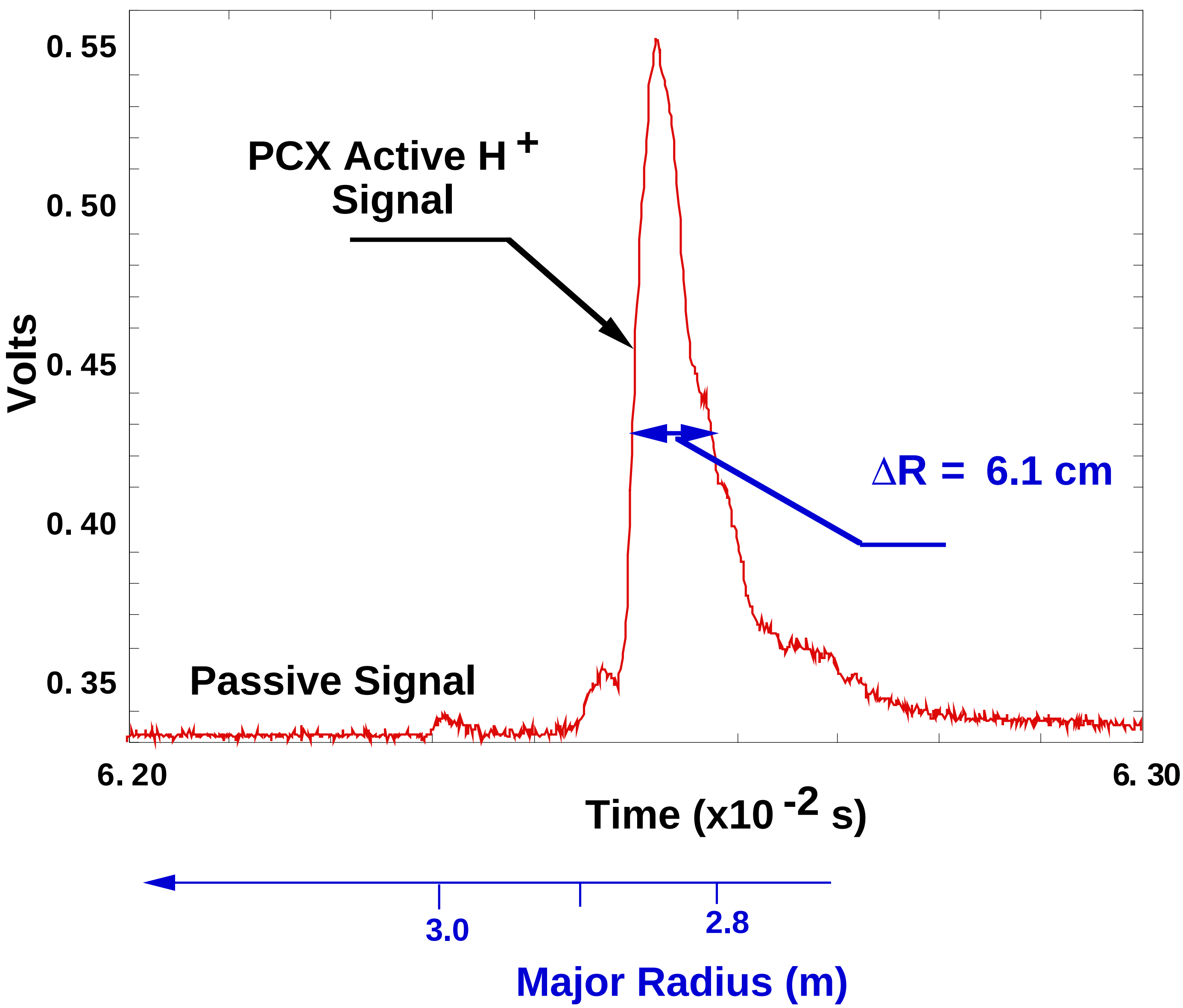
- The H^o flux observed by the NPA can be expressed as:

$$\Phi\, H^o(E) = n_{H^+} n_{C^{5+}}\, f\, H^+(E)\, \sigma\, v_{H^+}$$

where n_{H^+}, $n_{C^{5+}}$ are the densities of H^+ and C^{5+} ions.

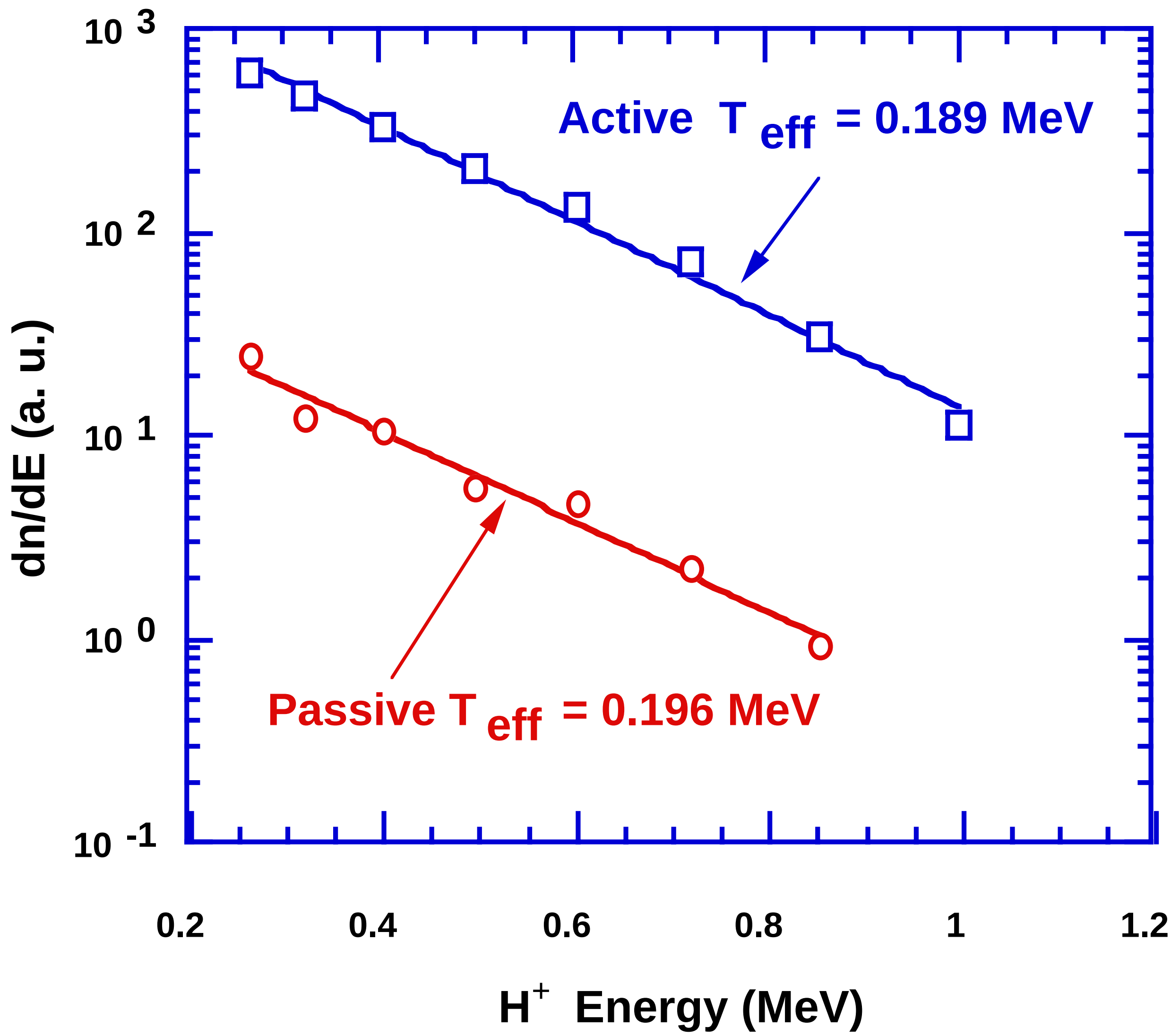
- In the case of the RF-driven ions in TFTR, this yields $dnH^+/dE \sim f\, H^+(E)$ averaged over the RF resonance layer because the $n_{H^+} n_{C^{5+}}$ product is constant if the RF resonance is located at the plasma core as illustrated by the schematic above.

Active PCX Signals Reflect the Profile of the H^+ Resonance Layer



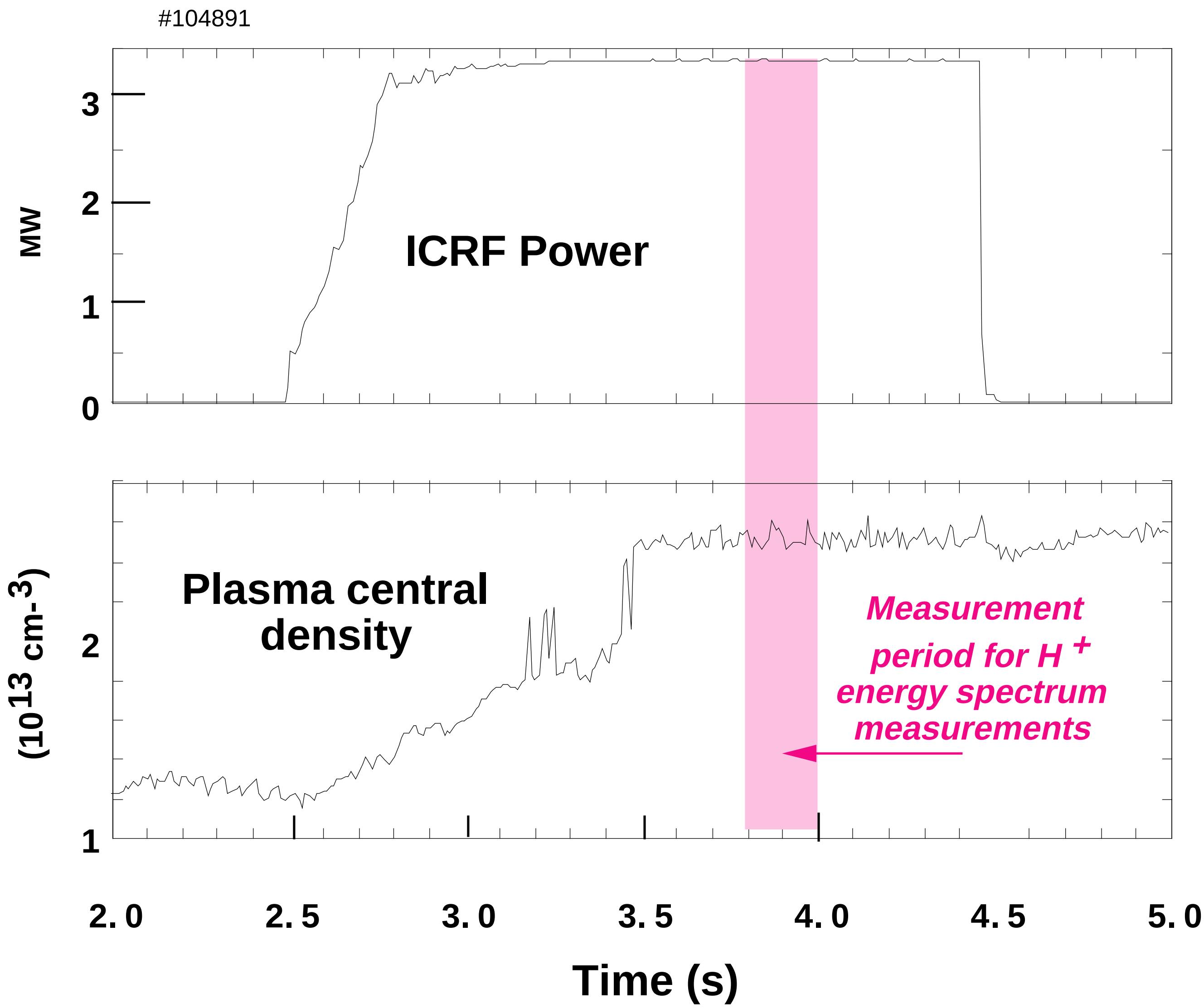
- The radial position and shape of the H^+(E = 0.72 MeV) signal measured by the PCX active diagnostic correlates with the profile of the resonance layer for fundamental H^+ RF heating in D plasma.

Good Agreement is Observed Between Active and Passive Measurements of H^+ RF-driven Ion Energy Specta



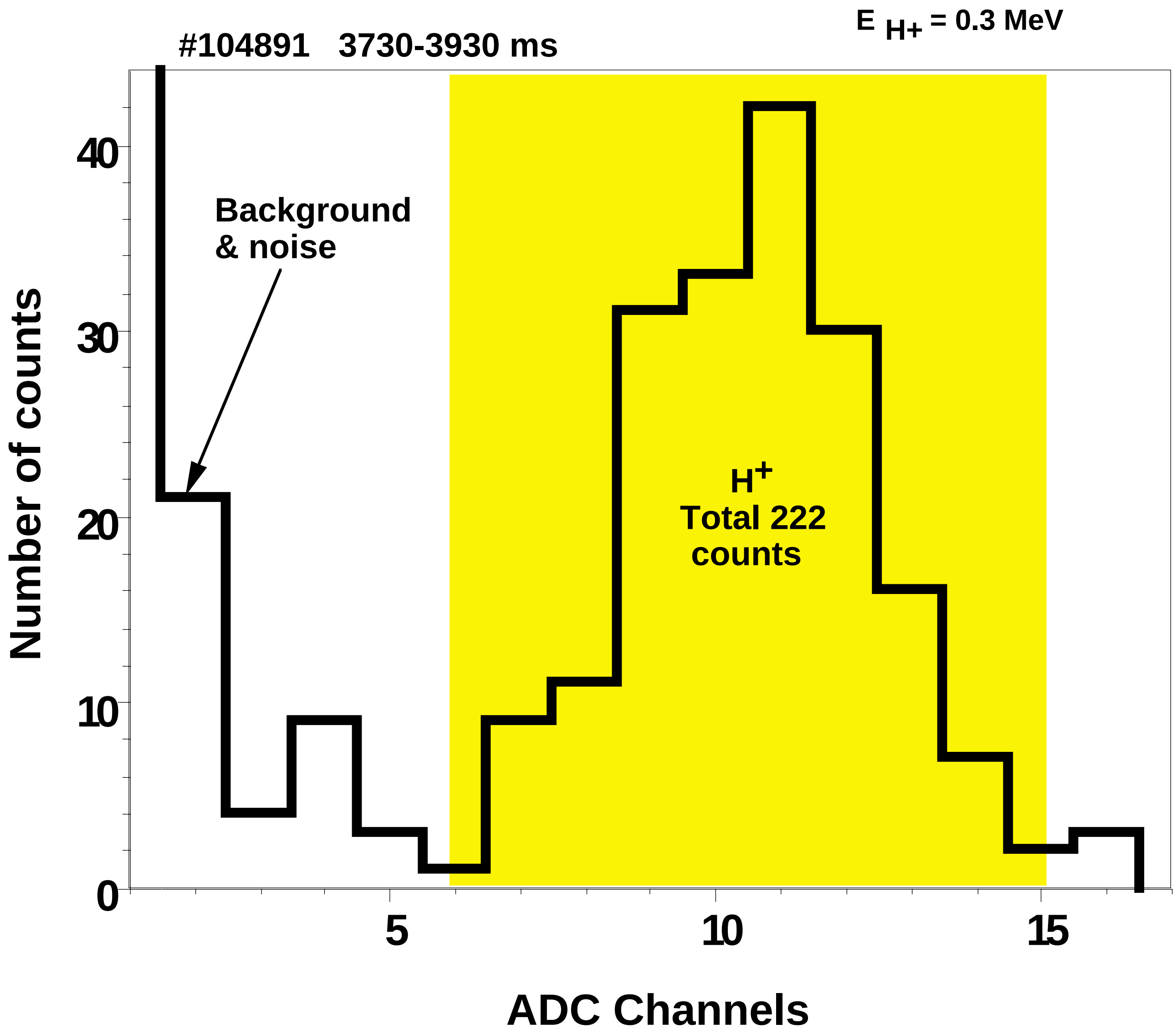
- Both active and passive spectra are for on-axis heating with P_{RF} = 2.1 MW, F = 43 MHz and Ne(0) = 5.10^{13} cm^{-3}.

H^+ Effective Tail Temperature (T_{eff}) was Measured during the RF Heating "Flattop"



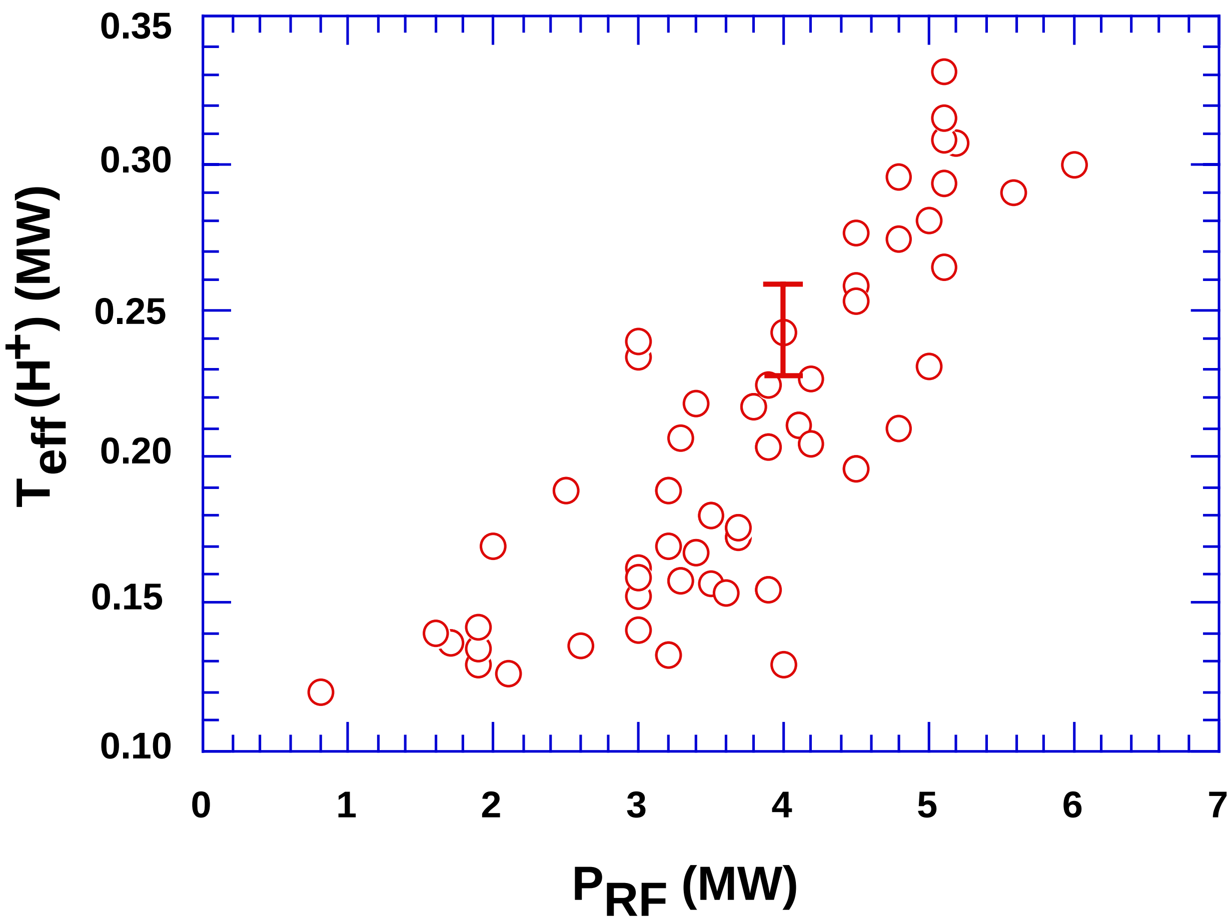
- PCX passive pulse height spectra were typically integrated over Δt = 200 ms.

H^+ Pulse Height Spectra are Well Separated from the n,γ Induced Background



- The pulse counting system consists of Cs(Tl) scintillators with 16-channel pulse height electronics implemented on each of the 8 NPA energy channels.

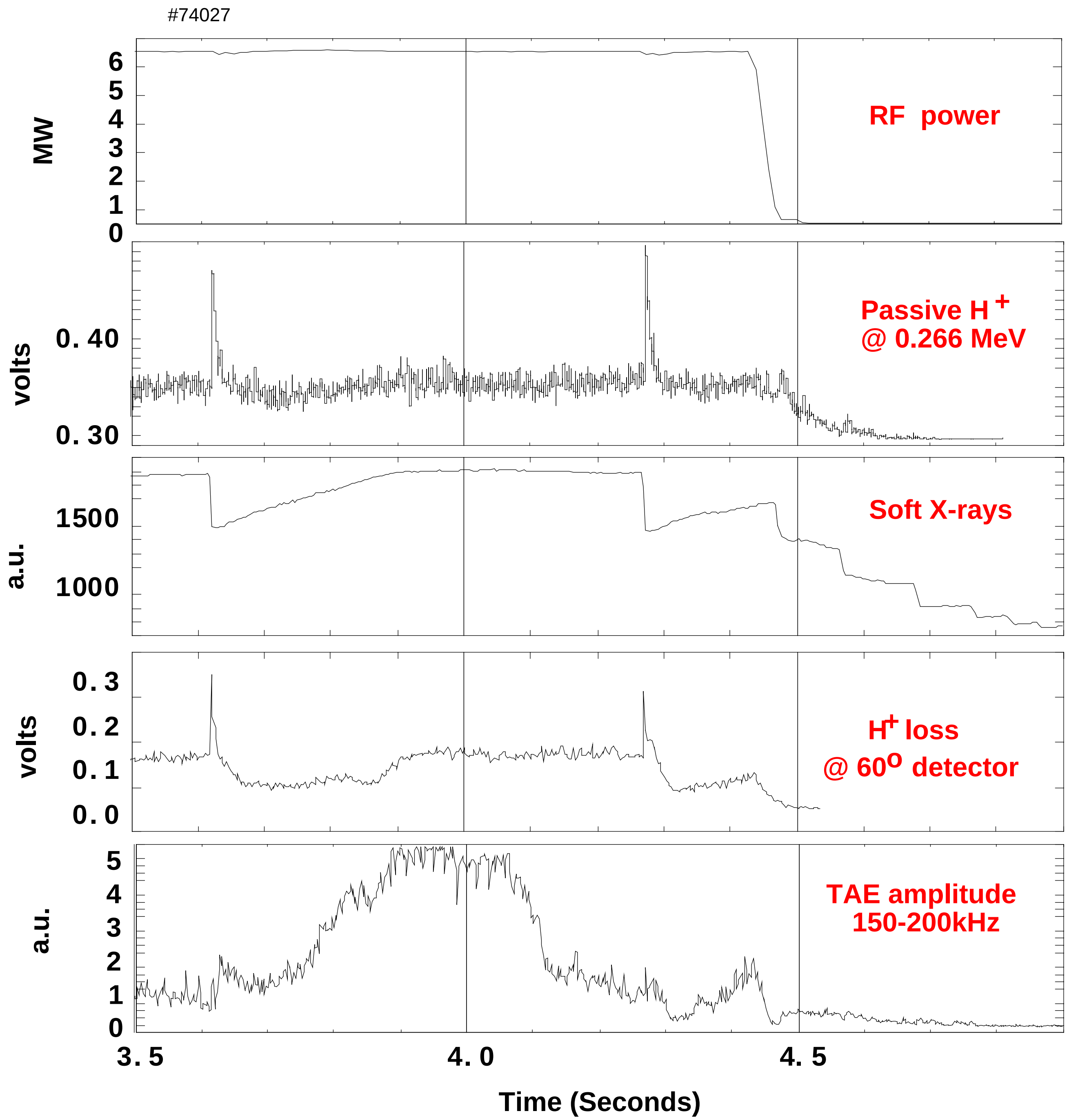
H^+ Effective Tail Temperatures (T_{eff}) versus RF Power for on-axis ICRF-Heated Deuterium Plasma in TFTR.



- A collection of 67 RF-heated discharges were analyzed 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.

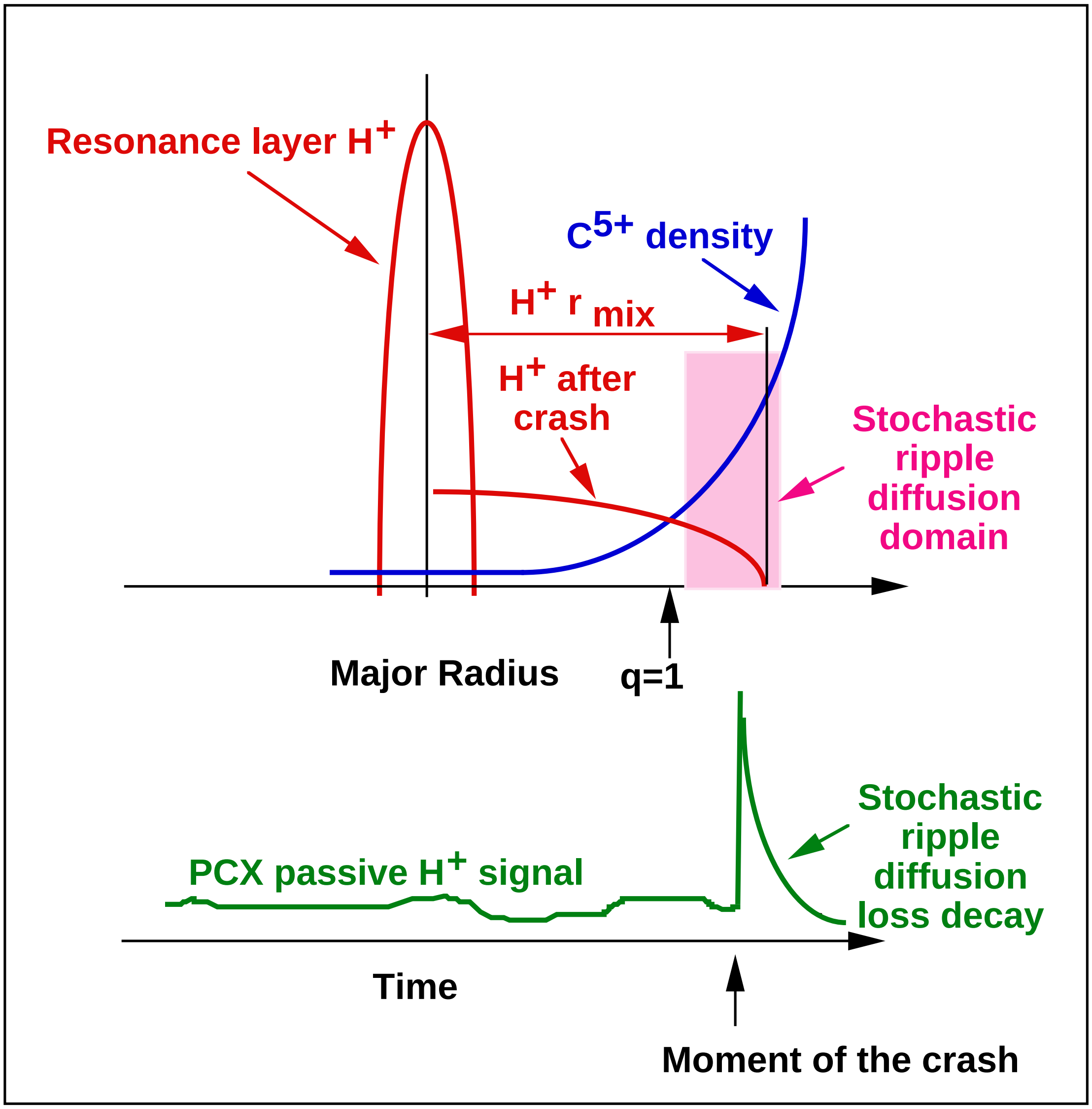
- T_{eff}(H+) increases monotonically with P_{RF} but even for P_{RF} ~ 6 MW, the values of T_{eff}(H+) do not exceed ~ 0.35 MeV.

Waverforms for a Discharge with Sawtooth Activity during RF-driven H $^+$ Minority Heating



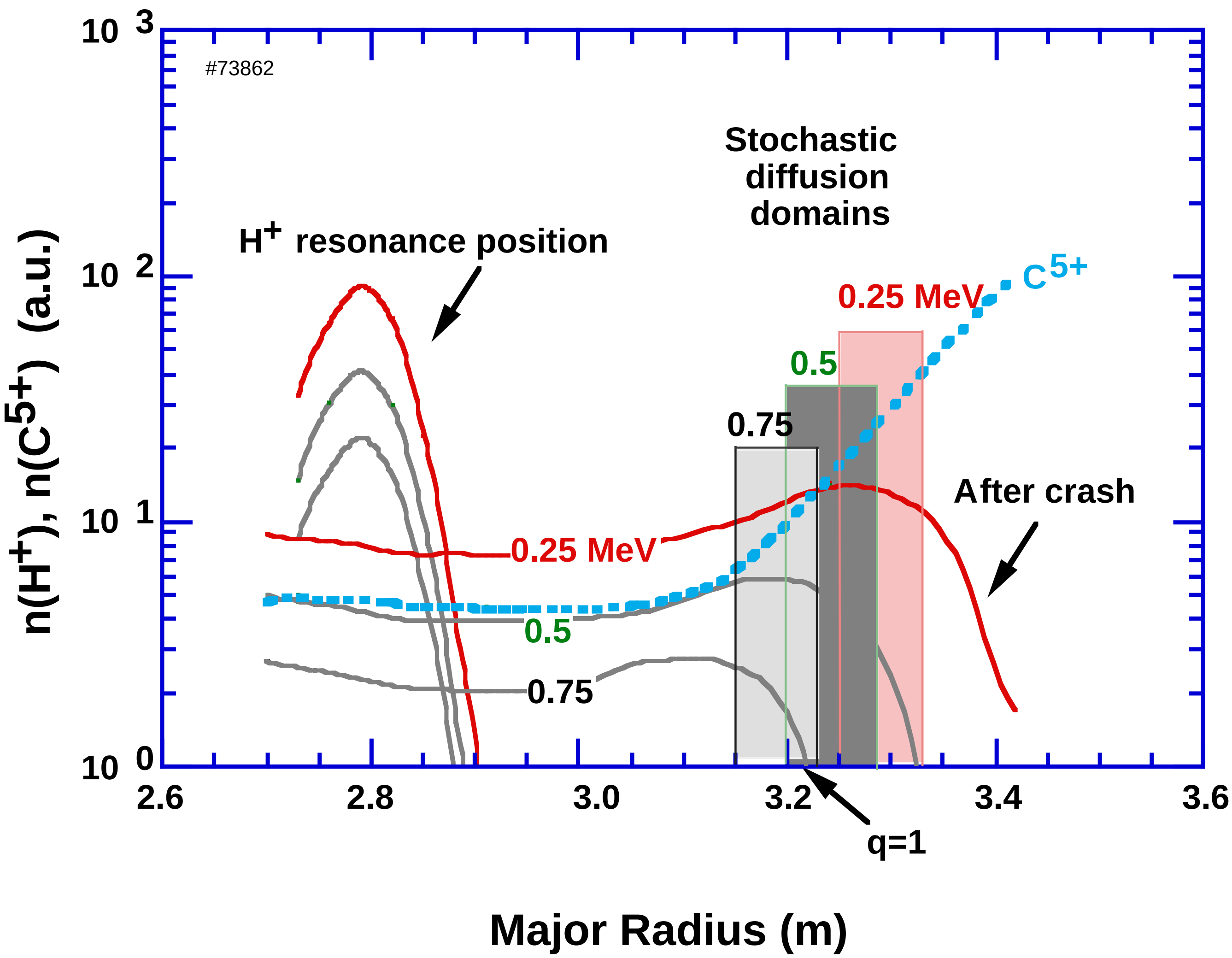
- RF power, passive H $^+$ signal (0.266 MeV), soft X-ray signal showing two giant sawtooth crashes, tail loss rate at the 60 ^{o} lost alpha detector and a Mirnov signal exhibiting the ICRF tail ion driven TAE.

Schematic Illustrating the Origin of H^+ Passive Signal Produced by H^+ Sawtooth Mixing



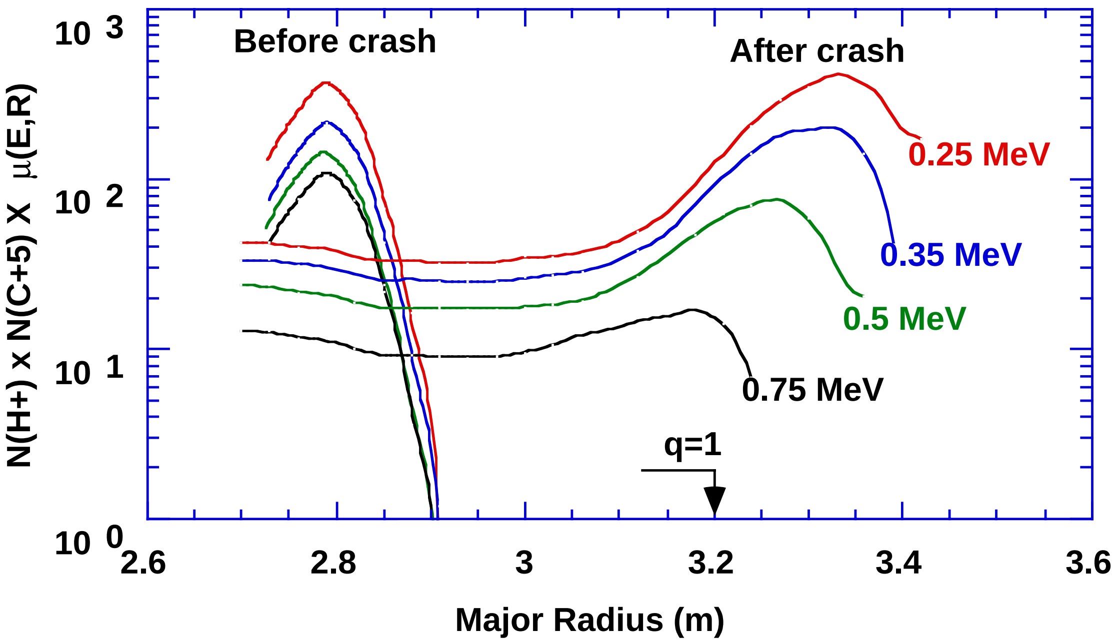
- Giant sawteeth redistribute the core-localized RF-driven energetic H^+ ions out to a region of increased C^{5+} density, which leads to the observed spike on the PCX passive signal.

Model for RF-driven H^+ Ion Sawtooth Mixing

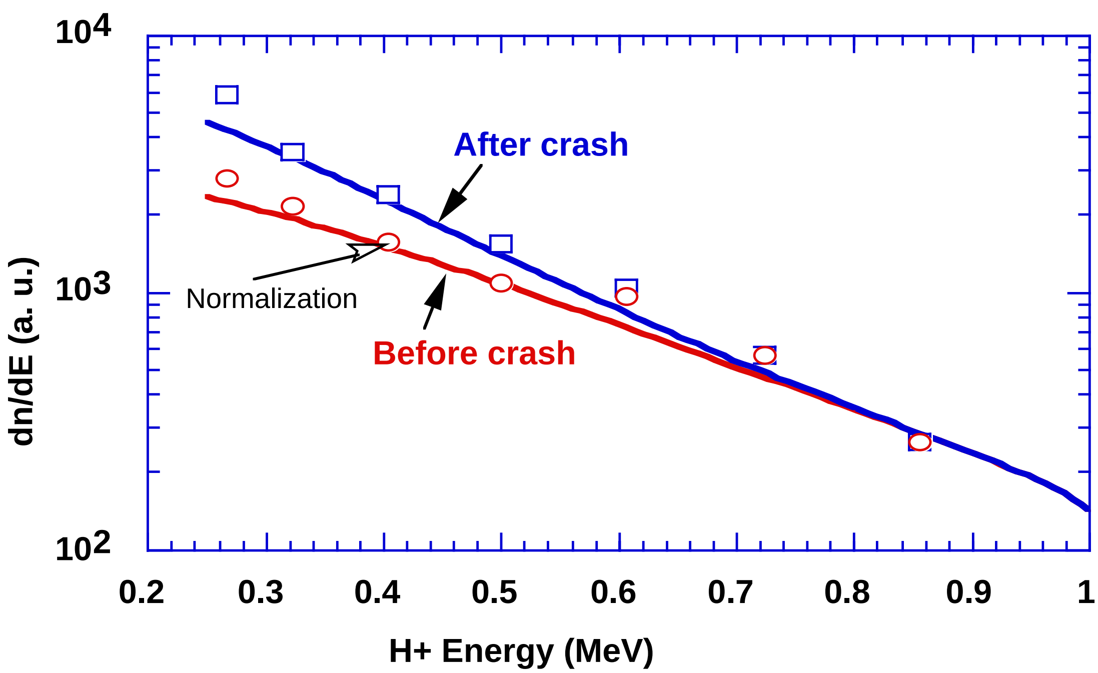


- Model for three H^+ energies (0.25 MeV, 0.5 MeV and 0.75 MeV) are shown before and after the crash.
- Adjustable parameter values used: E_{cri} = 317 keV, E_e = 1.4 kV/cm, and $t_{pr} = t_{cr}$ = 50 ms.
- Radial locations of the stochastic ripple domains for the noted H^+ energies are shown by the hatched regions. The dotted line is the C^{5+} density distribution.

Modeling of the H^+ Energy Spectrum Before and After a Sawtooth Agrees Well with PCX Measurements

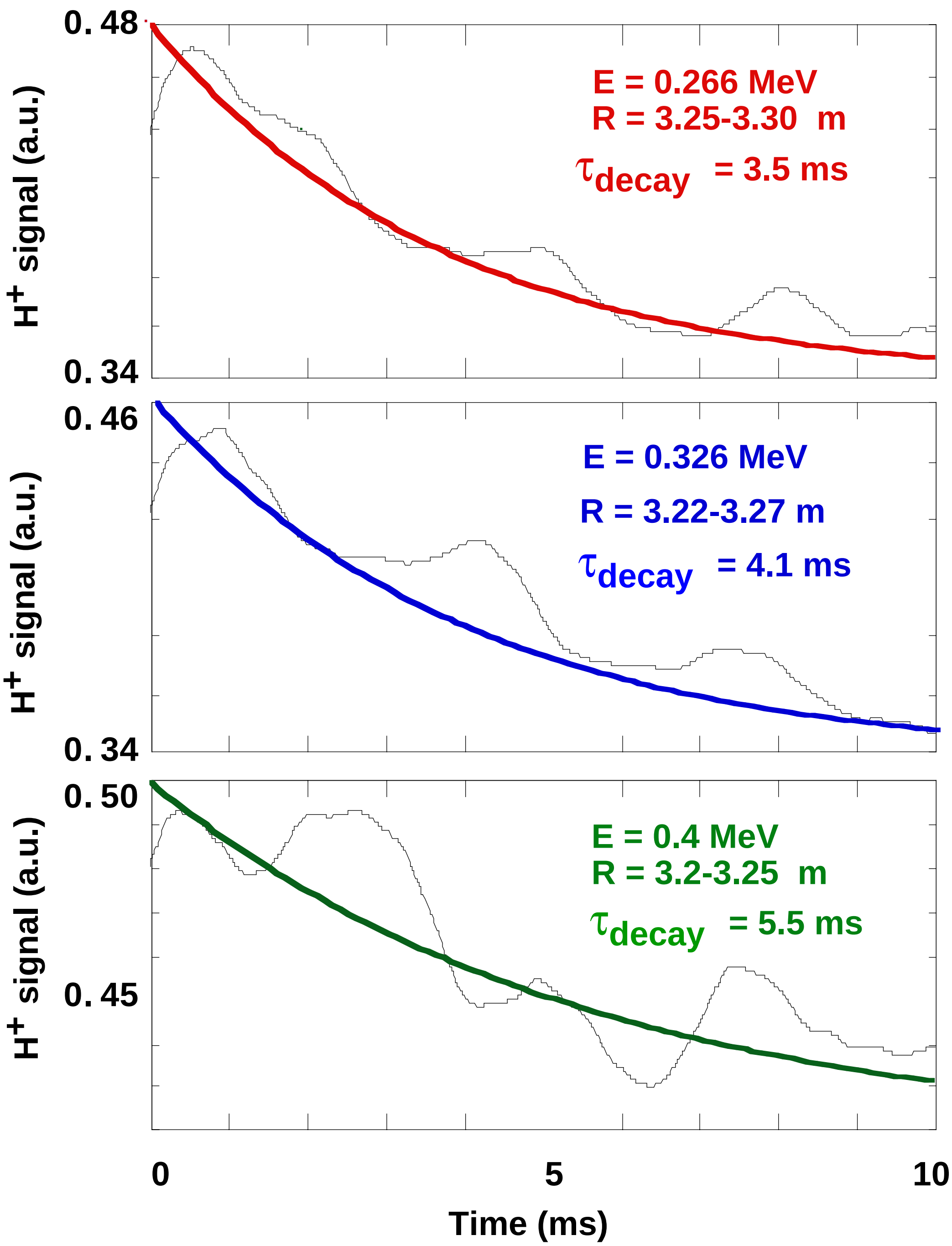


- Emissivity of the $H^+ + C^{5+}$ reaction vs major radius



- Measured energy spectra before and after the crash (symbols) and modeling results integrated over the observation line on the basis of the emissivity shown above (curves).

PCX Post-Sawtooth Signal Decay Time is Consistent with Calculated Stochastic Ripple Loss Rate



- **Decay of the experimental H+ signal (black curves) after the giant sawtooth crash are consitent with ORBIT code simulations of this decay, tdecay, due to stochastic ripple diffusion losses (colored lines).**

Summary

- Implementation of a passive pulse counting capability augmented the capability of the TFTR Pellet Charge Exchange diagnostic.

- The system consisted of CsI(Tl) scintillators with 16-channel pulse height analysis electronics on each of the eight NPA energy channels.

- Passive measurements of RF-driven energetic hydrogen minority ions verified operation of the pulse counting mode.

- Redistribution of RF-driven energetic H^+ ions due to giant sawteeth were observed using the passive mode.