Determination of the Radial Profile of Hydrogen Isotope Composition in TCV plasmas

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A direct measurement of the plasma neutral hydrogen isotope emission has been used to study particle transport in TCV. A Compact NPA, CNPA [1], with mass and energy separation, was used to measure transport and relaxation of hydrogen (H) particles in a deuterium (D) background plasma. A series of thermal H gas injections into a D plasmas, with simultaneous D-puff switch-off, leads to partial replacement of D ions by H. An interpretive algorithm has been developed to obtain information on the temporal behaviour of the radial H density profile.

1. Experimental setup. The results were obtained on TCV (R=0.88 m, a=0.25 m, $B_T \leq 1.54$ T) in Ohmic, low-density (n_e^{max}~$4x10^{19}m^{-3}$) and low-current L-mode discharges (I_p ~ 150 kA, T_e = 0.9 keV) in a limited configuration. The CNPA views the TCV plasma along a central horizontal view-line and measures the escaping neutral flux in 11 H energy channels (0.64–50 keV) and 17 D channels (0.56–33.6 keV). H pulses with duration 10-60 ms (period ~200ms) are injected during the current flattop of a D plasma centred in the TCV vessel ($Z_O \cong 0$). Following H-gas puff, optimised to maintain the plasma density, hydrogen CNPA count-rates increase by a factor of 2-5 and D rates decrease by ~1/2 (Fig.1). The H/D density ratio was estimated to increase from 5-10%, typical for pure D plasma on TCV, to 20-40% during H-gas injection. Due to low ion temperatures (~450eV), acceptable count rates may be obtained in the low energy (<6keV) CNPA channels (5 H and 7 D channels).

2. Interpretive algorithm. This algorithm uses the measured electron temperature and density profiles (from Thomson scattering), ion temperature profiles from Charge eXchange Recombination Spectroscopy, estimations of Z_{eff} profiles and numerical modelling of neutral density profiles and energy spectra of neutrals leaving plasma from the DOUBLE-TCV numerical code [2]. The energy spectra of the passive atomic flux ***J(E)*** emitted from the plasma into the NPA is the sum of fluxes in the plasma column along the view line of the analyser :

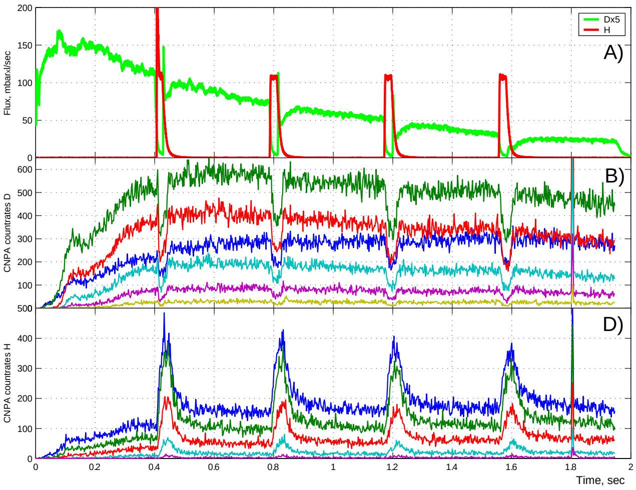

Fig.1: Rate of H and D gas injection (A) and CNPA counting rates for low energy deuterium (B) and hydrogen (C) channels.

$$J(E) = \Omega \cdot S \cdot \int_{-a}^{a} n_a \cdot n_i \cdot f_i(E) \cdot \langle \sigma_{cx}(v_{ia}) \cdot v_{ia} \rangle \cdot \gamma \cdot dz$$

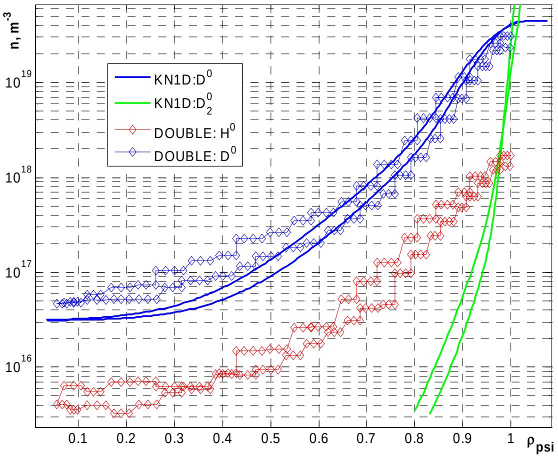

Fig.2. H^O, D^O and $D_2{}^O$ distributions along the CNPA view line.

where $\boldsymbol{n_a}$ and $\boldsymbol{n_i}$ are the densities of the atoms and ions, $\boldsymbol{f_i(E)}$ is the energy distribution function of the ions, $<\boldsymbol{\sigma_{cx}\ v_{ia}}>$ is the charge exchange rate coefficient averaged over the atom velocity distribution and γ is the attenuation factor (sum of processes resulting in loss of neutrals as they move from their point of birth to the NPA). The DOUBLE-TCV code uses a Monte-Carlo technique to calculate neutral distributions in the plasma, assuming a plasma column surrounded by a homogenous atomic gas density, specified by atomic neutral density and energy for each species defined at the last closed surface. The code simulates multi-component plasmas with two H mass species, together with He and one impurity component (typically carbon). The plasma geometry is introduced into the code as a poloidal flux map $\boldsymbol{\Psi(R,Z)}$. The code generates the following outputs: 2D distributions of neutral density of each mass species in the poloidal plane; neutral densities, emissivity distributions and CX-spectra for each component along specified NPA view lines. An emissivity function, defined as $\varepsilon(E,z) = n_a \cdot n_i \cdot f_i(E) \cdot \langle \sigma_{cx}(v_{ia}) \cdot v_{ia} \rangle \cdot \gamma$, gives the spatial distribution in the plasma from which the atomic flux of given energy originates. In this paper we use a “CX spectra” (F_{dc}) defined as $\dfrac{J(E)}{\sigma_{cx}(E) \cdot E}$, where $\boldsymbol{\sigma_{cx}}$ is the cross-section for charge exchange. The relationship between an energy distribution of the neutral flux from the plasma ($\boldsymbol{J(E)}$) passing through the NPA collimator and the number of pulses detected by a given NPA channel $\boldsymbol{N(E)}$ is $J(E) = \dfrac{N(E)}{\Delta t \cdot \Delta E \cdot \alpha_{\text{det}}(E)}$ where $\boldsymbol{\Delta t}$ is NPA integration time, $\boldsymbol{\Delta E}$ is the energy resolution of the NPA channel and $\boldsymbol{\alpha_{det}(E)}$ is the detection efficiency.

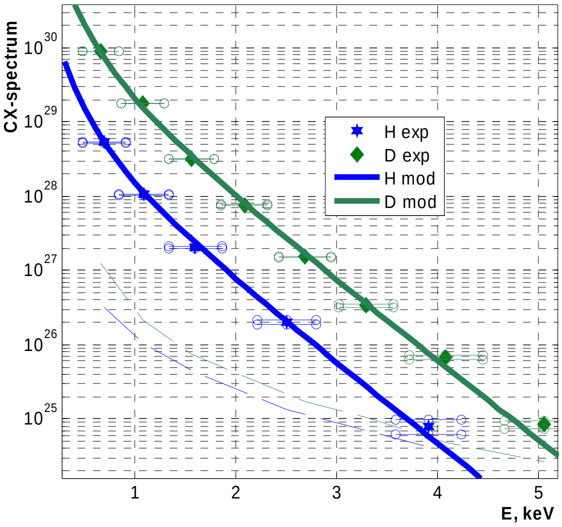

Fig.3. H and D CX-spectra before H-gas puff (experiment and DOUBLE-TCV simulation with n_H/n_D=6.2%)

The neutral density profiles calculated by the DOUBLE-TCV code (see Fig.2) are in good agreement with KN1D (Kinetic Transport Algorithm) for slab geometry [3] near plasma boundary (ρ>0.6). A simulation shows that the emissivity functions of CX-atoms with different energies reaching the NPA are separated in space. Particles with low energies mainly originate from the plasma edge whereas intermediate energies (2-5keV) originate from the plasma core. “CX spectra” (F_{dc}) of D and H from a DOUBLE-TCV simulation with a n_H/n_D ratio of 6% are in good agreement with the CNPA measurements (shown in Fig.3).

To recover the temporal behaviour of the radial H density profile during the H-gas puff the H density distribution is assumed to be a linear combination of the density base functions: $n_H(\rho)=\sum_i k_i \cdot n_i^{base}(\rho)$, with $n_i^{base} << n_D$. To analyse the transport of H in a D plasma we use base functions with flat, hollow and on-axis peaked n_H/n_D ratio (Fig.4-A). For each base function DOUBLE-TCV code calculates "base CX spectra" (Fig.4-B), a "CX spectra" generated by H ion population (***n_H***) should be a linear combination of "base CX spectra" with same ***k_i*** coefficients: $F_{dc}^{\mathrm{mod}}=\sum_i k_i \cdot F_i^{base}$. ***$k_i$*** coefficients can be found by a minimisation of the difference between "model" and "experimental CX spectra" $\left(\min \sum_k \frac{\left|F_{dc}^{\mathrm{mod}}(E_k)-F_{dc}^{\mathrm{exp}}(E_k)\right|}{F_{dc}^{\mathrm{exp}}(E_k)}\right)$. CX-spectra and density profiles recovered by this technique are shown in Fig.5.

3. Results and discussion. The temporal behaviour for the radial H density profile during and after the H-gas puff is shown in Fig.6. During the H-puff, the n_H/n_D ratio evolves from a hollow radial profile (<20 ms) to a flat profile (20-25 ms). After the puff, we observe hydrogen accumulation in the plasma internal region. From the temporal behaviour of the radial H density profile, we estimate the H ion confinement time for low density low current Ohmic L-mode TCV discharges as 15-25 ms, in reasonable agreement with particle confinement time measured on TCV by other methods. To explain the peaking of H ion density profiles in TCV discharges with H-puff, a plasma pinch must be considered. An estimate of transport coefficients from the particle transport equation $\Gamma=-D\nabla n+Vn$ yields a diffusion coefficient value of ~1 m^2/sec and negative pinch velocity of ~1 m/sec on intermediate (0.35 <ρ<0.65) plasma radius.

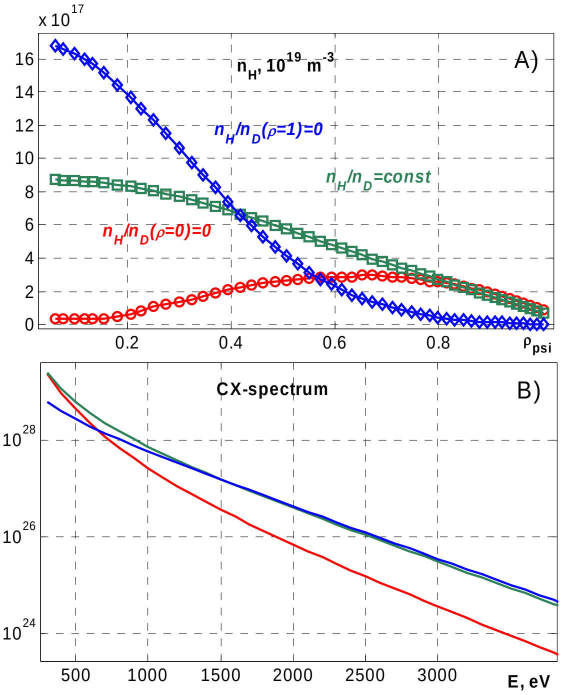

Fig.4. Density (A) and "CX-spectra" (B) base functions.

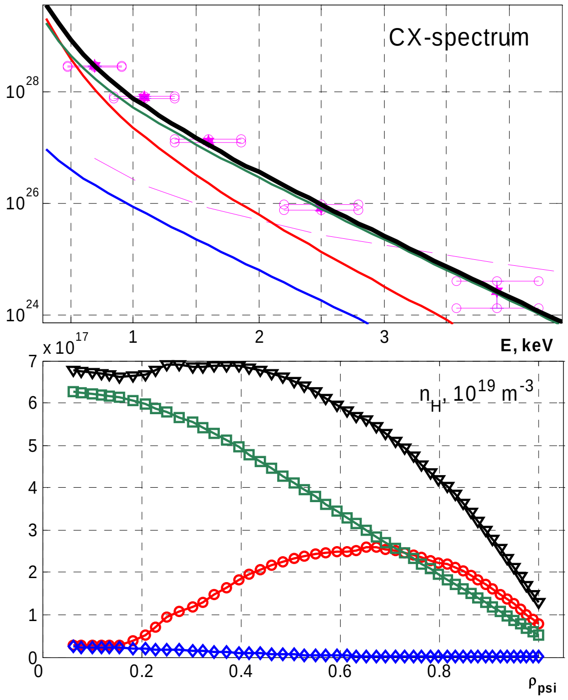

Fig.5 "CX-spectra" and H density profile reconstruction for 10-15 ms after H-puff switch on: "black" – reconstruction results, "colours" – contribution from each base function.

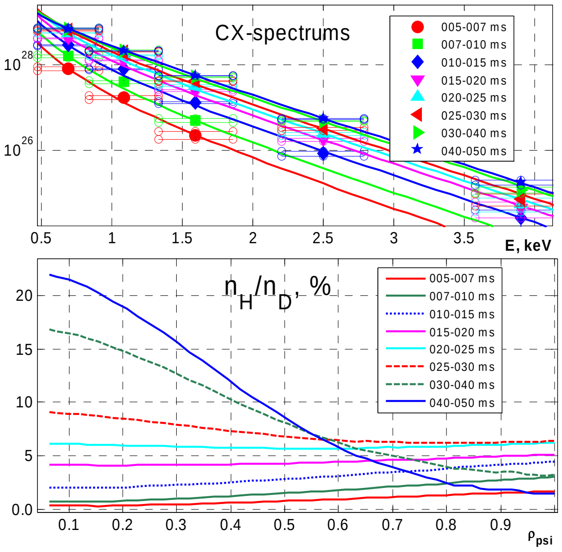

Fig. 6. “CX-spectra” and n_H/n_D density ratio of hydrogen population generated by H-puff during and after gas injection (0-25 ms).

An analysis of the temporal behaviour of CX energy spectra of the H population following the H-puff, shows its “CX-spectra” relax to the Maxwellian “CX-spectra” of D and background H in ~10-30 ms, significantly longer than the local ion-ion thermal equilibration time (<1 ms). This allows us to assume that, locally, all ion species in the plasma have the same temperature, and the change of the “CX-spectra” during the H-puff corresponds to H transport.

An increase of countrates in the D channels (or CX-flux) may be fitted with the simple model: $\frac{dN}{dt} = Q(t-\Delta t) - \frac{N}{\tau}$, where Q is proportional to the flux of H-gas injection, Δt is a delay in gas propagation from the flow measurement point to the plasma (~2ms) and τ is the “confinement” time (10-60 ms). CNPA observations of H CX-spectra for TCV discharges with different density show that “confinement” time increases with plasma density (Fig.7).

4. Summary.

- A compact neutral particle analyser (CNPA) has been successfully used to measure the hydrogen isotope composition in TCV plasma.
- A recovery algorithm of the temporal behaviour of the radial H density profile from NPA measurement was developed and used for TCV Ohmic L-mode low density, low current discharges.
- Described method may potentially be applied to study of particle transport phenomena in other machines.

An implementation of the described technique to operational domain of TCV Tokamak becomes increasingly complicated at high current by perturbation of CX measurement due to sawtooth activity, in H-mode by ELMs and in ECH discharges by the appearance of a suprathermal ion population.

1. F.V. Chernyshev et al., Instruments and Experimental Techniques, **47**(2) (2004) 214–220.
2. A.N. Kislyakov, M.P. Petrov and E.V. Suvorkin, Plasma Phys. Control. Fusion **43** (2001) 1775–1783
3. A.N. Karpushov et al., 31st EPS Conf. PP, London, ECA Vol.**28G**, (2004) P-2.152.

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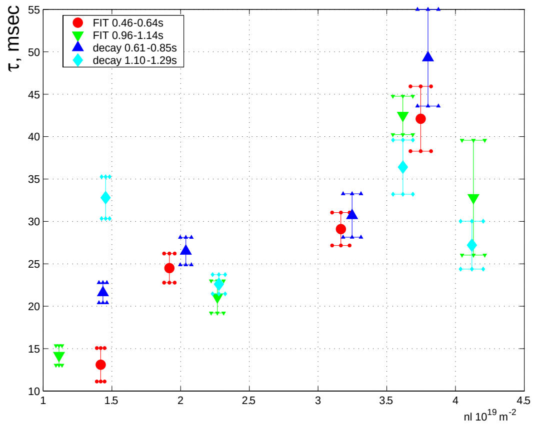

Fig.7 Dependence of hydrogen “confinement” time (τ) on plasma density.