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

Ecole Polytechnique Fédérale de Lausanne

A.N.Karpushov[1], B.P.Duval[1], Ch. Schlatter[1], H.Weisen[1], V.I.Afanasyev[2], F.V.Chernyshev[2], M.I.Mironov[2]

[1] *Centre de Recherches en Physique des Plasmas, Association EURATOM-Conféderation Suisse, EPFL, Lausanne, Switzerland*
[2] *Laboratory of Atomic Collision Physics of Ioffe Physico-Technical Institute, St.Petersburg, Russia*

This poster and accompanying papers can be downloaded at: http://crpplocal/pinboard/pinboard.php

INTRODUCTION

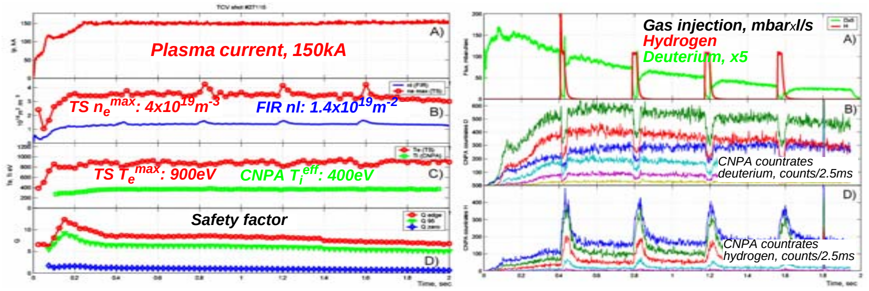
A direct measurement of plasma neutral hydrogen isotope emission has been used to study particle transport in TCV. A Compact NPA, CNPA [1,2], with mass and energy separation, was used to measure transport and relaxation of hydrogen (H) particles in a deuterium (D) background plasma using programmed H-gas puffs. The CNPA views the TCV plasma along a central horizontal view-line and measures the escaping neutral flux in 11 hydrogen energy channels (0.64-50keV) and 17 deuterium channels (0.56-33.6keV).

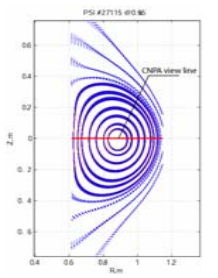
A series of thermal H gas injections into a D plasmas, with simultaneous D-puff switch-off, leads to partial replacement of D ions by H. Hydrogen pulses with duration 10-60 ms (period ~200ms) are injected during the current flattop of a D plasma centred in the TCV vessel (Z_O=0). Following H-gas puff, optimised to maintain the plasma density, hydrogen CNPA count-rates increase by a factor of 2-5 and D rates decrease by ~1/2. 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).

An interpretive algorithm has been developed to obtain information on the temporal behaviour of the radial H density profile. This algorithm uses the measured electron temperature and density profiles (from Thomson scattering), ion temperature profiles from Charge eXchange Recombination Spectroscopy [6], estimations of Z_{eff} profiles and numerical modelling of neutral density profiles and energy spectrums of neutrals escaping plasma with numerical codes. A Monte-Carlo DOUBLE-TCV code [3,4] was used for modelling of Charge-eXchange neutral fluxes emitted by a multi-component plasma. Kinetic Transport Algorithm for Atomic and Molecular Hydrogen in an Ionising Plasma (KN1D code) [5,7] has been used for verification of neutral density profile along NPA view-line calculated by DOUBLE-TCV.

From temporal behaviour of the radial hydrogen density profile we estimate hydrogen ion confinement time and transport coefficients (diffusion coefficient and pinch velocity).

Experimental scenario: H-gas injection

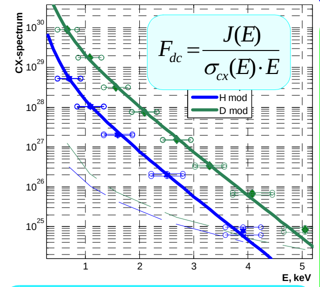




Parameters of low density, low current, ohmic (OH) L-mode TCV (R:0.88m, a:0.25m, B_T<1.54T) discharge elongation κ_{95}:1.4; triangularity δ_{95}:0.22; safety factor Q_{95}:6

- *A series of thermal hydrogen gas injections into deuterium background plasma, with a simultaneous switch-off of the main deuterium gas-puff, leads to partial replacement of deuterium ions by hydrogen.*
- *The CNPA views the TCV plasma along a central horizontal view-line (Zo=0).*

CX-spectra and Ion Temperature



$$F_{dc} = \frac{J(E)}{\sigma_{cx}(E)\cdot E}$$

Deuterium and hydrogen CX-spectra before H-puff (experiment and DOUBLE-TCV simulation with n_H/n_D=6.2%)

The energy spectra of 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 analyser

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

$$J(E) = \frac{N(E)}{\Delta t\cdot\Delta E\cdot\alpha_{det}(E)}$$

NPA countrate (N) <–> energy spectra of atomic flux (J(E))

For Maxwellian ion energy distribution in 0-dimensional model (T_i and T_e are constant along NPA view line) and low attenuation (γ_{att}=1), T_i is proportional to the logarithm of the slope of "Charge eXchange spectra" (F_{dc}) [9]

$$\frac{E}{T_i}+\frac{3}{2}\ln(T_i) \sim -\ln\left(\frac{J(E)}{\sigma_{cx}(E)\cdot E}\right) = -\ln(F_{dc})$$

In most situations, the plasma does not exhibit a single ion temperature and the attenuation may not be neglected

The ion temperature, inferred from the slope of (F_{dc}), depends on the energy, in this case $T_i^{NPA}(E)$ characterize slope of "CX-spectra".

$$\frac{1}{T_i^{NPA}(E)} = -\frac{d\ln(F_{dc})}{dE}$$

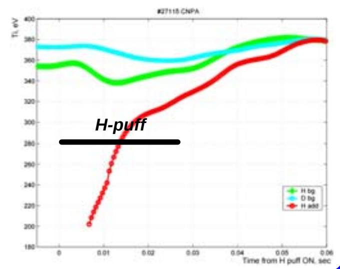
Subtraction of interpolated "background" from hydrogen "CX-spectra" allows to estimate temporal behavior of NPA "CX-spectra" and ion temperature of additional hydrogen population created by H-gas injection.

- *Energy spectra of additional hydrogen population relaxes to background Maxwellian CX-spectra in 10-30ms.*

Ion-Ion local thermalisation time is <1ms.

- *All ion species in plasma locally have the same energy distribution (temperature).*

Themporal variation of T_i^{NPA} of additional hydrogen population corresponds to hydrogen transport in plasma.



Effective CNPA "ion temperature" for [0.5 3.0] keV: deuterium and hydrogen interpolated "background" and subtracted additional hydrogen population (error bars ~15%)

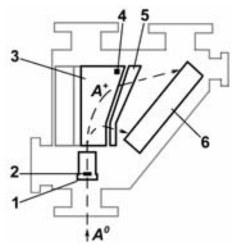
CNPA

Compact NPA [1,2] has been designed and manufactured in A.F.Ioffe Physico-Technical Institute (St. Petersburg, Russia)

Installed on TCV in 2004

Operating principles:

- magneto-electric separation, E||B scheme
- striping in 100 A^o diamond-like carbon foil
- 10kG NdFeB permanent magnet
- electrostatic acceleration of ions
- ion focusing at the detector area



Basic parameters:

two CEM arrays for detection of H and D (or D and He)

H: 0.64-50 keV (11 channels),

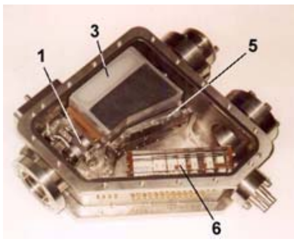
D:0.56-33.6 keV (17 ch.)

ΔE/E:0.6(for 0.6 keV) → 0.1(for >3 keV)

Operating regime:

counting with pulse amplitude discrimination

Acquisition time resolution	0.5-4 ms
Max. count rate	800 pulse/ms



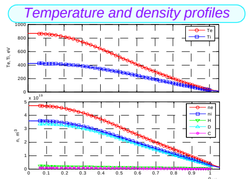
1 — stripping/acceleration unit; 2 — stripping foil; 3 — analysing magnet; 4 — Hall probe; 5 — analysing electrostatic condenser; 6 — detector array;

DOUBLE-TCV code

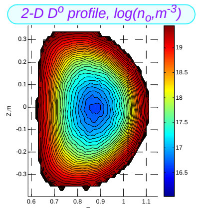
Simulation of CX fluxes emitted by tokamak plasma (Maxim Mironov, A.F.Ioffe PTI, March 2005). The code uses the Monte-Carlo technique to calculate neutrals distribution in plasma [3,4].

INPUT:

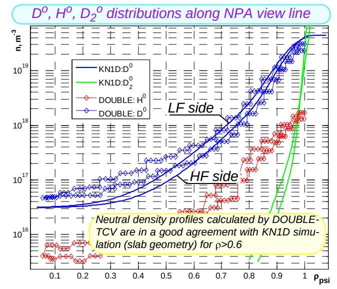
- Plasma geometry → poloidal flux map (Ψ(R,Z));
- Electron (TS) and ion (CXRS) temperature and density (TS) profiles;
- Impurity Z_{eff} and T_{imp} profiles, atomic mass and charge (carbon);
- Boundary conditions → edge (ρ=1) atomic neutral density and energy (H,D);



Temperature and density profiles



2-D D^0 profile, log(n_0,m^{-3})



D^0, H^0, D_2^0 distributions along NPA view line

OUTPUT:

- 2D distribution of total (wall+beam) neutral density of each mass species in poloidal plane;
- Neutral densities along NPA view lines;
- Emissivity distribution for each ion component along NPA view lines;
- CX spectrums for each ion component for each view line.

Recovery Algorithm

Hydrogen density distribution is assumed to be a linear combination of the density base functions:

$$n_H = \sum_i k_i\cdot n_i^{base} \quad \text{with} \quad n_i^{base} << n_D$$

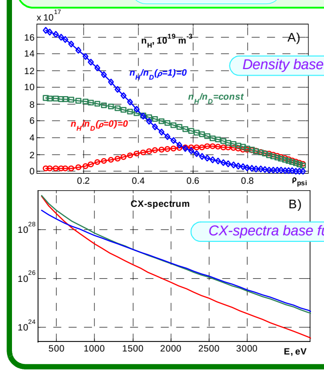
For each n_i^{base} calculates CX-spectra (F_i^{base})

Model CX spectra should be a linear combination of F_i^{base} with same k_i

$$F_{dc}^{mod} = \sum_i k_i\cdot F_i^{base}$$

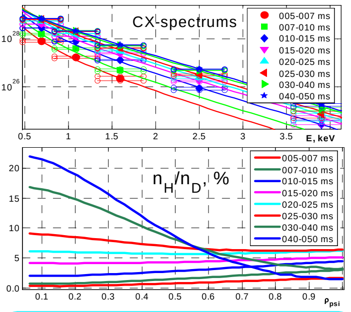
k_i can be found from minimization of difference between "model" and "experimental" CX-spectra

$$\sum_k \frac{\left|F_{dc}^{mod}(E_k)-F_{dc}^{exp}(E_k)\right|}{F_{dc}^{exp}(E_k)}$$

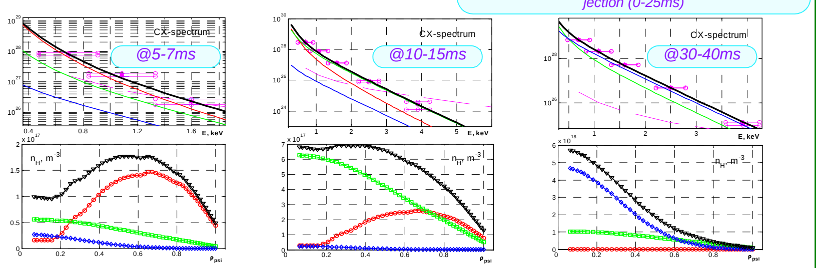


CX-spectra and hydrogen density profiles

- *During H_2-puff, the n_H/n_D ratio evolves from a hollow radial profile (<20ms) to a flat profile (20-25ms). After puff, hydrogen accumulation in internal regions has been observed.*
- *H^+ "confinement time" for TCV low density low current OH discharges is 15-25ms.*
- *To explain H-puff results from TCV, a plasma pinch must be considered.*
- *An estimation of effective diffusion coefficients yields a value ~1m^2/sec, pinch velocity is ~1m/sec.*

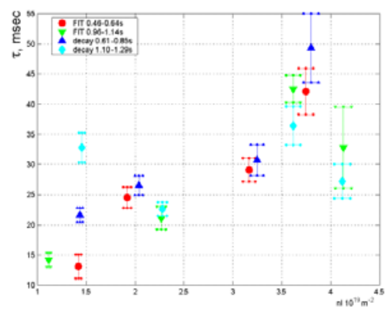


"CX-spectra" and n_H/n_D ratios (hydrogen population generated by H-puff) during and after hydrogen gas injection (0-25ms)



"CX-spectra" and density profile reconstruction, black – result, colours (1,2,3) – contribution from each base function

Density scan



Hydrogen "confinement" time vs. plasma density

An increase of counting rates (N) in CNPA deuterium channels (CX-flux) can be fitted according:

$$\frac{dN}{dt} = Q(t-\Delta t) - \frac{N}{\tau},$$

where Q is proportional to a flux of H-injection, Δt is delay in gas propagation from flowmeter to plasma (~2ms), τ is H-confinement time (10-60ms)

- *Hydrogen "confinement" time increases with increase of plasma density*

CONCLUSION

- 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.

References:

[1] F.V. Chernyshev et al.,Instruments and Experimental Techniques, Vol. 47, No. 2, 2004, pp. 214–220.
[2] F.V. Chernyshev et al., 30th EPS Conf. CFPP, St. Petersburg, ECA 27A (2003), P-4.71 (or http://www.ioffe.rssi.ru/ACPL/npd/npa05.htm)
[3] A.I. Kislyakov, M.P. Petrov and E.V. Suvorkin, Plasma Phys. Control. Fusion 43 (2001) 1775–1783.
[4] S.S.Medley et al., RSI, Vol.74, No.3, 2003, pp. 1896-1899
[5] B.LaBombard, KN1D, PSFC Research Report: PSFC/RR-01-03, MIT, Cambridge (2001) (http://www.psfc.mit.edu/library/01rr/01RR003/01RR003_ABS.HTML)
[6] P.Bosshard et al., 29th EPS Conf. PPCF, Montreux, ECA 26B (2002) P-4.120.
[7] A.N. Karpushov, et al., 31st EPS Conf. PP, London, ECA Vol.28G, (2004) P-2.152.
[8] A.N.Karpushov et al., 30th EPS Conf. CFPP, St. Petersburg, ECA 27A (2003), P-3.123.
[9] V.V.Afrosimov and A.I.Kislyakov: Neutral Particle Diagnostics of Plasma, International School of Plasma Physics, Varenna, Italy, Sept. 1982, p.289-310

Acknowledgments: This work was partly supported by the Swiss National Science Foundation.