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Recovery of Ion Parameters from NPA Measurements on TCV

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Introduction. A method to recover the ion temperature profile of TCV plasmas has been developed by modelling the measured energy spectra of the neutral deuterium fluxes varying the parameters of the T_i profile. A Neutral Particle Analyser (NPA) [1,5] is used on the TCV tokamak [2] to measure the energy spectrum of hydrogen and deuterium neutrals escaping the plasma. A Kinetic Transport Algorithm, (KN1D) [3], was applied to obtain neutral density profiles in the bulk plasma. The response of Charge eXchange energy spectra to plasma parameters was examined with a model prediction. Ion temperature profiles, evaluated by this method, were compared with the classical logarithmic CX-spectrum slope evaluation. Results based on analysis of NPA data were also compared with measurements from charge exchange recombination spectroscopy (CXRS) [4].

TCV [2] is a medium-sized tokamak (R=0.88 m, a=0.25 m, I_p < 1 MA, B_T < 1.54 T, plasma elongation 1-2.8) able to produce a plasma with the central electron density 0.5-15×10^{19} m^{-3}, an electron temperature over 10 keV with bulk central ion temperatures 0.3-1 keV. A 5-channel NPA, with electrostatic energy separation [1], measures the ion parameters [5-7]. The NPA voltage sweeps the energy channels to measure neutral particle energies in the range of (0.6→6.5 keV), with a time resolution of ≥13 ms viewing the plasma along a vertical chord (fig.1).

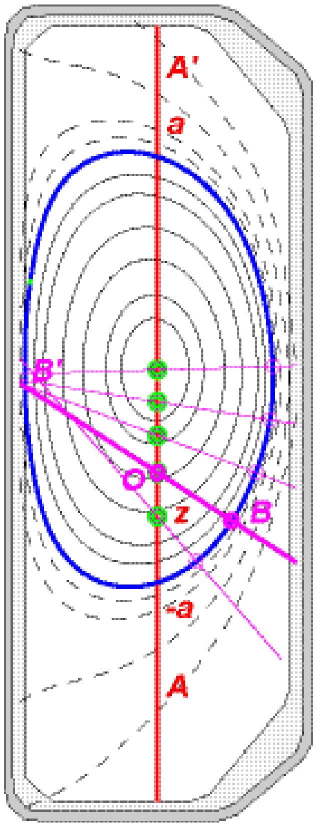

Fig.1: NPA observation geometry. AA' – NPA view line; BB' – chord for 1-D modelling; B – nearest point on plasma boundary for neutral particles calculation in point O.

CX spectrum and ion temperature. The energy spectrum of passive atomic flux ***J(E)*** traversing the plasma surface and entering the external instrument (NPA) is the sum of fluxes in the plasma column along the view line of the analyser [8]

$$J(E) = \Omega \cdot S \cdot \int_{-a}^{a} n_a \cdot n_i \cdot f_i(E) \cdot \langle \sigma_{cx}(v_{ia}) \cdot v_{ia} \rangle \cdot \exp\left[-\int_{-a}^{z} n_e(z') \cdot \sigma_{abs}(E, z') \cdot dz' \right] \cdot dz \,, \qquad (1)$$

where $\mathbf{\Omega S}$ is the acceptance of the analyser, $\boldsymbol{n_a(z)}$ and $\boldsymbol{n_i(z)}$ are the densities of the atoms and ions, $\boldsymbol{f_i(E,z)}$ energy distribution function of the ions, $\boldsymbol{<\sigma_{cx}(v_{ia}) \times v_{ia}>(z)}$ is the rate coefficient for the charge exchange (***z*** is a coordinate along NPA view line).

$\exp\left[-\int_{-a}^{z} n_e(z') \cdot \sigma_{abs}(E, z') \cdot dz' \right] = \gamma_{att}(E, z)$ is an attenuation factor, where $\boldsymbol{\sigma_{abs}}$ is the sum of cross-sections for processes ionising the neutrals as they move from the birth point to the spectrometer.

In our analysis it is assumed that the ion energy distribution is Maxwellian. In this case, for 0-dimensional model (T_i and T_e are constants along NPA view line) and low attenuation (γ_{att}=1), the ion temperature T_i is proportional to the logarithm of the slope of "Charge eXchange spectrum":

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

where the "CX spectrum" (F_{dc}) is defined as $\frac{J(E)}{\sigma_{cx}(E)\cdot E}$.

In most situations, the plasma does not exhibit a single ion temperature and the attenuation factor may not be neglected so the ion temperature, inferred from the slope of (F_{dc}), depends on the energy:

$$\frac{1}{T_i^{NPA}(E)}=-\frac{d\ln\left(F_{dc}\right)}{dE} \qquad (3).$$

In this work, the ion temperature profile is parameterised by the functional form:

$$T_i(\rho)=(T_i(0)-T_i(1))\cdot(1-\rho^2)^{kTi}+T_i(1) \qquad (4)$$

to minimise the difference between measured $\ln(F_{dc}^{NPA})$ and expected $\ln(F_{dc}^{calc})$ based on equations (1) and (2). The fitted parameters are on-axis ($T_i(\rho=0)$) and edge ($T_i(\rho=1)$) ion temperatures and ion temperature profile peaking (kTi).

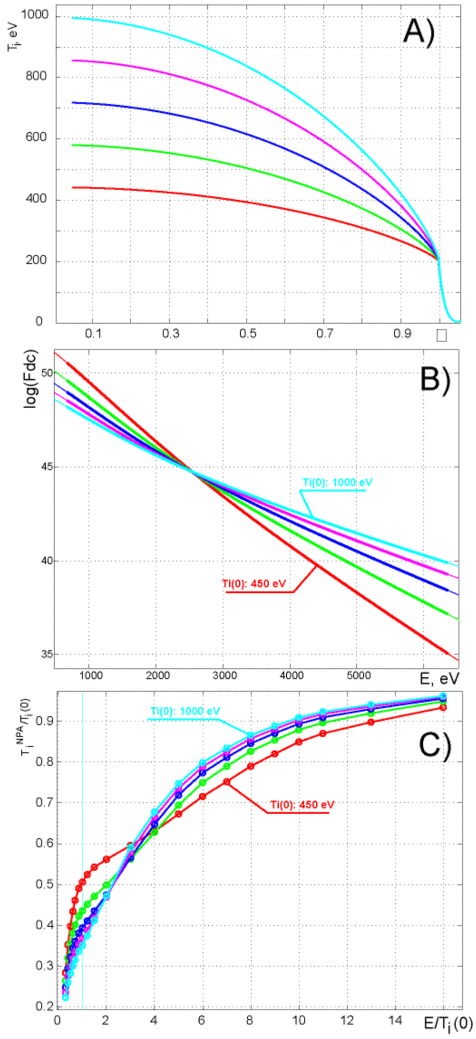

Fig.2: Central ion temperature scan (quasi-experiment). A) input ion temperature profiles; B) "CX-spectrums"; C) $T_i^{NPA}/T_i(0)$ ratios.

Model for neutral density. Energy spectra of neutral fluxes escaping plasma along an observation chord and measured by an NPA depend on the temperature and density profiles of the ions and electrons as well as on the density profile of the neutrals (1). Electron density and temperature profiles are available on TCV from Thomson scattering. A 1-D Space, 2-D Velocity, Kinetic Transport Algorithm for Atomic and Molecular Hydrogen in an Ionising Plasma (KN1D) [3], adapted for TCV, was applied to obtain a neutral density profiles in the plasma. This code offers a numerically rapid access to a neutral density profile as compared with Monte-Carlo codes (like EIRENE [9]) that are not routinely available on TCV, and thus permits an examination of the expected NPA behaviour for a wide range of plasma parameters.

The mean free path of "wall" neutrals in TCV plasmas is significantly smaller than a plasma minor radius ("optically thick plasma"). Thus, the main contribution to the neutral density comes from the neutrals moving over the shortest distance to the plasma boundary (BO line in fig.1). This justifies the use of a one-dimensional slab model for the calculation of the neutral density along the diagnostic chord (AA') in the plasma. We use a constant neutral molecular density outside the plasma as a boundary condition for the neutral density profile calculation. An example of atomic hydrogen neutral density profile calculation along NPA view line is shown in fig.3(B).

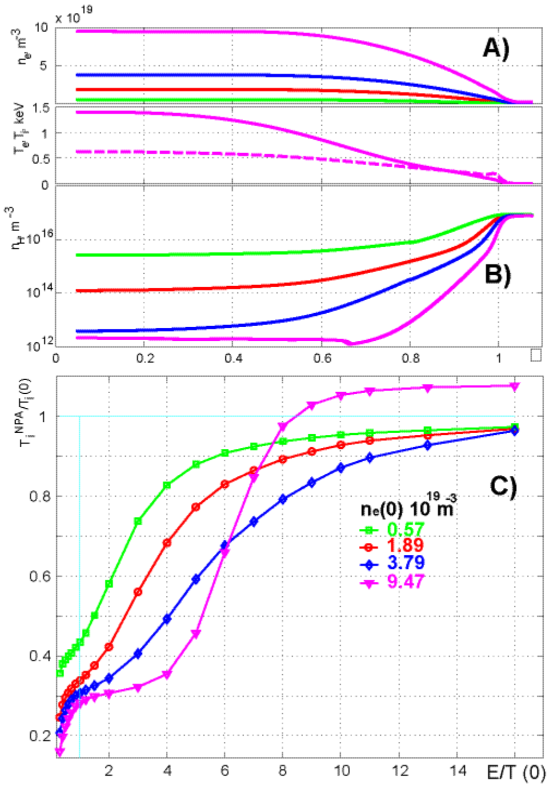

Fig.3: Plasma density scan. A) density, electron and ion temperature profiles; B) neutral density; C) $T_i^{NPA}/T_i(0)$ ratios.

CX spectrum response to plasma parameters. A quasi-experimental method is used to study response of CX spectrum on plasma parameters. In this method we calculate $J(E)$, F_{dc}^{NPA}, $T_i^{NPA}(E)$ for some chosen profiles of plasma parameters ($n_e(\rho)$, $T_e(\rho)$ and $T_i(\rho)$) and boundary condition (neutral molecular pressure outside plasma). It was found that "CX-spectrum" is very sensitive to the central ion temperature ($T_i(0)$ see fig.2(B)). For "passive" NPA measurements, an ion temperature (T_i^{NPA}) calculated on a fitted "NPA CX-spectrum" (fig.2(C)) is lower the actual central ion temperature ($T_i(0)$), except for high density plasmas where the recombination term in neutral density dominates (fig.3). For the NPA energy range *4-7* $T_i(0)$ the $T_i^{NPA}/T_i(0)$ ratio ranges from 0.5 to 0.9, increasing with decreasing plasma density and/or the ion temperature peaking factor. The $T_i^{NPA}/T_i(0)$ ratio strongly depends on the line integral of the plasma density (fig.3). The high energy tail of the CX-spectrum is dominated by plasma central region, and low energy part by the plasma edge (fig.4). This separation is stronger for high plasma density. The response of $T_i^{NPA}(E)/T_i(0)$ ratio to plasma density peaking, ion end electron temperature profiles for NPA energy ($E>3\ T_i(0)$) is less then 10% for the considered TCV experimental conditions.

T_i profile recovery for TCV plasmas. We use the following iteration procedure to recover a T_i profile from the NPA measurement: firstly, the neutral density profile was calculated by KN1D code from the experimental electron temperature and density profiles and an empirical approximation for ion temperature profile based on the NPA measurement. The ion temperature profile parameters were recovered from a minimisation of discrepancy functional (**Ψ**) between the model and experimental spectra. **Ψ** characterises the "goodness-of-fit" of the model:

$$\Psi = \left\langle \left| \ln\left(F_{dc}^{NPA}(E_k)\right) / \ln\left(F_{dc}^{calc}(E_k, T_i(\rho))\right) - 1 \right| \right\rangle_k , \quad (5)$$

where index k runs over all experimental energy points, F_{dc}^{calc} is the model function calculated according (1) for experimental ($n_e(z)$ and $T_e(z)$) and $n_a(z)$ from neutral transport code). A recovered ion temperature profile was used for the new neutral density profile of the next iteration. 2-3 iterations were usually sufficient to obtain a stable solution.

An example of T_i recovery is shown in fig.5. Recovered profiles are in a good agreement with carbon (C^{IV}) T_i profiles measured by CXRS technique. The discrepancy

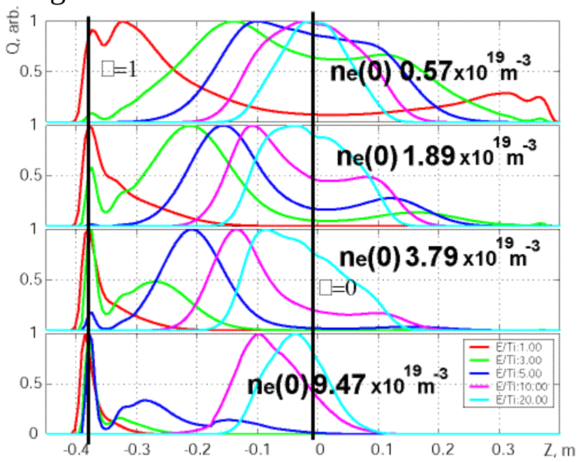

Fig.4: Contribution in CX-spectrum ($n_a \cdot n_i \cdot f_i \cdot \langle \sigma_{cx}(v_{ia}) \cdot v_{ia} \rangle \cdot \gamma_{att}$). Red – E=$T_i(0)$; cyan – E=20$T_i(0)$. See fig.3(A) for input profiles.

function (**Ψ**) has strong dependence on central ion temperature, ***T*$_i$*(0)*** and can usually be recovered with accuracy of ~10% (fig.6). We expect errors for edge temperature (***T*$_i$*(ρ=1)***) and peaking (***kTi***)) in the range of 30-70%.

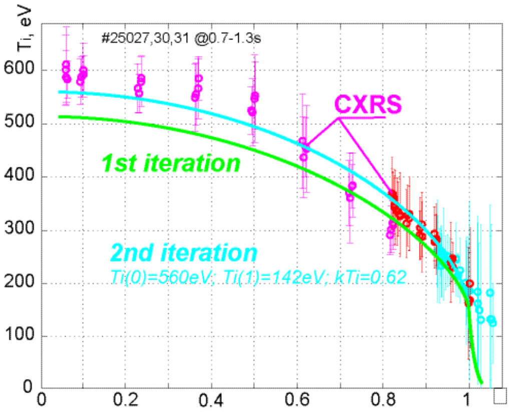

Fig.5: Ion temperature profiles, recovered from NPA measurement and CXRS.

Conclusions and discussion.

- A method of ion temperature profile determination from NPA CX measurement has been developed.
- For the ohmic phases of TCV plasma discharges, without neutral beam (DNBI) injection, $T_i^D(\rho)$ profiles are in a good agreement with CXRS measurements of carbon impurity temperature $T_i^{CVI}(\rho)$.
- A flexible computed algorithms for $T_i(\rho)$ recovery has been constructed.
- KN1D (Kinetic Transport Algorithm for Atomic Molecular Hydrogen) has been adopted for TCV.

The algorithm for T_i profile recovery was developed assuming a Maxwellian ion energy distribution function. A non-Maxwellian ion energy distributions (with a significant fraction of suprathermal ions) has been observed in low density TCV discharges with ECH. In such discharges a high-energy tail of CX spectrum is dominated by suprathermal ions [6].

An important limitation of described method is in the registration statistics of neutrals with energies high than ***10T*$_i$*(0)***. The approximation of homogeneous neutral hydrogen molecule pressure outside plasma is not sufficient for some plasma discharges with limiter configuration. A 2-D space neutral transport calculation is required to provide a better answer to this question.

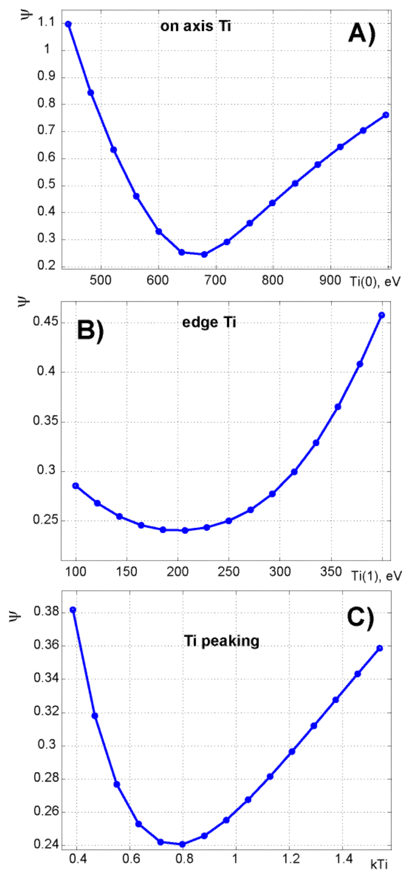

Fig.6: Dependences of discrepancy functional on parameters of ion temperature profile.

1. V.V.Afrosimov et al., *Sov. Phys. - Tech. Phys.* **20**(1), (1975) 33 http://www.ioffe.rssi.ru/ACPL/npd/npa01.htm
2. T.P.Goodman et al., Proc. 19th IAEA Fusion Energy Conf., Lyon, France, 2002 (IAEA, Vienna, 2002), CD-ROM file OV/4-2.
3. B.LaBombard, “KN1D”, PSFC Research Report: PSFC/RR-01-03, MIT, Cambridge (2001)
4. P.Bosshard et al., 29th EPS Conf. PPCF, Montreux, ECA **26B** (2002) P-4.120.
5. A. Karpushov et al., 29th EPS Conf. PPCF, Montreux, ECA **26B** (2002) P-4.119.
6. A.N.Karpushov et al., 30th EPS Conf. CFPP, St. Petersburg, ECA **27A** (2003) , P-3.123.
7. I.Condrea et al., 29th EPS Conf. PPCF, Montreux, ECA **26B** (2002), P-2.079.
8. V.V.Afrosimov and A.I.Kislyakov: *Neutral Particle Diagnostics of Plasma*, International School of Plasma Physics, Varenna, Italy, Sept. 1982, p.289-310
9. D.Reiter, “The EIRENE Code User Manual”, http://www.eirene.de/

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