ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Non-Maxwellian Ion Energy Distribution in ECH-heated plasmas on TCV

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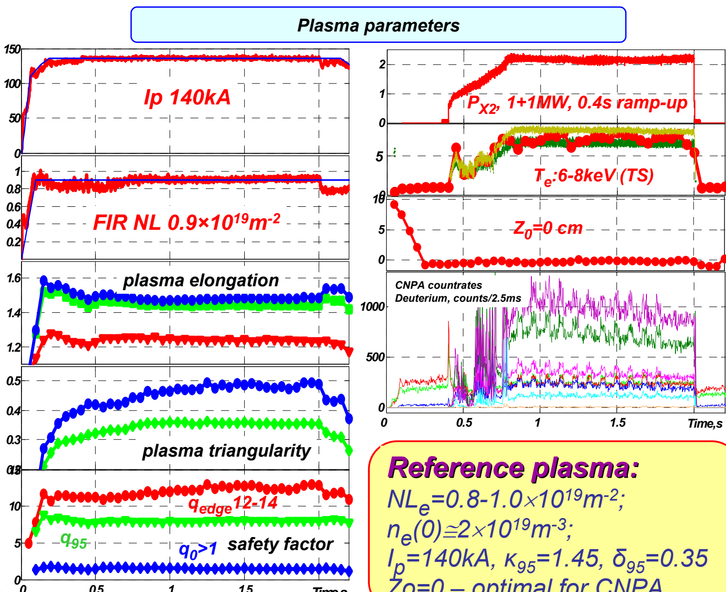
Introduction

- A suprathermal ion population has been observed in experiments on the TCV Tokamak (R=0.88m, a=0.25m), employed the X2 (82.7 GHz) EC system: up to 2.0 MW (4 gyrotrons) in X-mode.
- The flexibility of the ECH system permitted an investigation of the dependence of the properties of the hot ion distribution on plasma and ECH parameters.
- Earlier experimental observations [2] are expanded with plasma current and density scans and the employment of a new "Compact Neutral Particle Analyser" (CNPA [1]) featuring mass and energy separation over a broader energy range.
- *Confidence of NPAs data has been validated → suprathermal ion population on TCV is reality;*
- These experiments extend the experimental database required for understanding the mechanisms of suprathermal ion generation [3]
- *"Optimal" conditions for sup.ions has been found: on-axis CNTR-ECCD, low n_e, high T_e, I_p~140kA*

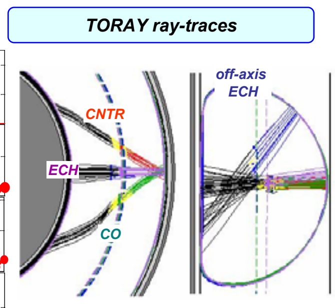
1. Karpushov A.N., et al., Rev. Sci. Instrum. 77, 033504 (2006).
2. Karpushov A.N., et al., 30th EPS Conf. on Controlled Fusion and Plasma Physics, St.Petersbourg, 2003, ECA Vol. 27A, P-3.123
3. **Schlatter Ch., et al., this conference (2006), P-1.149**
4. Bosshard P., et al., 29th EPS Conf. on Controlled Fusion and Plasma Physics, Montreux, 2002, ECA Vol. 26B, P-4.120.
5. Erckmann V. and Gasparino U., Plasma Phys. Control. Fusion 36, (1994) 1896-1962
6. Coppi B., Pegoraro F.; Pozzoli R.; Rewoldt G., Nucl. Fusion 16(2), (1976) 309-328

II. Optimal scenario

Plasma parameters



TORAY ray-traces



Reference plasma:
NL_e=0.8-1.0×$10^{19}m^{-2}$;
$n_e(0)$≅2×$10^{19}m^{-3}$;
I_p=140kA, κ_{95}=1.45, δ_{95}=0.35
Zo=0 – optimal for CNPA

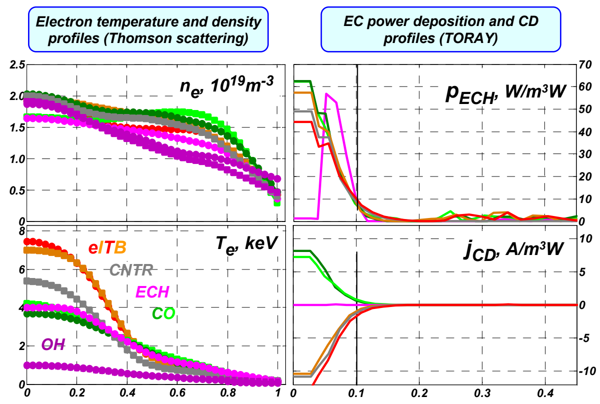
ECH setup:
2-X2 (1MW) on-axis (CNTR-CO-ECH)
2-X2 (1MW) off-axis ECH @ρ=0.4-0.6

EC power deposition and CD profiles are calculated by **TORAY**

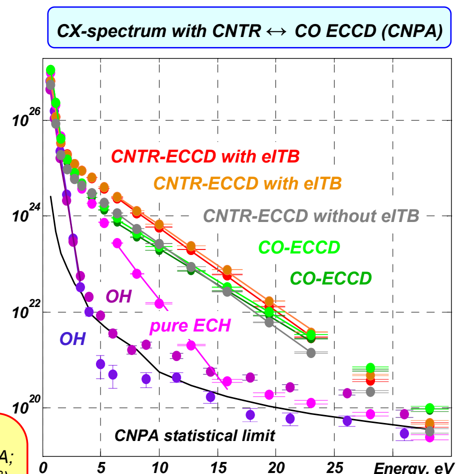
Real time X2 mirror movement permits the toroidal angle (CNTR-CO-ECH) scan in single shot for Zo=0.

IV. CNTR → CO ECCD

Electron temperature and density profiles (Thomson scattering) / **EC power deposition and CD profiles (TORAY)**



CX-spectrum with CNTR ↔ CO ECCD (CNPA)

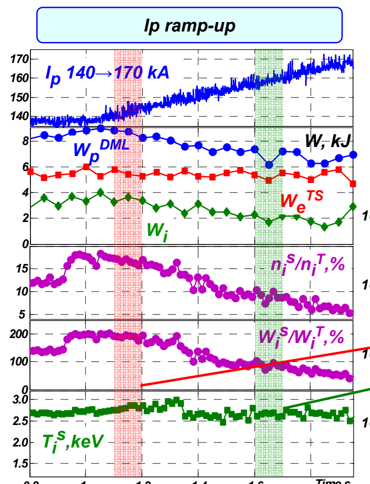


- Strongest effect on the suprathermal ion population in eITB plasmas with $n_e(0)$:1.7-2.1×10^{19} m^{-3}; Ip:140 kA; on-axis CNTR-ECCD (20 MW/m³, –5 MA/m³).
- n_i^S/n_i^T:~10-30%, W_i^S: up to a few times higher than W_i^T (bulk).
- n_i^S a few times lower without eITB with Te of 4-5 keV (in contrast to 7-8 keV with eITB).
- Difference between CO and CNTR-ECCD discharges may be related to changes in the plasma energy confinement.

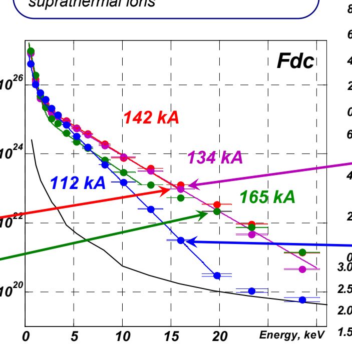
The suprathermal electron population with a density of a few percent and energies up to a few 100 keV has been measured by the ECE diagnostic in CNTR-ECCD with eITB.

V. Ip scan

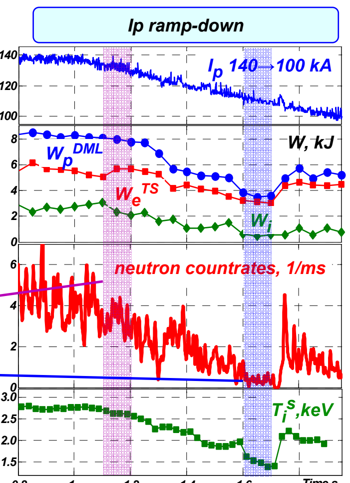
Ip ramp-up



$W_i \approx W_p - W_e$
Qualitatively the decrease of W_p(DML)-W_e(TS) can be explained as decrease of the energy content in suprathermal ions



Ip ramp-down

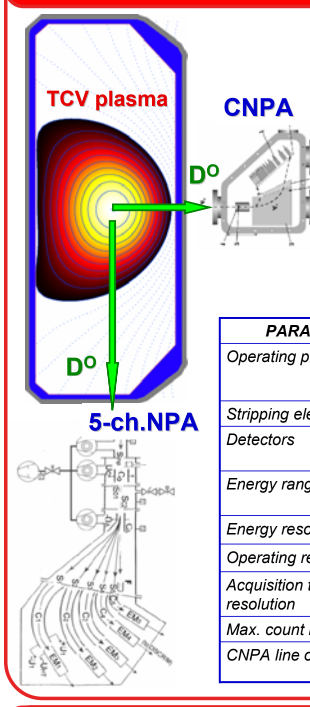


- The Fdc is sensitive to Ip;
- Ip 140→170kA: n_i^S decrease for intermediate energies (3-17keV), T_i^S≈const;
- Ip 140→110kA: T_i^S decrease, correlates with neutron countrate.

Linked with q-profile, sawtooth inversion radius

Neutron countrates monitored by He^3 neutron detector correlates with a high energy tail (E>20keV) of ion energy distribution.

I. Instrumentation



Diagnostics:

- *ion energy distribution (F_{dc})* was studied with ***28-channel "Compact Neutral Particle Analyzer"*** (CNPA) and ***"Five-Channel Energy Atomic Particle Analyser "*** (5-ch.NPA) [1]
- *electron temperature (T_e) and density (n_e)* profiles from ***Thomson scattering (TS)***
- total *plasma energy (W_p)* content from the ***diamagnetic*** measurement
- bulk *ion temperature profile (T_i)* from ***Charge-eXchange Recombination Spectroscopy*** (CXRS) [4]

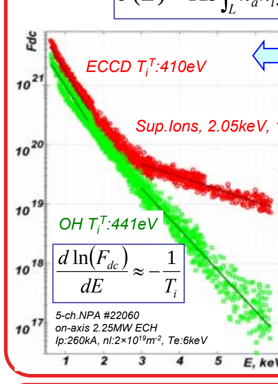
EC power deposition and current drive profiles are calculated by the TORAY ray-tracing code with magnetic equilibrium reconstruction from the LIUQE code

PARAMETER	Compact NPA	5-ch.NPA
Operating principle	magneto-electric separation, E‖B scheme; electrostatic acceleration of ions; ion focusing at the detector area	double electrostatic analysis; **high voltage swept** on analyzer plates and channel condensers
Stripping element	100 Å diamond-like carbon foil	nitrogen (N_2) filled stripping cell
Detectors	Channel Electron Multipliers (CEM) **two arrays for H and D**	Open Electron Multipliers (EMT)
Energy range	H:0.64-50 keV (11 channels), D:0.56-33.6 keV (17 ch.)	0.6-8 keV, 25-50 energy points during 13 ms sweeping period
Energy resolution (ΔE/E)	60%(for 0.6keV)–10%(for E>3keV)	10-18%
Operating regime	counting with pulse amplitude discrimination	
Acquisition time resolution	0.5-4 ms	up to 0.5 ms
Max. count rate	**800** pulse/ms	5000 pulse/ms
CNPA line of sight	along TCV major radius at horizontal midplane from an equatorial port	fixed vertical chord

III. CX-spectrum (Fdc)

$$F_{dc}(E) = J(E)/(\sigma_{cx}(E)\times E)$$

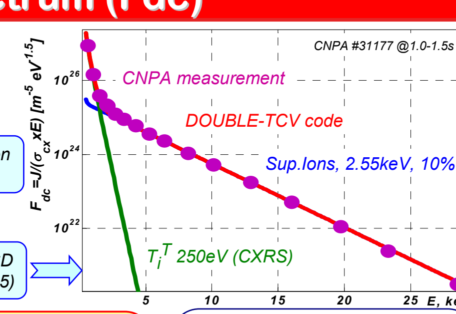
$$J(E) = \Omega S \int_L n_a n_i f_i \langle \sigma_{cx} v_{ia} \rangle \gamma_{att} dl$$



$$\frac{d\ln(F_{dc})}{dE} \approx -\frac{1}{T_i}$$

CNTR-ECCD modulation 5-ch.NPA (2002)

stationary CNTR-ECCD CNPA deuterium (2005)

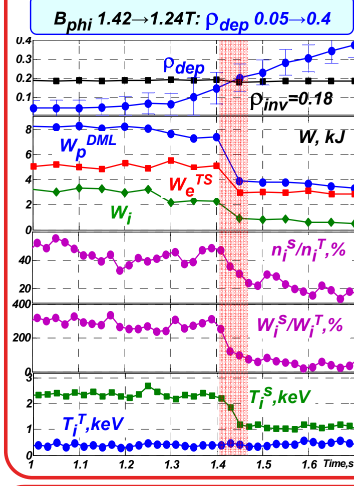


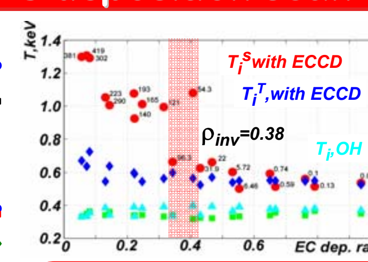
Parameters:
- T_i^S, 1.5-3keV temperature
- n_i^S/n_i^T, ≤30% density
- W_i^S/W_i^T ≤300% energy

NPA CX-spectra can be described as bi-Maxwellian

DOUBLE-TCV code:
Real TCV geometry (LIUQE)
Electron density and temperature from TS
1.9×$10^{19}m^{-3}$, 7.1keV, Z_{eff}:2.6
Bulk ion temperature from CXRS
230->250eV (×1.09)
Model for sup.ions:
2.55keV, 10%

VI. EC deposition scan

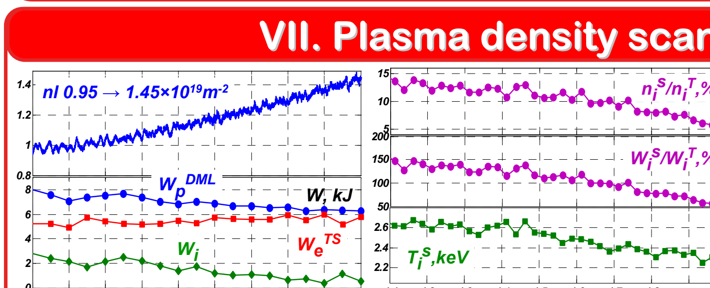




T_i^S and T_i^T vs. radius of EC deposition
20 shots (2002) from 5-ch.NPA

- The non-Maxwellian ion feature is not observed when the deposition location is outside the sawtooth inversion radius.
- The transition of ECCD deposition through ρ_{inv} leads to a decrease of the electron temperature and destroys the conditions necessary for generation of suprathermal ions.

VII. Plasma density scan



Suprathermal ions and density ramp-up

- W_i^S, n_i^S and T_i^S decrease with n_e.

linear density of 1×$10^{19}m^{-2}$, limited by the machine wall recycling (the lowest accessible in TCV with 2MW of ECH).

Discussion

- The generation of suprathermal ions may not be explained by the classical theory of two-body Coulomb collisions.
- The link between electron energy distribution (bulk electron temperature and suprathermal electrons) and the parameters of suprathermal ions confirms the importance of the electron energy distribution for energy transfer from electrons to ions.
- The experimental observation of the non-Maxwellian features on the ion energy distributions in the ECH heated TCV plasma is not inconsistent with the mechanisms resulting in the slide-away regime of the electron energy distribution [3,6]. Powerful on-axis ECCD leads to the formation of an electron energy distribution of which a considerable fraction tends to a slide-away. Modes in the lower-frequency ($\omega^2 \leq \omega_{pi}^2$) could resonate both with the electron and ion populations thus causing efficient anomalous energy transfer from the electrons to the ions.