Ion Temperature Fluctuations in ELMy H-mode of the X3 EC-heated Plasmas on TCV

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Subject: Measurement and interpretation of NPA data from ELMy H-mode with X3 ECH-heating on TCV

Q1: Effect of ELMs on bulk plasma ions ($f_i(\boldsymbol{r}^3,\boldsymbol{v}^3)$) ?

Q2: Can we extract information on bulk ion behaviour during ELMs from NPA measurements ?

Outline:

Experimental conditions – Quasi-stationary ELMy H-mode with X3

NPA measurement

- Instrumentation (5-ch.NPA + CNPA)
- Perturbation of the measured energy spectra of D^O
- Variation of “effective NPA ion temperature”

Possible interpretation of T_i^{NPA} perturbation

- Neutral density variation in plasma
- Electron temperature and density perturbations
- Electron-Ion Coulomb collisions (ion heating by electrons)
- Global power balance

Conclusion

Quasi-stationary ELMy H-mode with X3 ECH (QSEHM)

Tokamak à Configuration Variable

R:0.88m, a:0.25m, I_p<1MA, B_T<1.5T

1.5MW X3 ECH; cut-off ≤$11 \cdot 10^{19} m^{-3}$

3 gyrotrons, 118 GHz, top launch

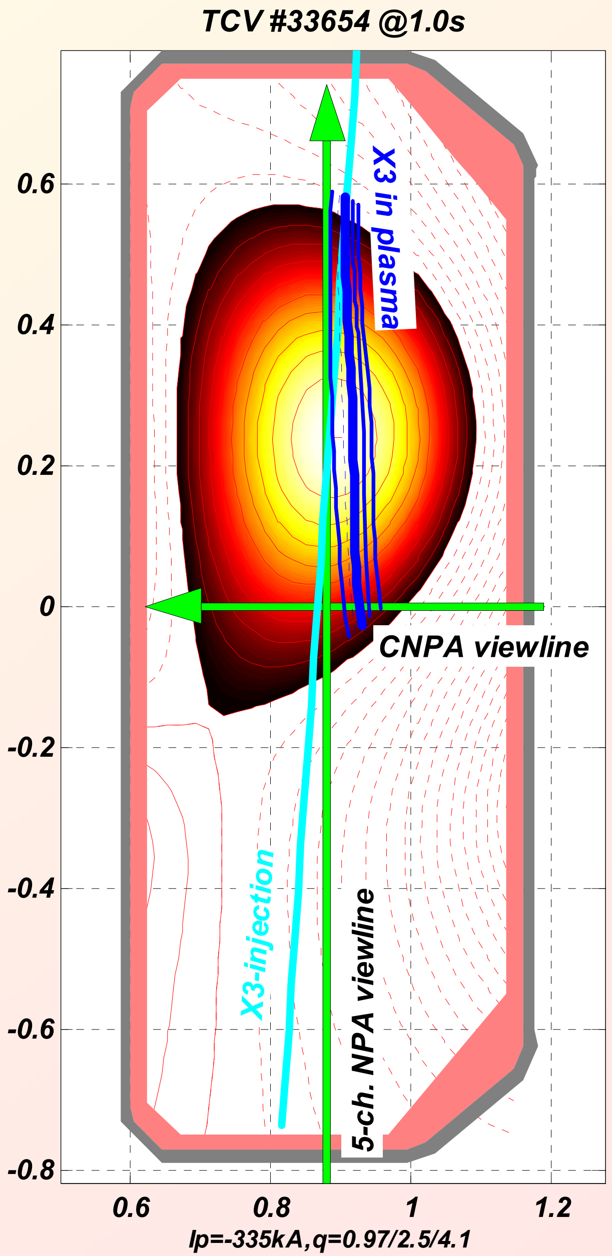
ELMy H-mode

P_{OH}:220kW;n_e:$5\text{-}7 \cdot 10^{19}$ m^{-3};I_p:300-350kA;

	OH, Type III ELMs	QSEHM with X3
T_e:	0.7-1.0keV	1.5-2.1keV
Period:	5...10ms	**20ms±10%**
ΔW_p:	4-5%	**15-20%** (per ELM)

2 gyrotrons, P_{X3}:700-800kW

Sawteeth sync with ELMs



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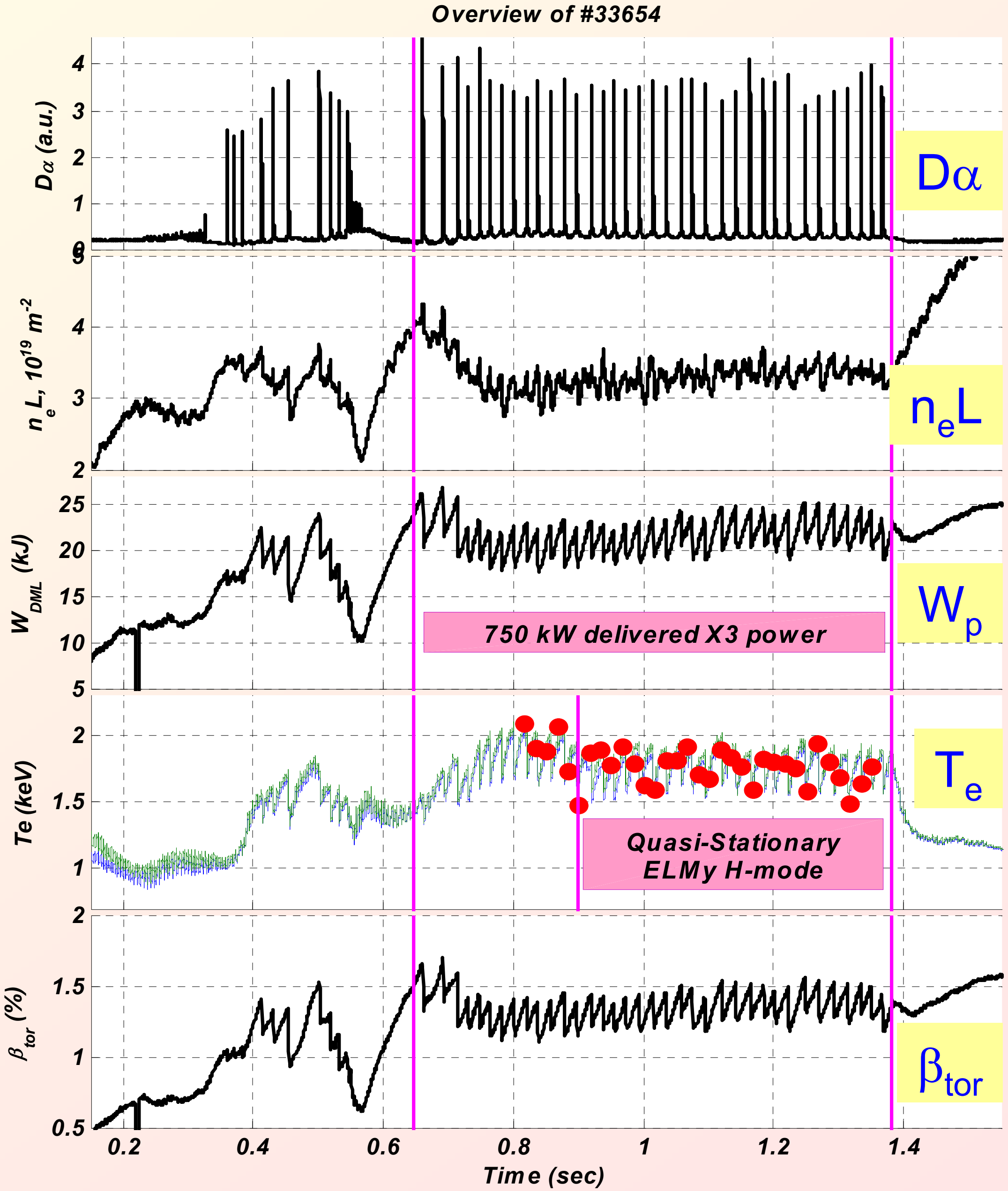
QSEHM+X3 is analyzed using coherent averaging technique

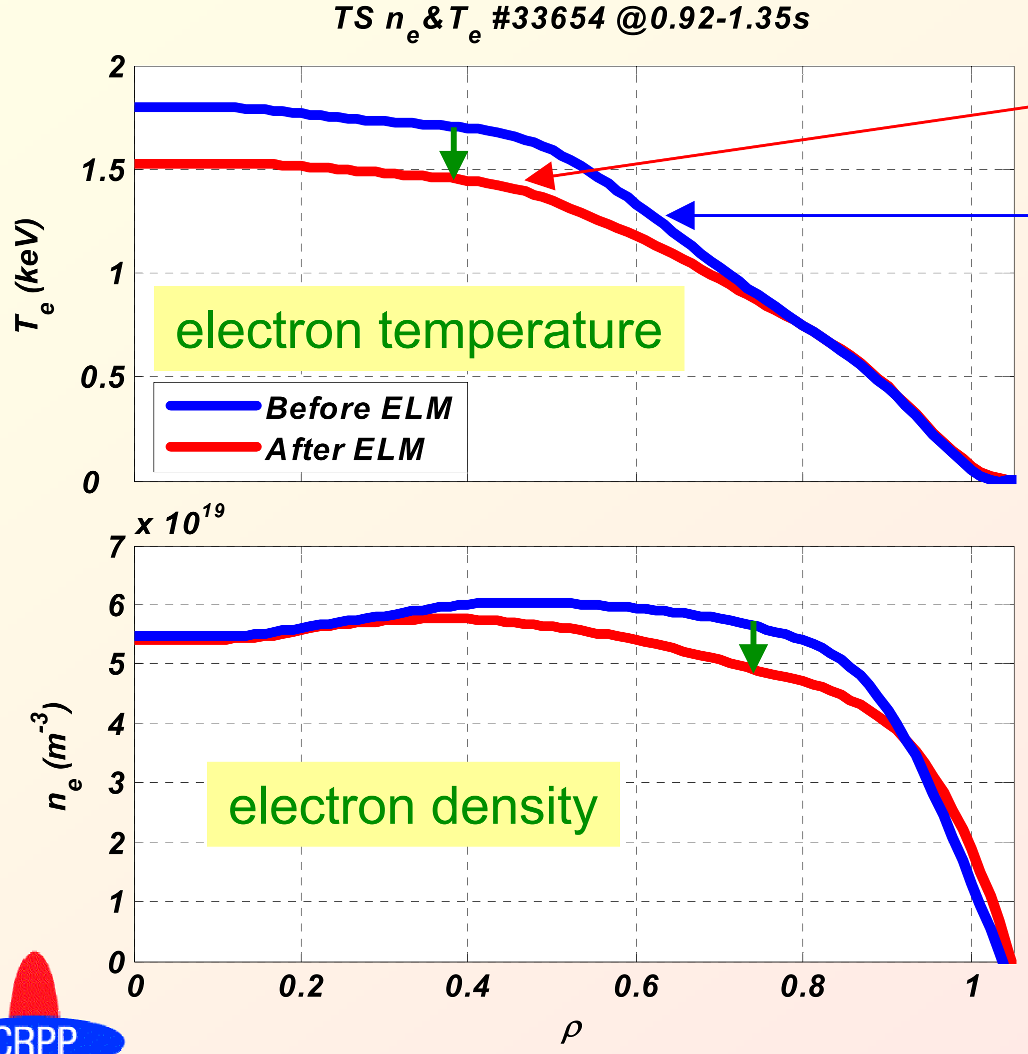


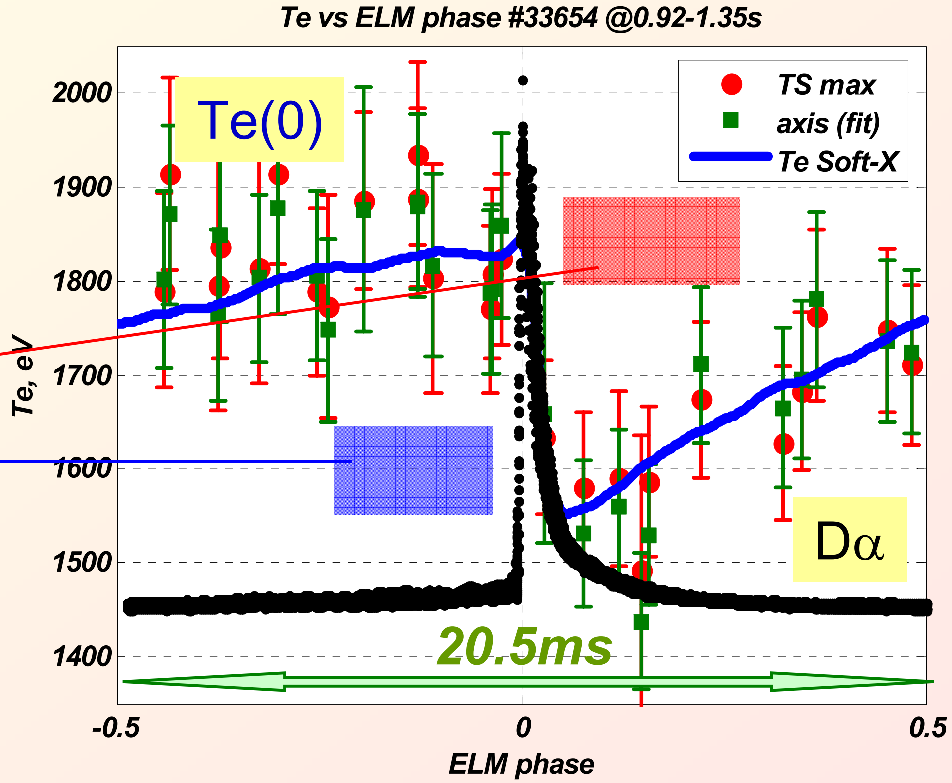
Electron temperature and density variation

Coherent averaging:

"ELM phase"≡ 0 @ peak of D-alpha

"-1" – previous, "+1" – next ELM



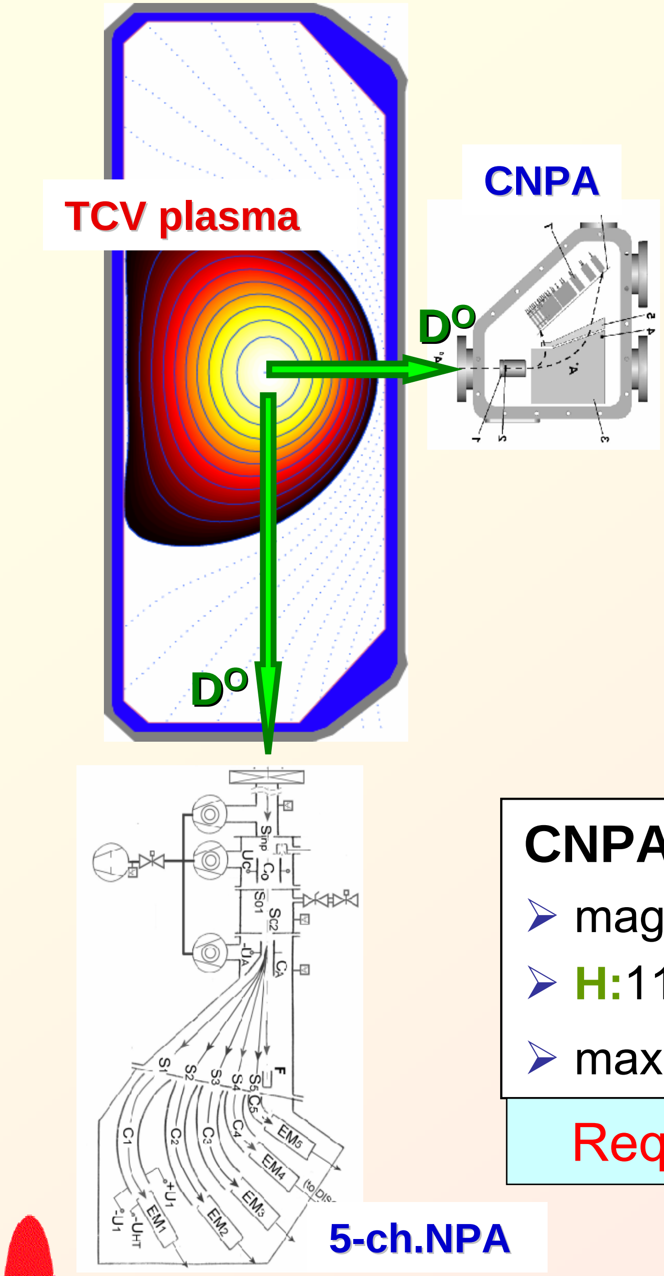


ELMs + sawteeth ⇒

n_e & T_e variations in plasma core

- fast (1-2ms) T_e^{core} decrease, ~10ms recovery time;
- $T_e(0.7<\rho<0.95)$ does not change;
- $n_e(0.4<\rho<0.9)$: ~10% decrease

Instrumentation (5-ch. and Compact NPAs)



Requirement: $\Delta t <<$ "ELM period"

5-ch.NPA "Five-Channel Energy Atomic Particle Analyzer "

- double electrostatic analysis ⇒ no mass separation;
- 5 channels, **0.6-8 keV** (0.8-3.5 keV in this work)
- acquisition time resolution **up to 50 μs**

  standard 1ms x 4096 time points per channel
- max. operational count-rate up to 10MHz,

  10000 counts/ms !☺

Allows to resolve individual ELM

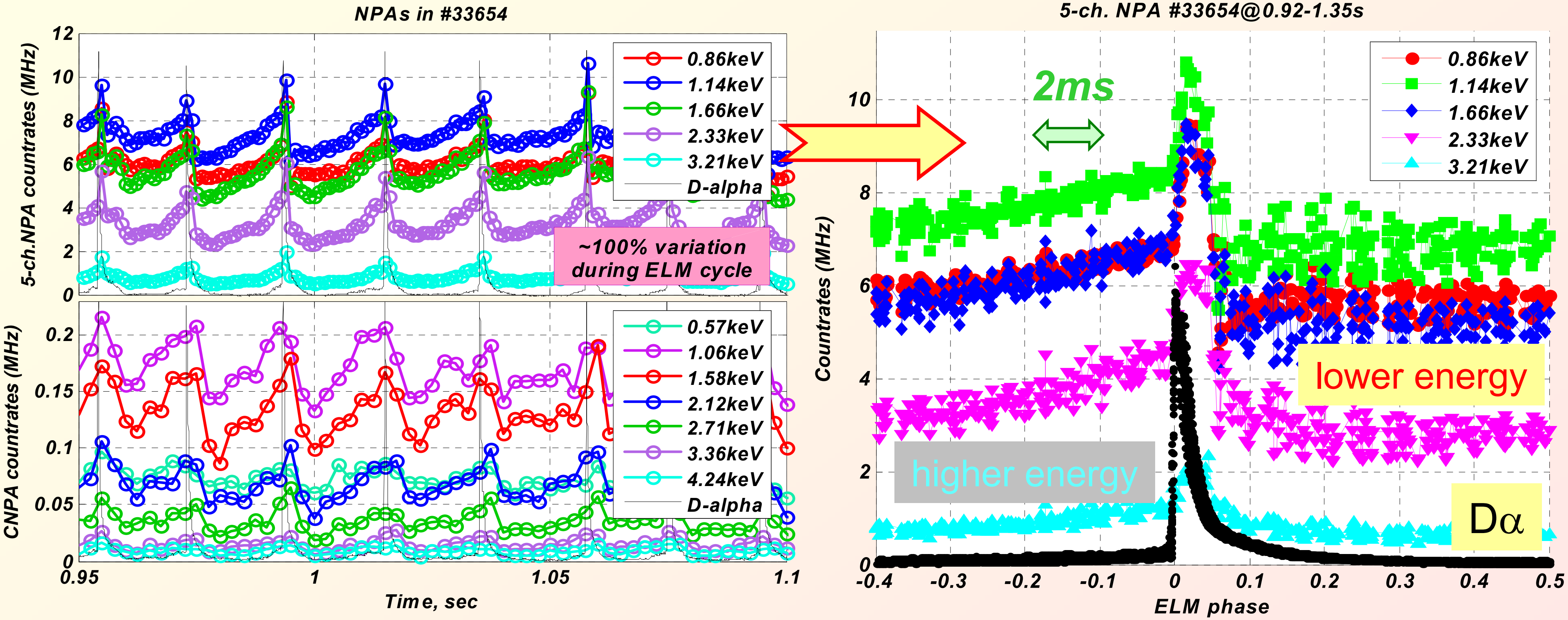
CNPA 28-channel "Compact Neutral Particle Analyser"

- magneto-electric separation ⇒ simultaneous H and D registration;
- **H:**11 channels, **0.64-50** keV, **D:**17 ch., **0.56-33.6** keV – fixed energy
- max. operational count-rate 0.5-0.8MHz, **500-800 counts/ms** ☹

Requires coherent averaging for analysis in ELMy regimes

NPA measurement (count-rates)

Coherent averaging:
D-alpha – conditional signal
5-ch.NPA count-rates – analyzed signals



Increase in neutral fluxes ~ 1.5–2x explained by edge neutral density increase resulting from plasma-wall interaction during ELM.

Temporal behavior depends on the energy

“NPA CX-spectra” & “effective NPA ion temperature”

NPA count-rate (N) ↔ energy spectrum of atomic flux (J(E))

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

energy spectrum of atomic flux (J(E)) ↔ plasma parameters

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

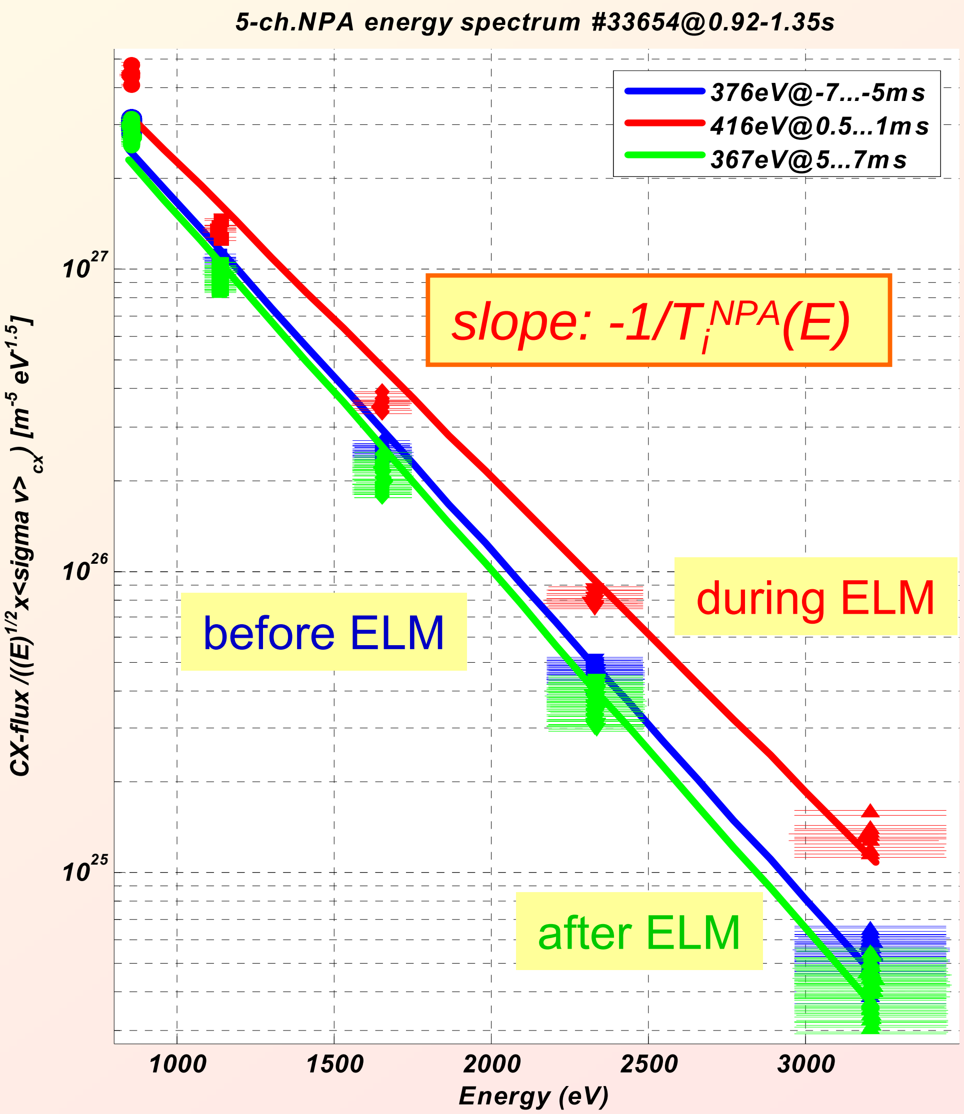
energy spectra of the atomic flux J(E) emitted from the plasma into the NPA is the integral of fluxes in the plasma column along the line of sight of the analyzer

“ NPA CX spectra”: $F_{dc}(E) = \dfrac{J(E)}{\sigma_{cx}(E) \cdot E}$

***effective NPA ion temperature**:*

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

characteristic of NPA CX-spectra

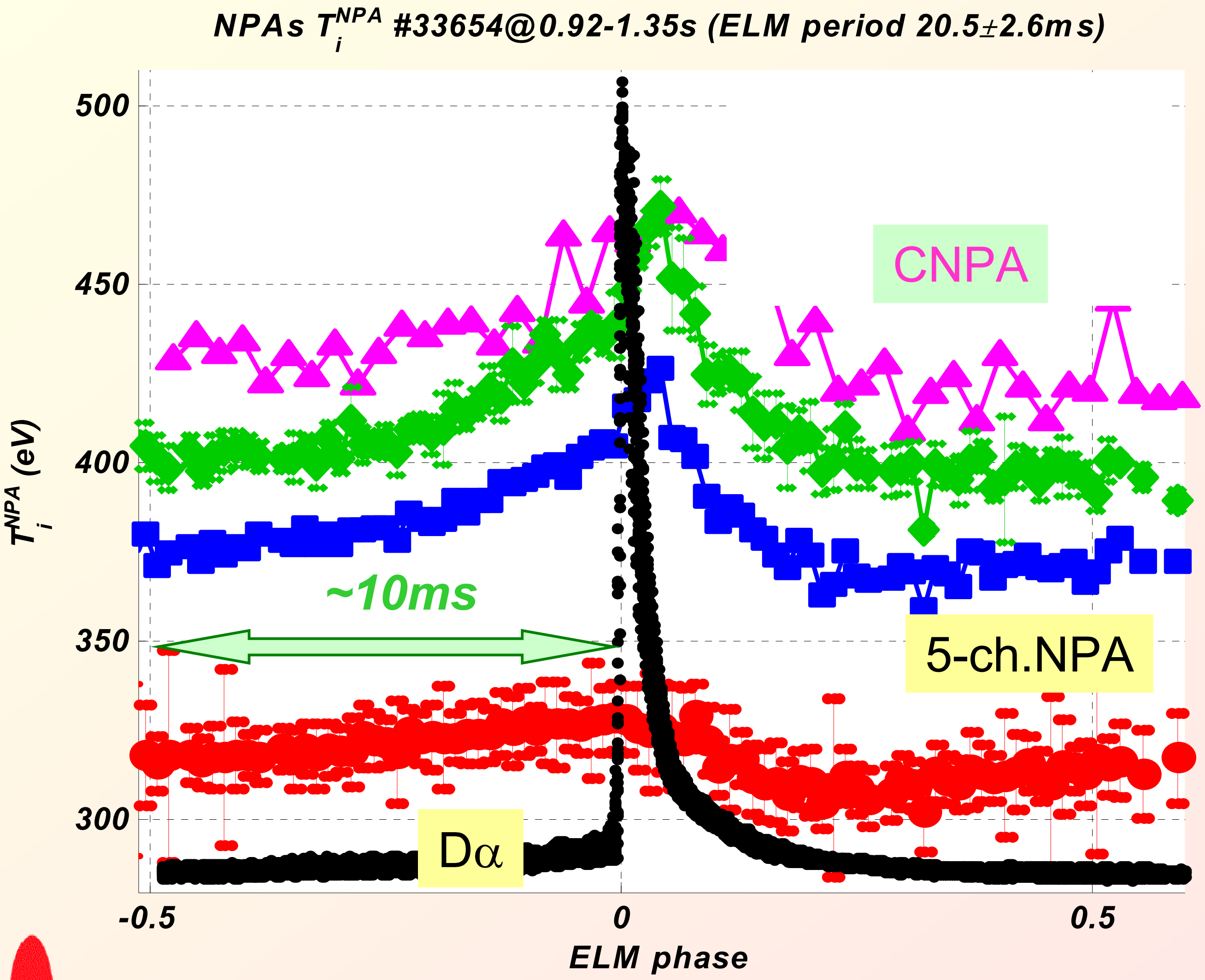

5-ch.NPA energy spectrum #33654@0.92-1.35s

- For **Maxwellian**, homogeneous, low density ($\gamma \equiv 1$) plasma: $\mathbf{T_i^{NPA} = T_i}$;
- ELMy H-mode on TCV: $\mathbf{T_i^{NPA}}(E{:}[1\text{-}10]T_i(0))$ = **[0.4-0.7] x $\mathbf{T_i(0)}$**

T_i^{NPA} variation vs. ELM phase

15% variation of T_i^{NPA} correlated with ELMs

- stronger at high energies;
- maximum ~1 ms after max. of D-alpha;
- slow build up before ELM;
- ~5 ms decay



Plasma effects causing $J(E)$ & T_i^{NPA} perturbations

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

- neutral density variation (**$n_a(z,t)$**) due to ELM related transient increase of plasma-wall interaction and neutral redistribution in the plasma;
- ion density (**$n_i(\rho,t)$**) and (γ**(n_e, T_e)**, attenuation) variation;
- ion temperature change (**$T_i(\rho,t)$**) from electron-ion collisions (**$T_e(\rho,t)$**) (Coulomb collisions);
- modification of ion energy distribution function (**$f_i(v^3,\rho)$**) due to ion redistribution in coordinate and/or velocity space.

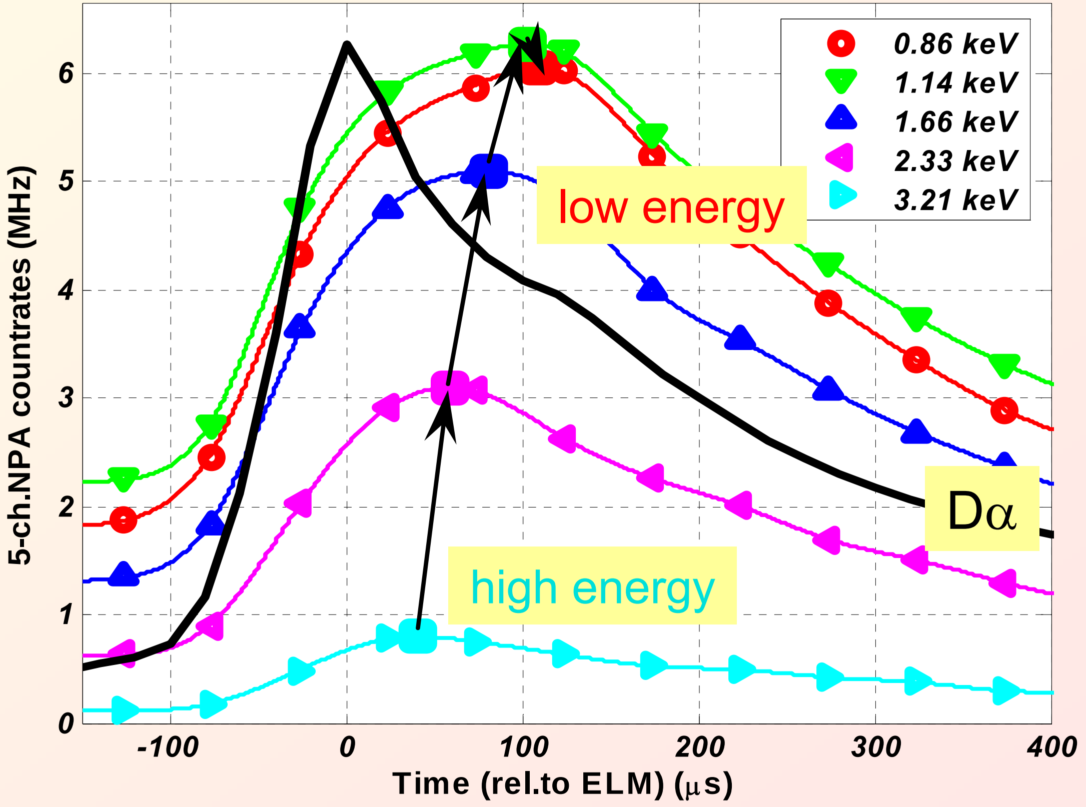
$dT_i(\rho)/dt$ may be const

$df_i(v^3,\rho)/dt \neq$ const

Neutral density variation

- Low energy neutral originate from plasma edge
- High energy particles from plasma core
- Effect of transient increase of neutral density should be stronger and faster on neutral fluxes at lower energies
- **BUT** experimental observations are inverse: flux-spikes in higher energy NPA channels occur earlier

NPA measurement with fast (50μs) time resolution



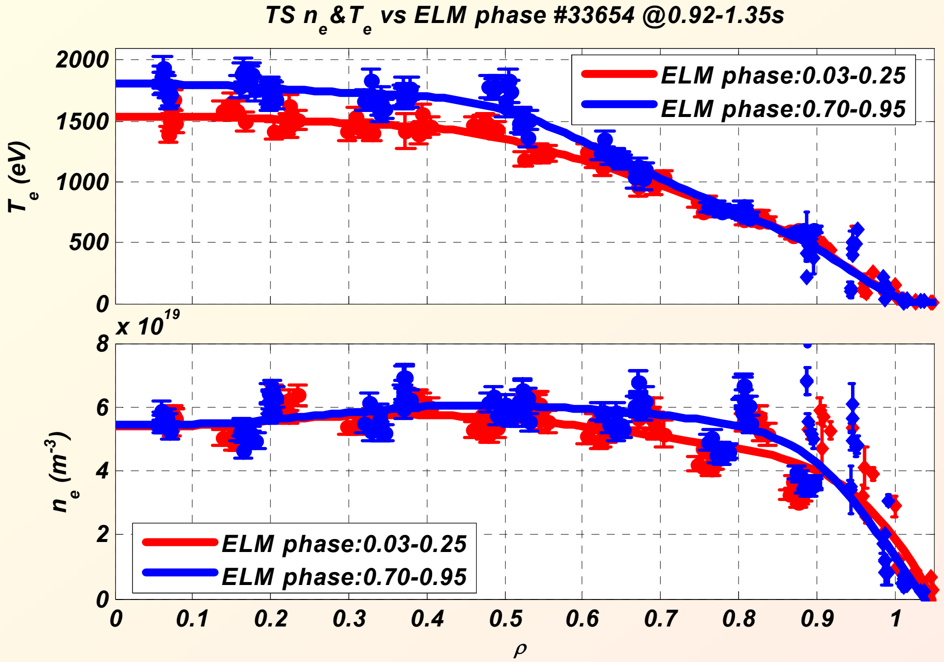
☒ The neutral density profile variation due to ELM related transient increase of the plasma-wall interaction can not explain the increase of T_i^{NPA} during ELM cycle ☹

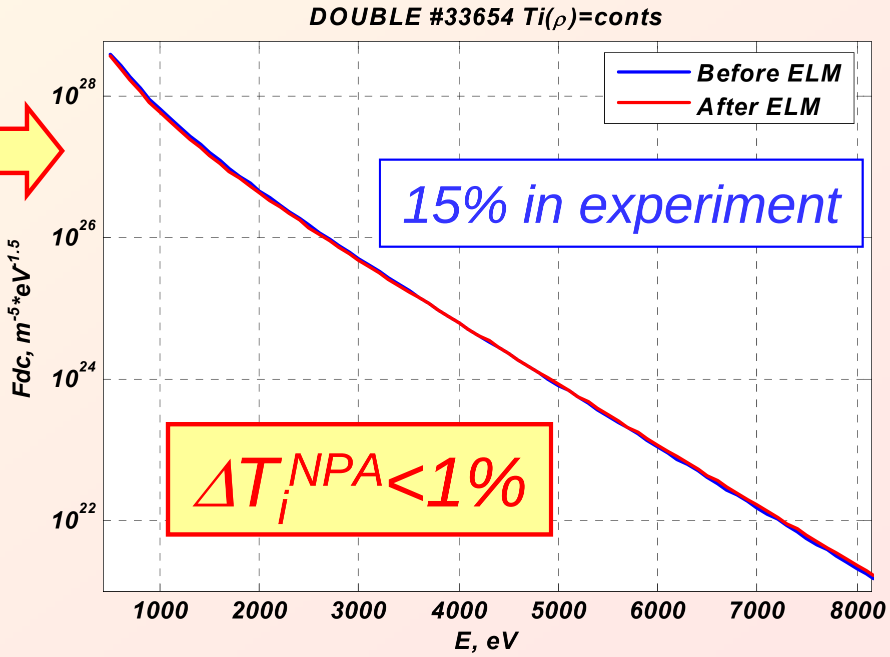
Electron density and probability

DOUBLE-TCV *code: modeling of neutral fluxes in NPA – J(E)*

- *$T_e(\rho,t)$, $n_e(\rho,t)$ – from experiment;*
- *$dT_i(\rho)/dt=0$ and $d(n_D/n_e)/dt=0$ – NO change in ion distribution;*
- *TCV plasma geometry*

Normalised CX NPA spectra





15% in experiment

$\Delta T_i^{NPA}<1\%$

☒ Expected T_i^{NPA} perturbation caused by electron density and temperature variation without change in the ion temperature (energy distribution) is negligible ☹

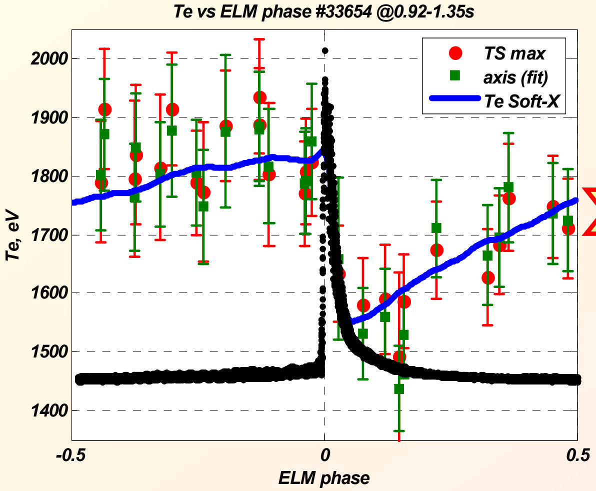
Power balance (e-i coulomb collision)

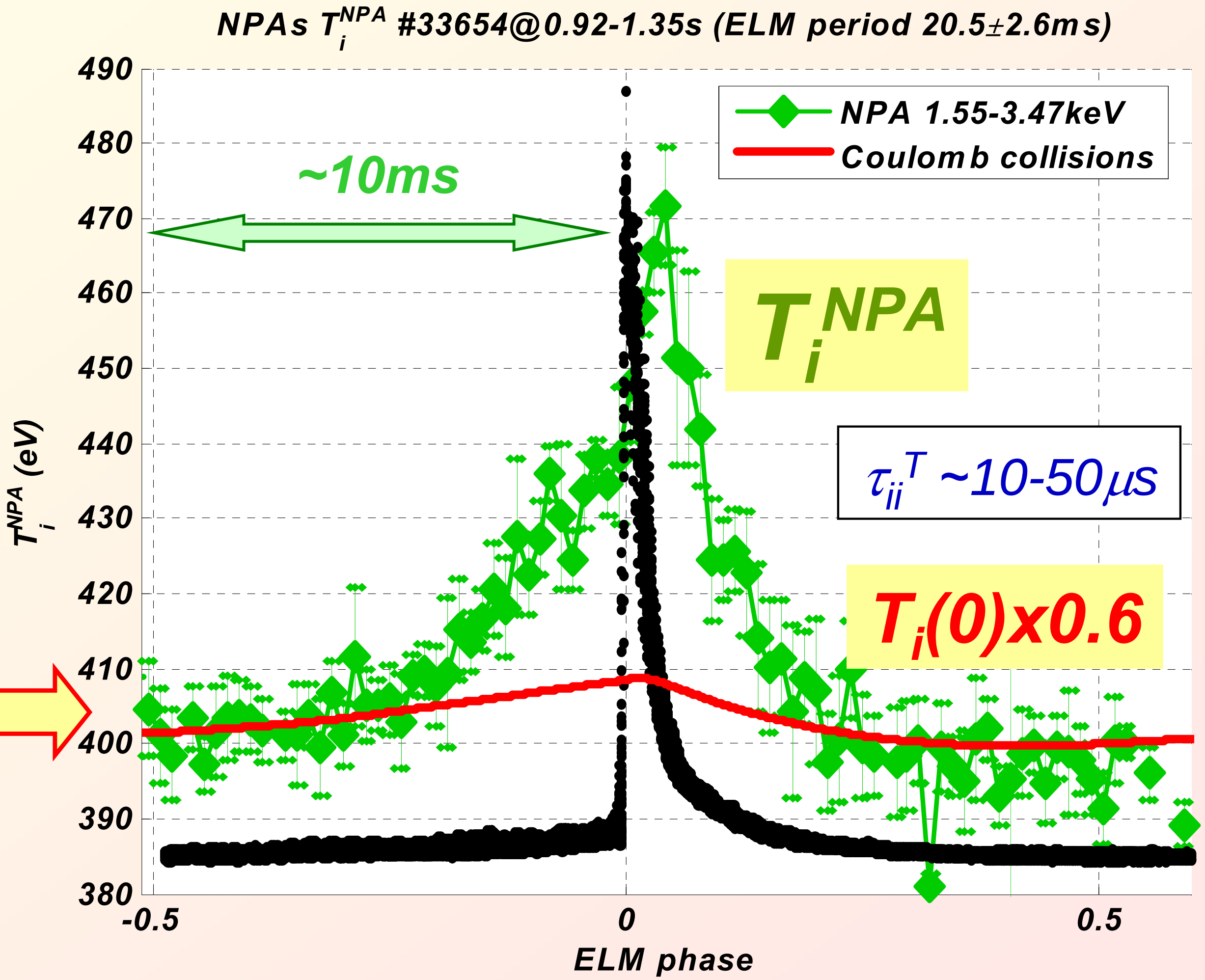
$$\frac{dT_i}{dt}=\frac{T_e-T_i}{\tau_{ei}^T}-\frac{T_i}{\tau_i^E}$$

$T_e(t)$ from experiment

$T_i^{NPA}/T_i(0)$=const,

τ_i^E~40ms, τ_{ei}^T ~60ms





☒ Change in Coulomb collisional electron-Ion power exchange due to $T_e(t)$ variation leads to a perturbation of ion temperature ($T_i(t)$) lower than 3% ☹

Discussion

Global power balance (speculation):

~+15% of T_i^{NPA} variation $\Rightarrow$ ~+15% of T_i (plasma ions) $\Rightarrow$ ~+15% of ΔW_i

$\Rightarrow$ ΔW_i ~+1kJ (at W_i=7kJ, W_e=15kJ, ΔW_p(per ELM)~-4kJ)

$\Rightarrow$ required power source for ion heating 0.3-0.5MW >> $P_{ei}^{coulomb}$=0.1MW

Discussion

Global power balance (speculations):

~~$\sim$+15% of T_i^{NPA} variation ⇒ $\sim$+15% of T_i (plasma ions) ⇒ $\sim$+15% of ΔW_i~~

~~⇒ ΔW_i $\sim$+1kJ (at W_i=7kJ, W_e=15kJ, ΔW_p(per ELM)$\sim$-4kJ)~~

~~⇒ required power source for ion heating 0.3-0.5MW >> $P_{ei}^{coulomb}$=0.1MW~~

NOT REALISTIC

⇒ modification of ion velocity distribution (small non-Maxwellian fraction)

☑ Ion redistribution in coordinate and/or velocity space remains a candidate for interpretation of the NPA measurement from the TCV ELMy H-mode plasma with X3 ECH 😐**???**

We have no physical model for ion redistribution mechanism in v^3 & ρ

Conclusion

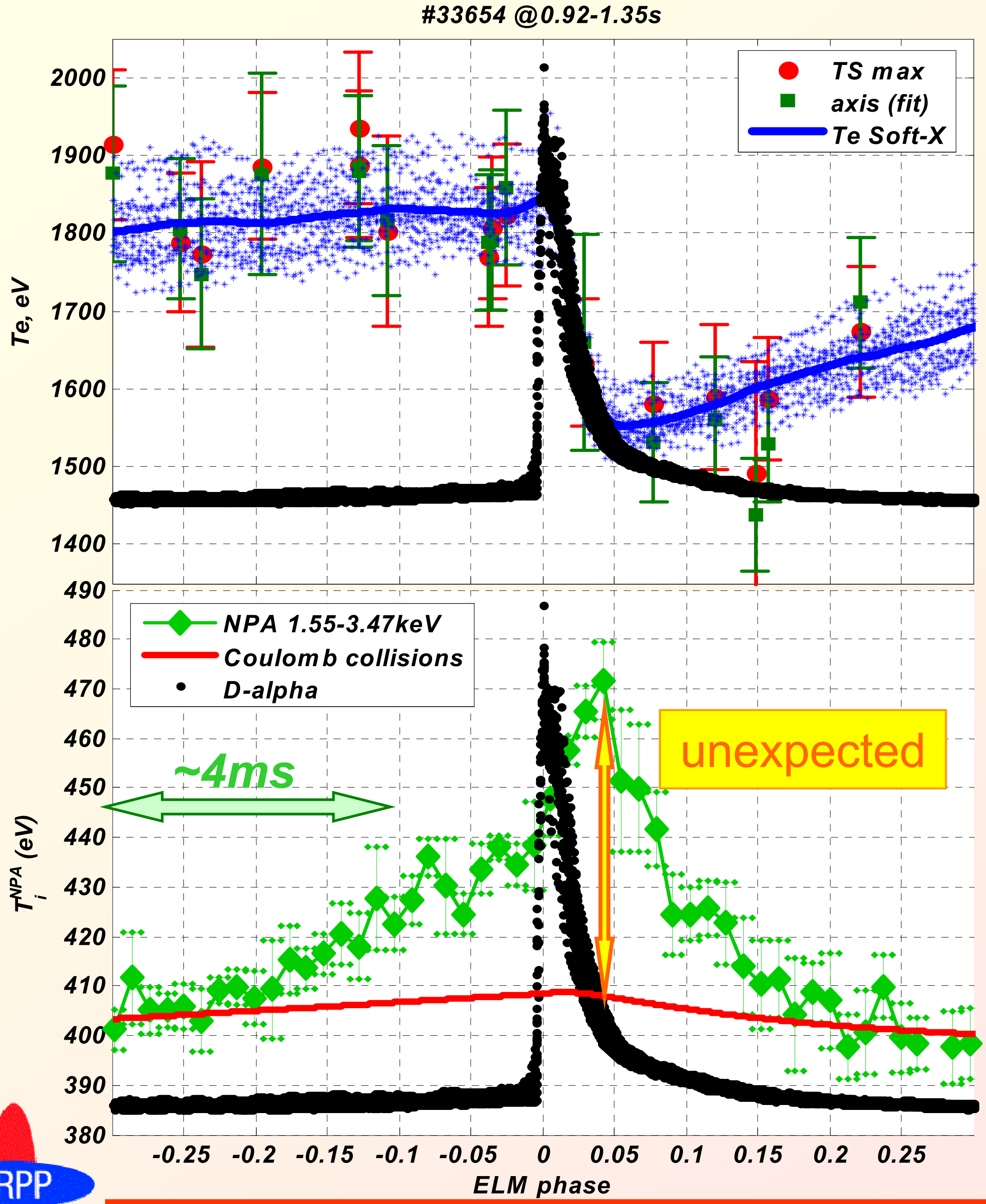
- The TCV ELMy H-mode plasma (QSEHM) with X3-heating is a “good” target for experimental studies of *J(E)* perturbations;
- NPA measurement allows to resolve ELM (+sawteeth) induced variations in the energy distribution of hydrogen isotope neutrals escaping plasma:
  - increase of neutral fluxes,
  - **increase of energy of neutrals (T_i^{NPA} ⇑);**
- The amplitude of “effective NPA ion temperature” perturbation is unexpected:

  We have no physical model for mechanism responsible for the change in $f_i(r^3,v^3)$!
- A set of experiments with NPA in ELMy H-mode X3-heated TCV plasma is planned for the 2008 experimental campaign :
  - different toroidal observation angles (tangential and orthogonal);
  - dependence on q-profile (I_p variation);
  - extend experimental database with faster NPA measurements

END of Presentation

Extra slides

T_e & T_i^{NPA}

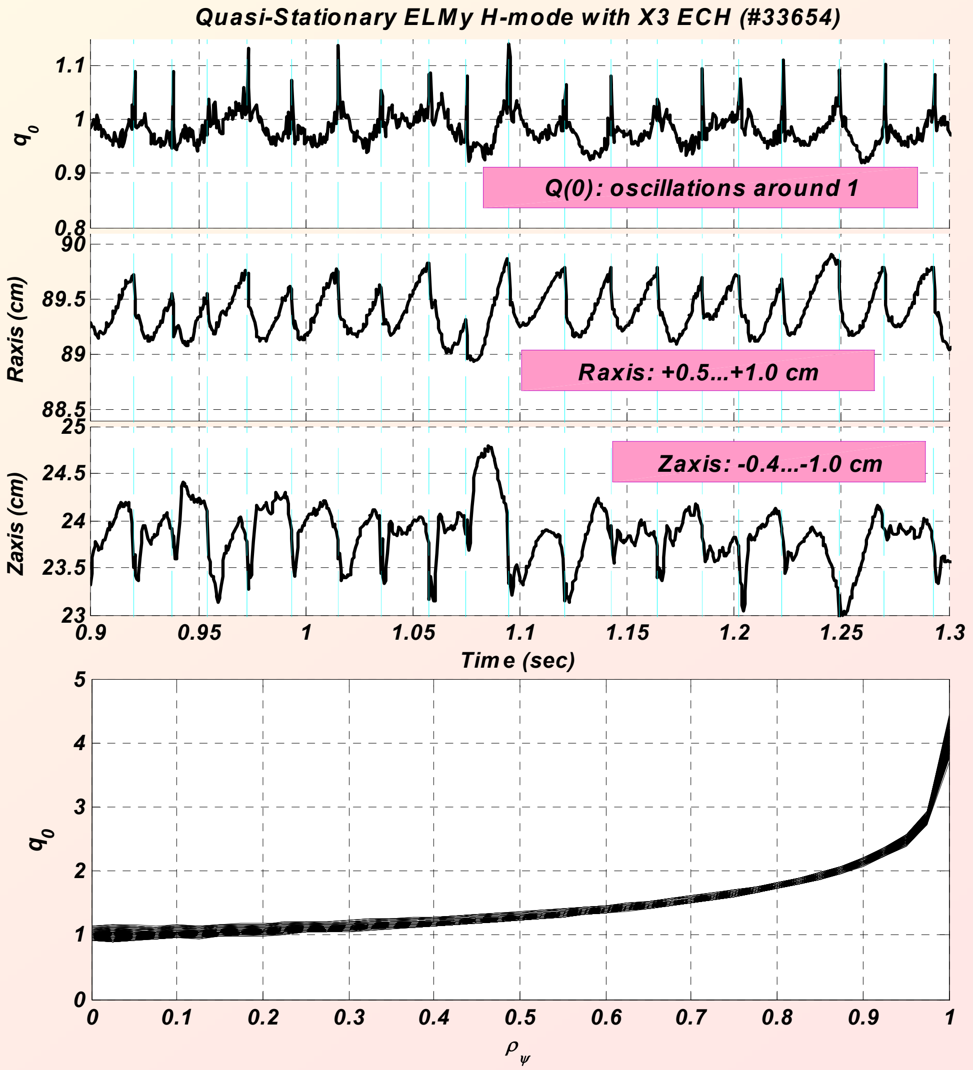

#33654 @0.92-1.35s
TS max
axis (fit)
Te Soft-X
Te, eV
2000
1900
1800
1700
1600
1500
1400
NPA 1.55-3.47keV
Coulomb collisions
D-alpha
~4ms
unexpected
T_i^{NPA} (eV)
490
480
470
460
450
440
430
420
410
400
390
380
-0.25
-0.2
-0.15
-0.1
-0.05
0
0.05
0.1
0.15
0.2
0.25
ELM phase

Plasma Oscillations

Sawteeth crashes and ELMs are accompanied by a variation of the axial safety factor (q_0) around 1 and plasma vertical and radial movement on a few mm.

Modes excitation can result in strong ion mixing, especially of trapped ions.

The ELM (or/and sawteeth) induced redistribution of ions is a good candidate to explain NPA observations in the TCV ELMy H-mode plasma.



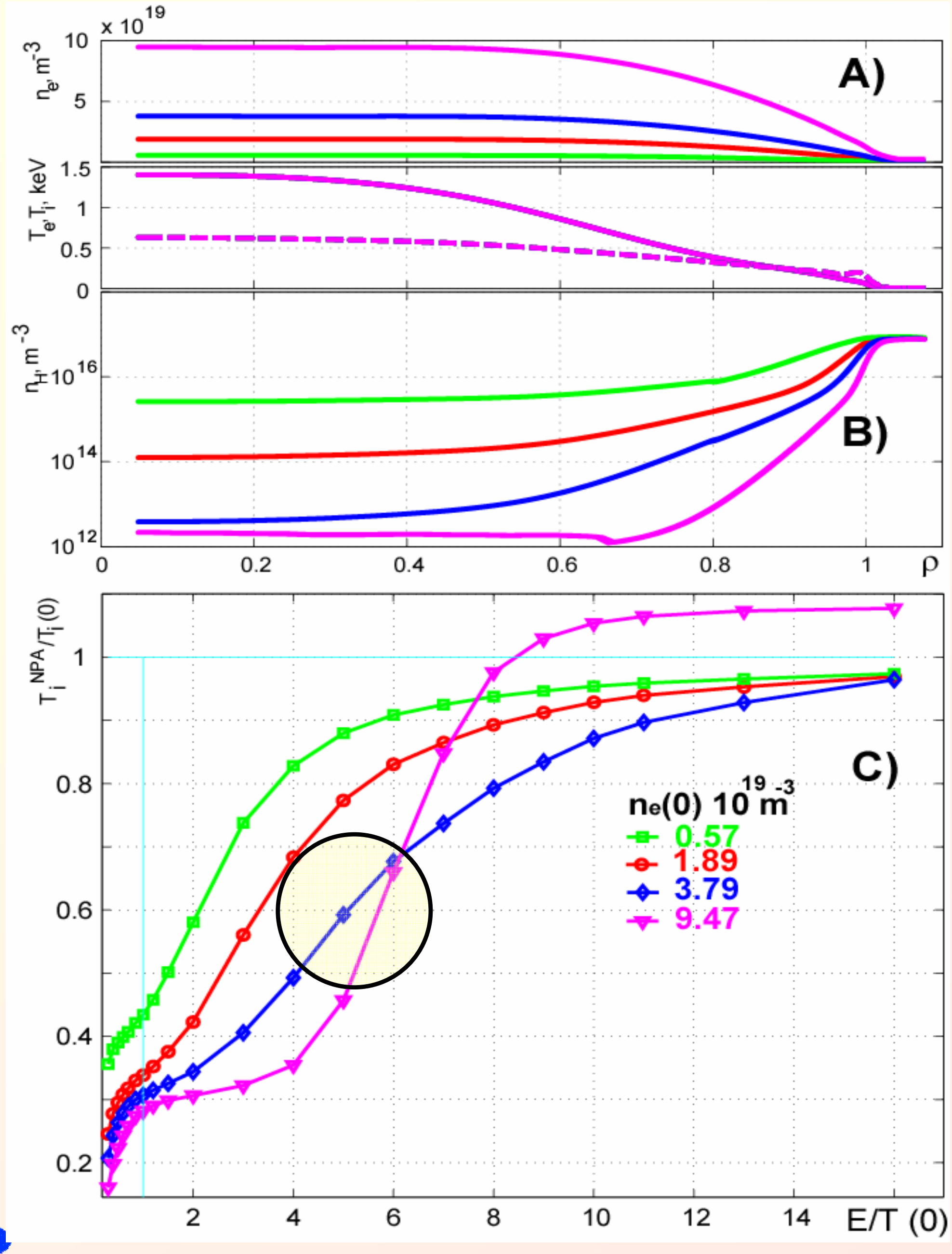
Quasi-Stationary ELMy H-mode with X3 ECH (#33654)

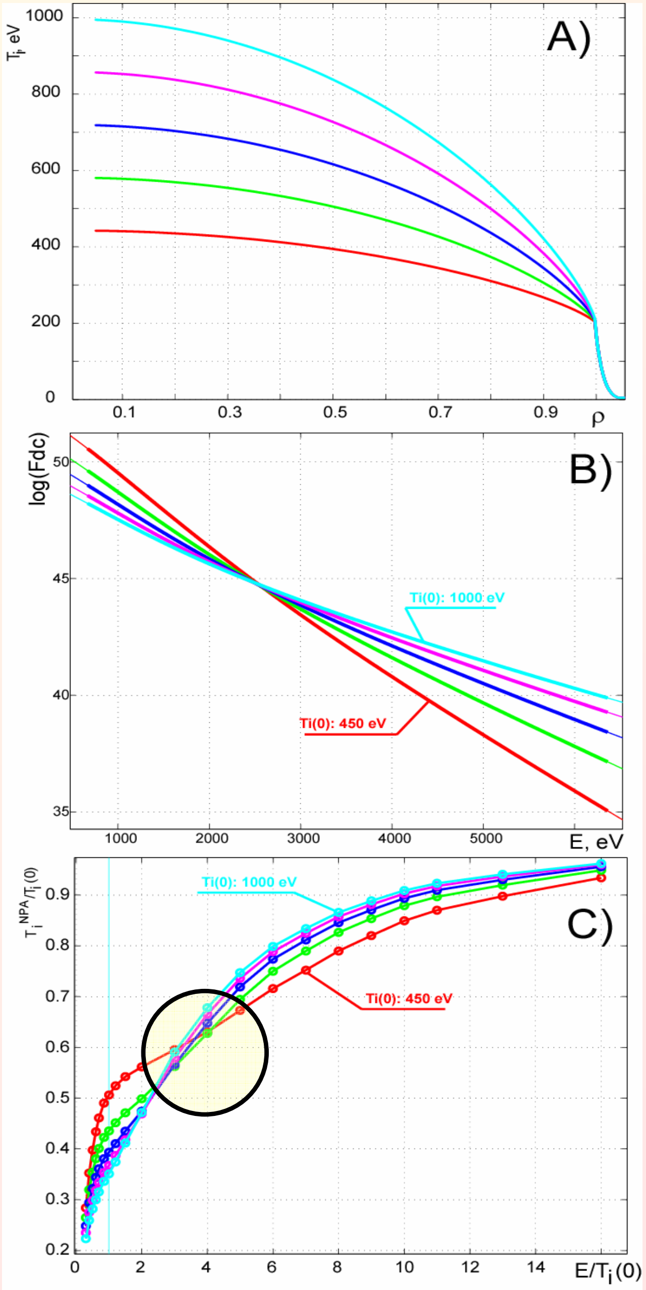
Q(0): oscillations around 1

Raxis: +0.5...+1.0 cm

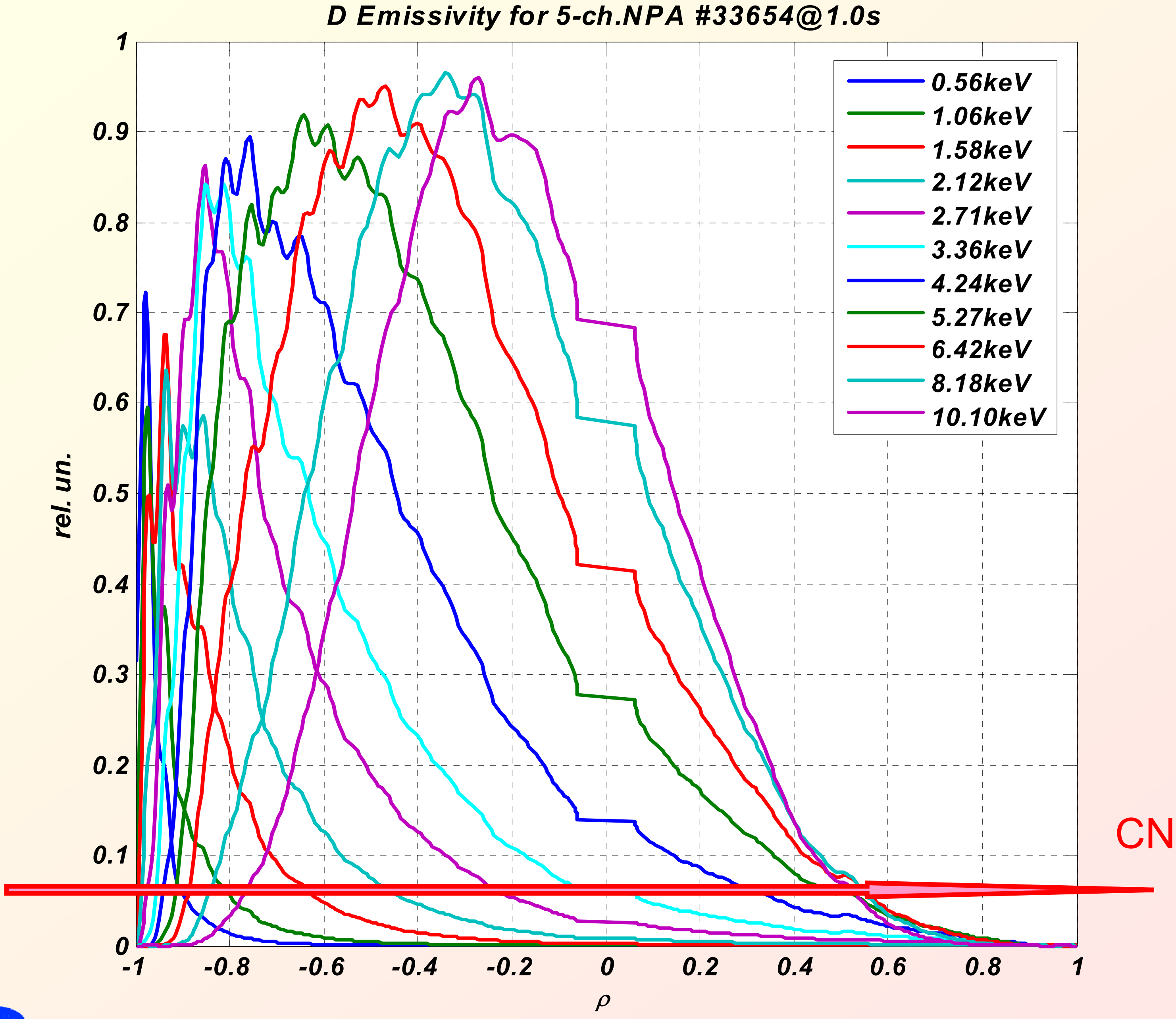
Zaxis: -0.4...-1.0 cm

From: Karpushov A.N., Duval B.P., LaBombard B., "Recovery of Ion Parameters from NPA Measurements on TCV", 31st EPS Conference on Plasma Phys. London, 28 June - 2 July 2004 ECA Vol.28G, P-2.152 (2004)



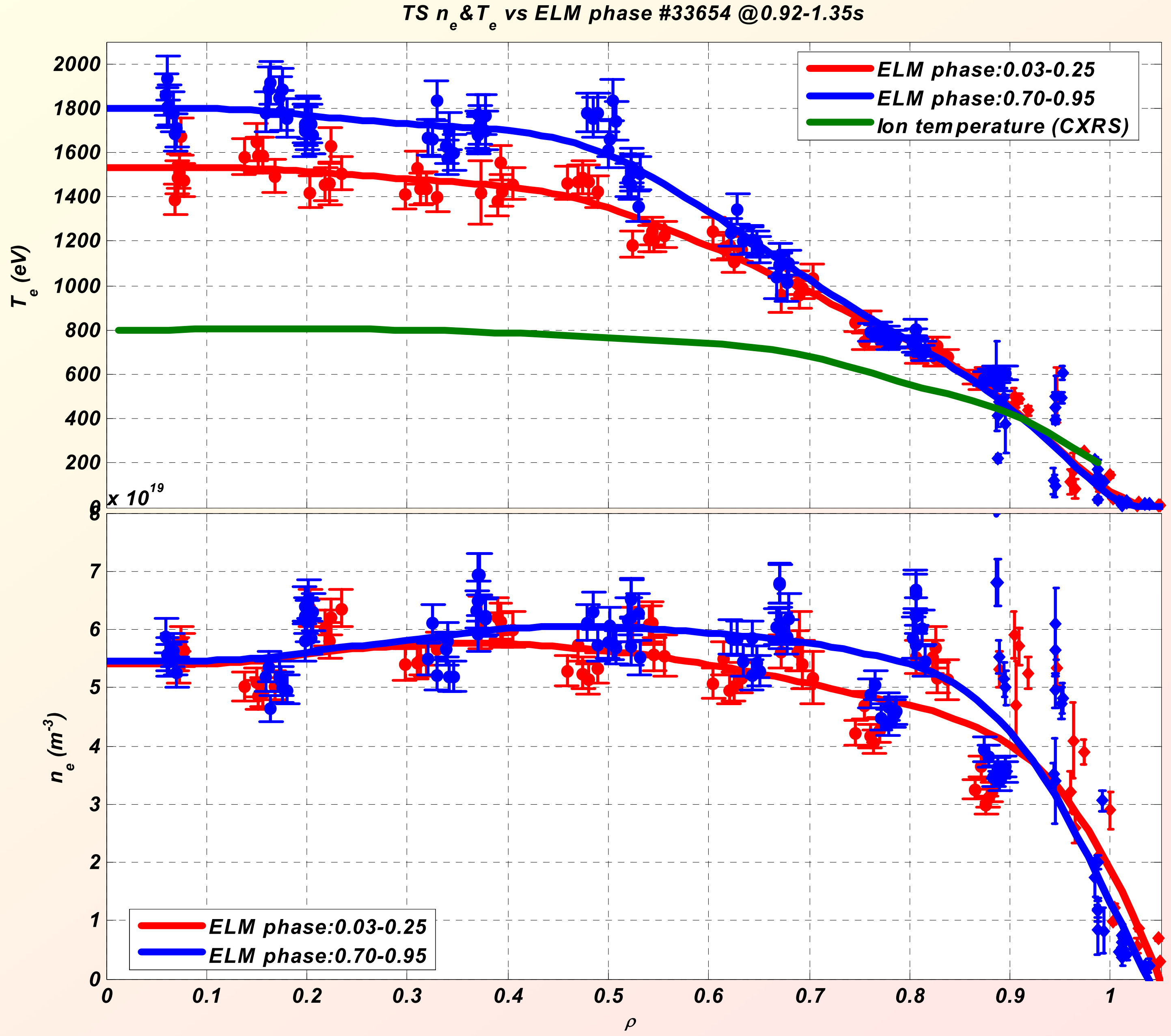


Emissivity function $n_a \cdot n_i \cdot f_i(E) \cdot \langle \sigma_{cx}(v_{ia}) \cdot v_{ia} \rangle \cdot \gamma$

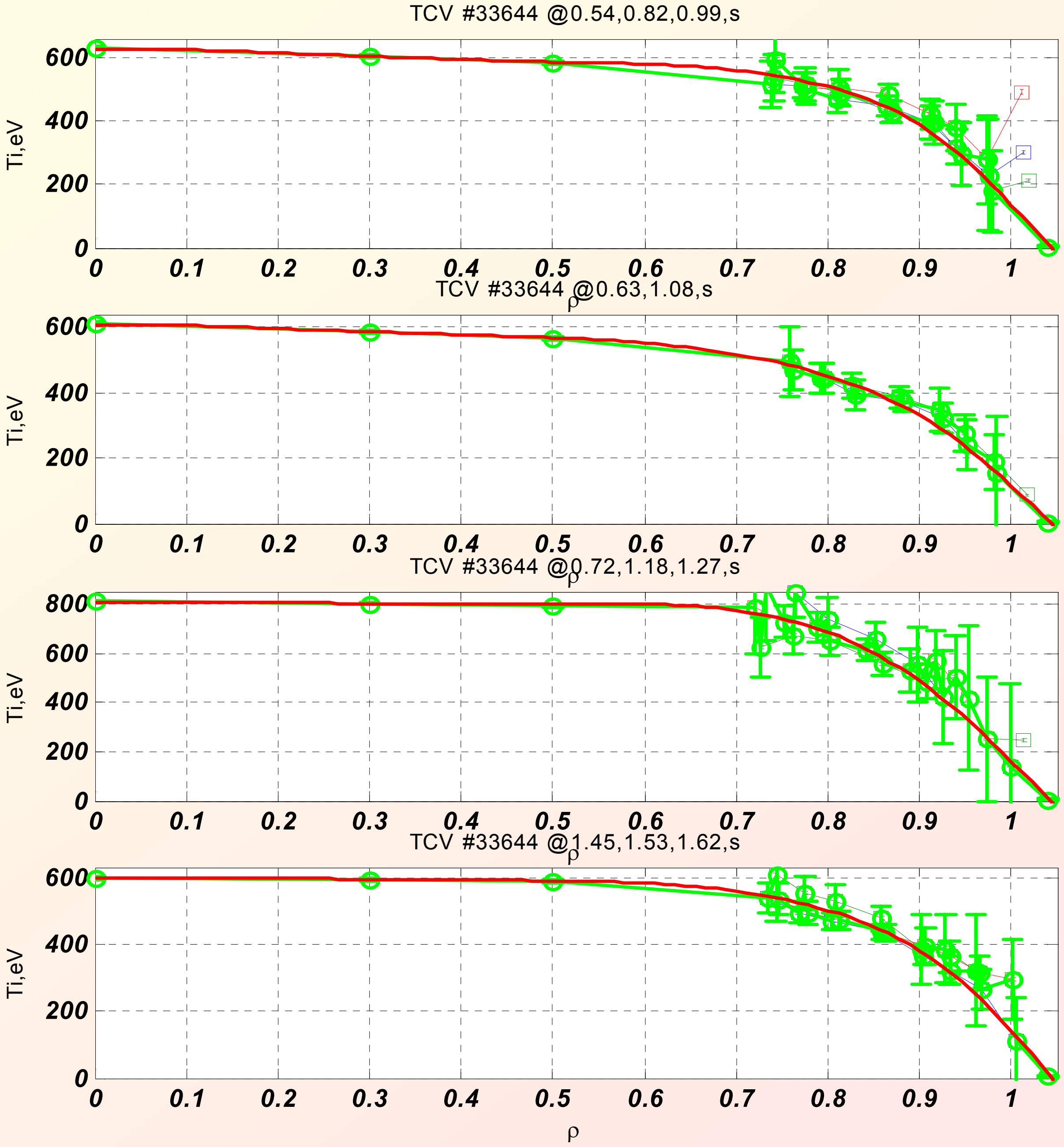


CNPA view-line

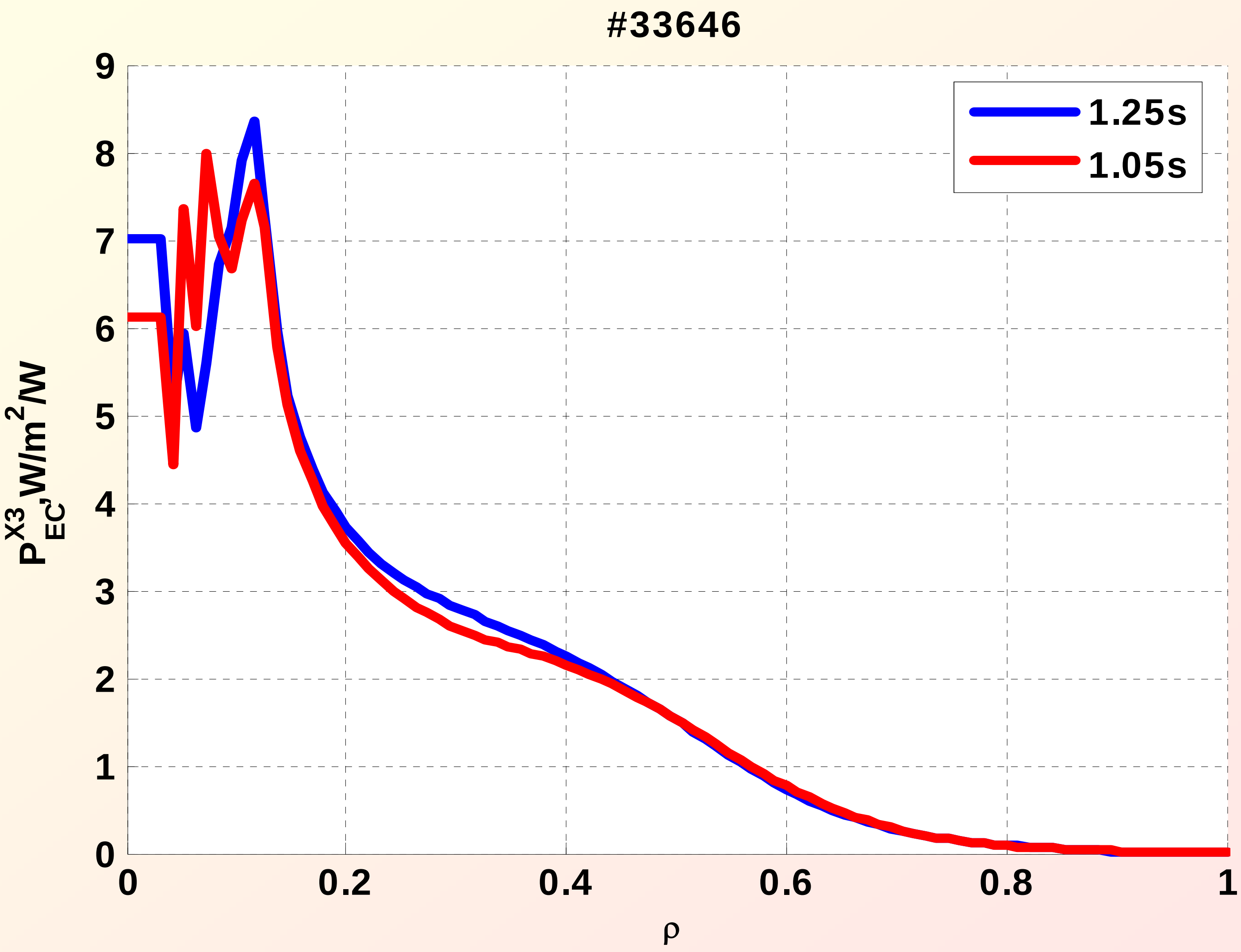
Electron density, electron and ion temperature profiles



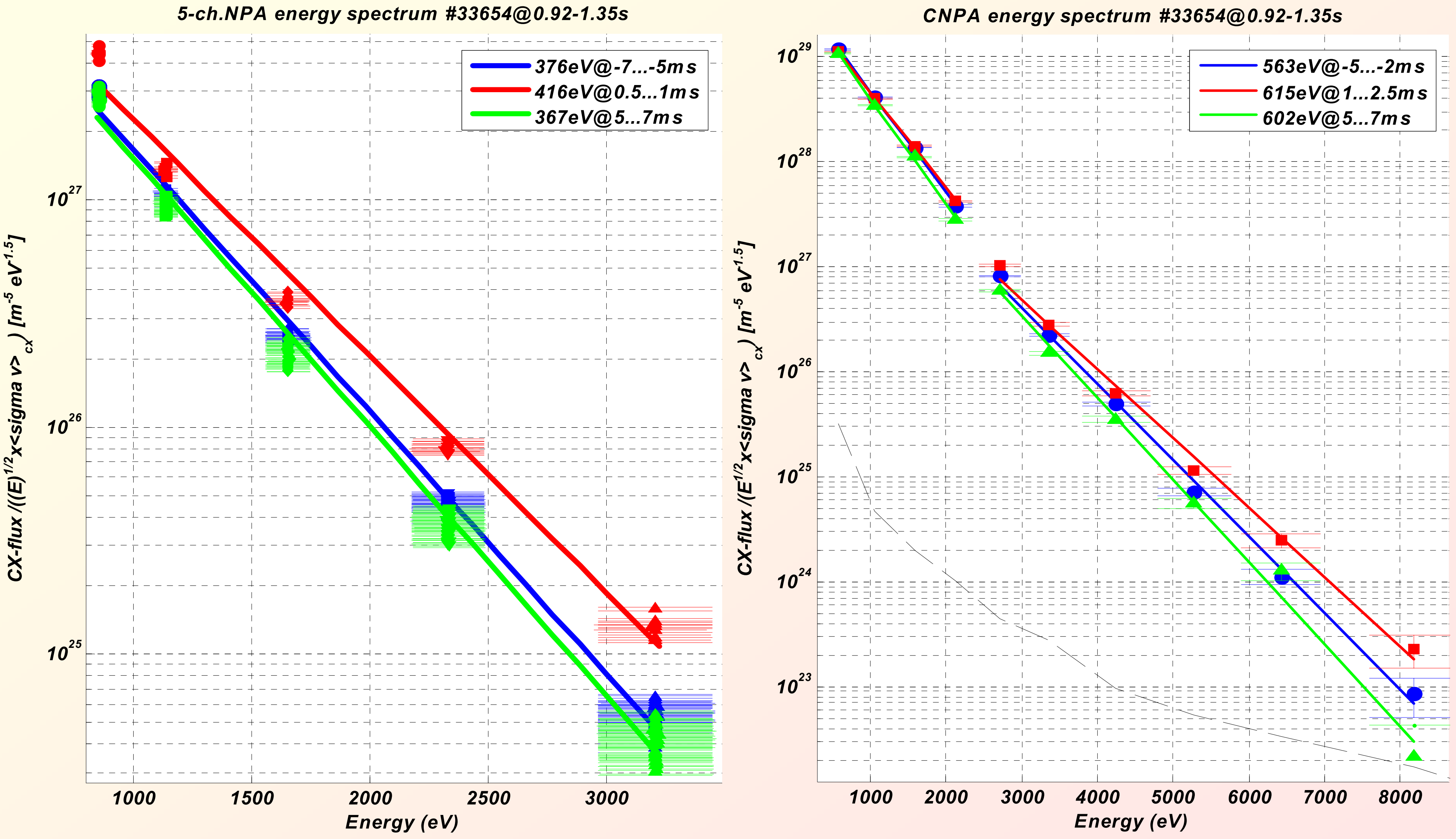
T_i^{CXRS} profiles



X3 Power Deposition



“NPA CX-spectra” (5-ch.NPA & CNPA)



References

TCV:

- F. Hofmann et al., Plasma Phys. Controlled Fusion 36, B277-B287 (1994).
- T. Goodman et al., Nucl. Fusion 43, 1619-1631 (2003).

ELMs and H-mode on the TCV:

- A.W. Degeling, et al., Plasma Phys. Control. Fusion 43, 1671-1698 (2001)
- Y.R. Martin, L. Porte and S. Alberti, Plasma Phys. Control. Fusion 48, A163-A169 (2006)
- L. Porte and the TCV Team, "Vertical Launch Third Harmonic Electron Cyclotron Resonance Heating of H-mode on TCV and Access to Quasi-Stationary ELM-free H-mode", Proc. of 17th Topical Conference on Radio Frequency Power in Plasmas, 07-09 May 2007, Clearwater, Florida, USA (will be published in ConferenceProceedings of the American Institute of Physics)

Thomson scattering (TCV):

- R.Behn, et al., “Edge profiles of electron temperature and density during ELMy H-mode in ohmically heated TCV plasmas”, Plasma Phys. Control. Fusion 49, (accepted for publication July 2007)

NPAs on the TCV:

- A.N. Karpushov, et al., Rev. Sci. Instrum 77, 033504 (2006)
- Ch. Schlatter, B.P. Duval and A.N. Karpushov, Plasma Phys. Control. Fusion 48, 1765–1785(2006)

CXRS on the TCV:

- P. Bosshard, et al., "Ion Temperature Behaviour and Ion Contribution to the Power Balance Measured by CXRS in Ohmic and ECR Heated Plasmas on TCV" , Proc. 29th EPS Conference on Controlled Fusion and Plasma Physics, Montreux, Switzerland, June 2002, ECA Vol. 26B, P-4.120 (2002)

Coherent averaging (TEXTOR):

- H.F. Tammen, et.al., Rev. Sci. Instrum 66(1), 327-329 (1995)