Preliminary analysis of central fast ion f_i, n_i, $T_{i\perp}$ inferred from the CX spectrum measured with the high energy NPA KF-1 for JET discharges with Tornado modes

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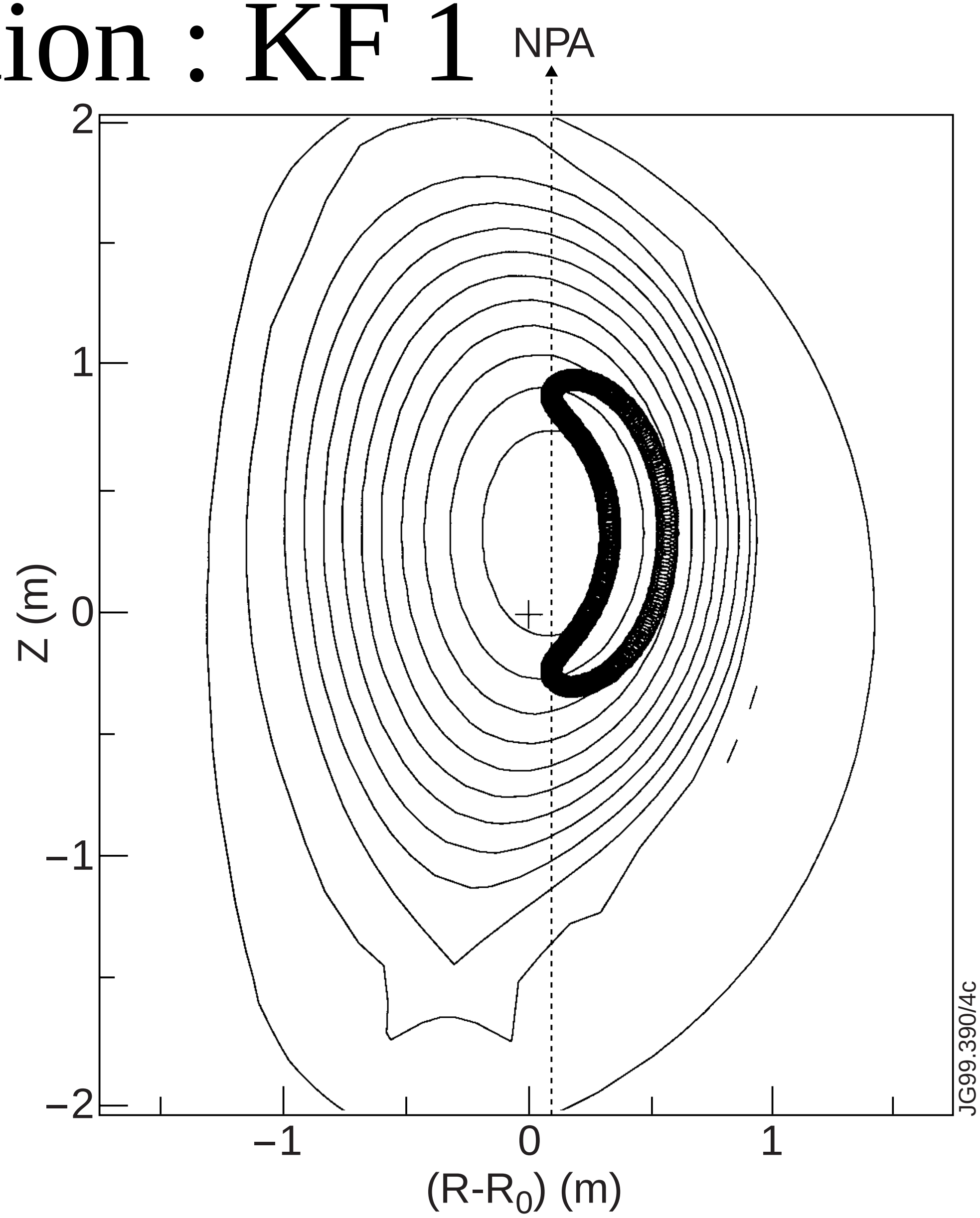
Introduction : KF 1

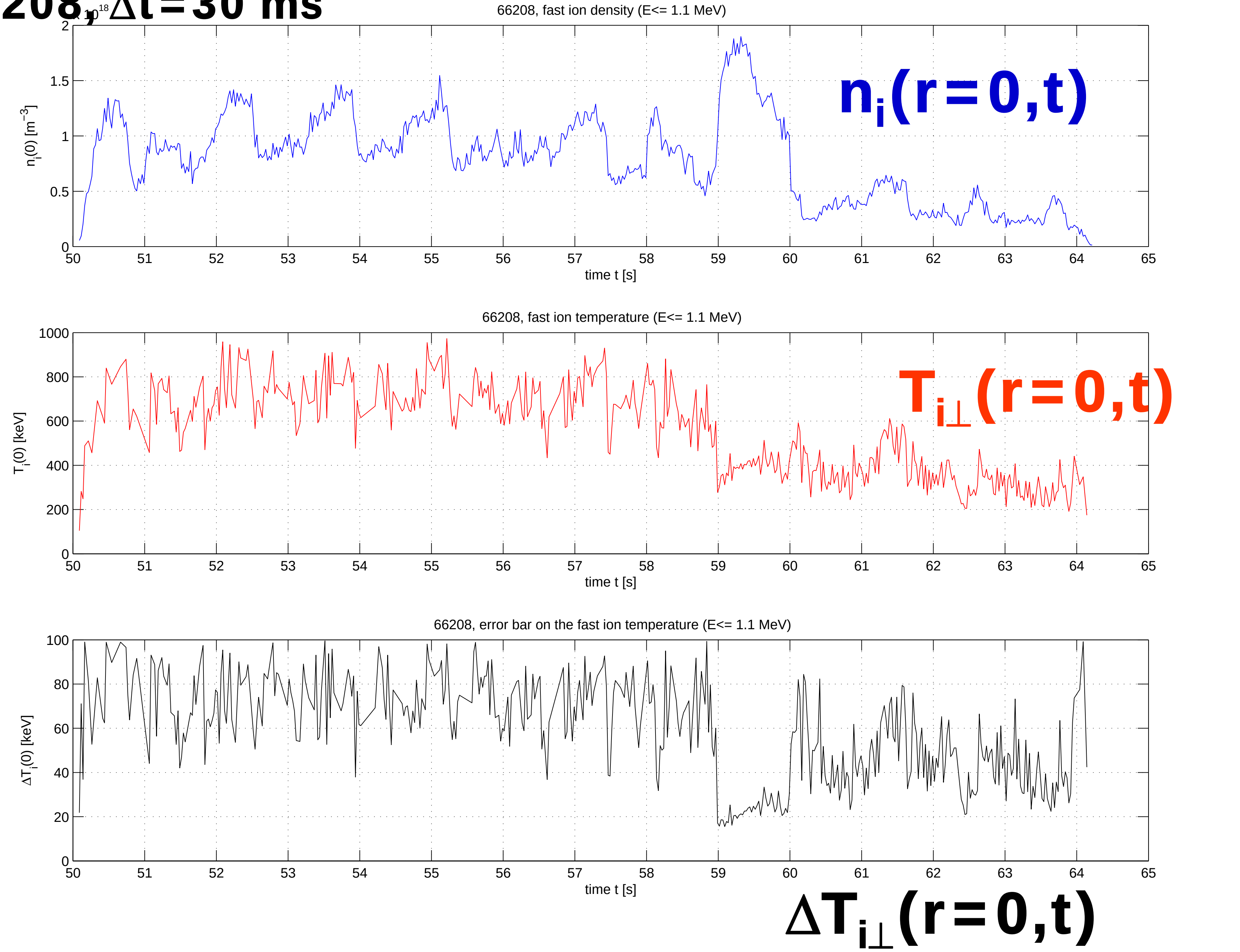
- High energy NPA, neutral flux measurement of hydrogen or helium species up to 4 MeV.
- Vertical line of sight, oct.4, R = 3.07 m
- Information on fast ion $f_{iFAST}(E)$, $T_{iFAST\perp}$ and n_{iFAST}



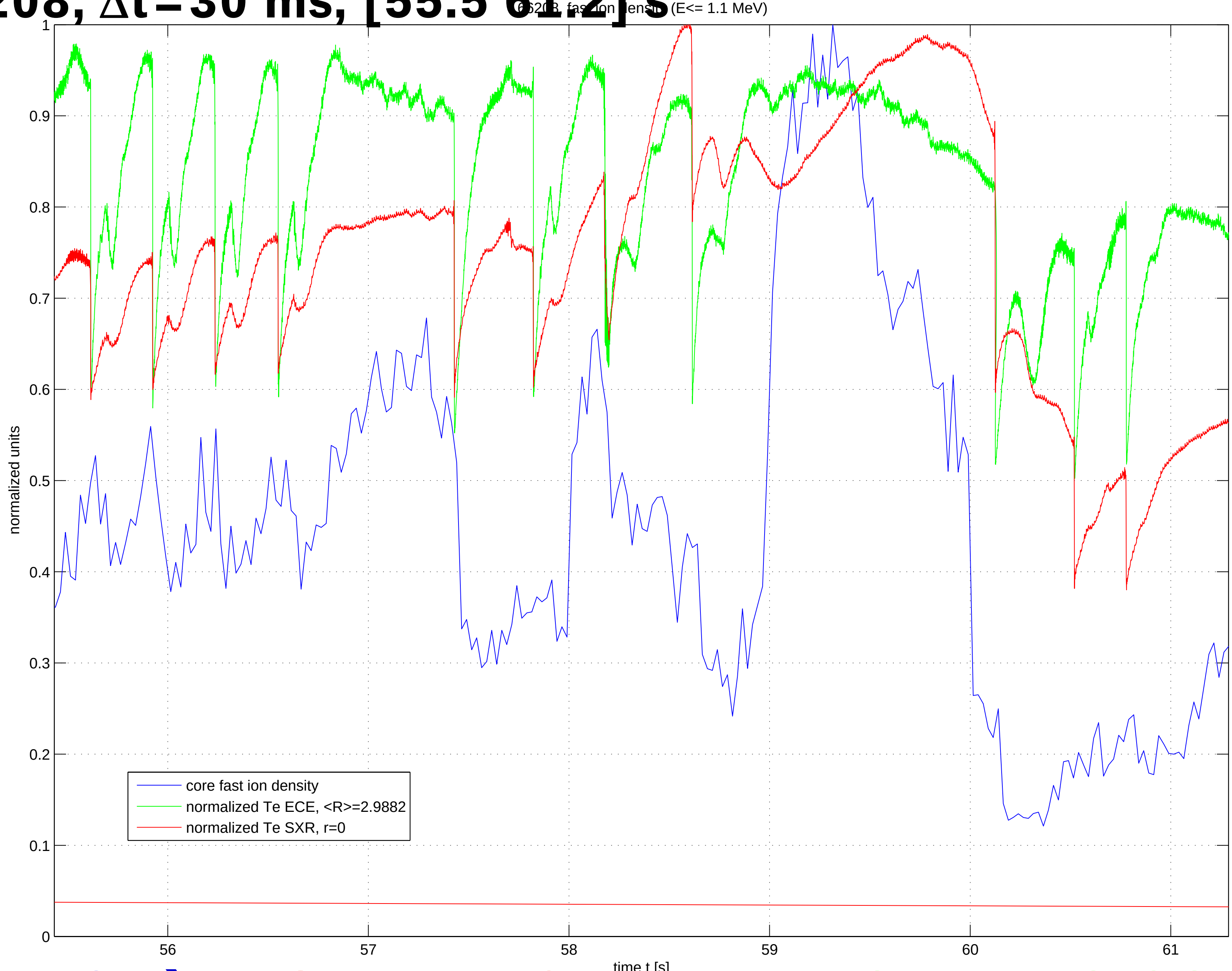
NPA data for Tornado mode session

- Hydrogen setup, measurement range 300..1100 keV
- Measurements for discharges 66204 onwards (gate valve didn‘t open for earlier shots)
- Sawteeth are clearly seen on the CX flux
- Raw analysis (calculation of f_i, n_i, T_i) with time resolution $\Delta t = 30$ ms done for 66207-66209
- Advanced analysis possible with $\Delta t \sim 5$ ms for f_i, n_i, T_i: (double the KF-1 acquisition time)

66208, Δt=30 ms

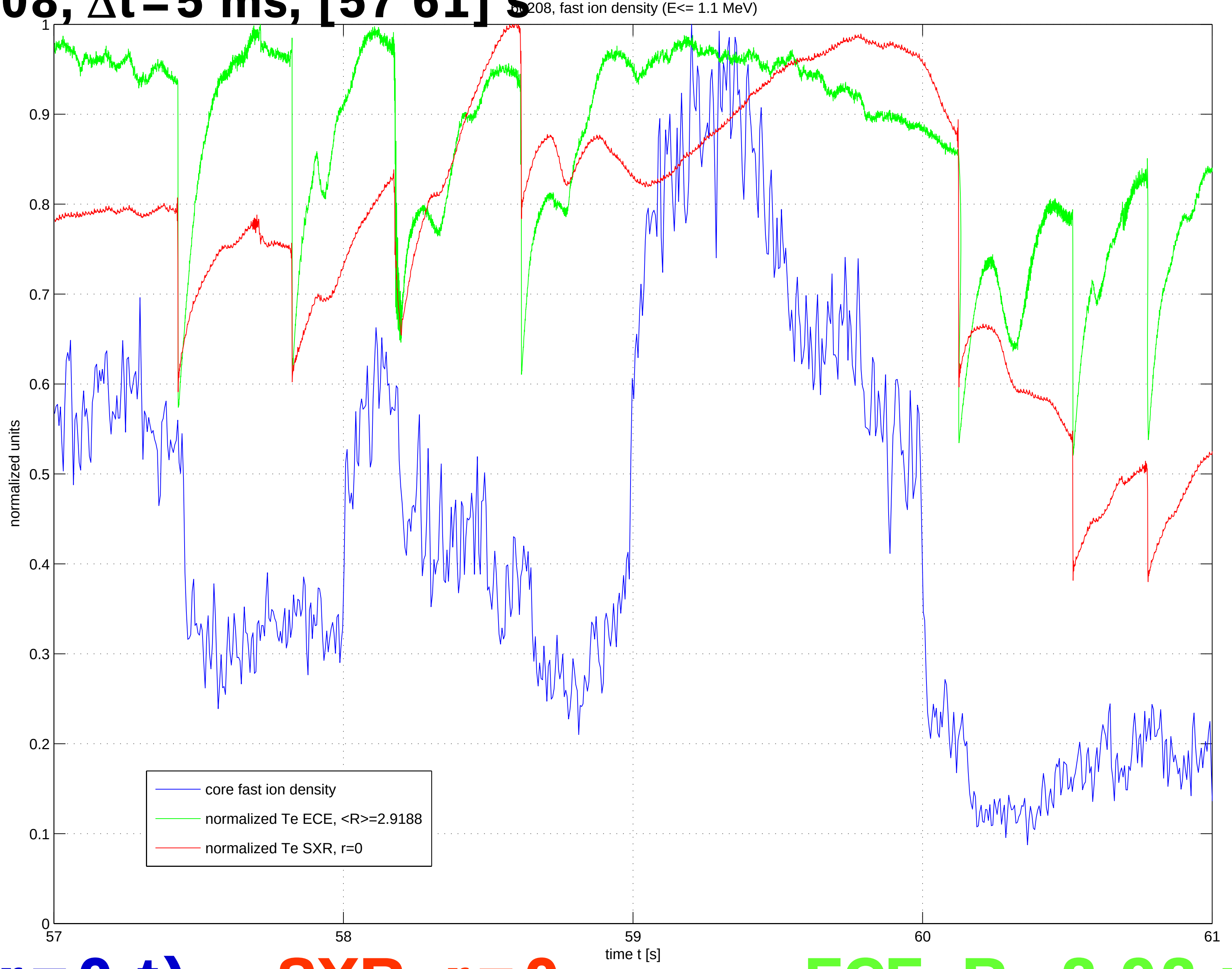


66208, Δt=30 ms, [55.5 61.2] s



$n_i(r=0,t)$ SXR, r=0 ECE, R~2.92 m

66208, Δt=5 ms, [57 61] s



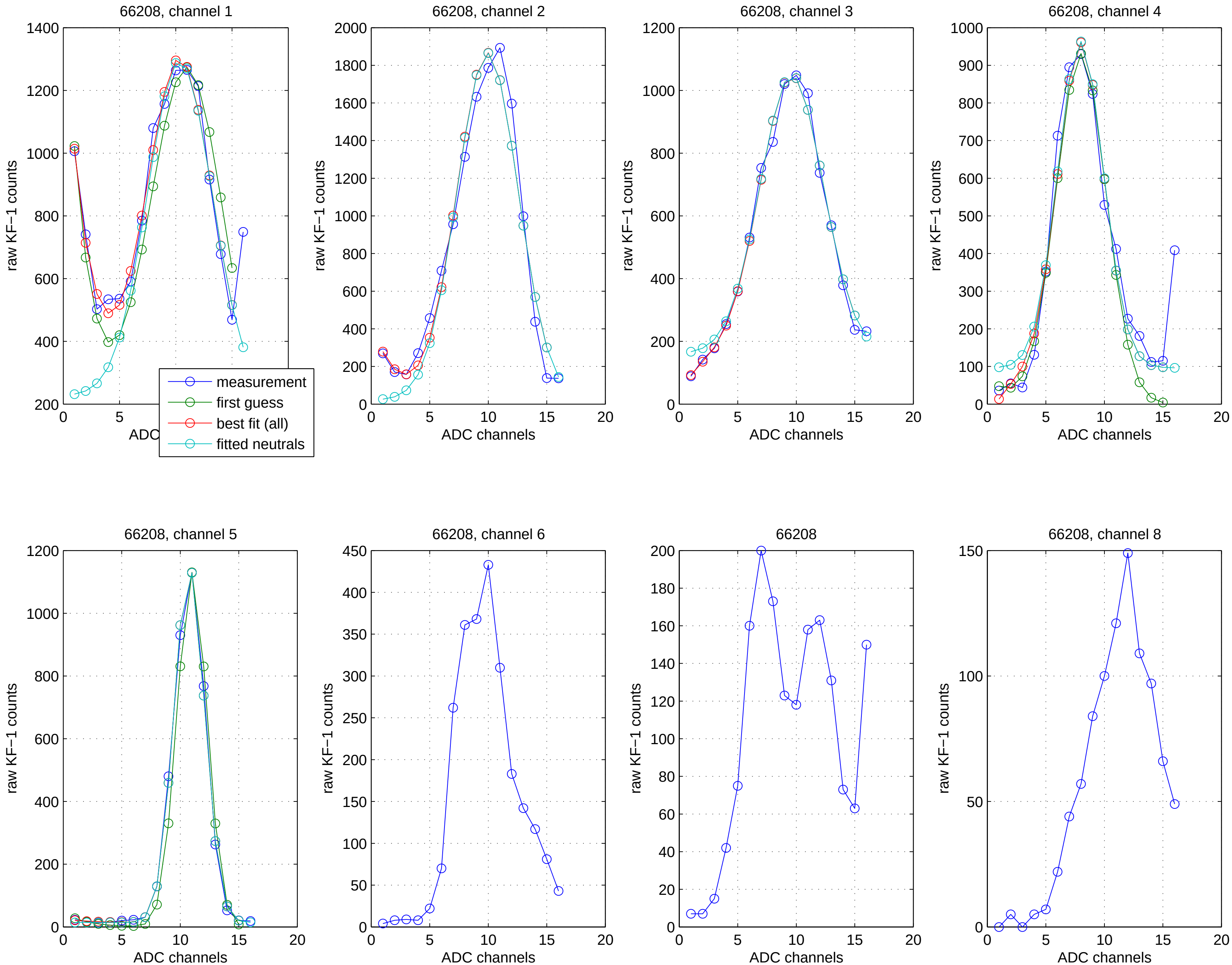
$n_i(r=0,t)$ SXR, r=0 ECE, R~2.92 m

Appendixes

- NPA measurement
- Neutron signal suppression
- IIN neutralization code (ion distribution function)
- Fast ion density (integration of fi)
- Inference of Ti (negative inverse of slope of fi)

Appendix: Fast ion dist. function $f_i(E)$

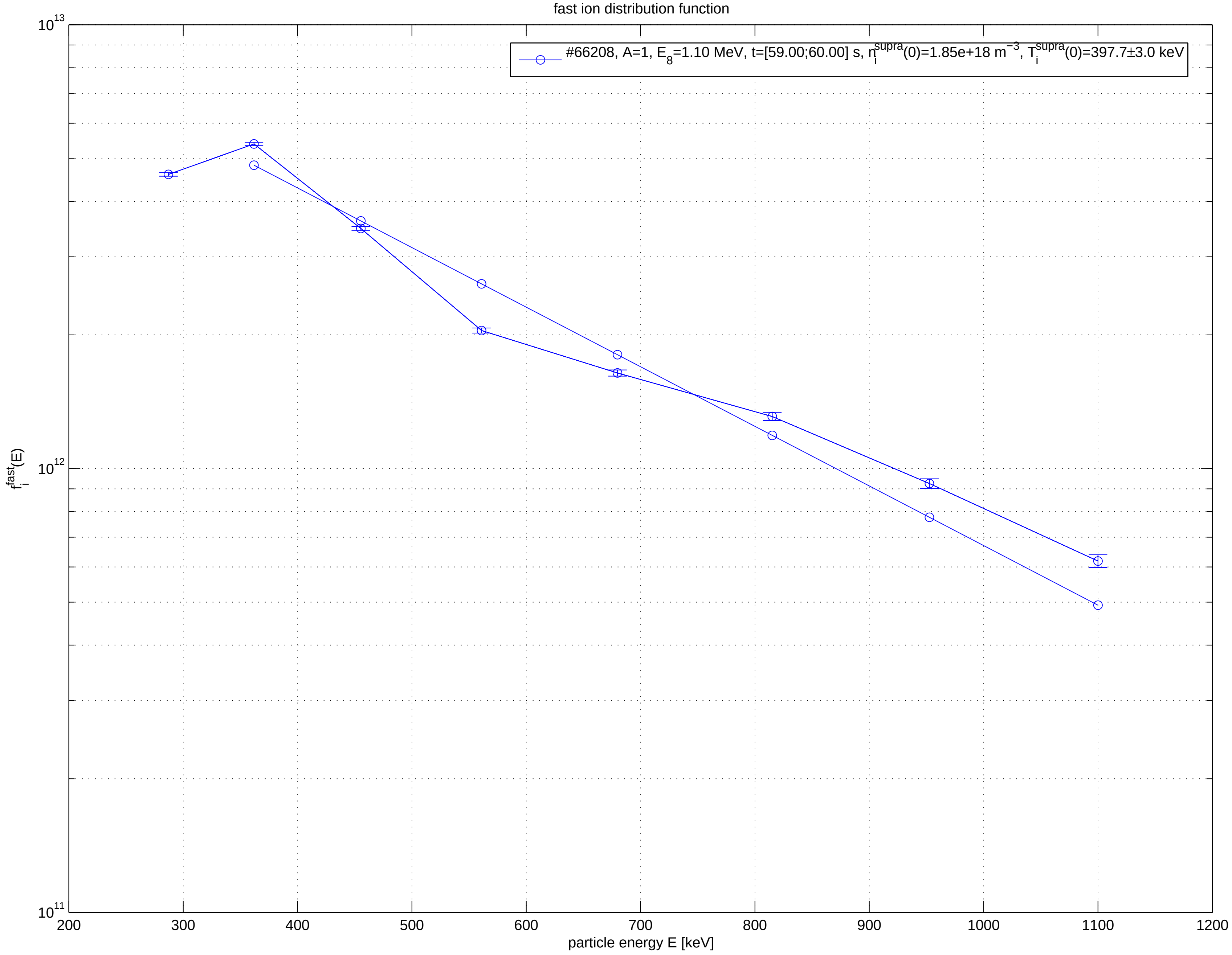
- $\mathbf{N(E) = (\Omega S) \cdot \Delta E \cdot \mu(E) \cdot \gamma(E) \cdot P_\upsilon(E) \cdot f_i(E)}$
- N(E): neutral count rate
- $f_i(E)$: fast ion distribution function
- $P_\upsilon(E)$: neutralization probability
- $\gamma(E)$: plasma transparency (re-ionization probability)
- ΔE: energy width of the detector
- $\mu(E)$: detection efficiency
- (ΩS): etendue of the detector



66208, channel 1
66208, channel 2
66208, channel 3
66208, channel 4
66208, channel 5
66208, channel 6
66208
66208, channel 8
raw KF−1 counts
ADC channels
measurement
first guess
best fit (all)
fitted neutrals

Appendix: Neutralization probability $P_{\upsilon}(E)$

- **I**mpurity **I**nduced **N**eutralization model (IIN)
  A.A.Korotkov et al., NF **37** (1997) 35.
- system of steady-state ion density balance equations for **bare**, **[H]-** and **[He]**-like impurities.
- RR with electrons, CX with impurities, thermal deuterium and NBI atoms.
- $P_{\upsilon}(E) = \sum_q \langle \sigma \upsilon \rangle_{CX_q / RR_q} \cdot n_q$
- Input parameters: impurity (He, Be, C) density ratios and confinement times, T_i, n_e, $n_{D,thermal}$, Z_{eff}



fast ion distribution function
#66208, A=1, E_8=1.10 MeV, t=[59.00;60.00] s, $n_i^{supra}(0)$=1.85e+18 m^{-3}, $T_i^{supra}(0)$=397.7±3.0 keV
10^{13}
10^{12}
10^{11}
$f_i^{fast}(E)$
200
300
400
500
600
700
800
900
1000
1100
1200
particle energy E [keV]

Appendix: Fast ion perp. temperature $T_{i\perp}$

- Distribution function of ICRF heated ions (*Stix, NF 15 (1975) 737*)

$$\bar{f}_i(E) \propto \frac{\sqrt{E}}{\bar{T}_\perp} \exp\left(-\frac{E}{\bar{T}_\perp}\right)$$

- inferred temperature

$$\frac{\partial}{\partial E} \ln \frac{\bar{f}_i(E)}{\sqrt{E}} = -\frac{1}{\bar{T}_\perp}$$

- Central perpendicular temperature
McClements et al, NF 37 (1997) 4

$$T_\perp(0) \cong \bar{T}(E^*)_\perp \left(1 + \frac{\bar{T}_\perp(E^*)}{2E^*}\right)$$

Appendix: Fast ion density n_i

- NPA:

$$n_i^{fast} = \frac{1}{E_{\max} - E_{\min}} \int_{E_{\min}}^{E_{\max}} f_i(E) \cdot dE$$

- Spectroscopy:

$$\alpha = \frac{H_\alpha}{H_\alpha + D_\alpha + T_\alpha} \propto \frac{n_H}{n_H + n_D + n_T}, \qquad n_D = n_e$$

$$n_i^{fast} = \frac{\alpha}{1-\alpha} n_e$$

- Fast particle energy measurement (NF33(1993)7)

$$W_{fast} = 4\pi^2 R_0 \int_0^a r \cdot \kappa(r) \cdot n_i^{fast}(r) \cdot \left[T_\perp + \frac{1}{2} T_\parallel \right] \cdot dr = \frac{4}{3}\left(W_{DIA} - W_{MHD}\right)$$

Assuming Gaussian density and temperature profiles

Appendix: error bars?

- $$\frac{\Delta f}{f} \approx \sqrt{\left(\frac{\Delta P_\upsilon}{P_\upsilon}\right)^2 + \left(\frac{\Delta \gamma}{\gamma}\right)^2 + \left(\frac{\Delta \mu}{\mu}\right)^2 + \left(\frac{\Delta N}{N}\right)^2} =$$
$$\sqrt{0.45^2 + 0.15^2 + 0.1^2 + 0.05^2} \approx 50\% \approx \frac{\Delta n}{n}$$
- The main source of uncertainties is the [H] electron donor density in the plasma core
- This can be improved by a better analysis of the input parameters
- $$\frac{\Delta T_\perp}{T_\perp} \approx 2 \cdot 10^{-3} \frac{\Delta \sigma_{CX}}{\sigma_{CX}} T_\perp \approx 10\%$$
- Main source: calculated C^5-ions CX-cross-section (20 %)
- NF 37 (1997) 35, NF 40 (2000) 975