Error estimation and parameter dependence of the calculation of the fast ion distribution function, temperature and density using data from the KF1 high energy NPA on JET

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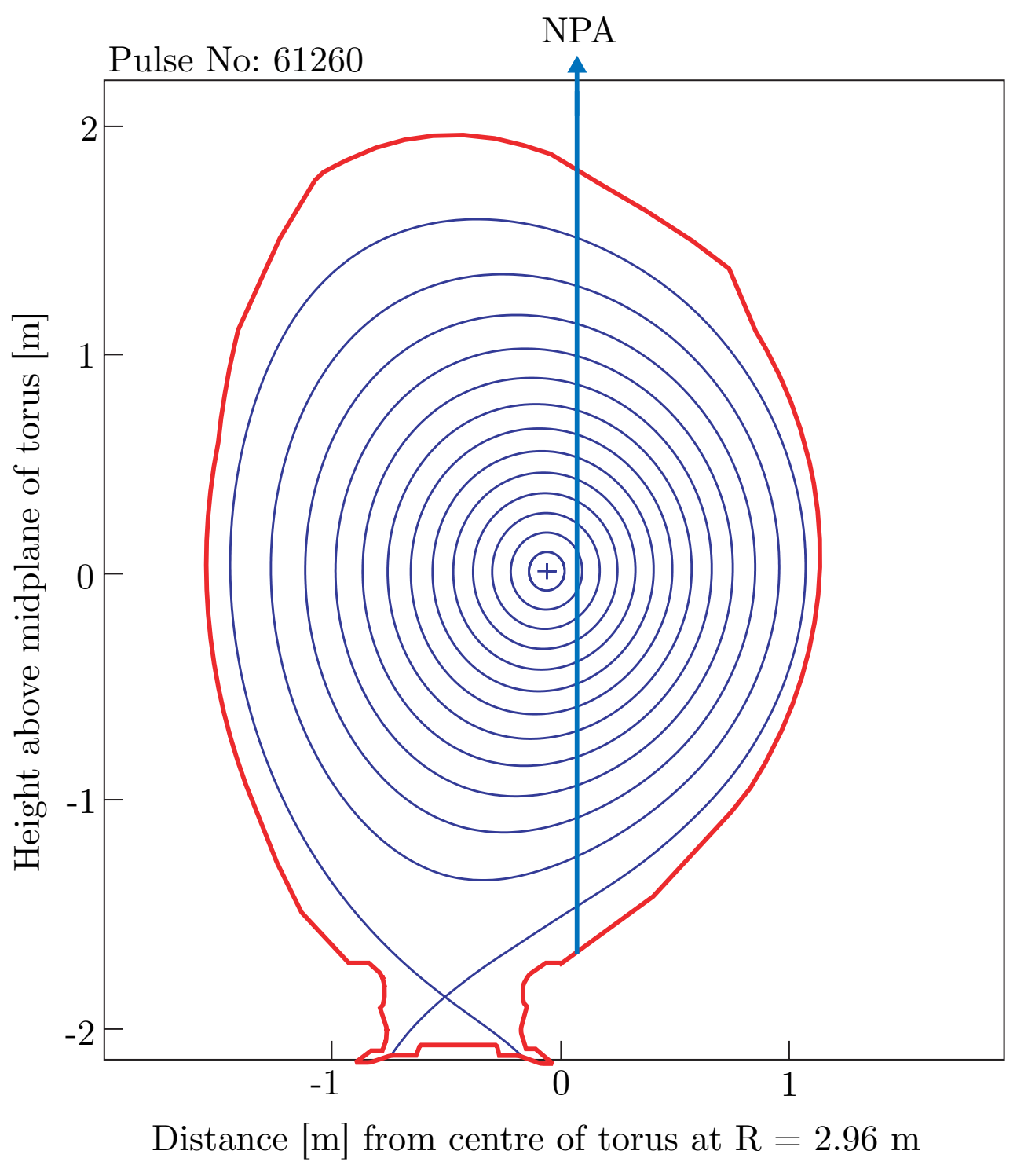
High energy NPA KF1

- high energy neutral particle analyzer (NPA)
- fluxes of H, D, T, ^{3}He and ^{4}He
- energy range 200 keV to 4 MeV
- vertical line of sight from top to down in octant 4 at R = 3.07 m



Fast ion distribution function $f^{i}_{fast}(E)$

- only core ions have velocity vector pointing towards the detector
- neutralisation probability $P_\nu(E)$ calculated using the Impurity Induced Neutralisation model (IIN) [1]
- IIN includes *radiative recombination* with electrons, *charge exchange* reactions with impurities, thermal deuterium and NBI atoms
- IIN equates a system of steady-state ion density balance equations for bare, [H]-, and [He]-like impurities
- reabsorbation of the neutrals by the plasma: plasma transparency $\gamma(E)$
- detector properties: étendue (ΩS), NPA channel energy width ΔE and channel detection efficency μ(E).
- neutral counts in NPA channel j:

$$N_j = (\Omega S)\cdot \Delta E_j \mu_j(E)\gamma(E)P_\nu(E)f_i^{fast}(E)$$

Fast ion perpendicular temperature

- Stix's expression for ICRF heated ions [5]:

$$\overline{f_i^{fast}}(E) \sim \frac{\sqrt{E}}{\overline{T_{i\perp}^{fast}}}\exp\left(-\frac{E}{\overline{T_{i\perp}^{fast}}}\right)$$

- perpendicular fast ion temperature (line of sight integrated) inferred from the slope of the logarithm of the fast ion distribution function:

$$-\frac{1}{\overline{T_{i\perp}^{fast}}} = \frac{\partial}{\partial E}\ln\left(\frac{\overline{f_i^{fast}}(E)}{\sqrt{E}}\right)$$

- central fast ion perpendicular temperature [3], where E° is the median energy of the range of measurements

$$T_{i\perp}^{fast}(r=0) \cong \overline{T_{i\perp}^{fast}}(E°)\left(1+\frac{\overline{T_{i\perp}^{fast}}(E°)}{2E°}\right)$$

Fast ion density

- fast ion density by integrating the fast ion distribution function over the energy range of the measurement

$$\overline{n_i^{fast}} \cong \frac{1}{E_8 - E_1}\int_{E_1}^{E_8}\overline{f_i^{fast}}(E)$$

Error bars

- dominant uncertainty for f_i^{fast} and n_i^{fast} is the [H]-like electron donor density in the plasma core (45 % uncertainty in the neutralization probability)

$$\frac{\Delta f_i^{fast}}{f_i^{fast}} \approx \sqrt{\left(\frac{\Delta P_\nu}{P_\nu}\right)^2 + \left(\frac{\Delta\gamma}{\gamma}\right)^2 + \left(\frac{\Delta\mu}{\mu}\right)^2 + \left(\frac{\Delta N_i^{fast}}{N_i^{fast}}\right)^2} = 50\%$$

- main source of uncertainty on the fast ion temperature is the calculated ^{5}C-ions charge exchange cross-section (20 %)

$$\frac{\Delta T_{i\perp}^{fast}}{T_{i\perp}^{fast}} \approx 2\cdot 10^{-3}\frac{\Delta\sigma_{CX}}{\sigma_{CX}}T_{i\perp}^{fast} \approx 10\%$$

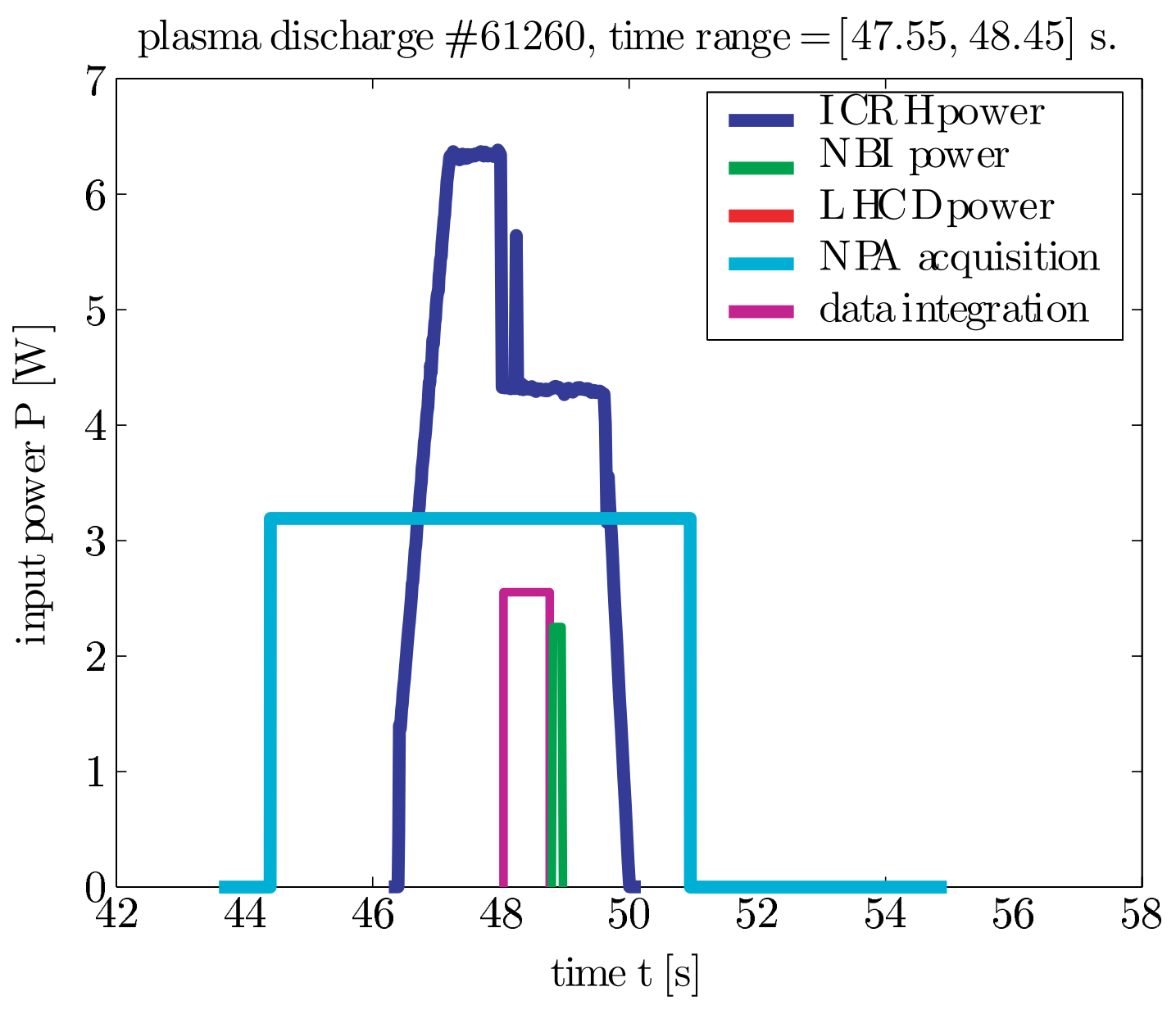
- *the error bar on the fast perpendicular ion temperature is fairly low*

Neutralization calculation input parameter analysis

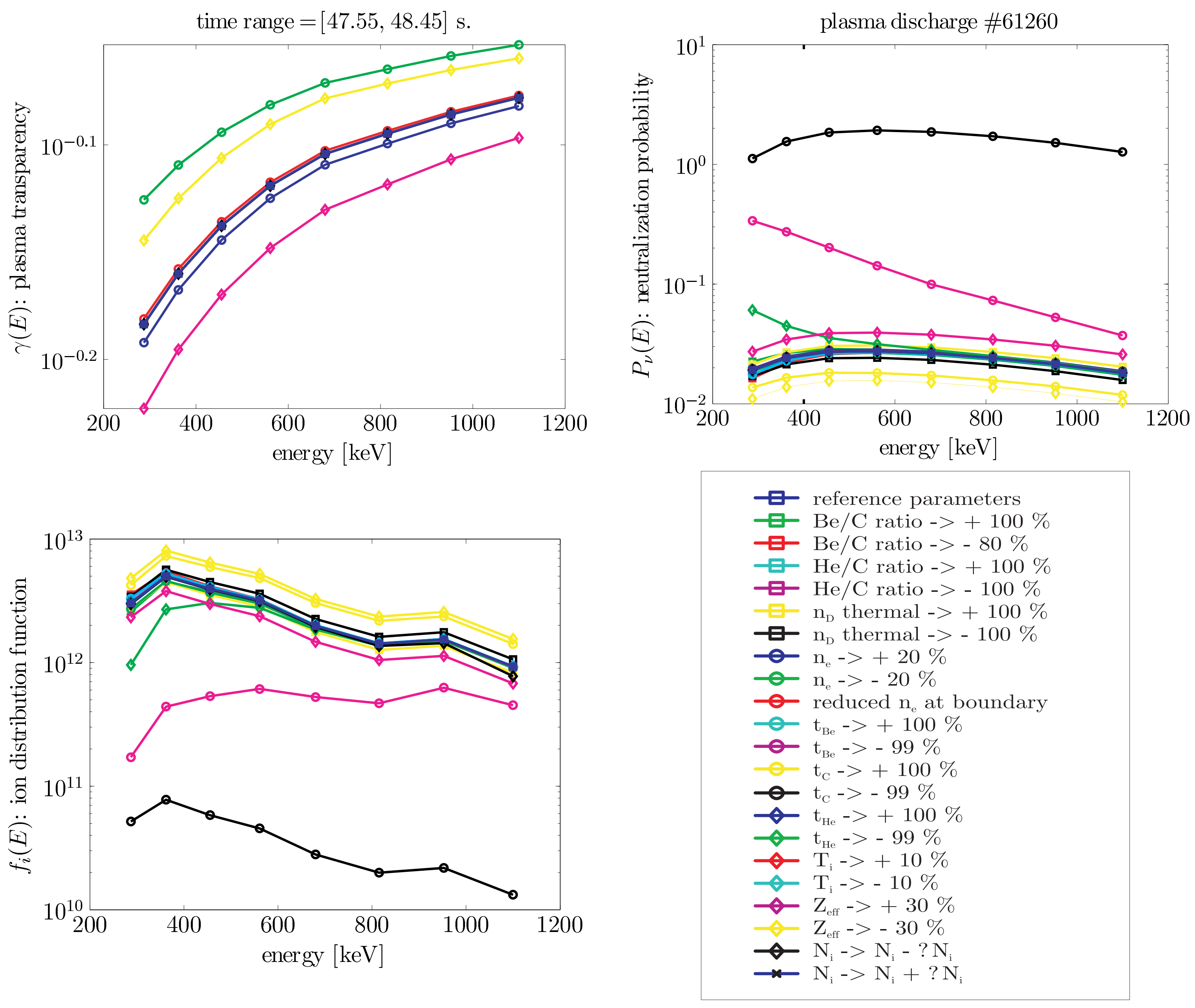
- What is the impact of uncertainties in the input parameters on f_i, n_i and T_i?
- Simulation with one input parameter modified at once, within its errorbar:
  - relative impurity concentrations Be/C and He/C ± 100 %
  - thermal deuterium density n_D ± 100 %
  - electron density n_e ± 20 %
  - empirical impurity confinement times τ_{Be}, τ_{He} and τ_C ± 100 %
  - ion temperature T_i ± 10 %
  - effective charge Z_{eff} ± 30 %
  - statistical Poisson error (< 5 % if possible) of the fast neutral counts N_i.

Test discharge 61260

- trace tritium campaign 2003
- H-minority ICRF heating at 1st harmonic.
- counts integrated over constant ICRF power interval, [47.55; 48.45] s
- B_T = 3.4 T, I_P = 1.8 MA,
- T_e = 7 keV, $n_e = 3\cdot 10^{-19}$ m^{-3}



Parameter scan



modified input parameter	ΔT_i [%]	Δn_i [%]
Be/C ratio -> + 100 %	5.6	-3.2
Be/C ratio -> - 80 %	-4.5	2.9
He/C ratio -> + 100 %	0.4	-0.1
He/C ratio -> - 100 %	-0.4	0.1
n_D thermal -> + 100 %	-0.6	-10.7
n_D thermal -> - 100 %	0.7	13.6
n_e -> + 20 %	-0.8	-1.7
n_e -> - 20 %	3.8	-5.2
reduced n_e at boundary	0.1	-0.4
τ_{Be} -> + 100 %	-2.4	2.3
τ_{Be} -> - 99 %	1630.9	-76.8
τ_C -> + 100 %	2.2	51.2
τ_C -> - 99 %	-4.0	-98.6
τ_{He} -> + 100 %	-0.2	0.1
τ_{He} -> - 99 %	39.5	-15.7
T_i -> + 10 %	0.0	-0.5
T_i -> - 10 %	0.1	0.6
Z_{eff} -> + 30 %	-2.0	-25.4
Z_{eff} -> - 30 %	2.0	64.4
N_i -> N_i - ΔN_i	-8.7	-2.9
N_i -> N_i + ΔN_i	8.7	2.9

- modification of most of the input parameters within their errorbars doesn't change the absolute value of the fast ion distribution function remarkably.
- Dramatic changes result when decreasing the impurity confinement times towards zero, but this makes physically not much sense (see later).
- Confinement of carbon (beryllium) change the neutralization probability and therefore f_i by 2 (1) order of magnitude.
- The modified shape of f_i by changing τ_{Be} or τ_{He} are due to the stronger energy dependence of the cross-sections for charge exchange [1].
- Z_{eff} affects neutralization and reionization, also seen in f_i
- inferred temperature T_i is - except for τ_{Be} or τ_C - very insensitive to the modified parameters, with changes below ± 10 %

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Impurity ion confinement in JET

- simple estimation of the ion confinement time τ from transport

$$\Gamma_Z = -Dn'_Z + \frac{r}{a} v n_Z$$

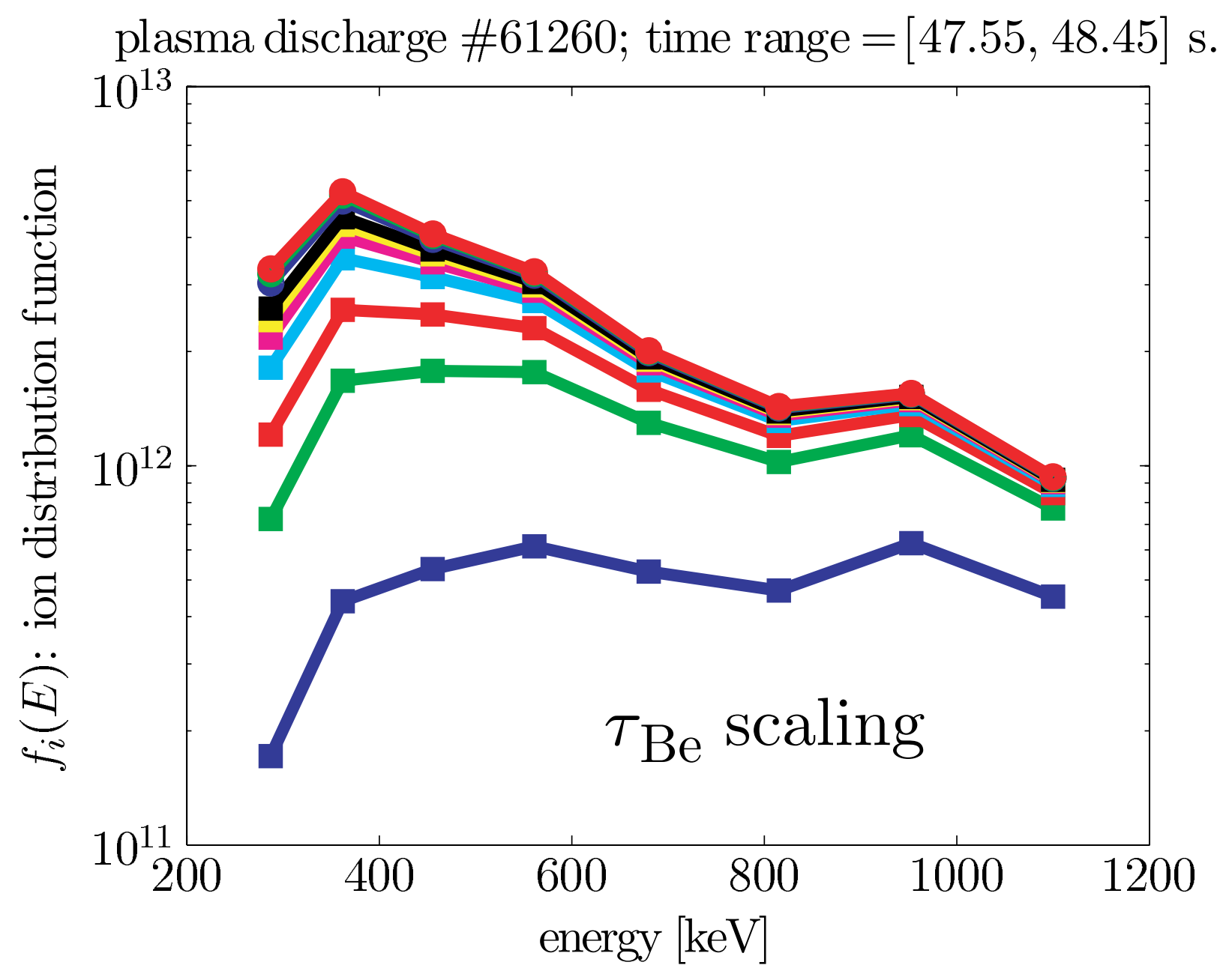
- for the impurity of atomic charge Z

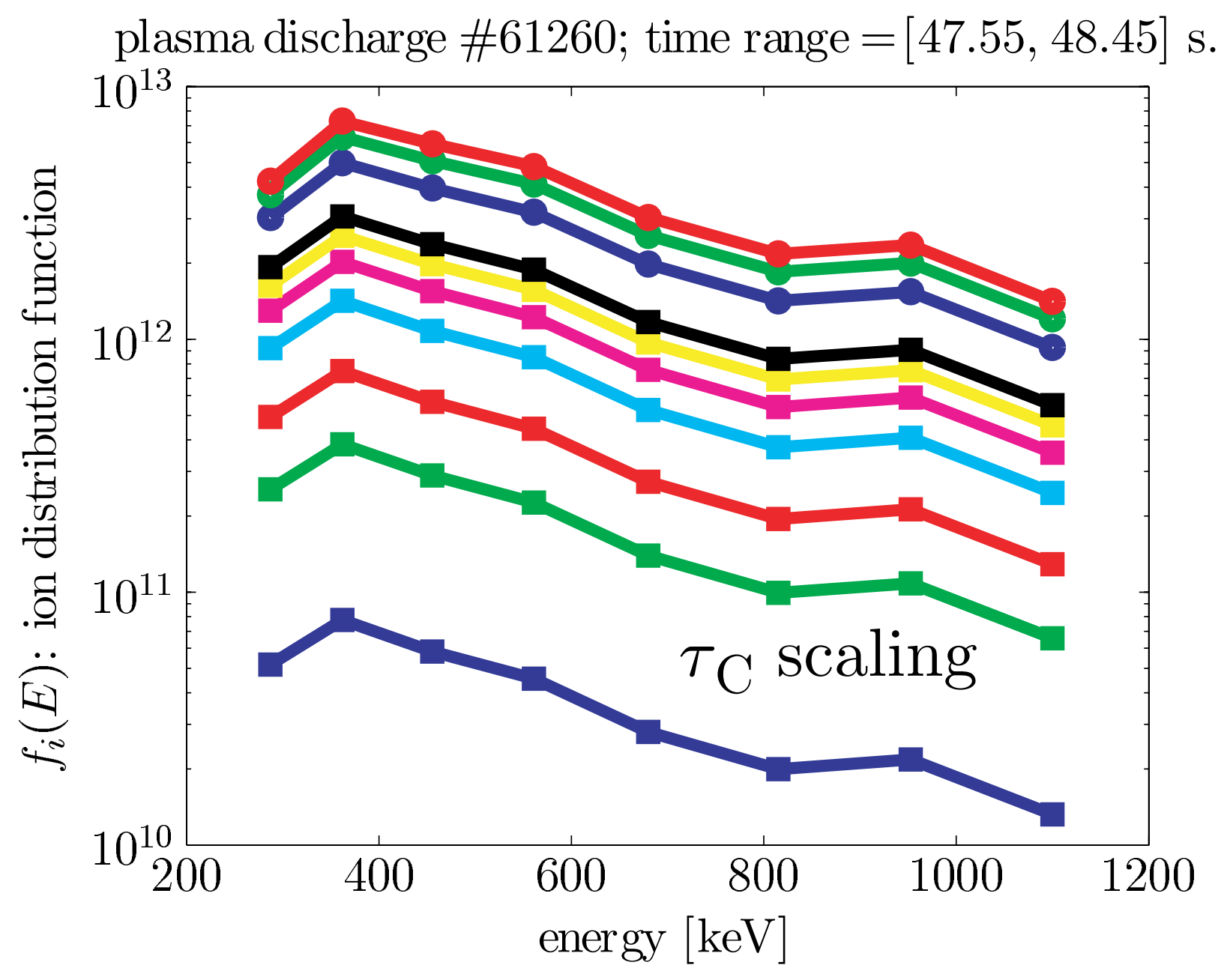
$$\tau_Z = \frac{n_Z}{\mathrm{div}\Gamma_Z}$$

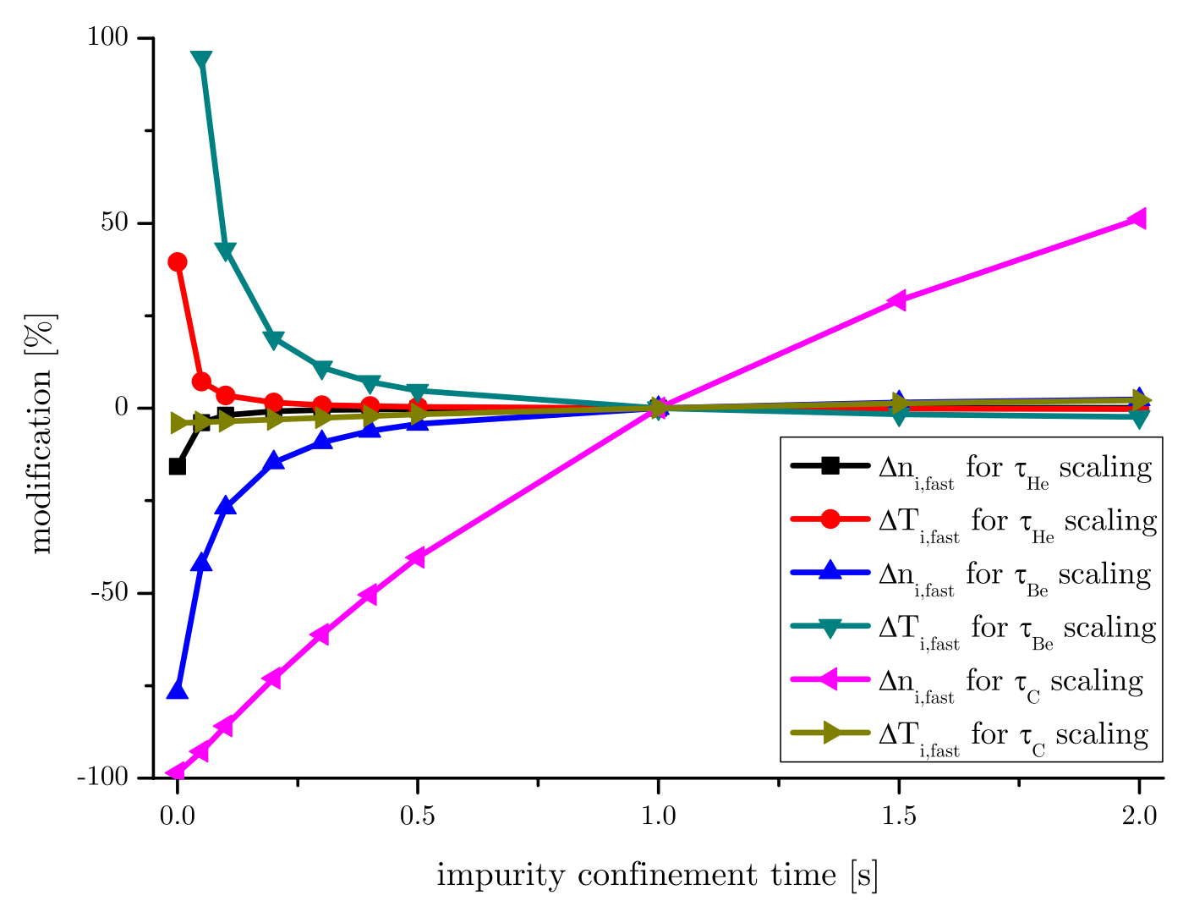
- for JET conditions $\tau_Z \approx 1$ s

Confinement time scaling

- scaling of $\tau = [0; 2]$ s for beryllium and carbon







■ $\tau = 0.00$ s
■ $\tau = 0.05$ s
■ $\tau = 0.10$ s
■ $\tau = 0.20$ s
■ $\tau = 0.30$ s
■ $\tau = 0.40$ s
■ $\tau = 0.50$ s
● $\tau = 1.00$ s
● $\tau = 1.50$ s
● $\tau = 2.00$ s

- Beryllium: around $\tau_{Be} \approx 1$ s the fast ion temperature and density do change only marginally.
- Carbon: no saturation of the absolute value of the fast ion distribution function around $\tau_C \approx 1$ s. A modification of τ_C by 50 % results in a change in density of about 30 %. Other than for He and Be, the cross-section for CX with background atoms is two orders of magnitude smaller at low energies and therefore the radial carbon transport characterized by τ_C more important in the calculation of the ionization balance
- However the fast ion temperature is not affected at all - due to the almost flat energy dependence of the CX-cross section for E < 1 MeV.

Alternative fast ion density measurements

- There are other methods to infer the fast ion density which gives the possibility for comparisons with the value obtained from the NPA.
- Spectroscopy measures the ratio of the emission line intensities of the hydrogenic species, i.e

$$\alpha = \frac{H_\alpha}{H_\alpha + D_\alpha + T_\alpha}$$

what, supposing $n_D \approx n_e$, is approximately

$$\alpha \approx \frac{n_H}{n_H + n_D + n_T}$$

therefore, for ICRF tuned to the hydrogen minority,

$$n_i^{fast} \approx \frac{\alpha}{1-\alpha}$$

with an uncertainty of about 30 %

- Another approach is given by the measurement of the fast particle energy, which is determined by [2]

$$W_{fast} = \frac{4}{3}(W_{DIA} - W_{MHD})$$

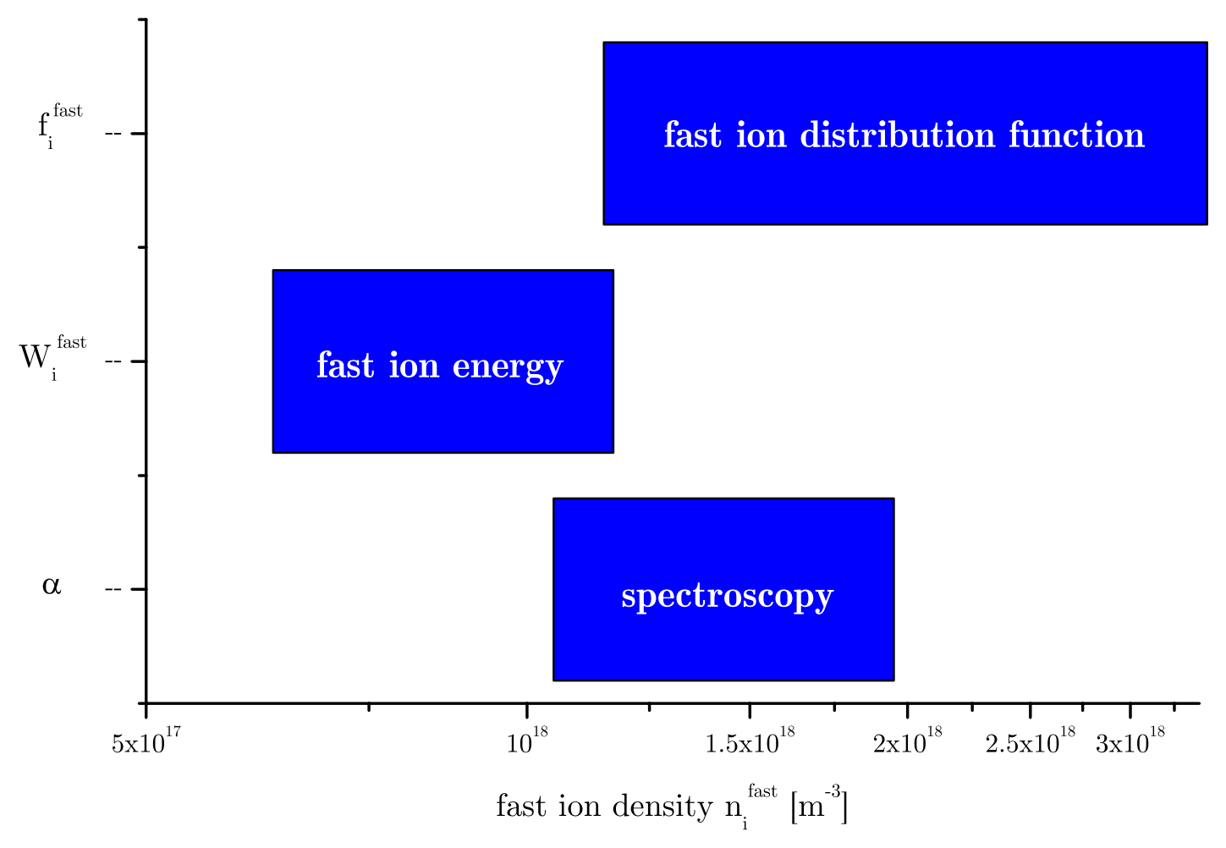
where W_{DIA} is the plasma energy measured by the diamagnetic loop and W_{MHD} is calculated by JET's equilibrium reconstruction code EFIT using magnetic measurements and MHD calculations. Knowing W_{fast}, the fast ion density is then obtained with an uncertainty of about 30 % using

$$W_{fast} = 4\pi^2 R_0 \int_0^a r\kappa(r) n_i^{fast}(r) \left[T_{i\perp} + \frac{1}{2} T_{i||}\right] dr$$

assuming gaussian density and temperature profiles and

$$T_{i||} = 0.1\, T_{i\perp}$$

Comparison of inferred fast ion densities



- With the cited precisions of the calculations of n_i^{fast} using spectroscopic measurements, agreement with the density inferred from the fast ion distribution function is found.
- This confirms the estimate of τ_C.
- By contrast, the fast ion energy approach gives a value that is almost 50 % lower. This approach needs to compensate the offset due to magnetic pickup in the coils, which is sometimes difficult to determine. Another reason for the disagreement may be the fact that electron density and/or temperature profiles are not gaussian.

Conclusion

- The present work outlined the reliable and robust measurement of the fast ion perpendicular temperature using experimental data from JET's high energy NPA KF1.
- The crude ⅡN-model permits to calculate the fast ion density with 50 % of uncertainty, with a refined analysis of the neutralization calculation input parameters the errorbars may be reduced well below. The inference of the fast ion density from NPA data is in agreement with edge spectroscopy measurements.

References

[1] A.A.Korotkov, A.Gondhalekar, and A.J.Stuart, *Impurity induced neutralization of mega-electronvolt energy protons in JET plasmas*, Nucl. Fusion 37 (1997), no. 1, 35-51.

[2] L.-G. Eriksson, T. Hellsten, and U. Willén, *Comparison of time dependent simulations with experiments in ion cyclotron heated plasmas*, Nucl. Fusion 33 (1993), no. 7, 1037-1048.

[3] K. G. McClements, R. O. Dendy, and A. Gondhalekar, *Interpretation of measurements of ICRF heated minority proton distributions in JET*, Nucl. Fusion 37 (1997), no. 4, 473-480.

[5] Thomas Howard Stix, *Fast-wave heating of a two-component plasma*, Nucl. Fusion 15 (1975), no. 5, 737-754.

[6] Duccio Testa and A. Gondhalekar, *Fast ion density measurements using high energy neutral particle analysis in JET*, Nucl. Fusion 40 (2000), no. 5, 975-988