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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JET high energy neutral particle analyzer measures the flux of fast neutrals originating from the plasma core. From this data, the fast ion distribution function f_i^{fast}, temperature $T_{i,\perp}^{fast}$ and density n_i^{fast} are derived using knowledge of various plasma parameters and of the cross-section for the required atomic processes. In this paper, a systematic sensitivity study of the effect of uncertainties in these quantities on the evaluation of the NPA f_i^{fast}, $T_{i,\perp}^{fast}$ and n_i^{fast} is reported. The dominant parameter affecting n_i^{fast} is the impurity confinement time and therefore a reasonable estimate of this quantity is necessary to reduce the uncertainties in n_i^{fast} below 50 %. On the other hand, $T_{i,\perp}^{fast}$ is much less sensitive and can certainly be provided with an accuracy of better than 10 %.

I. INTRODUCTION

KF1 is JET's high energy neutral particle analyzer (NPA) measuring the neutral flux of hydrogen and helium isotopes of energies ranging from approximately 200 keV to 4 MeV. The diagnostic has a vertical line of sight (from top to down in octant 4 at a radial position of R = 3.07 m, close to the magnetic axis at R = 2.96 m) which intersects the horizontal NBI beam in octant 4. From its measurements the fast ion distribution function $f_i^{fast}(E)$, the fast ion perpendicular temperature $T_{i,\perp}^{fast}$ and the fast ion density n_i^{fast} can be derived.

II. INFERENCE OF $f_i^{fast}(E)$, $T_{i,\perp}^{fast}$ AND n_i^{fast}

Fast ions in the plasma, described by a distribution function $f_i^{fast}(E)$ can be observed once they become neutrals, able to escape from the confining magnetic field. The neutralization of the ions is described by a neutralization probability $P_\nu(E)$. On their trajectory across the magnetic surfaces, the neutrals can be reionized again, which is quantized by a reionization probability $\gamma(E)$ - aka plasma transparency. The fraction of the flux of neutrals with energy E entering the solid angle Ω of the NPA detectors with étendue (ΩS) is registered with a detection efficiency $\mu_j(E)$, where the j^{th} channel energy width ΔE_j has to be taken into account. The measured neutral counts $N_j(E)$ in the NPA channel (counts due to neutrons are rejected by a pulse height analysis) measuring at energy E_j is therefore given by

$$N_j(E) = (\Omega S) \cdot \Delta E_j \cdot \mu_j(E) \cdot \gamma(E) \cdot P_\nu(E) \cdot f_i^{fast}(E) \quad (1)$$

Whereas the detector parameters are well known, a model is needed for the calculation of the neutralization and reionization probabilities. On JET, the **I**mpurity **I**nduced **N**eutralization model (**IIN**) was developed for this purpose (A.A.Korotkov and al., 1997). IIN includes radiative recombination with electrons, charge exchange reactions with impurities, thermal deuterium and NBI atoms and equates a system of steady-state ion density balance equations for bare, [H]-, and [He]-like impurities. The required input parameters are impurity (He, Be, C) density ratios, their respective confinement times, the ion temperature T_i, the electron density n_e, the thermal deuterium density $n_D^{thermal}$ and the effective charge Z_{eff}.
As pointed out in (A.A.Korotkov and al., 1997), the main source of uncertainties in the determination of the fast

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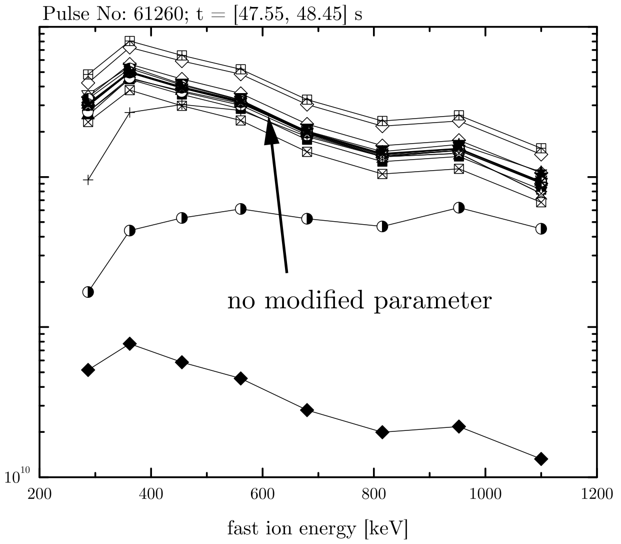

FIG. 1 Neutralization code input parameter impact on the calculation of the fast ion distribution function. △ represents the calculation of the neutralization probability using the reference parameters, the other curves were calculated by modification of one single input parameter. For the legend, refer to table I.

modified input parameter	$\frac{\Delta T_\perp(r=0)}{T_\perp^{ref}(r=0)}$ [%]	$\frac{\Delta n_i^{fast}}{n_i^{fast}}$ [%]
▲: 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$_i$ → $N_i - \frac{1}{\sqrt{N_i}}$	-8.7	-2.9
★: N$_i$ → $N_i + \frac{1}{\sqrt{N_i}}$	8.7	2.9

TABLE I The impact of input parameter modification on the fast ion temperature. With the reference parameters, the central $T_{i\perp}^{fast}(r=0)$ was 555 keV.

ion distribution function is the [H]-like electron donor density in the plasma core, which results in an uncertainty of 45 % in the neutralization probability. From eqn 1, the errorbar on $f_i^{fast}(E)$ is about 50% assuming a measurement with good counting statistics (i.e. Poisson uncertainty < 5 %).

The fast ion perpendicular temperature $\overline{T_{i\perp}^{fast}}$ is inferred from the fast ion distribution function using Stix's expression (Stix, 1975) for ICRF heated ions and therefore the perpendicular fast ion temperature can be inferred from the slope of the logarithm of the fast ion distribution function, i.e.

$$-\frac{1}{\overline{T_{i\perp}^{fast}}} = \frac{\partial}{\partial E} \ln\left(\frac{\overline{f_i^{fast}}(E)}{\sqrt{E}}\right) \tag{2}$$

where the bars over the quantities $\overline{f_i^{fast}}(E)$ and $\overline{T_{i\perp}^{fast}}(E)$ stand for line-of-sight integrated values. The central fast ion perpendicular temperature $T_{i\perp}^{fast}(r=0)$ is then given by the formula given in (McClements and al., 1997), i.e.

$$T_{i\perp}^{fast}(r=0) \simeq \overline{T_{i\perp}^{fast}}(E^*)\left(1 + \frac{\overline{T_{i\perp}^{fast}}(E^*)}{2E^*}\right) \tag{3}$$

with E^* is the median energy of the NPA measurements. The errorbars on $T_{i\perp}^{fast}$ are fairly low, since the main source of uncertainty on the temperature is the calculated C^5-ions charge exchange cross-section (20 %), resulting in (A.A.Korotkov and al., 1997) an error bar of ≈ 10 %. From the line integrated fast ion distribution function, it is straightforward to deduce f_i^{fast} by integrating $f_i(E)$ over the energy range of the measurement. The method used to calculate f_i^{fast} is calculated implies that the errorbars be set similarly to the fast ion distribution function, i.e. ∼ 50 % (A.A.Korotkov and al., 1997).

III. NEUTRALIZATION INPUT PARAMETER ANALYSIS

In this paper we present results from a study of the sensitivity of JET's code calculating the neutralization probability on its various input parameters and its impact on $f_i^{fast}(E)$, $T_{i,\perp}^{fast}$ and n_i^{fast}. The input parameters have been varied within their error bars.

For this purpose the plasma discharge #61260 from the 2003 trace tritium campaign C11 has been analyzed during the time interval $t = [47.55, 48.45]$ s, where ICRF heating (P = 4 MW) tuned to the H-minority at its 1st harmonic was present and no NBI was applied. The statistical error of the counts is below 3 % for this time interval, magnetic field B$_T$ = 3.4 T, plasma current I$_p$ = 1.8 MA, T$_e$ = 7 keV and n$_e$ = 3·10^{19} m^{-3} in the plasma core.

A. Fast ion distribution function and fast ion density

Figure 1 shows a compilation of such a procedure and its effect on the resulting fast ion distribution function. The modified parameters and their associated errorbars were the following: The relative impurity concentrations (Be/C and $He/Cratio \pm 100\%$), the thermal deuterium density $n_D \pm 100\%$, the electron density $n_e \pm 20\%$, the empirical impurity confinement times τ for Beryllium, Helium and Carbon $\pm 100\%$, the ion temperature $T_i \pm 10\%$, the effective charge $Z_{eff} \pm 30\%$ and the statistical Poisson uncertainty of the fast neutral counts N_i.

It is found that the modification of most of the input parameters, within their errorbars, doesn't strongly affect the absolute value of the fast ion distribution function. Large changes result when decreasing the impurity confinement times towards zero, but this does not make physical sense (see later). The confinement of carbon and - to a minor extent - Beryllium change the neutralization probability and therefore f_i^{fast} by 2 and 1 order of magnitude respectively. The modification of the shape of f_i^{fast} by changing τ_{Be} or τ_{He} is due to the strong energy dependence of the cross-sections for charge exchange (A.A.Korotkov and al., 1997). Z_{eff} affects neutralization and reionization, which is also seen in f_i^{fast}. Table I shows the values of the resulting n_i^{fast}.

B. Cross-check of the fast ion density n_i^{fast}

n_i^{fast} may also be determined using the ratio of the spectroscopic emission line intensities of the hydrogenic species (assuming $n_D \approx n_e$, with ICRF tuned to the hydrogen minority, equation 4) or the fast ion energy (equation 6)

$$\alpha = \frac{H_\alpha}{H_\alpha + D_\alpha + T_\alpha} \Rightarrow n_i^{fast} \approx \frac{\alpha}{1-\alpha} \tag{4}$$

$$W_{fast} = \frac{4}{3}\left(W_{DIA} - W_{MHD}\right) \tag{5}$$

$$W_{fast} = 4\pi^2 R_0 \int_0^a r\,\kappa(r)\, n_i^{fast}(r) \left[T_{i\perp} + \tfrac{1}{2} T_{i\|}\right] dr \tag{6}$$

where W_{DIA} is the plasma energy measured by the diamagnetic loop, W_{MHD} is calculated by the equilibrium reconstruction code EFIT using magnetic measurements and MHD calculations. The integral in equation 6 uses gaussian profiles with width of $\Delta = 0.3$ m with the usual assumption that $T_{i\|} = 0.1 \cdot T_{i\perp}$. Such considerations show agreement within the errorbars (± 30 %) with the density inferred from the fast ion distribution function.

C. Fast ion temperature $T_{i,\perp}^{fast}$

Since most of the input parameters only affect the absolute value of f_i^{fast}, the effect on the inferred $T_{i,\perp}^{fast}$ (depending on the slope of f_i^{fast} only) is rather weak (refer again to table I). Apart from the two non-physical impurity confinement times τ_C and $\tau_{Be} \to 0$, the inferred $T_{i,\perp}^{fast}$ is indeed found to be insensitive to the modified parameters, with changes below 10 %.

D. Impurity confinement times

To better understand the impact of τ, a further scan of these parameters was performed. For JET $\tau \gtrsim 1$ s, see the simple estimation in (A.A.Korotkov and al., 1997). Figure 2 shows how $T_{i,\perp}^{fast}$ and n_i^{fast} are altered when modifying τ in the range of $[0, 2]$ s. It is found that around $\tau \approx 1$ s the modifications by a scan of τ_{Be} and τ_{He} are negligibly small. Another picture is obtained when modifying τ_C, where no saturation of n_i^{fast} is observed. Other than for He and Be, the cross-section for charge exchange of C with background atoms is two orders of magnitude smaller at low energy. The radial carbon transport described by τ_C is therefore more important in the calculation of the ionization balance. $T_{i,\perp}^{fast}$ **is, however, not affected at all**, due to the almost flat energy dependence of the CX-cross section at low energy.

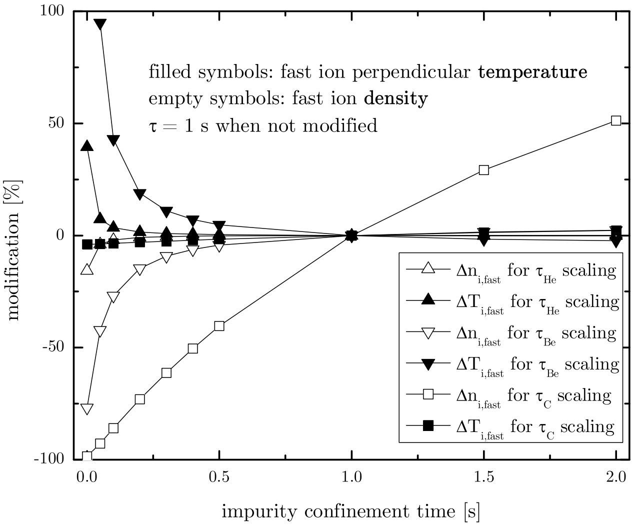

FIG. 2 n_i^{fast} and $T_{i,\perp}^{fast}$ in function of the different τ.

IV. CONCLUSION

The present work outlines the robust measurement of $T_{i,\perp}^{fast}$ using data from the high energy NPA KF1. The crude **IIN**-model permits a calculation of n_i^{fast} with 50 % uncertainty, with a refined analysis of the neutralization input parameter these errorbars may be considerably reduced. n_i^{fast} inferred from NPA data is in agreement with edge spectroscopy and fast particle energy measurements.

References

A.A.Korotkov, and al., 1997, Nucl. Fus. **37**(1), 35.
McClements, K. G., and al., 1997, Nucl. Fus. **37**(4), 473.
Stix, T. H., 1975, Nucl. Fus. **15**(5), 737.