EUROPEAN FUSION DEVELOPMENT AGREEMENT
JET

EFDA–JET–PR(05)01/09

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**See annex of J. Pamela et al, "Overview of JET Results ",*
(Proc.20 th IAEA Fusion Energy Conference, Vilamoura, Portugal (2004).

Preprint of Paper to be submitted for publication in Proceedings of the
16th Topical Conference on Radio Frequency Power in Plasmas
(Utah, USA, 11-13 April 2005)

ABSTRACT.
The code TORIC [1] solving Maxwell equations in toroidal axisymmetric plasmas in the Ion Cyclotron (IC) frequency range has been integrated in a package which includes: (1) an interface to the experimental data (Grad-Shafranov MHD configuration, density and temperature profiles), (2) the interface QLDCE [2] to a quasilinear Fokker-Planck solver for the electrons, (3) the quasilinear Fokker-Planck solver SSFPQL [3] for the ions, and (4) a subroutine which reevaluates the coefficients of the wave equations taking into account the suprathermal anisotropic tails of minority ions predicted by SSFPQL, so that their effects on wave propagation and absorption can be estimated by iterating TORIC. This package allows somewhat simplified but essentially selfconsistent simulations of heating and Current Drive (CD) in this frequency domain. Applications to Fast Wave CD have been made in [2]. Here we present the analysis of two IC heating experiments in ASDEX Upgrade (AUG) and in JET.

1. THE CODE SSFPQL.

The code SSFPQL [3] solves the quasilinear equations for ions heated at the fundamental and the first cyclotron harmonic, using the output of TORIC to build the quasilinear diffusion coefficient (QLDC) on each magnetic surface. The main simpli cations made by SSFPQL are:

i) The uniform-plasma Kennel-Engelmann quasilinear operator [4] is surfaceaveraged, neglecting several effects of toroidicity on IC heating (toroidal trapping, finite banana width, losses, . .).
ii) The collisional operator is linearized, assuming that the distribution of fast ions reaches steady state by losing energy on the background ions and electrons.

Exploiting assumption (ii), SSFPQL solves directly for the steady-state, and is, therefore, very fast: the distribution functions of two ion species (minority heated at the fundamental, majority at the rst harmonic) can be evaluated in less than 20sec on 100 magnetic surfaces on a laptop. Because of (i), SSFPQL cannot be regarded as a full substitute for a more sophisticated Fokker-Planck solver or for Montecarlo simulations [5], particularly for the most energetic ions. For the bulk of the hot ion populations it nevertheless predicts distributions in good agreement with those measured on AUG.

2. ITERATING TORIC.

Evaluating the coefficients of the wave equations for generic non Maxwellian plasmas requires a huge numerical effort, and would increase the execution time of TORIC by orders of magnitude. It is, therefore, a fortunate circumstance that the minority distribution function evaluated by SSFPQL can be approximated with reasonable accuracy by the superposition of two anisotropic Maxwellians (generalizing the well-known analytical approximations obtained by Stix [6])

$$F_m(v_{||}, v_\perp) = b_1 \frac{e^{-\left[(v_\parallel^2/\alpha_{\parallel 1}^2) + (v_\perp^2/\alpha_{\perp 1}^2)\right]}}{\pi^{3/2}\,\alpha_{\perp 1}^2\,\alpha_{\parallel 1}} + b_2 \frac{e^{-\left[(v_\parallel^2/\alpha_{\parallel 2}^2) + (v_\perp^2/\alpha_{\perp 2}^2)\right]}}{\pi^{3/2}\,\alpha_{\perp 2}^2\,\alpha_{\parallel 2}} \quad (b_1 + b_2 = 1) \qquad (1)$$

The parameters of this representation are determined by matching the logarithmic slopes and the parallel and perpendicular energy content of the distributions evaluated by SSFP proportional to velocity derivatives of F_m.With Eq. (1), the coef cients of the wave equations can be expressed in terms of the Plasma Dispersion Function Z. The contribution of the minority species to the coefficients of the wave equations [1] are

$$\delta\hat{L} = -\frac{\omega_{pm}^2}{\omega^2}\sum_k b_k\left[-\frac{x_0}{\alpha_{\|k}}\,Z\left(\frac{x_1}{\alpha_{\|k}}\right)\right] \tag{2}$$

$$\delta\hat{L}_i^{(2)} = \frac{1}{2}\,\frac{\omega_{pm}^2}{‰\omega_{cm}^2}\,\frac{v_{thm}^2}{c^2}\,\sum_k b_k\,\alpha_{\perp k}^2\left[-\frac{x_0}{\alpha_{\|k}}\,Z\left(\frac{x_2}{\alpha_{\|k}}\right)\right] \tag{3}$$

where $x_n = (\omega - n\Omega c_\alpha)/k_{||}n_{th\alpha}$ and the other notations are standard. Iterating TORIC including these contributions involves a greater number of evaluations of the function Z (each poloidal Fourier component of the electric field has its own k); the algorithm for this purpose, however, is quite efficient.

3. APPLICATIONS.

As an application, we present the simulation of two IC heating experiments in ASDEX Upgrade (AUG) and in JET [7]. Although the scenarios were similar (Hydrogen minority in Deuterium, at low concentration well within the minority regime; the main parameters are summarized in Table 1), and the coupled power densities almost identical, strong electron heating was observed in JET, but not in ASDEX Upgrade. The simulations reproduce well the observations, and allow to ascribe the different outcome to the lower collisionality and somewhat lower Hydrogen concentration of the JET plasma.

Figures 1 and 2 show the power deposition profiles evaluated by TORIC, and the power collisionally transferred to the electrons and the parameters of the minority distribution function evaluated by SSFPQL, in AUG and JET respectively. The absorbed power density in the central region is comparable in the two devices: the much larger plasma volume in JET is compensated by the larger total power available, and by a better focussing of the waves in the central region. In AUG the predicted peak effective temperature (logarithmic derivative of F_m (E) is $\simeq$ 35keV in the perpendicular, and $\simeq$ 15keV in the parallel direction. The former value agrees well with charge exchange measurement available up to about 100keV. In JET the predicted peak values are much higher, and more anisotropic: $T_{\perp eff} \simeq$ 320keV, $T_{||eff} \simeq$ 60keV. Except for minor differences in the power deposition profiles, these results are consistent with the analysis made in [7]. As a consequence of the high effective tail temperatures, in the core of JET $\simeq$ 80% of the power absorbed by the minority is thermalized on the electron ($\simeq$65% integrated over the entire plasma). The corresponding gures for AUG are $\simeq$ 45% in the core and $\simeq$ 35% integrated. The difference is due to the larger power per minority ion available in JET (both the total density and the minority concentrations being lower), and to the lower collisionality (by about a factor 4) of the JET plasma. Simulations scanning the total power and the minority concentration in the two devices confirm this interpretation.

COMMENTS AND CONCLUSIONS.

The main source of inaccuracy in these simulations is the fact that SSFPQL, in common with all surface averaged Fokker-Planck solvers, neglects the finite radial width of the orbits of the most energetic ions. Thus, while iterating TORIC with the minority distributions evaluated by SSFPQL shows some Doppler broadening of the power deposition profiles, the actual broadening is likely to be larger due to finite orbits effects. Nevertheless, simulations with the combined TORIC and SSFPQL codes reproduce well the experimental results, and help in their interpretation, with a modest numerical effort.

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	AUG Pulse No: 19314	**JET Pulse No: 52095**
Major radius	1.67m	2.95m
Plasma radius	0.47m	0.85m
Plasma composition	6% H in D	4% H in D
Central magnetic field	1.97T	2.77T
Ohmic current	836kA	2645kA
Central density	6.53 10^{19} m^{-3}	3.8 10^{19} m^{-3}
Central electron temperature	4.35keV	8keV
Central ion temperature	4.33keV	8keV
Applied frequency	30.5Mhz	42.0Mhz
Representative toroidal wavenumber	$n_\varphi = 12$	$n_\varphi = 24$
Position of minority resonance (r/a)	0.197 (h.f.s.)	0.070 (h.f.s.)
Estimated total power coupled	4MW	9MW

*The experimental profiles n and T have been used for ASDEX Upgrade; for JET the profiles of ref: [7] have been approximated analytically.

Table 1: Main parameters used in the simulations.

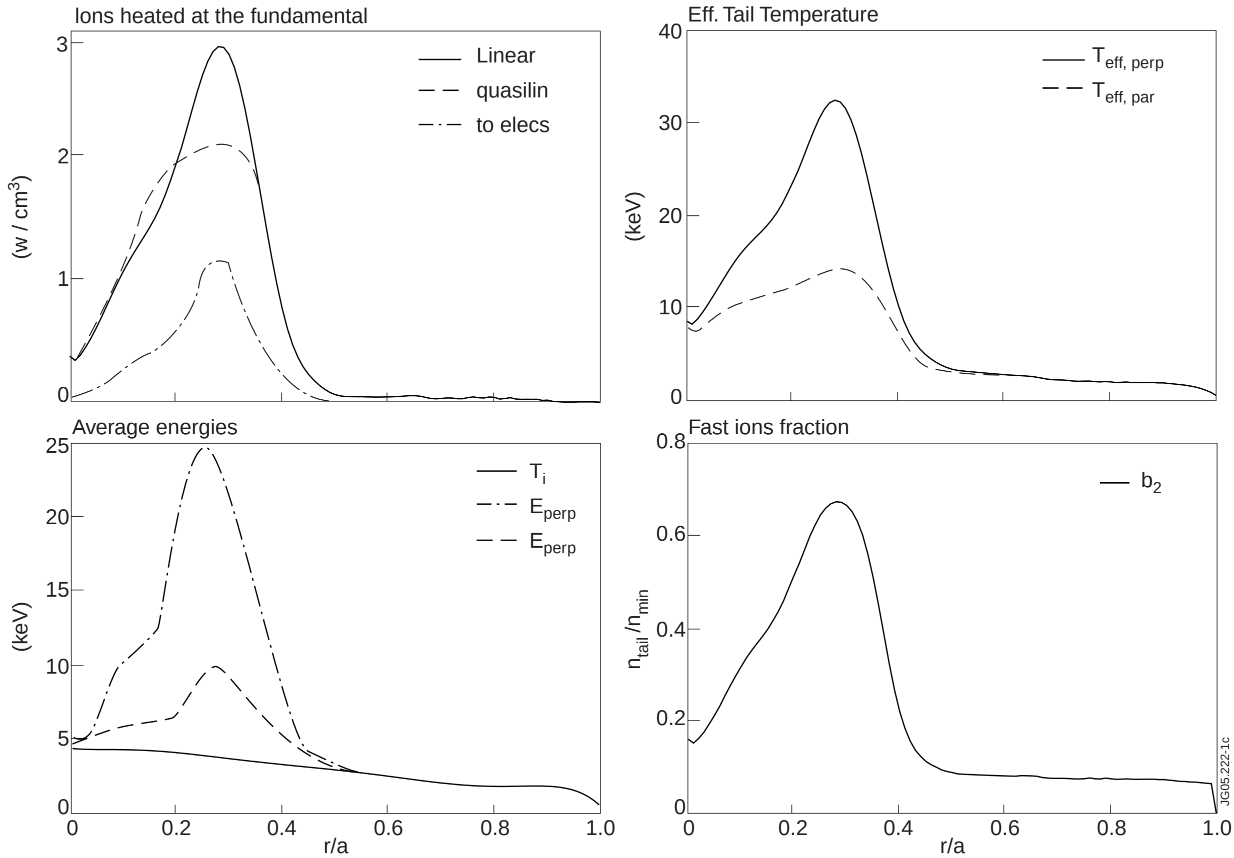

Figure 1: Results from TORIC and SSFPQL for ASDEX Upgrade.

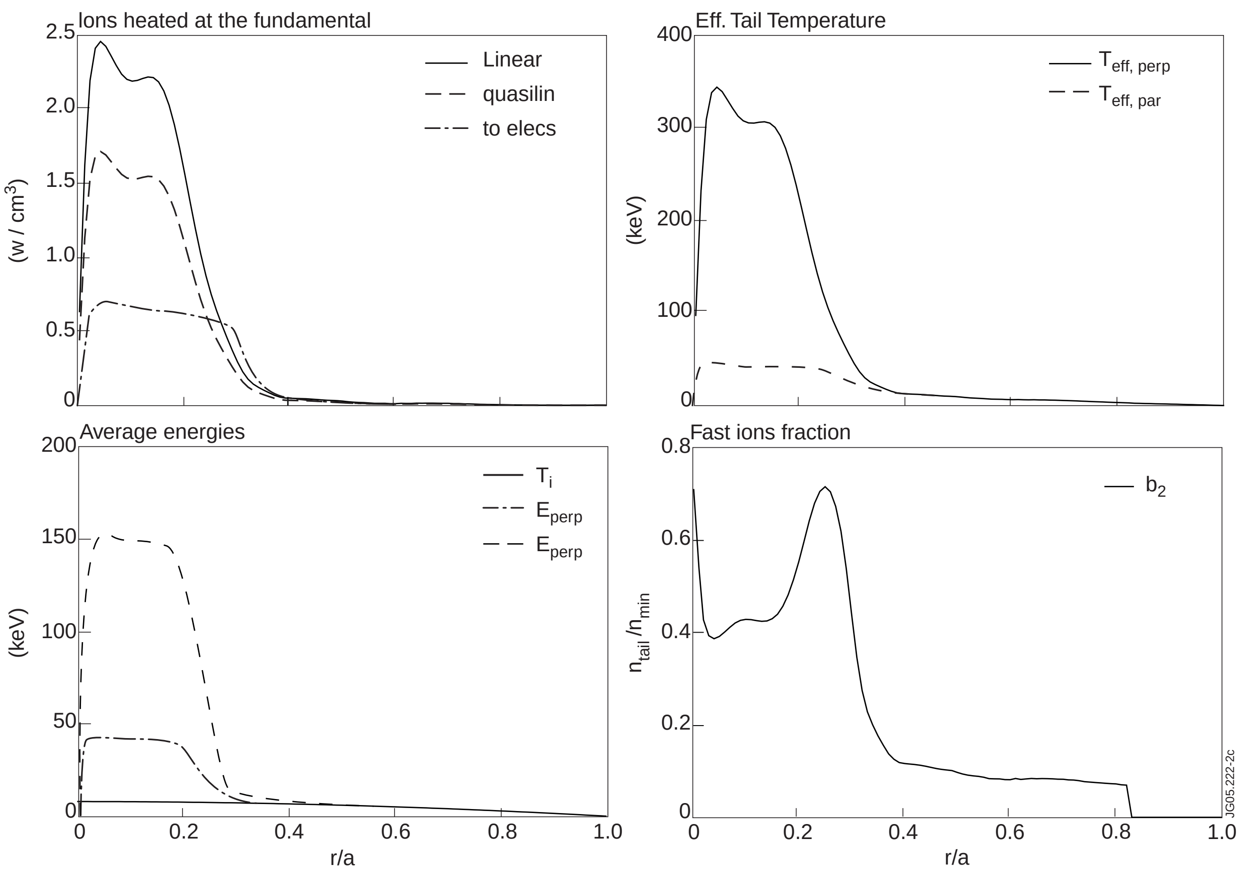

Figure 2: *Results from TORIC and SSFPQL for JET.*