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Transport in JET H-mode plasmas with beam and ion cyclotron heating

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Introduction - Ion Cyclotron (IC) Range of Frequency waves and neutral beam (NB) injection are planned for heating in ITER and other future tokamaks. It is important to understand transport in plasmas with NB and IC to plan, predict, and improve transport and confinement. Transport predictions require simulations of the heating profiles, and for this, accurate modeling of the IC and NB heating is needed.

Experiments were performed in JET comparing NB and IC heating in Type I ELMy H-mode plasmas in which the NB heating power $P_{\rm NB}$ was reduced when the IC power $P_{\rm RF}$ was turned on, keeping the total approximately constant. An example is shown in figure 1. The IC heating scheme was minority heating of trace H ions resonant at 42.5 MHz ($\Omega_{\rm IC} \simeq \Omega_{\rm H}$) near the plasma axis. The antenna set included the A2 and ILA systems.

The plasma current was 2.5 MA and the toroidal field 2.6 T. The total heating power was approximately twice the L→H threshold power. The experiment and an initial analysis of the transport and confinement has been described by Versloot, *et al.*, [1]. The analysis used the JETTO transport code with PENCIL for the NB heating and PION for the IC heating. Since that paper, measurements have been improved, and a more rigorous transport analysis has been performed. The new results show that both the ion and electron energy transport and confinement are degraded in the NB + IC phase. In both NB and NB + IC phases the ion energy transport is larger than the electron transport. The purpose of this paper is to describe the new analysis and results. Verification, validation, and implications for ITER are discussed.

Data and Methods - TRANSP is used to analyze nine plasmas from the scan. The NUBEAM Monte Carlo module simulates NB heating. A new, more accurate model for calculating effects of excited-states beam ionizations based on ADAS cross sections is used. The IC heating is simulated with the TORIC full-wave code coupled to TRANSP. The energy distribution of the IC resonant H species and its heating of the thermal plasma are computed by the FFPRF Fokker-Planck code.

The profile measurements used in TRANSP are: electron density n_e from high-resolution Thomson scattering; electron temperature T_e from electron-cyclotron emission; temperature, toroidal rotation, and density of trace carbon n_{carbon} from charge-exchange spectroscopy; and radiation emission P_{rad} from tomography of bolometry array data. Recently the T_e measurements were recallibrated resulting in increases sometimes as much as 15%. Profiles of Z_{eff} are computed using n_{carbon}. Input profiles are smoothed in the time and radial variables to get relatively smooth transport coefficients.

The TRANSP-TORIC runs were performed including the new data, careful sawtooth analysis, and a fine grid for TORIC. TRANSP uses the time-dependent boundary near the separatrix calculated by EFIT, and computes the internal equilibrium using the current, thermal, and fast ion pressure profiles.

For calculating the equilibria and energy transport fast ion pressures and heating profiles are needed. TRANSP-TORIC has been verified by benchmarking six alternative full wave solvers [2]. Approximate agreement for power deposition was achieved for TORIC and the majority of solvers.

Validity - The validity of the TRANSP-TORIC simulations are checked by comparing the simulated and measured perpendicular stored energy and neutron emission rates. The NB contribution $\mathrm{W}_{\perp}^{NB}$ decreases as n_e increases and/or as P_{NB} is reduced. The minority ion contribution $\mathrm{W}_{\perp}^{IC}$ increases with P_{IC}. The thermal plus $\mathrm{W}_{\perp}^{NB}$ plus $\mathrm{W}_{\perp}^{IC}$ tracks that measured by diamagnetic flux loops W_{dia}. An example is shown in figure 2-a). $\mathrm{W}_{\perp}^{IC}$ depends on the minority density. One uncertainty is the density of the H minority in the resonance region. This is assumed to have the same ratio to the bulk D density as the measured ratio of H and D-alpha emission in the edge. Since there is less uncertainty about $\mathrm{W}_{\perp}^{NB}$, tracking in time lends credibility to the simulation of $\mathrm{W}_{\perp}^{IC}$.

Various other uncertainties could cause the offset between the TRANSP-TORIC simulations and the flux measurements. Examples are systematic errors in the diamagnetic flux measurements, imprecision in the location of the pedestal (which has large consequences for the TRANSP-computed thermal energy), and uncertainties of the NB ion dynamics (possible anomalous beam ion losses are not included).

Agreement of the simulated and measured neutron emission rates from the DD fusion would add confirmation to the accuracy of the analysis. The TRANSP simulations are higher than measured during the NB-only phase. This discrepancy is typical of TRANSP modeling of deuterium plasmas in JET and other tokamaks. An example is shown in figure 2-b). The simulated and measured neutron emission rates are in closer agreement during the NB+IC phase when the NB power is reduced. This reduction of the difference seen in the NB phase could be related to increases in the densityis of impurities other than C during the IC. Increased emission from Ni and Cr lines were observed, but profiles for their densities were not measured so their effects are not included.

The Z_{eff} profiles computed using the measured carbon density increase during the NB + IC phases. The radiated power profiles also increase during the NB + IC phases. TRANSP simulations of P_{rad} assuming coronal equilibrium of the radiation also increase, but not as much as the measured profiles. This also suggests that there are additional impurities entering the plasmas during the NB + IC phase. Dilution caused by these could be the reason the difference between the simulated and measured neutron rates become closer during the NB + IC phase.

If there is significant IC acceleration of beam ions, which is not included in the TRANSP-TORIC simulation, the measured neutron emission rate could deviate to higher values relative to the simulated rate. There is no suggestion of this. In cases where the IC starts late and the measured neutron emission rate increases, TRANSP also predicts the increase. The beam-thermal rate dominates the simulations and since the measured P_{NB} is reduced during the IC, the simulated total rate decreases. The small contribution to the neutron rate from burn-up of trace T produced by deuterium-deuterium collisions is also modeled.

Comparison of the stored energy and neutron emission for one of the plasmas from the scan were shown in [3] The current results with recalibrated T_e achieved better agreement.

Results - The ion temperature T_i and toroidal rotation v_{tor} of the bulk D are computed from the carbon measurements by TRANSP. The central T_i and v_{tor} decrease during the NB + IC phase as P_{NB} decreases. The radial electric field, calculated from local force balance and v_{pol} calculated using NCLASS is dominated (except in the pedestal) by the v_{tor} contribution. The central T_e increases. The n_e profiles evolved through the change from NB to NB + IC.

The measured plasma profiles and computed heating profiles are used to compute the energy, momentum, and species transport coefficients. The partitions of direct IC wave heating are typically 11% to thermal D, 67% to the minority H, and 18% to electrons. The partitions of direct IC wave heating to beam ions and impurities are calculated by TORIC to be around 1% or less. The heating profiles from the H minority ions need to be included for transport analysis. An example of the stacked volume-integrated profiles are shown in figure 3. The partitions of NB plus direct wave plus minority heating are approximately equal for thermal ions and electrons.

The computed electron energy confinement coefficient χ_e is relatively small compared the thermal ion energy confinement coefficient χ_i. Comparisons for these and the total thermal ion and electron energy coefficient χ_{eff} and the momentum transport coefficient χ_ϕ for one of the plasmas are shown in figure 4-a). Results for χ_{eff} is lowest for the NBI-only phases of the discharges, and increases during the NB + IC phase, shown in figure 4-b). Comparisons of plasmas at times when n_e and the total powers are similar have larger transport in the NB + IC phase.

The flow shearing rate calculated from the radial electric field is smaller in the NB + IC phase. Reduction of flow shear suppression of turbulence could cause the increased transport during the NB + IC phase. The ion temperature scale length L_{Ti} decreased during the NB + IC phase. R / L_{Ti} is lower for plasmas with larger fractions of P_{RF} at fixed $P_{\mathrm{NB}} + P_{\mathrm{RF}}$.

One of the IC heating schemes proposed for ITER would use $\Omega_{\mathrm{IC}} \simeq 42$ MHz to heat trace He^3 at $\Omega_{\mathrm{IC}} \simeq \Omega_{\mathrm{He3}}$ and T with second-harmonic ($\Omega_{\mathrm{IC}} \simeq 2\Omega_{\mathrm{T}}$) absorption near the magnetic axis. The partition of electron and thermal ion heating is predicted [2] to be nearly equal, as for the JET scan. Higher energy transport during the NB + IC phase would not be optimal for ITER and should be studied further.

[*] See Appendix of F. Romanelli *et al.*, 23nd IAEA Fusion Energy Conference, Daejeon (2010).

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[1] T.W. Versloot, R. Sartori, F. Rimini, P.C. de Vries, *et al.*, Nucl. Fusion **51** (2011) 103033.
[2] R.V. Budny, L. Berry, R. Bilato, P. Bonoli, M. Brambilla, *et al.*, Nucl. Fusion **52** (2012) 023023.
[3] R.V. Budny, K. Indireshkumar, D. McCune, M.-L. Mayoral, J. Ongena, *et al.*, EPS 2009.

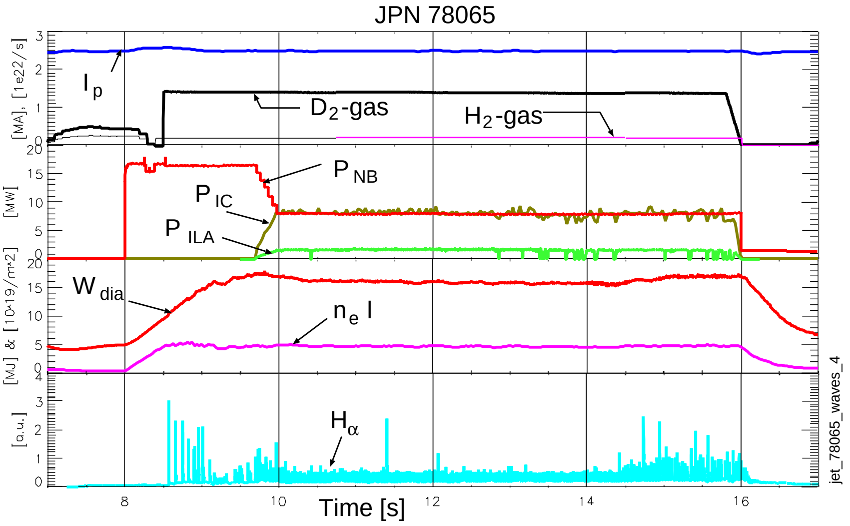

Figure 1: Time evolutions for one of the plasmas. The ILA and total IC powers are shown.

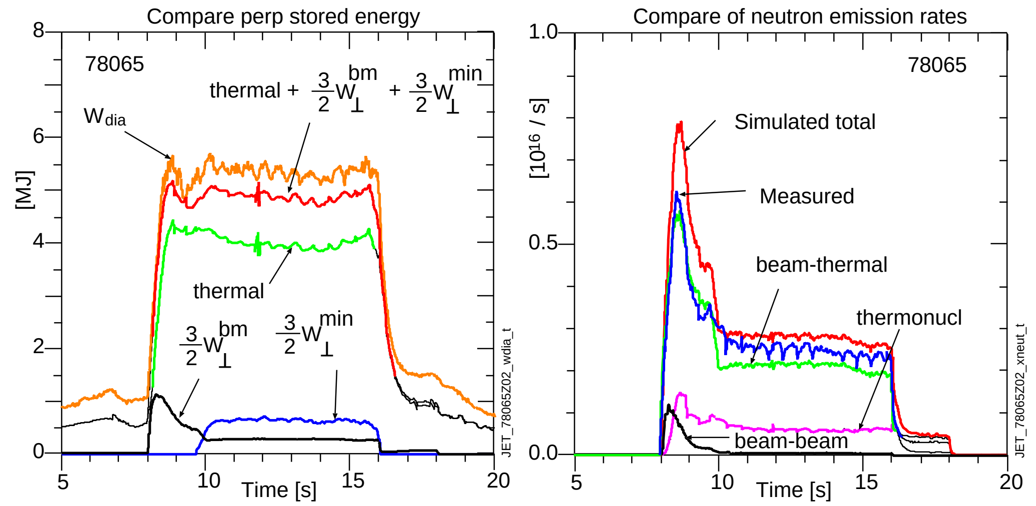

Figure 2: Simulated and measured a) perpendicular energies; b) neutron emission rates for the plasmas shown in figure 1.

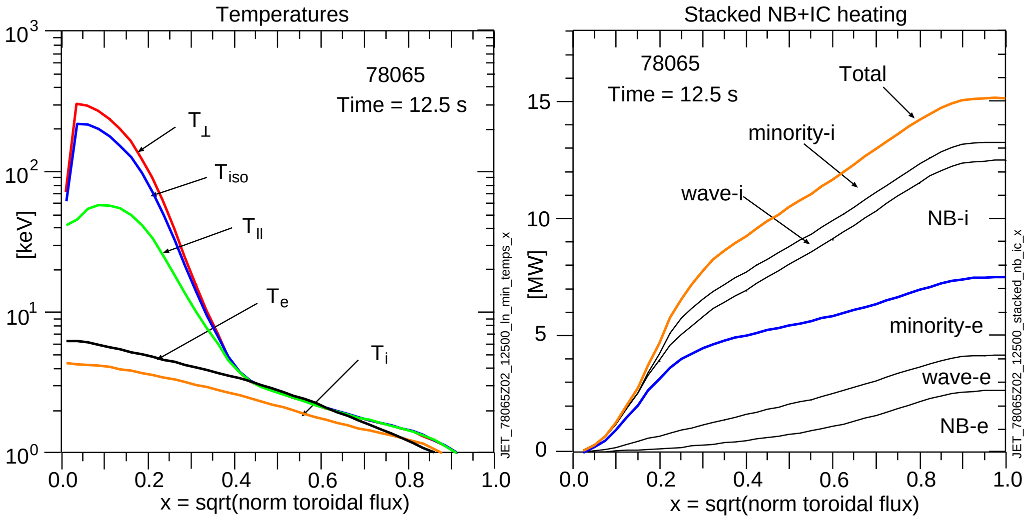

Figure 3: a) Comparison of plasma temperatures and equivalent bi-Maxwellian temperatures for the minority H; b) volume-integrated stacked NB and IC heating.

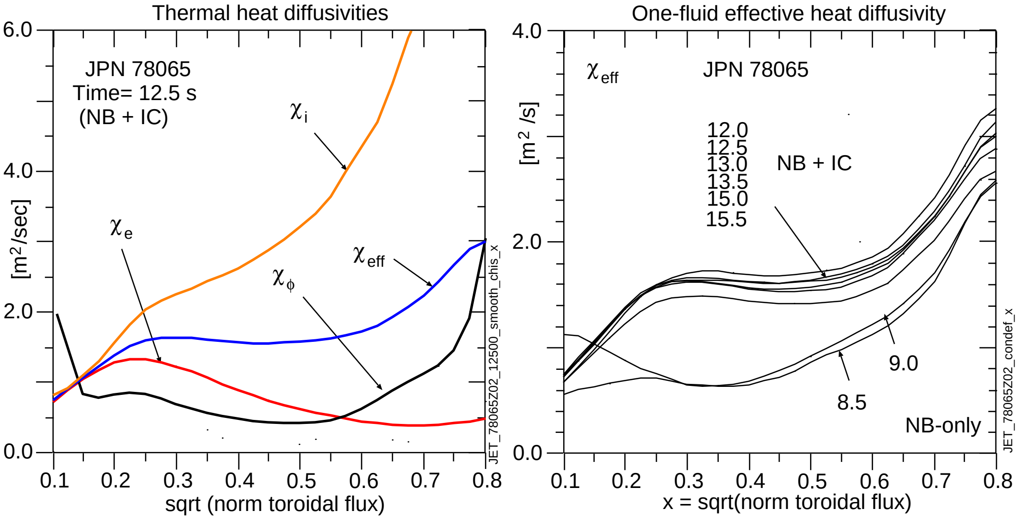

Figure 4: Simulated and measured thermal heat transport coefficients during the NB + IC phase for one of the plasmas. The n_e profiles are higher during the NB + IC phase.

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