

Integrated Core-Edge Modelling of Energy Confinement Degradation and Particle Content Saturation in JET ELMy H-Modes

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1. Introduction: Experimental observations, codes and models.

In JET H-modes with type I ELMs it has been observed that increasing the gas puff leads to increasing the frequency of ELMs (f_{ELMs}), and to energy confinement degradation. Moreover $\langle n_e \rangle$, the volume average density, increases with the gas puff rate up to a maximum, then saturates and even decreases [1]. It was also found that f_{ELMs} decreases with the isotope mass for otherwise similar plasma conditions [2].

For the interpretation of these observations we carried out simulations with the following transport codes: EDGE2D/NIMBUS (energy and particle transport and sources in the plasma boundary region); JETTO/SANCO (energy and particle transport and sources in the plasma inside separatrix) and COCONUT (Combined Codes Numerical Utility for Tokamaks). COCONUT is a unique and flexible tool linking EDGE2D/NIMBUS and JETTO/SANCO into a single time dependent code. The most important feature of COCONUT is that it makes it possible to model consistently energy and particle transport (including impurities) from the plasma core to the divertor targets.

With these codes we have used a mixed Bohm/gyro-Bohm transport model with a transport barrier at the edge where particle and energy transport coefficients are reduced to the level of the neoclassical ion thermal diffusivity, [3]. JETTO also includes a model of type I ELMs [4]. In this model ELMs are triggered when the pressure gradient in the transport barrier exceeds the stability limit for ballooning modes.

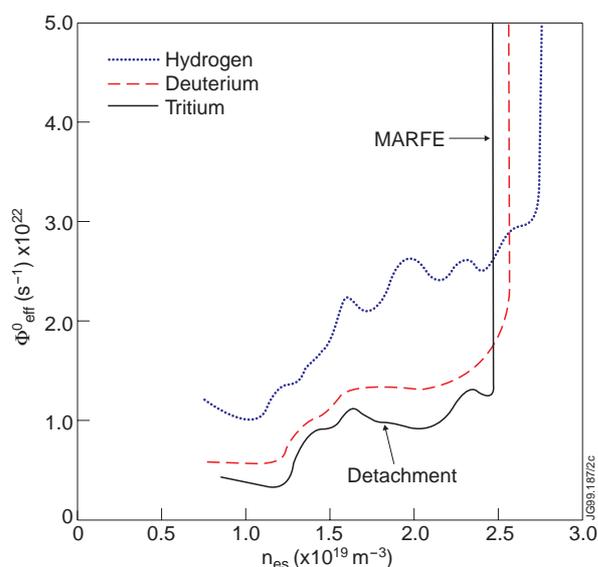


Fig.1 Φ_{eff}^0 versus n_{es} . Detachment and MARFEs predicted at high n_{es} are not found with type I ELMs.

2. 'Generic' predictions for quasi steady state regimes without ELMs.

EDGE2D/NIMBUS simulations including carbon as an impurity have been carried out assuming that the total neutral gas puff rate slightly exceeds the total loss of particles due to pumping and non complete recycling of neutrals. These quasi steady state conditions are relevant not only for ohmic and L-mode regimes, but also for H-mode discharges when phases between ELMs with moderate or low frequency ($f_{\text{ELMs}} \leq 100\text{Hz}$) are considered. Results of these simulations show that, as the outer mid-plane separatrix density n_{es} increases with gas fuelling, the plasma evolves towards detachment followed by a MARFE. This implies a hard density limit related essentially only to the SOL and

divertor physics. This result is 'generic', i.e. the same trend (but of course not the same density limit) is found independently of the type of JET divertor considered and for transport coefficients introduced to simulate L-mode and H-mode divertor results.

In connection with ELMy H-modes the most interesting ‘generic’ prediction refers to the total influx of neutrals Φ_{eff}^0 into the plasma core as function of n_{eS} . Fig.1 shows that decreasing the isotope mass in simulations is equivalent to increasing Φ_{eff}^0 . A possible (indirect) confirmation of this prediction is that in JET ‘similarity’ experiments a stronger gas puff was required with deuterium and tritium than with hydrogen to obtain same density and frequency of ELMs. (However a quantitative analysis of these experiments remains to be performed).

We anticipate at this point that for H-modes with type I ELMs the highest values of n_{eS} , where complete plasma detachment and MARFE formation are predicted in quasi steady state conditions, are not attainable in simulations when ELMs are properly modelled. This is in agreement with experimental observations.

3. Influx of neutrals into the plasma core, ELMs frequency, energy content.

Taking into account the experimental results showing an increase of f_{ELMs} with the external gas puff rate and with decreasing isotope mass, both of which imply an increase of Φ_{eff}^0 according to our simulations, we suggest that Φ_{eff}^0 itself plays an important role in determining f_{ELMs} . This may happen via the indirect effect of Φ_{eff}^0 on the barrier width. The modification of the barrier width may be due to the effect of charge exchange and of the modification of ionization sources on density, temperature and possibly on the fast ion distribution within the barrier region. These modifications imply a reduction of the ion orbits (in principle both thermal and non thermal) with increasing Φ_{eff}^0 . Proper testing of this idea implies a more complete model of ELMs than presently available in JETTO. In the absence

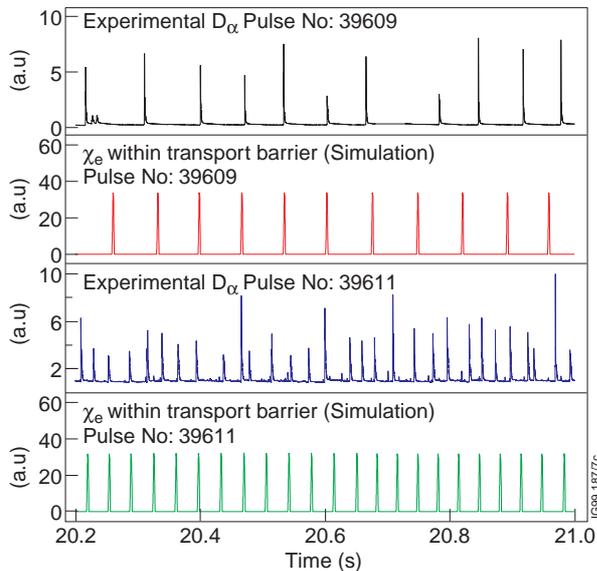


Fig.2 Experimental (from D_{α}) and computed (from increase of χ_e in transport barrier in JETTO) f_{ELMs}

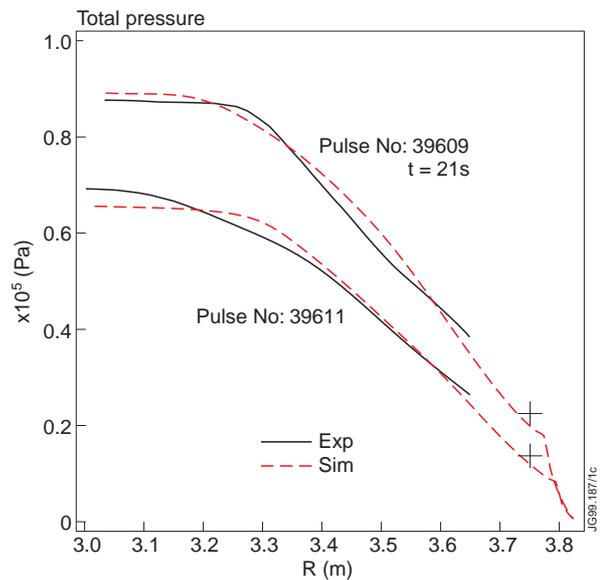


Fig.3 Experimental and computed pressure profiles corresponding to different gas puff rates and f_{ELMs}

of such a model we introduced an ad hoc reduction of the transport barrier width with increasing Φ_{eff}^0 . This allowed us to simulate JET density scan discharges at 2.5 MA, 2.5T.

Examples of the results obtained are given in figs 2 and 3. The variation of f_{ELMs} obtained in the simulations (fig.2) corresponds to a reduction of the barrier width from about 5 cm to about 2.0 cm. In these discharges the external puff increased from $1.4 \cdot 10^{22} \text{ s}^{-1}$ to $3.5 \cdot 10^{22} \text{ s}^{-1}$ with an increase of Φ_{eff}^0 from $0.7 \cdot 10^{22} \text{ s}^{-1}$ to $1.4 \cdot 10^{22} \text{ s}^{-1}$ according to EDGE2D/NIMBUS stand alone simulations.

The reduction of energy content as f_{ELMs} increases (fig.3) results in our simulations from a reduction of the pedestal energy and from a non local increase in transport predicted by the BOHM part of our transport model [3].

4. Results of COCONUT and soft density limit related to ELMs.

Integrated core-edge simulations have been carried out with the COCONUT code. As in [3] it has been assumed that particle and heat diffusivities D , χ_e , and χ_i , used in the boundary region by EDGE2D in COCONUT are the same as computed at the separatrix by the model in

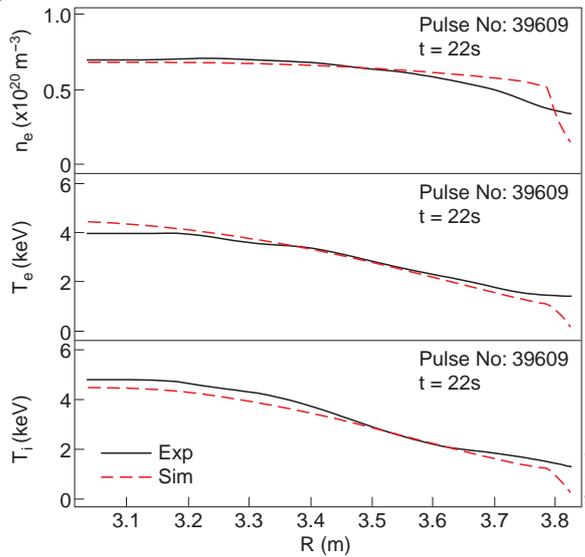


Fig.4 Experimental and computed profiles of electron density and electron and ion temperatures

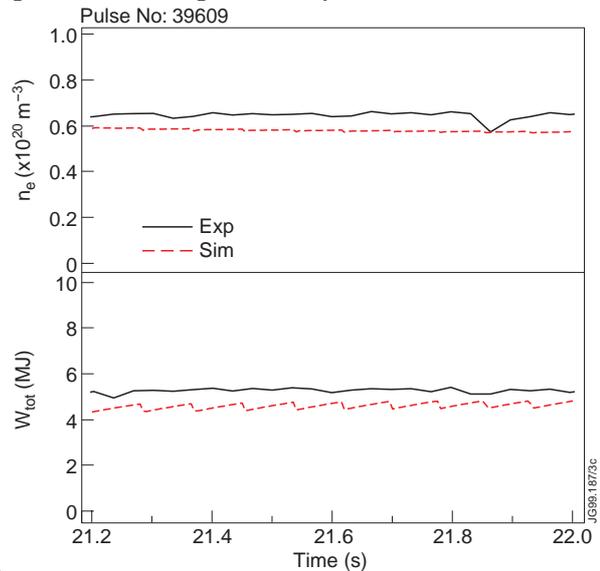


Fig.5 Experimental and computed time traces of average electron density $\langle n_e \rangle$ and energy content W_{tot}

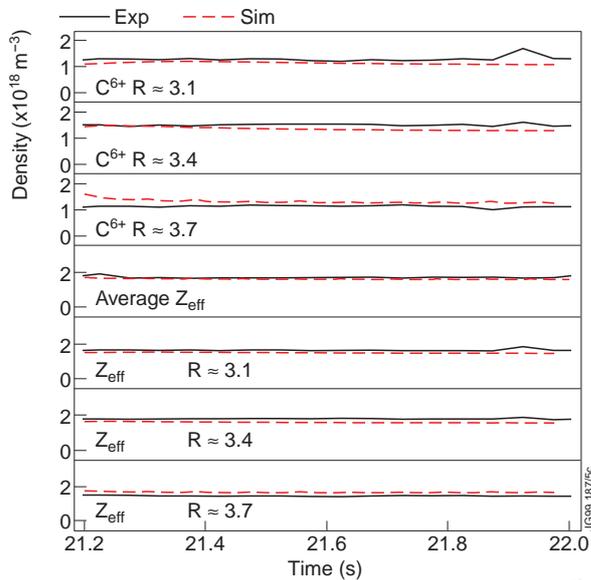


Fig.6 Experimental and computed time traces of C^{6+} density, average Z_{eff} and Z_{eff} at different radii

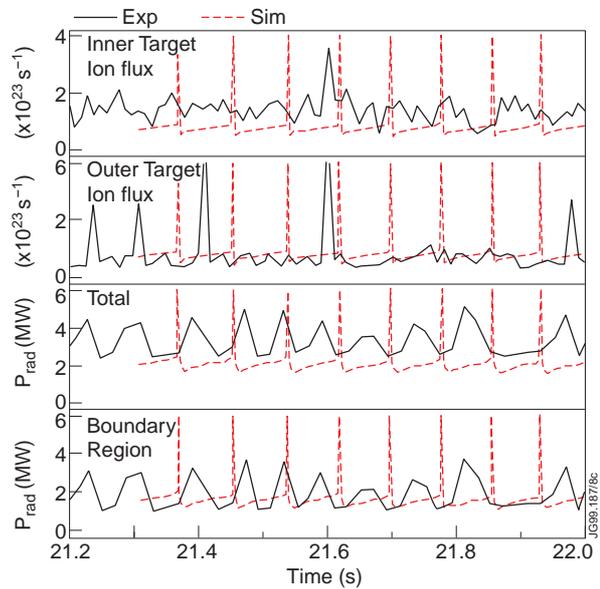


Fig.7 Experimental and computed time traces of total ion fluxes to divertor targets and of radiated power

JETTO. Moreover we assumed the same transport model for main ions and carbon impurities, including a convective velocity ('inward pinch') which is constant (≈ 5 m/s) in the boundary region and goes to zero at the top of the transport barrier.

Figs 4-7, which refer to JET discharge 39609 illustrate the possibility, unique to COCONUT,

to carry out consistent and complete simulations of the time evolution (including ELMs) of quantities in the plasma core and the divertor region. These simulations include sputtered carbon as an impurity. A constant sputtering yield coefficient 0.04 was assumed.

Fig.4 compares computed and experimental density profiles in the plasma core at a time during the quasi steady state phase of the discharge. Fig.5 compares the computed and experimental evolution of the energy content and of the average electron density during this phase. The electron density is computed taking into account the time evolution of the density profiles of carbon $C^{1+} \dots C^{6+}$ (see fig.6 comparing computed and experimental evolution of C^{6+} and Z_{eff} at different position in the plasma core). These profiles are evaluated by SANCO from the influx of carbon into the core given by EDGE2D. Similarly the temperature profiles and the evolution of the energy content take into account the impurity radiation (fig.7) which SANCO evaluates taking into account the impurity and electron density distribution (SANCO/JETTO) as well as the electron temperature distribution (JETTO). Fig.7 also shows a comparison of computed and experimental total ion fluxes to the divertor targets.

As important as complete and detailed simulations of discharges is the study of 'generic' features which strongly depend on both core and divertor physics. One such feature is the possibility that type I ELMs imply not only a degradation of energy confinement but also a 'soft' density limit at density lower than the hard density limit observed in L-mode discharges. This is illustrated in fig.8 which compares the time evolution of energy content and average

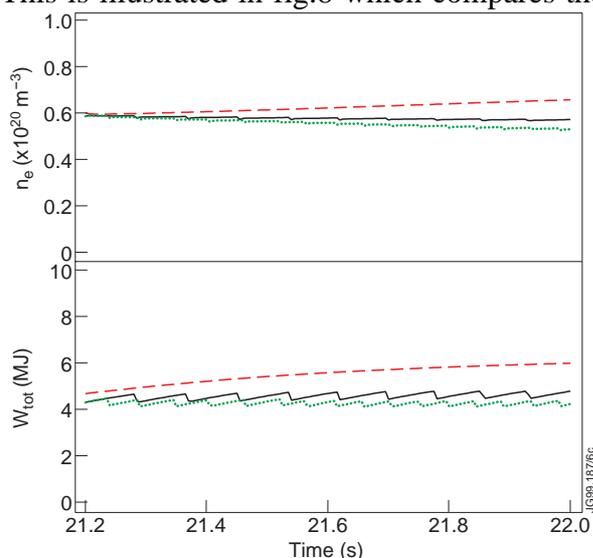


Fig.8 Time evolution of $\langle n_e \rangle$ and W_{tot} computed by COCONUT in the absence of ELMs and with ELMs

density without ELMs and with ELMs of different frequency. The external gas puff in the simulation was prescribed to lead to the same rate of increase of total particle content outside ELMs. COCONUT results indicate that, similar to what happens to energy, as the frequency of ELMs increases more particles are expelled from the plasma core due to ELMs. Most of these particles are pumped away (or absorbed by wall and divertor targets), thus $\langle n_e \rangle$ saturates or even decreases. As already pointed out this trend is in agreement with experimental results and might explain why complete detachment and formation of MARFEs are not observed in JET H-modes with type I ELMs.

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