A Description of ELM-Free H-modes in Terms of a Neoclassical Edge Barrier and a ‘Mixed’ Model for Energy and Particle Transport

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INTRODUCTION:

High performance in JET ELM-free H modes appears to be related to the edge temperature, which can reach several *keV*’s, contributing up to half of the stored energy. A model to compute these edge values must then be given in order to predict plasma confinement. The existence of a neoclassical transport barrier was assumed in *[1]*: transport inside the separatrix is reduced to ion neoclassical values on a width scaling with the ion poloidal Larmor radius $\rho_{\theta i}$. In this work we extend that model to include plateau effects, and most importantly include particle transport, using the JETTO transport. Particle confinement and recycling conditions are shown to be crucial factors for energy confinement and the evolution of the discharge, as observed in experiments.

ENERGY TRANSPORT MODEL IN THE CORE PLASMA:

We use a ‘mixed’ transport model *[2]*, which combines a gyroBohm ($\chi_{gB} = c_{gB}\sqrt{T_e}\,\nabla T_e / B_T^2$) and a Bohm-like term ($\chi_B = c_B (\nabla P_e / n_e B_T) q^2 a^2 < \nabla T_e / T_e >_{\rho>0.8}$):

$$\chi_e = \chi_B + \chi_{gB}$$
$$\chi_i = 2\chi_B + \chi_{gB} + \chi_{neo,i}$$

This model can be used to describe both L and H modes, due to the non local dependence of the Bohm-like term on $L_{T_a}^{-1} \equiv < \nabla T_e / T_e >_{\rho>0.8}$, the electron temperature scalelength averaged in the outer 20% of the radius, excluding the transport barrier.

EDGE TRANSPORT BARRIER:

We assume that in H modes, free from ELMs or other MHD activity, all transport coefficients are reduced to ion neoclassical values, on a width $\sim\rho_{\theta i}$ inside the separatrix. In the banana regime, relevant to JET high performance shots, the heat loss from the edge then scales as: $Q_{neo} \sim n_a \chi_{i,neo} T_a / \rho_{\theta i} \sim Z_{eff}\, n_a^2 / I_p$, and particle losses as $\Gamma_{neo} \sim Q_{neo} / T_a$.

An important energy loss term is due to charge exchange with cold neutrals: $P_{CX}\sim\Gamma_0 T_a$, where Γ_0 is the neutral influx from the edge. We write $\Gamma_0=\Gamma_{neo}+S^+$, with S^+ taking into account any sources in addition to the 100% recycling. When S^+ is small compared to the outgoing flux Γ_{neo}, then $P_{cx}\sim\Gamma_{neo}T_a$ and so total energy losses will retain the neoclassical scaling. Additional energy losses due to radiation P_{RAD} are included in the simulations, but are often negligible.

The scalings change when the edge approaches the plateau regime, when $\nu^*>0.1$. The energy losses are not independent of T_a anymore: $Q\sim n_a T_a^2$, and a pedestal saturation is expected.

From the given scalings some conclusions can immediately be drawn.

a) The best confinement will require low edge density, and low recycling conditions (wall conditioning).

b) Steady state can be reached only in three ways: stepping down the input power P; increasing n_a up to $\sim\sqrt{P}$; elming or other additional energy losses (e.g. increased radiation).

c) While n_a remains low (i.e. heat loss $Q\sim n_a^2$ small compared to P), a situation of near thermal runaway is created, with $\dot{W}\sim P-Q$. Typically both W and T_a rise on a timescale faster than n_a, so the plasma hits a local β-limit (e.g. ELM, 'slow roll over', etc.) before reaching steady state. This is typically the case of JET high performance discharges.

In the JETTO code the transport barrier can be simulated in two ways. Either it can be taken into account explicitly, reducing all transport coefficients appropriately on a few mesh points close to the separatrix, or the neoclassical fluxes can be imposed as Neumann boundary conditions, thus solving the transport equations only up to the transport barrier. The two methods have been shown to be equivalent (see later), but the former allows coupling with SOL codes, as EDGE2D *[3]*, and thus further validation against SOL measurements.

Semipredictive simulations, i.e. imposing the density profile from measurements, have been initially used to check some of the dependencies predicted by the model. A series of discharges was performed scanning density and current and optimizing the configuration for edge measurements. All relevant plasma characteristics were successfully reproduced, even for shots with the edge approaching the plateau regime. These simulations support the dependencies of the model on current and collisionality, but given the importance of n_a, modelling of particle transport is required.

FULL ENERGY AND PARTICLE SIMULATIONS OF ELM FREE H MODES:

The NBI particle deposition profile is a very important ingredient in the analysis. This was obtained from the TRANSP Montecarlo package. The source profile of edge cold neutrals is computed by the code FRANTIC, with the total influx given by $\Gamma_0 = \Gamma_{neo} + S^+$. When simulating an experimental discharge, S^+ can be imposed to reproduce the total particle content.

We describe the particle flow by using only an 'effective' diffusion term: $D_{eff} = f(\rho)\chi_e\chi_i/(\chi_e + \chi_i)$. The radial function $f(\rho)$ was chosen in one of the shots in order to reproduce the shape of the measured density profiles and the magnitude of Γ_0, and then kept constant in different shots. It turns out that in order to reproduce the experimental density profiles $f(\rho)$ must decrease from $f(0) \sim 1$ to $f(1) \sim 0.1$, though its exact form cannot be precisely determined (linear was used). This result can be interpreted as an indication for the existence of an inward pinch localized in the outer region of the plasma, in agreement with similar results from ohmic mode*[3]*.

All the main experimental measurements of hot-ion H modes have been satisfactorily reproduced, when S^+ is given as above. Typical density and temperatures profiles computed for a very high performance shot are given in *Fig.1,2*, together with experimental ones. Relevant time traces are given in *Fig.3*. The neutral flux Γ_0 grows up to $\sim 2\ 10^{21} s^{-1}$, in good agreement with the SOL modelling and measurements *[4]*.

To study the effect of recycling conditions we have scanned S^+, and run the simulations for a time longer than the experimental MHD-free period (usually <1.2 *s*). *Fig.4* shows the predicted time evolution for the stored energy, fusion reaction rate, and neutral influx: increasing S^+ causes higher n_a and lower T_a, leading to an increase in Γ_{neo} (and so Q_{neo}) even bigger than S^+ itself.

It is clear that low recycling is essential to high performance. Higher neutral influx will induce lower pedestal temperatures and increase transport everywhere, via $L_{T_a}^{-1}$. Natural saturation and even degradation of the high confinement phase is observed (*Fig 4*), because n_a grows in time ~linearly and so energy losses with $\sim t^2$, but the timescale on which saturation appear depends on recycling conditions, and it can be longer than the MHD free period.

The degradation of confinement can also be caused by an impurity influx: the increase in edge Z_{eff} enhances Γ_{neo} , and hence both Q_{neo} and P_{CX} , reducing pedestal and confinement (the increased radiation will also play a role). This effect can be used to simulate experimental confinement degradation ('slow roll over'), assuming a trigger event (MHD) to increase Z_{eff}.[5]

CONCLUSIONS:

The neoclassical transport barrier coupled with the 'mixed' transport model provides a reasonable description of the ELM-free H-mode. The scalings for energy and particle losses have been derived and tested in numerical simulations of experimental discharges.

Simulation of particle flows requires an 'effective' diffusion decreasing towards the edge, a possible indication for the existence of an inward pinch strongly growing in the outer region.

Energy and particle transport in hot ion discharges have been successfully simulated, including the prediction of pedestal values. High confinement is achieved when the energy losses through the barrier are small thus leading to high pedestal values, this in turn reduces the transport coefficients throughout the plasma.

The main energy losses are the predicted neoclassical heat losses and charge exchange with cold neutrals. Low recycling (wall conditioning) and low impurity content prove to be the main factors required to maintain the small energy losses necessary for high confinement.

REFERENCES

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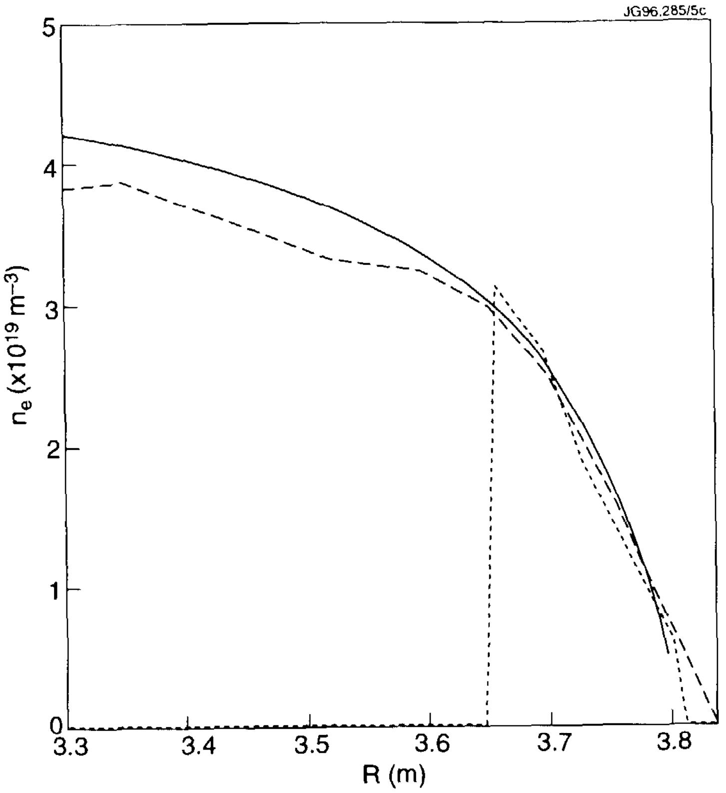

FIG.1 Computed (full line) density profile vs LIDAR(dashed) and reflectometry(dots), shot 33643, at t=53. *Note no discontinuity in gradient at the barrier (*R>3.75~m*). Reflectometry provides reliable information close to the boundary.*

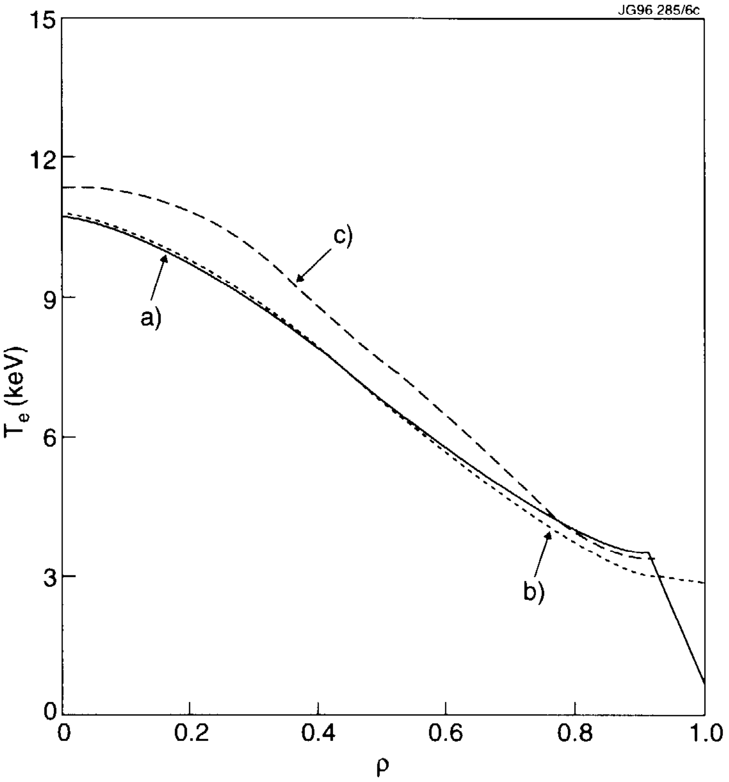

FIG.2 Profile comparison at t=53 *of measured (LIDAR, trace c) and computed* T_e *profiles, shot 33643. Trace a is computed imposing the barrier explicitly: the change in slope is clearly visible. Trace b was computed with the barrier imposed as Neumann boundary condition.*

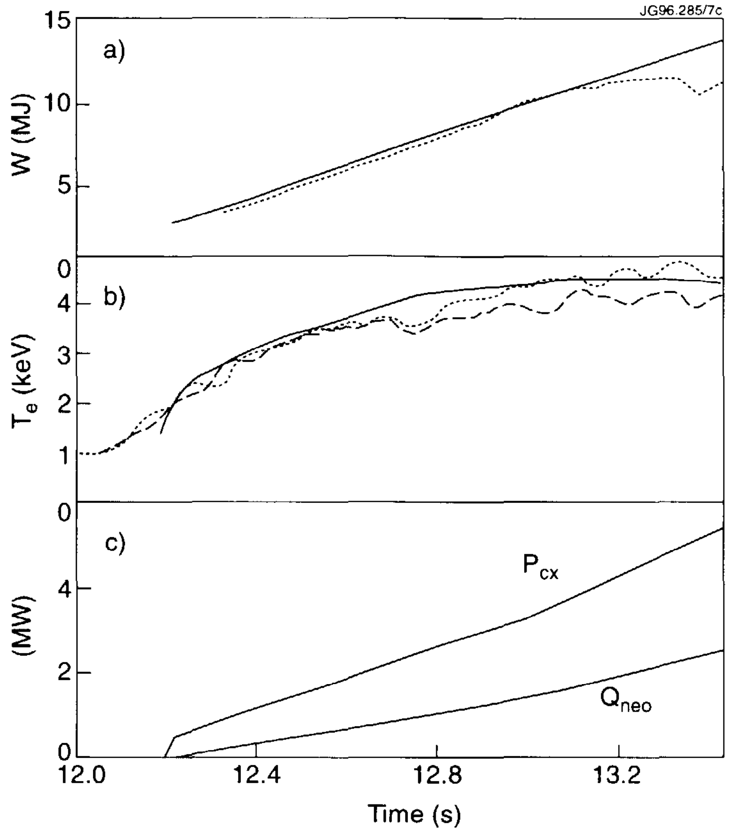

FIG.3 Measured and computed time traces for #33643. Note that experimentally the discharge suffers a 'slow roll over' at t~53.2, *followed by a giant ELM. a) thermal energy (full line is simulated) b)Edge ion temperature. Full line is simulated, the others are from charge. c) Simulated heat losses: full line is total neoclassical losses* Q_{neo}, *dotted line is charge exchange losses to cold neutrals,* P_{CX} . *Note the importance of* P_{CX}, *that nonetheless remains proportional to* Q_{neo}.

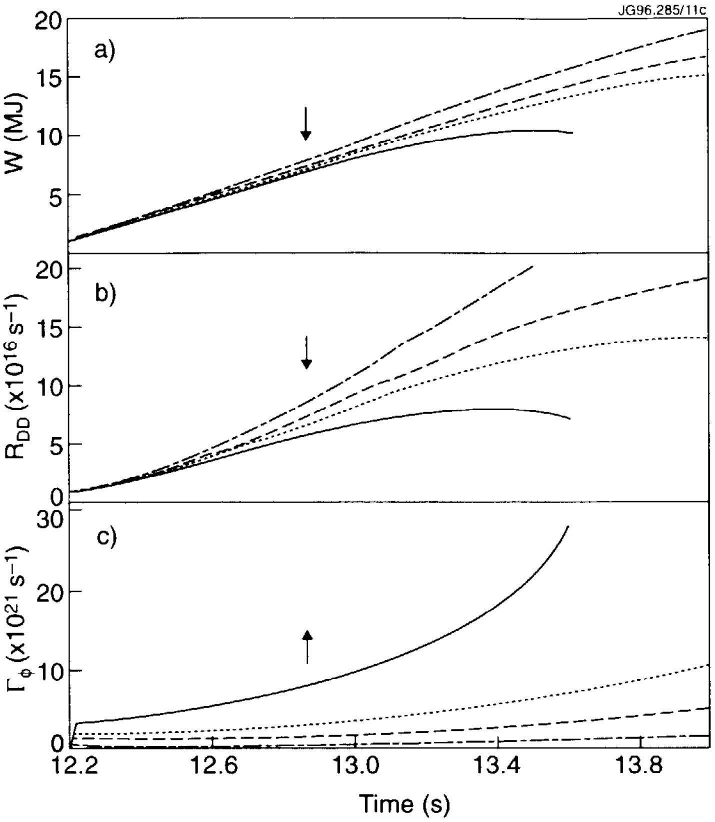

FIG.4 Scan in S^+ =0,0.5,1,2 x10^{21} . *a) energy content b) fusion reaction rate* R_{DD} *c) cold neutral influx from edge* Γ_{ϕ}. *The arrow indicates increasing* S^+.