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Routes to Ignition on ITER by means of Neutral Beams

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1. INTRODUCTION

The aim of this work is to assess the effect of Neutral Beams on ITER, principally in terms of the ability to ignite the plasma using Neutral Beam Injection (NBI). Previous work on Neutral Beams for ITER [1] modelled ITER using Rebut-Lallia-Watkins (RLW) transport [2] without taking the effect of an H-mode threshold power ($P_{L\rightarrow H}$) into account. The present work does use the L→H transition, models the ELMs explicitly and uses the JET transport model by Erba *et al* [3].

In this JET model, transport is split between a GyroBohm term (which is purely local) and a Bohm term which depends on the ***edge*** temperature. The model is implemented in the JET version of the 1_-D predictive PRETOR code [1,4] which is used to explore the route to ignition on ITER by NBI. Various beam energies are considered and the plasma rotation resulting from the momentum input of the beams is described. A complete description of this work is in [5].

2. MODELLING ASSUMPTIONS.

A 7.5% wide artificial barrier models the H-mode barrier. Transport inside this barrier is chosen such, that the ***global*** confinement is L-mode (τ_{96} [6,7]) or H-mode (ITER93-HE [6,8]). The threshold power (in MW) adopted by ITER for a major radius R (m), magnetic field B (T) and density n (10^{19} m^{-3}) is [6]:

$$\mathbf{P_{L\rightarrow H}=0.08n^{0.75}BR^2} \qquad \textit{(formula 1)}$$

Recent evidence from JET [9] indicates an isotopic mass A (amu) dependence:

$$\mathbf{P_{L\rightarrow H}=0.16n^{0.75}BR^2/A} \qquad \textit{(formula 2)}$$

ELMs are explicitly modelled by switching to the L-mode for a short period of time when the ballooning limit is exceeded over the H-mode transport barrier. The plasma energy loss ΔW per ELM for a plasma with energy W, input power P (MW) and surface area S (m^2) is [10]:

$$\mathbf{\Delta W/W=0.00124SB/P} \qquad \textit{(formula 3)}$$

ITER parameters and modelling information are taken from refs. [11-13]. The particle diffusivity D is chosen to be equal to the electron heat diffusivity χ_e and the particle pinches are zero. This implies flat density profiles. The radial momentum diffusivity χ_ϕ is chosen equal to the ion heat diffusivity χ_i.

A 2% Beryllium impurity has been assumed. All ion species are pumped at the edge with removal of 2% of the edge particle flux. NBI has a 6.5m tangency radius.

3. ELMY H-MODE SIMULATIONS

Fig. 1 gives an example of a simulation in which 100 MW of 1 MeV D^o NBI was applied to a I_p=21MA, B_t=5.7T, $n_e=3\cdot10^{19}$ m^{-3} plasma. The density is ramped to several final densities, in this case to 10^{20} m^{-3}. The dense appearance of the radiated power trace is due to the explicit modelling of ELMs. In the example in fig. 1, the helium concentration reaches 8% and the tritium concentration $n_t/(n_d+n_t)$ falls to 42% due to the D^O beam fuelling.

In fig. 2, the time slice between 301 and 305 seconds is expanded to show the ELM's. The 4% variation in stored energy due to the ELM's can clearly be seen. The increase in alpha power during an ELM is caused by the decrease in electron temperature (T_e) during an ELM, which enhances the slowing down of the large population of alpha particles present.

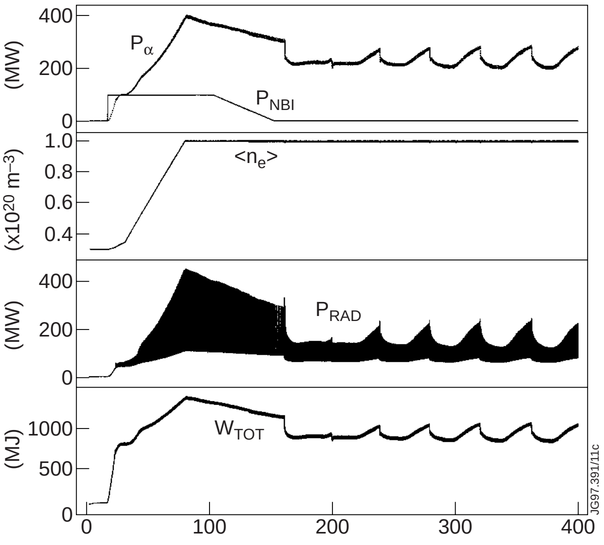

Fig. 1: Route to Ignition on ITER using 100 MW of 1 MeV NBI (a) Beam power and the α-power generated. (b) Density in units of 10^{19} m^{-3}.(c) Radiated Power in MW. (d) Total Stored Energy in MJ.

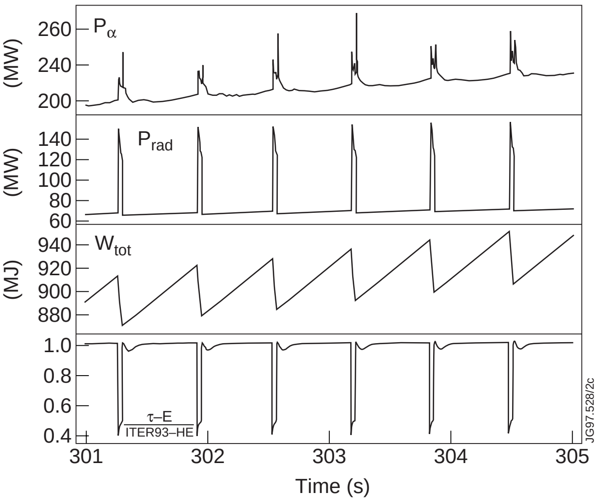

Fig. 2: Simulation detail of a 5 sec period from Fig. 1 with $<n_e>=10^{20}$ m^{-3}. *(a) Alpha Particle Power coupled to ITER. (b) The Radiated Power in MW. (c) The Stored Energy in MJ. (d)* $H_{ITER93\text{-}HE}=\tau_E/\tau_{ITER93\text{-}HE}$.

Fig. 1 shows that the minimum alpha power P_α for a 10^{20} m^{-3} plasma is just above 200 MW. If the threshold for the H→L back transition ($P_{H\rightarrow L}$) would be above 200 MW, ignition could not be sustained. Because P_α depends more strongly on density than $P_{L\rightarrow H}$, an ***ignition domain*** can be identified: it gives the lowest density at which ignition can be sustained for a given threshold power. This lowest density is strongly dependent on the modelling parameters assumed: confinement time; particle transport; helium pumping rate; Z_{eff}; sawteeth, etc. However, it is instructive to make the plot for the present modelling. Fig. 3 gives the lowest density necessary to sustain ignition versus $P_{L\rightarrow H}$. Without H-mode threshold,

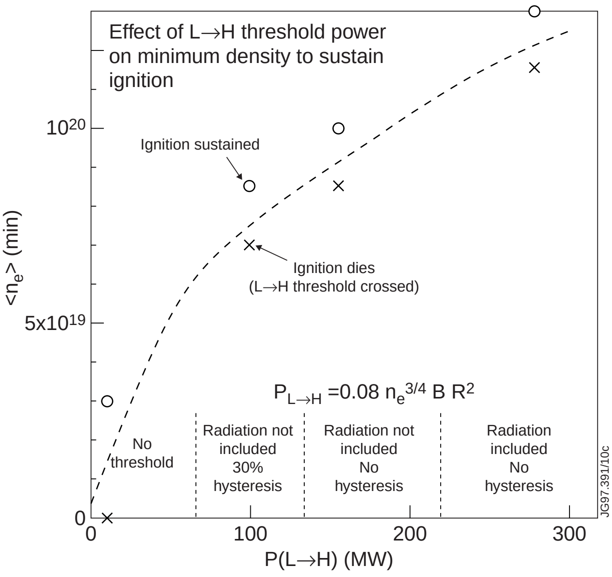

Fig. 3: Minimum Density to sustain ignition vs. $P_{L\rightarrow H}$. *Indicated on the horizontal axis are some assumptions on* $P_{L\rightarrow H}$.

ITER93-HE confinement would keep ITER ignited for almost any density. As soon as a threshold is introduced, the ignition domain shrinks as P_α must exceed $P_{L\rightarrow H}$.

Fig. 4 shows the deposition profiles of 100MW NBI into plasmas with densities in the range of n_e=7.0-14.5 10^{19} m^{-3}. Fig. 5 shows the fraction of beampower coupled to the ions. The remarkably similar profiles are caused by a nearly constant electron temperature, which arises because fusion power increases with density.

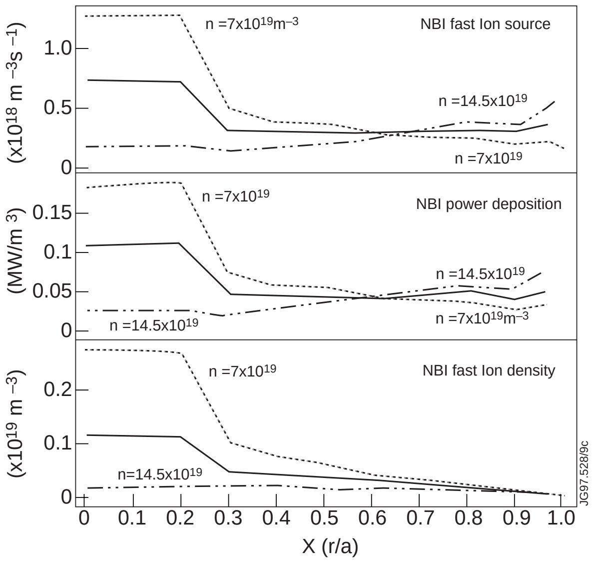

Fig. 4: Elmy H-mode Profiles. 100 MW 1 MeV Beams into $<n_e>$*= 7, 10 and 14.5* 10^{19} m^{-3}*.(a) NBI Fast Ion Source Rate Profiles.(b) NBI Power Deposition Profiles.(c) NBI Fast Particle Density Profiles.*

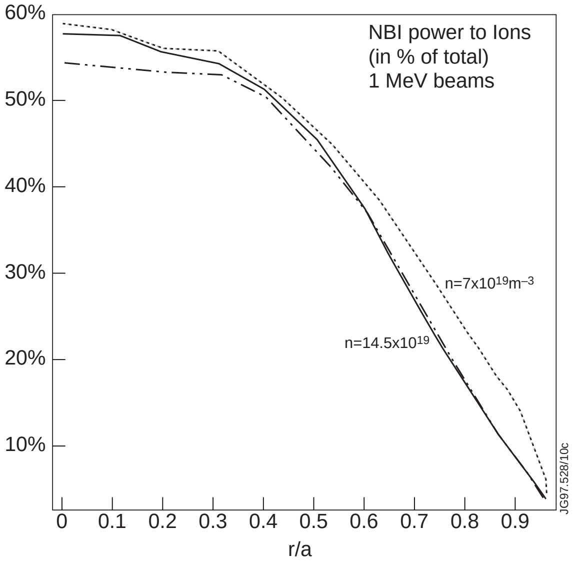

Fig. 5: Fraction of NBI Power coupled to the Ions in Elmy H-mode ITER Plasmas. 100 MW of 1 MeV Beams into plasmas with densities of $<n_e>$*= 7, 10 and 14.5* 10^{19} m^{-3}*.*

4. MINIMUM POWER TO IGNITE ITER

To achieve the H-mode in a n=$3 \cdot 10^{19}$ m^{-3}, B=5.7T plasma, at least 69 MW (NBI+α) is required inside the separatrix (*formula 1*). The minimum NBI power itself was found by running multiple simulations with different NBI power. Once the H-mode is established, the density is increased to 10^{20} m^{-3} and ignition is achieved. Very little additional power is needed during the density ramp.

We performed simulations for 5 different beam energies, ranging from 125 keV to 1 MeV. For each case we took $P_{L\text{-}H}$ from *formula 1* and a more optimistic version (**$P_{L\rightarrow H}=0.055n^{0.75}BR^2$** (*formula 4*)) which is more like *formula 2*. Moreover, it could be argued that the thermal power crossing the separatrix is relevant to achieving the H-mode, rather than the input power. **In that case the power radiated in the bulk of the plasma** (which is significant for ITER but not for present day tokamaks) **must be added to the power requirement**. Therefore, for each of these 10 cases we ran the case with radiated power added to the threshold power as well.

The resulting 20 cases are plotted in fig. 6. Added to the graph are 5 cases of simulations using RLW transport from ref. [1]. It can be seen that the beam energy makes little difference to the minimum power required to ignite ITER because all power that is deposited inside the separatrix ‘counts’. Major differences in the power requirement are caused by the physics assumptions. The key assumptions relate to $P_{L\rightarrow H}$ and the question whether the power flowing out past the separatrix, rather than the power coupled to the plasma is to be taken for the L→H threshold power.

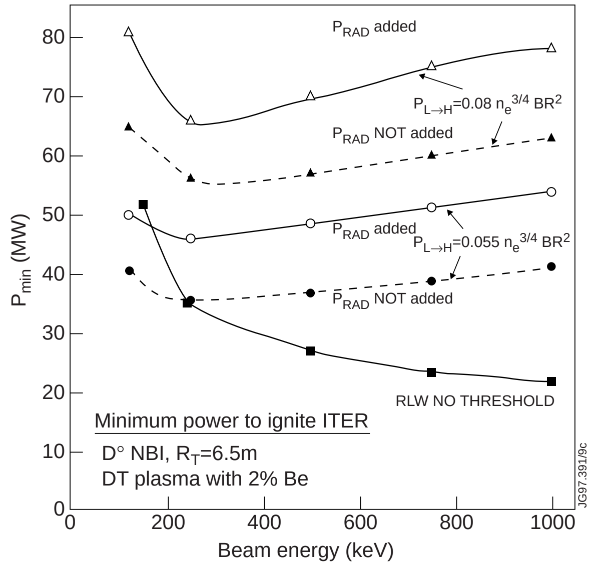

Fig. 6: “Minimum NBI Power to ignite ITER” vs. Beam Energy.(a) bottom: RLW model, $P_{L\text{-}H}=0$, from ref [1].(b) bottom dashed curve: $P_{L\text{-}H}$ from formula 4. (c) Middle solid curve: As (b), P_{rad} added.(d) Top dashed curve: $P_{L\text{-}H}$ from formula 1.(e) Top curve: as (d), P_{rad} added.

Low energy NBI (down to 250 keV) appears to make crossing the H-mode threshold slightly easier. This is because the low-energy NBI generates more alpha power in a low density plasma ($n=3\cdot10^{19}\ m^{-3}$). The extra alpha power is generated due to more central beam deposition, more beam power to the ions and more beam-plasma power. These benefits fall off sharply below 250 keV. The RLW case from [1] is more sensitive to beam energy (fig. 6) because in the absence of an H-mode barrier to keep the power in, the poorer penetration of the beams at higher density does matter.

5. PLASMA ROTATION

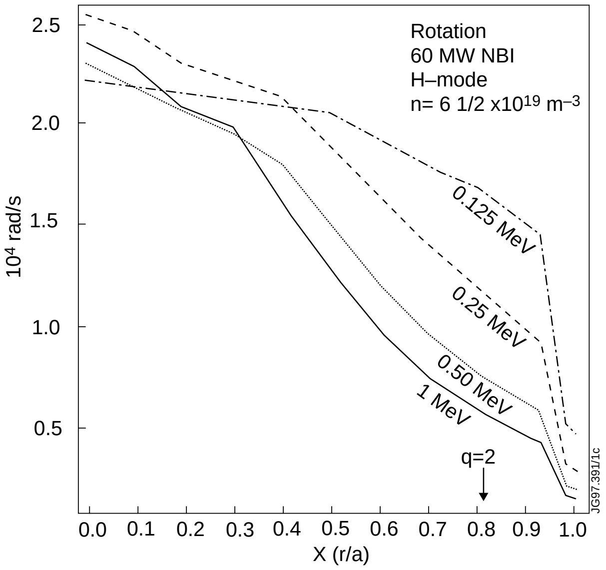

Fig. 7: Simulated Rotation Profiles during the density ramp in ELMy H-mode. 60 MW NBI into a $n_e=6.5\cdot10^{19}$ m^{-3} plasma.

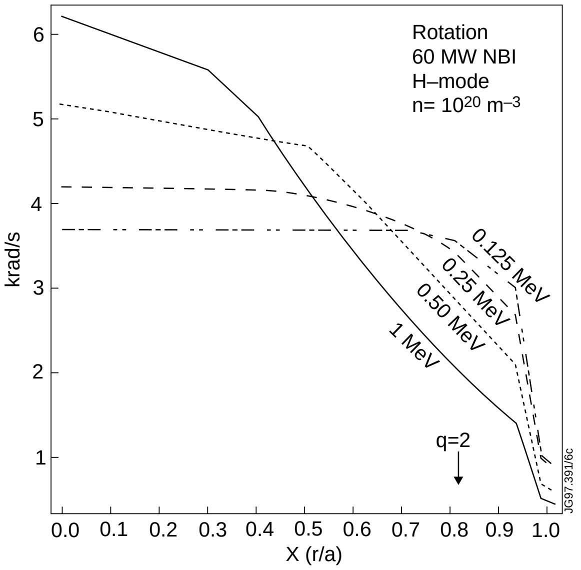

Fig. 8: Simulated Rotation Profiles during the flat top density in ELMy H-mode. 60 MW of Beams into a $n_e=10^{20}$ m^{-3} plasma.

Rotation profiles are plotted in figs. 7 and 8. Fig. 7 gives the rotation profiles for different beam energies at $n_e=6.5\cdot10^{19}\ m^{-3}$. It appears that the central rotation is not very sensitive to beam energy. The rotation at the q=2 surface (located near r/a=0.8) varies strongly with beam energy down to very low energies. Fig. 8 gives the rotation profiles for different beam energies at $n_e=10^{20}\ m^{-3}$. Due to the lack of penetration, low energy beams give a lower central rotation. Rotation at q=2, however, still benefits from reducing the beam energy down to 250 keV.

6. CONCLUSIONS

Neutral Beams provide an excellent means of bringing the ITER plasma to ignition. The minimum power to ignite ITER does not vary much with beam energy and is dominated by the L→H mode threshold power.

We consider the most realistic simulation to be that which uses the JET results for the H-mode threshold in DT [9] and ***adds*** the power radiated within the separatrix to this threshold. On this basis the curve with the open circles in fig. 6 shows that about 50 MW of NBI power is needed to ignite ITER. This figure is largely independent of beam energy but has a shallow minimum at 300 keV for D^o beams.

For inducing rotation a low energy NBI system is best. If very low injection energies are considered for ITER, however, NBI in the periphery of the plasma should be studied on present day machines, especially the effect on the H-mode threshold.

ACKNOWLEDGEMENT

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