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ITER OPERATING WINDOWS WITH VARYING DIVERTOR CONSTRAINTS

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ITER operation in ELMy H-mode has been modelled with self-consistent parameters for the core and edge using the Integrated Core Pedestal SOL Model (ICPS Model [1]) in the 1.5D Astra code. For the underlying turbulent energy transport in the core, the MMM95 [2] transport coefficients are used, and the anomalous particle diffusion coefficient is taken proportional to anomalous energy transport. Stabilization of the turbulent transport by a combination of $E \times B$ velocity shear and magnetic shear leads to a pedestal, whose height and width are self-consistently determined by limiting the pressure to the ballooning limit, expressed in terms of the s-α diagram, which plots magnetic shear s against normalised pressure α, calculated from theoretical formulas including aspect ratio, elongation, and triangularity [3]. In [1, 4] the limiting α determined from this diagram was multiplied by an enhancement factor F_α of two in order to fit experiments on JET and ASDEX-UG with beam heating. Recent experiments indicate that, in the absence of toroidal rotation resulting from toroidal momentum input, the pedestal in pressure may be lower, corresponding to a reduction of confinement by ~10%. For the JET simulation, a reduction of confinement of such a magnitude is obtained if the enhancement factor F_α is reduced from 2.0 to 1.0. For ITER, which is predominantly heated by alpha particles so that external toroidal momentum input is small, an enhancement factor of 1.0 is therefore appropriate.

The alternative, more pessimistic, core transport model GLF23 has also been investigated. Because this model is very stiff, the stabilization evoked above is insufficient to provide a realistic pedestal [4]. We have therefore applied the GLF23 coefficients only inboard of 80% of the minor radius; and retained the MMM transport with stabilization in the outer 20% to define the pedestal. In order to obtain reasonable agreement with the JET experiment, a recalibration of

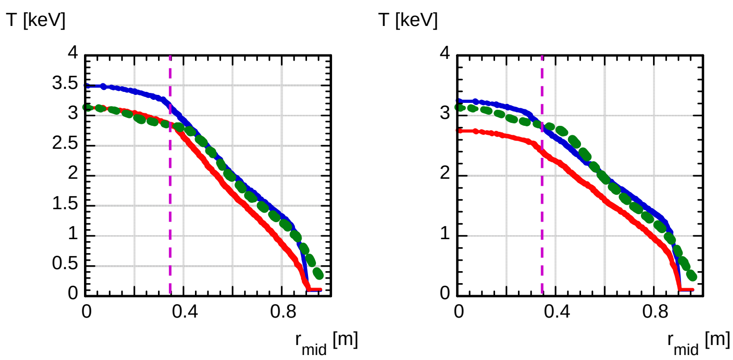

Fig. 1 – JET T_e profiles with core transport model: (left) MMM with F_α =2 (blue) & 1 (red), (right) GLF with F_α = 2.5 (blue) & 1.5 (red) experiment green dashed

F_α was necessary, which gave 2.5 for the case with toroidal momentum input and 1.5 for the ITER-like case with a reduction of confinement by ~10% to account for lack of toroidal momentum input. The JET profiles obtained are shown in fig. 1 and are seen to agree with experiment outside the sawtooth-dominated region (indicated on fig. 1 at ~0.35*a*).

The pressure obtained at the pedestal top in the simulations has been evaluated using a bilinear fitting technique as described in the documentation of the International Pedestal Database [8] and is compared with that predicted by the scaling formula of Sugihara [9]. As seen in figure 2, the simulated values agree with the scaling law to better than 30% for JET with MMM and GLF transport models for both values of the enhancement factor F_α, and the pedestal pressures simulated for ITER lie within 15% of the scaled values.

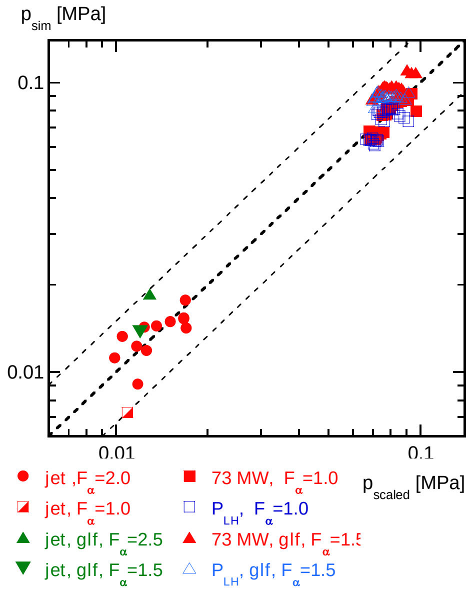

Fig.2 – Pressure at pedestal top obtained in the simulations plotted versus scaling law of Sugihara et al. [9]. Thin dashed lines indicate 30% deviation from scaling law.

For ITER modelling, the boundary conditions at the separatrix are given by scaling laws from 2D edge-modelling, so that core, SOL, and divertor conditions are mutually consistent. The operating space is traced out by trajectories at constant additional heating power with stepwise variation of density, mainly by core-fuelling. The peak divertor power load is held at or below the desired value (here 10 MW/m^2) by adjusting the gas puff. The operating window of ITER [5] is delimited by: (i) Q>5, (ii) P_{add}<73 MW, (iii) separatrix density below (90% of) the limit based on incipient divertor detachment [1,6,7], (iv) density below that giving maximum fusion power at given beam power as density increases, and (v) power conducted into the SOL larger than that required for LH transition (this provides some margin with respect to the LH back transition). These limits are shown on fig. 3 for simulations as described above with the MMM and the GLF models respectively. Note that the maximum beta normalised to the Troyon factor β_N is only 2.6 for the standard case inside the operating window, so that the beta limit does not constrain the operating window.

An operational limit to present experiments is observed to be the Greenwald density, corresponding to $n_e = 1.2\times10^{20}\ m^{-3}$ for ITER conditions at full current, which lies inside the operating window defined above. It has been argued in [1, section 7] and references therein that the density limit, which is the Greenwald density for present primarily gas-fuelled experiments and is found to be consistent with edge modelling when these experiments detach, should be extrapolated to ITER by using analogous edge modelling rather than direct scaling to derive the density limit for that device, which must be primarily core-fuelled (the FWHM in our modelling for core fuelling is ~ 29 cm). Such an approach gives the edge-based density limit (iii) above. Nonetheless, the effect of adopting the scaling approach and limiting operation to below the Greenwald limit is indicated in purple on the contour plots of density of fig. 3.

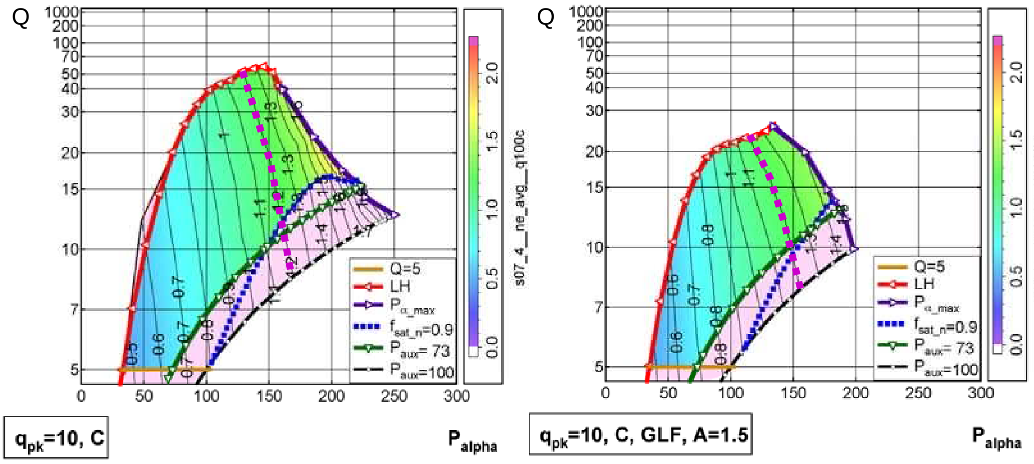

Fig. 3 – Operational window for ITER: average electron density $\langle n_e \rangle$ *[*$10^{20}\,\mathrm{m}^{-3}$*] in the plane* $Q - P_{\mathrm{alpha}}$ *[MW] for (left) MMM and (right) GLF core transport. Limits (i) through (v) as identified in the legend, and Greenwald density contour (purple dashed line) are indicated.*

Fig. 3 shows that the operating windows for both turbulent core transport models are sufficiently wide for the ITER mission, with maximum Q of ~50 and 25, and a maximum P_{alpha} of ~230 and 180 MW at Q's of ~15 and 13 for the MMM and GLF models respectively. Even at the Greenwald density, P_{alpha} in excess of 100 MW at Q=15 is possible for both transport variants.

It has been shown [1,4,5,6,7] that the density inside the separatrix is determined mainly by the direct core fuelling (e.g. pellets penetrating up to ~0.85*a*), but that SOL and divertor conditions are determined by the DT pressure in the divertor, i.e. the total throughput including gas puff divided by the pumping speed. If it were desired to reduce the throughput (e.g. to limit the recirculated DT), the peak power at the divertor plate could in principle be maintained at the same value by reducing the pumping speed if no other constraints apply. The operating space has accordingly been traced out (for MMM transport) with the pumping speed reduced down to one-third of that envisaged for ITER (fig. 4). The operating range is affected only below one-half the nominal pumping speed, when the core fuelling alone exceeds the throughput required to limit the peak power load to 10 MW/m^2 and no gas puffing is required in part of the window. This occurs in the upper-right-hand region where the edge density limit rather than the low-temperature limit is then applicable. Note that helium content does not significantly constrain the operating window because the SOL-divertor modelling includes neutral-neutral collisions, which reduce the back-streaming of helium into the core [10].

Since the operating windows are always specified for a ceiling of peak power per unit area equal to a given value q_{pk}, it is important to examine how the operating window is influenced by this chosen value. The major effect of reducing the q_{pk} limitation is caused by the increase in the throughput necessary to maintain this value of q_{pk} at a given point in the $Q-P_{\mathrm{alpha}}$ diagram, leading to a more severe edge density limit constraint, as seen on fig. 5.

It has thus been demonstrated that the pedestal pressures obtained with the ICPS model fit well with the scaling law derived from the pedestal database for JET and ITER, and that the operating window for ITER is adequate for the ITER mission for both MMM and GLF core transport models. Reduction of the pumping speed by up to a factor of two is possible without affecting the window significantly. A reduction in allowed peak power on the divertor plate constrains the operation at high fusion power via the edge-based density limit.

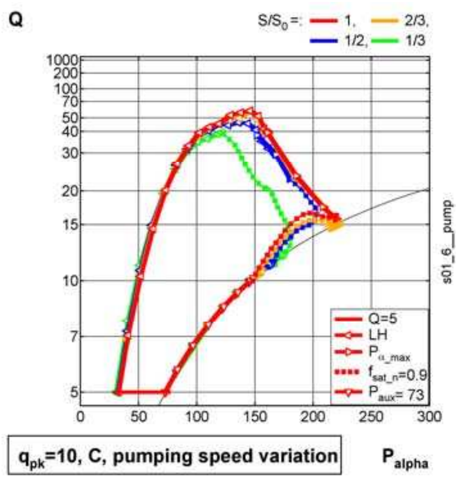

Fig. 4 – Operating windows for pumping speed 1, 2/3, 1/2, and 1/3 of normal (colours indicate case, symbols and line styles indicate active limit as in legend

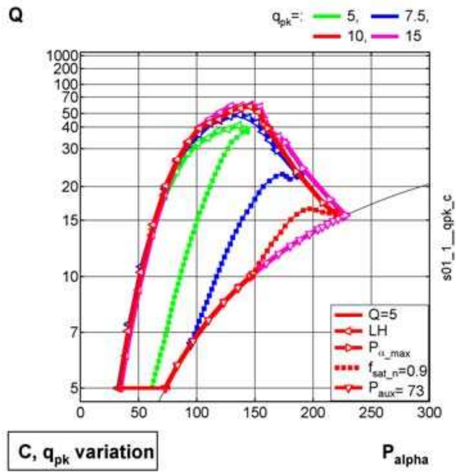

Fig. 5 – Operating windows for limiting q_{pk} of 5 , 7.5, 10, and 15 MW/m^2

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