Application of a 1-D Predictive Model for Energy and Particle Transport to the Determination of ITER Plasma-SOL Interface Parameters

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Abstract: The constraints of divertor operation have been applied to ITER core plasma simulations by imposing boundary conditions which describe the effect of the divertor. At the nominal average core density for ITER with the ICPS transport model stationary operation with a fusion power multiplier Q of 12 –16 is obtained and a reasonable operating range exists. The relaxation to these stationary conditions is very slow, and transient values of fusion multiplier are appreciably higher.

1. Introduction

The Integrated Core Pedestal Sol Model (ICPS Model) implemented in the 1.5D Astra code, which has been presented in previous publications (e.g. [1]), is updated and applied to ITER conditions in order to determine the core conditions consistent with scrape-off layer (SOL) parameters. For the simulations presented here, the 1.5D core calculation is coupled to the SOL parameters by imposing self-consistent boundary conditions obtained by fitting scaling laws to a database of B2-Eirene results [3-4].

2. Description of the ICPS Model

The ICPS model contains transport formulations for the plasma core as well as for the self-consistently determined pedestal region near the separatrix ([1] and references therein). In the core, both energy transport channels are described by critical temperature models, with a stiffness of 1 for electrons and 5 for ions, i.e. the temperature profiles are appreciably stiffer for ions than for electrons (the value of 3.5 for ions given in [1] should have been 5).

The model for non-classical transport can be summarized as follows (for the equations see [1]). In the core, the dominant ion energy transport is neo-classical plus ITG, the latter based on a modified IFSPPL model (e.g. shorter gradient lengths adjusted to a JET discharge). Electron energy transport is similar to the RLW model (the RLW critical gradient is modified to depend on shear and adjusted to JET). An Alfven drift term dominant at the plasma edge disappears once a certain edge β is achieved and thus can trigger the H-mode transition. The particle transport for helium and DT is formulated as the Ware pinch and a diffusion coefficient given by $D = 0.1\ (2\chi_e+\chi_i)$. Fuelling is accomplished by the inward neutral flux at the separatrix, to which is added pellet fuelling (approximated by fuelling inside the separatrix with a fall-off length of about 50 cm). The total helium source is determined by the fusion reactions, to which is added the inward neutral helium flux across the separatrix.

The non-classical transport is taken to be stabilized by radial electric field shear and magnetic shear. The effect of type I or type II ELM's is implemented as a time-averaged ELM model, which limits the pressure gradient to the ballooning limit by increasing transport equally for

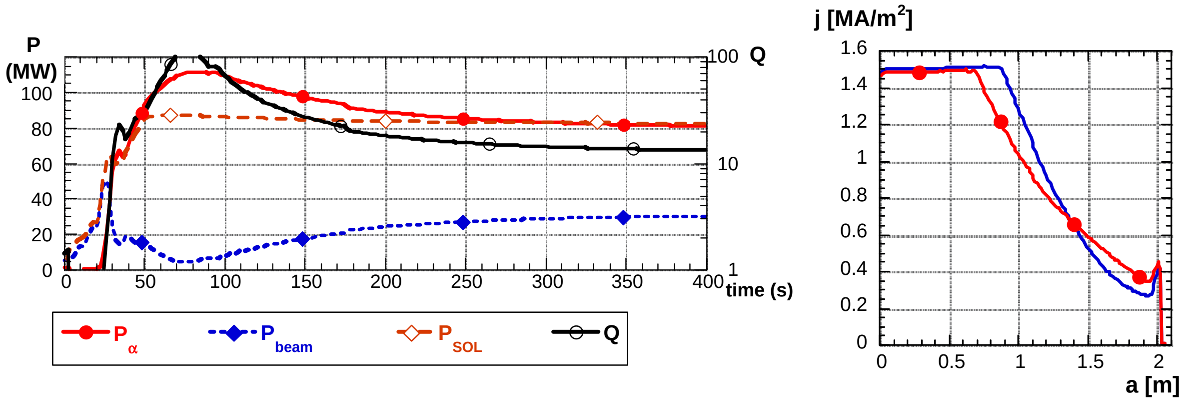

FIG.1.Relaxation to stationary conditions with S_{DT}=10 m^3/s, P_{SOL}~80 MW, $q_{pk} \leq 10$ MW m^{-2}, $\langle n \rangle$=1.×10^{20} m^{-3}. Left alpha power, heating power, and Q as a function of time, right current profiles early (100s,blue, no symbols) and late (400s, red with symbols).

both electrons and ions when this limit is reached. The associated particle transport coefficient is taken to be 30% of the heat transport coefficients.

3. Relaxation to Stationary Conditions

The Astra code calculates the time evolution of the radial profiles (1D) of the discharge with self-consistent 2D equilibrium for the magnetic surfaces. Thus, when the density and power are ramped up from the initial low β conditions, the equilibrium, i.e. the current distribution and the associated magnetic shear, relaxes from the initial conditions to the stationary state on the resistive time scale (100's of seconds in ITER with appreciable fusion power). As the expressions for anomalous transport depend strongly on magnetic shear, both explicitly (eq. 2 and 3 of [1]) and implicitly in the IFS/PPPL critical quantity (in eq. 1 of [1]), the pedestal and core confinement also relax on this time scale, leading to a slower relaxation of plasma parameters than at constant transport. Transiently, the fusion performance is enhanced over the stationary value (fig. 1), the enhancement depending on the rampup scenario (Q_{max}~120 here), relaxes in ~200s to Q = 14.3, and attains a stationary value of Q = 13. In the following sections, all results apply to close to fully relaxed conditions.

4. Coupling to the Scrape-Off Layer

The dramatically different characteristic time scales for the core plasma (100's of seconds) and the SOL (milliseconds) render a direct coupling of the two simulations impractical for parameter space exploration, even though this would be desirable for the investigation of transient effects such as ELM's. The approach chosen here is to apply boundary conditions at the separatrix for the core simulation, expressed as scaling relations derived from the 2-D computations for the plasma edge [3-4]. Presently, these include separatrix DT and He densities, separatrix ion and electron temperatures, and separatrix inward neutral DT and He fluxes (other impurities are not yet coupled). The neutral DT temperature is set to about one-half the ion temperature at the separatrix (i.e. ~150 eV) and the neutral helium temperature is held constant at 30 eV. The preceding quantities are calculated from the scaling relations using as inputs from the core calculation the power transported across the separatrix by electrons, that transported by ions, the fusion power, and the DT and He ion fluxes into the SOL. Control parameters for the core simulation are then the core fuelling flux Γ_{core} ("pellet" fuelling, set to give the desired core density), the gas puff flux into the vessel Γ_{puff}, the pumping speed in the divertor for DT S_{DT}, and the additional heating power P_{aux}. For the scans, P_{aux} is adjusted to give a power transported across the separatrix P_{SOL} approximately

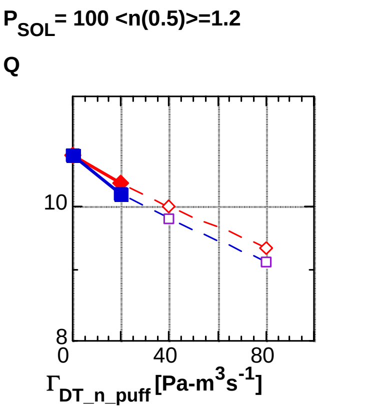

FIG.2. Effect of gas puff (0 to 80 Pa-m^3/s) and helium on Q (top with, bottom without helium scaling),

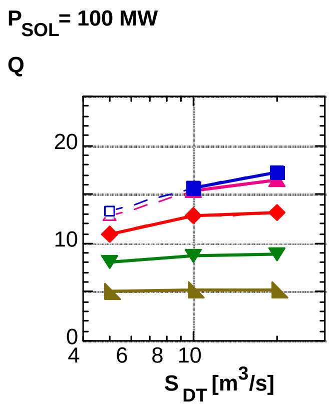

FIG.3. Variation of Q with pumping speed at (from bottom) ⟨n⟩ ~ **0.7**, **0.9**, **1.1**, **1.25** & **1.4**

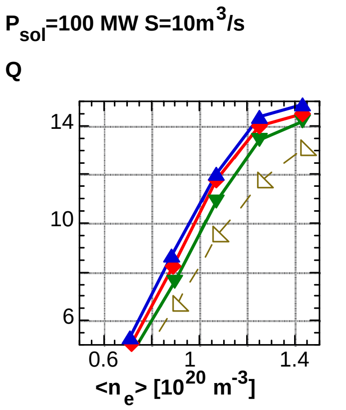

FIG.4. Variation of Q with allowable peak power for (top to bottom) $q_{pk} \leq$ **12.5**, **10**, **7.5**, **5.0**

(unless otherwise indicated, S_{DT}=10 m^3/s, P_{SOL}~100 MW, $q_{pk} \leq 10$ MW m^{-2}, ⟨n⟩ ~ 1.1×10^{20} m^{-3})

constant. Γ_{puff} is set for the desired maximum peak power q_{pk} on the divertor plate (using the scaling of [4]). Only the scaling of regime (a) (before saturation of n_{sep}) is employed; in the figures, points within regime (a) for which this scaling applies are plotted with solid symbols and continuous lines, points outside (scaling not applicable) are plotted with open symbols, and dashed lines connect the two regions, i.e. the end of regime (a) occurs somewhere on the dashed line between solid and open symbols.

5. Effect of Gas Puff and Helium

Increasing the gas puff Γ_{puff} increases separatrix density and separatrix fuelling, with a resulting slight decrease of core fuelling. As a result, the electric shear is reduced and the confinement is degraded, resulting in a decrease of Q (fig. 2). Here, Q of 10.9 without gas puff would be reduced to 9.1 if helium density at and helium flux across the separatrix are artificially held constant. The degradation of confinement with increased gas puff and/or separatrix density is qualitatively similar to experimental observations. This effect is reduced in the correct calculation with scaled helium (i.e. Q becomes 9.3 at high gas puff), because gas puffing reduces the separatrix helium density and neutral flux, thereby decreasing fuel dilution. The effect of helium variation is small because the latest B2-Eirene calculations, which include elastic helium collisions, give generally low helium concentrations in the SOL [3-5], so that fuel dilution in the plasma core is not problematic (here, $\langle n_{He}\rangle/\langle n_e\rangle$ goes from 1.6% to 1.3% as Γ_{puff} is increased).

6. Effect of Pumping Speed

Higher divertor pumping speed S_{DT} decreases the separatrix electron density, thereby increasing the electric field shear and improving the confinement in the model. In addition, the helium density and the neutral fluxes across the separatrix are also decreased. The improvement of fusion performance with increasing pumping speed is illustrated on fig. 3. For these simulations, the gas puff has been adjusted so that the peak power on the divertor plates q_{pk} is limited to a maximum value of 10 MW/m^2.

7. Effect of Varying the Allowed Peak Power on the Divertor Plate

According to the B2-Eirene results, the peak power on the divertor plates q_{pk} depends on P_{SOL}, the total particle flux Γ_{tot} (= Γ_{core} + Γ_{puff}), and S_{DT}. At constant P_{SOL} and pumping speed and in

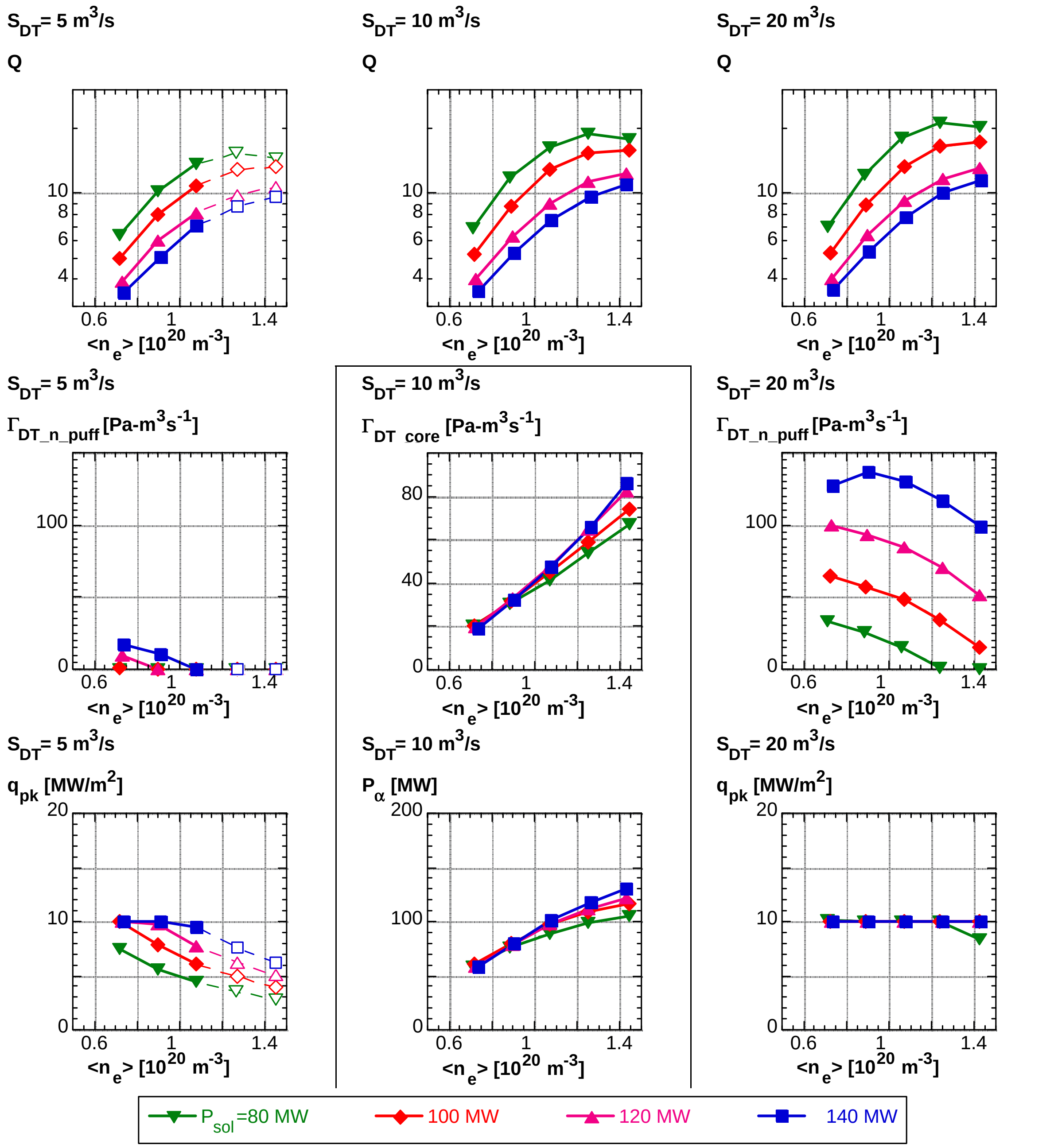

FIG.5.Illustration of core operational space. Columns are for S= 5,10, and 20 m^3/s resp. Abscissa of all plots is average density. Top line Q; second line Γ_{puff} (left & right) and Γ_{core} (middle). Third row q_{pk} (left & right) and P_{α} (middle). Core fuel and alpha power vary little with pumping speed.

the absence of non-helium impurities other than intrinsic carbon, limiting the allowable peak power to a lower value than the reference one therefore would require a higher gas puff. Since this tends to reduce core fuelling and to increase the separatrix density, the confinement would be degraded and a lower fusion performance would result (fig. 4). Conversely, a higher allowable power loading could improve fusion performance somewhat.

8. Core Operation Consistent with Divertor Conditions

The core operational space has been explored for a peak power load of 10 MW/m^2 on the divertor plate, by varying central density and pumping speed (fig. 5). For the scans, we have chosen to hold P_{SOL} approximately constant by varying P_{aux} as the density is varied, because this is a key quantity for the SOL and divertor plasma. For most curves, Q is seen to increase with density. Note that, for all cases, direct core fuelling is appreciably larger than the separatrix neutral flux, so that the Greenwald density limit is not likely to be a hard limit. Because of the stiffness of the core transport, the fusion power is relatively insensitive to heating power, and depends mainly on core density (similar to the behaviour in [6], which used different transport models). The fusion performance therefore increases with decreasing P_{SOL} because then this profile stiffness means that additional heating power decreases faster than fusion power. It increases with pumping speed, which improves confinement by lowering the separatrix density.

9. Discussion and Conclusion

The constraints of divertor operation have been applied to ITER core plasma simulations by imposing boundary conditions which describe the effect of the divertor. Only such an integrated approach leads to a set of resultant core parameters which are consistent with the divertor parameters and vary consistently with these. At the nominal average core density for ITER ($1.0\times10^{20}m^{-3}$) with the core transport model described above, stationary operation with a fusion power multiplier Q between ~12 and ~16 (with P_{fusion} between 390 and 440 MW respectively and P_{SOL} ~83 MW) is obtained for divertor pumping speeds between 5 and 20 m^3/s and peak divertor plate power loads up to 10 MW/m^2. Q values above 20 are accessible at $n_{Greenwald}$ and above, which is not unreasonable considering the predominant core fuelling. A reasonable operating range exists for all parameters (fig. 5). Higher pumping speeds, higher allowable peak power load, and higher density are generally favourable for maximizing Q. In the relevant regime, the fusion power is mainly determined by the direct core fuelling rate, and the peak power load on the divertor plate can be controlled almost independently by gas puffing. The relaxation to stationary conditions is very slow, and transient values of fusion multiplier close to ignition are obtained, appreciably higher than the fully relaxed values of 12-16 quoted above. Further work aims to investigate transport models based more on first principles ([6] and references therein) and to integrate also the intrinsic and seeded impurity behaviour into this treatment.

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