Transport Modelling of a Fusion Power Plant (DEMO)

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Introduction. In the last few years the EU fusion programme the "Power Plant Conceptual Study" (PPCS) has been conducted [1]. In parallel with environmental, safety and economic aspects this study puts forward also technology and physics bases of a fusion power plant. The physics properties, in particular, physics of divertor, core confinement and current profile control (current drive) are the very essential but still not well defined elements of this scoping study. A possible way to eliminate a number of ill-defined parameters and thus improve reliability of existing scaling-based predictions is transport simulation employing first-principle models of microturbulence. Such a theory-based approach is adopted in this contribution.

Simulation model. For transport description of the plasma core we selected the GLF transport model [2]. Credibility of this theory-based approach is supported by massive numerical and experimental efforts in the last years. Although the present-day comprehension of the core transport is relatively good there is a lack of understanding of pedestal physics. It is generally accepted that a pressure gradient in the pedestal is restricted by the ballooning limit. However, calculation of this limit is a quite subtle problem because plasma parameters (pressure, shear, safety factor, geometry) in this zone vary very rapidly, moreover, they all are strongly coupled so that occasional changing one of them can cause a long chain of related rearrangements that is very hard to trace. Instead of attempts to describe this zone by transport models and introducing uncertainties that are difficult or impossible to evaluate we shall prescribe the plasma pressure at the pedestal top and consider it as a free parameter.

As the next observation note that the density is expected to be supplied by a surface particle source (pellets or gas puffing) irrespectively of the pedestal transport. It means that prescribing the average plasma density at a given core transport one has to define the plasma density at the pedestal top, appropriately. Once the pedestal pressure is also prescribed it remains to adjust the pedestal temperature consistently that provides a complete set of boundary conditions. In this way a simulation model can be constructed that, in addition to the average plasma density, includes only one free parameter, the plasma pressure at the pedestal top.

Pulsed scenario. In PPCS, a steady-state scenario is considered as the main operational mode although pulsed operation is also admitted as a fall-back option. This analysis will be started with a pulsed scenario because it involves minimum of additional assumptions. Fusion powers calculated in 0D and 1.5D models for three different DEMO options [1] are compared in Table 1. The calculations (2nd line in Table 1) are performed for the fixed pedestal pressure of $p_{ped} = 200$ kPa that is adjusted to get close fit for the fusion powers required in PPCS. Under this assump-

Table 1. Fusion power (GW)

Model	A	B	C
Scaling-based (0D)	5.0	3.6	3.4
Theory-based (1.5D)	4.8	3.8	1.5

tion, the PPCS values for DEMO A and B are close to the results of transport modelling. Although numerous scalings for p_{ped} give a large scatter they typically predict much lower

value: $p_{ped} = 100$ kPa (e.g. [3]). Reduction of p_{ped} will result in a corresponding reduction of P_{Fus} that in the considered range of parameters scales approximately as $P_{Fus} \approx p_{ped}^{1.5}$. It follows that the GLF transport model predicts too low performance for the conventional pulsed scenarios. The difference is even more pronounced for DEMO C. This happens because the Model C DEMO is not compatible with the simple model discussed above. It should employ a kind of advanced scenario that will be considered below.

In frames of our transport model the average plasma density can be considered as an external parameter. However, the fusion power shows a very low dependence on density in the range $0.8 \leq \bar{n}_e/n_{Gr} \leq 1.4$ with weekly pronounced maximum at $\bar{n}_e = 1.2 n_{Gr}$. It happens because, at fixed p_{ped}, increasing the plasma density results in decreasing temperature and has no effect on the plasma pressure that is mainly responsible for the fusion power. Finally, it is important to emphasise that no additional heating is assumed here. If such a heating is applied it can increase the fusion power though the effect is small because of strong confinement degradation.

Advanced scenario. Alternative to the pulsed inductive regime with a relatively poor confinement could be an advanced scenario with an internal transport barrier (ITB). In order to include ITB description in our simulation model it was assumed that the turbulent transport is suppressed in a zone of a negative magnetic shear in line with [4]. Assume now that an off-axis external current drive (e.g. due to LH or/and EC) with power deposition at the plasma periphery, $\rho_{tor} \geq 0.7$, is applied. When the driven current is high enough then a reversed shear
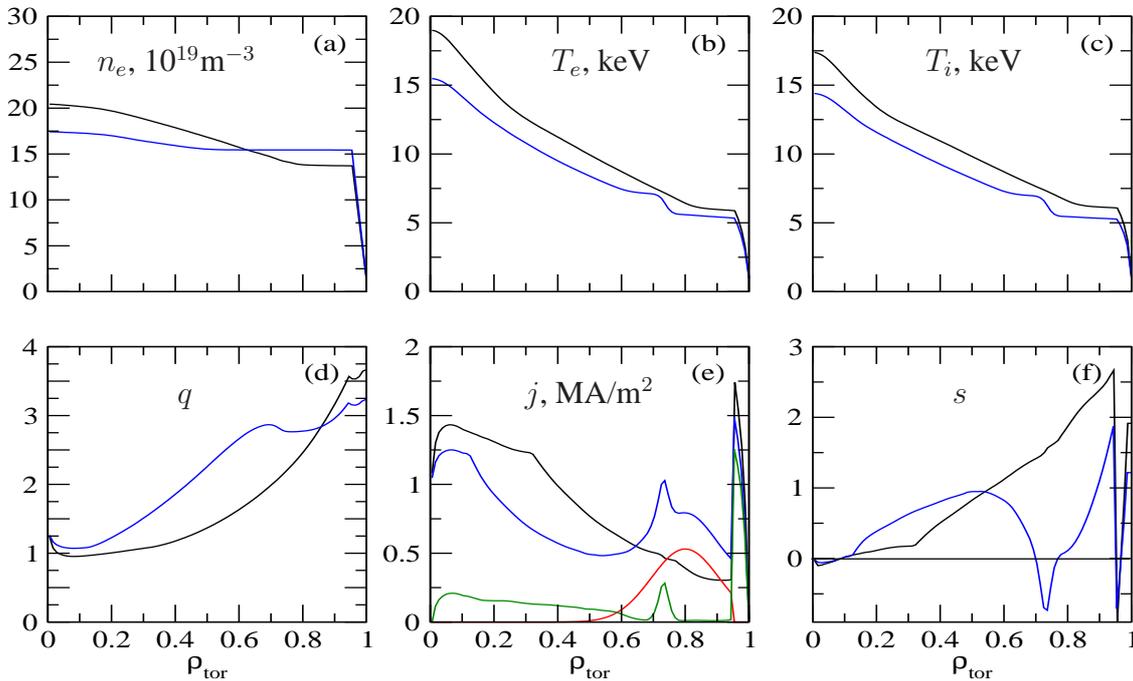

Fig. 1. ITB formation for DEMO C parameters: $R = 7.5$m, $B_T = 6$T, $I_{pl} = 20$MA. Plasma profiles are shown before (black) and shortly after (blue) applying external current drive. (a) Plasma density. (b,c) Electron and ion temperatures, respectively. (d) Safety factor. (e) The total current density, driven current (red) and the bootstrap current (green). (f) Magnetic shear.

zone can be formed as shown in Fig. 1(d,e,f). The latter is followed by a local suppression of the anomalous transport and building-up a gradient zone in temperature (Fig.1(b) and (c)).

This is accompanied with a pronounced local increase of the bootstrap current density. The maximum of the bootstrap current is shifted inside with respect to the maximum of non-inductively driven current. Such an alignment provides a capability of extending the negative shear region deeper into the plasma and, in turn, of broadening the ITB zone. On one hand, this process has a threshold in the external power: (i) the driven current should be large enough in order to create a seed negative shear region, (ii) this region must be sufficiently extended to result in a noticeable augmentation of the bootstrap current. On the other hand, above a certain level the secondary bootstrap current starts to grow uncontrollably.

Although this instability has a quite slow (skin-time scale $\approx 10^3$s) growth rate its evolution can have far reaching consequences. If this instability is saturated by a mechanism similar to the "current hole" formation then it opens a route to fully non-inductive steady-state operation with a high performance. Unlike the present-day observations this regime once formed should be stable (on the diffusive time scale) because the location of ITB is defined and controlled by the external RF source. However, there is a difference with the typical current-hole formation in todays tokamaks: ITB is started much further outside. Therefore, $q = \infty$ appears first not on the magnetic axis rather than around the plasma mid-radius. This corresponds to a very peculiar current profile that makes a assessment of MHD stability hardly possible.

Steady-state operation. Keeping in frames of our simulation model we will now consider another option. One can suppress the described bootstrap instability by a simple feedback algorithm

$$\frac{dP_{CD}}{dt} = \alpha_1(\overline{U}_{pl} - U_0) + \alpha_2\frac{d\overline{U}_{pl}}{dt}, \qquad \overline{U}_{pl}(t) = \int_{t-\Delta_t}^{t} U_{pl}(t)dt \qquad (1)$$

where P_{CD} is the CD power (actuator). Averaging over the time interval $\Delta_t = 1$s is introduced because instant value of the loop voltage $U_{pl}(t)$ can have quite erratic behaviour. The parameter U_0 defines the fraction of residual Ohmic current. In particular, $U_0 = 0$ corresponds to fully non-inductive operation. Finally, the two parameters $\alpha_{1,2}$ are adjusted to obtain desired properties of the control. The rule (1) is effective provided that driven and bootstrap currents are localised sufficiently close to the plasma surface where the loop voltage is measured. If the algorithm (1) is applied every 1 s it gives rather robust control of the bootstrap current fraction provided this fraction is not too high, in practice $\leq 60\%$.

Comparison of PPCS data with the transport modelling is presented table in Table 2. Despite the pedestal pressure is reduced with respect to Table 1 down to 100 kPa the fusion

Table 2. Advanced scenarios for DEMO-C model ($R = 7.5$m, $B_T = 6$ T).

Model	I_{pl}	P_{Fus}, GW	P_{add}, MW	n/n_G	I_{BS}/I	Q	U_0, V	p_{ped}, kPa
0D	20.1	3.41	112	1.5	0.63	30	–	–
1.5D	16	1.5	130	1.2	0.41	11.3	0.01	100
	16	2	122	1.2	0.49	16.3	0.005	100
	16	2.1	95	1	0.56	22.5	0	100

power increases. This pedestal pressure can be considered as quite plausible and results are not very far from predictions of PPCS. The only essential difference is reduction of the total plasma current that is necessary for keeping driven current fraction high enough.

Plasma profiles for the steady state scenario (the bottom row in Table 2) are shown in Fig. 2. Here the time averaged Ohmic current and the loop voltage are equal to zero and
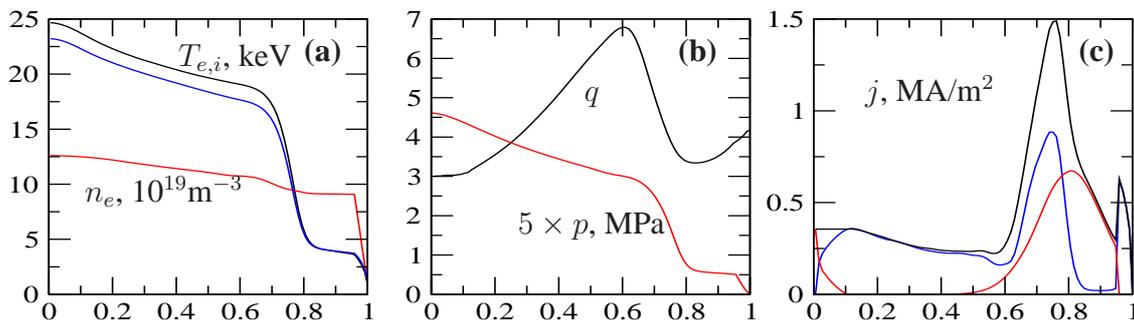

Fig. 2. Plasma profiles for a steady state scenario with the feedback control of the loop voltage. Here $R = 7.5$m, $B_T = 6$T, $I_{pl} = 16$MA. (a) Plasma density, electron and ion temperatures. (b) Safety factor q and plasma pressure p. (c) Total current (black), driven (red) and bootstrap (blue) current densities.

the feedback algorithm maintains the bootstrap current at the level of 8.9 MA. An extended zone of negative shear and improved confinement is localised around $\rho_{tor} = 0.75$ where the bootstrap current has maximum. Artificial seed current is added in the vicinity of the magnetic axis. A total of 40 kA of this current is needed in order to fill the central gap in the bootstrap current. The rest of 7.1 MA with a maximum at $\rho_{tor} = 0.8$. is assumed to be driven by an external source and is used as an actuator in the feedback scheme (1). Stability of this non-inductive scenario should be additionally examined. Preliminary results are discussed in [5].

Conclusions and outlook. Conventional pulsed scenarios for DEMO are hardly compatible with predictions of the GLF transport model and current pedestal models. Advanced approaches are required to achieve DEMO performance goals. In this paper, a steady-state non-inductive scenario is proposed. Improved confinement is due to negative shear largely created by the bootstrap current ($\approx 55\%$) and stabilised by externally driven current. This regime has evident attraction for high-Q steady state operation. Unfortunately, it is difficult to reproduce this regime in existing tokamaks because it requires (i) high power production in the plasma core, (ii) peripheral current drive with a high power at the initial trigger phase of the process at least. Studying this opportunity could be a challenging task for ITER operation. The regime will be further optimised with respect to plasma current, density, CD power deposition profile and other parameters. A stable route to the steady state distributions shown in Fig. 2 is subject of a separate study.

References

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