# DEVELOPMENT OF A PLASMA SCENARIO FOR THE EU-DEMO: CURRENT ACTIVITIES AND PERSPECTIVES

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## Abstract

In order for the first fusion reactor DEMO to accomplish its mission [1], it is necessary to identify plasma scenarios which both perform in terms of fusion power generation and are sufficiently stable to ensure the integrity and availability of the machine components for a long time. The activities undertaken for this purpose by EUROfusion Power Plant Physics & Technology (PPP&T) are summarized in this paper. Throughout the course of the current pre-conceptual design analysis phase for the European DEMO, it is necessary to define scenarios by considering from the early phases their compatibility with the available diagnostics, of the actuators for plasma control and with the response of the heating and current drive systems. A coupling between the 1D transport code ASTRA [2,3,4] and the control software Simulink has been performed, providing a tool able of simulating plasma behaviour while accounting for the constraints linked to the detectability of the signals and the delay and power limitations of the actuators responses [5]. In parallel, the numerous ongoing activities concerning the open issues which require addressing are reviewed. The reference scenario which is considered for the EU-DEMO is the so called "DEMO 1" [6], i.e. a pulsed configuration based on conservative physics assumptions and analogous, at least from a macroscopic level, to the ITER 15 MA ELMy-H mode. The main alternative concept developed is the so called Flexi-DEMO [7], which relies on a more advanced scenario compared to DEMO 1, with a large fraction of auxiliary current drive and a tailoring of the safety factor profile, in order to maximize the bootstrap current fraction and thus to achieve a long, or even steady-state discharge. However, the significant difficulties linked to an active ELM control suggest that other, more speculative ELM-free scenarios [8,9,10,11] might be more suitable for a reactor operation – in spite of their reduced fusion performance.

## 1. INTRODUCTION

In order for the first fusion reactor DEMO to accomplish its mission, namely to demonstrate nuclear fusion to be a technologically reliable source for the production of electrical energy [1], it is necessary to identify plasma scenarios which are, at the same time, both performing in terms of power generation and sufficiently robust to ensure the integrity and availability of the machine components for a long time. This leads to the following high-level plasma scenario criteria:

- Providing a sufficient amount of fusion power, which in turn requires possessing a high plasma confinement capability and being able to avoid the accumulation of impurities in the plasma core, both seeded and intrinsic.
- Requiring a sufficiently low auxiliary recirculated heating and current drive (H&CD) power during flattop in comparison to the expected electricity generation.
- Being disruption-free or as stable as possible against disruptions, both during the flattop and during the transients, planned and unplanned.
- Maintaining the heat load on the plasma facing components below the technological limits both during planned operation and off-normal events.

Various activities concerning the physics gaps of DEMO have been undertaken in the last years in EUROfusion PPP&T department, addressing both the peculiar aspects of plasma physics as well as the integration with the relevant engineering aspects, as an example H&CD design, pumping, fueling and diagnostics [12]. In our work, the current status of these activities is presented and reviewed.

## 2. BASELINE

In spring 2018, a new physics baseline for EU-DEMO 1 produced by means of the systems code PROCESS [13,14], has been released. The requirements of 2000 MW fusion power, 500 MW net electric power as well as the 2 hours burn time have been maintained. Table 1 summarizes the most relevant (physics related) parameters of EU-DEMO 2018 for the Flat Top (FT) plasma phase. The corresponding values of 2017 baseline are also reported for comparison.

TABLE 1. DEMO 1 Parameters FT phase

| | DEMO Physics 2018 | DEMO Baseline 2017 |
|---|---|---|
| $R$ [m] | 9.00 | 8.93 |
| $B$ [T] | 5.86 | 4.89 |
| $q_{95}$ | 3.89 | 3 |
| $I_p$ [MA] | 17.75 | 19.07 |
| $P_{fus}$ [MW] | 2000 | 2000 |
| $P_{sep}$ [MW] | 170.4 | 156.4 |
| $P_{aux}$ [MW] | 50 | 50 |

As one can observe, the main modifications with respect to the previous baseline are:

- Stronger magnetic field at (almost) the same radial size. This has been made possible by the improvement of the calculation method for the effective plasma charge $Z_{eff}$ which has led to a reduction of the size of the central solenoid, enabling a larger TF coil by maintaining the same major radius size.
- Larger safety factor at the edge. This makes the plasma configuration more robust against disruptions.
- Larger power crossing the separatrix. The employed figure of merit $P_{sep}B/q_{95}AR$< 9.2 MW T m$^{-1}$ benefits of the larger safety factor, in turns reflecting a larger power decay length $\lambda_q$ as a consequence of the widely employed Eich scaling [15,16].

The value of the auxiliary power $P_{aux} = 50$ MW represents an average for the necessary control power during the flat-top (e.g. for MHD control or for burn control), which in reality is not constant in time but can vary in accordance to the plasma control requirements. For DEMO 1, no explicit need for a plasma current drive (CD) is foreseen. Also, no final decision has been currently taken regarding which technology (EC, NB, IC) is charged of each H&CD function.

## 3. SAWTEETH (ST) CONTROL STRATEGY

Although the presence of ST might also possess some beneficial aspects, for example the increase of He flushing from the centre of the plasma, an uncontrolled crash is very likely to trigger Neoclassical Tearing Modes (NTMs), enhancing the risk of disruptions. The presence of a large, stabilizing fast particle population – namely the fusion born alphas – is expected to significantly increase the ST period, which implies in parallel a large amplitude ST crash. Preliminary investigations carried out following the empirical method proposed in [17] show that an acceptable ST period in DEMO to reduce the risk of NTM onset would be about ~10 sec., whereas the natural period is at least a factor 20 larger.

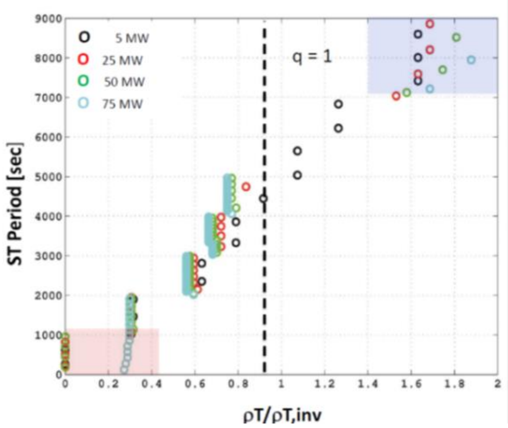


*FIG. 1. ST period vs. position of the EC injection, normalized to the inversion radius $\rho_{T,inv}$. The EC power is identified by the color scale of the symbols. The red shaded area identifies the points where the ST is destabilized, whereas the blue area identifies a complete stabilization for the entire plasma discharge.*

Consequently, an attempt of reducing the period by destabilizing the mode by means of ECCD has been shown to be extremely demanding in terms of auxiliary power (between 70 and 100 MW). For this reason, the strategy for the ST control assumed at the moment for DEMO is rather a stabilization of the mode, in order to obtain a controlled ST crash when the EC is turned off and a preemptive NTM stabilization is undertaken (see a more detailed description of this method in [18]). In Fig. 1, simulation carried out with ASTRA show that this strategy can allow a reduction in the required H&CD power up to a factor 3-5, and therefore, currently, the ST control power requirement for H&CD is set to 30 MW.

## INTEGRATED CORE/PEDESTAL PREDICTIVE MODELLING

Extensive predictive pedestal modelling using the EPED1 model of EU-DEMO around its operational point [19] identified several parameters that can affect the pedestal height. One of the key parameters was $\beta_p$, which determines the Shafranov-shift that in turn improves the pedestal stability leading to increased pedestal top pressure. However, the achieved $\beta_p$ in a given plasma condition in turns depends strongly on the pedestal height, as the latter sets the boundary condition for the core transport. Therefore, the coupled core-pedestal model has to be solved self-consistently with a core transport model and auxiliary heating as input (heating from fusion reactions is calculated self-consistently). We used a simple Bohm-gyroBohm model [20] for the core transport that together with the pedestal prediction was found to reproduce JET power scan results [21]. Fig. 2 shows the result of the self-consistent simulation. The predicted pedestal temperature raises with power as expected. However, the self-consistently calculated fusion gain decreases rapidly as the heating power is increased.

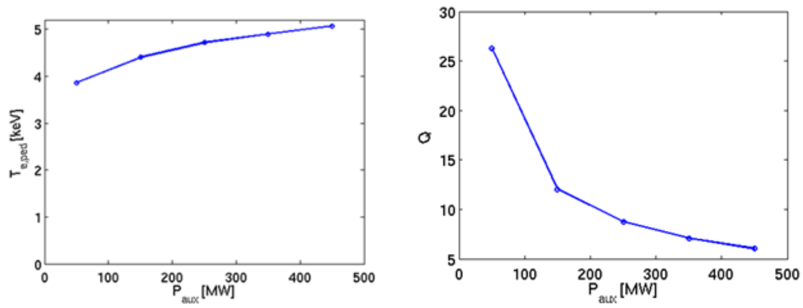


*FIG 2. The self-consistently calculated pedestal temperature (left) and the total fusion gain (right) as a function of the auxiliary heating power in EU-DEMO. Note that the Q = 40 value foreseen by PROCESS is not reached.*

## 4. SOLPS SIMULATIONS

Detachment is being investigated using a mixture of Ar and Xe impurities, where Xe is intended to radiate from the core and Ar lowering the temperature in the divertor enough to trigger detachment. In terms of upstream conditions, the parameter space explored so far covers a $P_{sep}$ range extending from 150 to 240 MW, with a fixed power level of 45 MW to electrons and the rest given to ions (other combinations are currently being analyzed). In all the most recent cases we focused on upstream density $2.7\text{x}10^{19}$ $m^{-3}$, thus around $0.5n_{GW}$. In a power scan aiming at determining the minimum required Ar injection for detachment, Xe was puffed at a constant rate of $2\text{x}10^{10}$ $s^{-1}$, while the minimum Ar injection required for detachment was found to vary between $2.5\text{x}10^{20}$ $s^{-1}$ (at $P_{sep}$ = 150 MW) and $4.0\text{x}10^{21}$ $s^{-1}$ (at $P_{sep}$ = 240 MW). This is a very strong dependence which seems to be motivated by the need to drive detachment along the complete target (as opposed to, for example, just at the strike point). More detailed analysis to clarify this point is under way. In our analysis, a proxy for detachment is adopted by checking if the electron temperature falls below 5 eV and the constant peak power load on the target (excluding radiation) falls below 10 $MW/m^2$. All cases run so far assume fluid neutrals, avoiding the time-consuming Monte Carlo transport code EIRENE, as well as an aggressive charge states bundling scheme for non-hydrogenic ions [22]. A few cases have been preliminarily provided for the development of synthetic diagnostics and to start the design of the pumping system, including also a He flux of $7\text{x}10^{20}$ $s^{-1}$ from the core, evaluated from the expected DEMO fusion power generation. The status of these activities is summarised in the next section.

## 5. SYNTHETIC DIAGNOSTICS AND PUMPING INVESTIGATIONS

In order to operate DEMO in a detached regime, an active control of the detachment evolution is necessary. In particular, the development of a strong X-point (MARFE-like) radiator within the confined region needs to be avoided because it can degrade the confinement and possibly lead to problems including disruptions [23,24]. Also, an accidental loss of detachment has to be detected fast enough. In present machines, the control of the detached regime has been obtained by means of impurity or deuterium seeding [25,26]. DEMO requires a divertor detachment diagnostic which is compatible in the long time with a nuclear environment. For these reasons, the feasibility of a detachment control based on visible and UV spectroscopy is going to be investigated. Spectroscopic measurements in different region of the divertor have been largely used to monitor the status of the detachment given their relatively easy implementation (for a review see [27]). More recently, the ratio of emission lines of nitrogen from different and equal ionization stages could be used to characterise the detachment evolution [28, 29]. On the same line, the ratio of Balmer-lines has been employed to measure the plasma recombination fraction along the outer divertor leg [30]. Based on these methods, a control signal for the divertor detachment based on spectroscopic measurements might be possible. With the purpose of having an overview of the detachment evolution, the divertor legs and the X-point area need to be diagnosed. Based on the DEMO equilibrium and the vessel design, a first draft of possible lines of sight (LOSs) has been developed (Fig.3 left). The LOSs have been implemented as synthetic diagnostic in the SOLPS simulations described above (Fig. 3 right) and synthetic spectra will be calculated as soon as kinetic simulations, i.e. including all the impurity ionization stages, will be ready. A detailed comparison of simulations at different detachment levels is foreseen.

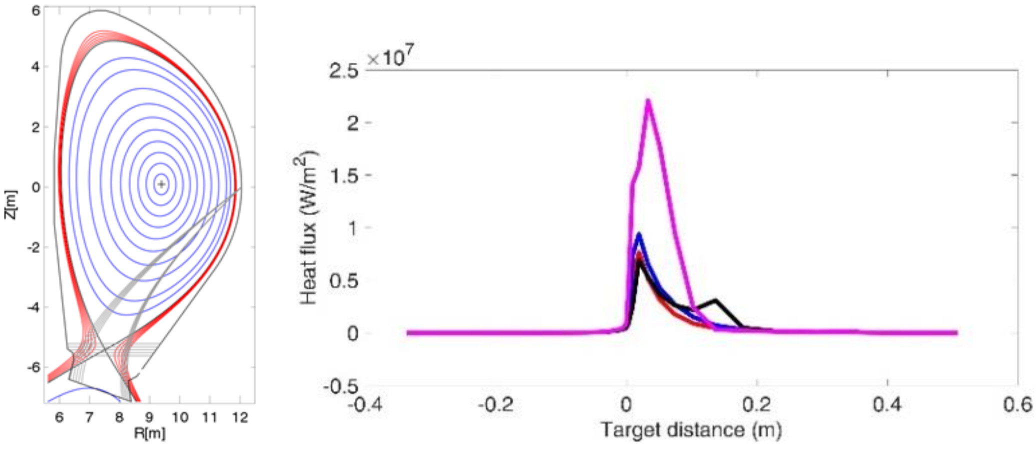


*FIG 3.(left) Example of lines of sight for the divertor detachment diagnostic.)*
*(right) Heat flux density profiles along the outer target for the 4 SOLPS cases selected for preliminary synthetic diagnostic development. The deepest attached case has $P_{sep}$ = 150 MW and Ar puff 3x10$^{20}$ s$^{-1}$, the extremely attached case has $P_{sep}$ = 200 (MW) and Ar puff 4x10$^{20}$ s$^{-1}$, other cases have intermediate values.*

The amount of helium ash which has to be removed by the torus pumping system is determined by the fusion power level. Although this He flux only represents a small fraction of the total exhausted gas (mainly D, T and impurities) which are passing through the divertor openings and through the port duct and into the pump inlets, it determines a concise requirement for the pumping performance of this coupled system: plasma – divertor – sub-divertor and port duct volume – in-port vacuum pump. The lower limit is defined by the maximum allowed core plasma fuel dilution due to He, which strongly depends on the He backflow from the divertor area. To verify this interface requirement, the feasibility of particle exhaust in DEMO shall be investigated in the near future with flow simulations using the engineering code ITERVAC, employing SOLPS profiles at the target as input. The aim is to quickly compute many designs while satisfying the aforesaid requirement enabling plasma operation.

## 6. EDGE LOCALISED MODES (ELMS)

Simulations performed with the code RACLETTE [31] have shown that even a single unmitigated ELM event in DEMO is sufficient to cause melting on the surface of the target plate W coating (the energy flux on the divertor having been determined by means of the empirical scaling suggested in [32]). This occurrence poses a serious question mark on all the active control methods – a reliability of 100% would be necessary, this engineering target clearly being impossible to meet. In view of this, a plasma scenario which is naturally ELM-free, as for example the QH-mode [8], the I-mode [9], or even a negative triangularity machine [10,11] would be extremely beneficial for the machine design, although current experiments suggest that the performance of these configurations in terms of plasma and energy confinement is reduced with respect to the standard ELMy H-mode.

## 7. ASTRA/SIMULINK COUPLING

One of the main targets for the plasma scenario development in the current pre-conceptual design analysis phase for the European DEMO is to address the scenario compatibility with the performance of the available diagnostics and actuators. For this reason, a coupling between the 1D transport code ASTRA and the control software Simulink has been performed, providing a tool able of simulating the plasma behavior while accounting for the limitations linked to the detectability of the signals, thus assuming realistic diagnostic properties, whilst also considering the delays and the power limitations of the actuator responses [5]. An example is given in Fig.4.

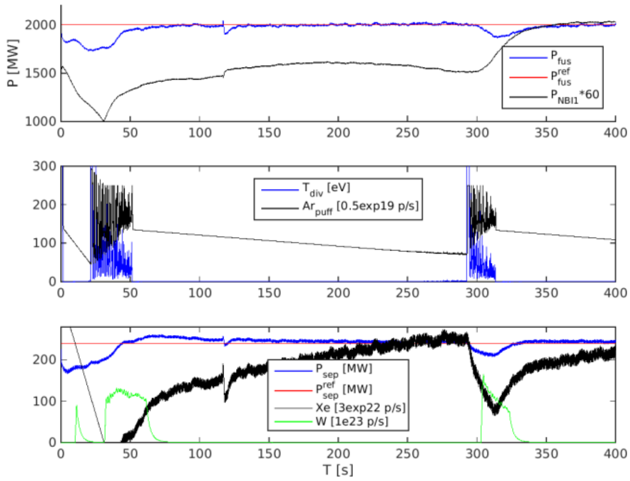


*FIG 4. Example of simultaneous fusion power and divertor detachment control. In the central plot, the Ar puff increases when the divertor detachment is lost. Loss of detachment causes an increase of W erosion at the plate (bottom), which requires the intervention of NB to maintain the fusion power at the required level of 2 GW(top) to contrast dilution. The coupling ASTRA/divertor model is described in [33,34].*

## 8. FLEXI-DEMO

The main alternative concept developed is the so-called Flexi-DEMO scenario, which has been conceived as the intermediate step between ITER and future fusion power plants in the "stepladder" approach [7]. Flexi-DEMO relies on more advanced scenarios as compared to DEMO 1, with a large fraction of auxiliary current drive and a tailoring of the safety factor profile which aims at maximizing the bootstrap current fraction. The idea behind Flexi-DEMO is to absorb all the uncertainties connected with the achievable energy confinement and stability limits of the machine by adjusting the discharge duration, whilst keeping however both the fusion power and required auxiliary power at a constant level in order to avoid significant repercussions on the balance of plant. At sufficiently high confinement (i.e. $H_{98} > 1.25$), a steady state operation becomes possible, with a bootstrap current fraction of ~60%. From the point of view of scenario integration, the main difficulty of Flexi-DEMO is linked to the constant necessity of a high auxiliary current drive (requiring ~100 MW launched to the plasma), which must be added on top of the other functions of the auxiliaries. In table 2, a comparison between the DEMO 1 baseline 2018 and the steady state Flexi-DEMO can be found.

TABLE 2 FLEXI DEMO Parameters during FT phase

| | DEMO Physics 2018 | Flexi-DEMO Steady State |
|---|---|---|
| $R$ [m] | 9.00 | 8.4 |
| $B$ [T] | 5.86 | 5.8 |
| $q_{95}$ | 3.89 | 4.6 |
| $I_p$ [MA] | 17.75 | 14.61 |
| $P_{fus}$ [MW] | 2000 | 2000 |
| $P_{sep}$ [MW] | 170.4 | 188.2 |
| $P_{aux}$ [MW] | 50 | 120 |

Also, at higher confinement and $\beta_N$, Flexi-DEMO is expected to be prone to Resistive Wall Modes (RWMs), needing therefore active Resonant Magnetic Perturbation (RMP) control coils, whose performance requirements are currently under investigation.

## 9. CONCLUSIONS

Current activities carried out inside EUROfusion PPP&T for the design of the European DEMO have been presented. A more detailed insight in PMU physics activities will be provided in the Nuclear Fusion publication after the upcoming conference. The development of the plasma scenario for the DEMO reactor aims to achieve a required fusion performance ensuring the machine's integrity at the same time, for safety considerations and investment protection. The integration of the plasma scenario with the technological constraints of diagnostics and actuators is, possibly, the most important and peculiar aspect of the EUROfusion PPP&T activities.

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