DEMO physics challenges beyond ITER

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The most natural choice in terms of plasma scenario for future, electricity producing fusion reactors like EU-DEMO consists in remaining close to the ITER baseline, as such configuration will rely on the largest available amount of experimental evidence at reactor relevant plasma parameters. Nevertheless, there are some aspects in which ITER and EU-DEMO have to differ, as the simple exercise of up-scaling from ITER to a larger device is constrained both by physical nonlinearities and by technological limits. In this work, the most significant differences between ITER and the current EU-DEMO baseline in terms of plasma scenario are discussed. Firstly, EU-DEMO is assumed to operate with a very large amount of radiative power originating both from the scrape-off layer and, especially, from the core. This radiation level is obtained by means of seeded impurities, whose presence significantly affects many aspects of the scenario itself, especially in terms of transient control. Secondly, because of the need of breeding tritium, the EU-DEMO wall is much more fragile than the ITER one. This implies that every off-normal interruption of the plasma discharge, for example in presence of a divertor reattachment, cannot rely on fast-shutdown procedures finally triggering a loss of plasma control at high current, but other strategies need to be developed. Thirdly, the ITER solution for the control of the so-called sawteeth (ST) has been shown to be too expensive in terms of auxiliary power requirements, thus other solutions have to be explored. Finally, the problem of actively mitigating, or suppressing, the Edge Localised Modes (ELMs) has recently increased the interest on naturally ELM-free regimes (like QH-mode, I-mode, and also negative triangularity) for EU-DEMO, thus deviating in a significant way from the standard ELMy H-mode adopted in ITER.

Keywords: EU-DEMO, ITER, plasma scenario, ELM-free regimes, ELMy H-mode

1. Introduction

In the European Research Roadmap to the Realisation of Fusion Energy [1], the role of ITER is acknowledged as crucial. ITER will be in fact the first machine demonstrating an energy gain from burning fusion plasmas. Also, ITER will be the first device allowing for the exploration of plasma conditions which are not accessible in present machines (e.g. the simultaneous achievement of high density and low collisionality, or dominantly alpha heated plasmas). For this reason, the most natural choice for the design of a EU-DEMOnstration [2] fusion reactor consists of assuming the ITER baseline as the starting point for the scenario definition, as no other scenario is likely to have such robust experimental evidence on support in reactor relevant conditions. The target fusion gain of ITER ($Q = 10$, where Q is the ratio between the generated fusion power, P_{fus}, and the power injected in the plasma P_{aux}) can however be shown to be insufficient for a net electric power production, in view of the non-unitary efficiencies associated both to the thermodynamic Rankine cycle and the H&CD wall plug efficiencies. Thus, an up-scaling from ITER – in terms of major radius, or magnetic field, or both – is unavoidable for the realization of an EU-DEMO with an "ITER-like" scenario. The extrapolation from ITER to EU-DEMO exhibits nevertheless strong nonlinearities, due to plasma physics and technology. Besides, the differences in ITER and EU-DEMO missions introduce further design constraints, so that some technical solutions adopted in ITER might not be compatible with the availability requirements of EU-DEMO. As a matter of fact, while ITER is still considered an experimental reactor, not supposed to breed its own fuel, according to the Roadmap

- EU-DEMO shall demonstrate a net electricity production.
- EU-DEMO shall breed its fusion fuel (tritium).
- EU-DEMO shall exhibit a sufficiently high availability, and thus a long lifetime of its components, to show the ability of successive, commercial Fusion Power Plants (FPP) to play a role in the energy market.

In this work, some of the most significant deviations from the ITER baseline scenario which have been introduced in EU-DEMO, as well as the reasons leading to their introduction, are discussed.

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2. EU-DEMO 2018 Baseline

In spring 2018, a new physics baseline for EU-DEMO produced by the systems code PROCESS [3,4] was released. The top-level requirements of 2000 MW fusion power and 500 MW plant net electric output power as well as 2 hours burn time have been maintained from the previous baselines, as discussed in more detail in [5]. Table 1 summarizes the most relevant (physics related) parameters of EU-DEMO 2018 for the flat-top plasma phase. The corresponding values of ITER 15 MA baseline scenario [6,7] are also reported for comparison.

	EU-DEMO 2018	ITER
R [m]	9.00	6.2
B_0 [T]	5.86	5.3
q_{95}	3.89	3
I_p [MA]	17.75	15
P_{fus} [MW]	2000	500
P_{sep} [MW]	170.4	89
P_{aux} [MW]	50	50
H_{98}	0.98	1
$< n >/n_{GW}$	1.2	~1
$< T >$ [keV]	12.49	8.9
β_N [% mT/MA]	2.5	1.8
$P_{sep}B/q_{95}AR$ [M W T /m]	9.2	8.2
P_{sep}/R [MW/m]	18.9	14.35
Pulse length [sec]	7200	600

Table 1. DEMO 1 relevant machine parameters according to the Physics Baseline 2018 and corresponding parameters for ITER. EU-DEMO data have been produced with the systems code PROCESS.

Density and temperature profiles of the 2018 EU-DEMO baseline, calculated with the transport code ASTRA [8,9,10], are shown in Fig.1. As mentioned in the introduction, the reference EU-DEMO scenario is analogous to the ITER 15 MA baseline scenario, both assuming a pulsed operation in ELMy H-mode [11] with a confinement time in line with the well-known IPB98(y,2) scaling [12]. There are however some aspects on which the two scenarios differ, although not immediately visible in the table above. These are analyzed in the following sections.

3. Core Impurity Radiation

One important point with respect to which ITER and EU-DEMO differ is the large amount of core radiation, which is necessary in EU-DEMO to protect the divertor and keep P_{sep} reasonably close to P_{LH}. In ITER, the unavoidable synchrotron and bremsstrahlung losses reduce the power carried by charged particles across the separatrix from the 150 MW of heating power P_{heat} (corresponding to 100 MW P_α plus 50 MW P_{aux}) to about 80 MW, which can be dealt with by the divertor in presence of seeded SOL impurities, like e.g. Ne or N [13]. The situation is however different in EU-DEMO, where, in absence of additional core radiation, the power P_{sep} would be larger than 350 MW, an amount which could not be radiated in the SOL without compromising the stability of the discharge. Thus, an high-Z impurity, e.g. Xe [14], is seeded in the EU-DEMO core, with the purpose of enhancing the fraction of power exhausted via radiation (which uniformly distributes on the very large first wall surface and does not concentrate on the small target wetted area) The energy flows for the two devices are depicted in Fig.2. The differences between P_{heat} and P_{sep}, and between P_{sep} and P_{target}, correspond to the core and SOL radiation amount, respectively.

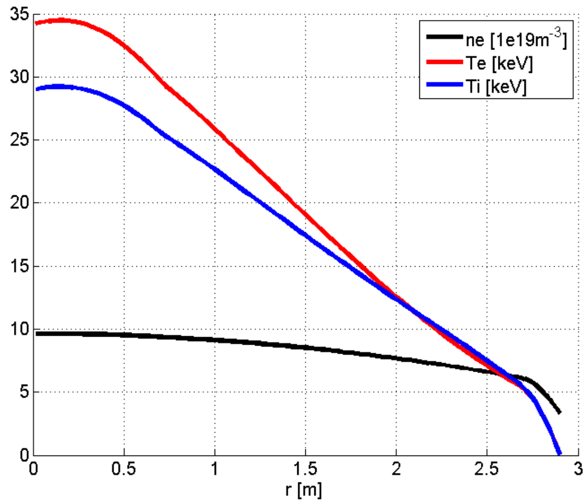

Fig 1. Density and temperature profiles for DEMO 1 Physics Baseline 2018 calculated with ASTRA.

Fig.3 shows the radiation power density profile corresponding to the calculated EU-DEMO equilibrium. As one can observe, the radiated power – which is mostly originating from the impurity line radiation, although also synchrotron and bremsstrahlung play a non-negligible role – is strongly localized in the plasma edge, where the temperature is favorable for Xe to radiate. Of course, Xe is expected to be present everywhere in the plasma core, but only in the plasma edge its cooling factor is sufficiently high to radiate significantly.

The presence of a core radiator has nevertheless a strong impact on the plasma control, in view of the large residence time foreseen for such species in the confined plasma. In Fig.4, an example of EU-DEMO plasma control simulation produced with ASTRA/Simulink [15] is shown. At $t = 200$ sec, the core radiation is artificially increased by introducing 1 mg W in the core. This has the effect of decreasing the plasma temperature, increasing in parallel also the total radiation from Xe – as, at lower temperature, the Xe average cooling factor throughout the plasma core increases. This accelerates the cooling of the plasma, leading to an unstable situation. As one can observe, the total radiation from the core almost doubles within a few seconds.

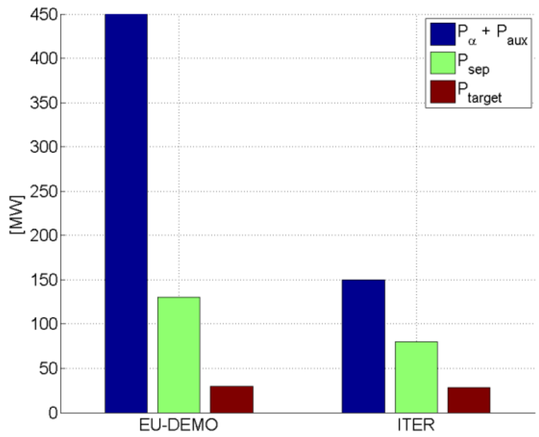

Fig. 2. Total heating power, power at the separatrix and maximum tolerable divertor power in ITER and EU-DEMO.

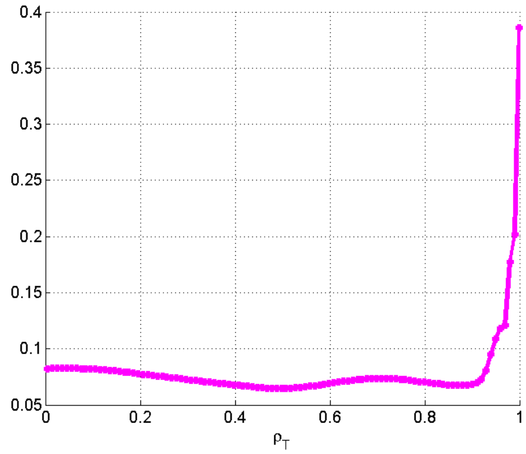

Fig. 3. Left: Total radiation power density profile in EU-DEMO. Synchrotron radiation, bremsstrahlung and line radiation from seeded impurities are considered, the latter being the dominant contribution. Most of the radiated power is localised in the pedestal region, where the temperature is favourable for the impurities (Xe).

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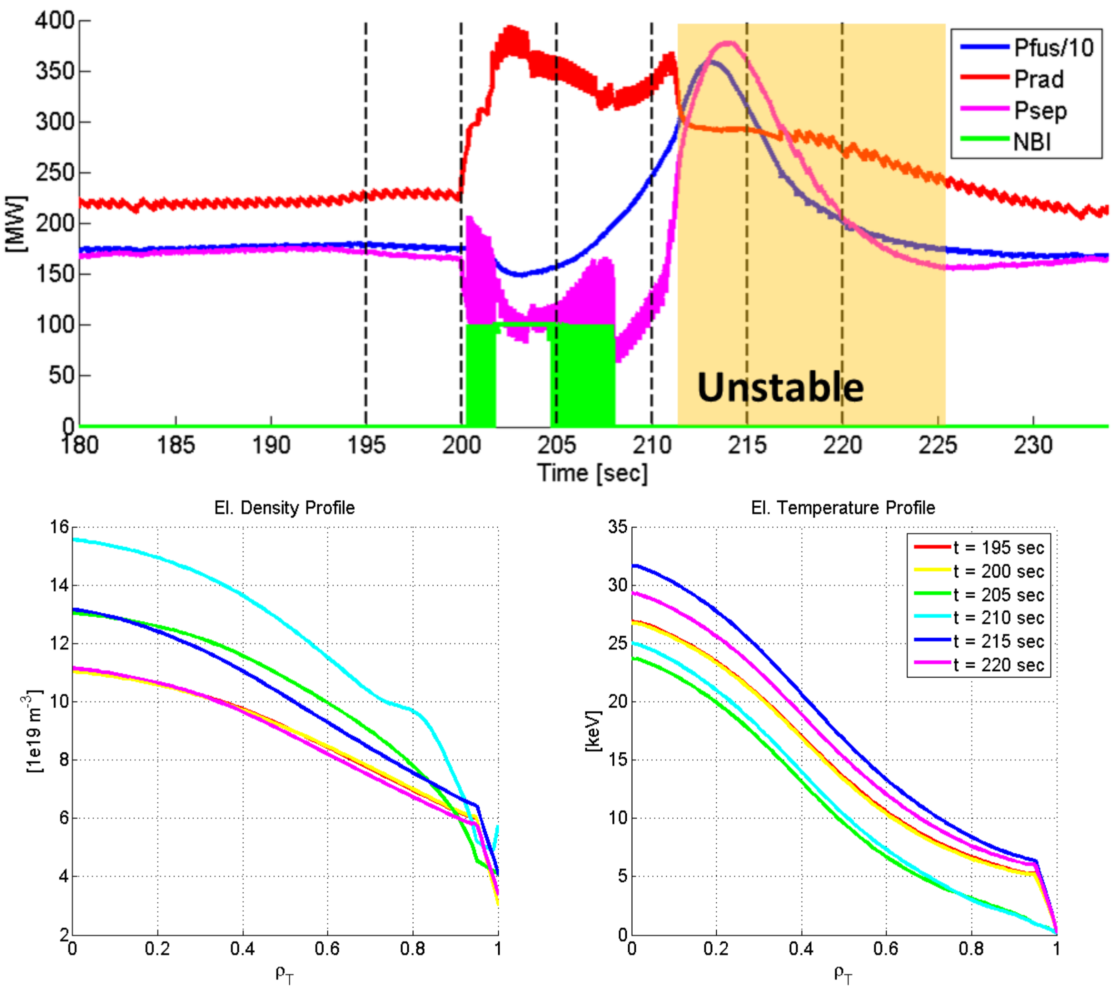

Fig. 4. Top: time traces of different power signals in presence of a radiative instability simulated with ASTRA/Simulink. The radiation was artificially increased in the numerical simulation by injecting 1 mg of W at $t = 200$ sec. The region shaded in yellow shows where the density limit is violated, and thus the numerical results are no longer valid as the plasma is unstable. Bottom: radial density and temperature profiles at different times – marked by vertical dashed lines in the top figure.

Turning on about 100 MW of NB is an insufficient measure to maintain the plasma hot and avoid a dangerous H-L transition, as shown in Fig.4. Thus the plasma controller tries to recover the lost fusion power by increasing the pellet injection frequency, to enhance central density.

This strategy is very effective, but also quite dangerous, as EU-DEMO is already operating close to the density limit, and an excessive increase of the plasma density can fatally compromise the stability of the discharge.

Ensuring the controllability of the plasma in presence of plasma transients (planned and unplanned) turned out as one of the main difficulties encountered up to now in the design of the EU-DEMO plasma scenario, and the presence of the impurities greatly enhances the complexity of the problem, which for the time being has not been fully solved yet.

3. Divertor Reattachment

Because of the necessity of breeding tritium, the EU-DEMO wall must be sufficiently thin, in order to allow the fusion generated neutrons reaching the breeding zone. The present first wall design foresees a ~3 mm metal layer (W and EUROFER) between the vacuum chamber and the fluid coolant (water or He) [16,17]. Such a fragile wall cannot withstand a contact with the plasma, unless the stored (kinetic and magnetic) energy is extremely low. Also, the foreseen sacrificial limiters for the wall protection during transients [18] would be damaged if $I_p > {\sim}5$ MA, whereas $I_p \approx 20$ MA during the flattop phase. Thus, any emergency plasma shut-down procedure which foresees a plasma/wall contact at high current, or in general a loss of plasma control, is not considered viable, as the consequences for the first wall might be too severe.

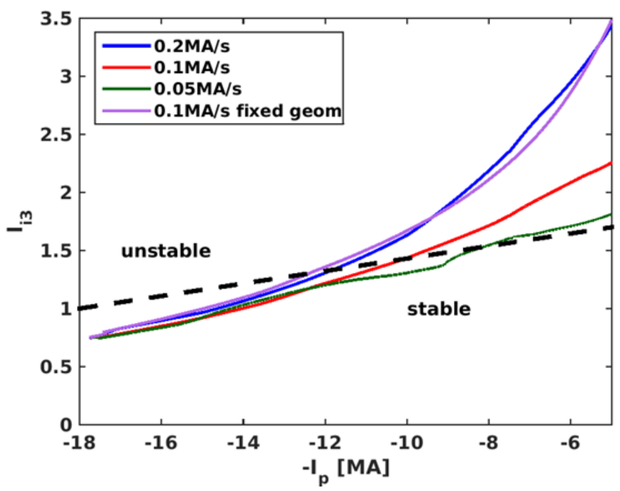

Fig. 5. Evolution of the internal inductance l_{i3} during ramp-down phases assuming different rates and assuming fixed geometry with 100kA/s. From the vertical stability analyses with standard profiles, values of l_{i3} above the dashed line cannot be controlled.

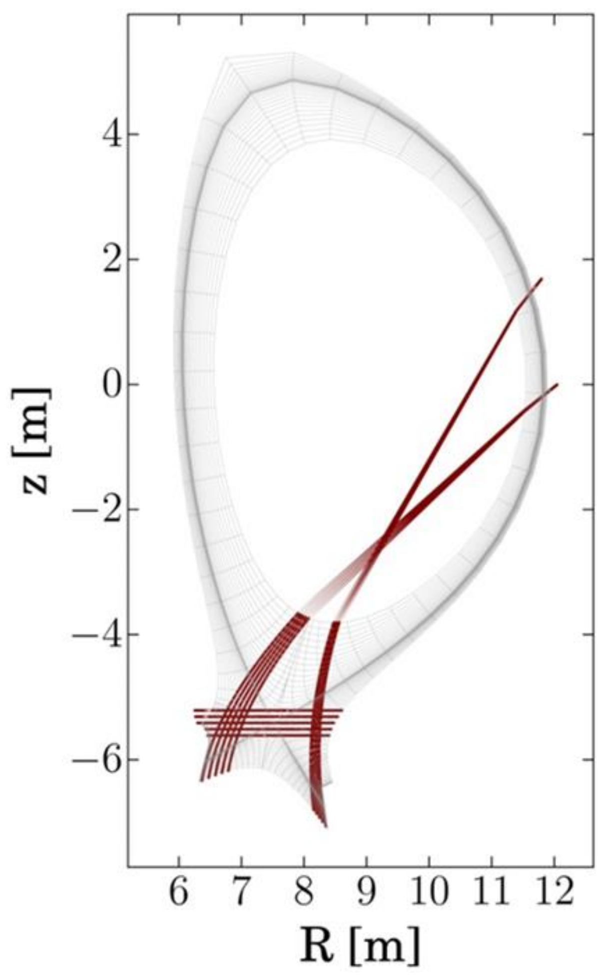

Fig. 6. Top: Example of lines of sight for the divertor detachment diagnostic. Due to the toroidally inclined sightlines the traces look curved in this 2D plot although in 3D they are straight.

A typical situation where a fast shutdown of the plasma is needed is the loss of plasma detachment at the divertor. Both ITER and EU-DEMO are operated with a (partially or fully) detached divertor, otherwise the heat flux on the target plates will exceed the technological limit of ~20 MW/m^2 [19]. It has been elsewhere shown [20] that, if detachment is lost in the current ITER-like lower single null divertor configuration of EU-DEMO, the heat flux to the coolant reaches CHF in about three seconds if no countermeasures are adopted. In EU-DEMO, the foreseen countermeasure is currently represented by divertor sweeping, which has been illustrated in [20,21] and which is able to let the target survive for some tens of seconds in presence of reattachment. This time lapse is required to ramp-down the plasma current without control losses. Dedicated simulations carried out with the code RAPTOR [22] have pointed out that, even by optimizing the plasma shape during the ramp as suggested in [23], the plasma current cannot be ramped down faster than ~0.1-0.2

MA/sec – at best – without losing the MHD stability of the plasma column. This is shown in Fig.5, where the stable region of the ramp trajectory is defined in terms of the internal inductance defined as in [12].

The situation is in different in ITER. In spite of the fact that disruptions – and plasma/wall contacts in general – are a very serious issue which must occur at the lowest possible rate [24], an abrupt discharge interruption via matter injection is one of the accepted strategies for the fast termination of the plasma. The ITER first wall, which has no requirements related to tritium breeding, is more robust, and thus a certain number of disruptive events is already foreseen during ITER operation [25], and divertor sweeping coils are not included in the machine design.

As divertor sweeping in EU-DEMO must be already active when the transition from attachment to detachment begins, it is necessary to install diagnostics able to detect a loss of plasma detachment at its onset, or even before it occurs. For these reasons, the feasibility of a detachment control based on visible and UV spectroscopy is investigated. Spectroscopic measurements in different regions of the divertor have been largely used to monitor the status of detachment given their relatively easy implementation (for a review see [26]). More recently, the ratio of emission lines of nitrogen from different and equal ionization stages could be used to characterize the detachment evolution [27,28]. Possibly, such method can be extended to other impurities, e.g. Ar. Along the same line, the ratio of Balmer-lines has been employed to measure the plasma recombination fraction along the outer divertor leg [29]. Based on these methods, a control signal for the divertor detachment with 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 vessel design, a first draft of possible lines of sight (LOSs) has been developed, as shown in Fig.6. The LOSs have been implemented as a synthetic diagnostic in some dedicated SOLPS simulations at different degrees of detachment, and synthetic spectra will be calculated as soon as kinetic simulations, including all impurity ionization stages, will be ready. Fig.7 shows an example of different radiation distribution in two SOLPS fluid cases in the transition from attached to detached divertor. The formation of a highly radiative region in front of the outer divertor plate, which should be detected by the diagnostics, is noticeable.

4. Sawteeth Control

Although the presence of sawteeth (ST) might also have some beneficial aspects, for example increasing He flushing from the centre of the plasma, an uncontrolled crash is very likely to trigger Neoclassical Tearing Modes (NTMs), which in turn risk initiating chains of events eventually leading to disruptions. The presence of a large, stabilizing fast particle population – fusion born alphas – is expected to significantly increase the ST period, which in turn implies a large amplitude (and therefore more dangerous) ST crash.

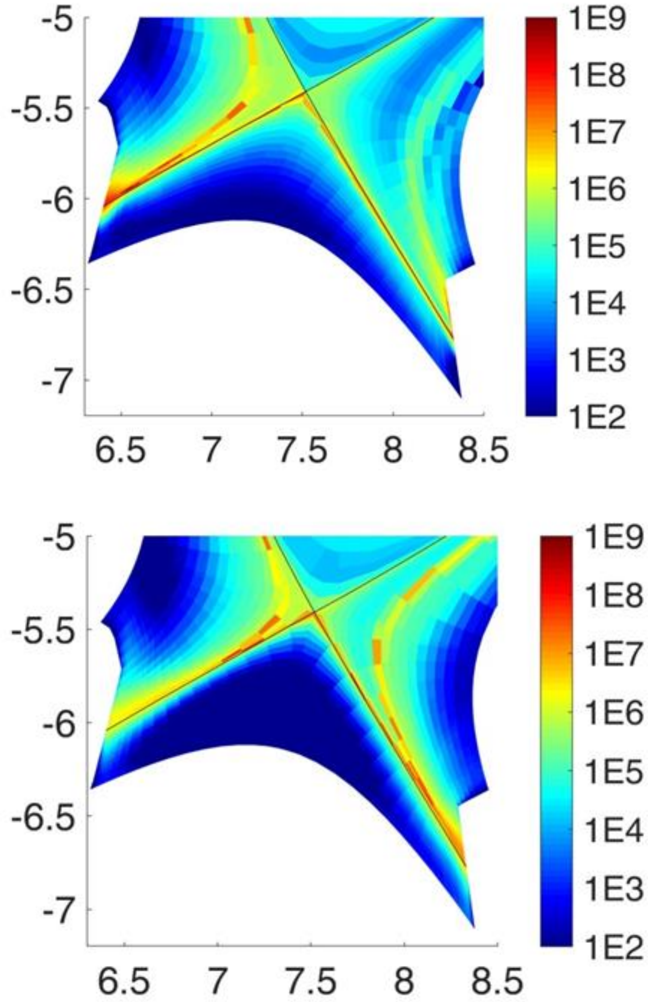

Fig. 7. Total radiation density (W/m3) in a barely detached case (top - with pressure ratio upstream to target close to one) and in a more strongly detached case (bottom - with pressure ratio ~4) calculated with SOLPS.

Preliminary estimates carried out following the empirical method proposed in [30] (and shown in Fig.8) show that, in EU-DEMO, an acceptable ST period to reduce the risk of NTM onset after the crash would be about 5-10 time shorter than the natural period. It is therefore to be expected that a ST control strategy based on destabilization of the mode until the required frequency (and amplitude) is obtained would be particularly demanding in terms of auxiliary heating. For this reason, it is currently foreseen that EU-DEMO must pursue a pacing of the ST rather than their destabilization – i.e. by means of CD, the ST crash is avoided by stabilizing the kink for a certain period of time. Then, CD is turned off and a ST crash under controlled conditions occurs. In parallel, a pre-emption of the NTMs is undertaken, in order to avoid the triggering of NTMs after the ST-crash (see a more detailed description of this method in [31]). In Fig.9, simulations carried out with ASTRA show that keeping ST stable even for a time comparable to the entire discharge duration allows a reduction in the required H&CD power up to a factor 3 compared to the

ITER destabilization approach. At this stage, the optimum duration of the ST pacing has not been assessed yet. In these simulations, the stability of the ST is modelled by employing the well-known critical shear criterion proposed by Porcelli et al. [32]. Currently, the ST control power requirement for the H&CD system design is set to 30 MW of ECCD. Alternative approaches, employing for example IC [33], or even extending the temporal duration of the NTM pre-emption phase to the whole discharge and avoiding any active control of the ST, are also considered.

The situation is much less critical in ITER, as can be observed in Fig.8. This is due not only to the fact that the alpha particle population is not as large as in EU-DEMO, but also because β_N is significantly lower (about 1.8 against ~2.5 in EU-DEMO – see Table 1). This reduces significantly the risk of NTM triggering after a ST crash, thus allowing the operation in presence of longer ST periods..

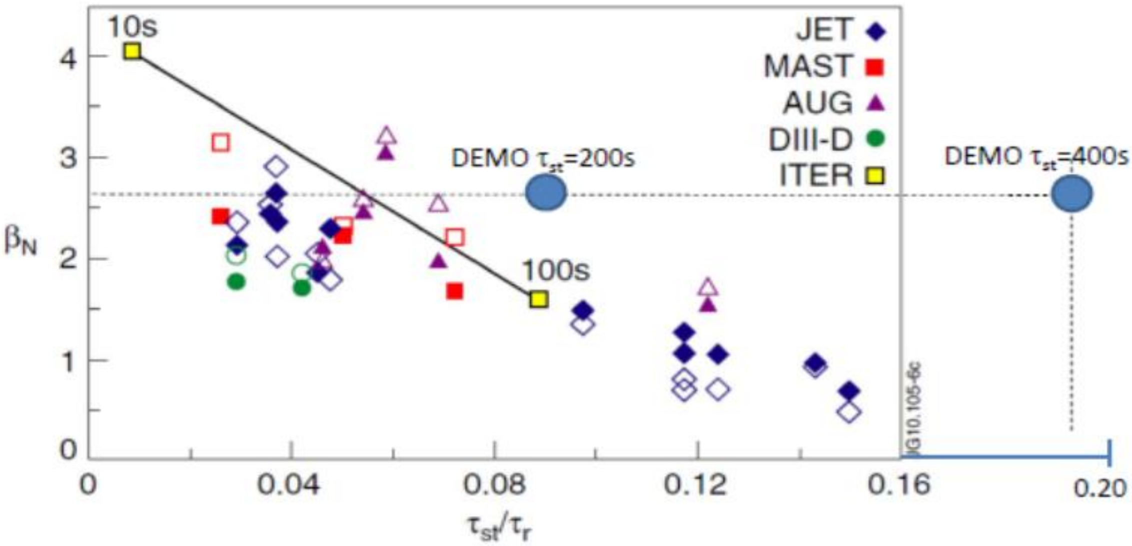

Fig. 8. Figure adapted from [27]. The experimental points identify the minimum β_N for the onset of NTM after a ST crash as a function of the ST period (expressed in plasma resistive time τ_r units). For the DEMO target value of β_N, the required ST period should then be lower than ~0.02 τ_r, whereas the expected natural period is a factor 5-10 larger, according to different estimates.

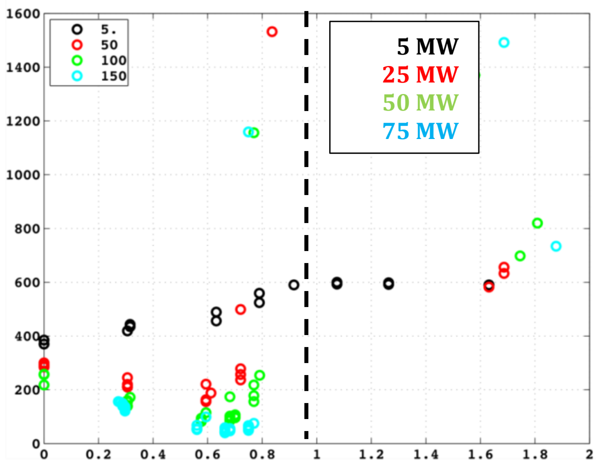

Fig. 9. Resulting ST period [sec] vs. position of the EC injection, normalized to the inversion radius coordinate. The EC power is identified by the color scale of the symbols. The vertical dashed line identifies the q = 1 surface.

A large ST crash has however the drawback of inducing large fluctuations in the fusion power and, in general, in the various loss channels. An active control of the plasma has to be foreseen in order not to lose the H-mode. Also, it is not clear whether the fast variation in P_{sep}, due to the complex interplay between fusion power, auxiliary power and core radiation (see Fig.10), could be safely dealt with by the divertor. This is subject of future analyses.

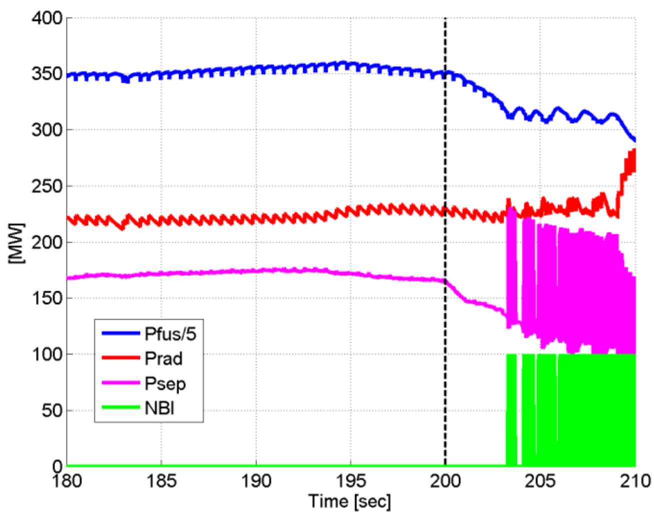

Fig. 10. Time traces for different power signals in presence of a large sawteeth simulated with ASTRA/Simulink. The ST occurs at $t\ = 200$ sec.

5. ELM-free regimes

A simple estimate from a scaling recently suggested in [34] indicates that, in EU-DEMO, a natural type I Edge Localised Mode (ELM) releasing 10% of the pedestal energy would deposit the equivalent of ≈ 10 MJ of energy in around one millisecond on the target plate. Simulations performed with the code RACLETTE [35] have shown that even a single ELM event of this kind will be sufficient to cause melting on the surface of the target plate W coating, and a few tens of these events will be able to ablate half of the total thickness of the W layer on the target.

This risk poses a serious question mark on the suitability of H-mode as a reactor scenario, since a reliability of 100% would be required to any chosen ELM mitigation or suppression method, a challenging engineering target to meet (even disregarding other drawbacks all active ELM mitigation or suppression techniques might have on the plasma performance). For this reason, a plasma scenario which is naturally ELM-free, as for example the QH-mode [36], the I-mode [37], or even negative triangularity [38,39,40] would be extremely beneficial for a machine like EU-DEMO, whose mission includes stringent availability requirements – to a much higher extent than ITER, which is an experiment.

Both QH-mode and I-mode have however a number of features which must be carefully considered when extrapolated to a reactor device – on top of the low amount of experimental experience available in comparison to the ELMy H-mode, which is by itself a serious drawback. In particular, the main concerns linked to the adoption of the QH mode in a DEMO machine are:

- Difficult accessibility: a high rotational shear in the edge seems to be the main ingredient to access the QH-mode. It is however unclear how this rotational shear requirement translates to a DEMO reactor scale, and also how to reliably obtain it (tangential NBI and also RMP coils [41] are possible candidates for this purpose, but both might exhibit difficulties in integration, especially if a large rotation is needed). There may also be an impact on the allowable toroidal magnetic ripple.

- Typically observed at low density – although reasonably high Greenwald fraction have been observed during ramps [42]. This might be due to the fact that current machines are not able to operate at high density and low collisionality at the same time. Thus, this might favourably extrapolate to ITER and EU-DEMO. However, this currently prevents the community from exploring in the experiments some extremely important plasma conditions, for example a QH-mode in presence of detached divertor.

Instead, the main concerns regarding an I-mode reactor are:

- Absence of density pedestal: in contrast to QH-mode, where there is some indication that the density can be recovered at DEMO scales, the absence of a density pedestal cannot be compensated for in extrapolation to a reactor size. This means that, at the same machine size in terms of radius and field, an I-mode reactor will most likely produce less power than the corresponding H-mode, this clearly impacting negatively on the costs.

- Larger threshold power than H-mode: the scaling for the LI transition power proposed by Hubbard et al., [43] indicates that the LI threshold has a weaker dependence on the magnetic field than the LH threshold. Nevertheless, at EU-DEMO parameters, one still observes that $P_{LI} > P_{LH}$, as the baseline magnetic field is not sufficiently high to take advantage of the weaker dependence on B. This is clearly going to exacerbate the problem of reaching divertor detachment by means of seeded impurities (incidentally: as for QH-mode, no experimental observation of detached I-mode plasmas is to our knowledge available). Furthermore, although ELM-free, the I-mode exhibits power "bursts" on the divertor target [44], whose nature is still under investigation – although they are observed to almost disappear when the plasma is operated sufficiently far away from the I-H transition

The possibility of exploring these regimes in ITER is at the moment debated. From the current understanding, there is some chance to have some QH-mode shots in ITER, but no I-mode, because the need of reversing the toroidal field direction would force an operation with counter-current NBI.

Clearly, no validation of negative triangularity L-mode can be expected from ITER, as it would require immense modifications to the whole machine architecture. This plasma configuration has recently received great attention from the fusion community, as it seems to be able to combine the robustness of L-mode with the confinement capability of an H-mode [45]. Such a solution would be extremely attractive for a reactor, if these features are confirmed by future investigations. Still, the question about which machine can validate such scenario at reactor relevant parameters before a DEMO is built remains open, as no negative δ equivalent of ITER is at the moment foreseen.

6. Conclusions

The role of ITER in the development of nuclear fusion as an energy source is of paramount importance, as only in ITER the exploration of reactor relevant, dominantly alpha heated plasmas can be performed. Nevertheless, the first attempts of designing an EU-DEMO, a machine charged of producing a net electrical power and of demonstrating the robustness of fusion as an energy source, have pointed out various aspects where the currently adopted ITER solution is not applicable. In the present paper, the most relevant differences related to the plasma operation have been discussed. Firstly, the role and the difficulties linked to the introduction of core radiation obtained by means of seeded impurities in EU-DEMO has been analyzed. Secondly, it has been acknowledged that a fast plasma termination with loss of plasma control at high current cannot be implemented in EU-DEMO, and thus other means to protect the PFCs during current ramps, as for example divertor sweeping when divertor detachment is lost, have to be included in the machine design. Thirdly, the ITER solution for the control of the so-called sawteeth instabilities (ST) has been shown not to be implementable in EU-DEMO by virtue of the excessively high control power requirements. Other solutions have thus been explored, and their consequences assessed. Finally, the problem of protecting the PFCs from ELMs has recently oriented the interest of the fusion community on naturally ELM-free regimes, like QH-mode, I-mode and negative triangularity, thus deviating from the ITER baseline ELMy H-mode. However, for these ELM-free scenarios, which at this stage are poorly explored and understood, the open question is whether there is a possibility to have a reliable scenario validation at reactor relevant parameters in ITER and, if not, on which machine can this take place in order to avoid a risky extrapolation from the existing small devices to a DEMO scale.

Acknowledgments

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