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Development of the plasma scenario for EU-DEMO: Status and plans

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ABSTRACT

This paper is part of a series of publications concerning the development of the European DEMO during the Pre-Concept Design Phase (2014-2020), and also describing the strategy for the next phase. In particular, it deals with the physics basis of the plasma scenarios employed for the definition of the various DEMO baselines released so far, and the assumptions adopted where necessary. In the course of the Pre-Concept Design Phase, some of these assumptions have been progressively replaced with the results of dedicated modelling activities or code developments in general, which are summarized here. The considered baselines, obtained with the systems code PROCESS, are the DEMO 2015, 2017 and 2018, based on an ITER-like ELMy H-mode confinement regime. In addition, since it is now essential to avoid ELMs, baselines with some of the characteristics of QH-mode and I-mode have been produced in 2019. It has been concluded that the present integrated plasma scenarios are not secure enough for an engineering design, so a strong programme to improve them is required and planned. A discussion on the main knowledge gaps, as well as the strategy to be adopted in the next phases to close them, is provided.

1. Introduction

The design of the prototype reactor European DEMO (in the following referred to as DEMO for simplicity) has concluded its Pre-Concept Design Phase (PCD, 2014-2020) with a Gate Review process [1,2]. This phase has represented the start of the DEMO design process, and was associated with an exploration of the parameter space in order to identify suitable reactor configurations able to satisfy all requirements agreed with the DEMO stakeholders [1]. Clearly, a valid design point has to fulfill simultaneously a very large number of constraints, originating from physics laws, diverse technological limitations as well as a minimum required performance to meet the mission targets and demonstrate fusion energy as a credible technology for electricity production. The results of such parameter space explorations in a broad sense have been summarized in another paper in this dedicated special issue [2]. Here, the discussion focuses on the plasma physics related aspects of this exercise, reviewing the assumptions and the knowledge gaps behind each of the released DEMO baselines. As stated in different publications in the past [3–6], DEMO has been conceived – at least initially – attempting to mimimise the differences from the ITER 15 MA reference scenario [7,8], i.e. focusing on a pulsed scenario in similar plasma transport regime. This approach was justified by the fact that scenarios based on ITER will have the strongest experimental supporting evidence. However, not all ITER solutions are directly applicable to DEMO, due to differences between the two devices, both in terms of size and, especially, in terms of ITER's wider mission. For this reason, in recent years, solutions with significant deviations from the ITER baseline have been explored as well. Most of the material produced in the framework of DEMO investigations has already been published. In this work, which has to be understood as a part in a more comprehensive series of papers on the DEMO PCD, the most relevant results are briefly summarized, and the essential references listed. For obvious reasons of readability and practicality, the level of detail is kept low. The interested reader is mainly referred to the references cited in this paper.

Each of the DEMO baselines presented here relies on a certain number of assumptions. That is, at the moment the available physics

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knowledge is not sufficient to model a DEMO scenario in a fully predictive way based on first principle theory. Rather, the associated uncertainties are quite large, and sometimes even a qualitative understanding of the underlying physics phenomena is missing. Clearly, this has to be improved before the reactor design is frozen, since too large uncertainties on the plasma performance, or significant epistemic uncertainties, may not allow the execution of the final, engineering design. For these reasons, the role of the DEMO physics activities in the next phase shall not only be limited to the definition of a plasma scenario fulfilling all constraints, but should also include a strong and constant interaction with the fusion community in a broad sense, to identify the critical gaps and close them in the most coordinated and efficient way (or equivalently, removing the assumptions by bridging the knowledge gaps, as discussed in Sec.4). This also encompasses a quantitative estimate of the uncertainties, as well as an effort to reduce them.

The paper is structured as follows: in Section 2, the main physics parameters of the various baselines are reviewed, and the assumptions or the investigations leading to these parameters are discussed, subdivided by topic. In Section 3, focus is given on ELM-free regimes and their applicability to DEMO, which along with the high main plasma radiation fraction is probably the largest deviation from the present ITER baseline considered so far. In Section 4, the strategy to address the knowledge gaps in the next phase is presented, and the approach to arrive at a plasma scenario and how it might be substantiated is illustrated. Conclusions are drawn in Section 5.

2. Baselines

Various DEMO baselines have been released during the PCD, produced with the systems code PROCESS [9,10]. The definition "baseline" indicates a design point consistent with a number of physics and technology constraints, determined by means of a systems code, which contains a number of simplified physics and technology models. Three variants of H-mode plasma baselines have been released, hereafter named after their publication year, namely 2015, 2017 and 2018. Baseline 2018 has been employed primarily for physics studies, while most engineering activities are based on 2017. The reason for this difference are given below. Since 2018, ELMy H-mode is no longer considered as the primary solution for the DEMO plasma scenario, in view of the high risks associated to active ELM mitigation [6,11], so other ELM-free regimes came into play. This does not mean that H-mode has been discarded, but simply that other scenarios are considered with higher level of priority until reliable reactor relevant ELM suppression or mitigation has been demonstrated at ITER. For this reason, QH-mode [12] and I-mode [13] baselines have been produced with PROCESS in 2019. Incidentally, also negative triangularity [14–16] is among the available options. However, due to the more radical modifications to the plant design, no corresponding DEMO baseline has been produced yet with PROCESS. A discussion on ELM-free regimes and their applicability to DEMO can be found in Section 3, where also the description of the two 2019 "ELM-free" baselines is detailed. Table 1 summarises the main physical parameters of all baselines. For comparison, the same quantities for ITER 15 MA baseline scenario (as in [7,8]) are reported as well. Hereafter, a discussion of the assumptions leading to these DEMO parameters and their variation across the baselines (limited to 2015, 2017 and 2018, i.e. the ELMy H-mode based ones) is provided.

2.1. Geometry

The major radius, which is an output for these PROCESS runs, has remained basically unchanged throughout the baselines at around 9 m. What essentially determines this number is the target of 500 MW of net electric power output (roughly corresponding to 2 GW fusion power) together with the confinement, assumed in line with the widely employed IPB98(y,2) scaling [17]. Note that the confinement time exhibits only a weak dependence on the magnetic field in this scaling, thus the radius remains the main factor, together with the plasma current. These are constrained by the limits on the safety factor q, which shall remain reasonably above 3 to reduce disruptivity. Incidentally, ITER currently relies on a $q_{95} = 3$ baseline scenario, but ITER has larger margins than DEMO on disruptivity, and in addition it aims at a lower β_N. Note that the radius is also a result of the need to fulfil the power exhaust related constraints, as discussed in Section 2.5. The aspect ratio A of DEMO has been set to 3.1, which is the ITER value. Preliminary scans of the aspect ratio have been carried out in the past, but since the effect of A has also complicated repercussions on the radial build and on the engineering in general, the PCD kept to a single value. Discussion on the aspect ratio variation is to be found in [2].

Table 1
DEMO Physics Baseline 2017, 2018, 2019, QH-mode, I-mode relevant machine parameters and corresponding values for ITER. DEMO data have been produced with the systems code PROCESS. The parameter f_{NI} represents the sum of the driven current fraction f_{CD} and of the bootstrap current fraction.The subscript "pt" indicates quantities at the pedestal top. Cells containing values fixed by input in PROCESS are highlighted in blue (color online). Note that not all baselines have been built with the same input parameter set.

	EU-DEMO 2015	EU-DEMO 2017	EU-DEMO 2018	EU-DEMO (QH-mode)	EU-DEMO (I-mode)	**ITER**
R [m]	9.07	8.94	9.07	8.94	9.47	**6.2**
A	3.1	3.1	3.1	3.1	3.1	**3.1**
B_0 [T]	5.66	4.89	5.86	5.74	6.45	**5.3**
q_{95}	3.25	3	3.89	3.93	3.87	**3**
δ_{95}	0.33	0.33	0.33	0.33	0.33	**0.33**
κ_{95}	1.65	1.65	1.65	1.65	1.65	**1.7**
I_p [MA]	19.6	19.07	17.75	18.27	20.63	**15**
f_{NI}	0.44	0.5	0.39	0.52	0.219	**~0.2**
f_{CD}	0.10	0.11	> 0.05	0.16	>0.05	**> 0.1**
P_{fus} [MW]	2037	1998.3	2012	1871	1274	**500**
P_{sep} [MW]	154	156.4	170.4	178.5	240	**89**
P_{aux} [MW]	50	50	50	76	50	50
P_{CD}/P_{aux}	1	1	0	0	0	**0**
P_{LH} [MW]	121	107.5	120.8	N/A P_{LH} = 138 MW	N/A P_{LI}= 265 MW	**52**
H_{98}	1.1	1.1	0.98	0.89	0.8	**1**
$\langle n\rangle/n_{GW}$	1.2	1.2	1.2	1.37	0.9	**~1**
$\langle T\rangle$ [keV]	13.06	12.8	12.49	11.31	10.37	**8.9**
$n_{e,pt}$ [1e20m^{-3}]	0.67	0.62	0.57	0.63	0.46	**~1**
$T_{e,pt}$ [keV]	5.5	5.5	3.7	4.6	2.7	**~3**
β_N [%mT/MA]	2.59	2.889	2.483	2.576	1.35	**1.8**
Z_{eff}	2.58	2.17	2.12	2.19	1.150	**1.78**
$P_{sep}B/q_{95}AR$ [MW T /m]	9.54	9.2	9.2	9.4	13.6	**8.2**
P_{sep}/R [MW/m]	17	17.5	18.9	19.8	25.34	**14.35**
Burn length [sec]	7200	7200	7200	7931	7200	**400**

2.2. Field and plasma shape

Possibly, the most significant change between baseline 2017 and the others is the significant drop (about 1 T) in the magnetic field for the 2017 baseline. The underlying idea was to increase the confinement time with a higher current and relax the technical constraints on the TF coils. This leads to a decrease in the safety factor q down to the limit of 3, which may exacerbate the stability of the discharge unacceptably, e.g. by pushing the $q = 2$ magnetic surface very close to the pedestal, increasing the risk of mode locking and of confinement loss by triggering of (2,1) Neoclassical Tearing Modes (NTM) (caveat: the MHD stability is not explicitly included in PROCESS). For this reason, the field was increased again in 2018, and the edge safety factor was significantly increased. Note that this has happened also as a result of an improved model in PROCESS for the central solenoid, which was found to provide the same flux swing with a smaller size, allowing TF coils to be increased in size and thus being able to provide a larger magnetic field without impacting on the overall radial build. This is why not all engineering activities started on 2017 baselines have been migrated to the latest baseline, since, apart from the magnets, which indeed switched to the new configuration, everything was assumed to be sufficiently compatible.

For the various DEMO baselines, magnetic equilibria for start of flat-top (SOF) and end of flat-top (EOF) have been created by employing the code CREATE-NL [18] for the different baselines [19–22], employing the data of PROCESS (plasma current, shape, internal inductance and β_{pol}) as input. These code results have been used as starting points for most of the investigations carried out and discussed on the previous (and in the following) sections. In addition, the calculations of CREATE-NL also provide the current evolution in the coils, given a certain reactor configuration. It is here stressed that the PROCESS results, or more exactly the models implemented in PROCESS, are often simplified and relying on simple extrapolation rather than on first-principle physics description. These results serve as a starting point for successive investigations, but do not represent a detailed design, as discussed in [2]. For this reasons, investigations with more complete, dedicated codes follow the release of each baseline. An example of these equilibria is given in Fig. 1.

Concerning other shaping parameters, the main role of the plasma elongation, obtained by stretching the plasma poloidal cross section vertically, is to best fit the vacuum chamber and to maximize the volume of plasma, especially at high toroidal field. The larger plasma elongation has a strong positive impact on the fusion performance [4], and hence allows a reduction of the machine major radius, all the other parameter being equal, and if no other constraints are encountered. Plasmas with elongations as in DEMO are vertically unstable, with a growth rate

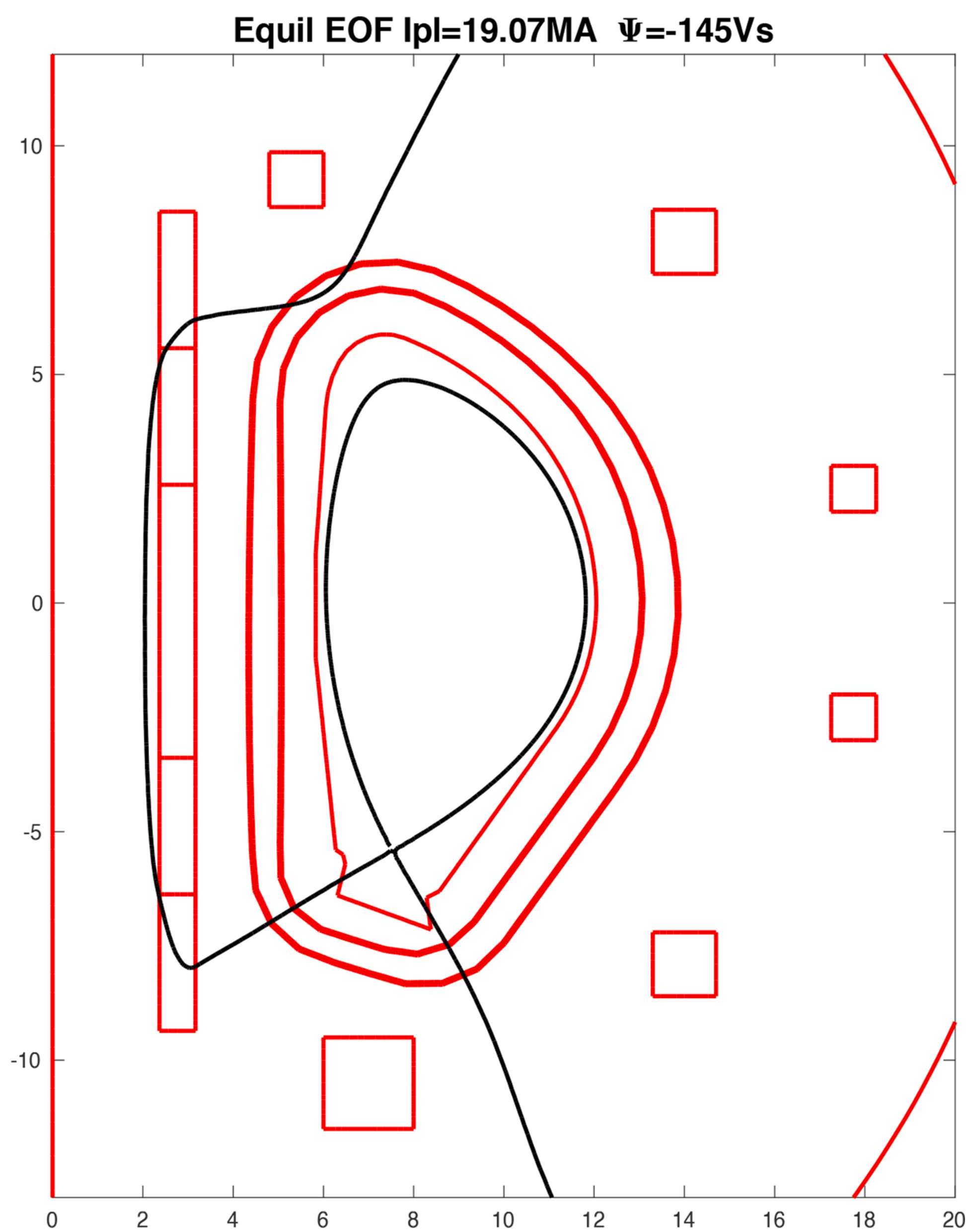

Fig. 1. Example of magnetic equilibrium (end of flat-top, in this case) produced with CREATE-NL and compatible with the major engineering constraints (forces and current/voltage limits in the coils). The figure is taken from [21].

which depends on its configuration and the surrounding conducting structures. For this reason, elongated plasmas need a specific vertical stabilisation (VS) control system, and the maximum achievable elongation is a design driver of the machine, and is one of the main input parameters used by systems codes to get an initial radial and vertical build. The two main requirements to define the maximum plasma elongation for DEMO are:

- Passive stabilisation: with the stability margin $m_s \geq 0.3$, defined as in [23]. A tool was developed to optimise and automatically design the first wall geometry, reducing the plasma wall distance and improving the VS performance, as discussed in [24].
- Active vertical stabilisation: with the VS system that needs to be able to vertically recover the plasma in case of 5 cm vertical displacement, ELM ($\Delta l_i = 0.1, \Delta\beta_{pol} = -0.1$) and minor disruption ($\Delta l_i = -0.1, \Delta\beta_{pol} = -0.1$), using the "best achievable performance controller", with a power pulse up to 500 MVA (limit set as a preliminary technological constraint, to be better addressed in the following phases).

Using the constraints above, the DEMO maximum elongation is set to $\kappa_{95} = 1.65$. While the above were developed by considering the ex-vessel superconductive coils as actuators, improvements could be achieved by using in-vessel resistive coils [25,26], and this will be assessed from the technological point of view in the near future.

Concerning triangularity, the value $\delta_{95} = 0.33$ has been carried over from ITER. It is important to underline that the effect of triangularity on the pedestal height was not considered until 2018, when the Saarelma empirical scaling [27] obtained with EPED [28] simulations was implemented in PROCESS – see discussion below.

Finally, some considerations on the Toroidal Field (TF) ripple. The TF ripple is a three-dimensional perturbation in the nominal toroidal magnetic field due to the finite number and toroidal width of TF coils in tokamak devices. It negatively affects fast ion confinement, increasing the potentially damaging heat flux they carry to the plasma-facing components. The TF ripple may also affect plasma rotation and locking, confinement, LH transition, edge pedestal characteristics, edge localized modes (ELMs) and ELM suppression [29].

Based on the physics research undertaken for ITER, for which a nominal maximum value of 0.5% is recommended [30], the present DEMO baseline foresees a maximum value of 0.3%, which is conservative wrt. ITER, to reduce even more the impact on the fast particle losses. This is achieved by using as a target value for the ripple equal to 0.6% within the systems code PROCESS (not shown in Table 1), and adding ferromagnetic inserts (FI, not modelled at the moment in the systems code) to reduce the ripple to 0.3% (note that the breeding blankets are expected to be ferromagnetic and will be included in the ripple stabilization). A wide scan and optimization of the effect of FI was carried out for different DEMO baseline configurations [31–34], by using the 3D code CARIDDI [35]. Investigations carried out inside the DEMO team on fast particle confinement have shown that losses and, correspondingly, associated loads on the PFCs are expected to be small. This is due both to the low field ripple the machine is designed to have, and, foremost, to the quite large clearance between the plasma and the wall (22.5 cm on the outer midplane [36]). For α's, in addition, the large size and current of the machine plays a role in reducing the prompt losses, since the ratio between the banana orbit and the minor radius is indeed quite small, and thus the particles born in the core have little chance of leaving the plasma before being thermalised.

Published studies [37] have found the heat load on the FW associated to NB fast ions losses to be well below the technological limits of 1 MW/m^2 [11], being of the order of 40 kW/m^2. More recent, unpublished studies have shown that this applies even in presence of a plasma separatrix corrugation due to MHD activity – i.e. the Edge Harmonic Oscillator (EHO) characterising QH-mode discharges, indicating a fraction of fusion α's leaving the plasma before thermalizing below 0.1% [38], leading to a heat flux on the first wall which is at least two orders of magnitude below the one due to core radiation. Also, it has been shown that α losses remain negligible even in the simultaneous presence of a large sawtooth crash and NTMs [39].

2.3. Heating and current drive

The main role of heating and current drive systems in DEMO is to provide heating during the ramp phases and for core temperature control purposes, as well as stabilise NTMs via localised current drive. Transient phases, which are anyway not captured by PROCESS, and the necessary actuators have been analysed in a separate publication [40] (although they are briefly discussed in Section 2.6 below). Bulk plasma current drive is at the moment not explicitly requested. Until 2017, it was assumed that the 50 MW of auxiliary power, included in the systems codes as a rough 0D approximation for the various plasma control requirements, also provided some current drive contributing to extending the pulse length, as visible in Table 1. Thereafter the current drive assumptions of that (in reality intermittent) 50 MW were removed, leaving them as purely contributing to plasma heating (and recirculating plant power consumption).

At the start of the design activities, a steady state alternative concept called DEMO 2 relying on a much higher auxiliary current drive (CD) was considered as well. That concept was then "absorbed" in the studies of the long pulse to steady-state concept Flexi-DEMO [41]. A study comparing the CD efficiency of different technologies was produced in this early phase [42]. All technologies showed a CD efficiency of 40-50 kA/MW, with electron cyclotron (EC) yielding the highest efficiency close to the magnetic axis, while NB performs better off-axis. An example is given in Fig. 2, concerning ECCD for Flexi-DEMO, where the better performance for absorptions close to the plasma centre is visible. In PROCESS, a value of ~45 kA/MW has been assumed for all baselines and technologies, with a strong simplification neglecting any dependence of the absorption on T and n profiles. This value is of course important also to determine the necessary flux swing the Ohmic Heating (OH) must provide to achieve the target pulse length, as well as for the final electrical power output by virtue of the large recirculating power involved in these CD-dominated configurations.

Recently, in view of the growing importance of EC in the DEMO design, an investigation of the beam broadening caused by plasma density fluctuations has been carried out, analogously to that performed for ITER [43]. The broadening which an EC ray undergoes in DEMO appears to be quite significant, mostly because of the large distance a ray has to travel from the separatrix to the absorption layer [44,45]. Changing the launching position (e.g. to launch from a dedicated upper port launcher, not foreseen at the moment), or driving the current for NTM control on the lower field side, have been shown to considerably improve the situation [45,46]. However this phenomenon may lead to an increase of the power pulses necessary for plasma control. Further investigations are foreseen in the next phase.

2.4. Confinement and pedestal

Until 2019, PROCESS was run with imposed shape for the profiles and imposed H factor (which is defined as the ratio between the machine confinement time and the confinement time calculated with the well-known IPB98(y,2) scaling). Note that PROCESS employs in input the so-called radiation corrected H factor, which was typically set to 1.1 in order to achieve standard H factor ~1. In the radiation corrected case, the power radiated from the innermost region, overlapping with the α-heating source, is subtracted from the power entering the scaling law, leading to a reduced power degradation [48]). This is of course an important simplification, since the H factor – or, equivalently, the confinement time – is in reality uncertain, and should be a result of modelling, rather than an input, as argued in [49]. For this reason, more

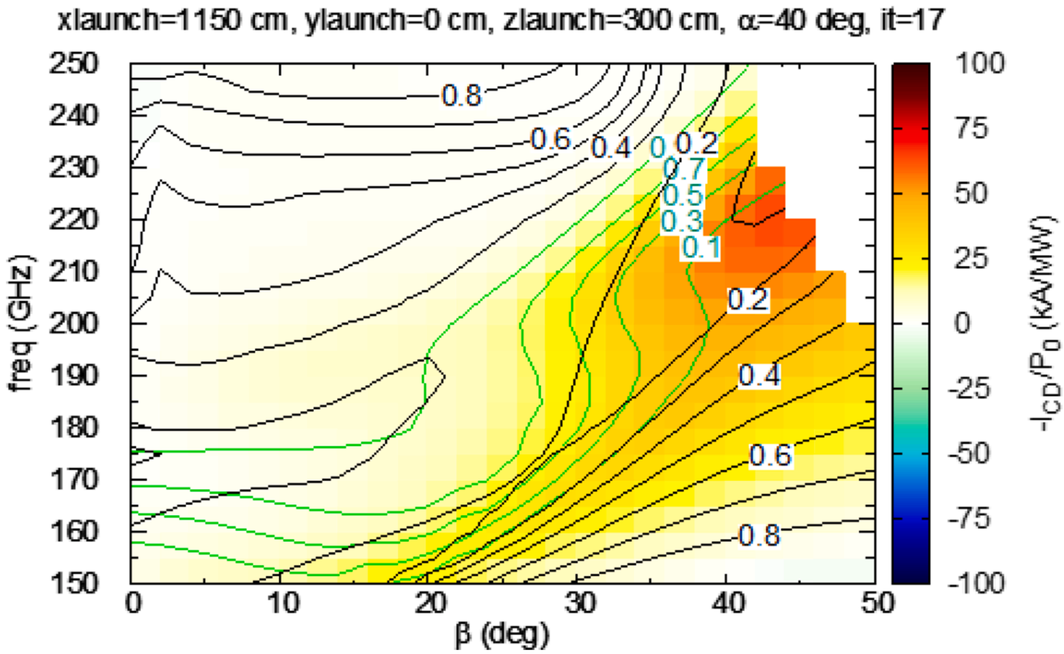

Fig. 2. EC current drive efficiency studies for Flexi-DEMO as a function of the wave frequency and the toroidal injection angle β for fixed poloidal injection angle α. Black lines represent the toroidal ρ where there is the maximum of the deposition, green lines represent the fraction of power absorbed at second harmonics, color axis is the kA/MW driven. The calculation was performed with GRAY [47].

comprehensive codes, able to calculate 1D profiles, have been employed to determine more precisely (although not fully self-consistently, i.e. without a complete pedestal model) the shape of plasma qualifying profiles. The codes employed have been METIS [50] and ASTRA/TGLF [51–54]. Generally speaking, the fusion power for a given set of engineering parameters was found to be 5-10% lower than for the systems codes. This is normally due to the fact that the fixed profile shape in PROCESS leads to a plasma temperature and density that is higher around mid-radius. Profiles produced in the framework of those investigations (see e.g. Fig. 3) have then been employed as a starting point

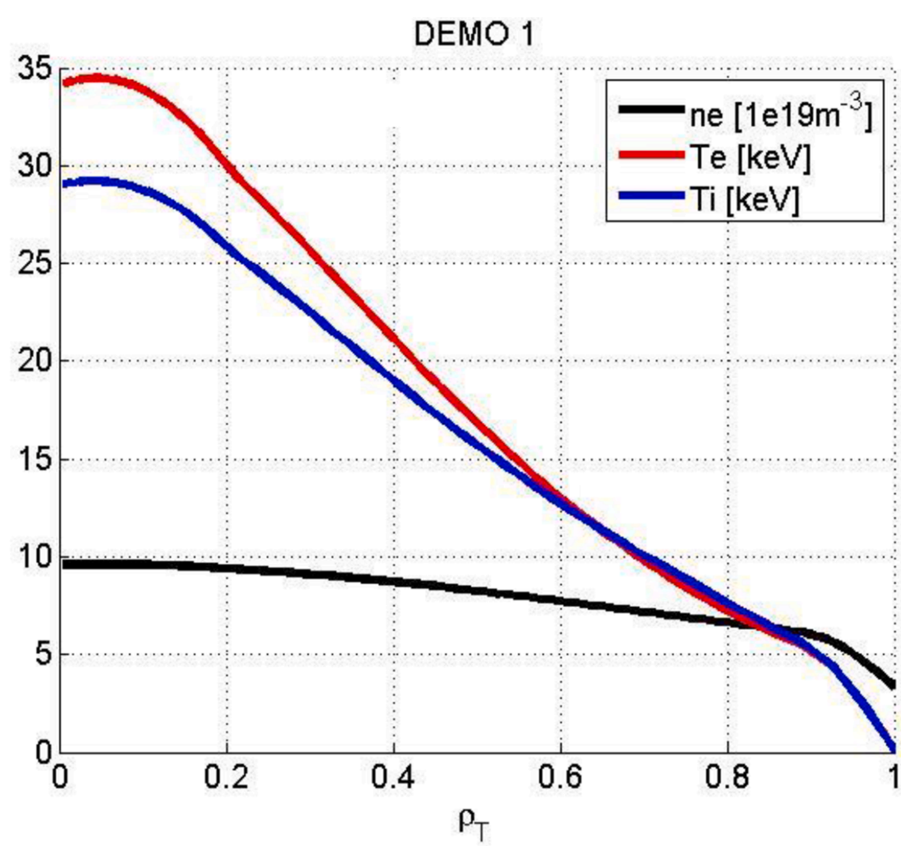

Fig. 3. Density and temperature profiles calculated with ASTRA for DEMO 2018. Figure is taken from [6].

for other activities. Note that, at the moment, in ASTRA/TGLF, some possibly beneficial effects such as the turbulence stabilization due to fast particles (see e.g. [55]) are not fully taken into account.

In addition, for a better understanding of the transport coefficient, various gyrokinetic calculations with GENE have been carried out as well. By virtue of the long simulation time, the goal has been limited to compare GENE results with the transport coefficient from TGLF at few radial positions, rather than reproducing an entire profile. Again, transport coefficients have been found to be higher than the corresponding quasilinear cases (TGLF), although the potentially beneficial effect of fast particles was again neglected. This point deserves more understanding effort in the future, in order to avoid DEMO plasma to underperform relative to that predicted by systems codes.

In the QH-mode baseline 2019, the profiles are no longer imposed, but the simplified transport solver code PLASMOD [56] coupled to PROCESS is used as transport solver for the core (not the pedestal), with transport coefficients not renormalized to yield a specific fusion power. In that way, the H factor becomes an output for any given pedestal assumption (like for ASTRA/TGLF, but now embedded in the systems code, thus influencing the calculation of the machine build), and a reduction in the fusion power compared to the previous baselines is shown (in this case, major radius was an input). This is not due to any particular assumption distinguishing QH-mode from H-mode, as discussed below, but simply by the adoption of a different transport model. By virtue of an improved calculation of the plasma resistivity by taking into account in more detail the charge state of the impurities, the pulse length is shown to increase. Furthermore, a more detailed divertor model, namely the Kallenbach model [57] was used. The model allows an estimate of the necessary Ar concentration to achieve detachment, and, coupled with PLASMOD, of the effect of the seeded impurities migrating in the core on the discharge performance [26], which was completely neglected in the previous releases. In this sense, the QH-mode baseline represents a significant improvement in the modelling standard of DEMO baselines.

The pedestal top pressure has been evaluated by employing the standard EPED code, i.e. assuming the pedestal is limited by peeling-ballooning modes [27], without considering whether this is compatible with the expected transport. In particular, a scaling law has been set up, relating the pedestal top pressure as far as stability is concerned to a number of plasma physics and engineering parameters (and valid only in proximity of DEMO plasma conditions, see Fig. 4). Such a scaling law has been implemented in PROCESS and in ASTRA-Simulink, allowing a self-consistent prediction of the pedestal top pressure, which at the same time depends on (via peeling-ballooning stability) and determines the achievable global plasma β. In fact, in 2015 and 2017, both pedestal top temperature and density were imposed. Thereafter, only the density was still imposed (typically at $0.85n_{GW}$), but the temperature was on the contrary calculated with the scaling (note that, in this way, the line-averaged density is an output of the code). It is of course an important goal for the forthcoming phases to develop a predictive model for pedestal density, temperature and width, and for different confinement regimes (i.e. not only peeling-ballooning as for ELMy H-mode, but for various pedestal limiting modes, like e.g. the EHO of QH-mode). This requires, however, a coupling between a pedestal model and a core transport model, to capture the mutual influence. In this direction, a second scaling law has been derived for the evaluation of the fusion power as a function of the pedestal top parameters, this scaling applying not only for H-mode but also for other regimes [58], assuming that the core transport is correctly captured by TGLF from the pedestal inwards for all regimes. The central role of the pedestal for determining (or limiting) the achievable fusion power level has been also re-stated in [59], where the extrapolation to DEMO of various experimental and numerical cases referring to existing facilities has been analysed. This is a consequence of the fact that high peaking of the ion temperature is in reality difficult to achieve, due to profile stiffness.

2.5. Core radiation, SOL and divertor

As discussed in [36], DEMO has been designed by having the 0D figures of merit of ITER for the divertor protection quoted in Table 1 as a guideline, namely $P_{sep}B_T/q_{95}AR$ and P_{sep}/R – see also the discussion in [61]. In order to achieve this result however, a large fraction of the heating power (predominantly fusion α's) must be radiated from the core region and distributed on the large first wall, see Fig. 5 – a thorough

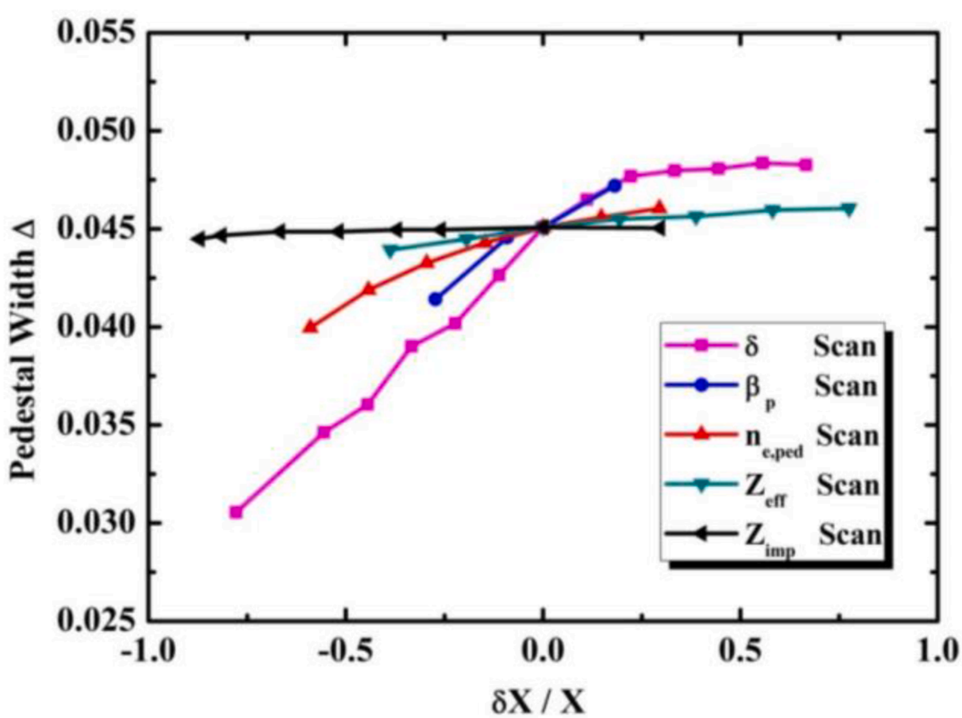

Fig. 4. Dependency of pedestal width (normalized to machine major radius) on the relative variation of various plasma parameters. Figure is taken from [60].

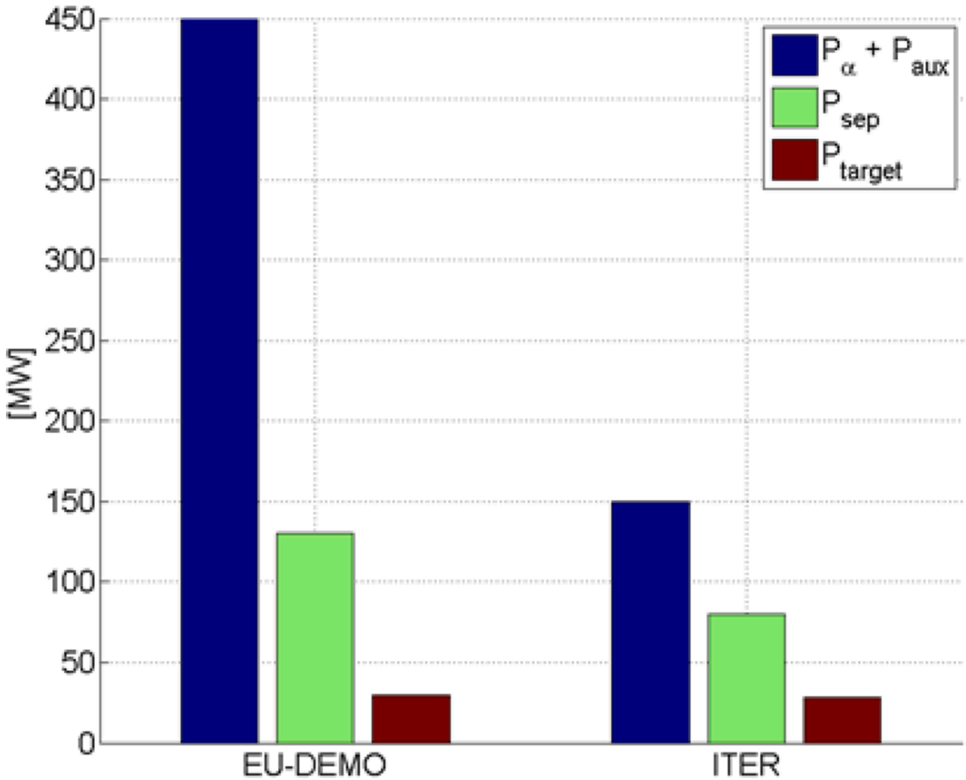

Fig. 5. Total heating power, power at the separatrix and the power deposited on the divertor in ITER and DEMO. The difference between blue and green columns are due to core radiation (line, synchrotron and bremsstrahlung), the difference between green and red to SOL dissipation. Data for DEMO are taken from ASTRA simulations. Figure is taken from [6].

analysis of the impact of this choice can be found in [11]. To obtain this, high-*Z* impurities, e.g. Xe, have to be seeded in the reactor. The power at the separatrix can sometimes be much larger than P_{LH}, since PROCESS always tends to converge on the maximum achievable value of P_{sep} compatible with the assumed divertor capability (the concentration of Ar to achieve detachment is not calculated, nor, obviously, its effects on the core plasma, unless the Kallenbach model is employed). The choice of employing a core radiator has however consequences, and the implications on the plasma controllability are significant, since they can lead to runaway radiative instabilities as discussed in [6,40]. On the contrary, investigations concerning the intrinsic impurity W have shown very limited risk of W influx at reactor relevant parameters, by virtue of the strong neoclassical effects [62].

The activity on SOL and divertor carried out only refers to the ITER-like LSN configuration, with a large fraction of the power crossing the separatrix dissipated via line radiation of the seeded impurities, namely Xe, with Ar employed as a SOL radiator (concerning alternative divertor configurations, the reader is referred to [63,64]). The goal is to achieve a detached state, and thus a low heat flux on the target which is compatible with the exhaust capability, in combination with a low plasma temperature to minimise erosion. The main tool for the investigation of the SOL/divertor has been SOLPS. Many fluid cases have been launched in the past years (see e.g. [65]) with the purpose of understanding the possibility of achieving detachment with different seeded impurities, and also the conditions at which detachment can be reached. Later on, attempts to produce the first DEMO cases with kinetic neutrals have been made. This greatly enhances the level of physics detail of the simulation, and hence the reliability of the results, at the price of significantly higher complexity and thus longer computational time.

Although, as mentioned, no well-established fully detached reference case with kinetic neutrals exists at the moment, there are indications that a steady-state working point with acceptable heat flux on the target and electron density at the separatrix exists [66]. The Ar injection rate (of the order of 10^{19} p/sec) is found to be compatible with reactor operation (also in view of the large size of the device if compared to the Ar ionisation mean free path), although the He concentration at the separatrix, having imposed a core source corresponding to 2 GW of fusion power, still seems high (~10%). It is noted here that the lack of predictive capability of SOL and divertor codes is not a DEMO peculiarity. Rather, it reflects the state of the art of the current numerical tools (interpretative to a good extent but not quantitatively predictive in all circumstances), and has to be improved in the next phase.

In parallel, other simulations of core/SOL coupling, concentrating in particular on the influence of the SOL impurities on the core fusion performance, have been produced with COREDIV [67], also referring to other DEMO configurations than the baseline – e.g. at lower energy confinement conditions, which might be relevant for some ELM-free modes [68]. Finally, an attempt of understanding how the filamentary (or "blobby") transport extrapolates to DEMO has been undertaken [69]. In general, the effects of filamentary transport, although highly uncertain, appear reasonably low in view of the scarce energy transport associated. Consequences of blobs on the FW design under pessimistic assumptions have been analysed in [11,25] and references therein, finding the impact limited, and anyway relatively easy to minimize via wall shaping. Also, the risk of highly enhanced erosion due to filamentary transport appears low.

2.6. Transients

Although, as mentioned, transient phases and the necessary actuators therefore have been analysed in separate publications in this special issue [25,40], a brief discussion on their role is here reported. In fact, transients have important repercussions on the design as a whole, but at the same time they are not easily described by a tool like a systems code. For this reason, the development of a dedicated modelling tool, labelled as "flight simulator", is one of the major priorities of the next DEMO phase, as discussed in detail in Section 4. This tool is intended to model all transient phases, and, subsequently, to help developing and qualify a diagnostic concept for their control, as well as to determine the engineering requirements for the actuators (H&CD, position and shape control, matter injection).

Transients are broadly subdivided in planned and unplanned, the former indicating the access and exit from burn phase, the latter indicating instead all these accidental events which, when no countermeasure is taken, can lead to a disruption.

Regarding planned transients, the plasma current ramps to access and terminate the plasma are quite critical in DEMO, since the number of constraints that they have to fulfil is quite large [40]. As discussed in [25] and references therein, after the breakdown the plasma touches the outer midplane limiter and as the plasma current reaches ∼5 MA, it enters the diverted phase. In this initial sequence the plasma is purely ohmically heated, so that limiter erosion is not increased too much. During ramp-up, a sufficient ion heating has to be guaranteed to achieve a self-sustaining fusion burn. An efficient ion heating scheme may boost the fusion power from the early phases, thus relaxing the requirements in terms of necessary auxiliary heating power. During ramp-down, one of the main issue is linked to the control of radiative instabilities, since the interplay between the decrease in fusion power and a possible increase of the impurity radiation may quickly lead to sudden losses of energy confinement, potentially driving a disruption.

In general, ramp-up and down require a strong involvment of the actuators, both H&CD as well as plasma shape and position control. For this reason, the definition of a ramp trajectory will profoundly affect the design requirements of the machine, also in terms of electrical power absorption in a phase where no or little fusion power is generated. Furthermore, power exhaust is found to be critical, since high power flows have to be expected even when the plasma density is low. In this sense, it is clear that a systems code generated "baseline" as described before, albeit very important, cannot possess all necessary information to determine the design constraints. The development of a flight simulator appears therefore as unavoidable.

Concerning unplanned transients, the current status of the studies of disruption avoidance, and the related development of a diagnostics concept can be found in [70]. Vice versa, the consequences of disruptions, as well as the design solution to mitigate them, are broadly explored in [25].

3. ELM mitigation and ELM-free regimes

It has been recognised that the heat load associated with ELM events on a large tokamak reactor is largely incompatible with the integrity of PFC on fpy time scales [11], see Fig. 6. To mitigate this risk, the main strategy at the moment is to consider naturally ELM-free regimes as priority in view of the challenging availability and reliability requirements posed by active mitigation schemes [6]. This will be pursued at least until there is strong evidence in support of active ELM mitigation at reactor relevant conditions. In fact, one single unmitigated ELM event can lead to melting on the divertor target [11], so the reliability which has to be demonstrated is essentially 100%, this encompassing not only the flat-top phase, but also the ramps to enter or leave the burning phase. Preliminary assessments of the possibility of ELM-mitigation via RMP coils have been carried out [71] (other methods, like e.g. dedicated pellet injection, have not been considered at the moment). Although it was shown that mitigation is possible, no clear prediction was provided about the extent ELMs can be mitigated. It is important to mention however that those investigations assumed ex-vessel coils (whereas in ITER, in-vessel coils are present which should be more effective). No modelling is available at present which considers in-vessel coils instead.

Various reviews of the knowledge gaps to be filled in order to conclude on the suitability of ELM-free (or "tiny"-ELM) regimes in DEMO have been produced [72], anticipating the work of two dedicated Ad-hoc Groups on ELM-free regimes [73] and negative triangularity

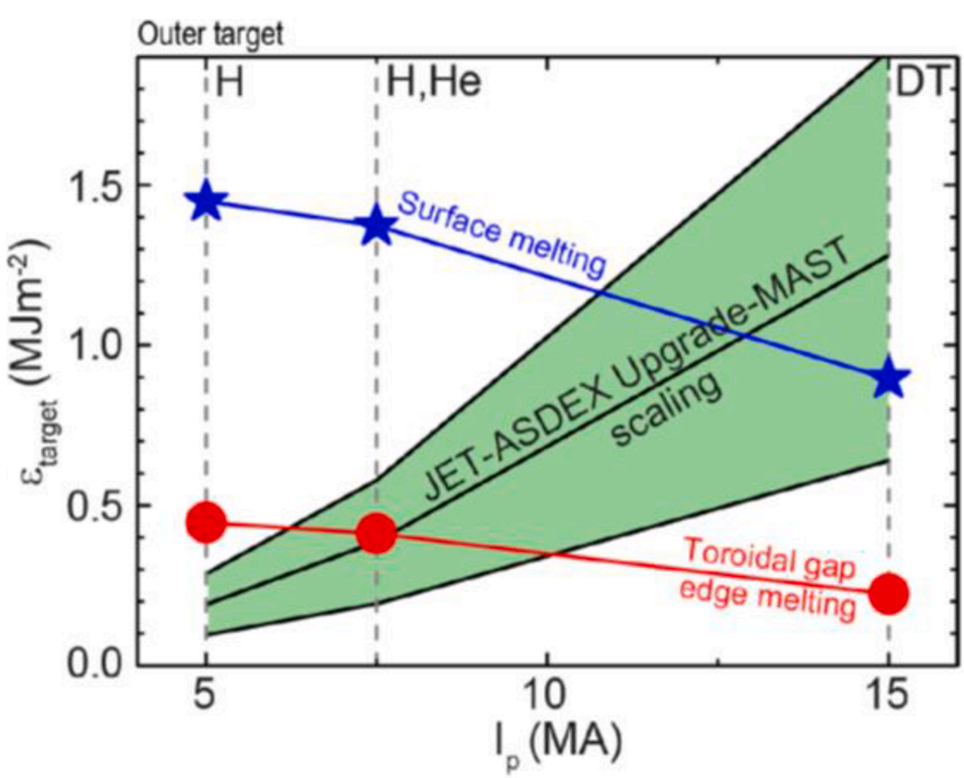

Fig. 6. Energy deposited on ITER target by a single ELM event as a function of the plasma current following a multi-machine scaling, and related damage. The safety factor $q = 3$ and $\Delta W_{ELM} = 5.4\%$ have been kept constant. Figure is taken from [79]. DEMO would lie outside this figure at ∼20 MA, with the acceptable ELM energy being lower that the scaled one by more than one order of magnitude.

[74], the latter being dealt with separately because a different path has to be followed in order to qualify that solution for a DEMO reactor – there exists a few facilities able to host such a configuration, and no device optimized for it. Also, there is no ITER equivalent machine with NT planned to be built at the moment, and no NT discharge is foreseen in ITER as well. Although no NT baseline has been released for the time being, as discussed in Section 2, some preliminary studies on a NT DEMO have nevertheless been started.

The QH-mode baseline produced with PROCESS is, in reality, an H-mode baseline, since the pedestal model in PROCESS cannot capture the differences between an ELMy H-mode, peeling ballooning limited pedestal and and the EHO limited plasma, while the confinement of QH-mode is assumed to be comparable to the corresponding H-mode for the same engineering parameters. The only difference QH-mode introduces at this level is the increased heating power, since QH-mode may need a certain level of rotation to be sustained, and this could be achieved for example via NBI [75]. Incidentally, it is at the moment not clear whether the high poloidal flow shear is a necessary condition at all, or only for the access, or also for the sustainment of the QH-mode. In the latter case, QH-mode may then be understood as an active ELM-suppression method, thus problematic for the reasons elucidated above. The increase is however just estimated, without any particular investigations on support – although verifications have been done *a posteriori* [76]. However, the QH-mode baseline exhibits important differences with respect to the previous ones in terms of code development, as previously mentioned. This justifies the discrepancy in the parameters.

Turning to the I-mode baseline, these improving features (PLASMOD and the Kallenbach model) were not yet used. It did however have different assumptions than the H-mode ones concerning threshold power to access the mode (for QH-mode, Martin scaling was employed as for H-mode, in absence of any other scaling) and for the confinement. For the first point, Hubbard scaling [77] was employed, whereas for the confinement an *H*factor of 0.8 was assumed, yielding the value of P_{sep} as reported in Table 1, and the pedestal top density was lowered to $0.65n_{GW}$, in agreement with the existing literature [78]. The result is a quite unattractive baseline. For eliminating the ELMs, the power exhaust problem is exacerbated via a higher P_{sep}, in spite of the fact that a solution with P_{sep} marginally lower than P_{LI} was optimistically accepted, see Table 1, and the fusion power is significantly reduced in spite of a somewhat larger radius. Note also that the constraint on 500 MW of electrical power was relaxed for I-mode. Possibly, a more careful optimization shall be carried out to design a more convincing baseline, e.g. by exploiting the weaker dependency of P_{sep} on the field than the H-mode case. This is the subject of future work.

4. Plans for the concept design phase

The PCD Phase has clearly pointed out the need of DEMO plasma scenario to rely on a more solid physics basis, as well as the necessity of an approach allowing the identification of design-driving priorities (these originating from a continuous interaction with the engineering design). The strategy for the identification of one or more viable scenarios for DEMO to be carried out in the future DEMO Central Team (DCT) [1] will be articulated in two main types of activity:

- Global scenario visions, i.e. guiding and integrating the individual areas, providing the link between plasma scenario development and the wider DEMO design.
- Coordinate a piecewise approach to individual challenges and opportunities, fostering the development of the necessary capabilities, experimental and theoretical (i.e. not only relying on what exists, but addressing the community with goal-oriented development requests).

The PCD experience shows that new scenarios need to be identified, since no scenario appears to be at the same time robustly characterised and suitable for the DEMO mission, for the reasons elucidated above. Therefore, it is reasonable to explore a range of final state plasmas with the desired characteristics, and in parallel explore whether these are physically consistent internally and with engineering constraints, and other external interfaces. Initially, assumptions would be used to fill knowledge gaps, replacing these assumptions with knowledge later. To achieve this, it will be necessary to combine experimental experience, theoretical knowledge, driving innovations in both experiments and theory. It must be ensured that enough options are explored, requirements for each technical and capability area are set, suitable output (with uncertainty bands) in time for the key DEMO decision points are produced. Selected and developed scenarios must fundamentally not be taken as predictions at this stage, but genuinely used as a "what if" analysis. They shall be a framework to develop confidence bands, if the uncertainty in each element, including gaps in knowledge and models (epistemic uncertainties, challenging to model), are to be translated to quantitative uncertainty in the performance. Assumptions and uncertainties can also be regarded as opportunities for improvement and innovation.

Two critical and complementary tools will be developed to enable scenario identification, development and qualification: an improved systems code (SYS) and a full discharge simulator, or flight simulator (FS). The precise roles of each, and their relation to deeper models, are likely to evolve, but an initial plan is here presented.

4.1. Systems code (SYS)

In the future DCT, a high level tool for the evaluation of the impact of the identified plasma scenarios on the whole plant architecture has to be foreseen and developed. This encompasses also, for example, the impact of unconventional plasma shaping as well as divertor configurations, high-level performance, P_{fus} etc. Furthermore, the tool shall be capable of evaluating, at least in a comparative way, the costs associated with a certain design choice, taking into account all the interfaces between the various systems, in order to evaluate the relative feasibility and merit of different scenario solutions.

This tool will be an advanced systems code (henceforth SYS) with more detailed reduced models than present ones, and it will be an important verification of the compatibility of the plasma scenario with all technological design solutions. In parallel, this tool shall allow the carrying out of sensitivity analyses to assess the robustness of the chosen plant solution versus the uncertainties in the assumptions. The SYS code will have annexed codes capable of higher fidelity (e.g. Finite Elements Analysis – FEA), but with limited integration. Part of the work in developing the reduced codes will be to ensure the correct compromise between integration and detail/generality and, most importantly, define the limits of the SYS code.

4.2. Flight simulator (FS)

Alongside SYS, a sophisticated theory-based integrated modelling tool **(hereafter indicated as "flight simulator", FS)** will be needed to handle the whole pulse dynamics, transitions (pedestal formation, divertor detachment), control aspects, disturbances and transients [80], since it has been learned in the PCD Phase how strong the impact of transients and higher order physics (e.g. ELMs) on the machine design can be. Indeed this tool will probably be the basis for the scenarios entered into the SYS, this latter being however more complete with regards to the description of engineering aspects and constraints on a plant level. **FS** should also have the capability of exploring the consequences of different assumptions, approximations and theory models and, early on, semi-empirical models, as a part of the assessment of confidence and uncertainty at each stage. **FS will be employed** to explore the behaviour and thus viability of scenarios, as well as later guide the operation. For example, how well the disturbances can be controlled, e.g. minor dynamic changes in heating and fueling systems and whether the plasma can be returned to the nominal point without becoming unstable (or even moving to a disruptive trajectory).

Note that, in spite of having limited engineering model content in comparison to SYS, the FS can indeed provide important constraints/ requirements to the engineering design of DEMO. For example, the necessary performance requirements for the plasma control actuators (e.g. vertical position control) cannot be captured by a static snapshot, which is what SYS typically produces, but it has to be augmented by dynamic simulations, perhaps initially with some significant headroom (e.g. in PFCs, power supplies and coils, H&CD capabilities and geometric space for excursions).

It is important to underline that, at the beginning, some of the knowledge gaps which have to be closed will consist of the development of models to be then integrated in SYS and FS for scenario qualification as well. So to say, the scenario and the tools for its qualification will evolve in parallel, this making the process intrinsically iterative and nonlinear.

4.3. Identification of knowledge gaps

The programme has to be broken down in many parts, by virtue of the complexity of the plasma scenario as an investigation object. All parts have deep direct and indirect interactions. For this reason, relevant interfaces have to be identified. An example of this subdivision of the problem into parts and corresponding interfaces is visualized in Fig. 7. A flat-top plasma scenario is identified (at a SYS level) once the following requirements have been met:

- Internal requirements within each region of the plasma: requirements which are associated with one part (e.g. in the proposed subdivision in Fig. 7, the "natural" absence of type-I ELM instability is associated primarily to the pedestal part).
- Interface and integration requirements across the plasma: requirements which are associated with the interface or cooperation between two (or even more) different parts (e.g. the range of acceptable values for the power crossing the separatrix is determined by the requirements of SOL, pedestal and what can be radiated from the core plasma, and the SOL turbulence and thus SOL width may be influenced by the pedestal turbulence).
- Engineering constraints: constraints originating from the technological side (e.g. the maximum allowable heat flux on the target plate in steady-state; loss of fast ions causing local heating; pellet injection geometry).

Note that the requirements (and the engineering constraints) do not refer solely to the flat-top phase, but also to the ramps, and in general to how stationary operation is reached and exited. A preliminary exploration is made with FS, with implications passed to SYS, as for other dynamic aspects mentioned above. There is however a fourth aspect on top of the constraints, namely the assumptions:

- Assumptions: working hypotheses which need further verification or changing at a later stage (e.g. a certain density peaking factor is prescribed). For the definition of the assumptions, a certain degree of "creativity" is admissible, with the obvious caveat that a less robust assumption has a lower chance of being proven to be realistic at later stages. A knowledge gap is defined as a missing piece of information initially replaced by an assumption, or by a simplified model. This information can be obtained from theory, experiment or, especially, from a positive synergy among the two.

Before requesting to the community to address a given set of knowledge gaps, it is necessary to explore, with SYS and FS, whether the target flat top plasma scenario (with initial assumptions) would in any case be generally compatible with the DEMO requirements and constraints from other systems. In addition, a sufficiently capable SYS and FS would be able to evaluate whether a quantitative deviation from the chosen assumptions would still lead to viable scenarios, or not – i.e. identify the allowable uncertainty range compatible with DEMO success. Assuming they are capable of achieving the latter, it will also be able to guide how the assumptions or boundary conditions would need to change to turn a unviable solution to a viable one. These requirements will guide the development of a SYS and an FS that are trusted by the engineering and science experts.

4.4. Scenario qualification

In order for a scenario to be accepted as viable, it is necessary that:

- Each assumption is eliminated or accepted as correct within a certain, quantified range of uncertainty. Equivalently stated, each knowledge gap has to be closed to a degree where the remaining uncertainty leads to a risk acceptable for the stakeholders, and

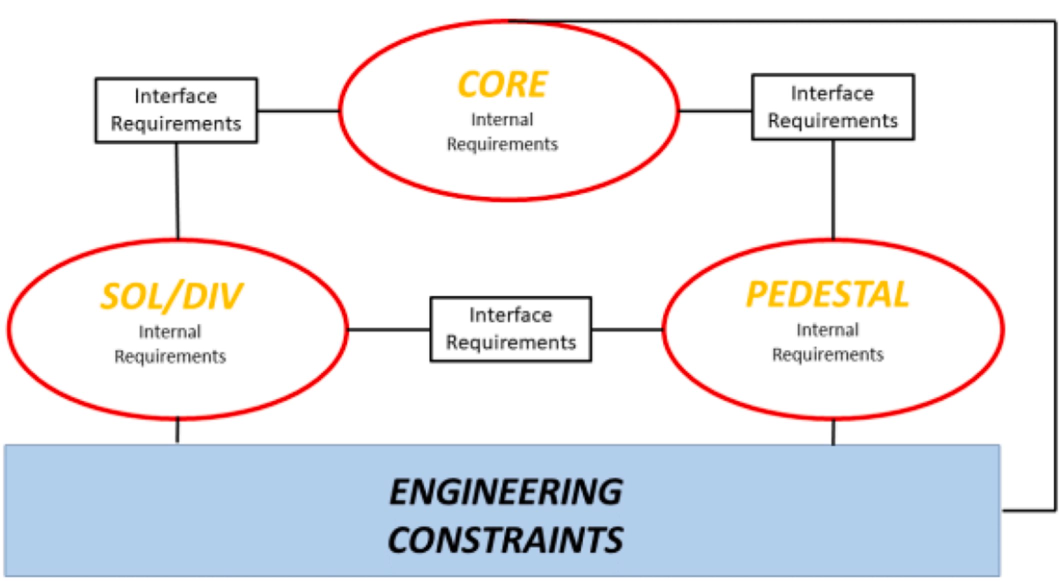

Fig. 7. Plasma parts, their requirements and their interfaces following the terminology introduced here.

compatible with the flexibility range or margin in the engineering design. The assessment of assumptions contributes thus to the establishment and corroboration of the DEMO plasma physics basis, here intended as sort of living document or database which justifies in the long term the chosen DEMO design.
- The full end-to-end scenario has to be shown to be achievable and controllable and the uncertainties estimated, e.g. via FS (this focus on controllability being complementary to SYS verification). Note that the controllability requirement may lead to design modifications as well.
- All requirements (both interface and internal) are shown to be simultaneously fulfilled, even when known uncertainties (with their associated range) are taken into account. This is normally primarily achieved by means of both SYS and FS. Both have to have uncertainty propagation and quantification tools embedded, with SYS being more detailed on the engineering side and FS able to explore the consequences due to the unavoidable variations in plasma and actuator performance.

Consequently, one of the main activities the fusion community has to carry out is the reduction of uncertanties in understanding, and in assessing the extrapolation to reactor scale. This is arguably accomplished primarily by theory and modelling, aiming at a first-principles description of the phenomena impacting on the design, with experiments serving as a partial check, as well as as a mechanism to identify unmodelled phenomena. The proposed workflow is represented in Fig. 8.

The qualification of the plasma scenario can fail in two different ways:

- An assumption is shown to be wrong. Then the assumption shall be changed and the process shall normally restart, depending on the impact of the assumption on the result (at the later stages of qualification there should be no significant assumptions left). This demands short cycle time.
- The performance/controllability is inadequate or uncertainties remain too high to provide acceptable risk for the stakeholders.

If there is no way identified for reducing the uncertainties or removing the performance limitations, it is then the duty of the decision makers whether to:

- Change the plant requirements by involving the stakeholders.
- Change (significantly) the plasma scenario – possibly introducing new fundamental assumptions which then need to be reduced or removed via the process described in the next Section. This is meant to be a much more radical change than simply modifying an assumption, which can instead happen many times before the final consistency check. Also this may require the involvement of the stakeholders.
- Accept the (now quantified) risk due to large uncertainties.

Obviously, changing the engineering plant requirements may lead to substantial delays in the project (mitigated if faster design tools can be developed), and probably correspondingly in an increase of the costs (unless the new requirements can be met by a lower cost solution). DEMO decision organs have thus to be aware of this before taking the decision of changing requirements – but this goes beyond the scope of the present paper.*Role of theory and experiment*

In order for a plasma scenario to be acknowledged as adequate for DEMO, a basis both in terms of theory and modelling and in terms of experiments is required. It is important to stress that the experimental and theoretical investigations have to be combined to develop solutions – e.g. experiments designed to challenge and stimulate theory, and both theory and experiment used in explorations of the new solution space.

Currently, there are gaps in theory and modelling, as well as in the experimental capability, which means that some of today's observations have limited physics understanding, which can undermine confidence in models – these epistemic uncertainties need to be estimated, a partly separated conceptual challenge. The theory and modelling tools need a strategy, and the setting of requirements, just as much as experiments do (for example diagnostic capabilities may need to be significantly changed, to help better confront and drive theory).

The closure of knowledge gaps towards the qualification of a plasma scenario for DEMO has been divided into three categories, or phases:

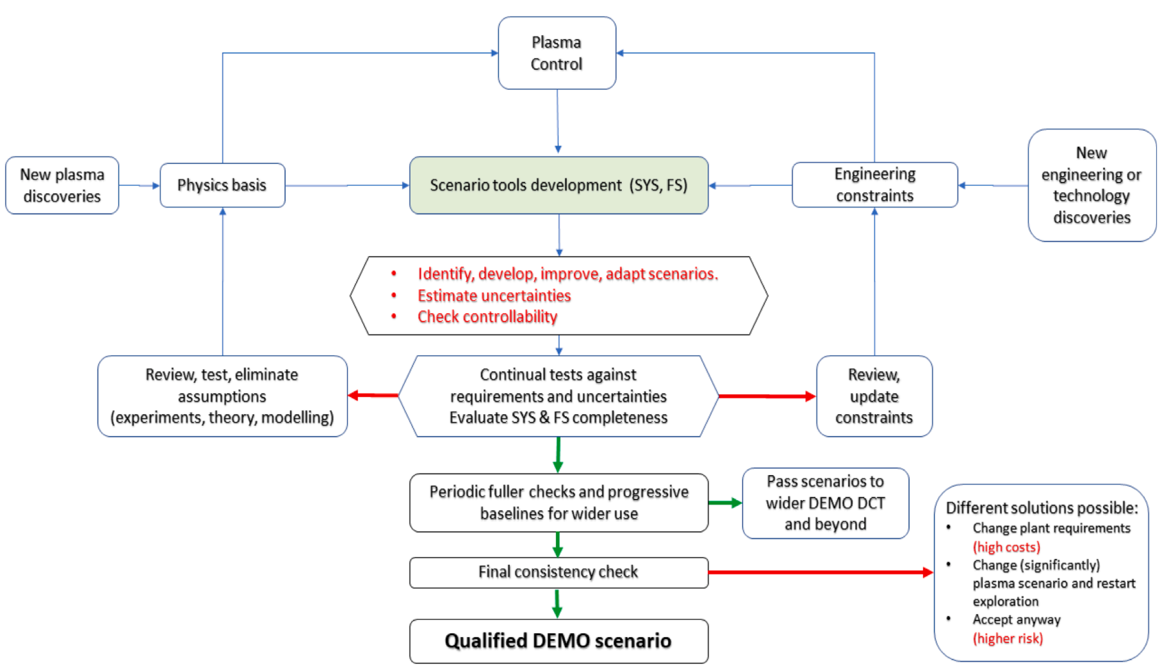

Fig. 8. Workflow of plasma scenario identification and qualification. Green arrows identify positive responses, red arrows negative responses. The definition and qualification of a plasma scenario evolves in parallel with the development of SYS and FS, and in a continuous way.

- Identification of path(s) to a solution. In the first phase, one has to show that the relevant physical mechanisms are indeed observable in the present experiment, or predicted with a high level of confidence in numerical simulations, and translate to DEMO parameter regimes. If they are predicted to only exist beyond the regimes of present experiments, the robustness of the modelling needs to be much greater.
- Demonstration. In this phase, one has to demonstrate in detail how the assumed physical mechanism achieves the goal at DEMO relevant conditions, or at least there are clear indications that an extrapolation to DEMO is possible.
- Qualification. In the latter phase, the mechanism has to be explained in as quantitative form as possible, in order to minimise the associated uncertainties and allow a careful evaluation of the final DEMO performance, and operational regimes that accommodate the uncertainties.

The process needs to be open for new findings, as depicted in Fig. 8. The process of knowledge gaps closure has been schematically depicted in Fig. 9.

Currently, the DEMO Physics Basis is composed of various items which are found in different status with respect to the above classification. Consequently the various phases for the different gaps are not strictly intended to follow one another in a chronological order (e.g. some gap may be in the first phase when others are in the third). The various phases for each gap should not be understood as chronologically separated. Goals pertaining to different phases (e.g. demonstration and qualification) can (and actually are encouraged to) be investigated in parallel. Alongside this, a development plan is needed for the integration tools, especially the flight simulator and systems code, since, as already stated, the development of SYS and FS proceeds in parallel with the scenario qualification.

Example of knowledge gaps are:

- Physics mechanisms limiting the pedestal below ELM onset (e.g. in QH-mode and I-mode as discussed above).
- Quantitative prediction of conditions to establish a reliably controllable detached divertor.

It is however important to stress that the activities already carried out in these areas have provided a robust basis of results, from where the analysis can start. There are in fact also elements whose understanding is already quite developed and well-established, in view of the large experimental and theoretical experience accumulated in the past years. One could mention for example:

- Global ideal MHD (equilibrium and many stability issues)
- Transport of energy and particles in the plasma core.

Additionally, they have facilitated the identification of the most critical areas where the future analysis shall concentrate.

5. Role of ITER results for DEMO

In the European Research Roadmap to the Realisation of Fusion Energy [81], the role of ITER is acknowledged as crucial. ITER will be in

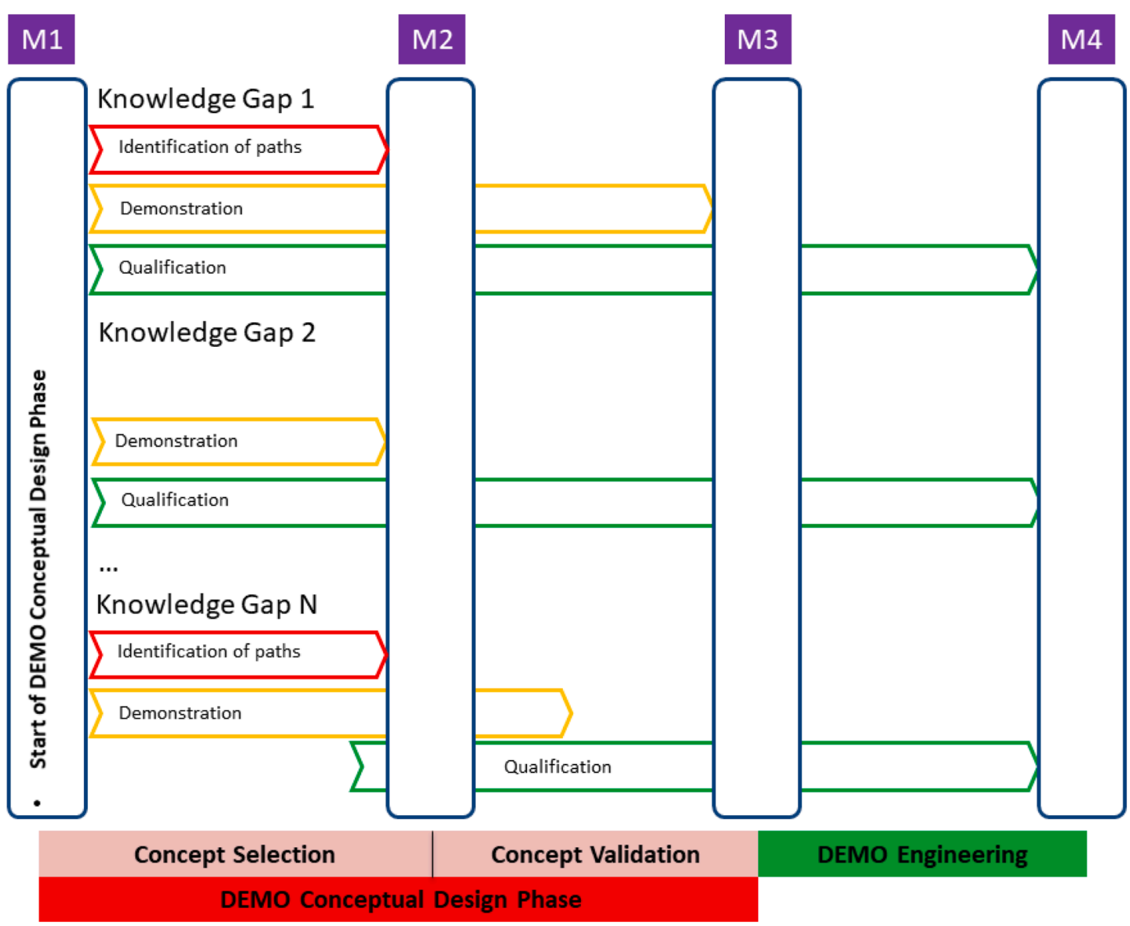

Fig. 9. Sketch schedule for the assessment of the experimental knowledge gaps in correspondence with DEMO milestones (M1-M4, here deliberately not defined since outside the scope of the paper). Knowledge gaps are found in different states at the moment. Nevertheless, all of those should conclude the first phase before M2, the second before M3 and the third before the end of the engineering phase M4. Also, note that the various phases can be run in parallel even for a single gap.

fact the first machine demonstrating the generation of fusion power at a level greatly exceeding the external heating power needed to sustain the plasma. 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). In view of the realisation of DEMO, it is clear that a validation of plasma scenario(s) in ITER is an essential step, in order to avoid a too large (and therefore risky) extrapolation from small devices to an electricity producing reactor.

As thoroughly discussed in the previous paragraphs, all EU-DEMO baselines have been defined under the assumption that ITER is going to "confirm our plasma physics expectations", i.e. that the plasma performance will extrapolate from ITER following the current physics knowledge (e.g. the IPB98(y,2) scaling for the confinement time). The reason behind this approach is that, in case ITER will indeed confirm our understanding, a "valid" DEMO design would already be available, this being at the same time the safest and quickest path towards the production of fusion electricity ("safest", since it will rely on ITER results, which minimise the extrapolation need, "quickest" since the design work would have been already carried out to a large extent). In fact, according to the roadmap, the DEMO engineering design is supposed to start before ITER enters the DT phase. In this sense, one important role of ITER is to provide information on reactor *operation*, which is at least as important as the understanding of physics *per se*.

An open question would be, what would happen to DEMO if ITER plasmas behave in a significantly different way than expected. If the deviations are in the "positive" direction (e.g. the confinement is found to be much better than expected, or the heat channel in the SOL λ_q is found to be much broader than current predictions), they could be taken into account in the machine design without affecting it, or maybe even relaxing some design constraints and thus simplifying it. So, for example, if the confinement is higher than what predicted by the IPB98 (y,2) scaling, there would be margin to decrease the plasma current while keeping the target fusion power fixed and the transport stiff. This may allow for longer pulses with the same central solenoid flux swing, and also will increase the robustness of the scenario against disruptions by raising q_{95}. So, in other words, there should be no big repercussion on the DEMO schedule if ITER works much better than planned. The opposite case, namely if ITER shows a worse performance than expected in some areas, has on the contrary no simple solution. It depends very much on how large those deviations are, and whether they can somehow be absorbed by moderate, dedicated design changes. Otherwise, a large impact on the DEMO schedule has to be expected, unless enough margin can be bult in, or there is reason to suppose that the differences between ITER and DEMO will compensate. Also, systems engineering tools are being developed to make design modifications as straightforward as possible, since it is in fact expected to necessitate this as the technology progresses. That is, the DEMO design is not ossified in its current form and the tools for dealing with required design changes are already part of the programme.

Finally, an important point concerning ITER is the possibility of developing and exploiting there some ELM-free scenarios. Clearly, ITER has not been optimised for other plasma configuration than ELM-y H-mode, but at least some ELM-free scenarios can in principle be observed there (a more complete discussion on the topic can be found in [6]). With this respect, the possibility of testing an ELM-free regime in ITER represent a sort of "advantage" towards its qualification for DEMO. Regimes clearly incompatible with ITER, like e.g. negative triangularity, would in fact require an intermediate qualification step between the proof of principle on small devices and the exploitation at reactor scale, which at the moment remains highly speculative.

6. Conclusions

One of the main conclusions of the PCD phase is that, at present, no plasma scenario appears qualified for a reactor DEMO for two reasons: first, not all problems seem to have a solution similar to these adopted in ITER, able to satisfy the stringent DEMO standards and, second, in some cases the phenomenological understanding is too weak to safely extrapolate the scenario to larger scales. Thus, the identification of a suitable plasma scenario for the future shall encompass both the fulfilment of technological and performance requirements, it should also lead and inspire research tackling the most significant challenges and bridging the knowledge gaps, up to a level where the uncertainties can be managed by the designers (achieving no uncertainties is of course an unrealistic goal). In recent years however, the knowledge has been significantly increased, allowing the identification of the critical areas where the effort has to be concentrated. On this solid understanding of the challenges and a wide knowledge base, DEMO will enter the Concept Design Phase. A close collaboration with the plasma physics community has been recognized as crucial, and will be strengthened.

CRediT authorship contribution statement

M. Siccinio: Writing – original draft, Investigation, Software. **J.P. Graves:** Writing – review & editing. **R. Kembleton:** Investigation, Supervision. **H. Lux:** Investigation, Supervision. **F. Maviglia:** Investigation, Writing – original draft. **A.W. Morris:** Writing – review & editing. **J. Morris:** Investigation. **H. Zohm:** Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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