UKAEA-CCFE-PR(21)31

M. Siccinio, J. P. Graves, R. Kembleton, H. Lux, F. Maviglia, A. W. Morris, J. Morris, H. Zohm

Development of the EU-DEMO physics basis for plasma scenario: status and plans

Development of the EU-DEMO physics basis for plasma scenario: status and plans

M. Siccinio, J. P. Graves, R. Kembleton, H. Lux, F. Maviglia, A. W. Morris, J. Morris, H. Zohm

This is a preprint of a paper submitted for publication in
Fusion Engineering and Design

Development of the EU-DEMO physics basis for plasma scenario: status and plans

M. Siccinio[a,b*], J. P. Graves[c], R. Kembleton[a,d], H. Lux[d], F. Maviglia[a,e], A. W. Morris[d], J. Morris[d] and H. Zohm[a,b]

[a]EUROfusion Consortium, Garching bei München, Germany
[b]Max-Planck-Institut für Plasmaphysik, Garching bei München, Germany
[c]École Poytechnique Fédérale de Lausanne, Swiss Plasma Centre, Lausanne, Switzerland
[d]Culham Centre for Fusion Energy, Abingdon, United Kingdom
[e]Associazione EURATOM Enea, Frascati, Italy

This paper is part of a series of publications concerning the development of the European DEMO during the pre-conceptual design phase (2014-2020). In particular, it deals with the physics basis employed for the definition of the various DEMO baselines released, and the assumptions adopted where necessary. In the course of the pre-conceptual design phase, some of these assumptions have been progressively replaced with 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 EU-DEMO 2015, 2017 and 2018, based on an ITER-like ELMy H-mode confinement regime. In addition, a QH-mode baseline and an I-mode baseline have been produced in 2019, and are analysed here in detail as well. Furthermore, a discussion on the main knowledge gaps, as well as the strategy to be adopted in the next phases to close them, relying on the contribution of the European and international fusion research, is provided.

Keywords: EU-DEMO, reactor, physics basis, systems code

1. Introduction

The design of the prototype reactor EU-DEMO just concluded its pre-conceptual design phase (Pre-CD, 2014-2020) with a Gate Review process [1,2]. This phase has represented the start of the EU-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 [3]. 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 [4-7], EU-DEMO has been conceived – at least initially - attempting to mimimise the differences with the ITER 15 MA reference scenario [8,9]. This approach is justified by the fact that such a scenario will be the closest to commercial reactor conditions with significant 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 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 EU-DEMO investigations has already been published. In this work, which has to be understood as a part in a more comprehensive series of paper on the DEMO Pre-CD, 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 knowledge is not sufficient to model a DEMO scenario in a fully predictive way. 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 error bars on the plasma performance 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 encompasses, also, the 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

author's email: mattia.siccinio@euro-fusion.org

parameters are discussed, subdivided by topic. In section 3, focus is given on ELM-free regimes and their applicability to DEMO, which is probably the largest deviation from ITER. In section 4, the strategy to address the knowledge gaps in the next phase is presented. Conclusions are drawn in section 5.

2. Baselines

Various EU-DEMO baselines have been released during the Pre-CD, produced with the systems code PROCESS [10,11]. 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. This apparent discrepancy is justified below.

	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	> 5%	0.16	>5%	**5-10%**
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	N/A	**52**
H_{98}	1.1	1.1	0.98	0.89	0.8	**1**
$< n >/n_{GW}$	1.2	1.2	1.2	1.37	0.9	**~1**
$< T >$ [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**

Table 1. EU-DEMO Physics Baseline 2017, 2018, 2019, QH-mode, I-mode relevant machine parameters and corresponding values for ITER. EU-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.

Since 2018, H-mode is no longer considered as the primary solution for the EU-DEMO plasma scenario, in view of the high risks associated to active ELM mitigation [7,12], 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 the same level of priority until reliable reactor relevant ELM suppression/mitigation has been demonstrated at ITER. For this reason, QH-mode [13] and I-mode [14] baselines have been produced with PROCESS in 2019. Incidentally, also negative triangularity [15-17] 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 [8,9]) are reported as well. Hereafter, a discussion of the assumptions leading to these parameters and their variation across the baselines (limited to 2015, 2017 and 2018, i.e. the ELMy H-mode based ones) is provided.

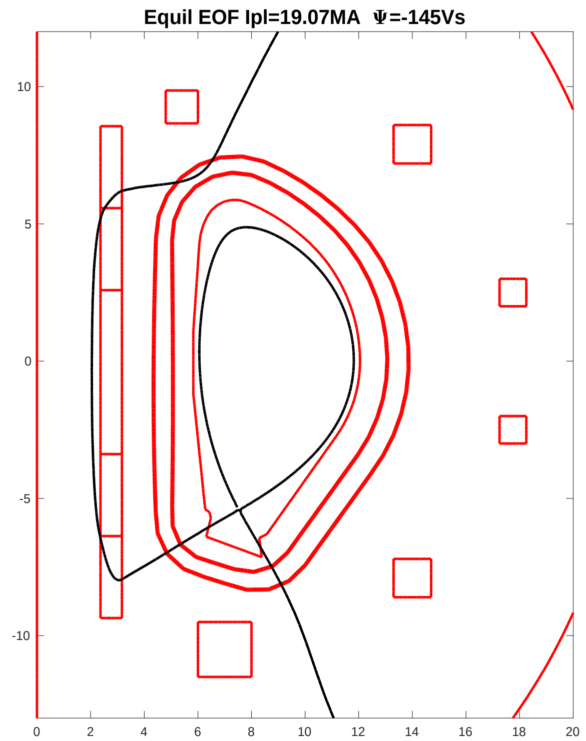

Fig. 1. Example of magnetic equilium (end of flat-top, in this case) produced with CREATE-NL and compatible with the major engineering constraints (forces and current/voltage limits in the coils). The figure is taken from [22].

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 requirement 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 [18]. Note that, in this scaling, the confinement time exhibits only a weak dependence on the magnetic field, thus the radius remains the main knob, together with the plasma current which is however constrained by the limits on the safety factor q, which shall remain reasonably above 3 to reduce disruptivity. Note that the radius is also a result of the need of fulfilling 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 important repercussion on the radial build and on the engineering in general, their discussion is to be found in [3].

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. 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 in PROCESS is not explicitly included). For this reason, the field has was increased again in 2018, and the edge safety factor was significantly increased. Note that this has happened also subsequently to an improved model 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. Therefore why all engineering activities started on 2017 baselines have not 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 [19] for the different baselines [20-23], 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, these calculations also provide the current evolution in the coils, given a certain reactor configuration. 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, to maximize the volume of plasma, especially at high toroidal field. The larger plasma elongation has a strong positive impact on the fusion performance [5], and hence allows reduction the machine major radius, all the other parameter being equal, and if no other constraints are encountered. An elongated tokamak plasma is vertically unstable, with a growth rate 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 [24]. 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 [25].

- Active vertical stabilisation: with the VS system that needs to be able to vertically recover the plasma in case of 5 cm vertical displacement event (VDE), 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 ≤ 500MW (limit set as a preliminary technological constraint, to be better addressed in the following phases).

By using the constraints above, the EU-DEMO maximum elongation is set to $\kappa_{95} = 1.65$. While the above considerations were developed by considering the ex-vessel superconductive coils as actuators, improvements are foreseen by using in-vessel resistive coils [26]. It is however important to stress that DEMO, like ITER, has to be designed to still be operable also without in-vessel coils, by virtue of the difficulty of maintaining them (assuming that they can be integrated in DEMO, which is still uncertain at this stage). Thus, it is unlikely that these limit will undergo significant changes.

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 been considered until 2018, when the Saarelma empirical scaling [28] obtained with EPED [29] simulations was implemented in PROCESS – see discussion below.

Finally, some considerations on the Toroidal Field (TF) ripple. The TF ripple is a tridimensional perturbation in the nominal toroidal magnetic field due to the finite number and toroidal extension of TF coils in tokamak devices. It negatively affects fast ion confinement, increasing the potentially dangerous 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 [30]. Based on the physics research undertaken for ITER, for which a nominal maximum value of 0.5% is recommended [31], 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%. A wide scan and optimization of the effect of FI was carried out for different DEMO baseline configurations [32-35], by using the 3D code CARIDDI [36]. Investigations carried out inside the EU-DEMO team on fast particle confinement have shown that losses and, correspondingly, associated loads on the PFCs are expected to be quite 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 (about 22.5 cm on the outer midplane [37]). For α's, in addition, the large size 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 have little chance of leaving the plasma before being thermalised. Published studies [38] have found the heat load on the FW associated to NB losses to be largely below the technological limits of 1 MW/m^2 [12], 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 [39]. Also, it has been shown that α losses remain negligible even in the simultaneous presence of a large sawtooth crash and NTMs [40].

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 [41]. Plasma current drive is at the moment not explicitly requested. Until 2017, it was assumed that 50 MW of auxiliary power was necessary for that purpose, as visible in Table 1. Thereafter, that assumption was relaxed, but the 50 MW – now purely contributing to plasma heating – was maintained, to mimick the (in reality intermittent) power for the various plasma control requirements described in [37]. Incidentally, the assumption that no current is driven by control auxiliary systems is conservative, since in reality Electron Cyclotron Current Drive (ECCD) for NTM control, for example, indeed drives current. This contribution has however been neglected from plasma current requirements, but is taken into account in more detailed DEMO scenario modelling.

In the early DEMO phases, an alternative concept called DEMO 2 relying on massive auxiliary CD was considered as well. That concept was then "absorbed" in the studies of the steady-state concept Flexi-DEMO [42]. A study comparing the CD efficiency of different technologies was produced in this early phase [43]. All technologies showed a CD efficiency of 40-50 kA/MW, with 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. In PROCESS, a value of ~45 kA/MW has been assumed for all baselines and technologies. This value is of course important also to determine the necessary flux swing the Ohmic Heating (OH) must provide to achieve the target 2 hrs pulse, as well as for the final electrical current output by virtue of the large power involved.

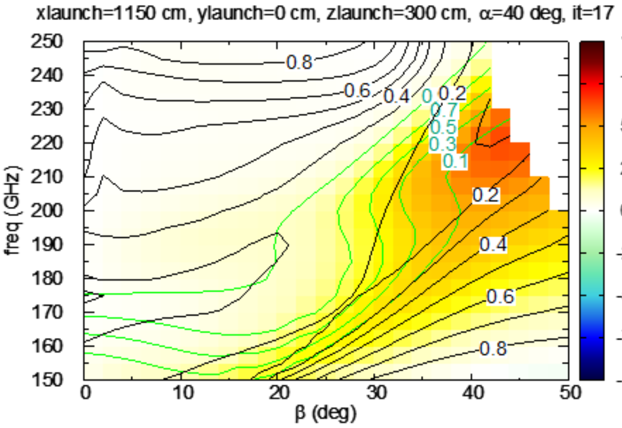

Fig. 2. EC current drive efficiency studies for Flexi-DEMO as a function of the wave frequency and the toroidal injection angle β for fixed poloidal injection angle α. The calculation was performed with GRAY [48].

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 [44]. The broadening 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 [45,46]. Changing the launching position (e.g. from a dedicated upper port launcher, not foreseen at the moment), or driving the current for NTM control on the lower field side launching from the equatorial port, have been shown to considerably improve the situation [46, 47]. However this phenomenon may lead to an increase of the power 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. 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, part of the power radiated from the core. i.e. the one radiated from the innermost region, is subtracted to the power entering the scaling law, leading to a reduced power degradation [49]). 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 [50]. For this reason, more comprehensive codes, able to calculate 1D profiles, have been employed to determine more precisely (although not fully self-consistently) the shape of plasma qualifying profiles. The codes employed have been METIS [51] and ASTRA/TGLF [52-55]. Generally speaking, the fusion power for a given set of engineering parameters was found to be 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 too high around mid-radius. Profiles produced in the framework of those investigations (see e.g. Fig. 3) have then been employed as a starting point 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. [56]) are not fully taken into account.

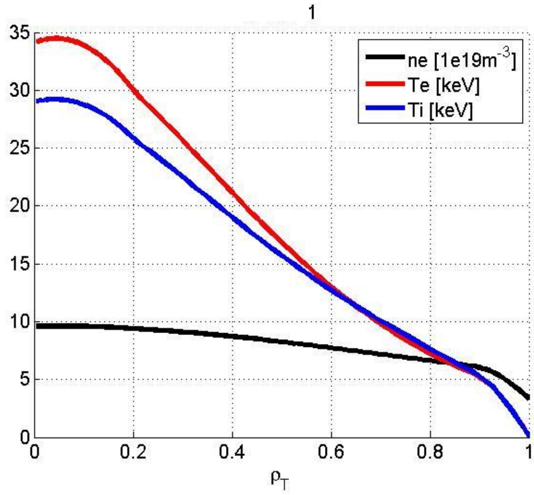

Fig. 3. Density and temperature profiles calculated with ASTRA for DEMO 2018. Figure is taken from [7].

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 for the transport coefficient with TGLF at few radial positions, rather than reproducing an entire profile. Again, transport coefficients have generally speaking been found to be higher than the corresponding quasilinear cases (TGLF). This point deserves more understanding effort in the future, in order to avoid DEMO plasma to underperform relative to that predicted by dedicated integrated simulations.

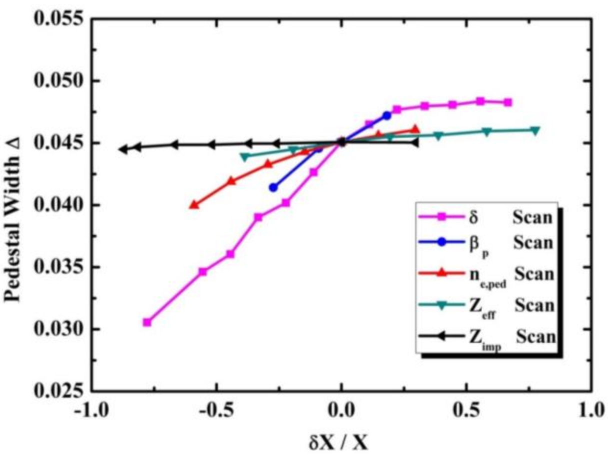

Fig. 4. Dependency of pedestal width (normalized to machine major radius) on the relative variation of various plasma parameters. Figure is taken from [61].

In the QH-mode baseline 2019, the profiles are not any longer imposed, but the code PLASMOD [57] coupled to

PROCESS is used as transport solver. In that way, the H factor becomes an output, 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. Also, 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 quite detailed divertor model, namely the Kallenbach model [58] was used. Calculation model allows also the necessary Ar concentration to achieve detachment, and, coupled with PLASMOD, the effect of the seeded impurities migrating in the core on the discharge performance [28], which was completely neglected in the previous releases. In this sense, the QH-mode baseline represents a turning point in the modelling of DEMO baselines.

The pedestal top pressure has been evaluated by employing the standard EPED code, assuming the pedestal is limited by peeling-ballooning modes [28]. In particular, a scaling law has been written, relating the pedestal top pressure 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 as a function of the engineering parameters only, 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 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 [59], assuming that the core transport is correctly captured by TGLF from 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 [60], 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 [37], EU-DEMO has been designed to match almost exactly the 0D figures of merit of ITER for the divertor protection quoted in Table 1, namely $P_{sep}B_T/q_{95}AR$ and P_{sep}/R – see also the discussion in [62]. 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 analysis of the impact of this choice can be found in [12]. To obtain this, high-Z impurities, like e.g. Xe, have to be seeded in the reactor. Note that PROCESS yields the smallest machine possible for the given constraints, and for this reasons it tends to minimize the radiation, since impurities dilute the plasma and enhance Z_{eff} . Thus, 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 divertor figures of merit. The choice of employing a core radiator has however consequences, and the implications on the plasma controllability are remarkable, as discussed in [7,41]. On the contrary, investigations concerning the intrinsic impurity W have shown very limited risk of W influx at reactor relevant parameters, due to the strong neoclassical outward pinch [63].

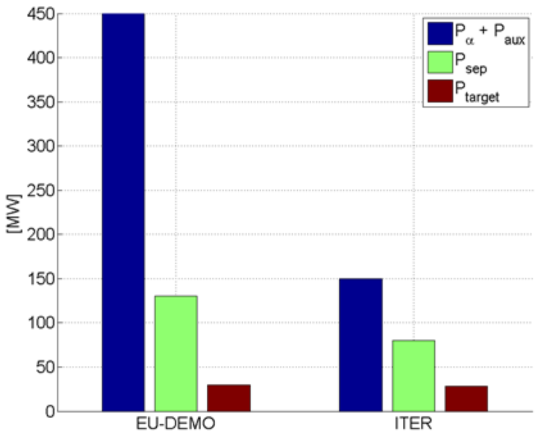

Fig. 5. Total heating power, power at the separatrix and maximum tolerable divertor power in ITER and EU-DEMO. The difference between blue and green columns are due to core radiation (line, synchrotron and bremsstrahlung), the difference between green and red to SOL dissipation. Data for EU-DEMO are taken from ASTRA simulations. Figure is taken from [7].

The activity on SOL and divertor carried out in PPP&T 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 configurations, the reader is referred to [64,65]). The goal is to achieve a detached state, and thus a low heat flux on the target which is compatible with the exhaust capability, associated 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. [66]) 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 neutral have been made. This greatly enhances the level of physics detail of the simulation, at the price of significantly higher complexity and thus longer computational time.

Although, as mentioned, no well-established fully detached reference case with kinetic neutral exists at the moment, there are indications that a steady-state working point with acceptable heat flux on the target, density at the separatrix exists [67]. Also, 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). It is here noted that the lack of predictive capability of SOL and divertor codes is not a DEMO peculiarity, but it reflects the state of the art of the current numerical tools (interpretative to a good extent but not quantitatively predictive in all circumstances).

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 [68], 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 [69]. Finally, an attempt of understanding how the filamentary (or "blobby") transport extrapolates to DEMO has been undertaken [70]. 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 most pessimistic assumptions have been analysed in [12,71] and references therein, finding the impact limited, and anyway relatively easy to minimize via wall shaping.

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 [12], see Fig.6. To mitigate this risk, the chosen strategy at the moment is to consider naturally ELM-free regimes as prioritary in view of the challenging availability and reliability requirements posed by active mitigation schemes [7], at least until there is strong evidence in support at reactor relevant conditions (since, potentially, one single unmitigated ELM event can lead to melting on the divertor target [12], 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 [72] (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). No modelling is at the moment available which considers in-vessel coils instead – the impact of this choice potentially being large on the mitigation effectiveness.

Instead, the possibility of adopting small-ELM or naturally ELM-free regimes in DEMO is under consideration. Recently the study had achieved the same priority as ELMy H-mode [7]. Various reviews of the knowledge gaps to be filled in order to conclude on the suitability of ELM-free regimes in DEMO have been produced [73], anticipating the work of two dedicated Ad-hoc Groups on ELM-free regimes [74] and negative triangularity [75], 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.

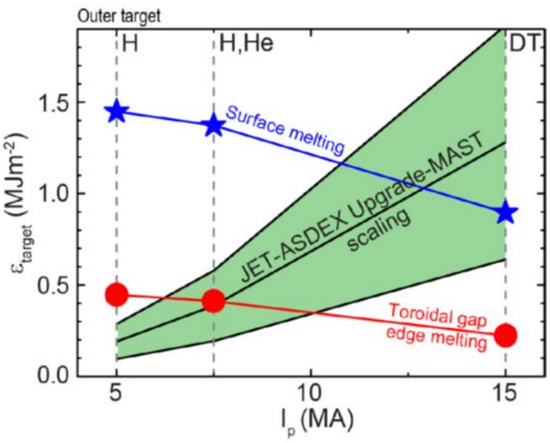

Fig. 6. Energy deposited on ITER target by a single ELM event as a function of the plasma current following a multi-machine scaling, and related damage. Figure is taken from [80].

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 [76]. The increase is however just estimated, without any particular investigations on support – although verifications have been done *a posteriori* [77]. However, the QH-mode baseline exhibits important differences with respect to the previous ones in terms of code development, as previously mentioned. This explains the discrepancy in the parameters. These improving features (PLASMOD and the Kallenbach model) were instead not employed for the I-mode baseline, which however had 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 [78] was employed, whereas for the confinement an H factor of 0.8 was assumed, and the pedestal top density was lowered to 0.65 n_{GW} , in agreement with the existing literature [79]. The result is a quite unattractive baseline. For eliminating the ELMs, the power exhaust problem is exacerbated via a higher P_{sep} and the fusion power is significantly reduced in spite of a somewhat larger radius. 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 strategy for the definition of a viable scenario for EU-DEMO to be carried out in the future DEMO Central Team (DCT) [1,2] 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 in the EUROfusion research units, forcing 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).

Past 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, and in parallel explore whether these are 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. In parallel, it will be necessary to seek ways to attain final states, combining experimental experience, theoretical knowledge, driving innovations in both experiments and theory. The physics group of the DCT, responsible for the scenario as a whole, must ensure enough options are explored, set the requirements for each technical and capability area, generating suitable output (with uncertainty bands) for the key DEMO decision points, support and guide the development of new capabilities. 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, 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).

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 to it codes capable of higher fidelity, 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.

It is therefore crucial that the development of such a SYS is initiated in the early phases of the DEMO Conceptual Design phase.

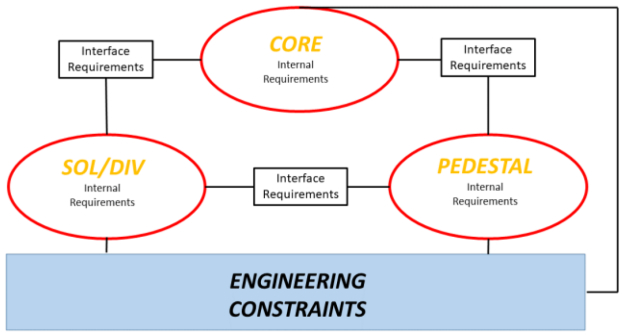

Fig.8: Plasma parts, their requirements and their interfaces following the terminology introduced here.

Flight Simulator (FS)

Alongside SYS, a sophisticated theory-based integrated modelling tool will be needed to handle the whole pulse dynamics, control aspects, disturbances and transients [81], since it has been learned in the pre-CD phase how strong the impact of transients 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. The tool 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. This tool might double as a “flight simulator” (henceforth FS), needed to explore the behaviour and thus viability of scenarios, as well as later guide the operation.

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, 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 consists 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 ist qualification will evolve in parallel, this making the process intrinsically iterative and nonlinear.

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.8. A flat-top plasma scenario is identified (at a SYS level) once the following requirements have been met:

- Internal requirements: requirements which are associated with one part only (e.g. in the proposed subdivision in Fig.8, the “natural” absence of type-I ELM instability is associated only to the pedestal part).
- Interface and integration requirements: 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, since the SOL turbulence 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 as well) 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, to be achieved under the guidance (or at least with the involvement) of the DCT.

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 a FS that are trusted by the engineering and science experts.

Scenario qualification

In order for an apparently viable scenario to be accepted, 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 compatible with the flexibility range in the engineering design. The assessment of assumptions contributes thus to the establishment and corroboration of the DEMO 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 both by means of 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 consists of the reduction of error bars on 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 for verification. The proposed workflow is represented in Fig.9.

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).
- 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 developed and removed. 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, 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.

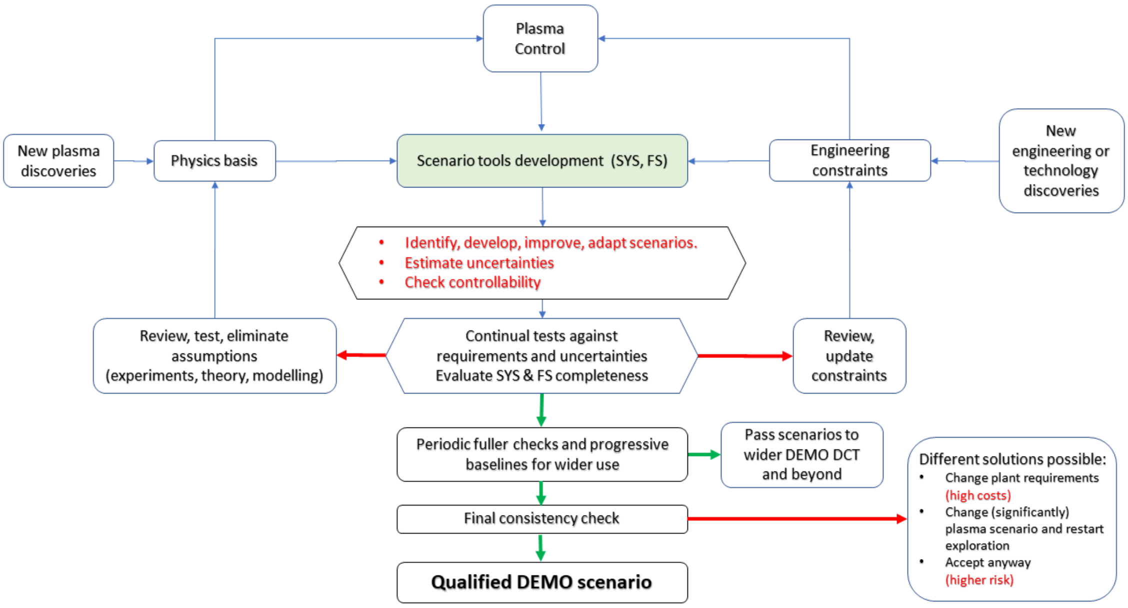

Fig.9: Workflow of plasma scenario identification and qualification. Green arrows identify positive responses, red arrows negative responses. The definition and qualification of a plasma scenario evolves in parallel with the development of SYS and FS, and in a continuous way.

Role of theory and experiment

In order for a plasma scenario to be acknowledged as adequate for EU-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. The theory and modelling tools need a strategy, and the setting of requirements, just as much as experiments do (where 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 EU-DEMO has been divided into three categories, or phases:

- 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.

Also, the process needs to be open for new findings, as 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). Also, 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 will be 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:

- Maximum achievable pedestal-top pressure in absence of ELMs
- Amplitude of energy fluctuations
- Stability of pedestal against fueling (especially if not peeling-ballooning limited)
- Transport coefficient for He and impurities
- Stability conditions for radiative layer
- Attainment and control of detached divertor

It is however important to stress that the activities 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)
- Core transport
- Stabilisation of NTMs

Also, they have allowed identifying the most critical areas where the future analysis shall concentrate.

5. Conclusions

One of the main conclusions of the Pre-CD phase is that, at the moment, no plasma scenario appears qualified for a reactor DEMO, and this is for two reasons: first, not all problems seem to have a solution, at least among the ones to be proven 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 (no uncertainties is of course an unrealistic goal). In recent years however, many things have been done, and the knowledge has been significantly increased, allowing the identification of the critical areas where the effort has to be concentrated. On this solid basis, EU-DEMO will enter the Conceptual Design phase. A close collaboration with the physics community has been recognized as crucial, and will be pursued.

Acknowledgements

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

References

[1] Federici G. et al., this special issue
[2] Holden J. et al., this special issue
[3] Kembleton R. et al., this special issue
[4] Wenninger R. et al., 2015 Nucl. Fusion 55 063003
[5] Wenninger R. et al., 2017 Nucl. Fusion 57 016011
[6] Federici G. et al 2019 Nucl. Fusion 59 066013
[7] Siccinio M. et al., 2020 Fusion Eng. and Des. 156, 111603
[8] Aymar R. et al., 2002 Plasma Phys. Control. Fusion 44 519
[9] Green B. J. and ITER International Team and Participant Teams, 2003 Plasma Phys. Control. Fusion 45 687
[10] Kovari M. et al., 2014 Fusion Eng. and Des. 89 3054
[11] Kovari M.et al., 2016 Fusion Eng. and Des. 104 9
[12] Maviglia F. et al., 2021 Nucl. Mat. Energy 26, 100897
[13] Burrell K. H. et al., 2002 Plasma Phys. Control. Fusion 44, A253
[14] Whyte D. et al., 2010 Nucl. Fusion 50, 105005

[15] Camenen Y. et al., 2017 Nucl. Fusion 57, 086002
[16] Medvedev S. Yu. Et al., 2015 Nucl. Fusion 55, 063013
[17] Kikuchi M. et al., 2019 Nucl. Fusion 59 056017
[18] Uckan N.A. 1989 ITER physics design guidelines, ITERTN-PH-8-6 (http://www.iaea.org/inis/collection/NCLCollectionStore/_Public/21/068/21068960.pdf?r=1)
[19] Albanese R., Ambrosino R. and Mattei M., 2015 Fus. Eng. Des. 96, 664
[20] Ambrosino R., Final Report 2019, https://idm.euro-fusion.org/?uid=2NML4K (unpublished)
[21] Ambrosino R., Final Report 2018, https://idm.euro-fusion.org/?uid=2MYDA3 (unpublished)
[22] Ambrosino R., Final Report 2017, https://idm.euro-fusion.org/?uid=2MZLXK (unpublished)
[23] Albanese R., Final Report 2014 https://idm.euro-fusion.org/?uid=2MA2HJ (unpublished)
[24] Portone A., et al. 2005 Nucl. Fusion 45, 926
[25] Maviglia F. et al., 2017 Fus. Eng. And Des. 124, 385
[26] Maviglia F. et al., this special issue
[27] Bachmann C. this special issue
[28] Siccinio M. et al., 2018 Nucl. Fusion 58 016032
[29] Snyder P.B. et al 2009 Phys. Plasmas16 056118
[30] Urano H. et al., 2011 Nucl. Fusion 51, 113004
[31] Saibene G. et al., 2007 Nucl. Fusion 47, 969
[32] Villone F., Final Report 2014, https://idm.eurofusion.org/?uid=2ANZQQ (unpublished)
[33] Villone F., Final Report 2015, https://idm.eurofusion.org/?uid=2M97UY (unpublished)
[34] Villone F. Final Report 2016, https://idm.euro-fusion.org/?uid=2N7XF5 (unpublished)
[35] Villone F. Final Report 2019 https://idm.euro-fusion.org/?uid=2MUNQ3 (unpublished)
[36] Albanese R. et al., 1997 Advances in Imaging and Electron Physics, Vol. 102
[37] Wenninger R. et al 2017 Nucl. Fusion 57 046002
[38] Varje J. et al., 2019 Fus. Eng. and Des. 146, Part B, 1615
[39] Bustos Ramirez G. et al., 2020 Final Report https://idm.euro-fusion.org/?uid=2NT4R6 (unpublished)
[40] Kurki-Suonio T. et al., https://idm.euro-fusion.org/?uid=2MCWAE (unpublished)
[41] Siccinio M. et al., this special issue
[42] Zohm H. et al., 2017 Nucl. Fusion 57 086002
[43] Zohm H. et al., 43rd EPS on Plasma Physics, Helsinki 2016
[44] Snicker A. et al., 2018 Nucl. Fusion 58 016002
[45] Snicker A., Final Report 2020, https://idm.euro-fusion.org/?uid=2N3EMQ (unpublished)
[46] Snicker A. Final Report 2019, https://idm.euro-fusion.org/?uid=2MY3ZC (unpublished)
[47] Snicker A. in prep for Nucl. Fusion (IAEA 2021)
[48] Granucci G. et al., Final Report 2018 https://idm.euro-fusion.org/?uid=2MFGNC (unpublished)
[49] Lux H. et al., 2016 Plasma Phys. Control. Fusion 58 075001
[50] Fable E. et al., 2018 Fusion Eng. and Des. 130, 131
[51] Artaud J. F. et al., 2018 Nucl. Fusion 58, 105001
[52] Pereverzev G.V., 1991 IPP Report 5/42
[53] Pereverzev G.V. and Yushmanov P.N., 2002 IPP Report 5/98
[54] Fable E. et al., 2013 Plasma Phys. Control. Fusion 55 124028
[55] Waltz R. E. et al., 1997 Phys. Plasmas, 4:2482
[56] Citrin J. et al., 2013 Phys. Rev. Lett.111, 155001
[57] Ellis, K., et al., “The next step in system modelling: The integration of a simple 1D transport and equilibrium solver”, EPS conference, Prague (2018)
[58] Kallenbach A. et al., 2016 Plasma Phys. Control. Fusion58, 045013
[59] Palermo F. et al., 2019 Nucl. Fusion 59 096010
[60] Fable E., Final. Report 2019, https://idm.euro-fusion.org/?uid=2MHN2Y (unpublished)
[61] Saarelma S. et al., Final Report 2017 https://idm.euro-fusion.org/?uid=2MQCZH (unpublished)
[62] Siccinio M. et al., 2019 Nucl. Fusion 59 106026
[63] Angioni C., Final Report 2014, https://idm.euro-fusion.org/?uid=2MPLVR (unpublished)
[64] Militello F. et al., 2021 Nucl. Mat. Energy 26, 100908
[65] Reimerdes H. et al., 2020 Nucl. Fusion 60, 066030
[66] Subba F. et al., 2018 Plasma Phys. Control. Fusion 60 035013
[67] Subba F. et al., in prep.
[68] Ivanova-Stanik I. et al., 2020 Fusion Eng. and Des. 161, 11193
[69] Pericoli Ridolfini V. et al., 2020 Nucl. Fusion 60, 126041
[70] Carralero D. et al., 2017 Nucl. Fusion 57 056044
[71] Maviglia F. et al., this special issue
[72] Zhou L. N. et al., 2018 Nucl. Fusion 58 076025
[73] Viezzer E. et al., 2018 Nucl. Fusion 58 115002
[74] Happel T. et al., 2019 https://idm.euro-fusion.org/?uid=2NF9QF (unpublished)
[75] Zohm H. et al., https://idm.euro-fusion.org/?uid=2N29CN (unpublished)
[76] Garofalo A. M. et al 2011., Nucl. Fusion 51 083018
[77] Vincenzi P. et al., 2021 Fusion Eng. and Des.163, 112119
[78] Hubbard A. E. et al., 2017 Nucl. Fusion 57 126039
[79] Ryter F. et al., 2017 Nucl. Fusion 57 016004
[80] Pitts R. et al., 2019 Nucl. Mat. and Energy 20 100696
[81] Janky F. et al., 2019 Fusion Eng. and Design 146 Part B, 1926