Impact of the plasma operation on the technical requirements in EU-DEMO

M. Siccinio[a,b*], W. Biel[c], E. Fable[b], T. Franke[a,b], F. Janky[b], P. T. Lang[b], M. Mattei[d], F. Maviglia[a,e], F. Palermo[f], O. Sauter[g], M. Q. Tran[g], S. Van Mulders[g], H. Zohm[a,b]

[a]*EUROfusion Consortium, Garching bei München, Germany*
[b]*Max-Planck-Institut für Plasmaphysik, Garching bei München, Germany*
[c]*Forschungszentrum Jülich, Jülich, Germany*
[d]*Consorzio CREATE, Università della Campania, Napoli, Italy*
[e]*Associazione EURATOM Enea, Frascati, Italy*
[f]*Culham Centre for Fusion Energy, Abingdon, United Kingdom*
[g]*École Politechnique Fédérale de Lausanne, Swiss Plasma Centre, Lausanne, Switzerland*

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The plasma design point during stationary phase operation of EU-DEMO has been described extensively in the past, and the assumptions employed for its definition have been supported by various investigations. However, a stationary snapshot is by far not sufficient to ensure the actual operability of the plasma scenario. On the contrary, both normal and off-normal transients have a strong impact on the machine design, providing the most challenging requirements to the actuators. This has to be accounted for in the design from the early phases on. In this paper, the main requirements originating from plasma operation, studied during the Pre-Concept Design Phase, are briefly reviewed. These encompass the so-called planned transients, e.g. plasma current ramps, access and termination of the burn phase or plasma fueling with pellets, but also the mitigation of off-normal events which may lead to a disruption, e.g. the divertor reattachment or an uncontrolled increase of radiation after a sudden W influx from the wall.

1. Introduction

In the present special issue concerning the EU-DEMO Pre-Concept Design Phase (PCD), the technological constraints [1] and the physical constraints [2] which led to the identified stationary operation point have been highlighted and reviewed. However, albeit important, the definition of a stationary reactor working point is per se largely not sufficient to provide all requirements for the machine design. On the contrary, the EU-DEMO experience during PCD has shown transients to be crucial, being indeed the most significant design drivers.

Broadly speaking, there exist two main categories of transients. Firstly, there are the so called "planned" transients, which are part of the regular machine operation, like e.g. the current ramp up and ramp down to access and terminate the burn phase (it is herewith recalled that EU-DEMO is a pulsed device [1,3]). Then there are the "off-normal" transients, which ideally should never take place, but whose occurrence can realistically not be excluded, and thus mitigations have to be foreseen. An example of these events is a sudden increase of core radiation after an uncontrolled impurity inflow, e.g. tungsten as intrinsic impurity. The machine, and its actuators in particular, have to be designed to ensure that such transients do not evolve to a disruption, which is an event that has to be avoided at any cost because of its large impact on the availability of the plant, or on its integrity [4]. The main interfaces with the plasma considered here are i) the Heating and Current Drive (H&CD) auxiliaries, and ii) the fueling and pumping systems. Other important actuators as magnetic coils for position and shape, as well as the whole DEMO diagnostic concept, are described in detail in other papers in this Special Issue [4,5].

In this paper, focus is given to the requirements the EU-DEMO plasma poses to the main actuators for its control, concentrating on the most relevant aspects of the dynamic phases. The work carried out in the PCD on these aspects will be here briefly reviewed, with focus on the latest results which, at the moment, represent the chosen EU-DEMO solution. Part of the results discussed here have already been published in other journals. For these, only a short description will be given, referring the interested reader to the corresponding publications. Goal of the present paper is in fact to provide a short overview on the status of the EU-DEMO investigation on these aspects, either illustrating the latest development or referring the reader to the latest papers on the topic.

The paper is structured as follow: in section 2, the requirement for H&CD auxiliaries are discussed, distinguishing between off-normal and planned transients. In section 3, the fuelling and pumping results, together with a brief discussion on the divertor reattachment, are illustrated. Conclusions are drawn in section 4.

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

2. H&CD

As discussed in [6], H&CD systems in EU-DEMO are in charge of key functions :

- Assisted plasma break-down
- Plasma heating during plasma current ramp-up to burn, and ramp down
- Radiative (sometimes called "thermal") instability (RI) control
- Temperature control of core plasma during burn phase (as part of burn control)
- Magneto Hydro Dynamic (MHD) control (sawteeth, neoclassical tearing modes (NTM)) by localized current drive
- Bulk plasma current drive. At the moment, this is not explicitly required in the DEMO baseline, but it may change in the future.

Currently, it is assumed that EU-DEMO can host no more than 130 MW of H&CD power in the available ports [7]. The EU-DEMO baseline currently foresees Electron Cyclotron (EC) only as H&CD method. This solution is however not final yet, and the exploration of the potential role of Neutral Beams (NB) and Ion Cyclotron (IC) is still ongoing. In the following, in fact, also simulations employing NB are shown, assuming a 50%-50% equipartition energy distribution and a broad deposition (ca. 0.1 range in $\Delta\rho$ in the centre) . To cope with the requirements list above, the available power has to be optimised for deposition in different plasma regions. The current (2020) H&CD configuration attributes the power for the various functions as follows [6]:

- 30 MW available to be injected in the plasma centre, to be employed during ramps and for core temperature control, as well as for breakdown.
- 30 MW at "mid-radius" for the control of NTM (the precise location obviously depends on the safety factor profile, i.e. on the position of the resonant surfaces, which is presently not exactly established). These can be used also during the ramp-up for plasma heating.
- 70 MW to be injected at the pedestal location to counteract RI events. This is necessary since this is the region where radiation can increase quite rapidly because of the presence of seeded impurities, which radiates more if the temperature drops as discussed in [2]. Also, this power can be made available for heating to burn during plasma current ramp-up (although this surely represents a sub-optimal solution).

In the following, this will be referred to as 30-30-70 configuration. This configuration arises from a compromise between the various requirements. Especially concerning radiative instability, it allows the control of events only up to a certain magnitude. As stated several times in the following, this configuration does not look optimal, and would very likely undergo modifications in the next EU-DEMO phase. In particular, the fact that the largest amount of power is allocated for functions that may be necessary only few times in the entire plant lifetime is quite inconvenient. This will require further effort in the next phases.

2.1 Plasma Breakdown

To shorten the necessary dwell-time between one pulse and the successive to about ~10 minutes [1,3], EU-DEMO will initiate each pulse with an EC-assisted breakdown. The use of EC allows to start the plasma at a higher gas pressure in the vacuum chamber and with a higher content of impurities, thus saving pump time, than if relying on the central solenoid and on the coils only. In fact, by virtue of the large EU-DEMO volume and of the very low pressure required for a purely ohmic start-up, the assisted breakdown seems unavoidable to ensure the dwell time between successive pulses remaining short. This strategy has been validated both in existing machines and via numerical simulations during the PCD [8,9]. For a comprehensive review on the topic see e.g. [10]. The order of magnitude of the requested EC power is ~5 MW – depending on the exact value of the pressure which can be reached during the dwell time, as well as the actual impurity concentration in the gas, which is at the moment quite uncertain (it also crucially depends on the wall outgassing). This value is relatively low compared to the installed power, and thus even an increase due to a higher impurity concentration is not expected to cause any particular problem (at least for H&CD, while other aspects, not covered here, may indeed be impacted). Note that it is required to EC to reach the plasma on the high field side – where the breakdown will most likely take place. This is doable by employing the launchers for central heating (204 GHz), whose cold resonance position crosses the external part of the breakdown plasma in case of inboard breakdown.

2.2 Ramp-up and ramp-down

The plasma current ramps to access and terminate the plasma are quite critical in EU-DEMO, since the number of constraints that they have to fulfil is quite large. In fact, they should be aiming for:

- Minimise flux consumption allowing a longer flat-top, i.e. energy production phase.
- Avoid the loss of vertical control of the elongated plasma while β_{pol} and l_i are changing. This implies, also, avoiding large and fast oscillations in these quantities.

- Avoid an excessive heat load on the divertor (i.e. larger than 10 MW/m^2). This is particulary complex since, during both ramps, the density is clearly lower than during the flat-top phase, thus detachment will be more difficult to achieve (the heat flux in attached conditions being anyway higher than the limit).
- Avoid an excessive impurity radiation. It is very likely that the EU-DEMO plasma will contain impurities, both intrinsic and extrinsic, already during ramp-up. If the kinetic profiles are such that radiation starts to grow fast (i.e. when the cooling factor increases while temperature decreases), a very large amount of H&CD power may be required to counteract this. This is of course undesirable, since a high H&CD power injection may become dangerous for the divertor, and in any case the radiation increase may go out of control and cause a disruption.

As discussed in [11], after the breakdown the plasma touches the outer midplane limiter as the current of ~5 MA is reached, then it progressively enters the diverted phase. In this initial sequence the plasma is purely ohmically heated so that limiter erosion is not increased too much.

At the moment, the modelling activity is carried out in a partially open loop, i.e. snapshots of the magnetic equilibria during the ramps are produced with the code CREATE-NL [12], assuming linear ramps in β_{pol} and l_i – see e.g. [13,14]. These shapes are compatible with the EU-DEMO vertical control system at a current ramp rate of $\pm$0.2 MA/s (where the sign depends on whether the current is ramped up or down. These equilibria are then used as input for RAPTOR [15] and Fenix, a flight simulator based on ASTRA-Simulink and validated on ASDEX-Upgrade [16-20], where the evolving kinetic profiles are calculated. It is important to stress that, at the moment, no "reference" ramp trajectories have been established. Optimisations have been carried out with respect to some aspects of this multi-faceted problem, but no global optimum has been set yet. In the following, examples of ASTRA and RAPTOR results, for ramp-up and ramp-down respectively, are shown.

In the ASTRA ramp-up case visible in Fig.1 and 2, the following optimisation criteria have been adopted:

- The current was ramped up at 0.1 MA/sec, i.e. reaching the imposed flat-top value after 200 sec.
- On the contrary, the density was ramped up slower, so to reach the flat-top value (1.2 n_{GW}) after 600 sec. Rationale for this choice is allowing the turbine to follow the slow increase of fusion power, maximising its exploitation for electrical energy production– the power produced during the ramps would be deployed otherwise. The possibility for the turbine of following a load which is varying 10%/minute is discussed in [21,22].
- The power crossing the separatrix shall always be < 200 MW. This is a quite rough criterion to ensure divertor protection. As discussed in various past publications ([11,23] and references therein), Xe is the seeded impurity employed as a core radiator to decrease the power at the separatrix. Note that this criterion is violated for a short time at t ~ 350 sec, i.e. in correspondance of the H-L transition (Fig.2).
- The use of H&CD is minimised, i.e. auxiliaries are turned immediately off as soon as the fusion power is large enough to sustain the H-mode. Reasons are explained in more detail below. In this example, a EC-only machine is assumed (i.e. only the electron channel is heated).

Trajectories of the relevant quantities are shown in Fig.1. Transport has been determined employing a Bohm-gyro Bohm scaling for the thermal conductivities, adjusted to achieve an imposed H factor (1 for H-mode and 0.5 for L-mode). As one can see, after about 700 sec (i.e. ~100 sec after the end of the density ramp) the fusion power reaches ~90% of its final value. Then, the convergence to the target 2 GW [2] takes a long time, about additional 1500 sec. This quite long time is due to the low resistivity of the hot DEMO plasma, and the subsequent long current diffusion time which hampers the profiles relaxation. This is visible e.g. looking at the q_0 time traces (while q_{95} converges much faster). A solution to this would consist of delaying as much as possible the access to H-mode, thus keeping the plasma temperature low. This has however the problem that a late H-mode access would lead to excessive "spikes" both in the power crossing the separatrix, but also in β_{pol} and l_i (poloidal beta and internal inductance, respectively), exacerbating the problem of power exhaust and vertical position control. The strategy employed here consists of reducing as much as possible the usage of H&CD power, so to maximise the plasma resistance (and the corresponding current diffusion speed) without accessing H-mode on a too late stage.

The use of EC only in this example is an aspect which deserves some comment. The adoption of a single technology for H&CD in DEMO is favoured by technological consideration [6,7,24], and at the moment the DEMO baseline is endowed with EC only [24]. However, the pure electron heating might lead to an excessively large T_e/T_i ratio, especially right after the HL transition, as visible in Fig. 2. The thereto connected risk is linked to the fact that ion temperature gradient turbulence (ITG) become more effective at high T_e/T_i, increasing significative the thermal conductivity on the ion channel, and this can lead to difficulties in achieving high fusion power, which requires a high ion temperature. The possibility of employing other technologies, like NB or IC, in order to achieve a direct ion heating, is currently under investigation in the DEMO group, and thus modifications to the baseline may occur in the future. In fact, a later heating of ions may be very costly in terms of auxiliary power, if not impossible, again by virtue of the high energy transport.

Concerning the position control of this ramp trajectory, the time trace of β_{pol} and l_i are shown in Fig.2. As one can see, the inductive flux consumption (here expressed in terms of loop voltage) is largely dominant on the resistive part as long as the current is ramped. This is an consequence of the high temperature of the DEMO plasma with respect to present tokamak discharges. At this stage, a "closed loop" analysis is still missing (i.e. it has to be proven that the time traces of β_{pol} and l_i are indeed compatible with the snapshot equilibria and do not lead to position control problem), although such traces do not seem to exhibit any clear issue. At the moment, the EU-DEMO group is developing a so-called flight simulator [2], with which such simulations will be self-consistently carried out in the near future.

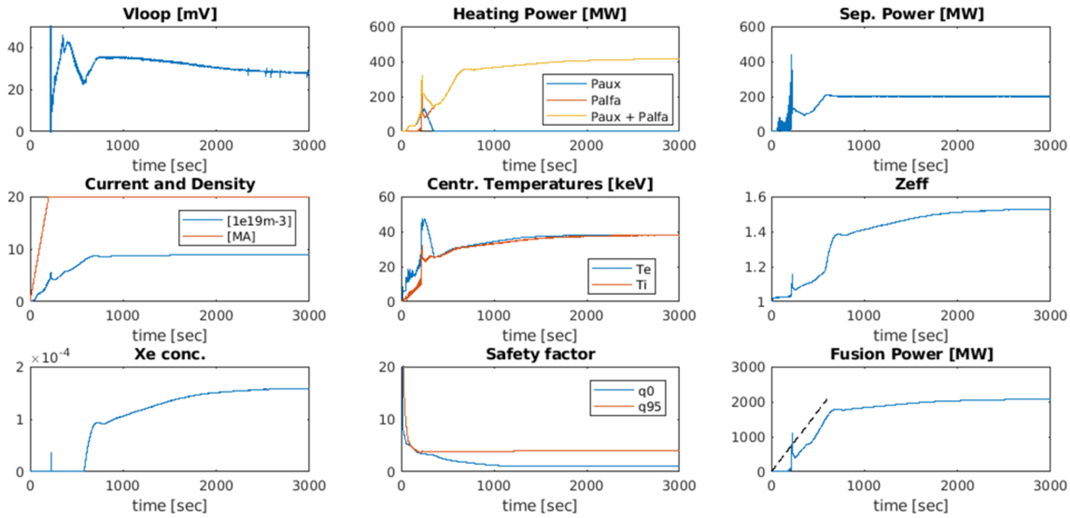


Fig. 1. Relevant quantities of a ramp-up trajectory of EU-DEMO. The criteria with which such case has been defined in the main text. In the bottom right figure, where fusion power is plotted, the dashed line indicate a 600 sec. P_{fus} ramp, i.e. the ideal target case for the turbine.

Turning to RAPTOR, results for ramp-down indicate a quite lower feasible (average) current ramp rate than what assumed in producing the snapshot, i.e. at around 0.1 MA/sec, or even below. This can be seen in Fig.3, which is an extension of Fig.5 in [23]. Various cases have been analysed, with different times and temperatures for the HL back transition and different ramp rates. More in detail, hot/cold L indicates the assumption on the H confinement factor for L mode phase of the ramp-down (hot L has $H = 0.75$, cold has $H = 0.5$. Instead, early/late HL indicates the assumed timing of the HL transition, which is initiated at respectively 20% or 40% of the total time window of the ramp-down. Combining these two factors, 'early HL, cold L' is a best-case scenario for the l_{i3} evolution, since the lower temperatures enhance the outward current diffusion. Note that, again, this is still not a fully consistent simulation, since the position and shape control has not been optimised on the "real" ramp-down trajectory. Thus, margin for some improvement can be expected, especially if in-vessel coils will be included in the DEMO design. Note also that in the cases presented here, Z_{eff} is decreasing in time to avoid the risk of radiative collapse of the plasma. This has however repercussions on the l_i evolution, slowing down the current profile and thus the relaxation of the profiles. In other words, a higher Z_{eff} might improve the stability margins with respect to position control, at the price however of a higher risk of radiative instability. As previously mentioned, the development of tools for the self-consistent simulations is still ongoing, this allowing for the future optimisation of such trade-offs.

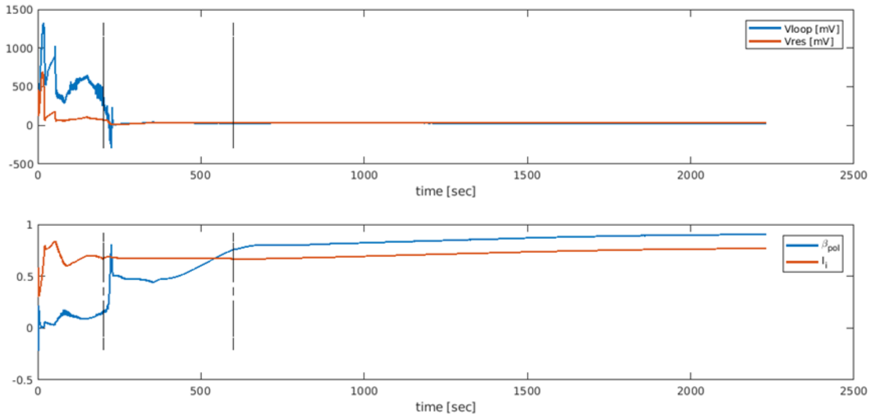


Fig. 2. Loop voltage (top), β_{pol} and l_i (bottom) for the ramp-up case shown in Fig.1. In the top panel, the total loop voltage and its resistive fraction are shown. Black vertical lines identify the end of the current ramp (200 sec) and the end of the density ramp (600 sec).

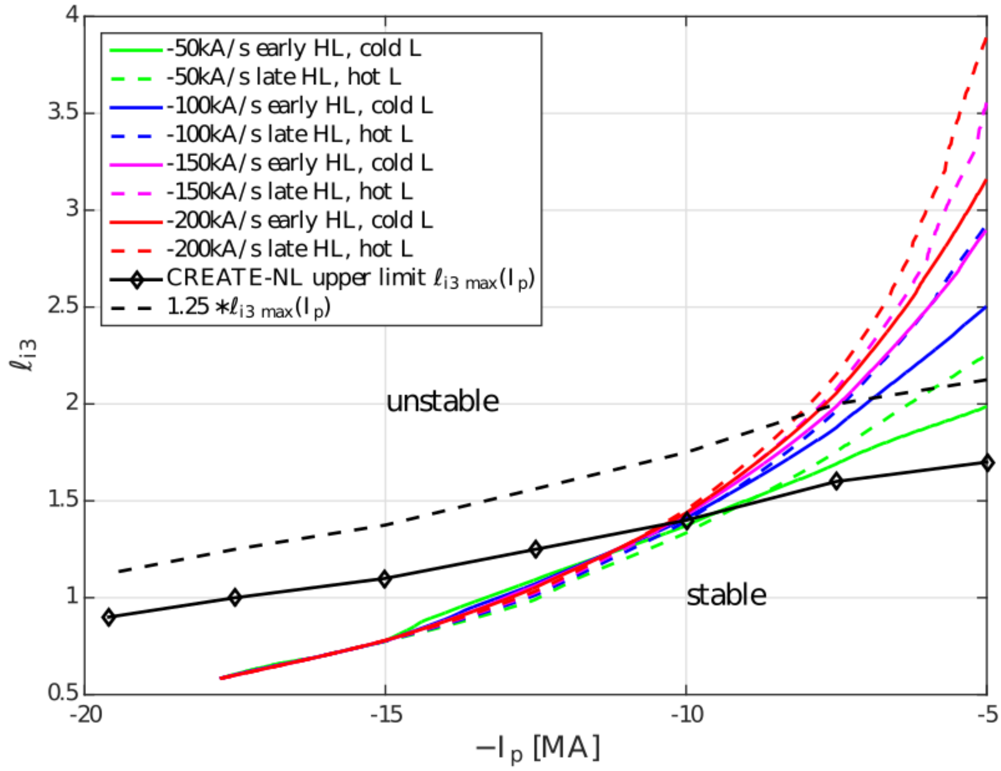


Fig. 3. Corresponding evolution of the internal inductance as a function of the plasma current during ramp-down phase. The definition of "hot","cold", "early" and "late" is to be found in the main text. The black diamond line indicates the maximum allowable internal inductance compatible with the imposed magnetic equilibria, while the dashed line corresponds to the same value multiblied by 1.25 – i.e . allowing for some margin.

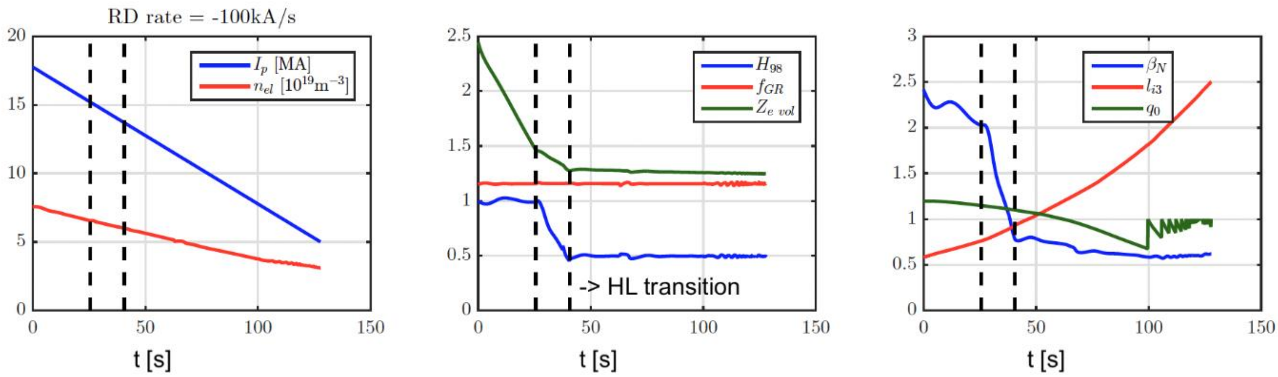
Fig. 4 shows an example of RAPTOR trajectories of the most relevant quantities for the best case scenario, i.e. the early HL, cold L. In this case, the use of both NB and EC has been foreseen. **In** EU-DEMO ramp-down process **it will be necessary** to employ auxiliary heating, even if the plasma has to be shut down. This occurrence is linked to the fact that the impurities in the plasma (both seeded and intrinsic) are enhancing their line radiation emissions when the plasma temperature decreases, while in parallel fusion power decreases as the current decreases, since the density has to be reduced on the same footing to remain below the Greenwald limit. In order to avoid a runaway situation, where the increased radiation caused by plasma cooling enhances the plasma cooling itself and viceversa, the plasma has to be heated up while being turned off**, as already happens on present tokamak experiments during the ramp-down of highly radiative discharges** . A quick removal of impurities from the plasma is not a viable solution. Firstly because there is no efficient actuator for that (the pump is quite slow). Secondly, even if there would be a method, a certain amount of core radiation is needed to protect the divertor during the transient phases, avoiding large "peaks" in the power crossing the separatrix. It is finally noted that further margin of improvement with respect to the increase of l_i by optimizing the ramp down traces of plasma current and elongation. Earlier simulations indicated that by ramping down I_p and κ faster in the initial phase of the ramp down, the increase of inductance can be kept below 25% above the safety limit for the 100kA/s ramp down (even with the unfavourable assumptions of late HL and hot L). Note however that those simulations did not yet include impurities and line radiation, and hence did not ramp down Z_{eff}.

2.3 MHD Control

The two more relevant MHD instabilities an EU-DEMO plasma can undergo are the sawteeth (ST) and the neoclassical tearing modes (NTM), in view of its ITER-like q-profile with $q_0 < 1$ and $q_{95} \geq 3$ and its relatively high $\beta_N \approx 2.6$ [2]. A discussion on ST and their control in DEMO has been reported in [23]. Due to α-particles and very low current diffusivity, ST are in fact amost stable, with an expected period of several hundreds of seconds. This makes any strategy based on its pacing or destabilisation quite expensive in terms of H&CD power, as H&CD have so to say to work against a very large, stabilising α-population. For this reason, an approach based on NTM pre-emption [25], associated with a free evolution of the ST has been preferred. In more recent times, new plasma configurations based on the so-called flux pumping [26] have gained attention. This equilibria avoid the onset of ST by means of a saturated MHD mode which clamps q_0 close to 1, but without triggering any ST, nor any large oscillation in general.

Control of NTMs is based on EC, driving current inside the island and thus replacing the vanishing bootstrap current [27]. The allocated EC power is discussed in [24], while the diagnostics for their detection are illustrated in [5]. One of the issues which require further investigation is the broadening of the beam due to density fluctuations [28,29]. In fact, due to the long distance a beam has to travel across the device amplifies greatly the de-focusing the beams undergo because of the density fluctuations in the SOL. This can lead to an increase in the necessary power for the NTM suppression, and, potentially, may require changes in the machine architecture.

Finally, RWM are not expected to be unstable in view of the expected low values of β_N. In the past, advanced plasma scenarios with higher β_N (i.e. above the no-wall limit) were also considered [30]. Currently however, this does not represent the primary option for DEMO.



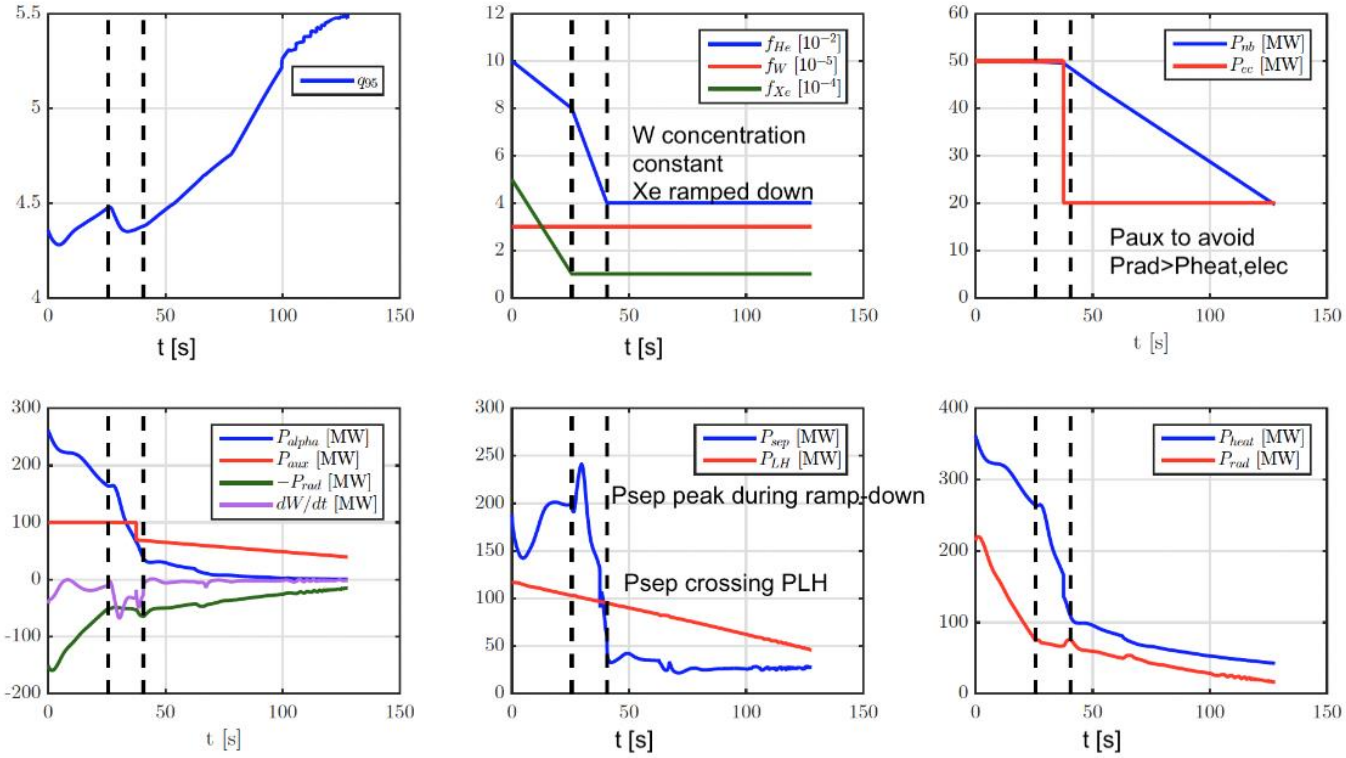


Fig. 4. Evolution of main plasma quantities during a ramp-down case at -100 kA/s produced with RAPTOR. According to the definitions introduced in Fig.3, this is an early HL, cold L case, i.e. the best case scenario. This ramp trajectory is marginally unstable (in terms of position control) if the criterion $1.25l_i$ is adopted – see Fig.3.

2.4 Radiative instability control

As previously mentioned, and as discussed in [2,23], EU-DEMO is characterised by a large amount of core radiation power, necessary to keep P_{sep} reasonably close to P_{LH} and thus to protect the divertor. This radiation is obtained via seeded Xe. The presence of a core radiator has nevertheless a strong impact on the plasma control, in view of the long residence time expected for such species in the confined plasma, which implies that no "fast" method exists to remove Xe from the core if radiation becomes excessive. A typical situation in which the radiation increase can become dangerous is the accidental influx of a W "flake" in the plasma core (it is here recalled that EU-DEMO is endowed with a full-W first wall, which might undergo embrittlement and cracking at microscopic and even macroscopic levels due to particle fluxes, especially during transients, and therefore tiny W particles could be eroded during plasma operation. The behaviour of W in terms of line radiation is in fact similar to Xe, so the effect of such influx leads to a sudden rise in the radiative losses. This has the effect of decreasing the plasma temperature (and thus the α-heating), increasing in parallel also the total radiation from Xe – as, at lower temperature, the Xe average cooling factor throughout the plasma core increases. This accelerates the cooling of the plasma, leading to an unstable runaway situation which, if uncontrolled, can lead to a disruption. Fig. 5 shows the evolution of P_{rad} after the introduction of a W flake of 1 mg at t = 200 s. As one can see, the excursion is both quite fast and quite large.

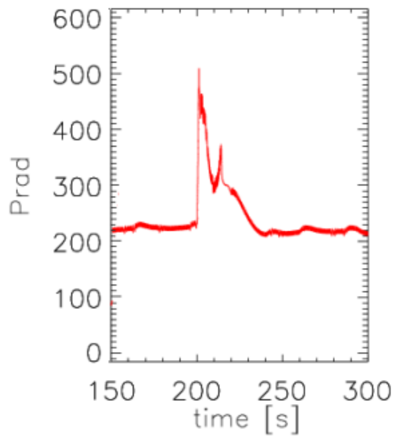


Fig. 5. Evolution of plasma line radiation when a W flake of 1 mg is introduced (at $t = 200$ sec). Power is expressed in MW.

In these circumstances, the plasma controller tries to recover the lost fusion power by increasing the pellet injection frequency, and enhance central density, and also heating the plasma edge (where radiation is mostly located, since it is where the temperature is favourable for the impurities to radiate). This strategy is very effective, but also quite dangerous, as EU-DEMO is already operating close to the density limit [2], and an excessive increase of the plasma density can fatally compromise the stability of the plasma discharge. On the other hand, H&CD alone cannot help in recovering the fusion power on such short time scales, since at DEMO conditions all technologies (EC, IC and NB) primarily heat electrons, and the equipartition time to ions is quite slow. The main role of the H&CD auxiliaries is instead to counteract the enhanced electron line radiation due to the presence of W, this being mostly localised in the pedestal region, where the temperature is favourable. A careful balance between H&CD actuators and pellets injection has to be individuated to make such off-normal transients treatable. The most convenient approach seems to be increasing alternatively the temperature (via H&CD) and the density (via higher frequency pellet injection), in order to limit the overshoot in fusion power (which can possibly be difficult to control in terms of plasma position, and may cause a disruption) [31]. Fig.6, 7 and 8 shows an example of successfully recovery of the discharge after a W flake event. Note the alternance of NB and pellet injection shown in Fig.7. The oscillations of β_{pol} and l_i shown in Fig.8, albeit significant, have been shown to still be compatible by the position control system with ex-vessel coils – thus same conclusions are expected for the in-vessel coils case. Note that no assessment of the technological feasibility of such control operations with NB has been carried out yet. This has to be understood simply as a power subdivision amongst ions and electron in the simulations.

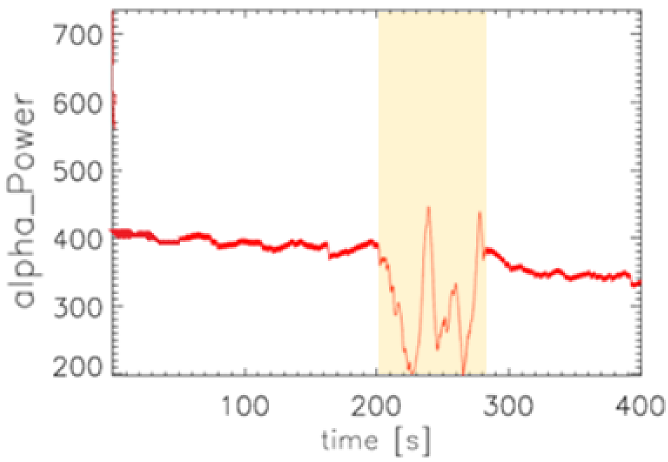


Fig. 6. Evolution of fusion α-power when a W flake of 1 mg is introduced (at $t = 200$ sec). Power is expressed in MW. After large oscillations, the discharge has bee successfully recovered. **The occurrence of the instability has been highlited with a light yellow shading.**

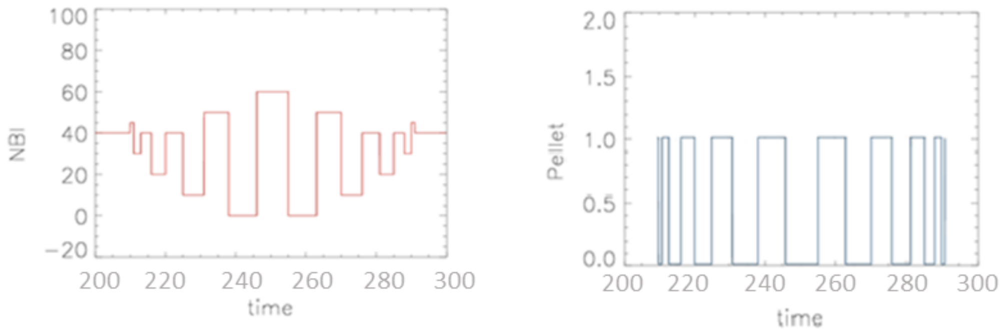


Fig. 7. Use of NBI (MW) and pellet injection (here 0 – 1 indicates injection off and on, respectively) to counteract to the W-flake event in Fig.4, 5 and 6. The pellet size, as discussed in the next section, amounts to 2*10^21 particles.

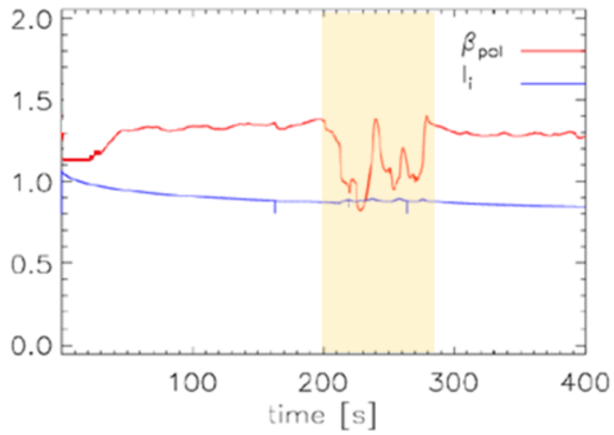


Fig. 8. Evolution of β_{pol} and l_i when a W flake of 1mg is introduced (at t = 200 sec). Oscillations are quite large but still recoverable by the position control system. **The occurrence of the instability has been highlited with a light yellow shading.**

At the moment, 70 MW H&CD power have been allocated in EU-DEMO to react to such events, as discussed above. Clearly, this power, albeit very large, cannot rescue the plasma under any circumstance. In particular, the W-flake event dynamics changes a lot as a function of the size of the flake. The maximum amount of W which allows a recovery of the discharge with the available EC power was found around ~10 mg [31]. Note incidentally that the more peripherally the H&CD power is injected, the larger W-flake event can be controlled. Clearly, above a certain mass of W, there is no way to recover the plasma, nor this can be a requirement for the control system but, rather, it should become a requirement for the designers. It has to be stressed that this quantity is related to the size of the W-flake released from the wall in a complex manner, and quantitative assessments of this relation are under way.

As mentioned in the beginning, this power allocation is however still not final, and can undergo changes if better control solutions are found. It is clearly not desirable to allocate the largest amount of the available H&CD auxiliary power just to control events that have to be very rare (i.e. a few times during the entire machine operation, to be better quantified), by virtue of the high disruption risk thereto connected. Furthermore, the final injection position has to be determined also by other factor, like e.g. the possibility to employ the same power for ramps, otherwise the available power to access and terminate the burn may be insufficient.

3 Fuelling and pumping

A detailed review of the pumping systems for EU-DEMO can be found in [32,33] and references therein. From the plasma side, the input profiles for neutral pressure (hydrogen isotopes and He) are taken from SOLPS cases [34,35], and for this problem the necessity of employing a kinetic neutral modelling is considered as central. An important constraint in DEMO is to ensure that the pump is able to exhaust a He flux equal to the He generation from fusion reactions, allowing at the same time a sufficiently low He concentration in the core (< 10%), in order to obtain the sustainment of a **stationary** discharge. This crucially depends on the He transport behaviour, both in the core and in the SOL, which is at this stage mostly unknown (at least concerning SOL). A review of the knowledge on He transport and its extrapolation to DEMO is contained in [36]. Further studies are foreseen in the next phase.

Concerning pellets, integrated modelling taking into account the technological limitations on the pellet launcher design as well as the plasma response (inward transport) to a pellet transit and ablation has been carried out [37,38]. This has been developed by coupling ASTRA with a scaling derived from HPI2 simulations for modelling pellet ablation. HPI2 is a pellet ablation-deposition code valid for any magnetic and plasma configurations. It computes the pellet ablation, taking into account thermal ions and electrons and the suprathermal ions generated by the plasma heating systems; the drift model to calculate the final particle deposition profile is based on the compensation of the cloud polarization by parallel currents [39]. Actually there are many trade-offs to be taken into account when optimizing pellet size and pellet injection systems. Smaller pellets tend to penetrate less deep inside the plasma, and thus depositing the matter further outside of the core region, which is of course undesirable. On the contrary, larger pellets can penetrate deeper, but the associated excursions in fusion power are larger, and this is not optimal from a control point of view. Plus, in case of missing pellet delivery (as the pellet success rate is < 90% in present pellet centrifugues and pellet guideline systems), the impact on the plasma is more significant (note that, clearly, for a given mass injection rate, larger pellets have to be less frequent). This is summarized in Fig. 6, using the EU-DEMO plasma flight simulator. Beyond their capability of fueling, a recent study has demonstrated the potential of pellets to host admixed auxiliary gases needed e.g. for radiative cooling. Host pellets were found to supply such gases more efficient and with shorter response times than gas puffing [40].

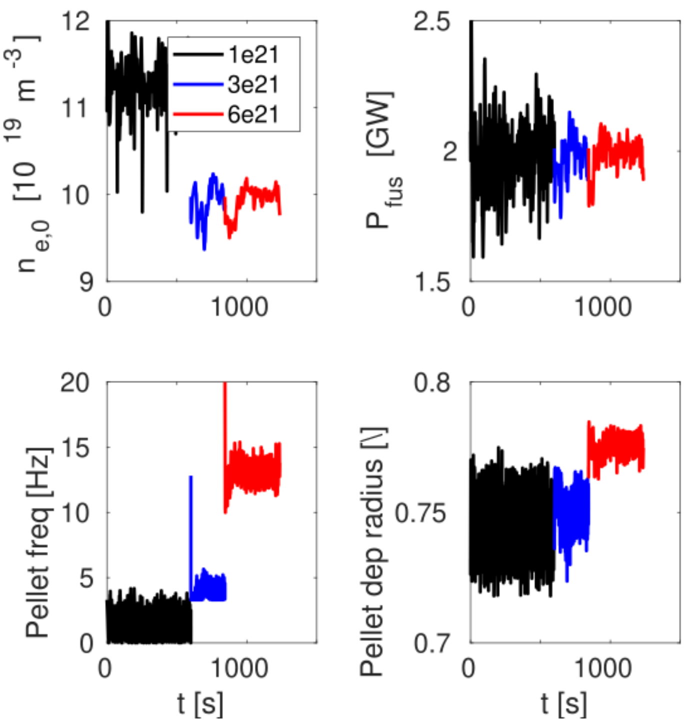


Fig. 9. Comparison of different pellet size for a given mass injection rate (pellet size in terms of particle content is given in the legend on the top left figure). The first panel shows the density in the core, the second panel the fusion power, the third panel the pellet fired, the fourth panel the pellet penetration. As one can see, larger pellets can penetrate more deeply in the plasma and allow a lower injection frequency, but the associated fluctuations in terms of density and fusion power are much larger, and in presence of a pellet delivery failure the decrease and oscillations in fusion power start to become significant.

These investigations yielded an optimal fuel injection rate of around $7*10^{21}$ particles/sec, with a pellet size of $2*10^{21}$ particles, i.e. relatively small - recall that the DEMO plasma chamber contains $\sim10^{23}$ particles [38]. It is important to stress this is not the only injection system in EU-DEMO, since the control of the plasma separatrix density is best performed via gas puff, as the optimization of a pellet system for both core and SOL density control would be quite difficult (e.g. in terms of pellet size, or pellet penetration, since the matter to sustain the separatrix density should not penetrate too far in the core). Gas puff is also easier to integrate than an additional, dedicated pellet launcher. The requirements for gas puff method are currently under investigation with SOLPS, but most likely the gas puff will be larger, in particles/sec, than the pellet injection of about one order of magnitude [34,35], with the actual number crucially depending, amongst others, on divertor compression and installable pumping speed. This is in line with recent published ITER-related results [41].

3.1 Divertor reattachment

A typical situation where such emergency shutdown is needed is the loss of plasma detachment at the divertor. EU-DEMO is operated with a detached divertor, the heat flux on the target plates exceeding the technological limit of ~10 MW/m^2 otherwise [42]. It has been elsewhere shown [43] that if the plasma divertor detachment is lost in the current ITER-like lower single null divertor configuration of EU-DEMO, the heat flux in the coolant reaches the critical heat flux in about three seconds if no countermeasures are adopted. As discussed in [23], an emergency shut-down of the plasma is not a viable solution, since even at the highest current ramp rate achievable (Fig.3) the procedure will be way too slow to allow the divertor surviving. Also, an abrupt plasma termination (which *de facto* consists of a mitigated disruption) is not attractive for EU-DEMO, since it also may cause relevant damages to the plasma facing components (see [11]). Thus, one needs to ensure that, by any emergency termination, a diverted configuration in DEMO down to very low values of the plasma current has to be maintained.

In EU-DEMO, the foreseen countermeasure is currently represented by strike point sweeping. This strategy has been discussed in [43,44] and allows the target surviving for some tens of seconds in presence of reattachment. This time lapse is required to ramp-down the plasma current without control losses (when returning to the detached state turns out to be impossible, but also in that case divertor sweeping may nevertheless be necessary by slow transitions, depending on the currently unknown time scale of reattachment). As divertor sweeping in EU-DEMO must already be active when the transition from plasma attachment to detachment begins, it is necessary to install diagnostics able to detect a loss of plasma detachment at its onset, or even before it occurs. For these reasons, the feasibility of a detachment control based on visible and ultraviolet (UV) spectroscopy is currently investigated [45]. Also, a suitable control strategy has to be identified, in order to minimize the occurrence of reattachment events.

It is important to stress that divertor reattachment appears to be a very important design driver, with profound impact on the machine architecture and posing important limitations to the available design space, as discussed in [1,11,43].

4. Conclusions and outlook

In the present paper, the investigations concerning the definition of requirements for the available diagnostics and actuators have been reviewed. In particular, focus has been given on the role of H&CD, plasma fueling and pumping. In brief summary, these requirements are, for the planned transients:

- 5-7 MW H&CD auxiliaries for plasma breakdown
- 130 MW H&CD auxiliaries for current ramps (up/down). This number may actually be reduced once the ramps trajectories will be better optimised.
- 30 MW H&CD for MHD control (sawteeth or NTM pre-emption) during flat-top. This number also may be reduced if the advanced scenario with flux pumping is adopted.
- At most 30 MW for burn control, but most likely this number will be reduced (see also the discussion in [5])
- $7*10^{21}$ p/sec injected via pellets of $2*10^{21}$ p, plus about ~10^{23} p/sec injected via gas puff (the exact number to be better qualified).

While for the off-normal transients:

- 70 MW H&CD auxiliaries to be deposited in the edge for control of radiative instability (with the caveat that only events up to a certain size of W flakes falling into the plasma can be recovered, thus in parallel there is a requirement for the designer to avoid by DEMO first wall design that larger events can occur)
- Divertor sweeping to protect the divertor in case a current ramp-down by reattachment is necessary.

In spite of the significant achievements, which have allowed to draw important conclusions on the entire plasma operation concept in EU-DEMO, there are still many open points which need further assessment in the future. These are for example:

- Which H&CD technology mix is the most attractive for the DEMO operation? EU-DEMO is exploring an ECRH-only option in the Conceptual Design Phase.
- Are the 70 MW foreseen for radiative instability control compatible with divertor protection? Could they be effectively employed for the ramps as well?
- Is the expected size of W flakes entering the plasma, and the successive radiative instabilities, controllable, or would a disruption be unavoidable? In the latter case, the allocation of 70 MW of H&CD in the edge region would be unuseful. Also, a more precise characterisation of the possible W-flake events (e.g. expected size of the flake, frequency, etc.) is needed to provide more substantiated requirements.
- Is it possible to have a He exhaust scheme allowing the He concentration in the core to remain below critical values, leading to fuel dilution?
- Is the plasma strike-point sweeping a sufficient mitigation for divertor reattachment? For example, would the erosion increase in such a way, that the plasma will be anyway too polluted to remain stable? How many reattachment events can be tolerated in the DEMO lifetime, especially in presence of significant erosion? Is the plasma sufficiently stable if ramped down in presence of sweeping?

The main lesson learned, however, is that transients are indeed adding strong design constraints to those determined by the stationary operational point. Also, the problem of plasma controllability has to be tackled at an integrated level, since the interdependency of the various phenomena is too deep to be disentangled. For this reason, the priority is to develop modelling tools able to reproduce the discharge and the actuators on a holistic level [2]. First step in this direction will be the inclusion of magnetic control in ASTRA-Simulink, together with a continuous update of the models driven by the development of plasma physics knowledge. Also, the process will be carried out systematically, in order to ensure that all main events do possess adequate countermeasures.

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