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EU DEMO transient phases: main constraints and heating mix studies for ramp-up and ramp-down

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Abstract

EU DEMO studies for pulsed (DEMO1) and steady-state (DEMO2) concepts are currently in the pre-conceptual phase [1]. DEMO1 aims at producing about 2GW of fusion power with a burn time of approximately 2 hours. Within EUROfusion Power Plant Physics and Technology department, DEMO scenario modelling is carried out as part of the validation of feasibility and performance of DEMO designs. One of the most challenging activities deals with numerical investigations of DEMO1 transient phases including ramp-up and ramp-down. Studies on ramp-up have been carried out to highlight the effects of different ramp-up options in terms of robustness of the access to the desired flat-top scenario. A dedicated heating power during ramp-up, additional to the one required during flat-top, appears to be necessary for a reliable access to H-mode and plasma burn initiation and is estimated of the order of 50-100MW depending on present uncertainties on L-H transition scaling to be used. Current ramp-rate and heating power have been chosen also in order to allow plasma position controllability, investigated in terms of the achieved internal self-inductance and poloidal beta. Additional power requirements and integration of different systems which are relevant for DEMO heating mix assessment are here discussed.

Ramp-down phase in DEMO poses specific issues on vertical stability given the distance of control actuators from the plasma. Ramp-down trajectories with controllable plasma boundaries have been coupled to transport studies showing the necessity of additional ramp-down heating power to avoid radiative plasma collapses. Off-axis power deposition helps plasma controllability, together with a current ramp-rate≤100kA/s. Plasma radiation also dominates the H-L transition, which is investigated and appears to be a critical step in terms of plasma control.

Introduction

Within EUROfusion Consortium the design of a demonstrative fusion reactor, DEMO, is currently in the pre-conceptual phase [1]. Two tokamak concepts are under investigation: a pulsed reactor (DEMO1) and a steady-state reactor (DEMO2). In this work we concentrate on DEMO1, which is a near-term solution based on ITER H-mode baseline scenario. A description of DEMO1 with the scenario used for this work can be found in [2]. The reference flat-top scenario is characterized by following main parameters: plasma current I_p=19.6 MA, average electron temperature $\langle T_e \rangle \sim 13$ keV, average ion temperature $\langle T_i \rangle \sim 12$ keV, central electron temperature $T_{e,0} \sim 27.4$ keV, average electron density $\langle n_e \rangle \sim 8 \cdot 10^{19}$ m^{-3}, central electron

density $n_{e,0}$~1*10^{20} m^{-3} and additional flat-top heating power $P_{add,FT}$=50MW. DEMO1 is supposed to produce 2GW of fusion power with a discharge duration of ~2h. DEMO scenario investigation is one of the activities of the Power Plant Physics and Technology department, and a summary of recent modelling activities can be found in [3], [4]. Investigations on DEMO1 ramp-up and ramp-down phases started as well, with particular attention to the role of heating systems.
DEMO1 ramp-up (RU) has to give fast and robust access to the target flat-top (FT) scenario. Moreover a proper optimization of H&CD systems could result in swing flux saving and consequent extension of discharge duration. There are at the same time many constraints due to technical limitations, e.g. poloidal field coil capabilities, which should be taken into account.
The ramp-down (RD) phase is critical too, and not symmetric with respect to RU. It must ensure a robust and safe discharge termination, which, in case of a pulsed reactor, will be carried out routinely. Power balance is critical due to high losses from confinement degradation (H to L transition) and radiation, which should be replaced by adequate additional heating. In particular, the control of radiation and an effective plasma heating are crucial to avoid a radiation collapse. The control of plasma position from poloidal coils can result critical especially in case of high plasma internal self-inductance. In agreement with previous studies [3] the flat-top (FT) power system considered in the present work is NBI with some additional EC power during ramp-up (RU) and ramp-down (RD), although the final H&CD mix will be decided at a later step in DEMO R&D.

A parametric study for DEMO1 ramp-up (RU)
To explore different RU options, a parametric study by means of METIS code has been performed. METIS (Minute Embedded Tokamak Integrated Simulator), developed as part of CRONOS suite [5], is a fast integrated tokamak simulator which models the plasma by scaling laws coupled with simplified source models (0.5D). Aim of the work is to arrive to a RU optimized in terms of a combination of several quantities as e.g. RU duration, flux consumption, total installed H&CD power and internal inductance li. Different RU options have been investigated and compared. In this work the FT additional power ($P_{add,FT}$) provided by a NBI system is switched on approximately at the end of the RU to avoid shine through problems (density limit scaled from ITER [6], as a conservative estimate: $\langle n_e \rangle$ ~3*$10^{19}$$m^{-3}$). The RU duration is mainly driven by plasma position control issues. A figure of merit for plasma position control is the internal inductance, which should be kept within certain limits depending on coil capabilities. Figure 1 shows the internal self-inductance during RU trajectories with different ramp rates (plasma current linearly increasing with time). A faster RU rate allows lower li (easier plasma position control), but a slower RU rate is less demanding in terms of coil limitations. A possible compromise suggested by our studies is a ramp rate in the order of 100kA/s corresponding to a RU duration of ~200s. Note that limitations on maximum currents and voltages in the positioning control components are not known in the present design status and they might critically have an impact on a more refined determination of the RU duration. Systematic METIS simulations clearly showed that, within the physics assumption implemented in the code, some dedicated additional power, $P_{add,RU}$, is needed during the RU to reach a robust reactor working point. The most challenging requirement proved to be overcoming the L-H transition, in order to get rapidly plasma with improved confinement properties and begin the burn phase. In the case represented in figure 2 (referring to a fast, 120s long, RU), the L-H threshold is estimated from the conservative scaling by Martin [7]. This scaling foresees a threshold of 163MW during FT. H mode is reached at the end of the RU at a lower density with respect to FT to lower the power needed to exceed the L-H threshold. In this phase the 50 MW of $P_{add,FT}$ adds up to the 100 MW of

dedicated $P_{add,RU}$, making a total of 150 MW. Since $P_{add,RU}$ has to be provided as soon as possible during RU, i.e. also at low plasma density values, in the simulation EC power was assumed instead of the FT NBI system. These studies suggest that about 150 MW of total additional power (RU+FT) should be installed to secure an early and robust access to H mode, although further RU optimizations might modify the present guess. Note also that soon after the H mode is reached, thanks to the power coming from fusion reactions, only $P_{add,\ FT}$ is needed, mainly for burn control purposes.

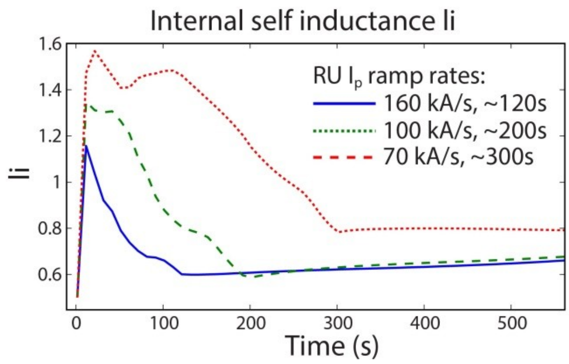

Figure 2: Internal self-inductance for different RU current ramp rates

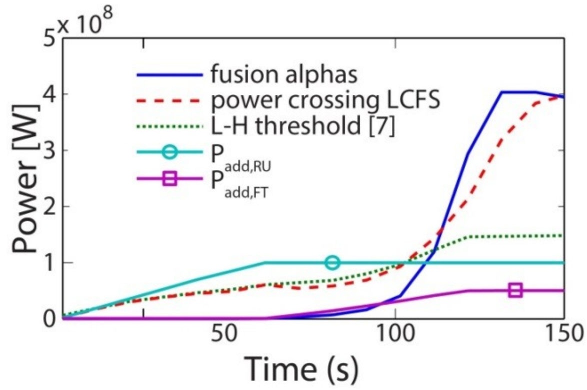

Figure 1: Power balance for L-H transition during RU

A trajectory validation for DEMO1 ramp-down (RD)

The aim of this work is to validate a ramp-down trajectory consistent in terms of vertical stability. Plasma boundaries produced by CREATE NL free boundary equilibrium code [8] has been passed as input to a plasma transport simulation done by means of JINTRAC suite of codes (1.5D) [9]. CREATE NL code has been successively used to assess the feasibility of the trajectory investigated in terms of coil capabilities. In order to simplify the complex JINTRAC ramp-down simulation, the effective charge Z_{eff} has been prescribed to be radially constant with Xe as representative impurity. Line radiation has been also prescribed to reach a convergent simulation. A ramp-down trajectory has been simulated running from 19.6MA to 5MA (the end of the diverted plasma phase). Plasma current (I_p) is set to linearly decrease, together with the boundary plasma density and the target electron density (n_e) value for gas puff feedback. This has been done to keep a constant Greenwald fraction (n/n_G) below destabilizing limits. The FT NBI system is switched off when reaching the lower density limit due to shine through losses (density limit scaled from ITER [6]: $<n_e>\sim 3*10^{19} m^{-3}$). L-H threshold power is calculated using Martin scaling [7]. Two trajectories with different current ramp rates within coil capabilities have been compared: one at 100 kA/s and the other at 80 kA/s (figure 3). The 100kA/s trajectory shows high radiation losses (due to high Z_{eff} and T_e), which, considering the decreasing fusion power, have to be compensated by a total additional heating power (FT+RD) up to 100 MW. In this simulation the RD power system is an on-axis EC source. The high central heating and the edge cooling due to radiation result in a peaked current density profile, leading to a plasma internal inductance (li) exceeding 2 at I_p~8MA, as shown in figure 3. CREATE NL post-analysis confirmed that, to control a plasma with so high li, coil requests would become very demanding. The plasma is also likely to collapse in the final ramp-down phase due to unbalanced radiation losses. Radiation in fact rules the ramp-down, and in this sense impurity transport plays a crucial role, as it was previously highlighted for DEMO flat-top in [10],[11]. The ramp rate of the second trajectory is decreased to 80 kA/s and Z_{eff} is linearly reduced to 1.2 at the end of ramp-down to lower the bremsstrahlung radiation. The prescribed line radiation is gradually decreased too in order to reduce the edge cooling. The NBI switch-off is performed by steps and a EC source is used (with a maximum power of 40MW), orientated off-axis at the end of RD when the current density peaking is maximum. This trajectory successfully reaches the end of the plasma diverted phase, with a H-L back transition at ~7.5MA and li always below 2 (figure 3). This should allow plasma controllability avoiding plasma vertical instabilities. For this trajectory the total installed power (FT+RD) reaches 90MW.

Conclusions

Within the physics assumption implemented in METIS code, this study shows the need of further additional dedicated RU power (beside to 50 MW flat-top power). Using Martin L-H scaling [7], about 150 MW of total auxiliary power (RU+FT) are suggested to secure a robust access to H mode. The transport study of ramp-down highlighted issues for plasma control and the need of an effective heating systems mix to compensate for high radiation power losses. Slower Ip ramp rate and off-axis heating can help to reach a successful RD trajectory. Anyway, there is space for further optimizations both for RU and RD based on the results here presented. Possible optimizations can concern timing, evolution and description of actuators (i.e. density control and H&CD systems) and a more accurate modelling of radiation and impurity transport.

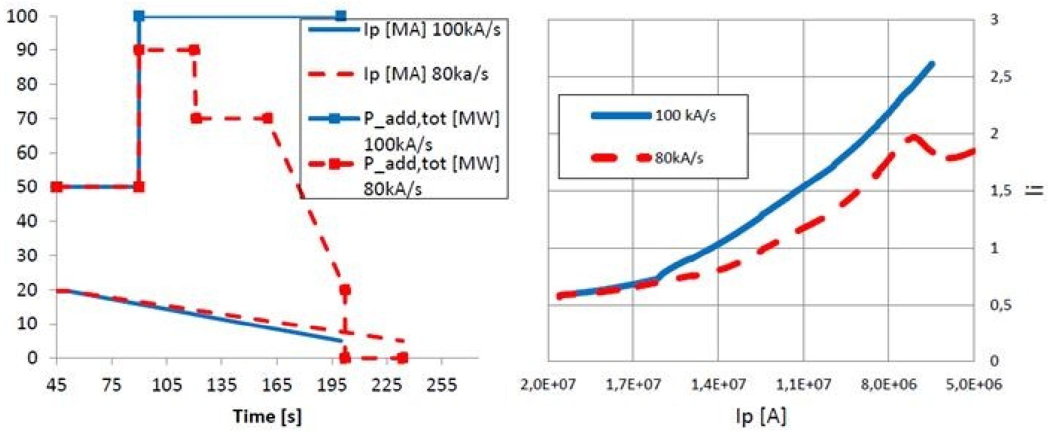

Figure 3: comparison of RD trajectories with different current ramp rates

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References

[1] Federici G. et. al, Fus. Eng. Des. 89, 882-889 (2014)
[2] Wenninger R. et al., "The physics and technology basis entering European system code studies for DEMO", accepted Nucl. Fusion (2015)
[3] Giruzzi, G., et al., Nucl. Fusion 55, 073002 (2015)
[4] Wenninger R. et al., Nucl. Fusion 55, 063003 (2015)
[5] Artaud J. F. et al., Nucl. Fusion 50, 043001 (2010)
[6] Polevoi A.R. et al., Nucl. Fusion 53, 123026 (2013)
[7] Martin Y. R. et al., J. of Phys.: Conference series, 123.1 012033 (2008)
[8] Albanese R. et al., Fusion Engineering and Design, 96-97, pp. 664-667 (2015)
[9] Romanelli M et al., Plasma and Fusion Research 9, 3403023 (2014)
[10] Vincenzi P. et al., Nucl. Fusion 55, 113028 (2015)
[11] Zagorski R. et al., Nucl. Fusion 53, 073030 (2013)