

DEMO Exhaust Challenges Beyond ITER

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The European fusion roadmap foresees a demonstration fusion reactor (DEMO) [1] to follow ITER with the aim of demonstrating the production of electricity in a fusion plant. Table 1 lists parameters of several recent EU designs: DEMO1 (pulsed, conservative physics and technology assumptions), DEMO2 (steady state, more optimistic physics and technology assumptions) designs. The designs are tokamaks in H-mode operation with a closed fuel cycle. In comparison to the ITER ($Q = 10$) design the European DEMO design options have significantly higher fusion power, higher β_N , higher temperature across the whole profile, higher fueling rate and higher core radiation fraction. Also there are more challenging engineering requirements (e.g. closed fuel-cycle) and consequently more restrictive engineering boundary conditions when compared to ITER. Due to this there is a number of areas, in which the physics challenges of DEMO - mostly related to the feasibility or the cost of the device - go considerably beyond the ones for ITER. This paper addresses the important subset of these additional challenges, which concentrates around the topic of power exhaust.

DEMO Wall Loads

In the recent EU concept design analysis of the first wall of DEMO it is assumed to have W as armour material and water or He as coolant. In DEMO the requirements of electricity generation and tritium self-sufficiency lead to challenges for an efficient heat removal from the first wall. As the coolant temperature is considerably higher than in ITER and beyond the operational

Table 1: Overview of EU design parameters for DEMO1 and DEMO2 and an alternative DEMO2

	EU DEMO1 2015	EU DEMO2 2015	EU DEMO2 2015 (Alt)
$R[m]$	9.1	7.5	7.5
A	3.1	2.6	3.1
$B_T [T]$	5.7	5.6	6.5
$I_P [MA]$	20	22	18
H (rad. cor.)	1.1	1.4	1.4
$\beta_{N,tot} [\%]$	2.6	3.8	3.8
$f_{bs} [\%]$	35	61	64
$P_{sep}/R [MW/m]$	17	20	20
$\tau_{burn} [h]$	2	steady state	steady state
$P_{el,net} [MW]$	500	953	941

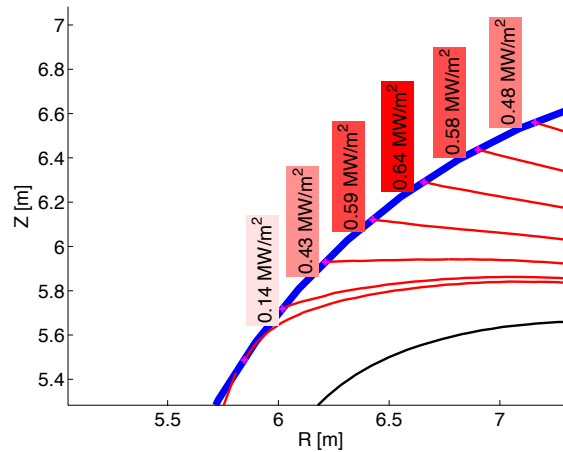


Figure 1: Power flux density to the inner top section of the DEMO first wall based on field line mapping: Vessel wall (blue) and intersecting field lines (red). It is assumed that $\lambda_q = 170\text{mm}$

window of Cu, EUROFER despite its relatively low thermal conductivity ($\sim$ one tenth that of Cu) is currently foreseen as structural material in this area.

Considering these conditions leads to a power flux density limit of $1.5\text{MW}/\text{m}^2$ for water cooling and $1.0\text{MW}/\text{m}^2$ for He cooling respectively [2]. In comparison to this more than 50% of the first wall of ITER is specified for more than $3.5\text{MW}/\text{m}^2$ [3]. To identify at an early stage possible problems in this respect the development of the DEMO Wall Load Specification has been initiated. It has been reported that the peak power flux density during flat-top operation on the wall due to radiation can reach up to $0.45\text{MW}/\text{m}^2$ for DEMO relevant conditions [2], which is based on the assumption that in addition to the core radiation 100% of $P_{sep} = 150\text{MW}$ is radiated from the SOL.

Another important load component onto the first wall originates from thermal charged particles. To assess this, a heat flux density profile in the outer midplane has been mapped along the field lines to the first wall. It is assumed that the total $P_{sep} = 150\text{MW}$ is transferred by thermal charged particles from the outer midplane to the first wall. The main zone of wall interaction in the breeding area is in the inner top region of the device. Using the extrapolated midplane power fall off length $\lambda_q = 0.8\text{mm}$ [4] leads to negligible heat loads onto the first wall. Figure 1 displays the situation using $\lambda_q = 170\text{mm}$ [3] as most extreme value, which might apply in the mid to far SOL for DEMO plasmas with an intense blob activity [5]. This results in a peak power flux density of $0.64\text{MW}/\text{m}^2$. Similarly as in ITER [6], it has to be investigated by which factors the heat loads are enhanced when considering several types of deviations of the device and the plasma from the idealized situation assumed so far. The risk is recognized that this could lead to heat loads intolerable for EUROFER-based first wall technologies.

ELMs in DEMO

Similarly as in ITER, ELMs in DEMO can harm divertor PFCs by energy impact. The relevant limit is the melt limit of W, which is defined by the heat impact factor $\eta = \Delta W / (A\sqrt{t}) \approx 50\text{MJ}/\text{m}^{-2}\text{s}^{-0.5}$. Assuming that the heat impact duration is similar in ITER and DEMO, leads to an identical limit in the relative ELM energy density of $\Delta W / A \leq 0.5\text{MJ}/\text{m}^2$. Figure 2 displays the dependence of $\Delta W / A$ on the relative ELM size $\Delta W / W$ for various assumptions. The most optimistic assumption (blue) is that the ELM broadening b [7] has a constant value of 6. The most pessimistic assumption (red) is that $b \propto \Delta W / W$ for $\Delta W / W > 1\%$ and $b = 1$ below. These assumptions correspond to a limit in $\Delta W / W$ of 0.84% and 0.14% respectively for

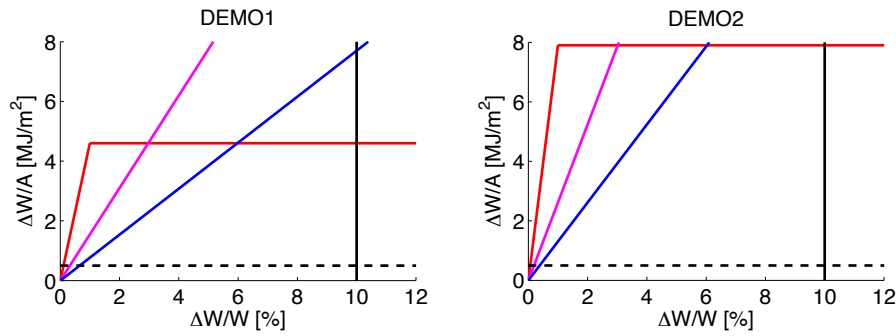


Figure 2: Dependence of the ELM energy density on the relative ELM size for various assumptions: Left: DEMO1, Right: DEMO2. Red: $b = 1$ and $b \propto \Delta W/W$, Magenta: $b = 3$, Blue: $b = 6$. The dashed line marks the limit of 0.5 MJ/m^2 . The vertical line represents the extrapolated natural relative ELM size for DEMO.

DEMO1. Considering the anticipated relative size of natural type I ELMs in DEMO of 10% [4], this means that a mitigation in terms of $\Delta W/W$ by a factor of 15 to 90 is required for DEMO1 (DEMO2: 25-150). Other limits, which should be addressed, are related to main chamber heat loads and ELM impurity flushing.

In view of this significant mitigation necessity a robust strategy to deal with ELMs needs to be a key component of any DEMO concept. No recent device is able to simultaneously operate in the DEMO range for normalized collisionality ν^* and Greenwald density fraction. Based on the assumption that pedestal physics dominates in this context, mitigation methods that are demonstrated for DEMO relevant collisionalities ($\nu^* \approx 0.05$) need to be identified. For RMP ELM-mitigation [8] and the QH-mode [9] this is fulfilled, while the I-mode [10] has so far only been observed for $\nu^* > 0.1$. Other alternatives to consider are ELM pacing by pellets or vertical kicks.

For all candidate methods for ELM mitigation in DEMO open R&D needs have to be addressed:

- RMP: Characterize penalty in confinement and investigate feasibility of coil integration
- QH-mode: Clarify access conditions at low torque
- I-mode: Determine the extent of the operation window between I-mode threshold and H-mode threshold
- ELM pacing by pellets / vertical kicks: Extrapolate $\Delta W(f_{ELM})$ and broadening; Expand data base and physics understanding; Investigate impact on gas balance (pellets) and control systems (vertical kicks)

Key Size Drivers

The size of DEMO is the main driver of its capital costs. It turns out that the major radius R is driven amongst others by parameters related to H-mode operation and divertor protection. Figure 3 shows the dependence of R on $f_{LH} = P_{sep}/P_{LH,scal}$ ($P_{LH,scal}$: [11]) and P_{sep}/R from a calculation with PROCESS minimizing the major radius at fixed $P_{el,net} = 500 \text{ MW}$ and $\tau_{burn} = 2h$. For each P_{sep}/R , f_{LH} has a minimum value corresponding to the highest achievable value of the magnetic field at the inner TF coil leg. To achieve sufficient confinement quality and controllability of the plasma it might be necessary to control f_{LH} towards a higher value, which would lead to a significant increase of R .

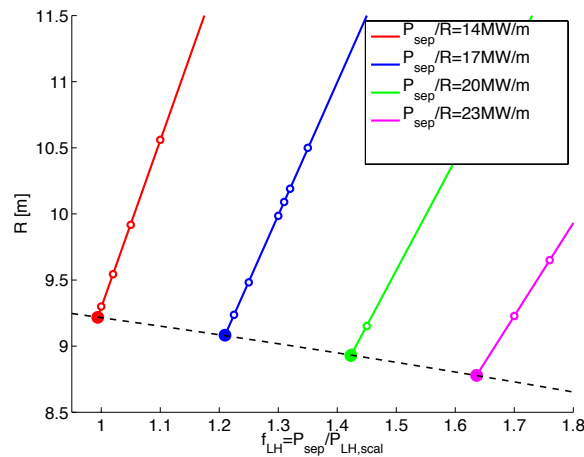


Figure 3: Dependence of the major radius on f_{LH} and P_{sep}/R from PROCESS calculations

The 95% confidence interval of the ITPA threshold scaling for ITER [11] ranges roughly from 50% to 200% of $P_{LH,scal}$. In DEMO $P_{LH} = 2P_{LH,scal}$ would roughly correspond to doubling the major radius. Consequently all possibilities to reduce this uncertainty need to be exhausted. This includes activities towards an improvement of the understanding of the LH-transition. Also it is necessary to develop a new scaling of the H-mode threshold power including more DEMO-relevant data (e.g. data from metal wall devices [12, 13] and high radiation plasmas). It might be helpful to include Z_{eff} as a scaling parameter. Furthermore a better characterization of a possible dependence of P_{LH} on the X-point height / shape [12] and identification of the key physics parameter governing this dependence is desirable especially for closed divertors, which are the option foreseen for DEMO.

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