Nuclear Materials and Energy 24 (2020) 100767

Contents lists available at ScienceDirect

Nuclear Materials and Energy

journal homepage: www.elsevier.com/locate/nme

Simulation of the first wall shielding during upward VDE in DEMO

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ARTICLE INFO

Keywords:
Numerical simulation
DEMO
TOKES
VDE

ABSTRACT

First simulations of the DEMO first wall damage during the upward VDE of 0.6 GJ residual plasma energy in the core have been performed using the TOKES code. The simulations revealed two qualitatively different modes of the hot plasma core cooling. In the first of them, we proposed to call the weak shielding mode, the estimation of tungsten amount, vaporized from the wall during VDE is reduced from 5.7 kg for simulation without the shielding to $5 \cdot 10^{-4}$ kg, the melted pool depth at the wall surface remains almost the same 158 µm without shielding and 140 µm for the weak shielding; the amounts of melted W are 77 kg and 23 kg correspondingly.

In the second one – the fast radiation cooling mode – which arises due to 15% increase of the initial core energy loss rate, the vaporized W penetrates directly to the hot core and radiates the plasma energy at least 5 times faster than in the weak shielding mode. As a result, the entire vertically displaced core is cooled by radiation during less than 1 ms, the W amount, vaporized during VDE is reduced to 0.8 kg, the melted pool depth is 92 µm and the amount of melted W is 60 kg.

1. Introduction

The present DEMO design assumes the first wall (FW) of the vacuum vessel is fully armoured with tungsten. One of the key risks of this strategy is that high energy density transients will be sufficiently powerful in DEMO to cause local melting of W surfaces in the high heat flux (HHF) areas of the wall. The most dangerous for the first wall transients in tokamaks are the disruptions and the vertical displacement events (VDE). VDE is an abrupt break of the core plasma stability due to magnetohydrodynamic (MHD) instabilities, which leads to vertical movement of the plasma core upwards or downwards till the core touches the FW. Direct contact between the core plasma and FW will cause huge heat fluxes to the FW at the touching spots. During cooling down of the vertically displaced core, the heat flux to the wall temporarily increased by several orders of magnitude. Unmitigated VDEs in DEMO will corrupt the FW, causing melting, melt splashing and vaporization.

Even in existing tokamaks FW is melted during VDE, despite negligible core energy content in comparison with DEMO: plasma thermal energy in JET is less than 5 MJ and up to 1.3 GJ in DEMO. Direct extrapolation of the transient heat flux parameters to DEMO predicts severe melting and vaporization of FW causing intolerable damage. However, tungsten vaporized from the target at the initial stage of the VDE can create a plasma shield in front of the target, which effectively protects the target surface from the rest of heat flux.

This plasma shielding effect is a complex physical phenomenon, combining MHD convection and diffusion of the tungsten plasma shield with conversion of the transient heat flux from the core into radiation heat flux. Radiation from the plasma shield redirects the heat flux to FW sections, neighbouring the spot of direct plasma-wall contact, thus reducing the maximum heat load at the touching position. Similar effects occurs at the divertor targets during the unmitigated disruptions. Effectiveness of the plasma shielding for divertor target protection has been investigated experimentally and numerically for ITER disruptions in [1–5] and numerically for the DEMO disruptions [6]. However, the results of these simulation cannot be directly extrapolated to the DEMO VDE because the shielding efficiency depends nonlinearly on the disruptive heat flux. Besides, the shielding depends nontrivially on the geometry of the magnetic field and of the wall close to the interaction position.

A realistic estimation of the heat flux to the FW and the wall damage requires simulations of heat and plasma transport in the vertically displaced core and in the wall. These simulations of DEMO VDE have been performed using the two-dimensional integrated tokamak simulation code TOKES [7,8]. The TOKES code numerically simulates the dynamics of thermonuclear deuterium–tritium plasma in the DEMO core, in the SOL, and calculates heat flux to the tokamak walls and heat transport inside the solid walls. It takes into account phase transitions

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https://doi.org/10.1016/j.nme.2020.100767
Received 25 November 2019; Received in revised form 16 June 2020; Accepted 18 June 2020
Available online 24 June 2020
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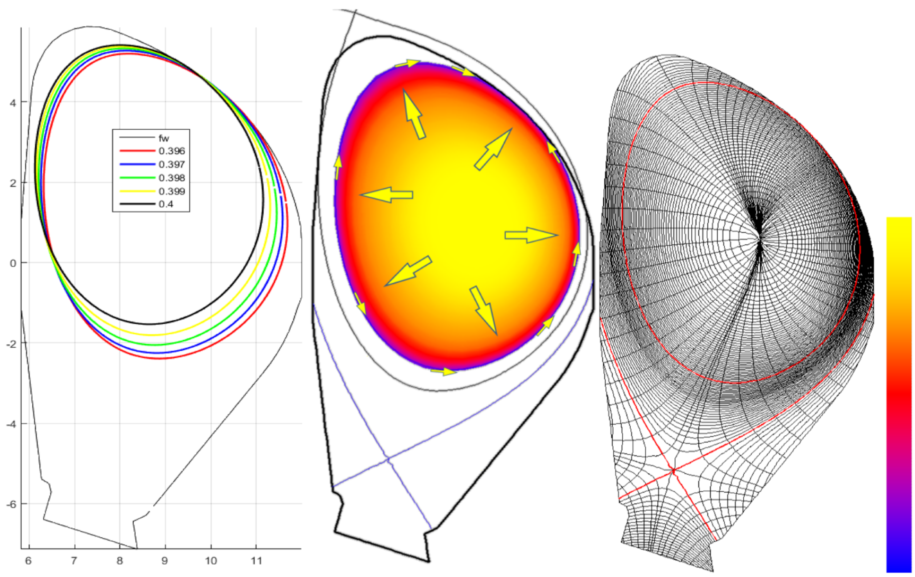

Fig. 1. Hot core motion during VDE simulated with the CREATE-NL + code is illustrated in the left panel. Shown are consecutive core positions, starting from the first wall touch at 0.396 s and separated by 1 ms. Position of the vertically displaced core when it touches the wall is in the central panel. Colour scale shows the plasma temperature distribution inside LCFS, yellow arrows indicate the plasma heat flux direction. Corresponding magnetic configuration and the TOKES calculation grid aligned with the magnetic field are plotted in the right panel. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

of the wall material (W), including melting and vaporization. After vaporization begins, TOKES simulates the dynamics of vaporized W in vacuum vessel, W ionization and W-D-T plasma dynamics, including photonic radiation. The aim of the simulations is to estimate the FW damage. This estimation is done assuming that the plasma having thermal energy of 0.6 GJ inside the displaced core is released onto the FW.

2. The TOKES model for VDE simulations

The initial phase of VDE, when the DEMO core loses stability and starts to move upwards has been simulated using the CREATE-NL + code [9] and its results has been used as input for the TOKES simulations. CREATE-NL + simulations of several consecutive shifted core positions after it touches the wall are shown in Fig. 1. But CREATE-NL + simulations does not take into account wall heating, vaporization and the influence of the vaporized material onto the core plasma. This is the aim of TOKES simulations. However, TOKES simulation of the plasma-wall interaction with moving magnetic configuration is difficult. Instead, we proposed to simulate this interaction in frozen magnetic configuration (when the hot plasma core touches wall) and to neglect the core motion. This assumption has been justified with the TOKES simulations, which show very fast thermal quench of the core (less than 1 ms), so the core shift during this time is negligibly small, see Fig. 1, where the core at the first touch of the wall is shown in red and the core after 1 ms – in blue. The TOKES simulations assume that the magnetic configuration after touching the wall remains unchanged and the hot core plasma interacts with the wall due to turbulent cross-field thermoconductivity and diffusion inside the last closed magnetic flux surface (LCFS). Outside the LCFS, where magnetic field lines crosses the wall, the heat and the particle fluxes are directed to the wetted wall area due to thermoconductivity and convection along the field surfaces. The initial state for the TOKES simulations and the calculation grid are also shown in Fig. 1.

The disruptive cross-field heat and particle fluxes inside the LCFS are simulated in the TOKES code using a special model. This model, described in [1], approximates the disruptive increase in cross magnetic field transport by adjusting the cross-transport coefficients. TOKES simulates the fluxes inside the LCFS using the Rechester and Rosenbluth's [10] assumption that disruptive MHD turbulence during TQ results in destruction of magnetic surfaces, when the field lines wander ergodically with small amplitude. As a result the cross-transport coefficients for electrons and ions became proportional to the parallel transport coefficients, but with smaller amplitude. These amplitudes have been adjusted to ensure the TQ flux characteristic rise time of 1–2 ms. This fit has been performed in a separate TOKES runs with plasma shielding switched off, i.e. FW at the plasma touching position was heated, melted and vaporized, but the vaporized W was 'removed' so as not to affect the core plasma dynamics. Excluding the W plasma from these simulations has been done to determine the TQ parameters per se and to calculate the reference FW damage for comparison with simulations that includes shielding.

3. Simulation results

First simulations have been performed without taking into account the shielding by vaporized W, which assumed that W does not interact with the core plasma. They allowed fitting the cross-transport thermoconductivity and diffusion coefficients for electrons and ions to ensure the cross-field heat flux rise time of ~ 1 ms, see red curves in upper panel of Fig. 2, showing the time dependences for total power crossing LCFS. Further gradual decrease of the power is not fitted; it follows from the temperature dependences for the transport coefficients. Corresponding simulation has been performed taking into account W plasma and with the same coefficients as has been fitted in the previous simulation. The results of these simulations are shown in the central panel in Fig. 2.

Comparison of these two simulation results revealed the influence of the W plasma shield on the TQ dynamics and on the wall damage. In these cases the dynamics of the core cooling are almost the same: the time dependences for total power crossing LCFS are similar, only the total power maximum in the case with shielding is ~ 15% less than without shielding. But the heat fluxes to the wall differ significantly. In case without shielding the heat flux to FW depends only from the power crossing LCFS. As a result the surface temperature at the plasma touching point increases till the vaporization temperature and then remains almost constant during ~ 2 ms. During this time the heat flux excess over the value, necessary to maintain the vaporization temperature at the surface, is spent on intense surface vaporization, reaching $1.9{\cdot}10^{25}$ W atoms in this case.

In contrast, the heat flux to FW with shielding depends not only from the power crossing LCFS, but also from the shielding efficiency of W plasma, produced from vaporized W. As a result, the time dependences for wall heat flux and wall temperature are identically the same as without shielding up to the vaporization point, but after start of vaporization the heat flux drops due to the shielding by evaporated and

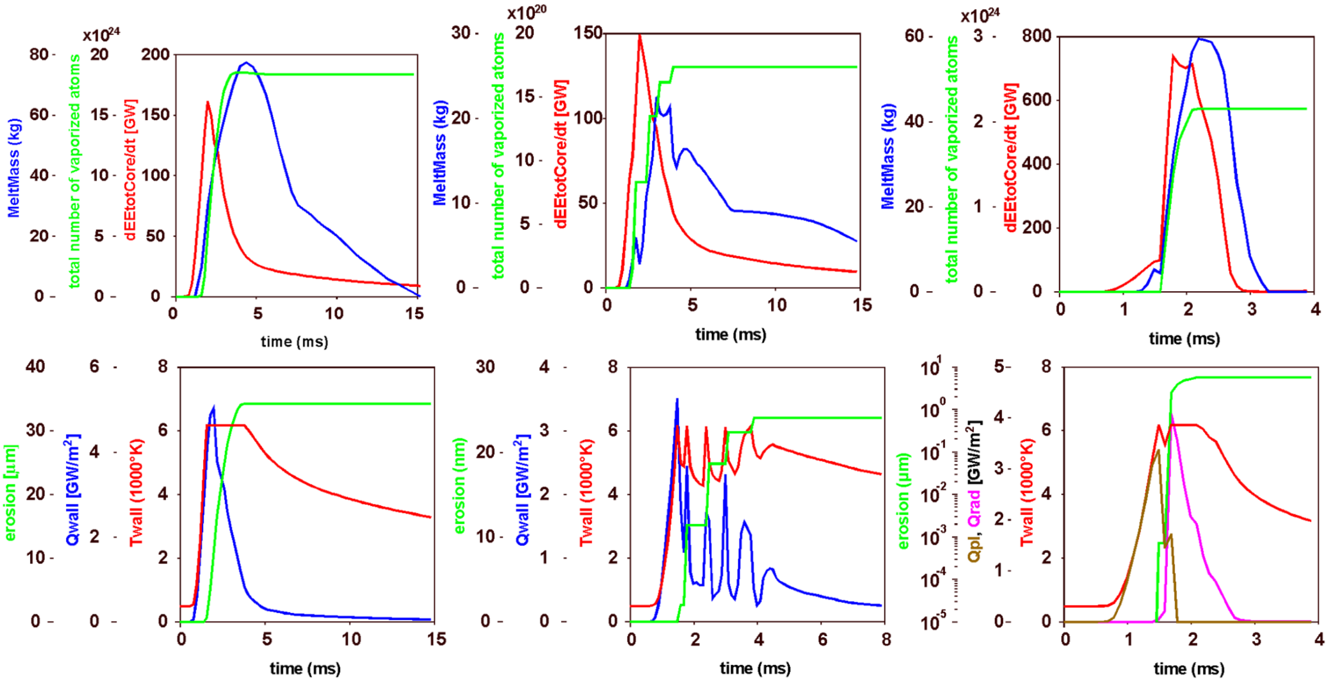

Fig. 2. Comparison of the TOKES simulation results for 3 cases: without the shielding (left column), for the weak shielding mode (middle column) and for the fast radiation cooling mode (right column). Upper panels show time dependences for total power, crossing LCFS as well as for amounts of vaporized and melted W. Lower panels compare heat fluxes to the wall with surface temperature and the wall erosion by vaporization. Q_{wall} is the total heat flux to the wall, Q_{pl} and Q_{rad} are the plasma heat flux and the radiation heat flux separately.

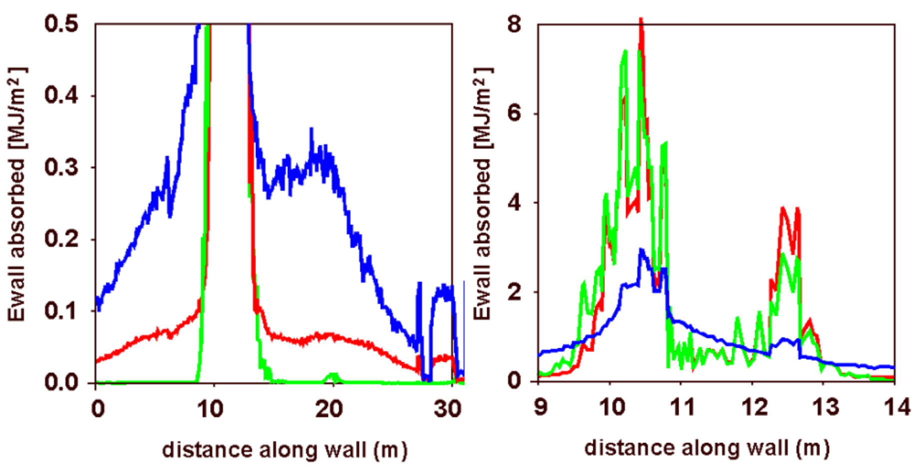

Fig. 3. Patterns of total energy density deposition onto the wall projected onto poloidal section. The hot plasma core touches wall at about 10 m coordinate. Green curves correspond to the case without the shielding; heat flux is deposited on the wetted spots only. Red curves show the case with the same heat flux from the core, in weak shielding mode. Blue curves are the case with 15% faster TQ, which corresponds to the fast radiation cooling mode. Right panel is a blow up of the left one at the spot of touching between the plasma and the wall. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

ionized W, see lower middle plot in Fig. 2. The decrease in the wall heat flux causes a decrease in surface temperature and stops vaporization. After stop of vaporization the shield is diluted due to the cross-field diffusion and due to the W plasma expansion along the magnetic field. The shield dilution causes heat flux increase, which in turn increases surface temperature up to vaporization. The process is repeated several times as seen from lower middle panel in Fig. 2. Vaporization of W proceeds in the form of several small shocks, as illustrated in the same plot. The shielding efficiency by tungsten plasma is so high, that total W vaporization from the wall drops on four orders of the magnitude, to $1.7{\cdot}10^{21}$ W atoms. The wall heat flux excess (which was spent for vaporization in case without shielding) is converted to radiation and redistributed onto surrounding wall for several tens of meters, as seen in Fig. 3. Expansion of the W plasma along the magnetic field lines is shown in Fig. 4. As seen in this figure, W plasma expands along the magnetic field, diffuses mainly outside of the LCFS and almost does not penetrate inside it. As a result, the time dependence for the power crossing LCFS is almost the same as without shielding (the difference is of a few percent). The core energy is mainly deposited to the wall as plasma flux (79% of the initial core plasma energy) and radiated is 21% of the initial energy. We call this shielding mode as 'weak'. Total melted W mass maximum in the weak shielding mode is reduced from 77 kg without shielding to 23 kg; the maximum melt depths are comparable: 158 μm without shielding and 140 μm for the weak shielding, see Fig. 2.

The simulations without shielding, illustrated in Fig. 5, shows a small difference in the wall heat flux and in the wall damage if the power crossing LCFS increases on 15%: the plasma heat flux onto the wetted wall area increases on ~ 15%, the wall surface temperature reaches the vaporization value approximately 0.1 ms earlier and the amount of vaporized W differs by ~ 30%. However, even this small increase on 15% for the power crossing LCFS resulted in sharp change in the core cooling rate, wall damage and even physics of the core cooling itself due to the shielding. Simulations, performed for these two cases revealed that the weak shielding mode is converted into a 'fast radiation cooling' mode after some threshold value for the power crossing LCFS.

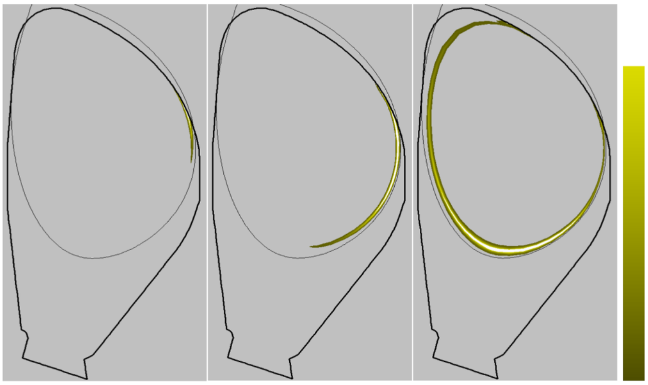

Fig. 4. W density pattern evolution in case of VDE in the weak shielding mode at 3 time moments: 2.4 ms (just after wall vaporization start; the colour scale maximum is $3{\cdot}10^{19}$ m^{-3}), at 6 ms (the colour scale maximum is $1{\cdot}10^{19}$ m^{-3}) and at 20 ms (the colour scale maximum is $5{\cdot}10^{18}$ m^{-3}) from the first touching between the core and FW. Tungsten plasma expands along the separatrix, slightly diffuses across it and surrounds the hot core. This plasma radiates small part of the heat flux from the core.

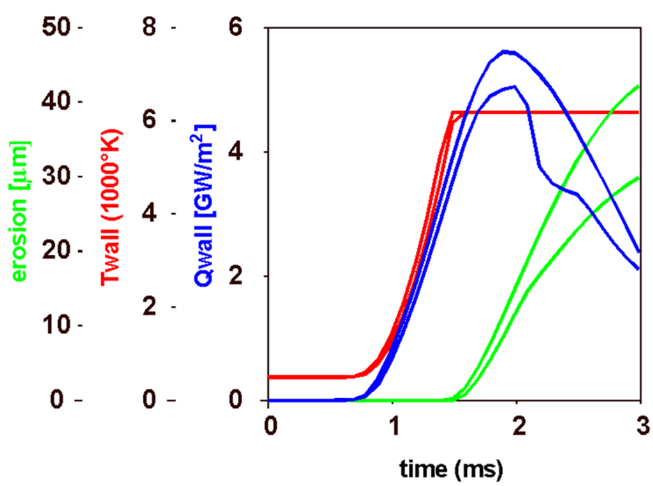

Fig. 5. Comparison of the wall heat fluxes, wall temperatures and the wall erosion depths for two cases, lower and higher the threshold separating the weak shielding mode and the fast radiation cooling mode. Both simulations have been performed without shielding, to compare small difference in flux, performing huge consequences. The power, crossing LCFS is ∼ 15% different in these modes.

Below the threshold all vaporized W is immediately ionized close to the vaporization point, then the W plasma expands along the magnetic field, as shown in Fig. 4 and shields the vaporized surface. Above the threshold, when W vaporization rate is ∼ 3 times higher, the beginning of the vaporization process is the same, see left panel in Fig. 6. But, after some time, the increased number of W atoms cools down the outer layer of the core plasma, so the next portions of W vapour does not ionized there and penetrate deeper inside the core, perpendicular to the magnetic field. Deeper inside the core, where the plasma temperature is still high, these W atoms are ionized and the W plasma radiation power increases in front of the vaporized surface, as seen in the middle panel of Fig. 6. Radiation from W plasma does not shielded by vaporized neutral W and the radiation source is located very close to the vaporization spot. This arrangement leads to instability, which developed after a certain threshold value for the vaporization rate: the more tungsten is vaporized, the higher radiation heat flux in vicinity of the vaporization spot and the higher vaporization rate, as illustrated in Fig. 6. As a result, the W wall vaporized faster and faster injecting a stream of neutral W gas, which propagates inside the core and cools it down during 2–3 ms. This situation is quite different from the shielding of the divertor targets during unmitigated disruption, investigated in [6]. The main difference is that during VDE the hot core plasma is located very close to the vaporization spot, so vaporized W gas can immediately penetrate into the hot core plasma and cool it down by radiation. In contrast, W vaporized from the divertor targets is several meters away from the core and cannot reach it directly; it should be ionized, the W plasma should be transported on ∼ 10 m along the magnetic field and then diffused inside the core. As a result, cooling of the core during VDE can be much faster than the core cooling during unmitigated central disruption.

The simulation results of the fast radiation cooling mode are shown in right pair of plots in Fig. 2. During first 1.5 ms the power crossing LCFS grow with the same rate as without shielding, but then it increases sharply to ∼ 750 GW due to radiation, so the core is cooled in less than 1 ms, as illustrated in upper right panel. Lower right panel shows that during first 1.5 ms, when the wall erosion is zero, heat flux to the wall is due to the plasma from the core (brown curve). Then, after the start of wall vaporization, the plasma heat flux drops to zero due to the shielding, and instead radiation heat flux (magenta curve) grows to a comparable value and ensures the wall vaporization. Main wall heat flux in the fast radiation mode is due to radiation from W plasma; it is distributed over several tens of meters distance with moderate energy density of 0.1–0.3 MJ/m^2 and the peak value drops from 8 MJ/m^2 to less then 3 MJ/m^2, see Fig. 3.

Estimation of the DEMO wall damage during the fast radiation

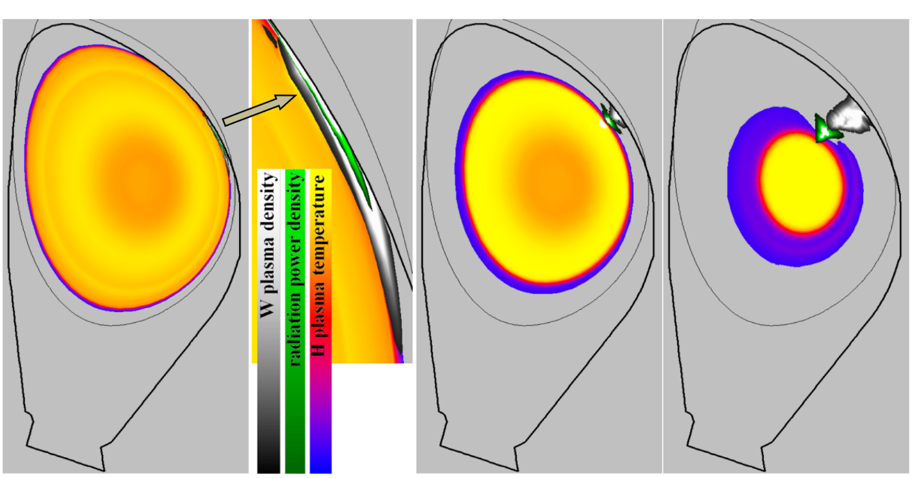

Fig. 6. Dynamics of the W plasma (gray scale) cloud expansion from the vaporization point, of the core plasma temperature (blue-red-yellow scale) cooling and radiation power density (green scale) simulated with the TOKES code for the fast radiation cooling mode. Shown are T_e, n_i and P_{rad} at 3 time moments: immediately after wall vaporization start, in the course of the core cooling and final moment just before total cooling of the core. The second panel is a magnification of the vaporization point at the first panel. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

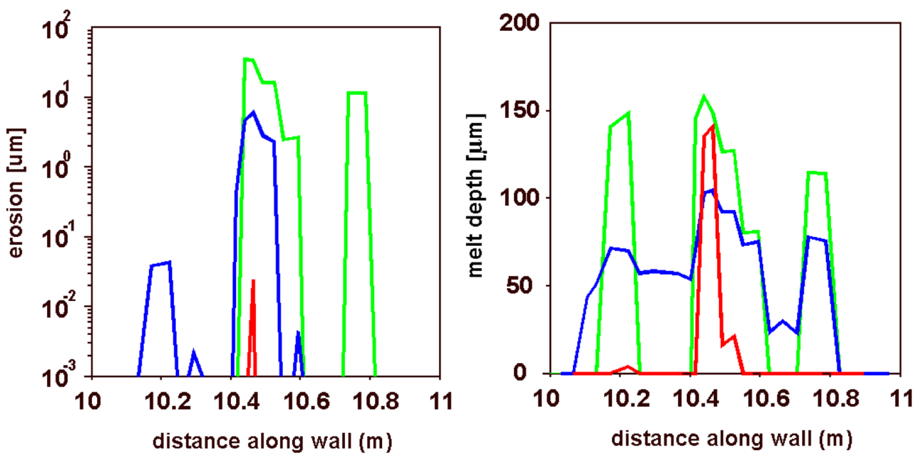

Fig. 7. Final vaporization erosion profiles shown in left panel and melt pool profiles along the poloidal wall section at max melt mass. Green curves correspond to the simulation without shielding, red correspond to the weak shielding mode and blue – to the fast radiation cooling mode. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

cooling mode, simulated with the TOKES code, is lower than the damage without taking into account the shielding. Total number of vaporized W atoms is $2.1 \cdot 10^{24}$, ten times lower, total melted W mass maximum is 59.5 kg and the melt pool depth maximum is 92 µm.

4. Conclusions

First simulations of the DEMO first wall damage during the upward VDE of 0.6 GJ residual plasma energy in the core have been performed using the TOKES code. The simulations revealed two qualitatively different modes of the hot plasma core cooling. The first of them we proposed to call the weak shielding mode and the second one – the fast radiation cooling mode. In the weak shielding mode W vaporized from the wall is ionized directly after vaporization; the W plasma expands mainly along the magnetic field lines and shields the vaporization spot on the wall. As a result, the estimation of tungsten amount, vaporized from the wall during VDE is reduced from 5.7 kg for simulation without the shielding to 0.5 g in this mode. However, the maximum of melted pool depth at the wall surface remains almost the same 158 µm without shielding and 140 µm for the weak shielding; the amounts of melted W are 77 kg and 23 kg correspondingly. The depth of the melt pool is mainly dependent on time, not on the heat flux value (if this value is large enough), see the analytic model for plasma shielding in [1]. This is why the maximum of melted pool depth in the weak shielding mode and with no shielding are almost the same. A more than threefold difference in the molten mass for these modes is due to a narrower melt region in the weak shielding mode, see Fig. 7. In all modes vaporization starts at the point of maximum heat flux and vaporized W shields not only the vaporization spot, but the neighbouring regions also. In the weak shielding mode radiation is weak and distributed on a large distance along the separatrix, see Fig. 4, so its contribution to the wall heat load of the region of vaporization and melting is minor. As a result, the two side peaks of melting without shielding are drastically reduced in the weak shielding mode, compare green and red curves in Fig. 7.

In contrast, in the fast radiation cooling mode, which arises due to 15% increase of the initial core energy loss rate, the vaporized W penetrates directly to the hot core and radiates the plasma energy at least 5 times faster than in the weak shielding mode. This drastic increase of the core plasma energy loss rate is due to the unstable positive feedback between the radiation power from the W plasma cloud produced due to the wall vaporization and the vaporization rate. As a result, the entire vertically displaced core is cooled by radiation (which dominates in this mode) during less than 1 ms, the W amount, vaporized during VDE is reduced to 0.8 kg, the melted pool depth maximum is 92 µm and the amount of melted W is 60 kg. Radiation from the shield is strong enough and redistributes the plasma heat load over large wall area; therefore, in the fast radiation cooling mode melted is a large strip of ~ 1 m wide, but the melt depth is decreased due to faster heating by the radiation, see Fig. 7.

One should note that our simulations assume toroidal symmetry of the VDE, which is not always the case, so real plasma heat flux to the wall may be higher due to the flux concentration in toroidal direction. The simulations has been performed for one plasma energy in the core. For more comprehensive understanding of the plasma-wall interaction during VDE a parametric study with variation of the residual plasma energy in the core is necessary.

CRediT authorship contribution statement

Sergey Pestchanyi: Conceptualization, Methodology, Software, Writing - original draft. **Francesco Maviglia:** Supervision, Writing - review & editing.

Declaration of Competing Interest

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

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. The authors would like to thank Fabio Villone and Tim Hender for their contribution to the Disruption simulation, we use as input in TOKES.

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