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Simulation of the divertor targets shielding during major disruption in DEMO

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Abstract

Simulation of the divertor target damage during thermal quench of the disruption in future DEMO tokamak has been performed using the TOKES code. This parametric study includes the damage estimation for disruptions of the plasma energy E0 in the DEMO core in the range of 0.4 to 1.3 GJ. According to the simulations, the maximum melt depth on the divertor targets is ~80 μm, independent of the energy content in the core. The melted pool maximum area grows from ~20 m^2 for 0.4 GJ disruption to ~120 m^2 for 1.3 GJ disruption. Maximum erosion depth is 4 μm for 1.3 GJ disruption and decreases to less than 1 μm with decreasing E_0. Total quantity of vaporized tungsten ranges from $2\cdot10^{21}$ to $3\cdot10^{24}$ atoms for disruptions of 0.4 – 1.3 GJ. An additional parametric study has revealed weak dependence of the results, from the characteristic widths λ_q of the disruptive flux in the Scrape-Off Layer (SOL).

1. Introduction

The present DEMO design assumes the divertor 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 divertor. The most dangerous transient in tokamaks are the disruptions. A disruption is an abrupt break of the core plasma stability due to magnetohydrodynamic (MHD) instabilities, which leads to the total cooling down of the core plasma. During Thermal Quench (TQ) of the disruption, the heat flux through the separatrix temporarily increased by several orders of magnitude. Unmitigated disruptions in DEMO will corrupt the divertor targets, causing melting, melt splashing and vaporization.

In existing tokamaks the target damage is negligible because of moderate core energy content. Direct extrapolation of the transient heat flux parameters to DEMO predicts severe melting and vaporization of the divertor targets causing intolerable damage. However, tungsten vaporized from the target at the initial stage of the transient 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 backwards and to surrounding walls, thus reducing the maximum heat load at the Separatrix Strike Positions (SSP). Effectiveness of the plasma shielding for divertor target protection has been investigated for ITER disruptions in [1]. However, the results of the ITER simulation cannot be directly extrapolated to DEMO because the shielding efficiency depends nonlinearly on the disruptive heat flux. Similar investigations, performed for DEMO disruption parameters and reported in this paper, show new physical effects due to almost a 5-fold increase in the core plasma energy from 280 MJ in ITER to 1.3 GJ in DEMO.

A realistic estimation of the heat flux to the divertor targets requires simulations of heat and plasma transport in SOL and in the core. These simulations of DEMO disruptions have been performed using the two-dimensional integrated tokamak simulation code TOKES [2,3]. 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 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 divertor target damage. This estimation is done assuming that the total plasma thermal energy is released onto the divertor targets. This assumption is too pessimistic, because a considerable amount (potentially a majority) of the plasma energy is irradiated by impurities injected into the core by the disruption mitigation system. That means the target erosion evaluated by the simulations performed is the upper limit for the values, which can be used for estimation of DEMO safety. Additional simulations of disruptions with partial energy release have also been performed.

2. Fitting the disruption parameters in the TOKES code

The plasma particle and thermal flux to the divertor targets during the disruption causes melting and vaporization. The disruptive fluxes 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 particle and heat fluxes inside the core and to the SOL using the Rechester and Rosenbluth's [4] assumption that disruptive turbulence 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 duration of 1-2 ms, in accordance with the estimations in [5], see Fig. 1. This fit has been performed in dedicated TOKES runs with plasma shielding switched off, i.e. the divertor target was heated, melted and vaporized, but the vaporized W was not taken into account in plasma dynamics. This has been done to exclude the influence of the plasma shield on the disruption parameters and to calculate a reference target damage for comparison with real simulations which includes shielding.

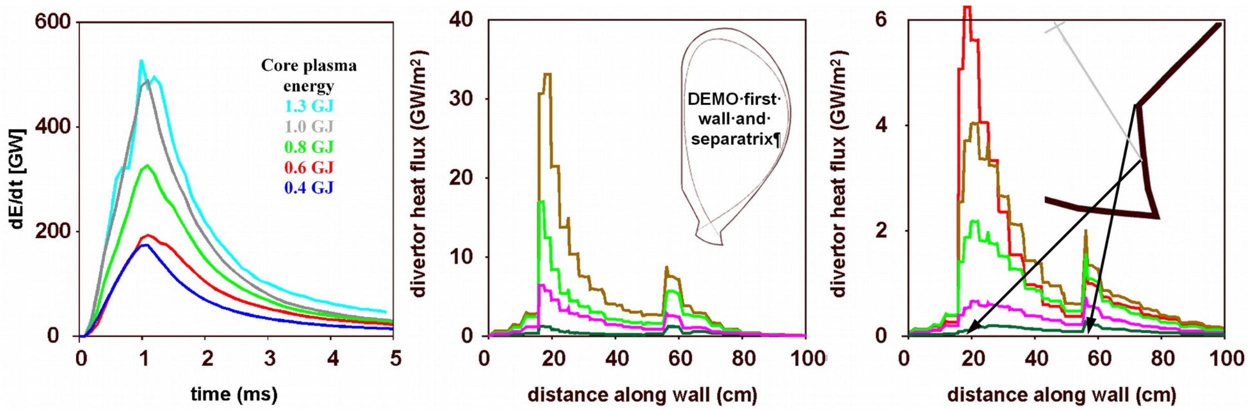

Fig. 1. TOKES disruption simulation results without shielding. Time dependence of the total power crossing the separatrix for various core energies are shown in the left panel. Disruptive heat flux distributions along the outer divertor target at different time moments are shown in the middle panel for 1.3 GJ total core plasma energy and in the right panel for 0.4 GJ. Coordinates of the outer SSP and of the outer baffle peak are indicated by arrows.

Estimations for the heat flux width in the SOL are rather uncertain because of large extrapolation distance from modern tokamaks. The stationary width value ranges from 1 to 5 mm and the disruptive width broadening – from 3 to 10, see, for example, [5,6]. Taking this into account we decided to perform simulations with the e-folding width λ_q at the thermal quench of the simulated disruptions of ~1.5 cm in the central plane of the SOL and to perform additional parametric study varying the λ_q parameter. To meet these requirements the cross-field thermoconductivity and diffusion coefficients in TOKES are assumed to be constant across the SOL and their values are adjusted in such a way so that the parallel heat flux channel in SOL fits this value. The heat flux in the SOL is formed in TOKES as interplay of (electron and ion) cross-field thermoconductivity and cross-diffusion through the separatrix combined with the parallel electron and ion thermoconductivity and convection along the magnetic field. All these processes resulted in heat flux at the divertor targets. Footprints of total heat flux due to the above listed processes are shown in Fig. 1 for two simulation variants, 1.3 GJ and 0.4 GJ. One can see that the heat flux distribution along the target can be very roughly approximated as exponential and the e-folding width λ_w for the heat flux at the target can be recalculated to the equivalent λ_q at the midplane. An additional smaller peak at the baffle top is due to an increase of the tilting angle between the magnetic field and the target surface. Tracing the peak along the magnetic configuration reveals that it corresponds to ~2.2 cm from the separatrix at the midplane. This value is very close to $\lambda_q \sim 1.5$ cm, which leads to a rather large increase of the flux at the baffle.

3. Major disruption simulation results with shielding

After the start of the disruption, the heat flux to the divertor targets grows in time, causing a rapid increase in their temperature. The flux profile along the target has a maximum close to the SSP (the flux profile is shown in Fig. 1). The target vaporization starts at this point. Fig 2 illustrates target surface temperature growth due to the disruptive heat flux and the structure of the plasma shield. Intense W vaporization, which influences the incoming heat flux, starts at around 6000K and almost all the vaporized W is immediately ionized. This W plasma shields the surface, so the disruptive heat flux arriving to the target decreases, and is radiated in the vapour cloud. At this point the decrease of the surface heat flux stops the growth of the surface temperature. The structure of the plasma shield along the magnetic line is shown in Fig. 2. Dense W plasma of the shield is located close to the target. Temperature of this plasma is rather low and radiation from there is negligible because of the low temperature. This dense W plasma ‘cushion’ has a sharp edge, which propagates along the magnetic field from the target. In front of this edge the W density (N_W) is negligible and T_e remains rather high, of several keV, everywhere in the SOL. The main radiation region is in front of the expanding W plasma shield, where T_e drops to 100-200 eV (corresponding to the maximum tungsten luminosity). Thus, almost all the plasma heat flux from the core is stopped in this intermediate region of the shield and radiated to all surrounding walls. The heat flux, required for the target vaporization, feeding the shield, is provided by this radiation.

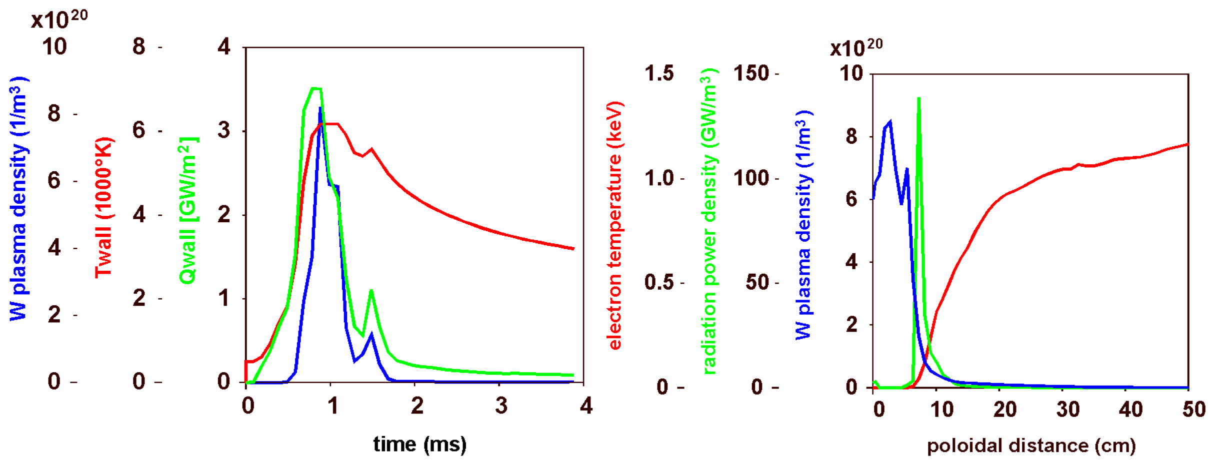

Fig. 2. The result of TOKES simulation for disruption of E_0 = 0.4 GJ. Left panel illustrates start of the divertor target shielding. The time dependences for the wall heat flux at the SSP (green), for the wall surface temperature at the SSP (red) and for the W plasma density in the cell adjacent to the SSP are displayed. The right panel shows longitudinal structure of plasma shield, which consists of 3 regions: 1) dense W plasma close to the target (which is at the coordinate origin) with small T_e; 2) T_e rise outside the W plasma cushion; and 3) sharp radiation power density (P_r) peak in the intermediate region of 100-200 eV.

In tokamaks the 1D longitudinal shield structure, described in the previous paragraph is valid for cross-sections of the real 2D shield, which is illustrated in Fig. 3. The structure of the 2D shield is essentially the same as in 1D: it consists of a dense and cold W plasma cushion close to the target, of T_e rise in front of the 'cushion' edge; the plasma heat flux from the core is converted into radiation in the intermediate region of the shield. However, these regions are 2D, see Fig. 3.

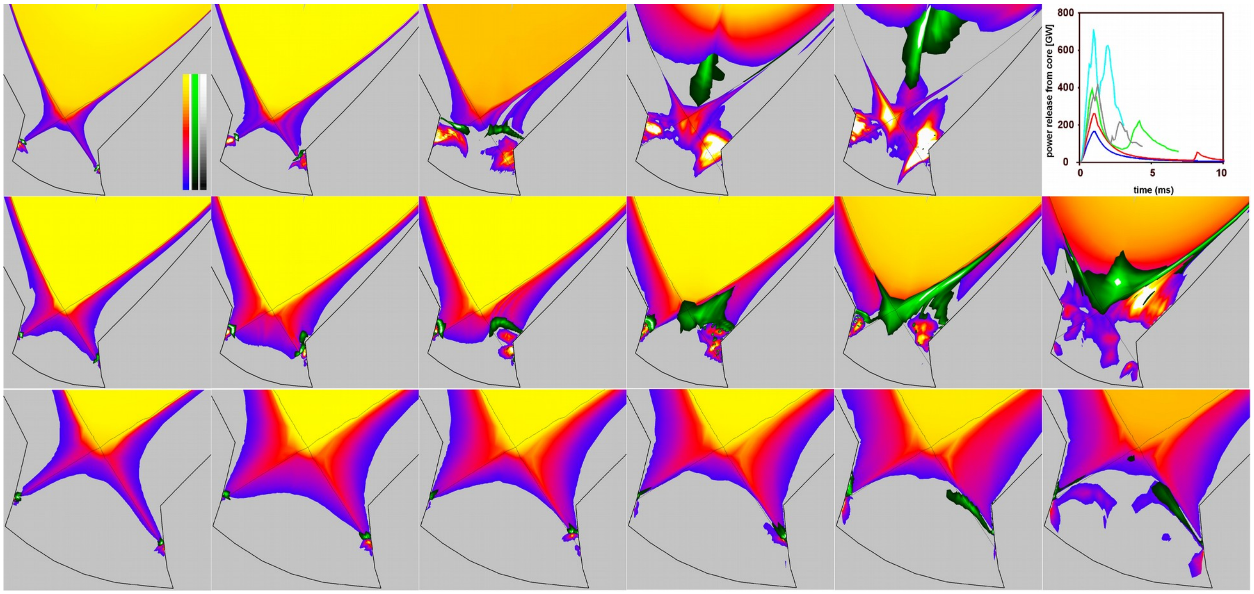

Fig. 3. The result of TOKES simulations for 3 disruptions of various initial core energies E_0. Lower line of plots corresponds to E_0 = 0.4 GJ at time moments of 1, 2.4, 4, 6, 10 and 20 ms. Middle line corresponds to E_0 = 0.6 GJ at time moments of 0.6, 1, 1.2, 2, 4 and 8 ms. Upper line corresponds to E_0 = 1.3 GJ at time moments of 0.3, 0.5, 0.8, 1.5 and 1.8 ms. Colour scales are for T_e (blue-red-yellow), N_W (blue-red-yellow) and P_r (green). The upper-right insert shows time dependences for power release from the core for E_0 of 0.4 (blue), 0.6 (red), 0.8 (green), 1 (grey), and 1.3 (cyan) GJ. The first peak on the curves is due to the turbulent plasma energy flux through the separatrix, the second is due to direct radiation power from the core, caused by W plasma influx into the core.

A series of disruption simulations, including the shielding effect, has been performed using initial plasma energy values in the core of 0.4, 0.6, 0.8. 1.0, and 1.3 GJ. The plasma shield dynamics during the disruption of 0.4 GJ core plasma energy is shown in the lower panel of Fig. 3. Relatively moderate heat flux from the core in this case results in a rather stable plasma shield position. After the initial target vaporization and shield formation close to SSP it moves very slowly during the disruption time, remaining close to the divertor target at all time. The power released from the core in this case rises sharply during the first 1.5 ms and then monotonically decreases with time, see the blue curve in the upper right insert in Fig. 3.

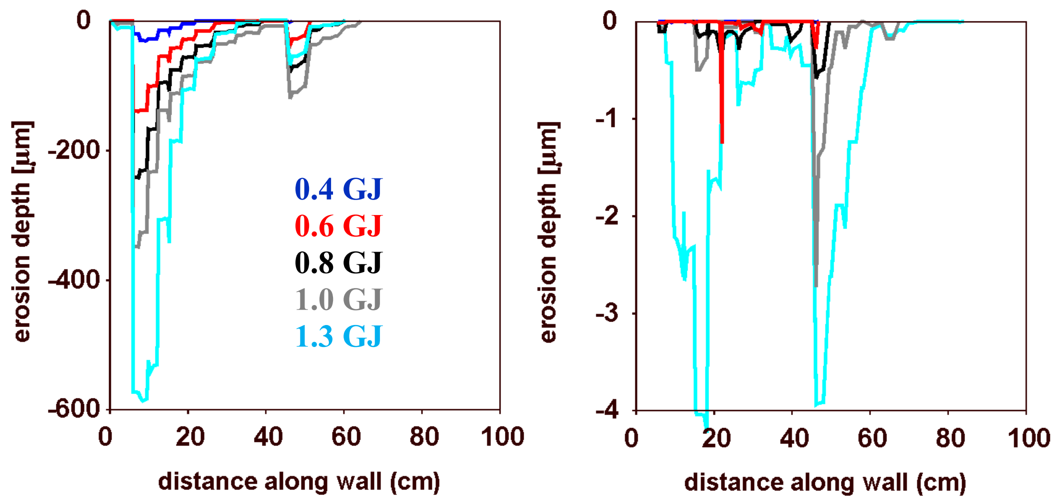

Fig. 4. A comparison of vaporization erosion craters, produced during the disruption of the core plasma energy, is indicated with different colors for different plasma initial thermal energies. The right panel displays the target erosion produced by the disruption with the plasma shielding. The left panel displays the crater profiles are calculated without taking into account the shielding.

For the higher core energy content E_0=0.6 GJ the result is qualitatively similar, at least at the start of the disruption, as it is possible to see in the middle sequence of plots in Fig. 3. In this case the vaporization is more intense, so the shield expansion resulted in W plasma arrival to the x-point with noticeable density. This plasma diffuses through the separatrix inside the core and starts to radiate from there. As a result, part of the core thermal energy is radiated directly from the core. This radiation is visible as a small peak on the red curve at ~ 8 ms and as a large radiation power spot inside the core, close to the x-point on the last 2D plot of this case.

The upper line of plots in Fig. 3 illustrates disruption with the higher energy value of 1.3 GJ. The influx of W plasma inside the separatrix becomes faster and more intense with the increasing disruption energy E_0. As a result, the larger part of the core energy is radiated directly from the core, thus decreasing the plasma heat load to the divertor targets. In the disruption of E_0=0.6 GJ only 12% of the energy is radiated from the core and for the E_0=1.3 GJ disruption 56% is radiated directly from the core according to the TOKES simulations.

A parametric study of the damage, produced by the disruptions of various energy has revealed that the depth of the vaporization erosion crater, calculated without taking into account the plasma shielding effect, overestimates the target damage by at least two orders of the magnitude, see fig. 4. The maximum erosion of the targets after this is ~4 μm. The next most damaging factor for the divertor targets is the surface melting and melt splashing. Neglecting the shielding in estimating the surface melt pool parameters leads to a rather high melt depth values up to ~0.6 mm for the disruption of 1.3 GJ. Simultaneously, the maximum melt area without shielding remains restricted to less than 60 m^2. The realistic estimation, accounting for the shielding, resulted in a quite different melt damage pattern: the maximum melt depth value is ~80 μm almost independent of the disruption energy, while the melt area maximum increases up to 2 times in comparison with the simulations without shielding. It is possible to explain this effect considering that the shield decreases heat flux to the SSP and redistributes this flux to other areas, thus decreasing the melt depth and increasing the melted area. The maximum melt pool area grows from ~20 m^2, for E_0=0.4 GJ, to ~120 m^2 for the maximal disruption energy of 1.3 GJ.

The total amount of tungsten, vaporized during the disruption varies from $2 \cdot 10^{21}$ to $3 \cdot 10^{24}$ atoms, for the disruptions of 0.4 and 1.3 GJ respectively. Corresponding estimations, performed without shielding, gives 2-4 orders of magnitude larger values. The summary of the results of the parametric study, including the comparison between the estimations done with and without the shielding, are given in Fig. 5.

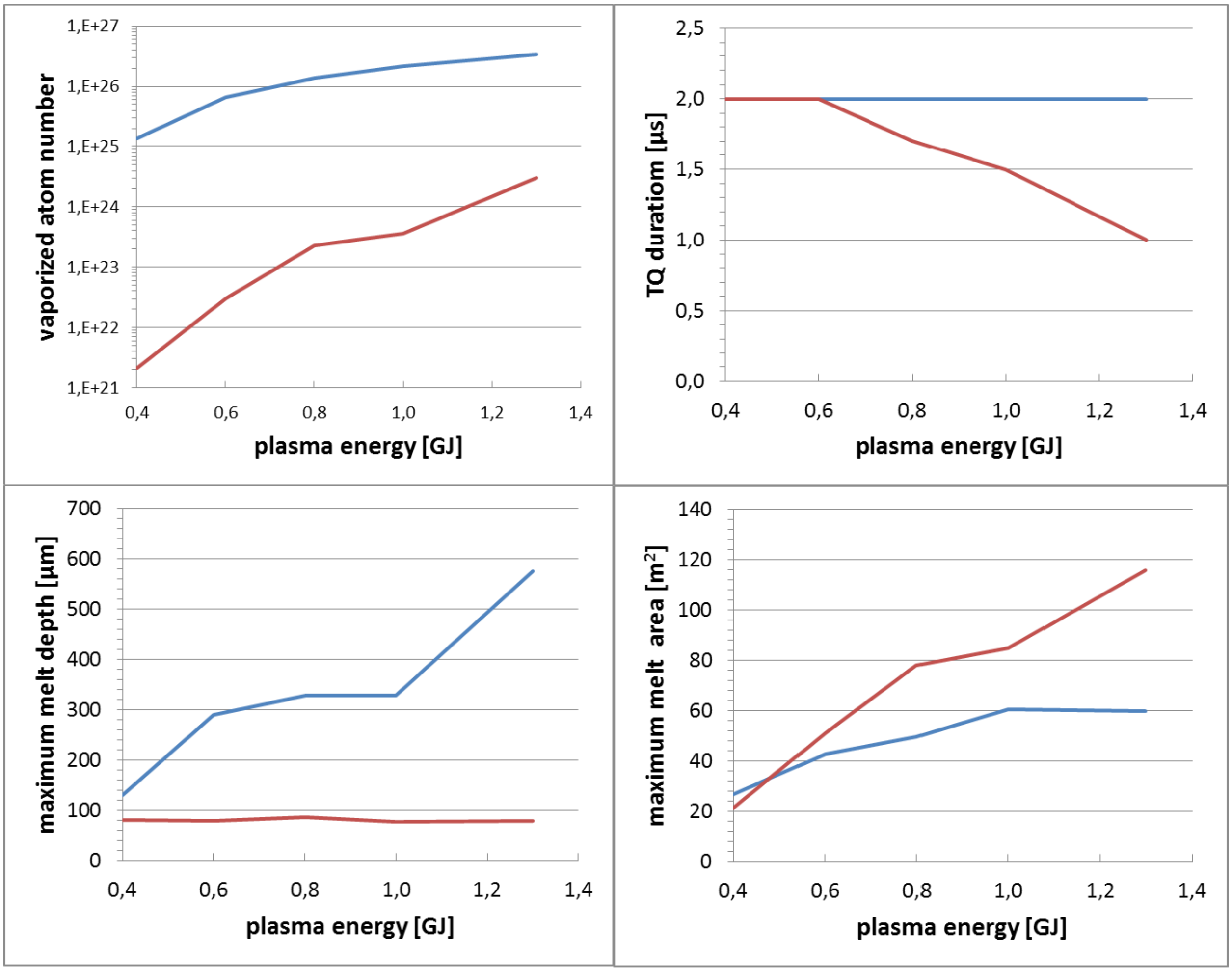

Fig. 5. Divertor target damage resulting from the parametric studies with disruptive core plasma energy.

The DEMO disruption parameters are extrapolated from modern tokamaks. This extrapolation is rather uncertain, because plasma energy content in DEMO is more than two orders of magnitude higher than that in modern tokamaks. Taking this fact into account, a special parametric study has been performed to reveal the TOKES results sensitivity to variations of the characteristic width λ_q for the disruptive heat flux inside the SOL. The results of this parametric study for the disruption of 0.8 GJ core energy are shown in Fig. 6. Variation of the λ_q in the interval from 0.5 cm to 2 cm has resulted in a small variation of the maximum melt depth and maximum melted area. The total amount of vaporized tungsten varies 2.5 times with variation of

λ_q, but this is also a small variation in comparison with the variation of this value of 3 orders of magnitude, which occurs with the variation of the core plasma energy in the investigated range.

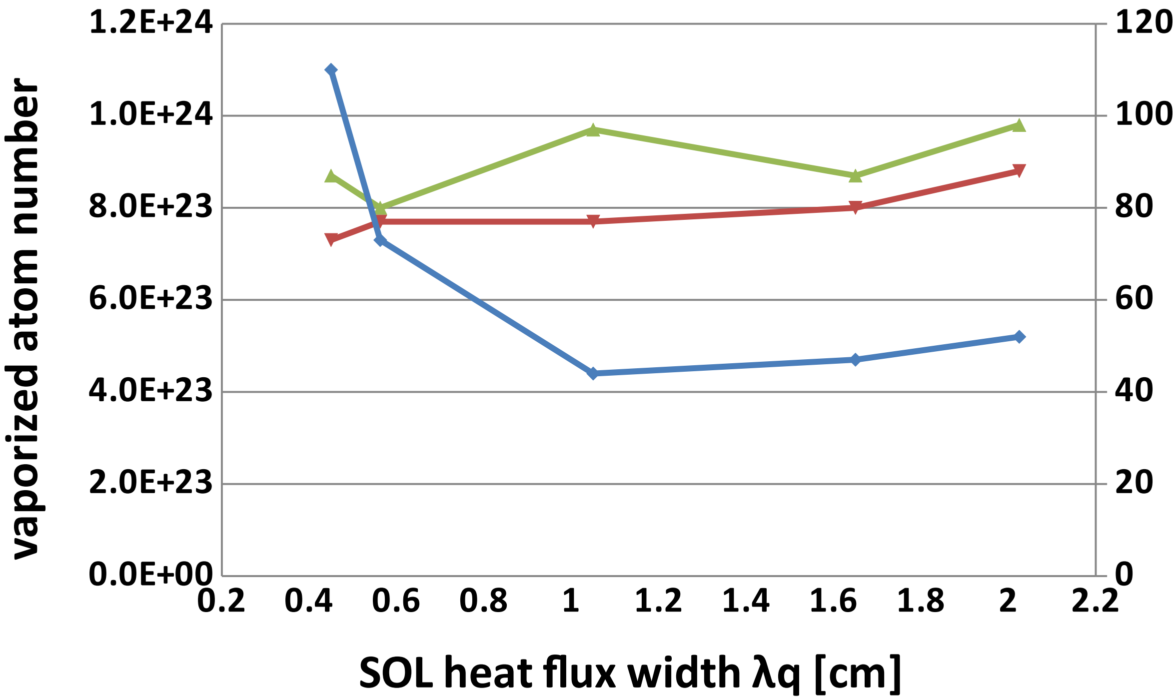

Fig. 6. TOKES results for DEMO disruption simulations with the core plasma energy of 0.8 GJ. Displayed in the figure are the dependences of the divertor target damage from the SOL heat flux characteristic width λ_q at the midplane. The left axis and blue curve correspond to vaporized W atom number, the red curve is the maximum melted area (m^2) and the green curve is the maximum melt depth (μm), both in the scale of the right axis.

4. Conclusions

The simulation of divertor target damage during thermal quench of the disruptions in the present DEMO tokamak design has been performed using the TOKES code. Intense disruptive heat flux to the target resulted in the target heating, melting and vaporization. The vaporized target material (tungsten) produces a W plasma shield in front of the vaporized surface, which protects the target surface from the rest of the incoming heat flux. The plasma shield is a complex, non-linear phenomenon, which drastically decreases the vaporization damage and the melting damage of the target. TOKES simulates the disruptive heat flux on the targets taking into account the plasma shielding. Special attention has been given to the comparison of the damages obtained with and without shielding. A parametric study includes the damage estimation for the disruptions of 0.4, 0.6, 0.8, 1.0 and 1.3 GJ of plasma energy in the DEMO core.

In all these simulation the TOKES parameters have been fitted to ensure the TQ time duration of 1-2 ms and a heat flux characteristic width of 1.5 cm at the outer midplane of the SOL. According to the simulations, the maximum melt depth on the divertor targets is ~80 μm independent of the energy content in the core, which illustrates the high nonlinearity of the shielding process. Corresponding estimations performed without shielding lies in the range of 120 – 600 μm, proportional to the core energy. On the contrary, the melted pool maximum area grows from ~20 m^2, for 0.4 GJ disruption to ~120 m^2, for the maximal disruption energy of 1.3 GJ. Corresponding estimation without shielding gives smaller values from 26 m^2 to 60 m^2.

Even more drastic difference has been found between estimations of vaporization erosion parameters with and without shielding. TOKES simulation with the shielding gives 4 μm maximum erosion depths for 1.3 GJ disruption; this value decreases to less than 1 μm with decreasing E_0. The estimation of the maximum erosion without shielding is 600 – 30 μm. The total amount of vaporized tungsten ranges from $2 \cdot 10^{21}$ to $3 \cdot 10^{24}$ atoms for disruptions of 0.4 – 1.3 GJ. Corresponding estimations, performed without shielding gives 2-4 orders of the magnitude more.

All these results show that the estimation of the disruptive target damage, performed without taking into account the plasma shielding, leads to results that are too conservative. Accounting of the shielding drastically reduces the estimation of the target damage.

It has to be noticed the relatively large heat flux and corresponding damage of the outer baffle top, which, in the considered design, is located very close to the separatrix (the magnetic surface which hits the top is only 2.2 cm from the separatrix at the midplane, where the heat flux width is 1.5 cm). Also the inclination angle between the magnetic field and the baffle surface is too large, and it will need to be smoothed out in the future more detailed design.

An Additional parametric study of the divertor target damage dependence of the characteristic widths of the disruptive heat flux in the SOL has revealed weak dependence of this parameter, at least in the interval $0.5 \text{ cm} < \lambda_q < 2 \text{ cm}$.

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