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ABSTRACT
A major concern for ITER operation in H-mode with high fusion gain is the occurrence of disruptions which can damage Plasma-Facing Components (PFCs) and therefore limit their lifetime. Moreover, Runaway Electrons (RE) can be generated and produce additional damage to the first wall. The closest experiments to study and verify numerical codes for ITER is JET ITER-like wall experiments with Be first wall and W divertor. Predictive numerical simulations of RE impact on the typical Be tiles are performed using the codes ENDEP and MEMOS. This work is focused on estimations of after effects of RE impact on the JET Be FW and determination of critical parameters of RE beams resulting in melting of Be tiles. Simulations predict that Be PFC melting can occur at relatively low current density of RE beam ranged between 2 and $12kA/m^2$.

1. INTRODUCTION
A major concern for ITER operation in H-mode with high fusion gain is the occurrence of disruptions which can damage plasma-facing components (PFCs) and therefore limit their lifetime. It is expected [1] that during several milliseconds of the disruption about 50 % of plasma energy can be dumped onto the First Wall (FW) during the so-called Thermal Quench (TQ). Moreover, runaway electron (RE) can be generated and further damage the FW [2,3]. To mitigate the transient heat loads to the first wall Massive Gas Rnjection (MGI) of noble gases or gas mixtures is proposed to be used prior to disruptions. However, MGI can in specific cases also cause the generation of RE during the MGI TQ, with following localized heat loads by RE impact.

During JET experiments with the graphite FW, the generation of a RE beam has been observed in MGI with Ar [2,3], which leads to hot spots formation at upper CFC plates with the temperatures of up to 1500^oC. Avoidance of RE production as well as disruption mitigation has been demonstrated with MGI using Ar/D_2 mixture with 10% Ar only. Since 2011 JET operates with the new ITER-like wall (ILW) with beryllium FW [4]. Formation of RE due accidently low density operation was observed, which leads to minor melting of poloidal Be limiter but didn't hamper the further operation with ILW. Experiments with massive gas injections are currently carried out at JET and no further RE production has been observed so far. During these experiments generation of RE with following impacts of RE beam at the Be tiles might occur but is still not observed [5].

Recent numerical simulations of beryllium armour damage by RE beam having exponentially decaying distribution function on energy **E** $(\mathbf{f(E)\sim exp\ (-E/E_0)})$ with $E_0 = 12.5MeV$) for ITER scenarios [6] using the Monte-Carlo code ENDEP [6,9] and the melt motion code MEMOS [10,11] demonstrated significant PFC damages due to surface melting and evaporation. Sparse numerical simulations of PFCs damage performed by runaway impact [6-9] demonstrated huge melting of the metallic PFCs of up to several millimeters depth. Melting and noticeable evaporation of the Be FW tiles can occur during the MGI experiments at JET with generation of the runaway electrons.

Numerical simulations of after effects of RE impact at the JET CFC FW were carried out using the codes ENDEP and MEMOS, and reasonable qualitative and quantitative agreements between simulation results and experiments at JET were demonstrated [6]. In this work we focus on estimations of consequences of RE impact on the JET Be FW using 2D and 3D versions of the codes ENDEP and MEMOS. Numerical simulations are performed including geometrical peculiarities of the Be tiles. The JET dedicated simulations are done for RE having exponentially decaying distribution functions on energy **E (f(E)~exp (−E/E$_0$)** with E_0 ranged between 3 and 8MeV. The RE beam energy density and the ratio of transversal electron energy to longitudinal energy in the magnetic field were varied. Detailed temperature evolution and spatial distributions over Be tiles as well as melting, evaporation damage are simulated for single Be tiles installed in JET. Melting thresholds are determined as function of heat load density, current density of runaway electron beam, and duration of RE beam impact τ ranged between 1 and 4 ms. Numerical simulation demonstrated that Be PFC melting can occur at relatively low current density (2-12 kA/m^2), which is significantly less in comparison with the current density of RE beam expected at JET (data listed in [2] for experiments with JET CFC FW). Calculated melt layer thickness is about several hundred microns with re-solidification time exceeding 20 ms.

2. PREDICTIVE MODELING OF RE IMPACT ON A SINGLE BE PFC IN JET

Simulations of impact of the runaway electrons at a single Be tile of the ILW in are divided by two steps. At the first step volumetric energy deposition functions are calculated using the Monte Carlo code ENDEP. The features of the Monte Carlo code ENDEP are described in [6]. At the second step the code MEMOS are applied for the calculations of temperature distributions inside the Be tile with taking into account temperature-dependent thermo-physical properties of Be.

Numerical simulations are carried out for the typical Be tiles installed at the upper dump plate in JET target (see Fig.1). Typical parameters used in these predictive simulations are based on the data measured in JET experiments with CFC FW [2]: typical REs current up to 0.5MA, beam radius of about 0.5m, (current density up to 0.6 MA/m$_2$), heat deposition time is about several ms. It can be expected that parameters of potential RE beams in the case of ILW will not significantly deviate from the parameters given above. The total wetted area is expected to be of 0.6m^2.

It is assumed that incident electrons will move along the toroidal magnetic field line rotating with the gyro frequency. Thus, the incident angle of the impacting electrons strongly depends on the gyro parameters and magnetic field direction (α angle between target surface and magnetic field lines, B = 3.0T). The gyro radius is determined by the ratio of electron kinetic energy across magnetic field and total electron kinetic energy. E_{tr}/E_e. Inclination angle of the toroidal magnetic field lines (B = 3T) to the plane is about α~3° , (β~20°) so inclination angle to the target surface field lines γ~20° (Fig.1). A set of simulations are carried out for $E_{tr}/E_e = 0$ (electrons move along magnetic field lines without rotations), and $E_{tr}/E_e = 0.02$ with variation of the exponentially decaying RE distribution E_0: 3, 5, 8MeV (the range of REs energies expected in JET – 1-10MeV). Moreover, the simulations are performed for two scenarios of width of wetted area along the tile surface L=1 cm (D = 3mm) and L = 0.5cmm (D = 1.5mm). Parametric MEMOS simulations are performed for scenarios with rectangular time shape and pulse durations τ = 1, 2, 3, and 4 ms for different heat load fluxes of runaway electron beam in the range of W ~ 0.5–6MW/cm^2.

In the case of $E_{tr}/E_e = 0$ with L=1 cm, the impacting energy is deposited rather uniformly inside the Be tile (see Fig.2) and about 40% of impacting energy are passes through the tile with escaping primary and secondary electrons. The RE current density drops by 35% as shown in Fig.2 and Table 1. In the table and figures the quantities are abbreviated as Q_0 – total energy of impacting RE beam at the surface, Q_{abs} – total energy absorbed in the tile, N_0 – total number of impacting electrons at the surface, N_{ph} – total number of X-ray photons escaping from the tile surface, N_e – total number of electrons escaping from the tile surface. With increase of the ratio E_{tr}/E_e more electrons passes through the tile and for case $E_{tr}/E_e = 0.02$ less than 40% of impacting energy absorbed in the tile and the RE current density drops less than 26% . Reduction of the wetted area by a factor 2 (L = 0.5cm) leads to a drop of the absorbed energy and increase of the number of runaway electrons passed through the tile. Efficiency of X-ray generation in all simulated scenarios is rather low (see Table 1) and about 0.4 % of impacting energy is irradiated by bremsstrahlung.

In the MEMOS simulations the single Be tile is heated by RE beam using calculated energy deposition functions as input data. MEMOS simulations are performed for scenarios with rectangular time shape and pulse durations τ = 1, 2, 3, and 4 ms for different heat load fluxes of runaway electron beam in the range of W ~ 0.5- 6 MW/cm2.

In Fig.3 typical temperature distributions inside the Be tile at the end of the RE impact are demonstrated for two scenarios. Dependences of the maximum surface temperature versus heat load density are shown in Fig.4 for different scenarios of the RE impact. The same dependences of the maximum surface temperature versus density of RE current are shown in Fig. 5. Density of RE current j and heat load density W are connected by the following expression $j = W/(q\langle E\rangle)$ with q - electron charge, $\langle E\rangle$ - mean energy of runaway electrons in the beam. Such dependences allow us to determine the melting thresholds for all calculated scenarios. The melting threshold in the current density of RE beams depends on the pulse duration as $1/\tau$ (Fig.6). Calculated values of the melting threshold (ranged between 2 and 12 kA/m^2) is much less than the expected in JET current density of runaway electrons [2] (up to 500 kA/m^2). Small increase of the RE beam current density above melting thresholds by 10-20% results in the Be melting up to several hundred microns with rather long re-solidification time (>20ms) (See Fig.7). Predictive simulations demonstrate that with taking into account expected wetted area of 0.6 m^2 the RE current of 10 kA can produce melt layer of 500 microns thickness at the Be tiles of the upper dump plates in JET.

CONCLUSIONS

Predictive numerical simulations of RE impact on the typical JET Be tiles are performed for JET ILW aiming estimations of after effect of RE impact. The Monte Carlo code ENDEP and the code MEMOS are used.

The current densities of RE beam causing melting of Be tiles (melting thresholds) are determined for different potential scenarios of REs heat loads and ranged between 2 and 12kA/m^2. Small increase of the RE beam current density above melting thresholds by 10-20% results in the Be melting up to several hundred microns with rather long resolidification time (>20 ms).

Further comprehensive 2D and 3D ENDEP and MEMOS simulations should be carried out to predict melt damage to Be plates for different mechanisms, such as VDEs, of heat loads, which might in JET.

ACKNOWLEDGEMENT
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E_0 (MeV)	L(cm)	E_{tr}/E	Q_{abs}/Q_0	N_{ph}/N_0 (photons)	N_e/N_0 (electrons)
3	1	0	0.59	0.025	0.64
5	1	0	0.60	0.03	0.65
8	1	0	0.57	0.03	0.66
3	0.5	0	0.48	0.024	0.70
5	0.5	0	0.44	0.026	0.75
8	0.5	0	0.41	0.028	0.78
5	1	0	0.60	0.03	0.65
5	1	0.02	0.39	0.025	0.74

Table 1:

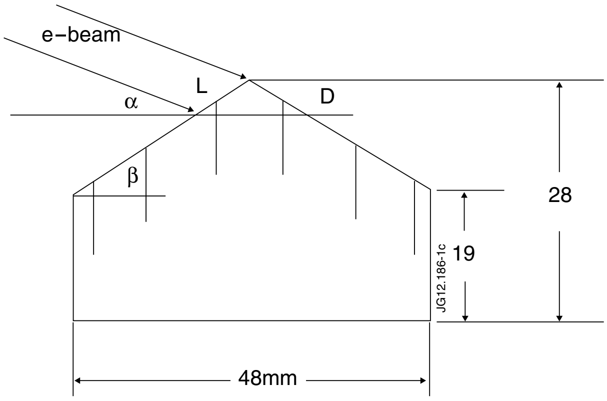

Figure 1: Sketch of typical Be tile installed in upper dump plate in JET ILW.

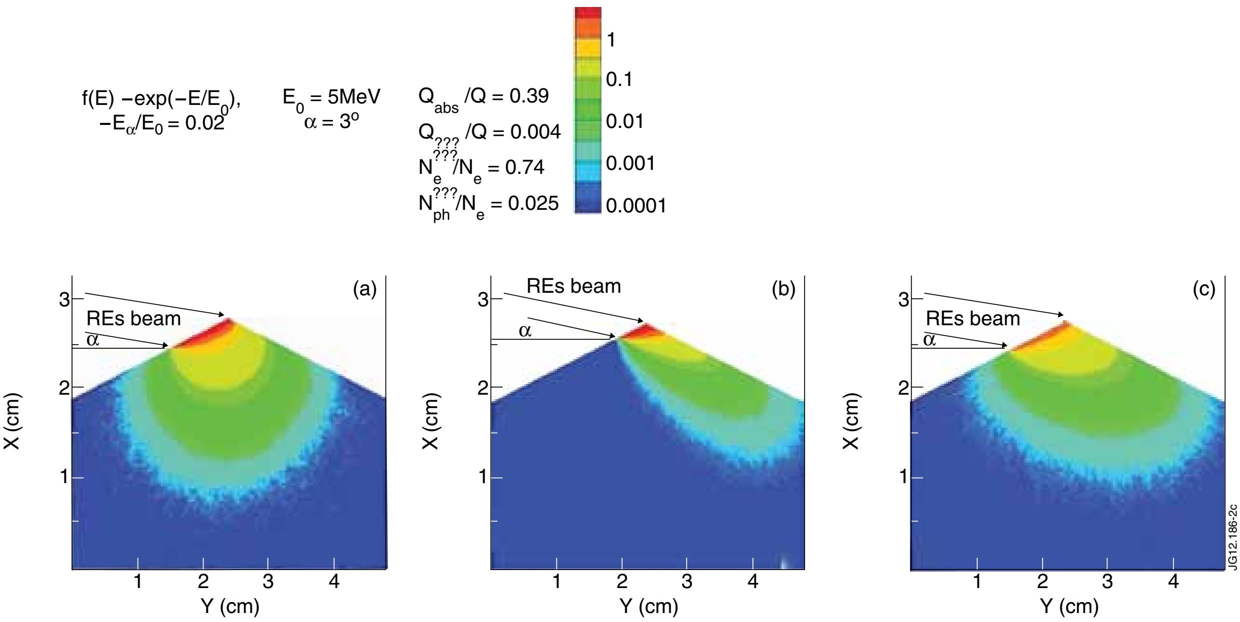

Figure 2: Normalized function of absorbed energy inside the Be tile. a) L = 1cm (D=3.4mm), $E_{tr}/E = 0$; b) L = 0.5 cm (D = 1.7mm), $E_{tr}/E = 0$; c) L = 1cm (D = 3.4mm), $E_{tr}/E=0.02$.

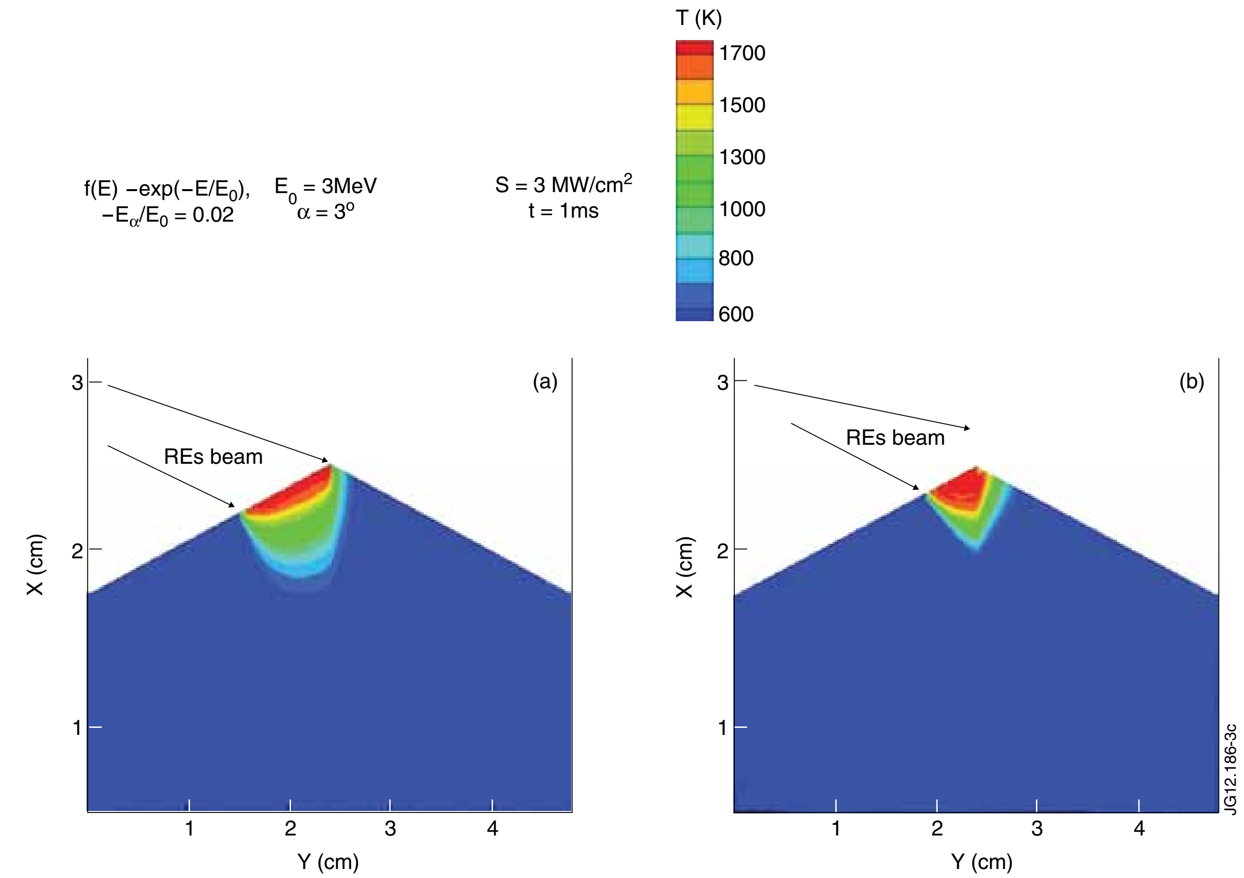

Figure 3: Typical temperature field inside the Be tile for two REs load scenarios. Time moment 1 ms corresponds to the end of pulse. a) L = 1cm (D = 3.4mm), $E_{tr}/E = 0$; b) L = 0.5cm (D = 1.7mm), $E_{tr}/E = 0$.

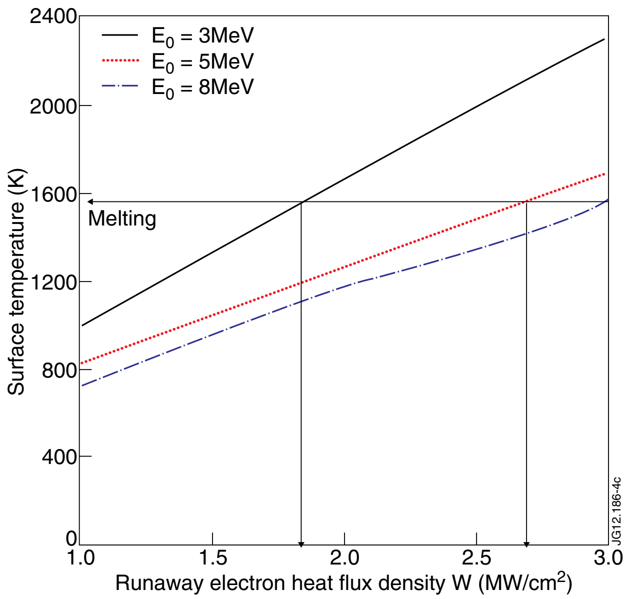

Figure 4: Dependencies of maximum Be surface temperature on density of REs heat flux W for different scenarios.

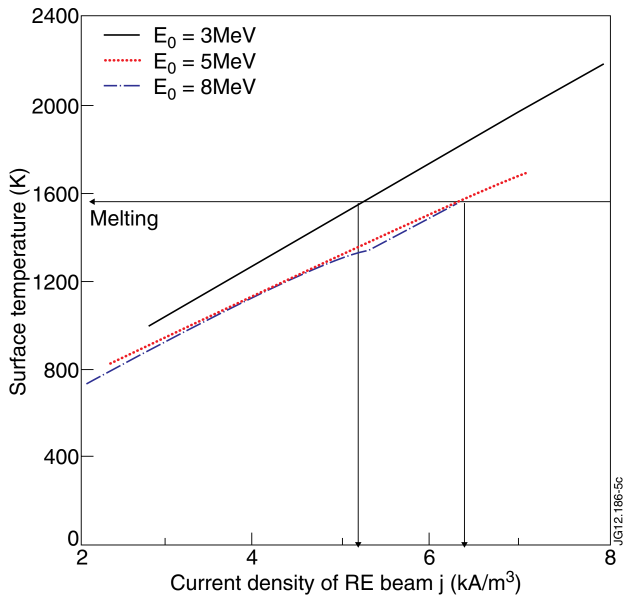

Figure 5: Dependencies of maximum Be surface temperature on current density of REs beam j for different scenarios.

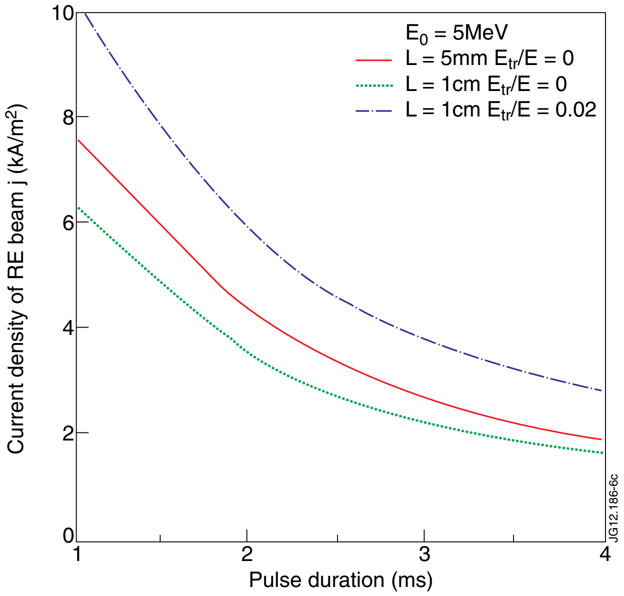

Figure 6: Dependence of current density of REs beam corresponding to the melting thresholdon pulse duration for scenarios with $E_0 = 5MeV$.

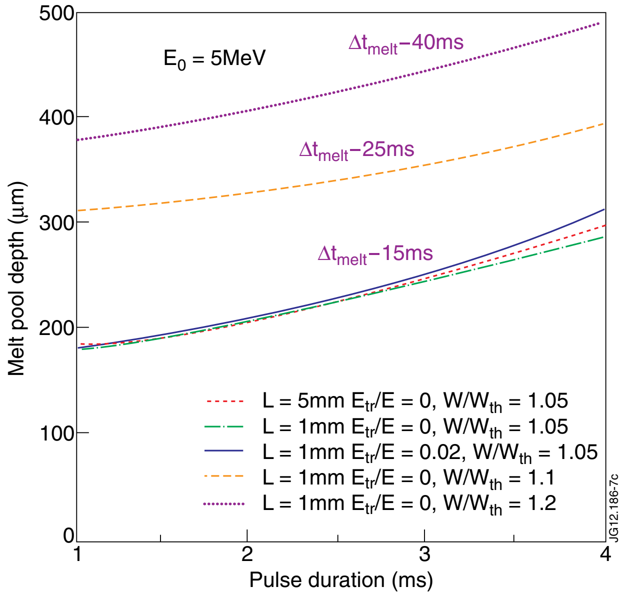

Figure 7: Dependence of maximum of melt pool depth on pulse duration for scenarios with $E_0 = 5MeV$ and different heat loads exceeding the melting thresholds W_{th}.