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B. Bazylev, G. Arnoux, W. Fundamenski, Yu. Igitkhanov, M. Lehnen
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B. Bazylev[1], G. Arnoux[2], W. Fundamenski[3], Yu. Igitkhanov[1], M. Lehnen[3]
and JET EFDA contributors*

JET-EFDA, Culham Science Centre, OX14 3DB, Abingdon, UK

[1]Karlsruhe Institute of Technology, P.O.Box 3640, D-76021 Karlsruhe, Germany
[2]EURATOM/CCFE Association, Culham Science Centre, Abingdon, Oxon, OX14 3DB, UK
[3]Institut für Energieforschung - Plasmaphysik, Forschungzentrum Jülich, Trilateral Euregio Cluster,EURATOM-Assoziation, D-52425 Jülich, Germany
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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 further damage the first wall. Numerical simulations of consequence of RE impact at the PFCs are carried out for JET and ITER conditions. This work is focus on the benchmark of the codes (ENDEP and MEMOS) used for predictive modeling for ITER with experimental observations of RE beams in JET. Reasonable qualitative and quantitative agreements between numerical simulations and experiments at JET are demonstrated. Numerical simulation carried out for Be first wall demonstrated that mechanism of the surface evaporation significantly influence on melt layer thickness for metallic PFCs under RE impact.

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 miliseconds of the disruption more than 50% of plasma energy is dumped onto the first wall during the socalled Thermal Quench (TQ). Moreover, Runaway Electron (RE) can be generated and further damage the first wall. To mitigate the transient heat loads to the first wall Massive Gas Injection (MGI) of noble gas is proposed to be used prior to disruptions. However, MGI can in specific cases also cause the generation of Runaway Electrons (RE) during the MGI TQ, with following localized heat loads by RE impact. For instance at JET, the generation of a RE beam has been observed in MGI with Ar, but not with other noble gases or gas mixtures with deuterium [2]. In case of MGI with Ar and generation of RE beam an increase the temperature of upper CFC plates up to 1500^{o}C was detected. The last experimental results on RE–FW interactions observed in MGI at JET are presented in [3]. Sparse numerical simulations of PFCs damage performed using runaway impact parameters [4-6] demonstrated huge melting of the metallic PFCs of up to several millimeters depth. Unfortunately, such important process as material vaporization from the armour surface was not taken into account. Vaporization neglecting can lead to essential overestimation of the melting depth. Recent numerical simulations of beryllium armour damage by monoenergetic RE beam (with electron energy E = 15MeV) for ITER using the Monte-Carlo code ENDEP and the melt motion code MEMOS [7] demonstrated significant PFC damages due to surface melting and evaporation. These simulations were carried out for the monoenergetic RE beams of different relativistic electron energies. However, simulations of the PFCs damage using monoenergetic RE beams inadequately describe this phenomena because the exponential distribution of RE on energy ($f(E) \sim \exp(-E/E_0)$) was observed in experiments.

In this work we focus on the benchmark of codes used for predictive modeling for ITER with experimental observations of RE beams in JET. For clarification of consequences of RE impact on the JET first wall and parameters of RE beams during MGI the numerical simulations are performed including most important peculiarities of the JET first wall using the codes ENDEP [7] and MEMOS

[8-9]. The JET dedicated simulations were done for different RE distribution functions on energy E focusing on exponentially decaying distribution ($f(E) \sim \exp(-E/E_0)$, $E_0 = 5, 8, 10$MeV). The RE beam energy density and the ratio of transversal electron energy (E_{tr}) to longitudinal Energy (E) in the magnetic field were varied in wide ranges. Detailed temperature evolution and spatial distributions over CFC tiles installed in JET during the RE impact were simulated.

The calculated temperature and cooling rate of the areas heated by RE as functions of heat load density are compared with the experimental data showing good qualitative and quantitative agreement. This allowed adequate predictive simulations aiming at consequences of RE impact on the Be first wall and the clarification of tolerable RE beams parameters during MGI in ITER. Those simulations are done for exponentially decaying RE distribution ($f(E) \sim\sim \exp(-E/E_0)$, E_0=12,5 MeV) RE and the expected energy loads.

2. NUMERICAL SIMULATIONS OF RUNAWAY ELECTRONS IMPACT FOR JET EXPERIMENTS.

Simulations of impact of the runaway electrons generated during MGI experiments at JET at the CFC first wall are divided by two steps. At the first step volumetric energy deposition functions are calculated using the Monte Carlo code ENDEP. At the second step the code MEMOS are applied for the calculations of temperature distributions inside the CFC target with taking into account temperature-dependent thermo-physical properties of the CFC.

The Monte Carlo model describing propagation of relativistic particles inside materials is based mainly on the pair collisions approximation. Long distance electronelectron interactions are taken into account statistically in frame of multiple-scattering model. The following processes are included in the Monte Carlo model: 1) electron-electron scattering, 2) electron-electron collisions (long distance), 3) electron-nuclear scattering, 4) Bremsstrahlung, 5) Compton scattering, 6) Auge processes, 7) photo ionization & recombination, 8) electron-positron interactions, 9) electron & photon avalanche simulations. Most features of the Monte Carlo model are described in detail in [10]. The density effect correction; which reduces the effectiveness of the long distant collisions due to polarization of the material [11] is also taken into account.

Numerical simulations are carried out for the sandwich target design: 2cm CFC layer at the top of target and 1cm Cu layer at the target bottom. It is assumed that incident electrons move along the toroidal magnetic field line rotating with the Larmor frequency. Thus an incident angle of the impacting electrons strongly depends on the Larmor parameters and magnetic field direction (α angle between target surface and magnetic field lines, B = 3.5 T). The Larmor radius is determined by the ratio of electron kinetic energy across magnetic field and total electron kinetic energy. E_{tr}/E_e . Simulations are carried out for $\alpha = 5$ and 10 degree, set of the $E_{tr} / E_e = 0, 0.05$, and for the exponentially decaying RE distribution with $E_0 = 5, 8, 10$MeV (the range of RAEs energies expected in JET – 3-30MeV).

For the parallel electron impact $E_{tr} /E_e = 0$ with $\alpha = 5$ impacting energy is mostly deposited near

the surface (see Fig.1) and less than 20% of impacting energy are reflected with escaping primary and secondary electrons. With increasing of the ratio E_{tr} / E_e electrons penetrate deeper and deeper, electron reflection drops down, and energy deposition function becomes more slopping. The energy deposition functions is very smooth for parallel impact and rather large inclination angle $\alpha = 10$. More than 80% of the incoming energy is absorbed in the target for all calculated scenarios. Calculated energy deposition functions are used as input parameters in the code MEMOS for further simulations.

In the MEMOS simulations the CFC target is heated with by RE beam having the Gaussian spatial profile of the energy deposition with the half-width H_w=10 cm and the ebeam width of 10 cm. The heat load ranged between Q= 0.5 MJ/m^2 and Q= 3.5 MJ/m^2 with τ = 0.2 ms, rectangular t-shape, and initial target temperature of 500^o K are assumed. Heat conductivity coefficient is approximated by the expression: $\kappa = 4.8 + 136.4/(1 + T/300)$, which gives κ = 73Wm/K at 0^{o}C, and κ = 42Wm/K at 500^{o}C.

Dependences of the maximum surface temperature versus heat load density are shown in Fig. 2 for different scenarios of the RE impact. Parallel impact of RE with $\alpha = 5$ gives maximal increase of the surface temperature. Dependences of the surface temperature and the cooling rate (dT/dt) on time for the scenario with parallel impact of RE under $\alpha = 5$ (Figs 3,4) most closely correspond to the experimental results obtained at JET (Fig. 2 [3]). The cooling rate during first 10ms estimated from the experimental data is about 10–20K/ms, which is in good agreement with simulated one for this scenario. To compare in more detail results of the simulations with the data obtained at the JET experiments the dependence of surface temperature on heat loads has to be transformed to the dependence of surface temperature on RE current. To do this transformation it is assumed, that RE electrons produce ohmic heating of CFC target of surface area about S ~ 0.03m^2. Dependence obtained in experiments $\Delta T \propto AI^{1.96}$ (Fig. 3 [3]) confirms this assumption. Assuming that the electric conductivity of CFC is obtained from Wiedemann- Franz-Law and is about $R \sim 1.8 \cdot 10^{-9}$ ohm for RE the penetration length into graphite target $\Delta \sim 0.2$mm and $R \sim 1.3 \cdot 10^{-9}$ ohm for $\Delta \sim 0.15$mm, one can estimate the value of ohmic current, I (Q) in the target which corresponds to the heat load due to RE impact, QMJ/m^2:

$$I(\Delta T) \approx \sqrt{\frac{Q(\Delta T) \cdot R}{\tau \cdot R}}$$

Dependence of I (ΔT) is plotted in the Fig.5 for two cases of different resistivity corresponding to different penetration lengths mentioned above. Comparison shows a reasonable qualitative and reasonable quantitative agreement with experiment (Fig.3. [3]).

3. NUMERICAL SIMULATIONS OF BE ARMOUR DAMAGE UNDER RAES IMPACT.

To estimate consequence of RE impact on Be FW for the expected ITER conditions the following numerical simulations are carried out for the sandwich target design: 1cm Be layer at the top of target and 1cm Cu layer at the target bottom. It is assumed that incident electrons move along the

toroidal magnetic field line (B = 5T) rotating with the Larmor frequency. Simulations are carried out for $\alpha = 1.5$ degree, set of the $E_{tr}/E_e = 0, 0.05$, and for the exponentially decaying RE distribution with $E_0 = 12.5$MeV (the range of RE energies expected in ITER – 1–50 MeV).

In case of the parallel electron impact $E_{tr} / E_e = 0$ impacting energy is mostly deposited near the surface (see Fig. 6) and less than 45% of impacting energy are reflected with escaping primary and secondary electrons. Increasing of the ratio Etr / Ee electrons leads to larger penetrate depth, electron reflection drops down, and energy deposition function becomes more slopping.

Numerical simulations of the Be armour damage caused by the RE action are carried out for the Be bulk armour. The Be target is heated with by RAEs beam having the Gaussian spatial profile of the energy deposition with the half-width $H_w = 10$cm and the ebeam width of 5cm. The heat load ranged between $Q = 5$MJ/m^2 and $Q = 40$MJ/m^2 with $\tau = 10$ms, rectangular t-shape and initial target temperature of 500^o K are assumed.

Numerical simulations demonstrate that impacting RE heat the targets and for the most investigated here scenarios temperature significantly exceeds the melting temperature, the maximum surface temperature exceeds 2000K at the armour surface. Due to so high temperature of the melted material huge evaporation of the Be occurs. A lot of the absorbed energy is going for evaporation. Due to this fact much less energy spends to the melting and therefore the final depth of melting pool slightly exceeds 1 mm for Q>35 MJ/m^2 scenarios (see Fig.7). Melting threshold corresponds to Q> 5MJ/m$^{2.}$ Significant evaporations starts for heat loads Q>12MJ/m^2 and evaporation depth reaches about 47μm for heat load $Q = 40$ MJ/m^2. Melt layer exist rather long time up to 0.2s, that is very dangerous because of melt layer instability causing splashing.

CONCLUSIONS

Numerical simulations of consequence of RE impact at the PFCs are carried out for JET and ITER conditions using the Monte Carlo code ENDEP and the code MEMOS. This work is focus on the benchmark of the codes used for predictive modeling for ITER with experimental observations of RE beams in JET. Reasonable qualitative and quantitative agreements between numerical simulations and experiments at JET are demonstrated. Numerical simulations of Be armour damage under the runaway electron heat loads are carried out. Numerical simulation demonstrated that mechanism of the surface evaporation significantly decreases the melting by several times that is more favorable for ITER FW armour.

ACKNOWLEDGEMENT:

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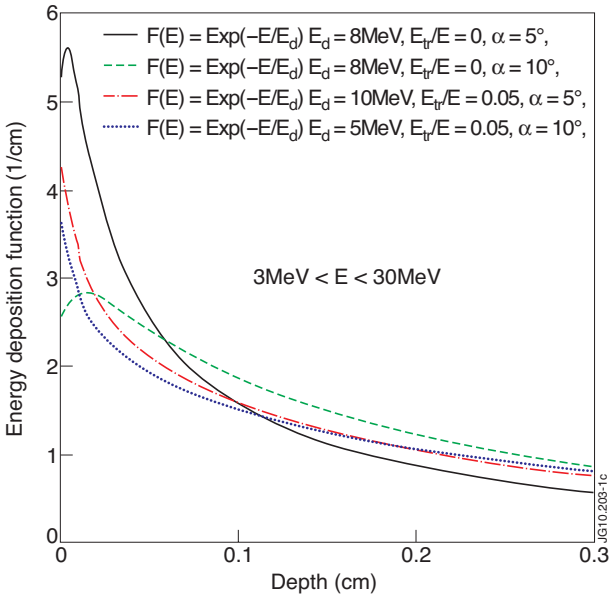

Figure 1: Runaway electron energy deposition function inside CFC/Cu JET armor for different scenarios of energy ratio E_{tr}/E, field inclination angle, and exponential distributions of RE on energy ($f(E) \sim \exp(-E/E_0)$)

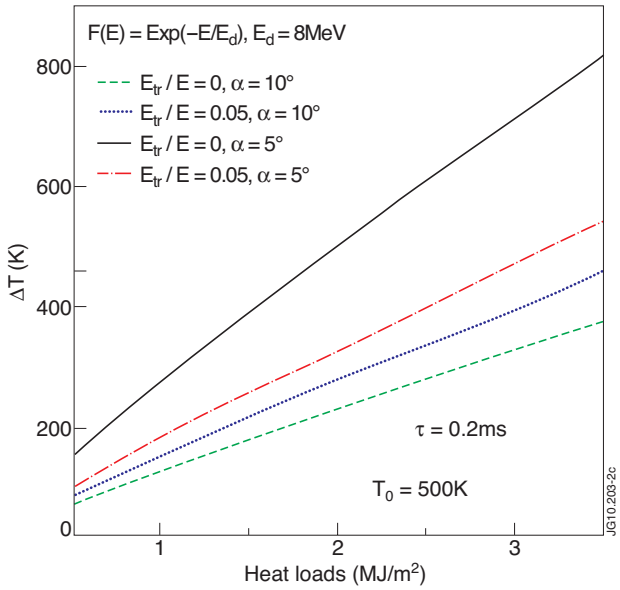

Figure 2: Dependence of surface temperature rise at the center of RE impact spot as function heat loads for different scenarios of RE impact.

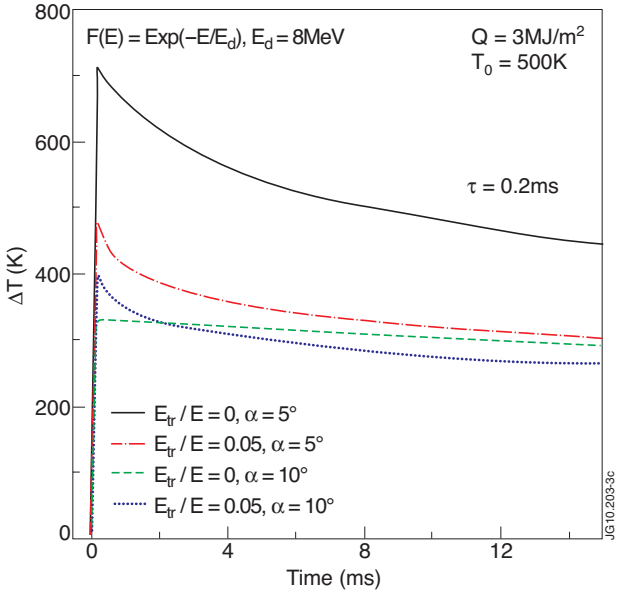

Figure 3: Dependence of surface temperature at the center of RE impact spot as function of time for different scenarios of RE impact.

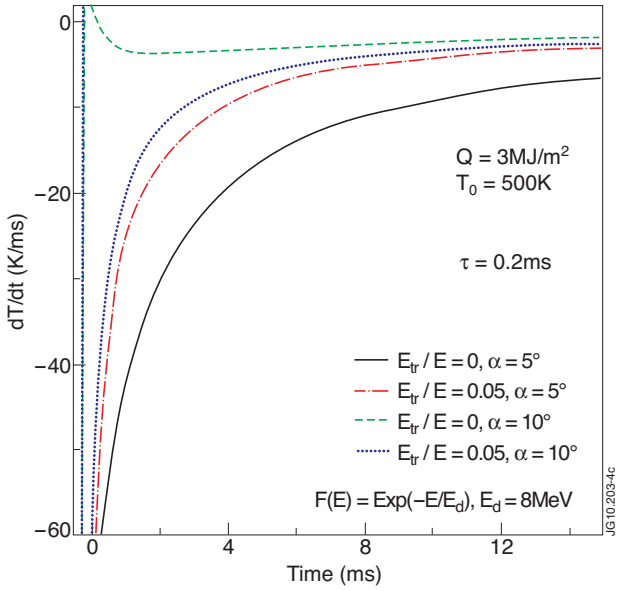

Figure 4: Dependence of the cooling rate (dT/dt) at the center of RE impact spot as function of time for different scenarios of RE impact.

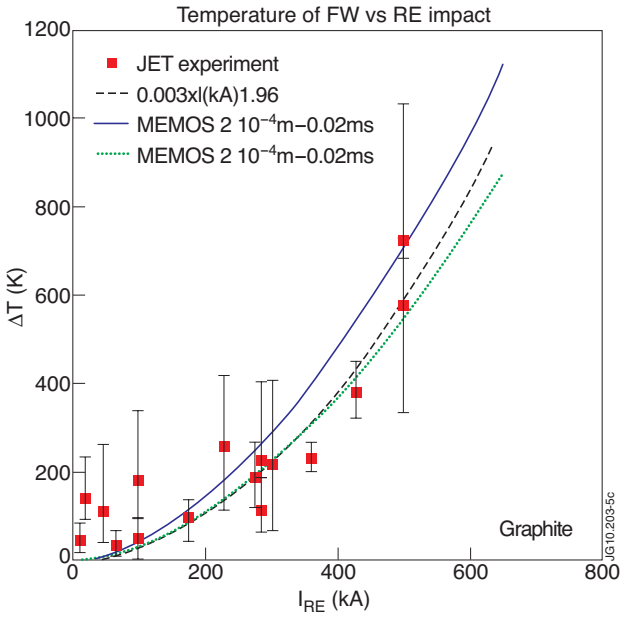

Figure 5: Average energy increase measured on the JET FW due to RE impact as a function of the RE current - read squares; dashed curve is fit; the blue and green curves correspond the MEMOS results, shown on Fig.3 and for two values of penetration depth of 0.2 and 0.15mm.

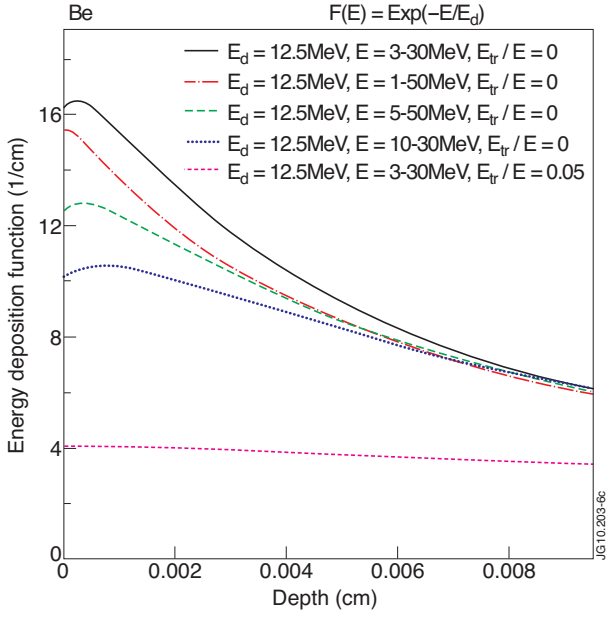

Figure 6: Runaway electron energy deposition function inside Be/Cu ITER-like armor for different scenarios of energy ratio Etr/E, field inclination angle, and exponential distributions of RE on energy ($f(E) \sim \exp(-E/E_0)$)

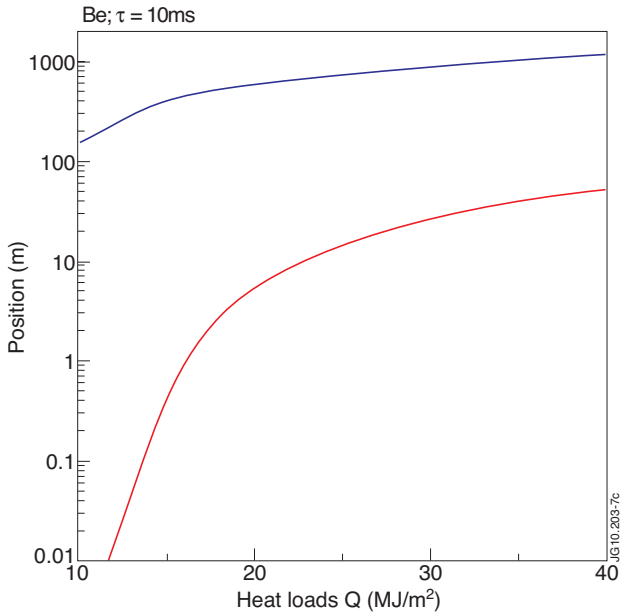

Figure 7: Damage of Be and bulk target caused by runaway electrons beam: melt pool and evaporation depths as function of heat loads. Reference scenario E_0 = 12.5MeV, α = 1.5 degree, parallel impact.