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Dust production in ITER-FEAT off normal events and target screening by dust particles

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1. Introduction

In CBMs thermal stress due to pulsed heat loads results in breaking of lattice bonds. As consequence of intense cracking macroscopic layers are destroyed [1] and dust is produced [2]. Once dust particles are emitted their motion in the evolving plasma shield due to drag forces imposed by the surrounding plasma shield and the reduction of radiative energy transfer due to the moving dust cloud have to be modelled.

This paper discusses brittle destruction of vertical graphite targets during thermal disruptions and of FWs during RAE impact. The model used in the numerical simulation of brittle destruction is discussed and where available experimental results from simulation facilities are compared with numerical results. Moreover first results from a 2D numerical simulation of the two fluid problem of evolution of the plasma shield and the dust cloud with FOREV-2 are discussed as a first step to a consistent modelling of macroscopic erosion.

2. Brittle destruction of graphite

The estimations on brittle destruction of graphite as discussed here are based on a phenomenological approach using a threshold energy value for onset of brittle destruction. From e-beam experiments with volumetric energy deposition this value was determined to be 10 kJ/g [3]. Hot plasma impact results in surface heating RAE impact in volumetric target heating. This is calculated by Monte Carlo [4]. The evolution of surface temperature and of profiles of temperature and accumulated specific energy in the bulk are calculated by solution of the 2D heat conductivity equation [5].

2.1 Simulation experiments

Fig. 1 shows a comparison of measured and calculated total mass loss (evaporation and brittle destruction) for CFC graphite for the JEBIS facility with perpendicular impact of 70 keV electrons of peak target heat load of 1.8 GW/m^2 and 2 ms pulse duration. Included in Fig. 1 is the calculated mass loss due to brittle destruction. A mass loss of 1 mg corresponds to an erosion depth of 65 microns. The size of the dust particles typically is a few microns.

In plasma gun experiments with surface energy deposition peak power densities up to 350 GW/m^2 were used to initiate and investigate brittle destruction in pyrolytic graphite targets with perpendicular impact of the hot plasma [6]. The total erosion was 0.4 µm. Dust particles have been detected. However the fraction of eroded material due to brittle destruction is unknown. The calculated total and macroscopic erosion as function of the damage threshold value is shown in Fig. 2a. When comparing with the experimental erosion value of 0.4 µm it is concluded that for surface energy deposition the same damage threshold value of 10 kJ/g can be applied for virgin graphite. Fig. 2b shows the relation between the damage threshold energy and the surface temperature of graphite. The total external pressure from the impacting plasma and the plasma shield is about 20 bar resulting in considerable overheating of surface near graphite layers as seen from Fig. 2c showing the calculated time evolution of the surface temperature of a graphite target in such plasma gun experiments.

2.2 Tokamak conditions

Numerical results on total erosion and brittle destruction under RAE impact of energy density of 50 MJ/m^2, impact energy of 15 MeV and inclination angle of 1^o are shown in Fig. 3 for CFC graphite for different target heat loads and different damage threshold values. For 0.5 GW/m^2 the specific energy within 100 ms remains below 9 kJ/g. There is occurring only evaporation. Reducing the damage threshold value to 8 kJ/g increases brittle destruction considerably and evaporation drops down to 10 microns. Now brittle destruction also occurs for 0.5 GW/m^2.

Fig. 4 shows calculated preliminary brittle destruction values for vertical graphite targets under hot plasma impact for two different peak target heat loads as function of the damage threshold energy value. For peak target heat loads up to 30 GW/m^2 brittle destruction is occurring only for damage threshold values below 8.5 kJ/g. The error bars indicate the influence of the radiation energy transfer through the dust cloud region with two different absorption coefficients for radiation calculated from the estimated particle density and the cloud size. The target screening by the dust cloud still needs a consistent modelling. Predamaging of graphite with moderate crack formation might have been occurred during preceding off normal events. Brittle destruction then finally might develop in the predamaged sample for damage threshold values well below 10 kJ/g what might result in considerable macroscopic erosion.

3. Target screening by dust particles

For numerical simulation of dust particle behaviour in a plasma shield and evaluation of macroscopic erosion the 2D multifluid code FOREV-2 is used [7]. A horizontal graphite target and a peak target heat load of 100 GW/m^2 were assumed. The plasma shield motion and plasma densities in the poloidal plane are shown in Fig. 5 without dust particles. The plasma shield moves along the target surface away from the separatrix strike point (SSP) thus depleting the shielding there. In case of dust particles it is assumed that the target is covered with particles of characteristic size of 1 μm. Levitation is assumed to occur at vaporization temperature. The particles start with a velocity of 10^4 cm/s perpendicular to the target.

Due to the stochastic nature of particle levitation it is assumed that the first mesh is homogeneously filled with particles. The particle transport is calculated in the hydrodynamic approximation treating the dust as a gas with density equal to the number of particles per unit volume and gas velocity equal to the mean particle velocity. The equations for particle transport are

$$\frac{\partial N_d}{\partial t} + \mathbf{div}\left(N_d V_d\right) = 0$$

$$\frac{\partial V_d}{\partial t} = \frac{F_{drag}}{M_d}$$

with N_d the density of particles, $\mathbf{V_d}$ their mean velocity, $\mathbf{F_{drag}}$ a drag force and M_d the particle mass. For numerical solution of the particle motion the same technique is applied as for the motion of the plasma shield [7]. The drag force $\mathbf{F_{drag}}$ imposed by the surrounding plasma shield ions is obtained from a kinetic approach by integration of the momentum transfer of the plasma shield ions resulting in

$$\mathbf{F_{drag}} = C\rho_{pl} V_{thi}\, \Delta \mathbf{V}\, S_d$$

with ρ_{pl} the plasma density, V_{thi} the thermal velocity of the plasma shield ions $\Delta\mathbf{V} = \mathbf{V_{plasma}} - \mathbf{V_d}$ the relative velocity between particles and ions, S_d the cross section of the particles and C a coefficient of order 1 depending on the shape of the particles. For calculation of $\mathbf{F_{drag}}$ it is assumed that the ions impinge on the rear and front side surfaces of the particles with a Maxwellian shifted by $\pm\Delta\mathbf{V}$. Fig. 6 shows the calculated motion pattern of the dust particles together with the evolving plasma shield. Evaporation of dust particles is taken into account. It is assumed that all radiative energy transferred to the particles is spent for vaporization. The vaporized mass contributes to the plasma shield. In this first simulation it is assumed that the radiative energy transfer from the plasma shield to the target is not influenced by the dust particles resulting in an underestimation of the target screening by the particles.

4. Conclusions

Brittle destruction of graphite under RAE impact produces rather large amounts of dust. Graphite as FW material thus would cause safety problems. Brittle destruction of vertical graphite targets under hot plasma impact could be of concern if fatigue effects would reduce the damage threshold which was determined for volumetric energy deposition. Occurrence of predamaging effects resulting in reduced damage threshold values and increased brittle destruction of graphite still needs to be investigated experimentally and theoretically. First 2D numerical simulations of the two fluid problem of evolution of plasma shield and dust cloud were performed with the aim to arrive at a consistent modelling of macroscopic erosion and of erosion of targets covered by layers of dust.

5. References

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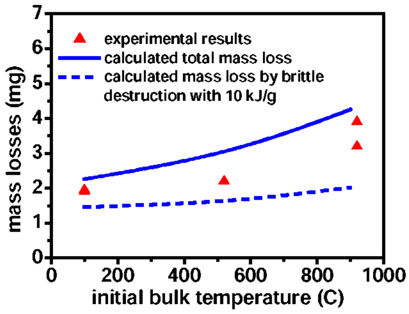

Fig.1. Total mass loss for CFC graphite for JEBIS conditions with 70 keV e-beam, pulse duration 2 ms, absorbed heat flux 1.8 GW/m^2.

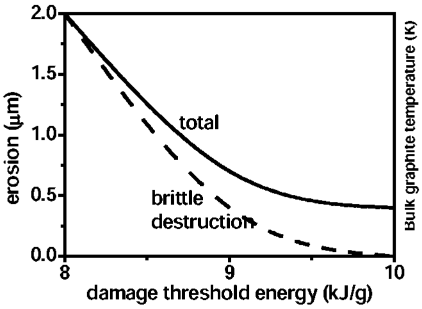

Fig.2a. Calculated erosion for perpendicular pyrolytic graphite targets for MK-200 UG gun facility.

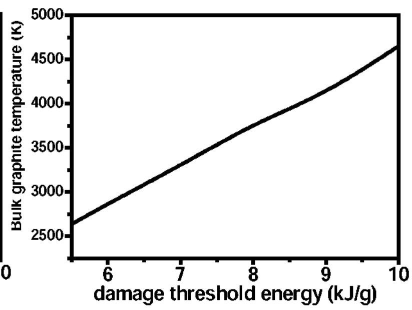

Fig.2b. Damage threshold energy and related bulk graphite temperature.

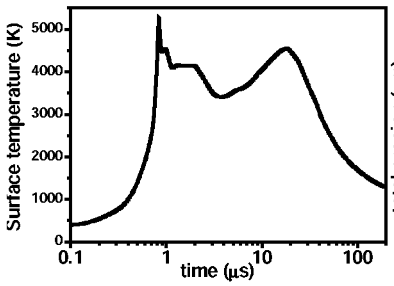

Fig.2c. Evolution of surface temperature of a graphite target in plasma gun experiments with peak target heat load of 300 GW/m^2.

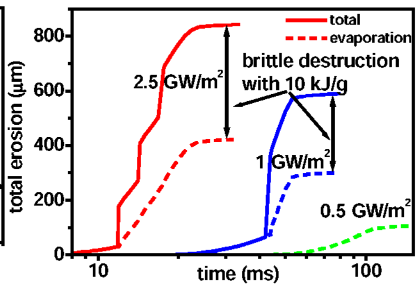

Fig.3. Total erosion and evaporation of CFC graphite for 15 MeV runaway electrons. Target heat load is 50 MJ/m^2. The inclination angle of the hot electrons is 1°.

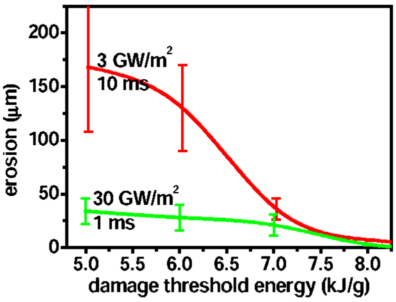

Fig.4. Calculated brittle destruction of vertical ITER-FEAT graphite targets as function of damage threshold energy for two different off normal events.

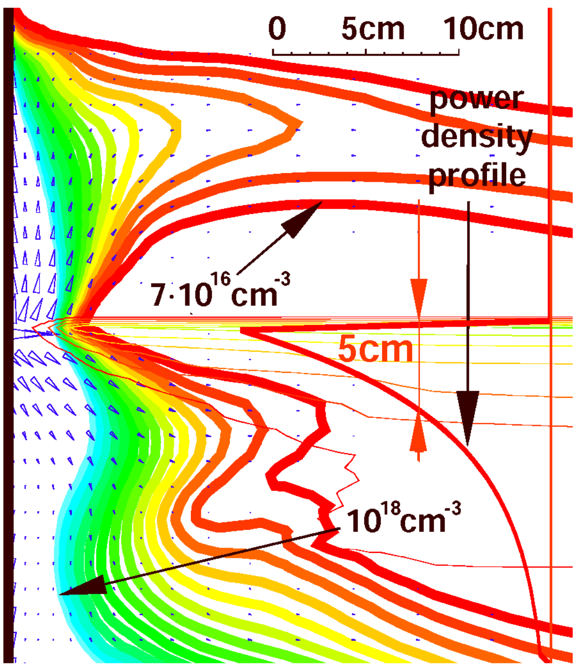

Fig.5. Density contours and plasma flow pattern for horizontal graphite target, peak target heat load 100 GW/m2 at 0.4 ms.

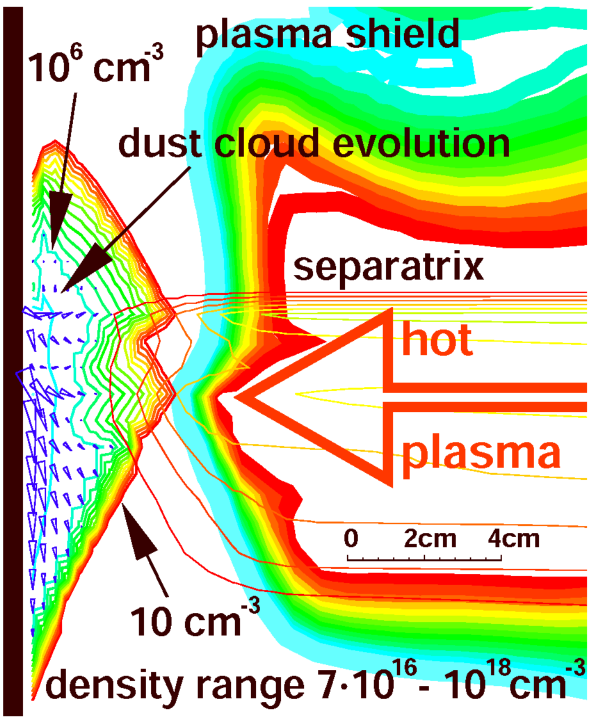

Fig.6. Motion pattern and densities in the dust cloud and plasma shield particles at 0.4 ms.