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# Material response due to simulated plasma disruption loads

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**Abstract**

The paper is focused on the problem of understanding key items of high heat flux plasma-material interaction during abnormal events: the net power flux that reached the target surface and the nature of the target erosion. As to first the results of direct measurements of visible radiation ($\Delta\lambda = 400–800$ nm) flux on the target surface are presented. It is shown that visible radiation power flux emitted inside spectral range $\Delta\lambda = 400–700$ nm can be characterised by the level of $P_R \leq 1$ GW/m$^2$ typical of experiments performed at the VIKA facility during irradiation power of $P_{irr} \sim 80$ GW/m$^2$. It is also shown that the existence of the strong guide magnetic field of $B \sim 2$ T results in a change in the behaviour and microstructure of the (Al) metal melt layer. © 2000 Publishe by Elsevier Science B.V.

*Keywords:* Plasma disruptions; Visible radiation flux; Abnormal events; Irradiation power

## 1. Introduction

The behaviour of Plasma Facing Components (PFCs) due to tokamak off-normal events (such as plasma disruptions and edge localised modes) has always been a serious problem, in spite of the considerable amount of research performed so far. A clear understanding of this problem has to be based on both modelling and experimental simulation efforts. One of the most important problems in this activity is calculating the power flux parameters at PFCs surface (by taking into account the shielding effect of material plasma layer formed above material surface) as well as understanding the role of the different physical mechanisms in material erosion. The corresponding data of simulation experiments are needed first of all to benchmark the numerical codes in order to help predicting PFCs life-time in future fusion devices.

The power flux at the target surface during high power plasma irradiation was mainly determined by radiation power flux emitted from shielding layer (SL) and the heat conduction power flux through the latter [1]. As a first step towards the evaluation of such a power flux, the values of net power flux absorbed by materials in the process of plasma irradiation were measured. These values

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can be characterised by the level of $P_{abs} \cong 3$–5 GW/m$^2$ for all the materials tested (Al, Cu, W, SS, graphite) for irradiation power $P_{irr} = 60$–120 GW/m$^2$ and magnetic field values of $B = 0$–2.5 T [2]. It is anticipated that these values are similar to the average level of power flux that reached the target surface.

As a second step for an accurate evaluation of the power reaching the target surface direct measurements of visible radiation power flux on the target were performed and are described in this paper.

The results of the study of the influence of a magnetic field on the behaviour of metallic targets melt layer during high power plasma irradiation are also described.

## 2. Experimental conditions

The experiments described below were performed at the VIKA facility [3]. The long-pulse coaxial plasma accelerator — the source of high heat plasma streams — was used in the mode of targets irradiation with specific power flux $P_{irr} \leq$ 100 GW/m$^2$. The level of irradiation power is quasistationary during pulse duration ($\tau_p = 0.36$ ms). The effective diameter of plasma stream is $d_p \approx 0.04$ m. Irradiations were performed in the presence of magnetic field $B = 0$–3.8 T.

The registration scheme of visible radiation power flux at the target surface is given in Fig. 1. The quartz fiber ($l = 5$ m — length, $d = 1$ mm — diameter) transports light to monochromator and photomultiplier (PM). The target hole axis is inclined to 45° in order to exclude the influence of light from plasma gun gap on the radiation registered.

A 20 W power tungsten lamp was used for absolute calibration of this optical tract. The calibration was performed for the wave length $\lambda =$ 550 nm.

The samples with the square $S = 25 \times 25$ mm$^2$ and thickness 10–15 mm were used for irradiation.

## 3. Experimental results

### *3.1. Measurements of visible radiation power flux at the target surface*

The registration (through the quartz fiber) of the spectra observed of SL plasma radiation for graphite target in visible spectral range was mainly undertaken to the purpose of determining the general characteristics of the radiation flux on the target surface.

The presence of carbon spectral lines CII, CIII and CIY, the most intensive being the lines CII ($z = 1$), is typical for such spectra (Fig. 2). The short-wave boundary of registered radiation spectra is limited by the light absorption in 5 m long fiber, long-wave boundary — by the spectral sensitivity of registration media (film). The considerable growth of continuum intensity in long-wave region of registered spectra needs to be noted as well.

The spectra thus obtained allowed to select wave length values for calibration and study of the line radiation dynamics (with use of a monochromator). The consolidated time dependencies from main carbon lines intensity are given in Fig. 3. One can see that the time delay for a sharp growth of carbon lines intensity is $\tau_d \sim 30$–50 μs that corresponds to the real irradiation

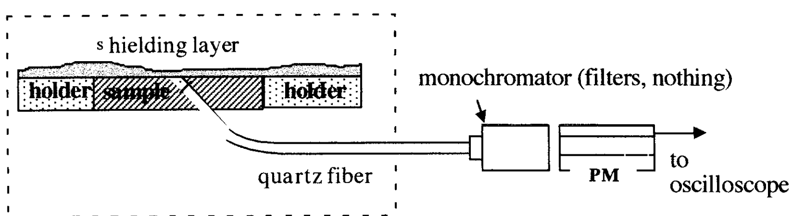


Fig. 1. Scheme of the measurements of visible radiation from shielding layer.

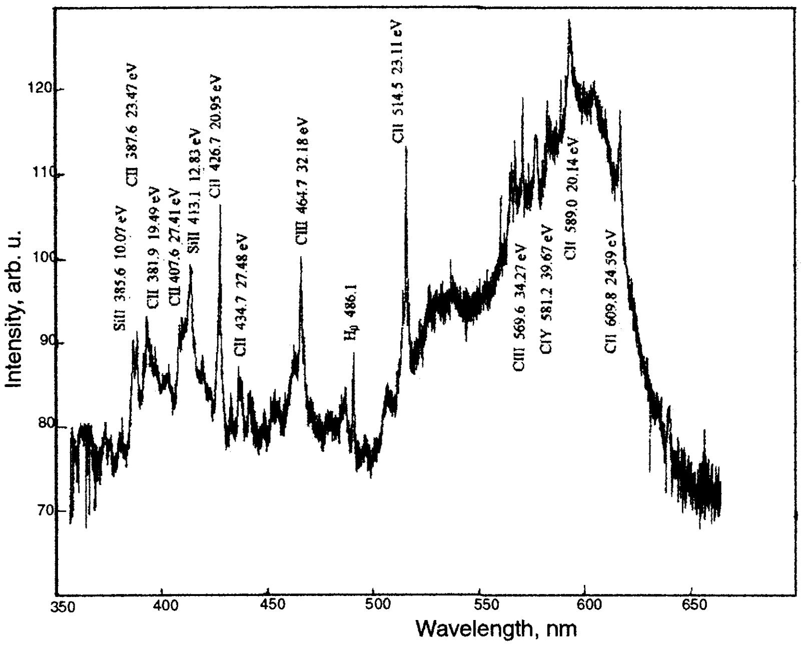


Fig. 2. Observation spectrum of visible radiation from shielding layer.

power front. The average level of these lines intensity can be generally characterised as a quasistationary one during $\sim 0.2$ ms of irradiation. The details of this behaviour depend on the wave length registered and the irradiation conditions.

The absolute values measured of radiation power flux with $\lambda = 550$ nm were integrated for spectral interval $\Delta\lambda = 400$–$700$ nm. The values obtained of the visible radiation power flux can be characterised by the level $P_{sp} \sim 30$–$35$ kW/cm$^2$ in the absence of a magnetic field and $\sim 3$ times more in the presence of 2.5 T normal magnetic field.

### 3.2. *Influence of a magnetic field on the behaviour of metal melt layers*

The study of the influence of a normal magnetic field on the behaviour observed of surface melt layer (ML) was performed for some metals such as Al, Cu, Ti and W.

It has been previously shown [4] that intensive splashing under dynamic plasma pressure ($\sim 1$ MPa for VIKA experiments) is typical for metals with a high power ($P_{irr} \cong 10$–$100$ MW/cm$^2$) plasma irradiation in the absence of a magnetic field. It results in the observed marks of intensive radial flows of the molten metal, wave-like structure of the metal surface after irradiation, and ejection of erosion products such as droplets. In the case of big samples the splashed metal is

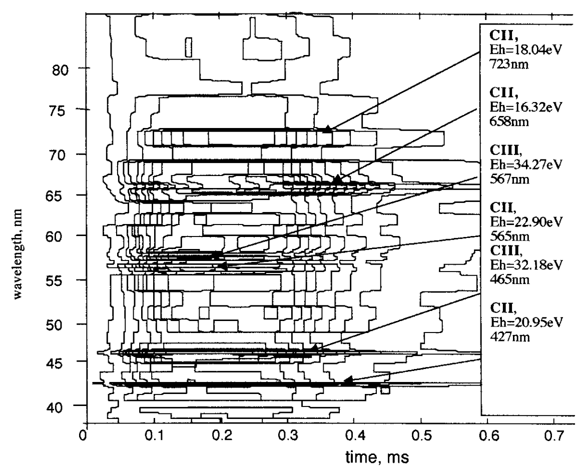


Fig. 3. Dynamics of line radiation intensities.

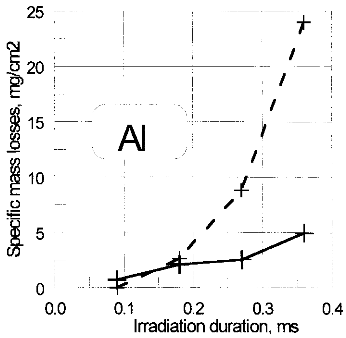


Fig. 4. Dynamics of specific mass losses of Al under plasma irradiation power flux $P_{irr} \cong 80$ GW/m$^2$ for the cases of the absence (dotted line) and the presence of 2.5 T magnetic field (solid line).

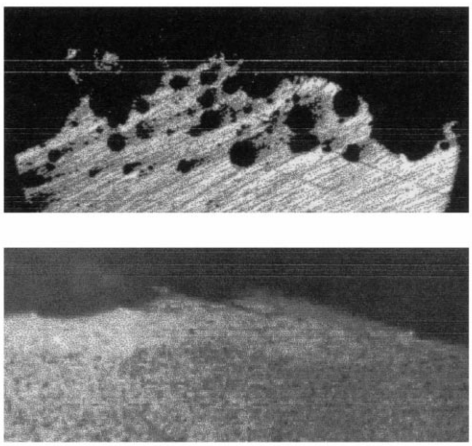

Fig. 5. Photos of the micro-structure of the surface layer of Al samples irradiated by plasma heat flux $P_{irr} \cong 80$ GW/m$^2$. Top — in the presence of 2.5 T normal magnetic field, bottom — in the absence of magnetic field.

redeposited around the erosion crater. This behaviour is quite different during the application of normal magnetic field. The radially flowing molten metal (such as Al, Cu, W) is sufficiently suppressed for $B = 1.3–2.5$ T. No appreciable erosion products are observed around the erosion crater. On the contrary, as far as metals with a bad electro-conductivity (Ti) are concerned, these values of the magnetic field are not sufficient to suppress the radial movement of the molten material. It was also checked that magnetic field $B = 0.6$ T is not sufficient to stop the liquid Al from flowing and splashing.

The suppression of liquid metal splashing resulted in the reduction of mass losses observed. Moreover the difference in the erosion rate (for $B = 0$ and $B = 2.5$ T) was observed with time delay (Fig. 4). The latter depends on both the magnetic field strength and the irradiation power and, naturally, the type of metal. For Al the reduction of total mass losses observed achieves $\sim 6$ times.

The above mentioned influence of a magnetic field on ML behaviour also affects the microstructure. So, in the absence of a magnetic field one can observe modified surface layer with an unbroken structure, but the latter is very porous in the case of irradiation in the presence of a magnetic field (Fig. 5).

## 4. Discussion and conclusions

The first experimental measurements performed of visible radiation power flux at the surface of (graphite) target give first of all the data for the comparison with numerical simulation codes. According to the data of numerical simulation for the ITER-like case [5], most of the radiations reaching the target surface are generated by a thin plasma layer of SL with a temperature close to 'the ionisation temperature' $T_{ion} \sim 1$ eV. Assuming a Plank distribution of the spectral intensity of total radiation from such layer, the level of radiation power flux measured inside the spectral range $\Delta\lambda = 400–700$ nm gives the calculated value of total radiation power flux at the target surface $P_{tot} \sim 0.5$ MW/cm$^2$. This is in a qualitative agreement with both level measured of power absorbtion and the data of the above mentioned calculations. Also, quasistationary character of radiation flux onto the target surface is in accordance with the theoretical predictions.

As to possible contribution of heat conduction channel to the total power flux at the target surface one can note that according to numerical simulation [5] the heat conduction flux from SL is equilibrated by the heat flux $P_{vapor} = n\mathrm{V}kT$ carried by the vapor flow from the target surface.

So, on the basis of both the measurements performed (of absorbed power flux and radiation power flux on the surface) and the numerical simulation, one can deduce that the radiation flux from SL determines the total power flux at the target surface.

It is interesting to observe that the values of radiation power flux measured are closed to the average level of power flux spent for the vaporisation of graphite mass losses measured (0.53 mg/ $cm^2$). It needs to be noted that the main part of the power flux at the target surface is spent for the growth of internal heat content of irradiated material in the experiments described. When the energy content in the surface melt layer (for metals) achieves the needed level, the volumetric vaporisation (boiling) is additionally increased by the surface vaporisation and determines a total erosion. Intensive melt layer losses because of splashing do not allow to reach this phase in the absence of a magnetic field and this loss is the main physical erosion mechanism observed. Typically only $\sim$10–20% of absorbed power is spent for substance phase conversion [2].

The absence observed of any visible marks of erosion products such as droplets redeposited around erosion crater agree with the calculations result [5] due to its complete vaporisation as a result of absorption of vapor cloud radiation. However this needs further and specific simulation experiments with detailed measurements, before a final conclusion is drawn concerning PFCs life-time during abnormal events.

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