

## Turbulent diffusion of divertor vapor-cloud across inclined magnetic field during a tokamak disruption

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### 1. Introduction

Disruption event in large tokamak is followed by an interaction of intense plasma stream with the divertor plates. ITER disruptive heat loads will result in a sudden evaporation of plasma-irradiated material and the formation of near-surface vapour-plasma cloud. This dense target plasma layer effectively protects the surface from further excessive evaporation. Most of the incoming plasma energy is transformed by this target plasma into photon radiation and the net heat load to the surface decreases.

Magnetic field affects dynamics of the target plasma and effectiveness of the plasma shield. At perpendicular plasma impact the target plasma expands along the magnetic field lines upward the plasma stream; transverse motion is basically inhibited. Thus a total mass of vaporised material shields the surface at perpendicular plasma impact.

There are indications that in an inclined magnetic field the target plasma drifts along the plate surface across the magnetic field lines [1]. Rapid drift of the vapour cloud causes a loss of vaporised material and direct contact of hot diffusing vapor with other divertor components. This phenomenon can result in both increase of net material erosion and contamination of whole divertor volume by the erosion products.

Since ITER disruptive heat loads are not achievable in existing tokamaks, plasma/material interaction is studied in simulation experiments and numerical modelling. Present paper summarises recent results of experimental and theoretical studies of target plasma dynamics.

### 2. Experimental facility

Experiments were carried out at the MK-200UG facility (Fig.1) at TRINITI. It consisted of MK-500 pulsed plasma gun; 9.5-m length drift tube filled with a longitudinal magnetic field and a target chamber with attached diagnostic tools. The plasma gun was fed from 1152  $\mu\text{F}$  capacitor bank. The gun operating voltage was of 25 kV that corresponded of 360 kJ capacitor energy storage.

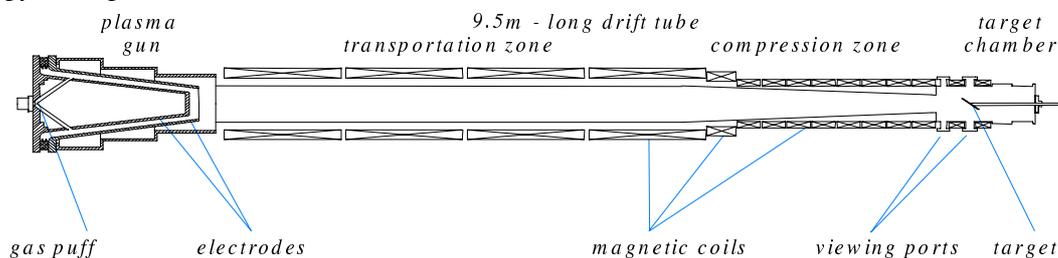


Fig. 1 Principal scheme of MK-200UG.

The drift tube consisted of 6.5-m cylindrical part and of 3-m a conical one. Diameter of the cylindrical tube was of 30 cm and reduced at the conical section towards its exit to 15 cm. The longitudinal magnetic field strength in the cylindrical tube was of 0.7 T and rose up to 2.5 T along the conical part. Supersonic plasma stream was radially compressed and effectively magnetised passing through the increasing magnetic field.

Samples to be exposed were placed at the end of the drift tube in the target chamber of 30-cm diameter and of 50-cm length filled with a longitudinal magnetic field of 2 T. Plasma stream parameters in the chamber were as follows: energy density up to  $q = 1.5 \text{ kJ/cm}^2$ , power density  $W = (30-40) \text{ MW/cm}^2$ , pulse duration  $\tau = (40-50) \mu\text{s}$ , velocity  $V = (6-7) \cdot 10^7 \text{ cm/c}$ , density  $n = (2-6) 10^{15} \text{ cm}^{-3}$ , temperature  $T_i \leq 600\text{eV}$ ,  $T_e \leq 200\text{eV}$ , beta value  $\beta = 0.3$ , plasma stream diameter  $D = 6 - 7 \text{ cm}$ .

Targets were made of MPG-8 graphite. Target length was of 15 cm, width – 10 cm (target size along a sight axis). Center of the target was placed at the stream axis.

The facility was equipped by a set of diagnostic tools intended for investigation of the target plasma. Optical interferometry was applied in measuring the electron density in the target plasma with time resolution of  $0.5 \mu\text{s}$  and 2D-space resolution of 1 mm. Spectrum of carbon target plasma was analyzed by means of soft X-ray and VUV transmission grating spectrometer. Kodak 101-01 film was used as a recorder with known sensitivity in the range of wavelength 2 - 1500 Å. The spectra provided 1.5 mm spatial and 2 Å spectral resolution.

Standard high-streak camera was applied for producing images of the target plasma in visible light. The camera produced above 500 images in a single series with a  $0.5 \mu\text{s}$  exposure of one frame and a  $2 \mu\text{s}$  interval between frames.

In the present experiment carbon target plasma radiated mainly in VUV spectral range. Eight-frame camera making VUV images of the target plasma with 2- dim. space and a high time resolution was designed. The camera was based on MCP (microchannel plate) with the partitioned incident surface. The MCP unit was coupled with phosphor and fiber optics plate. The Kodak 2484 film was used to record the detected images. The 8-frames MCP camera was placed behind a 4x2 pinhole array, which was used to image a plasma region of interest. Gating pulser provided 100 ns per frame exposure with adjustable interframe time. Intervals between the sequential exposures can be varied from 0 to  $5 \mu\text{s}$  in different runs. The maximum total exposure time was of  $40 \mu\text{s}$  that corresponds to target plasma life.

### 3. Experimental results.

Perpendicular and  $20^\circ$  tilted graphite targets were exposed to the hydrogen plasma stream. As for perpendicular as for tilted target a cloud of dense target plasma arose in front of the irradiated surface within  $1 \mu\text{s}$ . In experiments with perpendicular plasma impact a cloud of the

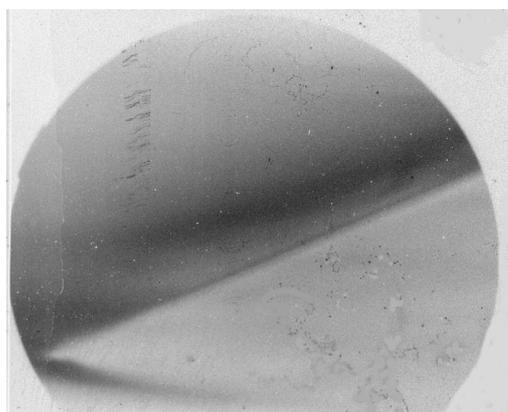


Fig.2 Time-integrated image of carbon plasma at tilted target (negative).

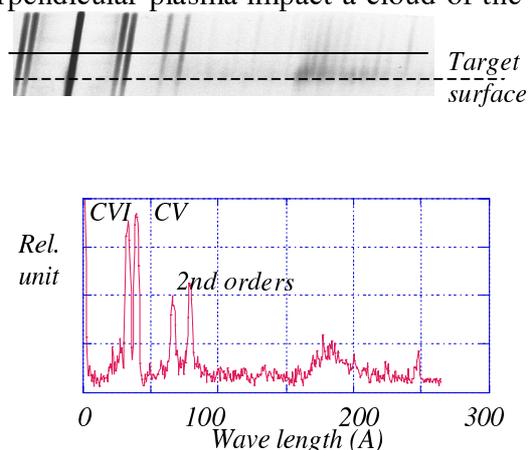


Fig.3 Spatially resolved spectrum (top) and its scan at 0.6 cm distance from tilted target .

target plasma expanded mainly along the magnetic field lines upwards the plasma stream with the velocity of  $4 \cdot 10^6$  cm/s. Transverse motion was inhibited due to a strong magnetic field. Contrary to perpendicular plasma impact at inclined plasma incidence a bulk of the target plasma was localized in the vicinity of the tilted surface during the whole interaction process. Thickness of the target plasma layer was restricted to 2-3 cm. Electron density in this layer was  $n_e \leq 5 \cdot 10^{17}$  cm<sup>-3</sup>.

Fig.2 shows time-integrated negative image of carbon target plasma produced with 1-frame MCP camera. A radiation from target plasma was integrated during the whole time of plasma/target interaction. The image was done in spectral interval  $\lambda = 0-2000$  Å. A total field of view on this frame is 8 cm. One can conclude that a thickness of the target plasma layer remained below 2.5 cm during the entire process.

Radiation of the carbon target plasma belonged mainly to spectral interval (0-400) Å that indicated existence of rather high temperature plasma. Fig.3 demonstrates spectrum of carbon plasma formed at tilted graphite. Top figure shows space-resolved carbon spectrum within 1.3 cm distance from the surface (dash line). Spectrum at a distance of 0.6 cm (solid line) is represented in bottom figure. It is clearly seen that carbon plasma emits spectral lines CV and CVI. This fact indicates that a high temperature carbon plasma of several tens eV existed.

Carbon target plasma drifted on the tilted surface downwards the plasma stream from the point of plasma impact and left the target surface. Interferometer measurements showed a jet of dense plasma behind the tail edge of the tilted target. The electron density in this plasma jet was around  $4 \cdot 10^{17}$  cm<sup>-3</sup> at times 10 μs and it remained at this magnitude during the interaction process. Thus there was a continuous loss of vaporized material from the tilted target.

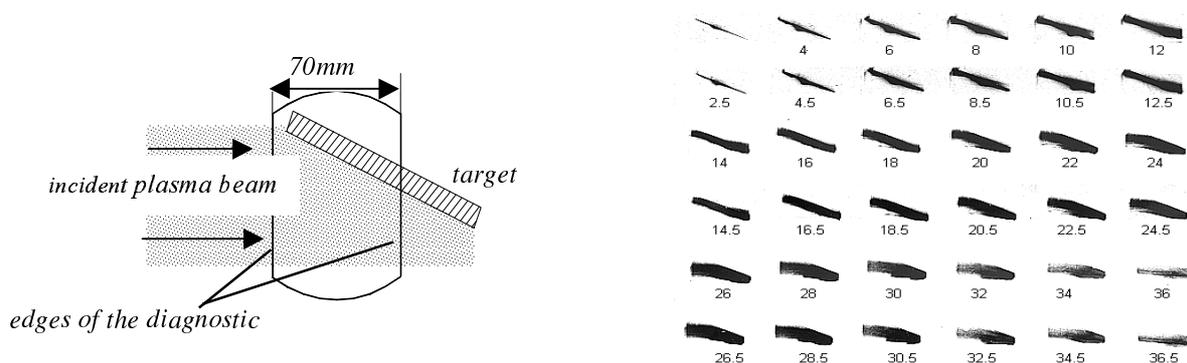


Fig.4. Relative position of target and incident plasma beam (left figure) and sequence of frames (negatives) produced by high speed camera. Time shown for each frame is in microseconds.

Fig.4 shows dynamics of carbon plasma at tilted graphite registered by means of high speed framing camera. It is clearly seen that at the initial stage of interaction (2-12.5 μs) the target plasma moved along the tilted surface. A luminous spottiness arose on the surface at time 2 μs and then (at  $t = 14$  μs) it left the field of view. From analysis of the photos taken at times 2 – 12.5 μs a velocity of the spottiness motion was estimated to be around  $4 \cdot 10^5$  cm/s.

Fig.4 represents images produced in the visible light; meanwhile the target plasma radiated mainly in VUV spectral range at  $\lambda < 400$  Å. Therefore a velocity of the target plasma drift may be different from the magnitude mentioned above. VUV images of the target plasma produced with 8-frames MCP camera demonstrates that the target plasma initially expanded with the velocity of  $2 \cdot 10^6$  cm/s perpendicular to the surface. Then the plasma expansion became slower and a thickness of the target plasma layer remained at magnitude of 3 cm. Target plasma layer usually looked rather homogeneous and any conclusion on its dynamics along the surface could hardly be derived from VUV images. But in certain shots target plasma had irregular structure.

Among the whole experimental database there were selected such series of frames in which adequate spottinesses are seen on two consequent frames.

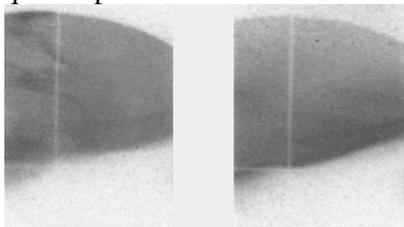


Fig.5 Pair of sequential MCP-frames showing dynamics of carbon plasma at tilted target

Fig.5 illustrates typical example. This figure shows the spottinesses on the border of the target plasma layer for two times separated by interval of 2  $\mu$ s (Geometry was the same as in Fig.2. Cross on the photos was a center of diagnostics port). From analysis of the whole available MCP images of the target plasma a velocity was estimated to be  $V = 4 - 6 \cdot 10^5$  cm/s.

Thus analysis of the target plasma images of 20° tilted graphite target produced in VUV and visible light shows the drift of carbon plasma with the velocity around  $5 \cdot 10^5$  cm/s in contrast with the normal incident case. Taking into account a high carbon plasma temperature it becomes clear that the transverse plasma motion at tilted surface can not be explained by classical mechanism of plasma diffusion and can be a consequence of the turbulence existing. The turbulence may arise in the target plasma due to distortion of the magnetic field lines by plasma pressure. This question demanded a theoretical analysis.

#### 4. Modeling.

Numerical calculations using the 2-D HEIGHTS Computer Package indicate that the drift velocity  $V_{\perp}$  is about  $0.1-0.4 \cdot 10^5$  cm/s in both cases [2]. Therefore large drift velocity in case of a tilted target can be explained by existence of turbulent diffusion. Main mechanism of this process is the balloon mode of flute instability arising due to distortion of magnetic field lines by vapor pressure. The turbulent drift velocity can reach high values up to  $V_{\perp} \leq 10^6$  cm/s. High losses of vapor plasma along the tilted target surface results in decreasing  $V_{\parallel}$  and consequently in limitation of the vapor cloud region. Existing of turbulent expansion of plasma cloud can result in filling the closed divertor system with hot vapor that must be taken into account in design and lifetime considerations.

#### 5. Summary.

Graphite targets oriented perpendicular and inclined to magnetic field lines were exposed to intense hydrogen plasma stream. The main attention was focused on dynamics of carbon target plasma. The cloud of target plasma arose in front of the target within 1  $\mu$ s. Carbon target plasma demonstrated emission of CV and CVI spectral lines which indicated existence of rather hot plasma with a temperature of 40-50 eV.

Experiment with perpendicular plasma impact showed that the target plasma expands upward the plasma stream along the magnetic field lines and it produced a long plasma column. Velocity of longitudinal plasma expansion was of  $4 \cdot 10^6$  cm/s. Transverse motion was basically inhibited. At inclined incidence a bulk of the target plasma was localized in the vicinity of the surface in the layer of 2-3 cm thickness. Target plasma drifted along the tilted target surface across the magnetic field lines with the velocity around  $5 \cdot 10^5$  cm/s. The measured plasma drift can not be explained by classical plasma diffusion and it seems to result from existence of plasma turbulence.

#### 6. Remark

This work was supported by ISTC project No539-98.

#### References

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