# TESTING OF CFC TARGETS BY PLASMA HEAT FLUXES RELEVANT TO ELMS AND MITIGATED DISRUPTIONS IN ITER

***V.M. Safronov*[1], *N.I. Arkhipov*[1], *I. Landman*[2], *V.M. Strunnikov*[1],**
***D.A. Toporkov*[1], *A.M. Zhitlukhin*[1]**

***[1] State Research Center of Russian Federation Troitsk Institute***
***for Innovation and Fusion Research, 142190 Troitsk, Moscow reg., Russia***
***[2]Forschungszentrum Karlsruhe, IHM, Postfach 3640, 76021 Karlsruhe, Germany***

Carbon fibre composite (CFC) was irradiated by hot plasma streams at plasma gun facility MK-200UG. The CFC targets were tested by plasma loads relevant to Edge Localised Modes (ELM) and mitigated disruptions in ITER. Onset condition of CFC evaporation and properties of evaporated carbon were studied by use of infrared pyrometry and visible spectroscopy.

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## 1. INTRODUCTION

Some key issues remain in the ITER design associated with the response of the armour materials to thermal energy deposited during Edge Localised Modes (ELMs) and mitigated disruptions. They include the erosion effects in the armour materials, the resultant production and transport of impurities in tokamak plasma during and after the ELM, and the potential for plasma contamination during the inter-ELM phase. These effects are not fully understood and require further experimental and theoretical studies.

The heat loads on the ITER divertor target are expected [1] to be:

- 0.5…4 MJ/m$^2$ in time scale of 0.1…0.5 ms for Type I ELM;
- 2…13 MJ/m$^2$ in time scale of 1…3 ms for thermal quench phase of disruption.

The expected heat loads are not achievable in the existing tokamak-machines. Therefore the divertor armour materials are tested by use of other devices such as powerful plasma guns [2-4] and e-beam facilities [5,6], which are capable to simulate, at least in part, the loading conditions of interest. Experimental results are used for validation of the numerical models developed for simulation of the armour behavior during ELMs and disruptions [7-9].

Carbon fibre composite (CFC) and tungsten are foreseen as candidate armour materials for ITER divertor. The present work refers to experimental investigation of CFC armour. The CFC targets were tested at plasma gun facility MK-200UG by plasma heat loads relevant to the ITER Type I ELMs and mitigated disruptions. A threshold of CFC evaporation has been measured and properties of the evaporated carbon have been studied as a function of the plasma heat load. First testing of CFC cut has been performed also.

## 2. EXPERIMENTAL

The basic scheme of the MK-200UG facility is shown in Fig.1. The facility consists of a pulsed plasma gun, a long drift tube and a target chamber.

The plasma gun is fed from 1152 µF capacitor bank. In the present experiment the operating voltage was 13 kV. It corresponds to about 100kJ of energy stored in the capacitor bank.

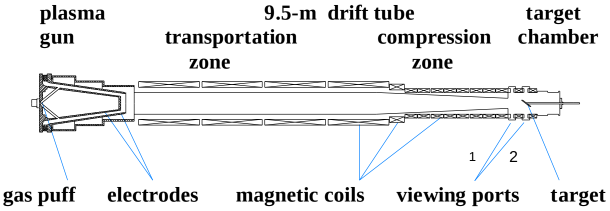

*Fig.1. Basic scheme of MK-200UG facility*

The plasma gun injects a hydrogen plasma stream into the drift tube, consisting of 6.5 m cylindrical part and of a conical one with a length of 3 m. Diameter of the cylindrical tube is 30 cm. At the conical section, the tube diameter reduces towards its exit from 30 cm to 15 cm. The cylindrical tube is filled with a 0.7 T longitudinal magnetic field. The magnetic field rises from 0.7 T up to 2.5 T along the conical part. In the magnetic cone, a quick magnetization of the plasma stream occurs and after that the plasma moves strictly along the magnetic field lines.

The CFC targets are placed in the target chamber equipped by the diagnostic tools. The targets are tested at a varying plasma load. The plasma load is varied by means of variation of the magnetic field in the target chamber: the larger magnetic field, the larger plasma heat load. The plasma load grows with the magnetic field because of increasing plasma density; plasma stream velocity and impact ion energy remain unaltered. Parameters of hydrogen plasma stream at the target position are listed in Table1.

*Table 1. Plasma stream parameters*

| | |
|---|---|
| energy density | q = 0.6…1.5 MJ/m$^2$ |
| power density | w = 10…30 GW/m$^2$ |
| pulse duration | $\tau$ = 0.05…0.06 ms |
| impact ion energy | $E_i$ = 2…3 keV |
| plasma density | n = (0.5…2)$\times10^{20}$ m$^{-3}$ |
| plasma pressure | P < 1 bar |
| diameter | D = 6…10 cm |

The table shows the energy density measured at the axis of the plasma stream. A real plasma load on the target surface $q_s(r)$ depends on a radial position r of the target and on an angle $\alpha$ of the target inclination in

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respect to the stream axis $q_s(r) = q(r) \sin \alpha$. In the present experiment, the CFC targets were tested by plasma load varying in the range 0.1…1 MJ/m$^2$.

The CFC targets have a rectangular shape with a face surface 25 x 25mm and 45 x 25mm and thickness 10mm. The targets are equipped by thermocouples for the measurement of absorbed energy.

A temperature of the target surface was measured by use of infrared pyrometer over a whole period of plasma/surface interaction. Visible and EUV spectroscopy was applied for analysis of the evaporated carbon.

## 3. EXPERIMENTAL RESULTS

Onset condition of CFC evaporation was studied by the following method: CFC target was exposed to increasing plasma load; a temperature of the exposed target surface was measured by infrared pyrometer; an appearance of carbon vapor was detected by means of spectroscopy. The performed investigation has shown:

- measurable but a very weak evaporation starts at plasma load $q = 0.15$ MJ/m$^2$;
- intense evaporation of CFC occurs at plasma heat load $q > 0.2$ MJ/m$^2$;
- evaporation is surely absent at $q < 0.1$ MJ/m$^2$.

A temperature of the target surface increases with the plasma heat load q and it runs up to a maximum magnitude T = 3700…3800 K (Fig.2) at $q = 0.2$ MJ/m$^2$, when the intense evaporation starts. At further increase of the plasma load up to $q = 1$ MJ/m$^2$, the temperature remains unaltered. (It should be noted that the pyrometer was adjusted for temperatures above 2000 K, therefore a tail part of the plot in Fig.2 is not correct.)

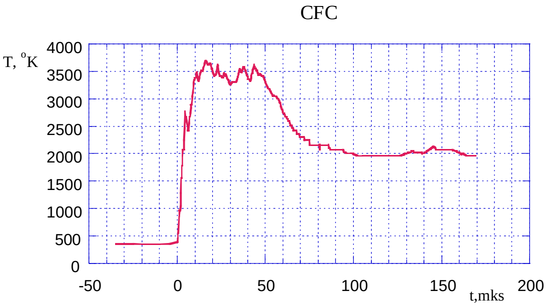

*Fig.2. Surface temperature of CFC target exposed to plasma stream at heat load 0.24 MJ/m$^2$*

By means of visible spectroscopy and photography it was measured that the evaporated carbon moves from the target surface along the magnetic field lines. Transverse motion is negligible. A first front of the carbon cloud moves with a velocity $V = (1…2) \times 10^4$ cm/s.

Spectrum of the evaporated carbon consists of separate spectral lines, continuous spectrum is observed near the target surface only, at distances 1…2 mm. At heat load $q < 0.2$ MJ/m$^2$, carbon vapor emits mainly in the visible spectral range. EUV spectral lines CV (40.3Å) and CVI (33.7 Å) (Fig.3) appear at heat load $q = 0.2$ MJ/m$^2$ and $q = 0.3$ MJ/m$^2$ correspondingly. Analysis of the obtained spectral data gives a temperature of the evaporated carbon about T = 10 eV for plasma load of $q = 0.2$ MJ/m$^2$ and T = 30 eV for $q = 0.3$ MJ/m$^2$.

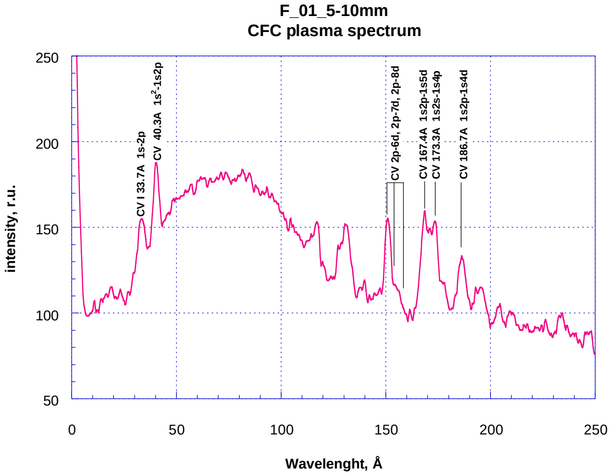

*Fig.3.EUV spectrum of carbon plasma at q = 0.32 MJ/m$^2$*

Electron density $n_e$ of carbon plasma was evaluated from Stark broadening of spectral line CIV (4658.3 Å). Table 2 illustrates a magnitude of $n_e$ as a function of the plasma load. Density was measured at times t= 10…15 µs after a start of plasma/target interaction at a distance 0.5 cm from the target surface.

*Table 2. Electron density of carbon plasma*

| Plasma load, MJ/m$^2$ | Electron density, cm$^{-3}$ |
|---|---|
| 0.15 | Not measurable, $n_e << 10^{16}$ |
| 0.17 | $1.4 \times 10^{16}$ |
| 0.20 | $1.6 \times 10^{17}$ |
| 0.25 | $1.8 \times 10^{17}$ |
| 0.30 | $2.0 \times 10^{17}$ |
| 0.37 | $2.1 \times 10^{17}$ |

According to the obtained data, a density of the evaporated carbon grows with increase of the plasma load. At first, the density grows quickly: small variation of the plasma load from $q = 0.17$ MJ/m$^2$ to - 0.20 MJ/m$^2$ results in increase of the density by a factor of 10. At larger plasma loads $q > 0.20$ MJ/m$^2$ the density rises slightly and it remains practically constant value $n_e = 2 \times 10^{17}$ cm$^{-3}$. These findings indicate that a threshold of intense CFC evaporation is about $q = 0.2$ MJ/m$^2$.

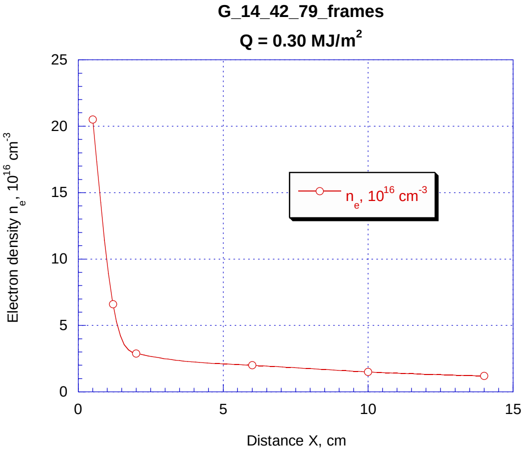

*Fig.4. Space distribution of electron density in front of CFC target (plasma heat load 0.3 MJ/m$^2$, time 13 µs)*

Fig.4 shows a space distribution of electron density in front of the target. The density is maximal near the surface and it reduces steeply with a distance. Carbon target plasma consists of a dense near-surface plasma ($n_e=2\times10^{17}cm^{-3}$) and carbon plasma corona ($n_e=(1…2)\times10^{16}cm^{-3}$), which expands from the target surface with a velocity V = (1…2)×$10^4$ cm/s. Taking into account that the plasma corona consists mainly of $C^{+3}$ ions we can conclude that a density of carbon ions is $n > 10^{15}$ $cm^{-3}$ that is larger than a density of tokamak plasma. It means that during ELMs, large amount of carbon impurities might move from the divertor to main chamber and it might cause a radiative cooling of tokamak plasma.

CFC consists of PAN carbon fibres, which are parallel to the face target surface, and perpendicular pitch fibres. PAN fibres have smaller thermal conductivity than the pitch fibres and therefore the PAN fibres should evaporate at smaller heat loads and more intensively than the pitch fibres. This assumption has been verified.

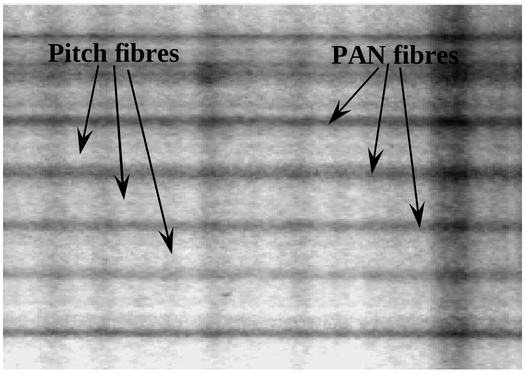

*Fig.5. Image of plasma irradiated CFC surface*

Fig.5 presents image of the exposed CFC surface. It is clearly seen a modulation of radiation over the exposed target surface: there are dark PAN fibres and light pitch fibres. PAN fibres evaporate stronger than the pitch fibres therefore they look darker. There was tested also CFC cut, in which PAN and pitch fibres are oriented at 45 degree to the face surface. It was found that a radiation is fully homogeneous over a whole surface of the exposed cut.

## CONCLUSIONS

CFC targets were tested by hot magnetized plasma streams at heat loads q = 0.1…1 MJ/m2 and pulse duration 0.05 ms. The obtained results are the following:

- Intense evaporation of CFC starts at q = 0.2 MJ/$m^2$ and surface temperature $T_s$ =3700…3800 K.
- At q = 0.2…03 MJ/$m^2$, electron density of carbon plasma is of $n_e = 2\times10^{17}$ $cm^{-3}$ at 0.5 cm distance.
- Carbon plasma corona ($n_e = (1…2)\times10^{16}$ $cm^{-3}$) moves from the target surface along the magnetic field lines with a velocity (1…2)×$10^4$ cm/s.
- Carbon plasma consists of $C^{+2}$ – $C^{+5}$ ions. Temperature of evaporated carbon is T = 10-30 eV at q = 0.2-03 MJ/$m^2$.
- In standard CFC target, PAN fibres evaporate more intensively than pitch fibres. In CFC cut, all fibres evaporate with equal rate.

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## ИСПЫТАНИЕ С-С КОМПОЗИТА ПРИ ТЕПЛОВЫХ ПЛАЗМЕННЫХ НАГРУЗКАХ, ХАРАКТЕРНЫХ ДЛЯ ELM И ОСЛАБЛЕННЫХ СРЫВОВ В ИТЭРе

***В.М. Сафронов, Н.И. Архипов, И. Ландман, В.М. Струнников,***
***Д.А. Топорков, А.М. Житлухин***

С-С композит был подвергнут воздействию потоков высокотемпературной плазмы на установке МК-200UG. Мишени из С-С композита испытывались при плазменных нагрузках, характерных для ELM и ослабленных срывов в ИТЭРе. Начальные условия испарения материала и свойства испаренного углерода исследовались при помощи инфракрасной пирометрии и видимой спектроскопии.

## ІСПИТ С-С КОМПОЗИТА ПРИ ТЕПЛОВИХ ПЛАЗМОВИХ НАВАНТАЖЕННЯХ, ХАРАКТЕРНИХ ДЛЯ ELM І ОСЛАБЛЕНИХ ЗРИВІВ В ІТЕРі

***В.М. Сафронов, Н.І. Архіпов, І. Ландман, В.М. Струнніков,***
***Д.А. Топорков, А.М. Житлухін***

С-С композит був підданий впливові потоків високотемпературної плазми на установці МК-200UG. Мішені з С-С композита випробувалися при плазмових навантаженнях, характерних для ELM і ослаблених зривів в ІТЕРі. Початкові умови випару матеріалу і властивості випаруваного вуглецю досліджувалися за допомогою інфрачервоної пірометрії і видимої спектроскопії.