Novel Electron Beam Based Test Facility for Observation of Dynamics of Tungsten Erosion under Intense ELM-like Heat Loads

Leonid Vyacheslavov[1, 2, a)], Aleksey Arakcheev[1, 2, 3], Alexander Burdakov[1, 3], Igor Kandaurov[1], Alexandr Kasatov[1, 2], Victor Kurkuchekov[1, 2], Konstantin Mekler[1], Vladimir Popov[1, 2], Andrey Shoshin[1, 2], Dmitriy Skovorodin[1, 2], Yuriy Trunev[1, 2], Alexander Vasilyev[1, 2]

[1] *Budker Institute of Nuclear Physic SB RAS, Novosibirsk, 630090, Russia*
[2] *Novosibirsk State University, Novosibirsk, 630090, Russia.*
[3] *Novosibirsk State Technical University, Novosibirsk, 630092, Russia.*

[a)]Corresponding author: vyachesl@gmail.com

Abstract. A test facility developed at the Budker Institute is designed for experimental simulation of effects of ITER-scale transient heat loads on plasma facing materials. Employing a long-pulse electron beam for creation of transients has advantages of low direct pressures on surface of material and lesser limitation of power density by vapor shielding. In addition, relative modest attendant background light allows using a set of diagnostics for observation of erosion dynamics. The set includes fast imaging in the near infrared, scattering of light of continuous wave laser on target surface and on droplets ejected from the melt layer.

INTRODUCTION

Transient heat loads due to ELM type I or major disruptions are considered the main factor responsible for damage of tungsten surface in the ITER divertor. Different techniques are preparing for mitigation of heat load however some number of unmitigated transient events cannot be excluded. In these cases the heat loads can reach energy density Q_h=5-80 MJm^{-2}, power density q_h=5-25 GWm^{-2} over the heating time τ_h=0.3–3 ms for type I ELMs and major disruption. These heat loads correspond to maximal heat flux parameter values F_{HF}=600-2000 MJ m^{-2} s$^{-0.5}$ [1, 2]. Such extremal impacts go well beyond the conditions in the modern tokamaks. For this reason special test facilities are built to test material under intense transient heat loads. The most advanced of them are the quasi stationary plasma accelerators (QSPAs). However, the plasma stream produced by QSPAs is not ideal substitution to plasma in the ITER divertor. It creates too high plasma pressure on tungsten surface and on melted layer moreover the power density absorbed by the tungsten is limited by vapor shield effect [3] by the value q_h=4.4-4.6 GWm^{-2}. It corresponds to heat flux parameter F_{HF}=70-100 MJ m^{-2} s$^{-0.5}$ [4]. Long pulse electron beam (LPEB) produces negligible direct pressure and has much higher limit of absorbed power density due to vapor shied effect [5]. Besides, LPEB creates relatively low background light which facilitates operation of diagnostics. All the above makes LPEB attractive for simulation of transient heat load under conditions different from those in QSPAs. The following text presents a short description of the test facility based on LPEB, which is developed at the Budker Institute , and some of the obtained experimental results.

TEST FACILITY

Electron Beam Source

The test facility is based on a high-power sub-millisecond electron beam injector with a plasma emitter. Total power of the device is up to 7 MW with a typical pulse duration of 0.1 – 0.3 ms. Target is placed in magnetic field of ~0.2 T, which is used to compress the electron beam and for generation of intense energy load on an area of 1-2 cm^2. Temporal shape of the heating has rectangular profile with sharp edges. The cross-sectional distribution of the energy load has a dome-like form with a full width at half maximum of 9 – 12 mm depending on magnetic field. The machine is able to provide 15 GWm^{-2} in maximum at high-power operating mode and F_{HF} >250 $MJm^{-2}s^{-0.5}$. The details of the facility operation with the tungsten target are described elsewhere [6].

Diagnostics Layout

The facility is equipped with two sets by four diagnostic ports as it can be seen from figure 1. Set 1 is located in the target plane and is designed for observation of the ablation plume from the side closer to the target. Here spectroscopy with spatial resolution is employed as well as dust measurements system, which consisted of small angle light scattering and fast CCD and ICCD cameras. Typically we use 1.4 megapixel CCD cameras with minimal exposure time of 7 µs and 0.8 megapixel ICCD with minimal exposure 1 µs. Set 2 is located at 41 cm from the target closer to the electron beam injector and is employed for frontal observation of the target. Here we utilize fast imaging of the target in the near infrared spectral region and in the light of continuous 532 nm laser. Rejection of parasitic plume light in the latter case is provided with narrow band (0.2 nm and 1 nm) spectral filters centered at the laser wavelength. The technique of in situ imaging of tungsten target with the laser illumination is considering in reference [7]. The small angle light scattering system includes 3 channels for collecting light scattered within following angular ranges relative the direction of probing laser beam: θ1=0.01-0.03 rad, θ2=0.7-0.09 rad, θ3=0.1-0.12 rad. For these angles, the laser wavelength in use, and opaque particles the Fraunhofer diffraction is a good approximation that simplifies estimation of dynamics of sizes and density of particles ejected from the melt layer. Fast imaging of the particles provides data for temporal variation of particle velocity. An analysis of experimental data can be found elsewhere [8].

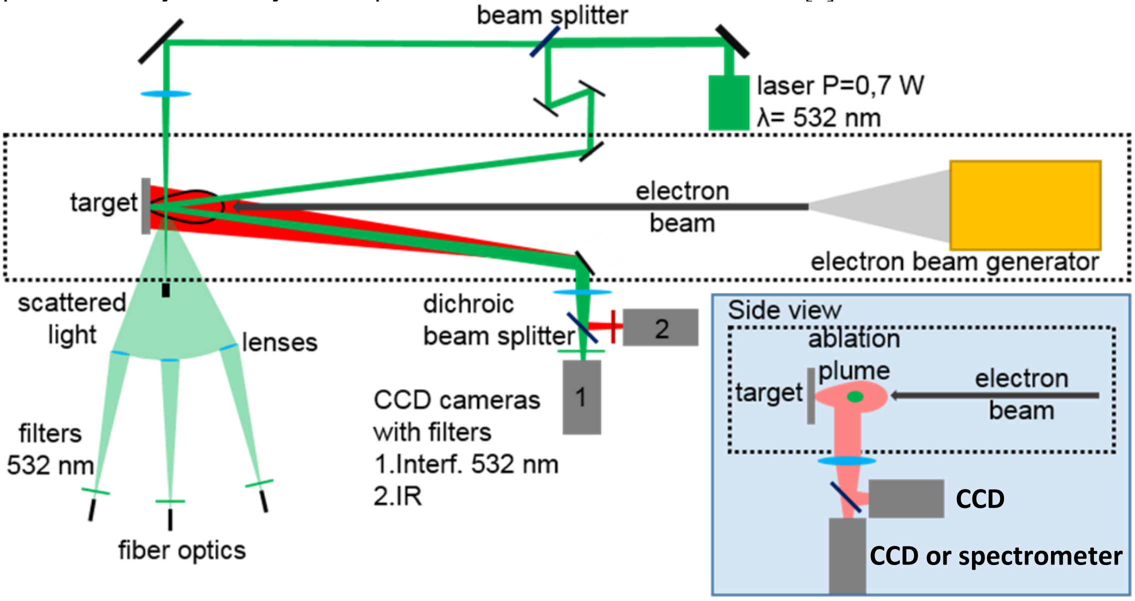

FIGURE 1. Schematics of the optical diagnostics. Surface erosion is observed using CCD camera in the near infrared (NIR) range and CCD camera with green laser light illumination and narrowband interferential filter. Also 3-channel laser scattering system and position of spectrometer are shown.

EXPERIMENTAL RESULTS AND DISCUSSION

Spectra of the Ablation Plume

An example of spectral measurements of the tungsten ablation plume is shown in figure 2. Here the experimental spectrum is shown in black while spectral lines of neutral and single ionized tungsten from the NIST database [9], which are convolved with spectrometer instrumental function, are marked by green. Reasonably good correlation of spectral line positions with low level of background light exhibit a minor contribution of other spectral lines besides the above mentioned tungsten lines. Tungsten spectral lines are weak at wavelength above 860 nm where about 1% of total line emission is contained. This fact suggests that imaging in the near infrared region above 860 nm can permit observation of tungsten surface modification at high temperatures.

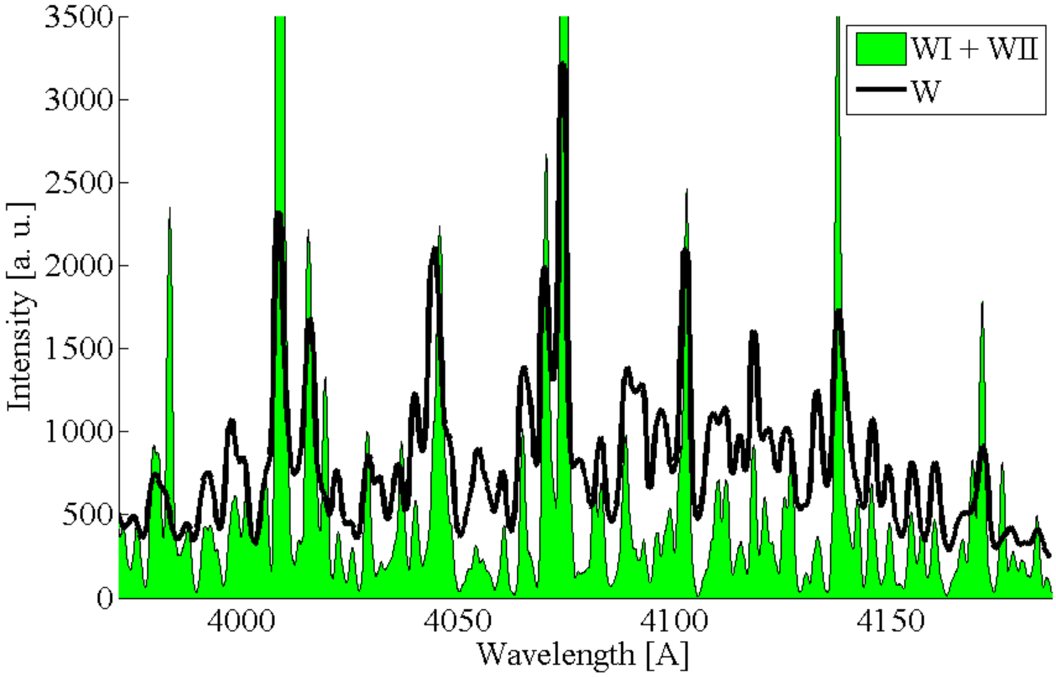

FIGURE 2. Spectrum of tungsten ablation plume (black) and WI and WII spectra convolved with the instrumental function (green)

Figure 3 shows the tungsten WI and WII spectrum shown in red with typical spectral sensitivity of CCD camera equipped with a NIR spectral filter (in blue). Significant separation of spectra of tungsten plume emission and the sensitivity of the CCD is clearly seen.

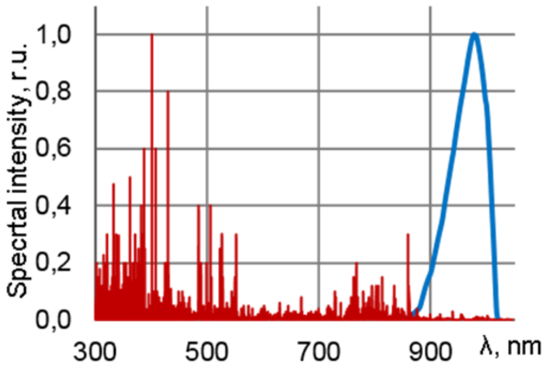

FIGURE 3. Comparison of the system spectral sensitivity and WI and WII spectra. Red line: spectra of tungsten, blue: sensitivity of the CCD camera with infrared spectral filter.

Imaging of Melt Tungsten

Application of CCD cameras to fast imaging of melted layer during the heating pulse is shown in figure 4.

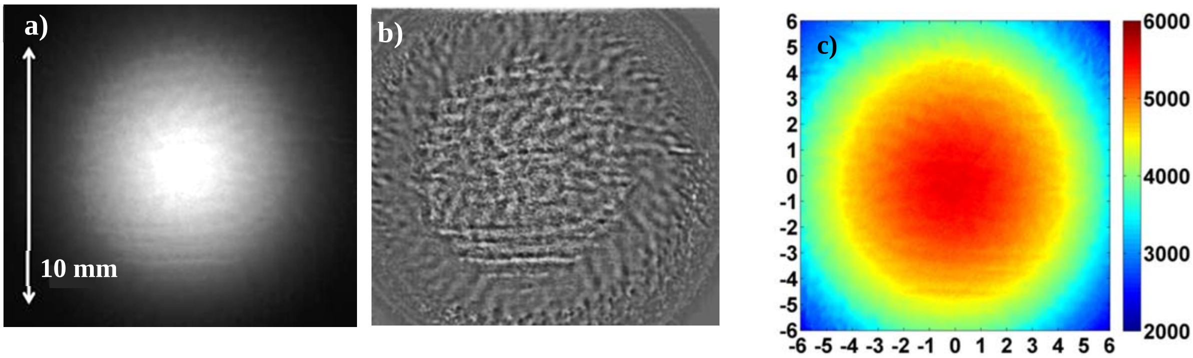

FIGURE 4. Thermal image of the tungsten target obtained during the heating pulse within last 10µs before the pulse end (a), and the same image as (a) but filtered by the high-pass spatial filter (b); temperature profile, obtained from thermal image using the absolute calibration (c).

Spatial non-uniformities of size ≤ 1 mm are faintly visible in the thermal image but become clearer (b) after subtraction of smoothed bell-like temperature profile from the initial image (a). The preliminary temperature profile recovered from the thermal image with the use of absolute calibration with the tungsten ribbon lamp shows the wide area at temperature above the melting point. The temperature of central part of the melted area with diameter of 5-6 mm approaches the boiling point at the atmospheric pressure. Typically, an intense emission of droplet occurs at high heat loads basically from this central region [8]. To relate melt layer motion and droplet ejection the CCD imaging system was upgraded. The upgrade includes operation of 4 independent CCD cameras, which are seeing the same area on the tungsten target. The cameras are triggered independently with adjustable delay. Figure 5 shows 4 frames with exposition time of 10 µs and relative delay from each other of 20 µs. The heating pulse length is 0.2 ms and exposure time for CCD start at 0.12, 0.14, 0.16 and 0.18 ms that means that all images are obtained during the heating pulse. The images are high pass filtered similarly to figure 4b. The frame spatial dimension is 14x14 mm. Here again the pattern with characteristic sizes near 1mm is clearly seen. Considerable variation of the pattern between frames separated by 10 µs signifies that melt movement occurs rather fast.

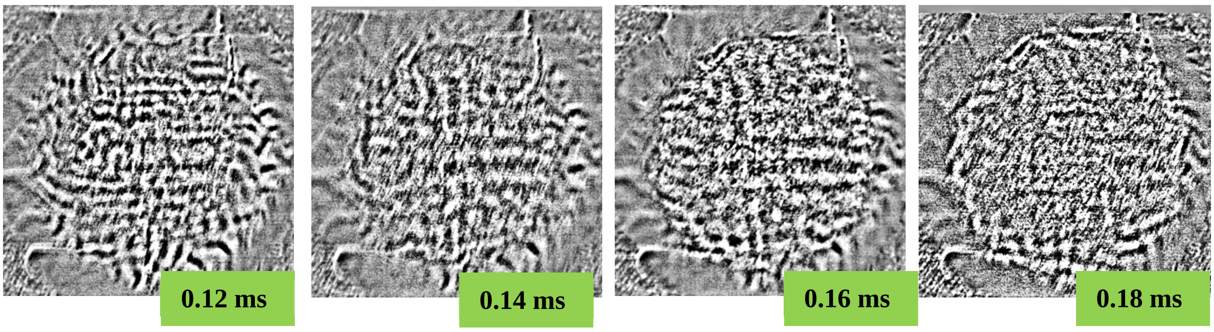

FIGURE 5. NIR images of tungsten melt layer obtained during a single heating pulse of length 0.2 ms and filtered with digital spatial high-pass filter. Start time of each frame with exposure of 10 µs is shown under each image. The each image covers the area 14x14 mm on the target.

CONCLUSION

An electron beam with duration of 0.1-0.3 ms and power up to 7 MW is applied for simulation of the ITER-scale transient heat load on tungsten target. The power density, absorbed by the target, reaches 15 GWm^{-2} in the high-power operating mode with FHF >250 $MJm^{-2}s^{-0.5}$ at the area of 5-7 mm in diameter. The new test facility based on this electron beam uses a set of diagnostics that are novel for this research field: small angle scattering of continuous wave (cw) laser and fast target imaging during the heating process. The imaging can be performed in two modes simultaneously: in the light of cw laser and in the near infrared range. It permits observation of dynamics of tungsten melt layer and is important for elucidation of mechanism of droplet ejection from the melt layer. Small angle light scattering is designed for investigation of dynamics of melt structure as well as for estimation the amount of ejected material. Preliminary results showing temporal variation of small-scale structure of melt layer are presented.

ACKNOWLEDGMENTS

The work at the electron beam facility was supported by Russian Science Foundation (project N 14-50-00080). Study of the target surface melt dynamics was partially supported by RFBR, research project No. 15-32-20669.

REFERENCES

[1]. R.A. Pitts et al., J. Nucl. Mater. 438 (2013) S48
[2]. M. Shimada et al., J. Nucl. Mater. 438 (2013) S996
[3]. D.I. Skovorodin et al., Phys. Plasmas, 23 (2016) 022501
[4]. I.E. Garkusha et al., J. Nucl. Mater. 390-391 (2009) 814
[5]. V. Popov et al., Theoretical Modeling of Shielding for Plasma Flow and Electron Beam Heating, AIP Conf. Proc. (these proceedings)
[6]. Yu.A. Trunev, et al., Heating of tungsten target by intense pulse electron beam, AIP Conf. Proc. (these proceedings)
[7]. A.A. Vasiliev et al., Observation of the Tungsten Surface Damage under ITER-relevant Transient Heat Loads during and after Electron Beam Pulse, AIP Conf. Proc. (these proceedings)
[8]. A.A. Kasatov et al., Observation of Dust Particles Ejected from Tungsten Surface under Impact of Intense Transient Heat Load, AIP Conf. Proc. (these proceedings)
[9]. http://physics.nist.gov/PhysRefData/ASD/lines_form.html