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Study of plasma-surface interaction at the GOL-3 facility

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ABSTRACT

The review presents experimental studies of plasma-surface interaction and materials behavior under plasma loads done in the multiple-mirror trap of the GOL-3 facility. In the experiments for the PSI, the energy density in the extracted plasma stream varies from 0.5 to 30 MJ/m^2. Parameters of near-surface plasma measured by a set of diagnostics are reviewed. Surface patterns of targets exposed to the plasma are analyzed. The erosion depth depends on the energy loads—it rises from 0 to 600 μm at 0.5 and 30 MJ/m^2, correspondingly. Cracking and evolution of graphite and tungsten surface morphology are discussed. The enthalpy of brittle destruction of graphite (10 kJ/g), which determines the threshold of bulk damage of targets irradiated with a charged-particle flux with large penetration depth, was determined. Comparison of different facilities for PSI studies are presented. Heat flux play a key role to the target surface erosion.

1. Introduction

Plasma-surface interaction is one of the main problems of fusion reactors that will affect the performance of ITER and future reactor-type machines. This problem is very important because it has not been solved yet, even for reactors that are now under construction. Let us consider this problem by the example of ITER—the biggest international tokamak being created in France now. Different plasma instability events can occur in tokamaks. According to the first predictions (1990s) for ITER disruptions and edge localized modes (ELMs), the energy density of the plasma flow to the divertor plates can reach 100–150 MJ/m^2 in case of disruptions and 10 MJ/m^2 with ELMs [1]. The modern fusion machines cannot produce plasma streams with energy loads close to the ITER disruption values. Irradiation of targets with high-power plasma streams is modelled using linear magnetic machines, like open traps and plasma guns. The surface irradiation is also simulated with electron beams and lasers, but they reproduce only the energy loads on targets without plasma stream. The most powerful plasma streams (up to 50 MJ/m^2 in a magnetic field of up to 5 T) can be produced in the open trap GOL-3, located in Novosibirsk. First experiments with irradiation of targets with loads of over 10 MJ/m^2 per shot demonstrated the target erosion depth to be more than 200 μm in case of graphite and tungsten [1–3]. After that, the estimation of allowable loads for future fusion machines (including ITER) was lowered. Now the energy loads on the ITER divertor surfaces associated with the Type I ELMs are expected to be up to 0.5–10 MJ/m^2 during 0.1–0.5 ms [4]. To prevent unacceptable erosion, cracks, melting and other damage to the divertor targets, it is necessary to restrict the energy loss per single ELM [5]. An acceptable lifetime of the ITER divertor (3000 full power pulses) under ELM erosion requires a peak ELM energy flux at the divertor of 0.6 MJm^{-2} (for $t = 250$ μs) or 0.85 MJm^{-2} (for $t = 500$ μs) [4].

Unlike some other simulation facilities, in the irradiation experiments at GOL-3 most energy is carried by decelerated beam electrons and fast plasma electrons, which have relatively big penetration depth. Nevertheless, comparison of tungsten targets under

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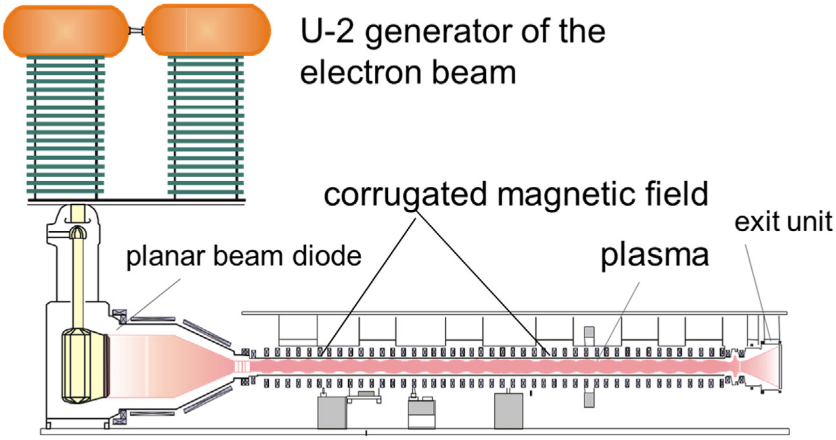

Fig. 1. Layout of the GOL-3 facility. U-2 generator consist of high-voltage impulse generator and magnetically insulated diode of ribbon geometry. Explosion emission cathode made of carbon fiber.

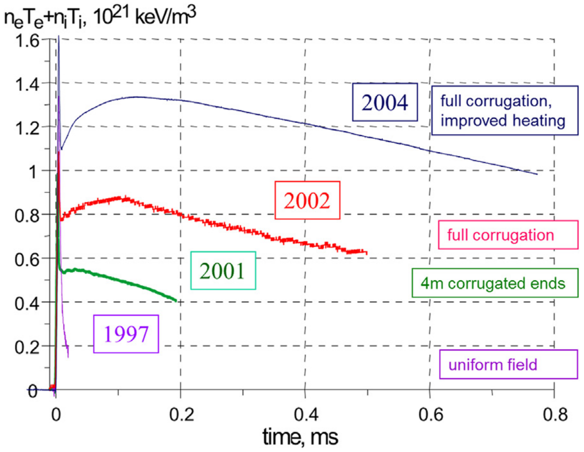

Fig. 2. Waveforms of plasma pressure at GOL-3 facility with different magnetic configurations of central solenoid.

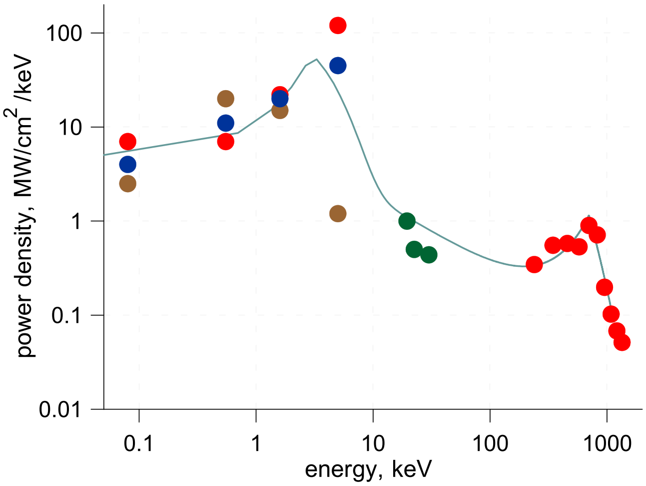

Fig. 3. Energy distribution of fast electrons in exit unit of GOL-3. Initially all electrons have energy 1 MeV.

the same power loads at the GOL-3 facility and the quasi-stationary plasma accelerator QSPA Kh-50 [6] demonstrated that under the energy density loads applied (>1 MJ/m^2), the evolution of the surface morphology under plasma irradiation is similar in the two devices [7,8].

During disruption in tokamaks, there form runaway electrons with big current (up 10 MA [9]) and big energy (up to 20 MeV [9] or hundreds MeV in the first predictions [10]), which have big penetration depth, and thus fast electrons in the plasma stream of GOL-3 can better simulate conditions of ITER disruptions than other plasma facilities.

Besides, previous experiments enable comparison of irradiation at the GOL-3 facility with that at the electron beam facility JUDITH-1 [11] and the Nd:YAG laser [5,12,13]. The different techniques showed, in general, similar damage behaviours and the same damage thresholds [14,15]. Heat loads play a key role in the erosion of plasma facing components (PFCs) under ITER-like transient events [7,8,14].

2. GOL-3

The primary physical objective of the GOL-3 facility is the development of a multiple-mirror magnetic confinement scheme for fusion [16–18].

The main aims of the experiments were:

- study of the mechanism of plasma heating and confinement (fast electron and ion heating and suppression of plasma instabilities) [19–26];
- study of electron beam-plasma interaction (two-stream instability, stability of supercritical current [27], turbulence, electron conductivity suppression, THz wave irradiation [28] and others) [29–33];
- study of multiple-mirror confinement of hot dense plasma [34–36];
- study of plasma-wall interaction [1,2,3,7,37,38,39,40,41,42,43,44];
- development of techniques (electron beam and neutral beam injectors [45,46], diagnostics [47–54], plasma generators [55] and others) for next-step open-trap machines [16,56];

The fusion research program based on the concept of multiple-mirror confinement was suggested by Budker, Mirnov and Ryutov [57]. A multiple-minor trap is a set of linked magnetic mirror cells that form a corrugated magnetic field. In such a system, if plasma density is high enough, its expansion along the magnetic field becomes diffusion-like due to the effective “friction force” between the magnetic field and plasma particles. The main advantages of this approach are the technical simplicity and the absence of density and beta limits.