The PLM-2 plasma device for full-scale tests of fusion reactor materials with stationary plasma loads: design parameters

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Abstract. The PLM-2 linear magnetic plasma device is designed for the steady-state hours-long plasma confinement. It is the upgraded PLM plasma device. Its parameters will provide the relevant fusion reactor plasma loads on materials. The machine is designed both for fundamental studies of plasma-surface interactions under conditions of high heat and particle fluxes, and for the tests of plasma-facing components under realistic plasma conditions in the high-heat-flux facility. The PLM-2 facility is an advanced linear plasma device uniquely capable of producing plasma conditions similar to those expected in the divertors of the fusion reactors such as ITER, fusion neutron source FNS and DEMO under conditions of steady-state operation. In this article, we describe the PLM-2 design parameters. The PLM-2 device has no analogues in Russia; its parameters are similar to those of the most high-power devices in the world, such as the MAGNUM-PSI, and it is going to be built in Moscow at National Research University “MPEI”.

1. Introduction

For the design and construction of fusion reactors, including ITER, the fusion neutron source FNS and DEMO fusion reactor, the full-scale tests of materials, mock-ups and prototypes of the wall and divertor plates are required [1, 2]. The divertor plasma in a fusion reactor will be characterized by the high density (≥10²¹ m⁻³) and the low electron temperature (Te ≤ 5 eV), which will result in the high heat (≥15 MW m⁻³) and particle fluxes (up to 10²⁴ m⁻² s⁻¹ or 1.5 × 10⁷ A⋅m⁻²) [1, 2]. Under assumption of the ion acceleration in the electrostatic sheath, the ions will have energies below 50 eV. For most materials, the transient localized heat fluxes caused by the Edge Localized Modes (several GW m⁻² for 0.5–2 ms) can lead to material erosion, melting and vaporization, and become a serious problem in respect to the lifetime of the plasma-facing components. For these purposes, the available technologies for testing materials with beam loads are not sufficient, despite the fact that they provide high-power total heat flux onto the materials. It is extremely important to ensure adequate plasma loads onto the materials. The understanding and control of plasma-wall interactions are of importance for the successful deployment of nuclear fusion reactors. The linear plasma devices, such as the MAGNUM-PSI [3], the PISCES [4], and the NAGDIS facilities [5], have been used to study the plasma-surface interactions under fusion-relevant conditions. In these devices, the achievable flux density is typically less than 5–10 W/m² in steady-state operation, which is 2–3 times lower than that expected in the divertors of ITER and future fusion reactors, such as FNS. The design and construction of the PLM-2 linear plasma generator at National Research University “MPEI” in Moscow will
provide the high steady-state plasma flux for testing fusion materials. An overview of the current status of the PLM-2 design can be considered in this connection.

2. Scientific purposes and design criteria of the PLM-2

2.1. The plasma-surface interaction
The PLM-2 is designed as an upgrade of the PLM device [6, 7]. It is aimed at studies of the plasma-surface interactions under conditions when the mean free path of the particles released from the surface by means of reflection, thermionic emission or erosion is less than the plasma size, so that these particles become trapped in the plasma-surface interaction region. The ionization mean free path strongly depends on the plasma density in front of the surface; it is in the range of 0.5–4 mm for \(n_e = (1−4) \times 10^{20} \text{ m}^{-3}\). This is less than the plasma beam width, which, in the PLM-2, is approximately 35 mm. Hence, every particle, which left the test target surface as a result of erosion, on average, will experience more than 10 cycles of erosion/redeposition events before it can eventually escape from the plasma beam. The particle flux onto the surface is so high that every surface atom collides with the reactive particles from the plasma with a frequency higher than the inverse time of local surface relaxation. As a result, the surface atoms are driven into the states, which are far from equilibrium. Low-energy ions (≤10 eV) with the kinetic energies of the order of the interatomic binding energies, can very efficiently transport their energies to the surface that simulates the conditions of the fusion reactor. The problems of edge plasma, strong turbulence and cross-field turbulent transport [8], changes in the surface morphology [9, 10] under conditions of high-power plasma-surface interaction will be investigated at the PLM-2 facility.

2.2. Design criteria
The PLM-2 is designed to create plasma conditions similar to those expected in the divertors of ITER, the FNS and DEMO fusion reactors and the large scale TRT tokamak. The main design criteria can be summarized as follows:

- Plasma conditions should correspond to the divertor plasma, i.e. hydrogen/deuterium plasma with high density and low temperature and helium used as a process gas should be produced. It will operate at pressures of approximately few Pa.
- Neutral gas pressure around the test target should be determined by the recycling at the target.
- The magnet using the conventional copper coils is designed. In the next step of upgrading, the superconducting magnet with a magnetic field induction of approximately 3 T will be constructed.
- The target geometry should enable large targets to be exposed at a small angle with respect to the magnetic field (2–3 degrees).

Design parameters of the PLM-2 linear magnetic trap providing the relevant reactor plasma loads on materials and construction elements are as follows:

- The longitudinal magnetic field should be 0.25 T, the maximum magnetic field over the cross section is up to 3 T;
- The plasma diameter should be 3.5–10 cm;
- The discharge duration in the steady-state operation should be up to 500 minutes or more;
- The plasma electron density should be up to \(10^{19}−10^{20} \text{ m}^{-3}\);
- The energy of ions flowing to the target should be 1–300 eV;
- The ion flux on the target should be \(10^{23}−10^{25} \text{ m}^{-2} \text{s}^{-1}\);
- The stationary thermal load onto the target material should be more than 15 MW m\(^{-2}\);
- High-fluence/long timescale should be provided due to the steady state operation capability;
- Stationary cooling of wall and targets, testing of modules with water, two-phase combined-cycle, liquid metal cooling should be provided;
- ICR plasma heating at frequencies of 0.5–27 MHz, and the use of helicon antennas should be provided;
the module is required with high-power beam heat loads (similar to extreme loads during ELMs and disruptions in the fusion reactor divertor) on a target (up to 2 GW/m² with a duration of up to 1 ms at a repetition frequency of up to 20 Hz);
- there should be the possibility of operation in the “detached” mode (an analogue of the closed tokamak divertor mode);
- the chamber should contain the liquid metal (LM) wall elements/limiters of lithium, tin, lithium/tin alloy and others;
- the technology for plasma control and turbulent heating of plasma by electrodes under voltage should be used;
- the possible tested materials are tungsten, molybdenum, steels, graphite, lithium, tin, tantalum, nickel, titanium, iridium, platinum, iron, copper, and composite alloys.

Figure 1. (a) General view of the PLM-2 facility with copper coils. (b) Schematic of the PLM-2. (c) Plasma source section (PLM); schematic of discharge chamber (SS) and magnetic system: (1) cathode, (2) tantalum screen, (3) permanent Nd magnets, (4) magnetic coils, (5) anode, Cu, (6) SS ring of the anode, and (7) diagnostic port. (d) View of the PLM device.

The plasma source is based on the section presently developed for the PLM [6, 7] which is a linear magnetic trap with the 8-pole multi-cusp magnetic field with the cathode producing hot dense plasma supplied to the target by a magnet. A set of diagnostics will be used to analyze the plasma and the wall material during and after exposure.
The system is complemented by a high power laser system for transient heating of the plasma-exposed surface.

3. Target system
The target manipulator will be constructed to provide high adaptability in terms of the shape and size of the sample to be exposed. The multitarget holder will make it possible to install the disc-shaped samples and to sequentially expose them to the plasma beam. The samples will be installed onto the intense water-cooled system with dispersive flux which allows achieving the cooling flux of more than 20 MW/m². The manipulator will be developed to provide the exposure of targets with the sizes and shapes, which can vary in a wide range. The maximum target dimensions will be of 500 × 100 mm. The holder will be equipped with a target consisting of tungsten monoblocks with an inclination angle of 2–5°, which are similar to the tungsten plates that are planned to be used in the ITER first wall.

4. Conclusions and future plans
The PLM-2 linear plasma device is designed both for the fundamental studies of plasma-surface interactions under conditions of the extreme heat and particle fluxes loading the surface, and for the tests of plasma-facing components under realistic plasma conditions in a high-heat flux facility. The PLM-2 device has no analogues in Russia; its parameters are similar to those of the most high-power devices in the world, such as the MAGNUM-PSI, and it is going to be built in Moscow at National Research University “MPEI” as the upgraded PLM device. The design parameters, the resources of the PLM-2 device for steady-state plasma operation, which can be achieved with the conventional copper coils at the peak heat loads on target of 15 MW/m² were described. In addition, before performing the steady-state plasma tests in the PLM-2, the ELM-simulation system using the superimposed high-power e-beam pulses will be developed. The peak power density during the e-beam pulses will be approximately 300 MW/m². This system will be complemented by a high power laser system for transient heating of the plasma-exposed surface. This makes it possible to compare the damages caused by the steady-state plasma processing and laser heating. The adaptable target system and the system of intense cooling with dispersive flux make the PLM-2 a unique facility to study the resistance to high-power loads of the candidate plasma-facing fusion materials and components. Presently, the main efforts are focused on the development of the design criteria, as well as on the possible improvements the PLM plasma device. In the next year, the construction of vacuum and magnet systems will be ready for the start up operation and commissioning of the PLM-2.

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