RF-heating system of helicon-type for PLM-2 plasma device: design parameters

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Abstract. The PLM-2 linear magnetic plasma device is for steady-state stationary hours-long plasma confinement with parameters providing the relevant fusion reactor plasma loads on materials. The machine is designed both for fundamental studies of plasma-surface interactions under high heat and particle fluxes, and as a high-heat flux facility for the tests of plasma-facing components under realistic plasma conditions. In the PLM-2 plasma device, a plasma heating ICR system will be created using a helicon antenna. Production of plasma by using helicon waves is known as helicon discharge, and the plasma produced by using the helicon discharge has a totally distinct character where the enhancement of the plasma parameters takes place at particular conditions. Helicon discharges produce higher density plasma at a comparatively lower given input power than any other RF or DC discharges, and also the plasma is least contaminated due to the presence of the antenna out-side the chamber.

1. Introduction

For the design and construction of thermonuclear fusion reactors including ITER, fusion neutron source FNS, and DEMO fusion reactor, full-scale tests of materials, mock-ups and prototypes of the wall and divertor plates are required [1]. The divertor plasma in fusion reactor will be characterized by a high density \( \geq 10^{21} \text{ m}^{-3} \) and a low electron temperature \( (T_e \leq 5 \text{ eV}) \) leading to high heat \( \geq 15 \text{ MW/m}^2 \) and particle fluxes (up to \( 10^{24} \text{ m}^{-2} \text{s}^{-1} \) or \( 1.5 \times 10^{5} \text{A/m}^2 \)) [1]. Assuming ion acceleration in the electrostatic sheath, the ions will have energies below 50 eV. Transient localized heat fluxes caused by Edge Localized Modes (several GW·m\(^{-2}\) for 0.5 —2 ms) can lead to material erosion, melting and vaporization for most materials, and represent a serious concern for the lifetime of the plasma-facing components. The available technologies for testing by beam loads are not sufficient for these purposes, despite the fact that they provide a powerful total heat flux to the materials. It is extremely important to ensure adequate conditions of plasma load on materials. The understanding and control of plasma-wall interactions is of importance for the successful deployment of nuclear fusion reactor. Linear plasma devices, such as the MAGNUM-PSI [2], the PISCES facilities [3], the NAGDIS facilities [4], have been used for the study of plasma-surface interactions under fusion-relevant conditions. The achievable flux density in those devices is typically less to 5-10 W/m\(^2\) in steady-state, a factor of 2-3 lower than what is expected in the divertor of ITER and future fusion reactor like FNS. The development of the PLM-2 linear plasma generator at National Research University “MPEI” in Moscow is filling this gap to provide a high flux steady-state plasma for fusion material test.
2. PLM-2 plasma device

PLM-2 is designed as an upgrade of the PLM device [5] to study plasma-surface interactions under the regime which is reached when the mean free-path of the particles released from the surface, via reflection, thermoemission or erosion, is smaller than the plasma size so that they are trapped in the plasma-surface interaction region.

The PLM-2 (fig.1) is designed to generate plasma conditions similar to those expected in the divertor of ITER, fusion reactors FNS, DEMO and large scale tokamak TRT. The main design criteria can be summarized as follows:

- Divertor relevant plasma conditions, i.e. a plasma with high density and low temperature with hydrogen/deuterium and helium as a process gas. It will operate at pressures around a few Pa.
- Neutral pressure around the test target determined by the recycling at the target.
- The magnet by use of conventional copper coils is designed. In the next upgrade step, superconducting magnet around a 3 T will be constructed.
- A target geometry allowing large targets to be exposed at a shallow angle with respect to the magnetic field (2-3 degrees).

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

- longitudinal magnetic field - 0.25 T, section of a magnetic field up to 3 T;
- diameter of the plasma - 3.5 — 10 cm;
- discharge duration – stationary steady-state, up to 500 minutes or more;
- plasma electron density - up to 10^{19} - 10^{20} m^{-3};
- the energy of ions in the flow to the target is 1–300 eV;
- ion flux on the target ~ 10^{23} - 10^{25} m^{-2} s^{-1};
- stationary thermal load to the target material - more than 15 MW m^{-2};
- high fluence/long timescale due to steady state capability;
- cooling of wall and targets - stationary, testing of modules with water, two-phase combined-cycle, liquid metal cooling;
- A module with powerful beam heat loads on a target - up to 2 GW / m^2 with a duration of up to 1 ms with a frequency of up to 20 Hz (similar to extreme loads at ELMs and disruptions in a divertor of a fusion reactor);
- the “detached” mode, an analogue of the closed tokamak divertor mode;
- liquid metal (LM) wall elements / limiters of lithium, tin, lithium/tin alloy and others;
- technology of plasma control and turbulent heating of plasma by electrodes under voltage;
- the tested materials are tungsten, molybdenum, steels, graphite, lithium, tin, tantalum, nickel, titanium, iridium, platinum, iron, copper, composite alloys.

The plasma source is based on the section presently developed in the PLM [5] which is a linear magnetic trap with a 8-pole multi-cusp magnetic field with the cathode produced a hot, dense plasma guided to the target by a magnet. A set of diagnostics will be employed 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. Scientific purpose and design criteria of RF-heating system

3.1. The ion cyclotron heating systems

Research on thermonuclear fusion with confinement in magnetic fields started in the 1950s in open and closed installations led to the creation of electrodeless methods for heating plasma by RF and HRF at levels of input powers of tens of MW. Thermonuclear research has shown that for electrodeless creation and heating plasma, the most rational use of resonance phenomena in a magnetized plasma, namely, electron cyclotron resonance (ECR), ion cyclotron resonance (ICR). They make it possible to invest energy only in a certain component of the plasma and thereby ensure high efficiency of the required process. After R. W. Boswell's [6] discovery that the helicon discharge can effectively create a plasma with a density of up to $10^{20}$ m$^{-3}$, intensive research on its properties and applications began all over the world. A helicon wave or simply a helicon is an electromagnetic circularly polarized wave propagating in plasma along an external constant magnetic field $B_z$ [7]. The electric field of helicon waves in a cylindrical coordinate system has the following form:

$$\mathbf{E}(r, \theta, z) = \mathbf{E}(r)e^{i(m\theta + k|\parallel - \omega t)}$$

Where $\mathbf{E}(r)$ is function describing the wave transverse structure; $m$ - azimuth index (the number of field variations in azimuth); $k|\parallel$ - longitudinal wavenumber. The frequency $\omega$ for helicon waves lies in the range:

$$\omega_{ci} \ll \omega \ll \omega_{ce}, \omega_{pe}$$

Where $\omega_{ci,ce} = q_i, q_eB/m_i, m_e$ are cyclotron frequencies of ions and electrons, respectively. $\omega_{pe}$ is plasma frequency electrons.

Currently, there are various linear installations using a Helicon antenna for additional plasma heating, such as IShTAR tested [8] in Belgium, Proto-MPEX [9] in USA, and others.

3.2. Design criteria

The ICR plasma heating system (Fig. 2) consists of a discharge chamber, a helicon antenna; a RF-source and a matching network. The discharge chamber is made up of a ceramic, which has a small coefficient of thermal expansion and must be capable of transmitting electromagnetic waves generated by the antenna to interact with the plasma. The ceramic chamber (Fig. 3) has a length of 16 cm, an outer diameter of 7 cm and an inner diameter of 5 cm. Choosing the antenna type: the geometry of the helicon antenna was chosen as a right-hand half helical Nagoya type III with azimuthal mode $m = +1$. The length of the antenna is approximately 13 cm, and it is made up of copper strips of 0.5 cm thickness and 1.5 cm width (Fig. 4). The antenna is connected to a matching network and RF-source through a coaxial transmission line. The HFP Corporation manufactured RF generator model number GL-13.2-7A with frequency of 13.56 MHz is used to power the antenna via a Navio Match Network 3155405-300 produced by Advanced Energy automatic matching network. The RF generator can supply RF power up to 5kW and has an inbuilt output resistance of 50 Ohms.
The matching network (Fig. 5) consists of two variable capacitors, the load and tune capacitors, the capacitors can be tuned manually after changing them into the manual mode if the matching is not proper in the automatch mode. The task of matching is to equate the load resistance (antenna, plasma) with the resistance of the RF generator to eliminate power loss. The matching network allows guaranteed operation with the active component of the RF-load from ~1 to 30 Ohms and with the reactive component from $j25$ to $j130$ Ohms. Capacitor resistances are calculated using the following formulas [10]:

$$C_1 = \frac{(1 - (1 - 2R)^2)^{1/2}}{2R}, \quad C_2 = \frac{1}{X - \frac{1}{C_1}}$$

(3)

Smith charts are used to describe and determine the complex load resistance. The Smith Chart is an infinite complex plane collapsed by a conformal mapping into a plane bounded by a unit circle. This is a powerful auxiliary tool for calculating microwave circuits and it provides an understanding of the principle of matching complex resistances and much more. It is necessary to matching the complex load resistance $Z_L = R_L + jX_L$, represented in the diagram (Fig. 6) by the point $Z_L$, with the signal source having an internal resistance of $Z_0$ Ohms at a frequency of 13.56 MHz.
3.3. Magnet system

The PLM-2 device will have a dual magnetic section. The first section will be similar to the magnetic system of the PLM device. The section is the linear magnetic trap. The second section is going to be used to compress the plasma to the parameters of the peripheral plasma of full-scale thermonuclear fusion reactors. The ceramic tube will be placed coaxially inside the superconducting coils with current. The coils have independent power supply and current regulation, can move along the pipe, and thus the required magnetic configuration is established in the discharge chamber. The magnetic field of such a system for the PLM-2 device will have values from 0.5T to 1T. The characteristic plasma frequencies were calculated. With a frequency of 13.56 MHz, the condition for the existence of a helicon wave is fulfilled at values of the magnetic field from 0.5T to 1T (formula 2). The superconducting coils will be made of HTS tapes. It will allow to increase a magnetic field to 3 T. A thermostat will be added in magnetic system because of coils work with temperature around 70 K.

4. Conclusion and future plans

The PLM-2 linear plasma device is designed both for fundamental studies of plasma-surface interactions under extreme heat and particle fluxes, and as a high-heat flux facility for the tests of plasma-facing components under realistic plasma conditions. The PLM-2 device has no analogues in Russia, with parameters similar to the most powerful device in the world, like MAGNUM-PSI, it will be constructed as upgrade of the PLM device at NRU “MPEI”, Moscow. Superconductive magnetic system will allow us to get the plasma to the parameters of the peripheral plasma of full-scale thermonuclear fusion reactors. Also it will make possible to study superconductivity and various related fields of science.

The design parameters, the capabilities of the PLM-2 device for steady-state plasma by the use of conventional copper coils, with maximum heat loads on target of 15 MW·m⁻² are described in this paper. In addition, ELM-simulation system will be developed to superimpose powerful e-beam pulses before the steady-state plasma test in the PLM-2. The peak power density during the e-beam pulses is about 300 MW·m⁻². This system will be complemented by a high power laser system for transient heating of the plasma-exposed surface. This provides the opportunity to compare the damages induced by a steady state plasma and heating induced by the laser. Flexible target system and active cooling with dispersive flux make PLM-2 a unique facility to study the power handling of candidate plasma-facing fusion materials and components. The main work presently focuses on the design criteria also improvements the PLM plasma device. In the next year, the construction of vacuum and magnet systems should provide the start up operation and commissioning of the PLM-2.

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