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High heat flux capabilities of the Magnum-PSI linear plasma device

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ABSTRACT

Magnum-PSI is an advanced linear plasma device uniquely capable of producing plasma conditions similar to those expected in the divertor of ITER both steady-state and transients. 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. To study the effects of transient heat loads on a plasma-facing surface, a novel pulsed plasma source system as well as a high power laser is available. In this article, we will describe the capabilities of Magnum-PSI for high-heat flux tests of plasma-facing materials.

1. Introduction

The divertor plasma in ITER will be characterized by a high density ($\geq 10^{21}$ m^{-3}) and a low electron temperature ($T_e \leq 5$ eV) leading to high heat (≥ 10 MW m^{-2}) and particle fluxes (up to 10^{24} m^{-2} s^{-1} or 1.6×10^5A m^{-2}) [1]. Assuming ion acceleration in the electrostatic sheath, the ions will have energies below 50 eV, at the divertor strike-point. In addition, the very high transient localized heat fluxes caused by so-called Edge Localized Modes (several GW m^{-2} for 0.5–1 ms) is high enough to lead to material erosion, melting and vaporization for most materials, and represent a serious concern for the lifetime of the plasma-facing components.

The understanding and control of plasma–wall interactions is of paramount importance for the successful deployment of nuclear fusion energy and rely on facilities able to reproduce the expected plasma conditions. However, with the exception of the Alcator C-Mod tokamak [2], neither existing tokamaks nor laboratory devices were capable of mimicking closely enough the conditions expected in future fusion reactors. Linear plasma generators, such as the PISCES facilities at UC San Diego [3,4] or the NAGDIS facilities at the University of Nagoya [5], have long been used for the study of plasma–surface interactions under fusion-relevant conditions. The achievable ion flux density in those devices is typically limited to 1×10^{23} m^{-2}s^{-1} in steady-state, a factor of 10 lower than what is expected in the divertor of ITER. In addition, it is currently not possible to generate very short (∼ms) high power density transient plasmas. Instead, high power lasers are used to combine a plasma environment and transient heat fluxes and get some insights into the effects of ELMs on plasma-exposed surface [6,7], albeit missing the transient particle flux associated with an ELM. Powerful plasma guns [8] can be used to study the effect of powerful transient plasma pulses on surfaces, albeit in the absence of continuous plasma loading. Filling the gap between those existing devices and future reactors lead to the development of the Magnum-PSI linear plasma generator [9,10] which began operations in the beginning of 2012 [11] and provides for the first time the combination of a high flux steady-state plasma and frequent ELM-like plasma pulses. An overview of the current status of Magnum-PSI can be found in [11]. In this contribution, we will focus on the description of the high-heat flux capabilities of the device.

2. Scientific purpose and design criteria of Magnum-PSI

2.1. The strongly-coupled regime

Magnum-PSI has been designed to study plasma–surface interactions under the so-called 'strongly-coupled' regime which is reached when the mean free-path of the particles released from the surface, via reflection or erosion, is smaller than the plasma size so that they are trapped in the plasma–surface interaction region. In the case of the chemical sputtering of graphite by hydrogen plasmas, for example, for $0.3\ \text{eV} \leq T_e \leq 2$ eV, the ionization of the

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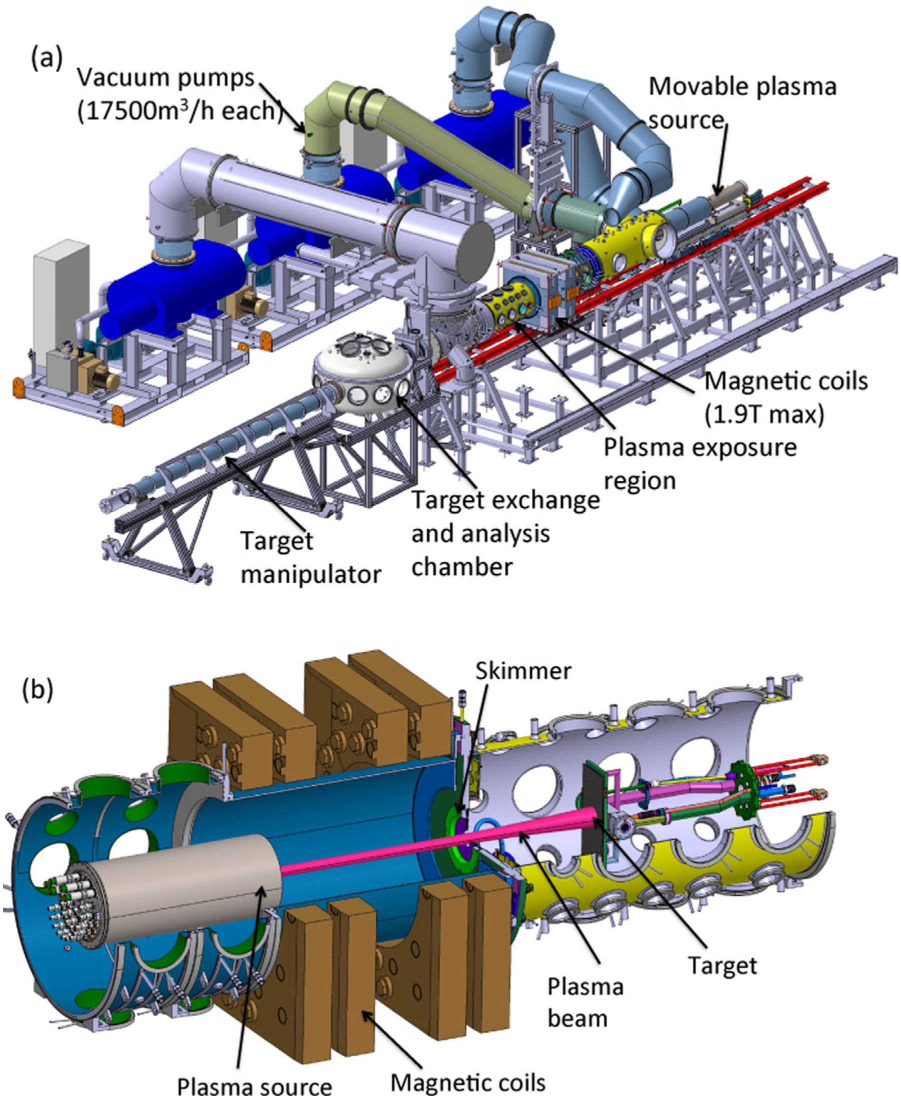

Fig. 1. Schematic overview of the Magnum-PSI linear plasma device. (a) Global view of the device with a description of the main components, (b) cut-out view through the vacuum vessel illustrating the geometry of the magnetic coil arrangement as well as a typical plasma exposure.

hydrocarbons released from the surface primarily occurs through charge exchange. The ionization mean-free path strongly depends on the plasma density in front of the surface and for instance decreases from 3.2 mm for $n_e = 1 \times 10^{20}\ m^{-3}$ to 0.8 mm for $n_e = 4 \times 10^{20}\ m^{-3}$. This has to be compared with the Full-Width at Half Maximum of the plasma beam which is about 25 mm in Magnum-PSI. As a consequence, every eroded particle will experience a cycle of erosion/re-deposition events before it can eventually escape the plasma beam. Modeling shows that every CH molecule eroded from the surface, for a density of $4 \times 10^{20}\ m^{-3}$, will visit the surface in average 19 times before actually escaping the plasma beam [12]. This gives rise to strong re-organization of carbon surfaces with the quick growth of large carbon particles which are re-deposited on the surface [13].

In addition, the particle flux to the surface is so high that every surface atom is visited by reactive particles from the plasma with a frequency higher than the inverse local surface relaxation time, driving the surface into states far from equilibrium. Low-energy ions (≤10 eV), having kinetic energies in the range of the interatomic binding energies, can transfer their energies very efficiently to surface atoms thus enhancing adatoms mobility, leading to enhanced surface diffusion and reactivity for example. Those conditions promote self-organization effects and the appearance of novel structures, an overview of which is presented in [14].

2.2. Design criteria

Magnum-PSI was designed to generate plasma conditions similar to those expected in the divertor of ITER, 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 as a process gas. The choice was made to use a high-pressure plasma source, the so-called cascaded arc source [15], which typically operates at pressures around 10^4 Pa, which is to be compared with the pressure of a few Pa in typical LaB_6 assisted arc discharges [3].
- Neutral pressure around the target determined almost entirely by the recycling at the target, i.e. that the influx of cold neutrals from the source should be negligible in front of the ion flux. This requires the use of differential pumping which has to be optimized for the high gas flows required for the plasma generation. More details about the design of the differential pumping can be found in [16].