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New linear plasma devices in the trilateral euregio cluster for an integrated approach to plasma surface interactions in fusion reactors

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ABSTRACT

New linear plasma devices are currently being constructed or planned in the Trilateral Euregio Cluster (TEC) to meet the challenges with respect to plasma surface interactions in DEMO and ITER: i) MAGNUM-PSI (FOM), a high particle and power flux device with super-conducting magnetic field coils which will reach ITER-like divertor conditions at high magnetic field, ii) the newly proposed linear plasma device JULE-PSI (FZJ), which will allow to expose toxic and neutron activated target samples to ITER-like fluences and ion energies including in vacuo analysis of neutron activated samples, and iii) the plasmatron VISION I, a compact plasma device which will be operated inside the tritium lab at SCK-CEN Mol, capable to investigate tritium plasmas and moderately activated wall materials. This contribution shows the capabilities of the new devices and their forerunner experiments (Pilot-PSI at FOM and PSI-2 Jülich at FZJ) in view of the main objectives of the new TEC program on plasma surface interactions.

1. Introduction

Plasma surface interactions will decisively determine the availability and thus the economy of a fusion reactor because of their impact on lifetime of the first wall (erosion) and on safety (tritium retention and dust production). In view of plasma surface interactions in ITER and DEMO new challenges have to be met:

- extended operational regimes with respect to particle and heat flux densities onto plasma facing components, both steady-state and transient:
- the use of toxic first wall materials (Be in ITER)
- the presence of Tritium
- the impact of neutron irradiation onto first wall material

To meet the challenges just described, the use of a large variety of facilities is needed: experiments on tokamaks and stellarators are necessary since the topology of the magnetic field plays an important role and the non-linear dependence between wall and plasma performance must be addressed. Dedicated plasma-wall interaction facilities on the other hand are important to address questions for which magnetic confinement devices are either not suitable at present (e.g. large fluences at steady state conditions) or not available (e.g. because of limited flexibility and time constraints). In addition, better diagnostic access in general allows more detailed investigations of dedicated PSI processes compared to what is possible in tokamaks or stellarators.

The Trilateral Euregio Cluster (TEC) will address the urgent research needs described before and exploit the capabilities of linear plasma facilities with a suite of new devices (MAGNUM-PSI at FOM, VISION I at SCK-CEN and JULE-PSI at FZJ), which are presented in this contribution with their forerunner experiments (Pilot-PSI at FOM and PSI-2 Jülich at FZJ).

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Table 1
Overview of the main specifications of the new linear devices in the TEC.

New challange	MAGNUM-PSI	JULE-PSI	VISION I
Reactor like divertor conditions (steady state loads)	Yes, divertor simulator	No, but reactor like plasma fluence and ion energies	No
Reactor like transient heat loads	Yes, pulsed plasma source under development	Yes, JUDITH (electron beam facility inside Hot Cell), additionally laser heat pulses in JULE-PSI	No
Tritium	No	No T-plasma but moderate T handling capabilities	Yes
Toxic materials (Be)	No	Yes	Yes
Neutron activated materials	No	Yes	Yes, but limited to moderately activated samples

The main objectives of the new TEC research program on plasma surface interactions are:

- Investigation of erosion and re-deposition for lifetime prediction of plasma facing components and contamination of plasma
- Investigation of tritium retention (and removal) for safety and fuel cycle
- Investigation of dust production for safety
- Investigation of structural integrity of the plasma facing components under the influence of high particle and heat fluxes including irradiation
- Investigation of processes in boundary plasma
- Development of advanced boundary plasma and plasma surface interaction diagnostics and control tools
- Development and validation of computational models for interpretation and prediction to fusion reactors

2. The TEC PSI facilities

The TEC research programme will be conducted with a suite of new and complementary devices to meet the urgent challenges described before, their characteristic properties for this mission are summarized in Table 1. As can be noted the devices can altogether address all challenges stated before, and the plasmas can cover the conditions in ITER with respect to particle flux density and ion energy ($E_i = 3T_e + 2T_i$) from the wall to the divertor strike zones (parameters taken from [1], cf. Fig. 1).

Note, that the attainment of higher ion energies in linear devices requires target biasing or additional RF heating (as foreseen in MAGNUM-PSI [4]) and that the particle flux densities depicted are normal to the target surfaces. The very particle high fluxes delivered from the cascaded arc source in MAGNUM-PSI will allow to realize ITER flux conditions at inclined surfaces because it matches both densities and temperatures of the ITER divertor strike point as seen in Fig. 2. Here, ITER parameters are show in comparison to the plasma parameters already realized in the forerunner experiments PILOT-PSI and PSI-2.

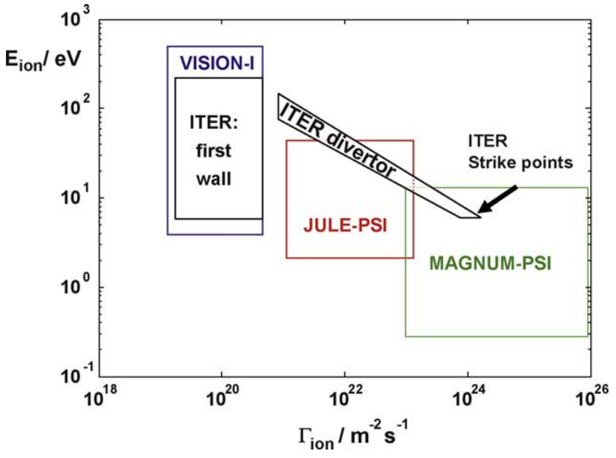

Fig. 1. Parameter range of plasma flux density and ion energies for the new TEC devices in comparison to plasma parameters expected at the wall and in the divertor of ITER (taken from [1]).

2.1. MAGNUM-PSI

The MAGNUM-PSI machine at FOM (cf. [4] for an extended description of the device), currently under constructions at FOM Rijnhuizen, The Netherlands, will employ a high-pressure cascaded arc source [5]. A prototype of the source has successfully been tested at the Pilot-PSI machine [6], the forerunner of MAGNUM-PSI and proved the plasma parameters anticipated for MAGNUM-PSI and listed in Table 2.

The plasma in MAGNUM-PSI is magnetized, steady-state ($B = 3T$, generated by SC coils) with a large cross section (80 cm^2), characterized by high particle flux (up to 10^{25} H$^+$ ions $m - 2s - 1$ at normal incidence) and simulates the conditions expected in the ITER divertor. It will allow to investigate both the processes in the plasma (including detachment) and at the surface. The resulting steady state heat flux density of up to 40 MWm^{-2} perpendicular to the targets facilities reactor relevant heat flux tests. Moreover, a pulsed operation mode of the source is under development aiming at a transient power flux density of 2 GWm^{-2} for 0.5 ms to simulate transient loads [7]. Neutron damaged or toxic material cannot be handled but it is envisaged to simulate the impact of neutron activation by in situ high energy ion beam irradiation [4].

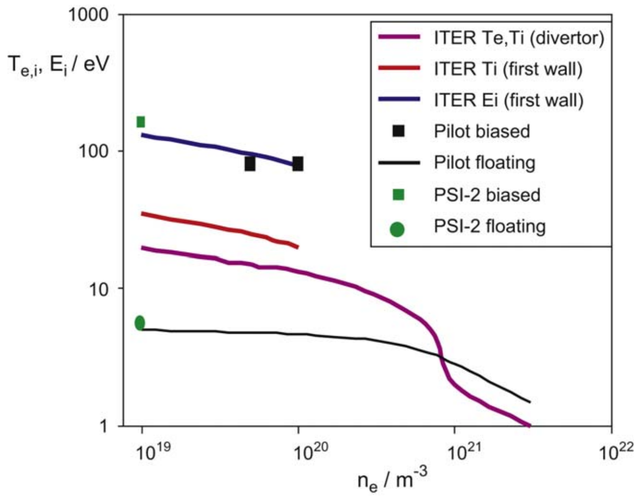

Fig. 2. Parameter range of electron densities, temperatures and ion energies for the forerunner devices Pilot-PSI [4] and PSI-2 [3] in comparison to plasma parameters expected in t ITER (taken from [2] [1]).

Table 2
Plasma parameters in front of the target of the new TEC devices (following the description in [13]): n_e – electron density, $T_{e,i}$ – electron and ion temperature, Γ^+ – ion flux density, p_n – neutral pressure, B – magnetic field, d – plasma diameter.

	MAGNUM-PSI	JULE-PSI	VISION I
$n_e(\mathrm{m}^{-3})$	$10^{19}-10^{21}$	$10^{17}-10^{19}$	$10^{16}-10^{17}$
$T_e(\mathrm{eV})$	0.1 – 10	1 – 20	5–20
$T_i(eV)$	$\simeq T_e$ higher E_i with biasing	$\simeq 0.5T_e$ higher E_i with biasing	50–500 using biasing
$\Gamma^+(\mathrm{m}^{-2}\mathrm{s}^{-1})$	10^{23}–10^{25}	10^{21}–10^{23}	10^{20}–10^{21}
$p_n(\mathrm{Pa})$	<3	0.01	0.05–0.5
$B\,(\mathrm{T})$	3.0	0.1	0.2
d/mm	100–150	60–150	250

MAGNUM-PSI is equipped with a flexible target system consisting of a user-defined target head, a target manipulator and a target exchange chamber, which allows for unique flexibility to investigate different target materials and to handle inclined targets.

2.2. JULE-PSI and JUDITH

A new laboratory to study plasma-surface interactions with both toxic and neutron activated materials is planned in the Hot Material Laboratory of FZJ. The concept consists of

- A target exchange and surface analysis chamber for activated and toxic materials equipped with laser aided diagnostics (Laser induced desorption, laser induced ablation and laser induced breakdown spectroscopy, cf. [8] [9]) to determine fuel content and material composition. Both the plasma device and the analysis chamber shall be located inside a Hot Cell.
- A linear plasma device equipped with the target exchange chamber to expose neutron activated and toxic PFC samples to reactor-relevant plasma fluences and ion energies (JULE-PSI).
- A non-nuclear twin device to JULE-PSI not located inside the Hot Cell but in the same building (a controlled area). Both twins share the high power diagnostic lasers and the power supplies.

The specific scientific objectives of the linear plasma device JULE-PSI and of the integrated surface analysis station are investigations on:

- Erosion of n-damaged plasma facing components (PFCs), the impact on surface morphology/microstructure
- Fuel retention of n-damaged PFCs
- Plasma surface interaction with Be
- Mixed systems (Be–W–C), re-erosion of deposits
- Fuel retention in W–Be compounds
- Influence of surface temperature on plasma surface interaction
- Combination of high heat loads and plasma exposure, synergistic effects
- Analysis of Be/T samples (JET, ITER): surface characterization and fuel inventory
- Fuel removal with use of toxic reactive gases

Fig. 3 shows a sketch of the JULE-PSI device with the target exchange chamber attached, Fig. 4 illustrates the arrangement of the laser-based surface diagnostics foreseen for JULE-PSI.

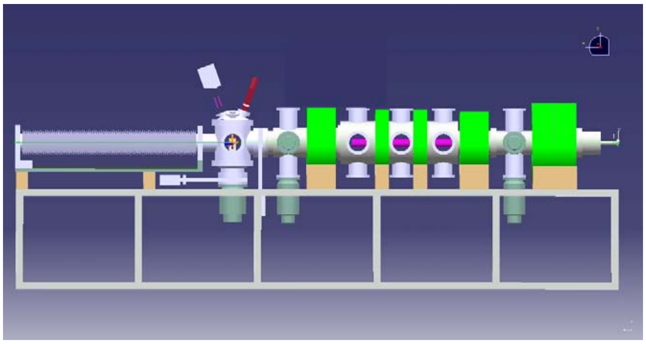

Fig. 3. Sketch of JULE-PSI with the linear plasma generator, the target analysis and exchange chamber and the target manipulator (from right to left).

To meet these objectives JULE-PSI will be a steady state linear plasma generator based on a low pressure high current arc discharge, which allows for reactor relevant particle fluence and ion energies. It is based the PSI-2 Berlin device [10] which has been moved from Berlin to Jülich and been assembled as PSI-2 Jülich to provide a test bed for JULE-PSI. Operation of PSI-2 Jülich has started in January 2011. The stationary plasma is produced between a cylindrical, heated cathode made from LaB_6 (heating power of the cathode 6.5 kW, discharge current up to 1000 A, discharge voltage up to 200 V) and a hollow anode made of Mo. The use of a planar cathode is under consideration to improve the homogeneity of the plasma cross section.

From the source region the plasma is guided by an axial magnetic field of 0.1 T (produced by copper coils) towards the target region. The particle flux density can reach up to $10^{23}\,\mathrm{m}^{-2}\mathrm{s}^{-1}$ (normal incidence with respect to the target and a factor 10 below the flux densities expected for the ITER strike points), the heat flux density up to $1\,\mathrm{MWm}^{-2}$, the plasma diameter amounts to 50–150 mm (cf. also Table 2). ITER relevant particle fluences of $10^{27}\,\mathrm{m}^{-2}$ (one ITER discharge in the $Q = 10$ inductively driven scenario) can thus be obtained in about 3 h plasma duration in the PSI-2 device.

The targets will be heatable to temperatures above 1000 °C to investigate the effects of hot walls in a DEMO type reactor. In contrast and complementary to MAGNUM-PSI, JULE-PSI is not foreseen as a divertor simulator, as heavy particles are not magnetized in the moderate magnetic field and neutrals recycling at or eroded from the material surface are not ionized close to the target to a large extent. The non-nuclear twin device outside the Hot Cell aims at a more detailed plasma characterization with plasma diagnostics which cannot be integrated into the Hot Cell because of complexity and maintenance issues and to expose non-activated reference samples.

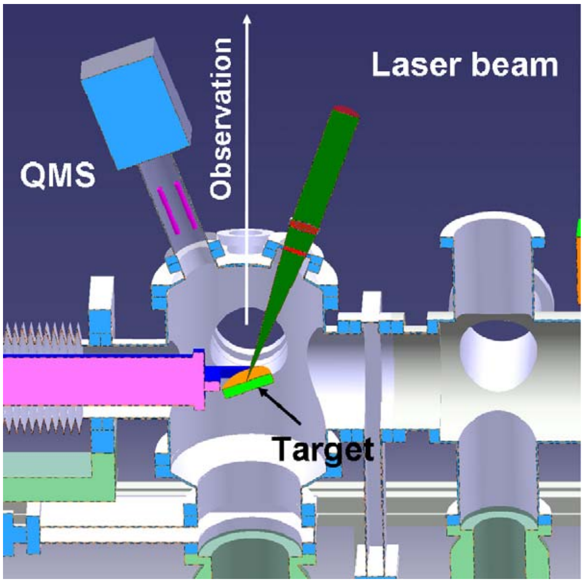

Fig. 4. Arrangement for laser-aided sample analysis in the target chamber of JULE-PSI.

The high heat flux e-beam test facilities JUDITH-1 and JUDITH-2 are already existing at FZJ. They are used for both cyclic, quasi-stationary thermal loads up to approximately 1 MWm^{-2} and transient thermal loads with extreme power densities in the GWm^{-2} range and pulse durations of a few milliseconds or shorter to simulate ELMs are applied (cf. [11] for a technical description). One of the e-beam facilities (JUDITH-1) is and will be operated inside a Hot Cell, the second e-beam facility (JUDITH-2) is located in a controlled area but outside the Hot Cells and can test Be samples already now. Together with the new plasma device described before, comprehensive PSI studies on neutron activated and toxic fusion materials with special emphasis on synergistic effects will be possible including a thorough diagnostic coverage. The neutron irradiation has to take place off-site within the current concept (e.g. in nuclear fission reactors for the initial years of operation).

The assembly of the forerunner experiment PSI-2 Jülich is currently (September 2010) close to completion, commissioning and first plasma operation are planned for end of 2010. Operation of PSI-2 Jülich aims to assess the reliability of the plasma device (especially the source) needed for a later operation of JULE-PSI inside a Hot Cell, and to test a prototype target exchange and analysis chamber and the diagnostic set-foreseen for the later application at JULE-PSI. While the in situ characterization of the PSI processes is carried out by means of optical spectroscopy and Quartz-Micro-Balance (QMS) [12], the in-vacua sample analysis will be performed by laser aided diagnostics (Laser induced desorption, LID, laser induced ablation, LIA and laser induced breakdown spectroscopy, LIBS, cf. [8] [9]) to determine fuel content and material composition. For that purpose, two Nd:YAG lasers are available at FZJ (LID-QMS: pulse energy > 100 J, pulse duration 1 – 3 ms, detection of the desorbed fuel gas by Quadrupol Mass Spectrometry (QMS), LIA-QMS, LIBS: pulse energy > 5 J, pulse duration <15 ns, detection via line-of-sight QMS for LIA, optical spectroscopy for LIBS, cf. [9] for details).

In parallel to the construction and commissioning of PSI-2 Jülich, the HML (Hot Material Laboratory) building is undergoing a substantial refurbishment (replacement of the ventilation) which is scheduled until end of 2011. Design and construction of JULE-PSI is currently being planned to be finalized until 2015.

2.3. VISION I

The plasmatron VISION I [13] located at SCK-CEN MOL (B) will allow to study plasma surface interactions with Beryllium and Tritium contaminations and moderately activated samples. The plasmatron can produce plasmas with a flux density up to 10^{21} m^{-2}s^{-1} corresponding to typical plasma conditions close to the ITER first wall. The energy of ions hitting the target with a diameter of 250 mm can be increased by biasing up to 500 eV. The steady-state plasma is generated between two heated W cathods and a water-cooled anode with permanent magnets on the external surface to provide a multipolar magnetic field of 0.2 T. The device has been commissioned with Ar, D and D/He plasmas outside the T laboratory beginning of 2010 and is now already moved to the T laboratory but licensing is still ongoing to operate with tritium plasma.

Preliminary studies of deuterium retention in W–Ta alloys were performed with the plasmatron VISION I [14]. The special configuration of the plasma generation in VISION I is very compact but the comparison of the results obtained with literature proved to give reliable measurements.

3. Summary and outlook

Linear plasma devices are capable to meet important challenges for PSI research in support of ITER and DEMO. We have described the complementary characteristics of three new linear plasma devices in the Trilateral Euregio Cluster (MAGNUM-PSI, JULE-PSI/JUDITH and VISION I). This devices are embedded into excellent infrastructure for modeling diagnostics and analysis an nuclear operation. They provide a unique combination of specific capabilities to close knowledge gaps for plasma surface interaction in future fusion reactors related to extended power and particle flux regimes and nuclear operation, which cannot be closed on toroidal confinement devices prior to ITER and a future nuclear device such as DEMO.

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