REACTOR-RELEVANT PLASMA-MATERIAL INTERACTION STUDIES IN LINEAR PLASMA DEVICES

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The article provides an overview on the reactor-relevant plasma-material interaction studies in linear plasma devices. The studies contribute to solving critical problems of tokamak-based fusion reactors and are complimentary to the research in the present tokamaks. Unique capabilities of particular linear plasma devices allow them to treat specific issues of plasma-material interactions in ITER and future reactors. Several examples of this research are given. The prospects of the research in new devices are outlined.

I. INTRODUCTION

Plasma-wall interaction (PWI) is one of the most critical issues with respect to the performance, safety and availability of ITER and future fusion reactors[1]. The plasma-wall conditions in a tokamak reactor are defined by high particle and heat fluxes to the wall, both steady-state and in transient events, i.e. edge-localised modes (ELMs) and disruptions. The wall will be eroded under the bombardment by the plasma. The eroded materials will be transported within the plasma chamber and re-deposited, particularly on remote wall components. Here, a significant amount of radioactive tritium can be stored through co-deposition.

The presence of impurities will influence the PWI processes by both physical and chemical interactions. Carbon, tungsten, beryllium, helium and divertor cooling species (argon, neon or nitrogen) will be present as impurities in the ITER plasma[1].

High-energy neutrons from the fusion reactions can lead to a change of structural properties of the wall materials, such as embrittlement and swelling. In ITER, the expected fluence of neutrons is rather low (~1 dpa) and is not considered as a threat. In contrast, in a future full-scale reactor during its total operation time the dose will exceed 100 dpa, having significant consequences for the wall performance.

These PWI processes can lead to reduced availability of ITER and future reactors through the shortened lifetime of the wall components and through the limitations by safety regulations, including the restricted amount of tritium retention and dust production. These issues need urgently to be addressed, both in the experiments and by the modelling, to improve the predictions and to optimize the solutions for ITER and beyond it.

Modern large-scale tokamaks are close to ITER with respect to many relevant discharge parameters, such as operational scenario of H-mode and magnetic field configuration. However, there are still significant gaps for some crucial PWI factors, like ion fluxes and fluences at the strike point, temperature of the plasma-facing components, use of activated materials and elementary composition of the plasma and the wall. Linear Plasma Devices (LPDs) offer the possibility of closing these research gaps at moderate costs. The versatility of LPDs to produce stable, steady-state multi-species plasmas is unique. The materials of choice can be exposed to the pre-selected conditions to simulate the environment of the reactor plasma boundary.

There are many facets of the reactor-relevant PWI research. They range from very plasma-specific (e.g. impurity transport in a tokamak) to very material-specific (e.g. development of new materials) and wall-component-specific (e.g. testing of wall components in high-heat-flux facilities). The focus of this contribution is on the plasma-material interaction (PMI) studies, i.e. what happens to the materials under the plasma exposure with reactor-relevant conditions. The contribution provides an overview on the PMI-oriented research in LPDs, including the recent scientific highlights and the prospects of LPDs in contributing to the solution of the wall material problems for fusion reactors.

II. PMI RESEARCH IN LINEAR PLASMA DEVICES

II.A. Schematic View of Linear Plasma Device and Parameters of Material Exposure

There is a variety of set-ups of LPDs including different types of plasma sources, magnetic field configurations, vacuum systems and material target manipulators. However, the general set-up for a PMI experiment in LPD is rather simple. It consists of a

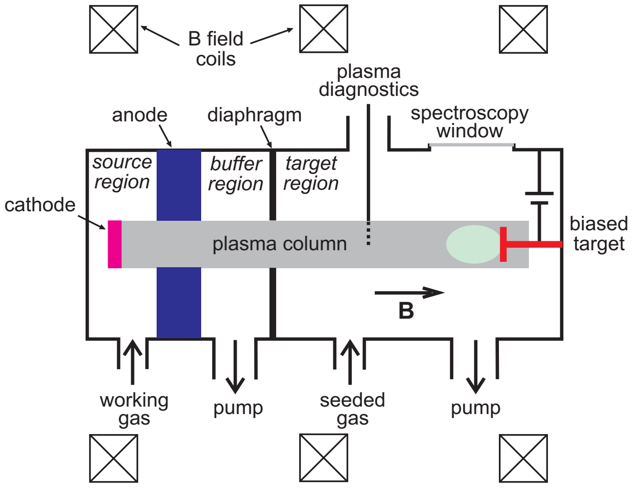

Fig. 1. Schematic view of a linear plasma device for PMI studies.

cylindrical vacuum chamber within a solenoid (Fig. 1). The vacuum chamber is usually subdivided in several regions. In the source region, the plasma column is formed, then proceeding through the buffer towards the target region along the B field. The buffer and target regions are separated by a vacuum diaphragm to allow for the differential pumping of the introduced gas. The necessity of the differential pumping is given by the different requirements for the optimal gas pressures in the plasma source and at the target. In the target region, the plasma parameters are measured, e.g., by a Langmuir probe or by a Thomson scattering diagnostic. The region of the plasma-target interaction is usually monitored by various spectroscopic methods.

The present generation of the LPDs, such as PISCES-A[2] and –B[3,4] at the University of California in San Diego, USA, NAGDIS-I[5] and –II[6] at the Nagoya University, Japan, and PSI-2[7,8], formerly at the Max-Planck Institute for Plasma Physics in Berlin, now been reassembled at the Forschungszentrum Juelich, Germany, typically incorporate an arc DC plasma generator with heated LaB_6 cathode (see section II.B) and a plasma chamber with a solenoidal magnetic field of ~0.1 T. A plasma column of ~10 cm in diameter is formed to uniformly expose material samples of several cm size. The typical ionization degree is of a few percent.

The exposure parameters in LPDs can not completely match the conditions in a tokamak, i.e. the complexity of the magnetic field configuration of a divertor. However, the PMI relevant parameters of material exposure in present LPDs come quite close to the conditions expected in the ITER divertor (Table I). Even if the particle density and, therefore, the flux is about one order of magnitude smaller than at the strike point in ITER, it can be compensated for the total dose by a long, several hours, exposure, gaining a fluence corresponding to about one ITER pulse. The incident ion energy can be varied by applying a negative target biasing. The material sample temperature can be controlled by adjusting the heating by plasma and external heating and cooling of the target. The plasma species composition can be changed using the external gas seeding. The heat pulses produced by transient events in tokamaks can be simulated in the LPD by a special bias scenario or by high-power laser pulses. An overview of plasma parameters and experimental capabilities of several LPDs can be found in Ref. 9.

TABLE I. Typical parameters of material exposure in LPDs compared to the conditions in the ITER divertor.

Parameter	Typical LPD	ITER divertor
El. temperature	1 – 20 eV	1 – 10 eV
El. density	$10^{18} - 10^{19}$ m^{-3}	~10^{20} m^{-3}
Ion flux	<~10^{23} m^{-2}s^{-1}	$10^{24} - 10^{25}$ m^{-2}s^{-1}
Ion fluence	<~10^{27} m^{-2} per exposure	$10^{26} - 10^{27}$ m^{-2} per 400 s pulse
Incident ion energy	~10 – 100 eV (negative bias)	~10 eV
Wall (sample) temperature	300 – 2000 K	500 – 1000 K
Impurities	All relevant	C, Be, W, He, Ar, N_2

Obviously, the PMI research in LPDs and tokamaks is complimentary. LPDs have, however, some advantages with respect to present tokamaks.

- In present LPDs ion fluences relevant to the ITER divertor can be reached, while in present tokamaks the typical fluence is one or two orders of magnitude lower.
- The research in LPDs is very flexible. It includes good control and reproducibility of exposure parameters. Independent parameter variations in a multi-dimensional parameter space are possible. The LPDs have generally better accessibility and higher reliability and better capabilities of the in-situ sample analyses.
- The PMI research in LPDs is more cost efficient than in tokamaks. Both the costs of construction and of exploitation are much higher for tokamaks.

II.B. Plasma Source

Most of the present LPDs employ a DC arc plasma generator with a heatable LaB_6 cathode (see e.g. Ref. 10 for the description of the PISCES plasma source). The schematic view of this type of plasma source is shown in Fig. 2. The LaB_6 cathode is typically disc-shaped with a diameter of ~10 cm. The cathode is heated up to a temperature of 1900 K by a tungsten or carbon heater of several kW power. At this temperature, LaB_6 emits an electron current of 20 A/cm^2. The anode is a piece of tube in the simplest case. In some devices, the anode is shaped according to the geometry of the magnetic field to optimize the plasma production and reduce the erosion of the anode material. The anode is usually grounded, while the cathode unit is put at a negative potential. An arc

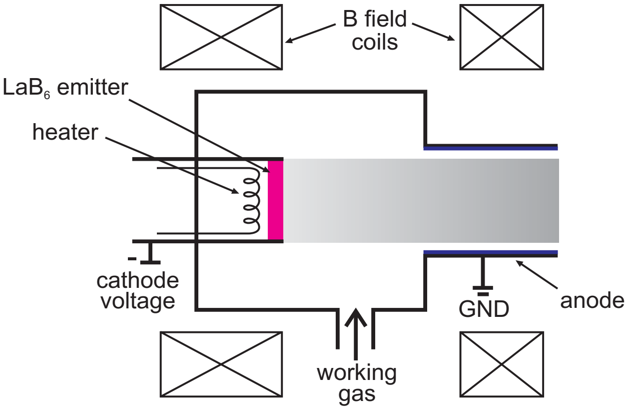

Fig. 2. Schematic view of an arc discharge type plasma generator with a heatable LaB_6 cathode.

current of up to ~1 kA can be drawn at a voltage of a few 100 V. To remove the heat in the steady-state operation, water cooling is applied to all relevant components.

Some new LPD projects, aiming at increasing the plasma production rates to match the flux in the ITER divertor of ~10^{24} $m^{-2}s^{-1}$, will incorporate alternative types of plasma generators. The Magnum-PSI machine[11], currently under constructions at FOM Rijnhuizen, The Netherlands, will employ a high-pressure cascaded arc source[12]. A prototype of the source[13] has successfully been tested at the Pilot-PSI machine[14], the forerunner of Magnum-PSI. For the PMTS project[15] in Oak Ridge National Laboratory, USA, the installation of a helicon plasma source is planned.

II.C. Analysis of Material Samples

The material surface changes its elementary composition, chemical state and morphology under plasma bombardment. The material can be eroded or, on the contrary, a layer of deposition can appear on its surface. To get the full picture of what happens to the material during the exposure, it is important to collect as much data as possible by various surface analysis techniques. Many of the techniques include a model to transfer the directly measured quantities into the sought-after parameters. For example, in the optical ellipsometry a model of the light propagation in thin layers is needed to transfer the measured parameters of light polarisation into the layer thickness and the coefficients of refraction and absorption. Those models rely on correct and precise input parameters. Therefore, a cross-check of the determined quantities between various methods is desirable.

The laser beam based techniques, such as laser induced desorption spectroscopy (LIDS), laser induced ablation spectroscopy (LIAS) and laser induced breakdown spectroscopy (LIBS) are a powerful tool to determine the amount of stored hydrogen in the samples (LIDS), their chemical composition in the presence of the background plasma (LIAS) or in the plasma locally created by the laser beam itself (LIBS)[16].

Ion beam analysis (IBA) techniques rely on a high energy (~1 MeV) ion beam. They include nuclear reaction analysis (NRA), Rutherford back-scattering (RBS), proton induced X-ray emission (PIXE) and enhanced proton scattering (EPS) and allow for a quantification of the material composition.

Electron beam based techniques include scanning electron microscopy (SEM), energy- and wavelength-dispersive X-ray spectroscopy (EDX and WDX, respectively) and Auger electron spectroscopy (AES). SEM, EDX and WDX are often combined in one single analysis device. SEM is used to visualize the surface structure with a resolution down to ~1 nm, while EDX, WDX and AES are used to determine the chemical composition of the sample.

X-ray photoelectron spectroscopy (XPS) and X-ray diffraction analysis (XRD) are two examples of X-ray based techniques. XPS provides the elementary composition as well as the chemical state, e.g. carbidization, of materials. XRD detects the crystalline structure of materials.

Other frequently applied techniques are thermal desorption spectrometry (TDS) for the analysis of the hydrogen retention in samples, secondary ion mass spectrometry (SIMS) for the depth resolved material composition, weight-loss measurements by high precision balances and surface profilometry by mechanical and optical tools.

The sample surface gets deactivated and impurity contaminated when exposed to the air after the experiment. Therefore, the immediate analysis of the samples during or after the experiments is desirable. According to where and when the material analysis occurs, it can be separated in in-situ, in-vacuo and ex-situ analysis. The in-situ analysis is the real-time measurement of material surface properties during the exposure. The in-vacuo analysis occurs after the experiment, but without exposing the sample to the air. The ex-situ analysis is conducted after the transportation of the samples in the air; it is often referred to as post-mortem analysis.

An example of in-situ analysis in the DIONISOS facility[17] at MIT, USA is given in Fig. 3(a). Here, an ion beam accelerator is used for the ion beam analysis simultaneously with the plasma exposure. Fig. 3(b) shows the in-vacuo surface analysis station of PISCES-B[4]. The samples are extracted from the target station by a swing-linear manipulator and inserted in the surface analysis station, where AES, XPS and SIMS techniques can be applied.

Despite their advantages, in-situ and in-vacuo analysis solutions have drawbacks of high complexity and costs. Therefore, most of the experiments still rely on the ex-situ analysis techniques. Another reason for the

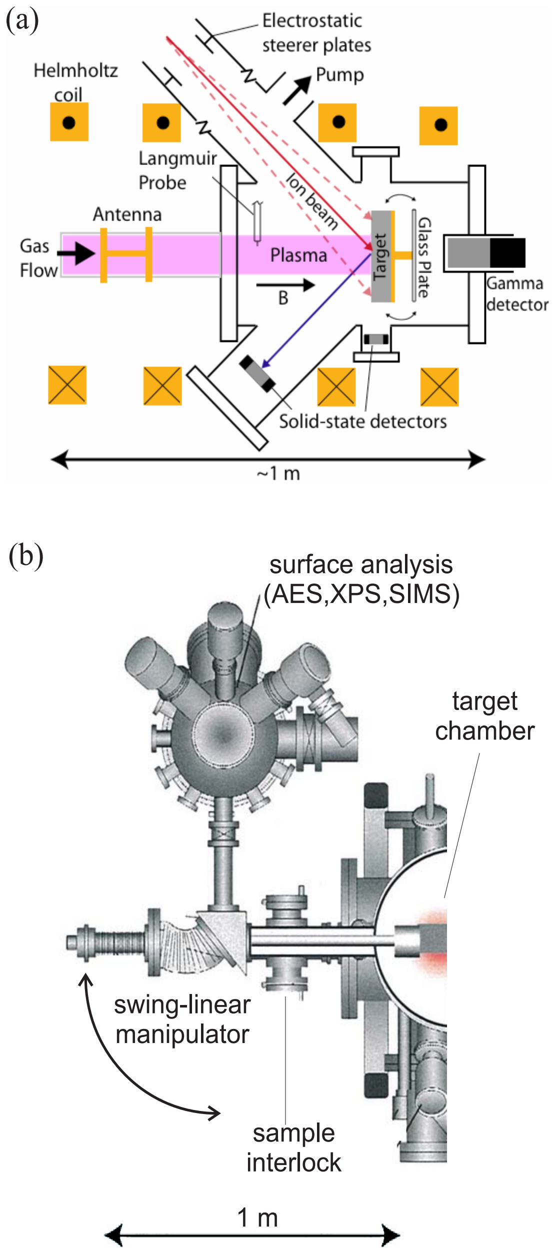

Fig. 3. (a) in-situ IBA in DIONISOS[17]; (b) in-vacuo analysis of PISCES-B[4].

frequent use of ex-situ is that the material samples can be mailed to a laboratory specializing in the particular analysis technique, thus increasing the quality of analysis.

II.D. Examples of PMI Research in Linear Plasma Devices

As it has been stated in section II.A, the main advantages of LPDs with respect to modern tokamaks are high particle fluence and well-controlled exposure conditions, i.e. plasma composition, incident ion energy and sample temperature. Therefore, the research in LPDs is often aimed at effects distinctive for high fluence or specific exposure conditions. Topics of high importance for ITER, such as carbon chemical erosion[8,18], high-Z material blistering[19-22] and W-fuzz formation by He irradiation[23,24], have been studied across different LPDs.

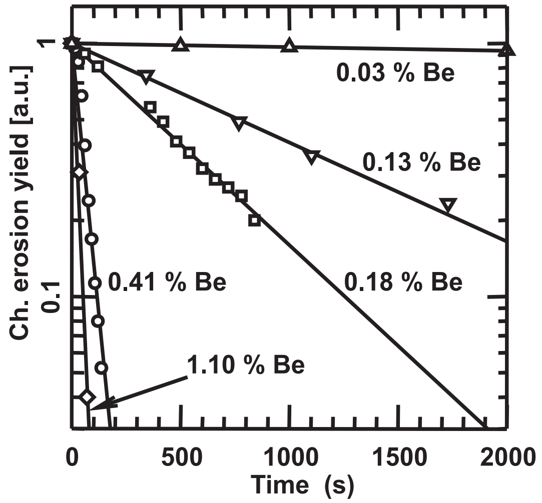

Fig. 4. Mitigation of chemical erosion of carbon by beryllium seeding in PISCES-B[25].

Of special importance are unique features of particular LPDs, resulting in their specific scientific missions. One example is the capability of the PISCES-B device to operate with beryllium[4]. Special safety requirements have to be fulfilled when operating with Be because of its toxicity. PISCES-B is installed in an air-tight enclosure with a secured access for personnel through a lock system. Be is introduced in the plasma by a high-temperature effusion cell. It has been found in the experiments with a graphite target and deuterium plasma that the yield of chemical erosion of carbon Y_{ch} decays exponentially after the start of Be seeding[25,26] (Fig. 4). The characteristic time τ of the decay can be described as

$$\frac{1}{\tau} \propto f_{Be}^{2} \times \exp\left(-\frac{E_a}{T_s}\right) \qquad (1),$$

where f_{Be} is the concentration of Be in the plasma, E_a is the effective activation energy of the process and T_s is the surface temperature. The effect of chemical erosion mitigation has been attributed to the formation of a protective Be carbide layer and is potentially favourable for ITER.

The addition of Be to the plasma has also an influence on the D retention in graphite samples[27] (Fig. 5). The beryllium seeding results in a formation of a protective beryllium carbide layer, which appears to prevent the in-bulk diffusion of deuterium, thus reducing the retention. Admixture of He reduces the retention especially effective at the ITER relevant low ion impact energies E_i.

The NAGDIS-II facility employs a high-pressure

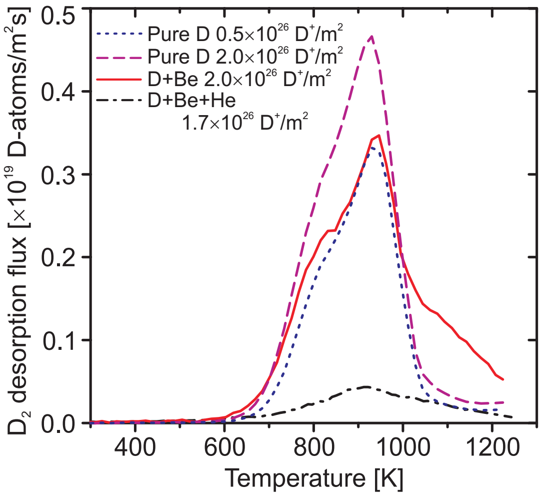

Fig. 5. TDS spectra of mass 4 (D_2) from ATJ graphite samples exposed to pure D plasma with a D fluence of $\Phi = 0.5\times10^{26}$ m^{-2} (dotted line), pure D plasma with $\Phi = 2\times10^{26}$ m^{-2} (dashed line), Be containing plasma with $\Phi = 2\times10^{26}$ m^{-2} (full line) and mixed D/Be/He plasma with $\Phi = 1.7\times10^{26}$ m^{-2} (dashed-dotted line). All exposures were done at $T_s = 720$ K and $E_i = 35$ eV.

plasma generator[6] which allows the device to reach an electron density of up to 10^{20} m^{-3}. At these high densities the physics of plasma detachment, crucial for the operation of the ITER divertor, can be studied.

The Pilot-PSI device[14], the forerunner experiment of Magnum-PSI, can operate in a pulsed regime with a magnetic field of up to 1.6 T, producing an ion flux of up to 10^{25} m^{-2}s^{-1}. Pilot-PSI is thus contributing to the PMI research at ITER-relevant high particle fluxes. In particular, the database for the flux dependence of the carbon chemical erosion has significantly been extended with the Pilot-PSI data[28].

As it was mentioned in section II.C, the DIONISOS experiment is equipped with a high-voltage ion beam accelerator[17]. Not only it is used to investigate the dynamics of PMI processes by the in-situ ion beam analyses, it also provides an option to study the effects of the material irradiation by the beam particles. Such studies are important in view of material damage by the high-energy neutron irradiation in fusion reactors.

The TPE device[29] in Idaho National Laboratory, USA is installed inside a compact air-tight enclosure, glove box, and is, therefore, capable of operating with moderate amounts of tritium and low-activated material samples.

Mirror confinement type devices are also contributing to the reactor relevant PMI research by using their high particle and heat flux plasmas. In the GOL-3 multi-mirror trap at the Budker Institute in Novosibirsk, Russia, ITER relevant studies on the influence of simulated type-I ELMs on tungsten[30] and carbon-based materials[31] have been carried out. The Gamma 10 tandem mirror device at the Tsukuba University in Japan has recently initiated a project on PMI studies using one of the ends of the device as a source of a large diameter high heat plasma flow (E-Divertor project)[32,33]. Additionally, a novel divertor should be installed in the anchor region of Gamma 10 (A-Divertor) to combine the advantages of the axisymmetric mirror geometry with the tokamak-like divertor geometry.

II.E. Modelling of PMI in Linear Plasma Devices

To compare the experimental results from different devices, LPDs as well as tokamaks, numerical simulations are used. The simulation models are validated by benchmarking against experiments and then applied to the predictive modelling for next-step devices. One of the most frequently used PMI modelling tools, the 3D Monte-Carlo code ERO, has been adapted for the linear geometry and used for the simulation of experiments in PISCES-B and Pilot-PSI[34].

II.F. Prospects of PMI Research in Linear Plasma Devices

The next-generation LPDs are aimed to fill specific gaps in the PMI research towards ITER and the reactor. One of such scientific gaps are particle and heat fluxes in present LPDs lower by about one order of magnitude than in ITER (cf. section II.A). To increase these parameters, operation in a high magnetic field with a novel plasma source and additional plasma heating is necessary. The Magnum-PSI machine[11] will incorporate a high-pressure cascaded arc ion source and superconducting magnetic field coils, producing a steady-state field of 3 T. The plasma will additionally be heated ohmically and by a helicon wave. The projected electron density of ~10^{20} m^{-3} and temperature of 1–5 eV are relevant to the ITER divertor. The target will be inclined to simulate the divertor geometry. Magnum-PSI will be able to produce a particle flux of ~10^{24} m^{-2}s^{-1} and a heat flux of ~10 MW/m^2.

The PALOMA project is the PMI part of the integral fusion technology project TechnoFusion proposed in Spain[35]. PALOMA will incorporate a LPD based on the Magnum-PSI and Pilot-PSI technology of the cascaded arc plasma source and a high (~1 T) superconducting magnetic field, combined with a quasi-stationary plasma accelerator (QSPA).

The PMTS project[15] will use a helicon plasma source with additional RF heating. After the initial phase with copper magnets the installation of superconducting coils for a field of ~1 T is foreseen. Projected are an ion flux of up to 10^{24} m^{-2}s^{-1} and a heat flux of up to 20 MW/m^2.

Another scientific gap on the road to the fusion reactor is the testing of materials pre-exposed to high-energy neutrons. After the neutron irradiation the materials are activated and subjected to corresponding safety restrictions. The devices for the testing of such materials must be installed inside a glove box in the case of a moderate level of radioactivity or inside a hot cell when operating with highly radioactive samples. Hot cells are shielded nuclear radiation containment chambers. Lead is usually used as the shielding material.

The plasmatron VISION I[9] will be installed inside a glove box at the Belgian Nuclear Research Centre in Mol. It will be capable of operating with beryllium, tritium and neutron irradiated samples.

The JULE-PSI project, currently in planning at Forschungszentrum Juelich, Germany, envisages a LPD installed in the hot cell with an integrated in-vacuo analysis station. It will be capable of using toxic and highly activated materials to contribute in this reactor-relevant PMI field. The PSI-2 device[8] has been transferred to Juelich for the use as the pilot experiment outside the hot cell. Components and technological solutions will be tested at this “cold” device before transferring them to the JULE-PSI device in the hot cell.

III. SUMMARY

Linear plasma devices provide unique capabilities for the reactor-relevant PMI research. The research in LPDs is both flexible and cost-effective and is complimentary to the studies in present tokamaks. The value of the research in LPDs increases if it is aimed at specific open issues for ITER and the reactor. The main purpose of the new generation of LPDs is to close the scientific gaps on the road to the reactor, such as high particle and heat fluxes and the performance of neutron irradiated materials. Mirror machines and other existing plasma devices can contribute to the reactor-relevant PMI research at moderate costs of hardware re-arrangement. To further improve the quality of the PMI studies in LPDs, the LPD-specific technology-oriented research is needed. It includes the development of novel plasma sources, solutions for vacuum systems to operate with high gas amounts, flexible target manipulators and in-situ/in-vacuo surface analysis methods.

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