PMTS2010: International Workshop on Requirements for Next Generation PSI Facilities in Fusion Research

Oak Ridge National Laboratory, Oak Ridge, TN, USA
August 31 – September 2, 2010

Summary Report

Introduction

An international delegation of researchers met in Oak Ridge, TN on August 31 to September 2, 2010 for a workshop to update the current state of plasma-surface interaction (PSI)-focused research facilities, and discuss the community's future plans and strategies to coordinate critically needed plasma-wall interaction data for ITER and continuing progress and outlook to DEMO. Discussion in the workshop revolved around four themes that emerged: 1) capabilities of existing devices, 2) advanced proposed and planned devices, 3) diagnostics and Lithium, and 4) theory and modeling.

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 and on safety (i.e., 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 (e.g., Li, or Be in ITER), the presence of Tritium, and the impact of neutron activation on first wall materials.

To characterize and understand plasma-surface interactions under these conditions, dedicated linear PSI facilities can be used, which allow for detailed investigations not possible in toroidal magnetic confinement devices. Sophisticated diagnostics for both the near surface plasma and the material surface itself are a prerequisite for comprehensive investigations. Linear PSI facilities have significant advantages with respect to the complexity and cost of operation for such diagnostics. Such experiments are complementary to studies in toroidal confinement devices, and the PSI program in both linear and toroidal devices shall be closely linked. However, linear devices are capable of investigating PSI in regimes beyond today's tokamak's capabilities, specifically the high particle flux and fluency regime since linear devices can operate in steady state, which no current tokamak can achieve. Such a combined program requires intense collaboration and a well-established network between different linear devices with complementary capabilities. Modeling is the essential tool to link and apply the results from linear PSI facilities to toroidal magnetic confinement devices and to allow extrapolations and predictions for future fusion devices such as ITER and DEMO.

Existing Devices and Capabilities

Motivation for current and continued research was extensively reported and based in the United States on a number of 'thrusts' in the Research Needs Workshop (ReNeW) strategic plan brought forward to the Department of Energy Office of Fusion Energy Science (DOE OFES) in 2009, and in Europe by the Fusion Facilities Review Panel report of 2008. The primary goal of these initiatives was to identify significant gaps in experimental science and facilities whose purpose is to unfold the physics of tokamak boundary layer plasma and its interaction with plasma-facing materials. Strong recommendations were made for research and development by upgrade of existing PSI devices, and creation of new devices with extended capabilities including the ability to heat exposed samples up to ITER and DEMO-relevant temperatures (i.e., 300 – 1200 °C), impinge ITER-like plasma conditions on a material target (i.e., electron/ion density up to 10^{21} /m^3, ion flux up to 10^{24}/m^2s, fluency of 10^{26}-10^{27}, steady state heat flux up to 20 MW/m^2 and transiently up to ~300 MW/m^2), and handling of both toxic materials like Beryllium, and neutron activated components like those expected in ITER (<1 displacement per atom (dpa) of damage) and DEMO (20-40 dpa).

Capabilities and latest research efforts of existing PSI facilities were given including PISCES-B (US), TPE (US), DIONISOS (US), GLADIS (IPP Garching), PSI-2 Julich (FZJ, TEC), QSPA (Ukraine), MP^2 (Korea), and the GAMMA-10 tandem mirror (Japan). Some specific machine reports include the following: PISCES has made much progress in studying the synergistic effects of the materials of interest to ITER (C, Be, and W), including the effect of Be on the mitigation of chemical erosion of carbon, Be-W alloying, deuterium loading on W surfaces, the formation of W-fuzz with helium bombardment, and the simulation of ELMs on W and Be using laser heat pulses. The GLADIS facility at IPP Garching incorporates two 1 MW neutral beams and is currently studying W7-X divertor plates, and W coatings on CFC tiles for the JET ITER-like wall (ILW), with plans to study DEMO-relevant W divertor materials. The DIONISOS machine at MIT includes the ability to study synergistic plasma and ion beam effects and is being upgraded with the capability to handle actively heated targets with temperatures of up to 1473 K, and active in-situ, real-time measurements using ruggedized solid state targets and active water cooling. The MP^2 device at NFRI is pursuing study of plasma-molten salt interaction (including vaporization, thermal evaporation, hydrogen retention, fluorine generation), and related effects in stainless steel. The GAMMA-10 tandem mirror is studying two divertor geometries – an axis-symmetric design and an end-mirror design, each using both ICRH and ECH power. The latter design provides up to 10 MW/m^2, which shows a strong attenuation of visible emission during ECH injection. This indicates that the high power ECH pulse (300 kW) has a significant effect on superimposing electron irradiation on the end loss ion flux. The effects of neutron-irradiation and tritium exposure are being studied on the Tritium Plasma Experiment (TPE) including beta radiation and surface damage which can potentially lead to bubble creation and changes in hydrogenic diffusion, permeation, and retention rates. Even a modest amount of tritium content in a plasma (0.5% T in deuterium) was found to change the penetration depth in tungsten, and a relatively small amount of neutron exposure (0.025 dpa) can change the retention of deuterium in tungsten by 30 to 40%. Tests on samples exposed to up to 2.4 dpa are ongoing. Finally, the TEXTOR tokamak in Germany is evolving into a facility for PMI research instead of strictly tokamak physics research. Divertor issues with tungsten are a current research topic of interest, including a collaboration with JET on the lower divertor plates using stacks of W lamellas and the investigation of tungsten melt layers with droplet formation.

While existing linear plasma simulators can explore many of the materials issues for ITER, a wider range of experimental parameters than is currently available will be needed to answer the materials questions for DEMO. Limitations of existing linear plasma devices discussed include the following: Normal incidence of mono-energetic ions, the ratio of plasma radius to ion gyro-orbit is on the order of unity, surface temperature typically coupled to incident plasma, transient effects are difficult to incorporate, and plasma size makes component mock-up testing difficult, quality assurance tests are not feasible.

The 1993 Plasma Facing Components generic facilities review panel report covers both physics and technology issues and discusses the need for different types of facilities. A review of this report in light of advances and changes in need over the past 17 years is strongly recommended. The specific research needs and requirements for new and existing devices must be well defined. Issues that are not sufficiently addressed by present devices include off-normal incidence, transients, neutron damage, hot walls, high ionization fraction/redeposition, dust production and high fluencies. Future research needs should include ion heating (angle of incidence variation and viscosity effects) at high magnetic fields and the ability to test large areas for realistic heat load studies. In addition, it was mentioned by several groups that both *in-situ* and *ex-situ* diagnostics would be key to advancing the science of the plasma material interface. Future linear plasma facilities will have to address long pulse and steady state materials issues, especially changing time constants as pulse lengths are extended.

New PMI Facility Initiatives

Devices introduced and discussed, both planned and proposed, include MAGNUM-PSI (FOM, TEC – 2010), VISION-I (SCK, CEN, TEC – 2011), JULE-PSI (FZJ, TEC - 2015), the ORNL-PMTS (ORNL – 2015), and the PALOMA Plasma Simulator (CIEMAT – 2016). These devices would, with overlapping capabilities, including ion heating to test angle of incidence variation and viscosity effects, have large area beams to ensure a sufficiently large region of uniform plasma conditions, have higher flux and fluency capabilities, test damaged and activated materials, incorporate the capability for ELM-like particle and heat loads, and the ability to provide a continuous thermal load for hot wall studies.

Representatives of Juelich presented their current strategy and plans for a linear PSI research facility, which is an integral part of the new program on plasma wall interactions within the Trilateral Euregio Cluster (TEC: FOM (NL), ERM-KMS and SCK-CEN (B), and FZJ (D)). The approach being taken utilizes multiple facilities (JULE-PSI with the e-beam facilities JUDITH-1 upgrade and JUDITH-2 at FZJ, MAGNUM-PSI at FOM and a smaller plasma facility in the Tritium Laboratory at SCK-CEN in Mol, B), each with rather specific goals, rather than a single integrated device. In particular, a modest facility with reduced parameters (fluxes, density) will be used with hot cell capability at FZJ in order to assess the effects of neutron damage including Be in addition to heat flux tests capabilities already existing with the JUDITH devices. Magnum PSI is being constructed as a more direct simulator of the ITER divertor, with appropriately high fluxes and density, and with the low temperature expected in the partially detached state.

The Magnum-PSI device is planned to come online in mid-2011. This large European facility was designed to ensure that system size is larger than typical length scales of important physics processes, i.e., a 10 cm diameter beam with 17 mm wide flat-top electron density, and a target size of 60x12 cm with an inclination angle of 5 degrees to the beam. The beam can provide steady-state heat fluxes of >30 MW/m^2, and 10 Hz operation at up to 2 GW/m^2, simulating the steady state and transient plasma of the first 5 cm of the ITER target. 1 MW of cooling is available for the docking station, and associated hardware systems. A water cooled target of up to 100 kg will be accommodated.

Several talks were given by ORNL staff, presenting an electrode less, helicon based, high power linear plasma facility, which is under consideration for proposal. This would be a more integrated user facility, with the possibility of being nuclear capable in order to study neutron damage effects while simultaneously matching the expected ITER divertor plasma conditions. Capabilities would include long pulse (100 seconds to CW), up to 20 MW/m^2 of heat flux (on a perpendicular target), a 100 kW source, 1.6 T, 10 cm diameter light ion (H, D, He) plasmas, electron temperature of 10 – 200 eV, inclusion of a hot cell enclosing both the target chamber (i.e., transportable/replaceable target casks), and the entire facility, possible use of robotic sample/cask manipulation. Extensive modeling has been carried out of both the plasma conditions and the helicon behavior. Multiple experiments were described that are being conducted on internal funding to reduce the risk in producing the planned plasma conditions. In discussion, it was suggested that rather than proposing a catchall experiment, the topics that are to be studied should be specified and a device designed to study those issues. A similar comment was that while the work towards a high power facility is interesting, we first need to discuss and agree on what that ultimate facility needs to provide in terms of performance.

Diagnostics and Li

A common theme of many presentations made in the workshop was that extensive diagnostic coverage was key to the success of any current and future linear plasma device. Four categories of diagnostics were discussed: plasma diagnostics for beam characterization, *in-situ* PMI diagnostics for real-time study of the target under plasma exposure, *in-vacuo* diagnostics for sample analysis after or between plasma exposures, and *ex-situ* sample analysis for detailed surface studies which cannot be done from the target or a nearby chamber. Comprehensive lists for each diagnostic area were recommended for use in a future device, with emphasis on diagnostics that can provide direct comparisons between linear and toroidal devices, and those that provide comparison between linear devices and their simulated models. In the design of a new device, it was recommended to spend considerable effort on the target-beam interface, target mount, and maximizing diagnostic access to the target. Thought toward specialized diagnostic development based on the mission of each individual linear device was also encouraged. For *ex-situ* instruments, focus was encouraged on diagnostic development in three areas of PMI research: surface morphology, surface/sub surface structure, and surface chemistry.

A presentation on the extensive diagnostic array planned for the JULE-PSI device including spectroscopy based on five spectrometers from low to high optical resolution, quartz microbalance, laser induced desorption / ablation, laser induced breakdown spectroscopy (LIBS), plus *ex-situ* diagnostics including TDS, SEM/EDX, NRA, RBS, SIMS, XPS, and glow discharge spectroscopy. Design and data from a new real-time ion beam diagnostic on DIONISOS was given, representing the first online, real-time surface analysis diagnostic to be incorporated on a linear plasma device.

While diagnostics on liner machines are typically cheaper than their counterparts on toroidal devices, significant challenges lay ahead for those on linear devices, especially in the areas using *in-situ* hot cells (leading to possible interference from radiation, contamination/activation of the diagnostic itself) and possible interference from stray fields of powerful RF sources in the linear device or significant vibrations and magnetic fields in analysis chambers.

Current and future use of Lithium in linear devices was also discussed extensively based on experience from NSTX (PPPL) and the University of Illinois. NSTX now incorporates the Liquid Lithium Divertor (LLD) whose early results have been encouraging, and diagnostics associated with the MAPP probe are under development. A significant number of Li-related facilities have operated successfully at the University of Illinois with promising results for continued and future application to tokamaks.

It is important to remember the modeling connection to linear machines, especially in the context of physics benchmarking and validation of codes for future use in more complex devices, e.g. toroidal devices. For example, it seems there is a base set of diagnostic needs on all potential linear devices that give upstream and downstream boundary conditions. Comments were made from the modeling group that having a consistent set form multiple linear machine would help benchmark the codes.

In a similar vein, the need to have similar diagnostic capabilities on linear machine and toroidal devices would help connect the modeling benchmark studies. To date, PMI studies in toroidal devices have mostly come from spectroscopy and imbedded Langmuir probes. These have given details on fluxes to first walls as well as information on erosion yields, etc. In the end, the diagnostics on linear machines should focus on non-invasive techniques that could directly translate to the more restrictive toroidal device environment.

PMI Theory and Modeling

Science at a linear PMI facility should be coupled with science of beam-surface experiments to provide bottom-up validation of the theoretical/simulation-based PMI models, providing predictive powers of the modeling toward the toroidal machines. PMI experiments with fusion relevant complex targets (W, Be, C, Li, varying T_{surface}) irradiated by plasma, containing ions, neutrals and molecules of H, C, W, Li, He, and seeded impurities, can be used to characterize erosion, sputtering, redeposition and retention at the PMI. In validating the modeling the key is complete (AMAP: 'as much as possible') characterization of both near surface plasma dynamics and material targets. Theory/modeling should be extended to include various distribution functions of the impacting particles as well as sheath and local transport effects. Comparison with beam-surface experiments would give understanding of the full extent of the plasma-induced synergy of particles, energies, and angles. Beam surface experiments do not suffice for the description of the nonlinear response of neither the surface nor the plasma itself, dynamically changed by the synergies of the plasma irradiation. This justifies the PMTS (as proposed by ORNL) necessarily as a bridge between phenomenological knowledge provided by the beam experiments and prediction of the realistic behavior of plasma-material interface in ITER and DEMO. In particular, it is essential to identify the places where computational modeling and experiment can both overlap for validation and where both the models and experiments have limits that can complement each other.

The applied theoretical methods depend on the parameters of the plasma and surface. The spatial/time scales in the solid are defined by the plasma-particle energies. These include quantum chemistry and quantum molecular dynamics at the fs-ps time scale (a sample size of tens of atoms), classical molecular dynamics (ps-ns time scale, nm lengths, thousands of atoms), as well as simplified binary-collision-cascade approximations for elastic processes at high energies, and kinetic Monte Carlo (MC), applicable up to 1 s time scales. The MC is "fed" by the probability rates derived from the atomistic approaches.

The interdependence of the plasma and surface processes makes it challenging to decouple the effects of plasma on the surface and emitted surface particles back to the plasma at multiple spatial and temporal scales. This requires a collection of multi-scale models appropriate/optimal for each spatial/time range. The challenge is how to connect the models across the entire range.

Modeling can also bridge results from a linear PMI facility to the actual environment of the tokamak.

Important challenges with PMI Theory and Modeling:

1. Strong Non-Linear aspects: 1) plasma-surface coupled system (both phases responding to each other) and 2) the non-linear mechanisms in each phase space separately (e.g. defect dynamics in solids, or powerful gas-phase – plasma phase interaction in the volume before the solid.) and, also, the synergy between various states of particles (energy spread, incident angle, etc.) on a solid surface
2. The basic physical interactions in the PMI are of an atomistic and stochastic nature, which has consequences for the development of appropriate modeling approaches, requiring multidisciplinary collaborative teams, from atomic physics, through plasma physics, to solid state and material sciences. This also opens many space-time scales across the PMI studies.

Overall Message

The stated goal of the workshop was to identify opportunities for present and future PSI facilities to provide critically needed plasma wall interaction information for ITER and continued progress toward DEMO. Over the course of the 3-day workshop, many issues were elucidated, and the current state of research at a subset of existing machines was reported. (See the above summary). Significant knowledge “gaps” were identified that have to be bridged for the success of fusion energy that can be approached through linear PSI devices. Existing devices already contribute; new devices are needed as well as continued theory and modeling efforts. Improved and innovative diagnostic techniques relevant to PMI are essential for toroidal and linear geometry, which are complementary. Along with the PMI science itself, these diagnostics are expected to emerge more cost effectively on linear devices, which are themselves less expensive and (in general) more accessible to diagnostics, diagnosticians and scientists. It is recommended, that co-ordination of the research in existing and new linear devices is strengthened and strong links to PSI research in toroidal confinement devices are essential. New PSI capabilities are indispensable to resolve the issues related to the knowledge gaps identified by the community (e.g. the U.S. D.O.E. ReNeW process and the European Fusion Facilities Review Panel). PMI facilities offer a (cost effective and) necessary path to investigate and address these issues in advance of ITER and DEMO.