# Research Thrust to Address PMI Knowledge Gaps for DEMO

L. R. Baylor, J. M. Canik, J. B. O. Caughman, S. Diem, R. H. Goulding,
D. L. Hillis, P. S. Krstic, F. W. Meyer, and Y. K.- M. Peng (ORNL)

## Purpose and motivation of white paper

The purpose of this white paper is to describe a research thrust for the R&D required to close the knowledge gaps in the PMI Theme area between ITER and DEMO, recently identified in the Greenwald panel report [1]. This R&D program would improve understanding and predictive capabilities including the lifetimes of the plasma facing components (PFC) and internal components, utilizing data obtained from existing PMI devices, and new and/or upgraded devices with extended capabilities. A more in depth discussion of the science underlying the issues discussed here can be found in a separate white paper [2].

## Gaps in PMI that can be addressed in non-toroidal experiments:

The knowledge gaps covered in the Plasma-Material Interface (PMI) theme encompass a wide variety of areas. These include the mechanisms underlying specific plasma-surface interactions and the design of PFCs and internal components, such as RF antennas and microwave launchers, that can survive and function in the nuclear DEMO environment. The approach to filling these gaps requires a strong theory and modeling effort supported by experimental validation. Certain knowledge gaps (e.g. SOL plasma widths, flows and turbulent transport) can only be addressed in toroidal systems. In this white paper we concentrate on gaps that can be explored using ion beams and dedicated linear plasma PMI devices. The reasons to explore gaps using this approach include 1) the ability to carefully control plasma exposure parameters throughout the full duration of the exposure, 2) excellent access for sample exchange and diagnostics, 3) the ability in the near term to provide very long sample exposure times with very high particle fluxes, 4) the ability in the near term to perform plasma bombardment of neutron damaged materials, and 5) the use of all these capabilities to provide data and experience contributing to the design of later toroidal PMI devices.

The Greenwald report classifies PFCs and materials as the only Tier 1 issues, requiring a "major extrapolation from the current state of knowledge, need for qualitative improvements and substantial development for both the short and long term." We believe that such issues require a substantial, multi-pronged effort in order to be properly addressed.

Examples of the gaps that can be addressed under this proposed thrust are as follows:

- *Erosion and Redeposition* - A fundamental knowledge of and the ability to predict the erosion and redeposition of material, including the synergy of multi-species plasmas and mixed materials, is required. Knowledge gaps remain in the basic processes that govern erosion; an example is the impact of mixed materials on chemical sputtering. In addition, the DEMO PMI will consist of thick layers of redeposited material, whose properties are as yet unknown.
- *Tritium retention and permeation* – Tritium control and accounting will be crucial for the success of DEMO. To achieve this, the processes that lead to retention and permeation of tritium in materials subjected to high plasma particle flux need to be understood.
- *Radiation transport* – The conventional divertor scenario results in an optically thick divertor at DEMO parameters. To be able to predict divertor operation under these conditions, the transport of this trapped radiation needs to be included in the plasma models.
- *Off-normal events* – The survival of plasma-facing materials to transients will set the limits on acceptable size and duration of off-normal events The damage to materials caused by both rare,

large events and frequent, smaller events must therefore be well characterized.

- *New materials and concepts* – The extreme environment expected in DEMO may require the need for new material developments/concepts. Exploration of materials and the characterization of promising candidates need to be performed to test their possible application to DEMO.
- *PFC component performance and lifetime* – Unprecedented exposures at high power densities and durations will challenge the design of PFCs. The heat transfer capabilities of neutron and plasma damaged components must be determined under CW high heat flux. Permeation of hydrogen isotopes into the cooling paths of PFCs needs to be assessed.
- *Neutron irradiated material*s – The high neutron fluence expected in DEMO will affect erosion and tritium retention properties of materials and heat transfer in components. Material interfaces will be strongly affected by the neutron damage. Thus characterization of neutron damaged specimens and validation of component performance models is needed.

## Proposed research thrust:

To address gaps for DEMO, extensive experimental and theoretical studies are required. We propose a thrust for enhanced modeling combined with measurements from both existing and new, dedicated PMI experiments that take advantage of simple geometries to enable high-throughput, well diagnosed material characterization.

A strong theoretical basis is required to further the understanding and prediction of the PMI. Modeling efforts span a range of complexity and assumptions, from exploration of elementary processes such as sputtering due to single-ion impact [3] to coupled codes modeling the full PMI environment, including for example sheath formation, erosion and material migration, and evolving surface concentrations of mixed materials [4]. Strengthened effort in these theoretical simulations, validated properly by measurement, can significantly increase understanding and predictive capabilities of the PMI processes.

Additional experimental studies of PMI utilizing dedicated devices can also aid in closing the PMI gaps. At the simplest level, ion beam facilities allow measurements of the elementary processes of chemical and physical sputtering, in an environment that allows full control of the energy, impact angle, and species of bombarding ions onto well-controlled and characterized target surfaces [5]. These experiments can produce databases of the atomic and molecular processes that are used in PMI modeling codes, and also serve as validation of computational simulations of elementary processes, allowing predictions to become closer to being made on a first-principles basis.

Facilities that perform plasma-bombardment of surfaces allow the study of synergistic effects that are not enabled by ion beam experiments. These experiments can allow PMI processes to be studied in a plasma environment with albeit fairly modest parameters compared to those expected in DEMO. For example, the PISCES facility achieves plasma densities up to $10^{19}$ $m^{-3}$ and temperatures of tens of eV (although higher impact energies can be achieved by target biasing), and bombards targets with particle fluxes up to $10^{23}$ ions/s and heat fluxes of less than 10 $MW/m^2$ [6]. While not simulating the DEMO divertor, certain integrated effects can be studied, e.g.: the impact of a plasma distribution on sputtering rates (as opposed to monoenergetic beams, as well as multiple species interactions. These experiments also allow macroscopic PMI processes to be studied, such as erosion and redeposition and hydrogenic retention, and can validate models of these processes, although not at the full DEMO plasma regime. As part of this research thrust, resources for both ion beam and plasma bombardment facilities would be increased.

Further synergistic effects are expected to be important in the DEMO PMI environment that can not be addressed in the experiments described above, however, motivating a new class of device. For example, the erosion and redeposition process will ultimately be determined by the properties of redeposited layers. To simulate this, an experiment needs to operate in the 'strongly coupled' regime where eroded material is ionized in the plasma and returned to the surface. This requires a device with characteristic dimensions larger than the neutral mean free path, which equates to a large plasma cross section operating at very high density ($>10^{20}$ $m^{-3}$). Furthermore achievement of erosion conditions relevant to DEMO requires particle fluxes greater than $10^{24}$ ions/$m^2$/s and the ability to run for extremely long pulses, which further enhance the redeposited layers. Very high density is also required for model validation in optically thick regimes to address the gap in radiation transport. Assessment of retention and permeation of tritium at DEMO relevant parameters requires the ability to test materials at very high temperatures (> 600 $^{o}$C). This can be readily achieved in the presence of very high plasma heat flux, which would also enable this device to perform tests of PFCs, such as divertor heat sinks. A very important capability would be the qualification to handle neutron-irradiated samples. The neutron damage that will be present in DEMO will have a profound impact on materials properties, affecting for example tritium retention, as well as, heat transfer and material joints in PFCs. The ability to measure these effects with rapid turnaround of experiments is needed.

## A New PMI Experiment

The new class of facility described above can be characterized by its ability to fully simulate the DEMO divertor. No non-toroidal experiment in the US is currently planned with this capability; the only device that qualifies worldwide is MAGNUM-PSI, being built in the Netherlands [7]. Concept development and preliminary experiments toward a linear PMI facility design have been initiated at ORNL. The device would have the following characteristics, which would fill many of the gaps requiring an integrated effects approach:

- Particle fluxes > $10^{23}$ $m^{-2}s^{-1}$, and plasma heat fluxes at the target up to 40 MW/$m^2$, delivered to plasma facing components (PFC) with inclined surfaces and operation at elevated temperatures (> 600C).
- Large plasma area, ~100 $cm^2$, in order to produce a strongly-coupled plasma simulating detached conditions in a divertor. This is also required to test small PFCs and sub-components, and multilayered materials used, for instance, in antenna structures and microwave launchers.
- Ability to handle hazardous materials, such as Be, and neutron irradiated material samples with significant dpa.
- Variable magnetic field, with maximum $|B| > 1$ T, to study its effects in the divertor.
- Progressively longer plasma durations, starting from $10^2$ s, and eventually to $10^6$ s (~week), respectively corresponding to the anticipated time constants of the physical processes of high-Z impurity migration [2], to trace hydrogenic species permeation in ferritic steel under fusion relevant operating conditions [8].
- Diagnostics for PMI including *in-situ* optical and mass spectroscopy, laser induced florescence, thermal desorption spectroscopy, quartz-crystal microbalances, as well *ex-situ* analysis of the target by UV and visible Raman spectroscopy, scanning and Auger electron microscopy, X-ray induced photospectroscopy, and atomic force microscopy. Measurements of plasma density, total ion flux, neutral density, and electron and ion energies will also be required using interferometers, Langmuir probes, retarding potential analyzers, spectroscopic diagnostics, etc.
- These experimental measurements would be used to validate the results from computational simulation of the plasma surface interactions in a multi-scale approach. These simulations will combine molecular dynamics (including development of appropriate mixed-material potentials) at the ns time scale and the kinetic Monte Carlo processes with longer time scales [2].

In addition, a PMI facility as described above would require a powerful plasma source (see appendix) that could be provided by:

- A helicon plasma source backed-up, if necessary, by a cold plasma source to provide operating densities over the range of 1 – $3x10^{19}/m^3$ while producing Te = 5 – 10 eV and parallel heat flux ~ 2 – 4 $MW/m^2$.
- ICH and EBW heating of ions and electrons

The facility would have capabilities not matched in existing linear PMI facilities. These include:

- No internal electrodes, allowing the source to be optimized to produce low impurity levels
- True CW operation with adequate cooling for steady state operation at maximum rf input power
- Steady state heat flux ≥ 20 $MW/m^2$ – higher pulsed
- The ability to produce high particle fluxes ≥ $10^{23}m^{-2}s^{-1}$ for a range of electron temperatures ≥ 5 eV, with ion energies up to 100 eV (or higher) produced by ICH – biasing is not required but can also be added. Ions in the device would be collisional up to at least 50 eV.
- The ability to test neutron irradiated materials

## Relationship to related PMI research

The envisioned R&D by this approach has the potential of establishing a broad understanding of the fundamental processes and their synergistic interactions, which in turn advances theory, modeling and simulation of these processes in fully toroidal configurations. These include establishing understanding and predictive capabilities including the lifetimes of the PFC and internal components, using data from very long duration, continuous plasma operations enabled by the PMI facility. This approach for PMI research, on the other hand, does not intend to address physical phenomena related to the interacting toroidal plasma outside the last closed flux surface in the toroidal configuration.

The envisioned PMI facility complements and extends the capabilities of current PMI research facilities, like the domestic PISCES facility and international Magnum–PSI facility, and promotes US competitiveness in this area. This facility is foreseen to be a user facility whose design is developed through PMI community participation.

**References**

1. Greenwald, M., et al., Priorities, Gaps and Opportunities: Towards A Long-Range Strategic Plan For Magnetic Fusion Energy, A Report to the Fusion Energy Sciences Advisory Committee, October 2007, http://www.ofes.fusion.doe.gov/FESAC/Oct-2007/FESAC_Planning_Report.pdf.
2. P. Krstic et al., "Fundamental science of the synergy of multi-species interactions in a high plasma-heat-flux environment", this meeting.
3. P. S. Krstic et al, Nucl. Instr. Meth. B, (2009) http://dx.doi.org/10.1016/j.nimb.2008.11.049
4. J. Brooks et al., "Thrust for Enhancing Modeling & Predictive Computations for PMI", this meeting.
5. H. Zhang and F.W. Meyer, J. Nucl. Mater. (2009), http://dx.doi.org/10.1016/j.jnucmat.2009.01.142.
6. G. Tynan, et al., "The PISCES Program FY04-06 Progress Report", UCSD-CER-06-06. http://cer.ucsd.edu/REPORTS/UCSD-CER-06-06.pdf.
7. H.J.N. van Eck et al, Fusion Eng. And Des. 88 (2007) 1878.
8. M. Abdou, Fusion Technol. **29** (1999) 1.

# Appendix: Plasma production and heating

Due to recent improvements in performance operating with light ions, it has become possible to consider the use of a helicon rf plasma source for use in generating the plasma for a linear PMI facility. High plasma production efficiency has been commonly observed for helicon sources using argon as the working gas[1-2], but high plasma densities and good plasma production efficiency have recently been achieved using hydrogen[3], deuterium[4], and helium[3]. For example, H plasma densities up to $2.6 \times 10^{19}$ $m^{-3}$, with $T_e \sim 6$eV have been produced in a 5 cm diameter source at ORNL with 4-6 kW input power [3]. Operation over a range of magnetic fields has also been demonstrated, with high density D plasmas produced in a source of similar design with |B| values in the plasma production region up to 0.15 T [4]. Observed scaling of plasma density with |B| suggests that it should be straightforward to operate at substantially higher |B| values [5].

There are several advantages in using a helicon source for plasma production in a PMI facility. The first is that the source has no internal electrodes. It is a fundamentally steady state device, with no parts requiring routine replacement. The lack of internal electrodes is expected to reduce the amount of impurities generated in comparison to an arc source. In addition, high gas utilization efficiency has been demonstrated, with nearly 100% ionization of incoming neutral atoms achieved [6]. This greatly reduces pumping requirements in comparison to those for a cascaded arc plasma source such as that used in MAGNUM-PSI [7]. Helicon sources can easily be designed to produce a large diameter plasma [4] without the need to combine many narrow plasma channels, as will be the case for MAGNUM-PSI. This will be necessary in the latter device to achieve the specified target plasma diameter of 10 cm, since the plasma diameter for a single source is ~ 1 cm [8]. Although the achievable average plasma flux would be lower for the helicon than for Magnum-PSI, it should still be possible to achieve values $> 10^{23}$ $m^{-2}$ $s^{-1}$. Total particle fluxes $> 10^{21} s^{-1}$ have been demonstrated in a helicon source using Ar, with 30 kW of input power [4].

A program is underway at ORNL to develop a large diameter (15 cm) light-ion (H, D, He) helicon plasma source suitable for use in a PMI facility. It will operate at significantly higher input power (up to 100 kW) and magnetic field (up to 1 T) than previous light-ion experiments, with neutral particle input $> 10^{21} s^{-1}$.

The helicon device is efficient in producing plasma particles, but is less efficient at coupling power to the plasma output stream. A combination of additional ion and electron heating can be used to produce a plasma with a substantially higher power flux. Ion heating can be accomplished using ion cyclotron heating (ICH) in a "beach" configuration, in which a slow wave is coupled from the high field side of the ion cyclotron resonance. The method has been successfully employed on at least one PSI research device, NAGDIS-II [9]. In experiments on the VASIMR VX-50 electric propulsion research device, acceleration of helicon-produced deuterium ions to energies ≥ 160 eV has been reported in a single pass through the resonance region, at plasma densities up to $10^{19} m^{-3}$ [10].

Electron heating via oblique O-X-B mode coupling (ordinary to extraordinary to electron Bernstein wave)[11] can be utilized for heating at the fundamental electron cyclotron resonance. For a magnetic field of 1 T on axis, readily available sources at 28 GHz can be used for fundamental EBW heating. Unlike electromagnetic waves, EBW absorption increases with decreasing temperature, hence good absorption is expected even for low temperature plasmas. This heating method was first demonstrated in the W7-AS stellarator and has since been used in overdense plasma experiments in stellarators, tokamaks, and STs [12]. EBW heating (via X-B mode conversion) has successfully been used in a linear device to heat electrons to 50 eV [13]. Modeling of O-X-B injection in a linear device would be required to provide the optimal launch angle and polarization. The combination of both ion and electron heating of the output plasma stream from the helicon source are expected to allow increasing the power flux to values in the range 20-40 MW/m$^2$.

1. R. Boswell and F. Chen, IEEE Trans. Plasma Sci. **25** (1997) 1229.
2. F. Chen and R. Boswell, IEEE Trans. Plasma Sci. **25** (1997) 1245.
3. M. Yoshitaka et al., Thin Solid Films, **506-507** (2006) 583.
4. J. Squire et al., “High Power VASIMR Experiments using Deuterium, Neon and Argon”, 30th Intl. Electric Propulsion Conf., Florence, Italy, September 2007, IEPC-2007-181, http://www.adastrarocket.com/Jared_IEPC07.pdf.
5. Y. Mori et al., Plasma Sources Sci. Technol. **13** 2004, p. 424.
6. J. Squire et al., Thin Solid Films, **506-507**, 2006, p. 579.
7. H. van Eck et al., Fusion Engineering and Design **82** (2007) 1878.
8. B. deGroot, Fusion Engineering and Design **82** (2007) 1861.
9. Y. Uesugi et al., Vacuum **59**, 2000, p. 24.
10. E. Bering, “High Power Ion Cyclotron Heating in the VASIMR Engine”, AIAA Aerospace Sciences Meeting and Exhibit, Reno, January 2007, AIAA-2007-586, http://www.adastrarocket.com/AIAA2007.pdf.
11. J. Preinhaelter et al., J. Plasma Physics **10** (1973).
12. H. Laqua, Plasma Phys. Control. Fusion **49** (2007).
13. V.K. Yadav et al., Phys. of Plasmas **11** (2004).