Addressing PMI science and PFC technology for ITER, FNSF and DEMO with MPEX (Material Plasma Exposure eXperiment)

D.L. Hillis, T. Biewer, J. Brooks (Purdue University), J. Canik, J. Caughman, R.H. Goulding, J. Lore, L. Owen, and Y-K. M. Peng

Oak Ridge National Laboratory - February 14, 2013

Research description

Mastering the science of plasma material interactions (PMI) and the technology of plasma facing components (PFCs) will be key to the successful exploitation of fusion energy. PFCs must be capable of exhausting the power leaving the core plasma (heat fluxes of ~5-10 MW/m^2), while avoiding excessive net deposition or erosion of the material surface in the presence of high ion fluxes ($\Gamma \sim 10^{24}$ m^{-2}s^{-1}). The continual gross erosion and redeposition will lead to surface layers that have been strongly modified by the plasma, which will have properties that are, at present, unknown. Further, control over the tritium inventory must be ensured, and performance maintained in the presence of intense neutron irradiation (on the order of ~50 dpa (displacements per atom)). Finally, this must be accomplished in a way compatible with good core plasma performance. PFC performance depends on both the material properties and on the characteristics of the impinging plasma, and a combination which satisfies these requirements has yet to be identified. A facility dedicated to improving the understanding of PMI physics, exploring potential PFC materials, testing material limits, and developing the associated divertor and first wall technology will reduce the risk and improve the designs of ITER, FNSF, DEMO and beyond.

Such a facility must be capable of producing a plasma with a wide range of parameters near the PFC surface. Taking the ITER divertor scenario as an example, conditions vary from a 'detached', cold ($T_e \sim 1$ eV) very dense ($n_e > 2 \times 10^{21}$ m^{-3}) plasma at the strike point to a hotter ($5 < T_e < 50$ eV) 'attached' plasma with reduced density ($10^{21} > n_e > 10^{19}$ m^{-3}) a short distance into the scrape-off layer (SOL). The detached strike point region is expected to be one of net deposition (because physical sputtering is minimal). While the lack of net erosion at these plasma parameters may be attractive (although the deposition would lead to surface morphology changes and possibly problems with flaking or poor heat transfer if the new layers are thick enough), tokamak operation experience has excluded a fully detached divertor as incompatible with sufficient core confinement, and so a hotter attached region is unavoidable. This region is expected to be a net erosion zone, which could limit the PFC lifetime. To evaluate a potential divertor material such as tungsten the erosion/redepostion mechanisms must be quantified and understood, and effective redeposition (of order 99% for high-Z materials) demonstrated.

Much of the needed PMI studies and PFC development could be performed in a simplified geometry (i.e., in linear plasma devices), provided that the needed plasma parameters can be reached. These devices offer a much reduced cost compared to tokamak operation, with better diagnostic access and dedicated experimental time for PMI/PFC studies. The prospects of operating linear plasma devices in near steady-state to perform tests at reactor-relevant ion fluences are also much better than for tokamaks (current pulsed tokamaks accumulate a fluence of ~10^{25} m^{-2}/yr only, which is about 5 orders of magnitude below what is needed). Such a device would allow rapid evaluation and the development of combinations of PFC designs and plasma conditions that satisfy the requirements listed above. Development of PFCs beyond the divertor components would also be enabled, such as studying particle-antenna interactions and improving RF launcher design. Testing in tokamaks will of course be necessary as well, especially to ensuring that the PFC and divertor plasma operation are compatible with core performance. High-power tokamak experiments will also be needed to develop methods for producing the plasma conditions at the PFC surface that are needed for satisfactory PFC operation. This includes controlling the divertor plasma temperature, and reducing the heat flux from the $q_{||} \sim$ GW/m^2 expected upstream to manageable levels of ~5-10 MW/m^2 perpendicular to the surface, which translates to plasma power loads of about 40-80 MW/m^2 parallel to the magnetic field (the plasma power loads are only a fraction of the total heat fluxes, which consist of plasma, radiation and neutral power fluxes). However, these issues can be addressed in short-pulse tokamaks. When combined with long-pulse tests on a linear device, this will allow first generation PFCs to be developed that satisfy the requirements for steady-state tokamak operation (which at present do not exist). A further advantage of a linear plasma device is the ability to study PMI processes on neutron irradiated samples. Although the damage rate due to plasma bombardment is several orders of magnitude greater than that due to neutrons, the lifetime of the PFC surface layer is limited in a net-erosion regime, so that the accumulated damage between the two processes can be comparable (e.g., if the net erosion rate is 99%, then the surface will be made up of atoms that have been sputtered and redeposited ~100 times, comparable to the ~50 dpa neutron damage expected in a reactor). A linear device capable of handling irradiated materials would allow an early test of the potential synergy between neutron damage and PMI, which has been already demonstrated in measurements of erosion [1] and tritium retention [2] on irradiated samples. This would further reduce the risk to the design and operation of a full-scale Fusion Nuclear Science Facility.

Description of MPEX

Ability of the facility to contribute to world-leading science: Grade A - absolutely central

MPEX is a linear device (See Fig. 1), which will expose material samples and "mock-up" sized plasma facing components to fusion reactor relevant plasmas. Its operational parameters are summarized in Table 1. It will be designed to test a large variety of candidate PFC materials

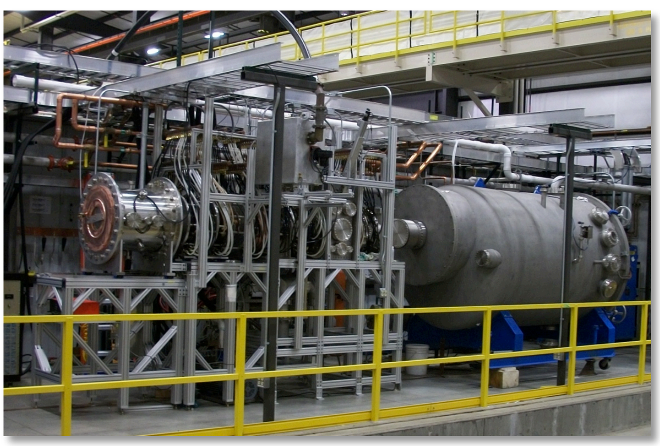

Fig. 1: ORNL prototype of MPEX

Table 1: MPEX Operational Parameters

Parameter	**Targeted value**
n_e source	up to 6 x 10^{19} m^{-3}
n_e target	up to 10^{21} m^{-3}
T_e source	up to 35 eV
T_e target	1 to 15 eV
T_i source	up to 20 eV
T_i target	1 to 15 eV
B target	1T
Plasma diameter	up to 10 cm
G_I target	10^{24} m^{-2}s^{-1}
Min angle of B to target	5 degree
P target, parallel	up to 40 MW/m^2
P target, perpendicular	10 MW/m^2

(solid, liquid, carbon-based, metallic, irradiated) under different experimental conditions (temperature, wall loading, etc.). MPEX will be a steady-state device utilizing superconducting coils with standard technology (NbTi). The plasma source system is chosen to be a helicon source combined with auxiliary RF-heating to heat electrons and ions independently. The helicon antenna has the advantage that the emitted circular polarized electro-magnetic waves can propagate in the plasma at much higher densities than other waves. The total RF heating power will be up to 900 kW. The magnetic field structure will be adopted to maximize the source and heating performance. This RF based plasma source approach has the advantage of low maintenance operation, as required for steady-state operation. It also has the advantage of having a tiltable target (12 cm x 60 cm) and access to conduction-limited transport as it appears in the SOL of a tokamak. This will permit the investigation of power load dissipation processes by impurity radiation, as well as permit the ionization of impurities to higher charge states, which is important for physical sputtering studies of tungsten.

Description of the facility's impact beyond the FES mission

MPEX has the potential for a strong impact in areas beyond PFC development, such as plasma processing and material synthesis. The unique low temperature, high density plasma regime is conducive to fast nanoparticle deposition and may be useful for the manufacturing of catalytic surfaces. This regime would also provide access to more basic plasma physics studies, such as the dynamics of dusty plasmas.

Context for the facility with respect to research gaps, needs and opportunities

The Greenwald report[3] 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." 19 Gaps were identified in the Greenwald Report related to the plasma-material interface for the preparation of DEMO and the technology facilities needed for DEMO oriented R&D. New PMI facilities will be indispensable to resolve the issues related to the knowledge gaps identified by the community (e.g. the U.S. D.O.E. ReNeW process[4] and the European Fusion Facilities Review Panel). ReNeW Thrust 10 entitled: "Decode and Advance the Science and Technology of Plasma-Surface Interactions", identified the need for a new Advanced PMI Test stand which could address the Gaps identified in the ReNew Report. More recent FESAC reports (Zinkle) indicate that "most existing US fusion technology test stands are no longer unique or world-leading. However, numerous compelling opportunities for high-impact fusion research may be achievable by making… moderate investment in new medium-scale facilities". The latest FESAC report of Rosner identifies Thrust 10 as among the 5 highest priority thrusts that were identified by ReNeW and endorses the need for new and upgraded PMI facilities to address the PMI Gaps identified in ReNeW. To address these PMI issues, ORNL in 2008 embarked on a design and development program to address such an advanced plasma source and PMI test stand, namely, MPEX.

Context of the facility relative to world effort

The current US linear plasma test stands (PISCES, TPE) cannot reach the intense plasma conditions of DEMO-relevant devices nor can they address the science of the strongly coupled plasma surface interactions. In addition, current US plasma generators are not able to produce high power thermal plasmas, but rely on biasing of the target. This precludes the tilting of the target away from normal incidence, and strongly changes the redeposition processes, which depend on the correct E and B fields, as well as, the correct geometry. Magnum-PSI in the Netherlands is able to reach DEMO-relevant fluxes, but only at plasma parameters close to the strike point, since their plasma source is limited to T <5 eV. Due to the use of normal conducting coils, Magnum-PSI is currently not able to operate steady-state and also cannot operate with shallow magnetic field angles to the target due to plasma source limitations. The reliance on internal electrodes (present in all existing devices mentioned here) can also lead to the emission of impurities, which can spoil the plasma surface interaction processes and their interpretation. This is particularly important for low temperature, high density, high fluence exposures, where small amounts of medium to high-Z impurities originating from electrodes will accumulate on the target. Finally, MPEX will have the advantage compared to Magnum of being able to address the PMI of irradiated materials. In summary MPEX will be the only device worldwide to do accelerated lifetime tests of W divertor components in a reactor relevant environment on realistic time scales.

Cost estimate for investment and operation; schedule

A detailed cost analysis for MPEX has not been completed. However, approximate costs can be estimated on the basis of the actual incurred costs of the Magnum-PSI facility, a similar sized project constructed in the Netherlands. The anticipated design and construction costs of MPEX will be below \$20M. Additionally \$4M will be required for diagnostics to be spread over several years. Operation costs are ~ \$6M/yr (based on Magnum-PSI experience) and includes manpower for scientific exploitation. An upgrade is planned to enable the investigation of neutron irradiated materials with a cost range of ~ \$0.5 - \$5 M, based on ORNL experience with radiated material handling facilities. A detailed cost estimate for handling radiated materials will need to be performed. It is expected that the design and construction phase of MPEX will take 5 years and will be followed by an upgrade for the investigation of neutron irradiated samples about 2 years after initial plasma operation. If the capability to operate with neutron irradiated materials is included from the start, data on plasma exposures of irradiated samples to reactor relevant lifetime fluence ($\sim 10^{30}$ m^{-2}) could be available in a time frame of 7 years after start of the MPEX project.

Readiness of the facility concept

Grade A - Ready to initiate construction

The MPEX facility was motivated in a series of “International Workshops on Plasma Material Interaction Facilities for Fusion (PMIF)”] and its science mission has been established. Since 2009 a series of experiments have been carried out to test the plasma source concept of MPEX. The helicon plasma source has operated with a coupled power of ~ 100 kW producing electron densities in a deuterium plasma of 4×10^{19} m^{-3}, which is close to the design requirements of MPEX. Simultaneously, electron heating (EBW and Whistler Wave) has been demonstrated at lower power levels. ICRF heating of helicon plasmas has already been demonstrated in plasma thruster applications. The linear plasma of MPEX has been modeled extensively with SOLPS to characterize the operating space. Pre-conceptual design studies have started on key technology subsystems and ORNL experiments on the prototype source, rf heating, and target system have mitigated most of the risks for the MPEX design.

References:

[1] B.I. Khripunov *et al*, J. Nucl. Mat. **390-391** (2009) 921.
[2] G.M. Wright *et al*, Nucl. Fusion **50** (2010) 075006.
[3] Greenwald Panel FESAC Report, October 2007.
[4] “Research Needs for Magnetic Fusion Energy Sciences - Report of the Research Needs Workshop (ReNeW)”, 2009, http://burningplasma.org/web/ReNeW/ReNeW.report.web2.pdf