Addressing PMI science and PFC technology for ITER, FNSF and DEMO

J. Rapp, July 27th 2012

Background

Mastering the science of plasma material interactions and the technology of plasma facing components (PFCs) will be key to a successful exploration of fusion energy.
Not only might impurities released from the PFCs impact the performance of a fusion reactor if they penetrate to the plasma core, but the limited lifetime of PFCs also has an impact on the availability of a fusion reactor and hence its economic operation. In the worst case plasma material interaction could even impact on the safety of the device by increasing the risk to an explosion through dust production or increased levels of tritium inventory.

The Strongly Coupled Plasma Surface Interaction regime

In steady-state operation there is a highly complex compressible flow of energy and particles in the boundary towards the plasma facing components. Any materials close to the plasma are subject to continuous radiation from the plasma, bombardment by neutrons and charge exchange neutrals. In steady state conditions, the power loads are highest in the divertor region. It is expected that PFCs in the divertor will be exposed to ion fluxes of $\Gamma > 10^{24}\ m^{-2}s^{-1}$. In addition high neutron fluxes will lead to irradiation damage of the material up to 150 dpa (displacements per atom). In the envisioned partially detached divertor regime the power from the plasma core will be dissipated by impurity radiation leading to manageable divertor heat fluxes of 10 MW/m^2 perpendicular to the surface, which translates to plasma power loads of about 40 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). The “cold” ($T_e \sim 1$ eV) and very dense ($n_e > 2 \times 10^{21}\ m^{-3}$) divertor plasma will lead to a so-called “strongly coupled plasma surface interaction” where the erosion products are trapped in the plasma and return to the surface in a modified form (as neutral or ionized molecule, dissociated atom or ion). Hence the plasma surface interaction determines the plasma composition in front of the target and has a feedback effect on the plasma surface interactions locally. This feedback effect will strongly modify the surface morphology in a non-linear way and has an impact on the surface conditions (surface area, temperature distribution, chemical activity…..), which determine erosion and re-deposition. In addition the bulk material properties are often changed to the extent that its “structural integrity” is compromised. The investigation of plasma facing materials, which are exposed to unprecedented high heat, particle and neutron fluxes simultaneously, experiencing changes of material properties in the proximity of the plasma surface, is a new field of science.

Value of linear plasma devices, when compared to toroidal devices

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. Plasma-wall interaction simulators (linear plasma devices) are important to address questions for which magnetic confinement devices are either not suitable (e.g. in delivering large fluences at steady state conditions) or not available (e.g. because of limited operational 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. Also a change of the plasma facing component or material sample can be easily done. In magnetic confinement devices post-mortem analysis is usually done after years of operation. This often causes problems with the interpretation of the data, since years or at least month of operation in different confinement and plasma conditions, including plasma shut down, vessel pumping, gas prefill, and plasma start-up, will not easily allow conclusions on the physical and chemical processes in retrospect. Limiter-lock systems or equivalent divertor probe-lock systems allow dedicated exposures. However, often the investigation of the plasma-surface interactions of specifically introduced samples is spoiled by the other wall materials (e.g. a W-sample in an otherwise all carbon device will be coated quickly with carbon). Those plasma-wall interaction simulators (or linear plasma-material test stations) will allow the investigation of single physical and chemical processes in a realistic fusion environment, providing critical data for modelling of the plasma-material interactions.

Need for new Plasma Material Test Station

To address the new science expected in the PMI regime of future fusion reactors it is necessary to build a new Linear Plasma Material Test Station, which can access the plasma conditions described above and will be able to test a large variety of target materials (solid, liquid, carbon-based, metallic, toxic, irradiated). The current US linear plasma test stands cannot reach the plasma conditions nor can they address the science of the strongly coupled plasma surface interactions. But it is not only a quantitative difference. Current US plasma generators are not able to produce high power thermal plasmas. Often the target is biased. This will strongly change the erosion and re-deposition, which depends strongly on the correct E and B fields as well as the correct geometry. Some devices overseas are able to reach the required plasma parameters but they do have the disadvantage that they are not designed to address the PMI of toxic and irradiated materials. Furthermore, all of the above mentioned existing devices have internal electrodes emitting impurities, which can spoil the plasma surface interaction processes and their interpretation drastically. 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. In order to access the necessary parameter range, which exceeds that of existing PMI test facilities by orders of magnitude, a new approach is required. This requires a high-density plasma source and sufficient heating power. The plasma source should be based on RF technology to avoid the production of unwanted impurities. Such a new device would be very cost effective with anticipated design and construction costs well below $20M.