ReNeW PWI. Peter Stangeby. 20 February 2009.

Diagnostic investments required to identify missing physics controlling PWI

It appears that only part of the physics controlling PWI has been identified. The ability to project the behaviour of future devices requires knowledge of the controlling processes. At a minimum the level of (partial) understanding must be sufficient to establish how to proceed empirically, which requires knowing how to *scale*. At present even that level of understanding of the SOL is largely lacking.

It is not surprising that understanding of the SOL is so incomplete: there have been several orders of magnitude more effort invested in confinement physics than in SOL physics, although the SOL is a considerably more complicated problem than the main plasma:

(a) at least 3 states of matter interact simultaneously and sometimes all 4

(b) the main plasma is 1D, to first order; the SOL is 2D and can, for some critical aspects, be 4D (3 spatial + temporal)

(c) partly because the SOL is 2D and partly because it is a very awkward shape - being very long, thin and twisted - SOL diagnosis is much more difficult than for the main plasma. Despite this, far smaller investment has been made in SOL diagnosis than in main plasma diagnosis. The controlling physics in the main plasma can sometimes be extracted, to zeroth order, directly from radial scan measurements of a few quantities. This is almost never possible in SOL physics, where the controlling physics can usually only be identified by the interpretation of a few disparate measurement made at various spot locations. **Present SOL diagnostic capability is seriously inadequate and is the main impediment to the identification of missing edge physics.**

One can define the edge quantities that characterize the e+D+T, i.e. fuel, plasma as being "zeroth order", with those quantifying the impurities as "1^{st} order", in that the latter are largely controlled by the former. It seems likely that until the 0^{th} order quantities are reasonably well known, there is not much chance of understanding, scaling or predicting the 1^{st} order quantities. Unfortunately, today the quantitative characterization of even the 0^{th} order SOL quantities is very sketchy. The 0^{th} order SOL plasma quantities are n_e, T_e and T_i (and information is needed on the energy distributions, not just the average energy), parallel flow velocity, perpendicular transport velocity, electric field. With enough knowledge of these quantities it might be expected that it will be possible to reliably understand, calculate, scale and ultimately predict from first principles the effluxes of particles and power from the plasma onto the solid surfaces, i.e. the sheath properties, which is the primary driver of PWI. On most tokamaks today, only n_e and T_e (w.o. energy distribution information and usually only time-averaged, i.e. w.o. fluctuation information) are measured regularly - at a few locations.

A spatially extensive set of edge measurements is required.

Understanding of aerodynamic lift and drag would have been impossible if the air velocity were measured at just one or two locations around airfoils; in fact, such measurements are typically made at dozens of locations. The SOL is much more complicated than air flow around an object and it cannot be expected that it will be possible to identify edge controlling physics with the spatially sparse diagnostic deployments we have today. Extensive sets of pop-up (or similar drive) probes could be used to map out the 4D distributions of n_e, T_e and electric potential (Langmuir probes);

parallel flow velocity (Mach probes); cross-field transport (turbulence probes); T_i and energy distributions of electrons and ions (gridded energy analyzers, although not too close to the separatrix).

Magnetically-activated probe drives of various types have been developed, including swing action [Smick, LaBombard and Pitcher, JNM **337–339** (2005) 281–285], which can provide deep penetration, 10's cms, and reciprocation [Smick and LaBombard, Rev. Sci. Instrum. **80** (2009) 023502], with the latter achieving penetration to inside the separatrix on C-mod, momentarily experiencing parallel power flux densities of 100's MW/m^2. Deployments of such probes are needed in large numbers, 10-30, around the periphery of tokamaks. Materials costs will be small but manpower requirements will be significant.

Thomson scattering is difficult to do in edge plasmas because of high backgrounds but it has been used successfully for many years on DIII-D to produce 2D mapping of n_e and T_e (with sweeping of the X-point). Thomson scattering is in principle capable of providing information on the electron energy distribution at locations to the separatrix and further in. Supplementing the Thomson interference filters with a high dispersion resolving instrument such as a Fabry-Perot would substantially extend the measuring capability of edge Thomson systems:

(i) The ability to detect the presence of a small component of fast electrons.

(ii) For the high n_e, low T_e of detached plasmas, collective scattering contributes to the scattered Thomson light as $\alpha = 1/k\lambda_{Debye}$ approaches 1. For $n_e = 6x10^{20}$ m^{-3} and $T_e = 0.8$ eV, $\alpha \sim 0.6$. For high values of α, the Thomson analysis method based on interference filters results in errors in measuring n_e and T_e (~20% at $\alpha = 0.8$). A Fabry-Perot would deal with this problem and would also provide a 2^{nd}, independent measurement of n_e (from shape of scattered profile, separate from the intensity).

(iii) At high values of α, measurements of T_{D+} are possible (also of Z_{eff}). Thus, with sweeping, 2D mapping of T_{D+} throughout the divertor.

Single-laser Thomson systems can only take 'snapshots' at regular intervals which are usually too far apart in time to resolve important dynamics. A multi-laser system (firing laser one, two, three in rapid succession) can overcome this, making images that follow the time evolution of n_e and T_e profiles as a 'blob' or ELM breaks away from the steep gradient region.

CER spectroscopy is also difficult to do in the edge because of the high background light level; however, new powerful pulsed ion diode neutral beam technology (10^6 A/m^2, 1 μs, 125 keV/amu) may permit extension of this valuable diagnostic technique to the measurement of T_i and parallel flow speed in to the separatrix and further, see e.g.:
http://fusion.gat.com/conferences/kstar/presentations/IDNB_proposal_KSTAR.ppt

Real time, *in situ* surface diagnosis of H-uptake, erosion, deposition, co-deposition, etc is required.

Turning to the 1^{st} order quantities that characterize the impurity aspect of PWI re consequences for the *plasma*: fortunately, this appears to be in fair shape since it is achieved spectroscopically and spectroscopic coverage is extensive on most tokamaks. In strong contrast, studies of the 1^{st} order quantities that characterize the impurity aspect of PWI re consequences for the *solid*, namely H-uptake, erosion, deposition, co-deposition, etc, are almost totally hamstrung on all tokamaks today because most of the experimental information is global: post mortem analysis provides spatial resolution but integrates over entire campaigns while some studies, e.g. of H-uptake, are for single shots but integrate over all internal surfaces. It is difficult or impossible to extract the controlling physics from such integral experiments. It is essential that *in situ* real time (at least between shots) surface analysis diagnosis be developed, for example, the in-place accelerator concept of Dennis Whyte, where a compact Radio-Frequency Quadrupole (RFQ), 1 MeV D^+ beam source and accelerator will be used to perform ion beam analysis of a large fraction of the tiles in the vessel. Between shots the diagnostic beam is steered poloidally and toroidally using the tokamak magnetic coils to make surface measurements at different poloidal locations. Neutrons and x-ray products are detected to provide measurements of D-retention and of erosion and deposition. If the ability to put heated samples on the wall is added then retention can be followed as a function of temperature and with thermal-desorption *in situ*, thus creating a surface-science lab in a tokamak environment. Such edge diagnostics may seem overly ambitious today but they are essential; they are also no more ambitious than many core diagnostic systems that have been successfully implemented.

Cross-field transport in the SOL has to be better characterized to be able to scale PWI at the main walls

Today we do not know how to scale the fraction of the power and particle efflux that goes to the walls, vs that to the divertor - for ELMs and non-ELMs. It remains to be established, indeed, if there is a fundamental difference between 'giant' intermittency (ELMs), 'moderate' intermittency (blobs) and 'tiny' intermittency (the fluctuations that extend down to amplitude levels at detection threshold – “non-ELMs”). The power load on the walls is important for obvious reasons but the particle load is also potentially critical: if there is enough impurity influx from the main walls, and if the divertor is sufficiently detached and cold, then there will be no net erosion in the divertor at all. Therefore, depending on the wall particle flux, which we don't know how to scale, there would appear to be a disconcertingly wide range of possibilities with regard to the viability of the substance of the divertor: the problem could range from net erosion being so fast that there is no practical solution for target survival - to the opposite problem, where the build up of deposits in the divertor is so rapid that the it becomes 'gummed up' too quickly to constitute a workable system.

Particle and power fluxes received by the walls needs to be measured systematically and 3-dimensionally (toroidally, poloidally, temporally) as functions of density, etc, in order to identify the scaling parameters. In order to make fundamental progress in this critical matter a greatly increased diagnostic investment is required in edge turbulence measurements including turbulence imaging, BES, advanced turbulence probes (upstream and in divertor), magnetic fluctuation measurements, etc. Close coupling of such measurements with turbulence models/codes is needed in order to eventually achieve for the edge plasma, the present good level of understanding of cross-field transport for the main plasma.