ReNeW PWI. Peter Stangeby. 20 February 2009.

The process of identifying the physics controlling PWI is significantly incomplete, preventing reliable scaling of PWI results to future devices.

PWI places at risk the successful development of MFE in a number of potentially show-stopping ways, including destruction of the walls, unacceptably high contamination of the confined plasma and unacceptably high tritium retention. PWI is largely controlled by the plasma outboard of the LCFS/separatix, the SOL. Transport along the SOL is fast and so most properties of the entire SOL effect PWI. We have limited understanding of the SOL - much less understanding than of the confined plasma.

It is not essential for the success - at least for the initial success - of MFE that understanding of the SOL be complete (aeroplanes flew before the mechanism of lift was known); however, 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 sometimes, in 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 demanding 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.

Considering the resource limitations, edge research has progressed remarkably well. Much, perhaps half, of the controlling physics has been identified and, to a significant degree, the questions to be answered have been identified.
Nevertheless, the task remains: to identify and characterize the physics controlling the SOL and PWI, at least sufficiently to know how to reliably extrapolate-scale from present devices to future ones.

<u>Identification of the physics controlling the SOL and PWI is significantly incomplete. Some examples.</u>

1. **The target power width** is the single most important practical quantity in PWI – and perhaps in MFE overall. It is essential that we know how to scale this quantity to future devices. Unfortunately, at

the present time it appears that we do not know how to do this reliably. The table below is from the 2007 update of the ITER Physics Basis, NF **47** (2007) S203, Chap 4 "Power and particle control":

Table 1. Scalings for dependence of SOL heat flux width and peak target heat flux with total target (or divertor) power load for a number of machines and multi-machine databases.

	λ_q	$q_{\max}$	Comment
Multi-machine: JT60-U, DIII-D and ASDEX-Upgrade (DIVI) [28]	$P_{\mathrm{div}}^{0.44\pm0.04}$	—	Scaling for λ_q mapped to outer mid-plane
Multi-machine: JT60-U, ASDEX-Upgrade [1]	$P_{\mathrm{target}}^{0.35\pm0.05}$	—	—
ASDEX-Upgrade (DIVI) (IR data) [3]	$P_{\mathrm{target}}^{0.52\pm0.05}$	$P_{\mathrm{target}}^{0.5\pm0.05}$	Type I and III ELMs included and partially detached plasmas.
ASDEX-Upgrade (DIVII) (IR data) [3]	$P_{\mathrm{target}}^{-0.1}$	$P_{\mathrm{target}}^{1.1\pm0.06}$	Type I ELMs and attached plasmas only.
DIII-D [30]	—	P_{div}^{1}	—
JET (IR data) [31]	$P_{\mathrm{target}}^{-0.13\pm0.08}$	P_{target}^{1}	Inter-ELM. λ_q from FWHM of profile at outer target.
JET (TC data) [18]	$P_{\mathrm{target}}^{-0.48\pm0.09}$	—	ELM-averaged. D (Type I ELMs) and He (Type III ELMs) discharges included. λ_q from the integral width of profile at outer target.

The authors make some sobering observations:
"Scalings for the dependence of the peak heat flux, q_{max}, and heat flux profile width, λ_q , with key discharge parameters have been developed on a number of experiments. The dependence on total target heat load, P_{target}, or the closely related power to the divertor, P_{div}, are summarized in table 1 for a number of these scalings. P_{target} (and P_{div}) will increase by more than an order of magnitude from current experiments to ITER, much larger than the extrapolation in other parameters such as toroidal magnetic field or density. ***The scatter in the power dependence from the various studies is large, even for different studies on a single device, and indeed both positive and negative dependences are reported for the λ_q scalings*** (emphasis added here)*……All that can be strongly concluded from table 1 is that there is a need for improved experimental measurements and a theory-oriented approach for making extrapolations for the target heat flux in ITER."*

2. Kinetic effects in the SOL and their influence on PWI. The SOL is typically of marginal collisionality for justifying use of fluid modeling. Unfortunately, fluid modeling, including fluid codes, are the only practical analysis tools available today for the SOL. Kinetic effects, however, may be controlling with regard to certain critical aspects of SOL/PWI behaviour. This appears to be evidenced in a number of ways, including the inability of current models to reproduce the radial electric field in the SOL, which in turn appears to underlie the inability of the models to reproduce the fast parallel flows measured in the SOL, see e.g. "Discrepancy between modelled and measured radial electric fields in the scrape-off layer of divertor tokamaks: a challenge for 2D fluid codes?", AV Chankin, DP Coster, N. Asakura, X. Bonnin, GD Conway, G Corrigan, SK. Erents, W Fundamenski, J Horacek, A Kallenbach, M Kaufmann, C Konz, K Lackner, HW Muller, J Neuhauser, RA Pitts and M Wischmeier, Nucl. Fusion **47** (2007) 479–489. The authors note:
"Examination of radial electric field (E_r) profiles in the scrape-off layer (SOL) of ASDEX Upgrade (AUG) and JET revealed large discrepancies between 2D fluid edge modelling and experiment…. Mismatches between modelled and experimental E_r may be caused by the recently established tendency for the SOLPS code to underestimate T_e in the divertor of AUG. It was attributed to non-locality of parallel transport of
supra-thermal, heat-carrying electrons originating upstream of the divertor, which are usually only weakly collisional and can penetrate, with few collisions, to the target….. ***The T_e and E_r discrepancies, as well as discrepancies between simulated and experimental parallel ion flows, raise a question of the validity of fluid codes for the plasma edge modelling and prompt the inclusion of kinetic effects into present-day 2D fluid codes which assume strong collisionality***."(emphasis added here).

Fast parallel flows in the SOL are likely to be a major influence on PWI: (a) the difference between *gross* erosion and *net* erosion (thus net deposition, thus also co-deposition retention of tritium) is due, in large part, to parallel transport; (b) for fast flow, parallel power transport to the targets is strongly influenced by convection; (c) fast parallel flow influences in/out pressure balance, which effects detachment.

Non-maxwellian electrons (and perhaps ions), appear to be implicated in the long-standing "sheath mystery", first identified in DIII-D about 2 decades ago and for which an explanation is still lacking: the measured sheath heat transmission coefficient γ_{sh} is of order unity near the strike point. One of the most basic aspects of the PWI is the ratio of particle to heat flux transferred from the plasma to an electrically floating solid surface. Using 'textbook' Debye sheath theory dating back to Langmuir we expect that power flux density / particle flux density ~ 7kT, i.e. $\gamma_{sh} \sim 7$. This PWI anomaly is about as basic as it gets: 1. a plasma in contact with a solid; 2. particles go from plasma to solid; 3. heat goes from plasma to solid; 4. experiment disagrees with modeling - and this for the most basic modeling task we have in edge physics. When such a fundamental PWI relation is in question, all aspects of PWI would appear to be in question.

3. **Detachment** is the potential solution to the divertor problem which has been most studied and is the solution ITER is relying on; nevertheless we have little understanding of this complicated plasma state. Even referring to it as "a" state may considerably underestimate the challenge. We often speak of "detachment", as if it were a single regime - like "sheath-limited" or "conduction-limited" - but the reality may be a number of substantially different regimes, characterized by small temperature differences, making for a rich variety of "Detachment Sub-regimes" – perhaps as different from one another as sheath-limited is from conduction-limited. The roles of ion-neutral friction, volume recombination, drifts, opacity, neutral-neutral collisions, excited molecules, de-magnetization of the ions, blobby transport, 3D effects, etc, seem likely to be significantly different for the different Detachment Sub-regimes. At present we have almost no understanding about the role and interaction of these potentially controlling effects.

This situation is reflected in attempts to model detachment: "*Several publications devoted to a detailed validation of the various SOL modelling codes with a detailed kinetic model for neutrals have emerged recently..... **One can draw the general conclusion from these modelling studies that the simulations generally fail to match quantitatively the experimental measurements under detached divertor conditions in hydrogenic plasmas**.*" (emphasis added here), V Krotov, D Reiter, RA Pitts, et al, PPCF **50** (2008) 105012. See also the 2008 PSI presentation of M Wischmeier: http://psi2008.ciemat.es/talks/ThursdayMorning/O-25_wischmeier_psi18.ppt.

"*The bottom line seems to me that it is rare that any of today's big fluid codes (UEDGE, EDGE2D, SOLPS5) get anywhere near a proper description of plasma detachment (energy and particles)….I find this situation disconcerting and somewhat worrying, given that without this mode of operation, which is predicted to occur for ITER with the very tools with which we cannot match today's devices usually at all, ITER simply will not be able to fulfill its mission."* RA Pitts, ITER, private communication, 13 Dec 2008.