Particle transport issues in the evaluation of ITER operation

W.A. Houlberg, A. Loarte, R.A. Pitts, A.S. Kukushkin, A.R. Polevoi

ITER Organization, St Paul-lez-Durance, France

Introduction

Density control in ITER will be critical for optimizing operation. Satisfying constraints on core, scrape-off-layer (SOL) and divertor fuel densities dictate the use of a combination of hydrogenic pellet and neutral gas injection to improve control. But operation in He plasmas during the initial non-nuclear operation will have to rely solely on gas injection in combination with recycle to meet all density constraints. Although penetration of hydrogenic pellets and neutral species are reasonably well understood for given plasma conditions, the transport properties of the ionized material in the plasma edge and SOL are far less well understood and will play a dominant role in determining core densities. Transport uncertainties over a wide range of conditions (start-up through ramp-down, H/He, D and DT phases, and density constraints) makes particle control a major challenge for ITER operation.

Density constraints

The core density is expected to be limited from above by the Greenwald density limit, i.e. $n_e \leq 6x10^{19}$ m^{-3} for half-current and toroidal field (7.5 MA, 2.65 T) operation, and $n_e \leq 1.2x10^{20}$ m^{-3} at full current and field. This empirical limit relates to the line-averaged density. But since it appears to be governed by edge physics, poor penetration of the fuel through the SOL may reduce this limit, while pellet fuelling combined with pumping may increase it. Without a more thorough understanding of the underlying physics, the upper limit on the core density has uncertainty that is difficult to quantify.

From below, the core density is limited by shine-through losses for neutral beam injection (< 4 MW/m^2 on the inner armour). Initial operation with 33 MW of 870 keV H^0 beams and later operation with 1 MeV the limit is $\langle n_e \rangle \geq 2.5\text{-}3.0x10^{19}$ m^{-3} [1]. Uncertainties in the stopping cross-sections, impurity content, density profile and the plasma temperature can easily generate an uncertainty of ±20% in these volume-averaged densities. ICRF coupling losses its efficiency as SOL density is reduced, but this ‘limit’ is yest poorly characterized.

Semi-detached divertor operation in H-mode plasmas is expected to constrain the electron density at the separatrix to a fairly narrow range as shown in Fig 1 from SOLPS scans. These are plotted against the pressure at the entrance to the pump duct (just below the dome) for 60

MW across the separatrix in D/DT or He plasmas, and also at 100 MW for D/DT plasmas to illustrate the dependence on power.

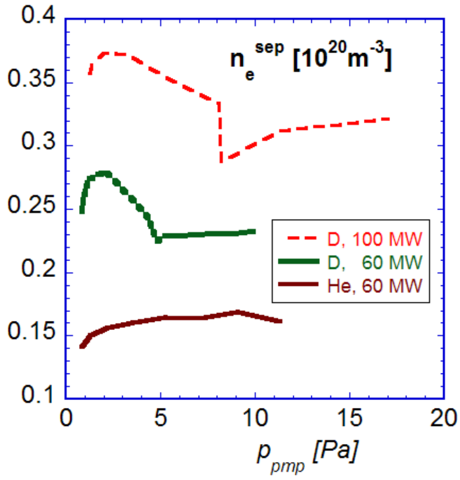

Figure 1: Separatrix density for operation with semi-detached divertor in D/DT and He plasmas.

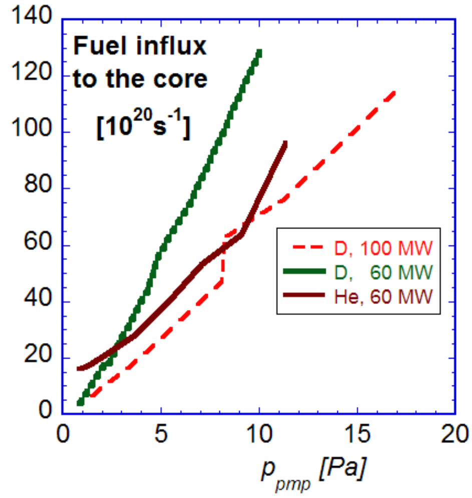

Figure 2: Fuel influx to the core for the same scan as in Fig 1.

Fuel penetration

The total fuel influx across the separatrix from the wall (gas plus recycle) is shown in Fig 2 for the same scans as in Fig 1. For this to satisfy the total fuel requirement the particle confinement time would have to be $\tau_p = \langle n \rangle V/S_p$ where $V \sim 830\ m^3$ is the nominal volume of an ITER plasma. For a core DT density of $\langle n \rangle \sim 10^{20}\ m^{-3}$ to produce the desired fusion power, this would require $\tau_p \sim 14$ s for $p_{pmp} \sim 5$ Pa and 60 MW across the separatrix ($S_p = 6x10^{21}\ s^{-1}$). However, it is unlikely that the 'natural' core density from these divertor and SOL conditions with gas injection and recycle would also satisfy the core density for the desired fusion power. With He operation the fusion power constraint is not applicable, but the constraint on minimum density to avoid excessive NBI shine-through is still operable.

The possibility of employing external control to raise the core density relative to the separatrix density in ITER hydrogenic plasmas is to be provided by inside pellet launch. Figure 3 illustrates the weak penetration relative to the plasma radius expected for various size pellets (either inside or outside launch) in baseline ITER inductive plasmas. Figure 4 shows the variation in mass deposition from different drift models for inside launch. The drift models do not consider possible losses from ELM triggering. Because the drift velocity is much greater than the pellet velocity (several km/s), the mass may penetrate before being rejected by the ELM it triggers as in present experiments. But the net fuelling effectiveness of the more shallow penetration for inside launch on ITER requires closer examination.

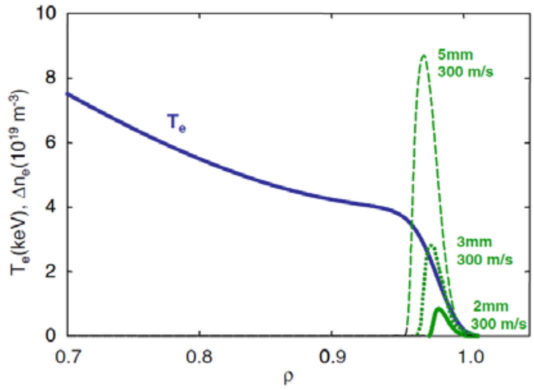

Figure 3: The expected penetration of 2, 3, and 5 mm length and diameter cylindrical pellets for baseline ITER inductive plasmas is not expected to extend beyond the pedestal [2].

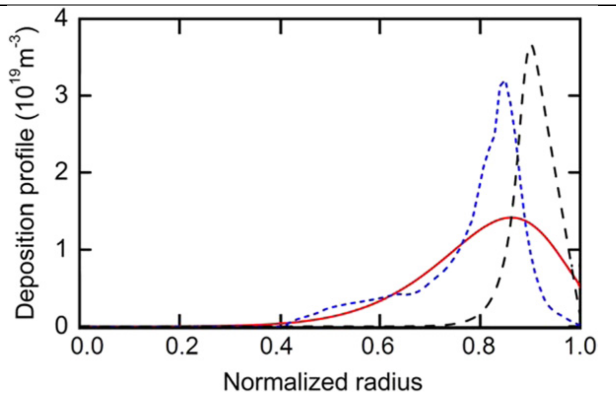

Figure 4: The predicted mass deposition for inside launch of 5 mm pellets varies significantly among drift models [3], although it is expected to be much deeper than represented by the ablation in all cases.

Particle transport properties

Particle transport properties remain the weakest part of the physics understanding for many reasons. For the fuel, the source intensity is uncertain because it varies toroidally and poloidally, and this contributes to the uncertainty in determining experimentally the radial particle transport properties inside the separatrix. Secondly, transport properties of the fuel are usually expressed in terms of an effective diffusivity, which masks the relative contributions of diffusive and convective terms. Thirdly, collisionality and the dominant turbulence mechanism are now recognized to affect the relationship between the turbulent diffusive and convective terms [4]. And finally, the convective terms may have contributions from multiple drives and symmetry breaking from ripple and field errors near the boundary.

Sorting out the various terms and their scaling generally requires carefully controlled experiments, such as examining the transient response to changes in plasma conditions. This has been exploited to separately identify impurity convection driven by the main ion density gradient and the ion temperature gradient: identification of ion temperature gradient screening in the core of DIII-D plasmas after transition to VH-mode [5], and in the pedestal where a scan over gas injection was used to vary the density and ion temperature gradients in the pedestal [6]. Steady-state analyses, however, can still reveal interesting scaling relationships. A plot of the gas source normalized to the plasma current against the pedestal density normalized to the Greenwald density has revealed an off-set linear relationship that has no apparent variation with the plasma current in JET discharges [7] – i.e. no systematic difference in either slope or intercept. From this it can be concluded that the natural pedestal density from a combination of recycle and transport processes is a constant fraction of the Greenwald density (i.e. proportional to I_p). It also indicates this relationship must be dominated by a correlation between the convective and diffusive terms since a dominant source contribution would be expected affect either the slope or intercept.

How large would the fuel pinch have to be at the separatrix in order to affect the fuelling estimates? We can take an example from Figs 1 and 2. For the D/DT case with $p_{pmp} \sim 5$ Pa and 60 MW across the separatrix, if $v_p > 0.4$ m/s the pinch term provides more influx of fuel to the core than the gas plus recycle.

Continuity of the transport processes across the separatrix goes farther than simply matching the density and fluxes at the separatrix because there are scale lengths for both neoclassical and turbulence processes that blur the mathematical discontinuity of the separatrix. Neoclassically, ions just inside the separatrix have a kinetic connection of the order of a poloidal gyroradius into the SOL, while ergodicity from ripple and field errors and the radial structures of turbulence also introduce continuity across the separatrix. Measurements on several devices indicate a continuity of pedestal transport characteristics for typically ~0.5 cm into the SOL.

Further theoretical and experimental R&D

ITER will have much weaker fuel penetration beyond the separatrix than in present devices – both from gas and recycle and from pellets launched from the inside of the torus. At the same time, it will require simultaneous constraints on the core and SOL/divertor that is further complicated by control of the D/T mix and impurities. Under these conditions, the intrinsic fuelling from convective terms – in particularly a particle pinch – becomes a very important element in assessing fuelling and pumping requirements. As we have discovered in low torque plasmas, there are secondary terms that take over the balance against the diffusive terms under low source conditions. Improved edge diagnostic capabilities in present machines, combined with the need to develop effective techniques for density control in ITER, call for a more integrated analysis of the particle transport properties from the core through the pedestal and into the SOL and divertor.

References

[1] A.R. Polevoi et al, Proc 22nd IAEA FEC (2008), IT/P6-6.
[2] L.R. Baylor et al, *Nucl. Fusion* **47** (2007) 443.
[3] B. Pégourié et al, *Plasma Phys. Control. Fusion* **51** (2009) 124023.
[4] C. Angioni et al, *Plasma Phys. Control. Fusion* **51** (2009) 124017.
[5] M.R. Wade et al, *Phys. Rev. Lett.* **84** (2000) 282.
[6] P. Belo et al, *Plasma Phys. Control. Fusion* **46** (2004) 1299.
[7] R. Sartori et al, 1oth IAEA TM on H-mode Physics and Transport Barriers, St Petersburg, Russia (2005).