Towards building a credible vision for a DEMO-class fusion reactor: Addressing the 'Knowledge Gaps' and 'Show-Stoppers' in Edge Plasma Transport

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As this fusion science community is aware, there are many 'gaps' that must be overcome in order to realize a credible DEMO-class fusion reactor – the recent Greenwald panel report [1] does a nice job of assembling these. But we must recognize that in the area of boundary-layer physics and plasma-wall interactions these gaps are extreme. In fact, some of these gaps boarder on the realm of 'impossible.' First among these is the 'power-handling gap', i.e., the order-of-magnitude or greater mismatch between the heat-flux densities that the plasma can deliver and heat-flux densities that material surfaces can reliably withstand.

Magnetic fusion has made remarkable advances over the past 4 decades, yielding ~4 orders of magnitude increase in plasma energy density times confinement time. We now know how to reach near-ignition conditions – ITER will be that realization. Unfortunately, the power-handling capability of first-wall surfaces cannot be similarly scaled; steady-state power removal of ~10MW/m^2 remains the practical limit. Until recently, such power handling limitations have not seriously impacted confinement experiments. Free of this constraint, fusion research has largely focused, with a high degree of success, on understanding and optimizing the confined plasma region. For ITER, this situation will change. Mitigation strategies (ELMs and disruptions) and appropriate operational constraints (*requiring* detached divertor operation, for example) are the first priority. Lacking this, divertor/first-wall components will be destroyed; ITER's scientific mission would not be realized.

In light of this reality, how can we design a credible DEMO-class fusion device, with a size like ITER but power output that is ~4-5 times higher? To do this, we must pursue two essential, complementary research thrusts. First, we need to confront the 'knowledge gaps' in edge plasma transport physics. For example, we lack a clear understanding of heat and particle transport dynamics in the boundary layer – yet this physics defines not only the level of plasma-wall interaction (heat flux 'footprints', particle fluxes) but also the boundary conditions imposed on the confined plasma (edge gradients, flows, impurity levels). Second, we must explore innovative concepts that can truly 'tame' the plasma-material interface – systems that control cross-field heat/particle fluxes, expand the plasma's interaction area ('footprint') with material surfaces, and lead to robust, plasma-wall interfaces with advanced materials, including liquid surfaces. Success in these two areas would provide credible solutions to DEMO's 'power-handling gap' and also address other urgent issues such as PFC lifetime, impurity control, dust production and control.

Thrust#1: Develop first-principles understanding of the processes that control plasma transport the SOL and divertor; embody this understanding in physics-based empirical scalings and first-principals numerical codes; develop tools to accurately predict and optimize the plasma boundary in a DEMO-class fusion reactor.

At present, we have no physics-based model that can accurately simulate the heat-flux power widths observed in tokamaks, let alone scale them to ITER and DEMO. Divertor target 'footprints' for ITER are estimated on the basis of empirical scalings from existing machines [2], leading to an effective 'power-width' (λ_p) at the outer midplane of only λ_p ~5 mm. This same width is assumed to apply for ELM and ELM-free periods. Yet, the reliability of this estimate is uncertain. Temperature gradient length measurements at the outer midplane suggest that λ_p scales with major radius and not much else [3]. In contrast, λ_p scalings from divertor heat-flux measurements [4] do not indicate a major radius scaling for λ_p and appear to vary with other parameters (P_{sol}, B_ϕ, q_{95}). In adopting λ_p ~5 mm for ITER, a fully attached divertor (P_{rad} ~ 20% P_{sol}) leads to surface heat fluxes on the order of ~40MW/m^2 in Q_{DT}=10 plasmas, which can only be tolerated for <~1 second. Semi-detached divertor conditions (P_{rad} ~ 70% P_{sol} with impurity seeding) therefore must be achieved to keep heat fluxes under ~10MW/m^2. Unmitigated ELMs in ITER (Q_{DT}=10, λ_p ~5 mm) yield energy depositions of ~10 MJ/m^2, a level that is 20 times higher than the damage threshold for tungsten and CFC [5]. Therefore, ITER has dictated that the maximum ELM energy shall be no more than 1/20th the natural level; this degree of ELM mitigation/control must be demonstrated prior to D-T operation. This situation is clearly unacceptable for designing a credible DEMO, a device with ~4-5 times the power flux density of ITER.

Our first line-of-attack must be to renew and strengthen existing plasma/divertor physics programs. We must focus resources (diagnostics, experimental time and manpower) to study the edge transport problem. Systematic measurements of λ_p and its mapping to the divertor target is an obvious first step; a proposed 2010 DoE Joint Facilities Milestone has such a goal in mind. But empirical scalings must ultimately be rooted in understanding; they should be cast in terms of the dimensionless parameters that underlie the transport physics. This requires a close-coupling among measurements, theory and first-principles numerical simulation.

In the past, 2-D transport codes (e.g., UEDGE, B2-Eirene, OSM-Eirene) have been essential to understand the overall behavior of the boundary and to help interpret measurements. Yet these codes contain *adjustable* transport coefficients, which embody diffusive and/or convective models for cross-field transport. In stark contrast, experiments show that such transport descriptions are woefully inadequate. Large amplitude fluctuations, critical-gradient transport dynamics and intermittent transport involving quasi-coherent structures (blobs, ELMs) dominate the edge plasma. These processes enhance main-chamber wall contact, drive strong plasma and impurity flows along magnetic field lines, impose 'flow boundary conditions' on the confined plasma and connect to density-limit physics – a phenomenology that is much more rich and complex than originally anticipated. **Edge plasma diagnostics are the critical first step to unfolding this complexity.** We must invest in systems that make measurements at multiple locations in existing plasmas: (1) advanced probes to measure flows, flow shear, and fluctuations in density, temperature, plasma potential, poloidal magnetic field, (2) Thomson scattering across the pedestal, scrape-off layer and divertor, (3) high-resolution spectroscopy to monitor flows, ion temperatures and impurity distributions, (4) turbulence imaging to follow detailed plasma dynamics with high spatial and temporal resolution.

Accurate kinetic models for transport along the magnetic field line are also lacking in many situations. This deficiency may account in part for the inability of 2-D codes to accurately reproduce divertor electron temperatures and radial electric fields in the boundary [6]. A related puzzle is the anomalous sheath heat-transmission factors – values at the divertor target that are markedly different from ~7 [7, 8], a fundamental quantity from plasma-sheath physics. Careful, dedicated measurements must be made (e.g., ion and electron distribution functions) to resolve this. Accurate descriptions of divertor detachment are also lacking. Alcator C-Mod's divertor, with its ITER-like neutral opacity, radiation trapping and high neutral densities, has been especially difficult to simulate [9]. Perhaps time-stationary 2-D codes can still be used, but these codes must begin to employ physics-based models of cross-field and parallel transport, as deduced from more detailed, first-principles turbulence simulations. Such time-averaged codes must also account for non-linear averaging of large amplitude fluctuations in density, temperature and potentials (parallel heat flux ~ $T_e^{7/2}$, sheath currents ~ $\exp[\phi/T_e]$).

The present generation of edge plasma turbulence codes (e.g., BOUT, DALFTI, ESEL) are impressive; they can reproduce much of the edge plasma phenomenology (blob-like propagation, intermittency). But, quantitative agreements (fluctuation spectra, transport levels and scalings) have yet to be attained. Despite this, a remarkably low level of effort is being expended to reconcile these deficiencies. New resources are required in this area (improved/expanded turbulence diagnostics, experimental time and focused manpower) to force the productive iteration between experiment and simulation: Where are the disagreements, what are the missing physical mechanism(s), how do we improve the code/diagnostics? We already have evidence that electromagnetic effects (Alfven dynamics) must be included in first-principles simulations; pressure gradients near the separatrix tend to scale with poloidal magnetic field strength squared in both L and H-mode plasmas. In this respect, electromagnetic plasma fluid-drift codes, such as BOUT and DALFTI (and gyro-fluid code GEM), appear to be on the right path. Yet, these codes remain to be fully tested in the plasma regimes where they should be valid. Do such codes accurately simulate the measured values of plasma transport, fluctuation spectra, including magnetic field fluctuations? If not, why not? As we attempt to understand more collisionless scrape-off layers and pedestal regions, gyro-fluid and gyro-kinetic descriptions for turbulence will be required (XGC, TEMPEST, GEM). However, we must learn to walk before we can run.

Thrust#2: Explore, develop and test advanced boundary layer/divertor concepts and heat-removal systems that can robustly handle the severe environment of a DEMO-class fusion reactor.

Improved physics understanding alone is not going to solve the power-handling gap for a DEMO-class device. Even if ITER demonstrates complete ELM and disruption suppression, steady-state heat fluxes onto a standard DEMO divertor target will be too high, unless drastic restrictions are imposed to DEMO's operational window, such as radiating ~80-90% of the output power [10]. This situation is not credible. We must develop and test new divertor/boundary concepts that can robustly handle this severe environment. These concepts must attack the problem along three key fronts: (1) increase the plasma-wetted area of the divertor target plate, (2) increase the radiated power in the open field-line region, and (3) through the use of advanced materials, increase the power handling capability (steady-state and transient) of the target surfaces.

A number of promising ideas have already been proposed along these lines. The 'Super-X' [11] and 'Snowflake' [12] divertor concepts increase the plasma-wetted area by magnetic expansion. Analyses using standard 2-D transport codes (with inadequacies noted above) show substantial reductions in divertor heat fluxes and target electron temperatures. Target surfaces located away from regions of high neutron fluence are a plus, increased magnetic shear may be a good thing to smear out blobs and ELMs. Concepts such as these need to be pushed forward and tested in confinement experiments. Moreover, such experiments are synergistic with our desire to understand/predict edge phenomenology.

At the limit of extreme poloidal-flux expansion, magnetic field lines become tangent to the target surfaces. This is thought to be a problem for implementing very-large 'expanded boundary'-type divertors, akin to the old Double-III experiment. However, cross-field plasma transport in this geometry is unknown. Perhaps plasma transport, neutral interactions, and interaction with the target material (liquid or solid surface self-alignment) can combine to make a robust heat removal system. Liquid metal target schemes, such as lithium-filled capillary-pores [13], have the attraction of self-renewal and may offer significant advantages in such geometries. Finally, and more speculatively, stochastic magnetic structures might be formed in the divertor volume to spread heat/particles across field lines. This is not unlike the RMP systems that attempt to control ELMs by enhancing transport in the pedestal region.

At a fundamental level, the 'power-handling gap' in DEMO arises from a simple fact: the volume apportioned for the plasma exhaust system in today's tokamaks is a ridiculously small for a DEMO-class device. We must change our vision of what DEMO will look like in its cross-section. A more substantial part of its volume must be set aside for a robust plasma heat-flux removal system – a system that will truly 'tame' the plasma-material interface.

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