Extrapolating Transport to the Burning Plasma Regime

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Physics Issues

The transport and confinement times obtained in burning plasma devices like ITER will strongly affect the achievable fusion gain, among other deliverables. Projecting the levels of transport (heat, momentum, particle) obtained in present-day devices to ITER is subject to appreciable systematic uncertainties, in addition to the standard (or statistical) uncertainties. Because the extrapolation in transport to ITER from present-day experiments is large, eliminating the sources of systematic uncertainty, or at least developing a methodology to correct for them, is critical to an accurate prediction. From an empirical or experimental point of view, systematic errors can potentially affect the "slope" and "offset" of the transport projection in parameter space.

To experimentally project transport to the burning plasma regime, the standard physics issues are to identify the relevant control parameters and measure the dependence of transport on each parameter that requires extrapolation. However, several possible pitfalls can complicate this approach and lead to systematic errors. First, the "slope" of the transport extrapolation with one parameter may be a function of other parameters (i.e., coupling effects). Another concern is that, barring theoretical guidance, there is no guarantee that the "slope" of the projection will continue outside the measured range. This is especially true if a transition to new physics occurs in the interval between the measured region of parameter space and the point of projection. Examples are the onset of a new, dominant microinstability, or an H-L transition. Even if a transition to new physics doesn't occur, a significant "offset" in the values of ion-to-electron temperature ratio or Mach number, for example, between present-day devices and ITER can result in an incorrect transport projection. To minimize this possibility, it is preferable to study plasma conditions that are as close to the burning plasma regime as possible.

While this white paper focuses on the experimental approach to extrapolating transport to ITER, a greater confidence will be gained by developing and validating a theoretical understanding of transport. This latter topic is covered in a separate white paper [1].

Dimensionless Parameter Extrapolation. A "wind tunnel" approach often can be used to project complex physical processes from a scale model. This method is based on the principle of similarity, which dictates that physical systems with the same dimensionless variables, but different physical variables, must exhibit the same physical behavior [2]. Unfortunately, a purely wind tunnel approach does not yield a realistic path to burning plasma devices because holding all of the dimensionless parameters constant requires us to scale from a larger to a smaller machine as the fusion power increases [3]. A practical modification to the wind tunnel approach is to measure the transport dependence on the one or two dimensionless variables that necessarily change between present-day and future burning plasma devices, such as the relative gyroradius (ρ^*) and collisionality (ν^*). A transport extrapolation to smaller ρ^* while keeping the other dimensionless variables fixed is the preferred scaling path, partly because there is a clear theoretical prediction that this scaling should be gyroBohm-like [4]. However, matching ITER's value of ν^* in present-day experiments has proven difficult because it requires excellent particle control, and in low aspect ratio tokamaks a projection in ν^* at fixed ρ^* looks as plausible as the reverse. Therefore, a high priority physics issue is to determine the scaling of transport in $\{\rho^*, \nu^*\}$ space.

Dimensional Parameter Extrapolation. Another, more common, approach is to determine the scaling of transport and confinement with dimensional parameters. These "engineering" parameters are generally closely related to the quantities directly controlled by the experimentalist, such as the magnetic field strength, plasma current, density, etc. The parameter dependence of transport and confinement is typically fit to power law scaling expressions, like the IPB98(y,2) scaling relation [5]. As long as atomic physics processes (or other non-plasma physics processes) are negligible, measurements of the transport dependence on either dimensionless or dimensional variables should yield compatible results. However, deducing a unified physical scaling from multi-machine confinement databases may be an ill posed exercise if different devices are dominated by different turbulent modes. Additionally, regression analysis of engineering variables is not guaranteed to produce a dimensionally homogeneous scaling relation; although such a constraint can be incorporated into the regression analysis, if the dataset is not well conditioned a meaningful result may not be obtained. A high priority physics issue is therefore to resolve any inconsistencies between dedicated experiments that measure the dimensionless parameter scaling of transport and regression analysis of multi-machine confinement databases.

Burning Plasma Relevant Conditions. Transport experiments in present-day devices with predominately co-NBI usually results in rapidly rotating plasmas with ion temperatures well in excess of electron temperatures. These are quite different conditions than those expected in ITER, which will have predominately electron heating and low torque injection. Another obvious difference is that burning plasmas will have a 50:50 ratio of D-T, whereas experiments with tritium are extremely rare in present-day machines. Extrapolating transport levels from such non-ITER-like conditions to ITER may result in incorrect projections. Therefore, a high priority physics issue is to study plasma conditions that are as close to the burning plasma regime as possible. In situations where this is not practical, then additional experiments should be designed to determine what effect the "offset" in plasma conditions will have on the transport projections. The definition of burning plasma relevant conditions should include processes that are thought necessary to reduce the heat flux on plasma facing surfaces.

<u>Research Requirements</u>

- A dedicated experimental campaign to determine the dependence of transport on dimensionless parameters in ITER-relevant conditions is generally preferable to deducing a scaling relation from regression analysis of a confinement database containing an *ad hoc* assortment of discharges.
- Need multi-machine studies of the transport dependence on ρ^* and ν^* to increase the range covered. Determine if the measured ρ^* and ν^* dependences are affected by non-ITER-relevant conditions (if not using dominant rf heating). Need to

reconcile the transport dependence on dimensionless parameters with our physics understanding of plasma turbulence.

- Work on multi-machine confinement databases should concentrate on ITER-relevant conditions. Reconcile any differences between transport and confinement scalings derived from experiments that vary engineering parameters and experiments that vary dimensionless parameters.

- Need to do transport studies using dominant rf heating to better simulate the burning plasma regime with strong electron heating and low torque injection. Determine the relative importance of the electron and ion loss channels in the burning plasma regime.
- Determine whether proposed scaling paths from present-day devices to burning plasma devices like ITER are likely to encounter "new" physics, such as crossing the H-L power threshold, changing the ELM type, or developing a different dominant microinstability. This necessitates knowledge of how transport is affected by close proximity to the H-mode power threshold.
- Determine the effect of ELM-mitigation techniques and radiative divertors on transport projections, especially in regard to the H-mode pedestal height. The role of transport stiffness in determining global confinement needs to be resolved.

<u>Research Thrusts</u>

While ITER will significantly extent the parameter space explored on tokamaks, it is not an ideal vehicle for transport studies. Answering burning plasma transport questions prior to and during ITER operation will require ancillary U.S. facilities. There should be a research thrust to upgrade at least one existing U.S. tokamak with the tools necessary to reproduce ITER conditions (with the exception of tritium operation), such as:

- Sufficient rf heating power to reach the ideal no-wall stability limit.
- High spatial resolution profile diagnostics.
- State-of-the-art fluctuation diagnostics covering the entire wavenumber range.
- Methods to mitigate/suppress ELMs in low collisionality plasmas.
- Radiative divertor operation; good particle control.

In addition, there should be an experimenal campaign to obtain the data listed in the research requirements above. The large scope of work necessitates that these campaigns be national and international, involving the USBPO and the ITPA organizations.

[1] "Toward a validated understanding of core thermal transport" by P.W. Terry *et al.*
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[3] C. C. Petty, Phys. Plasmas **15**, 080501 (2008).
[4] R. E. Waltz *et al.*, Phys. Rev. Lett. **65**, 2390 (1990).
[5] ITER Physics Basis, Nucl. Fusion **39**, 2137 (1999).