3.3.1.4 *Transport*

Maximizing the value of a BPX as a flexible scientific instrument for transport science

Overarching goals for transport science – Transport research on a BPX should be guided by goals identified by the transport community at the last Snowmass meeting, and endorsed program-wide in various forms since, including in the IPPA document:

1. Pursue the challenging yet realistic goal of developing comprehensive predictive transport models based on physically reasonable assumptions and well-tested against experiments. Theory/experiment comparisons should be done at the turbulence level.
2. Develop tools and understanding for the control of transport and transport barriers.

Therefore, a burning plasma physics experiment must have the following attributes:

1. It must have sufficient flexibility and diagnostics to stimulate the science required to improve predictive capability for steps beyond itself, including non-tokamaks.
2. It should enable the development of control tools for managing nonlinear pressure profile dynamics that may exist only in advanced burning plasma regimes.

Developing tools that modify the pressure through turbulence and transport manipulation would have high impact, and requires flexibility, excellent diagnostics, and adequate access.

Assessment summary – prospects for studying generic transport issues: In terms of plasma characteristics, including pulse length, all devices can provide important information on some aspects of pressure profile dynamics. Ignitor's mission places questions of pressure profile control outside of its mission. FIRE and ITER-FEAT can study dynamics and control, with ITER-FEAT possessing the most complete set of tools (see below). Scaling of core and edge transport at reactor-relevant dimensionless parameters, β, ρ^*, ν^*, and n/n_{GW} can be studied on ITER-FEAT and FIRE. Ignitor cannot match these dimensionless parameters as satisfactorally, owing to the lower β values. Diagnostic questions exist for all three devices.

Assessment summary – configuration flexibility: - A BPX must be able to have its configuration varied about its usual operating point. Needed flexibility includes capability that will increase the chances for access to advanced modes of operation (e.g. transport barriers) and for contributing broadly to plasma science. Desired flexibility elements include

   a. Density control (pumping and pellet injection, including inside launch pellets)
   b. q profile control and capability for long pulse operation.
   c. Perturbative heating capability of ions and electrons to test transport models
   d. Neutral beams, where possible, for heating and momentum input for rotation variation and variation of heat and particle deposition
   e. Shaping and elongation flexibility for internal inductance, pedestal, and ELM control.

All machines offer configuration flexibility that will enable advances in transport science to varying degrees. ITER-FEAT has the most comprehensive set of tools, followed by FIRE. Each device has limitations compared to present-day advanced tokamaks, however, and so advances will demand a robust base program working to complement the BPX research. For more background, find the table of the Integration Group regarding device flexibility.

ITER-FEAT's complement of 1 MeV beams (33 MW baseline), together with current drive capability from ECCD, LHCD (upgrade), and on-axis ICRF fast wave will allow for variations of rotational and magnetic shear, increasing the chances for access to advanced operating regimes. Simulations indicate that its current drive tools should enable the q profile to remain elevated and reversed. The various heating schemes will enable separate heating of electrons and ions and perturbative heating for model testing. Pellet injection capability, including HFS launch, is integral to the program, as is divertor pumping. Shaping variability ($1.85 < \kappa < 1.97$; $.48 < \delta < .58$) is limited compared to present-day AT's such as DIII-D, owing to the closed divertor geometry. More shaping flexibility, perhaps made possible during a period of low neutron fluence operation and reduced heat management requirements, would inform the science of pedestal physics and ELMs considerably.

FIRE's simulations indicate that its current drive tools (LHCD and on-axis ICRF) should keep q elevated or reversed in a steady-state configuration. Completely separable heating of ions vs. electrons is not possible, but the ratio is variable depending on whether He^3 minority or direct electron heating is employed. 120 keV neutral beam injection is posed as a possible upgrade. At present, such a beam can only be injected nearly perpendicular to the plasma current unless tangential access is enabled by reducing the number of TF coils. Shaping, while aggressive in its target values ($2 < \kappa < 2.1$; $.65 < \delta < .85$), is again limited in terms of variability compared to present-day AT's, as it is in ITER-FEAT, and for similar reasons. More flexibility, perhaps made possible during operations with reduced heat fluxes and relaxed divertor requirements, would enhance the studies of pedestal physics and ELMs. Pellet injection capability is integral to the program, as is divertor pumping.

Ignitor's q-profile control can be achieved through programming of the current rise phase, combined with ICRF heating over a wide range of currents. Simulations indicate that reversed shear cannot be actively maintained with the auxiliary systems planned (see Integration Group report). Pellet injection is planned and is an integral part of the program. Pumping is not presently in the design, but a pump limiter option is being studied. Studies that demand rotational shear control using deposition of momentum with beams will not be possible in the presently planned Ignitor program. While the range of shapes is not constrained by divertor requirements, it is uncertain how Ignitor will best inform the science of pedestal and ELM physics without a divertor.

Assessment summary: turbulence and profile diagnostics – Concerns exist for all three devices regarding certain profile diagnostics usually regarded as essential for transport studies, and especially turbulence diagnostics. This is in part a consequence of chosen priorities for development up until this time. Up until now, a major priority has been designing diagnostics aimed at protecting the machine and enabling control. ITER-FEAT has spent considerable resources developing its diagnostic set to this end. FIRE, being in the pre-conceptual design phase, has devoted far fewer resources to this issue. From discussions, it seems that Ignitor's attention to these diagnostic sets has not been a high priority as of yet. Developed turbulence diagnostics proposals are pointedly lacking, and this represents a concern for all three devices especially given the central scientific importance of these measurements to turbulence and its interpretation to burning plasma-related transport issues. The high density and line-integrated densities of these devices make beam-based profile diagnostics a challenge. All three devices propose to use reflectometry for density fluctuation measurements. While likely to succeed in the edge, its utility for the core in the absence of wavefront imaging needs to be assessed. All devices plan to measure temperature fluctuations from ECE emission. Finally, no proposal has been made for short wavelength fluctuation measurements in assessing electron thermal transport, yet this topic remains one of the most vexing in transport science and is critical regarding predicting the performance of any BPX. Discerning the behavior of the electron channel and associated turbulence in the presence of strong electron heating via alphas, and associated questions related to the sustainment of transport barriers, can only be answered in a BPX.

Predicting performance of a BPX

The measure of performance – Q = P_fus/P_ext, the ratio of fusion power produced to external power supplied. Q is important for energy economics. The fraction of alpha self-heating F =Q/(5+Q) α $nT\tau$ the "fusion product" is a less sensitive parameter more relevant to scientific goals. The BPX must have Q greater than 5 which amounts to more than 50% self-heating and preferably Q greater than 10 (66% self-heating) in the D-T phase. The controllability of self-heated devices within MHD stability boundaries is an experimentally open question that must be answered in a burning plasma device. The technology goals for material wall neutronics testing or power handling depend on some required P_fus per surface or circumference, and hence depend on achieving high Q at full design P_ext. Q=10 is the nominal goal of all current designs and the maximum design P_ext is generally set by the threshold power required to obtain good H-mode confinement in a non-burning (D-only) phase.

Uncertainty of extrapolated predictions Q=5F/(1-F) is a very sensitive parameter when F α $nT\tau$ exceed 50% and a variety of empirical and theoretical modeling methods are best used to determine its range. Empirical scaling laws for the energy confinement time τ (e.g. H98y2) typically have an RMSE of 15% so that $nT\tau$ (=τ^2P_ped /V) and F are uncertain by 30%. A specific prediction of Q=5 thus corresponds to 2.7 < Q < 9.3 [or Q=10 to 4.3 < Q < 30]. $nT\tau$is being extrapolated over a considerable distance particularly in the rho_star dimensionless variable. For gyroBohm scaling (typical of H-mode scalings) $nT\tau \alpha B^3 a^{5/3}$ at fixed a/R, q, κ, β, and ν*. This varies about 15-fold from JET to ITER-FEAT. Empirical scalings for τ have a shallow minimum in the RMSE. Thus for example a collisionless electrostatic gyroBohm scaling with an RMSE of 16.6% (slightly worse than 14.5% for y2) can obtain Q=30. (F=0.85) compared to Q=5 (F=0.5) for a y2 ITER-FEAT prediction. This more optimistic scaling does not have the beta-degradation of y2 and is supported by beta-scaling experiments in single machines. Global empirical confinement time statistical scaling rules for τ are typically combined with a 0D power balance dW/dt =P_ext + P_alpha - P_brem –P_ped where P_ped=W/τ is the transport loss power flowing to the H-mode pedestal or cold L-mode edge and P_ext = P_aux + P_oh. Plasma profile peakedness must be supplied or provided by core transport code models.

There has been considerable progress in the development of theory based core transport code models. Two physically comprehensive US models have been extensively benchmarked with the ITER profile database and used in this Snowmass 2002 assessment: MultiMode and GLF23renorm. The latter has been developed by fitting to gyrokinetic stability and nonlinear simulations. Both have comparably good RMSE ~ 10% fits to the total stored energy W_tot given the boundary conditions or the energy stored behind the H-mode pedestal W_ped =3Vn_pedT_ped (or equivalently the L-mode r/a > 90% edge). However both core models have a degree of stiffness and are very dependent on T_ped. A *perfectly stiff* core has T(0) linear in T_ped independent of P_ped. MultiMode is weakly stiff (e.g. T(0) α T_ped$^{0.3}$) and GLF23renorm is very stiff (e.g. T(0) α T_ped$^{0.7}$). The net result is that Q scales roughly as Vn_ped beta_pedB^2/P_ext$^{0.25}$ and Vbeta_ped^{2}B^4/P_ext$^{0.9}$ respectively. There is no theory based model for T_ped (or beta_ped). Empirical scaling models for the world database have been developed. A free fit suggests beta_ped α P_ped$^{0.3}$ and nearly independent of n_ped but it is generally believed that the P_ped power dependence obtains only at low P_ped and at high P_ped the ELMing H-mode pedestal pressure gradients are limited by MHD stability: beta_ped < (width_ped/R)s/q^2 independent of P_ped. Assuming saturation in P_ped, various P_ped independent statistical fits to beta_ped (or equivalent) have been obtained with RMSE of 30% typical of the best. For these MHD limit rules, the width_ped/R is fit to a combination of dimensionless variables like beta_pol_ped$^{0.5}$ or rho_star_pol_ped (or some fractional power of this). It is very difficult to distinguish these two variables in the pedestal data. In the first case the projected maximum beta_ped will tend to be comparable to present data but in the second case, beta_ped may decrease somewhat and be weakly dependent on n_ped. Thus in an MHD limited pedestal regime, the weakly stiff MultiMode model has Q α beta_ped and Q can increase with density and weakly with lower P_ext. In contrast the stiffer GLF23 projections with Q α beta_ped^2 are more sensitive to pedestal scaling and Q tends to be independent of operating density but increases almost inversely with decreasing P_ext. Indeed very large Q (essentially ignition or Q= infinity) is not precluded as P_ext is withdrawn, provided beta_ped does not decrease too much (again the issue of pedestal power dependence), and the decreased P_ped does not drop below the H-L transition power. The Q projections for cold edge L_modes are likely to have a similar dependence, but there exists no equivalent of a beta_ped (or beta_edge) database scaling. In any case beta_edge is likely to be strongly dependent on P_ped and not limited by MHD in L-mode.

Assessment Summary of BPX Performance: The Appendix to this Snowmass 2002 Report contains several individual reports with more extensive treatment of the transport physics discussed above and detailed performance projections. Here we provide only a summary: Applying standard empirical H-mode scaling rules for power access and global confinement time, it is expected that all three devices will achieve their goal of dominant self-heating F > 0.5 (Q=5) and F > 0.66 (Q=10) seems likely. The most widely tested theory based core models combined with a variety of semi-empirical scaling rules for the pedestals support this conclusion. Both ITER and FIRE with standard divertors are designed for full H-mode access and pulse durations of 2-3 current relaxation times with expectations for ITER somewhat more robust. Any added density profile peaking helps performance and the added the rotation from the 1MV NBI gives ITER an added reserve for better performance.

IGNITOR is not designed for H-mode but an alternative de-rated current “wall-separatrix” operation may well access a transient H-mode possibly limited by wall power handling. The baseline IGNITOR operation anticipates a cold (L-mode like) edge with significant ohmic heating comparable to the auxillary . L97 global scaling enhancements of about H=1.25-1.4 are needed for Q = 5-10 for peaked density profiles n(0)/<n> = 1.8 Such enhancements (with cold edges) and peaking have been obtained transiently but the database for this is not widely established and steady state demonstration discharges in existing tokamaks are needed. ITER under the same conditions of cold–edge and peaked density require L97 enhancements of 1.4-1.7. The core theoretical models used require hot (H-mode like) edges or pedestals for all devices to obtain Q=5-10.