Particle & Impurity Transport and Fuelling

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Physics Issues

The goal is to identify the remaining R&D needed to understand fuelling and particle transport, including impurity transport, in ITER. In particular, the differences between particle and impurity transport which are emerging from experiment and theory may turn out to be critical. In the case of fuelling, it is not simply uncertainties in the deposition of injected impurities but the interaction of particle transport with the ablatant that requires research.

Our understanding of particle and impurity transport has become increasingly sophisticated in the last few years. There is evidence for particle pinch in the low collisionality regime of ITER and gyrokinetic simulations predict that turbulence can cause particle pinches. While the pinch may lead to a peaked fuelling ion profile and the promise of increased reactivity, it also may suggest peaked impurity profiles and the threat of fuel dilution and enhanced energy loss due to radiation. Thermalized ash is just another light impurity when it comes to its transport description but it also has significant, well-known consequences. The description of particle and impurity transport that is emerging from experiment and theory is not a simple one: Charge dependence and mass dependence are quite apparent. Fuelling ions, light impurities and heavy impurities will transport in different ways to produce quite different spatial profiles. Fortunately, particle profile measurement techniques are sufficiently mature to support a research program. Initial experiments in the low collisionality regime of ITER provide some direction for the research. Although theory and theoretical simulations may not have matured to the point of making direct theory/experiment comparisons, they certainly indicate direction for the research.

Fuelling in ITER is by edge gas fuelling and core pellet fuelling. Core fuelling efficiency in ITER is critically dependent on both pellet and particle transport. Ideally, the pellet fuels the core. In fact, it is injected on the high field side to take advantage of drifts of the ablatant cloud outward along the major radius which simply optimizes its penetration toward the core. Even then, penetration depth is limited so that some fraction of the pellet is deposited as fuelling particles in the outer 15% of the plasma minor radius (thought to be the elm-affected region of the plasma). In addition to the normal transport processes, transport of the pellet-sourced ions are subject to those induced by the pellets themselves such as high density gradients and induced elms. Edge gas fuelling is not discussed here because of the large opacity expected for ITER. The issue is taken up in the whitepaper "Physics-based prediction of edge pedestal profiles under reactor-like conditions," J. W. Hughes, et al.

A high-risk (but enticing) area for research is impurity and particle control. The possibility for particle control is suggested by experiments in present tokamaks in which transport is stimulated by excitation of a turbulent mode. The fact that the particle transport differs among species could be leveraged to isolate control of particular species. In current experiments, the turbulent mode is excited by auxiliary heating. There is no direct extension to ITER, but maybe another control parameter such as rotation should be sought.

Research Requirements

Particle profiles range from hollow to peaked and depend on mass, charge of the ion as well as on plasma parameters. A particularly interesting example of the latter is the dependence on collisionality in which the fuelling ions and the heavy impurities (but not the light impurities) peak as collisionality is reduced toward the ITER expectation. Hollow impurity profiles are also commonly observed even in H-mode discharges. This range of behavior is extreme in terms of expected plasma outcomes for ITER and does not follow a simple prescription. Peaked and hollow profiles indicate that particle pinches are important.

Neoclassical expressions alone often do not predict particle profiles. The transport description that we have at present consists of a well-developed neoclassical theory and a turbulent transport theory that has made significant gains in the last few years. The Ware pinch of neoclassical theory is well known. The pinches extracted from gyrokinetic simulations have a complex dependence on charge, mass, and dominant turbulence mode and can be positive or negative.

A significant fraction of our research effort should be focused on the particle pinch. Complete sets of particle profiles are clearly required to describe the plasma transport. Low collisionality and H-mode discharges are of the most interest. Turbulence profiles are required as well.

Turbulence measurements of particle transport are crippled by lack of a diagnostic for potential fluctuations in critical regions of the plasma. In the edge, Langmuir probes provide the quantity. In previous generations of tokamaks, a heavy ion beam probe was used. A version of that diagnostic is not available in the current generation of devices. A potential diagnostic is needed for present machines or some means must be found to extrapolate results from smaller devices.

The research for ITER should be targeted on modes that are relevant to ITER. Given the high core heating, the dominant modes may be TEM and high-k modes. To make firm predictions about peaking and impurity accumulation, the ITER-relevant modes should be identified to guide our research on current devices and new satellite devices.

Core fuelling in ITER adds its own unique issues and adds several additional particle transport issues. Core fuelling is by pellet injection on the high field side which takes advantage of favorable drifts of the pellet ablation toward the plasma core. The details of the injection angle are areas for research. Even with that favorable drift, penetration depth is limited to slightly more that the outer half of the plasma minor radius. Particle transport will then affect core fuelling. Since there will be significant deposition in the outer 15% of the plasma minor radius (supposed to be the elm affected region of the plasma), transport of the pellet-sourced ions are subject to processes induced by the pellets themselves such as high density gradients and induced elms.

The effect of particle pinch on pellet fuelling is a critical research area. In the absence of a pinch and with limited pellet penetration, the large fuelling rate for ITER would strongly affect the divertor. On the other hand, a stong pinch may make detachment more difficult and may make pellet ELM pacing impossible. Core heating in ITER will excite turbulence which will certainly affect the pinch. The pinch is critical to understanding fuelling.

Particle peaking can be actively suppressed. Both ECRH and ICRF have been used for this. The suppression suggests a tool for investigations of particle transport. It also suggests that there may be means for controlling peaking. Auxiliary heating is not likely to be useful for this in ITER. Control of rotation and shear suppression is an obvious alternative that might be followed up. Theory-based attempts at control could also lead to better understanding of particle transport.

Elements of a Research Thrust

Comparison of experiment with theory to verify the pinch effects predicted by turbulence simulations.

The most relevant discharge regime is H-mode. Low collisionality is also important. Physics studies in both L-mode and ITB discharges can be used to explore transport dependencies. Measurement of the particle profiles is reasonably well established. Special efforts should be made to acquire the required turbulence data.

Develop a set of experiments using current drive to remove the Ware pinch.

The turbulence predictions focus on a pinch. Use of current drive will remove the Ware pinch from consideration and make these studies cleaner. The disadvantage is that current drive experiments have their own set of requirements, and these must be taken into account in the experimental design.

Control of particle profiles.

In present experiments, control of particle peaking is achieved by heating with ECRH or ICRH. The use of these in ITER will be limited simply because the local energy increment will be small. Other means may be available to modify the turbulent pinch and these should be sought.

The effect of pellet injection angle/launch location and the particle pinch on core fuelling.

This includes experiments on high field side injection, simulations with realistic particle pinch, and loss due to pellet-induced elms. Much of this is already on the ITPA high priority lists. The particle pinch is emphasized here.

Diagnostic for plasma potential

A diagnostic for potential fluctuations is needed for turbulent particle transport studies. Probes provide the data in the edge. In previous generations of tokamaks, the heavy ion beam probe provided this data. A potential diagnostic for the confinement region in current devices must be developed.

A satellite tokamak or a collection of devices are needed for study

ITER will not have the wide range of diagnostics required to conduct the detailed research described here. Unresolved aspects of these issues will remain when ITER starts simply because ITER is operating in a new regime. Satellite tokamaks and special purpose devices will be needed to resolve the physics issues.