Alpha particle transport in high temperature steady state reactor regimes

Initiative:

This initiative aims to understand the issues affecting fast ion transport in reactor relevant regimes and to develop well validated theoretical models and experimental tools to reliably predict and control fast ion transport in fusion reactors.

Perspective:

Theoretical analysis indicates that high temperature regimes relevant to reactor conditions such as ARIES RS (Te, Ti > 20 keV) are strongly unstable to Alfven eigenmodes[1]. A multitude of such modes may strongly affect the transport and loss of alpha particles from the plasma core, as evidenced by recent observation in DIII-D and NSTX[2,3]. Understanding the influence of multiple unstable modes on fast ion transport in present day devices is essential for making reliable projections to reactor conditions. To understand the anomalous transport of fast ions in reactor relevant regimes, detailed measurements and modeling of existing experiments are needed. However, major advances are required in both our measurement and modeling capability in order to develop the validated numerical and theoretical models that can reliably predict reactor performance. Detailed measurements and predictive understanding are essential in order to develop methods for the control of fast ion transport and their extrapolation to the burning plasma regime.

Requirements:

In order to understand the physics of fast ion transport in present experiments, it is essential to develop advanced diagnostics and modeling capability. Simulation capability needs to be developed that addresses the nonlinear evolution of fast ion instabilities on multiple temporal and spatial scales. For diagnostics, methods need to be developed and refined for measuring the internal properties of the instabilities and the fast ion collective motion. The combination of such advanced diagnostics and simulation tools applied to existing experiments can lead to dramatic advances in our predictive capability. Such understanding is essential to develop methods for the control of fast ion transport in reactor relevant regimes, including methods for the suppression of instabilities and for the control of the phase space distribution of the fast ions.

1. **diagnostics:**

   a. Fluctuation measurements: Currently we measure internal density, temperature and external magnetic field fluctuations Density and temperature measurements are used in part to infer the internal magnetic field fluctuations, however the inferred magnitudes are insufficient to account for the observed level of fast ion transport according to ORBIT analysis[4]. In order to resolve this mystery, advances are required on several fronts. For diagnostics, internal fluctuating magnetic field measurements are required in order to confirm or revise the estimated mode amplitudes from density and temperature measurements. In addition, it is recognized that there will be a significant electric field associated with low frequency Alfven modes coupling to the acoustic branch. These electric fields need to be directly measured and not simply inferred from density of temperature measurements. Developing a program for precision measurements of electric and magnetic fields in fusion plasmas with high sensitivity and spatial resolution represents a major programmatic commitment of time and resources. However, the benefits of such a program will go far beyond the specific application to Alfven eigenmode measurements.
   b. Particle Diagnostics: Currently there is a range of methods developed for internal (confined) fast ion and lost particle measurements. However, the implementation of these methods is inadequate to reconstruct a large fraction of the spatial and velocity space distribution of the fast ions. In addition the measurements performed for the most part cannot resolve the collective motion of the fast ions on the wave period. These limitations need to be overcome, both for confined and lost particle measurements. Resolving the phase space distribution of the energetic ions and their motion on the wave period time scale will lead to major advances in the understanding of the physics of anomalous fast ion transport in advanced confinement regimes.

2. Theory and Simulation:
   a. Multiple scales: Linear ideal MHD theory has been successful in identifying many of the modes observed in experiment. Perturbative fast ion extensions to ideal MHD have been successful in addressing the stability of many of the observed modes in tokamak plasmas.

However, ideal MHD cannot capture the fine scale structure of Alfvenic modes that may be important for anomalous fast ion and thermal transport. New gyrokinetic codes are now coming into use for assessing the fine scale structure of these modes on the ion Larmor radius scale.

In addition, the linear stability codes cannot address self consistently the level of transport induced by the instabilities that are observed. Particle following codes can be used to model particle motion in a prescribed field of modes, but the level of transport inferred from such calculations appear to grossly under estimate the level of induced loss.

Progress has been made in the nonlinear simulation of ideal MHD modes. However these simulations typically require initial conditions that ae far from marginal stability and hence lead to results that may not be directly applicable to experiment.

Experimentally, the distribution of fast ions and collective instabilities is determined self consistently on a particle slowing down time scale with the system likely remaining close to marginal stability. So far, no simulation capability has been able to address self consistently the interaction of the fast ions with the instabilities on a long time scale.

In order to validate nonlinear simulation codes against fast ion and mode amplitude measurements, the simulations need to deal with multiple time scales incorporating the particle sources and sinks in the analysis. Such simulation capability is far from what is currently available and will require a major investment in manpower and computational resources.

b. Theoretical models:
   Simulations on the transport or slowing down time scale for systems near marginal stability will require the development of reduced theoretical models and improved algorithms that lead to numerically stable and accurate solutions over many thousands of cycles of the underlying instability.

3. Transport control:
   a. As in thermal transport, the long term desire for energetic particle physics studies is to develop effective control tools to modify the stability and/or nonlinear behavior of

collective effects. These control tools can then be used in a variety of ways, from mitigating the deleterious effect of modes on fast ion transport to potentially channeling fast ion energy to the thermal ions, in current drive, enhancing rotation or other possibilities. The latter set of applications is best known as "phase space engineering". While the methods for such control cannot be identified at this time, it is clear that detailed phase space knowledge of the ions and their collective effects is essential to explore this physics. The initiative outlined above will naturally lend itself to the detailed understanding required for phase space engineering of the alphas/energetic particles.

[1] N.N. Gorelenkov, et. al. *Nucl. Fusion* 43 594 (2003)

[2] H. H. Duong, W. W. Heidbrink, T. W. Petrie, R. Lee, R. A. Moyer, J. G. Watkins, *Nucl. Fusion* 33, 749 (1993).

[3] E. Fredrickson, NSTX reference

[4] Heidbrink, W.W., et al., Phys. Rev. Lett. 99, 245002-1 (2007).