Critical Gradient Behavior of Fast Ions

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1 Introduction

Critical gradient behavior of fast ions has been observed in magnetic fusion experiments (MFE). This behavior seems to limit the amount of power that can be injected into the plasma core while the rest is simply lost to the wall. The losses (with sufficient energy) can damage the walls of future reactors. Therefore, it is important to understand this behavior to prevent costly damages. A fast ion diagnostic (called FIDA) that measures density profiles for a particular region in phase space shows increases with injected beam power until a critical gradient threshold is reached (see Figure 1). After that point, the profile becomes stiff and increasing the injected power no longer changes the profile.[2]

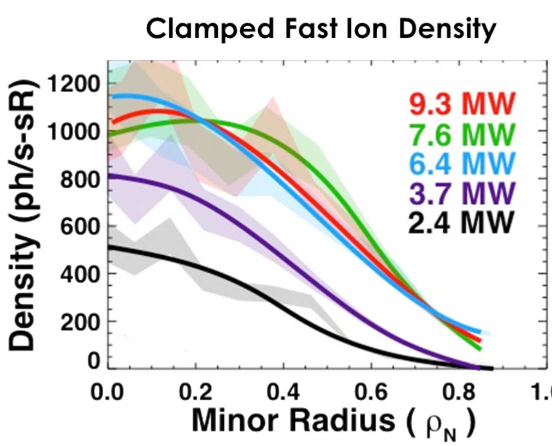

Figure 1: The FIDA diagnostic measures fast ion density in mostly co-passing orbits. Increase in beam power increases the density until the critical gradient threshold is reached. After that, the profile is resilient to further increases in the beam power.[2]

2 Self-Organized Criticality

The FIDA density profiles appear to be in a near-marginal state as increases in the flux of particles deposited by the beam do not continue to increase the magnitude of the profile. This behavior draws similarity to that of self-organized criticality (SOC). SOC is expected to appear in systems that are open and slowly driven with a local critical threshold and fast relaxation process.[4] In the case of MFE, the plasma is surrounded by vacuum where confined ions can be lost. System drive varies with neutral beam injection at different powers. The local critical threshold is intertwined with the fast relaxation process as the injection mechanism introduces local gradients. At a certain threshold, these gradients can drive wave particle resonances that facilitate local redistribution or transport processes depending on the strength of the resonances.

3 Critical Gradient

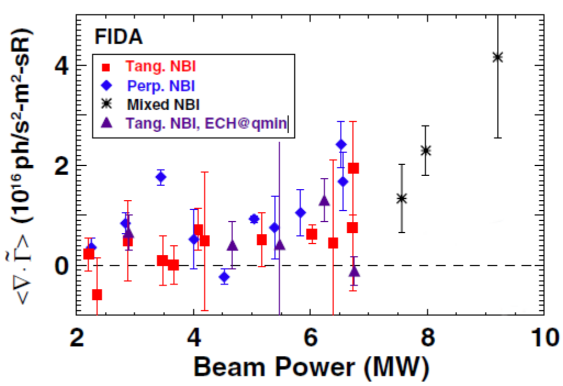

Figure 2: Calculated fast ion transport from the FIDA diagnostic show minimal transport at low beam power and a sudden increase in transport that seems to increase linearly with deviation from the critical gradient threshold located around $P \approx 6$MW.[2]

For critical gradient behavior, insignificant transport should occur below the threshold but considerable transport should occur above threshold. The evolution of the FIDA density profiles with increasing beam power certainly demonstrates this behavior. Below the threshold, transport of fast ions out of the plasma is not very prevalent causing the injected particles to be deposited into the plasma thus increasing it's density at an equilibrium state. Above the threshold, deposited particles undergo an additional transport mechanism which keeps the system in a near-marginal state and the profile remains unchanged. To quantify the transport, simulations are employed to calculate the profiles in the absence the additional transport mechanism. Subtracting the experimental values from the simulation yields the amount of transport for each case as seen in Figure 2. Initially, negligible transport is observed at lower beam power but after the critical gradient threshold, transport suddenly increases linearly with deviation from the critical point.

4 AE Induced Transport

The toppling mechanism that facilitates fast ion transport can be explained through wave particle resonances with Alfven eigenmodes (AEs) that are driven by density gradients. It can be seen from the CO_2 interferometer in Figure 3 that higher beam power excites more modes.

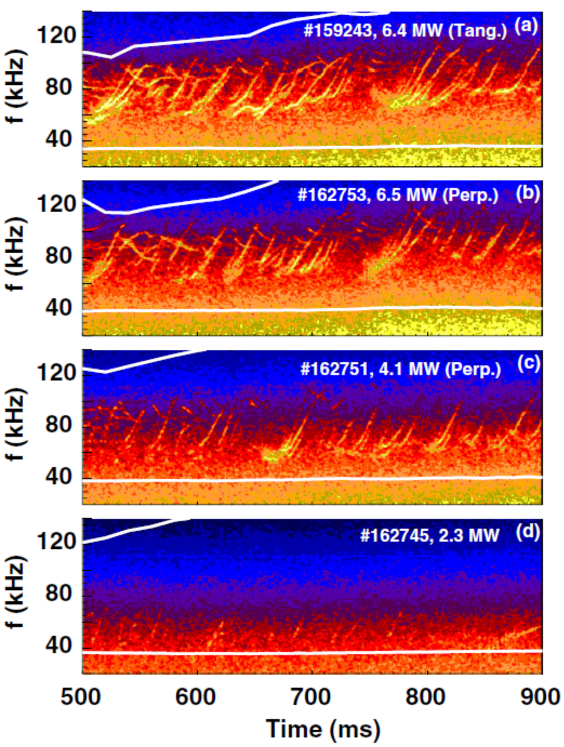

Figure 3: The CO_2 interferometer spectrogram shows little to no AE activity at lower beam powers and higher AE activity at higher beam powers.[2] Different injection geometries affect the amount of activity as shown in (a) and (b).

Additionally, temperature fluctuations measured by the electron cyclotron emission (ECE) diagnostic show AE amplitudes increasing with the injected beam power in Figure 4.

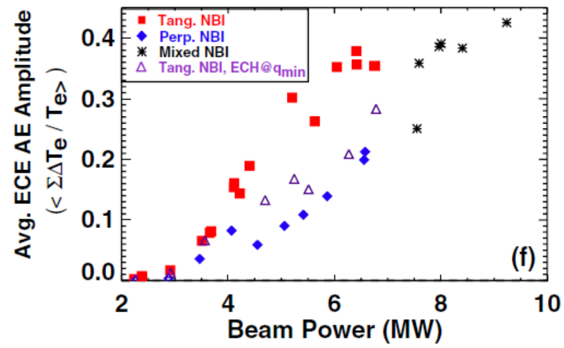

Figure 4: AE amplitudes measured by the ECE diagnostic show increasing amplitude with increasing injected beam power.[2] The different sets of points represent different injection geometries and heating combinations that affect AE activity. The threshold where AE activity increases is around $P \approx 3$MW.

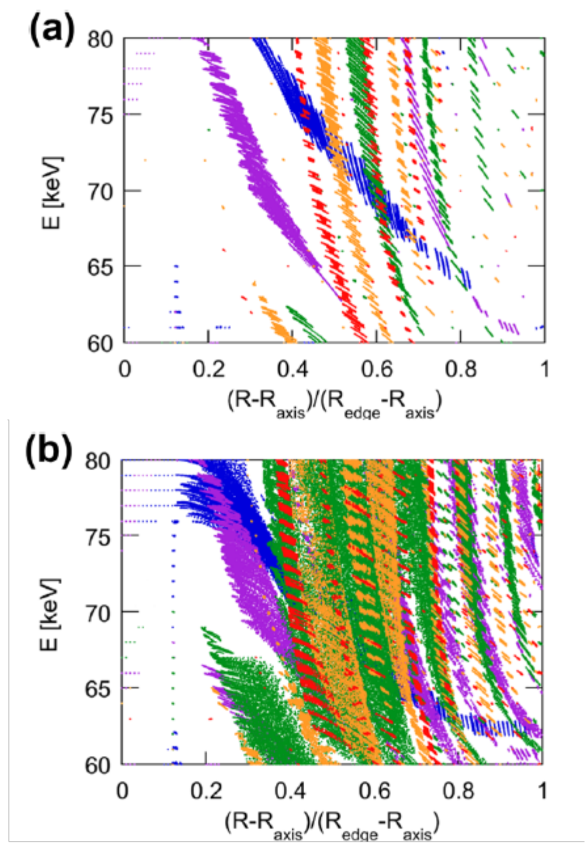

Figure 5: Particle trajectories from injected beam powers of (a) 1.56 MW and (b) 15.6 MW were simulated in the presence of AE perturbations.[6] The positions of particles trapped by AEs as they cross the midplane from the top to bottom are plotted in phase space. The different colors represent particles trapped by different eigenmodes (blue: n=1, purple: n=2, green: n=3, orange: n=4, red: n=5).

One thing to note is that the linear stability threshold for Alfven instability does not line up with the critical gradient threshold. This just means that the linear stability threshold found at $P \approx 3$MW (seen in Figure 4) does not set the critical gradient threshold found at $P \approx 6$MW (seen if Figure 2).

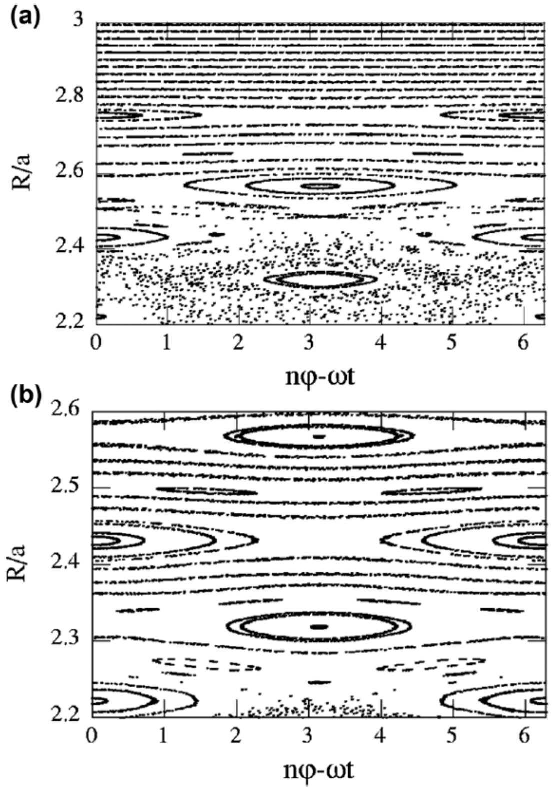

Figure 6: Phase space plots of particles trapped by AE resonances are shown. Normalized radii is plotted against the phase of the particle as it passes a poloidal angle. Plot (a) shows (at high AE amplitudes) a stochastic region around $R/a = 2.4$ to $R/a = 2.2$ while plot (b) reveals (at low amplitudes) that higher order islands eventually lead to the stochastic region.[5]

One explanation for the transport mechanism that sets the critical gradient threshold is island overlap from AE activity. At higher power where more multiple strong AEs are observed, phase space islands overlap to create a stochastic region where particles can freely diffuse.[6] In Figure 5, particle trajectories from beams with different injection powers were simulated in the presence of AEs. The positions of eigenmode trapped particles as they cross the midplane (from top to bottom) are plotted against their energy. The results show that there are few regions of resonance overlap at lower beam power (Figure 5(a)) while there are significant resonance overlap regions at higher beam power (Figure 5(b)). In addition, a single AE can also cause a stochastic region by island overlap with higher order islands which is shown in Figure 6.[5]

As a result from these stochastic regions, particles can enter loss orbits where they are transported out of confinement. A fast ion loss detector (FILD) measures particles on loss orbits on their way to hit the wall. Data from the FILD diagnostic (Figure 7) show a correlation between the amount of events with the beam power.[1] Aside from the obvious conclusion that there are more events associated with higher power, the distribution of events per signal is non-Gaussian with a fat tail leading to the suggestion of intermittent avalanches as the transport mechanism.[3]

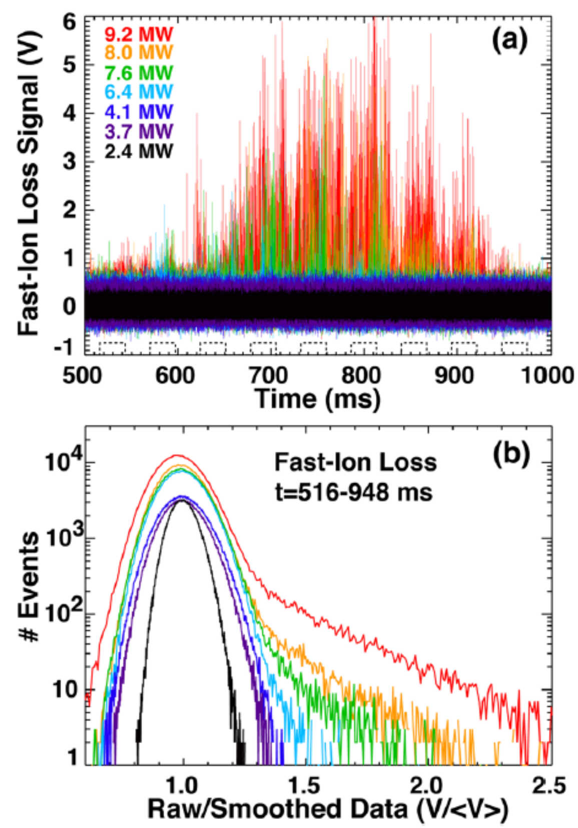

Figure 7: The FILD diagnostic measures increases in fast ion losses with increasing injected power in (a).[1] The distribution of the loss events (b) become more non-Gaussian and develops a fatter tail with increasing power.

5 Other Considerations

One thing that was glossed over in this discussion was the fact that the FIDA diagnostic is only sensitive to a specific portion of fast ion phase space. Be-

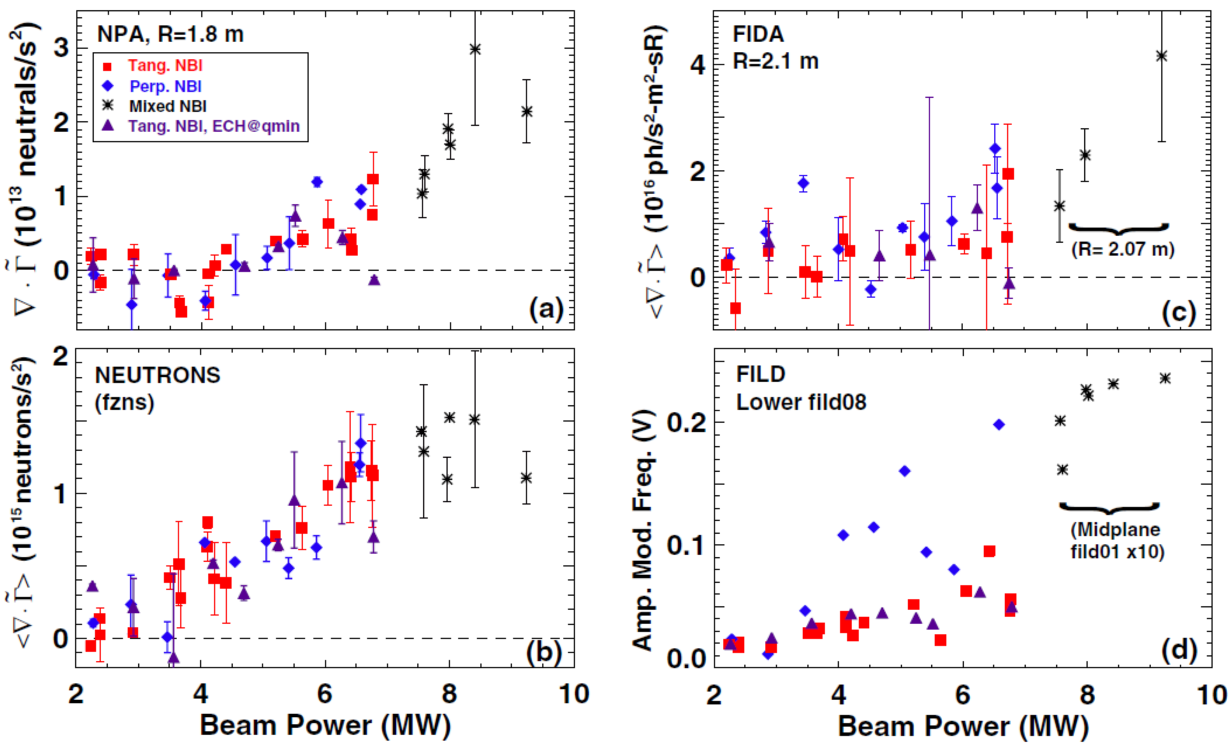

Figure 8: Transport measured by different fast ion diagnostics lead to different critical gradient thresholds due to the different sensitivities in phase space for each diagnostic[2]

cause of this, having multiple different diagnostics are useful to probe different parts of phase space. Using similar analysis to obtain the amount of transport for the FIDA diagnostic, transport relationships to beam power are obtained for different diagnostics shown in Figure 8. Clearly, all the critical gradient threshold locations don't match up. This is because AEs may resonate with particles in phase space regions that are sensitive to one diagnostic but not another. This complication is one of the reasons why modelling this behavior is difficult.

References

[1] C.S. Collins et al. Observation of critical-gradient behavior in alfvén-eigenmode-induced fast-ion transport. *Physical Review Letters*, 116(095001), 2016.

[2] C.S. Collins et al. Phase-space dependent critical gradient behavior of fast-ion transport due to alfvén eigenmodes. *Nuclear FUsion*, 57(086005), 2017.

[3] W.W. Heidbrink et al. Fast-ion transport by alfven eigenmodes above a critical gradient threshold. *Physics of Plasmas*, 24(056109), 2017.

[4] R. Sanchez and D.E. Newman. Self-organized criticality and the dynamics of near-marginal turbulent transport in magnetically confined fusion plasmas. *Plasma Physics and Controlled Fusion*, 57(123002), 2015.

[5] Y. Todo et al. Simulation of intermittent beam ion loss in a tokamak fusion test reactor experiment. *Physics of Plasmas*, 10(7), 2003.

[6] Y. Todo et al. Fast ion profile stiffness due to the resonance overlap of multiple alfvén eigenmodes. *Nuclear Fusion*, 56(112008), 2016.