MHD Stability of High Beta NSTX Plasmas*

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The National Spherical Torus Experiment, NSTX, has demonstrated high beta, with β_t up to 35% and β_N up to 7 having been achieved experimentally[1]. A variety of beta limiting instabilities have been encountered on NSTX and can be broadly classified as internal or external modes. It is generally observed that high-q and high toroidal rotation are necessary for sustained high-β operation, otherwise the onset of one of these instabilities can lead to β saturation or collapse.

β-Limiting Instabilities

The neoclassical tearing mode (NTM) is an internal mode which has been observed resulting in beta saturation and degraded overall performance in NSTX[1]. These modes grow slowly consistent with the value predicted by the modified Rutherford equation[2], and are a concern for ST operational scenarios which include high β_p and high bootstrap fraction[3]. NTMs can be avoided by operating at elevated q. but can still be triggered by sawteeth and ideal kink-like perturbations.

Often the fast ion component of the stored energy in NSTX is a significant fraction of the total (15-30%), giving a central fast ion pressure comparable to the thermal pressure. The m/n = 1/1 pressure-driven internal kink is computed to be ideally unstable in such discharges when high β_t and a large region of low magnetic shear with q ~ 1 are also present, This mode is one possible explanation for experimentally observed n=1 instabilities which often saturate and decay slowly in the presence of high toroidal rotation[4]. These modes can lead to β saturation, toroidal rotation damping, and sometimes rapid disruption.

The resistive wall mode (RWM) is an external mode which has been observed in NSTX when β_N exceeds the ideal n=1 no-wall stability limit that leads to strong rotation damping and β collapse[5]. RWM theory predicts that the mode may be stabilized through a combination of plasma rotation and energy dissipation[6,7]. This mode couples directly to the wall causing rotation damping which further destabilizes the mode. It must either be passively stabilized, or detected early in its growth and prevented from damping toroidal rotation and leading to beta collapse.

RWM Stability Physics

Bondeson and Chu calculated the inertia and ion Landau damping of MHD modes in a collisionless plasma from a drift-kinetic energy principle including trapped particle effects[8]. This work indicates that trapped particles decrease the effectiveness of ion Landau damping and increase the stabilizing Pfirsch-Schluter like toroidal inertia enhancement.

In contrast to work which focuses on the rotation at a particular q surface to determine stability[9], Bondeson and Chu predict a drastic change in the mode structure due to toroidal inertial enhancement of the flow when the rotation frequency exceeds the upper limit of the lowest branch of the Alfven continuum, i.e. when $\square_{\square}/\square_{A} > 1/(4q^2)$. Continuum damping is relevant in this case, so the entire rotation profile is important in determining stability. NSTX results confirm this conclusion.

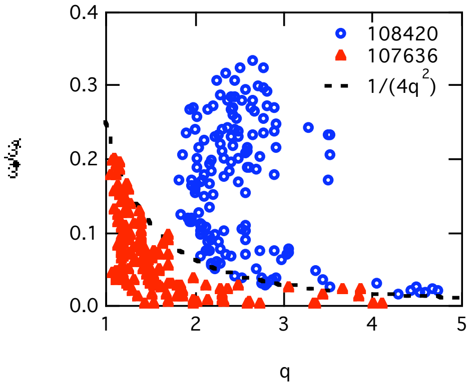

Figure 1: Two shot comparison of rotational stabilization

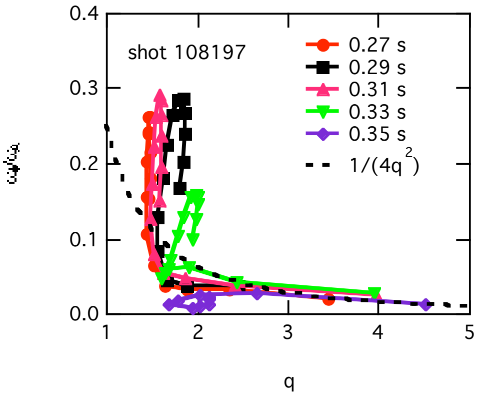

Figure 2: Partially stabilized shot

Plotting the toroidal rotation profile (measured by CHERS) normalized to the Alfven speed versus $1/(4q^2)$ for various NSTX discharges shows that having the normalized rotation above $1/(4q^2)$ across the entire plasma when $\square_N > \square_{N\ \text{no-wall}}$ is necessary for RWM stability. Figure 1 shows the normalized rotation across the entire profile for the series of time points when $\square_N > \square_{N\ \text{no-wall}}$ for two discharges. Time evolved EFIT reconstructions were performed to determine the equilibrium quantities[10]. The reconstructed q profiles from this analysis are slightly higher than values indicated by more well constrained reconstructions which are currently being tested.

Shot 108420 is rotationally stabilized across the entire plasma profile when $\square_N > \square_{N\ \text{no-wall}}$ and survives for approximately $18\square_w$ in the wall stabilized regime with no RWM collapse. This result is reproduced for over 1500 data points. In contrast, shot 107636 never has enough rotation and exhibits repeated collapses as $\square_N$ exceeds $\square_{N\ \text{no-}}$

$_{\text{wall}}$. In this discharge $\square_{N\ \text{no-wall}}$ is reached three times, and each time the plasma suffers a beta collapse restoring ideal stability.

Figure 2 shows a shot which has insufficient rotation for stability across part of the profile, including low order rational surfaces, as $\square_N$ exceeds $\square_{N\ \text{no-wall}}$. This shot survives in the wall-stabilized regime for ~ $3\square_w$ before experiencing a core rotation collapse and a terminating beta collapse. Discharges with similar rotation profiles all exhibit similar behavior.

For ion Landau damping to be a significant form of dissipation, the mode frequency in the reference frame of the ion gyrocenters has to be sufficiently large, leading to a minimum rotation frequency of $\square_{rot} > \square^{1/2} v_{ti}/(qR)$. Figure 3 shows the toroidal rotation profiles versus this damping parameter for the time interval where $\square_N$ exceeds $\square_{N\ \text{no-wall}}$ in shot 108420. Part of the profile has sufficient rotation for ion Landau damping, indicating that this dissipation mechanism should be operative in some portion of the plasma. Numerical studies must be performed to determine if this level of dissipation is sufficient to stabilize the RWM.

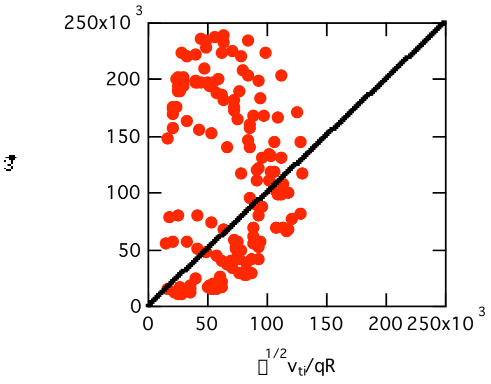

Figure 3: Rotation vs ion Landau damping parameter

RWM Detection

Internal $\square B_r$ and $\square B_p$ sensors have been installed in NSTX to measure slowly rotating and locked modes. The sensors have been installed in 12 toroidally symmetric locations with sensors of each type both above and below the midplane. The sums and differences of coil pairs are recorded allowing SVD analysis to determine modes n=1,2,3.

The background pickup due to slight sensor misalignments, non-identical sensor pairs, and the eddy currents in the surrounding conducting structures is subtracted using measured coil currents, loop voltages, and a signal proportional to the plasma current. An example of the mode detection results is shown in figure 4 for the upper B_p array, along with the signal measured by a midplane external B_r array. Figure 4(a) shows the toroidal Mirnov mode spectrum, indicating a n=1 that is slowing down and locking just before 0.7s. Signals above ~10 kHz are cutoff from the Bp sensors by shielding and these sensors are digitized at a rate of 5 kHz, so while modes in the range of 2.5-10 kHz are detectable, they will be aliased. Figure 4(b) shows that the n=1 mode becomes observable on the B_p array as soon as the mode drops below 10 kHz, well before the mode becomes observable on the external array.

Initial observations with these sensors for discharges with $\square_N > \square_{N\text{ no-wall}}$ may indicate the presence of RWM type growth, but are currently inconclusive. Discharge 112093 has a possible RWM collapse, but it is difficult to resolve the n=1 signal from the noise, as shown in figure 5. This discharge has $\square_N > \square_{N\text{ no-wall}}$ and exhibits a global rotation collapse. There is growth of the n=1 at the end of the discharge starting at ~0.47s, but the discharge becomes vertically unstable at ~0.49s. The n=0 signal from a vertical instability is readily removed by the mode detection algorithm, so it is possible that a global n=1 perturbation is triggering vertical displacement in this case.

The information from the internal sensors and a set of external radial field coils can provide dynamic error field correction and actively control modes which slowly rotate and grow[11]. An active control coil set is currently being installed on NSTX for this purpose. Calculations using the VALEN 3D code[12] to model the RWM, the control coils, and surrounding conducting structures indicate that NSTX plasmas with $(\square-\square_{N\text{ no-wall}})/(\square_{N\text{ ideal-wall}}-\square_{N\text{ no-wall}}) = 0.68$ can be stabilized with the coil being installed.

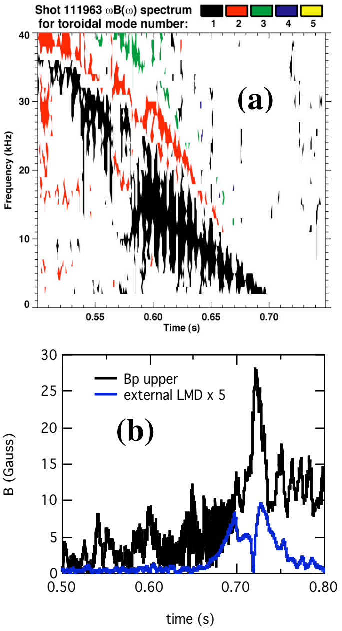

Figure 4: Observation of n=1 mode

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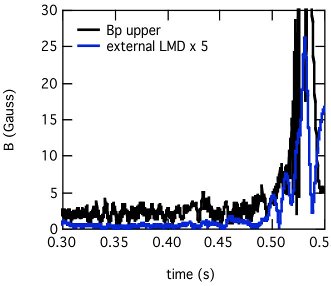

Figure 5: Possible RWM observation