Observation of MHD-induced Current Redistribution in NSTX*

J. Menard[1], M. Bell[1], R. Bell[1], D. Gates[1], S. Kaye[1], B. LeBlanc[1], F. Levinton[2], R. Maingi[3], S. Medley[1], D. Stutman[4], S. Sabbagh[5], K. Tritz[4], H. Yuh[2], and the NSTX research team.

[1] *Princeton Plasma Physics Laboratory, Princeton, NJ, USA*
[2] *Nova Photonics, Princeton, NJ, USA*
[3] *Oak Ridge National Laboratory, UT-Battelle, Oak Ridge, TN, USA*
[4] *Johns Hopkins University, Baltimore, MD, USA*
[5] *Columbia University, New York, NY, USA*

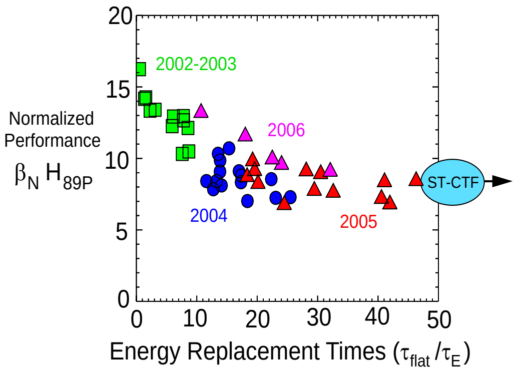

Figure 1 – Product of normalized beta and H-mode confinement enhancement factor relative to ITER-89P scaling vs. flat-top duration normalized to energy confinement time.

Recent experiments in the National Spherical Torus Experiment (NSTX) [1] have focused on extending the discharge duration by operating at high non-inductive current fraction utilizing enhanced plasma shaping [2] combined with the good confinement and broad pressure and current profiles of the H-mode. As shown in Figure 1, high pulse-averaged normalized performance as measured by the product $\beta_N \times H_{89P}$ has been sustained for several tens of energy confinement times at the level needed for a proposed spherical torus (ST) based Component Test Facility (CTF) [3]. For the longest duration discharges shown in Figure 1, the peak bootstrap fraction reaches approximately 50% matching the value expected to be needed in an ST-CTF. In addition, these discharges have pulse-lengths approaching 1.6s or approximately 5 current redistribution times τ_{CR} where $\tau_{CR} \approx 0.3$s. Since the peak non-inductive current fraction of 60-70% is significantly less than unity, the inductively-driven current profile might be expected to relax to a centrally peaked profile driving $q(0) < 1$ with concomitant sawtooth instabilities. A new Motional Stark Effect (MSE) diagnostic operable at low magnetic field strength ≥ 0.3 Tesla [4] has been utilized to constrain magnetic reconstructions of the parallel current density profile in an ST plasma for the first time. An important finding of the MSE-constrained reconstructions for the longest duration discharges of Figure 1 is that while q(0) does indeed slowly decrease toward unity, it remains elevated above 1 for the entire discharge. As show below, redistribution of Neutral Beam Injection (NBI) fast ions by core MHD activity apparently plays a key role in sustaining this elevated q profile.

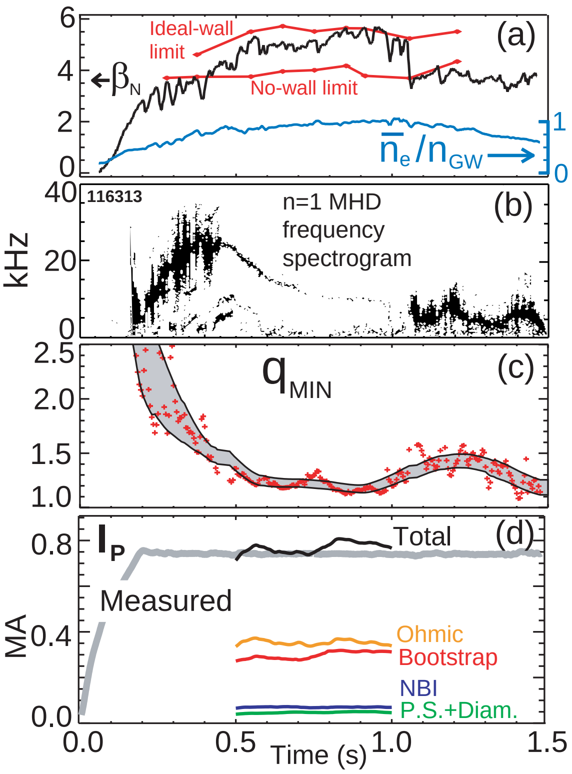

Figure 2 - (a) Normalized beta (black), calculated n=1 no-wall and ideal-wall stability limits (red), and line-average density normalized to Greenwald value (blue), (b) n=1 MHD activity frequency spectrogram, (c) reconstructed instantaneous (red) and 200ms time-average (gray) minimum q value, (d) measured (gray) and calculated total (black) plasma currents and inductive and non-inductive contributions.

The time-history of one of the longest discharges obtained thus far in NSTX is shown in Figure 2. As seen in Figure 2a, the normalized beta β_N is at or above 4 for over 1 second, and is above the calculated n=1 no-wall limit for approximately 0.6 seconds. Rotational stabilization of the resistive wall mode [5] allows access up to the calculated ideal-wall limit of β_N = 5.5-6 for t=0.8-1s. Figure 2b shows only weak n=1 MHD activity is present between t=0.5 and 1.05 seconds. However, after t=1.05s stronger n=1 activity is triggered resulting in significantly degraded confinement and reduced β_N (P_{NBI} is fixed at 6MW for t ≥ 0.2s). The late n=1 instability present after t > 1.05s is commonly observed and is apparently triggered by repeated excursions above the n=1 ideal-wall limit combined with operation near the Greenwald density limit. During the repeated β_N drops near the ideal-wall limit, no T_e inversion is observed as might be expected for sawtooth collapses. Instead, electron pressure drops are observed to peak in the outer half of the plasma minor radius consistent with external mode activity. Consistent with the apparent absence of sawtooth signatures, Figure 2c shows that q_{MIN} decreases very slowly during the period t=0.5-1.05s to a value of approximately 1.2 and stays above unity for the entire discharge. At the onset of the late n=1 activity, q_{MIN} increases abruptly to 1.5 and then slowly decreases again to approximately 1.2. MSE-constrained reconstructions allow the inductive current drive to be computed from the reconstructed electric field and neoclassical conductivity valid for low aspect ratio [6]. As is evident from Figure 2d, when the same neoclassical theory is used to compute the bootstrap current and the TRANSP NBI current drive contribution is included, very good agreement between the measured and predicted total plasma current is obtained.

As seen in Figure 3a, the calculated total parallel current density profile is also in good agreement with the reconstructed profile shape during the time interval when no large-scale MHD activity is present. In contrast, Figure 3b indicates a significant discrepancy between the reconstructed and calculated total current density in the plasma core during the period of late n=1 MHD activity shown in Figure 2b. During the same time interval of this apparent current profile anomaly, Figure 3c indicates there is also a discrepancy between the measured neutron rate and the neutron rate calculated by TRANSP. In Figure 3c, the calculated neutron rate has been scaled by a factor of 0.9 to match the measured rate prior to the late MHD activity in order to determine the fractional decrease attributable to the late n=1 MHD activity. Ultra-Soft X-Ray (USXR) array data [7] indicates the late n=1 MHD activity is core-localized and as shown in Figures 4a and 4b, magnetic island emission models [8] extended to simulate ideal displacements can fit the measured USXR data well. As shown in Figure 4c, the mode radial displacement profile peaks near normalized minor radius ρ = 0.4. The reconstructed q profile at this time indicates weak shear reversal (Δq = 0.1) with $\rho_{MIN(q)}$ = 0.4. These equilibria are calculated to be resistive interchange unstable (D_R>0) [9] for ρ=0.2-0.5 suggesting the mode is a saturated infernal or quasi-interchange mode.

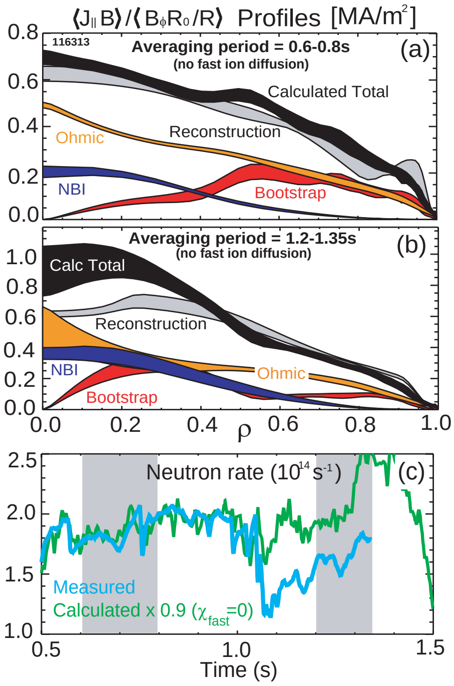

Figure 3 - (a) Comparison of the time-averaged reconstructed (gray) and calculated (black) parallel current density profile from t=0.6-0.8s, (b) from t=1.2-1.35s, and (c) measured (blue) and calculated (green) neutron rates assuming no anomalous fast ion diffusion.

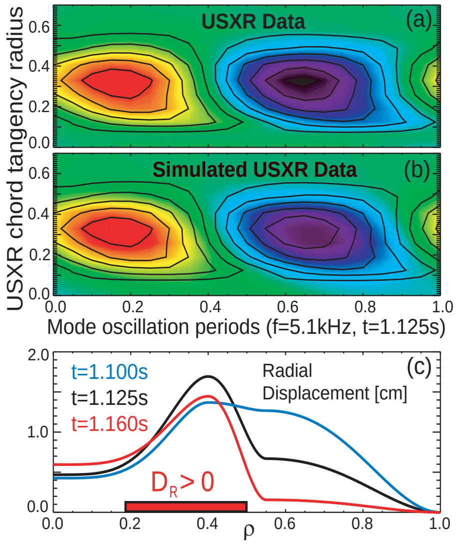

Figure 4 - Measured line-integrated USXR emission amplitude contours plotted versus chord tangency radius and time for one oscillation period, (b) best-fit simulated USXR emission amplitude assuming a 1/1 kink eigenfunction, and (c) reconstructed kink radial displacement amplitude profile at outboard midplane during mode saturation.

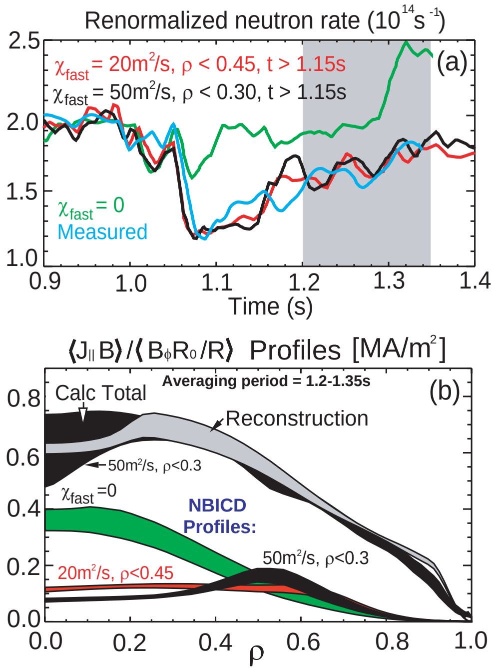

Figure 5 - (a) Comparison of the measured (blue) to calculated neutron rate, and (b) comparison of reconstructed (gray) and calculated total (black) parallel current density profile for t=1.2-1.35s for the best-fit fast-ion diffusivity model. NBICD profiles for the diffusivities of (a) are also shown.

Figure 5a shows that anomalous fast-ion diffusion localized to the plasma core can reproduce the measured neutron rate decrease attributable to the core interchange mode. For these TRANSP simulations of the mode-induced fast-ion diffusion, the diffusion radii were chosen to be consistent with the estimated mode displacement radius from the USXR data. Figure 5b indicates that such mode-induced fast-ion diffusion can convert a NBI current drive profile from centrally peaked to flat or even hollow resulting in a predicted total current density profile in agreement with the equilibrium reconstructions. The interchange-type instabilities described here also have the important characteristic that they become more unstable (with presumably larger saturated displacement amplitude and associated fast-ion diffusion) if the plasma β is increased or if q_{MIN} is decreased toward unity. These modes also become stable if q_{MIN} is increased above 1.4. Thus, interchange-type modes provide a self-regulating mechanism for redistributing fast-ions and maintaining an elevated q profile. Similar interactions between fast ions and tearing modes may play a role in sustaining “hybrid” scenarios proposed for ITER [10].

[1] S. M. Kaye, et al., Nucl. Fusion **45**, S168 (2005).

[2] D. A. Gates et al., Nucl. Fusion **46** (2006) S22-S28.

[3] Y.-K. M. Peng et al., Plasma Phys. Controlled Fusion **47** (2005) B263-B283.

[4] F. M. Levinton, et al., in preparation.

[5] A. C. Sontag et al., Phys. Plasmas **12**, 056112 (2005).

[6] O. Sauter, C. Angioni ,Y. R. Lin-Liu, Phys. Plasmas **9**, 5140 (2002)

[7] D. Stutman et al, Rev. Sci. Instrum. 70, 572 (1999)

[8] J. E. Menard et al., Nucl. Fus. **45**, 539 (2005)

[9] A. H. Glasser, et al., Phys. Fluids **18**, 875 (1975)

[10] M.R. Wade et al., Nucl. Fusion **45,** 407 (2005)

**This work supported by US DoE contract DE-AC02-76CH03073 at PPPL*