Multi-energy SXR characterization of stabilized resistive wall modes in NSTX

L. Delgado-Aparicio[1], K. Tritz[1], M. Finkenthal[1], D. Stutman[1], S. A. Sabbagh[2], J. Berkery[2], J. Levesque[2], R. Bell[3], S. Gerhardt[3], B. LeBlanc[3], J. Manickam[3], J. Menard[3] and L. Roquemore[3]

[1]*The Johns Hopkins University, Department of Physics and Astronomy, Baltimore, MD, USA*
[2]*Columbia University, New York, NY, USA*
[3]*Princeton Plasma Physics Laboratory, Princeton, NJ, USA*

ABSTRACT

The active control of the long-wavelength resistive wall mode (RWM) instability is expected to significantly improve the performance of future burning plasmas [1]. While in conventional aspect-ratio tokamaks the RWM has been studied and controlled for over a decade [2], in a high plasma pressure device such as the spherical tokamak (ST), the mitigation, control and understanding of the RWM become even more important. We present here a study, which contributes to the understanding the physics of RWM stabilization and control, based on the use of a multi-energy SXR array operated on the NSTX tokamak.

RWM EXPERIMENTS

RWM active-stabilization has been successfully tested in the National Spherical Torus Experiment (NSTX); a non-resonant $n=3$ magnetic braking field reduces the plasma toroidal rotation (Ω_ϕ) below a critical rotation (Ω_c) triggering the RWM while a superimposed $n=1$ active feedback field stabilizes the RWM for several energy confinement times [3,4]. The discharges we used were typical double-null diverted NSTX H-modes having: I_p=0.9 MA, B_t=0.45 T, $<\kappa>\sim2.3$ and $<\delta>\sim 0.6$ (see Figure 1 and ref [3]). The $n=3$ magnetic braking field as well as the $n=1$ active feedback were turned on simultaneously at approximately 0.45 s. The deuterium neutral beam injection had accelerating voltages of 90-95 kV and a total heating power of $P_{NBI}\sim$6.3 MW with neutron rates of the order of $\sim3.5\times10^{14}$ n/s [Figure 1-b)]. These actively stabilized H-

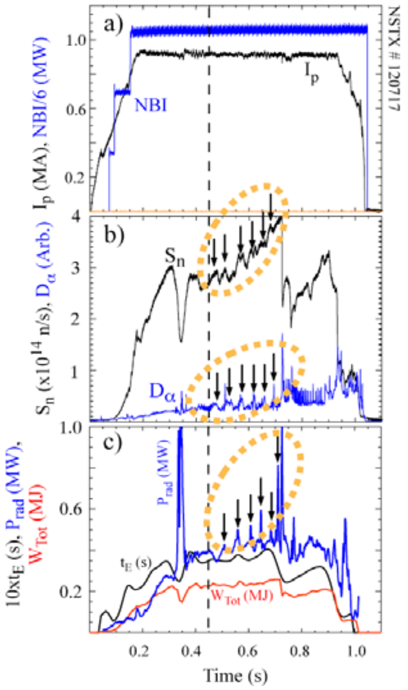

Fig. 1. a) I_p & P_{NBI}, b) S_n & D_α, and c) τ_E, P_{rad} and stored energy W_{Tot}.

modes did not experience an unstable RWM and continued to increase their β_N from 4.0 to 5.5 as the critical rotation continued to decrease throughout the major radius. The data in Figure 1-b) and -c) shows the low frequency (~25 Hz) features associated with the slowly rotating nature of the stabilized RWM [5]; the D_α signals suggest the presence of a strong edge activity during active-stabilization that correlates well in time with the signatures from the core neutron data. In addition, measurements obtained with a tangential bolometer also indicate transient increases in the total radiated power [5].

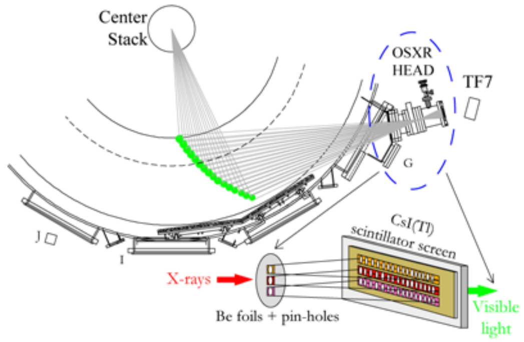

Fig. 2. Multi-energy tangential OSXR array.

RWM KINETIC DIAGNOSTIC

The main diagnostic used for describing the effects of the actively stabilized RWM on the background plasma is a tangential multi-energy soft X-ray array we operate in NSTX [5,9] (see Figure 2). This diagnostic has three identical groups of overlapping sightlines that view the same plasma volume at various energies using beryllium foils of different thickness; the selection of these SXR filters was such that their low, medium and high cut-off energies are also approximately equal to $1\times\langle T_e\rangle_l$, $2\times\langle T_e\rangle_l$, and $3\times\langle T_e\rangle$, where $\langle T_e\rangle_l$, is the line-average electron temperature in a typical NSTX discharge. The fast electron temperature measurements are thus obtained by modeling the slope of the continuum radiation from ratios of the radially inverted emissivity profiles. Due to the toroidal asymmetric nature of the RWM, the 1D Abel-inversion gives only an approximate description of the SXR emissivity profile.

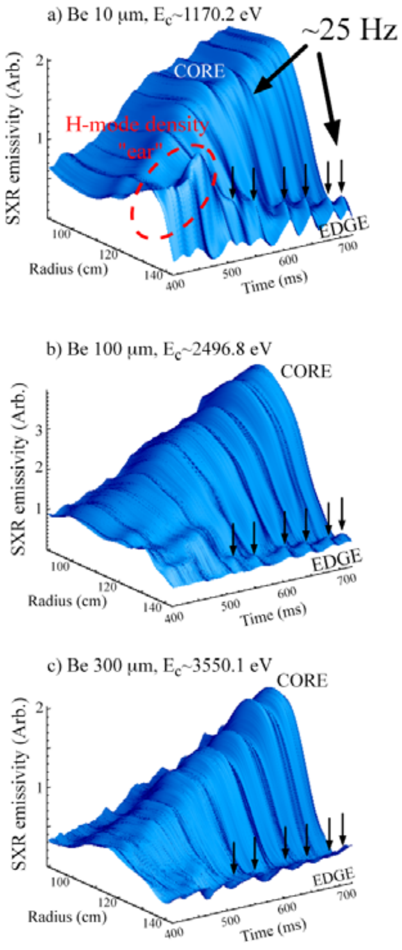

Fig. 3. Plots of the three ME-SXR emissivities for the actively-stabilized RWM.

The time histories of the multi-energy SXR emissivity profiles during the time of the active stabilization are shown in Figure 3 (see also references [5,10]). The low-energy emissivity shown in Figure 3-a) indicates first, that either the $n=3$

magnetic braking or the $n=1$ active stabilizing field may have been responsible for modifying the edge emisivity profiles at early times (see red dotted lines within $t \in [450,500]$ ms around R~140 cm). It can also be inferred from Figure 3-a) that the stabilized RWM carries an edge modulation with the characteristic frequency of ~25 Hz as described above, which in this case can be attributed to an electron and impurity density ($n_e \cdot n_Z$) edge activity; these peripheral perturbations seem to also travel radially inwards thus modulating the core emission.

DATA ANALYSIS

The medium- and high-energy SXR emissivities shown in Figures 3-b) and -c) are obtained using thicker beryllium foils having an enhanced diagnostic sensitivity to electron temperature fluctuations [7-8]. The effect of the RWM stabilization on the plasma core can also be observed in the “slow” ~25 Hz modulation of the medium- and high-energy reconstructions. The SXR emissivities obtained in similar H-mode plasmas but without active feedback indicated only peripheral mode structure (see Figure 4-a) and refs. [5,10]); the present observations show the existence of a stabilized RWM with an $n=1$ rotating frequency (~20-30 Hz) which is near the natural resonant field amplification (RFA) resonance [4]. The SXR-inferred “fast” T_e measurements for both a non-actively stabilized and an actively stabilized RWM are shown for comparison in Figure 4. This shows that the SXR-inferred T_e profiles for the non-actively stabilized RWM case are broad from the core to mid radius and that the electron temperature modulation is mainly located at the plasma edge. However, when the active-feedback mechanism stabilizes the RWM we find a strong core temperature modulation of the order of 50-100 eV (~10%), with a time history which is in good agreement with the slow evolution of the $n=1$ magnetic perturbation measured by the poloidal RWM coils [5,10].

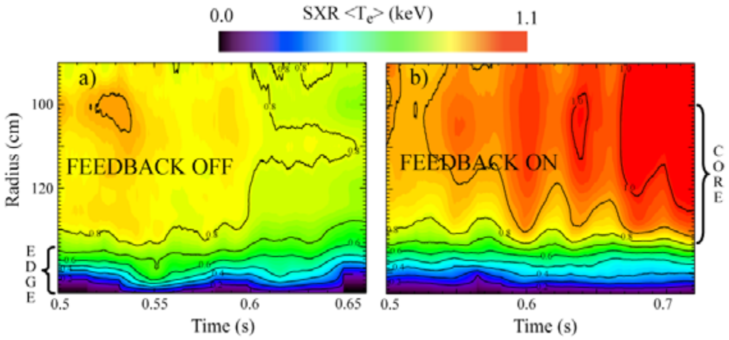

Fig. 4. Normalized contour plots of the SXR-inferred fast $T_e(R,t)$.

It has been reported elsewhere that the resonance between the mode and the precession drift frequency of hot ions can lead to a significant improvement of the RWM stability limits [11]. Using a high-throughput multi-energy diode array in a poloidal configuration we have also found low-amplitude MHD activity with mode frequencies ranging from 12-18 kHz throughout RWM stabilization, which appear before the edge perturbation (see Figure 5). Preliminary calculations at different ion energies and pitch angles indicate that the precession drift frequencies of energetic ions are of the order of 10-20 kHz and that this mechanism could have played an important role in the kinetic stabilization of RWM [12].

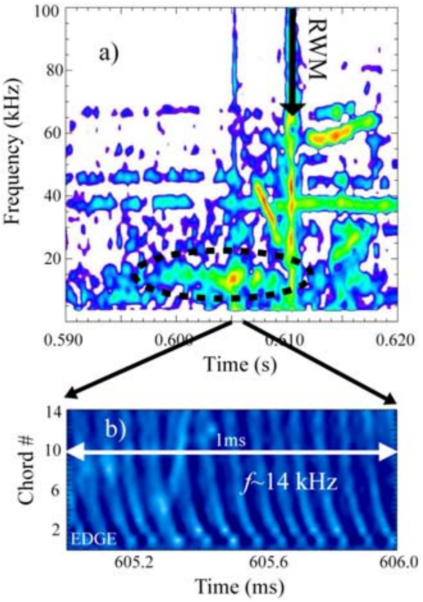

Fig. 5. A) Mirnov spectrogram and b) contour plot of SXR brightness before RWM.

In conclusion, the ME-SXR measurements suggests in good agreement with the magnetics, that in NSTX the mode is not entirely “rigid”, and that acting with the stabilizing coils on its external structure may transfer some of the perturbation to the interior of the plasma. These observations also indicate the existence of a stabilized RWM with an *n=1* rotating frequency (~20-30 Hz) which is near the natural resonant field amplification (RFA) resonance. This work was supported by the United States DoE grant No. DE-FG02-99ER5452 at The Johns Hopkins University and PPPL DoE contract No. DE-AC02-76CH03073.

REFERENCES

[1] O. Katsuro-Hopkins, *et al*., Nucl. Fusion, **47**, 1157, (2007).
[2] E. J. Strait, *et al*., Phys. Plasmas, **11**, 2505, (2004).
[3] S. A. Sabbagh, *et al*., Phys. Rev. Lett., **97**, 045004, (2006).
[4] A.C. Sontag, *et al*., Nucl. Fusion, **47**, 1005, (2007).
[5] L. Delgado-Aparicio, *et al*., Proceedings of the 50th Annual Meeting of the American Physical Society - DPP, November 17–21, (2008).
[6] L. Delgado-Aparicio, *et al*., Appl. Opt., **46**, 6069 (2007).
[7] L. Delgado-Aparicio, *et al*., J. of Appl. Phys., **102**, 073304, (2007).
[8] L. Delgado-Aparicio, *et al*., Plasma Phys. Contr. Fus., **49**, 1245 (2007).
[9] L. Delgado-Aparicio, *et al*., Nucl. Fusion, July (2009).
[10] L. Delgado-Aparicio, *et al*., PoP, to be submitted (2009).
[11] B. Ho, *et al*., Phys. Rev. Lett., **93**, 105002 (2004).
[12] J. Berkery, private communication, (2009).