# Overview of Physics Results from the National Spherical Torus Experiment

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Research on the National Spherical Torus Experiment, NSTX, targets the physics understanding needed to extrapolate plasma transport, stability, power handling, non-inductive sustainment, and advanced control techniques confidently toward the goal of a steady-state Fusion Nuclear Science Facility, pilot plant, or DEMO based on the ST. The unique ST operational space is leveraged to test physics theories for next-step tokamak operation, including ITER. Recent research has also examined implications for the coming device upgrade, NSTX-U, doubling field, plasma current and heating power to produce high beta plasmas at lower collisionality, $\nu$, for several current diffusion times (up to 5s pulses).

In NSTX, an increase in energy confinement is observed as $\nu$ is reduced with data extended down to $\nu^*_e = 0.05$ by lithium (Li) conditioning of first wall components. Nonlinear microtearing simulations [1] predict reduced electron heat transport at lower $\nu$ and match the experimental electron diffusivity, $\chi_e$, quantitatively (Fig. 1a). The computed scaling $\chi_e \sim \nu_e^{1.1}$ is consistent with the experimentally derived $B_t\tau_E \sim \nu^{*\,-0.8}_e$. The computed transport is dominated by magnetic flutter with high $\delta B_r/B \sim 0.1\%$ (Fig. 1b). A measured reduction in high-$k$ turbulence and computed $\chi_e$ are observed in H-mode, accentuated by Li wall conditioning. In L-mode, a computed reduction of $\chi_i$ and $\chi_e$ is consistent with $ExB$ shear stabilization of low-$k$ turbulence, which in turn reduces the high-$k$ fluctuations nonlinearly. Plasma characteristics change nearly continuously with increasing Li evaporation [2]: global energy confinement parameters improve (Fig. 2), edge transport declines, and ELMs stabilize due to alteration of the density gradient outside of the pedestal, with no Li accumulation in the

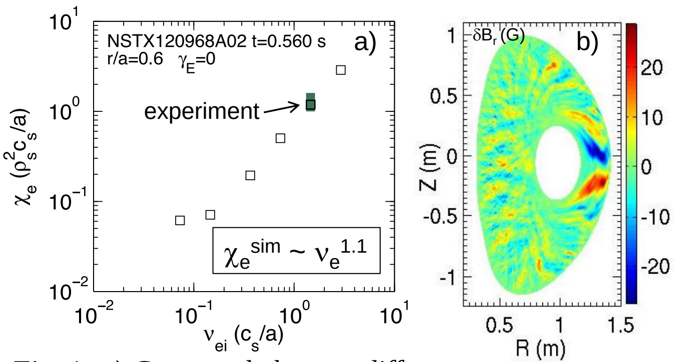


*Fig. 1: a) Computed electron diffusivity vs. electron collisionality; b) poloidal cross section plot of computed radial B field fluctuation.*

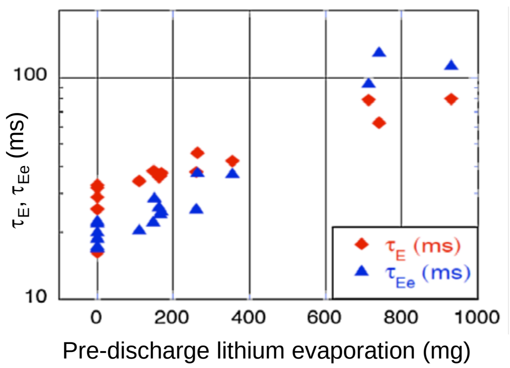


*Fig.2: Increase of total, and electron energy confinement time with increased pre-discharge lithium evaporation.*

core. In laboratory experiments, the role of oxygen is found to be key to understanding deuterium retention of Li-coated graphite and may explain the threshold Li amount required to generate the observed positive plasma effects. Beam-emission spectroscopy measurements indicate the poloidal correlation length, $L_c$, of turbulence in the pedestal increases at higher $n_e$ and $\nabla n_e$, decreases at higher $T_i$, and $\nabla T_e$, and is consistent with generic low-$k$ turbulence (wavelength $\Lambda$, $L_c/\Lambda \sim$ 1-2; $k_\perp\rho_s \sim$ 0.1-0.2). Inter-ELM studies using reflectometry show that the spatial structure of fluctuations exhibits ion-scale microturbulence. Intrinsic rotation changes are observed during ohmic plasma L-H transitions and are found to be correlated with changes in $\nabla T_i$, consistent with predictions from residual stress theory.

Global mode stabilization studies yield a new understanding of stability limits and are improving disruption avoidance. Stabilizing effects of collisional dissipation are reduced at lower $\nu$, but stabilizing resonant kinetic effects are enhanced [3]. Stronger RWM stabilization occurs near dissipative resonances, but almost no effect is found off-resonance (Fig. 3). Combined radial and poloidal field sensor feedback significantly reduced $n$ = 1 perturbations and improved stability. The disruption probability due to unstable RWMs is reduced by more than a factor of three in low $l_i$ plasmas with this control. Remarkably, disruptions are reduced mostly at high $\beta_N/l_i > 11$. Greater instability seen at lower $\beta_N/l_i$ is consistent with decreased kinetic RWM stabilization at plasma rotation between stabilizing resonances. Time-dependent analysis of active control reproduces experimental mode dynamics vs. feedback phase and illustrates optimal gain. A model-based RWM state-space controller proposed for ITER, which includes a 3D model of plasma and mode-induced wall currents, has produced long-pulse discharges exceeding $\beta_N = 6.4$, and $\beta_N/l_i = 13$. Physical effects of varying the covariant gain matrix and feedback phase are experimentally examined. Disruption precursor analysis for more than 2000 shots show 99% of disruptions can be predicted with ~10ms warning, with a false positive rate of only ~4%. Disruption halo currents can have significant toroidal asymmetry and can rotate toroidally (up to 7 transits; 2-3 more common) at 0.5-2 kHz. NTM marginal island width results show the relative importance of the enhanced stabilizing curvature effect at low aspect ratio, yielding less susceptibility to NTM onset even if the classical tearing stability index is near marginal. The amplitude and structure of GAEs and core localized CAEs are measured in beam-heated H-mode plasmas via reflectometry. In addition to Alfvénic modes, low frequency $n$=1 global kinks cause fast ion redistribution as measured by a fast ion $D_\alpha$ diagnostic. Full-orbit code calculations show redistribution from the core outward, and toward $V_{||}/V = 1$, consistent with reduced CAE stability (Fig. 4).

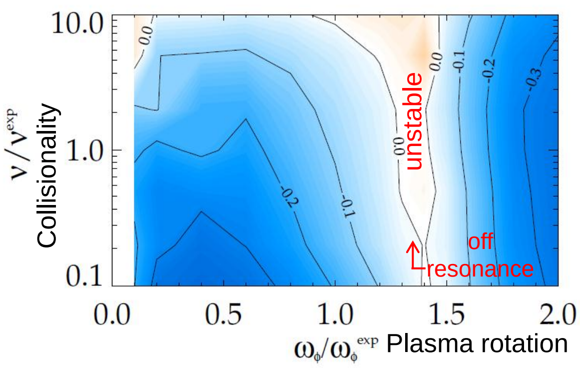


*Fig. 3: MISK computed kinetic RWM n = 1 stability vs. collisionality and plasma rotation.*

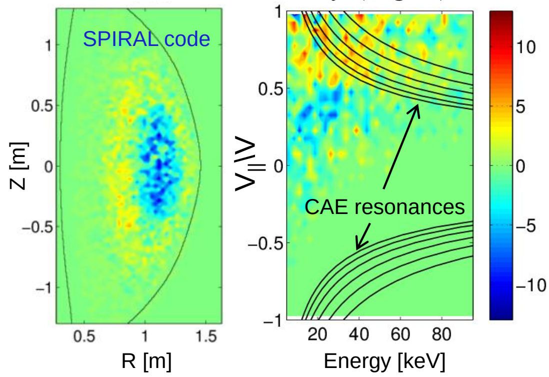


*Fig. 4: Fast ion redistribution by saturated kink mode.*

The snowflake divertor configuration enhanced by impurity-seeded radiative detachment has demonstrated a significant reduction in steady-state and ELM divertor heat fluxes, high core plasma confinement with reduced core impurities, and stable operation. The plasma-wetted area is increased up to 200%, X-point connection length 50-100%, and the divertor volume up to 60%. The peak divertor heat flux decreased from 7 to less than 1 MW/m$^2$, providing the basis for the heat flux reduction required in NSTX-U. Applied 3D field pulses with amplitudes below ELM triggering level show increased $D_\alpha$ intensity, indicating increased particle transport. Measured strike point splitting is qualitatively reproduced by EMC3-Eirene modeling. Toroidal asymmetry of heat deposition is observed during ELMs, or by application of 3D fields. While this can spoil radiative detachment due to increased pedestal $T_e$, additional gas puffing can restore detachment. Harmonic oscillations in the edge region at 2–7 kHz with $n$ = 2–7 have been reproducibly observed in ELM-free plasmas.

Experimental scenario development has accessed aspect ratio and boundary shaping planned for NSTX-U. Predictive TRANSP calculations project 100% non-inductive current (NIC) fraction at $I_p$ = 1MA, capability for an order of magnitude collisionality variation, and a factor of 3 reduction compared to NSTX for fully relaxed plasmas with $q_{min} > 1$. NIC fraction up to 65% is experimentally reached with NBI at $I_p$ = 0.7MA and high-harmonic fast wave CD at $I_p$ = 0.3MA. Coaxial helicity injection (CHI) has further reduced the inductive startup flux. L-mode plasmas ramped to 1MA require 35% less inductive flux when CHI is used. TSC simulations using CHI predict at least a doubling of the closed flux current for NSTX-U.

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[2] R. Maingi, S.M. Kaye, C.H. Skinner, et al., *Phys. Rev. Lett.* **107** (2011) 145004
[3] J.W. Berkery, S.A. Sabbagh, R. Betti, et al., *Phys. Rev. Lett.* **106** (2011) 075004