NSTX

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OFES FY 08 Q4 Review Report on NSTX Research Milestones

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For the NSTX Research Team

PPPL-OFES/DOE

October 27, 2008

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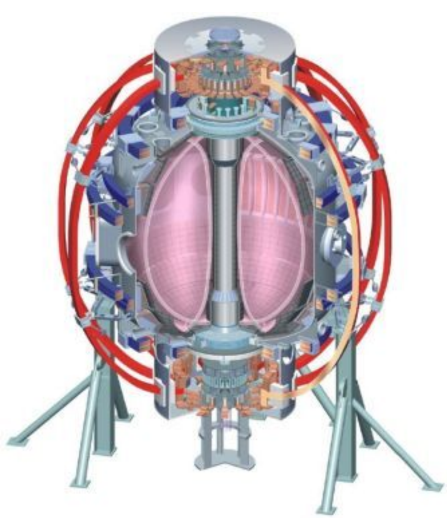

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IPP, Garching
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U Quebec

NSTX 5 year plan for 2009-13 was favorably reviewed

- "Proposed research clearly aims to position the ST as a candidate for future high priority US research missions, as articulated in recent FESAC reports
  - High heat flux facility for PMI research, as embodied in NHTX
  - Nuclear component testing, as embodied in ST-CTF"

- "The panel agrees that the proposed research priorities address these missions
  - 100% non inductive current drive
  - Particle and heat flux control
  - Non inductive start up and ramp up
  - Sustained high beta operation"

- "The major facility upgrades are appropriately sequenced:
  1. The liquid lithium divertor (LLD) is an innovative approach to density control
     - Potential for high reward, but no guarantee LLD will provide necessary control
     - Measuring and modeling effects associated with lithium will be critical to understanding the science and projecting future applications.
     - It is not clear that there is sufficient attention paid to this in the proposal.
     - A backup strategy for density control should be better developed
  2. The center stack upgrade is very well motivated and should be installed as soon as possible
  3. The second neutral beam source is essential to take advantage of higher B_T and current capability from center stack upgrade"

Outline

NSTX Research Milestones for FY2008:

- Joule milestone: "…evaluate the generation of plasma rotation and momentum transport, and assess the impact of plasma rotation on stability and confinement…"
  - Momentum transport
  - Momentum sinks
  - Effects of rotation on confinement
  - Effects of rotation on stability

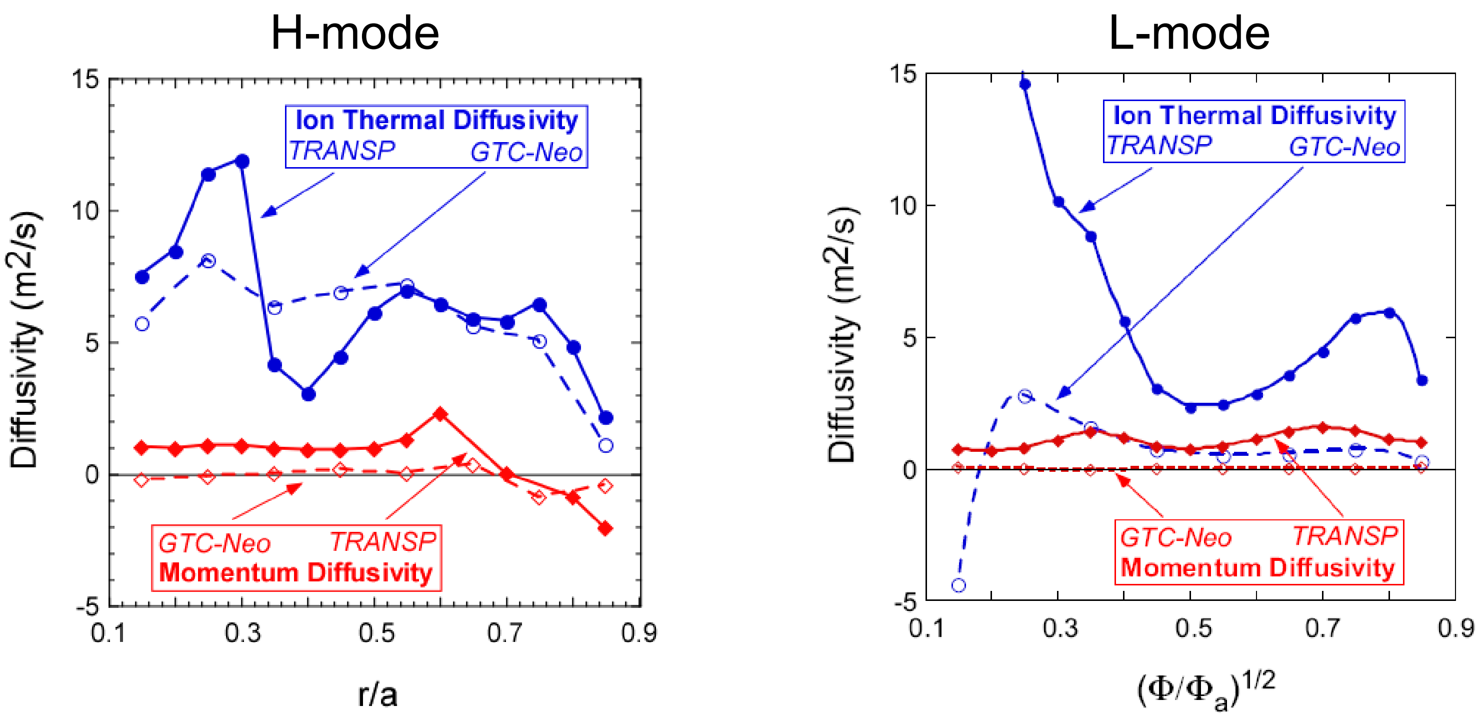
- R(08-1) Measure poloidal rotation at low A and compare with theory
- R(08-2) Couple inductive ramp-up to CHI plasmas
- R(08-3) Study variation and control of heat flux in SOL

A few additional highlights (there are many more!):

- Electron transport
- Li and ELM control
- Advanced scenarios and control

Momentum transport observed to be anomalous in all conditions studied thus far in NSTX

- $\chi_\phi >> \chi_{\phi,neo}$ in both H- and L-mode plasmas, irrespective of $\chi_i/\chi_{i,neo}$



Is χ_ϕ controlled by low-k turbulence?

Perturbative experiments can help determine this

Perturbative Momentum Transport Analysis Reveals Significant Inward Pinch in Outer Region of Plasma

Use NBI (core) and n=3 braking (edge) pulses to perturb rotation profile

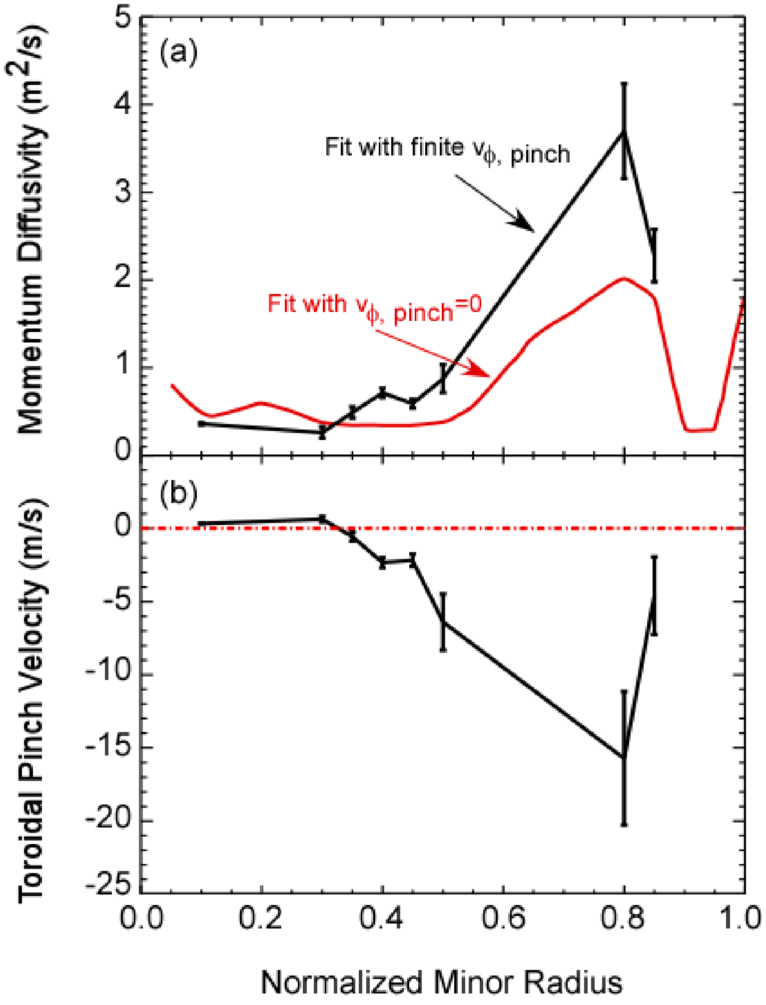
- Toroidal rotation evolves according to momentum balance
  - Rotation measured by CHERS
  - NBI torque only one considered
- Momentum flux governed by

$$\Gamma_\phi = mnR\left(\underbrace{\chi_\phi \frac{\partial V_\phi}{\partial r}}_{diffusion} - \underbrace{V_\phi V^{pinch}}_{convection}\right)$$

(Residual stress assumed to be 0)

- v and $^{\nabla}$v have to be decoupled to determine χ_ϕ and v_{pinch} independently
  - This requirement is satisfied in outer portion and in a limited spatial region in the core

(Solomon et al., PRL '08)



Calculated Pinch Velocities Agree Reasonably Well With Theories Based on Low-k Turbulence in Outer Region

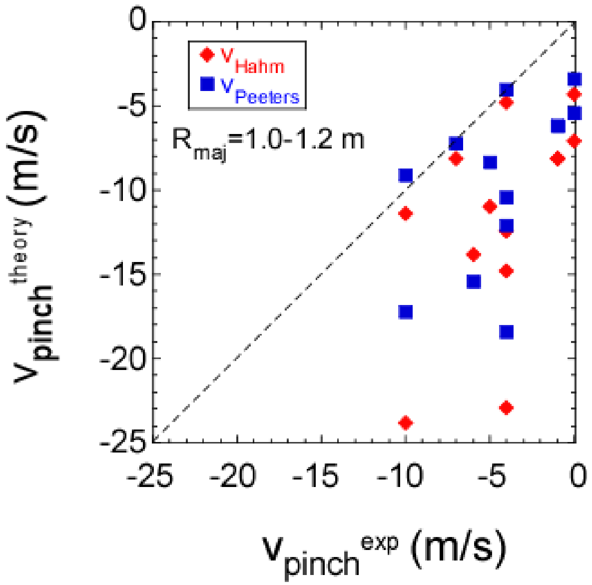
- Both based on low-k, but have different approaches
  - End up with similar expressions

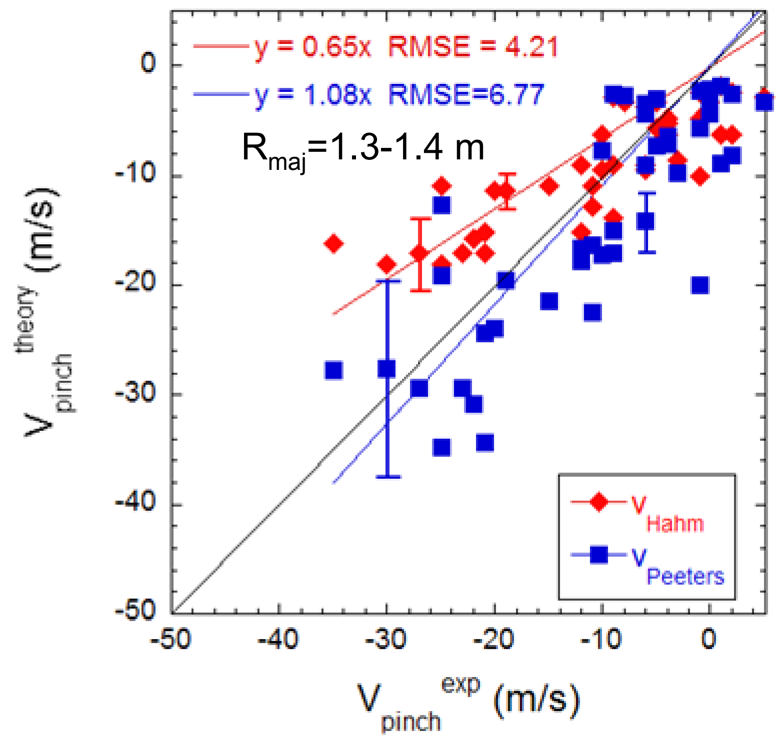
Peeters et al. (PRL, 2007)

$v_{Peeters}/\chi_\phi = [-4-R/L_n]/R$

Hahm et al. (PoP, 2007)

$v_{Hahm}/\chi_\phi = [-4]/R$





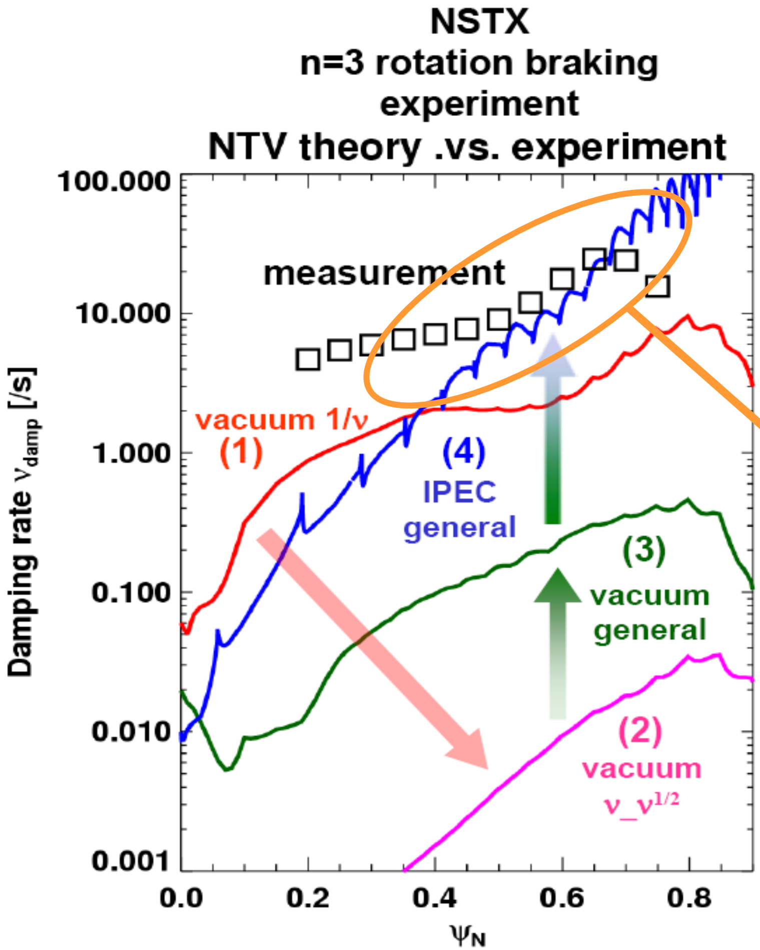
Why is there a difference between theories at high v_{pinch}? ***L_n dependence***

Why does theory match in outer region better than in core? ***ITG/TEM stable in core***

Neoclassical Toroidal Viscosity (NTV) theory has been extended using a generalized analytic treatment

- Generalized treatment for NTV transport describes dynamics of bouncing (ω_b) trapped particles subjected to magnetic + electric toroidal precession ($\omega_p = \omega_B + \omega_E$) and collisions ($\nu$) in a combined form:

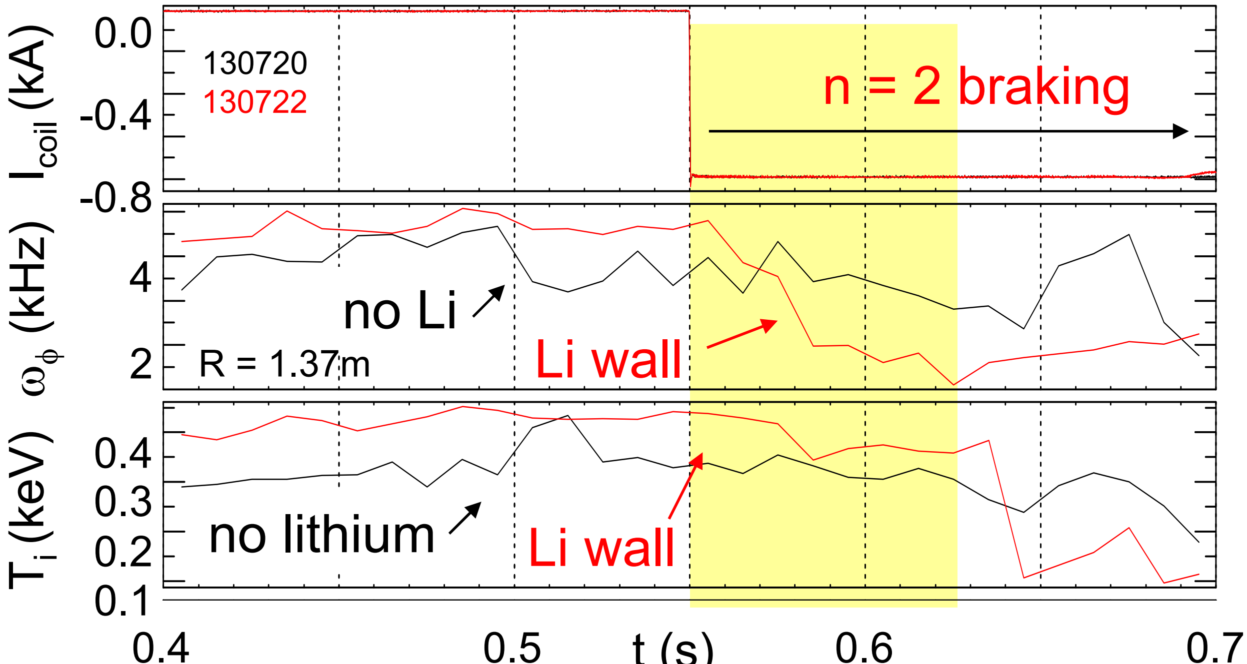
$$\nu_{damp} \simeq \frac{F_{NTV}}{2\pi f_\varphi R_0 M n_e} \text{ and } F_{NTV} \propto \frac{\nu_{eff}}{\left(\left(\ell\omega_b - n(\omega_B+\omega_E)\right)^2 + \nu_{eff}^2\right)} \left(\delta B / B\right)_w^2$$

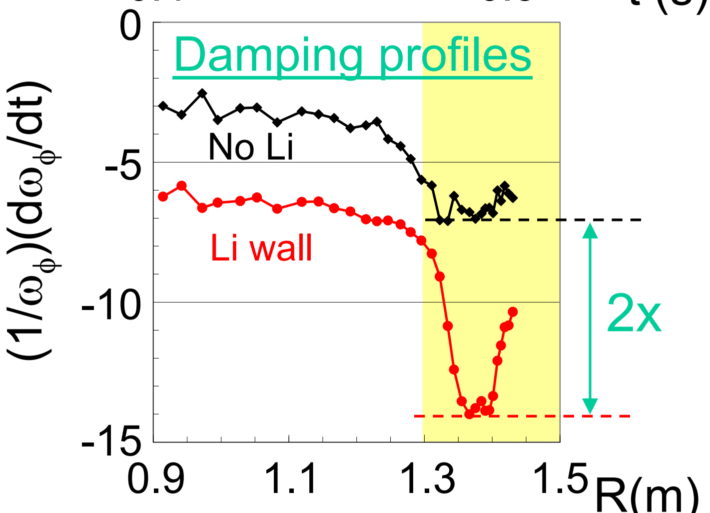


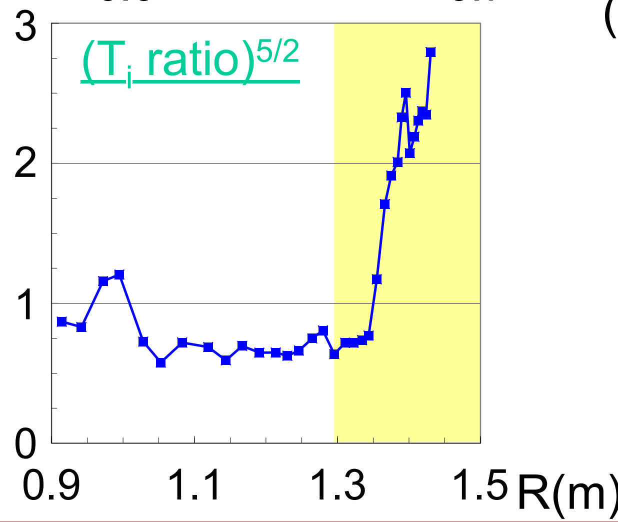
- Vacuum 1/ν approximation is most commonly used formulation
  – Ignores plasma response

Generalized NTV theory more consistent with NSTX flow damping results

Stronger non-resonant braking observed at higher T_i - consistent with $1/\nu$ NTV theory

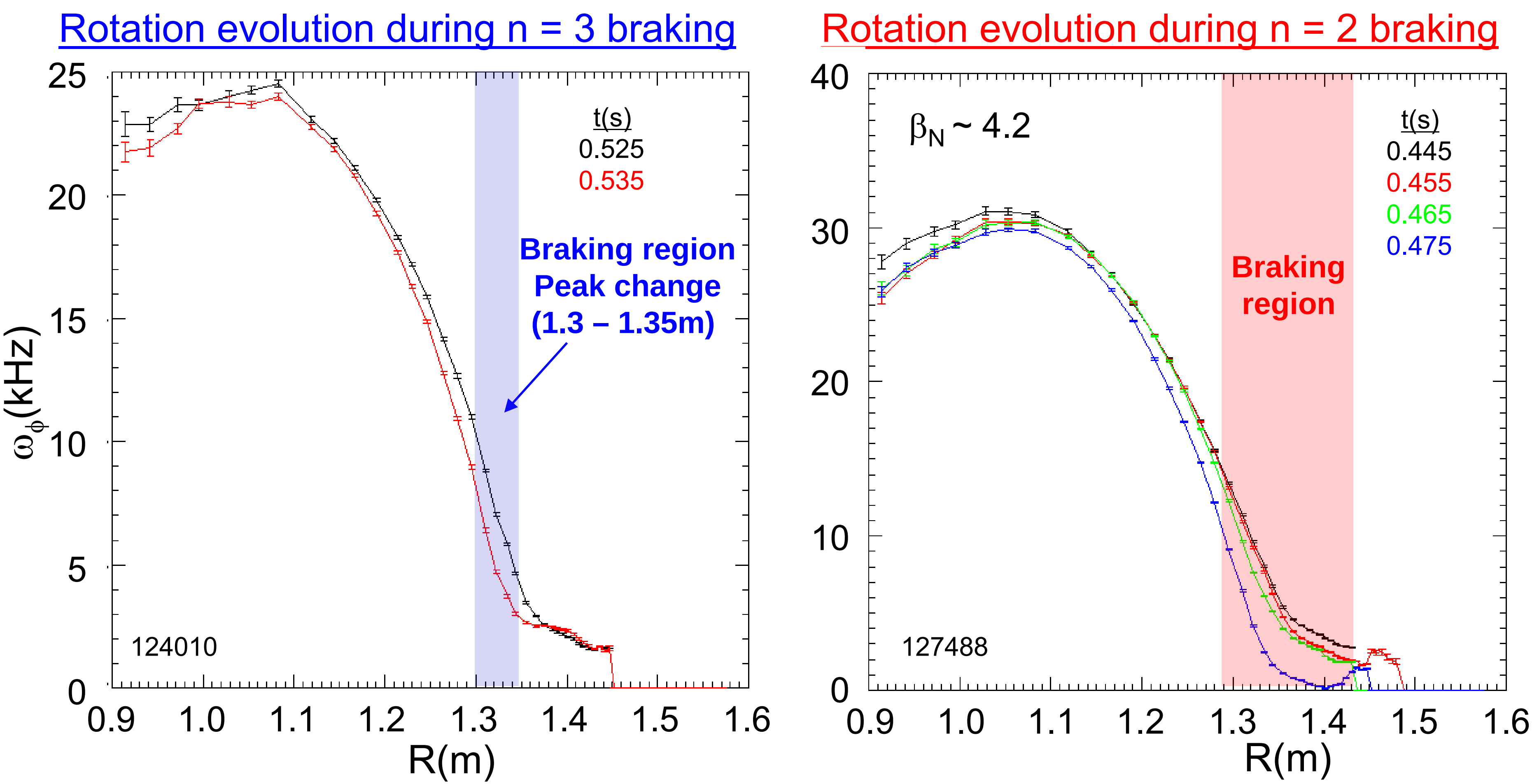






- Examine T_i dependence of neoclassical toroidal viscosity (NTV)
- Li wall conditioning produces higher T_i in region of high rotation damping
- Expect stronger NTV torque at higher T_i ($-d\omega_\phi/dt \sim T_i^{5/2}\, \omega_\phi$)
  - At braking onset, T_i ratio$^{5/2}$ = $(0.45/0.34)^{5/2} \sim 2$
  - Consistent with measured $d\omega_\phi/dt$ in region of strongest damping

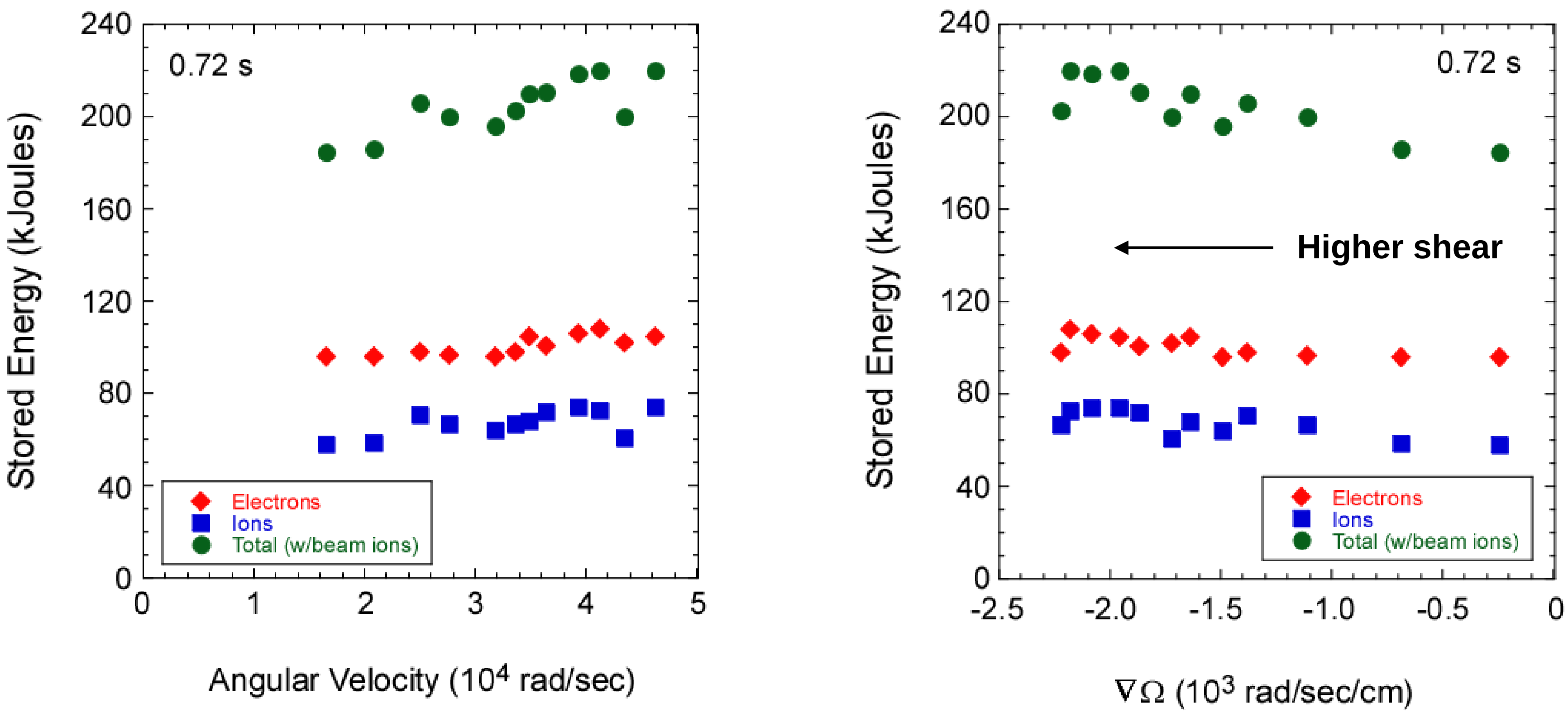
Applied n = 2 field produces broader braking profile than n = 3
(data to be compared with NTV theory)



- n = 2 configuration has strong n = 4, but little n = 1 (resonant) component

Increased rotation/rotation-shear increases plasma stored energy 20-25%

Increased fast ion stored energy accounts for ~1/2 of the increase

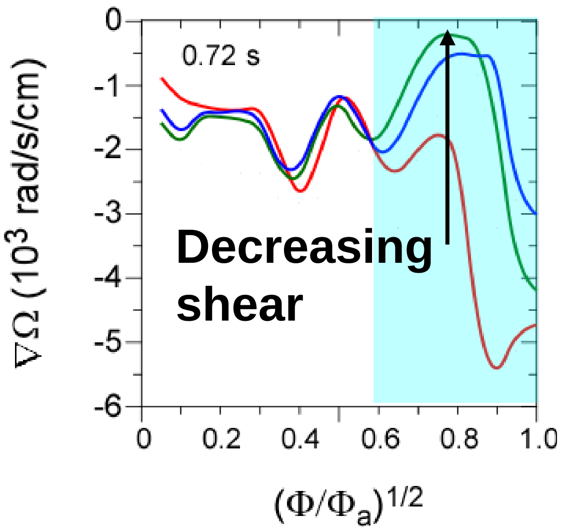


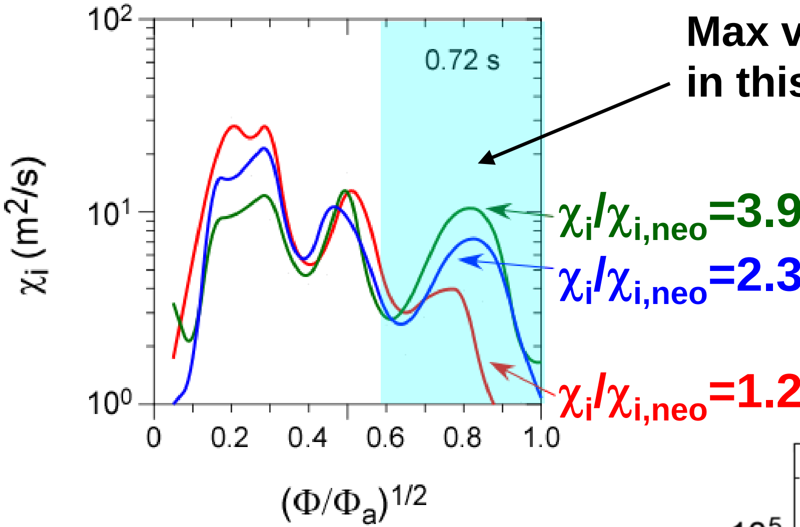
Rotation shear is acting on a small part of plasma

– improvement may be limited to that region

Near-edge rotational-shear strongly impacts local ion transport

Ion thermal diffusivity decreases with increasing rotation shear

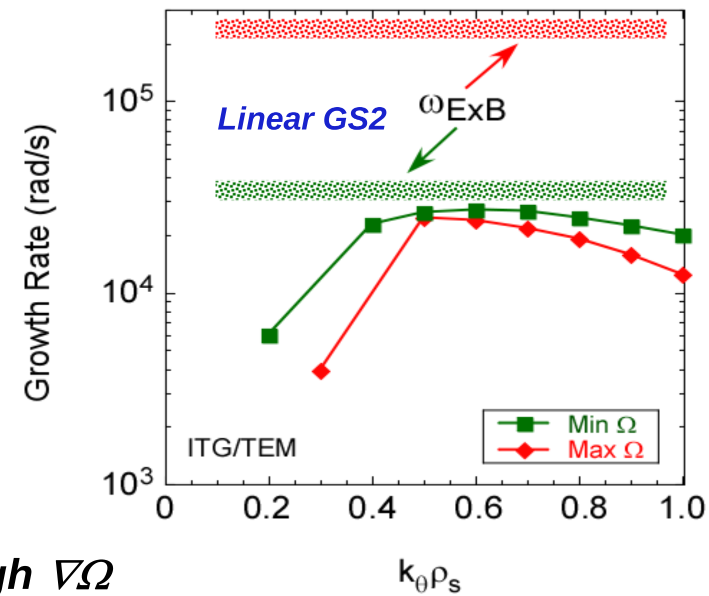




Max variation of $\nabla\Omega$ in this region

Non-linear calculations needed to determine magnitude of turbulence reduction and resulting heat flux levels

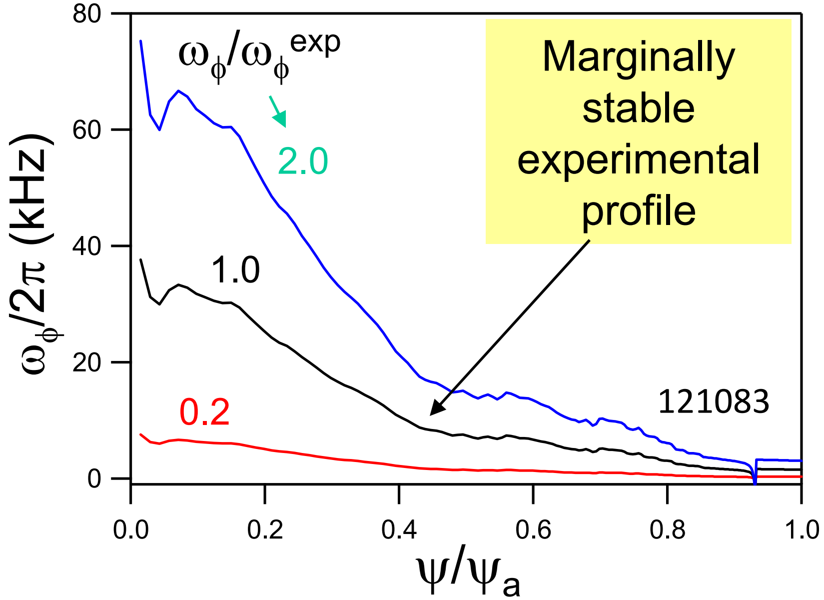
ExB shear may also be important for reducing high-k turbulence (Yuh, EX/P3-1)



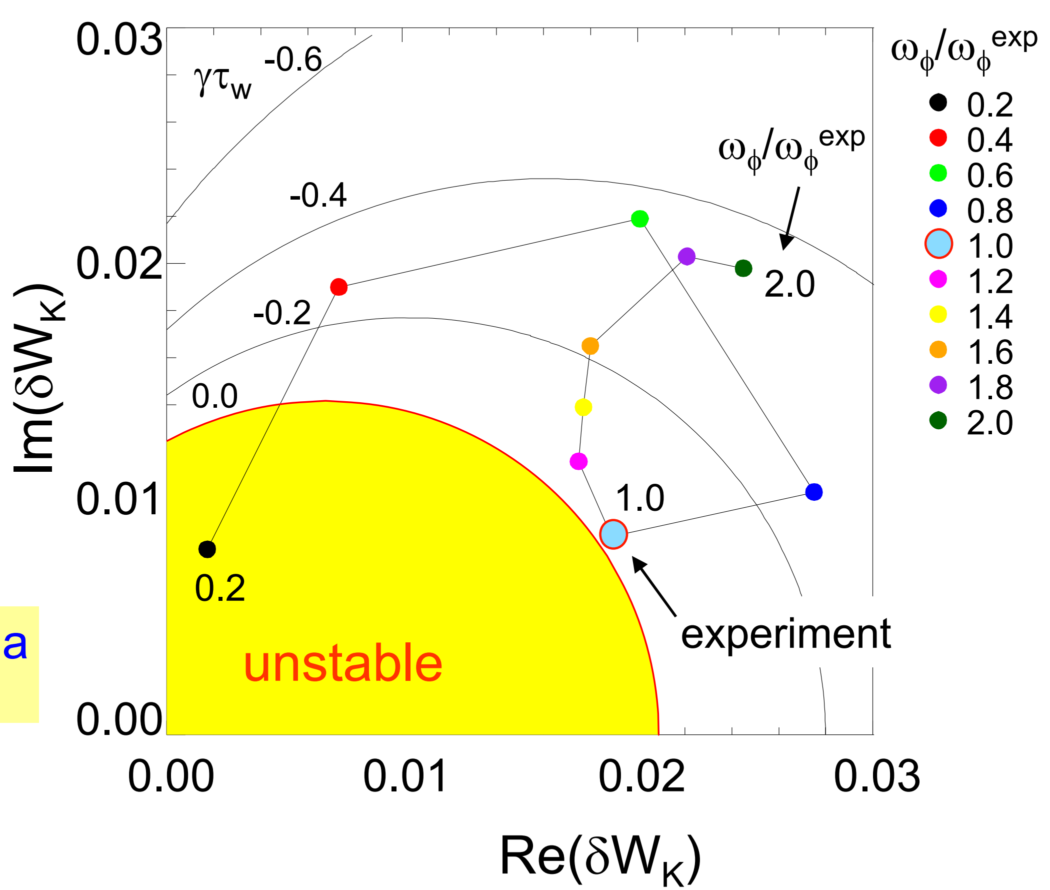
Modest decrease in χ_e (~30%) observed for low $\nabla\Omega$ → high $\nabla\Omega$

Kinetic modifications show decrease in RWM stability at relatively high V_ϕ – consistent with experiment

Theoretical variation of ω_ϕ



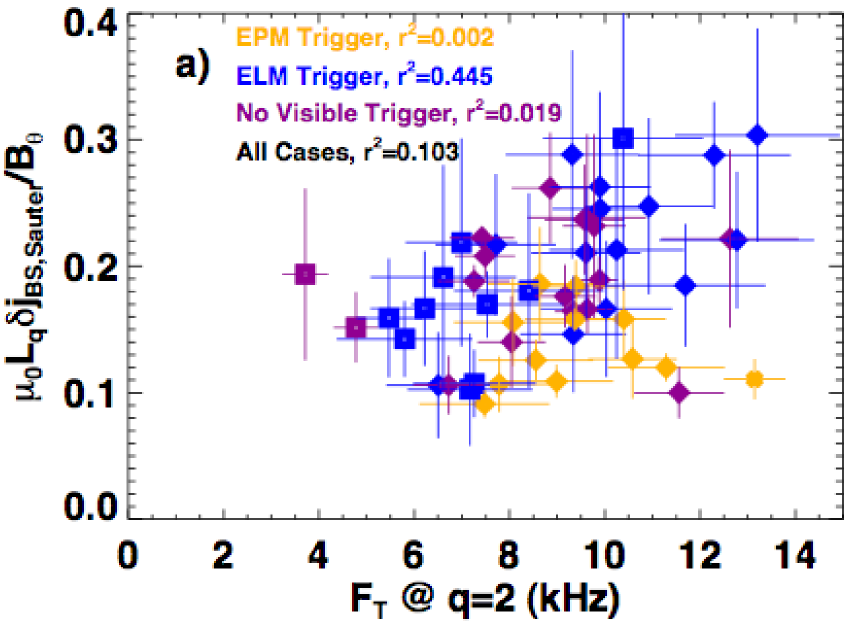
RWM stability vs. V_ϕ (contours of $\gamma\tau_w$)



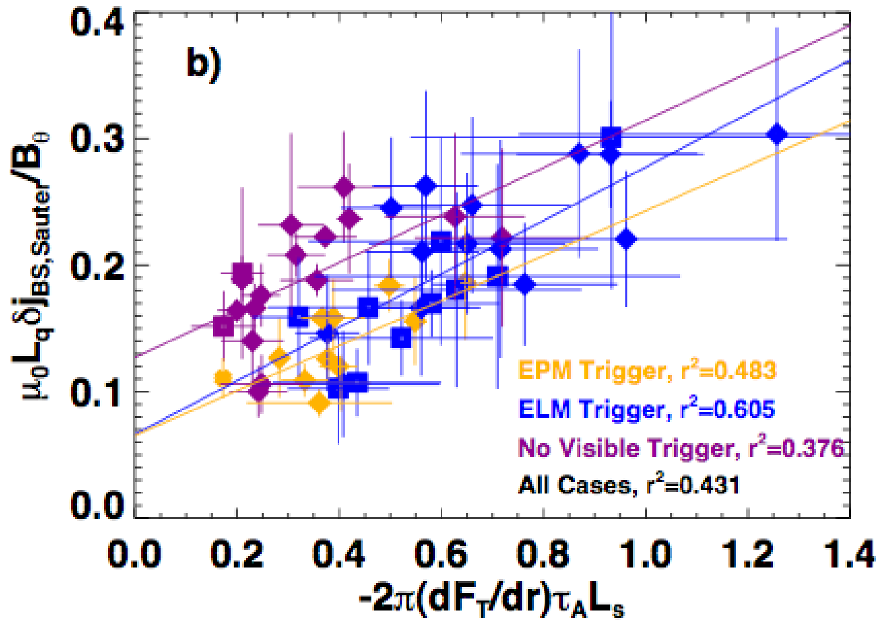
- Marginal stable experimental plasma reconstruction, rotation profile ω_ϕ^{exp}
- Variation of ω_ϕ away from marginal profile increases stability
- Unstable region at low ω_ϕ

Required drive for NTM onset better correlated with rotation shear than rotation magnitude

NTM Drive at Onset Only Poorly Correlated with q=2 (Carbon) Rotation

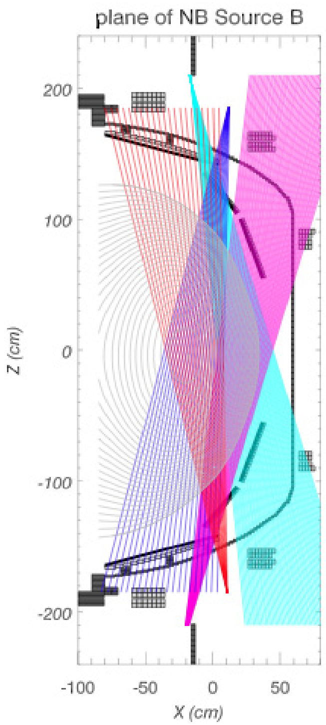


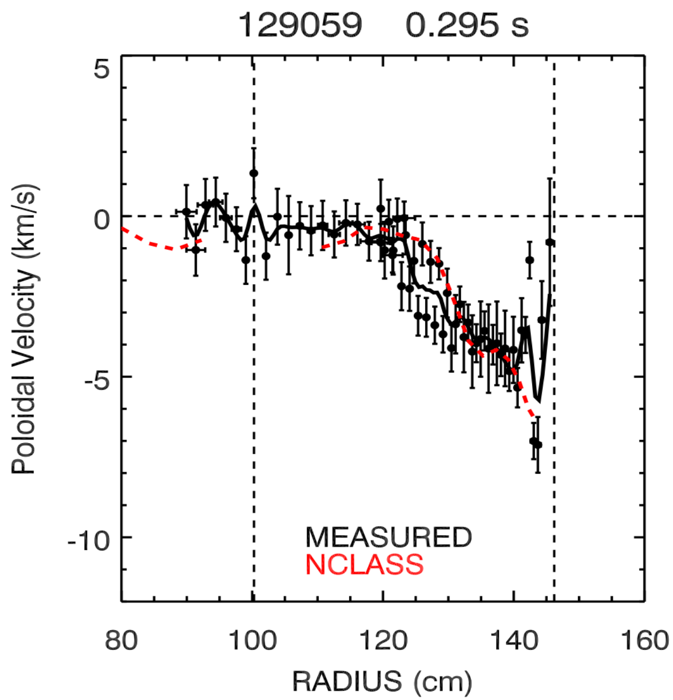
NTM Drive at Onset Better Correlated with Local Flow Shear

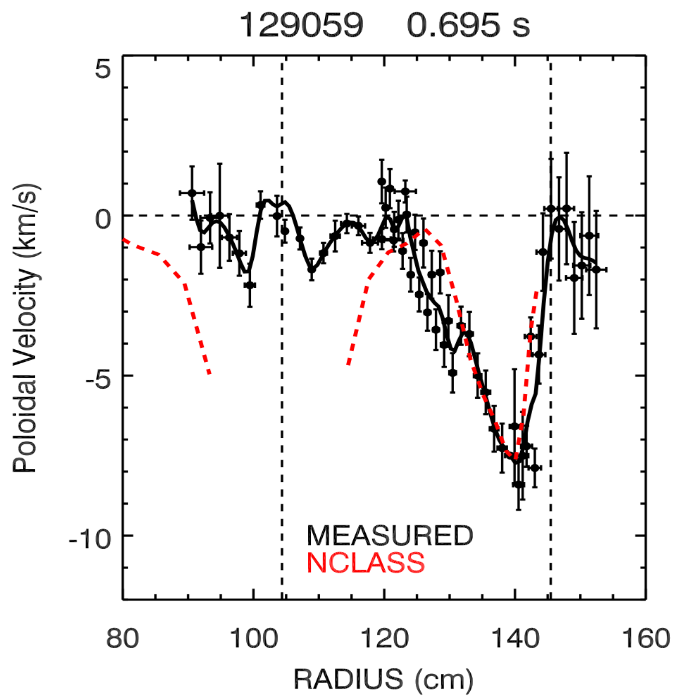


- For fixed V_ϕ, order of increasing onset drive: EPM triggers, ELM triggers, and "Triggerless"
- All trigger types have similar dependence on flow shear
  - Dependence likely to related to intrinsic tearing stability, not triggering

NSTX poloidal flow measurements are consistent with neoclassical theory computed with NCLASS/TRANSP

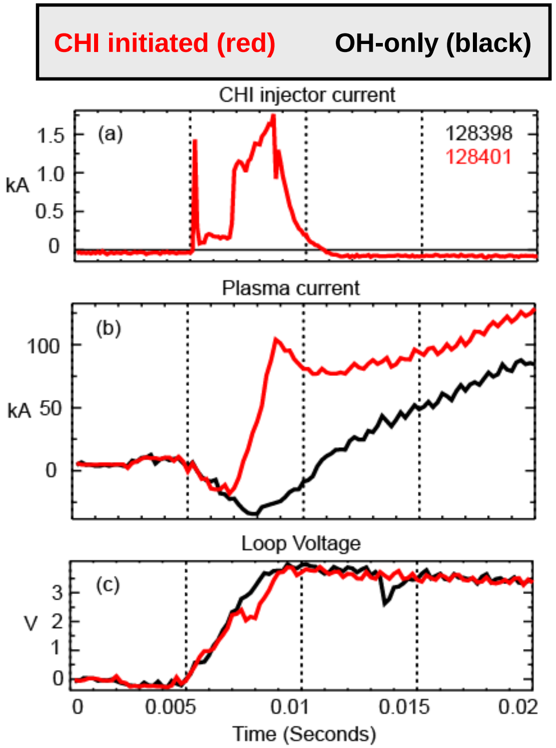


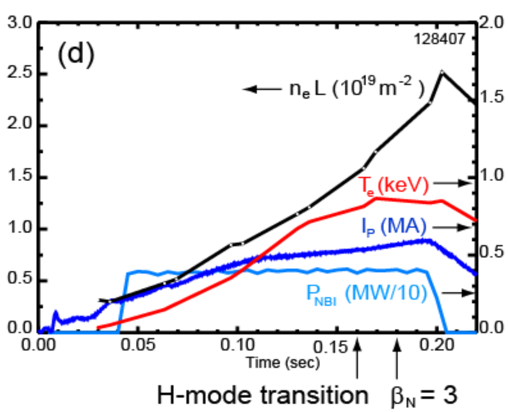




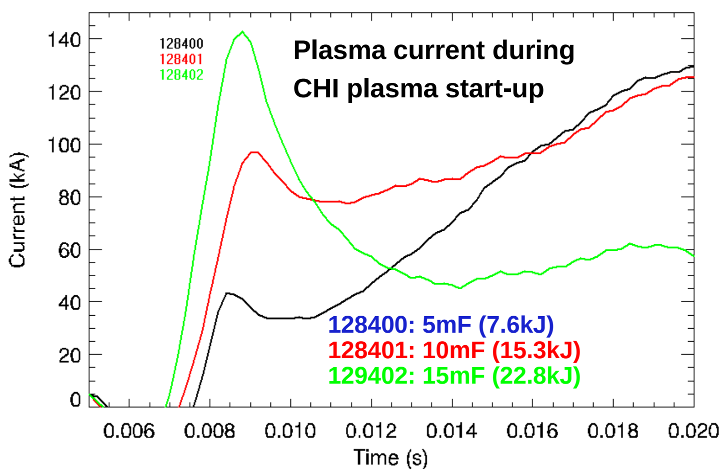
- Pseudo-velocity due to gyro-orbit finite lifetime effect is small in NSTX (≤ 0.5 km/s) compared to that apparent in TFTR (≤ 50 km/s).
  - In NSTX, this significantly reduces the uncertainty in comparing poloidal flux measurements to neoclassical theory.
- Higher-A tokamaks (DIII-D, JET) have reported v_θ inconsistent with neoclassical theory – aspect ratio difference? or pseudo-velocity effect?

NSTX experiments have demonstrated the compatibility of CHI start-up with subsequent high-performance plasma operation

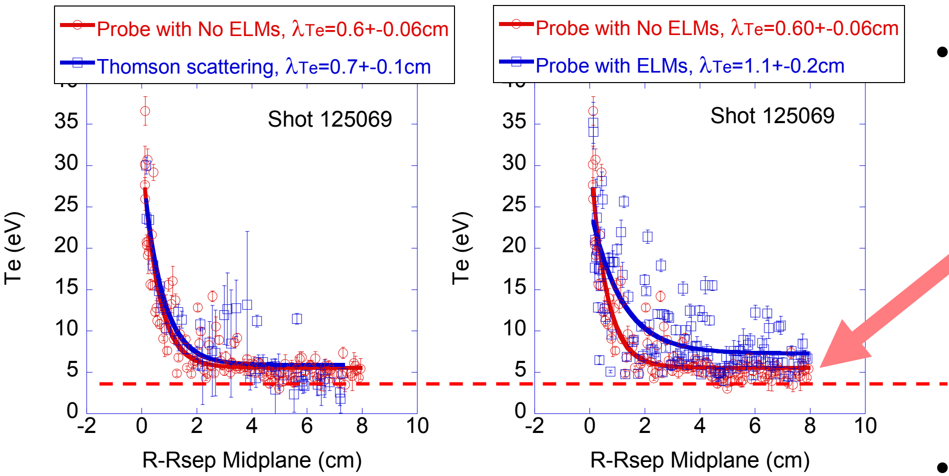




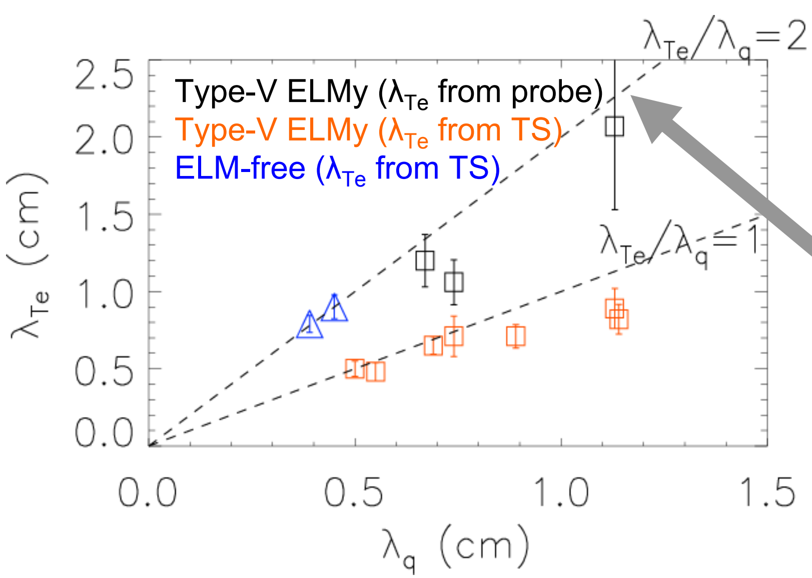
- 1.5 kA injector current → I_P = 100 kA
  - Current multiplication ~ 70
- Induction applied during I_P decay phase
- Inductive ramp-up with NBI heating
  - I_P reaches peak value of 700 kA, T_e → 800eV
  - Plasma transitions into an H-mode
- But, ramp-up plasma current does not increase with increased CHI start-up energy above ~15kJ capacitor bank energy
  - Observed increased O and C radiation in U/L divertor regions
  - → Use LLD plate as CHI electrode to reduce O anc C impurities
  - → Use absorber field-nulling coils to reduce impact of absorber arcs



Near-SOL parallel transport consistent with e-conduction, but far SOL transport not yet understood



- “Far” SOL midplane T_e and divertor heat-flux profiles exhibit large time-average offset from 0
  → fit with constant offset + exponential
  - Far SOL inconsistent w/ either conduction-limited or sheath-limited heat transport
  - **Intermittent cross-field transport important in the far SOL?**

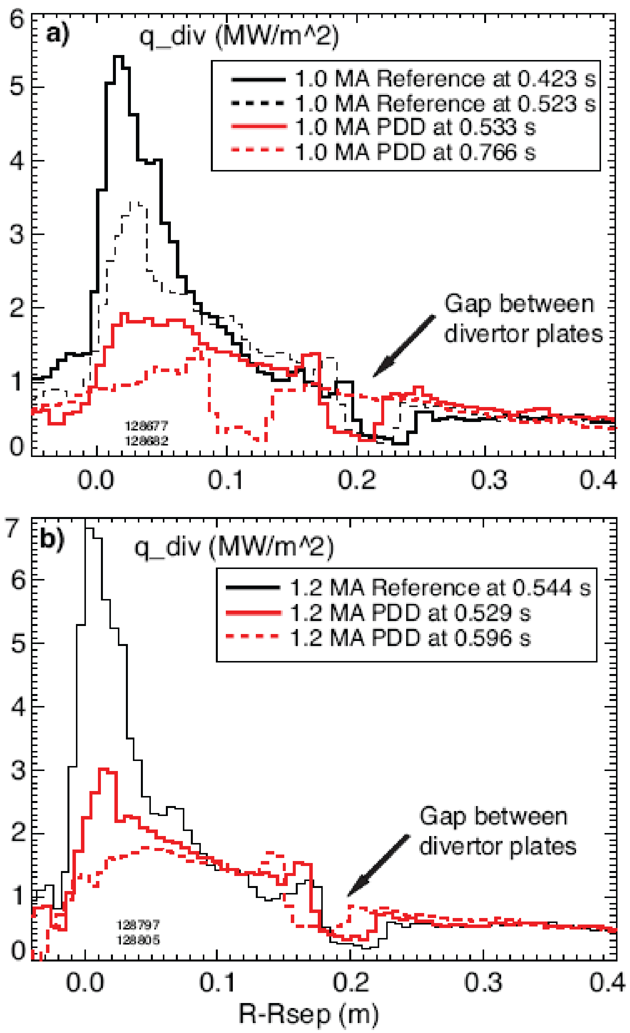


- In “near” SOL, T_e SOL width ≡ λ_{Te} depends on measurement technique and ELM/blobs
  - ELM free → λ_{Te} from reciprocating probe and Thomson scattering (TS) in good agreement
  - But, in ELMy H-mode λ_{Te} from probe is 2× TS λ_{Te}
    - Find if ELMs and blobs are removed from raw probe data, probe λ_{Te} is similar to that from TS
    - → Unfiltered probe data includes broadening effect of ELMs and turbulent blobs on SOL width

- $\lambda_{Te} / \lambda_q = \frac{7}{2}\left(\frac{T_e - T_{e1}}{T_e - Cq_1 T_e^{-5/2}}\right)$ ~ 2 expected if electron conduction is dominant (for flat T_e and heat flux profiles in far SOL)
  - Consistent with data – including ELM/blob effects

- ***Analysis of λ scaling with I_P, P_{NBI}, n_e in progress…***

Partially detached divertor (PDD) operation studied and extended to higher plasma current



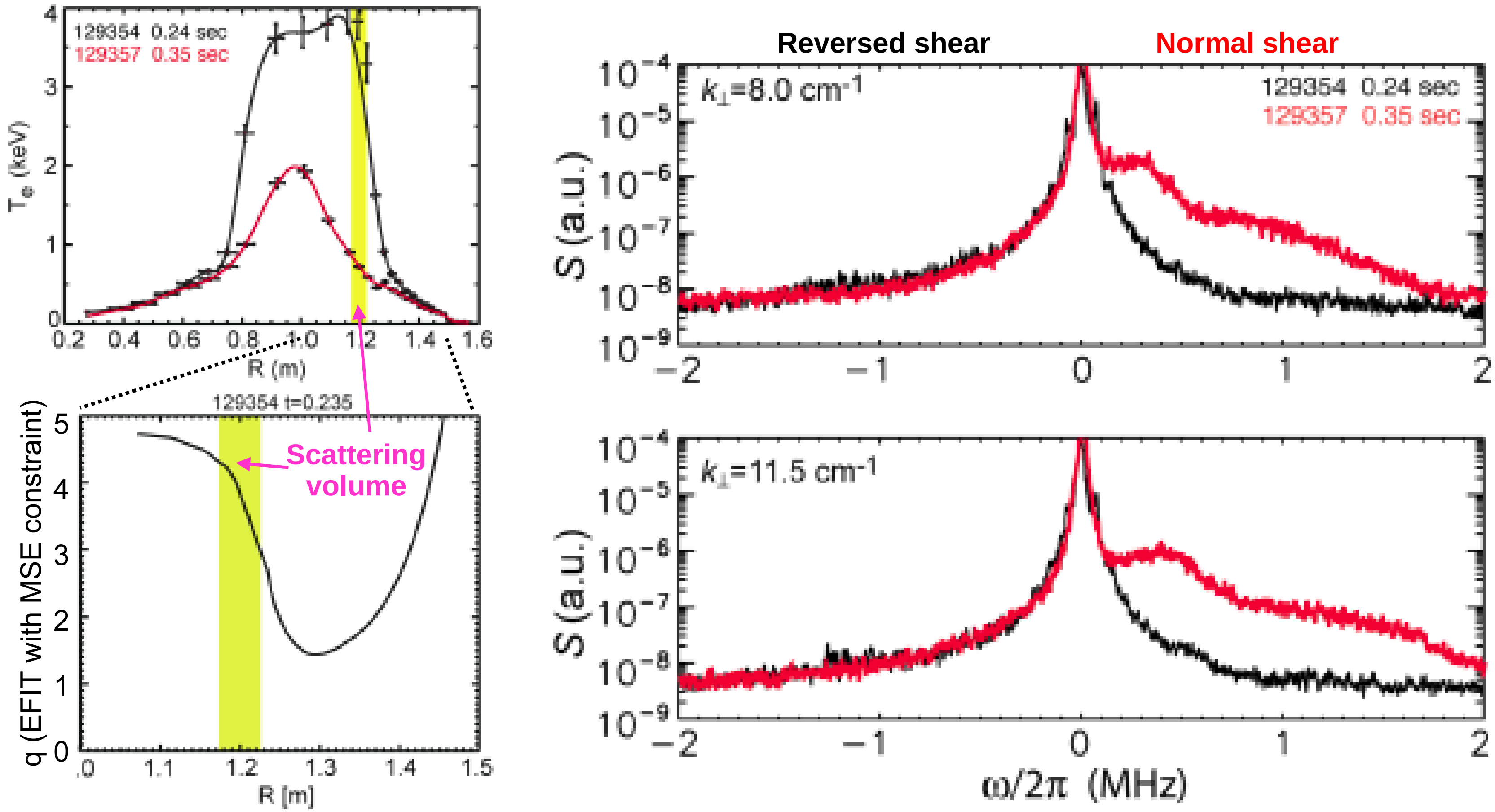
- Focus on high δ_L = 0.8 shape with high magnetic flux expansion (18 – 26), high SOL area expansion, and increased radiative plasma volume
  - Access to PDD was demonstrated in 1.0-1.2MA, 6MW NBI-heated discharges w/ divertor deuterium injection.
  - Plasma stored energy degraded by 5-15 % during PDD
- High-power and high-current conditions are most challenging for divertor heat flux mitigation in NSTX
  - Peak heat fluxes in the range 6 – 12 MW/m^2

Peak heat flux is observed to increase with plasma current 1MA → 1.2MA due to the decrease in the connection length $\propto$ q $\propto$ 1/I_P

- For 1MA → 1.2 MA, higher (~10-60%) D puff rates needed to achieve steady-state heat flux reduction from 4–10 MW/m^2 to 1.5 – 3 MW/m^2.
  - Further increases in gas puffing rate led to the formation of an X-point MARFE
  - Results suggest that further radiative divertor optimization will require active divertor pumping – LLD?

Electron Gyro-Scale Fluctuations Can Be Suppressed by Reversed Magnetic Shear in Plasma Core

- Suppression of Electron Temperature Gradient (ETG) mode by shear-reversal and high T_e/T_i predicted by Jenko and Dorland, Phys. Rev. Lett **89** (2002)



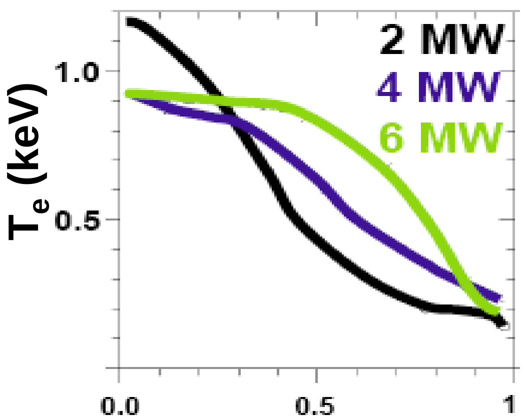
- Shear-reversal produced by early NB heating during plasma current ramp

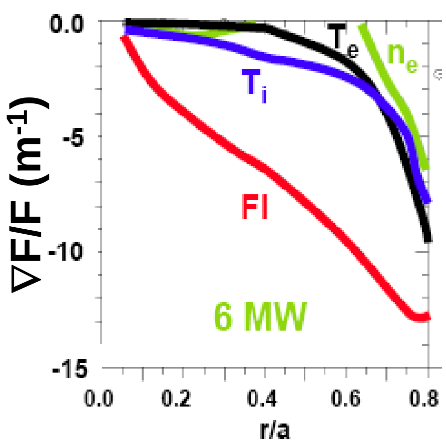
NSTX Investigating Role of High-Frequency MHD Modes in Core Electron Transport

- Observe "flat T_e" region in core of plasmas with high NBI power

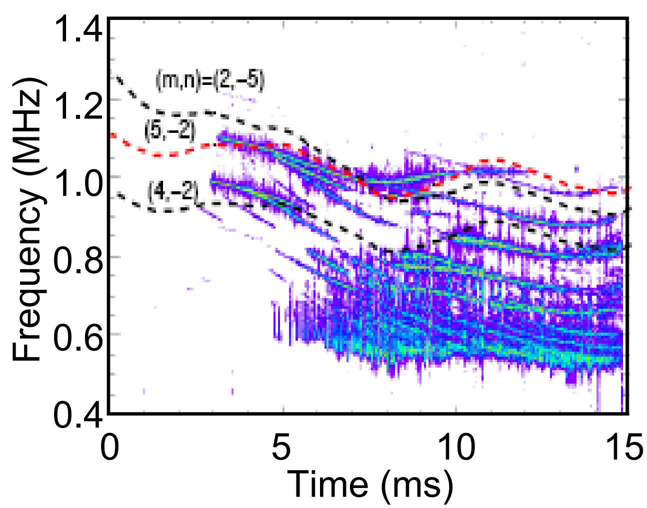
⇒ Implies mechanism for electron transport *not* driven by T_e gradient

- Global Alfvén Eigenmodes (GAEs) driven by fast-ion pressure gradient a possible source



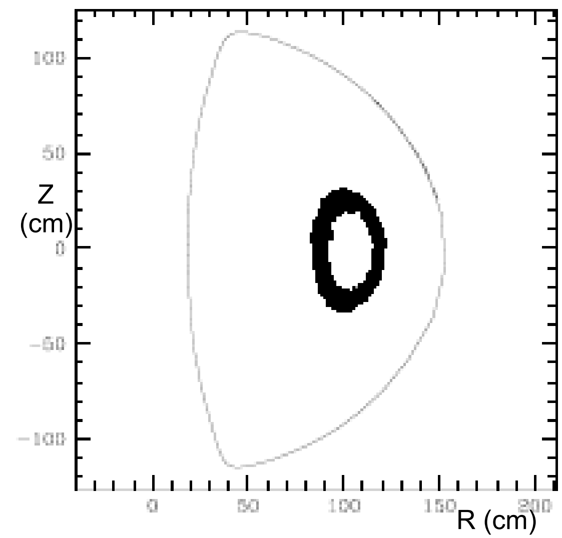


$$\omega_{GAE} \simeq v_{A0}(m - nq_0)/q_0R.$$



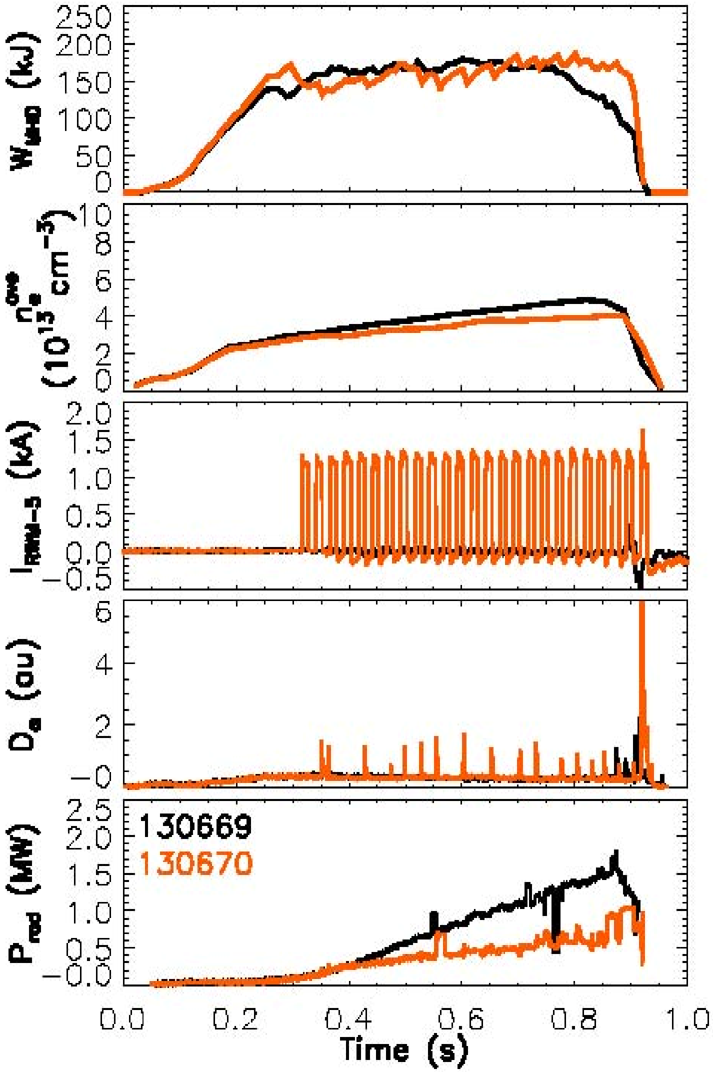
- GAEs localized near center
- Radial width $\propto m^{-1}$
- $f_{GAE} \sim f_{be}$ trapped electron bounce frequency

- ORBIT code modeling with GAE frequency and amplitude typical of NSTX
- After 3ms, see radial diffusion of electrons initially on a flux surface



Combination of Li and externally applied 3D fields offer means of understanding and controlling ELMs

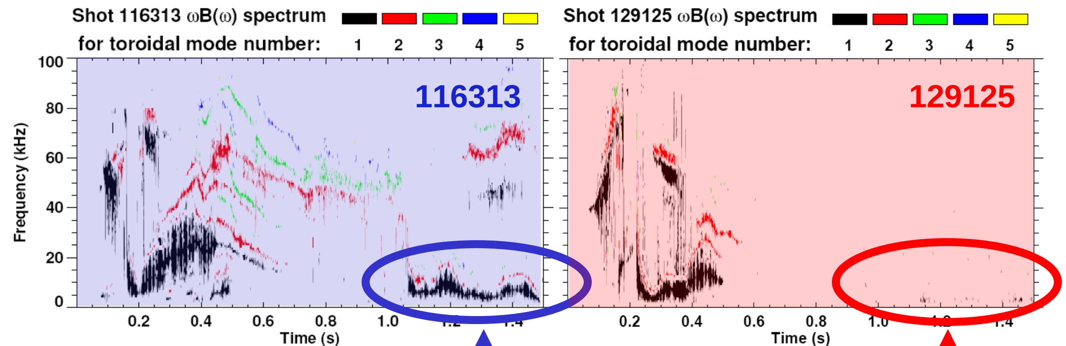
Shape: DN, κ=2.4, δ=0.8
RMP: n=3, 40Hz, 11ms duration

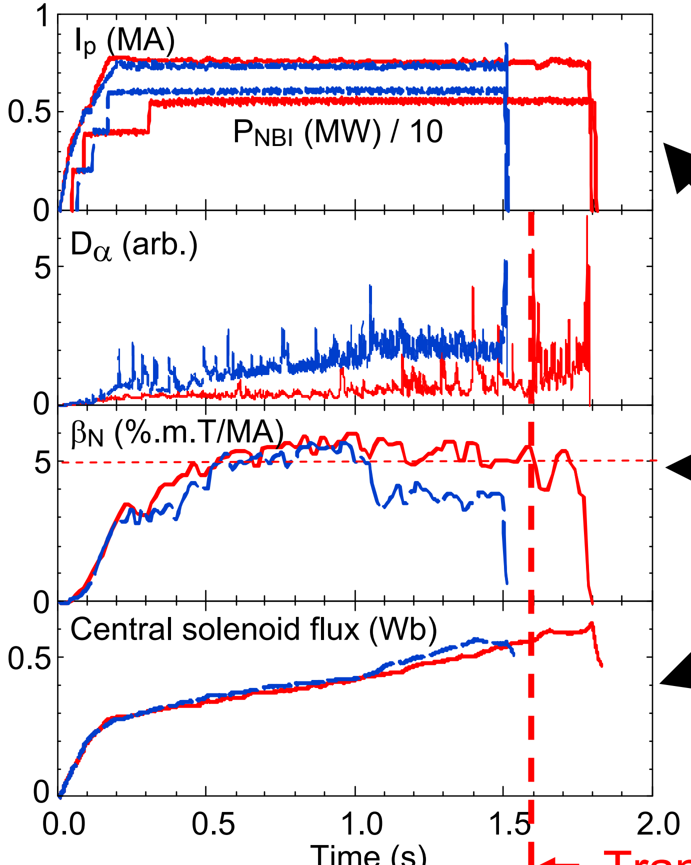


- ELM-free plasma produced using Li evaporation using dual-LITER system
  - Density rise, impurity accumulation and radiated power can be problematic in ELM-free H-mode scenarios
- Density rate-of-rise reduced using 3D resonant magnetic field perturbations (RMP) to trigger ELMs
  - ELM destabilization differs from the ELM mitigation/reduction observed on DIII-D/JET
  - RMP triggers ELMs with 50-80% reliability
- RMP ELM pacing offers beneficial reduction in impurity accumulation/radiation
  - Additional optimization required to reduce ELM size – higher elongation, more frequent RMP pulses?

n=3 Error Field Correction + n=1 RWM Feedback + Lithium Coating Extends High-β_N Discharges

116313 – no mode control or Li
129125 – with mode control + Li





Onset of n=1 rotating modes avoided

NSTX record pulse-length = 1.8s

Pulse-length limited by TF & OH coil heating

$\beta_N \geq 5$ sustained for 3-4 τ_{CR}

- EF/RWM control sustains rotation, high β

Flux consumption reduced by sustained high β + Li conditioning

- High elongation κ = 2.4 increases bootstrap current fraction

← Transition to phase with larger, more frequent ELMs

NSTX successfully completed all research milestones and produced many exciting results

- Joule milestone: "evaluate the generation of plasma rotation and momentum transport, and assess the impact of plasma rotation on stability and confinement…"
  - Momentum transport strongly influenced by turbulence-driven inward pinch
  - Actively comparing momentum sink from 3D fields to (new) generalized NTV theory
  - Effect of rotation on confinement is through ion channel and localized to large r/a
  - Kinetic effects important in understanding rotational stabilization of RWM, rotation shear effects important for NTM stability

- R(08-1) Measure poloidal rotation at low A and compare with theory
  - Measured poloidal rotation is consistent with neoclassical prediction
- R(08-2) Couple inductive ramp-up to CHI plasmas
  - Successfully coupled CHI to induction, but impurity production must be reduced
- R(08-3) Study variation and control of heat flux in SOL
  - Interpretation of near-SOL widths significantly improved, far-SOL "widths" a mystery
  - Shorter connection length impacts partially-detached-divertor (PDD) regime at higher I_P

- Electron-gyro-scale turbulence consistent with ETG, GAE may cause e-transport
- Li can suppress ELMs, and 3D fields can trigger ELMs → ELM control
- Li + error-field/RWM control help sustain high β_N → record pulse-lengths

NSTX FY 2009 research milestones:

- DOE Joule milestone: *"Conduct experiments on major fusion facilities to develop understanding of particle control and hydrogenic fuel retention in tokamaks"*
  - *…identify the fundamental processes governing particle balance by systematically investigating a combination of divertor geometries, particle exhaust capabilities, and wall materials.*
  - *…NSTX is pursuing the use of lithium surfaces in the divertor…*
- R(09-1) Understand the physics of RWM stabilization and control as a function of rotation
  - RWM stabilization mechanisms will be characterized over a wide range of plasma rotation and collisionality conditions
- R(09-2) Study how j(r) is modified by super-Alfvénic ion driven modes
  - Emphasis on the effects of *AE modes on the beam CD profile
- R(09-3) Perform high-elongation wall-stabilized plasma operation
  - Assess BS current at high k and q, and NBICD at low density - operating near the ideal-wall limit