NSTX-U Supported by U.S. DEPARTMENT OF ENERGY Office of Science

Edge plasma transport and microstability analysis with lithium-coated plasma-facing components in NSTX

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and the NSTX Research Team

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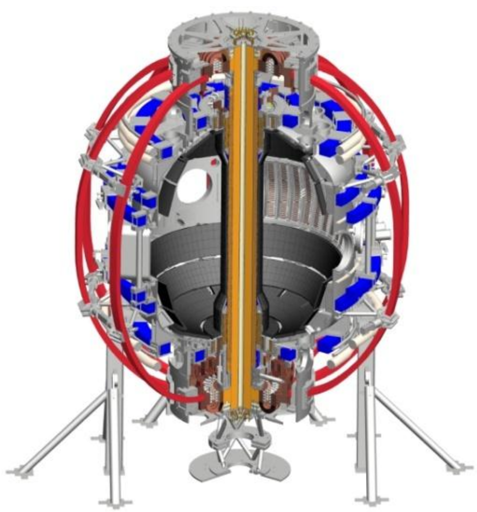

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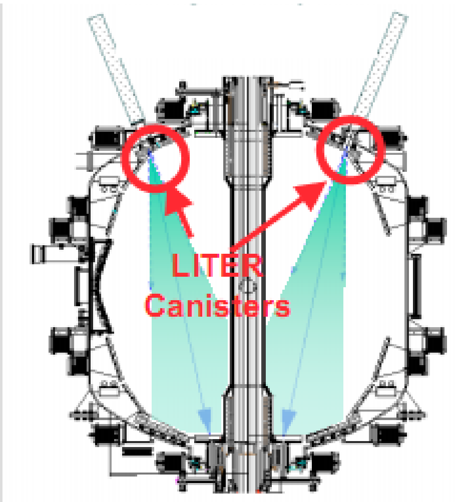
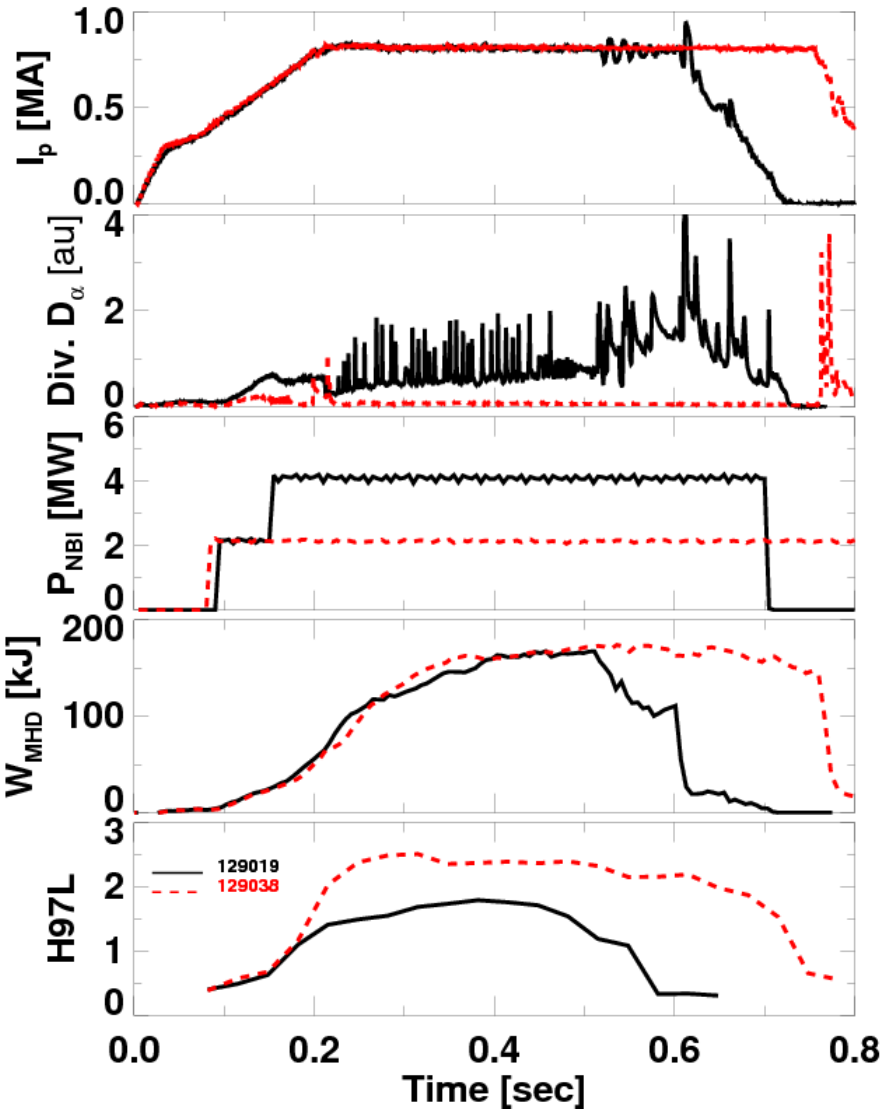
Type I ELMs eliminated, energy confinement improved with lithium wall coatings

Predicted* by L. Zakharov in 2005



~ 700mg Li between 129037 and 129038

* L. Zakharov, JNM 2007



Without Li, With Li

ELM-free, reduced divertor recycling

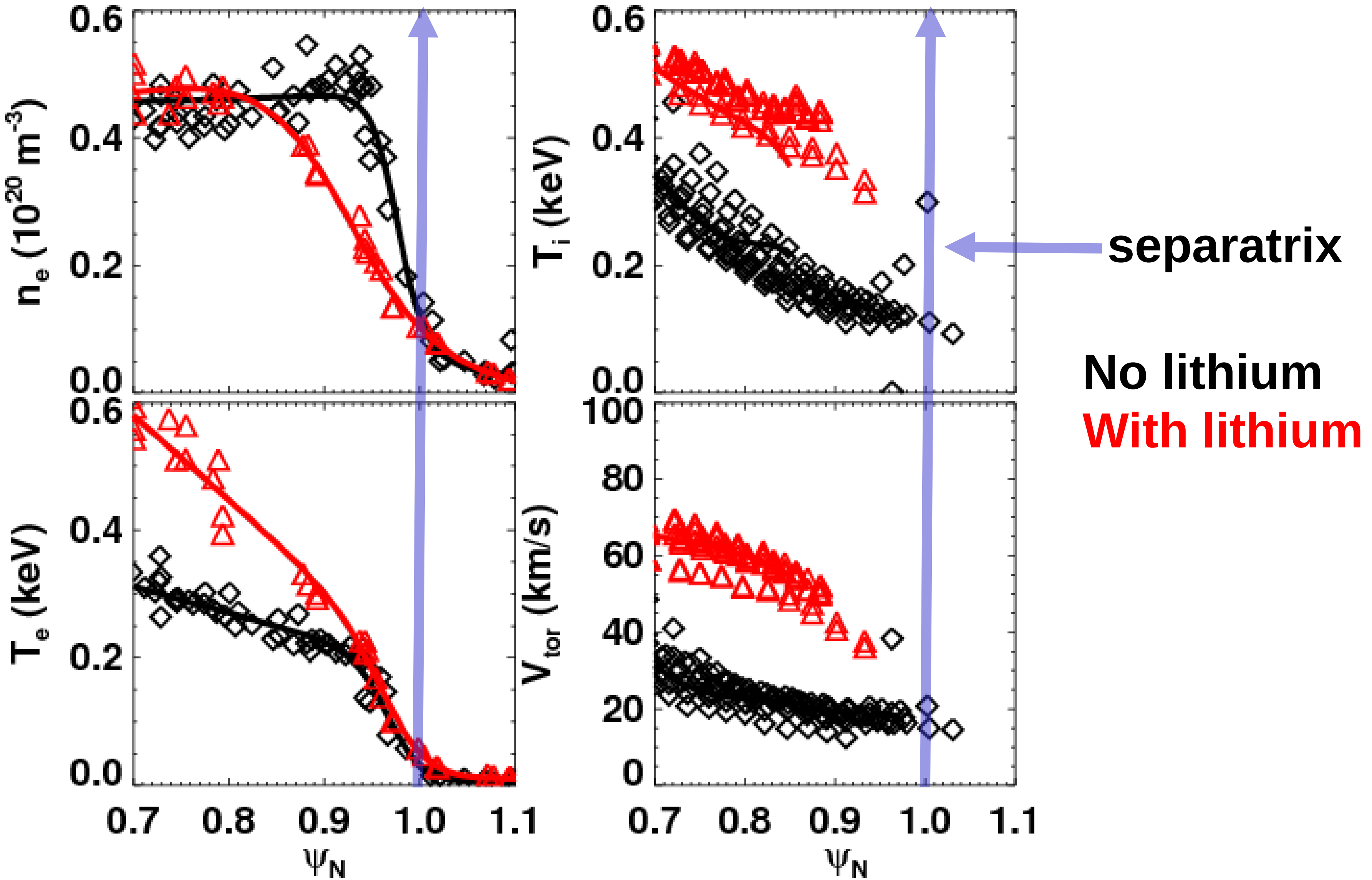
Lower NBI to avoid β limit

Similar stored energy

H-factor 40%↑

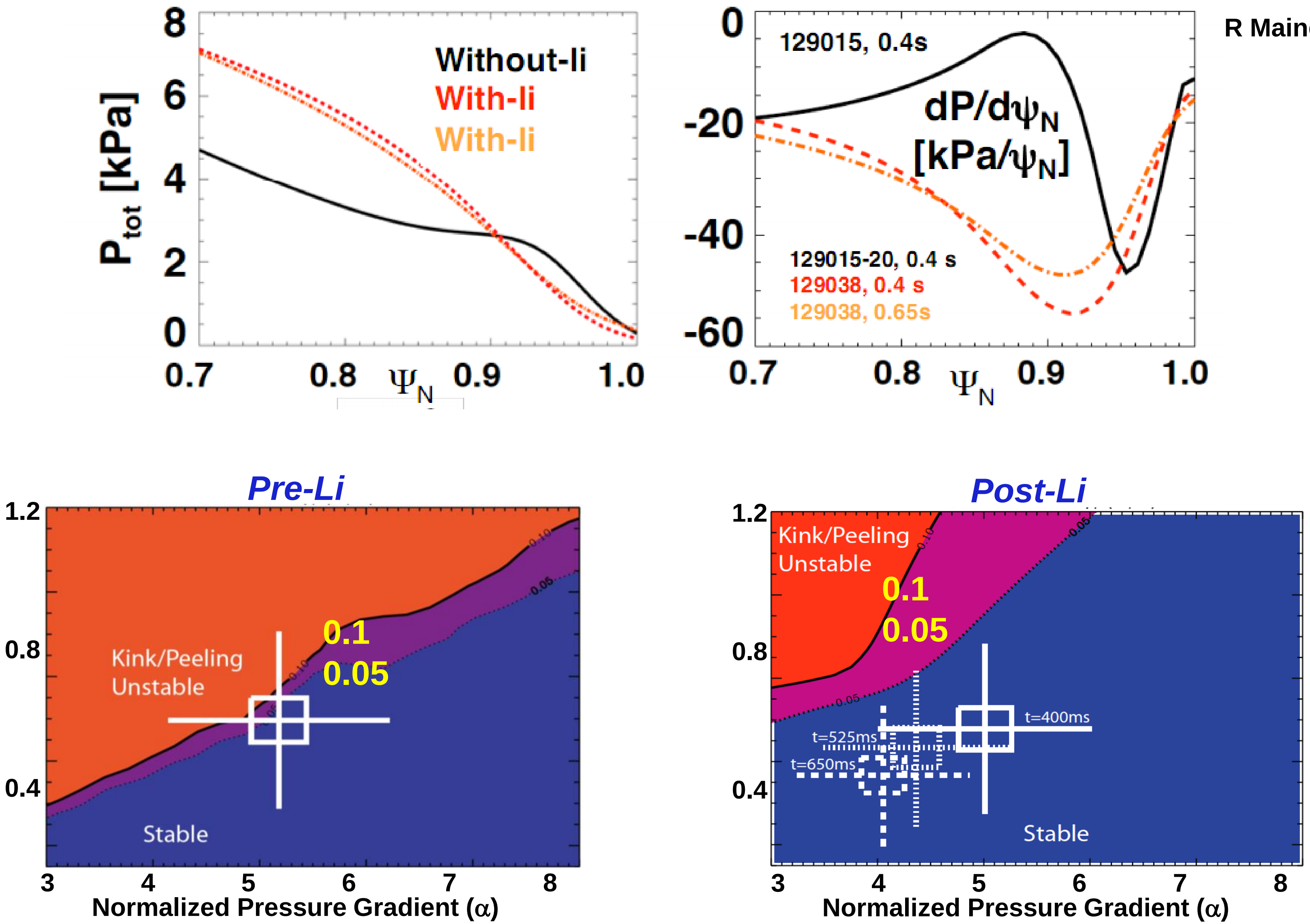
H. Kugel, PoP 2008
R. Kaita, IAEA 2008
M. Bell, PPCF 2009

T_e, T_i increased and edge n_e decreased with lithium coatings

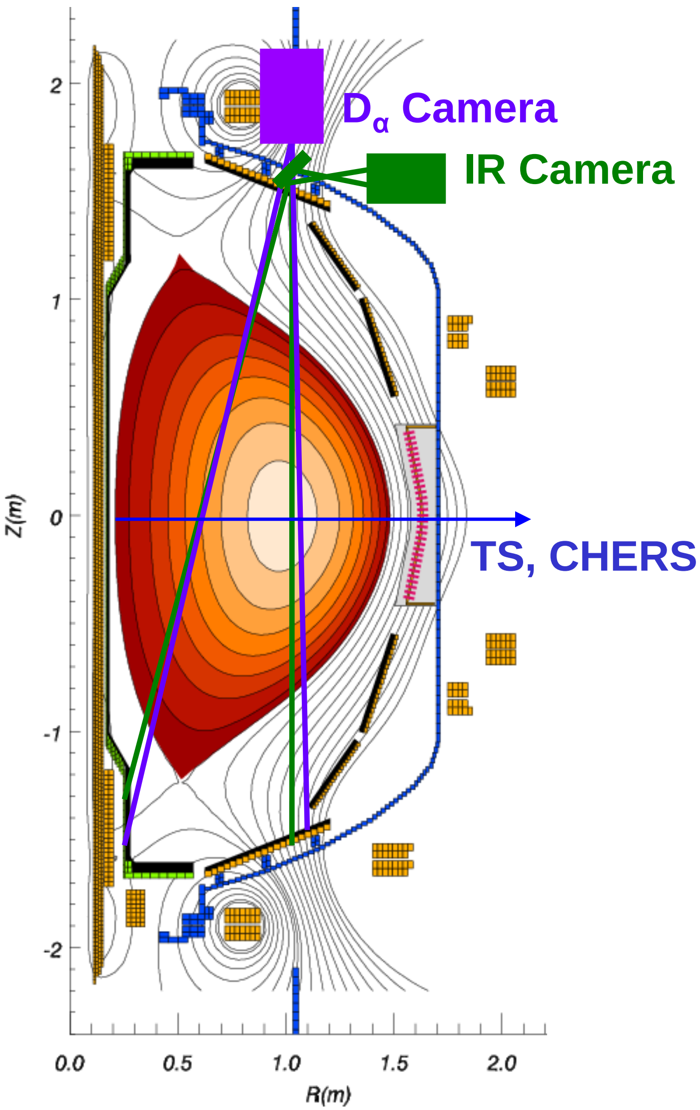


Peak pressure gradient moves inwards, p’ and j reduced outside ψ_N~0.95

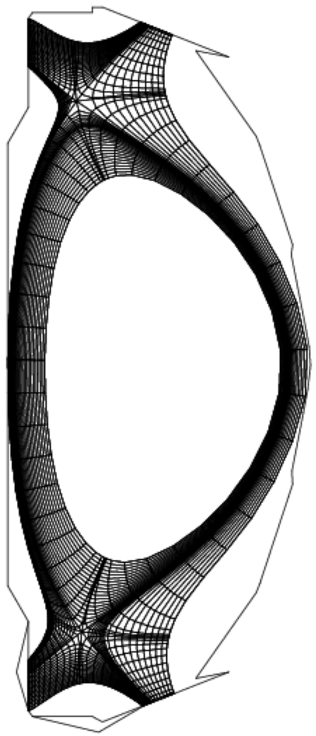
R Maingi, PRL 2009



Pre- and post-lithium discharges are modeled using SOLPS



SOLPS Grid

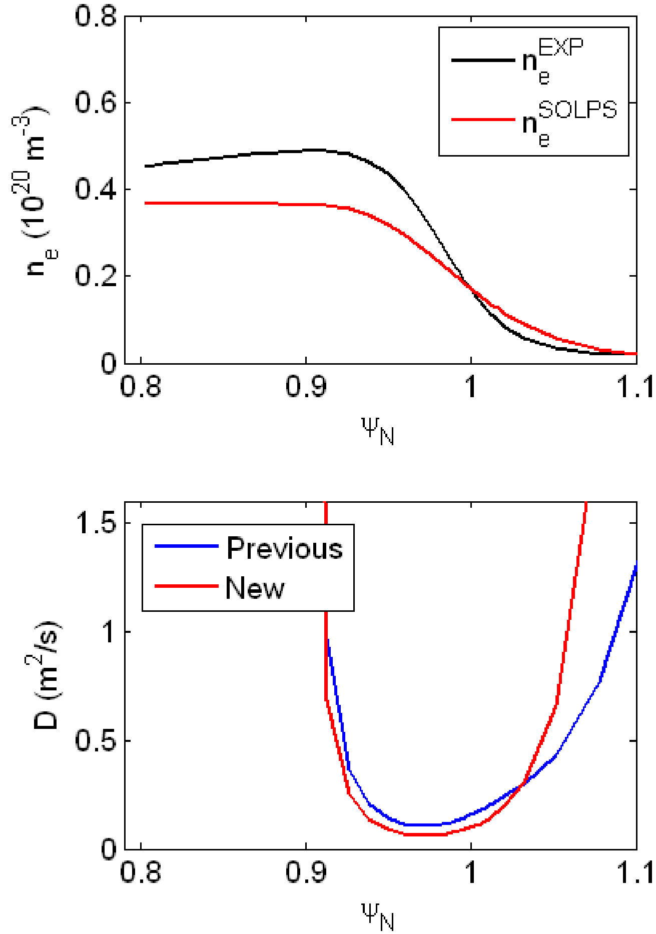


- SOLPS (B2-EIRENE: 2D fluid plasma + MC neutrals) used to model NSTX experimental data
  - ✓ Neutrals contributions
  - ✓ Recycling changes due to lithium

Parameters adjusted to fit data	Measurements used to constrain code
Radial transport coefficients $D_\perp$, χ_e, χ_i	Midplane n_e, T_e, T_i profiles
Divertor recycling coefficient	Calibrated D_α camera
Separatrix position/T_e^{sep}	Peak divertor heat flux

Procedure for fitting midplane n_e, T_e, T_i profiles

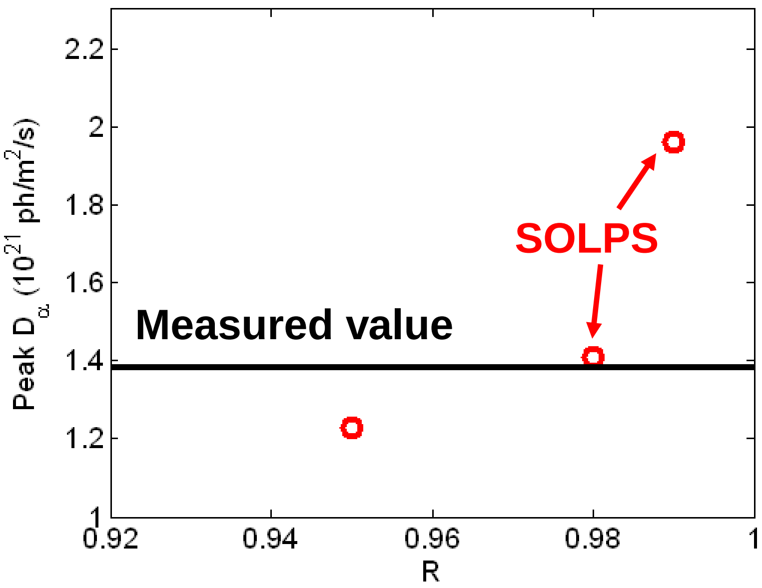
- Start with initial guess for $D_\perp$, χ_e,χ_i
- Run simulation for ~10% of confinement time
- Take radial fluxes along 1-D slice at midplane from code
  - Γ^{SOLPS}, q_e^{SOLPS}, q_i^{SOLPS}
- Update transport coefficients using SOLPS fluxes and *experimental* profiles
  - E.g., $D^{new} = -\Gamma^{SOLPS}/\mathrm{grad}(n_e^{EXP})$
  - Here we use fits to profiles used in stability calculations (Maingi PRL '09)
- Repeat until $n_e/T_e/T_i^{SOLPS} \sim n_e/T_e/T_i^{EXP}$



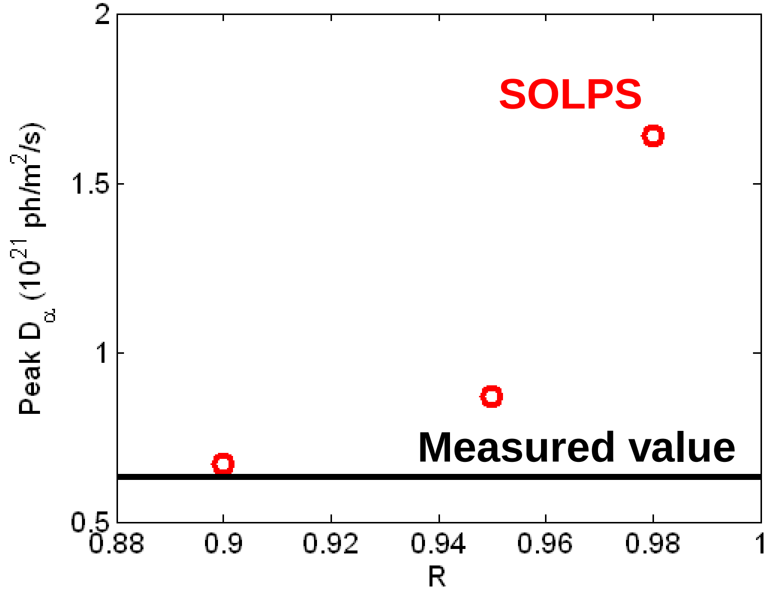
Peak D_α brightness is matched to experiment to constrain PFC recycling coefficient: lithium reduces R from ~.98 to ~.9

- For each discharge modeled, PFC recycling coefficient R is scanned
  - Fits to midplane data are redone at each R to maintain match to experiment
- D_α emissivity from code is integrated along lines of sight of camera, compared to measured values
  - Best fit indicates reduction of recycling from R~0.98 to R~0.9 when lithium coatings are applied

Pre-lithium



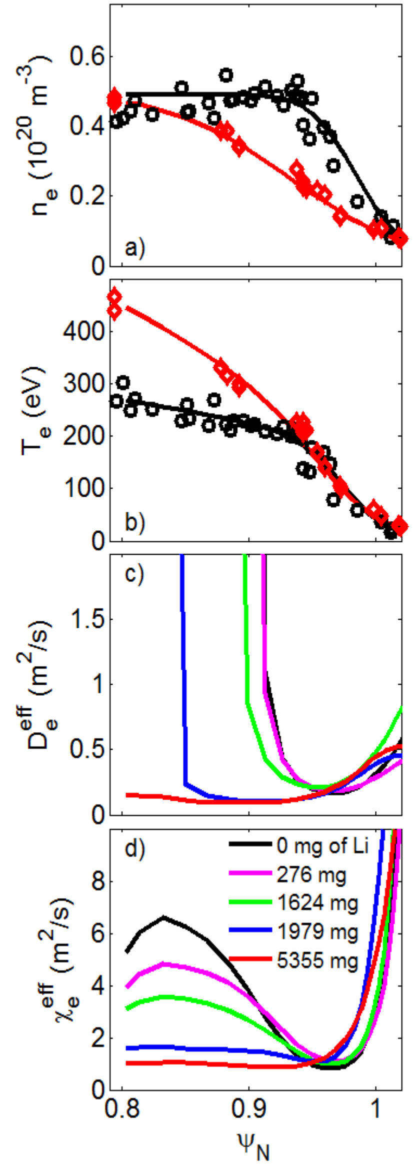
Post-lithium



Transport barrier widens with lithium coatings, broadening pedestal

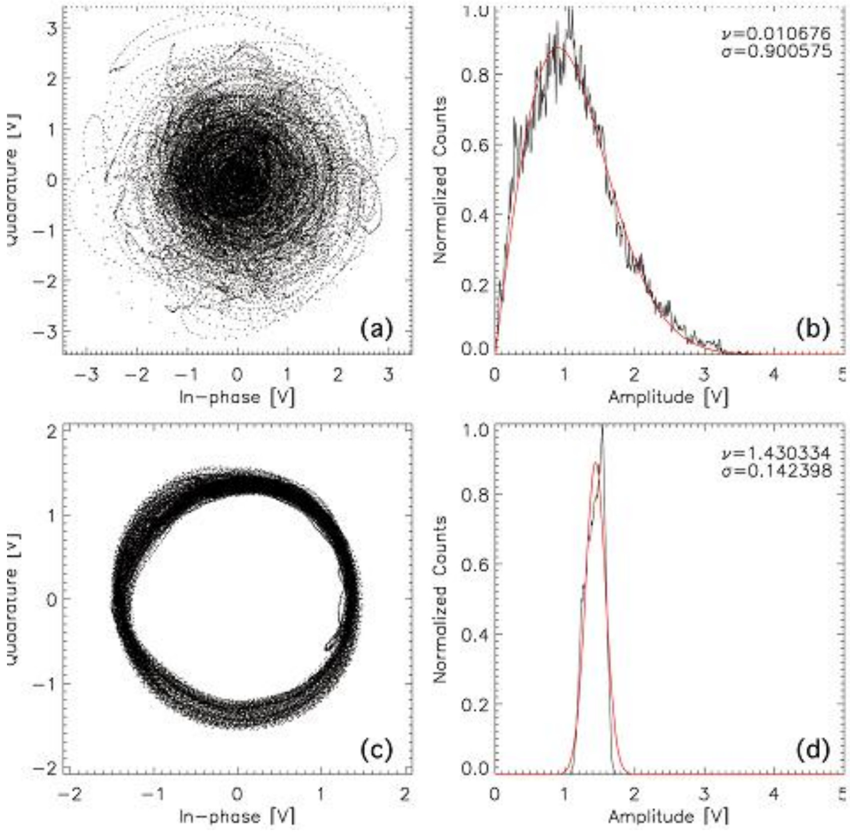
- Pre-lithium case shows typical H-mode structure
  - Barrier region in D, χ_e just inside separatrix
- Pedestal is much wider with lithium
  - $D_\perp$, χ_e similar outside of ψ_N~0.95
  - Low $D_\perp$, χ_e persist to inner boundary of simulation (ψ_N~0.8)
- Changes to profiles with lithium are due to reduced fluxes combined with wide transport barrier

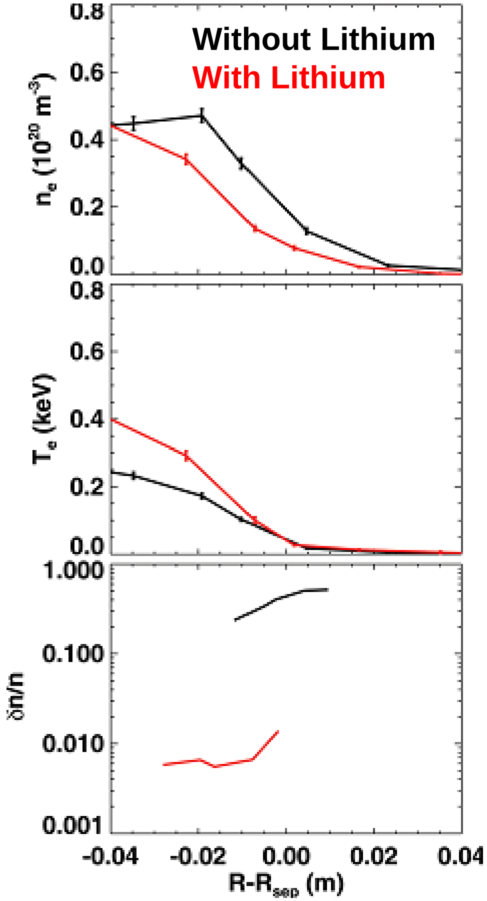
- Two regions show different transport response to lithium
  - Top of pedestal (ψ_N~0.8-0.95)
    - Large transport reduction (both D and χ_e)
  - Bottom of pedestal (ψ_N~0.8-0.95)
    - Transport similar with lithium
    - T_e profile is unchanged



Reflectometry shows reduced low-k turbulence in steep density gradient region

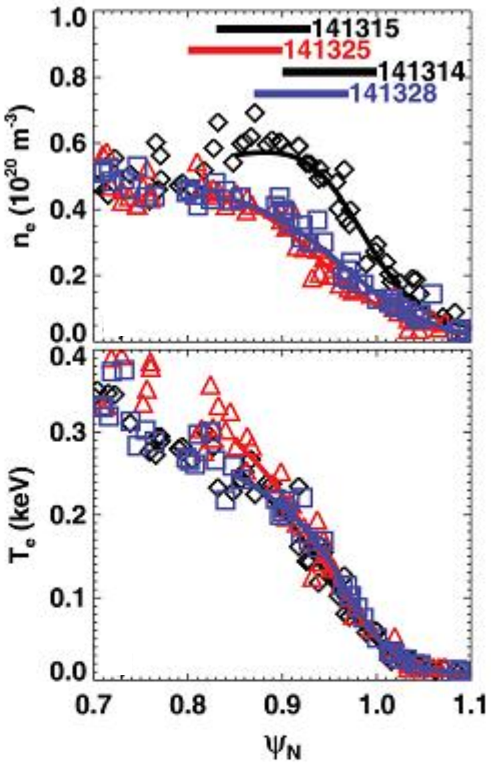
- Pre-lithium: strong amplitude and phase fluctuations
- Post-lithium: little amplitude fluctuation
- 3D simulations using Kirchoff performed to interpret fluctuation level

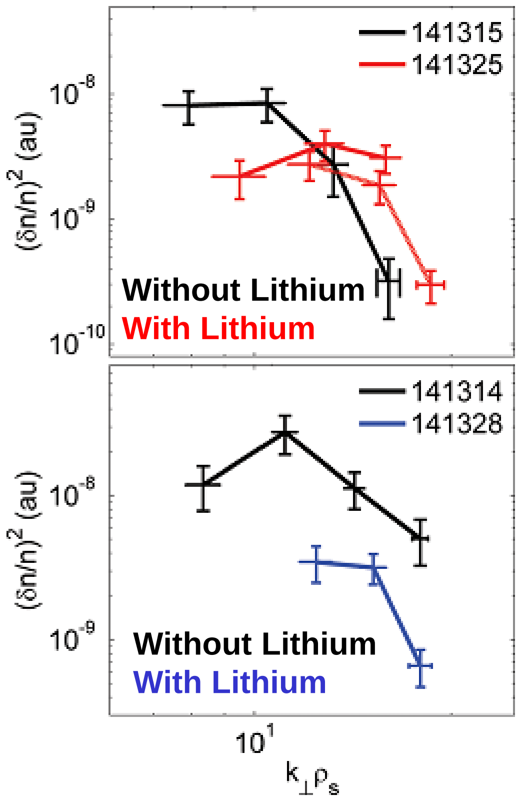




With power reduced so T_e profile matches pre-lithium case, high-k fluctuations reduced near pedestal top

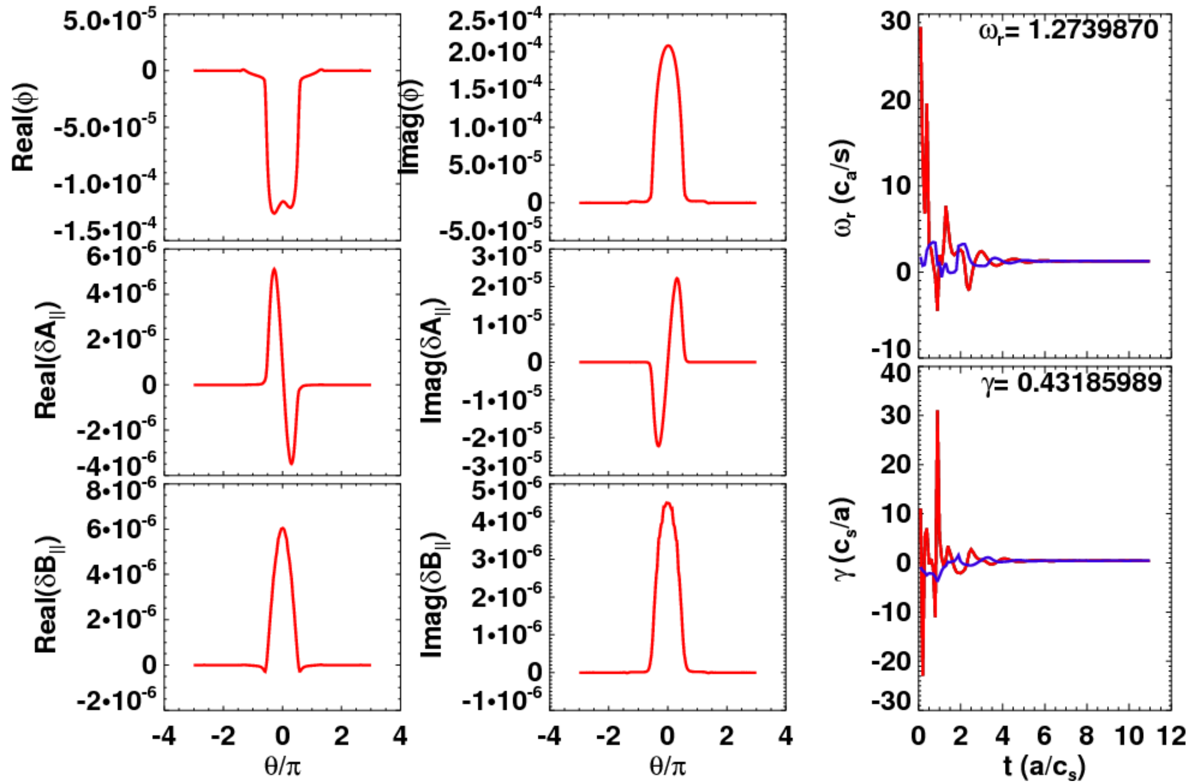
- Power varied in new discharges similar to those described above
- At 2MW with lithium, T_e profile similar to 5 MW pre-lithium
- Fluctuation amplitude measured with high-k scattering reduced across measured $k\rho_s$





Microstability of the NSTX pedestal with/without lithium is studied with GS2*

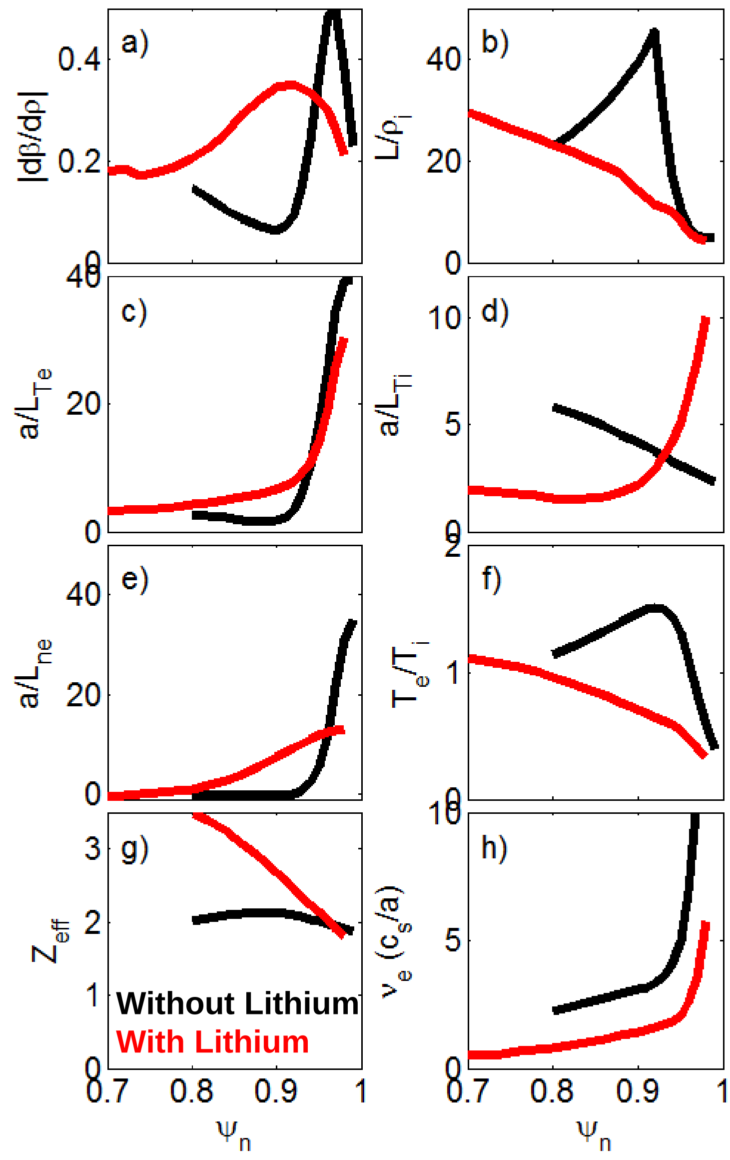
- Local, linear microstability examined with GS2 code
  - Finite collisionality and β
  - Fully electromagnetic ($\delta A_{||} + \delta B_{||}$)
  - Kinetic electrons, D and C^{6+} ions
- Realistic profiles and equilibria used in calculations
  - n_e, n_C, T_e, T_i from tanh profile fitting
  - Kinetically constrained equilibrium reconstructions



*M. Kotschenreuther et al, Comput. Phys. Commun. 88 (1995) 128.

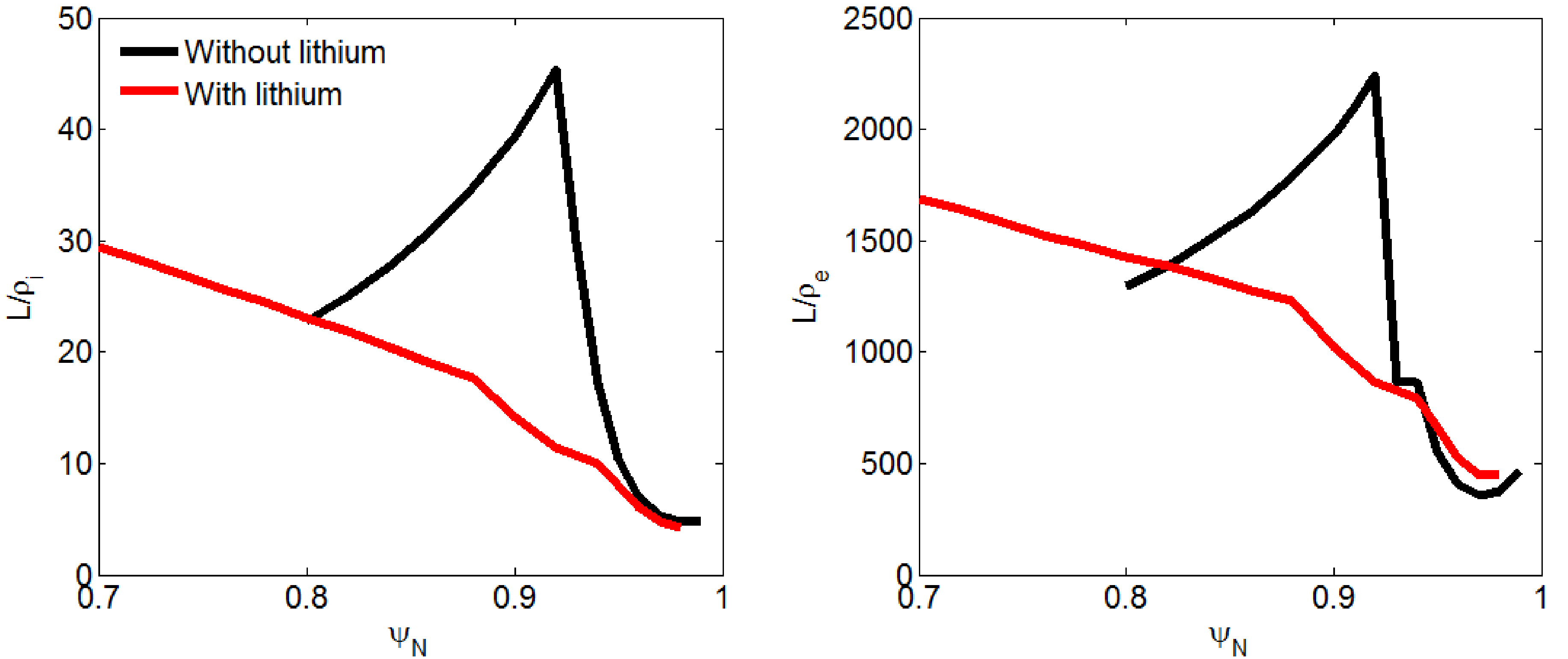
Summary of profiles used in calculations

- Peak pressure gradient moves inward from ψ_N=0.96 to ψ_N=0.9 with lithium
  - Pressure pedestal broader with lithium
- Collisionality reduced with Li
- Outside ψ_N~0.95
  - a/L_{Te} similar with/without lithium
  - a/Ln_e decreased with lithium
    - η_e increases
- Inside ψ_N~0.95
  - a/L_{Te}, a/L_{ne} increase with lithium
  - a/L_{Ti}, T_e/T_i decrease with lithium



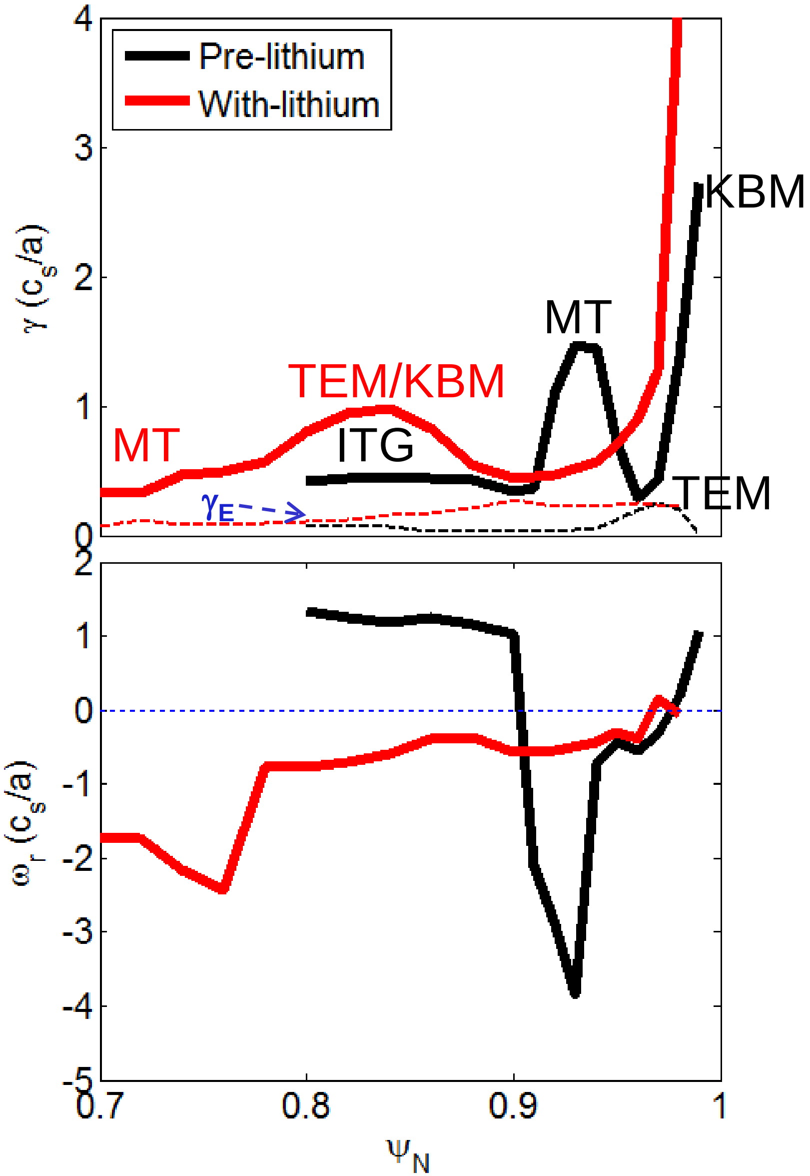
$\rho/L \ll 1$ is satisfied for electrons, not ions

- Local analysis used here for qualitative studies
  - Non-local effects will change results quantitatively for ion scales
  - Electron scales better satisfy ordering
- $\delta f/f \ll 1$ may also not be well satisfied
  - Will investigate using full-f approach in the future



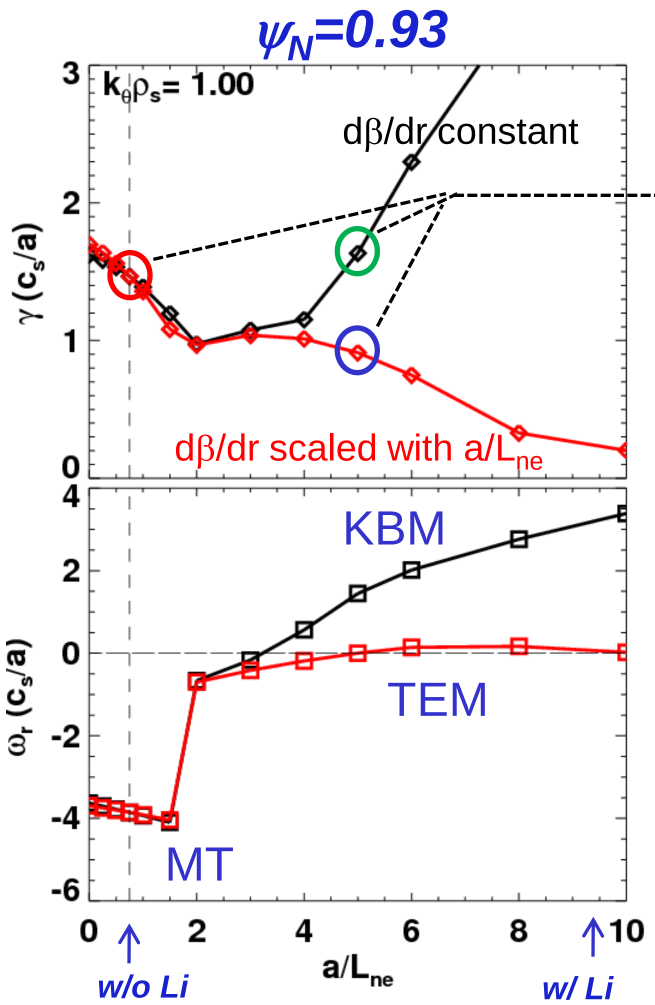
Radial profile of maximum low-k growth rate, freq

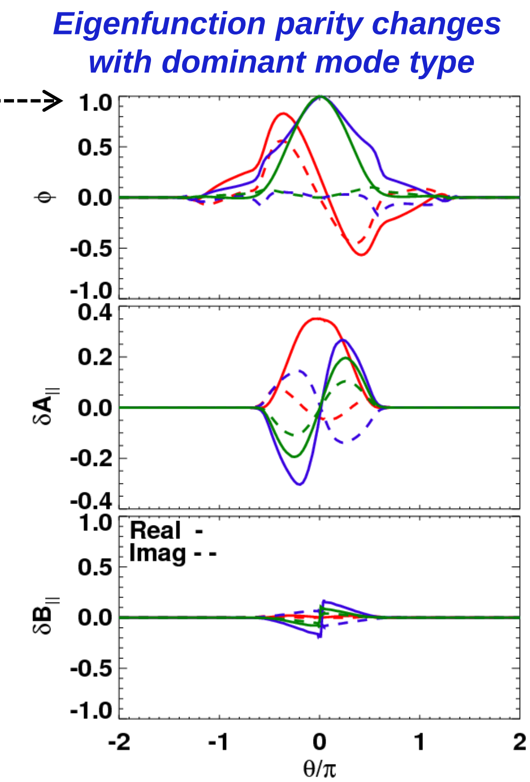
- Modes identified by scaling with parameters and eigenfunction parity (next slides)
- Four spatial regions evident without lithium
  - Pedestal foot (ψ_N>0.98)
    - γ is large, >> γ_E (KBM-like)
  - Within pedestal (ψ_N~0.96)
    - γ reduced, ~ γ_E (TEM-like)
  - Pedestal top (ψ_N~0.93)
    - γ large, >> γ_E (Microtearing)
  - Core (ψ_N<0.9)
    - ITG dominant, γ_E small
- γ profile has similar structure with lithium
  - Regions are broader (pedestal widens)
  - Edge modes are always TEM/KBM hybrid



Density gradient is stabilizing to MT modes dominant at pedestal-top without lithium

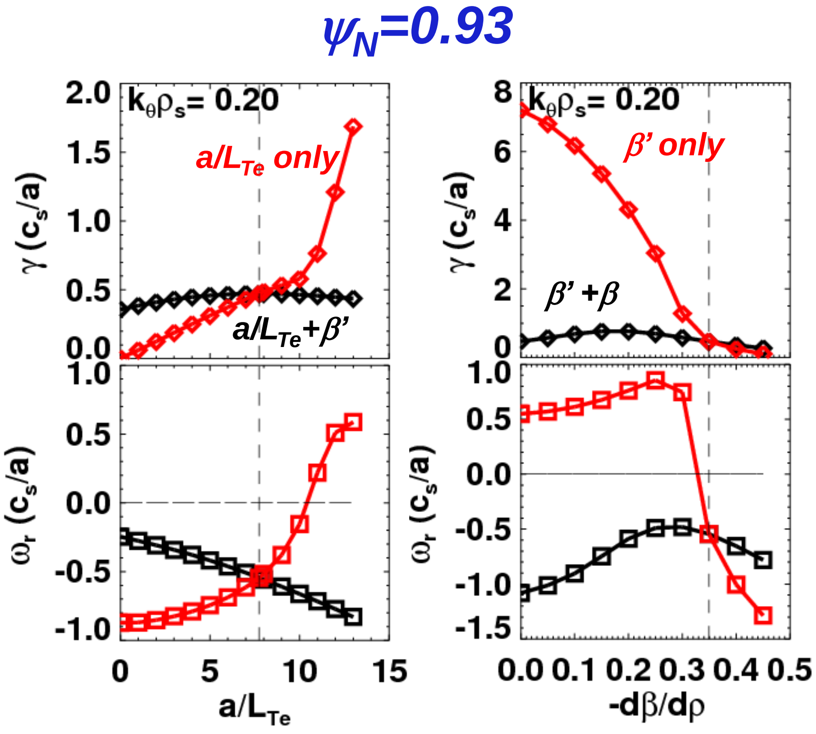
- Increasing a/L_{ne} stabilizes MT
  - TEM becomes dominant, with reduced γ
- If magnetic geometry is held fixed, KBM onset occurs at high a/L_{ne}
- With pressure gradient in geometry scaled consistently
  - No KBM onset
  - a/L_{ne} continues to be stabilizing
- Decreasing collisionality is weakly destabilizing at these parameters





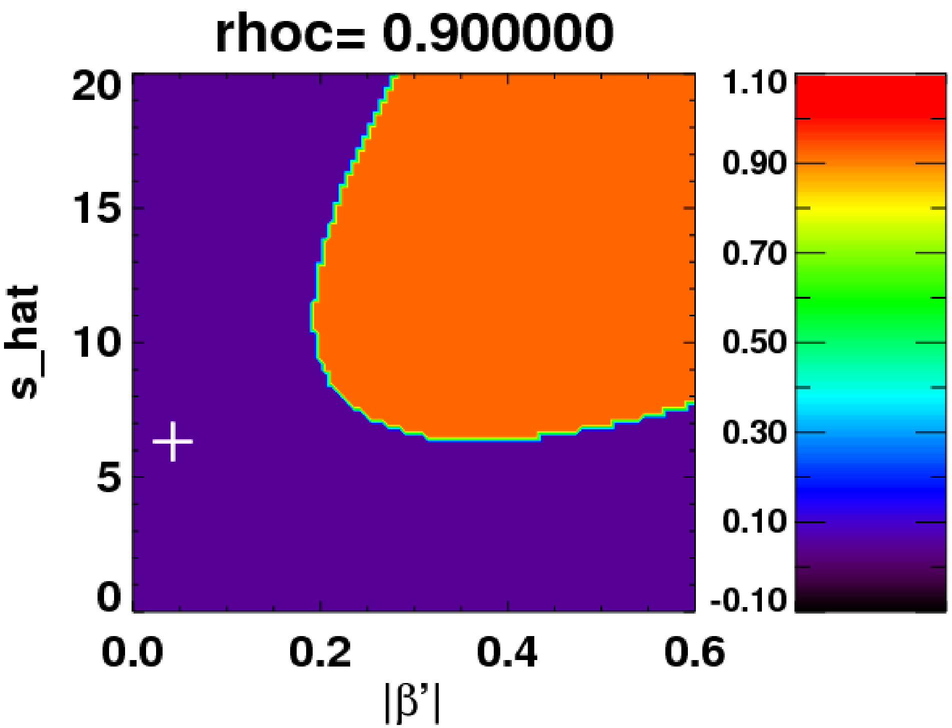
Increasing pressure gradient is stabilizing, has the strongest impact on growth rates with lithium

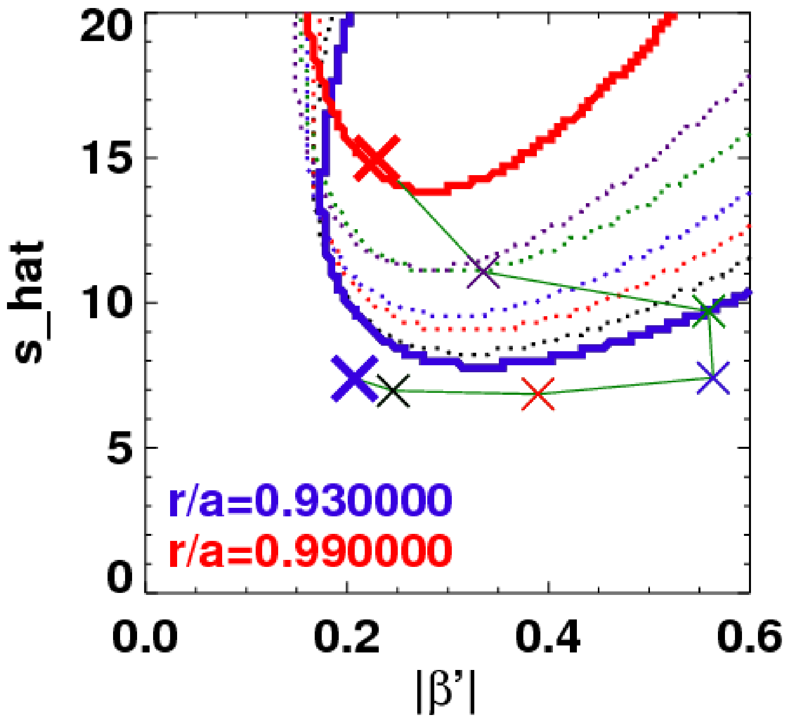
- Parameter scaling either done ‘individually’ or ‘consistently’
  - Individual: only a/L_{Te}, or $d\beta/dr$ scaled, all else fixed
  - Consistent: $d\beta/dr$ scaled with a/L_{Te}, β_e with $d\beta/dr$
- Increasing a/L_{Te} alone
  - Destabilizing (TEM-like)
  - KBM onset at high gradients
- Increasing a/L_{Te} consistently
  - No KBM, weak effect on γ
- $d\beta/dr$ alone:
  - Pressure gradient strongly stabilizing
  - KBM dominant at $d\beta/dr$ modestly below experiment
- β_e scaled consistently with $d\beta/dr$
  - No KBM observed; always TEM
  - Stabilization with $d\beta/dr$ much weaker



Ideal ballooning stability has been calculated

- ‘Ball’ module of GS2 used to calculate infinite-n stability
- Equilibrium from g-file used (kinetic efits, same as for GK calcs)
- Pressure gradient and shear are varied using Bishop relations for local equilibrium so stability boundary can be contoured

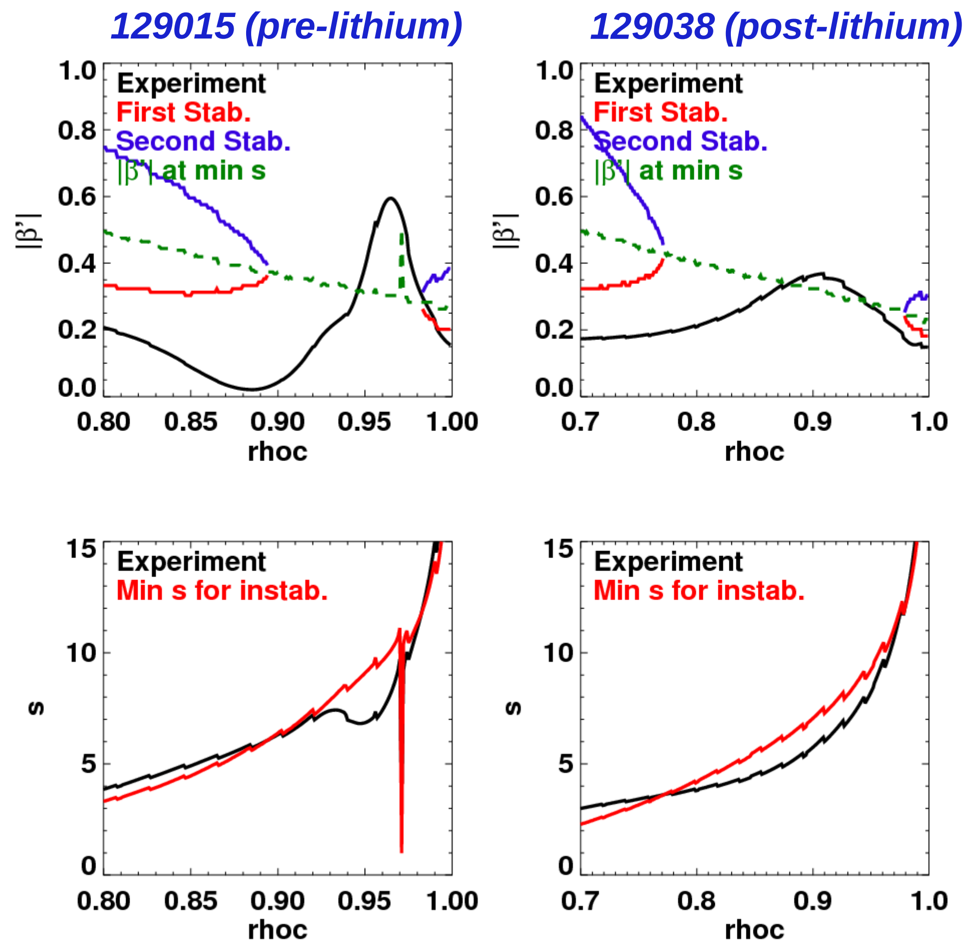




Summary of ideal ballooning results

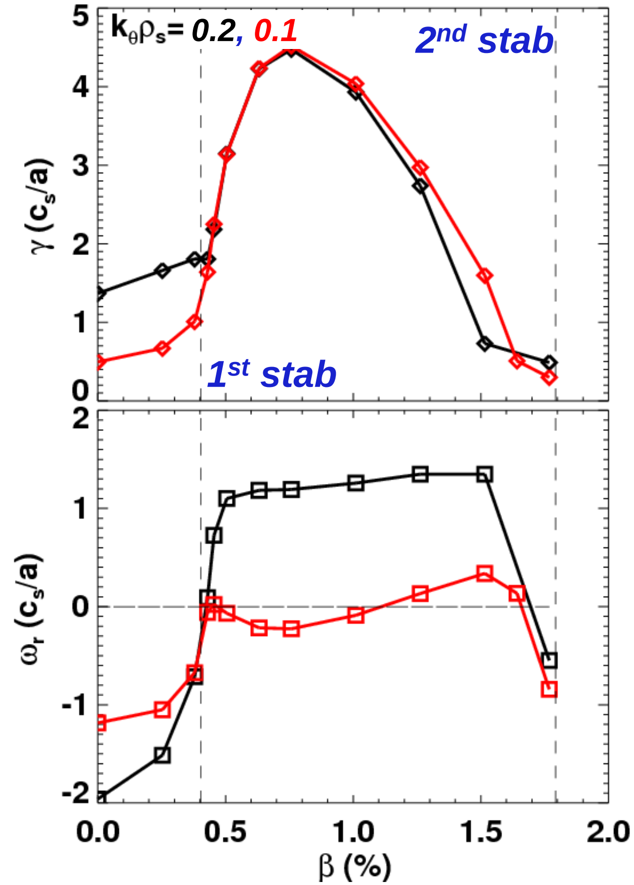
- 'Most' of the pedestal is ballooning stable
  - Very edge is close to boundary, but not the peak pressure gradient region
- Stability is due to shear being less than the minimum required to reach stability boundary
  - Increasing β' won't get you there
  - Error in shear could get you close, but even then the measured β' is a factor of two higher than first stability boundary (in pre- lithium case)
- Implies KBM onset must occur at lower shear than ideal for it to be limiting instability

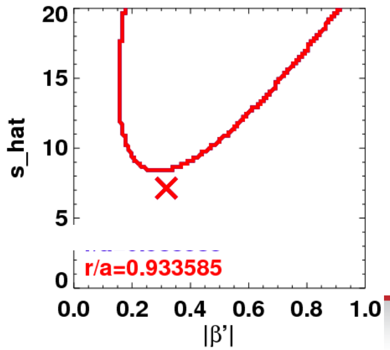
- ***In plots below, β' at first and second stability boundaries are calculated at fixed s***
- ***The minimum-shear point of the boundary is then calculated; β' at this point is plotted in upper frames, and s is shown on the bottom***



GS2 is used to calculate KBM stability

- 129038 (post-lithium), ψ_N=0.94
  - Within pedestal; peak p' is at ψ_N~0.91
- β_e of profiles, β' in equilibrium scaled self-consistently
  - s_hat set to 15 so first and second stability boundaries are clear
- KBM is unstable in ideally unstable region
  - Positive real frequency indicates KBM (checked via real/imag $\delta A_{||}$ phasing)
  - KBM onset and stabilization difficult to make out
    - sub-dominant near the ideal boundaries
    - Eigenvalue solver would clarify
  - Most unstable ky shifts from ~0.2 near first boundary to ~0.1 closer to second boundary
  - Increasing pressure gradient is stabilizing even within the ideally unstable region, not far past 1st stability boundary





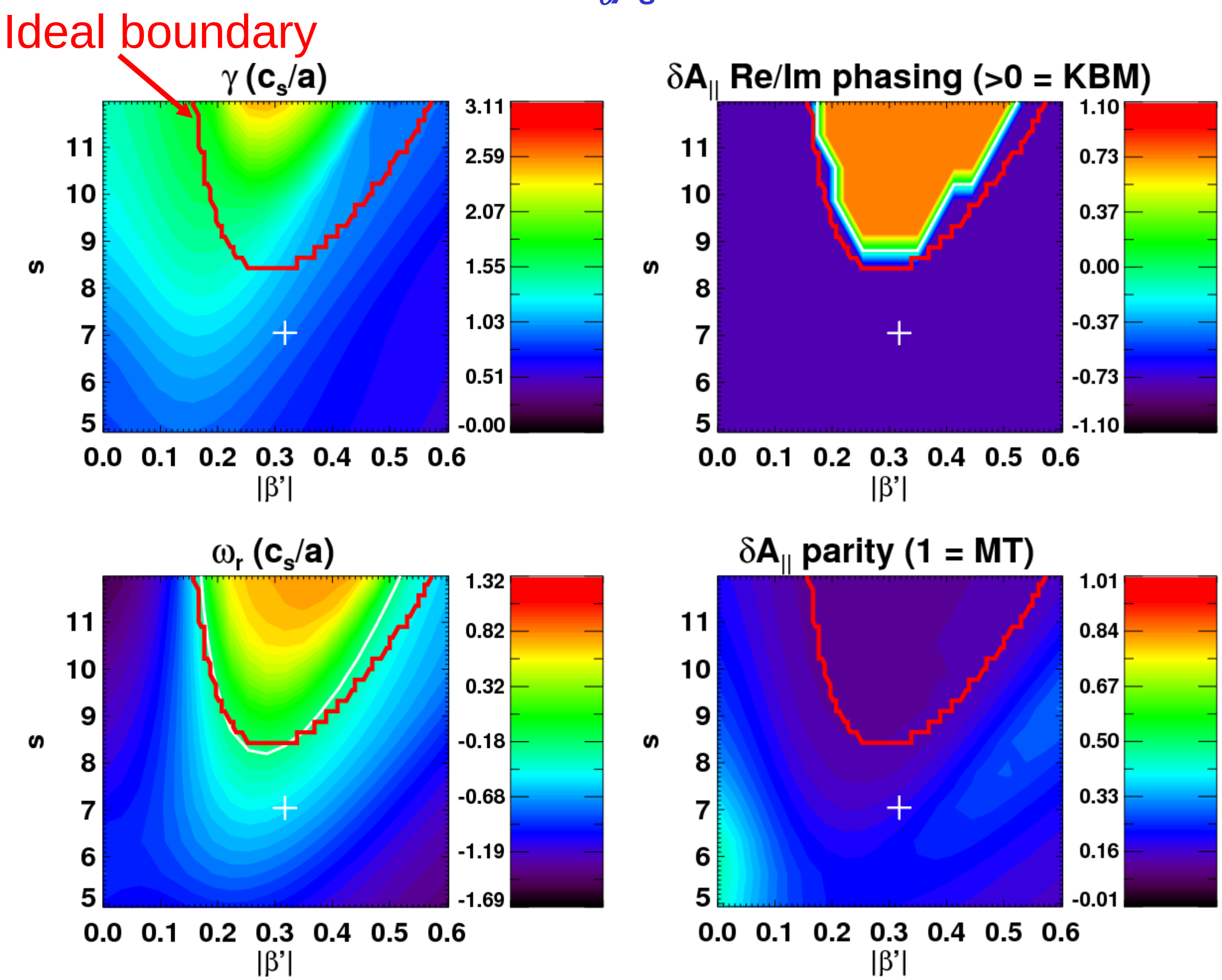
Kinetic ballooning stability tracks ideal

- GK calculations show KBM-unstable space very similar to ideal
- Smooth transition from TEM to KBM
  - No jump in ω_r
  - Hybrid TEM/KBM
- At NSTX operating point, pressure gradient is stabilizing
  - On second stable side
  - Can KBM clamp p'?
- Non-local effects are likely important
  - May close off second stability, similar to finite-n ideal MHD

129038 (post-lithium)

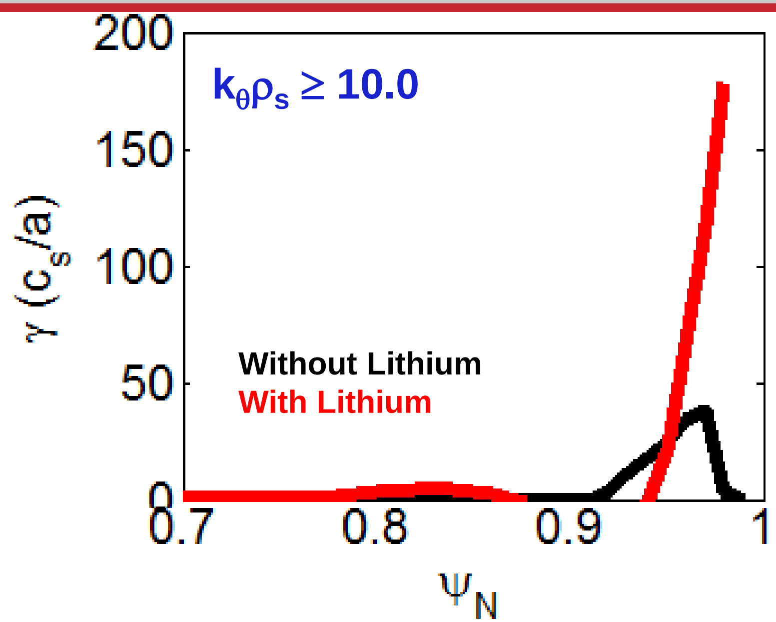
ψ_N=0.94

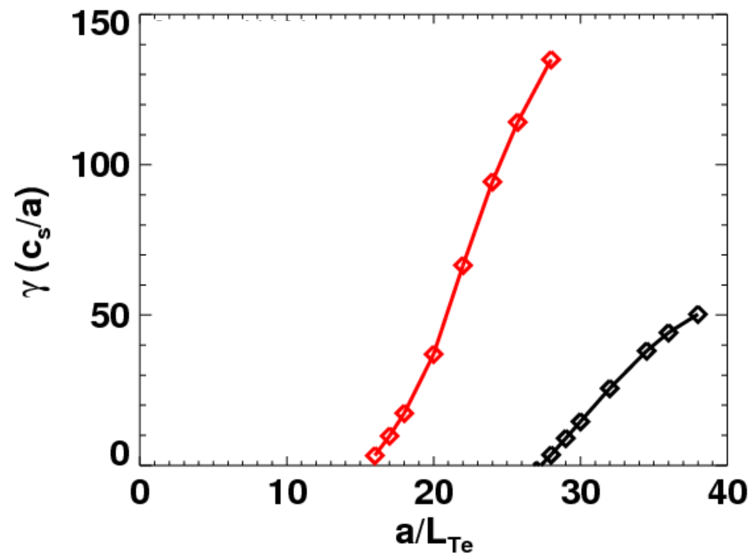
$k_\theta \rho_s$=0.2



ETG modes are unstable near the separatrix

- ETG is calculated to be unstable at plasma edge (ψ_N > 0.95)
- Growth rates significantly higher with lithium
  - a/L_{ne} is reduced, while a/L_{Te} is unchanged
  - $\Rightarrow \eta_e$ increases from ~1.5 to ~2
- Could play a role in keeping T_e profile clamped at edge
  - Important for P-B stability
- Nonlinear simulations ongoing to test if ETG transport is significant





Summary/conclusions/future work

- Two edge regions identified by 2D interpretive modeling of NSTX discharges without and with lithium
  - Near-separatrix (ψ_N>0.95): T_e clamped⇒pressure gradient reduced with density when lithium is deposited (important for ELM stability)
  - Pedestal-top (ψ_N~0.8-0.95): transport reduced with lithium (contributes to energy confinement increase)
- Microtearing is dominant at pedestal-top without lithium, is stabilized by the increased density gradient with lithium
  - Dominant mode becomes TEM/KBM hybrid, with growth rate on order of ExB shear rate over wider region
- ETG is destabilized with lithium
  - Could play a role in observed T_e stiffness
  - Need nonlinear simulations to test plausibility
- KBM is in second-stable region over most of the pedestal
  - But non-local effects could be important

EXTRA SLIDES FOLLOW

Pre-lithium E×B shear is determined from measured V_t, P_{C6+} profiles

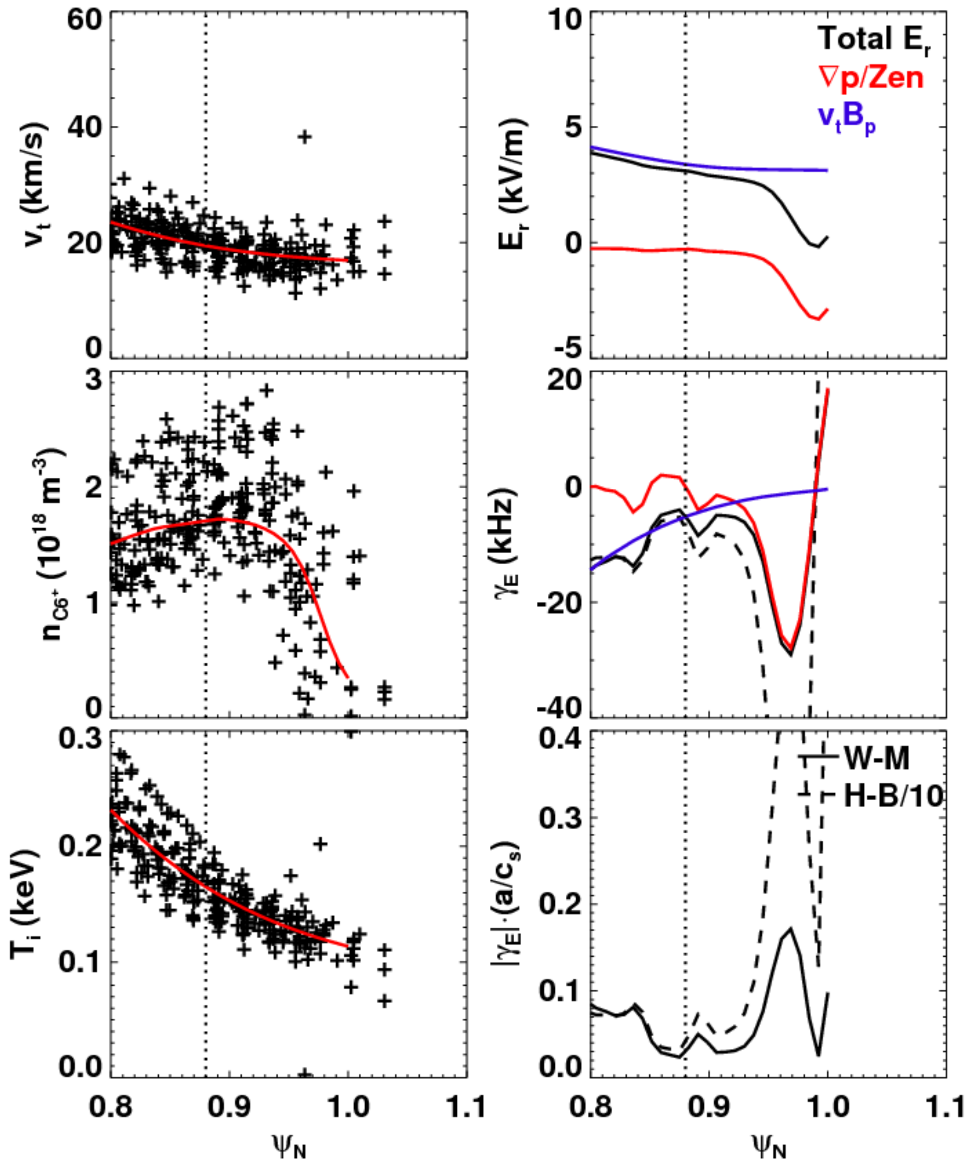
- Carbon toroidal rotation, pressure profiles used to estimate E_r
  - Poloidal rotation contribution small in other discharges (B_t~B_p) (Maingi, PRL '10)
- Shear rate calculated using two expressions
  - Waltz-Miller

$$\gamma_E = \frac{r}{q}\frac{\partial}{\partial r}\frac{E_R}{RB_p}$$

  - Hahm=Burrell

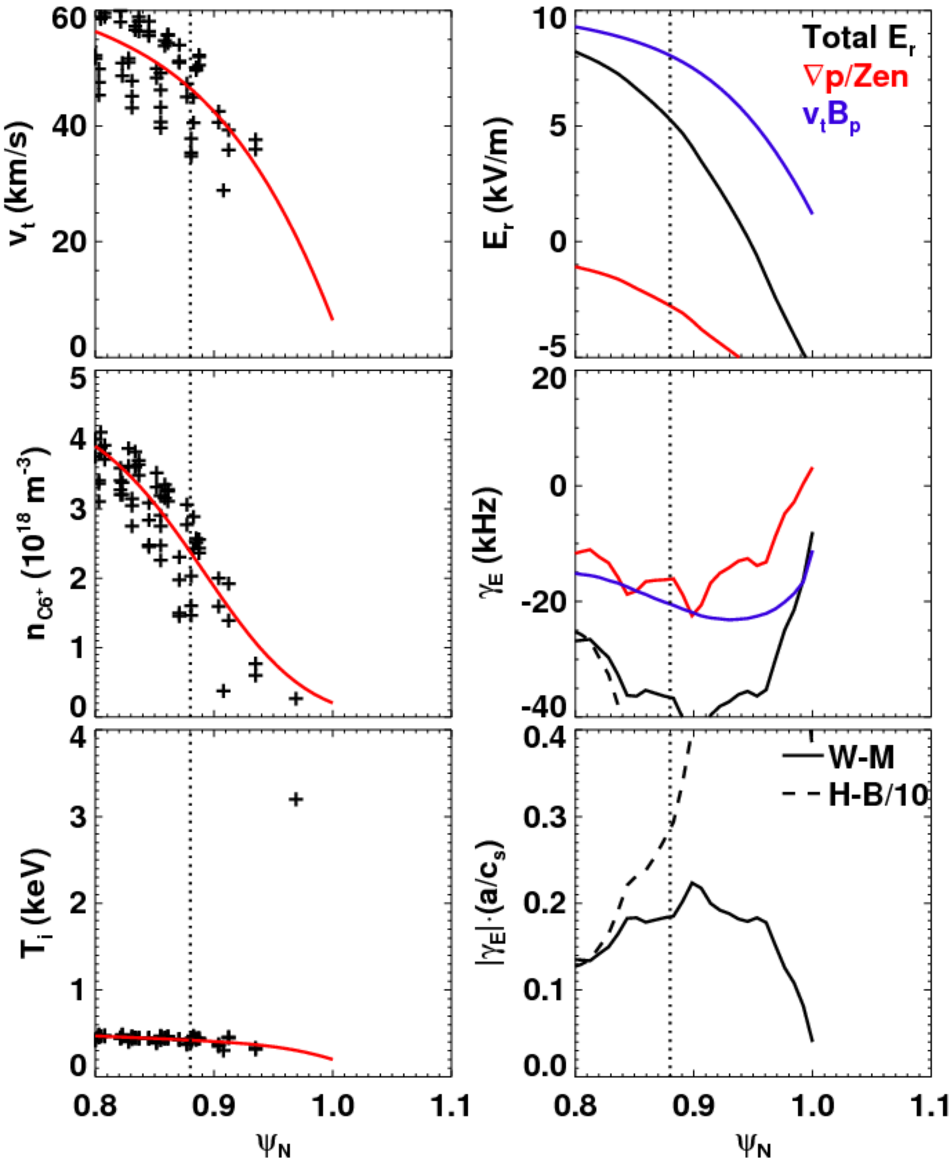
$$\gamma_E = \frac{(RB_p)^2}{B}\frac{\partial}{\partial \psi}\frac{E_R}{RB_p}$$

- Shear rate is largest within pedestal region
  - Narrow region with substantial pressure contribution



Region with large E×B shear becomes wider with lithium

- Values outside ψ_N~0.95 are extrapolations
- V_t, dV_t/dr are larger than pre-lithium case
- Pressure gradient gives significant contribution to γ_E over a wider radial range



Results are converged with grid size and time step

- N_θ = 72 works well in all cases
- $\Delta t \leq 0.01$, depends on radius (varies with γ, ω_r)
  - Also converged for dominance of two competing modes