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NSTX-U/PPPL Theory Partnership

Stan Kaye

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NSTX-U PAC-35
PPPL, Princeton University
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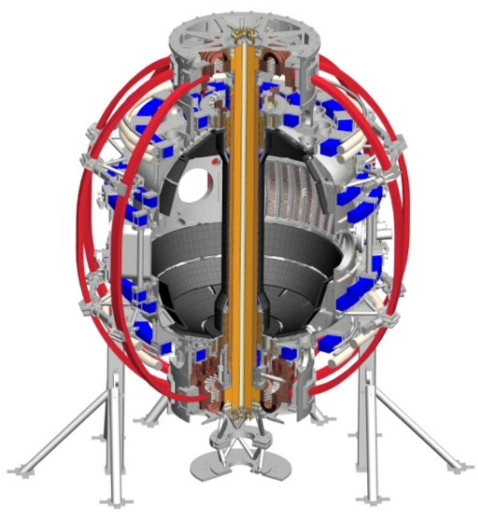

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*This work supported by the US DOE Contract No. DE-AC02-09CH11466

Longstanding NSTX(-U)/Theory Partnership

- Coordinated partnership with NSTX-U team within the NSTX/NSTX-U Topical Science Group framework
  - **Macroscopic stability**: J. Berkery, A. Boozer (*Theory)*, J.-K. Park
  - **Waves and energetic particles**: N. Gorelenkov, M. Podesta, G. Taylor
  - **Transport and turbulence**: W. Guttenfelder, G. Hammett, Y. Ren
  - **Boundary physics**: C-S. Chang, A, Diallo, V. Soukhanovskii
  - **Lithium physics**: M. Jaworski, C. Skinner, D. Stotler
  - **Solenoid-free startup**: S. Jardin, D. Mueller, R. Raman

- Partnership strengthened by ~$1M increment in 2014
  - Increase in direct funding of Theory by NSTX-U by ~2.5 FTE (4.9 FTE total)
  - Greatly expands range of topics that can be studied
  - Allows coverage of greater fraction for each researcher (generally >0.4 FTE each)
  - Synergistic support through Base Theory/SciDAC funding

PPPL Theory work is addressing topics critical to achieving the NSTX-U Five Year Plan Priorities

- Advance ST for Fusion Nuclear Science Facility (FNSF), including non-inductive operation
  - CHI reconnection physics (NI startup)
  - Non-linear wave-particle coupling (NI rampup)
  - MHD effects on NB current drive (NI sustainment)
- Develop solutions for plasma-material interface challenge
  - Processes setting SOL heat flux widths
  - Neutral particle distribution – edge atomic physics
- Explore unique ST parameter regimes to advance predictive capability - for ITER and beyond
  - Processes affecting electron transport in core
  - Role of high ExB and parallel flow shear
  - Understanding source and ramifications of soft and hard β-limits

The NSTX-U/Theory Partnership facilitates collaboration over a range of topics

- Waves and energetic particles: E. Belova, G.Y. Fu, N. Gorelenkov, E. Valeo, R. White
  - **CAE/KAW coupling**, development of reduced model for fast ion transport, coupling of kinks to AEs, non-linear wave-fast ion coupling
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- Edge physics: C.S. Chang, S.-H. Ku, D. Stotler
  - **SOL heat flux width**, edge bootstrap current, edge momentum source, neutral transport, GPI interpretation

- ***Theory support also provided directly through the NSTX program as well as by collaborators***

Will show representative examples from each area

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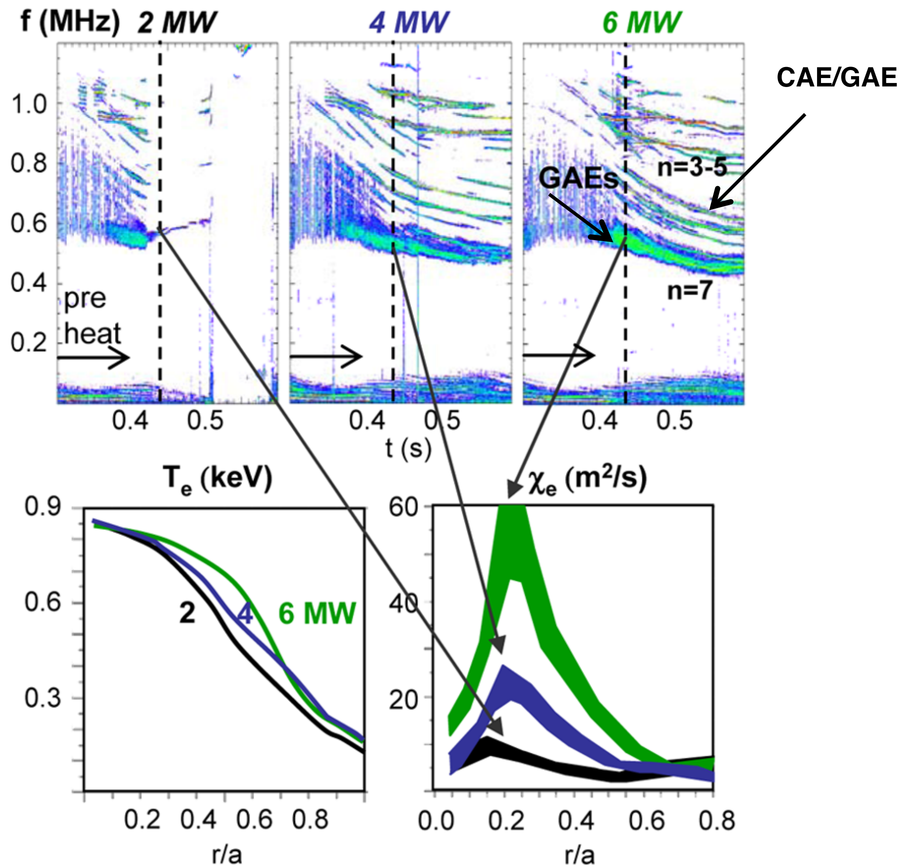
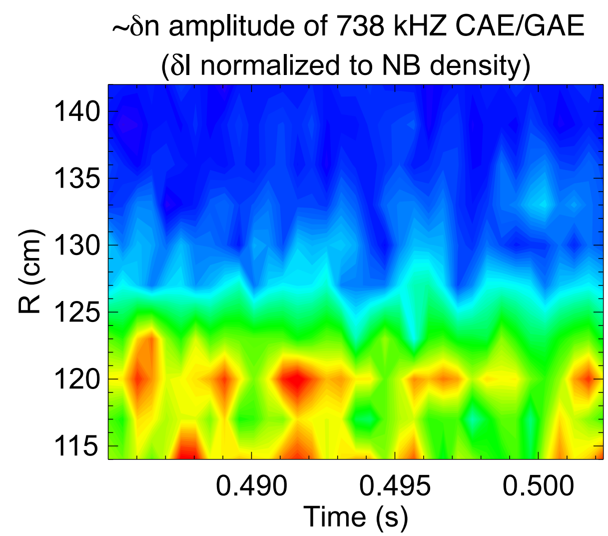
<u>EXP'T</u>: Large inferred anomalous core electron transport in presence of CAE/GAEs

- Observation of high frequency CAE/GAE modes in plasma core associated with flattening of T_e profile (Stutman et al., Tritz et al.)
  - High level of transport (10-100 m^2/s) inferred assuming classical beam physics



Stutman

BES spectra show mode amplitudes peaking from R=115 to 120 cm (r/a~0.2 to 0.3), in region of enhanced transport



Smith

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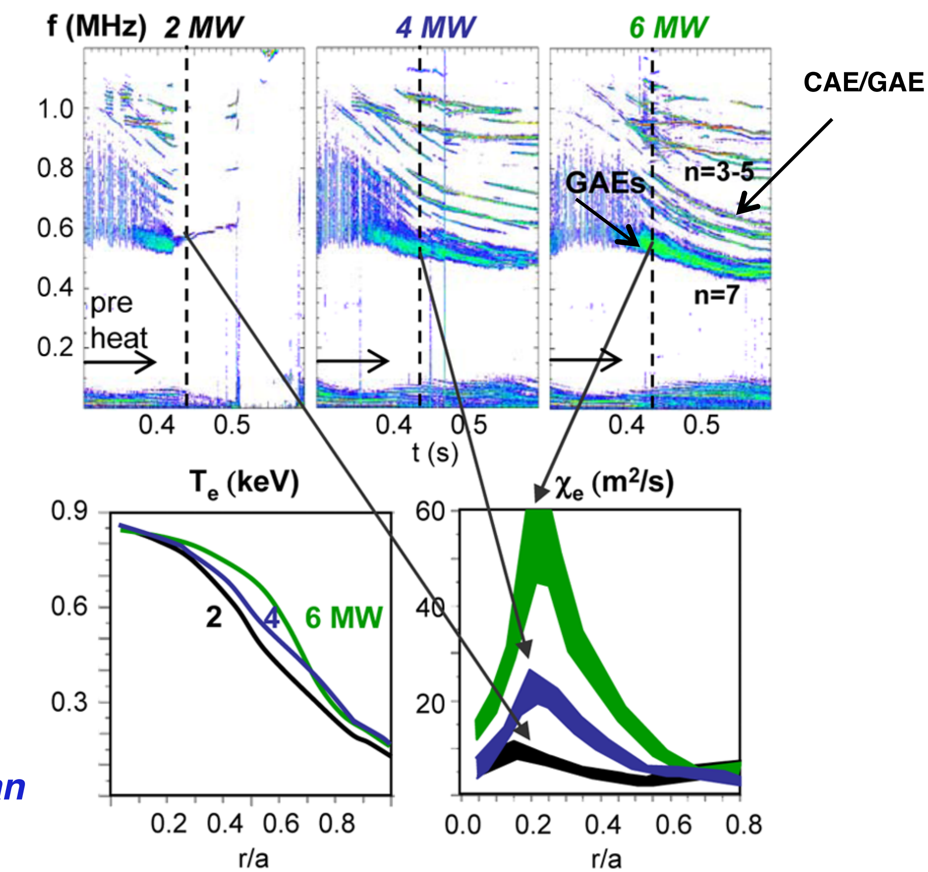

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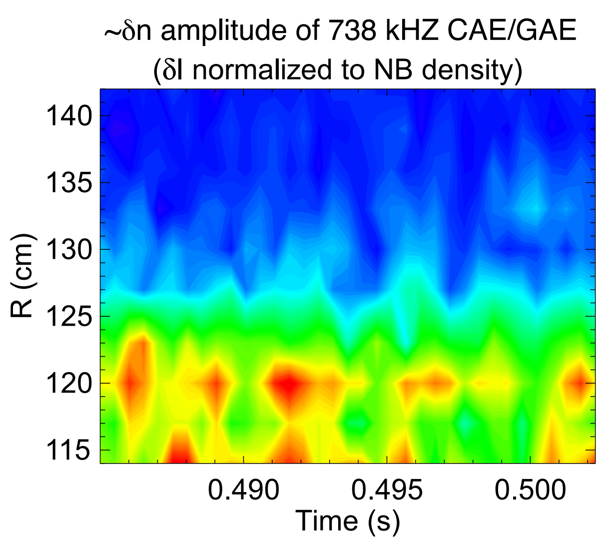


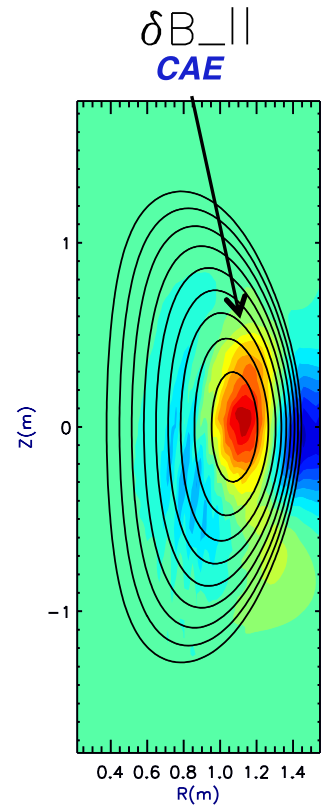
Smith

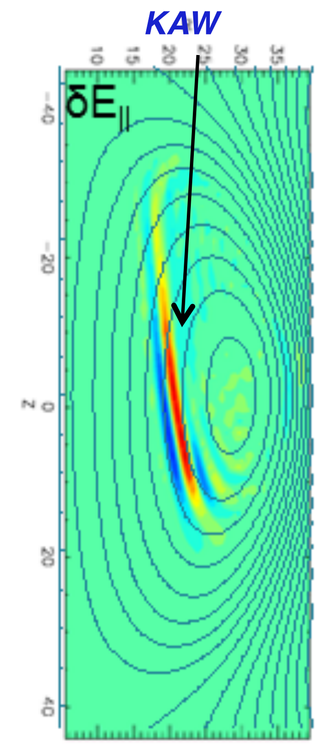
Is enhanced transport the full picture?

THEORY: New results suggest additional mechanism: energy channeling from NBI→CAE→KAW→electrons

- Fast ion physics may not be classical
- HYM simulations indicate Kinetic Alfvén Wave driven by CAE outside plasma center (at r/a~0.3)
- Some core NB power redistributed to this radius via energy channeling from NBI to CAE to KAW
  - KAW damps primarily on electrons
- Estimate power channeling of up to ~ 0.4 MW over range of realistic (inferred) mode amplitudes (for one mode)

Belova





⇨ Change in T_e profile due to both transport and heating profile modifications

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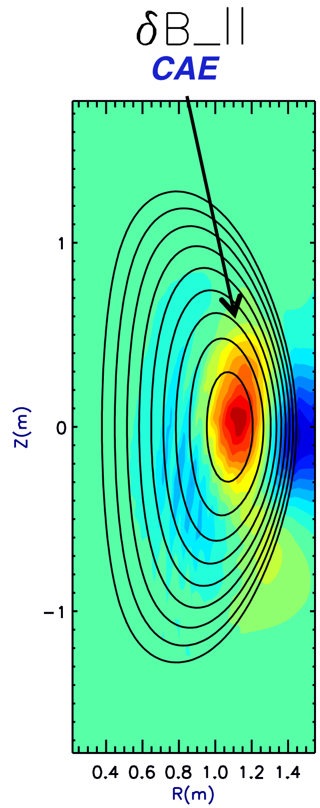

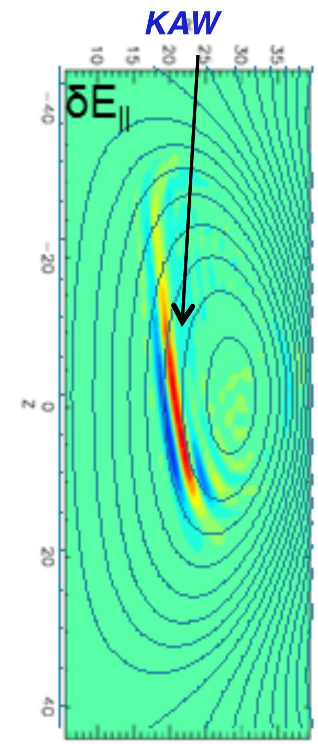

➡ Change in T_e profile due to both transport and heating profile modifications

Future Work: Perform non-linear HYM simulations to calculate actual level of energy transfer and effect on T_e; develop predictive capability

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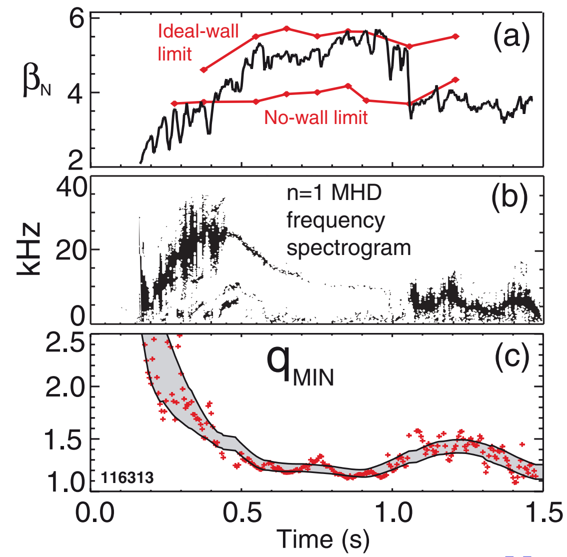
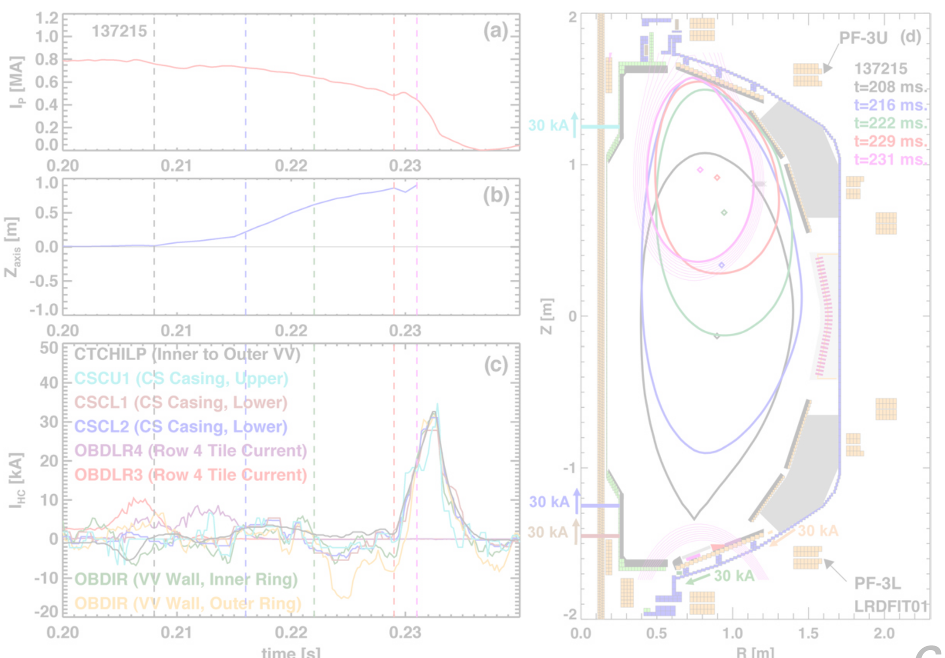
<u>EXP'T</u>: Soft beta limits and VDEs

- Soft β limit
  - Drop in β_n in response to onset of low-n internal MHD activity



Menard



Gerhardt

- VDEs
  - Both upward and downward VDEs observed
  - VDEs can lead to halo currents having up to 80 kA on the wall (downward)

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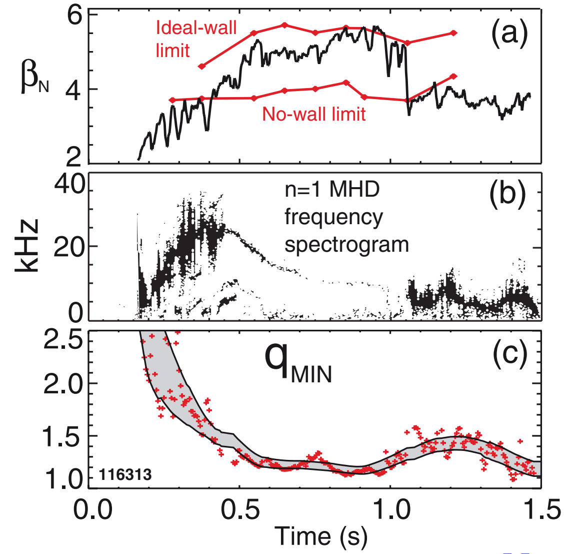

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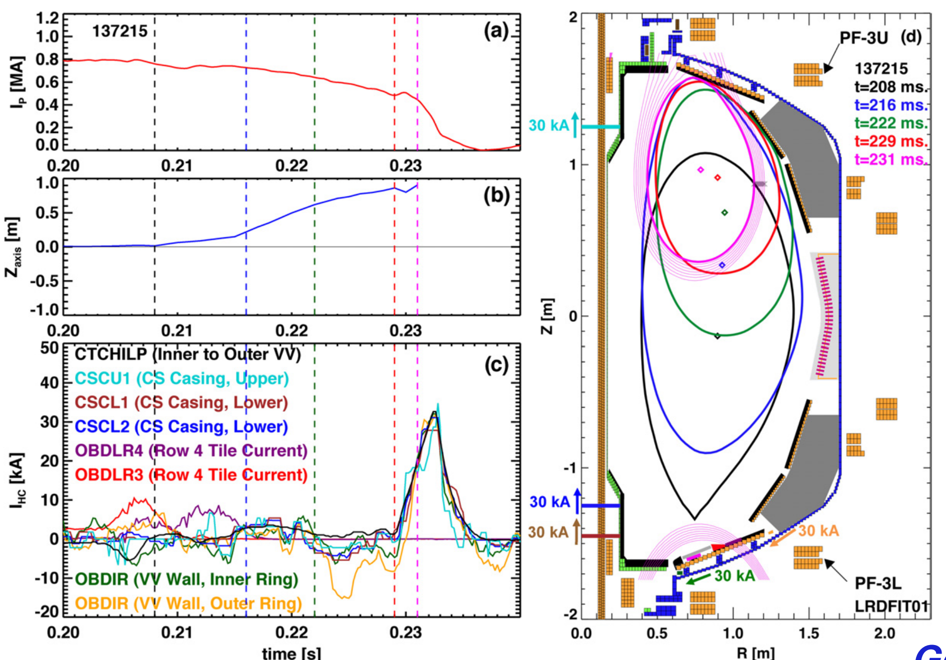

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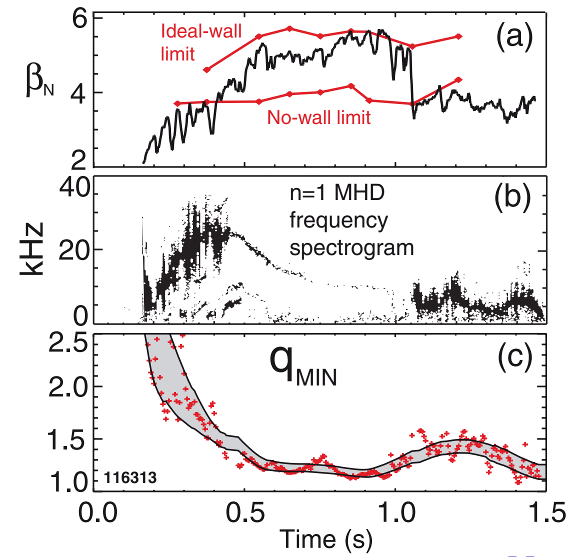

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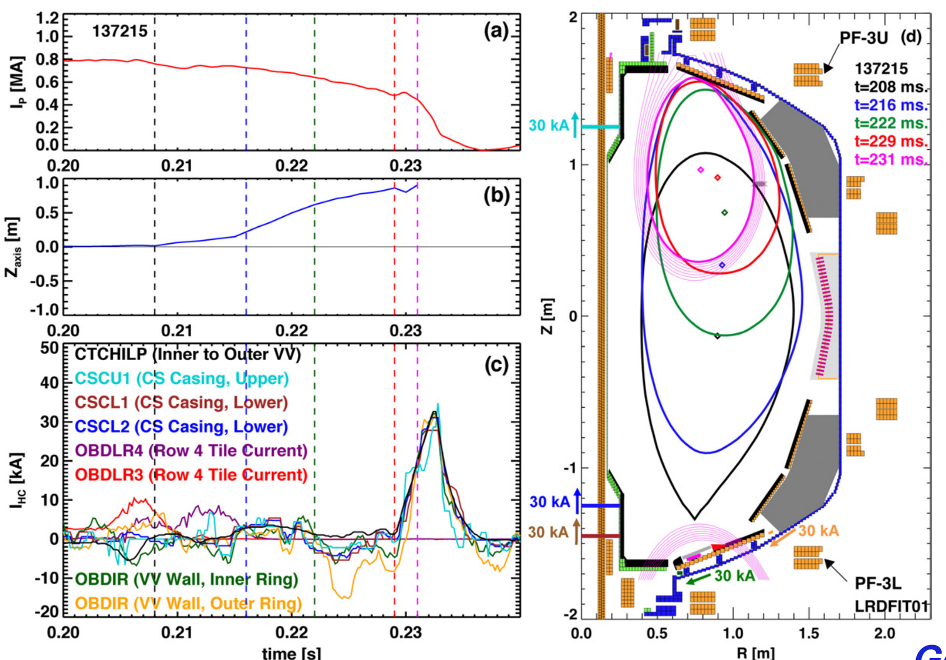

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  - VDEs can lead to halo currents having up to 80 kA on the wall (downward)

Can we develop an understanding of the sources and ramifications of these β limiting processes?

THEORY: *M3D-C*[1] *used to study both types of beta limiting processes*

- M3D-C[1] affords unique opportunity to study of stability on transport time scale for realistic η
- Linear/Non-linear, 2D/3D
  - Used for scoping control systems, transport models, etc.
  - Very well benchmarked against NIMROD for ideal & resistive stability
  - Also against GATO, ELITE

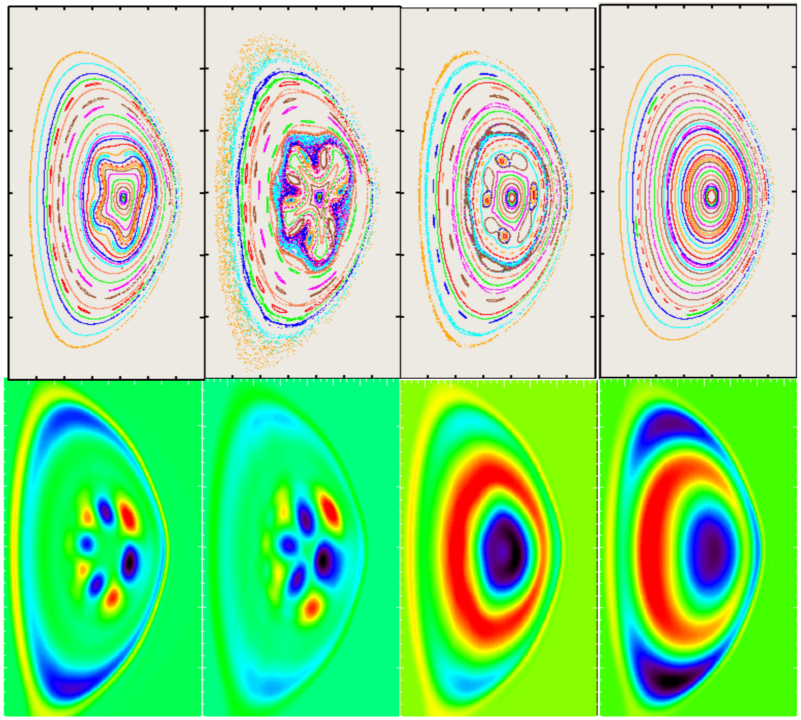
Poincare plots

3D Non-linear simulation of soft β limit

- As β limit is exceeded in center, surfaces deform, become stochastic, then heal
- First, pure n=3 (4/3 resonance), then non-linear, finally axisymmetric torus
- Net effect is enhanced transport

Jardin

ΔT_e



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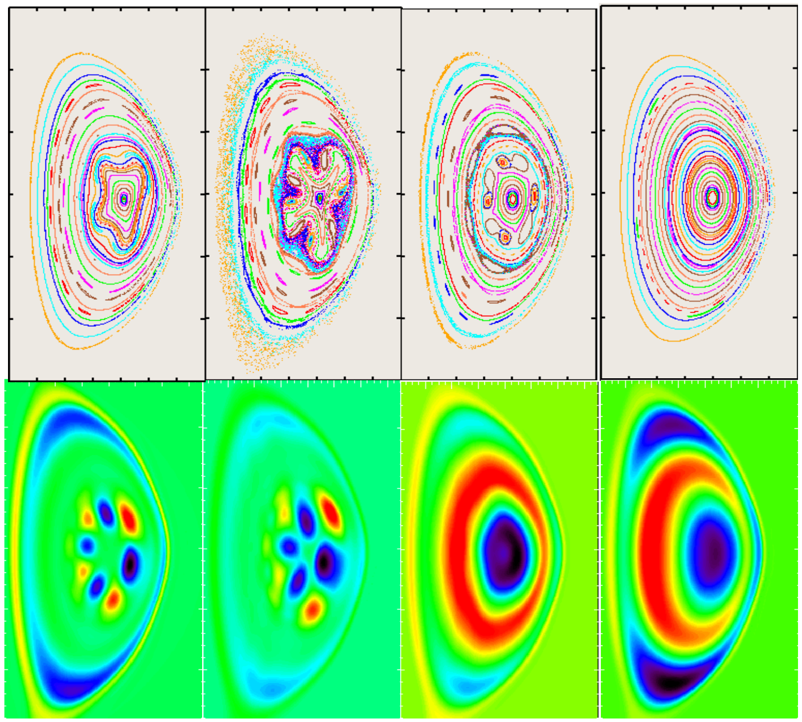

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Jardin

Future work: Perform calculations to determine effects of q-profile, rotation, etc. on modes

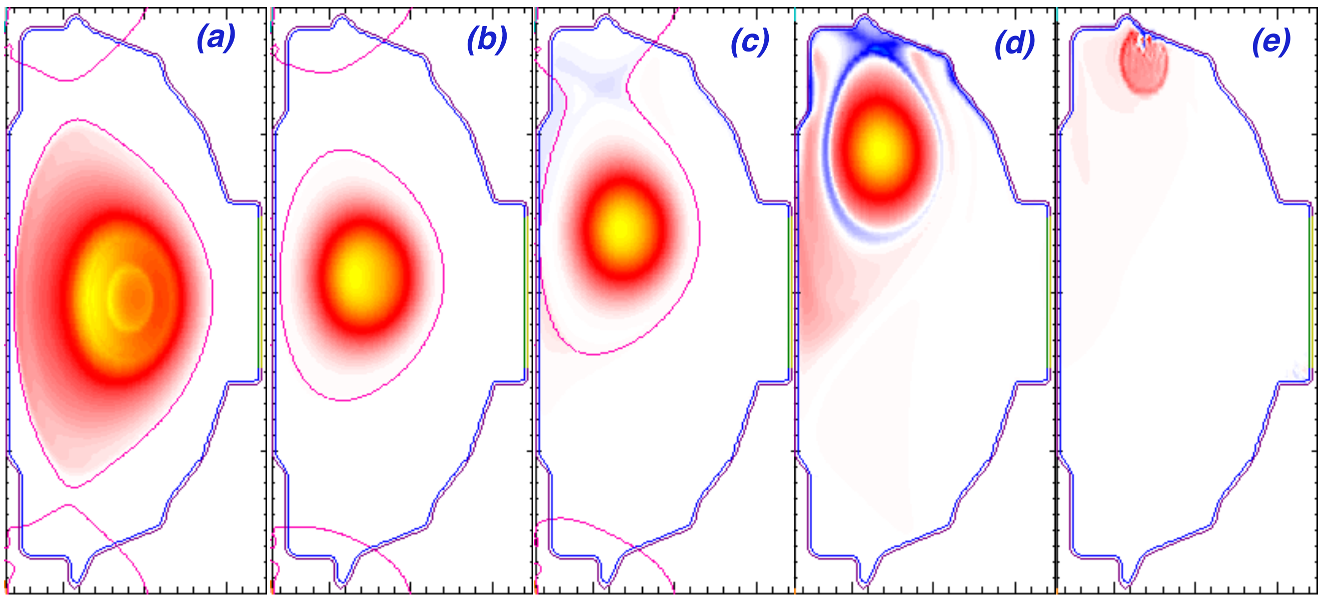
ΔT_e

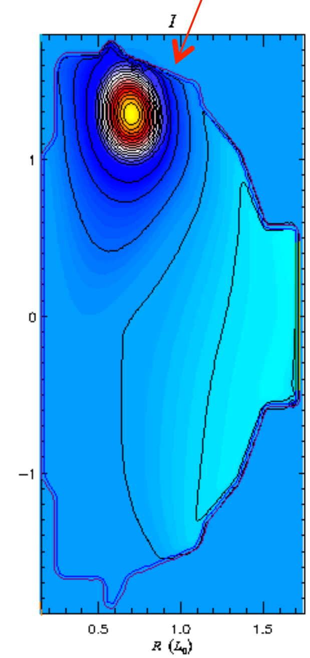
Simulations of VDEs have begun using M3D-C[1]

- Initial simulations from 2D low resolution calculation
  - Benchmark against earlier TSC results
- New capability is finite thickness wall

Note halo currents

Toroidal Current Density Evolution





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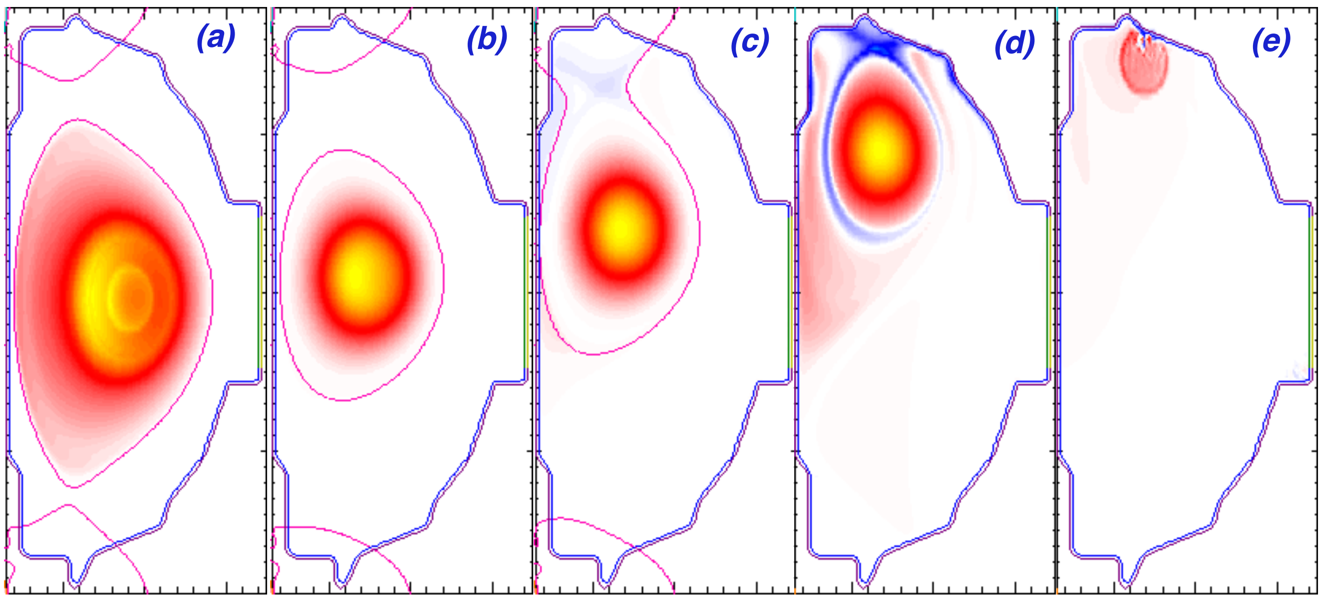

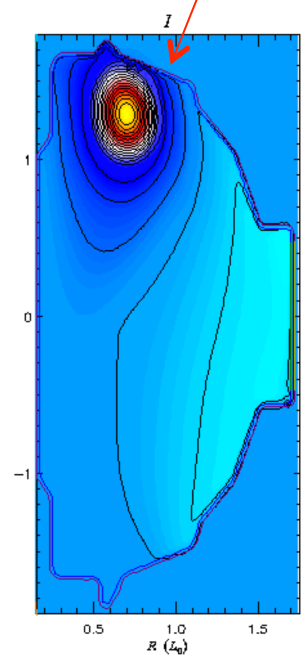

Jardin

<u>Future work: </u>Extend to 3D and realistic η to compute non-axisymmetric halo current distribution for validation against experimental measurements

JRT-16: Assess MGI disruption mitigation, disruption detection and avoidance

- Study gas assimilation efficiencies for MGI injection from multiple poloidal locations and evaluate impacts on divertor heat loads and halo currents
  - XGC1/DEGAS-2 to determine amount and distribution of radiation, runaway electron current, resulting edge profiles
  - M3D-C^1 to determine the dynamics of the MHD modes and their interactions with (e.g.) halo currents
- Develop algorithms for real-time MGI triggering based on disruption warning system such as locked mode sensors, state-space observers and RFA
  - Couple M3D-C^1 to a wall current code for designing sensors/probes, followed by verification and validation when NSTX-U starts to operate
  - Resistive wall/RFA capability has been added to M3D-C^1 (N. Ferraro/S. Jardin)
    - NSTX cases being studied

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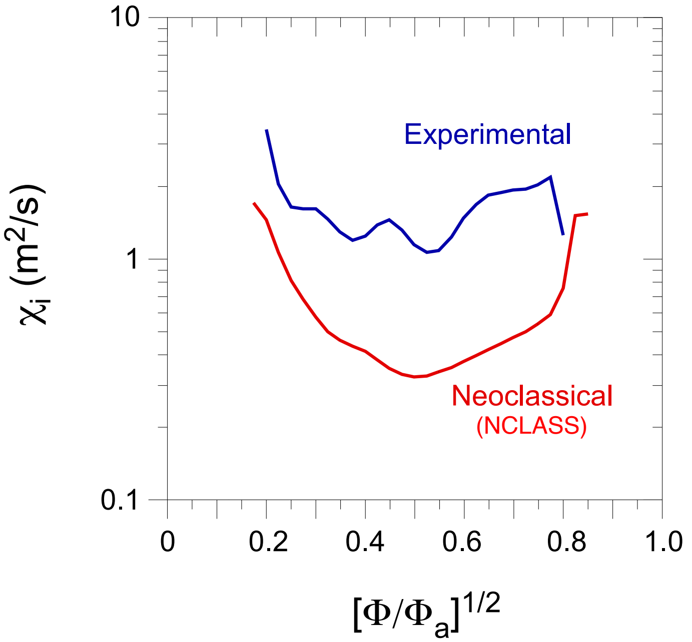
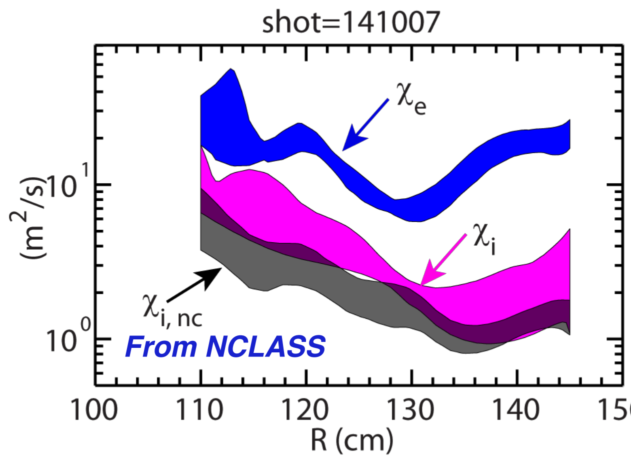
***EXP'T*: Source of anomalous transport in L- and H-modes**

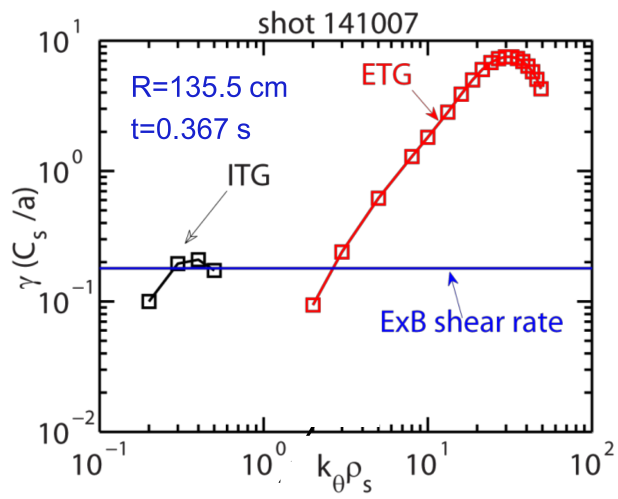
- **Ions**: Anomalous in L-mode, ~neoclassical in H-mode
- **Electrons**: R/L_{Te}-driven ETG (low β), microtearing (high ν_e*) in L and H

L-mode



H-mode





Ren

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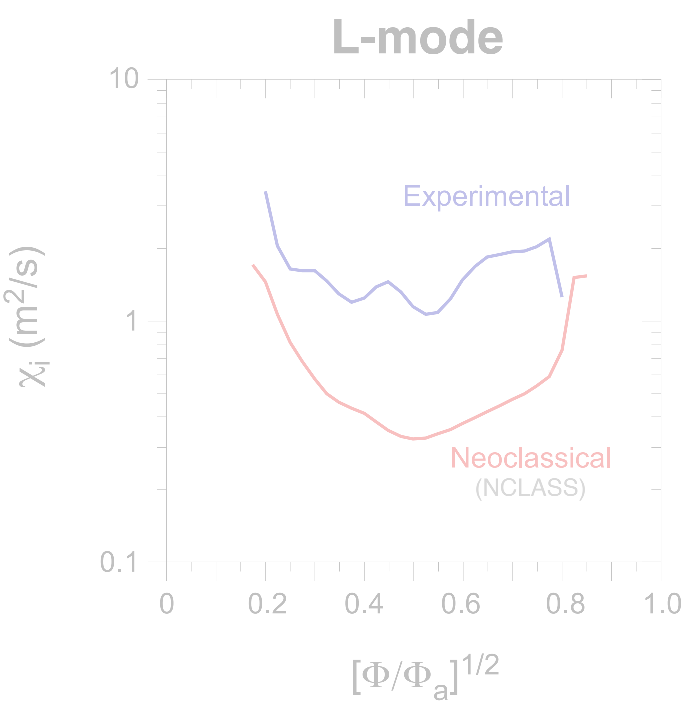
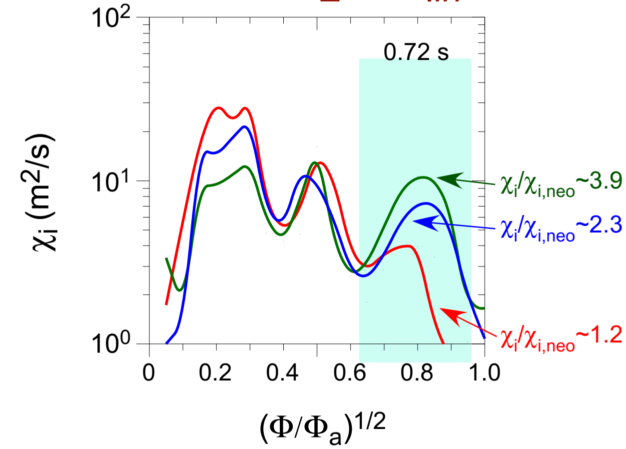
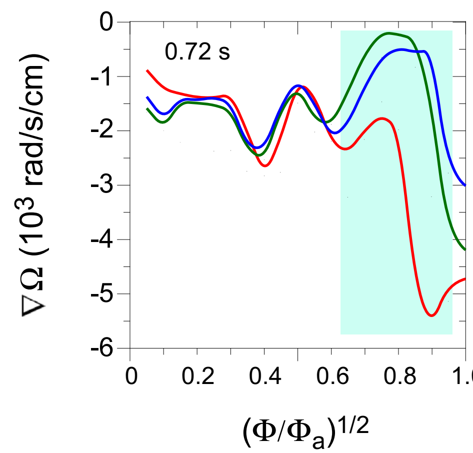


- Strong v_ϕ (ExB) shear can suppress low-k (ITG/TEM) instabilities (γ_E>>γ_{lin} from GK)





Kaye

H-mode

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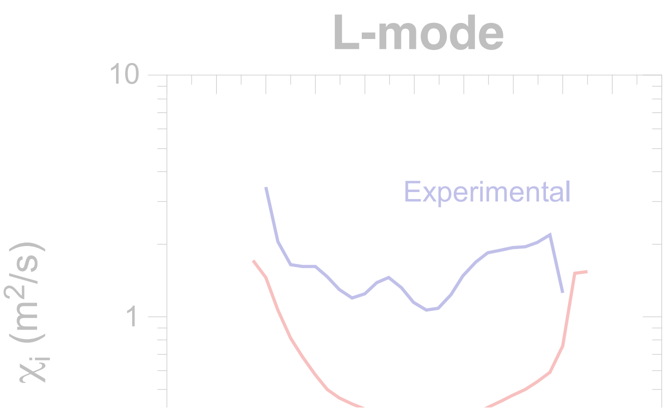
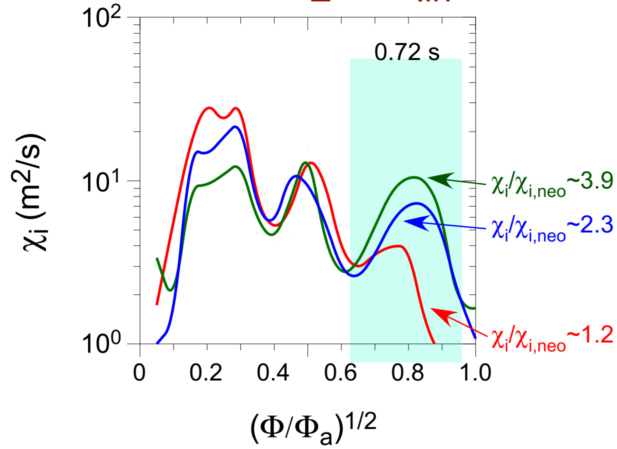
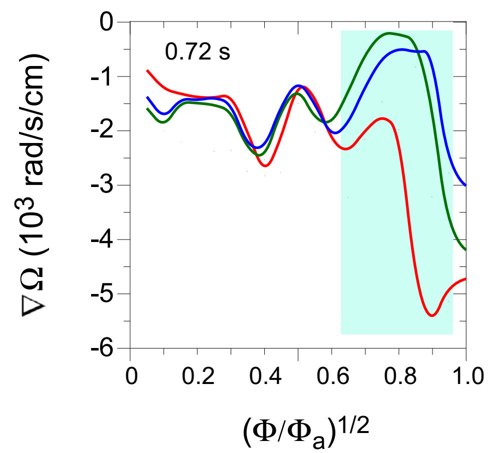


Can global gyrokinetic simulations shed more light on the transport processes with the relatively large scales and large ExB shears in low-B_T in NSTX plasmas?

- Strong v_ϕ (ExB) shear can suppress low-k (ITG/TEM) instabilities ($\gamma_E >> \gamma_{lin}$ from GK)

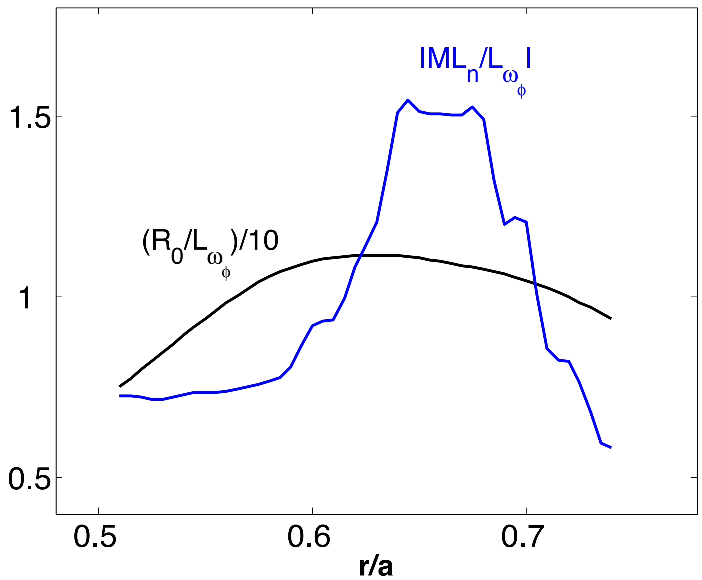


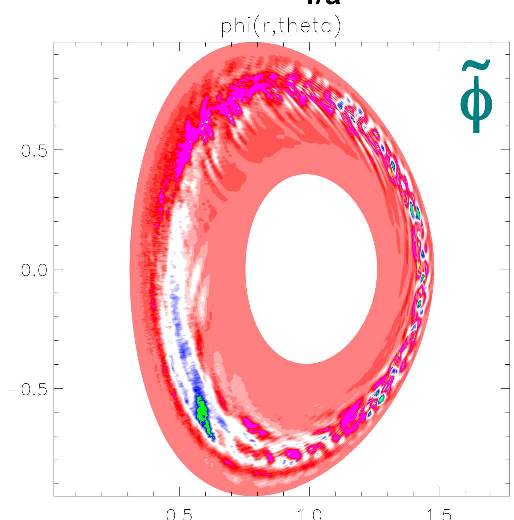


Kaye

H-mode

THEORY: Strong flow shear can destabilize Kelvin-Helmholtz instability

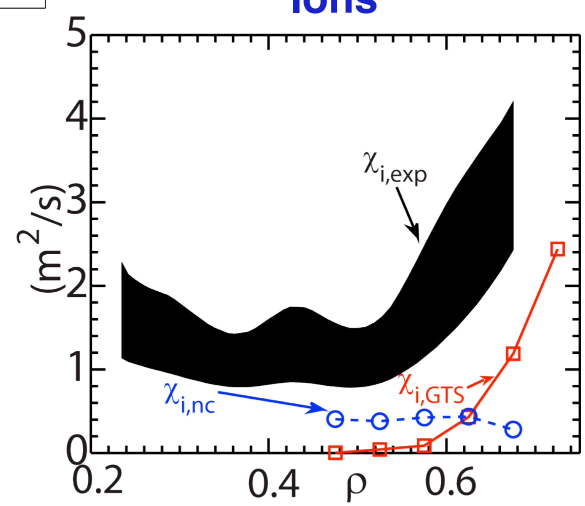




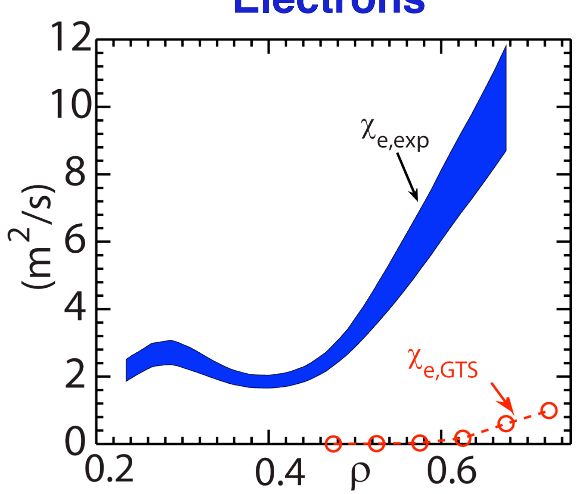
Wang

- Linear theory: $|ML_n/L_\omega|>1$ for instability
  - Non-linear global GTS simulations reveal presence of K-H in L-mode
  - K-H identified in simulation by finite $k_{||}$
- K-H/ITG + neo ion transport within factor of ~2 of expt'l level
  - e^- transport seriously underestimated

Ions



Electrons



Future Work: K-H in H-mode $\nabla n, \nabla T$-driven DTEM as source of collisionality scaling in H-mode

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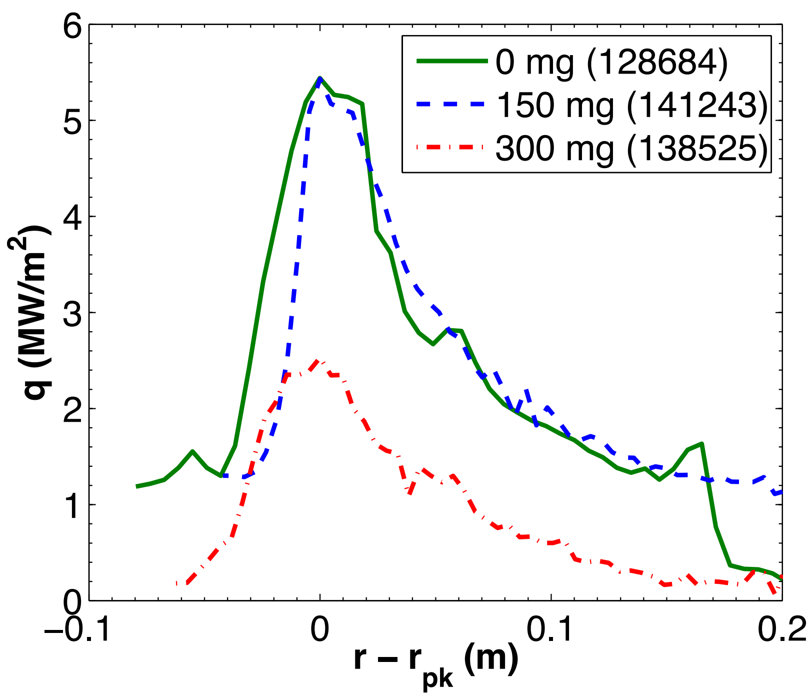
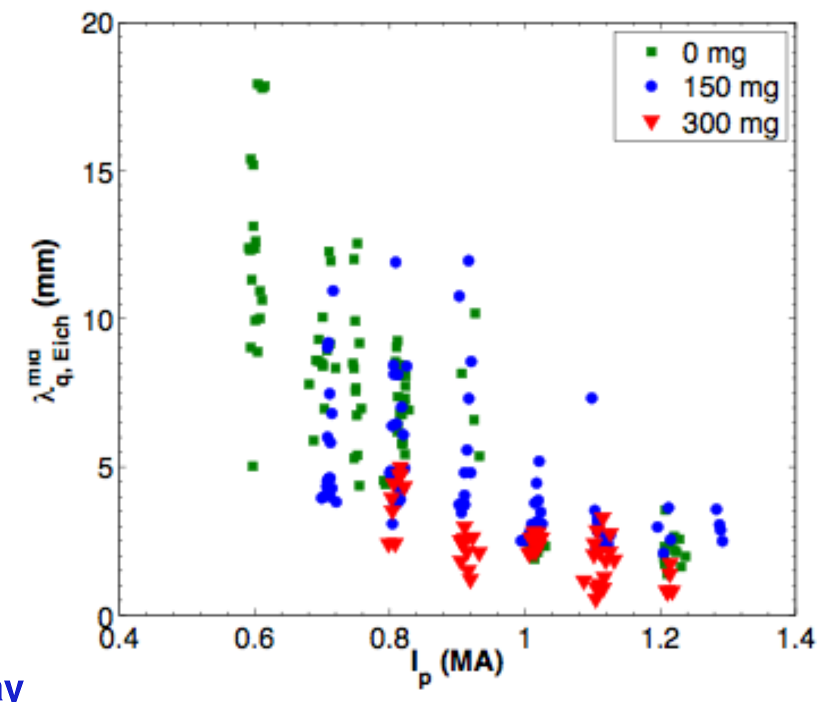
EXP'T: SOL heat flux width shows strong dependence on plasma current

- Li wall conditioning impacts heat flux width and magnitude
- Strong **contraction** of SOL heat flux width at midplane with I_p

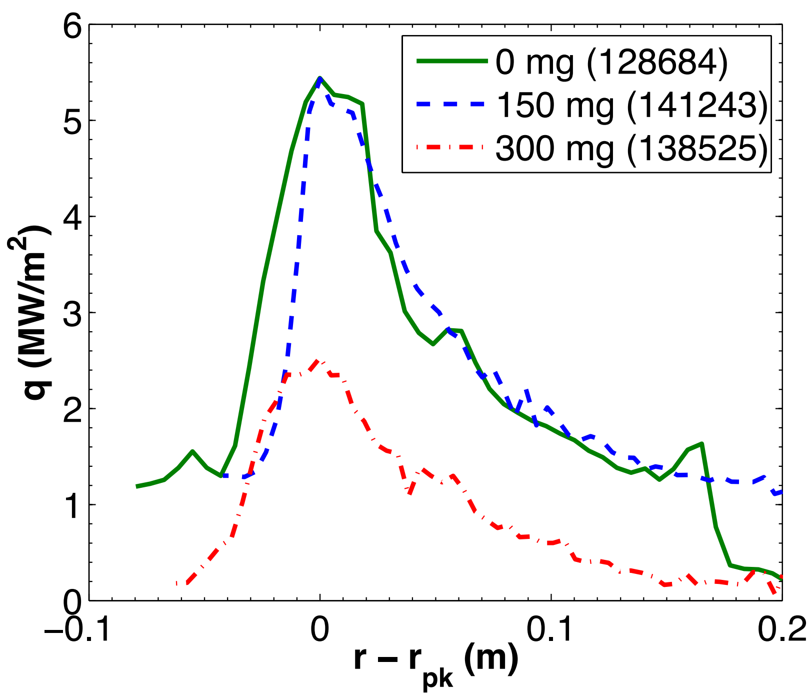


Gray



EXP'T: SOL heat flux width shows strong dependence on plasma current

- Li wall conditioning impacts heat flux width and magnitude
- Strong **contraction** of SOL heat flux width at midplane with I_p



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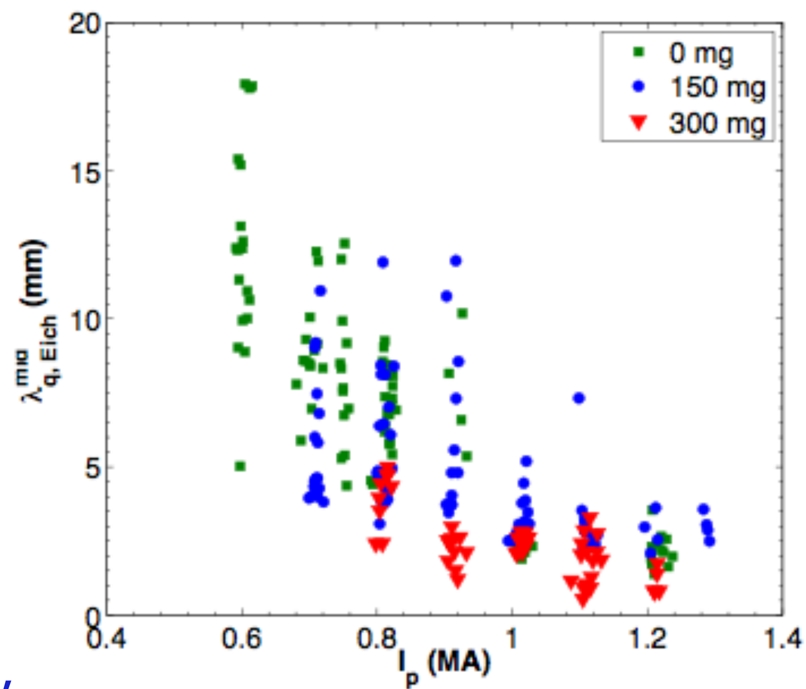


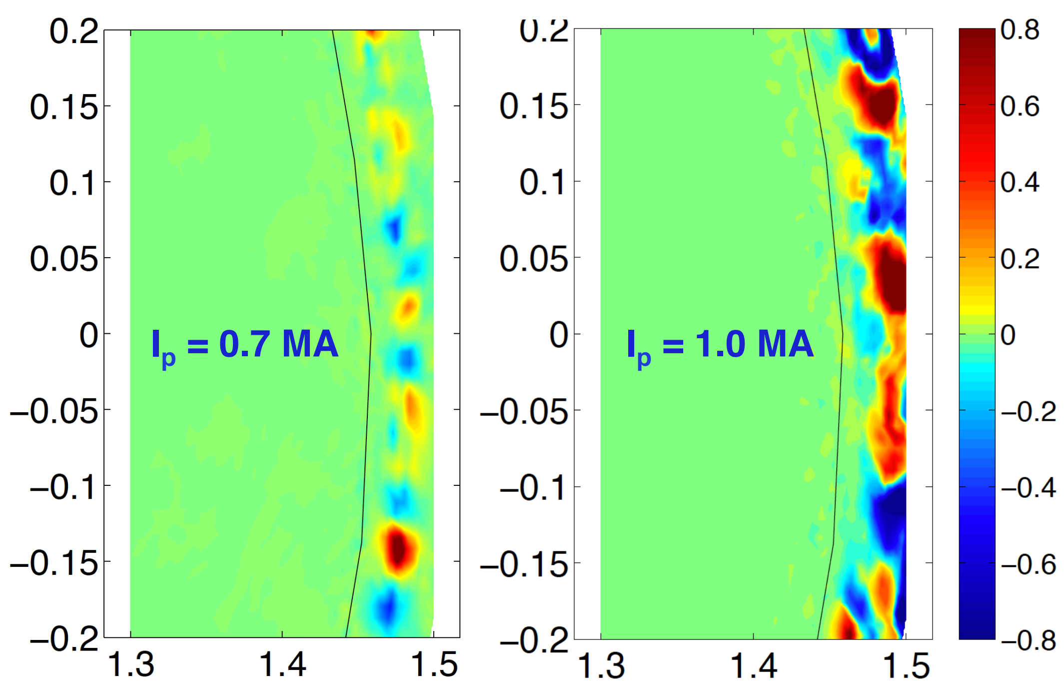
What is the underlying physics setting the SOL heat flux width and its scaling with I_p?

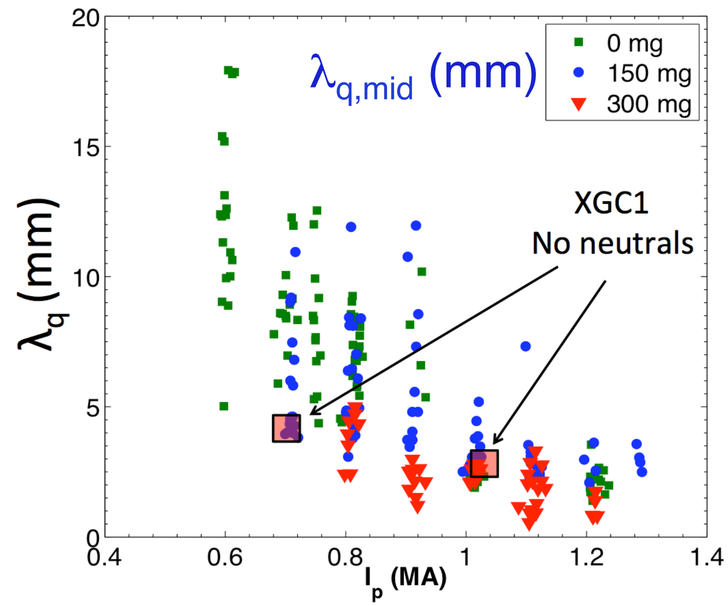
Theory: Collisionless XGC1 simulations indicate that the SOL heat flux width is set primarily by neoclassical processes

- XGC1 (collisionless) predicts "blob" related turbulence
- Blobs are stronger in SOL than in pedestal, and they are stronger at higher I_p

- Blobs do not appear to widen the heat load width above the neoclassical width ($\sim\Delta_{banana} \sim 1/I_p$ from XGC0)
- Predicted variation of $I_p^{-0.8}$ is consistent with observation (for 300 mg Li dep.)

300 mg Li deposition





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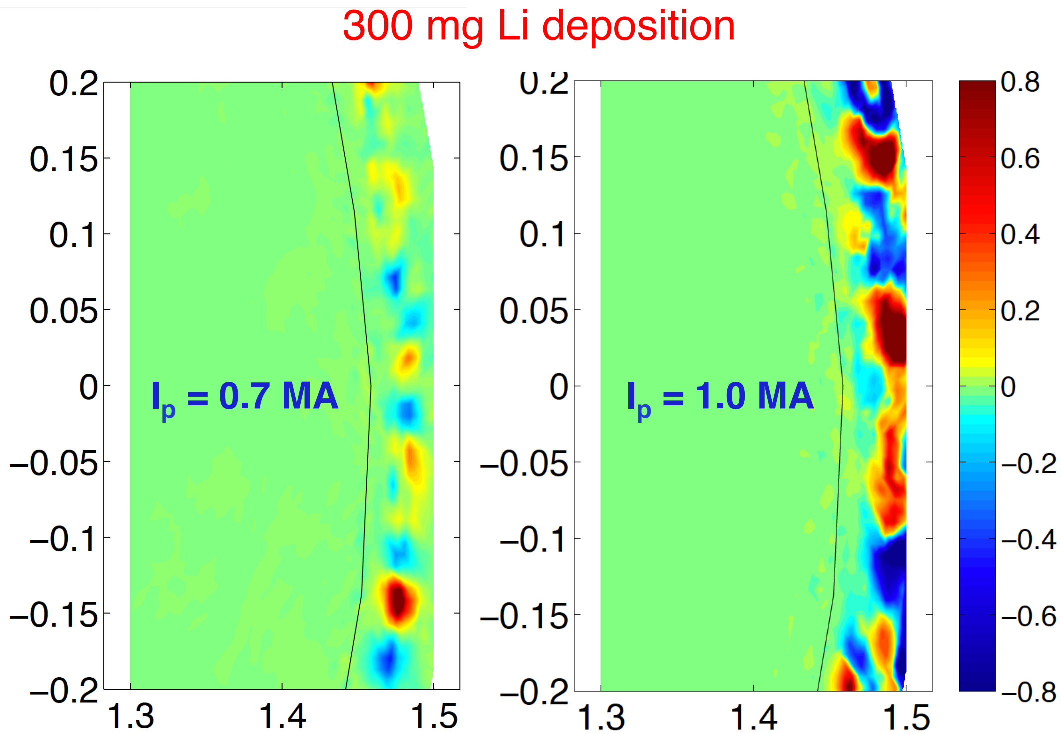
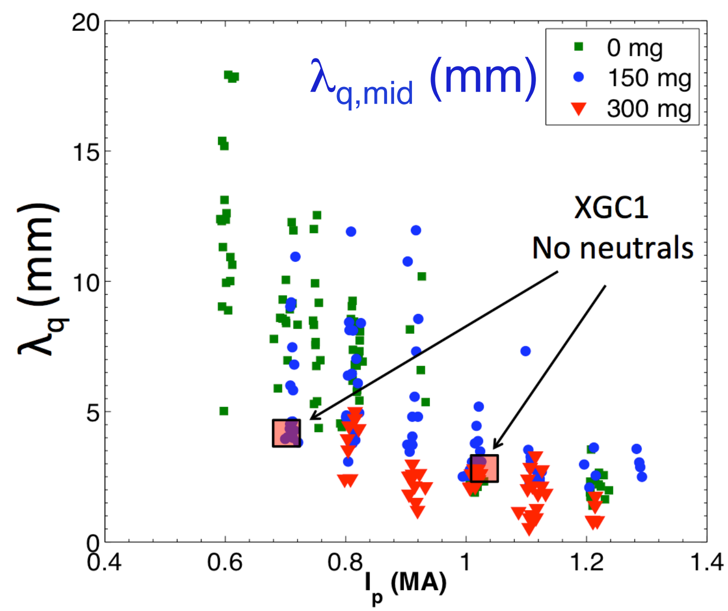




Future Work: Extend to finite collisionality and recycling to determine effect on SOL λ_q

NSTX(-U)/PPPL Partnership is focusing on issues critical to understanding ST physics and projecting to future devices

- Targeted funding from DOE has allowed for participation by a critical mass of people, and critical fraction of each person
- Theory integrated into NSTX physics results dissemination
  - Six theory-based NSTX contributions to IAEA
- Wish to continue effort (with cont'd incremental). High priority topics include:
  - **Macro**: Extend M3D-C^1 disruption studies to resistive 3D
  - **T&T**: Incorporate e-m effects into GTS, XGC-1 for microtearing
  - **EP**: Implement reduced model for fast ion transport in TRANSP
  - **Edge**: SOL heat flux widths from turbulence (XGC-1)
  - Leverage off theory work for experimental research planning
  - Expand integration of experimentalists into theoretical studies
    Enhanced synergy with DIII-D work (S. Jardin/N. Ferraro, W. Wang/C. Chrystal, C.S. Chang/D. Battaglia)

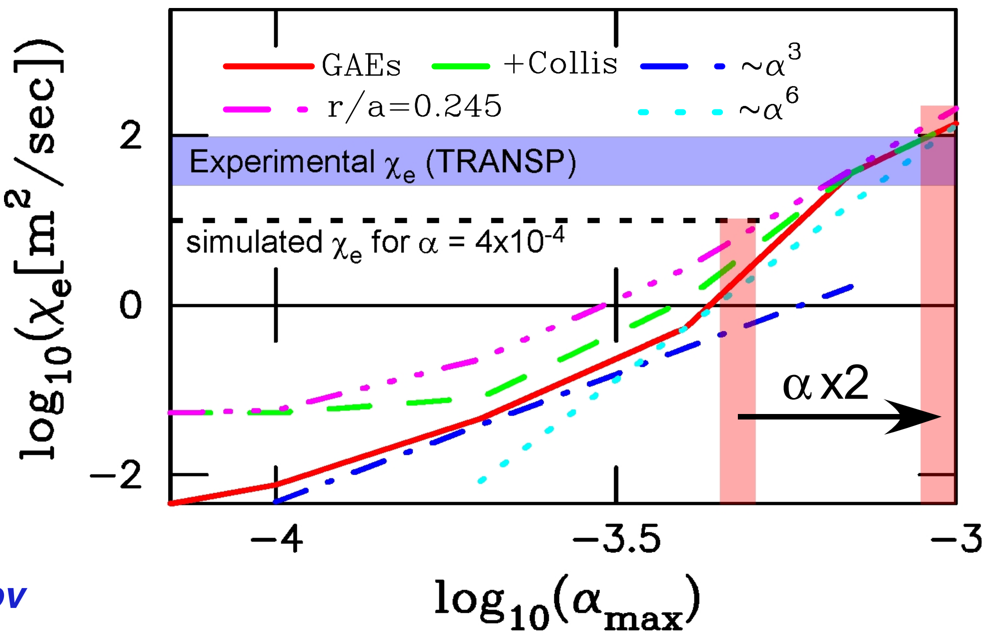
Backup Slides

THEORY: *Explore CAE/GAE induced transport levels*

- Initial studies focused on direct impact of modes on electron transport
  - Radial mode amplitude profiles taken from scattering, BES measurements
  - Electron transport inferred from ORBIT calculations in which amplitude of modes was varied

- α parameter related to $\delta n/n$
- $\alpha=4\text{x}10^{-4}$ corresponds to $\delta n/n\sim 10^{-3}$
- Modes bursting: max amplitudes may be 2 to 3x greater
- Brings inferred transport up to experimentally inferred values

Simulated electron thermal transport

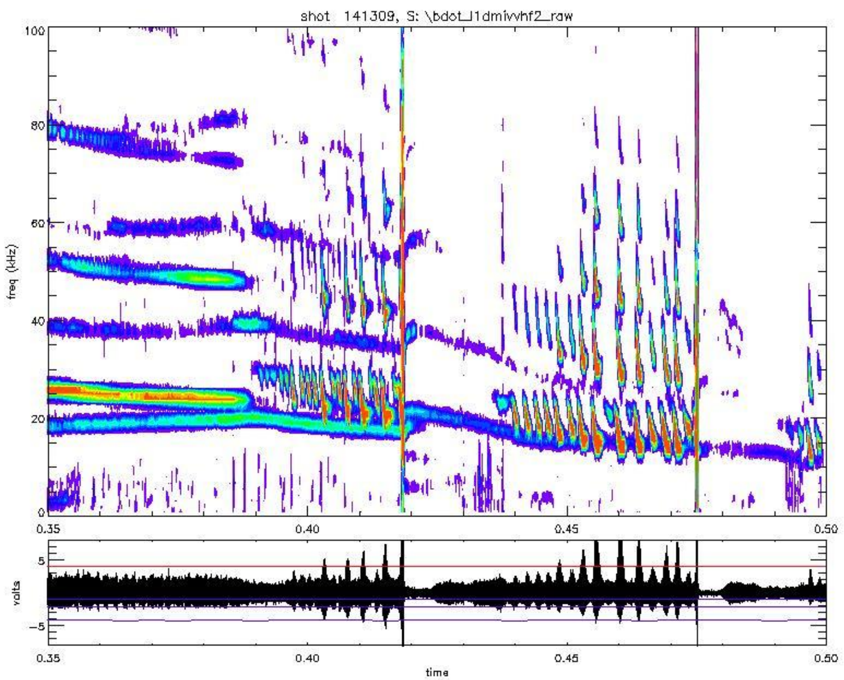


Gorelenkov

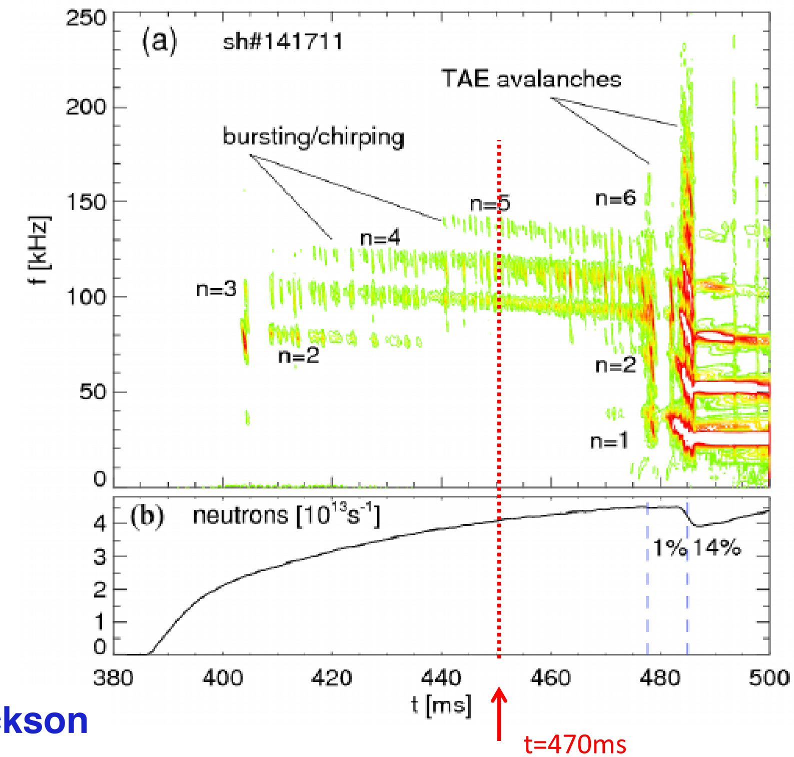
EXP'T: *Strong kink/Alfvén activity driven by NBs in NSTX*

- Expect similar activity in NSTX-U
- Can impact beam current drive profiles (positively or negatively) and goal of achieving 100% non-inductive ops

Kink/fishbone modes

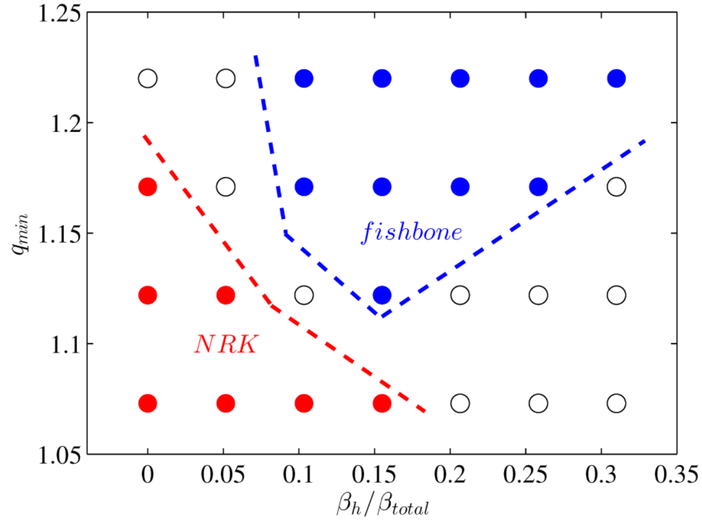


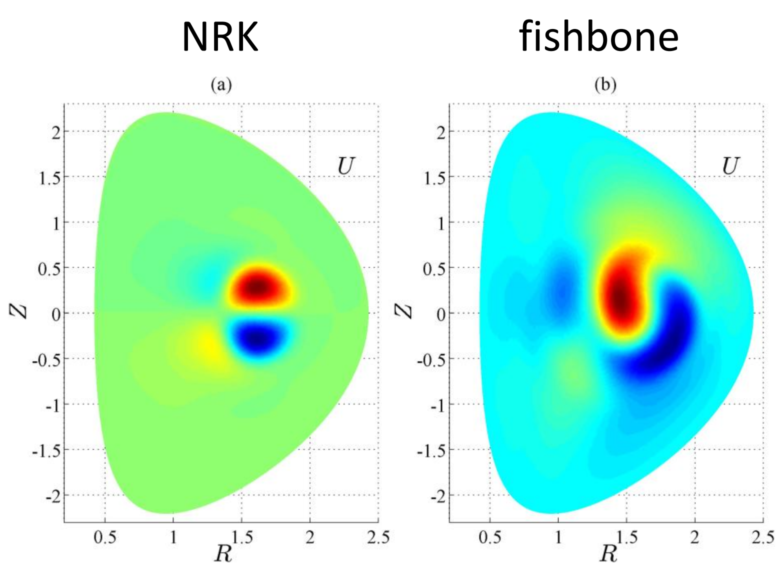
TAE modes/avalanches



Fredrickson

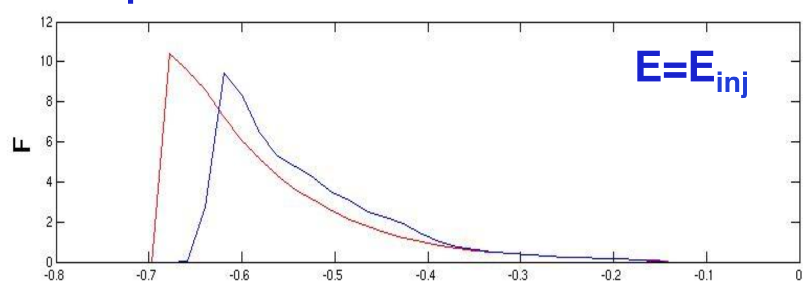
THEORY: *Physics of modes and impact on fast ion distribution*





- M3D-K to model modes and resulting fast ion transport
- Good agreement between model results and measured mode structure (radial, frequency)
- Substantial fast ion transport from kinks/fishbones/TAEs

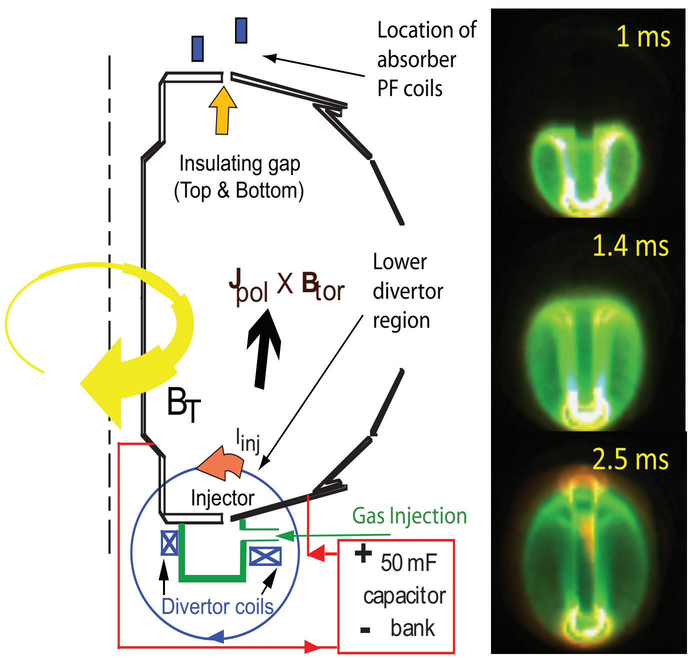
Multiple TAE-induced fast ion redistribution

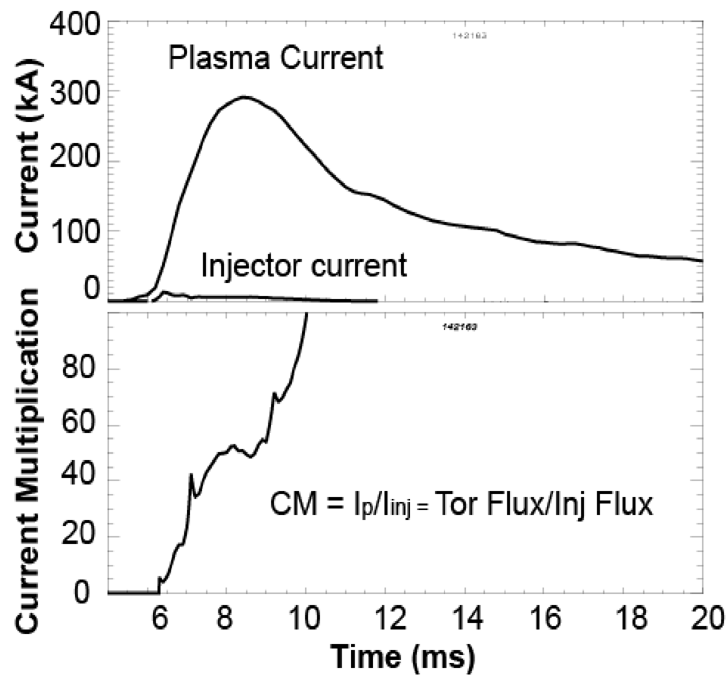


Fu

EXP'T: Non-inductive current startup

- Critical issue for fully non-inductive operation in next-step STs
- Co-axial Helicity Injection being studied on NSTX
- CHI has produced up to 300 kA startup current with large current multiplication factor (I_p/I_{inj})
  - Successfully coupled to induction for ramp-up



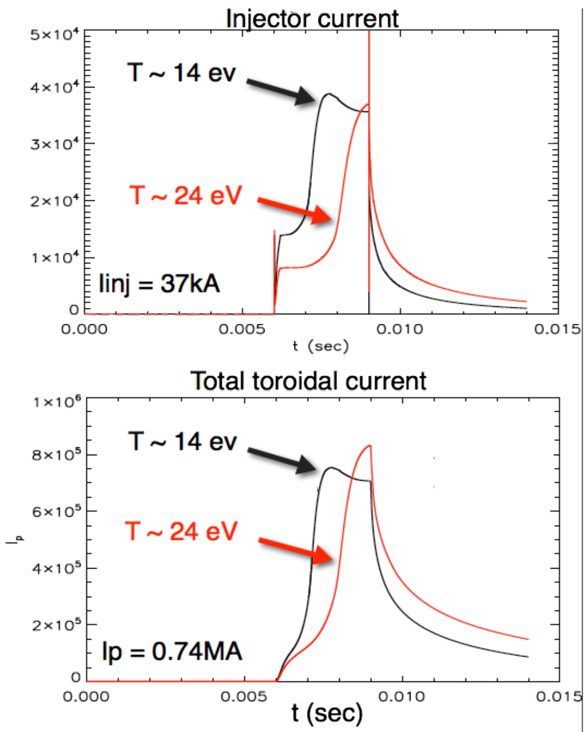


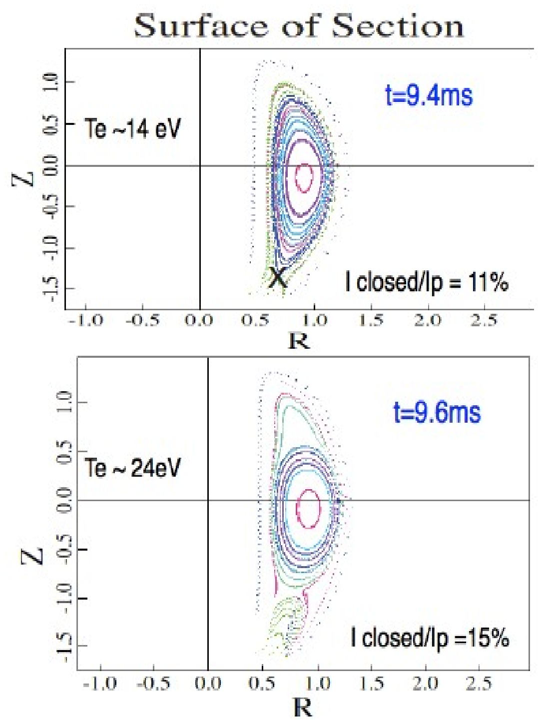
Raman

THEORY: Understand reconnection physics to extrapolate CHI performance to next-steps

- Resistive simulations have been performed using the extended-MHD NIMROD code

- Simulations with magnetic diffusivities similar to expt produce flux closure
- Flux closure/plasma current scales with injector voltage time decay, flux footprint as in experiment
- Simulations indicate Sweet-Parker type reconnection
  - Elongated current sheet
  - Current sheet width
  - Inflow/outflow





Ebrahimi

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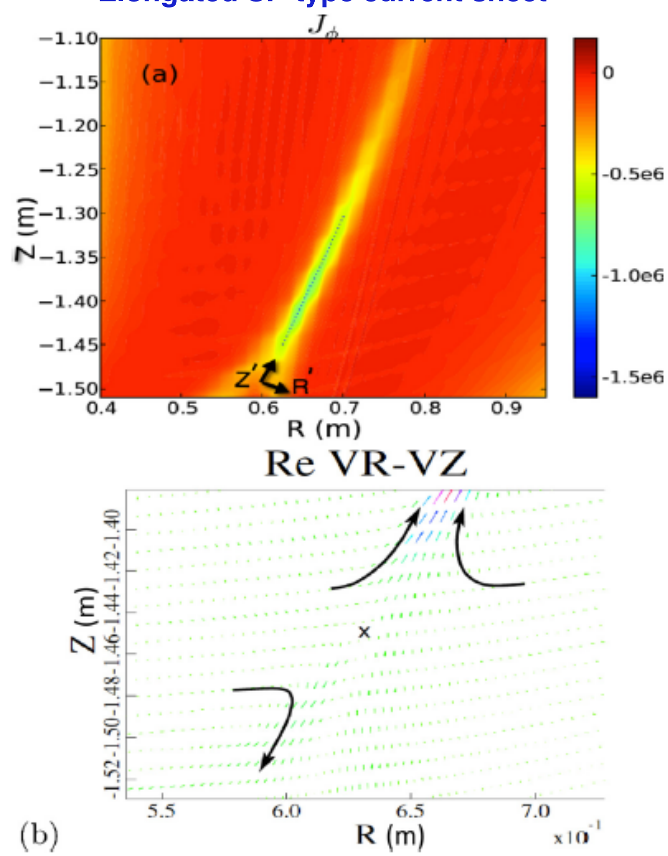
Elongated SP-type current sheet



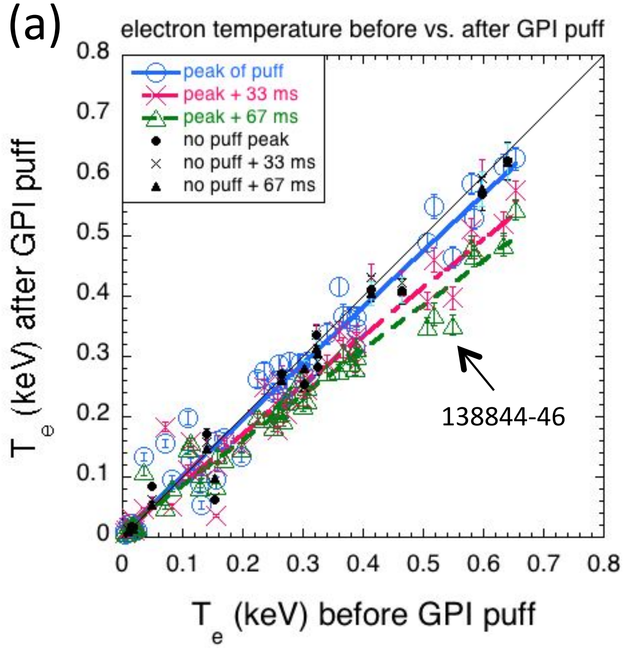
Ebrahimi

EXP'T: Knowledge of the thermal neutrals is critical to edge and core physics

- Thermal neutral density profiles impact: NB power deposition, fast ion c-x efflux to wall, drag on rotation/ZFs

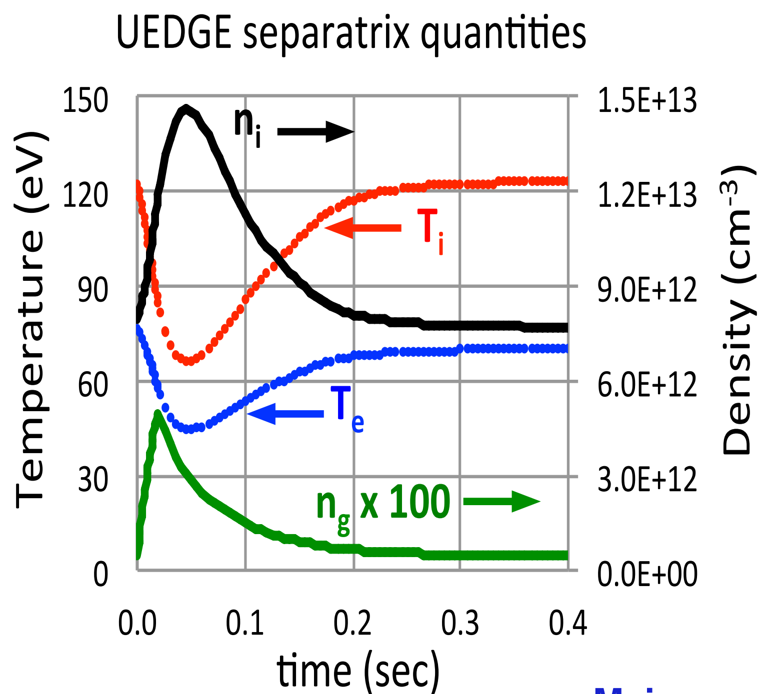
- GPI gas puff leads to small effect in edge temperature and density
  - No immediate effect
  - Slow change inside location of Δn_0

(a)



Zweben

- UEDGE simulations indicate immediate changes in n, T should be observed

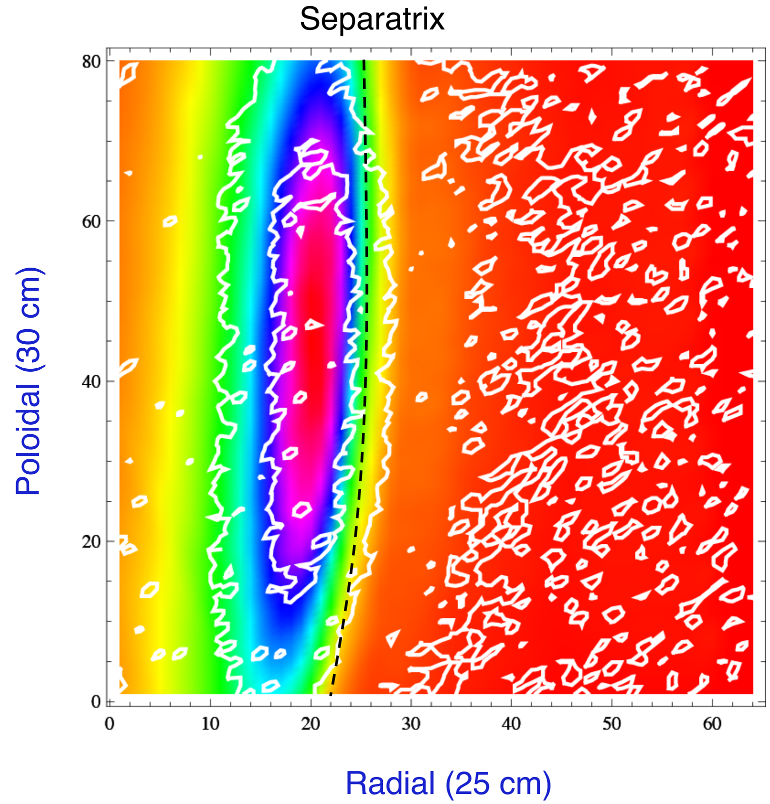


Meier

THEORY: Detailed DEGAS-2 simulations agree with the GPI results

- 3-D simulations input EFIT, n_e, T_e, n_D and gas puff rate from GPI
- Simulated power loss due to puff atomic physics negligible
  - Electron loss: 21 kW, Ion loss: 4 kW
  - Consistent with small effect on profiles
- Basis for understanding difference between DEGAS-2 and UEDGE results (study ongoing)

2D GPI light emission: expt'l contours (white) superimposed on DEGAS2 simulation results



Stotler