MHD, Transport and Boundary Studies and the Development of Integrated High-Performance Scenarios in NSTX

Supported by Office of Fusion Energy Sciences, Office of Science

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for the ***NSTX Research Team***

4th IAEA Technical Meeting on Spherical Tori & 14th International Workshop on Spherical Torus

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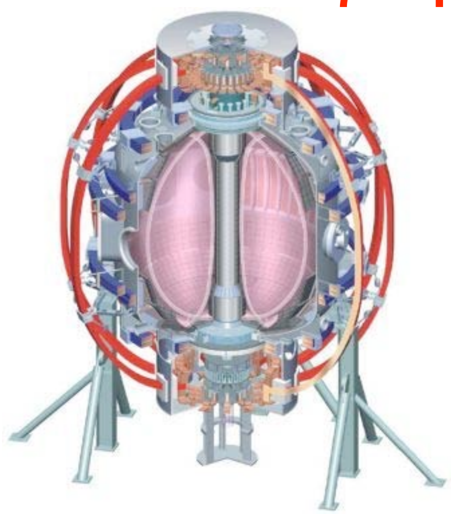
7 – 10 October 2008



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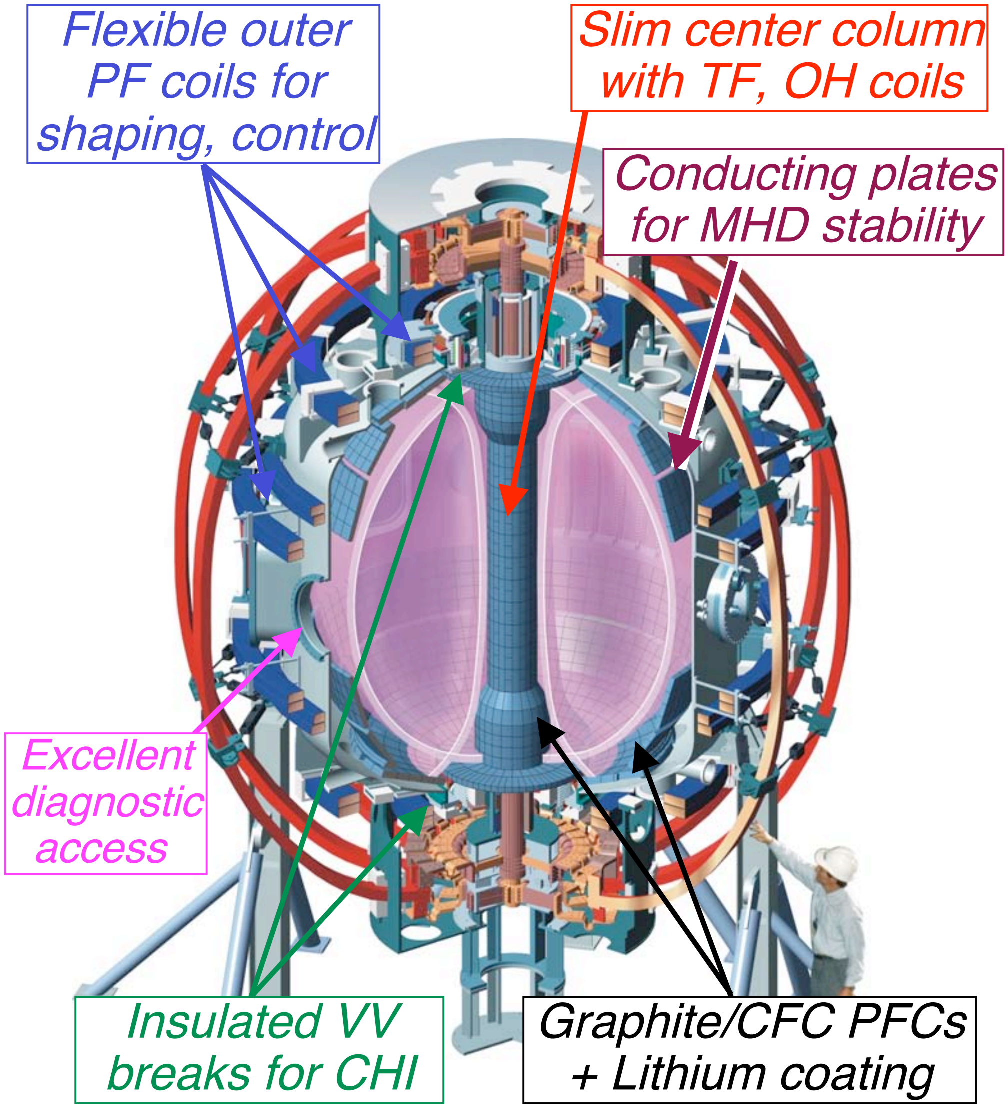
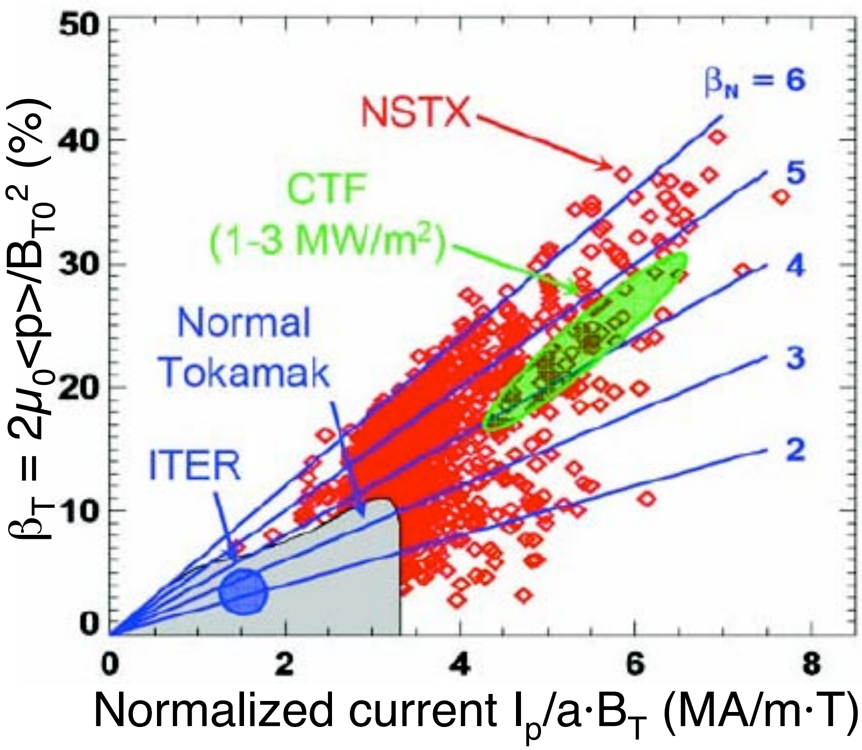
NSTX Designed to Study High-Temperature Toroidal Plasmas at Low Aspect-Ratio



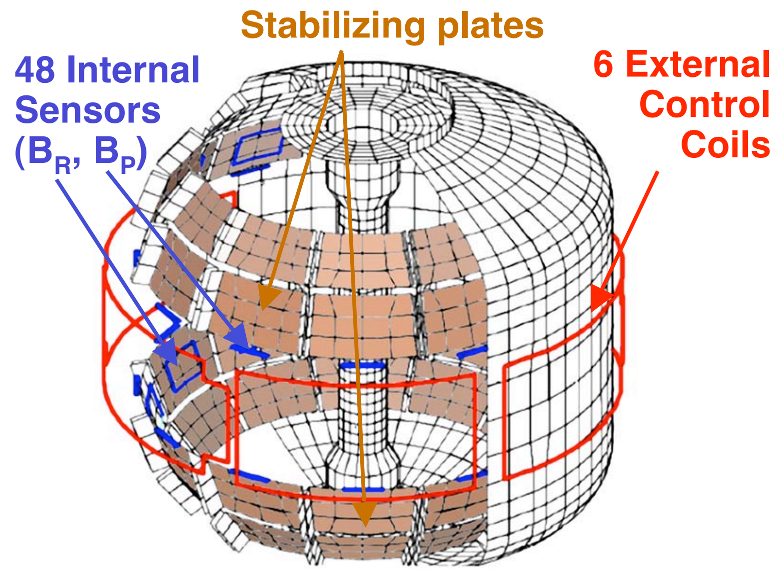
Aspect ratio A	1.27 – 1.6
Elongation κ	1.8 – 3.0
Triangularity δ	0.2 – 0.8
Major radius R_0	0.85m
Plasma Current I_p	1.5MA
Toroidal Field B_{T0}	0.4 – 0.55 T
(Pulse Length	~2 – ~1 s)
Auxiliary heating:	
NBI (100kV)	5 – 7 MW
(Pulse Length	5 – 2 s)
RF (30MHz)	6 MW (5 s)
Central temperature	1 – 5 keV
Central density	$\leq 1.2\times10^{20}m^{-3}$

MHD Studies Have Focused on Maintaining High Normalized-β Using Midplane Correction Coils

NSTX has demonstrated
high β_T and β_N transiently



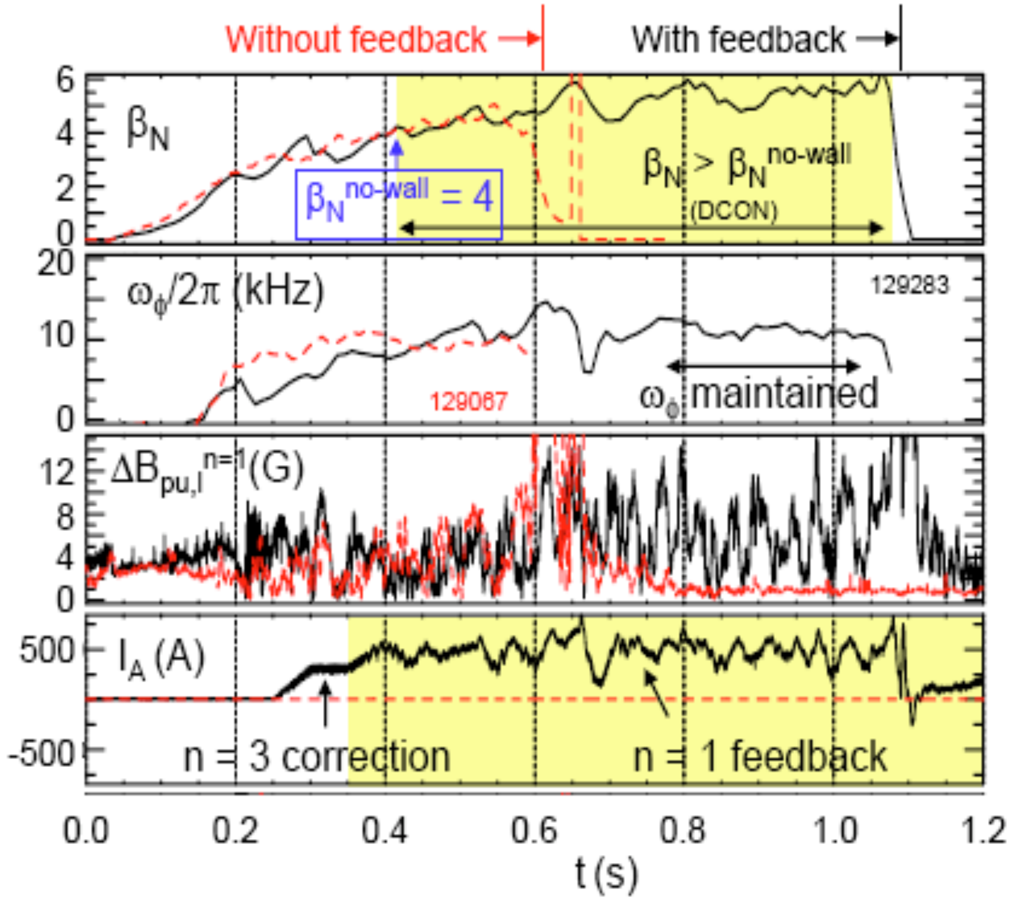
Non-axisymmetric coils provide capability
to extend high-β beyond wall time



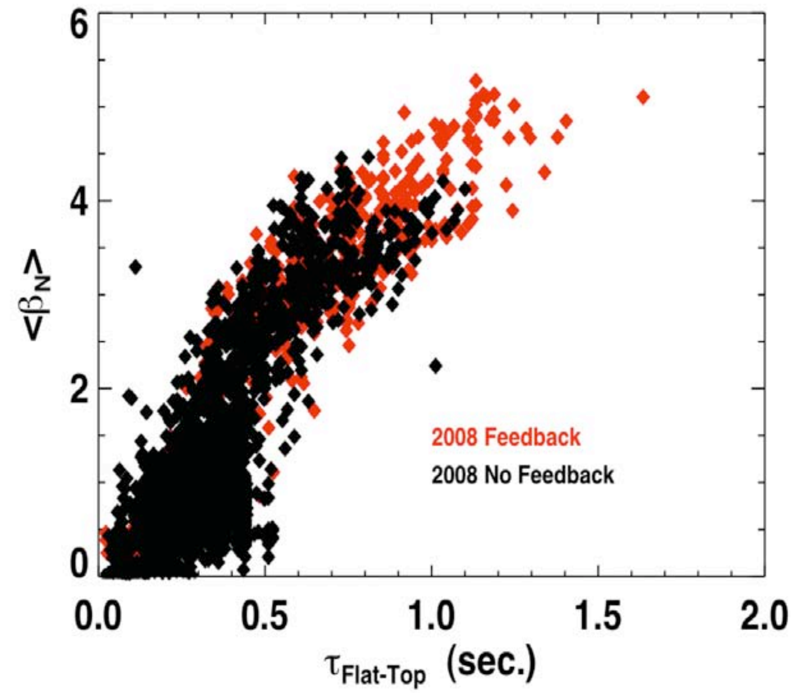
Coils powered by 3 Switching Power Amplifiers (3.5kHz, 1kA)
- Apply n = 1 & 3 or 2 (4) fields

- Experiments have attempted to optimize benefits of
  - Stabilization of external modes by conducting plates
  - Correction of intrinsic field errors which damp plasma rotation
  - Resonant Field Amplification and growth of Resistive Wall Modes

Correction of n = 3 Error Field Plus Feedback Control of n = 1 Mode Reliably Extends Duration of High-β_N Plasmas



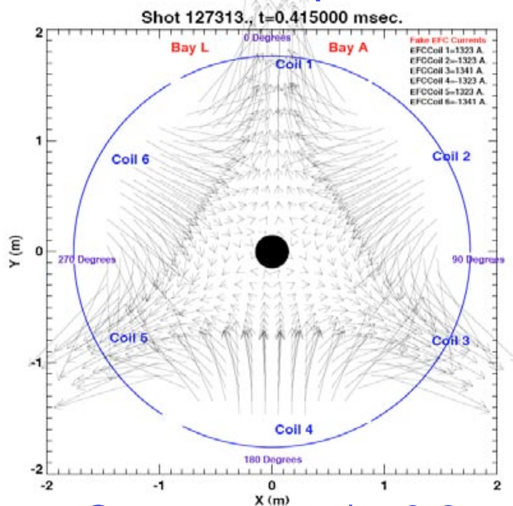
Optimized feedback scheme
<u>applied routinely in 2008</u>



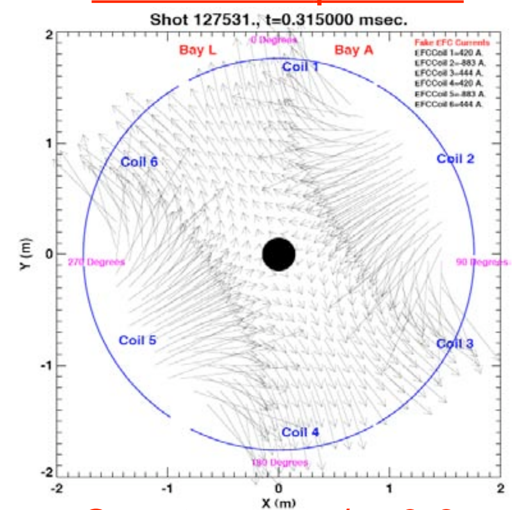
- Correction of n = 3 intrinsic error field maintains toroidal rotation
- Resistive Wall Mode can develop at high normalized-β: terminates discharge
- Feedback on measured n = 1 mode reliably suppresses RWM growth
  - Limitations on time response and applied mode purity explored for ITER

This Year, Compared Applied “Even Parity” to Previous “Odd Parity” Radial Field Perturbations

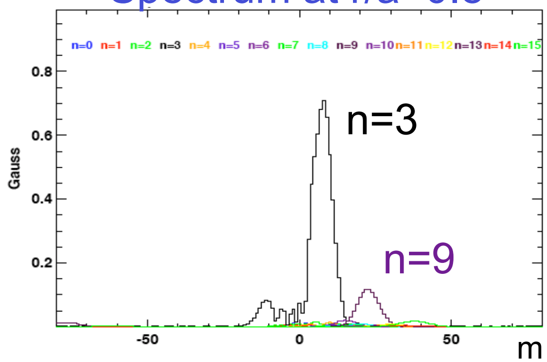
n = 3 field pattern



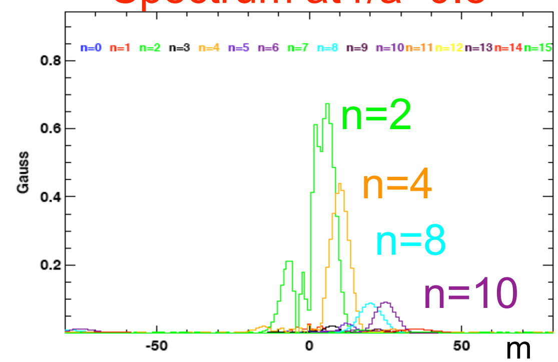
n = 2 field pattern



Spectrum at r/a=0.8



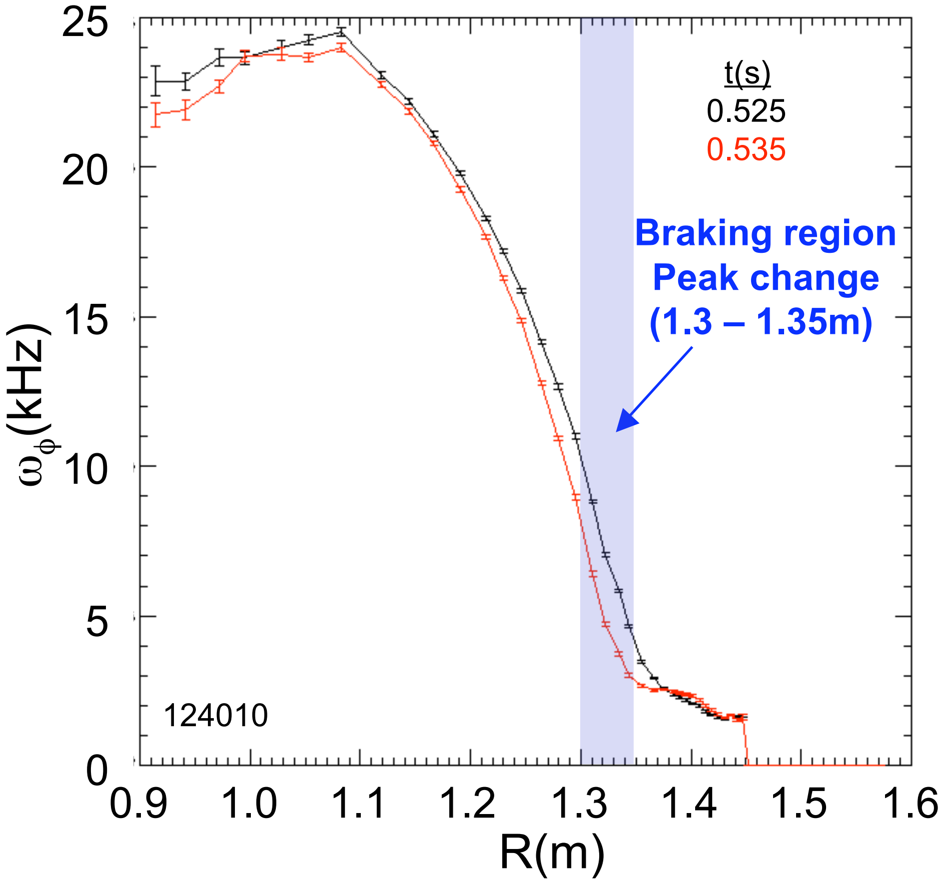
Spectrum at r/a=0.8



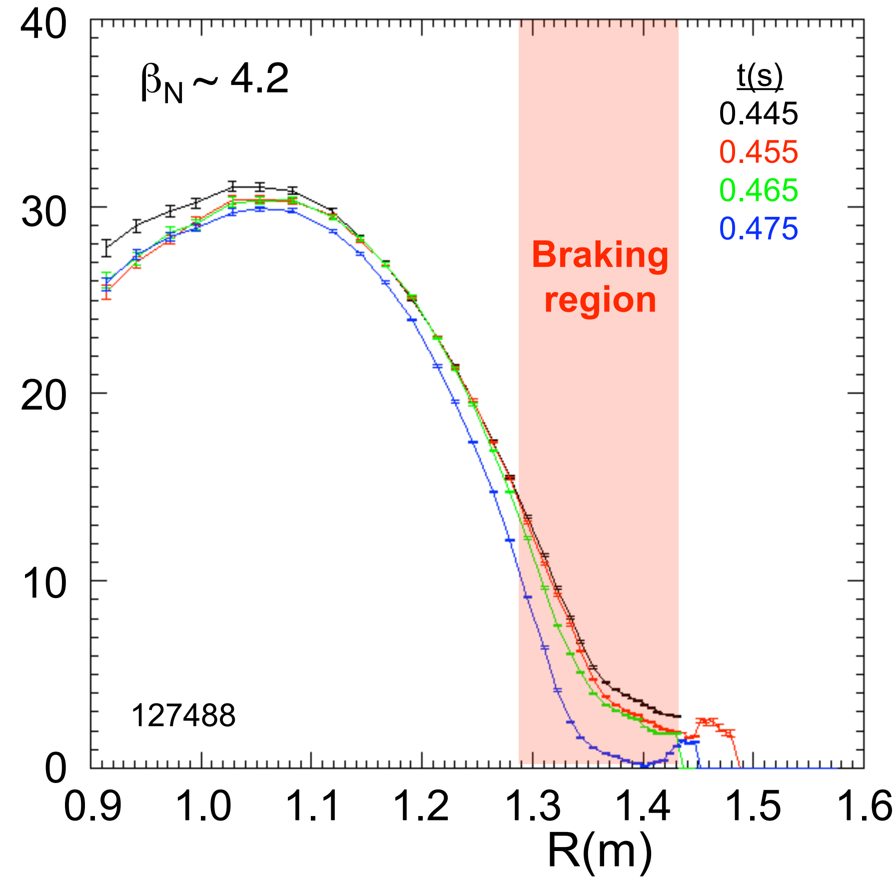
- Experiments determined that intrinsic n = 2 field errors are negligible in NSTX
  - No n = 2 amplitude or phase combination extended reference pulses
- Expect n = 2 to increase braking by neoclassical toroidal viscosity (NTV)

Applied n = 2 Field Produces Broader Non-Resonant Braking Profile than n = 3 Field

Rotation evolution during n = 3 braking

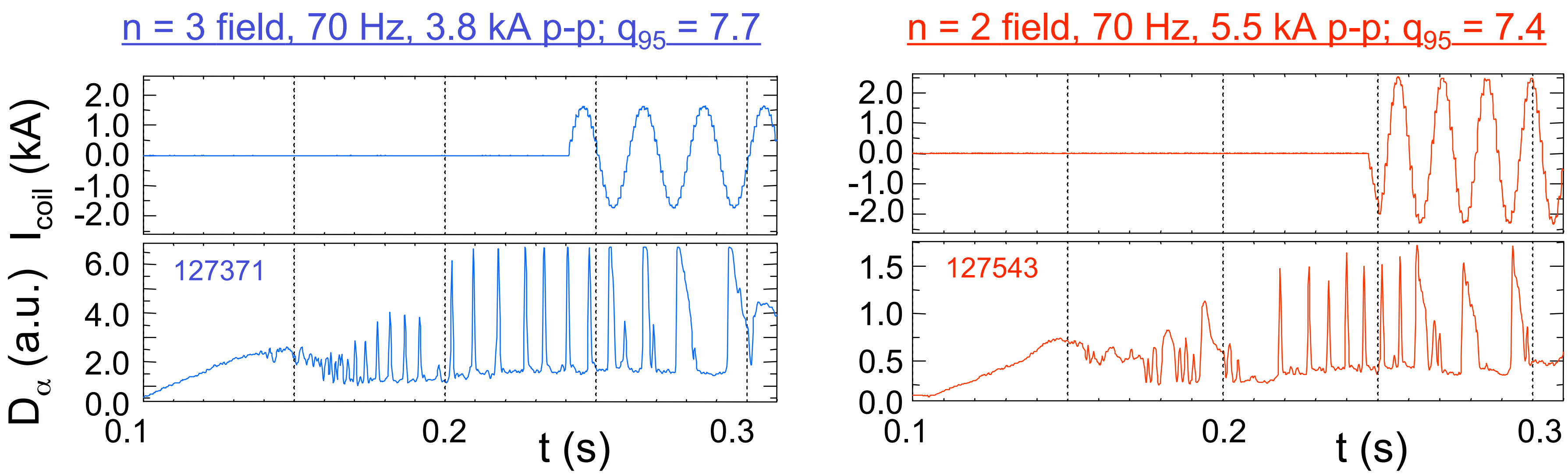


Rotation evolution during n = 2 braking

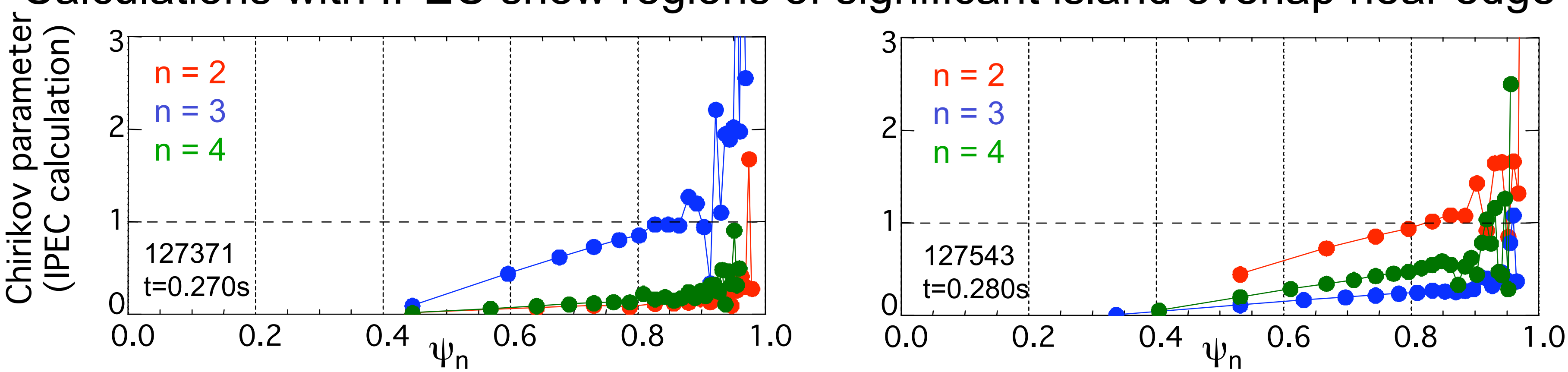


- n = 2 configuration has strong n = 4, but little n = 1 (resonant) component
- Recent experiment also shows stronger braking after lithium evaporation
  - Consistent with higher T_i and NTV in $1/\nu_i$ regime

Both n = 3 and n = 2 Applied Fields Affect ELM Behavior but Have Not Suppressed ELMs

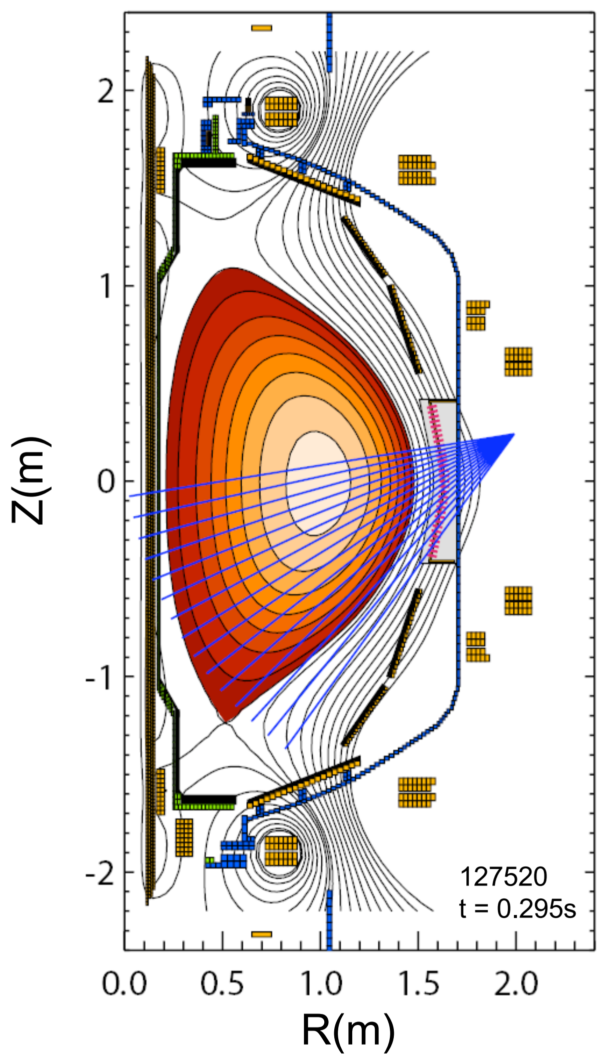


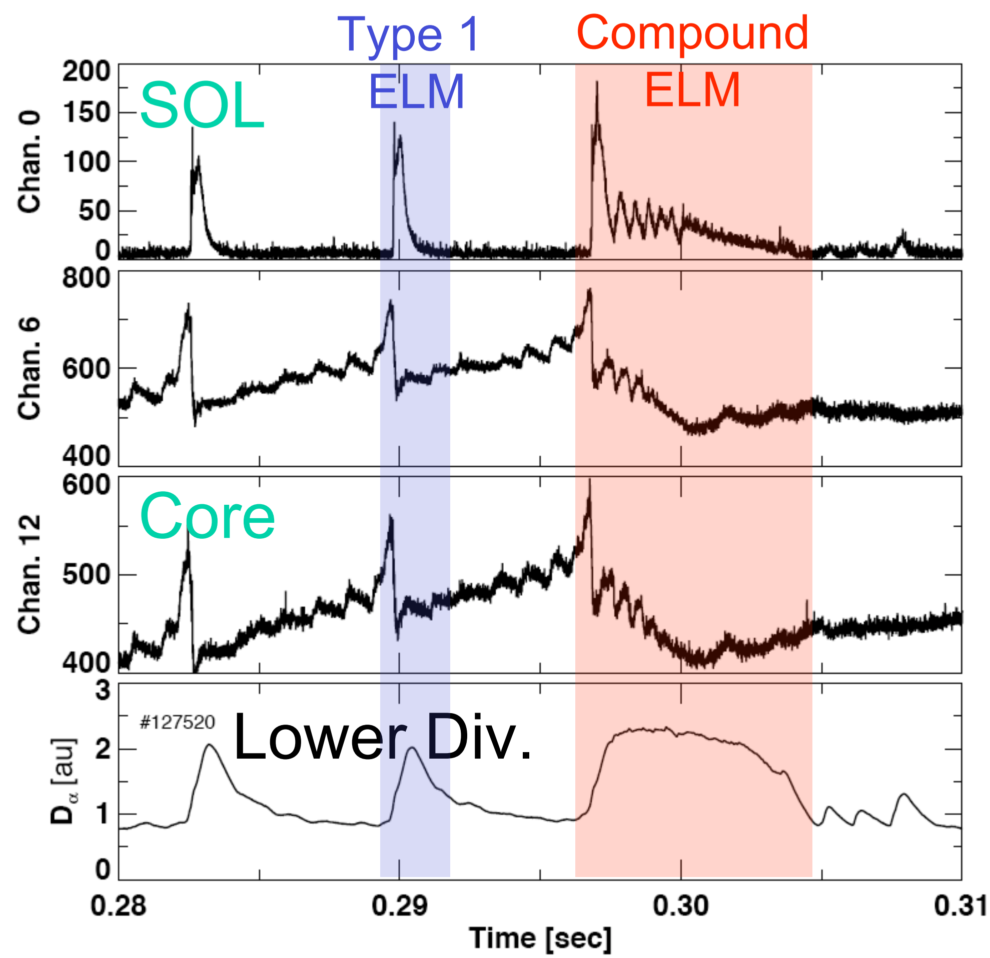
- ELMs increase in width and roughly match frequency of applied field
- Calculations with IPEC show regions of significant island overlap near edge



- Also tried mixed n = 2 + 3 spectrum with similar results

Change in ELM Behavior with RMP Results from Multiple ELMs/Filaments Coalescing

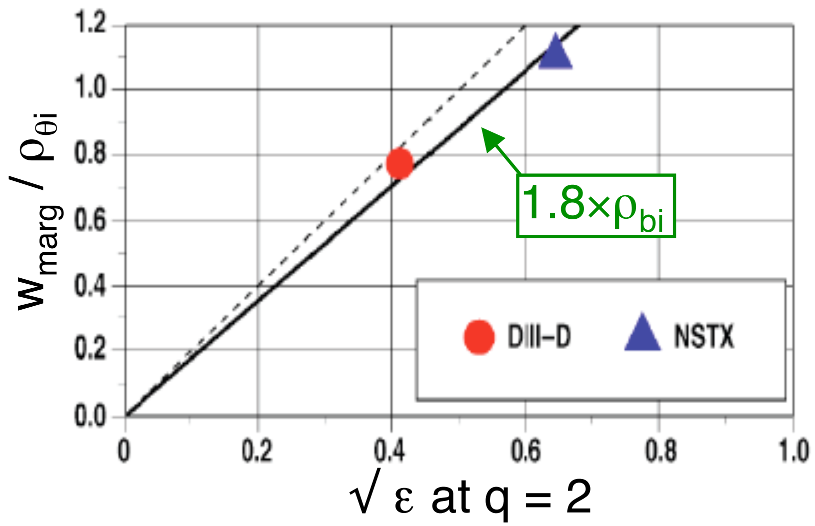




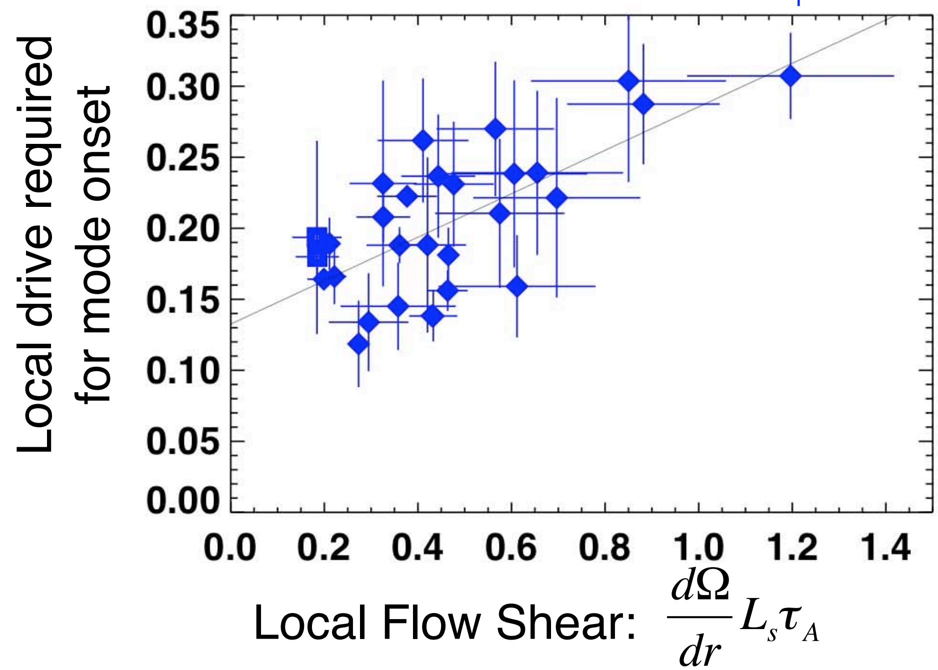
- In fast visible camera images
  - Single ELM shows one filament
  - Compound ELM shows multiple filaments

Experiments Have Studied 2/1 NTM Physics in High-β Plasmas

2/1 Marginal Island Width Scales with Ion Banana Width at q = 2



2/1 NTM onset threshold vs. V_ϕ shear



- Local mode drive ∝ $\mu_0 \langle \vec{J} \cdot \vec{B} \rangle_e L_q / \langle B_\theta \rangle$ ∝ local β_p
- Flow shear variation achieved by different NBI and *n* = 3 braking
  - Correlation with flow velocity itself is weaker
- Trend likely due to dependence of Δ' on local flow shear
  - Similar trends observed in co-/counter mix experiments in DIII-D

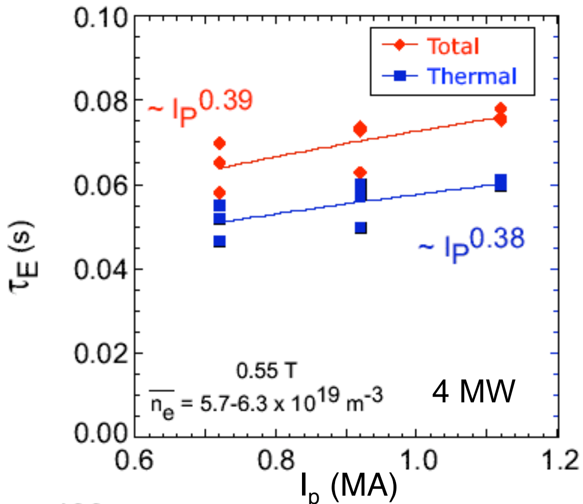
Scaling Experiments Have Revealed Role of Electron Transport in NSTX Energy Confinement

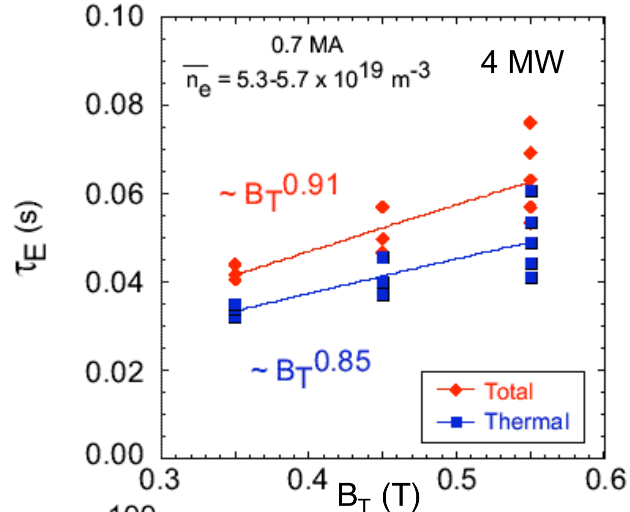
Weaker dependence of τ_E on I_p

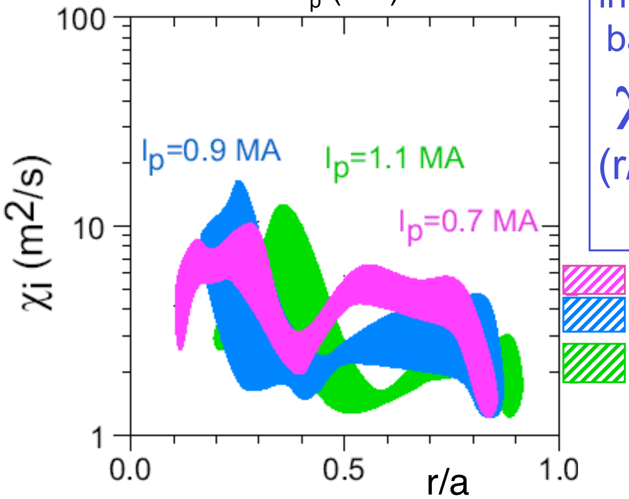
- $\tau_{E,ITER98y,2} \sim I_p^{0.93}$

Stronger dependence of τ_E on B_T

- $\tau_{E,ITER98y,2} \sim B_T^{0.15}$

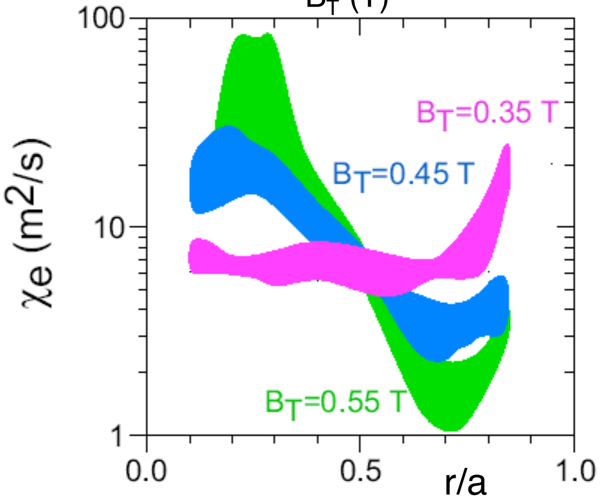






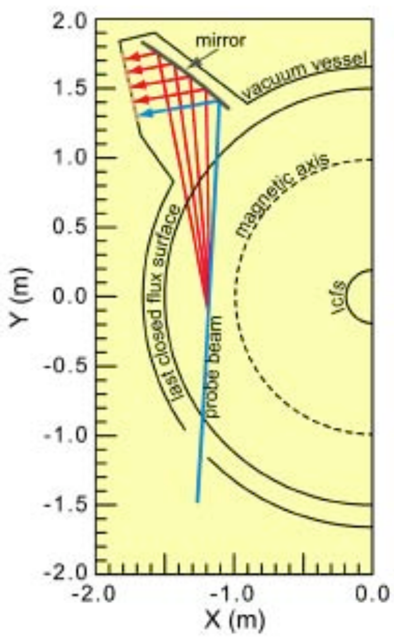
Neoclassical including finite banana width

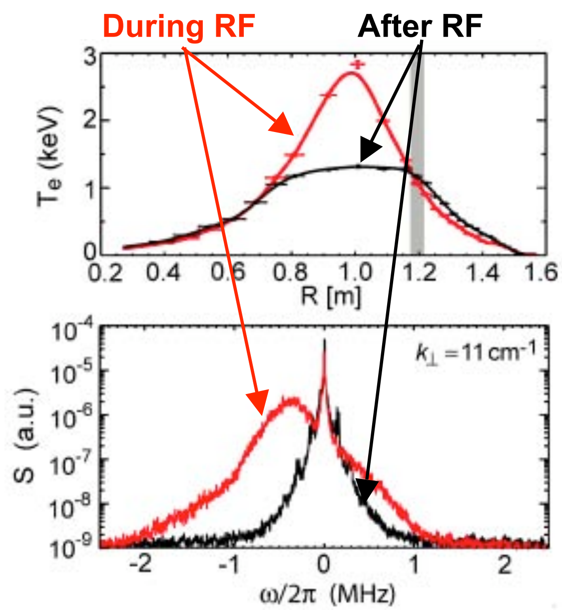
$\chi_{i,GTC-NEO}$ (r/a=0.5-0.8) $\propto I_p^{-1}$

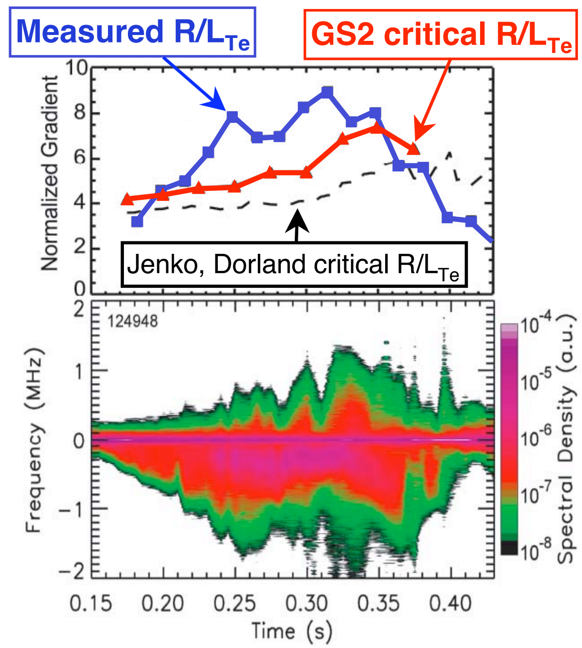


Heating Electrons with RF Waves Drives Short-Wavelength Turbulence in Plasma Core

- Fast waves at high harmonics of ion-cyclotron frequeny (HHFW) heat electrons through electron Landau damping and TTMP
- Fluctuations measured by low-angle forward scattering of 280 GHz μ-waves



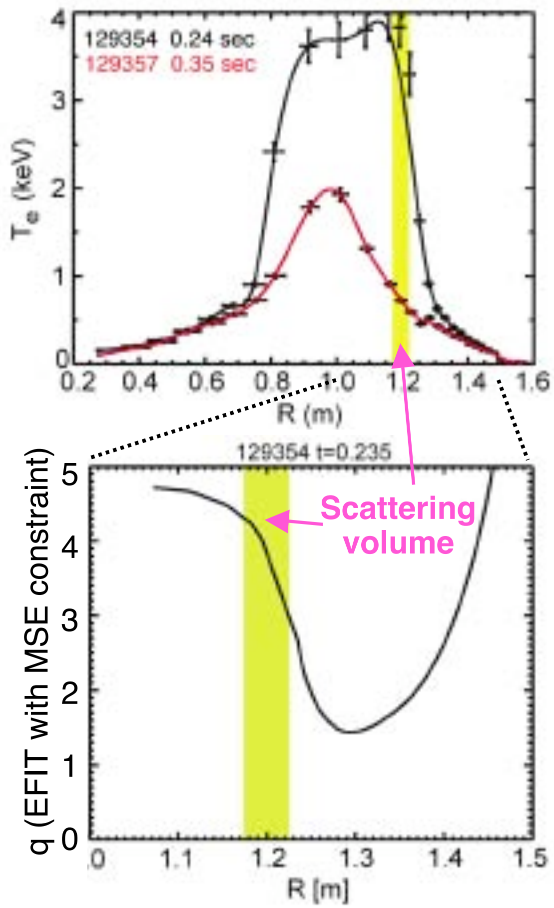


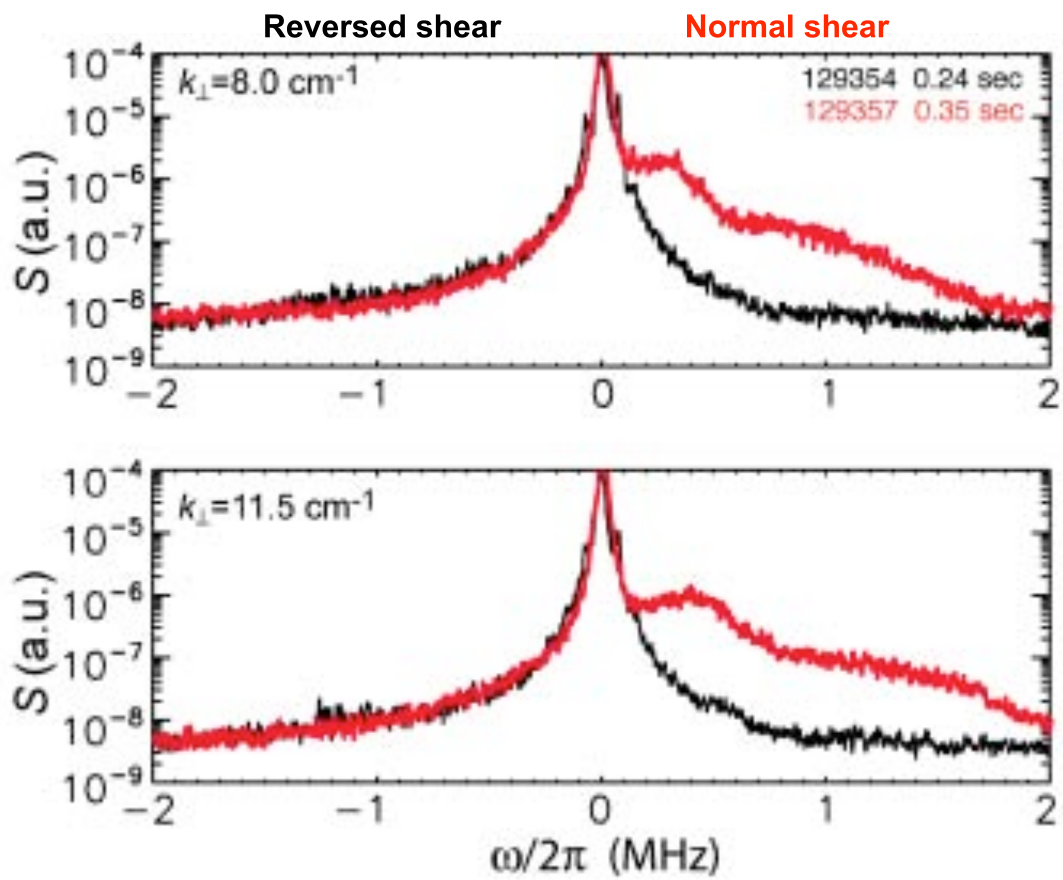


- Detected fluctuations in range $k_\perp\rho_e$ = 0.1 – 0.4 ($k_\perp\rho_s$ = 8 – 16) propagate in electron diamagnetic drift direction
  - Rules out Ion Temperature Gradient mode ($k_\perp\rho_s$ ~ 1) as source of turbulence
  - Reasonable agreement with linear gyrokinetic code (GS2) for Electron Temperature Gradient (**ETG**) mode onset

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

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





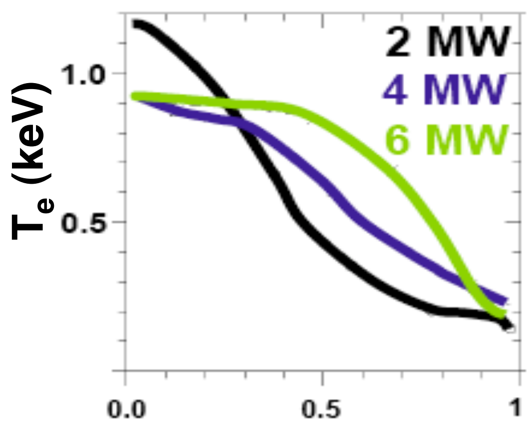
- Suppression of Electron Temperature Gradient (ETG) mode by shear-reversal and high T_e/T_i predicted by Jenko and Dorland, Phys. Rev. Lett **89** (2002)

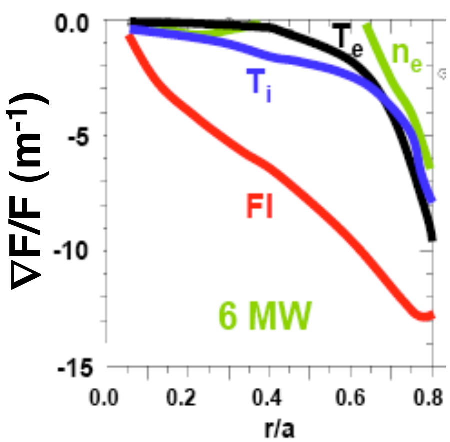
Now Investigating Role of High-Frequency MHD Modes in Core Electron Transport

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

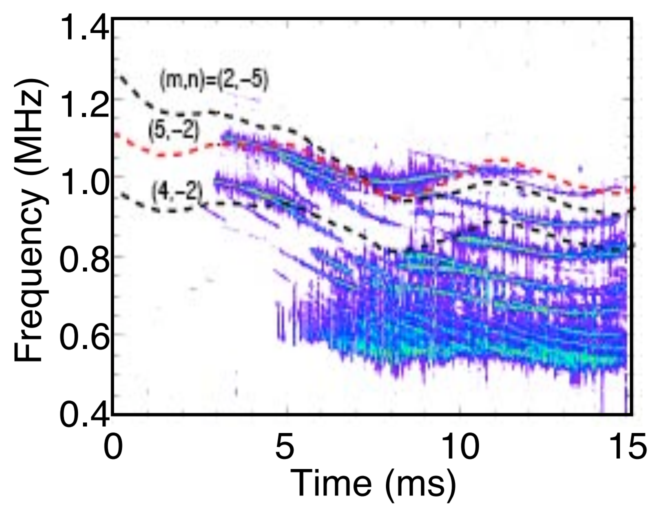
⇒Implies mechanism for electron transport *not* driven by T_e gradient

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



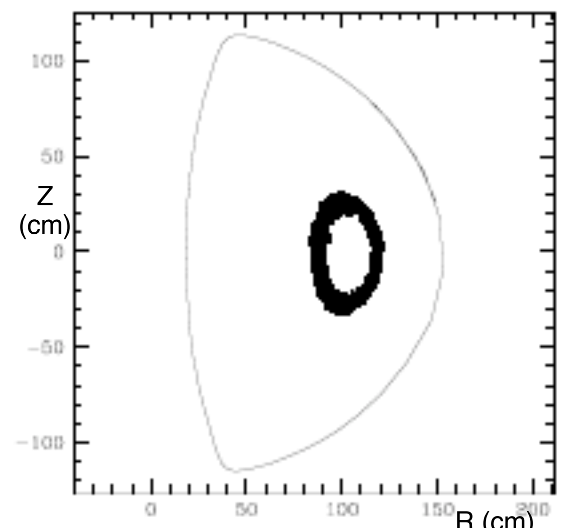


$$\omega_{GAE} \simeq v_{A0}(m - nq_0)/q_0 R.$$



- GAEs localized near center
- Radial width ∝ 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

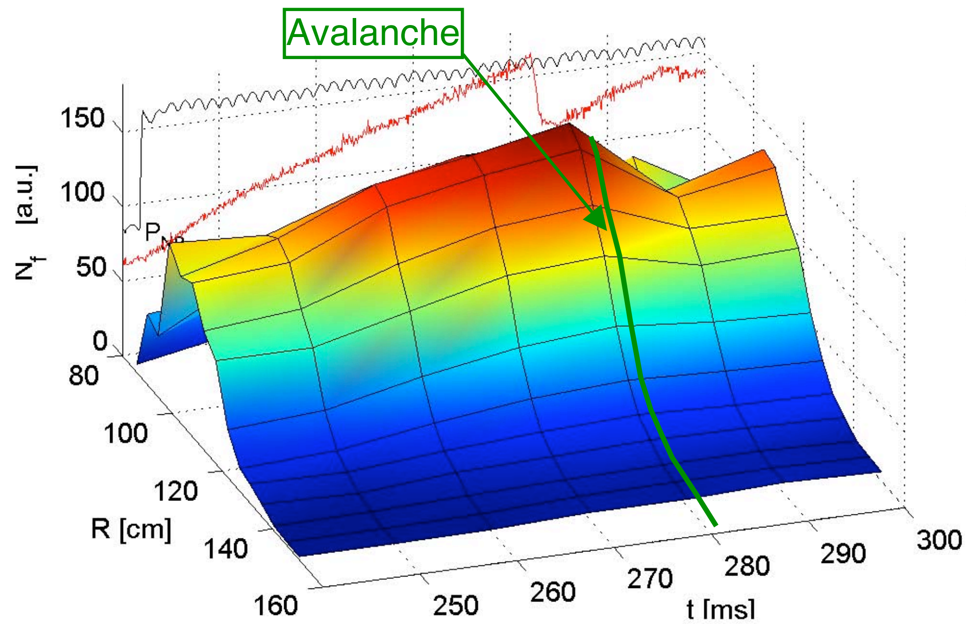


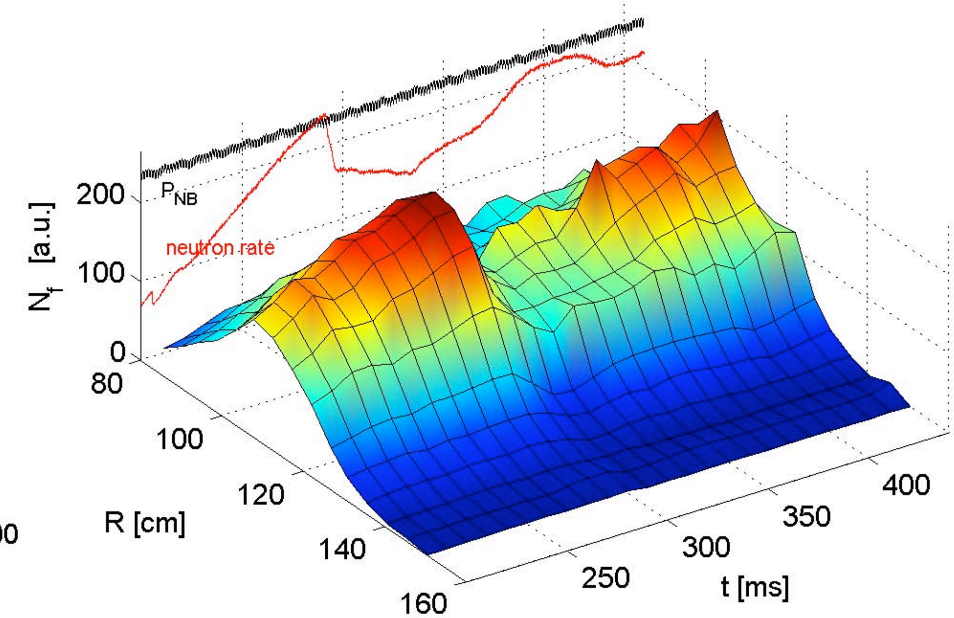
MHD Instabilities Affect Confinement of Fast Ions

- Density profile of fast ions (15 – 65 keV) deduced from Doppler-shifted D_α emission by energetic neutrals created by charge-exchange with NBI neutrals

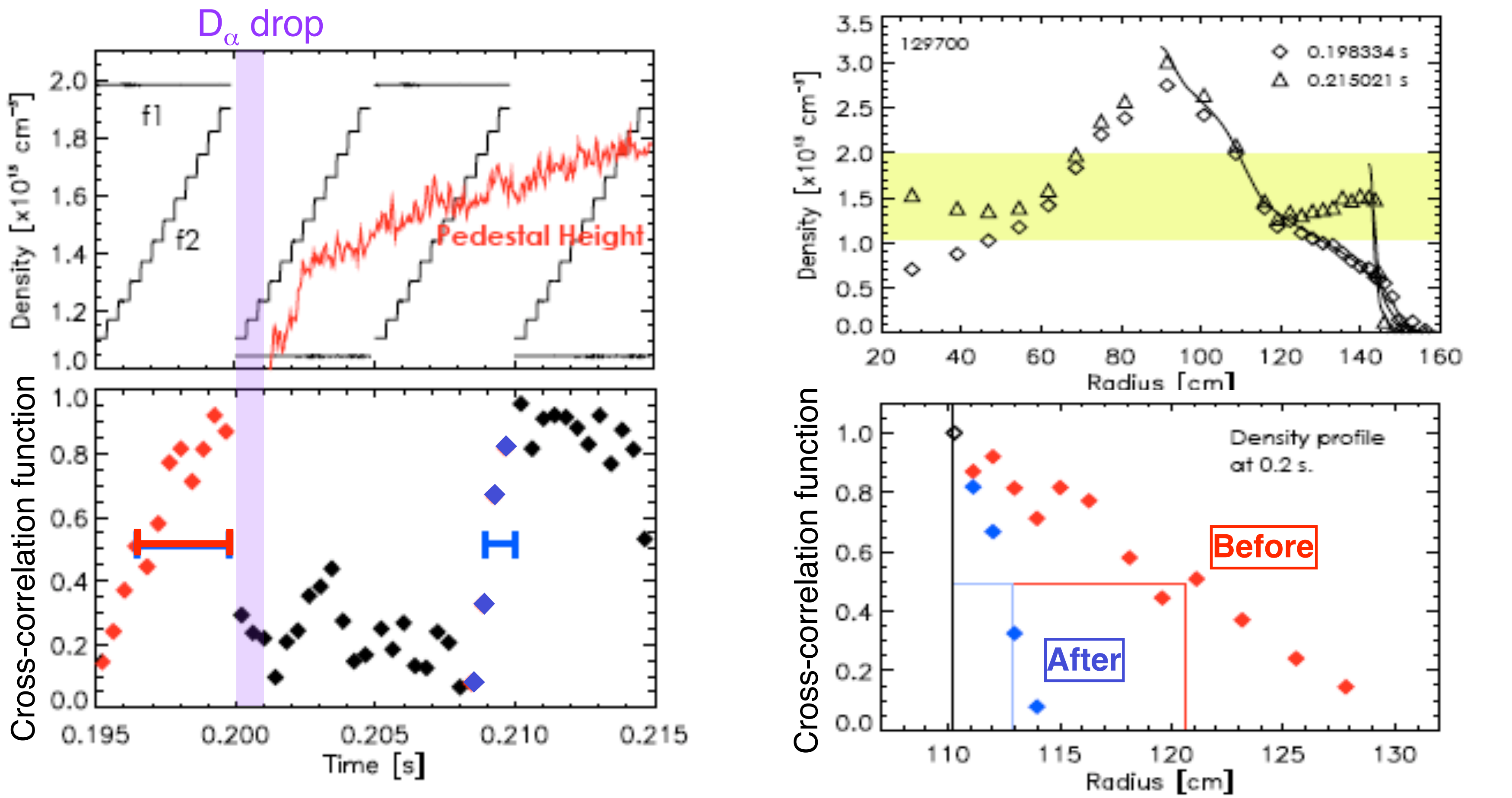
- During TAE avalanches, measured fast-ion losses up to 30%
  - Consistent with neutron rate drop
  - Profile remains peaked

- Low-frequency (kink) activity redistributes fast ions outwards
  - Can destabilize Compressional Alfvén Eigenmodes (CAEs) in outboard midplane region





Measured Change in Low-k Turbulence Across H-mode Transitions in Ohmically Heated Plasmas

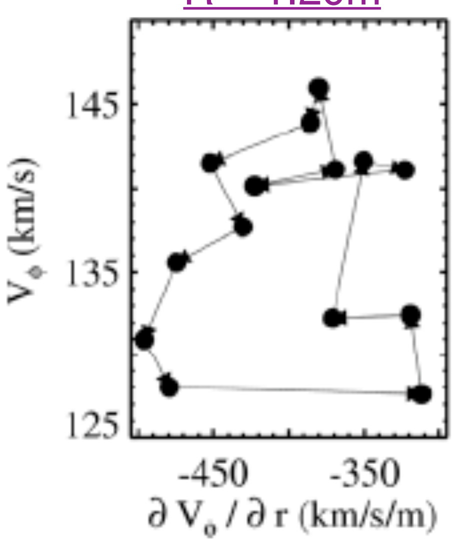


- Use fixed/swept frequency correlation reflectometer during period with monotonic density profile following H-mode transition
- Fluctuation characteristics change little except for a reduction in radial correlation length by factor 3 - 4

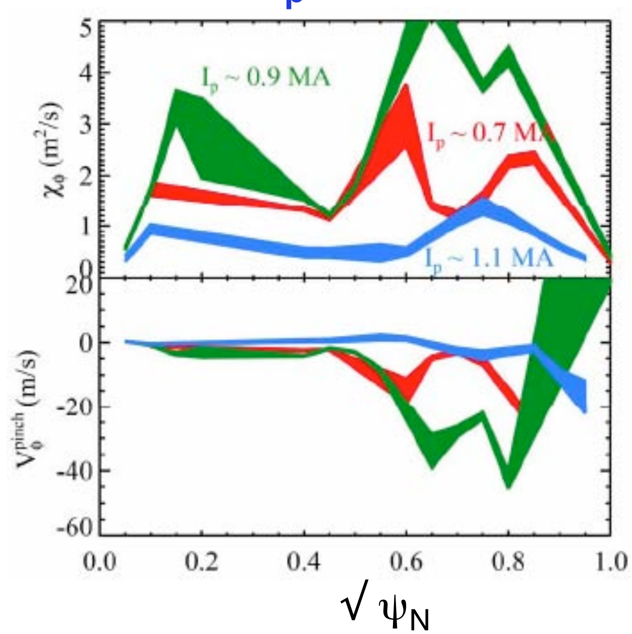
Momentum Diffusivity in H-mode Plasmas Does Not Show Clear Dependence on I_p or B_T

- Thermal transport does show ~neoclassical (B_θ) dependence
- Use transient n = 3 braking or NBI "blips" to perturb rotation profile
  - Decouple v_{tor} and ∇v_{tor} to separate diffusion and pinch terms, *but*
  - Analysis does not yet account for possible "residual" stress from turbulent wave/particle momentum interaction *(Diamond, Hahm, Gurcan; TTF07)*

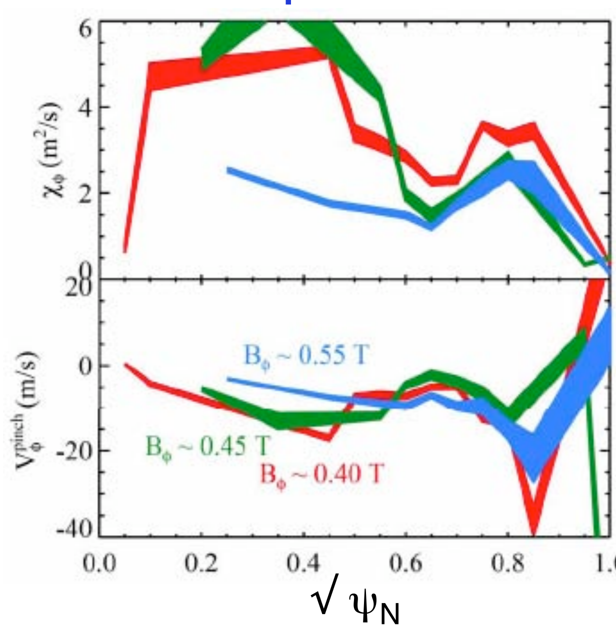
Over period 140ms after braking pulse
R = 1.20m



I_p scan

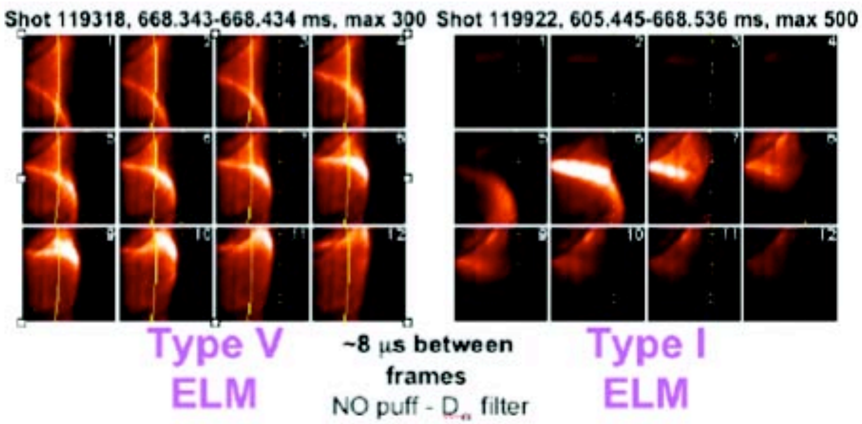


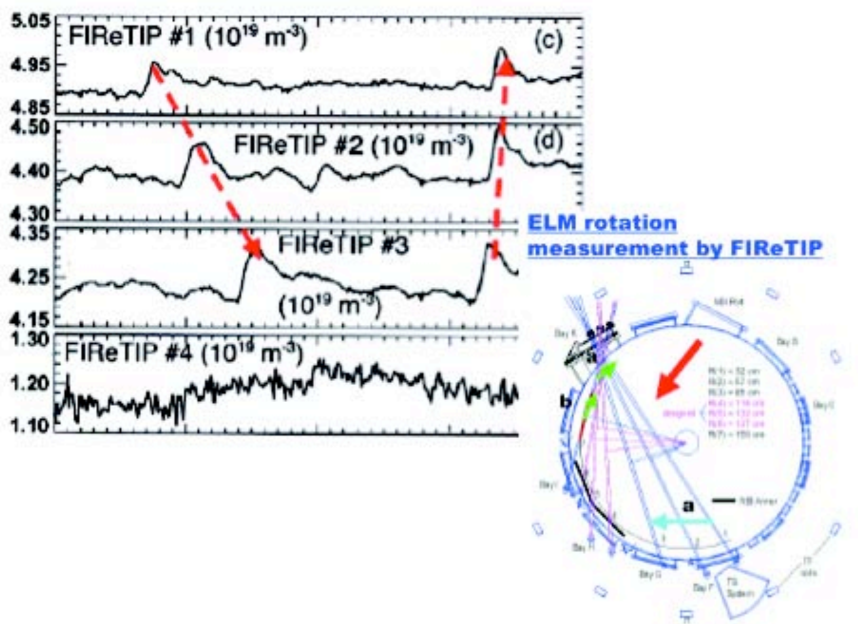
B_T scan



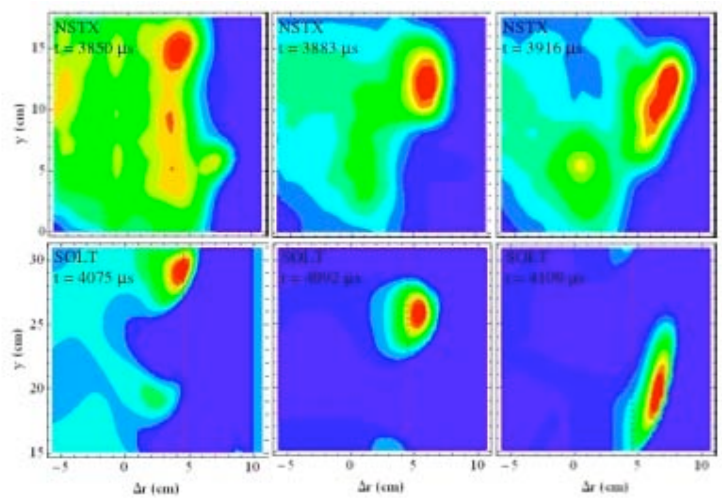
Imaging of Plasma Edge Contributing to Understanding Transient Edge Phenomena *(ELMs, Blobs)*

ELM dynamics and rotation measured





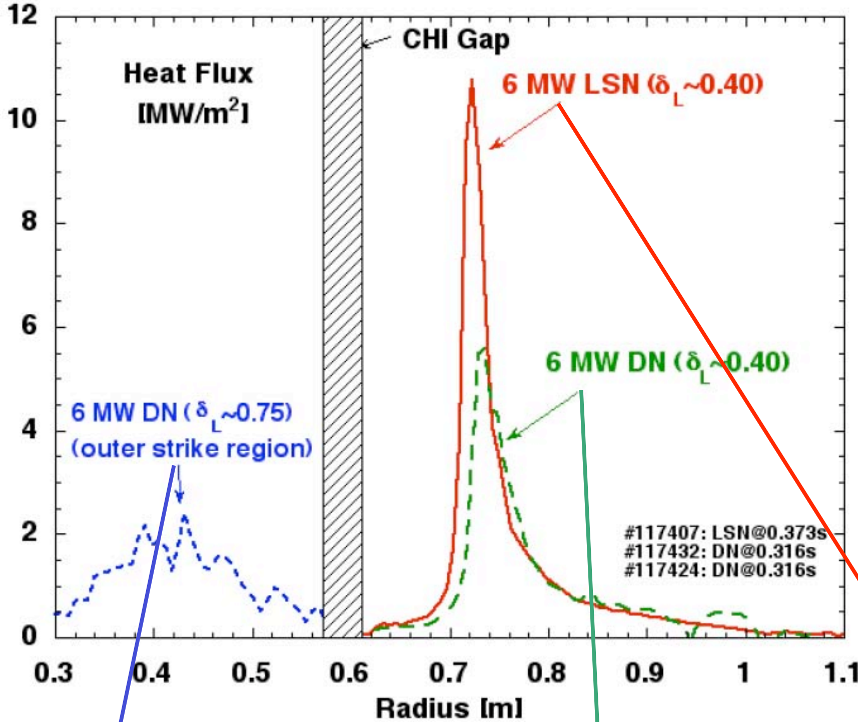
Simulations of "blob" propagation in NSTX SOL reproduce measured characteristics



D. A. D'Ippolito , IAEA FEC, 2008

- **SOLT** code models curvature-driven turbulence with coupled mid-plane and divertor regions, including flows
- Includes calculation of synthetic diagnostic images for comparison with GPI data

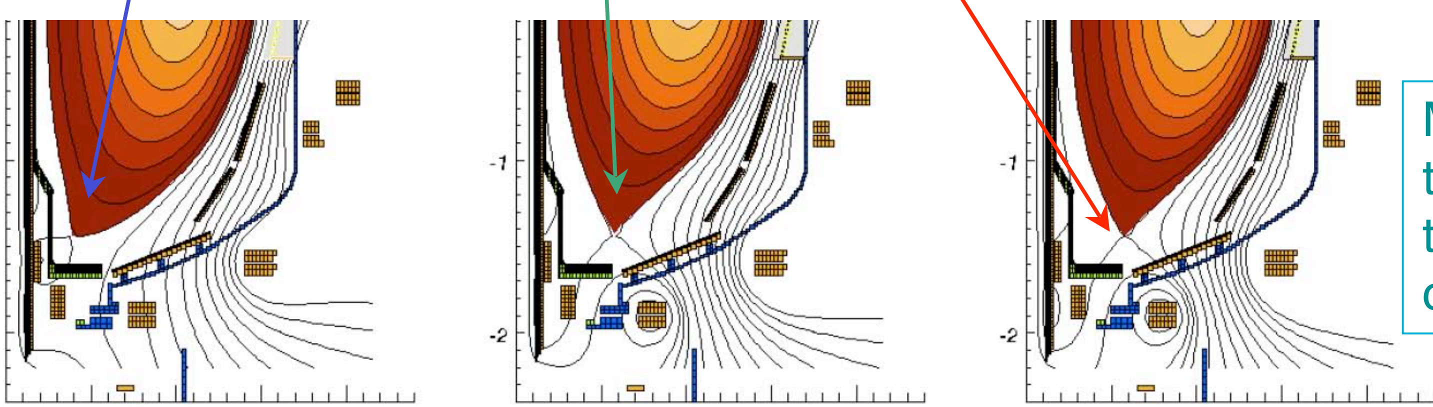
Peak Heat Flux on Lower Divertor Can Be Reduced By Plasma Shaping



- Compare configurations:
  - lower single-null (LSN), $\delta_X \approx 0.4$
  - double-null (DN), $\delta_X \approx 0.4$
  - high triangularity DN $\delta_X \approx 0.75$
- ELMs: Type I → Mixed → Type V
- Shape changes reduce heat flux

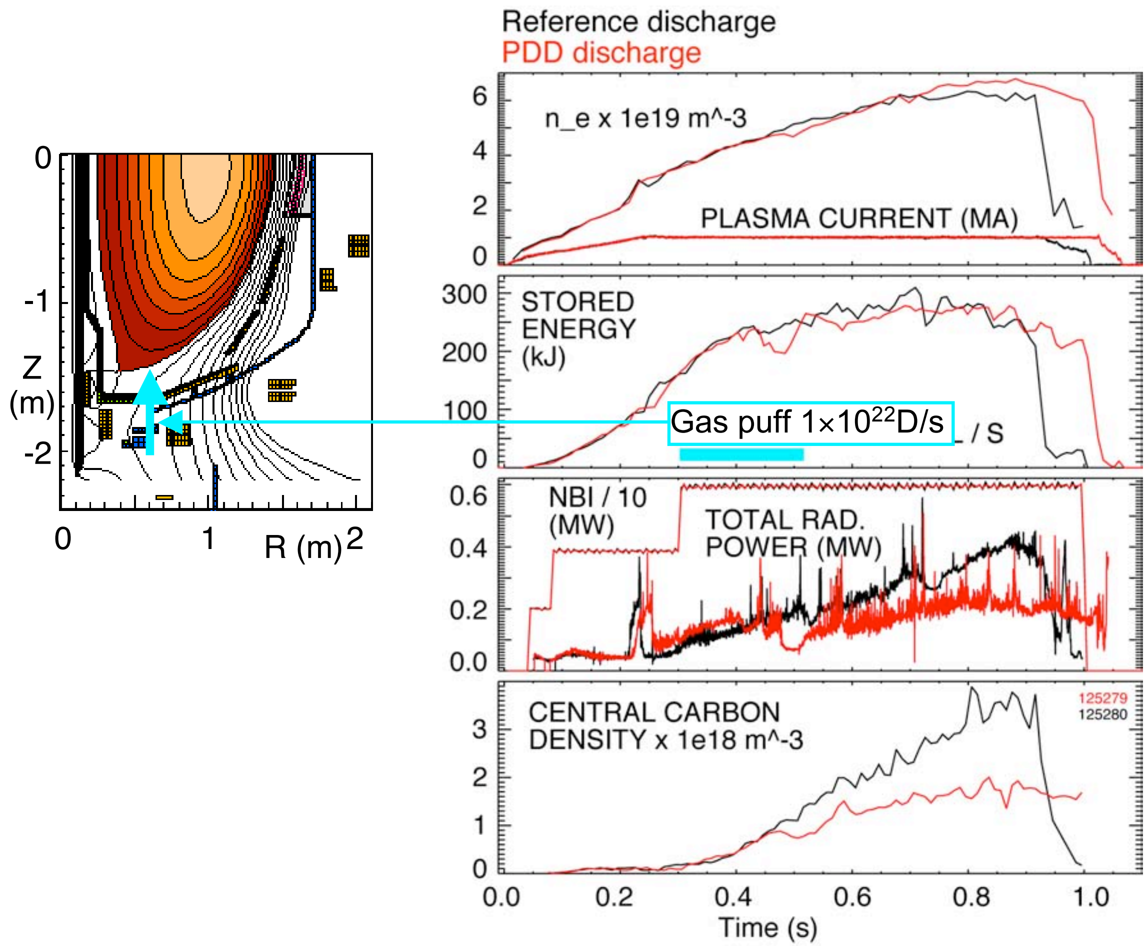
1 : 0.5 : 0.2

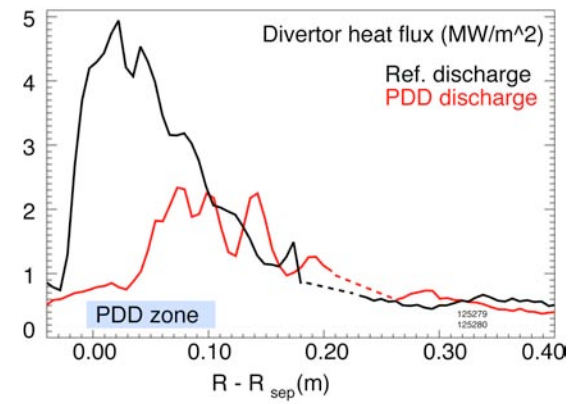
Load sharing | Flux expansion

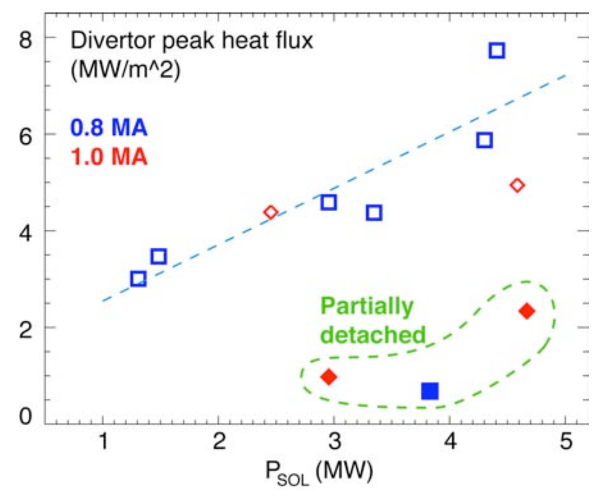


Measure heat flux to divertor with IR thermography of carbon tiles

Partial Divertor Detachment by Divertor Gas Puffing Reduces Peak Heat Flux Without Degrading Core







- Extended previous results to high-triangularity H-mode discharges
- Core radiation and carbon density reduced during partial detachment

NSTX is Exploring and Developing Lithium-Coated Plasma Facing Components

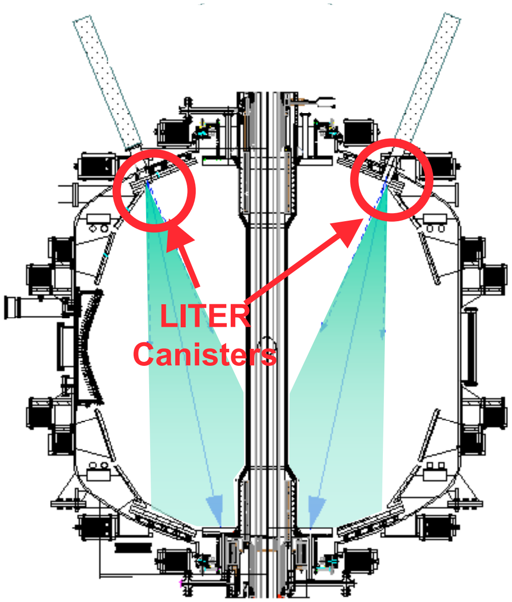
2005: Injected lithium pellets, 2 - 5 mg, into He discharges prior to D NBI shot

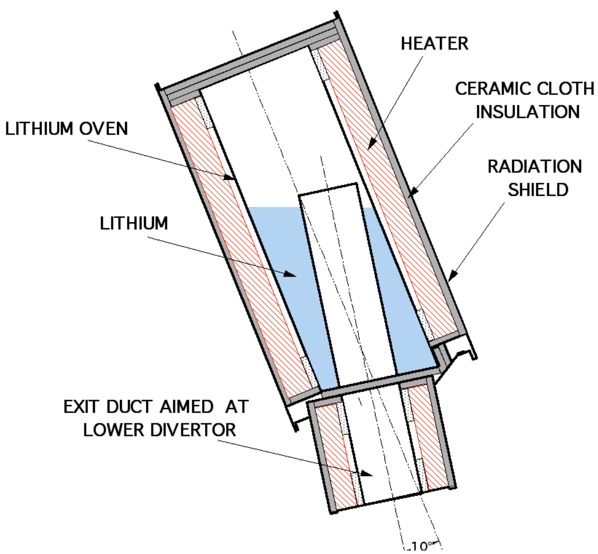
2006: LIThium EvaporatoR (LITER) deposited lithium on divertor between shots

2007: Enlarged nozzle, re-aimed at lower divertor to increase deposition rate

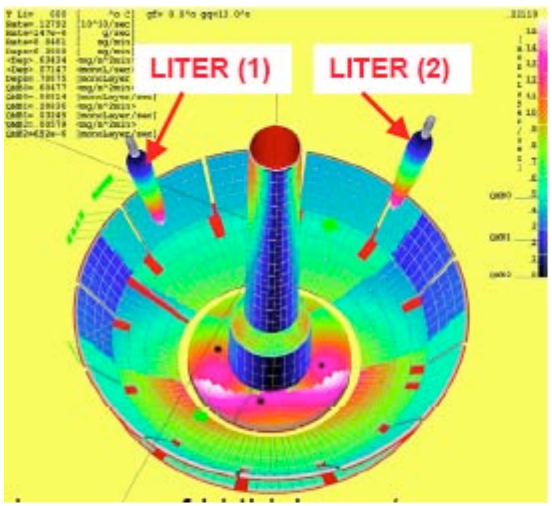
2008: Dual LITERs covered entire lower divertor; shutters interrupted lithium stream during plasmas; evaporated ~200g lithium (reloaded 3 times)

– Also used "lithium powder dropper" to introduce lithium through SOL

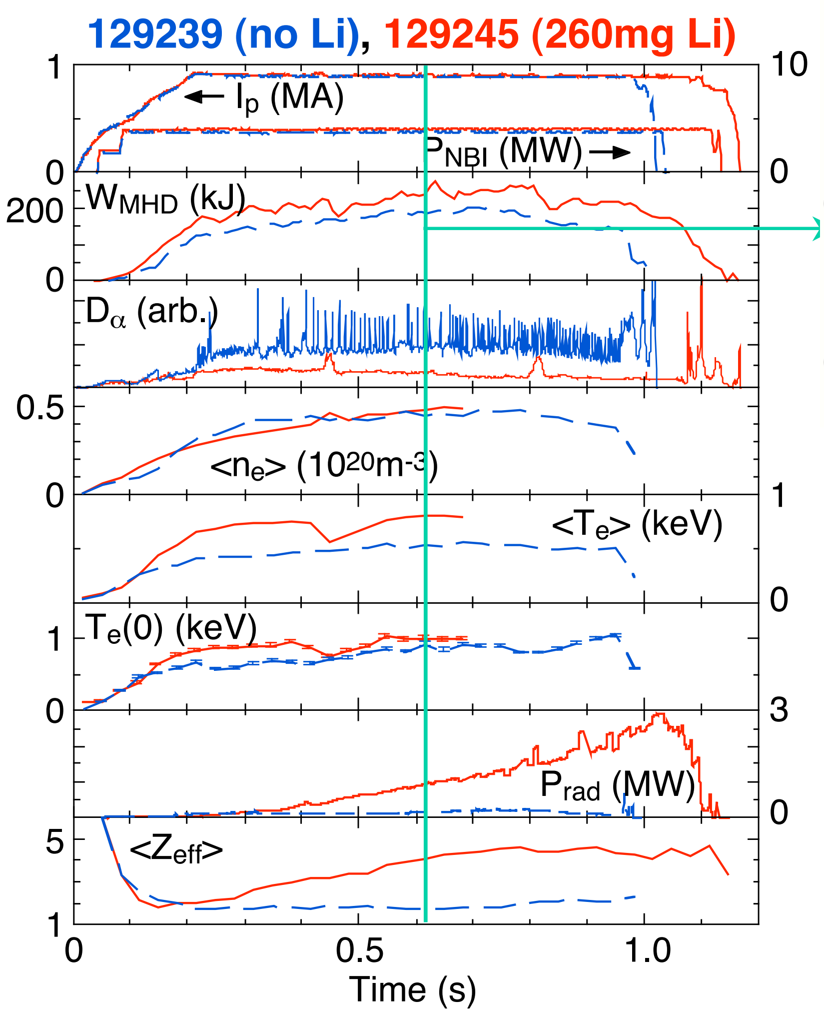


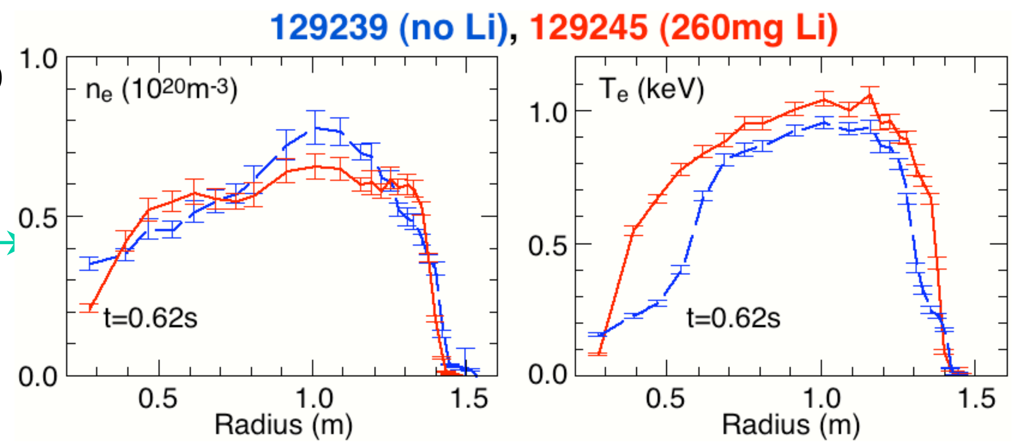


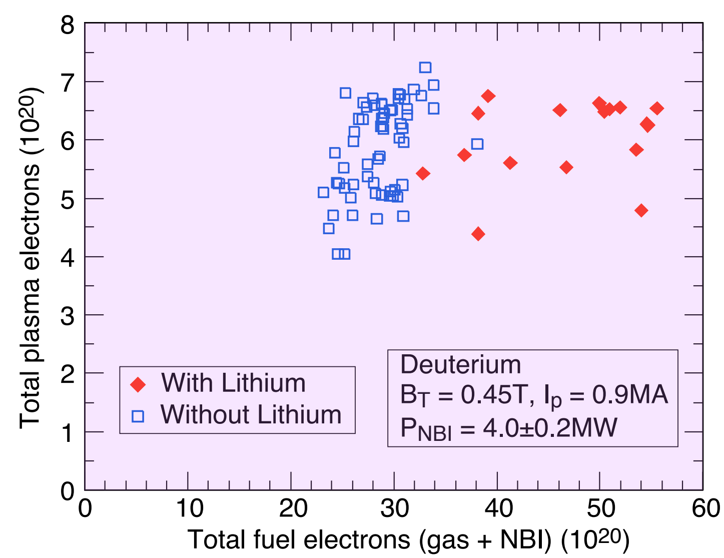
Modeled deposition pattern



Solid Lithium Coating Reduces Deuterium Recycling, Suppresses ELMs, Improves Confinement

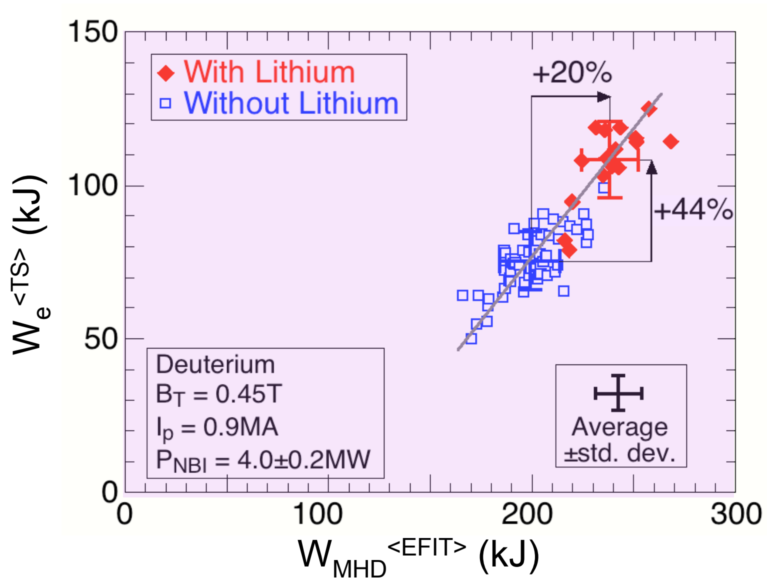


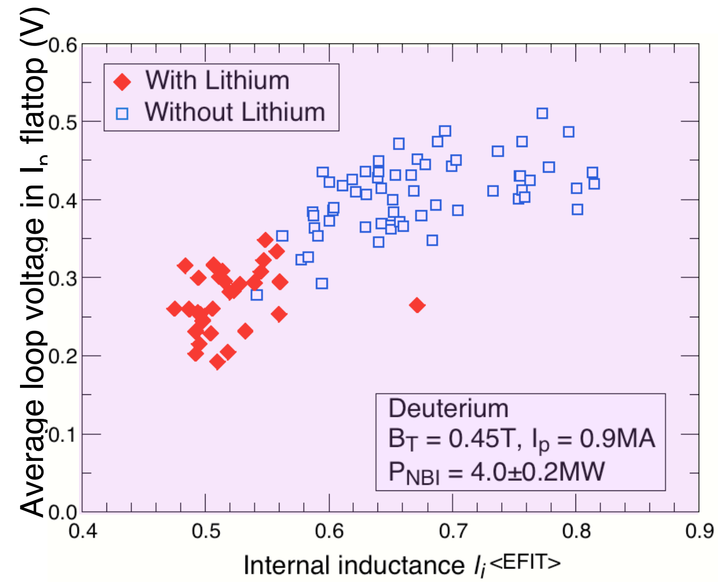


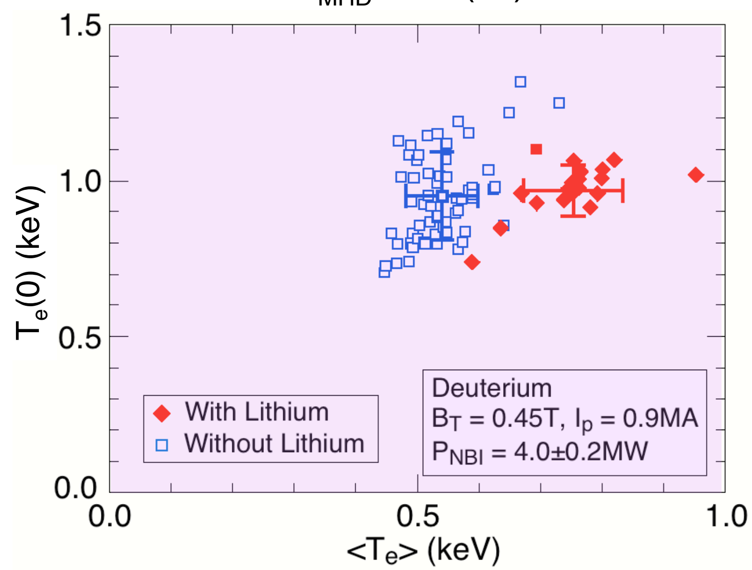


- Without ELMs, impurity accumulation increases P_{rad} and Z_{eff}

Improvement in Confinement with Lithium Mainly Through Broadening of Electron Temperature Profile





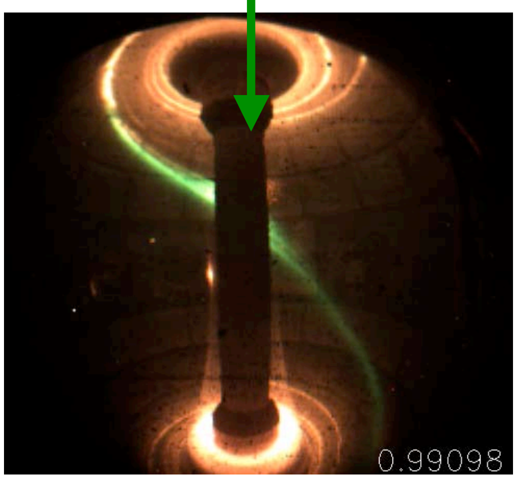


- Broader electron temperature profile reduces internal inductance l_i and inductive flux consumption in current flattop, despite higher Z_{eff}
- Lithium increases edge bootstrap current through higher p', lower collisionality

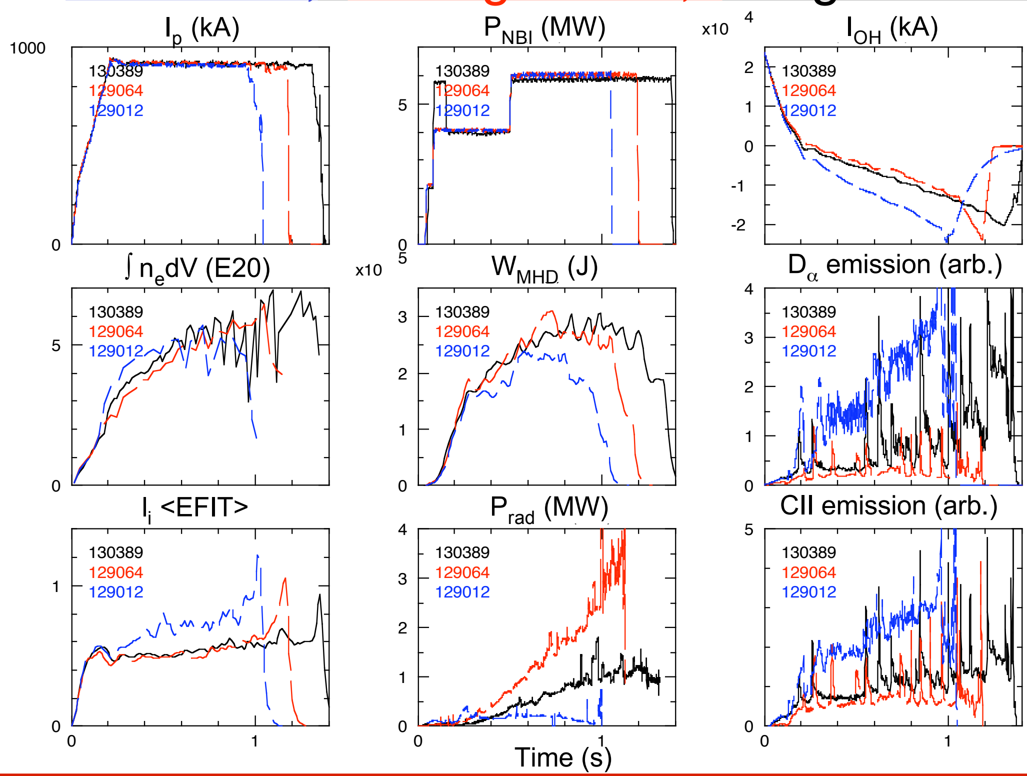
Lithium Coating by Dropping a Stream of Lithium Powder into SOL Produced Similar Benefits to LITER

- Lithium powder (~40μm) stabilized against rapid oxidation in air by surface coating of either Li_2CO_3 (<0.1%) or paraffin wax (<0.01% CH_2)
- Introduced by oscillating a piezo-electric diaphragm with a hole in the center on which the powder is piled
- Typical flow rates 5 – 40 mg/s: ***well tolerated by plasma***

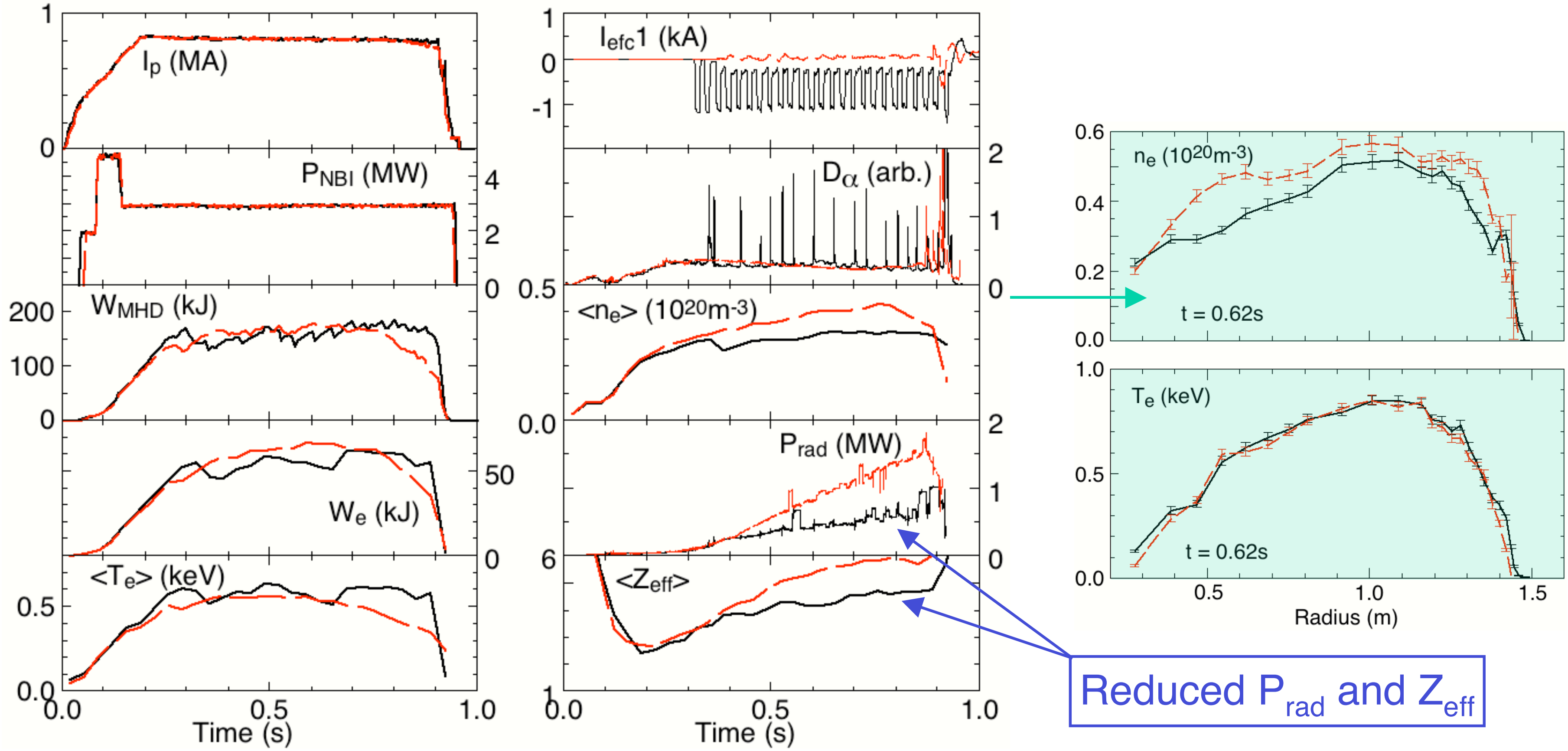
Lithium powder dropped from canister above during discharge



No lithium; 700mg LITER; 7 mg Powder



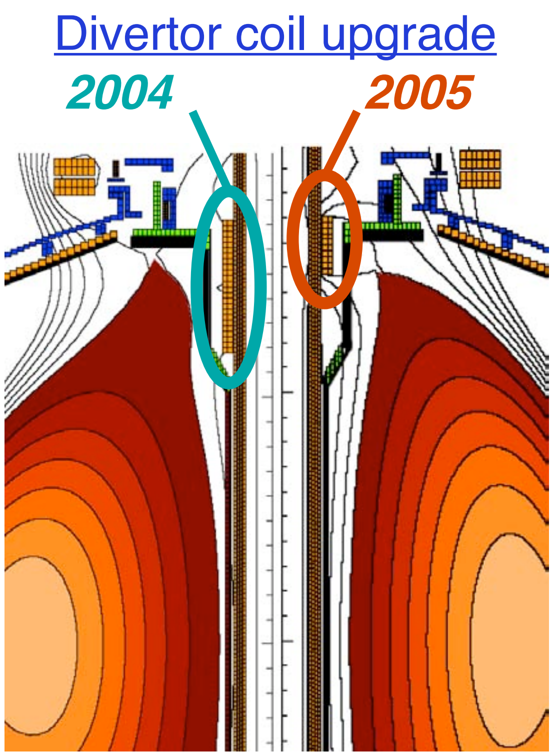
Midplane Radial-Field Control Coils Can *Induce* Repetitive ELMs in Lithium-Suppressed Plasmas

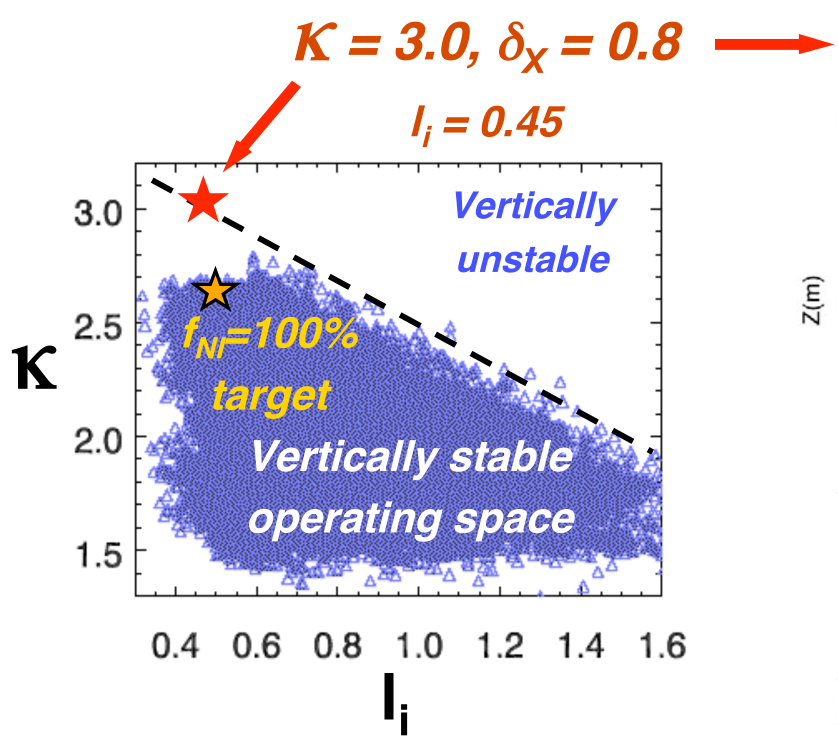


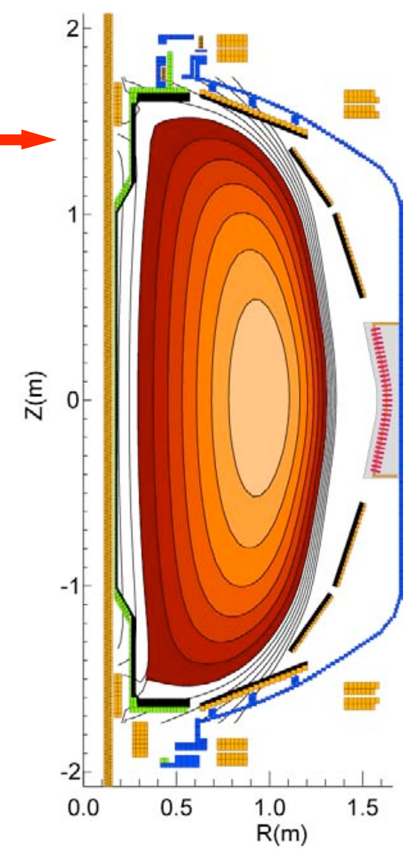
- n = 3 resonant magnetic perturbation applied
- 11ms duration pulse at 40Hz optimal for this shape (DN, κ=2.4, δ=0.8)

Optimized Plasma Shaping Can Increase β_P and Bootstrap Current Fraction at High β_T

- High elongation κ reduces $B_{P,av} = \mu_0 I_p / \int_C dl$, increases bootstrap current
  - Sustained $\kappa \geq 2.8$ for many t_{wall} by fast feedback
- Higher triangularity δ and proximity to conducting wall allows higher β_N
- Plasma rotation maintains stabilization beyond decay-time of wall current

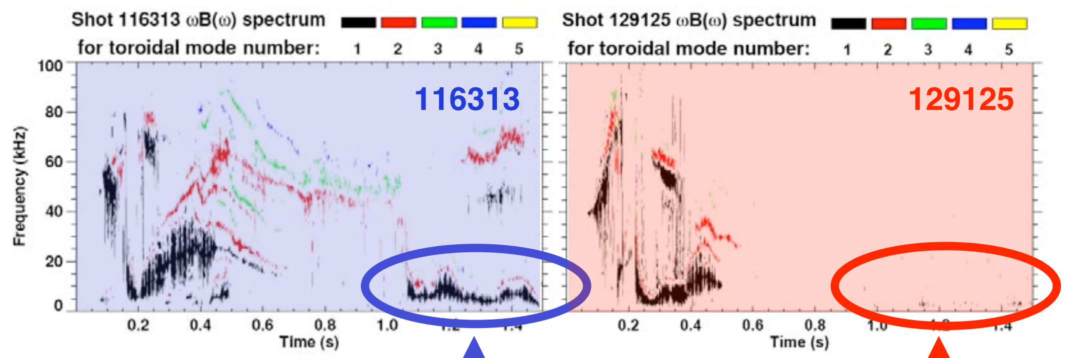




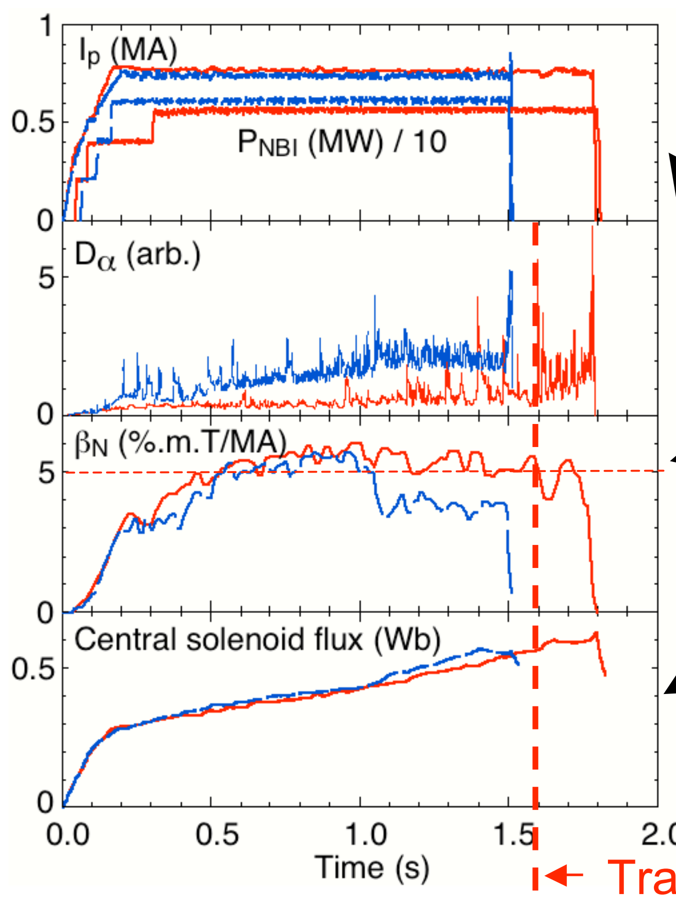


n=3 Error Field Correction With n=1 RWM Feedback and Lithium Coating Extends High-β_N Discharges

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



Onset of n=1 rotating modes avoided



NSTX record pulse-length = 1.8s

$\beta_N \geq 5$ 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

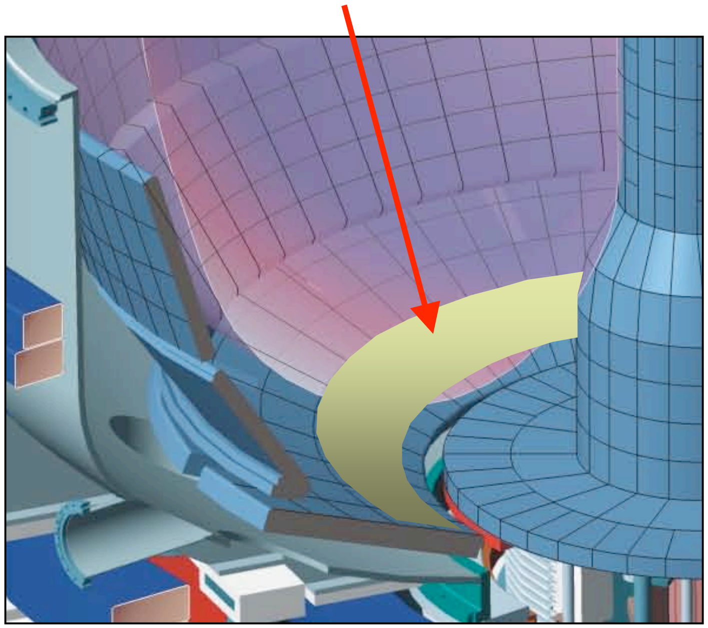
← Transition to phase with larger, more frequent ELMs

NSTX is Revealing New Physics in Toroidal Magnetic Confinement and Developing the Potential of the ST

- Extending the understanding of MHD stability at high β
  - Extending pulse length through active control of low-n modes
  - Investigating possibilities for ELM suppression and mitigation
  - Developing NTM physics and control techniques
- Investigating the physics of anomalous electron transport
  - Electron transport dominates as a result of ion-scale mode suppression
- Examining stability and effects of super-Alfvénic ions
  - Measuring transport due to spectrum of Alfvén eigenmodes
- Developing techniques to mitigate high heat fluxes on PFCs
  - Extreme flux expansion and creating radiative divertor
- Assessing the potential of lithium as a plasma facing material
  - Solid lithium coatings of PFCs reduce recycling, improve confinement
  - Liquid lithium divertor will be installed for experiments in 2009
- Making good progress towards goal of non-inductive sustainment

In 2009, NSTX Will Begin Investigating Liquid Lithium on Plasma Facing Components

Liquid Lithium Divertor (LLD)



- Replace rows of graphite tiles in outer lower divertor with segmented plates
- Molybdenum surface on copper substrate with temperature control
  - Heated above Li melting point 180°C
  - Active heat removal to counteract plasma heating
- Initially supply lithium with LITER and lithium powder dropper

- Evaluate capability of liquid lithium to sustain deuterium pumping beyond capacity of solid film
- Upgrade to long-pulse capability will require method for core fueling
  - Compact Toroid injection or frozen deuterium pellets