NSTX PPPL PRINCETON PLASMA PHYSICS LABORATORY *Supported by* U.S. DEPARTMENT OF ENERGY Office of Science

# Accomplishments and Results from the 2008 NSTX Run Campaign

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*Colorado Sch Mines*
*Columbia U*
*CompX*
*General Atomics*
*INEL*
*Johns Hopkins U*
*LANL*
*LLNL*
*Lodestar*
*MIT*
*Nova Photonics*
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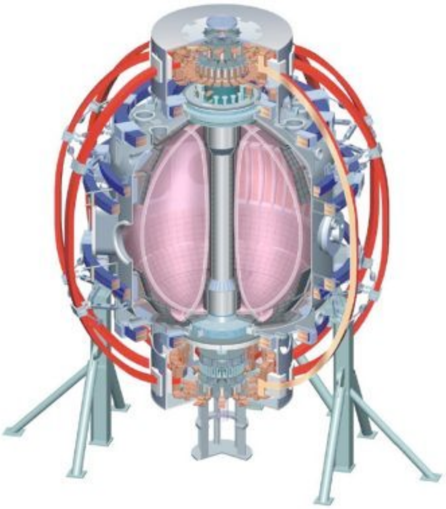
*UC Davis*
*UC Irvine*
*UCLA*
*UCSD*
*U Colorado*
*U Illinois*
*U Maryland*
*U Rochester*
*U Washington*
*U Wisconsin*

**M.G. Bell**
NSTX Run Coordinator for 2008

**25th Meeting of the**
**NSTX Program Advisory Committee**
**February 18 – 20, 2009**



*Culham Sci Ctr*
*U St. Andrews*
*York U*
*Chubu U*
*Fukui U*
*Hiroshima U*
*Hyogo U*
*Kyoto U*
*Kyushu U*
*Kyushu Tokai U*
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*RRC Kurchatov Inst*
*TRINITI*
*KBSI*
*KAIST*
*POSTECH*
*ASIPP*
*ENEA, Frascati*
*CEA, Cadarache*
*IPP, Jülich*
*IPP, Garching*
*ASCR, Czech Rep*
*U Quebec*

# FY08 Run Planned to Achieve Milestones and Address High-Priority Issues for ST Development and ITPA / ITER

- FY'08 program milestones
  - **Joule milestone: Evaluate the generation of plasma rotation and momentum transport, and assess the impact of plasma rotation on stability and confinement**
  - **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**
- Research to prepare for upgrades and to support ST development
  - Lithium program
  - Configuration optimization
- ITPA joint experiments and requests from ITER
  - High priority issues to which NSTX can make timely contributions
    - **ELM control and suppression by externally applied fields**
    - **RWM control with coils similar to ITER port-plug coil design**
    - **Vertical control requirements, VDE avoidance**

# NSTX Scientific Leadership for 2008 Run

| | Coordinator | Deputy |
|---|---|---|
| **Run coordination** | Michael Bell | Roger Raman<br>(U. Washington) |

| Topical Science Group | Leader | Deputy Leader |
|---|---|---|
| **Macroscopic Stability** | Steve Sabbagh<br>(Columbia U.) | Stefan Gerhardt |
| **Transport and Turbulence** | Stan Kaye | Kevin Tritz<br>(Johns Hopkins U.) |
| **Boundary Physics** | Vlad Soukhanovskii<br>(LLNL) | Rajesh Maingi<br>(ORNL) |
| **Wave-Particle Interactions** | Gary Taylor | Eric Fredrickson |
| **Solenoid-free Start-up and Ramp-up** | Roger Raman<br>(U. Washington) | Dennis Mueller |
| **Advanced Scenarios and Control** | David Gates | Jon Menard |

*Collaborator*

# NSTX Team Achieved 16.6 Run Weeks In 2008

- Exceeded milestone target of 15 run weeks
- Run lasted from Feb 18 through July 14 (21 calendar weeks)
- Schedule for experiments was developed at a weekly Program/Operations meeting chaired by Run Coordinator
  - Planned ahead by 1 - 2 weeks, adapting to availability of facility, heating systems, diagnostics and collaborator travel
  - Updated schedule on NSTX website as conditions changed
- Performed 43 Experimental Proposals and 12 Machine Proposals
  - Conducted up to 4 experiments (XPs and/or XMPs) on each run day

# Allocation of 2008 Run Time Matched Target Established at Outset and Reviewed by PAC 23

- At outset of run, ~20% of runtime was held in reserve and ~15% allocated to “cross-cutting and enabling” activities
  - Most of the XMPs were counted as “cross-cutting and enabling”
- For the 2008 run, 3 days were initially provided for specific ITER support

| Topic | Experiments performed | Run time guidance (%) | Run time used (%) |
|---|---|---|---|
| Macro-stability* | 8 | 12 | 16 |
| Transport & Turbulence* | 10 | 12 | 16 |
| Boundary physics* | 11 | 12 | 18 |
| Wave-Particle Interactions | 7 | 9 | 10 |
| Solenoid-free startup* | 1 | 10 | 11 |
| Advanced scenarios | 5 | 9 | 8 |
| Cross-cutting & enabling | 12 | 13 | 12 |
| ITER support | 2 | 4 | 9 |
| Initial reserve | | 19 | |

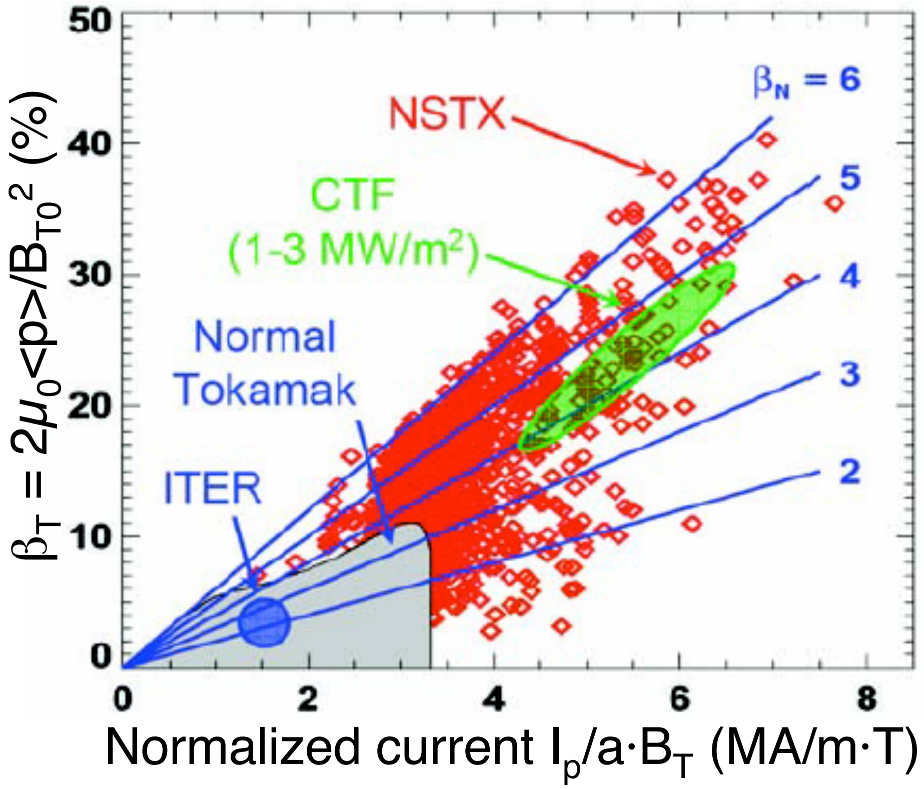
** with FY’08 milestone*

# Highlights of Results by Topical Area

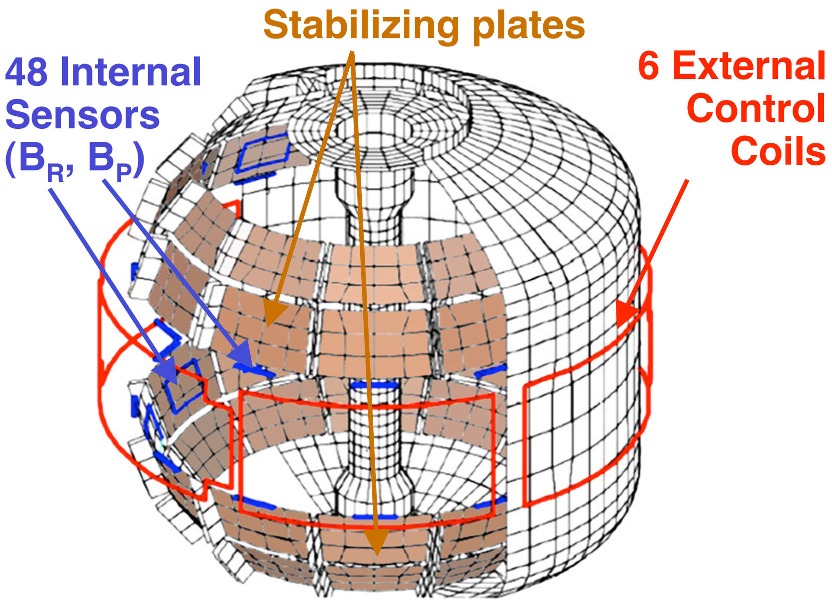
- Macrostability
  - Sustaining high normalized beta
  - Physics of neoclassical tearing modes
  - Limits for vertical stabilization
- Transport and Turbulence
- Boundary Physics
- Wave-Particle Interactions
- Solenoid-free Startup
- Advanced Scenarios and Control

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

NSTX has already demonstrated transient high $\beta_T$ and $\beta_N$



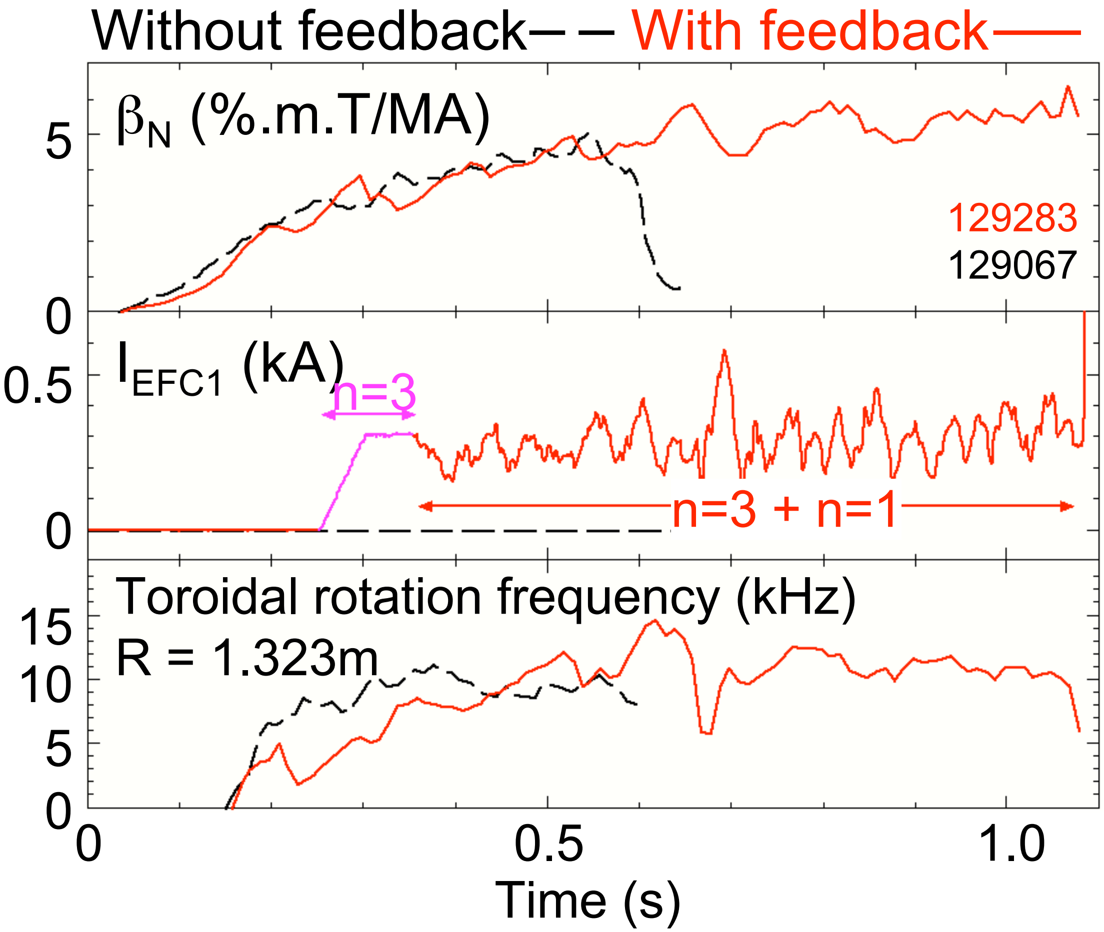
Non-axisymmetric coils provide capability to extend high-β beyond wall time



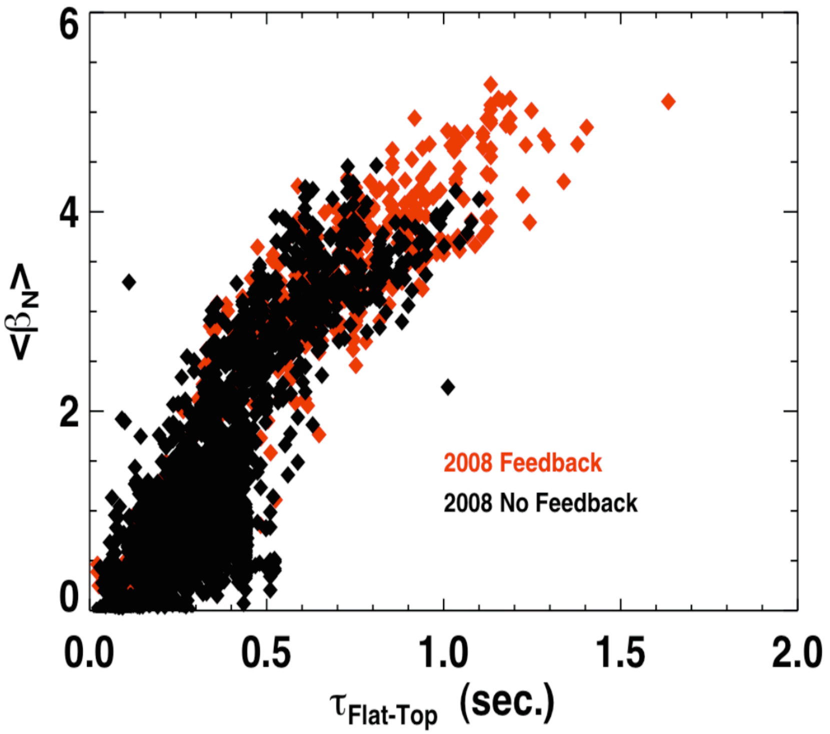
**Coils powered by 3 Switching Power Amplifiers (3.5kHz, 1kA)**

- Experiments have attempted to optimize benefits of
  - Correcting intrinsic field errors which damp plasma rotation
  - Suppressing Resonant Field Amplification and Resistive Wall Modes
  - This year investigated n = 2 (4) error-field correction as well as n = 1, 3

# Correction of n = 3 Error Field Plus Feedback Control of n = 1 Mode Reliably Extends Duration of High-$\beta_N$ Plasmas

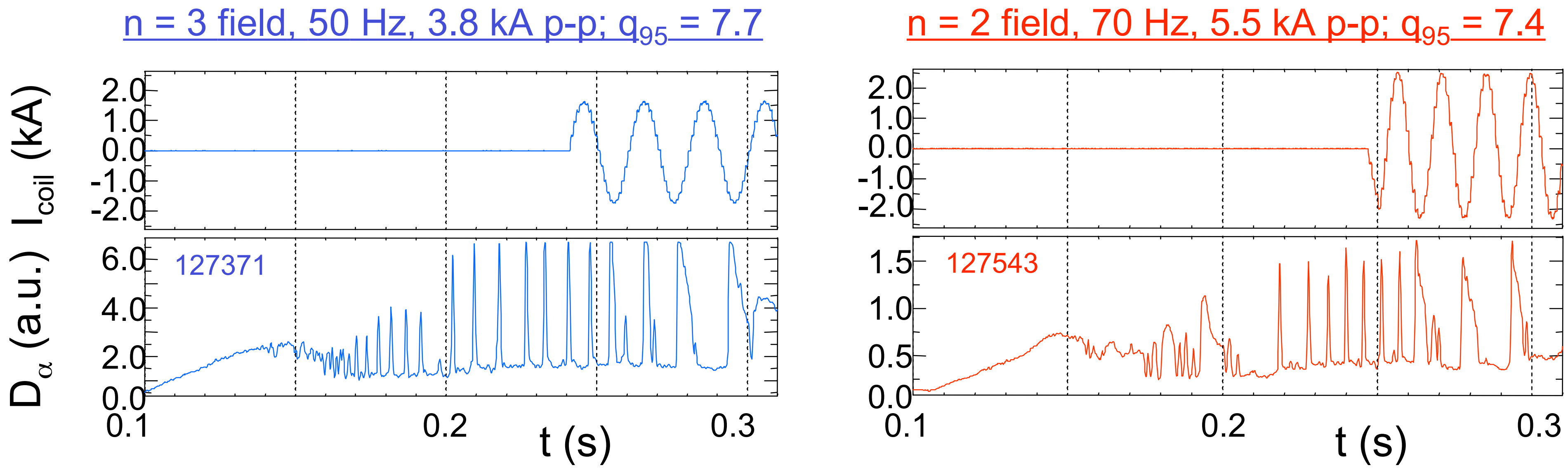


Optimized feedback scheme <u>applied routinely in 2008</u>



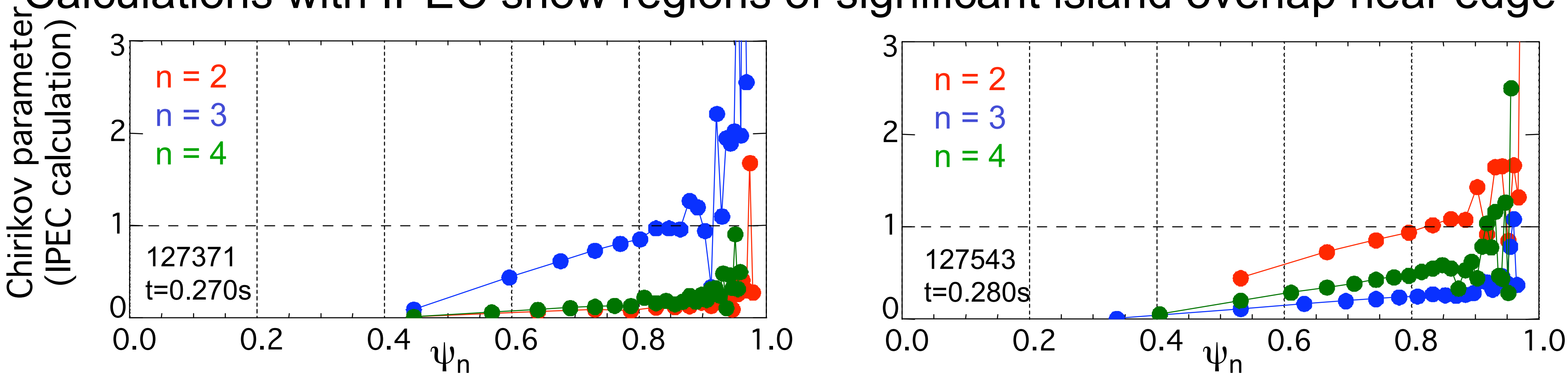
- Correction of n = 3 intrinsic error field maintains toroidal rotation
- Feedback on measured n = 1 mode reliably suppresses RWM growth
  - Limitations on time response and applied mode purity explored for ITER
- Intrinsic n = 2 field error found to be small: no correction necessary

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


n = 3 field, 50 Hz, 3.8 kA p-p; $q_{95}$ = 7.7

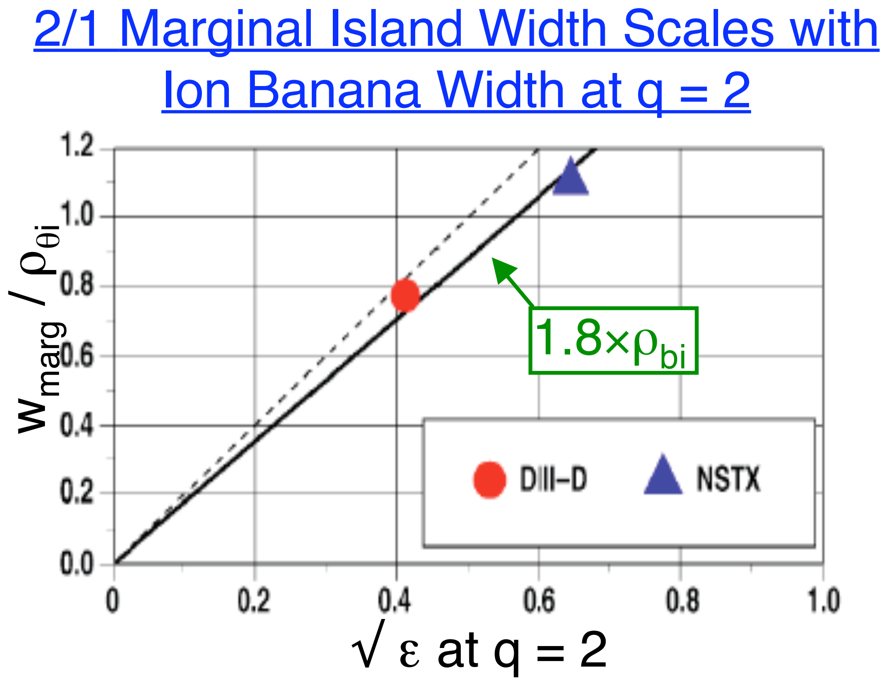
n = 2 field, 70 Hz, 5.5 kA p-p; $q_{95}$ = 7.4

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

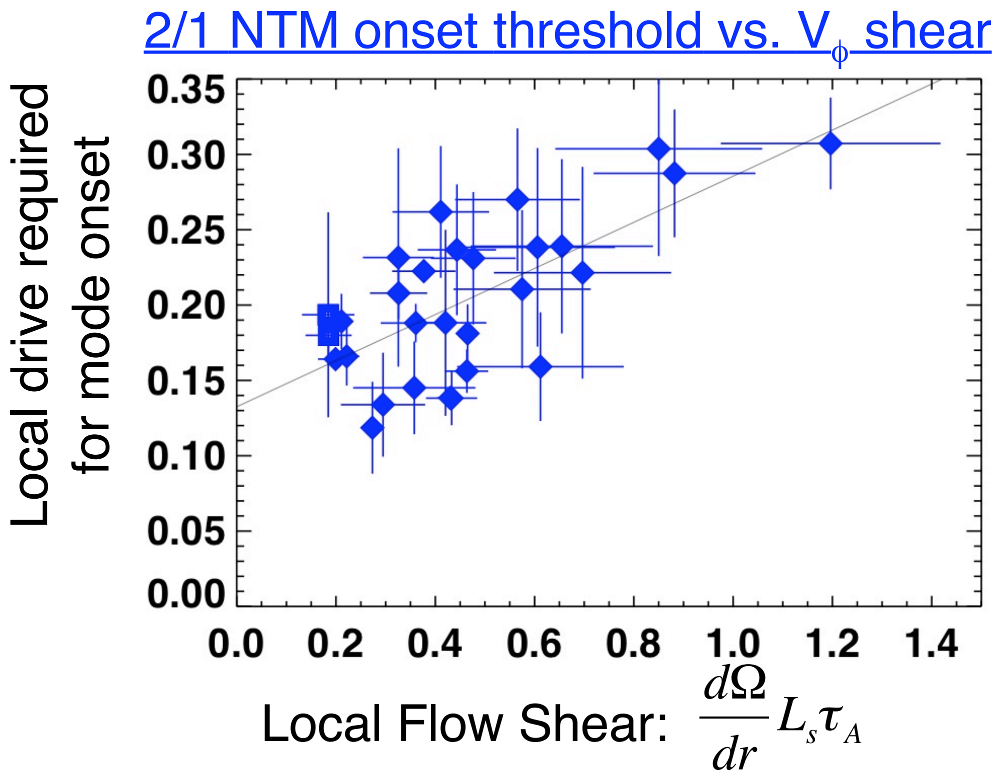


- Tried quasi-steady pulses & mixed n = 2+3 spectrum with similar results

# Experiments Coordinated with DIII-D 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. $V_\phi$ shear

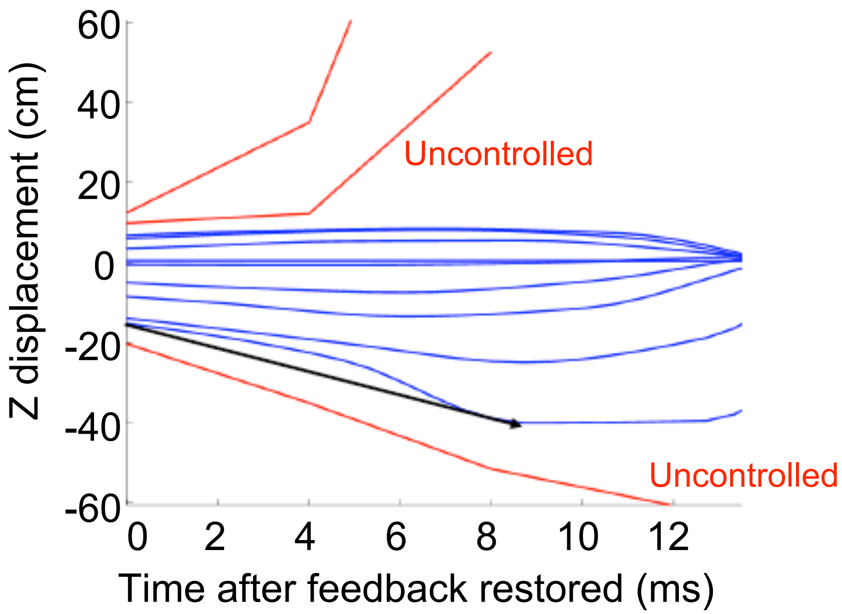
- Local mode drive ∝ $\mu_0 \langle \vec{J} \cdot \vec{B} \rangle_e L_q \big/ \langle B_\theta \rangle$ ∝ local $\beta_p$
- Flow shear variation achieved by different NBI and *n* = 3 braking
  - Correlation with flow velocity itself is weaker
- Trend likely due to dependence of Δ’ on local flow shear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

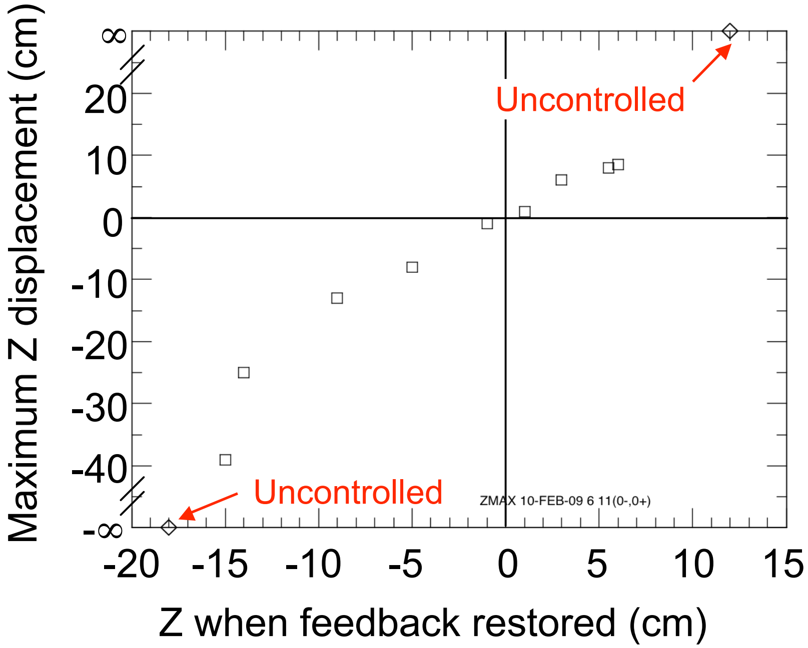
J(08)

S. Gerhardt, R. La Haye, R. Buttery

# Dedicated Experiment Measured Maximum Restorable Vertical Displacement for ITER

- Tolerable level of vertical displacement is a critical issue for ITER design
- NSTX experiment measured maximum excursion when vertical feedback was restored after an interval in which the plasma was allowed to drift vertically with feedback off



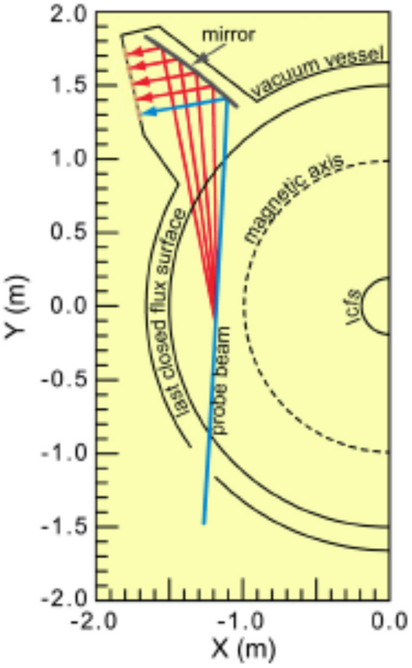


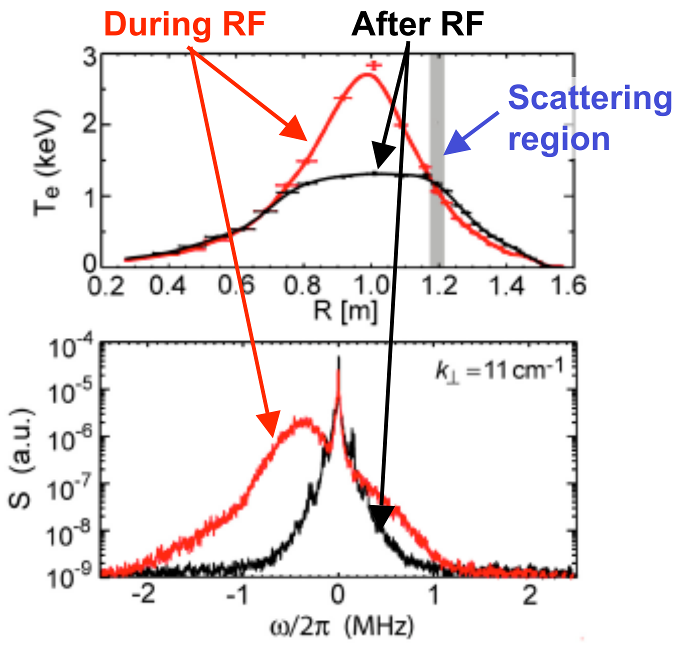
- NSTX response is not up/down symmetric
- $\Delta Z_{max}$ = **15.0** cm for downward, **6.6** cm for upward motion
- $\Delta Z_{max}/a$ = **23%** for downward, **10%** for upward motion

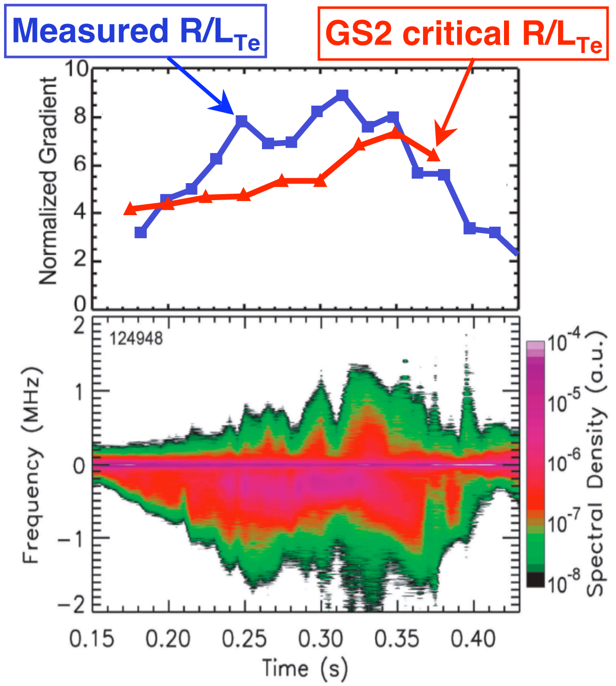
# Highlights of Results by Topical Area

- Macrostability
- Transport and Turbulence
  - Exploring the causes of anomalous electron thermal transport
  - Measurements of plasma flow and momentum transport
- Boundary Physics
- Wave-Particle Interactions
- Solenoid-free Startup
- Advanced Scenarios and Control

# High-k Fluctuations Occurring During RF Heating Consistent with Electron Temperature Gradient Modes



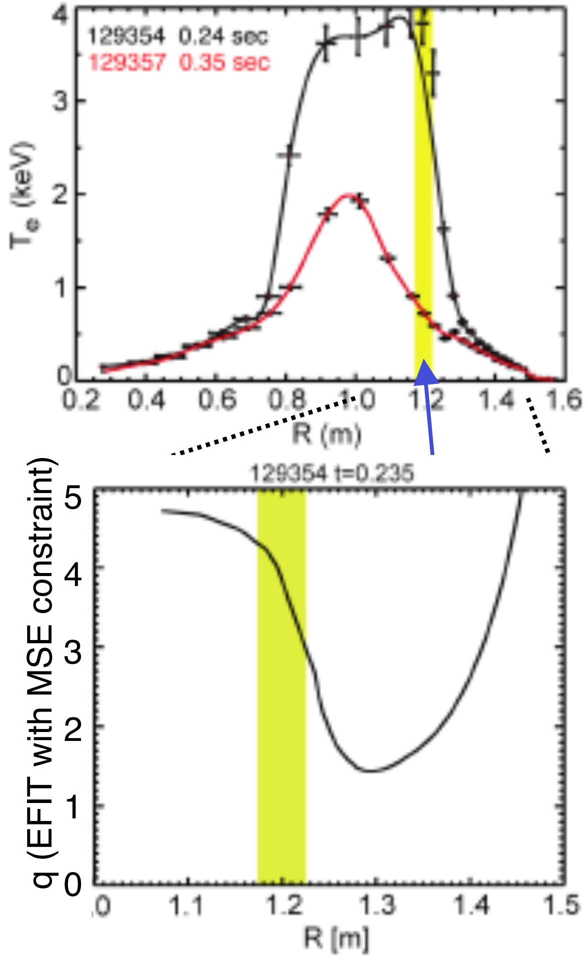


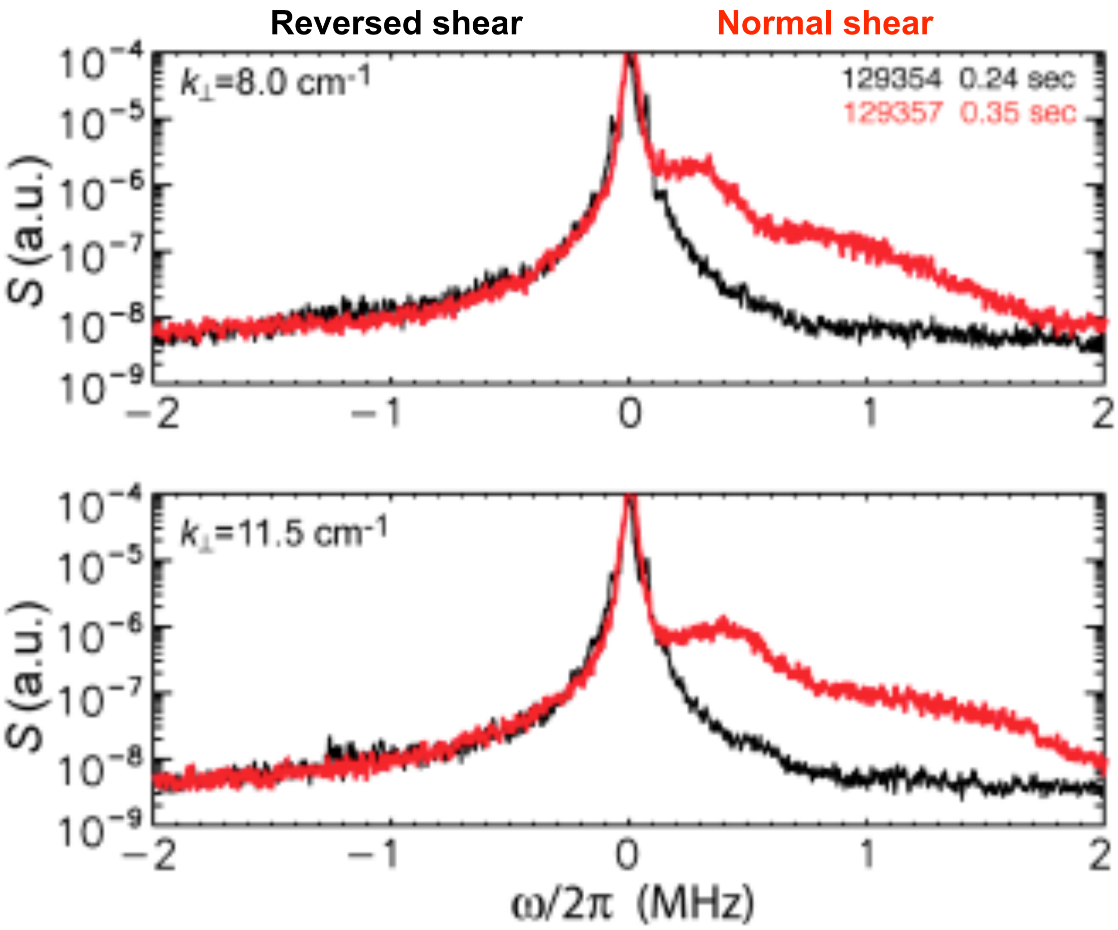


- Detected fluctuations in range $k_\perp\rho_e = 0.1 - 0.4$ ($k_\perp\rho_s = 8 - 16$) propagate in electron diamagnetic drift direction in plasma frame
  - Rules out ITG/TE modes ($k_\perp\rho_s \leq 1$) as source of turbulence
  - Agreement with linear gyrokinetic code GS2 for **ETG mode** onset

E. Mazzucato, D. Smith

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



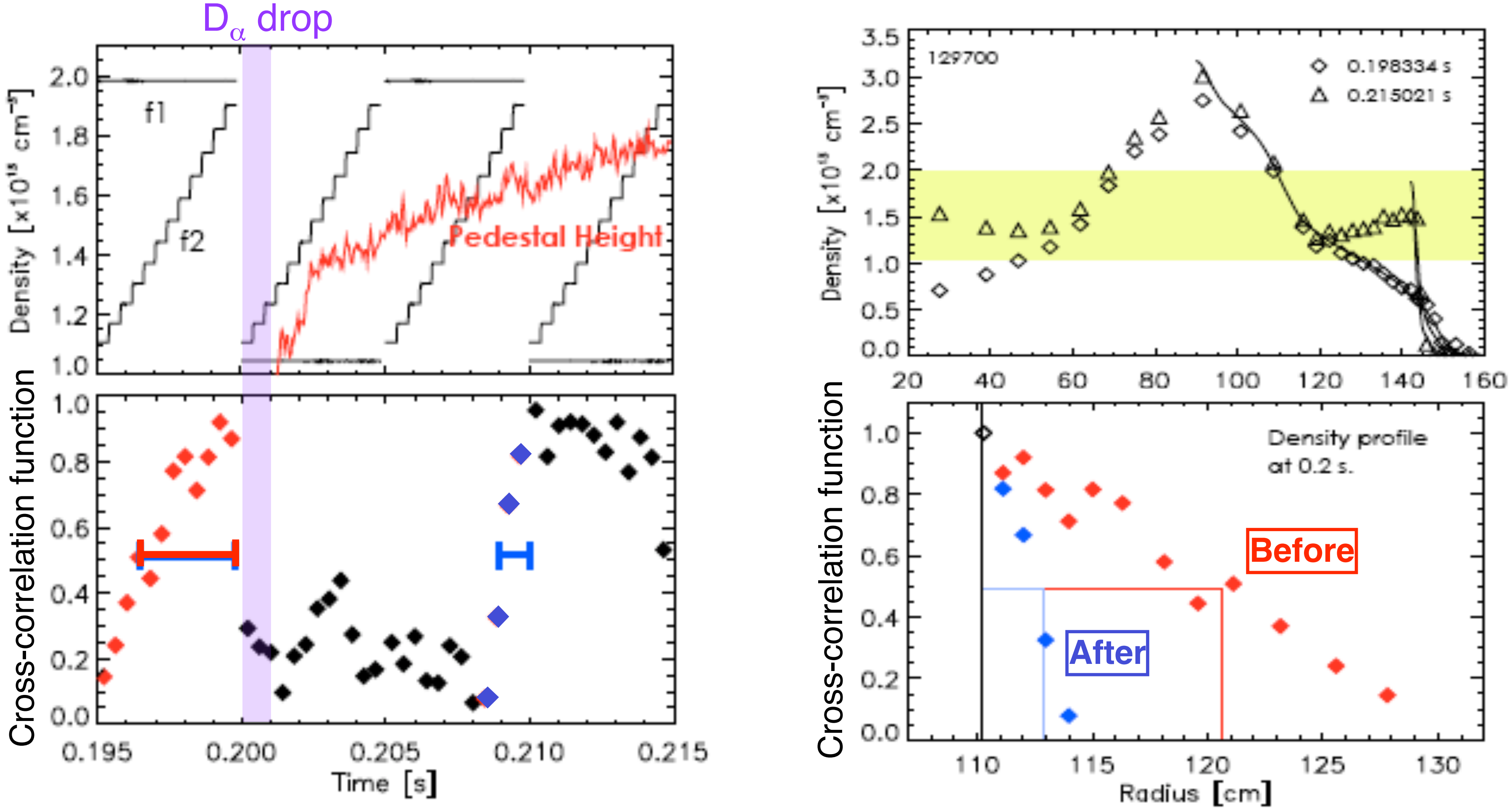


- Suppression of ETG by shear-reversal predicted by Jenko & Dorland (2002)
- Also investigating role of μ-tearing modes and GAE on e-transport in core

*E. Mazzucato, H. Yuh*

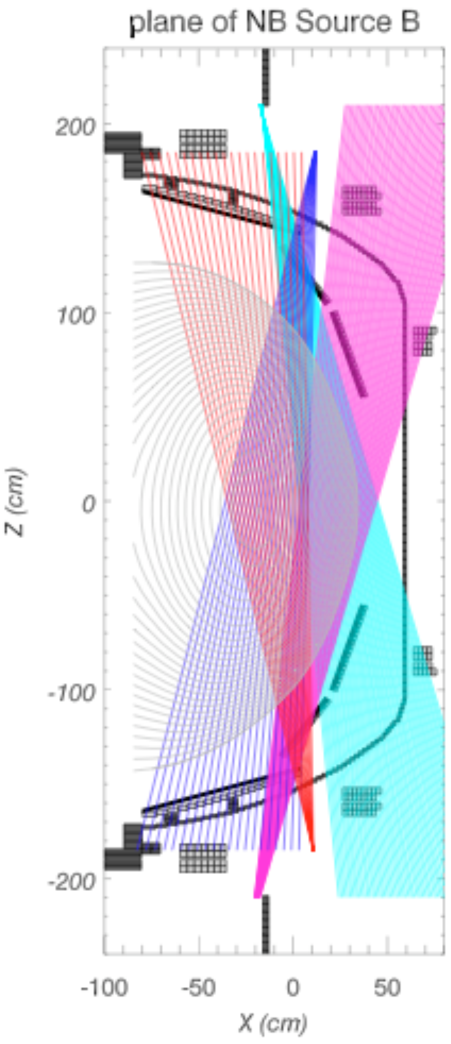
# Measured Change in Core Low-k Turbulence Across H-mode Transitions in Ohmically Heated Plasmas

- Use fixed/swept frequency correlation reflectometer during period with monotonic density profile following H-mode transition



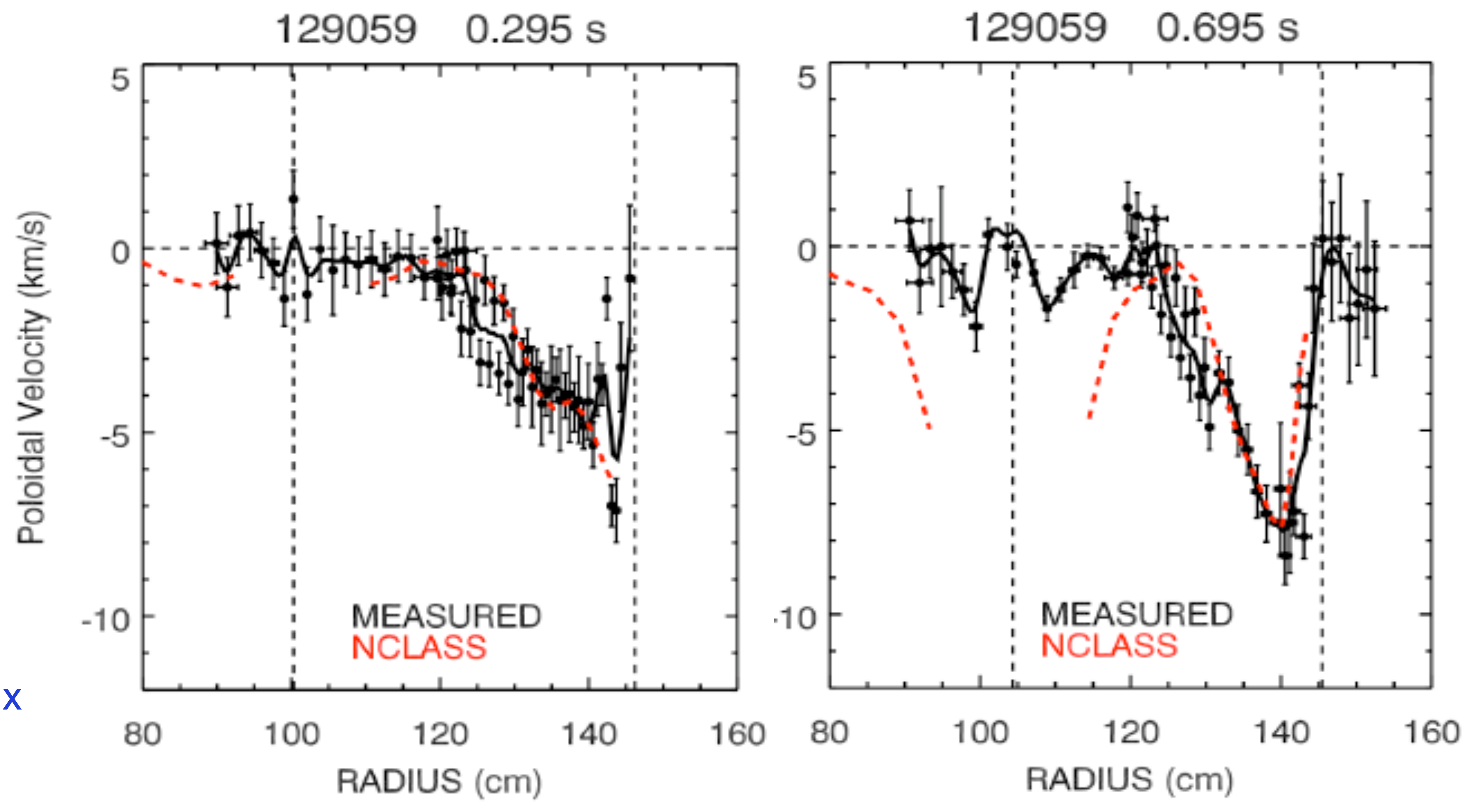
- Radial correlation length of fluctuations reduced by factor 3 - 4 after transition
  - Other fluctuation characteristics change little

# Initial Analysis of PCHERS Data Suggests Poloidal Velocity is Consistent with Neoclassical Prediction



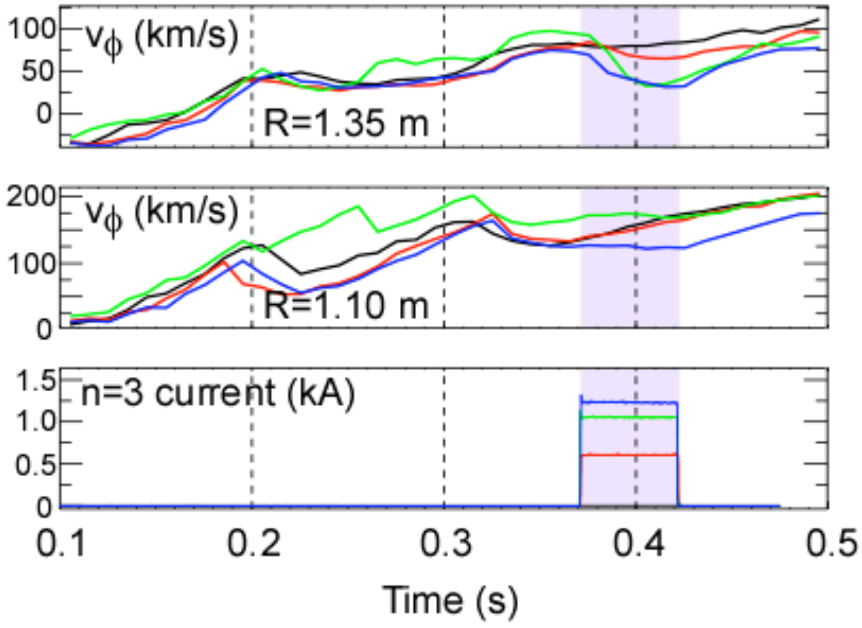
PCHERS sightlines and flux surfaces projected onto common poloidal plane

- PCHERS took data for all shots with NBI in 2008
- Full photometric calibration performed at end of run
- First analysis produces weighted chord average $v_\theta(R,t)$
- Now developing inversion to obtain local measurement



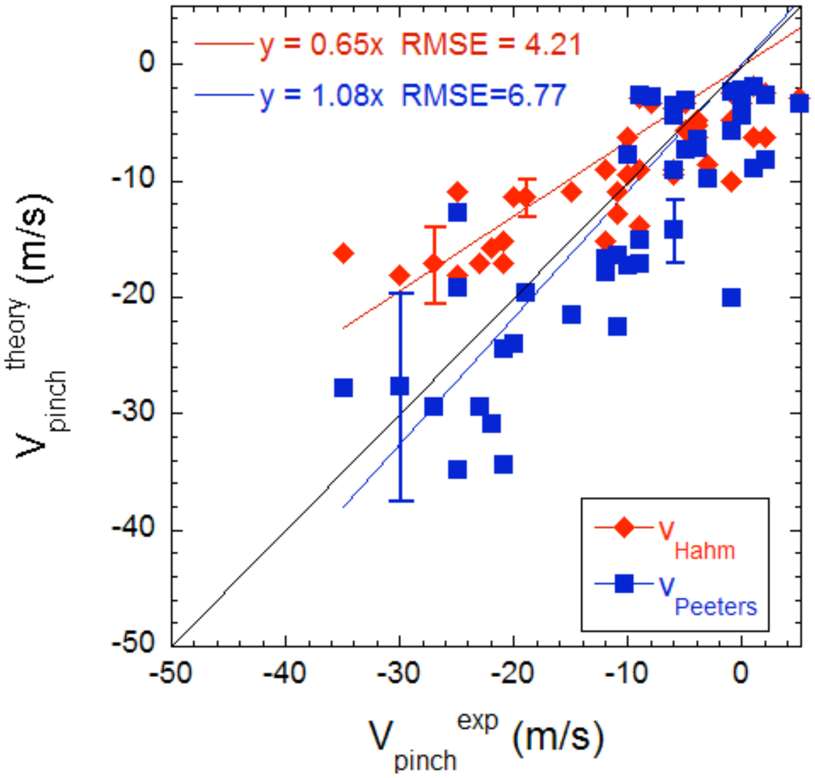
# Investigated Momentum Transport Using Transient Perturbations to Separate Diffusivity and Pinch Terms

- n = 3 braking pulses perturb rotation in outer region



- Determine $\chi_\phi$, $v_{pinch}$ after turn-off of n=3 pulse
  - NBI provides only known torque (calculated by TRANSP)

- Inferred pinch velocities in outer region agree reasonably well with theories based on low-k turbulence



Peeters *et al.* (PRL, 2007)
Hahm *et al.* (PoP, 2007)

# Highlights of Results by Topical Area

- Macrostability

- Transport and Turbulence

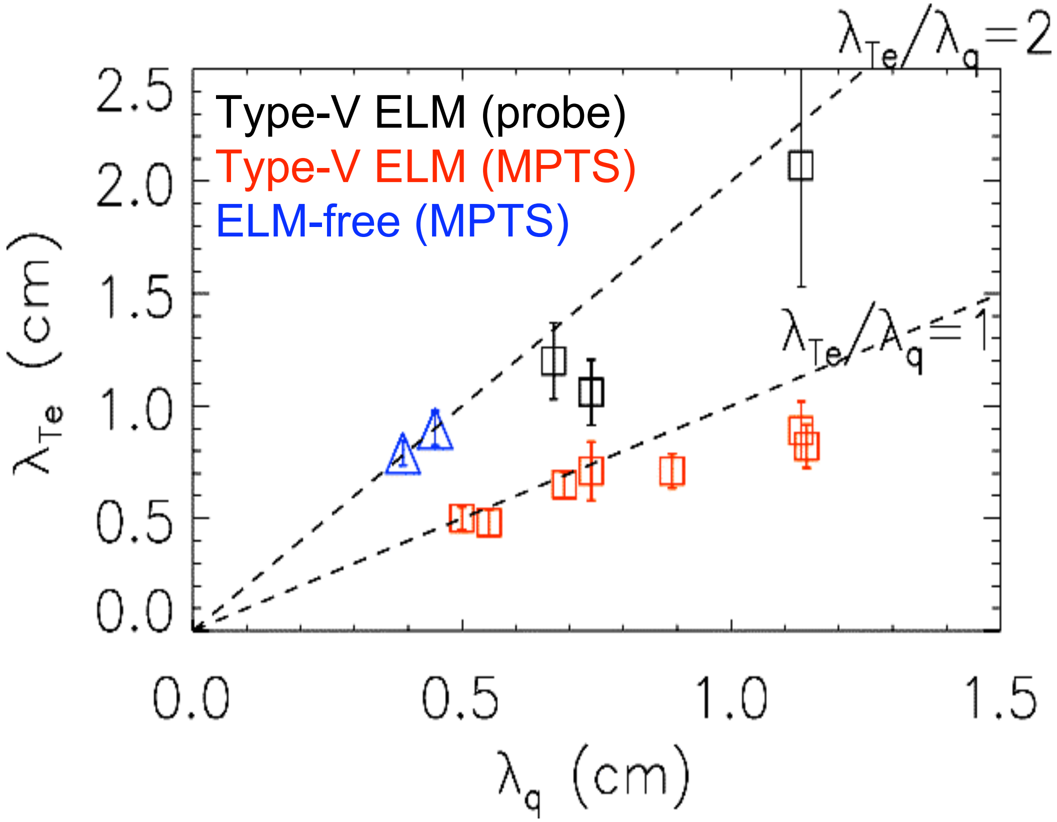
- Boundary Physics
  - Characterizing scrape-off layer transport and mitigating divertor heat fluxes
  - Effects of lithium coating of plasma-facing components
- Wave-Particle Interactions

- Solenoid-free Startup

- Advanced Scenarios and Control

# Fast Reciprocating Probe, MPTS and IR Camera Data Used to Characterize SOL Transport

- Fast reciprocating probe and MPTS measure $T_e$, $n_e$ profiles in SOL ⇒ $\lambda_{Te}$
- Map radial profile of divertor power flux from IR to midplane ⇒ $\lambda_q$
- In far SOL, add an offset to exponential to fit data satisfactorily
  - Possible consequence of intermittent “blob” transport in this region



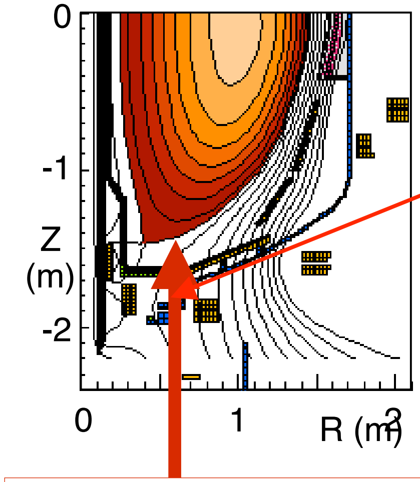
- If e-conduction is dominant

$$\lambda_{Te}/\lambda_q = \frac{7}{2}\left(\frac{T_e - T_{e1}}{T_e - Cq_1T_e^{-5/2}}\right)$$

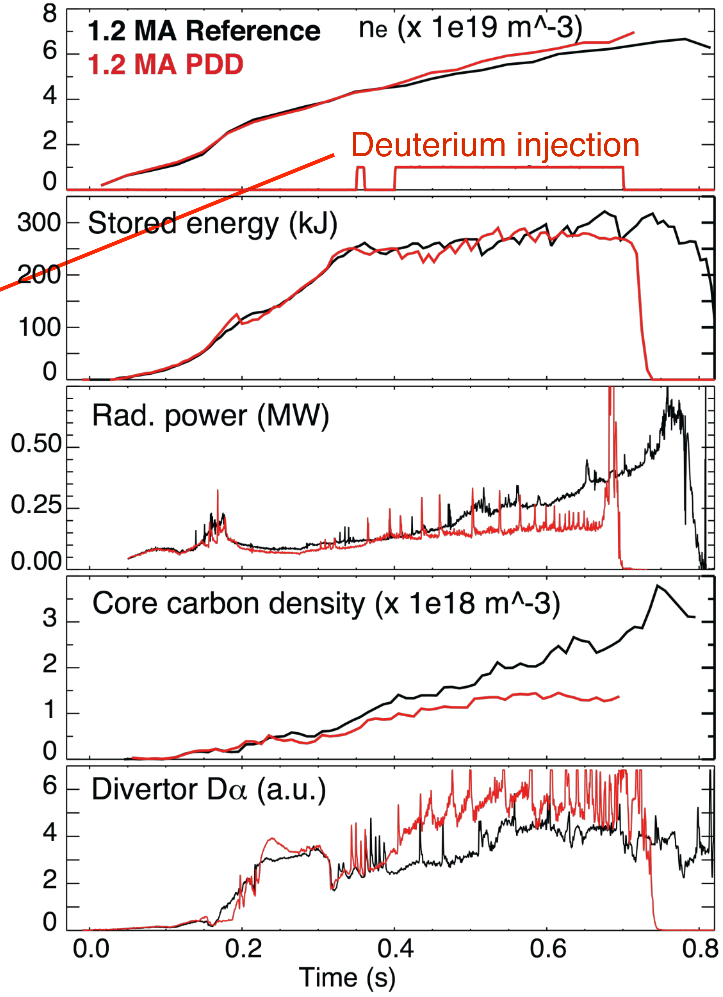
expected, assuming constant temperature $T_{e1}$ and heat flux $q_1$ in far SOL

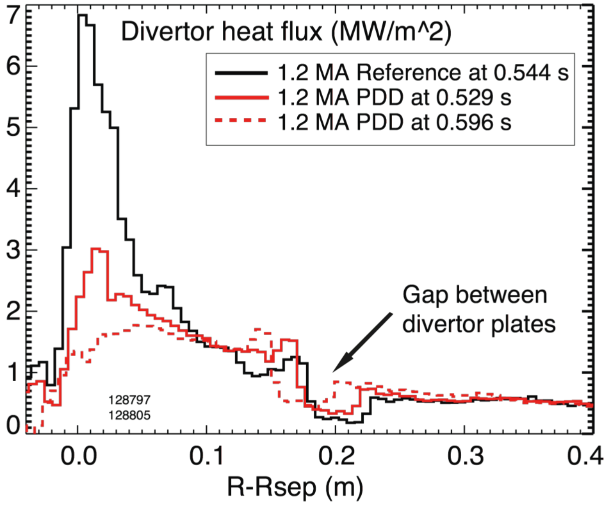
⇒ $\lambda_{Te}/\lambda_q \sim 2$

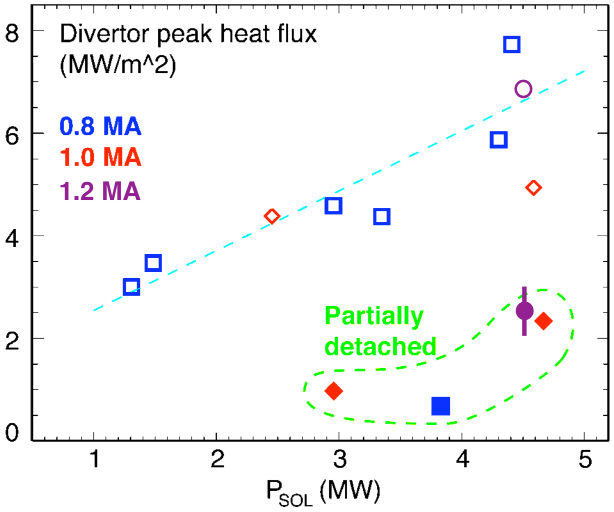
# Reduction of Peak Divertor Heat Flux by Partial Divertor Detachment Extended to High Current



Deuterium puffed through CHI gap into divertor SOL



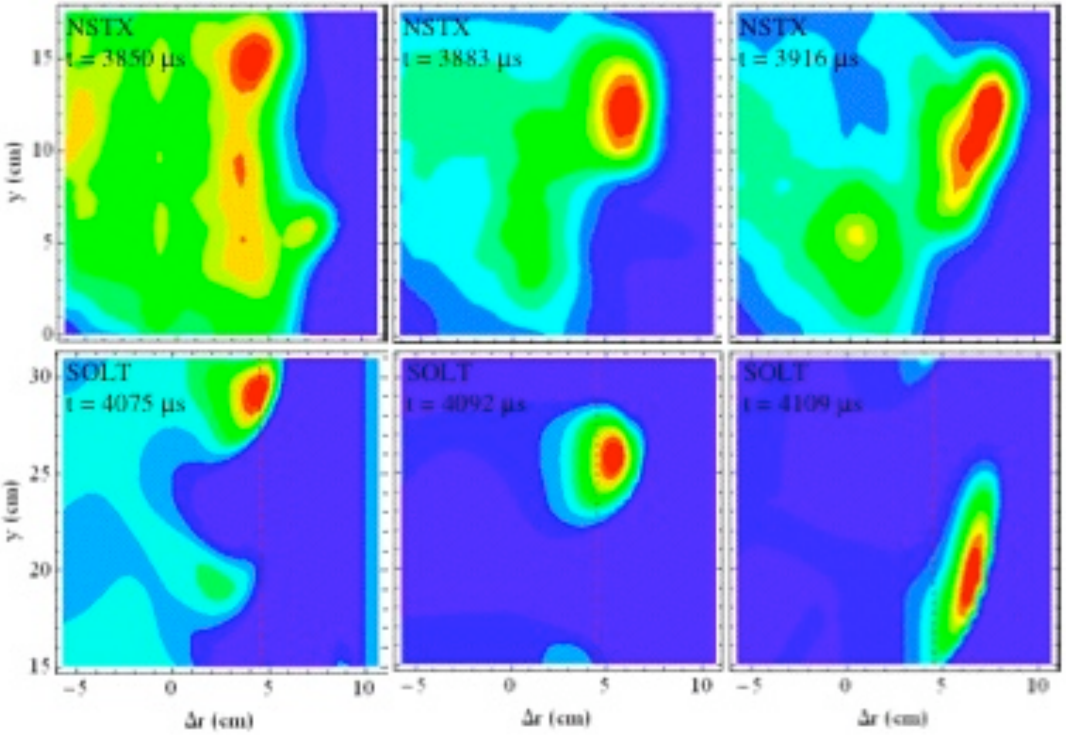




- Extended favorable results previously obtained for high-triangularity (high flux expansion) H-mode discharges at 0.8 – 1.0 MA
- Core radiation and carbon density reduced during partial detachment

# Simulations of “Blob” Propagation in NSTX SOL Reproduce Measured Characteristics

- **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



Gas-puff imaging (GPI) data

Modeled propagation of density “blob”

*D. A. D’Ippolito , IAEA FEC, 2008*

# Continued Exploring and Developing Lithium-Coated Plasma Facing Components

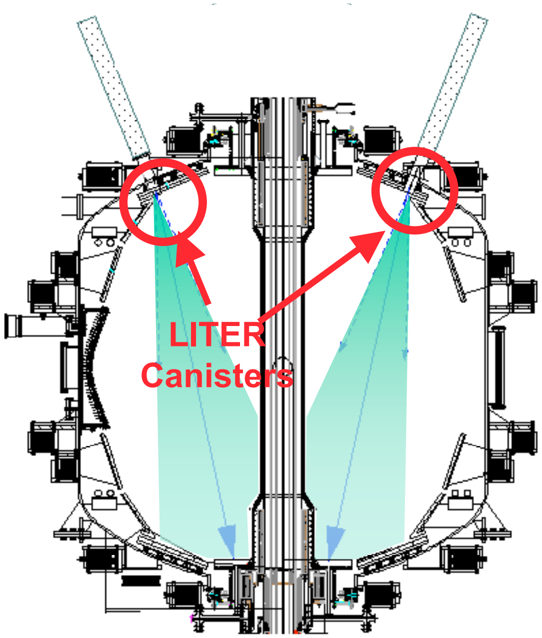
**2005**: Injected lithium pellets, 2 - 5 mg, into He discharges prior to D NBI shot

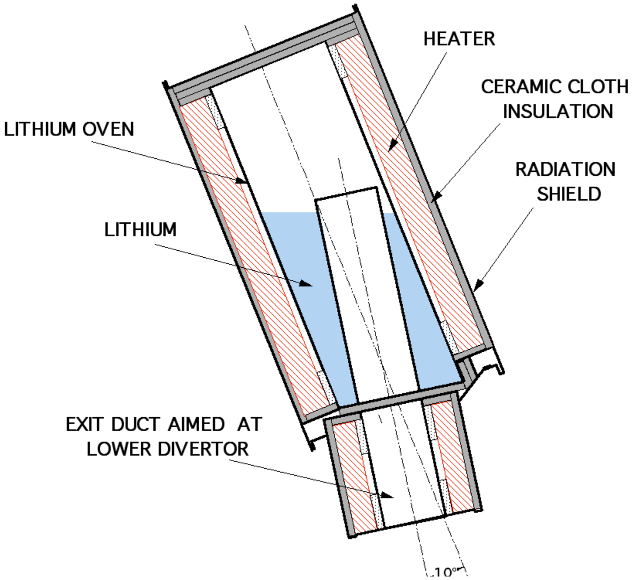
**2006**: LIThium EvaporatoR (LITER) deposited lithium on divertor between shots

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

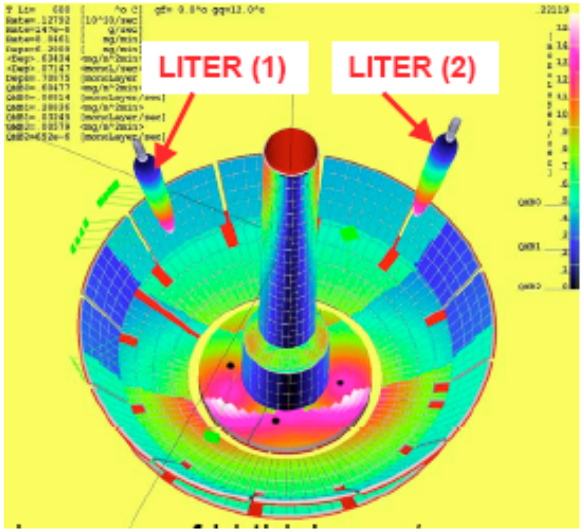
**2008**: Dual LITERs covered entire lower divertor; shutters interrupted lithium stream during plasmas; evaporated ~200g lithium (reloaded 3 times)

- Also used “lithium powder dropper” to introduce lithium through SOL

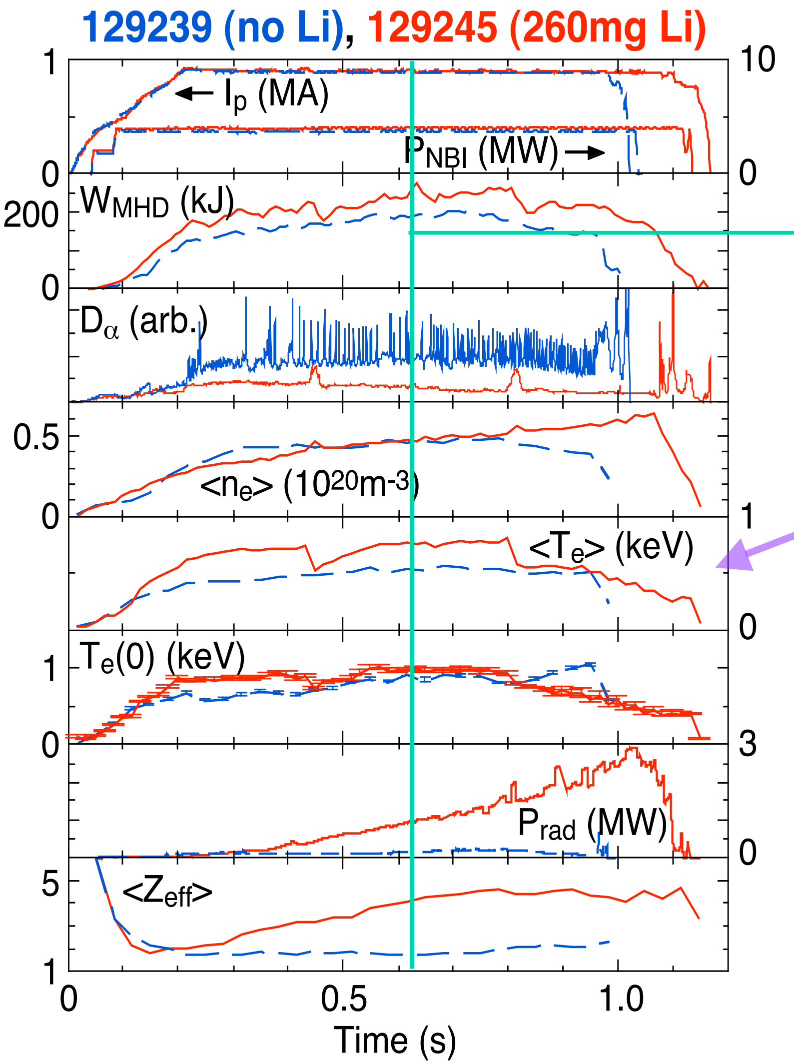




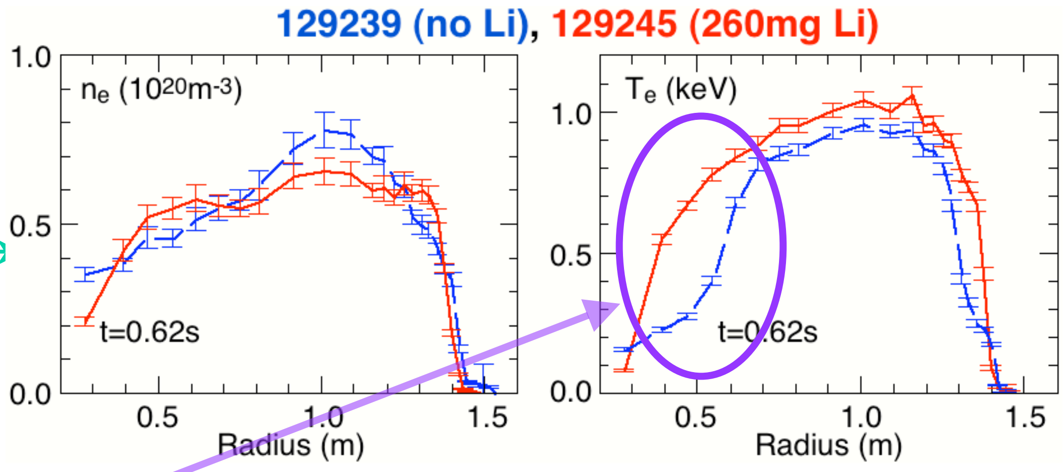
Modeled deposition pattern



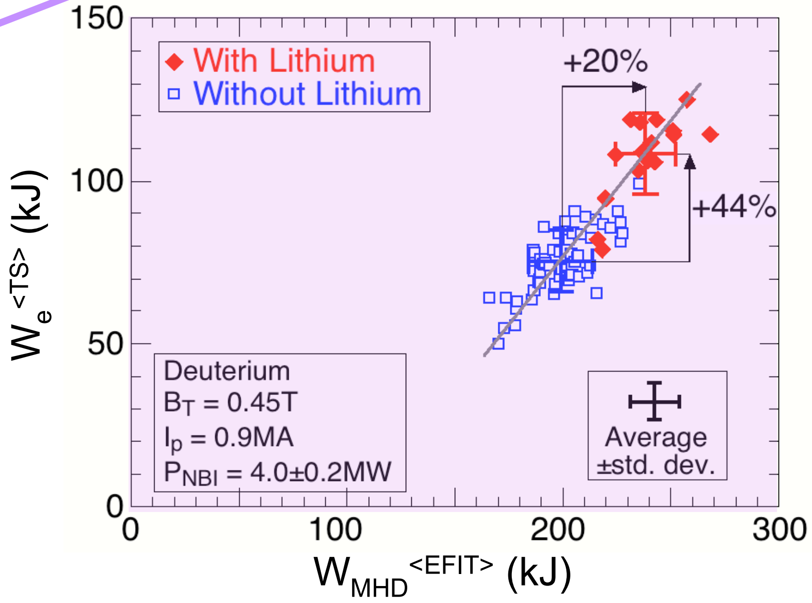
# Solid Lithium Coating Reduces Deuterium Recycling, Suppresses ELMs, Improves Confinement



129239 (no Li), 129245 (260mg Li)



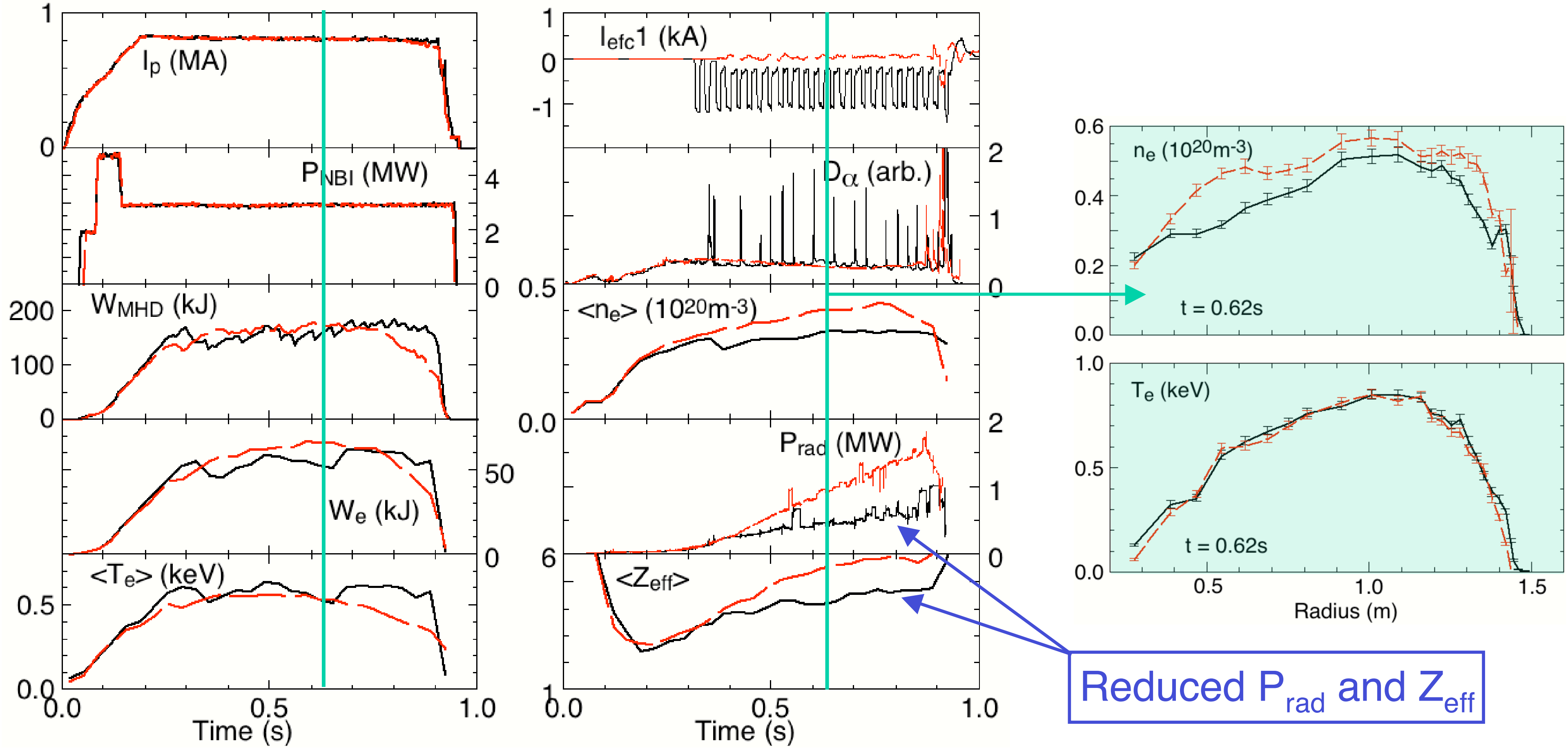
129239 (no Li), 129245 (260mg Li)



- Without ELMs, impurity accumulation increases $P_{rad}$ and $Z_{eff}$
- New CHERS data show lithium concentration small: ~ 0.1%

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

- Stability analysis (PEST/ELITE) indicates reduction of edge $n_e$, $P_e$ gradients responsible for stabilization of ELMs by lithium coating



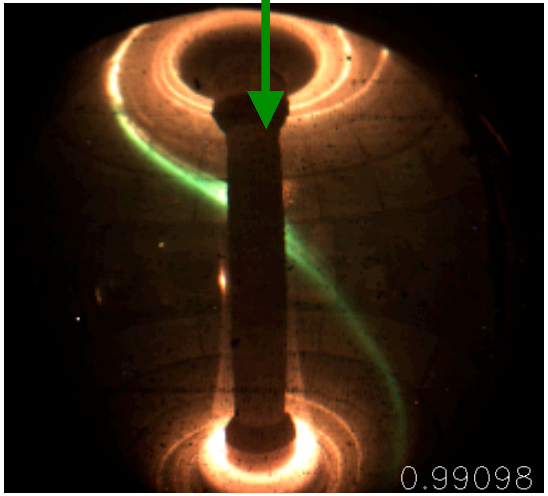
Reduced $P_{rad}$ and $Z_{eff}$

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

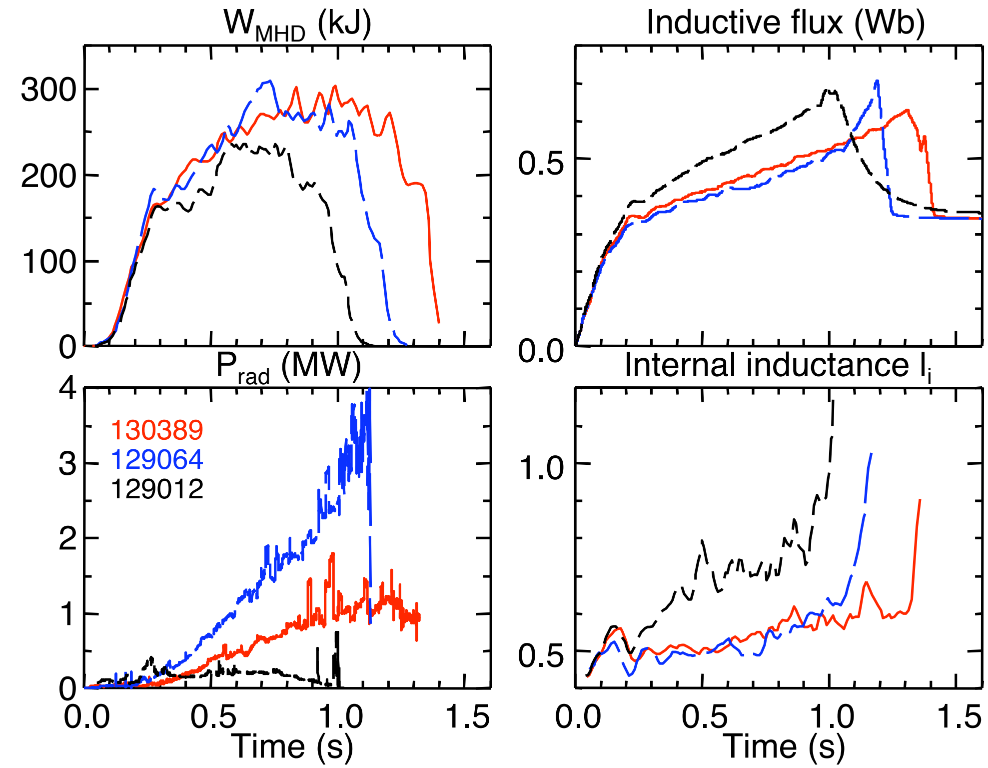
# Lithium Coating by Dropping a Stream of Lithium Powder into SOL Produced Similar Benefits to LITER

- 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; 700 mg LITER; 7 mg Powder



D. Mansfield

# Highlights of Results by Topical Area

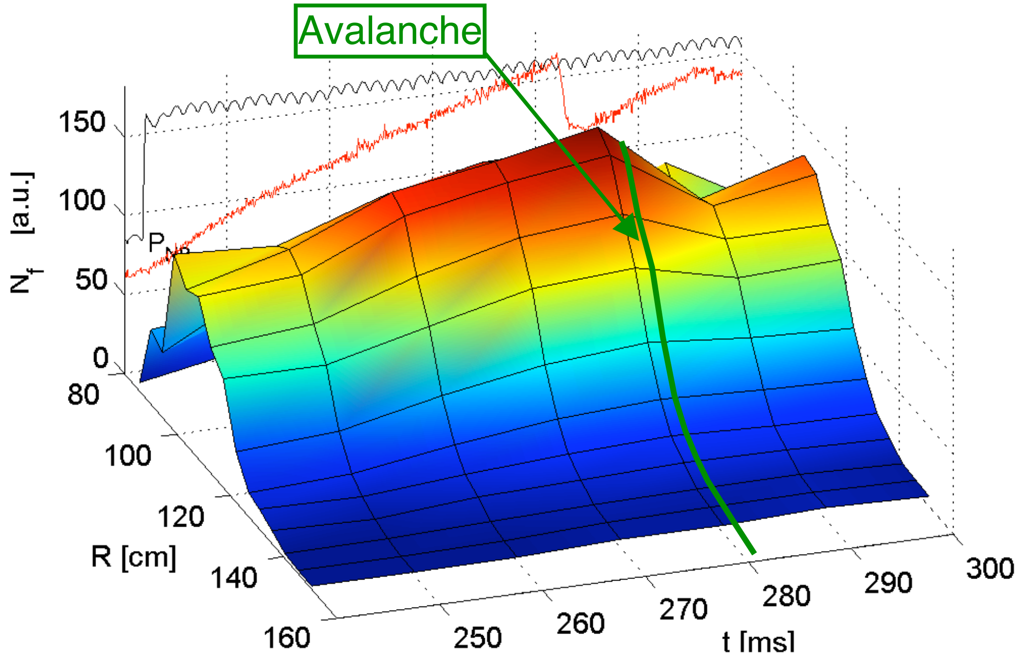
- Macrostability
- Transport and Turbulence
- Boundary Physics
- Wave-Particle Interactions
  - Transport associated with Alfvén-wave modes
  - Improving coupling of RF power for heating and current drive
- Solenoid-free Startup
- Advanced Scenarios and Control

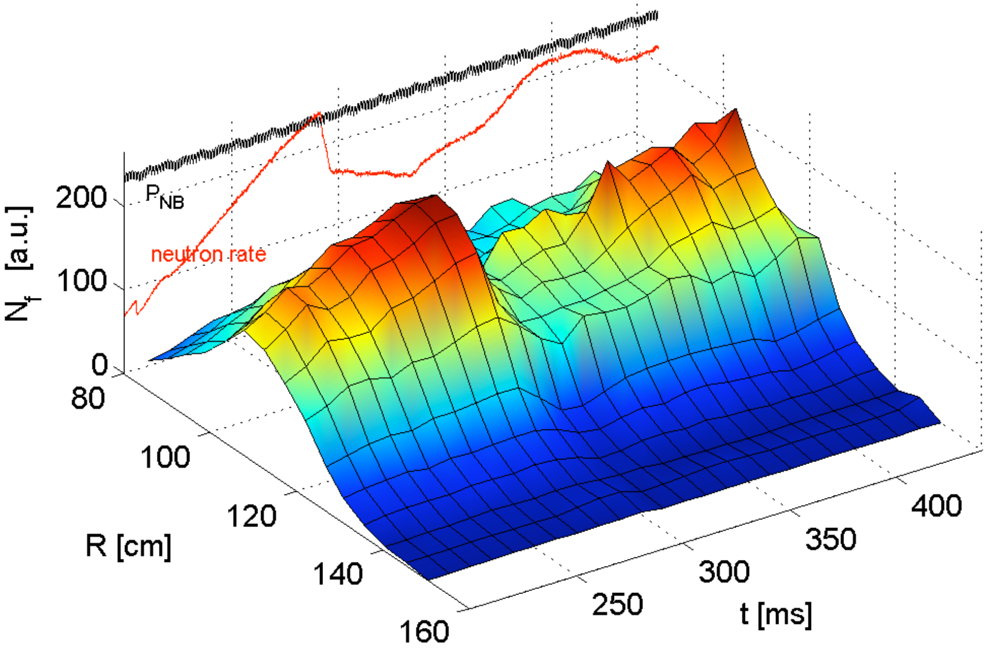
# New Fast-Ion Deuterium-Alpha (FIDA) Diagnostic Measured Response of Fast Ions to MHD Modes

- Density profile of fast ions (15 – 65 keV) deduced from Doppler-shifted $D_\alpha$ 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





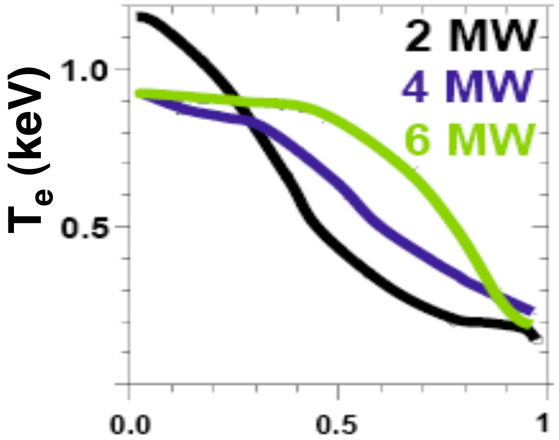
M. Podestá, W. Heidbrink

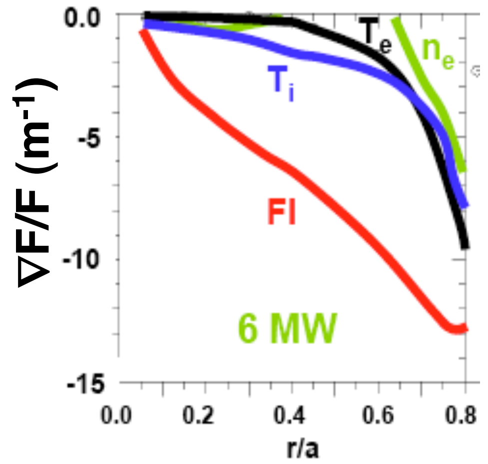
# Investigating Role of High-Frequency Modes in Core Electron Transport

- Observe “flat $T_e$” region in core of plasmas with high NBI power

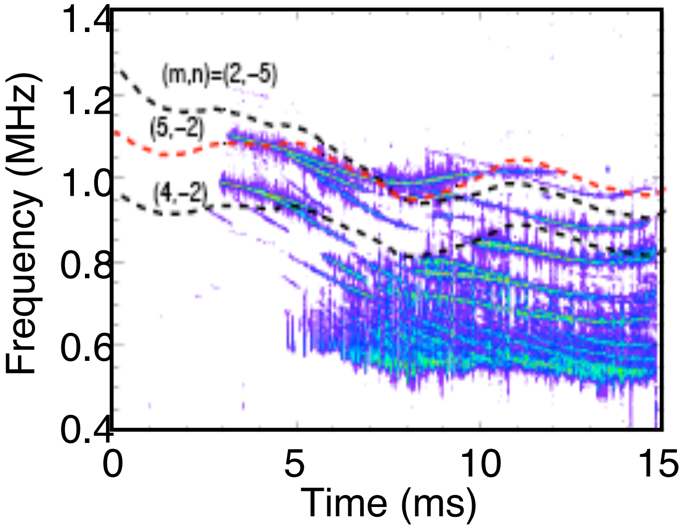
⇒Implies mechanism for electron transport *not* driven by $T_e$ gradient

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





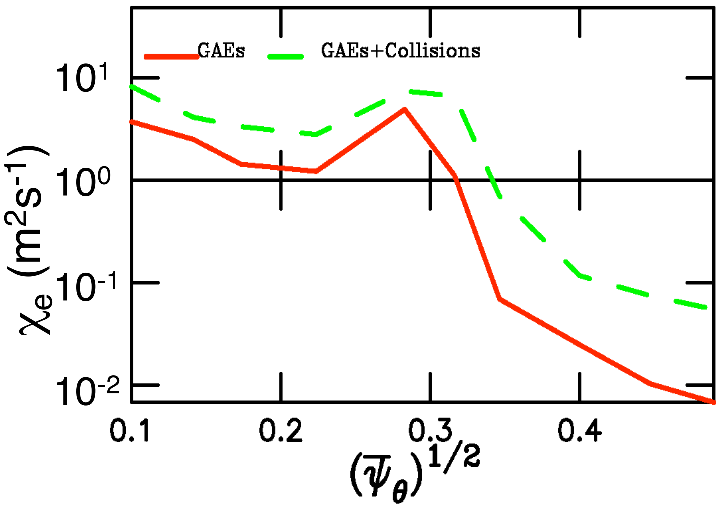
$$\omega_{GAE} \simeq v_{A0}(m - nq_0)/q_0 R.$$



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

## Modeling with ORBIT code

- Used 14 GAEs n = 1–8; m so f = 0.4–0.6 MHz
- Peak amplitude $\xi_r/R \sim 4\times10^{-4}$ consistent with reflectometry



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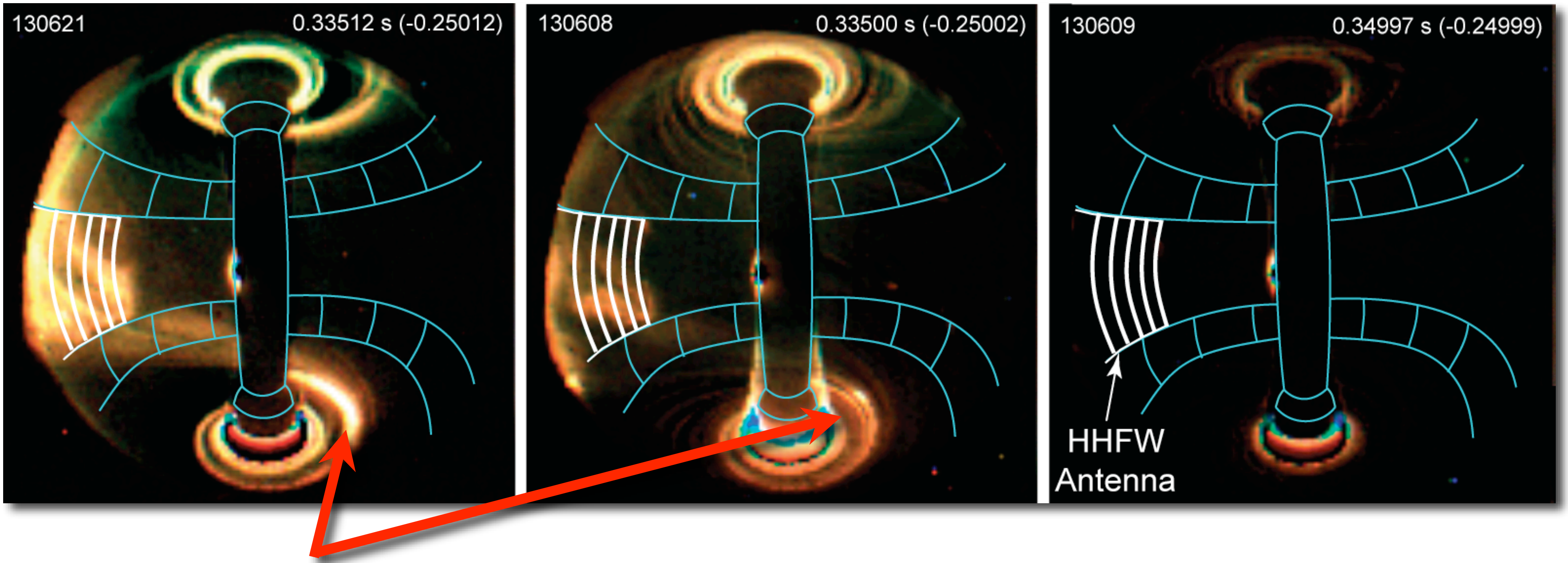
# Fast Camera Shows Strong Interaction Between HHFW Antenna & Divertor Along Field Lines

- Dependence on launched wave spectrum, field and edge density consistent with onset of wave propagation in SOL in front of antenna: $n_{crit} \propto B \times k_{||}^2/\omega$

$P_{HHFW}$ = 1.8 MW, $P_{NBI}$ = 2 MW, $I_p$ = 1 MA, $B_T$ = 0.55 T　　Without RF

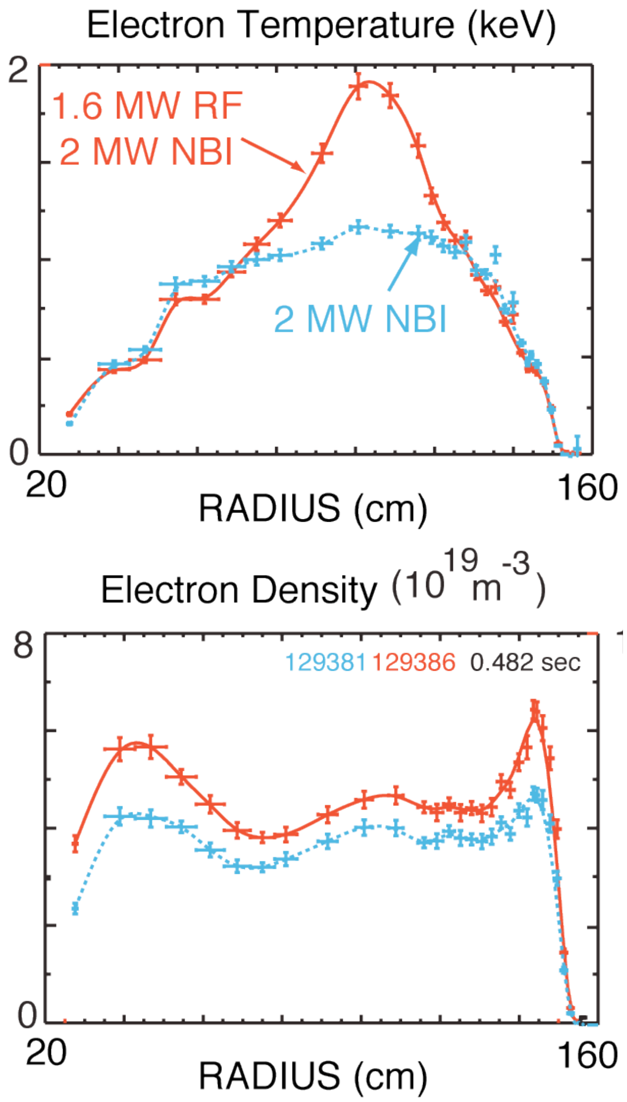
$\Delta\phi = -90°$, $k_{||} \approx 7\ m^{-1}$　　$\Delta\phi = -150°$, $k_{||} \approx 12\ m^{-1}$



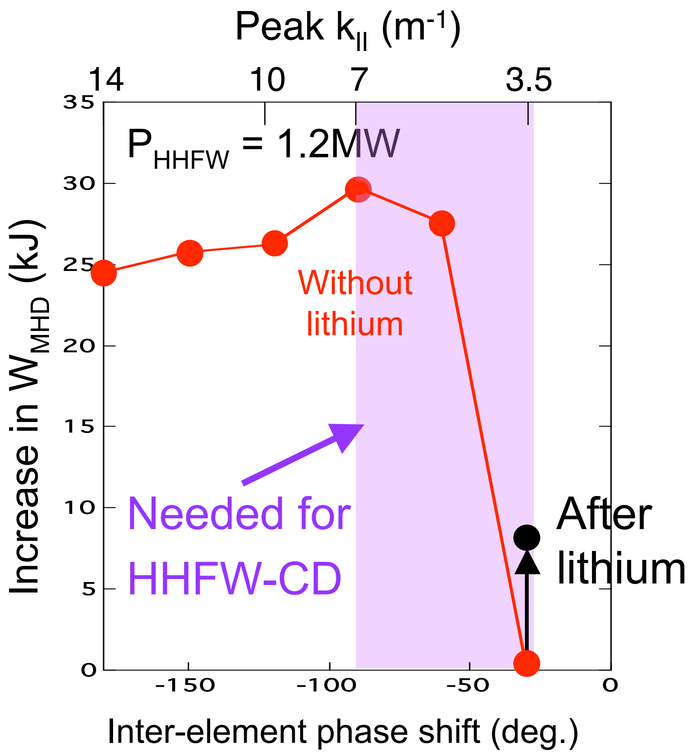
- Divertor “hotspot” more pronounced and persistent for $k_{||} \approx 7\ m^{-1}$ than $12\ m^{-1}$
- ITER issue: ICRH antenna designed for low $k_{||}$, so $n_{crit} \sim 1.4 \times 10^{18} m^{-3}$

# Lithium Coating Improves HHFW Heating Efficiency in NBI H-Modes and at Low $k_{||}$ for Current Drive

## Core Electron Heating in Deuterium NBI H-Mode



## Electron Heating by HHFW in Deuterium L-Mode



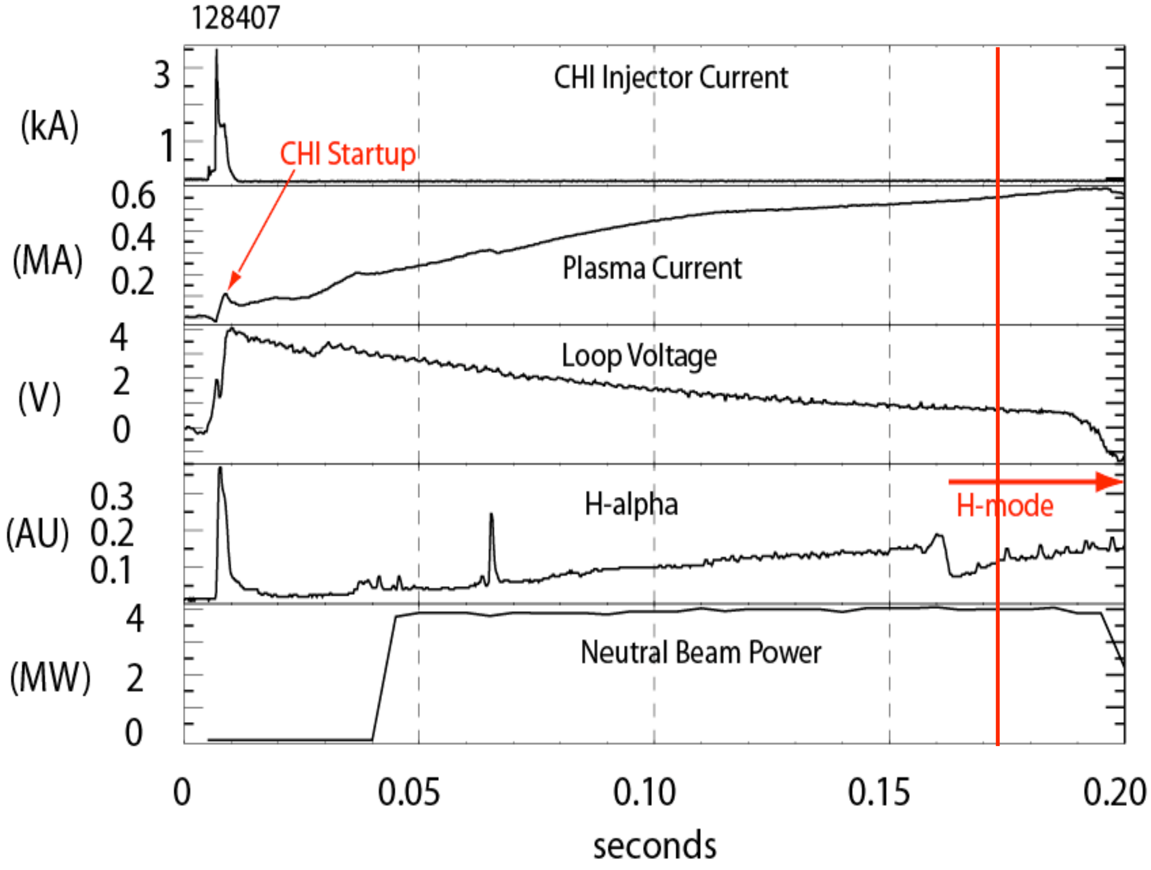
- Reflectometer measures reduced SOL density in front of antenna with lithium
  - Consistent with suppression of parasitic surface waves

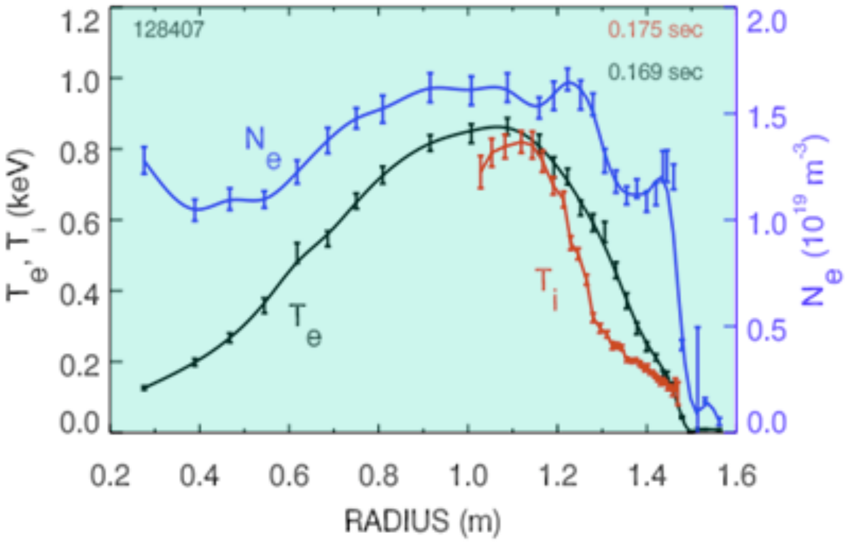
G. Taylor, P. Ryan, J. Hosea

# Highlights of Results by Topical Area

- Macrostability
- Transport and Turbulence
- Boundary Physics
- Wave-Particle Interactions
- Solenoid-free Startup
  - Transition from CHI initiation to inductive ramp-up
- Advanced Scenarios and Control

# CHI Initiated Discharge Successfully Coupled to Inductive Ramp-up with NBI and HHFW Heating

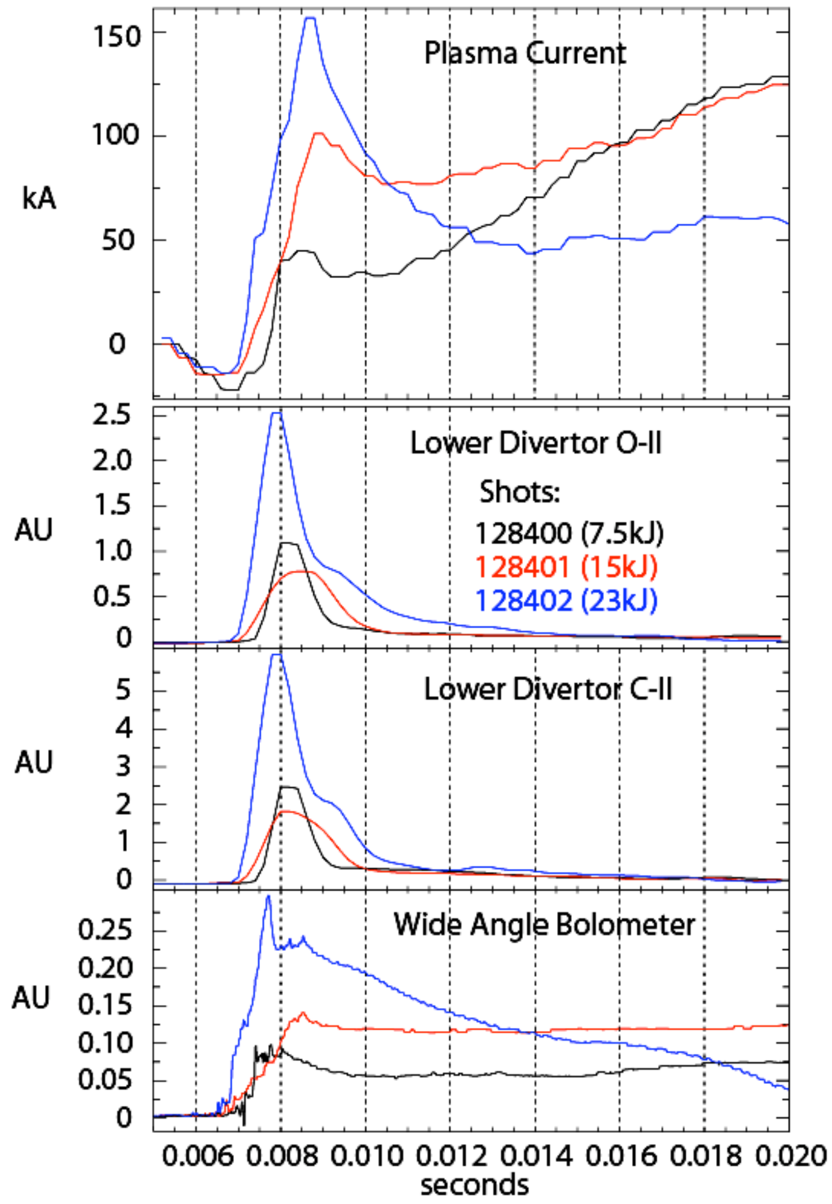




- Broad density profile during H-mode phase

- Discharge is under full equilibrium control
- Loop voltage is preprogrammed
- Discharge transitioned to H-mode at usual time

# Low-Z Impurity Radiation Needs to be Reduced to Improve Inductive Phase After CHI Initiation



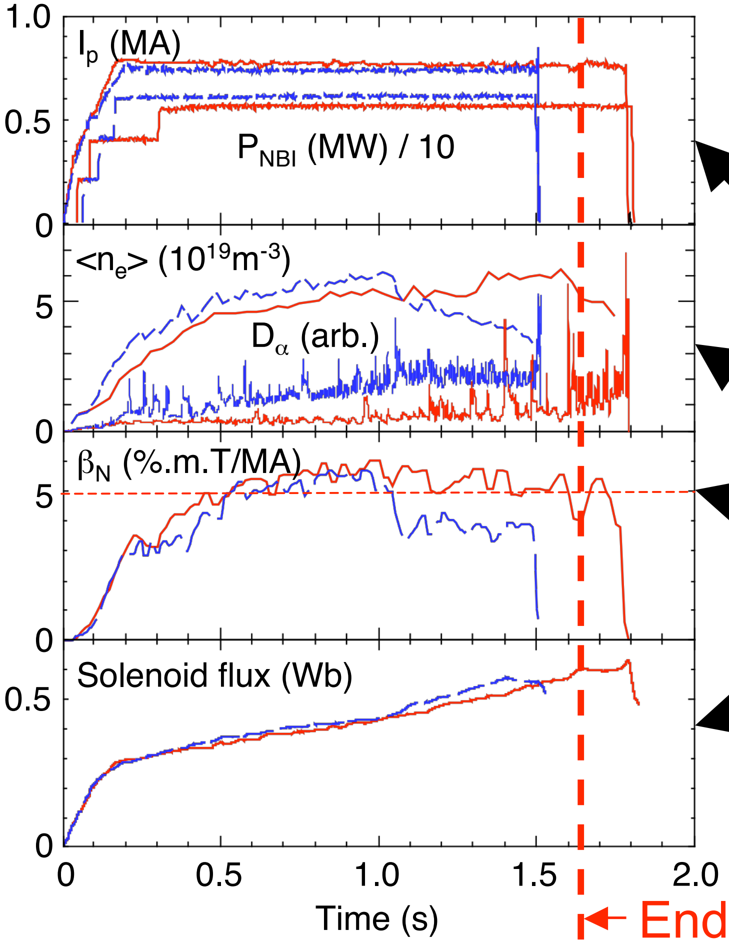
- Peak toroidal current increases with more CHI energy (more capacitors, same voltage), *but*
- Current decays more rapidly and inductive voltage fails to sustain it
- Radiation from C and O impurities increases sharply
- This tendency was not observed in experiments on HIT-II
  - Tungsten anode
  - Titanium gettering
- With lithium coating, CHI-initiated discharges were more reproducible

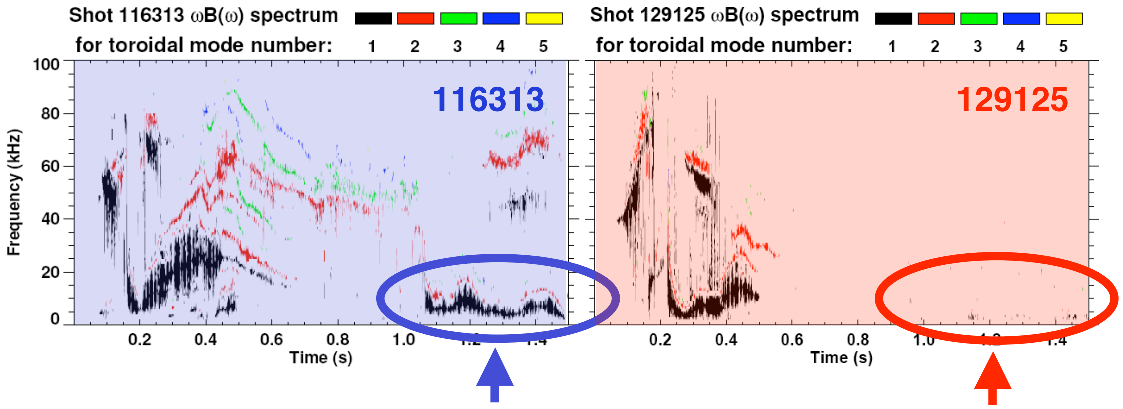
# Highlights of Results by Topical Area

- Macrostability
- Transport and Turbulence
- Boundary Physics
- Wave-Particle Interactions
- Solenoid-free Startup
- Advanced Scenarios and Control
  - Combining active control and lithium coating to extend high-performance plasmas

# n=3 Error Field Correction With n=1 RWM Feedback and Lithium Coating Extends High-$\beta_N$ 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

- Reached limit imposed by TF coil heating

Lithium helps control recycling, density

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

- EFC/RWM control sustains rotation, $\beta$

Flux consumption reduced by high $\beta$ + Li

- Lower density increases NBCD
- High elongation increases bootstrap current

End of TF flattop

*J. Menard, S. Gerhardt, S. Sabbagh, D. Gates*

# 2008 Research Revealed New Physics, Advanced the Potential of the ST and Addressed Issues for ITER

- Extending the understanding of MHD stability at high β
  - Extending pulse length through active control of low-n modes
  - Developing NTM physics and control techniques
- Investigating the physics of anomalous transport
  - Characterizing turbulence and nature of modes responsible
- 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
  - Investigating possibilities for ELM triggering and mitigation
- Examining stability and effects of super-Alfvénic ions
  - Measuring transport due to spectrum of Alfvén eigenmodes
- Making good progress towards goal of non-inductive sustainment
  - Transitioned from CHI initiation to inductive rampup
  - Improved coupling of HHFW with spectrum needed to ramp current
  - Extended pulse length by optimizing NBCD and bootstrap current