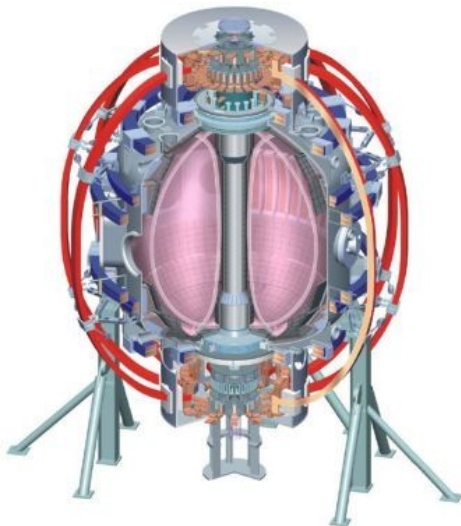


Accomplishments and Results from the 2008 NSTX Run Campaign

*College W&M
 Colorado Sch Mines
 Columbia U
 CompX
 General Atomics
 INEL
 Johns Hopkins U
 LANL
 LLNL
 Lodestar
 MIT
 Nova Photonics
 New York U
 Old Dominion U
 ORNL
 PPPL
 PSI
 Princeton U
 Purdue U
 SNL
 Think Tank, Inc.
 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
 NIFS
 Niigata U
 U Tokyo
 JAEA
 Hebrew U
 Ioffe Inst
 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 (U. Washington)
Topical Science Group	Leader	Deputy Leader
Macroscopic Stability	Steve Sabbagh (Columbia U.)	Stefan Gerhardt
Transport and Turbulence	Stan Kaye	Kevin Tritz (Johns Hopkins U.)
Boundary Physics	Vlad Soukhanovskii (LLNL)	Rajesh Maingi (ORNL)
Wave-Particle Interactions	Gary Taylor	Eric Fredrickson
Solenoid-free Start-up and Ramp-up	Roger Raman (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

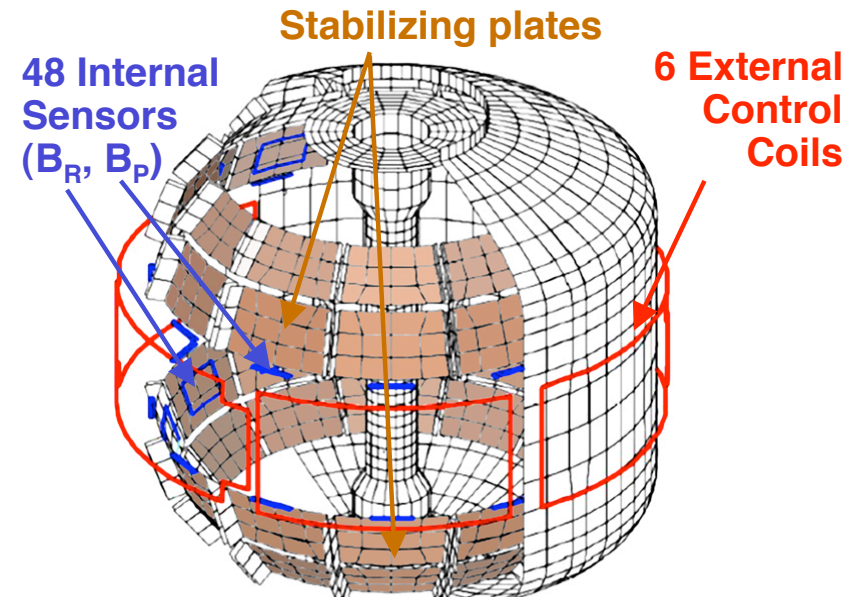
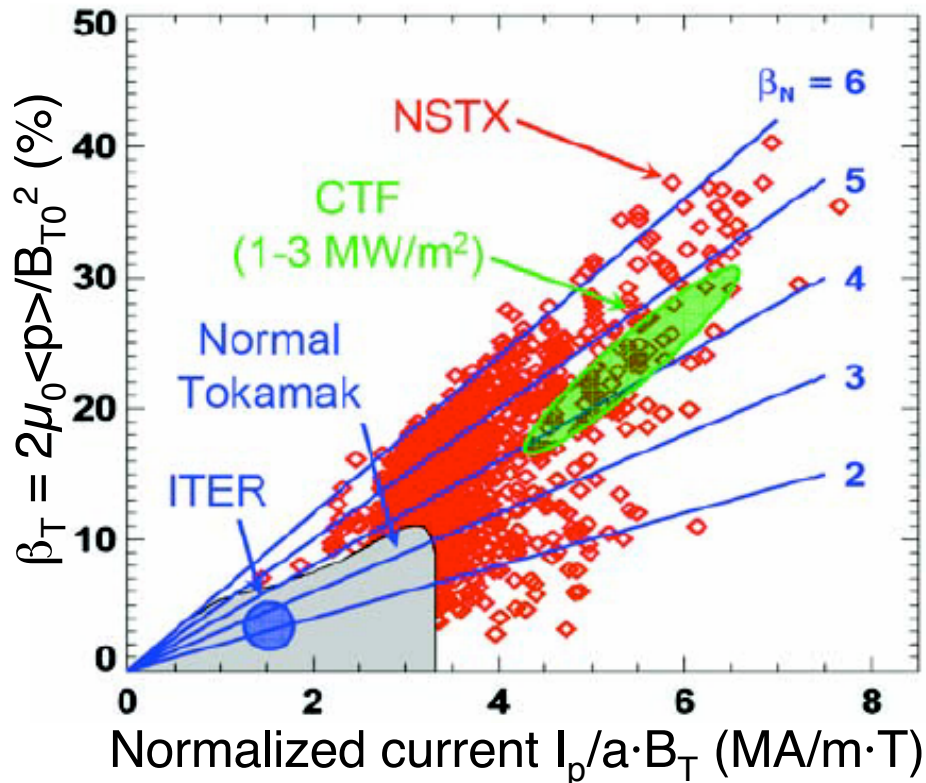
Highlights of Results by Topical Area

- **Macro-stability**
 - 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 β_T and β_N

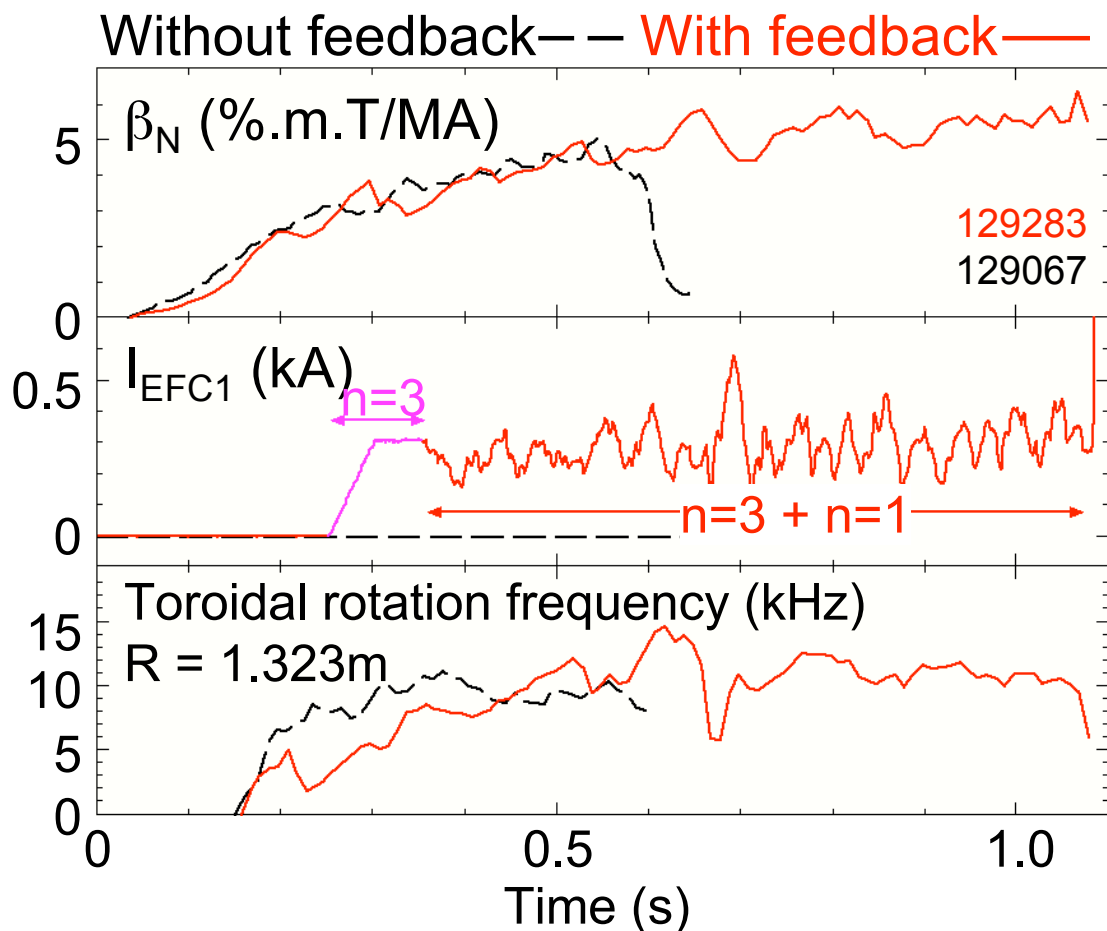
Non-axisymmetric coils provide capability to extend high- β beyond wall time



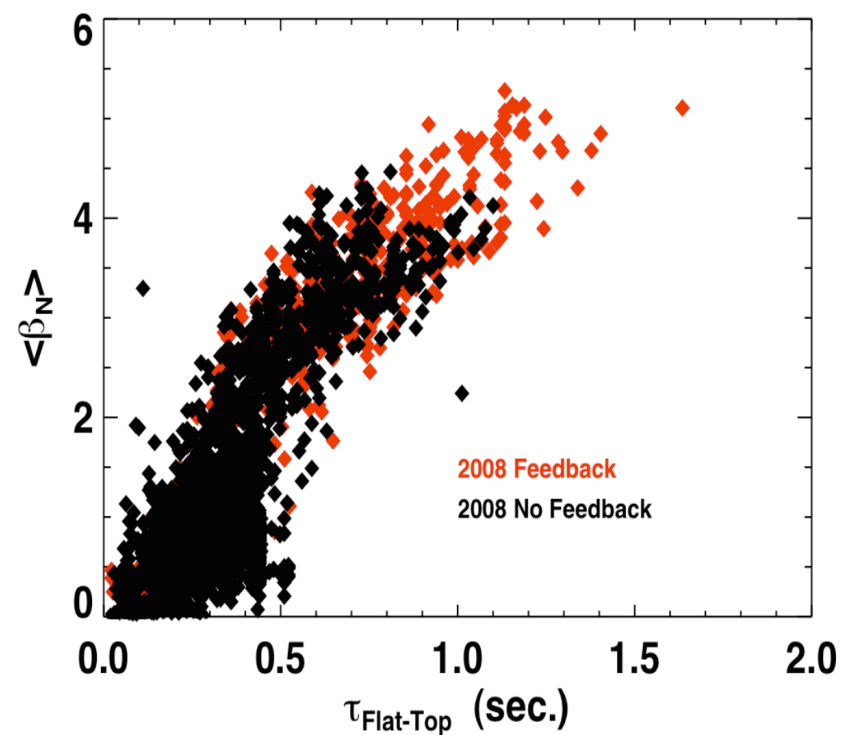
Coils powered by 3 Switching Power Amplifiers (3.5kHz, 1kA)

- 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- β_N Plasmas



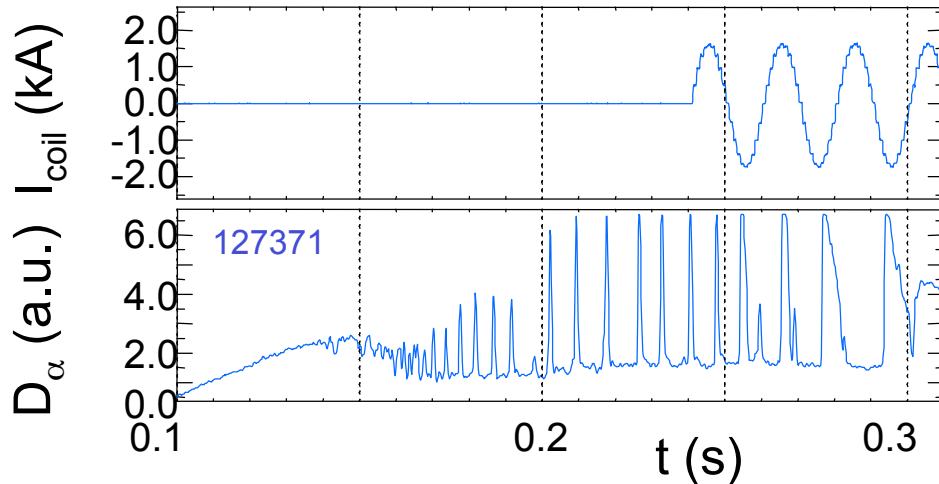
Optimized feedback scheme
applied routinely in 2008



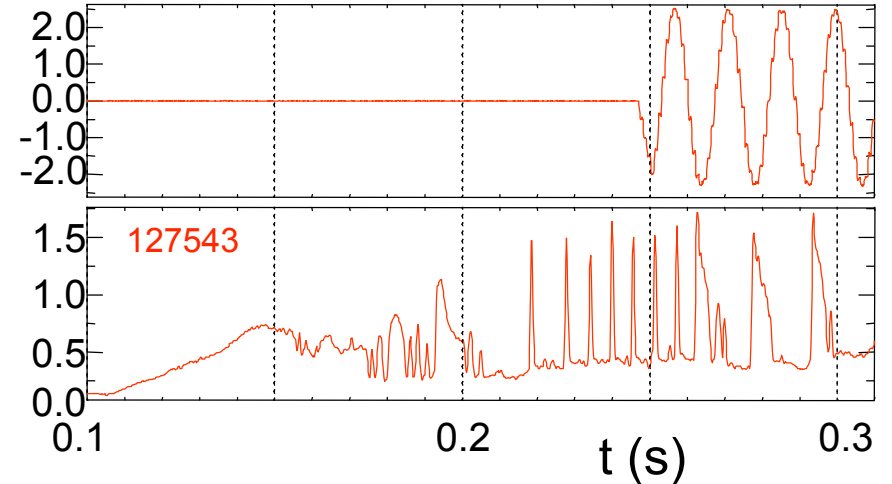
- Correction of $n = 3$ intrinsic error field maintains toroidal rotation
- Feedback on measured $n = 1$ mode reliably suppresses RWM growth
 - Limitations on time response and applied mode purity explored for ITER
- Intrinsic $n = 2$ field error found to be small: no correction necessary

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

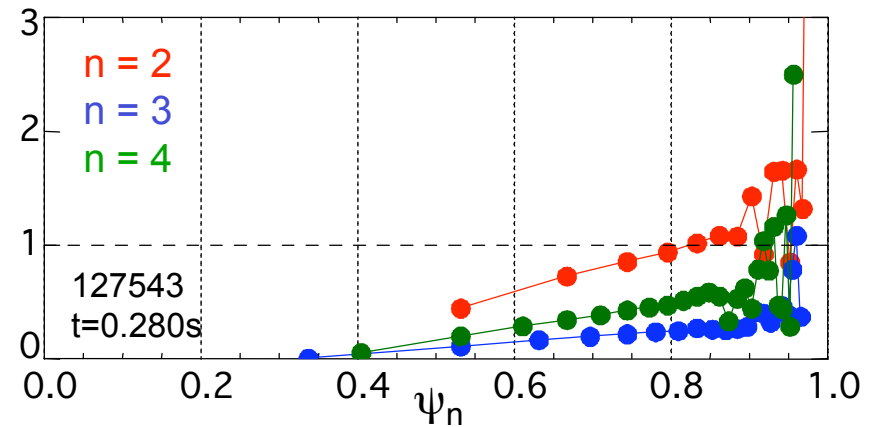
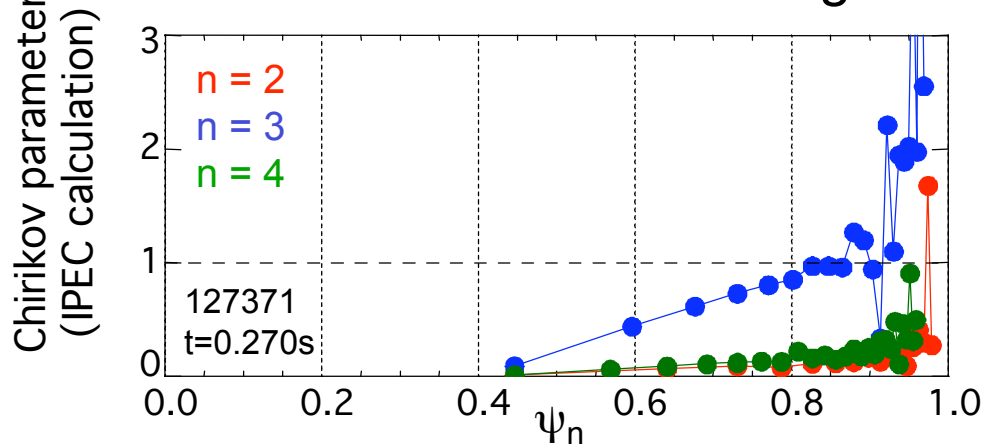
$n = 3$ field, 50 Hz, 3.8 kA p-p; $q_{95} = 7.7$



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



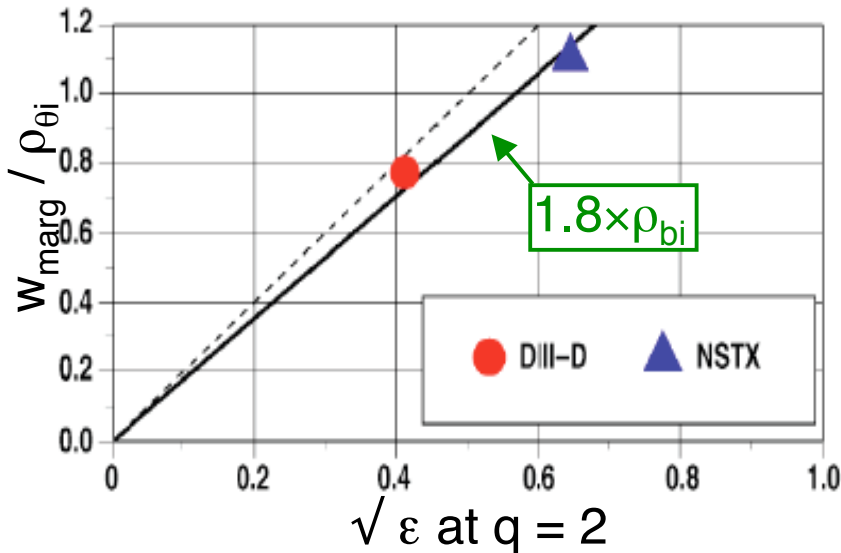
- ELMs increase in width and roughly match frequency of applied field
- Calculations with IPEC show regions of significant island overlap near edge



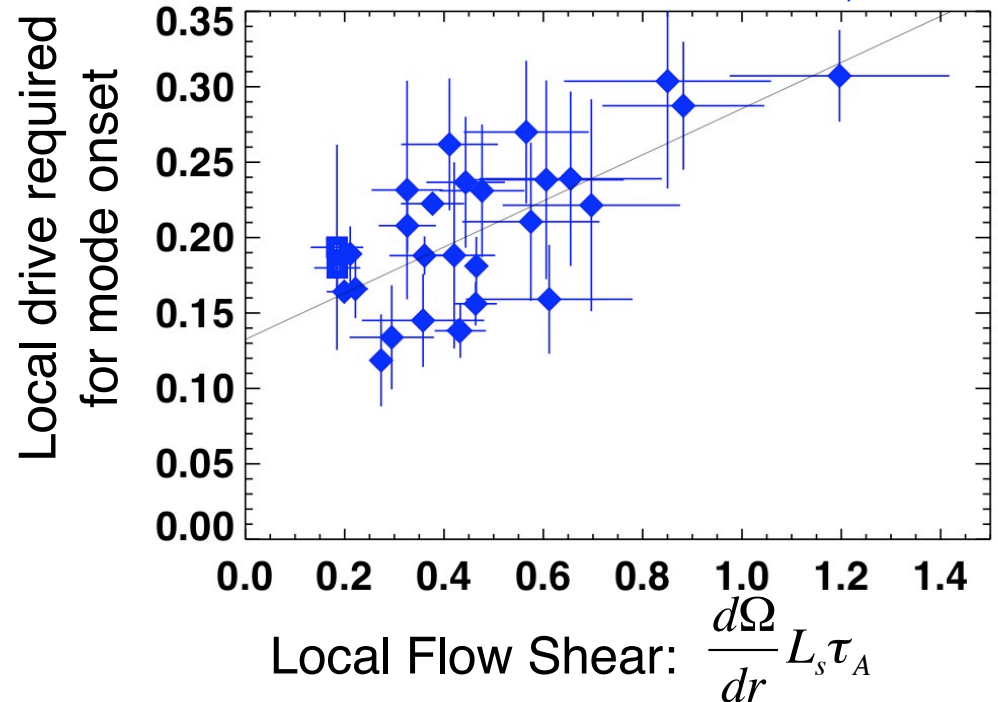
- Tried quasi-steady pulses & mixed $n = 2+3$ spectrum with similar results

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 $q = 2$



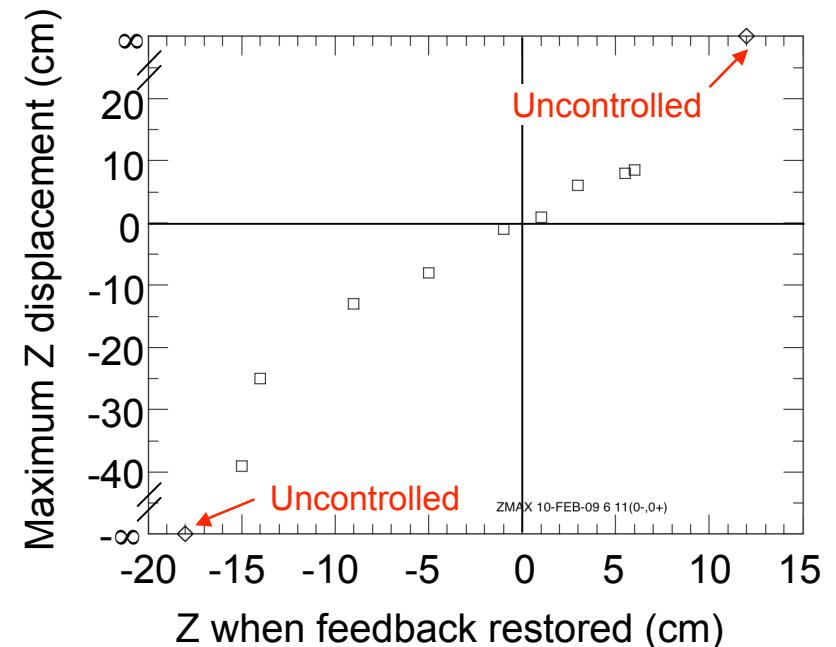
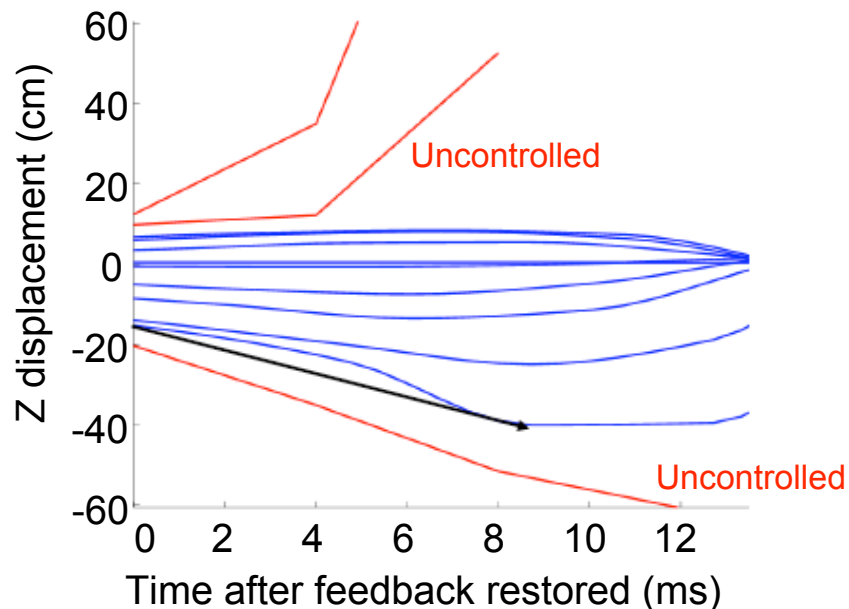
2/1 NTM onset threshold vs. V_ϕ shear



- Local mode drive $\propto \mu_0 \langle \vec{J} \cdot \vec{B} \rangle_e L_q / \langle B_\theta \rangle \propto \text{local } \beta_p$
- 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

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

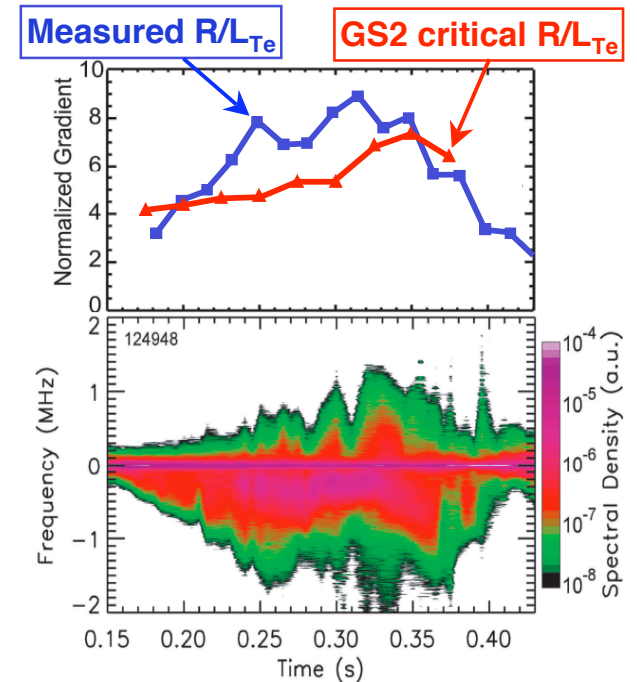
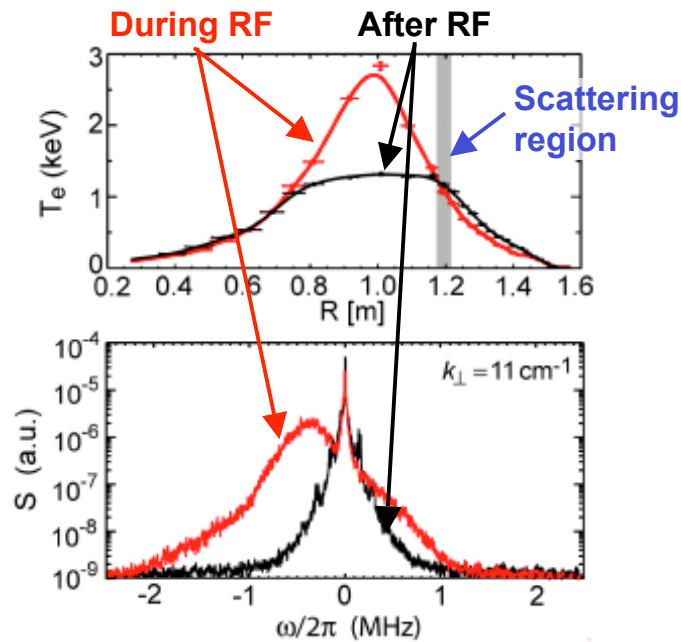
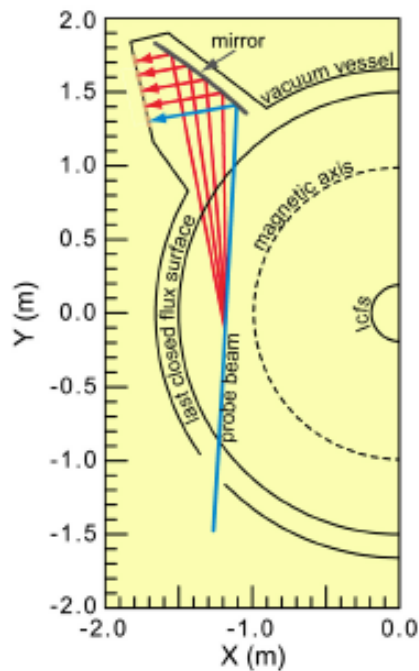


- NSTX response is not up/down symmetric
- $\Delta Z_{\max} = 15.0$ cm for downward, 6.6 cm for upward motion
- $\Delta Z_{\max}/a = 23\%$ for downward, 10% for upward motion

Highlights of Results by Topical Area

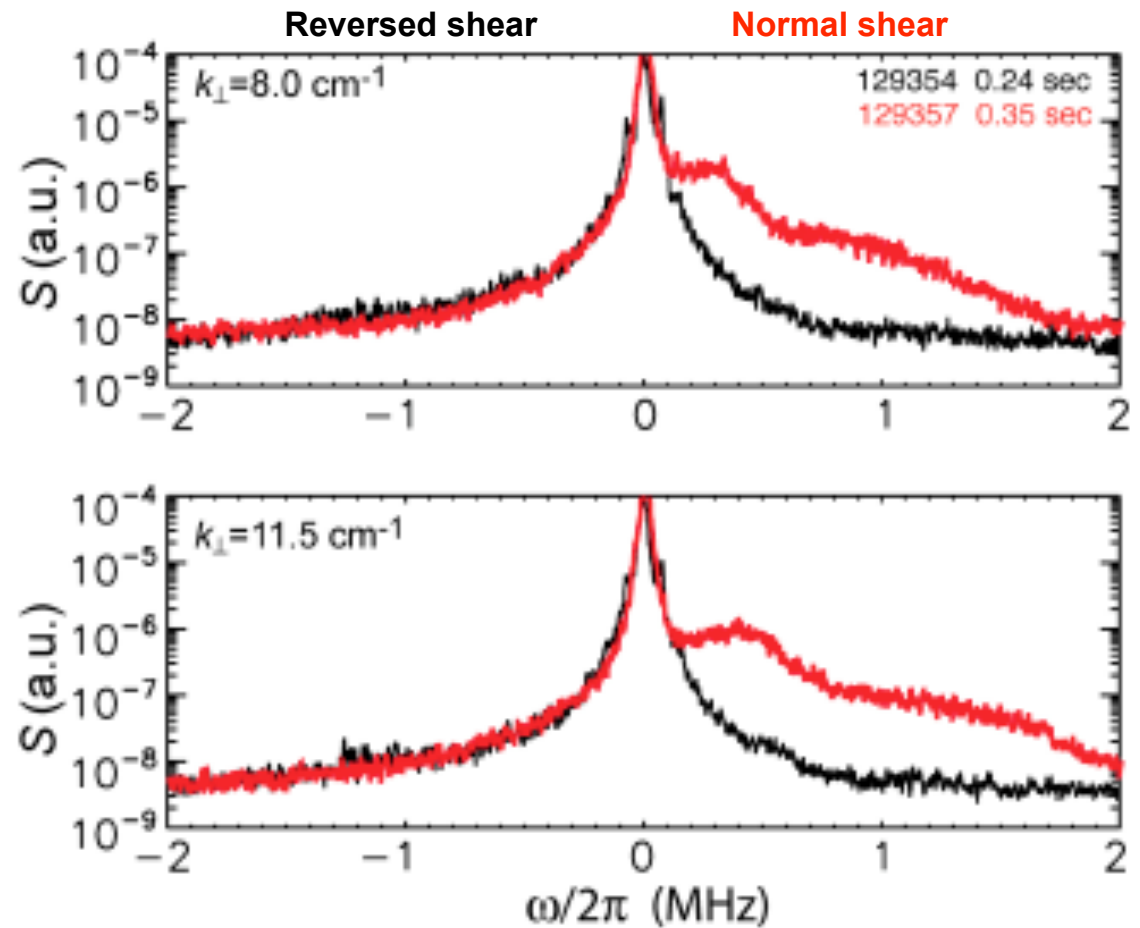
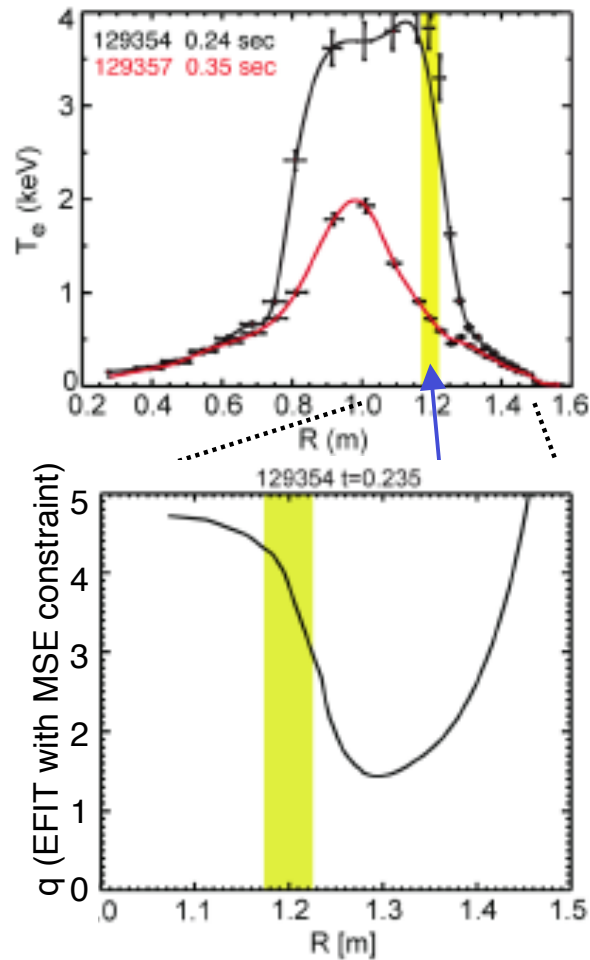
- Macrostability
- Transport and Turbulence
 - Exploring the causes of anomalous electron thermal transport
 - Measurements of plasma flow and momentum transport
- Boundary Physics
- Wave-Particle Interactions
- Solenoid-free Startup
- Advanced Scenarios and Control

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

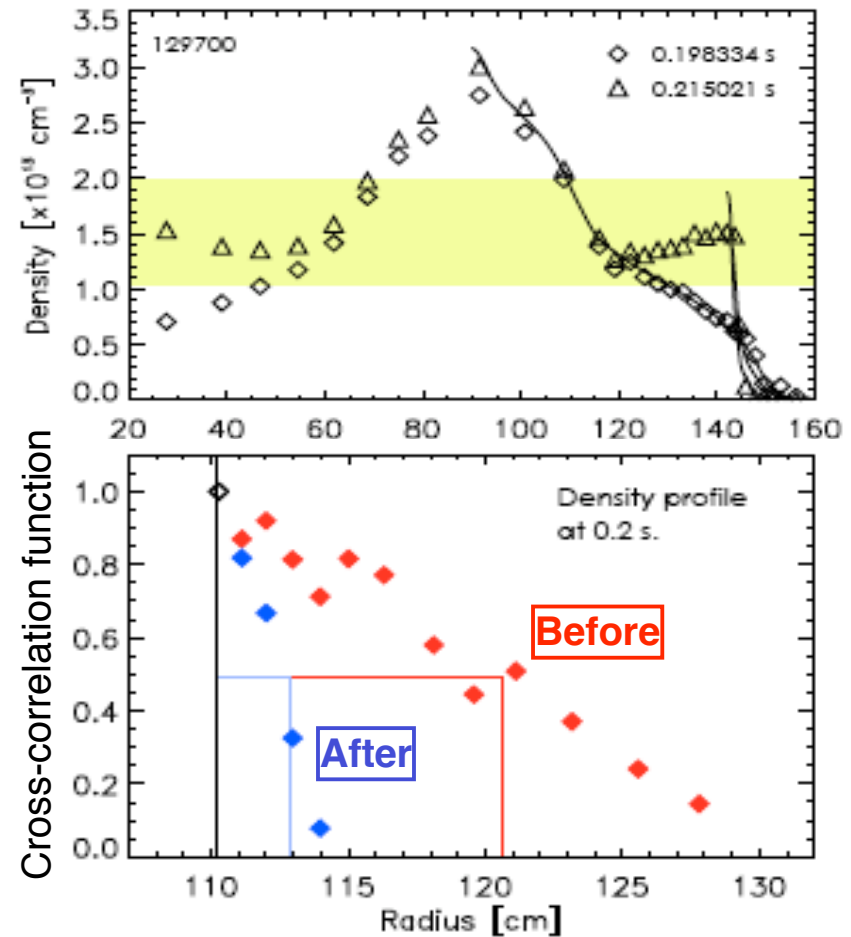
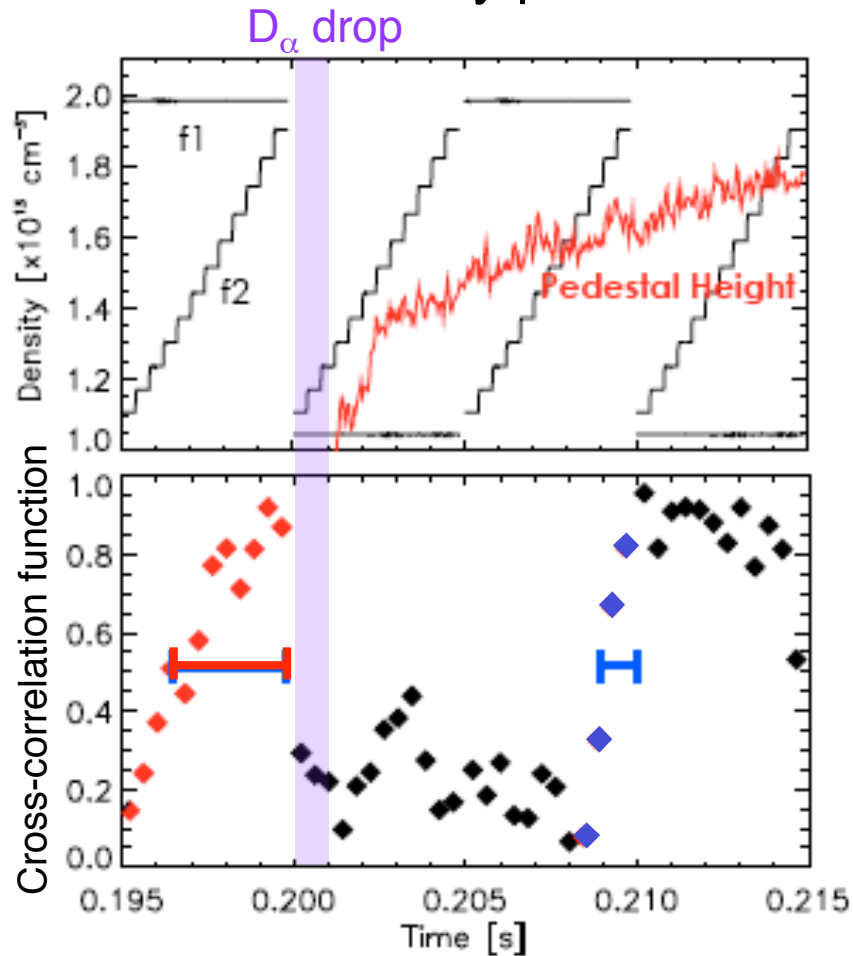
Electron Gyro-Scale Fluctuations Can Be Suppressed by Reversed Magnetic Shear in Plasma Core



- 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

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

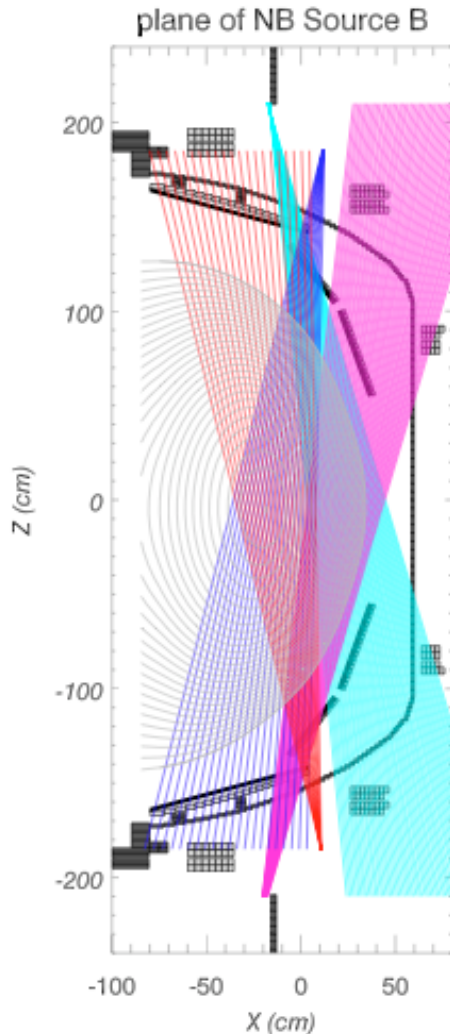
- Use fixed/swept frequency correlation reflectometer during period with monotonic density profile following H-mode transition



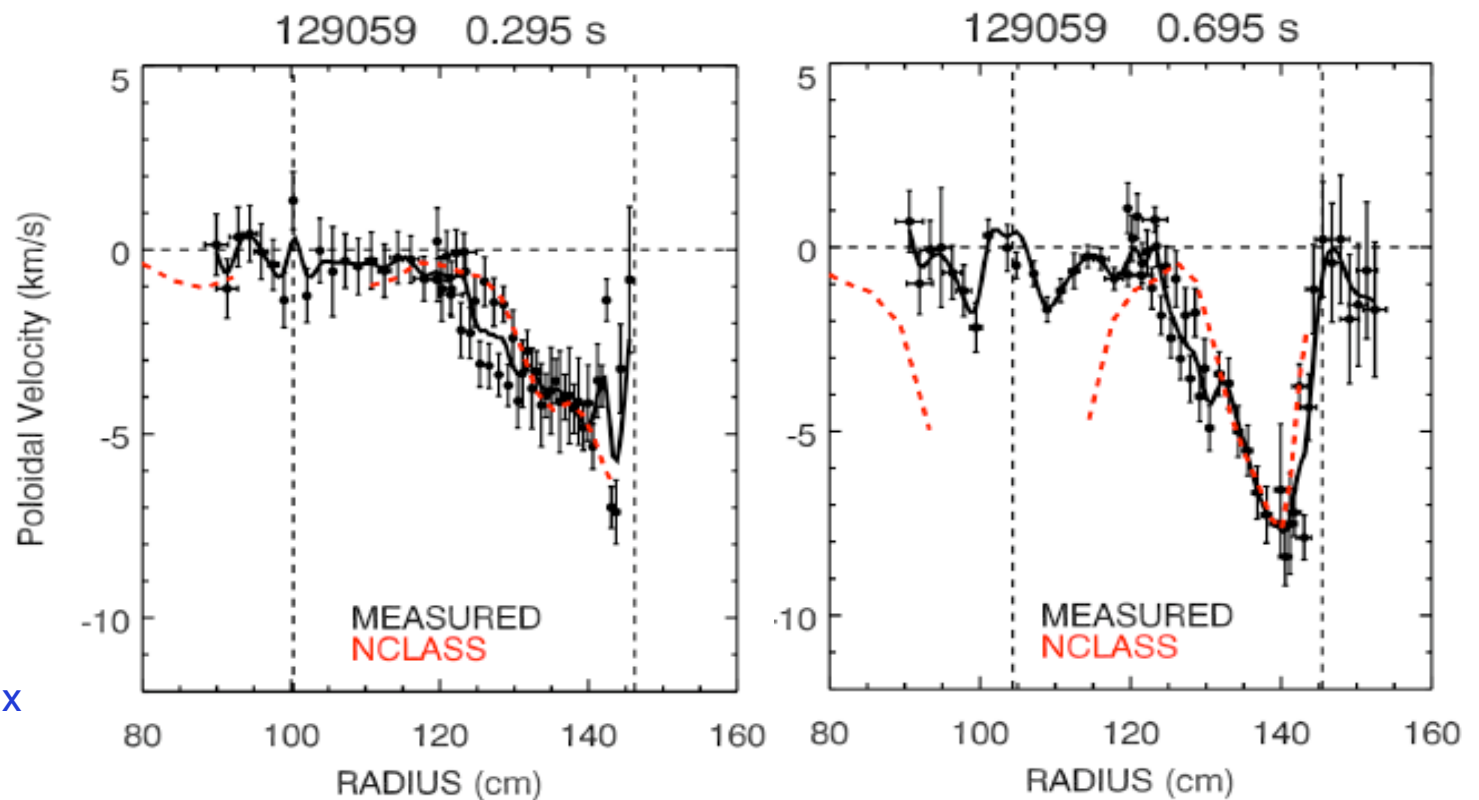
- Radial correlation length of fluctuations reduced by factor 3 - 4 after transition
 - Other fluctuation characteristics change little

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

- PCHERS 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

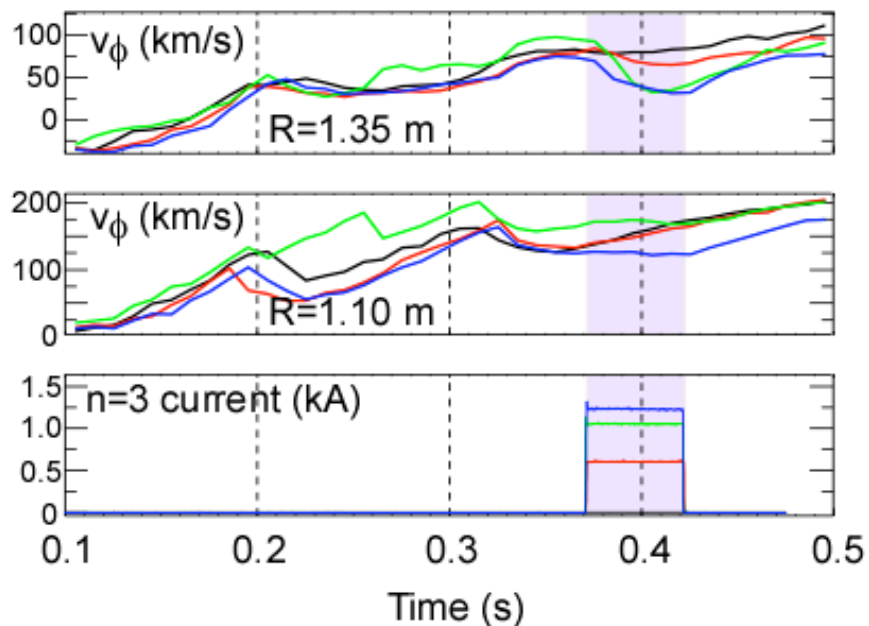


PCHERS sightlines and flux surfaces projected onto common poloidal plane



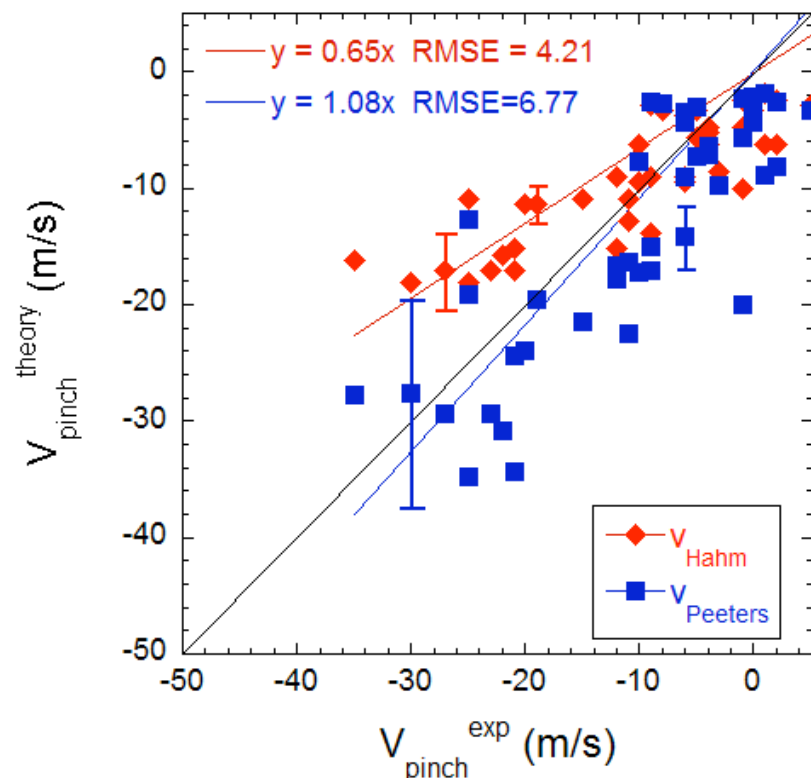
Investigated Momentum Transport Using Transient Perturbations to Separate Diffusivity and Pinch Terms

- $n = 3$ braking pulses perturb rotation in outer region



- Determine χ_ϕ , 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



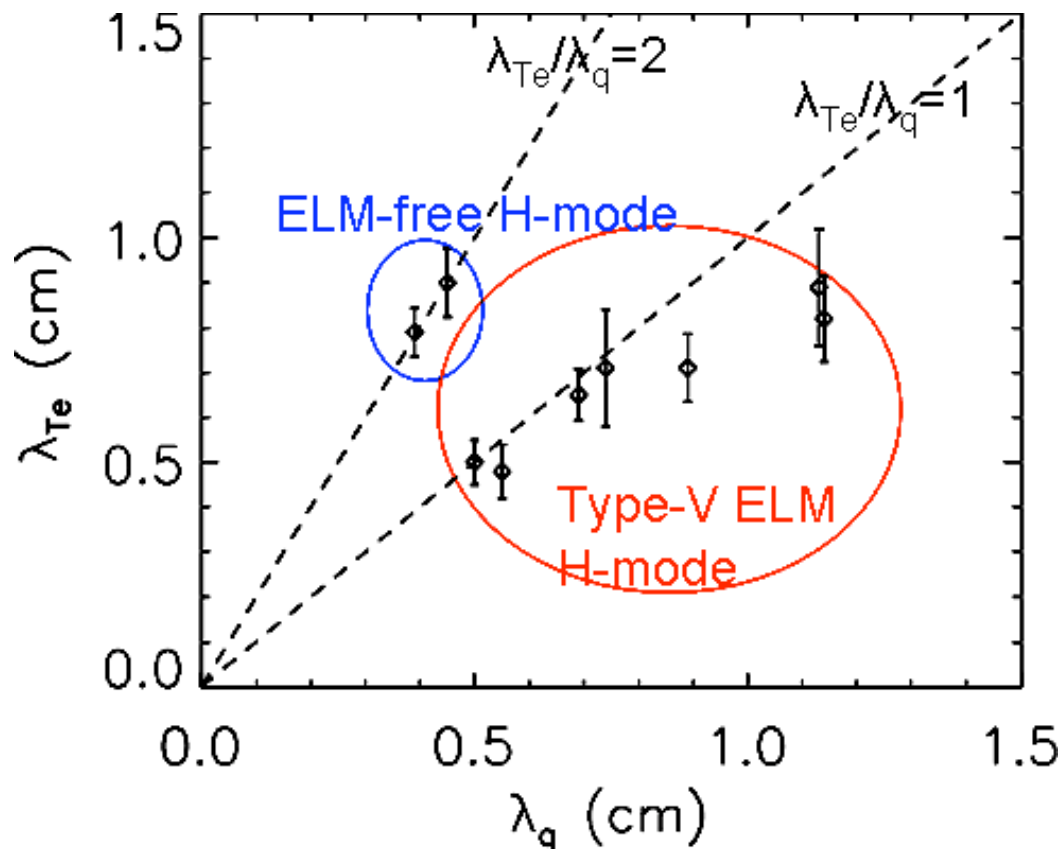
Peeters *et al.* (PRL, 2007)
 Hahm *et al.* (PoP, 2007)

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

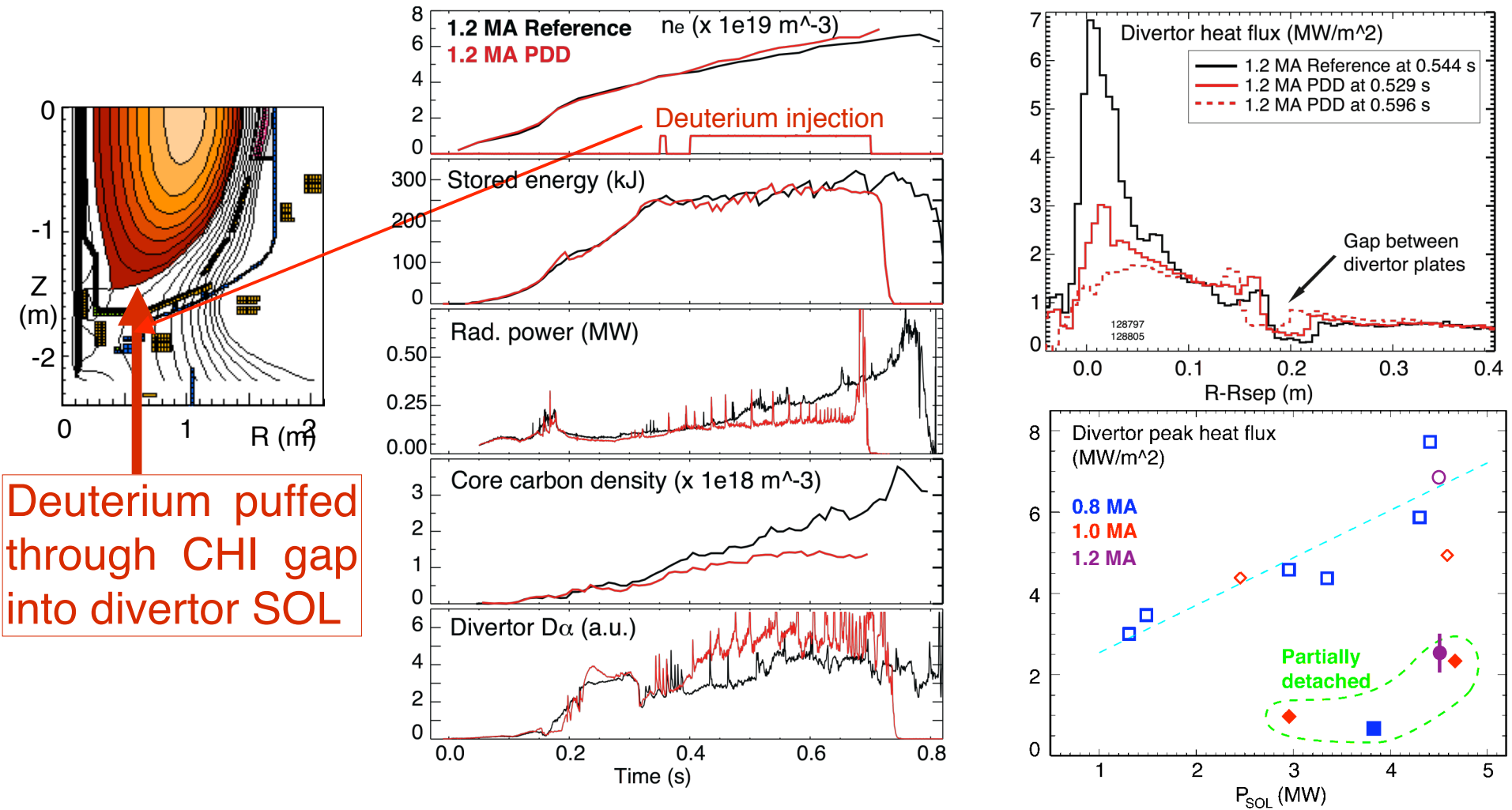
Fast Reciprocating Probe and IR Camera Data Used to Characterize SOL Transport

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



- $\lambda_{Te}/\lambda_q = 7/2$ expected if electron conduction dominates transport
- ELM-free H-mode:
 $\lambda_{Te}/\lambda_q \sim 2$
- Type-V ELM H-mode:
 $\lambda_{Te}/\lambda_q \sim 1$

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

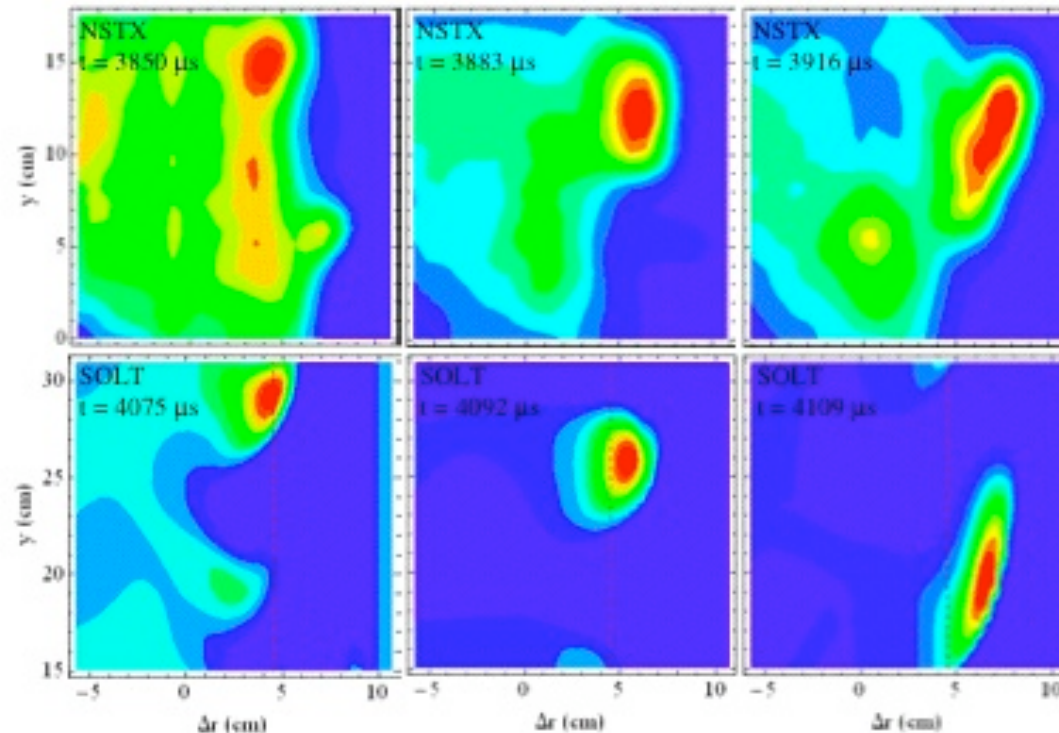
Simulations of “Blob” Propagation in NSTX SOL

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

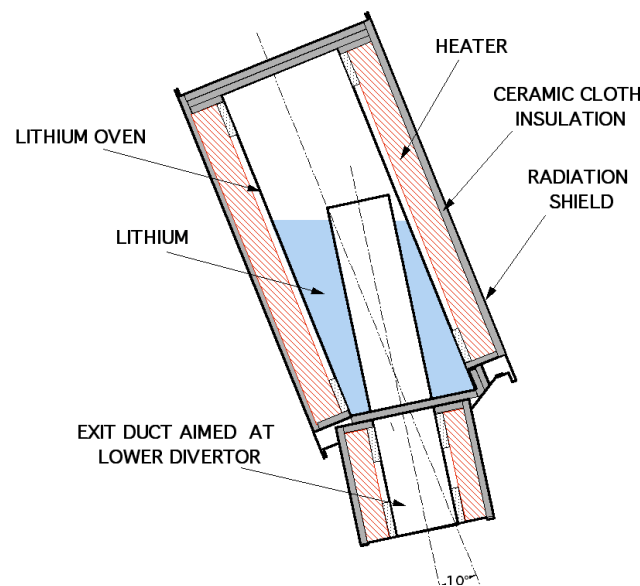
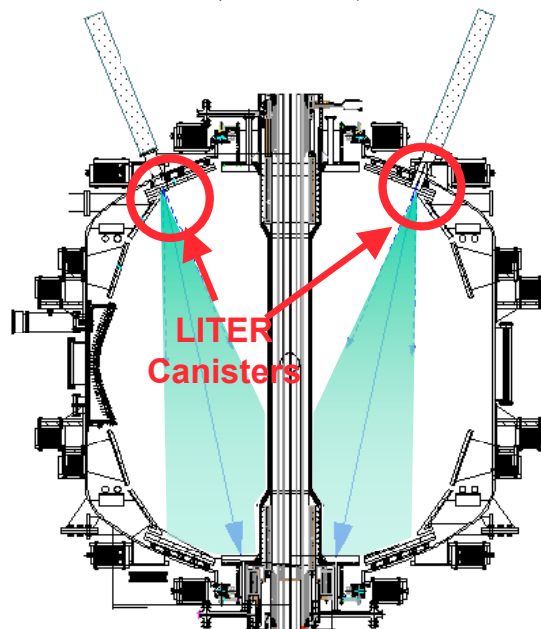
Modeled propagation
of density “blob”



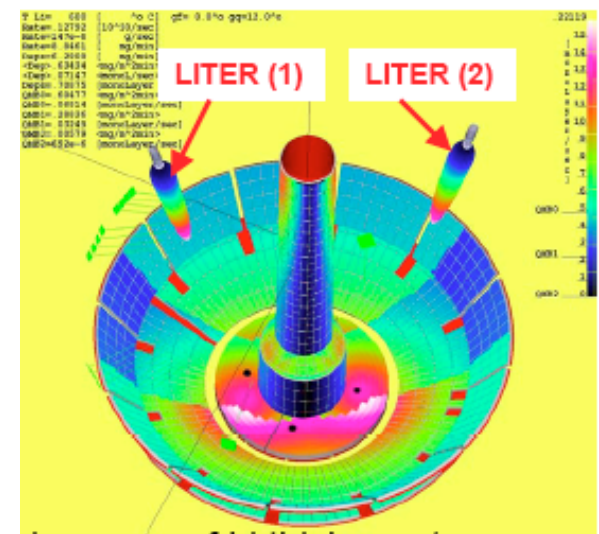
D. A. D'Ippolito , IAEA FEC, 2008

Continued Exploring and Developing Lithium-Coated Plasma Facing Components

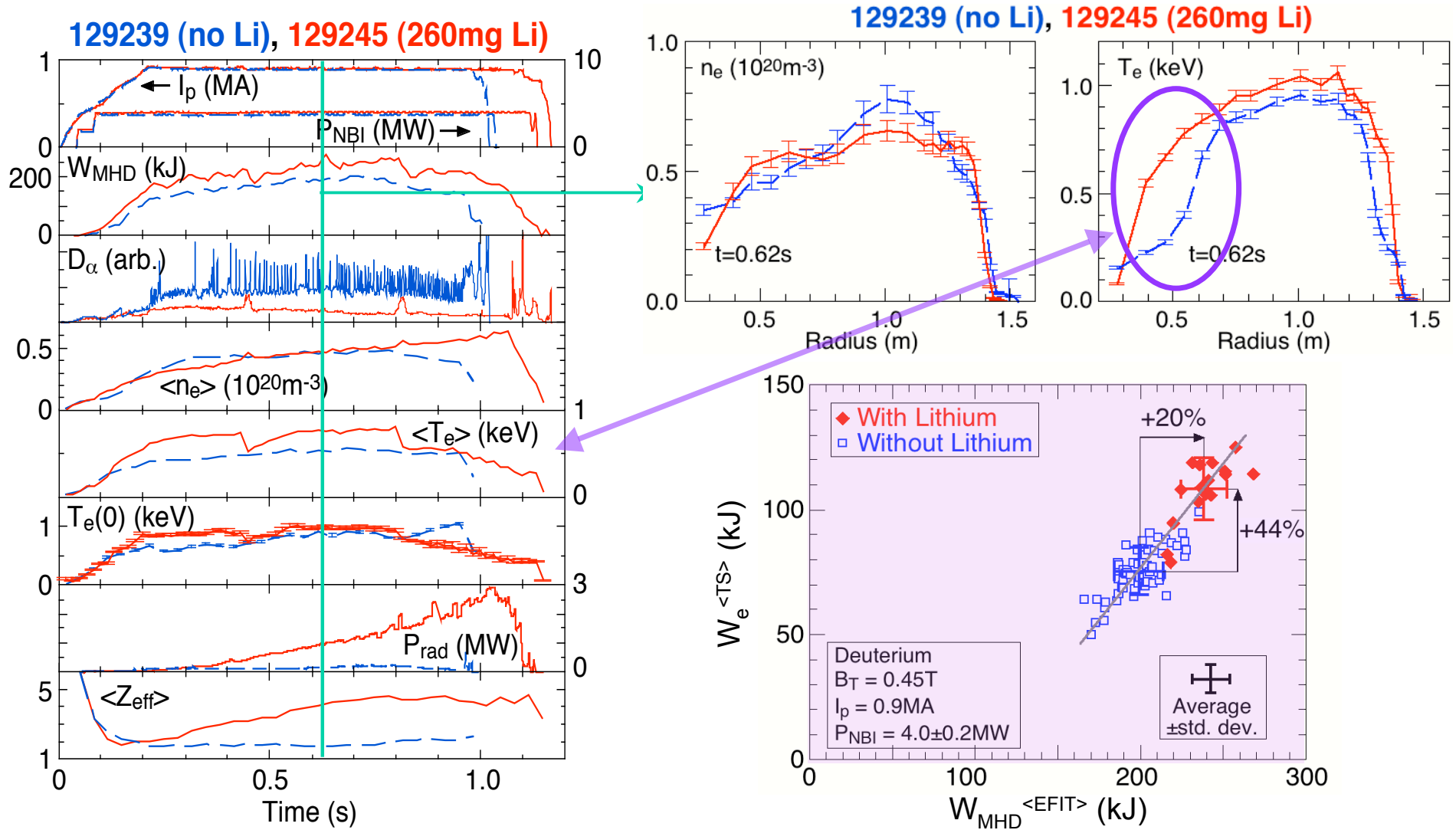
- 2005:** Injected lithium pellets, 2 - 5 mg, into He discharges prior to D NBI shot
- 2006:** LITHium EvaporatoR (LITER) deposited lithium on divertor between shots
- 2007:** Enlarged nozzle, re-aimed at lower divertor to increase deposition rate
- 2008:** Dual LITERs covered entire lower divertor; 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



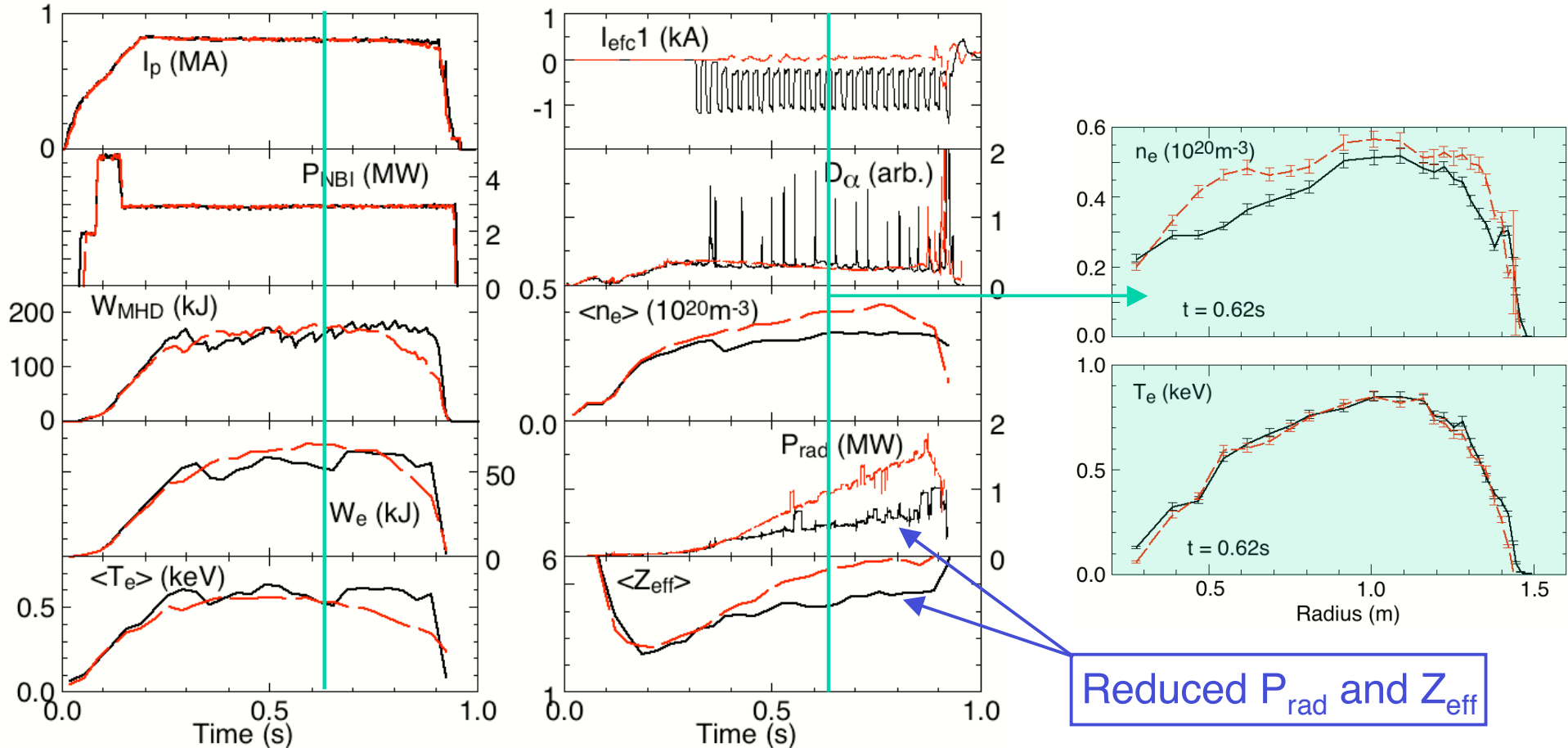
Solid Lithium Coating Reduces Deuterium Recycling, Suppresses ELMs, Improves Confinement



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

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

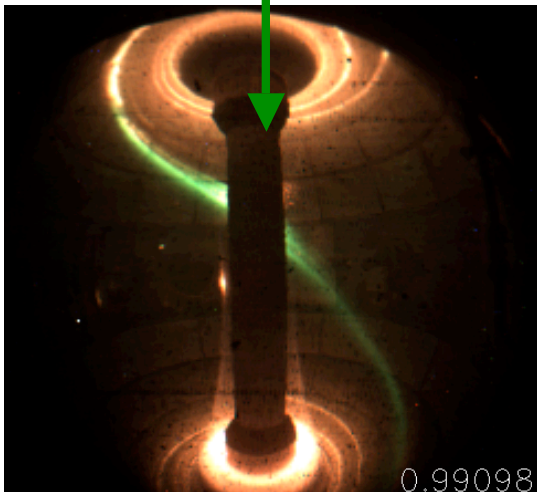


- $n = 3$ resonant magnetic perturbation applied
- 11ms duration pulse at 40Hz optimal for this shape (DN, $\kappa=2.4$, $\delta=0.8$)

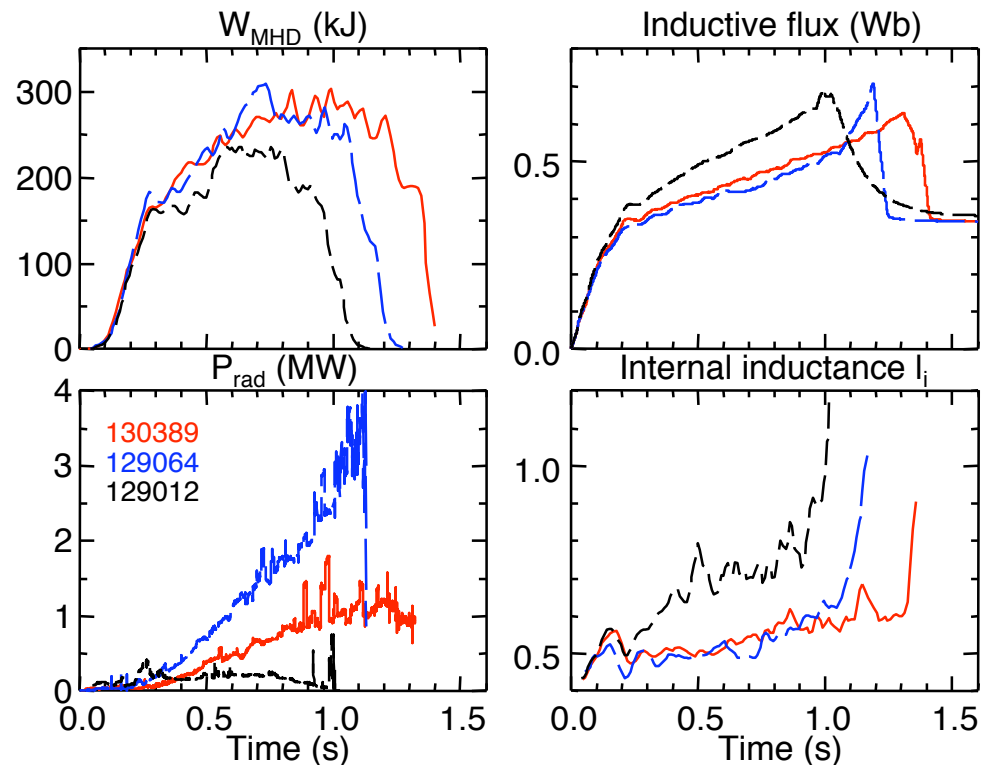
Lithium Coating by Dropping a Stream of Lithium Powder into SOL Produced Similar Benefits to LITER

- Lithium powder ($\sim 40\mu\text{m}$) stabilized against rapid oxidation in air by surface coating of either Li_2CO_3 ($<0.1\%$) or paraffin wax ($<0.01\% \text{CH}_2$)
- 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

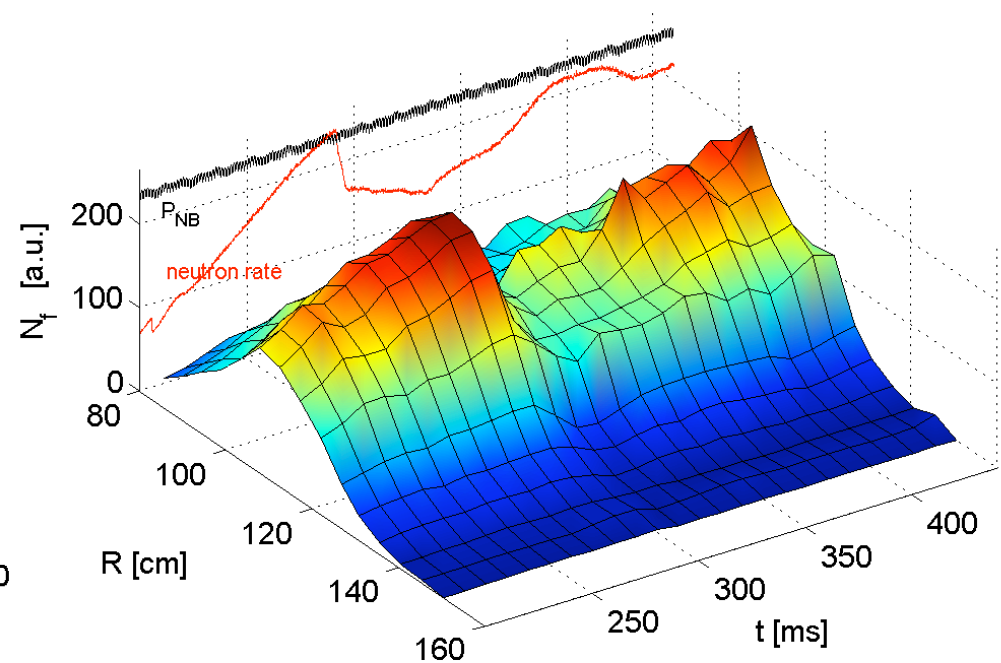
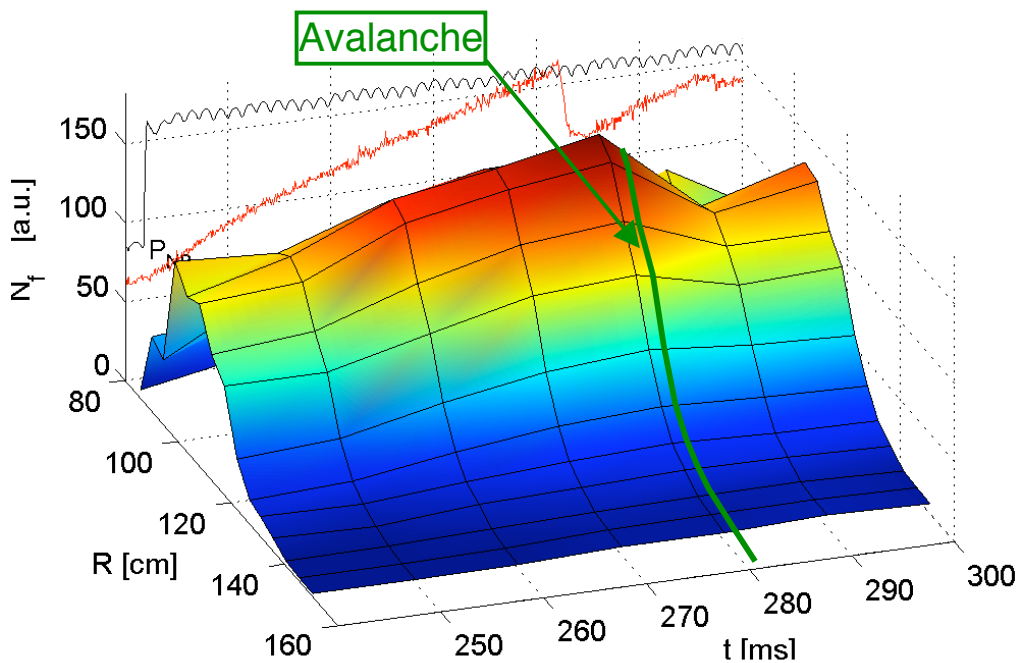


Highlights of Results by Topical Area

- 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

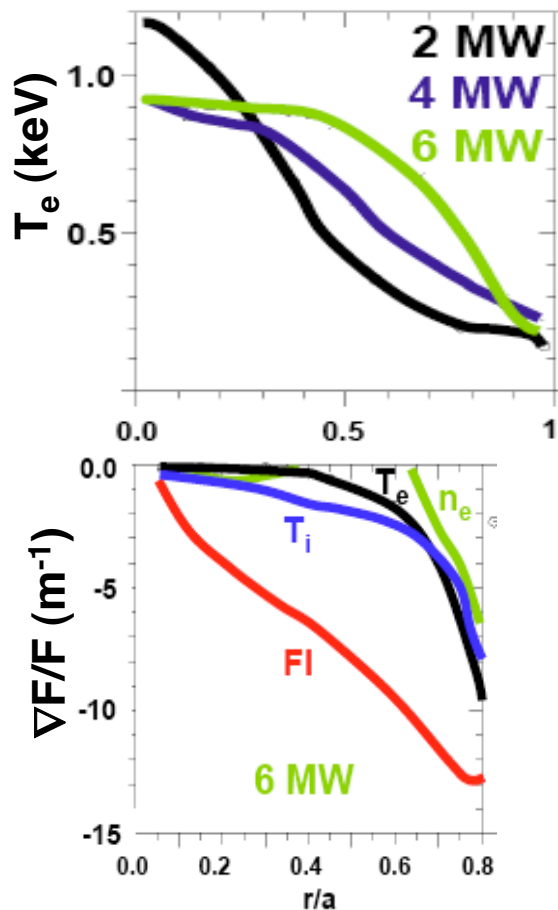
New Fast-Ion Deuterium-Alpha (FIDA) Diagnostic Measured Response of Fast Ions to MHD Modes

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

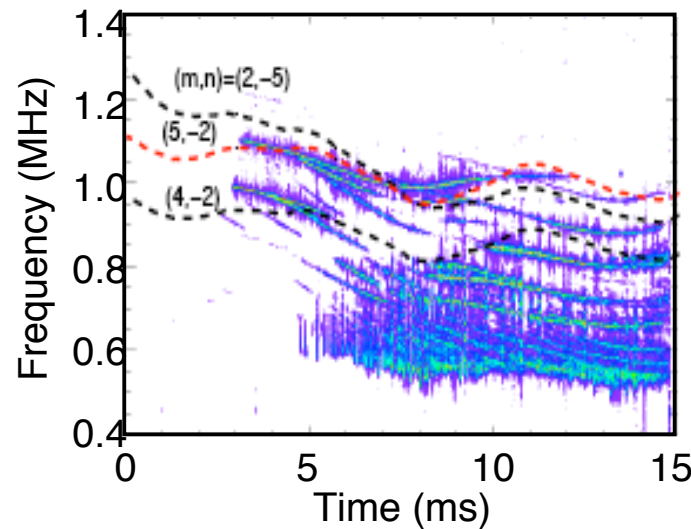


Investigating Role of High-Frequency Modes in Core Electron Transport

- Observe “flat T_e ” region in core of plasmas with high NBI power
 \Rightarrow Implies mechanism for electron transport *not* driven by T_e gradient
- Global Alfvén Eigenmodes (GAEs) driven by fast-ion pressure gradient a possible source



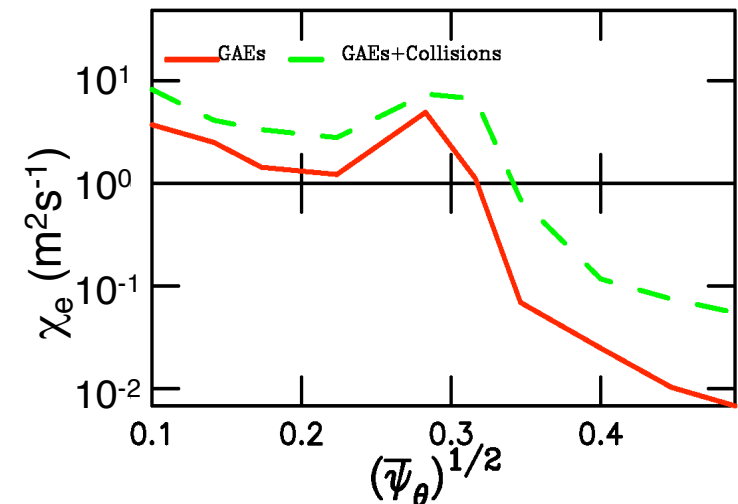
$$\omega_{GAE} \simeq v_{A0}(m - nq_0)/q_0R.$$



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

Modeling with ORBIT code

- Used 14 GAEs $n = 1-8$; m so $f = 0.4-0.6$ MHz
- Peak amplitude $\xi_r/R \sim 4 \times 10^{-4}$ consistent with reflectometry



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

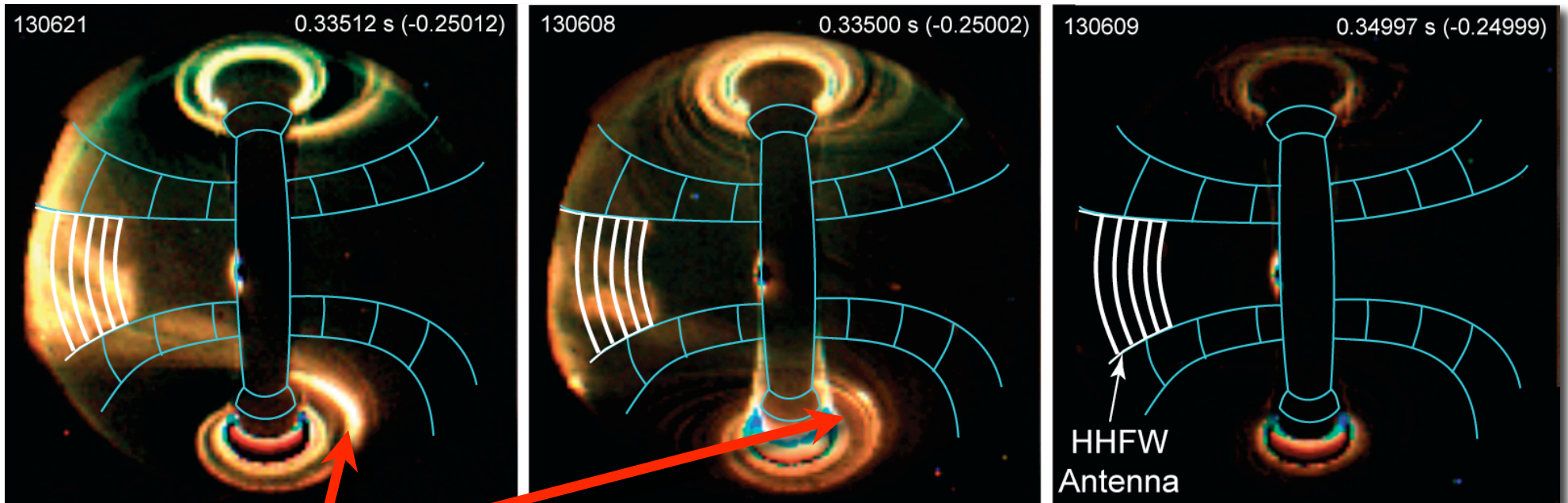
- Dependence on launched wave spectrum, field and edge density consistent with onset of wave propagation in SOL in front of antenna: $n_{\text{crit}} \propto B \times k_{\parallel}^2 / \omega$

$P_{\text{HHFW}} = 1.8 \text{ MW}$, $P_{\text{NBI}} = 2 \text{ MW}$, $I_p = 1 \text{ MA}$, $B_T = 0.55 \text{ T}$

Without RF

$\Delta\phi = -90^\circ$, $k_{\parallel} \approx 7 \text{ m}^{-1}$

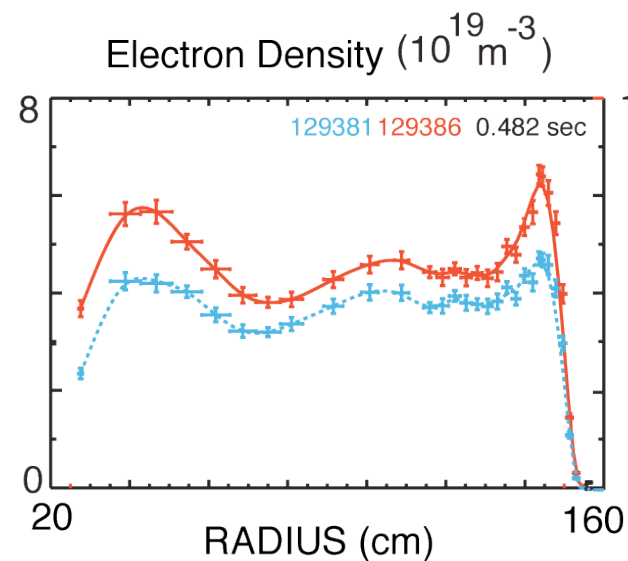
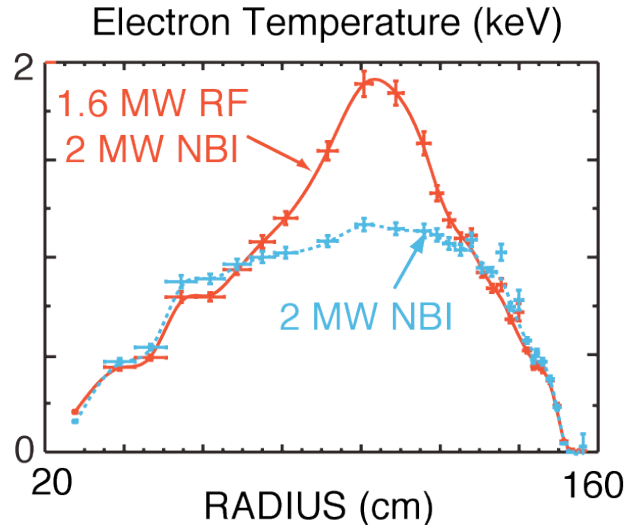
$\Delta\phi = -150^\circ$, $k_{\parallel} \approx 12 \text{ m}^{-1}$



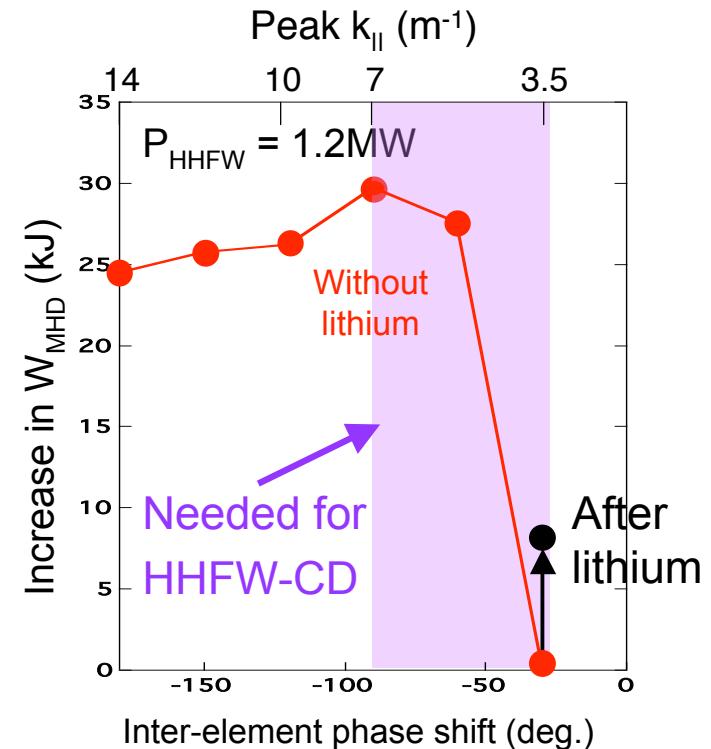
- Divertor “hotspot” more pronounced and persistent for $k_{\parallel} \approx 7 \text{ m}^{-1}$ than 12 m^{-1}
- ITER issue: ICRH antenna designed for low k_{\parallel} , so $n_{\text{crit}} \sim 1.4 \times 10^{18} \text{ m}^{-3}$

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

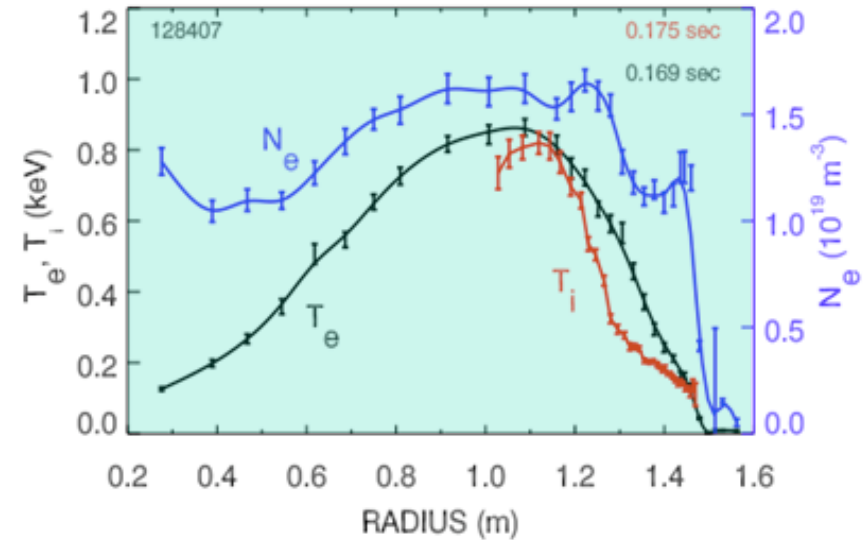
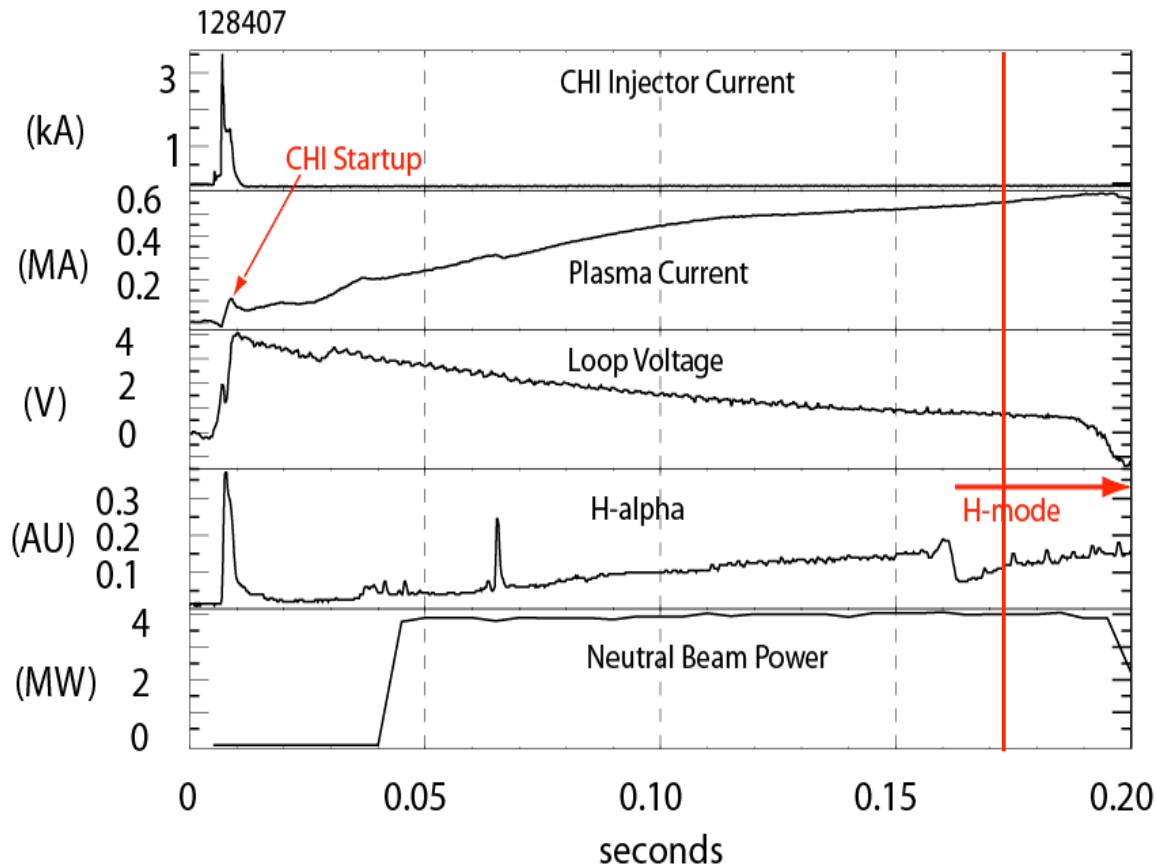


- Reflectometer measures reduced SOL density in front of antenna with lithium
 - Consistent with suppression of parasitic surface waves

Highlights of Results by Topical Area

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

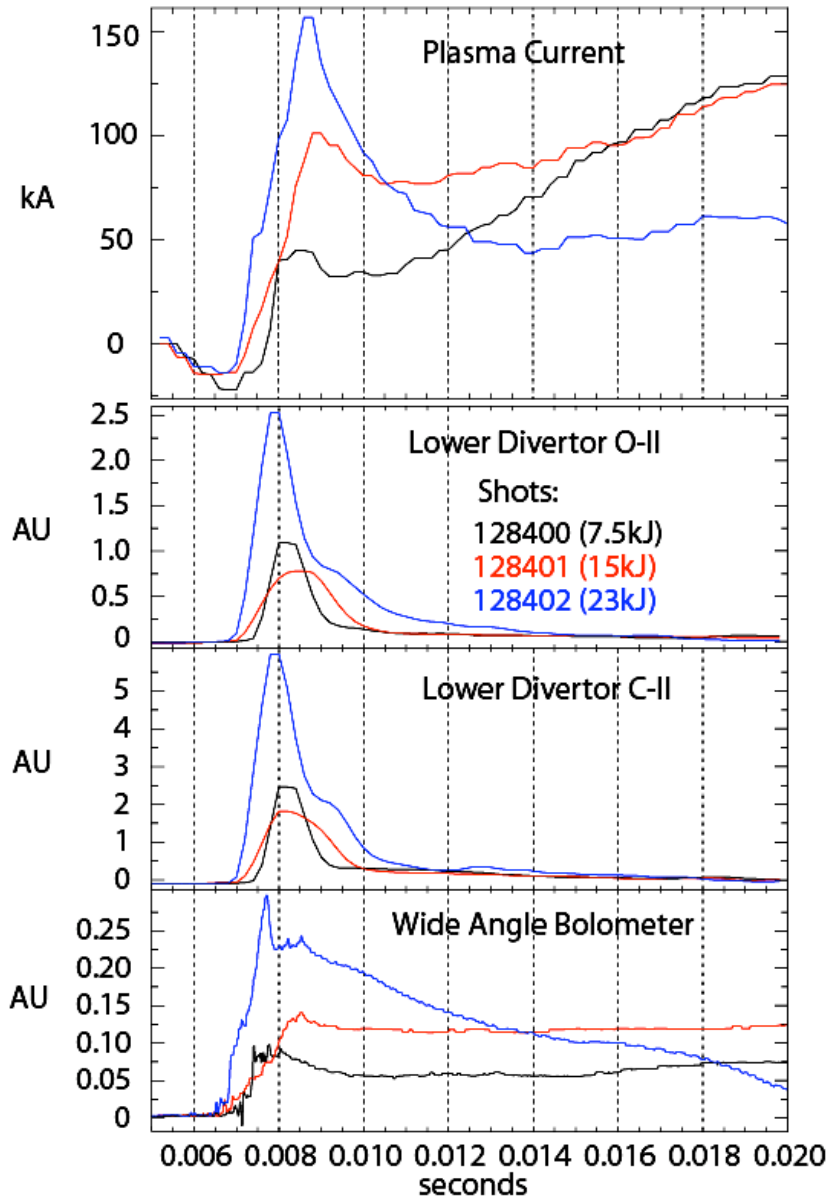
CHI Initiated Discharge Successfully Coupled to Inductive Ramp-up with NBI and HHFW Heating



- 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



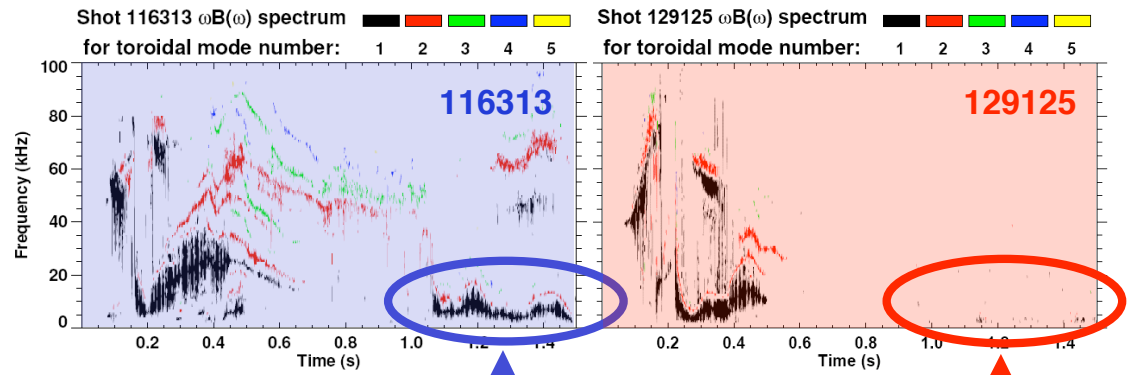
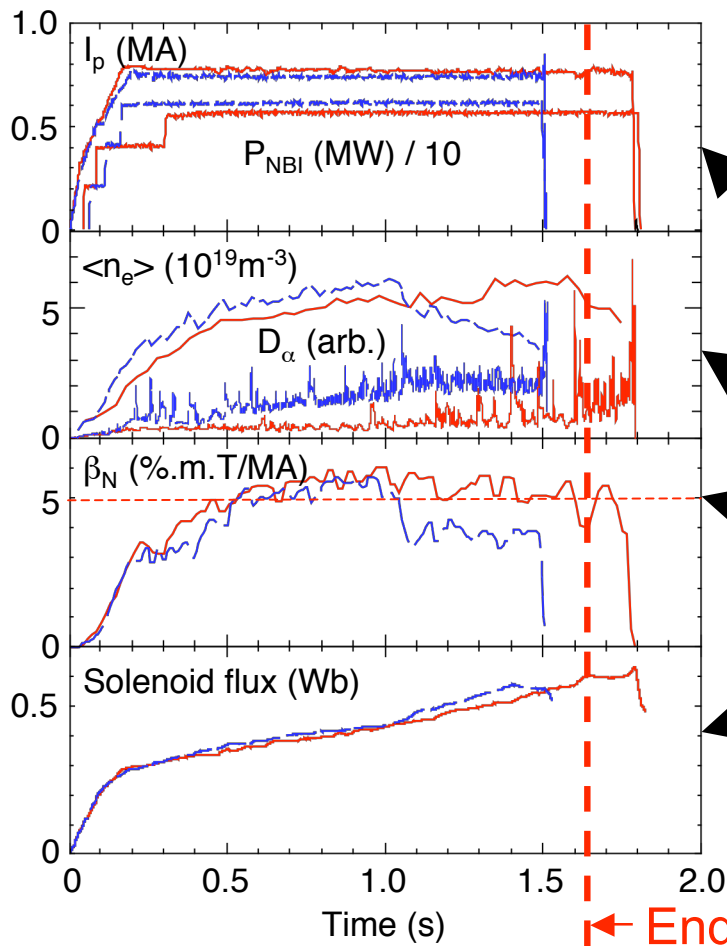
- Peak toroidal current increases with more CHI energy (more capacitors, same voltage), *but*
- Current decays more rapidly and inductive voltage fails to sustain it
- Radiation from C and O impurities increases sharply
- This tendency was not observed in experiments on HIT-II
 - Tungsten anode
 - Titanium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

– Reached limit imposed by TF coil heating

Lithium helps control recycling, density

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

– EFC/RWM control sustains rotation, β

Flux consumption reduced by high β + Li

– Lower density increases NBCD

– High elongation increases bootstrap current

← End of TF flattop

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