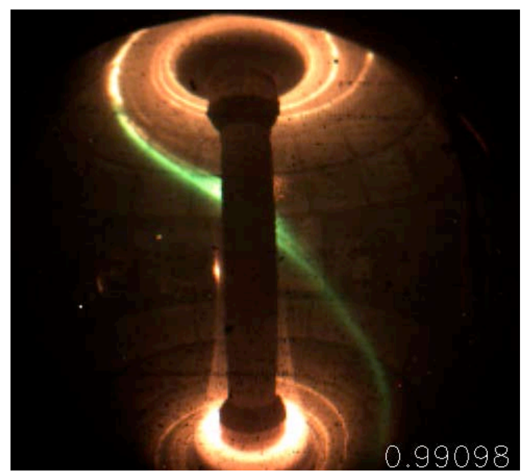
NSTX PPPL Princeton Plasma Physics Laboratory

Supported by Office of Fusion Energy Sciences — Excellent Science Attractive Energy — Office of Science — Department of Energy, United States of America

An Overview of Recent Results from the National Spherical Torus Experiment

M.G. Bell
Princeton Plasma Physics Laboratory
for the ***NSTX Research Team***

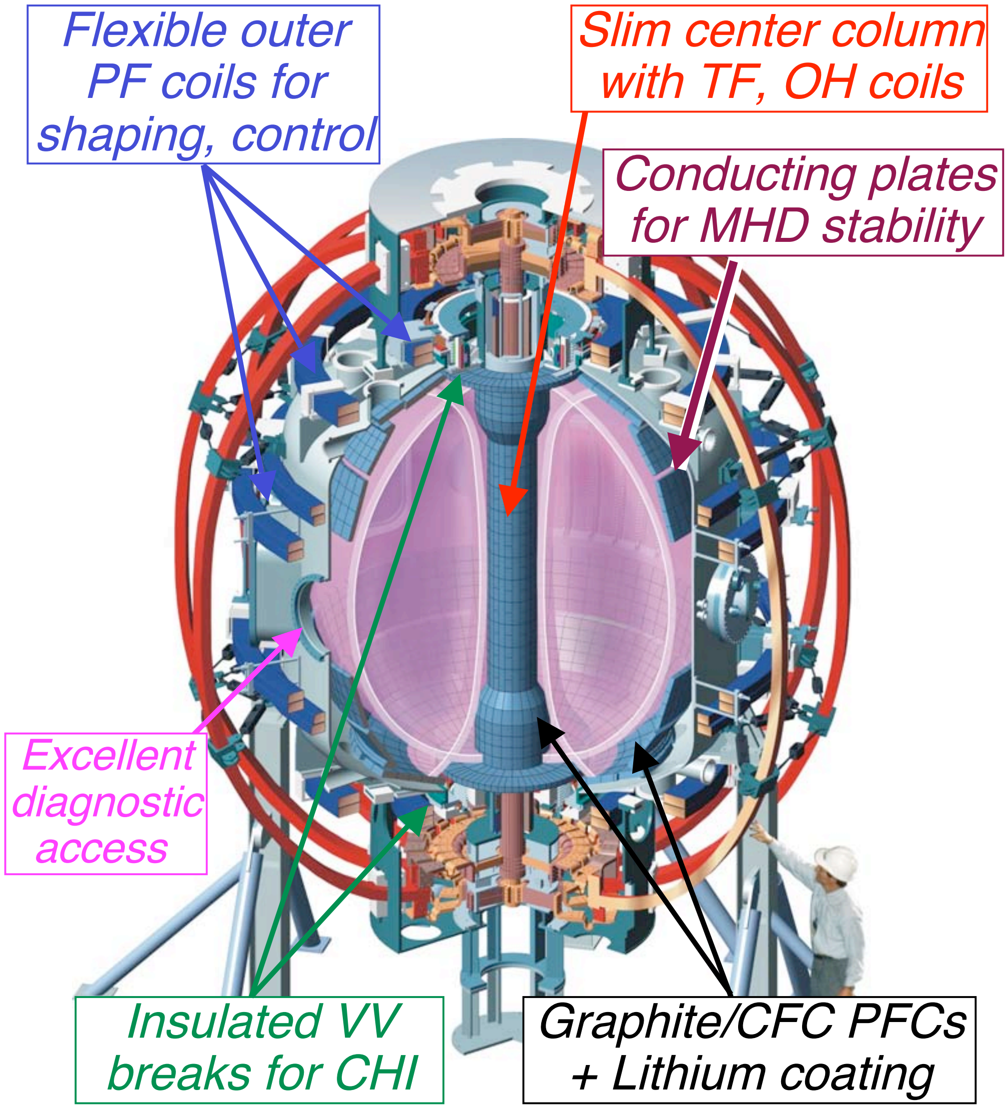
International Congress on Plasma Physics
Fukuoka
8 – 12 September 2008



College W&M
Colorado Sch Mines
Columbia U
Comp-X
General Atomics
Idaho NEL
Johns Hopkins U
Los Alamos NL
Lawrence Livermore NL
Lodestar
MIT
Nova Photonics, Inc.
New York U
Old Dominion U
Oak Ridge NL
PPPL
PSI
Princeton U
Purdue U
Sandia NL
Think Tank, Inc.
UC Davis
UC Irvine
UCLA
UCSD
U Colorado
U Maryland
U Rochester
U Washington
U Wisconsin

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

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	$\leq 1.2 \times 10^{20} m^{-3}$

NSTX Contributes to Toroidal Confinement Physics, Preparation for ITER and Fusion Energy Development

- Complements and extends conventional aspect-ratio tokamaks
  - High β: β_T up to 40%, $\beta(0) \sim 1$
  - Intrinsic cross-section shaping ($\kappa > 2$, $B_P/B_T \sim 1$)
  - Large fraction of trapped particles ($\sim\sqrt{(r/R)}$)
  - Large gyro-radius ($a/\rho_i \sim 30$–50)
  - Large bootstrap current (>50% of total)
  - Large plasma flow & flow shear ($M \sim 0.5$) – suppresses ion turbulence
  - High dielectric constant ($\varepsilon \sim 30$–100)
  - Large population of supra-Alfvénic fast ions ($v_{NBI}/v_{Alfvén} \sim 4$)
  - High divertor power flux (P/R) – challenges plasma facing materials
- Explores possibilities for a Plasma-Materials Test Facility or a Component Test Facility (CTF)
  - High heat flux or neutron fluence in a driven system

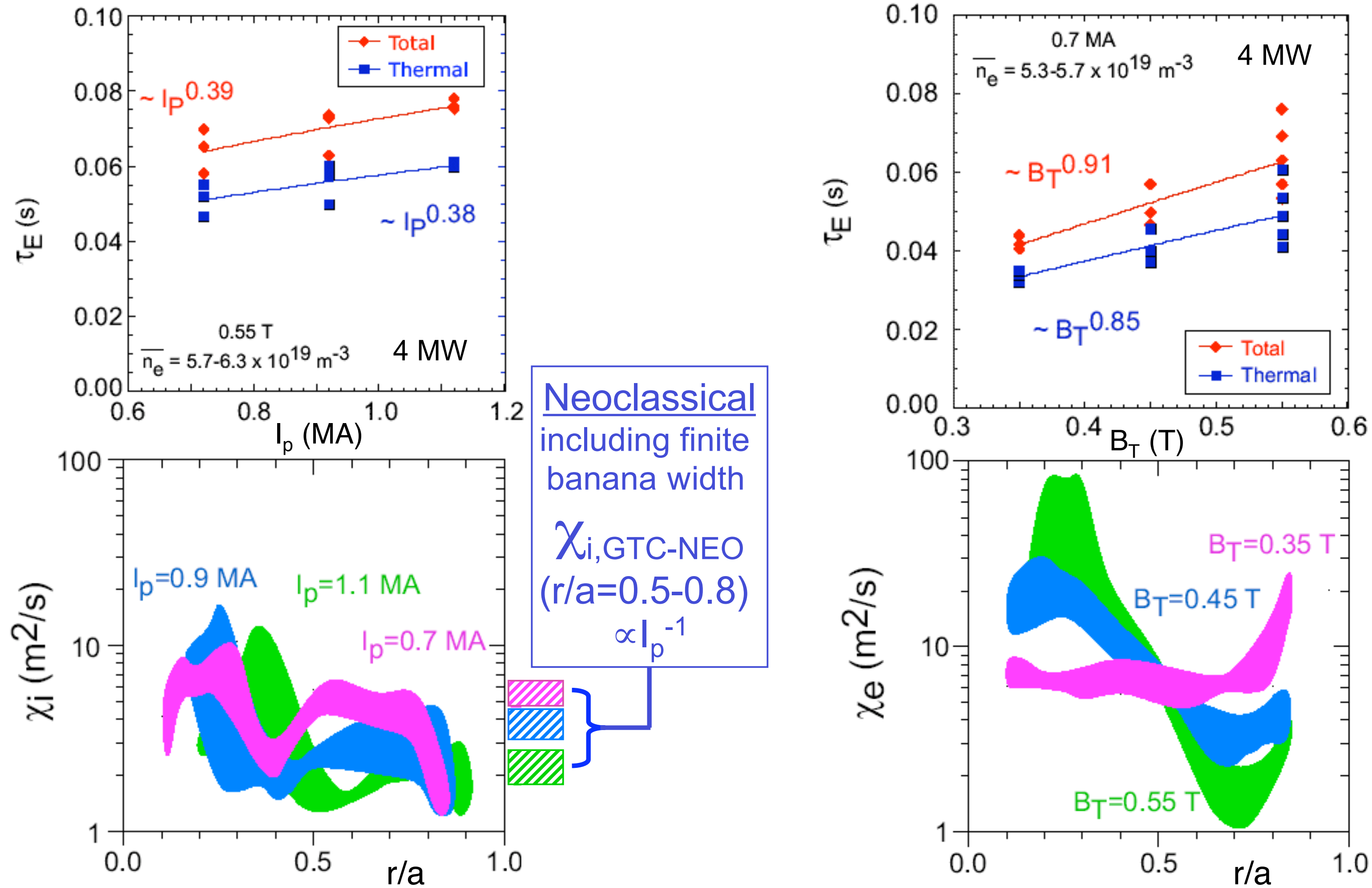
Scaling Experiments Have Revealed Role of Electron Transport in NSTX Energy Confinement

Weaker dependence of τ_E on I_p

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

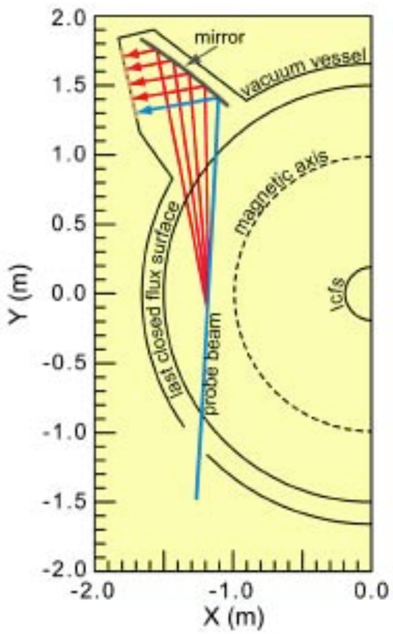
Stronger dependence of τ_E on B_T

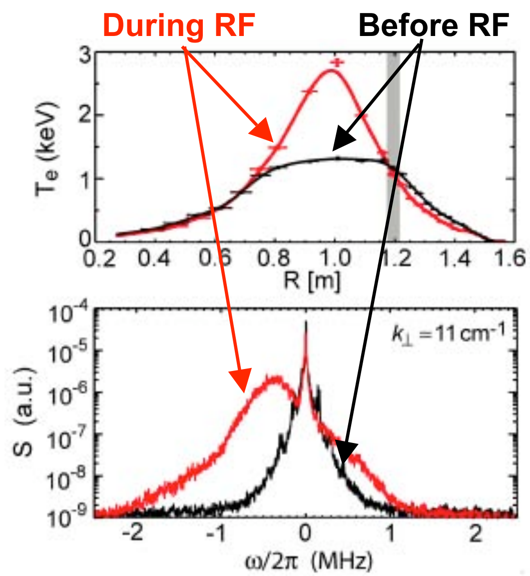
- $\tau_{E,ITER98y,2} \sim B_T^{0.15}$

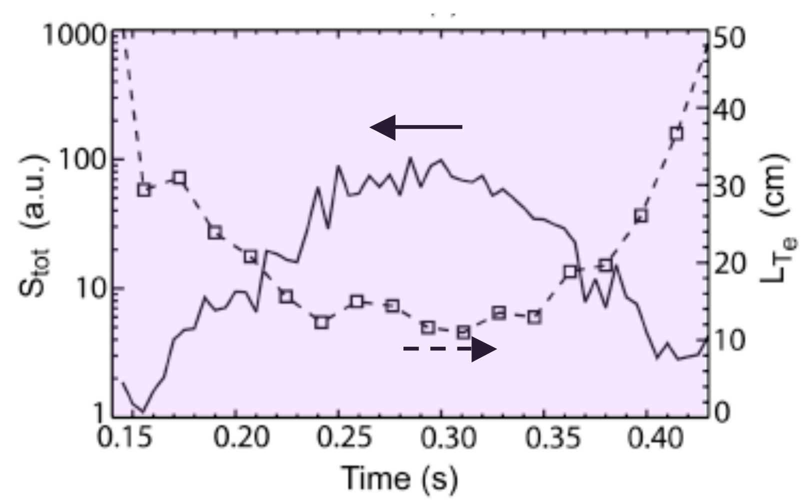


Heating Electrons with RF Waves Drives Short-Wavelength Turbulence in Plasma Core

- 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



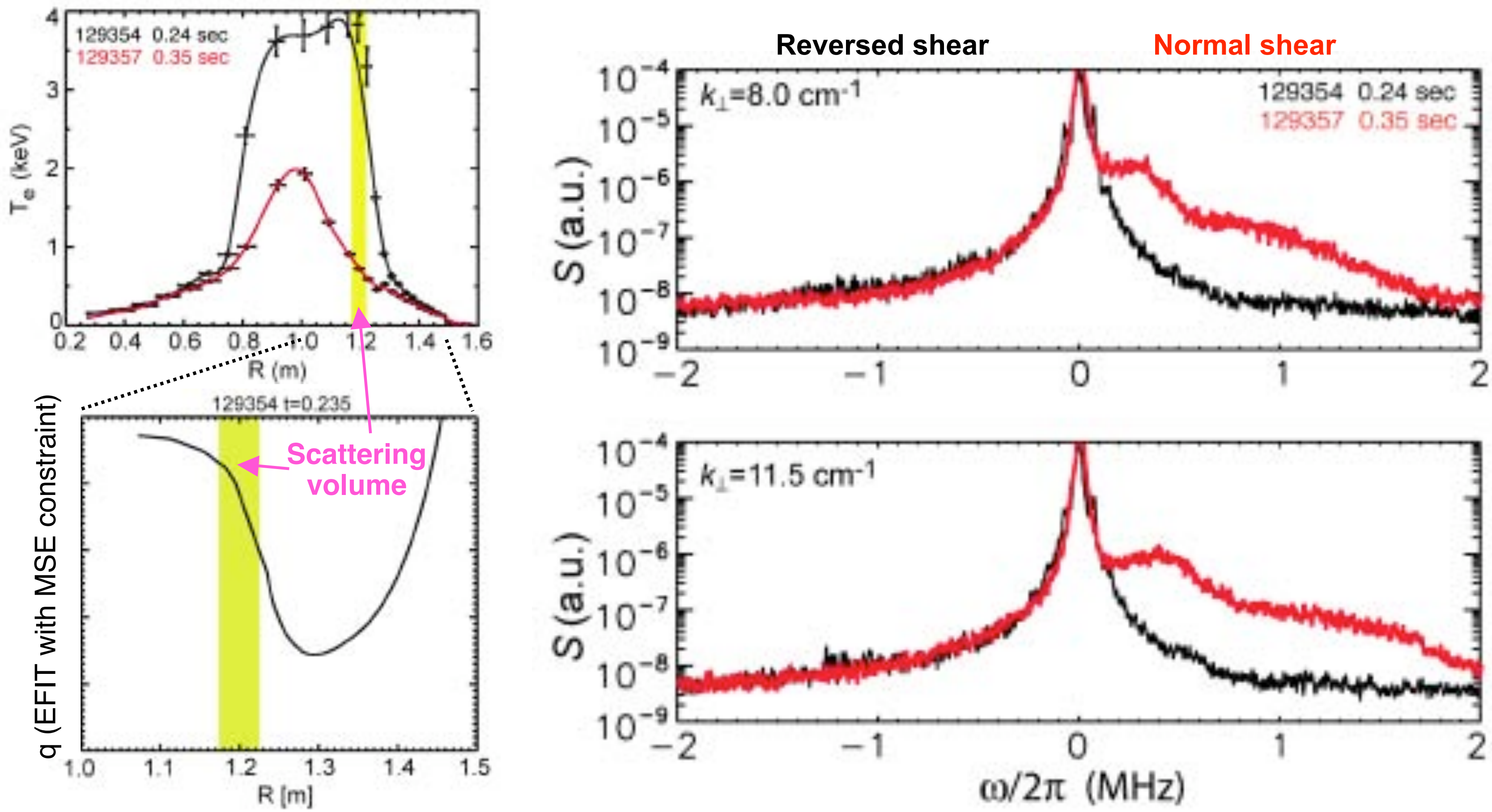




- Detected fluctuations in range $k_\perp\rho_e = 0.1 – 0.4$ ($k_\perp\rho_s = 8 – 16$) propagate in electron diamagnetic drift direction
  - Rules out Ion Temperature Gradient mode ($k_\perp\rho_s \sim 1$) as source of turbulence
  - Qualitative agreement with linear gyrokinetic code (GS2) for Electron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

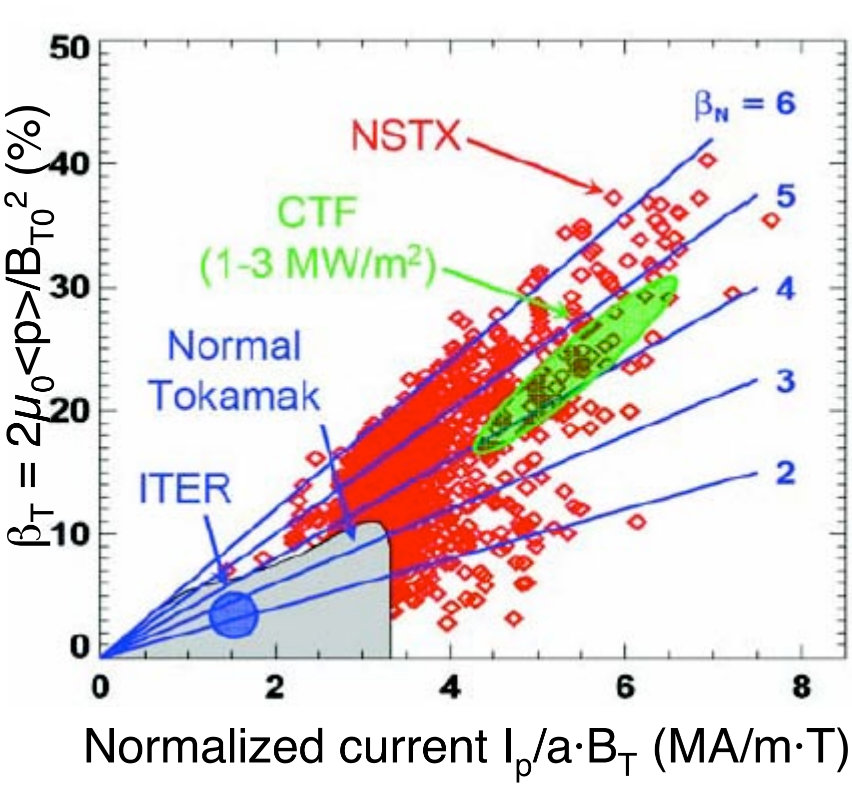
Electron Gyro-Scale Fluctuations Can Be Suppressed by Reversed Magnetic Shear in Plasma Core

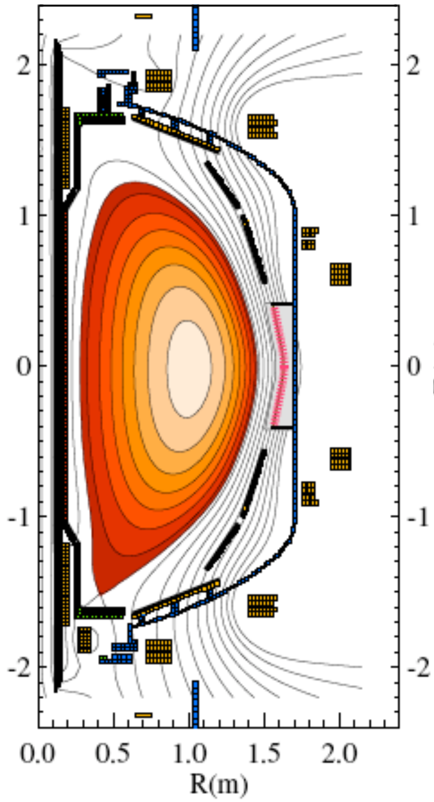
- Shear-reversal produced by early NB heating during plasma current ramp



- 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)

NSTX Extends the Stability Database Significantly

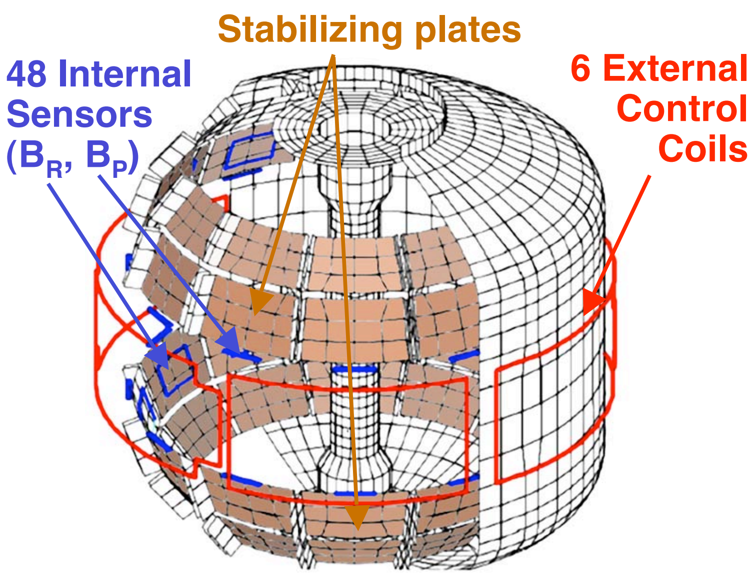




- $A = 1.5$
- $\kappa = 2.3$
- $\delta_{av} = 0.6$
- $q_{95} = 4.0$
- $l_i = 0.6$
- $\beta_N = 5.9\%\cdot m\cdot T/MA$
- $\beta_T =$ 40% (EFIT)
  34% (TRANSP)

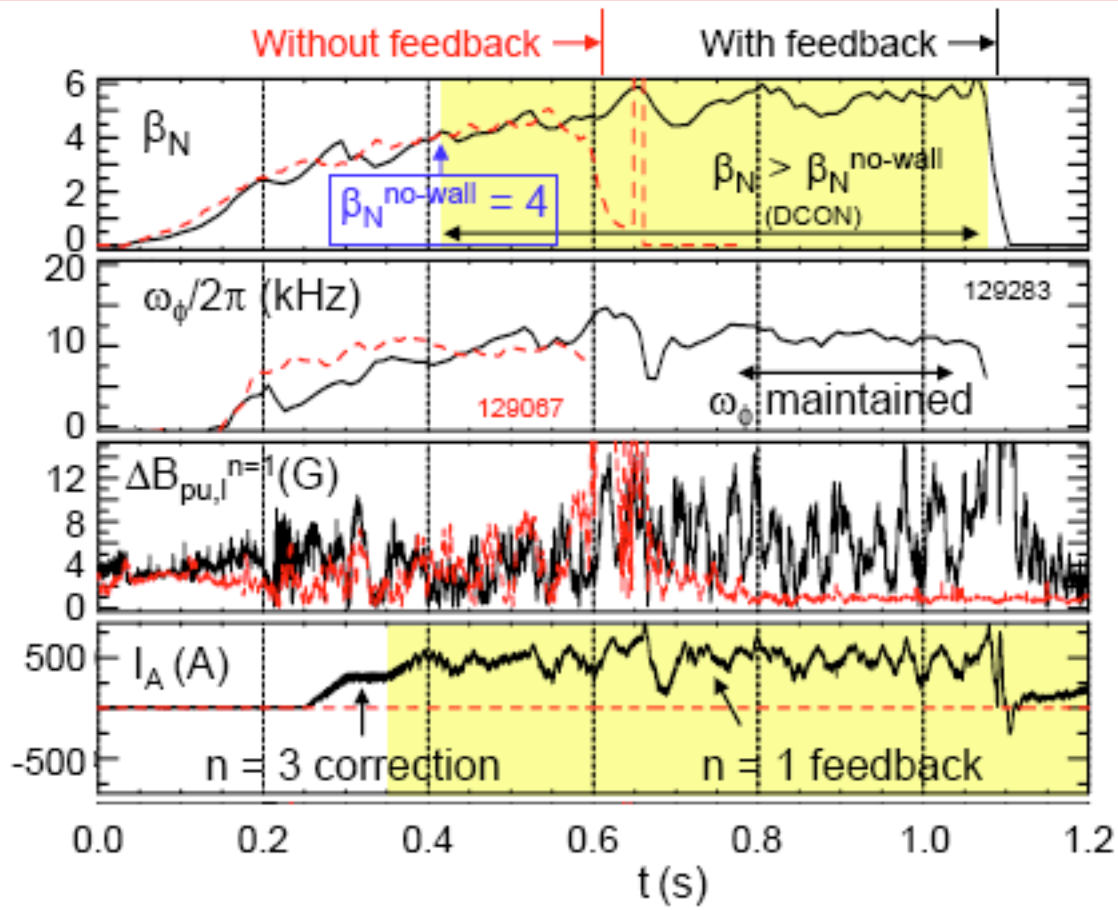
- Benefits of
  - Low aspect ratio
  - Cross-section shaping
  - Stabilization of external modes by conducting plates

Non-Axisymmetric Field Correction and Feedback by External Coils Extend Duration of High-β Plasmas



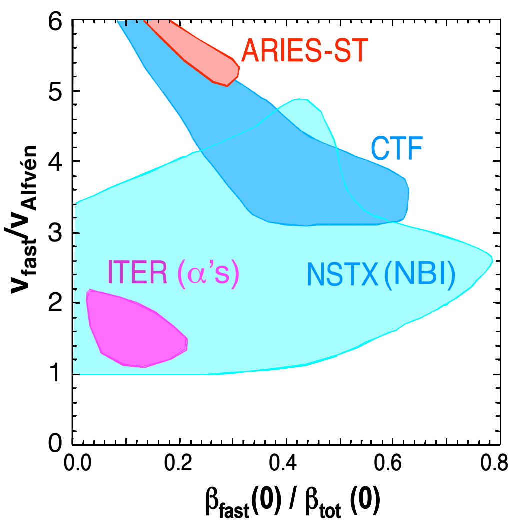
Coils powered by 3 Switching Power Amplifiers (3.5kHz, 1kA)

– Apply n = 1 & 3 or 2 (4) field components

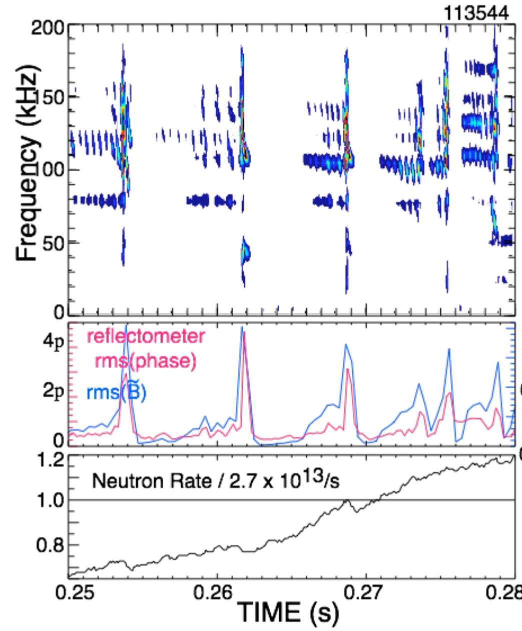


- Programmed correction of intrinsic n = 3 error field maintains toroidal rotation
- Resistive Wall Mode can develop at high normalized-β: terminates discharge
- Feedback on measured n = 1 mode reliably suppresses RWM growth
  – Limitations on time response and applied mode purity explored for ITER

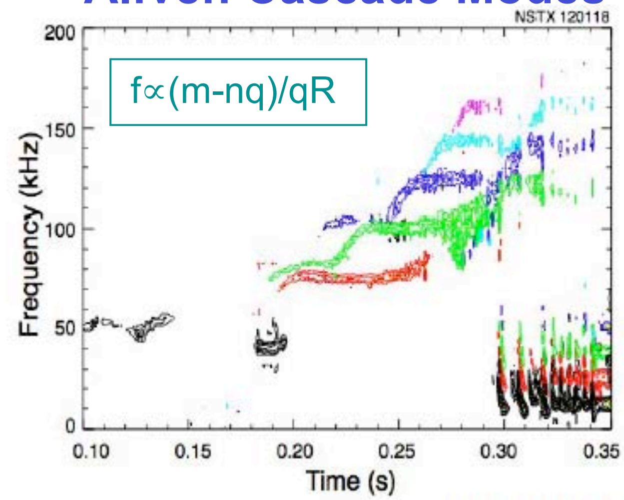
NSTX Accesses Fast-Ion Phase-Space Regime Overlapping With and Extending Beyond ITER

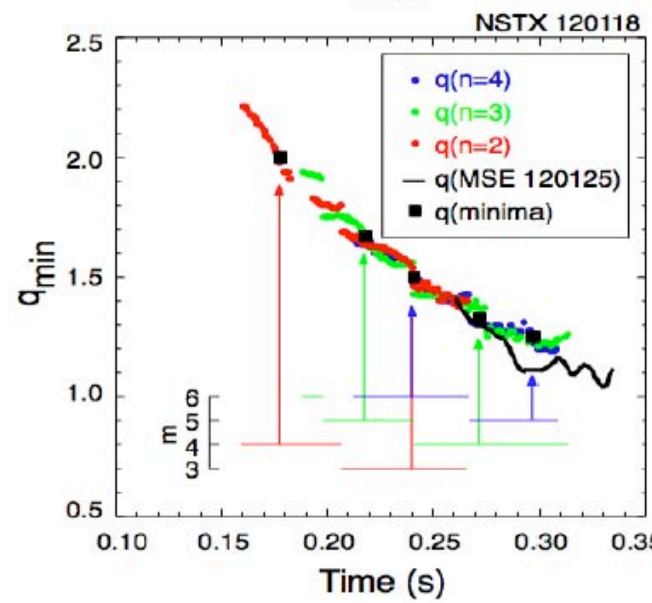


Multi-mode TAE bursts induce fast-ion losses



Alfvén Cascade Modes





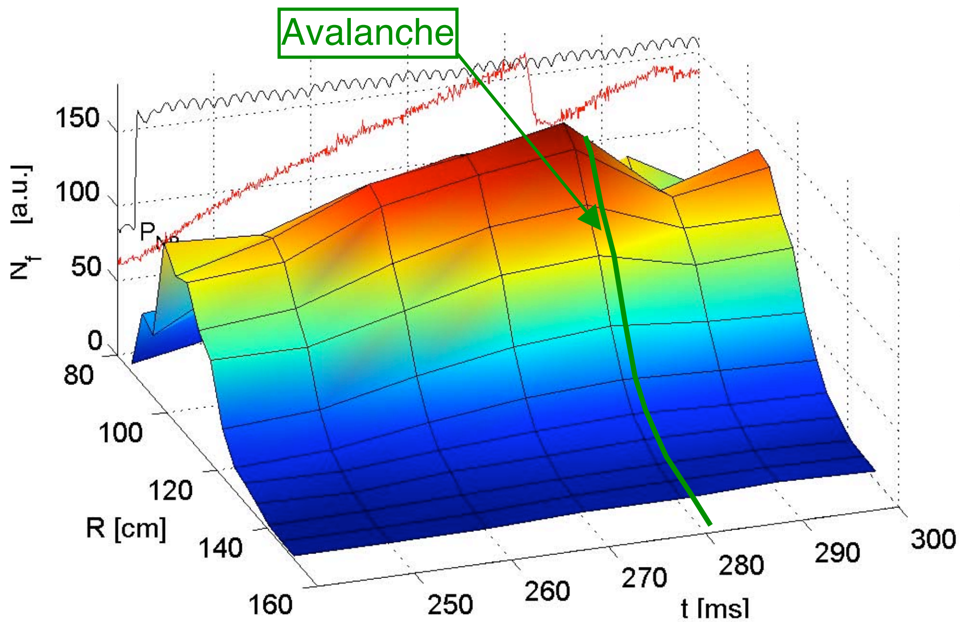
- Alfvén cascades observed at low β_e →
  - Reversed-Shear Alfvén Eigenmodes (RSAE)
- Frequency chirping indicates evolution of q_{min}
  - Matches q(r) analysis with MSE constraint
- Modes also observed in MAST device

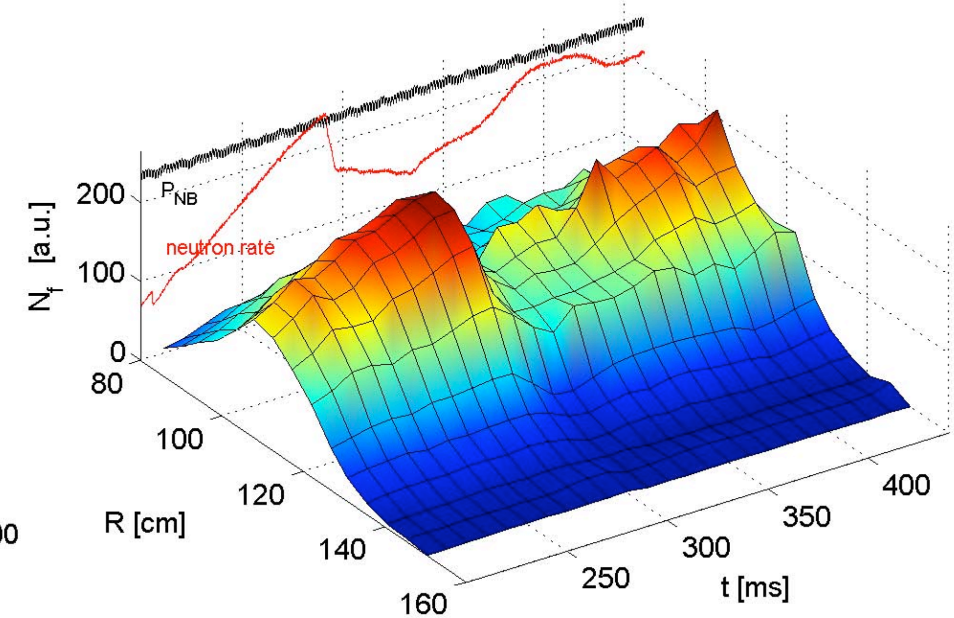
MHD Instabilities Affect Confinement of Fast Ions

- 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

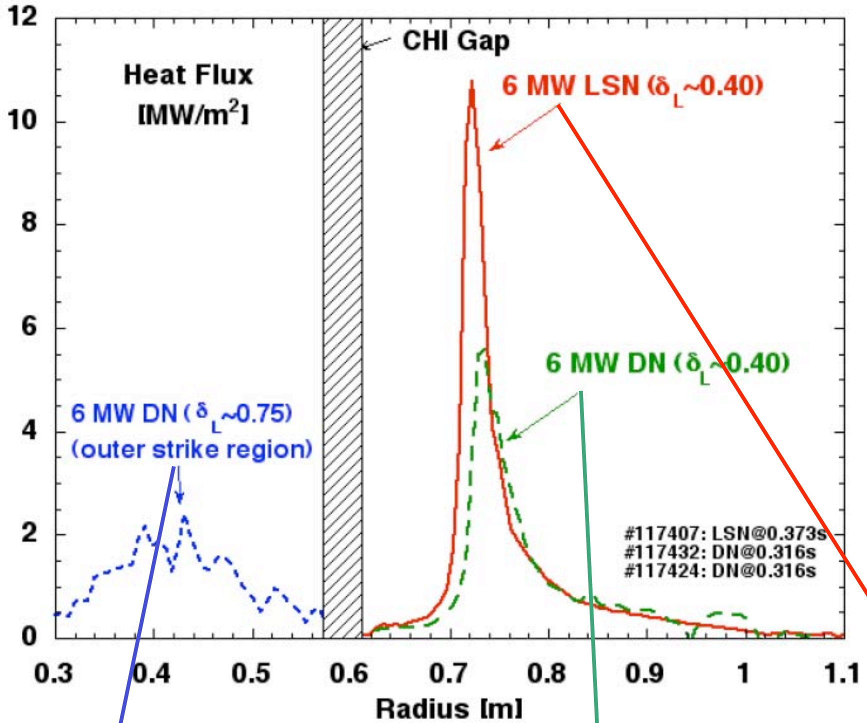
- During TAE avalanches, measured fast-ion losses up to 30%
  - Consistent with neutron rate drop
  - Profile remains peaked

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

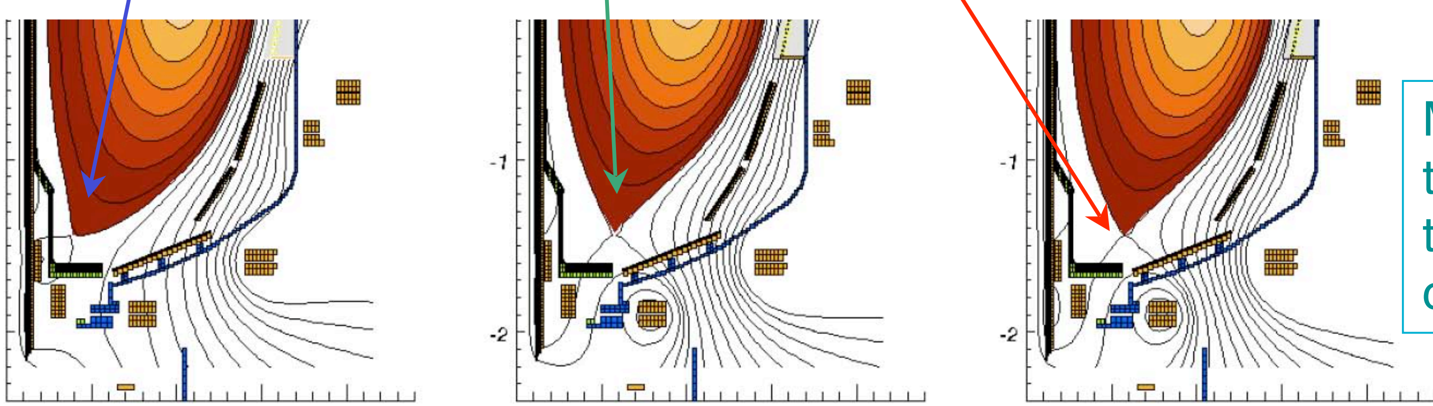




Peak Heat Flux on Lower Divertor Can Be Reduced By Plasma Shaping

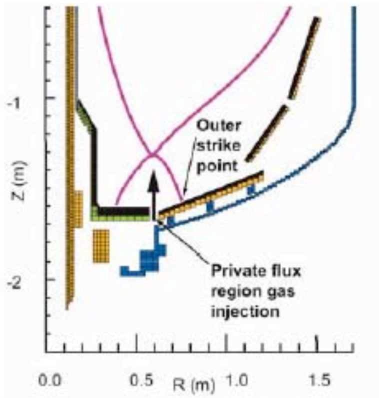


- Compare configurations with different triangularity at X-point δ_X
  - lower single-null (LSN), $\delta_X \approx 0.4$
  - double-null (DN), $\delta_X \approx 0.4$
  - high triangularity DN $\delta_X \approx 0.75$
- Flux expansion reduces heat flux
  1 : 0.5 : 0.2
- ELMs: Type I → Mixed → Type V
  (large) (small)

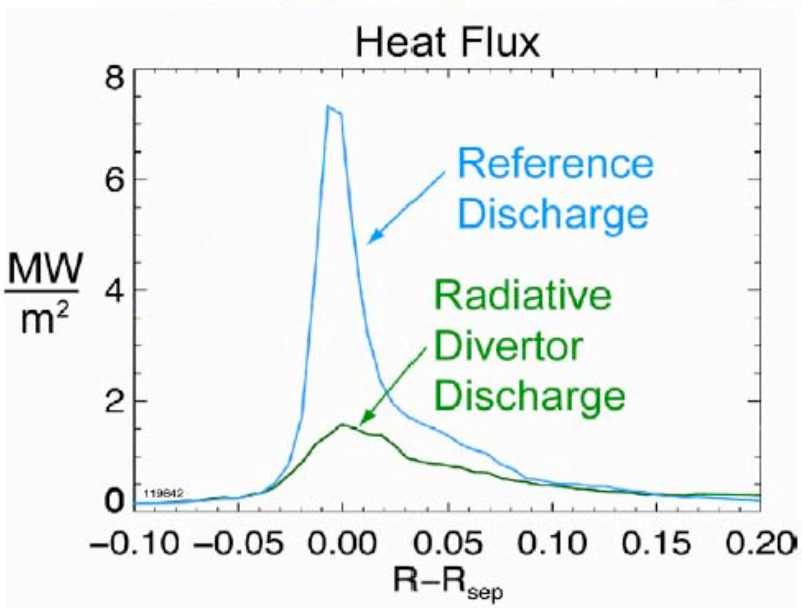


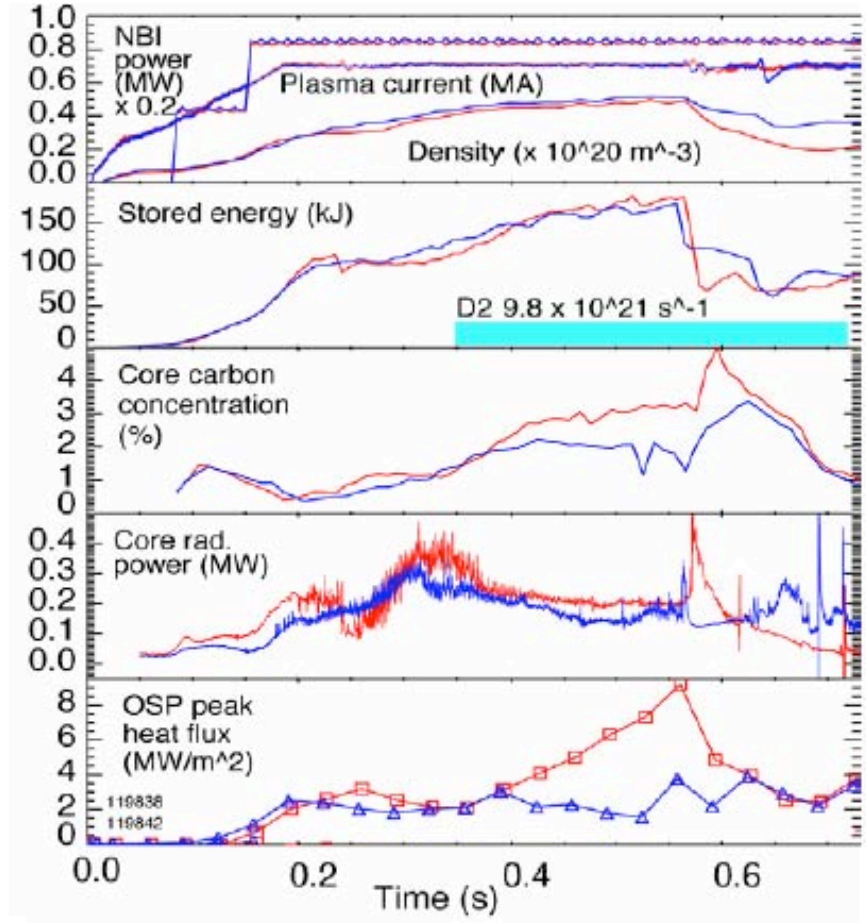
Measure heat flux to divertor with IR thermography of carbon tiles

Gas Puffing Near X-point Can Produce Radiative Divertor Without Affecting Core Confinement



Obtained by continuous D_2 injection through divertor gap into private flux region





- Outer strike point heat flux reduced to ~20%
- No change in H-mode τ_E

NSTX is Exploring and Developing Lithium-Coated Plasma Facing Components

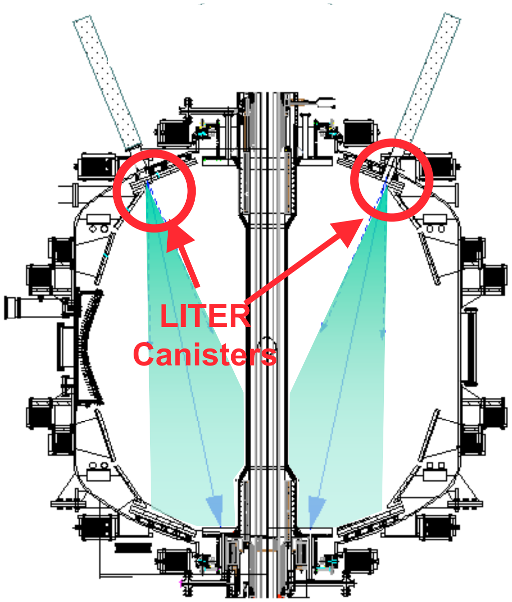
2005: Injected lithium pellets, 2 - 5 mg, into He discharges prior to D NBI shot

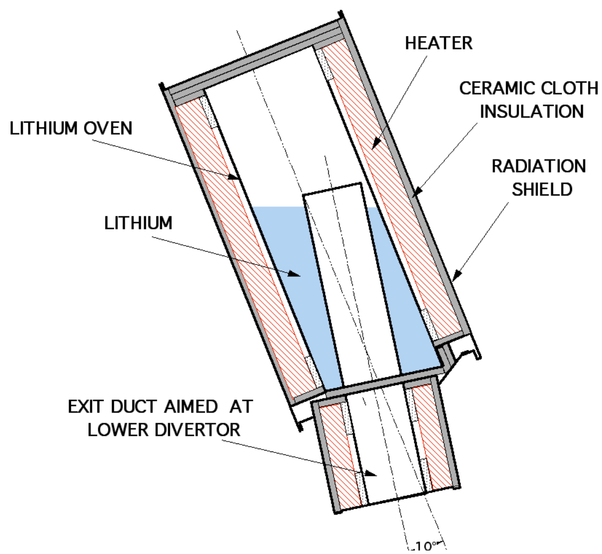
2006: LIThium EvaporatoR (LITER) deposited lithium on divertor between shots

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

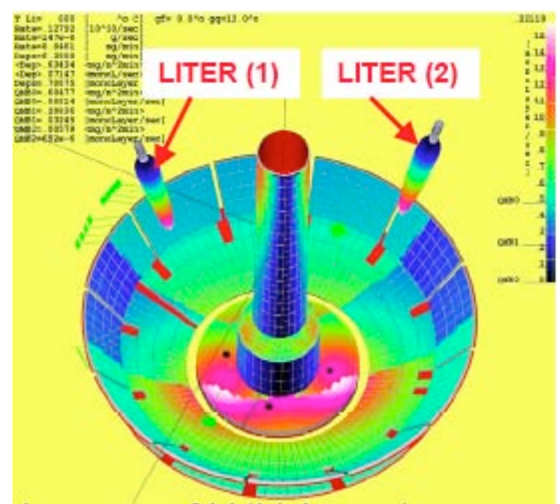
2008: Dual LITERs covered entire lower divertor; shutters interrupted lithium stream during plasmas; evaporated ~200g lithium (reloaded 3 times)

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

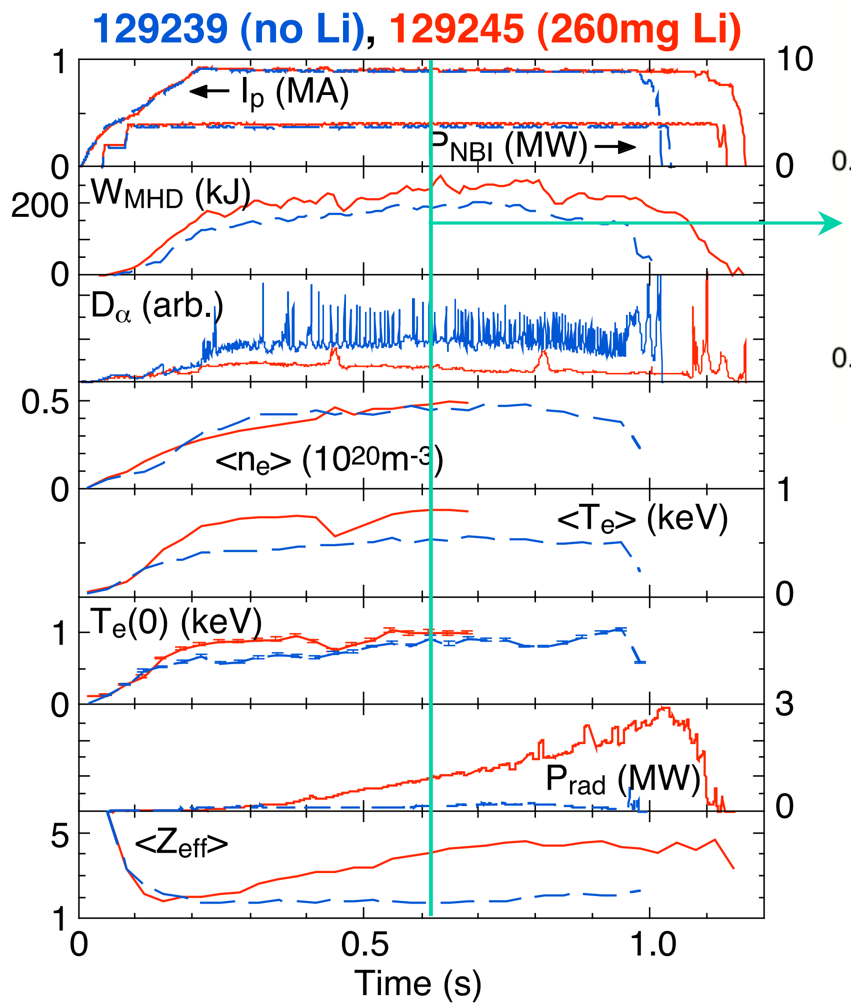


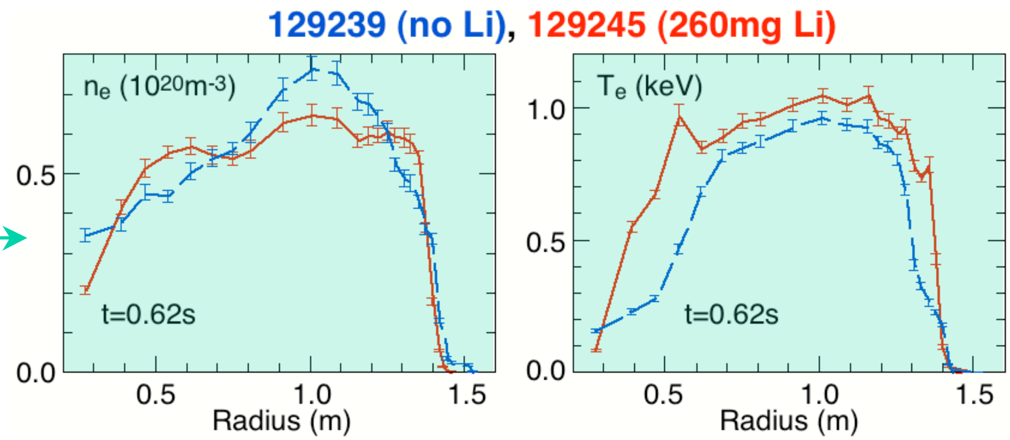


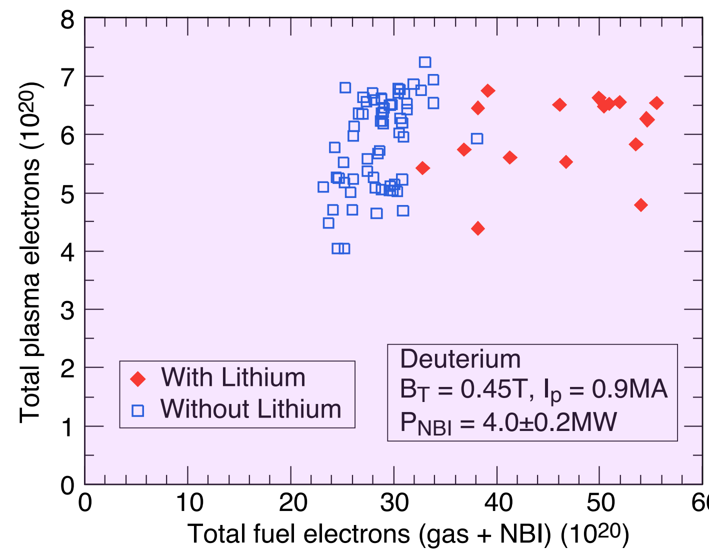
Modeled deposition pattern



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

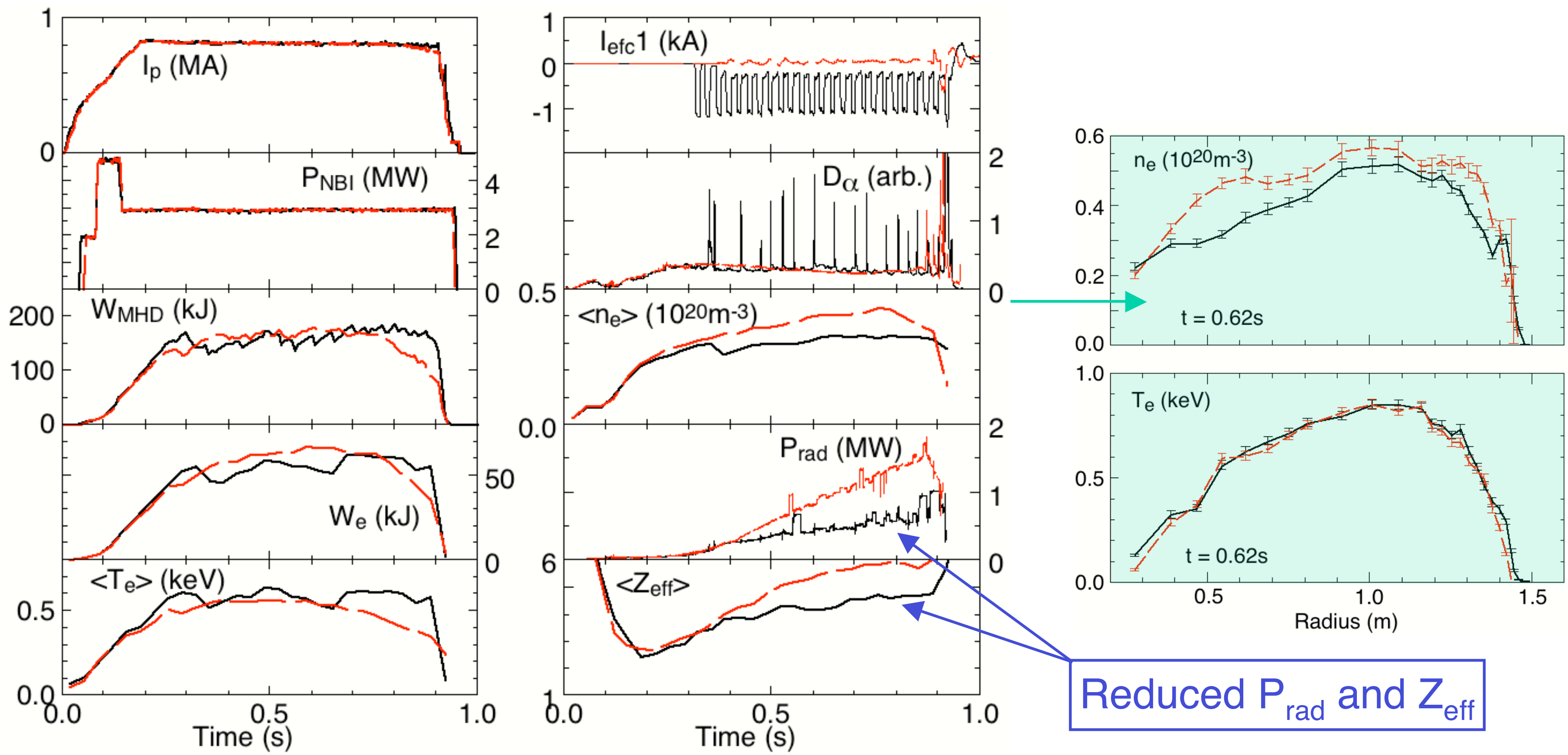






- Without ELMs, impurity accumulation increases P_{rad} and Z_{eff}

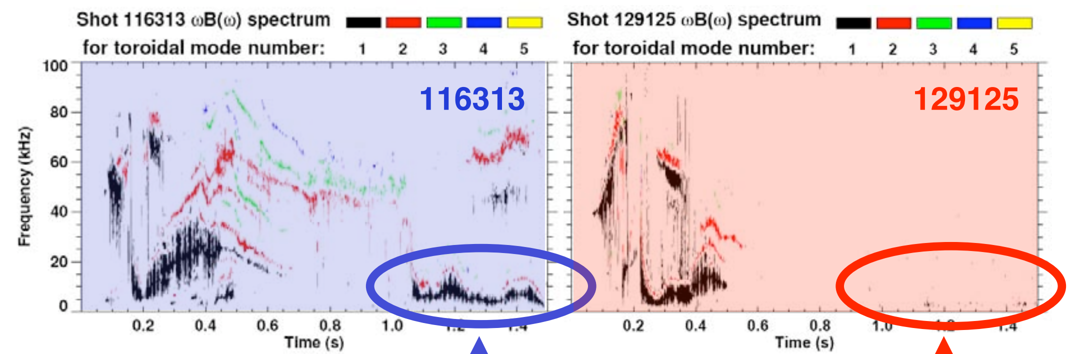
Non-Axisymmetric Midplane Coils Can Induce Repetitive ELMs in Lithium-Suppressed Plasmas

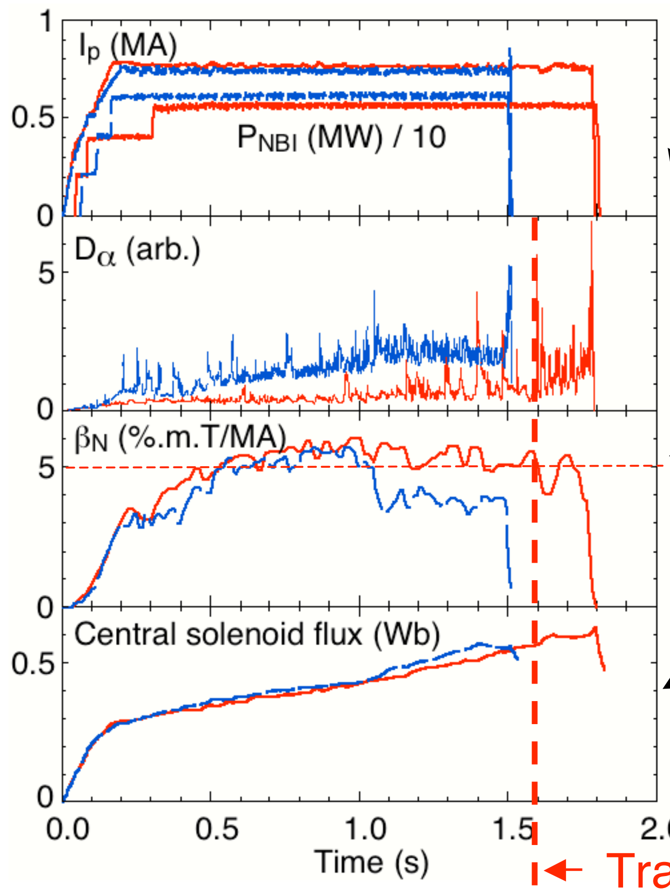


- n = 3 resonant magnetic perturbation applied
- 11ms duration pulse at 40Hz optimal for this shape (DN, κ=2.4, δ=0.8)
- RMPs have also modified ELM behavior in non-lithium ELMing plasmas

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

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

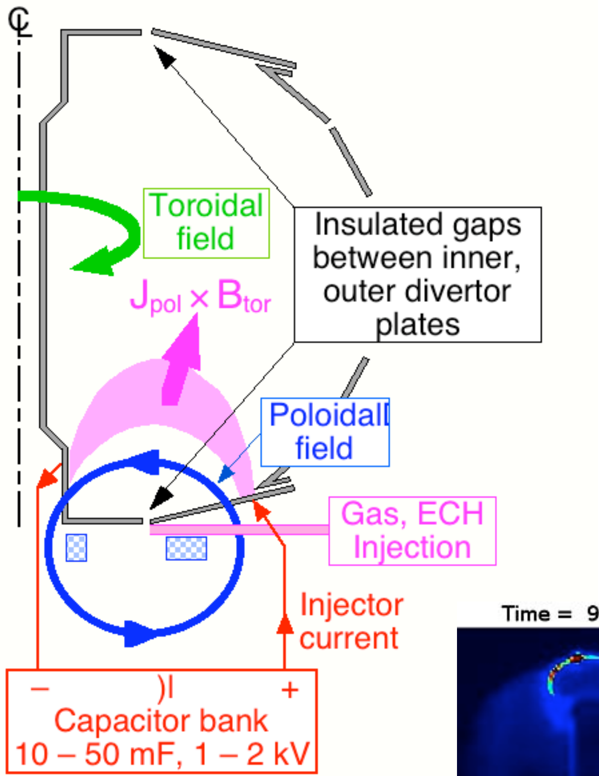
- EF/RWM control sustains rotation, high β

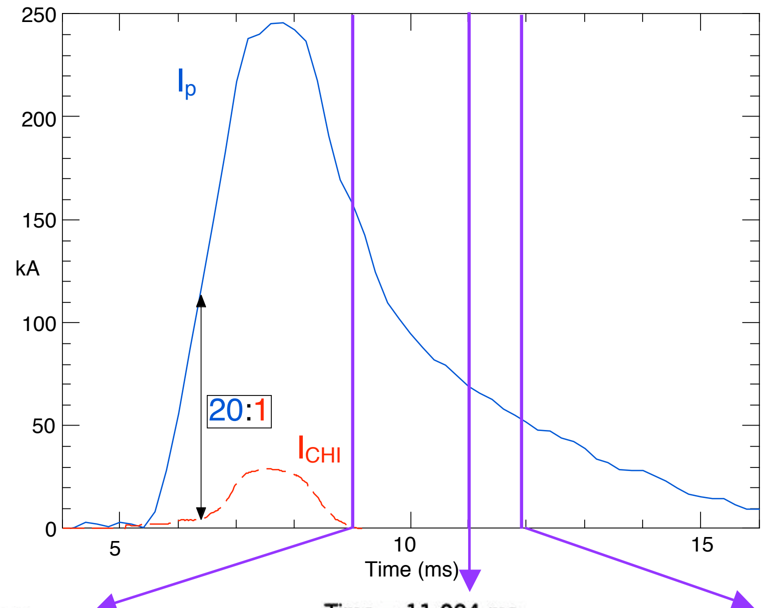
Flux consumption reduced by sustained high β + Li conditioning

- High elongation κ = 2.4 increases bootstrap current fraction

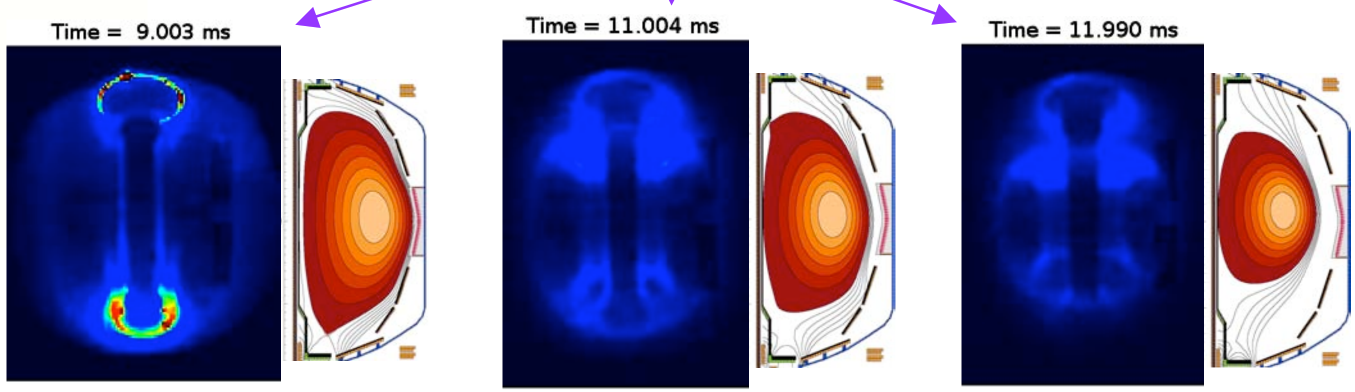
← Transition to phase with larger, more frequent ELMs

Coaxial Helicity Injection (CHI) Generated 160 kA of Toroidal Plasma Current in NSTX



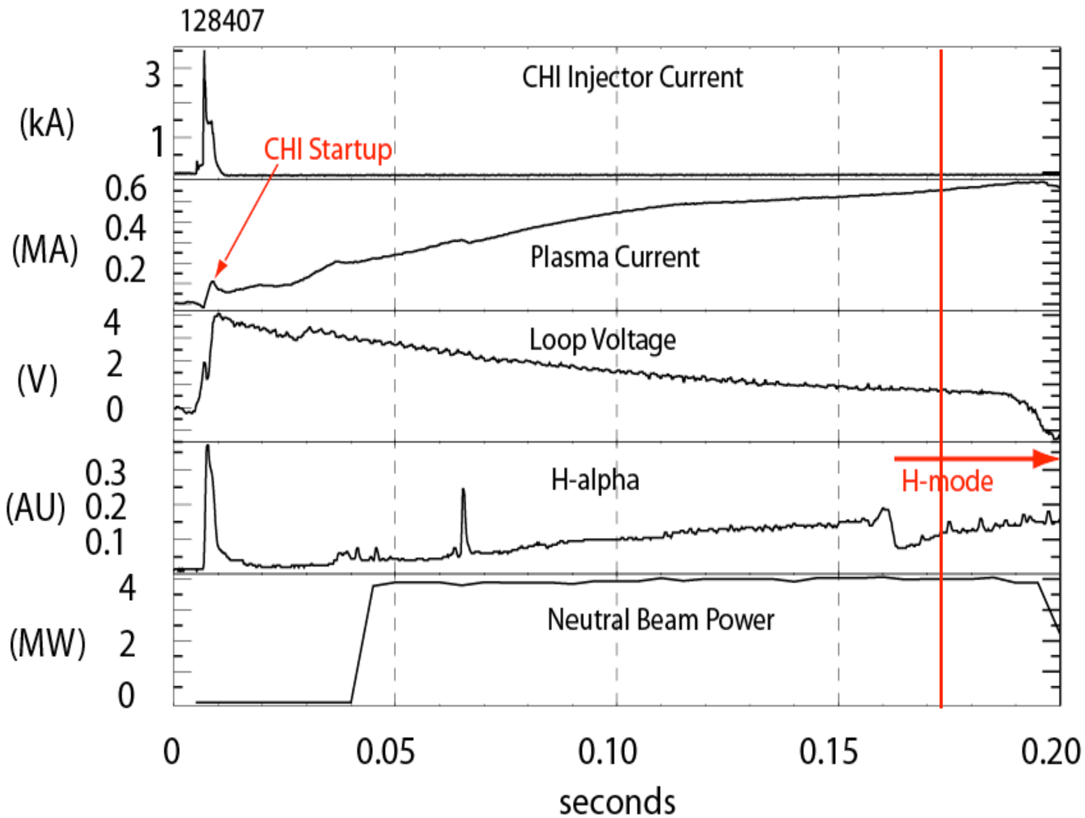


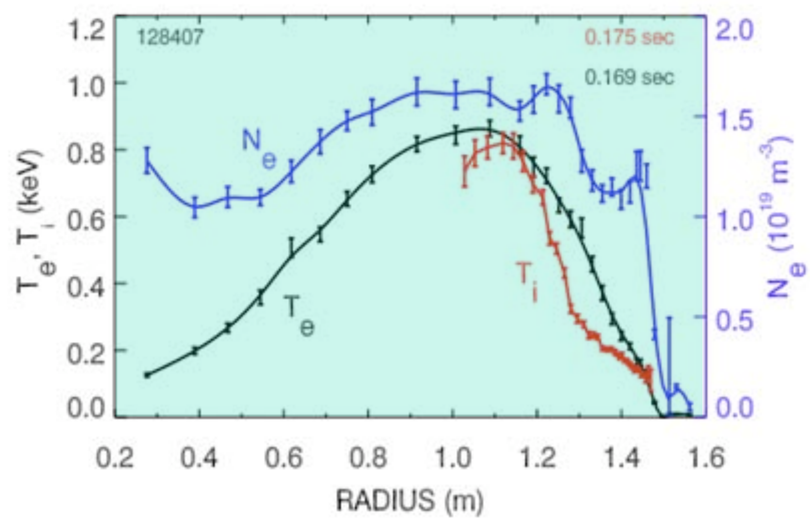
Toroidal plasma current after $I_{CHI} \rightarrow 0$ flows on closed surfaces



- After $I_{CHI} \rightarrow 0$, EFIT reconstructs detachment from injector and resistive current decay
  - Decay rate consistent with T_e = 10 – 20 eV

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





- Broad density profile during H-mode phase

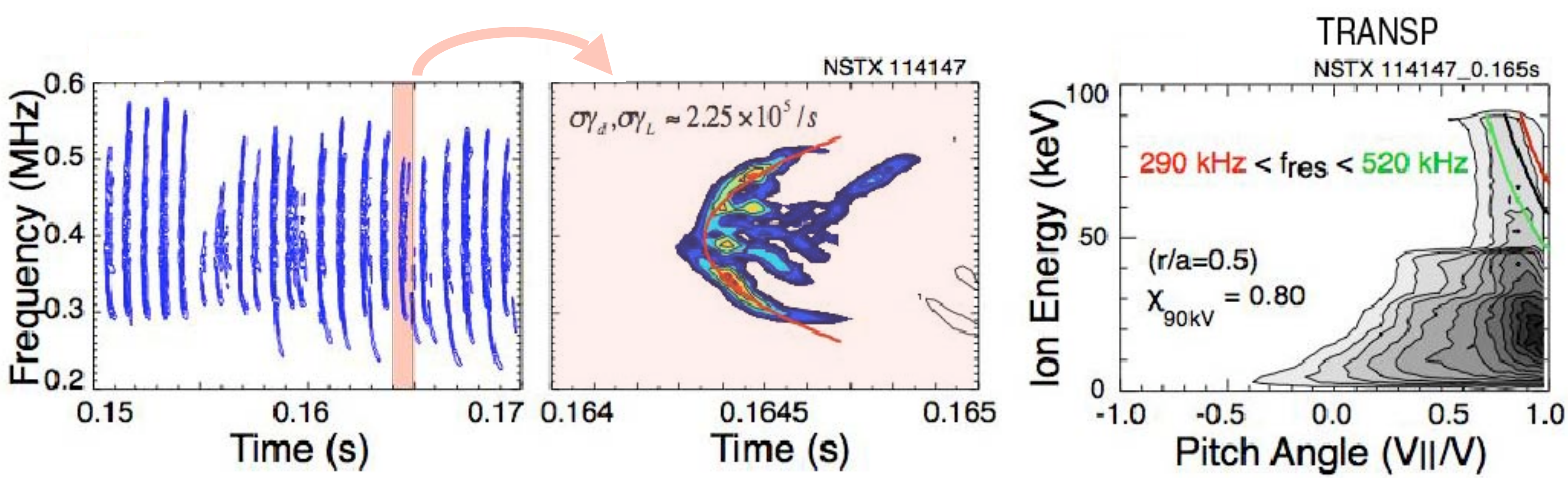
- Discharge is under full equilibrium control
- Loop voltage is preprogrammed
- With lithium coating, CHI-initiated discharges are more reproducible and reach higher currents with similar inductive flux

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

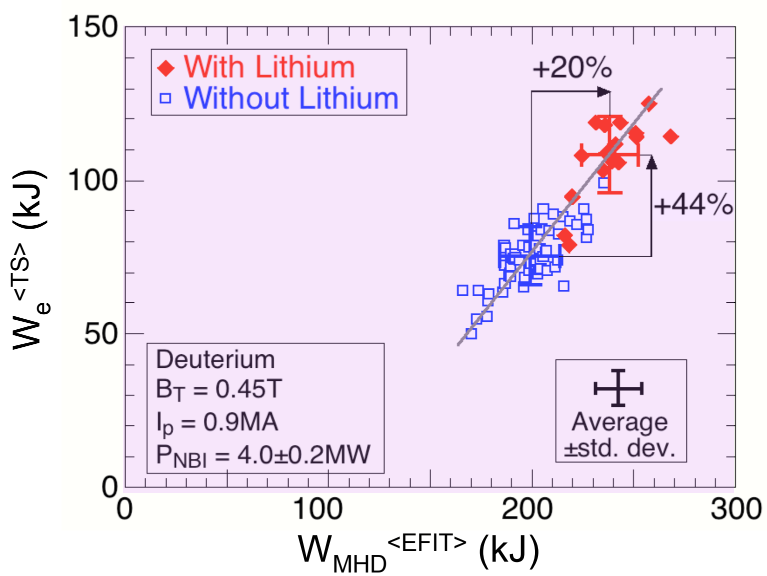
- Investigating the physics of anomalous electron transport
  - Electron transport dominates as a result of ion-scale mode suppression
- Extending the understanding of MHD stability at high β
  - Extending pulse length through active control of low-n modes
- Examining stability and effects of super-Alfvénic ions
  - Measuring transport of fast ions 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
- Developing alternate methods for plasma startup and sustainment
  - Coaxial Helicity Injection can replace inductive initiation

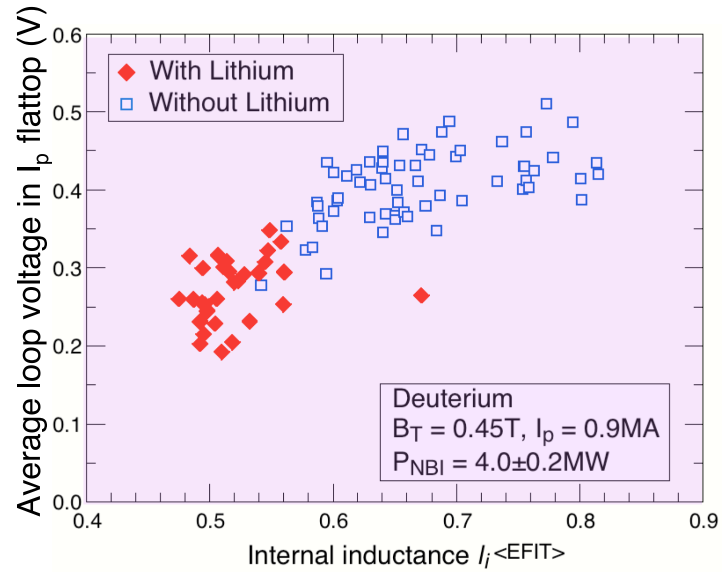
"Angelfish" MHD Phenomenon Identified as Form of Hole-Clump, Consistent with Theory

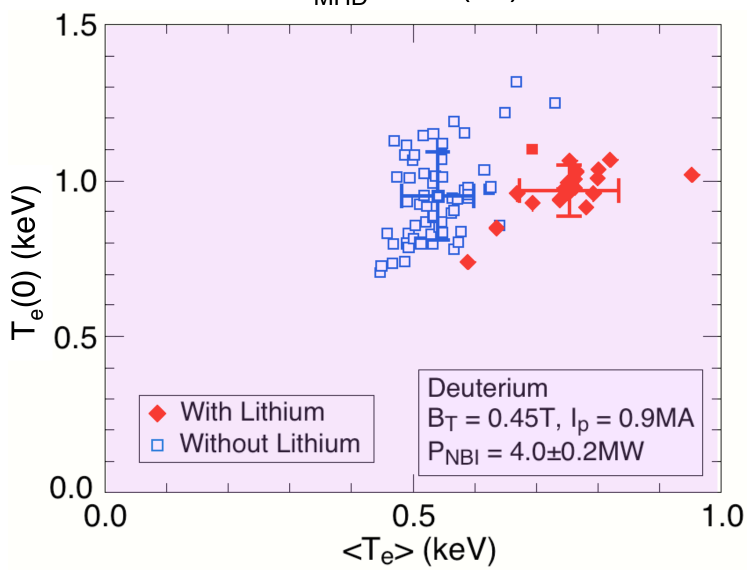
- Compressional Alfvén Eigenmode satisfies Doppler-shifted resonance condition for calculated fast ion distribution ($\omega = \omega_c - k_{||}v_{beam}$)
  - Fast ions modelled with TRANSP code using classical slowing down
- Growth rate from theory in reasonable agreement with observation
- Controlling fast-ion phase space can suppress deleterious instabilities
  - "Angelfish" instability suppressed by addition of HHFW heating



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



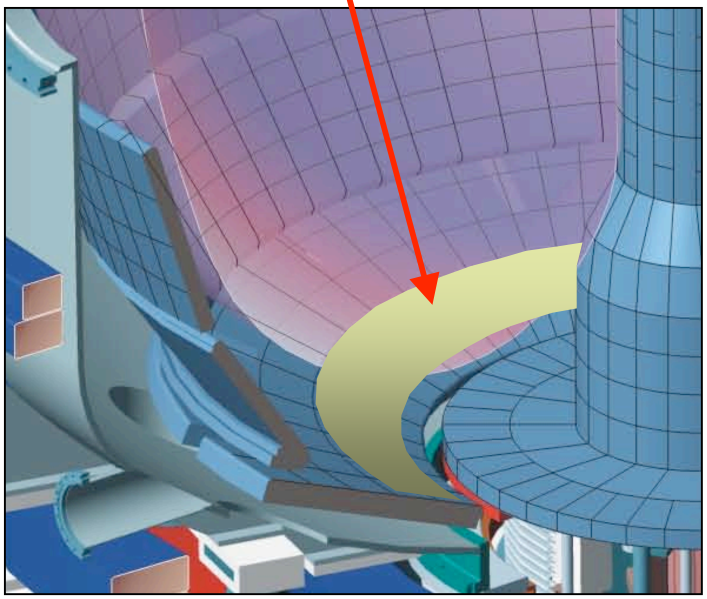




- Broader electron temperature profile reduces internal inductance l_i and inductive flux consumption in current flattop, despite higher Z_{eff}
- Lithium increases edge bootstrap current through higher p', lower collisionality

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