NSTX PPPL Princeton Plasma Physics Laboratory

Supported by Office of Fusion Energy Sciences — Office of Science

An Overview of Recent Results from the National Spherical Torus Experiment

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for the ***NSTX Research Team***

National Institute for Fusion Science

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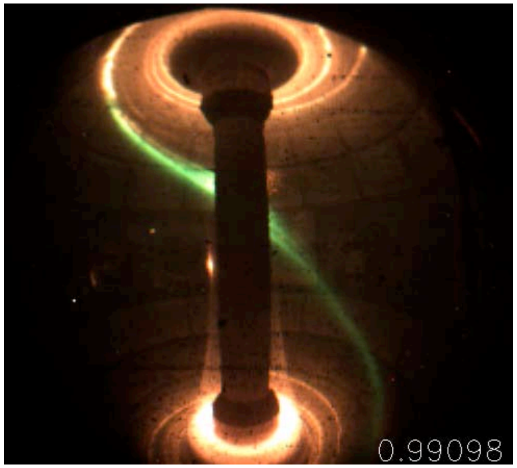

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IPP, Garching
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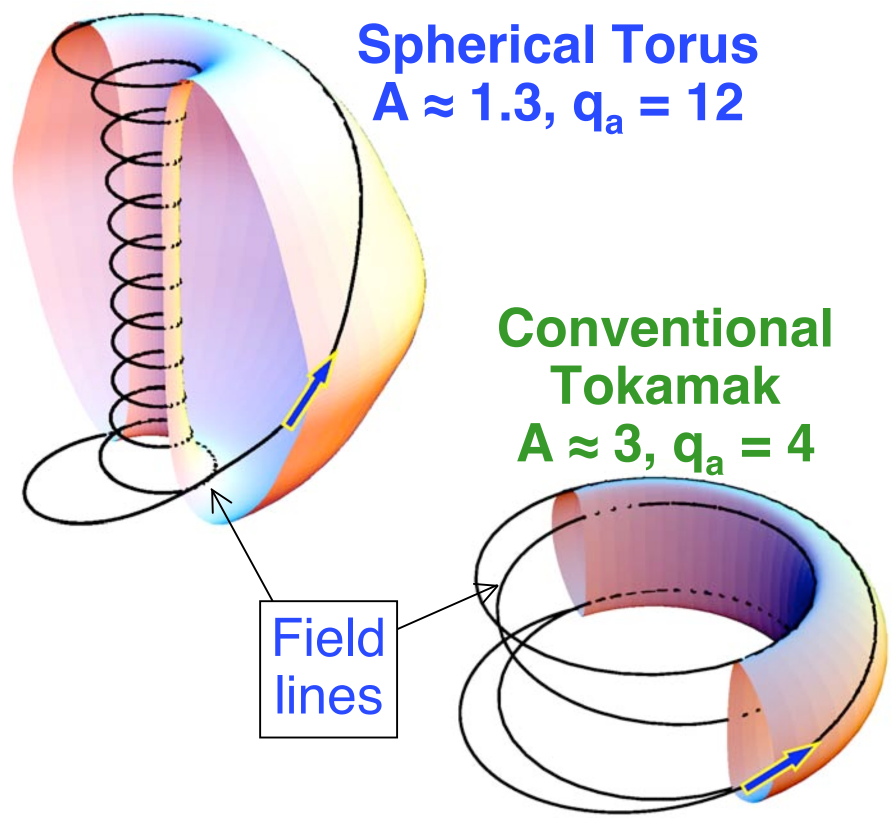
"Spherical Torus" Extends Tokamak to Extreme Toroidicity

- Motivated by potential for increased β *[Peng & Strickler, 1980s]*

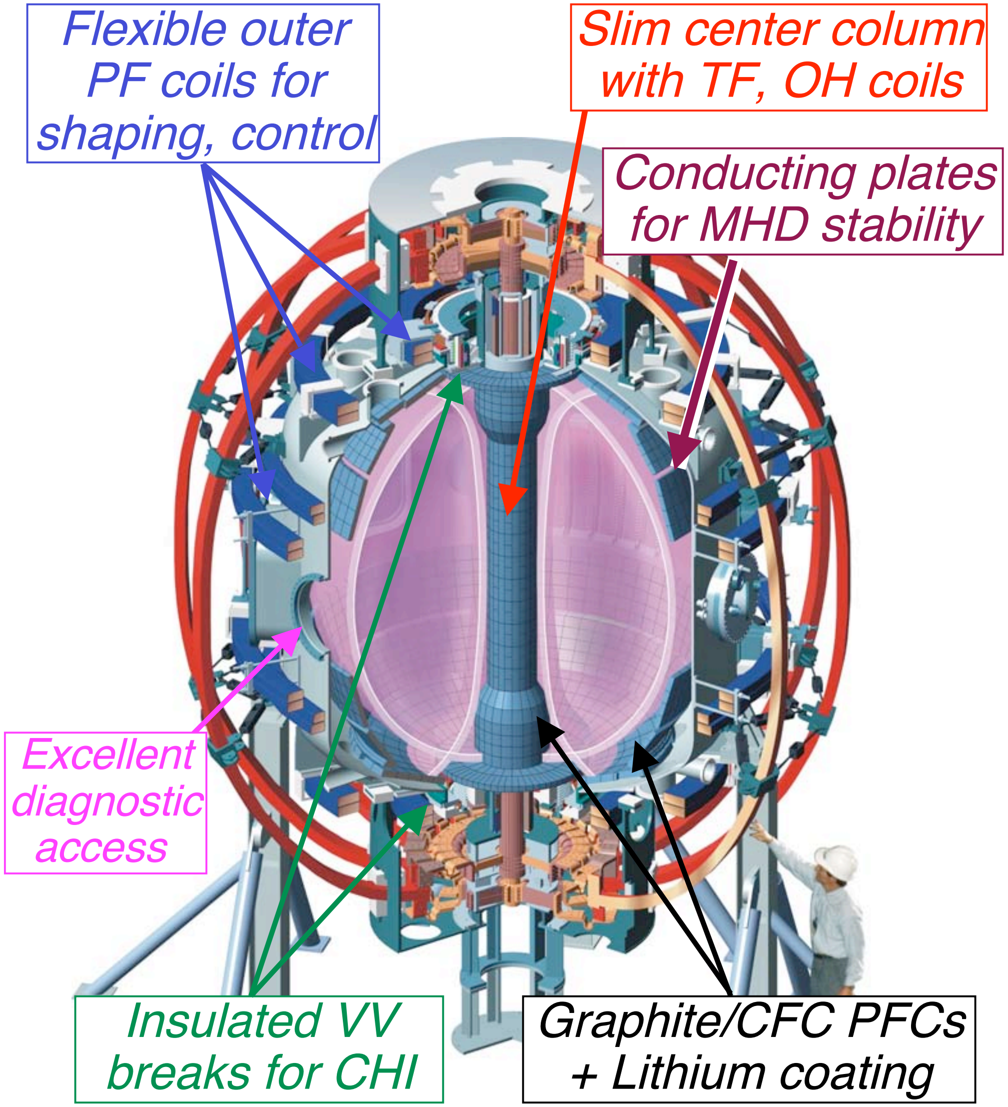
$$\beta_{max} \ (= 2\mu_0\langle p\rangle/B_T^2) \ = \ C\cdot I_p/aB_T \ \propto \ C\cdot\kappa/\mathbf{A}q$$

B_T: toroidal magnetic field on axis;
$\langle p\rangle$: average plasma pressure;
I_p: plasma current;
a: minor radius;
κ: elongation of cross-section;
A: aspect ratio (= R/a);
q: MHD "safety factor" (> 2)
C: Constant ~3%·m·T/MA
[Troyon, Sykes - early 1980s]

- Confirmed by experiments
  - **β_{max} ≈ 40%**
    [START (UK) 1990s]



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



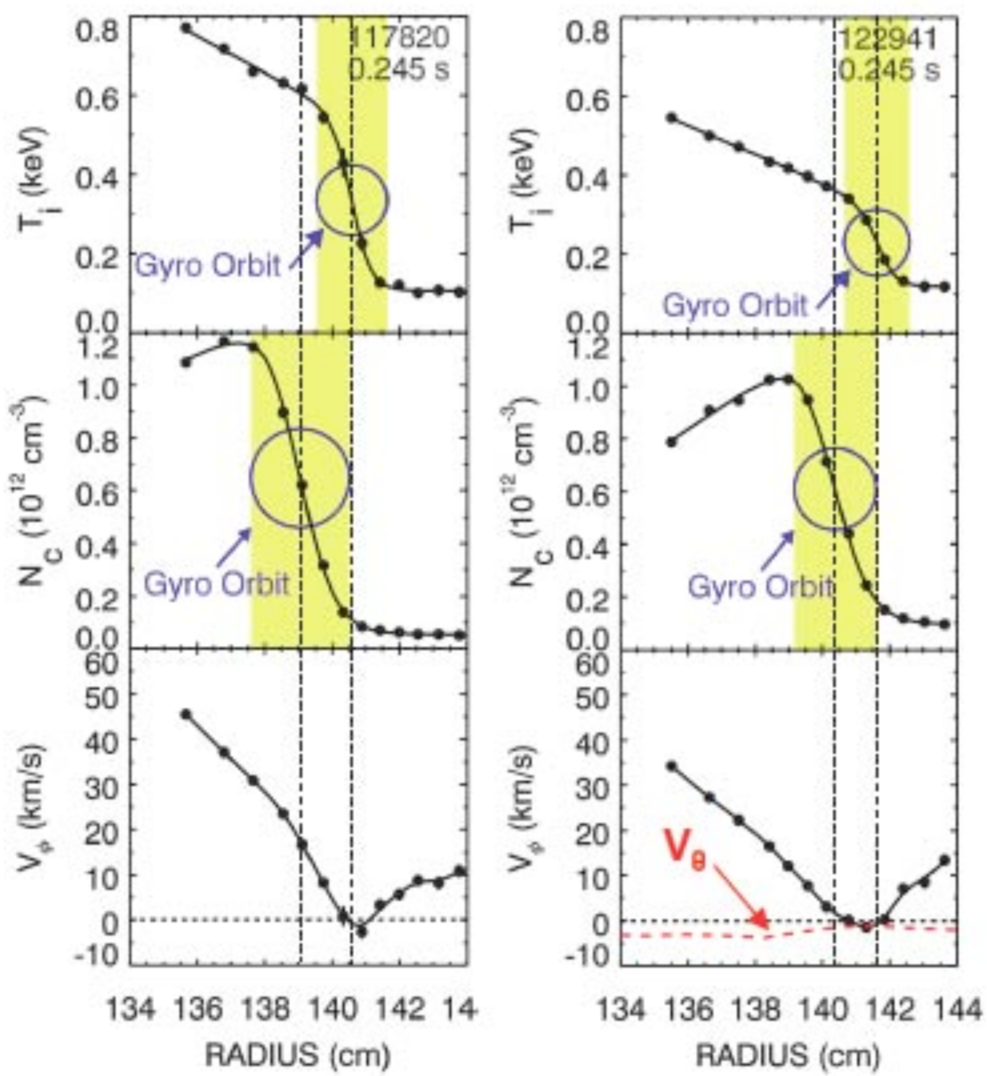
Aspect ratio A	1.27 – 1.6
Elongation κ	1.8 – 3.0
Triangularity δ	0.2 – 0.8
Major radius R_0	0.85m
Plasma Current I_p	1.5MA
Toroidal Field B_{T0}	0.4 – 0.55 T
(Pulse Length	~2 – ~1 s)
Auxiliary heating:	
NBI (100kV)	5 – 7 MW
(Pulse Length	5 – 2 s)
RF (30MHz)	6 MW (5 s)
Central temperature	1 – 5 keV
Central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

NSTX 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 ($M \sim 0.5$)
  – Predicted to suppress ion turbulence
- High dielectric constant ($\varepsilon \sim 30–100$)
  – Different regime for RF wave heating and current drive
- Large population of supra-Alfvénic fast ions ($v_{NBI}/v_{Alfvén} \sim 4$)
  – Physics of alpha particles in burning plasmas
- High divertor power flux (P/R)
  – Challenges plasma facing materials

Gyro-Radius Scale Gradients in Ion Profiles Observed in NSTX NBI-Heated H-mode Plasmas

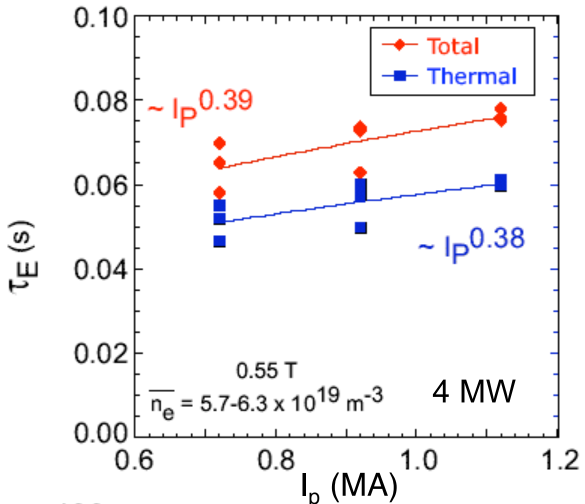
- Carbon C^{6+} ion temperature T_i, density n_C and toroidal velocity v_ϕ from Charge-Exchange Recombination Spectroscopy
- Preliminary measurements indicate small poloidal velocity
- ΔT_i = 250 – 450 eV over 2cm
- Gradient in n_C shifted inward from T_i gradient
- Carbon v_ϕ shows dip in region of T_i gradient
- Strong gradient in ion pressure implies large negative E_r and strong E_r gradients
- Significant distortion of ion orbits and modification of transport

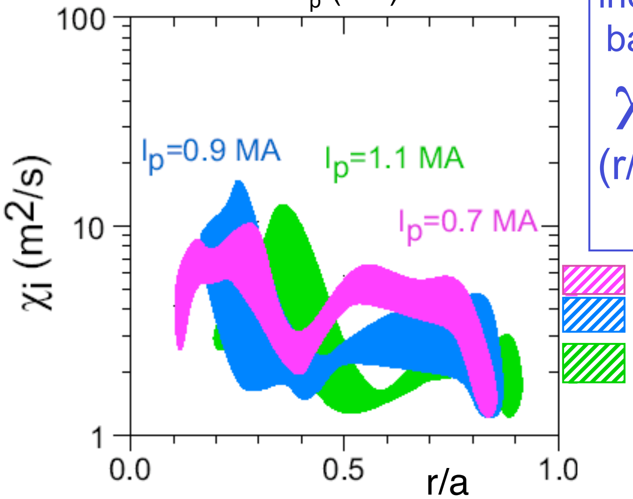


Scaling Experiments Have Revealed Role of Electron Transport in NSTX Energy Confinement

Weaker dependence of τ_E on I_p

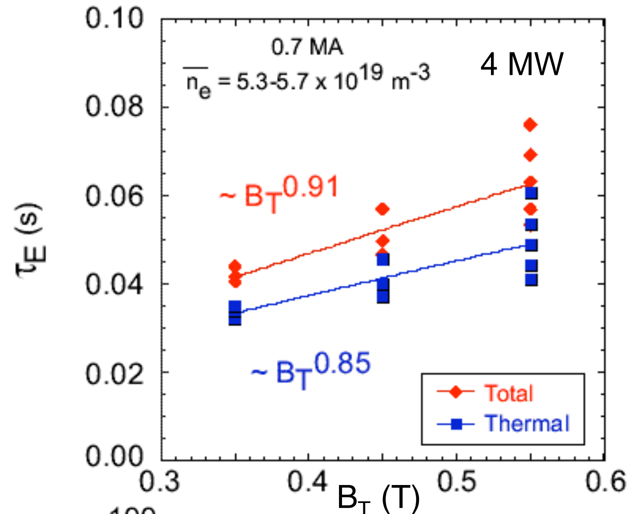
- $\tau_{E,ITER98y,2} \sim I_p^{0.93}$

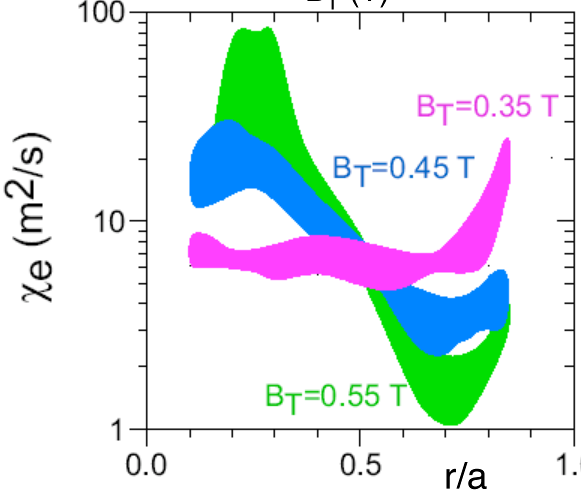




Stronger dependence of τ_E on B_T

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



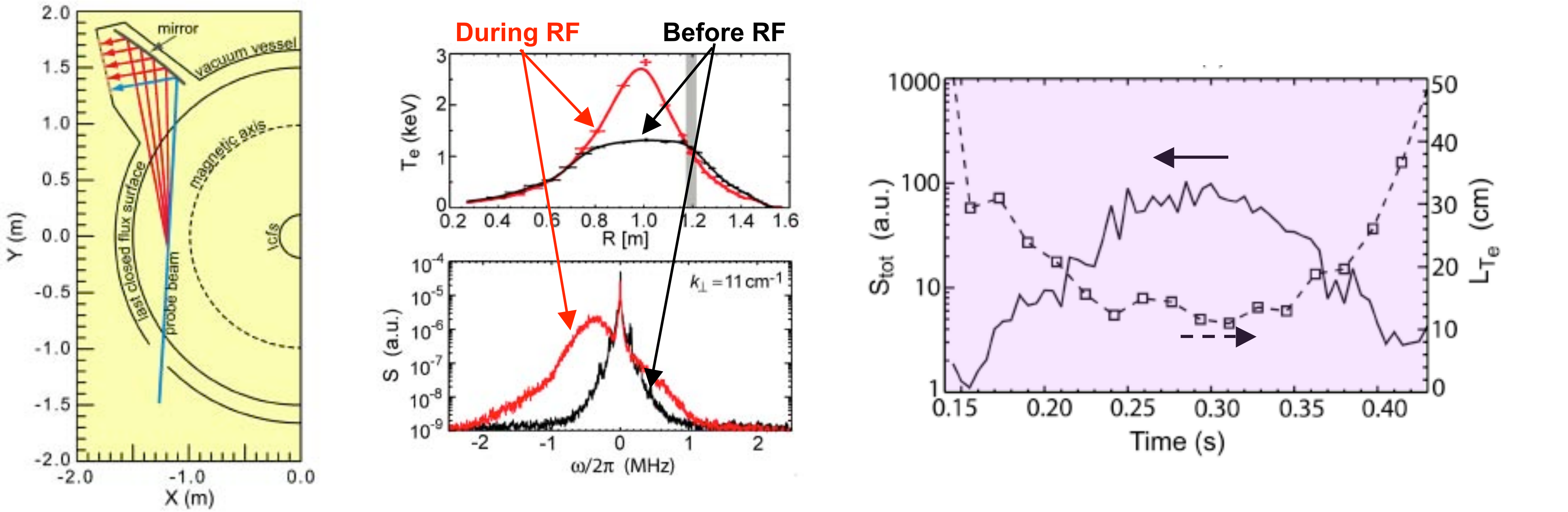


Neoclassical including finite banana width

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

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

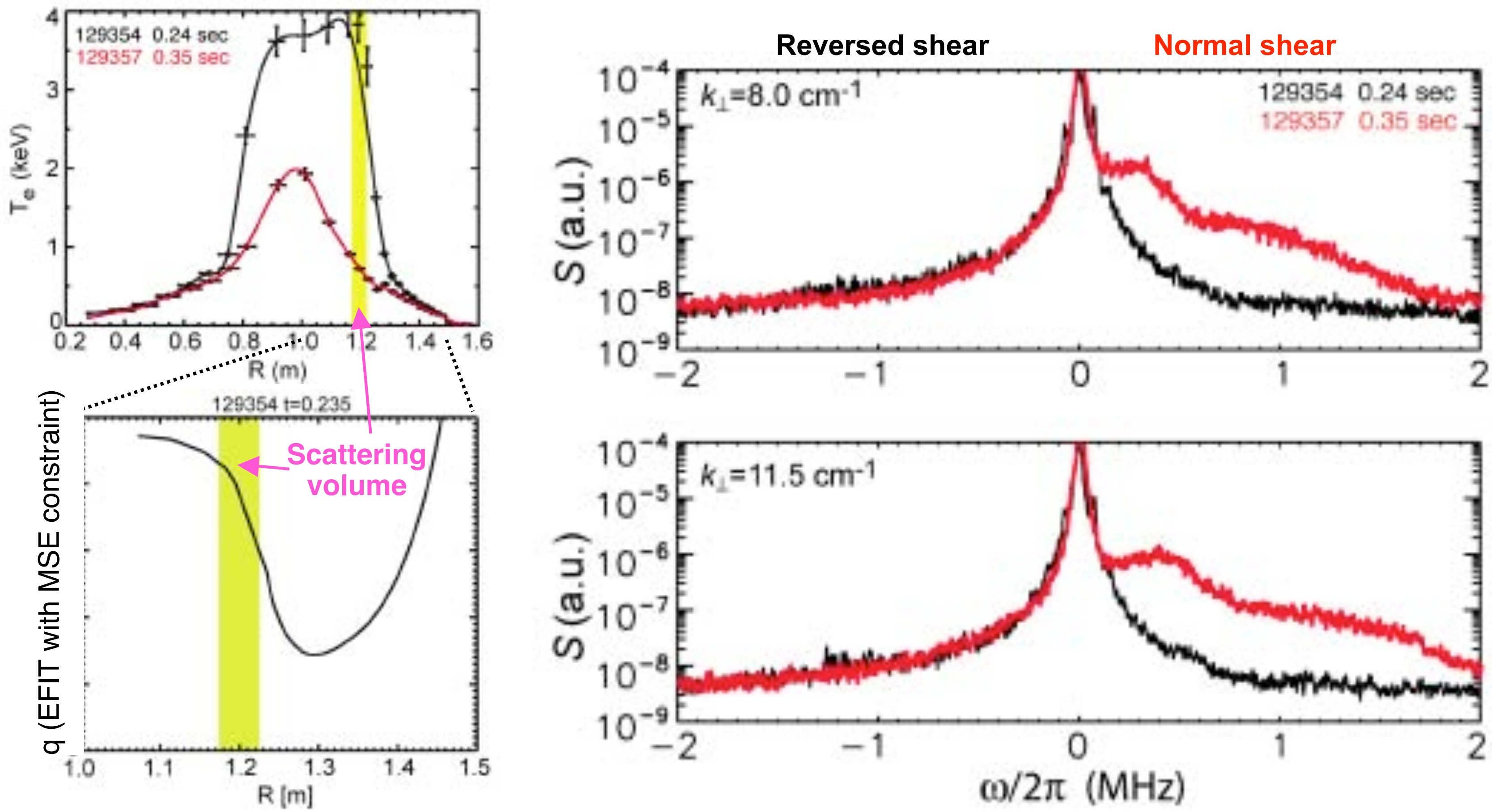
- Fast waves at high harmonics of ion-cyclotron frequeny (HHFW) heat electrons through electron Landau damping and TTMP
- Fluctuations measured by low-angle forward scattering of 280 GHz μ-waves



- 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 ($k_\perp\rho_s \sim 1$) as source of turbulence
  - Qualitative agreement with linear gyrokinetic code (GS2) for Electron Temperature Gradient (**ETG**) mode onset

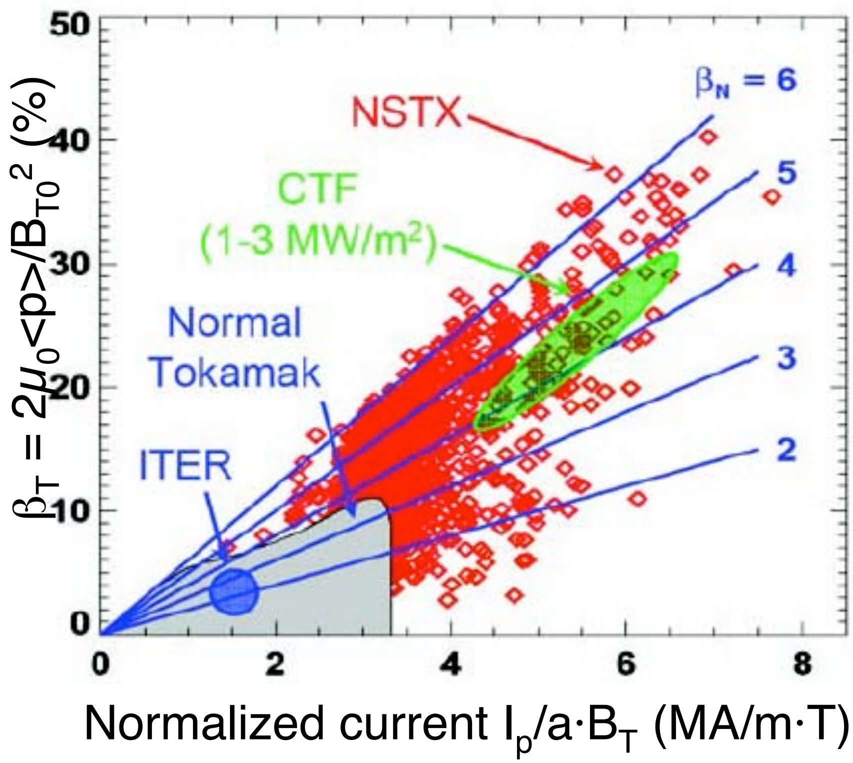
Electron Gyro-Scale Fluctuations Can Be Suppressed by Reversed Magnetic Shear in Plasma Core

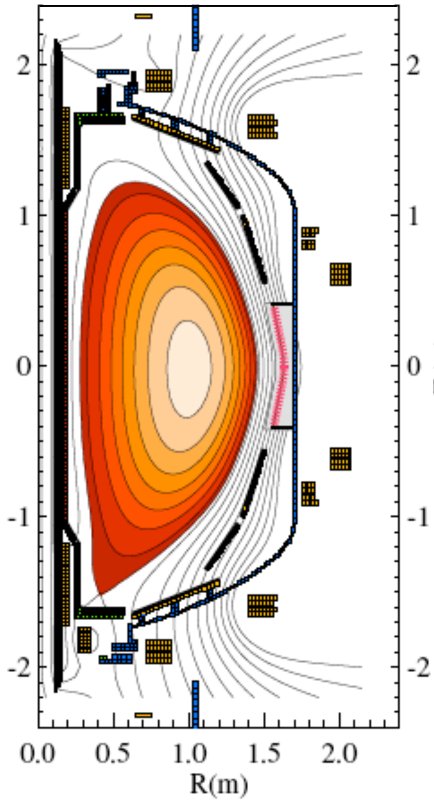
- Shear-reversal produced by early NB heating during plasma current ramp



- 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





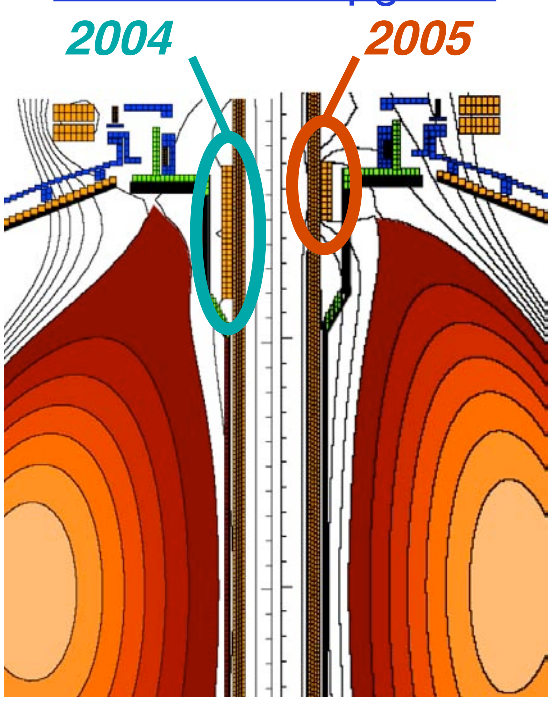
- $A = 1.5$
- $\kappa = 2.3$
- $\delta_{av} = 0.6$
- $q_{95} = 4.0$
- $l_i = 0.6$
- β_N = 5.9%·m·T/MA
- β_T = 40% (EFIT)
  34% (TRANSP)

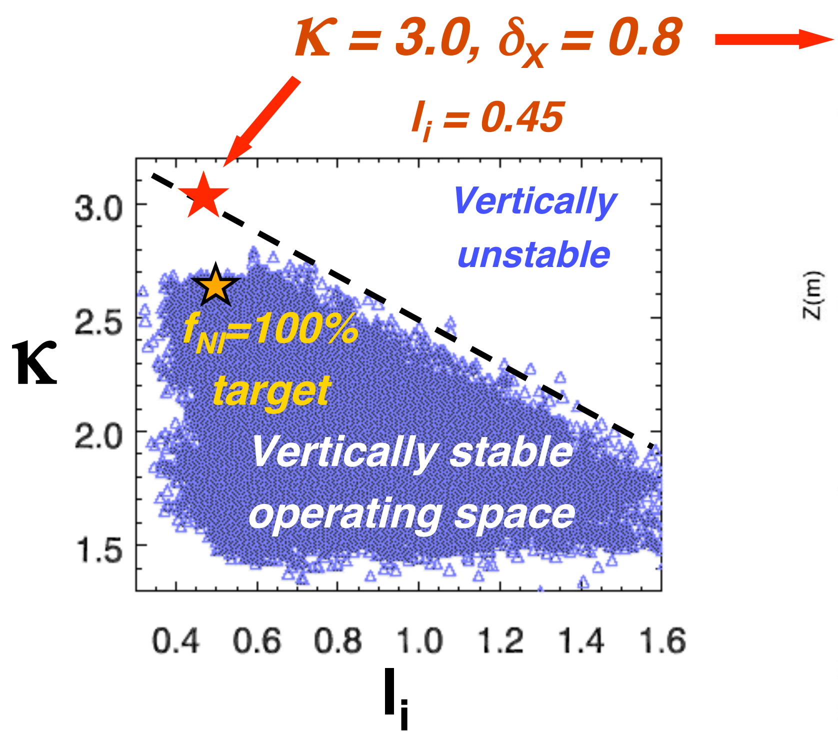
- Benefits of
  - Low aspect ratio
  - Cross-section shaping
  - Stabilization of external modes by conducting plates

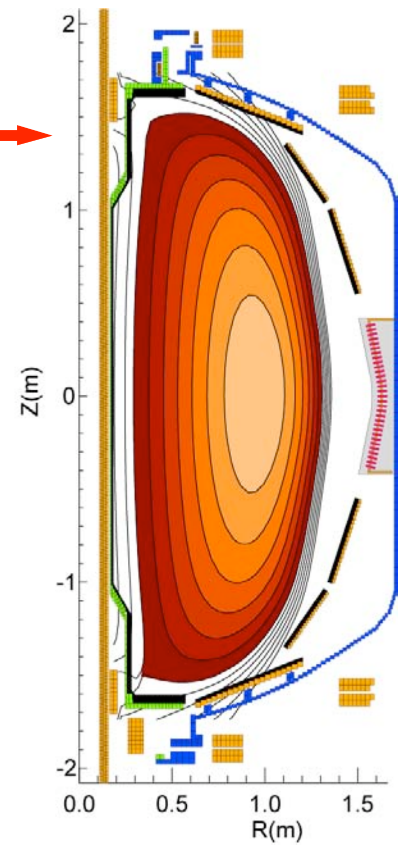
Optimized Plasma Shaping Can Increase β_P and Bootstrap Current Fraction at High β_T

- High elongation κ reduces $B_{P,av} = \mu_0 I_p / \oint_C dl$, 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

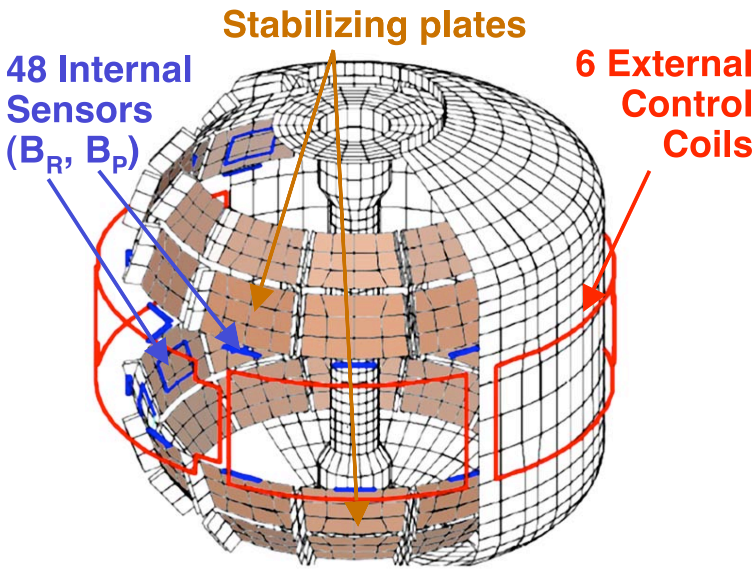
Divertor coil upgrade

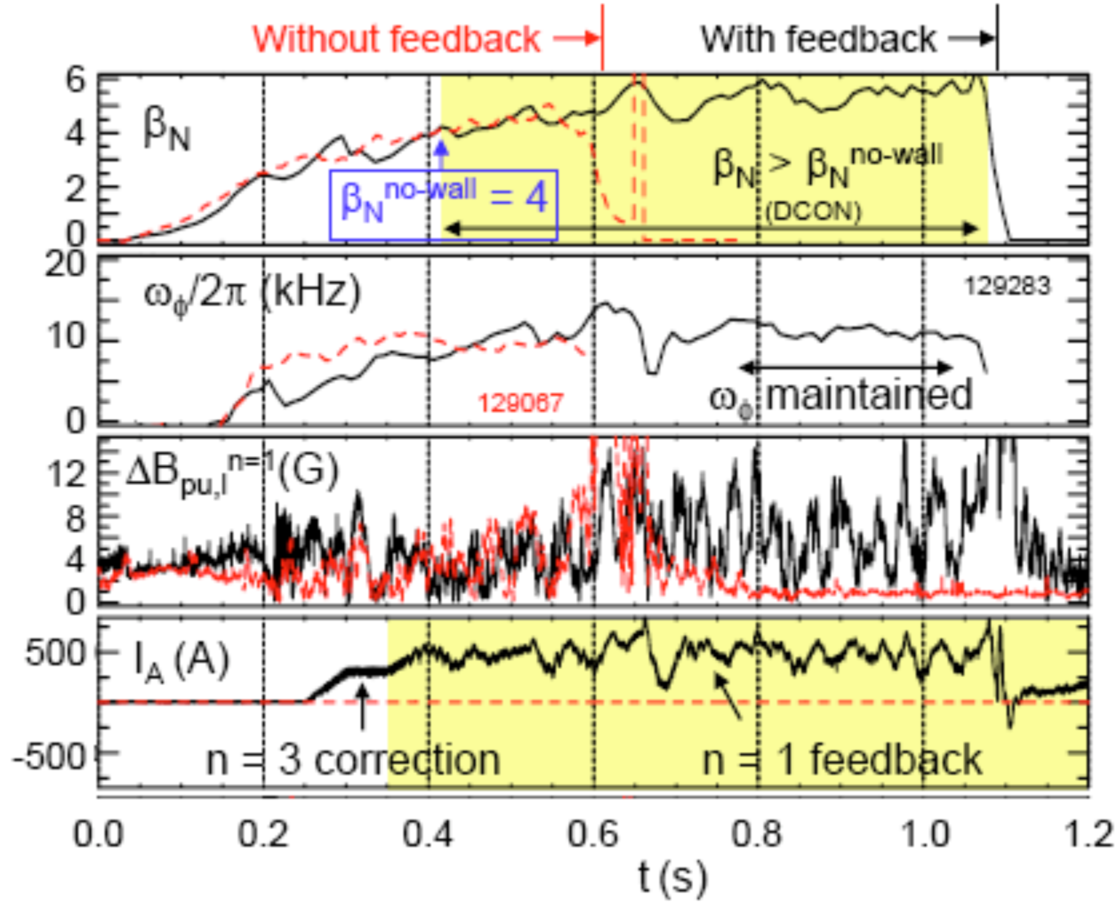






Non-Axisymmetric Field Correction and Feedback by External Coils Extend Duration of High-β Plasmas

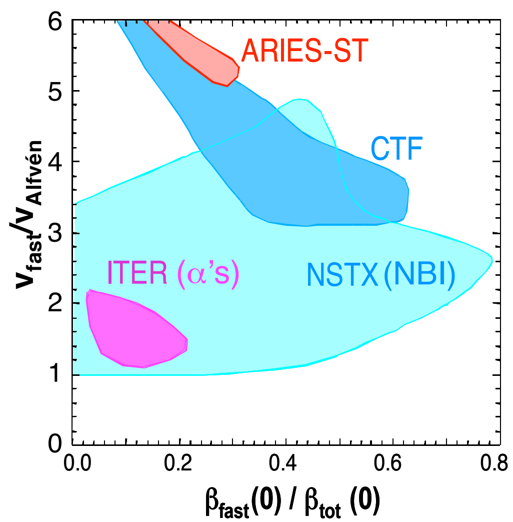




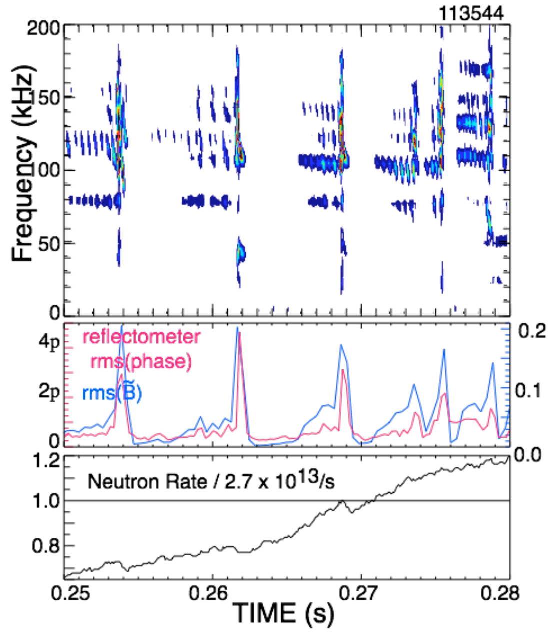
Coils powered by 3 Switching Power Amplifiers (3.5kHz, 1kA)
- Apply n = 1 & 3 or 2 (4) field components

- 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

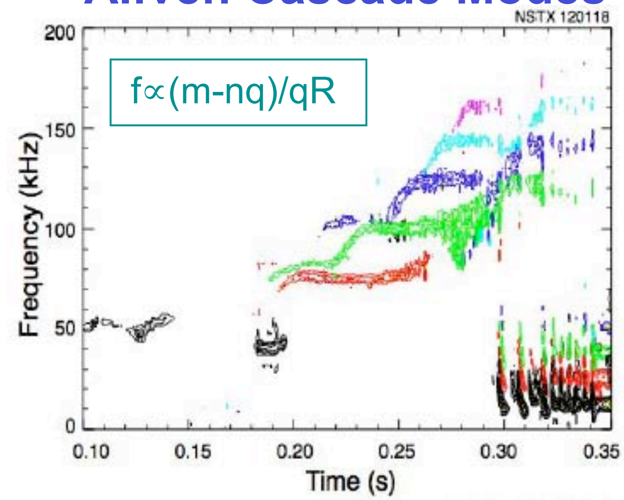
NSTX Accesses Fast-Ion Phase-Space Regime Overlapping With and Extending Beyond ITER

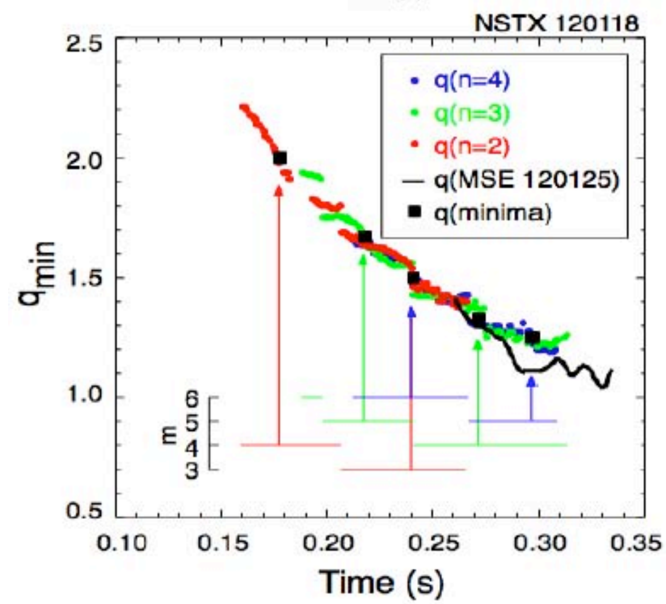


Multi-mode TAE bursts induce fast-ion losses



Alfvén Cascade Modes



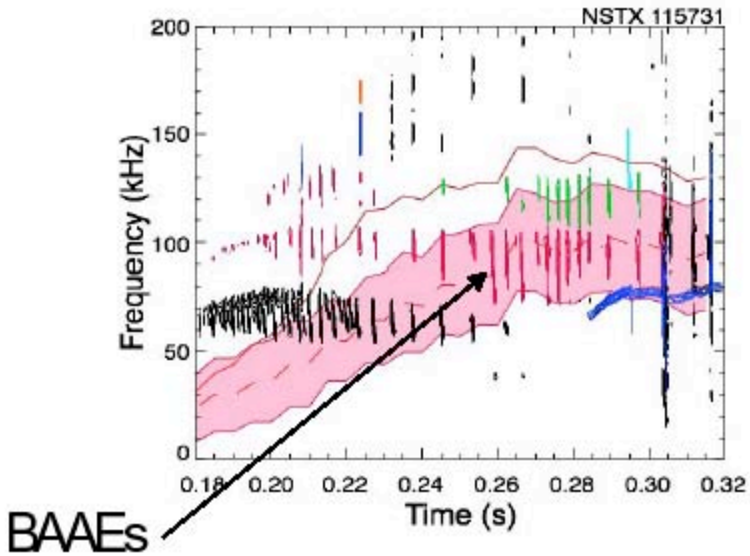


- Alfvén cascades observed at low β_e →
  - Reversed-Shear Alfvén Eigenmodes (RSAE)
- Frequency chirping indicates evolution of q_{min}
  - Matches q(r) analysis with MSE constraint
- Modes also observed in MAST device

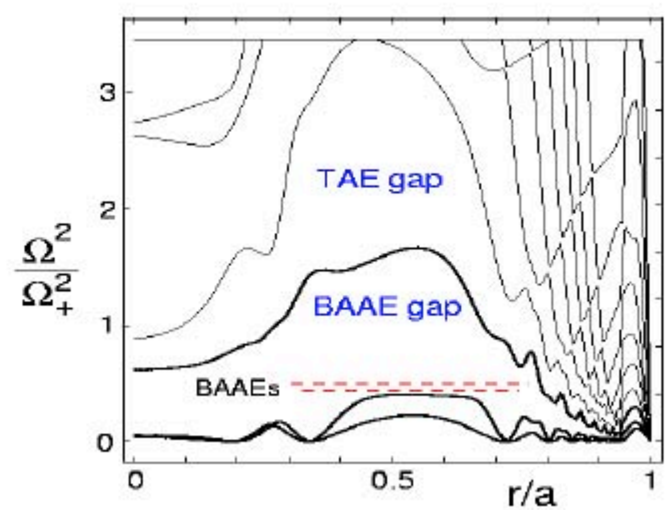
Identification of β-Induced Alfvén-Acoustic Eigenmodes (BAAE)

- Energetic particle driven modes frequently seen in NSTX at frequencies lower than those expected for TAE
- Couples two fundamental MHD branches (Alfvén & acoustic)

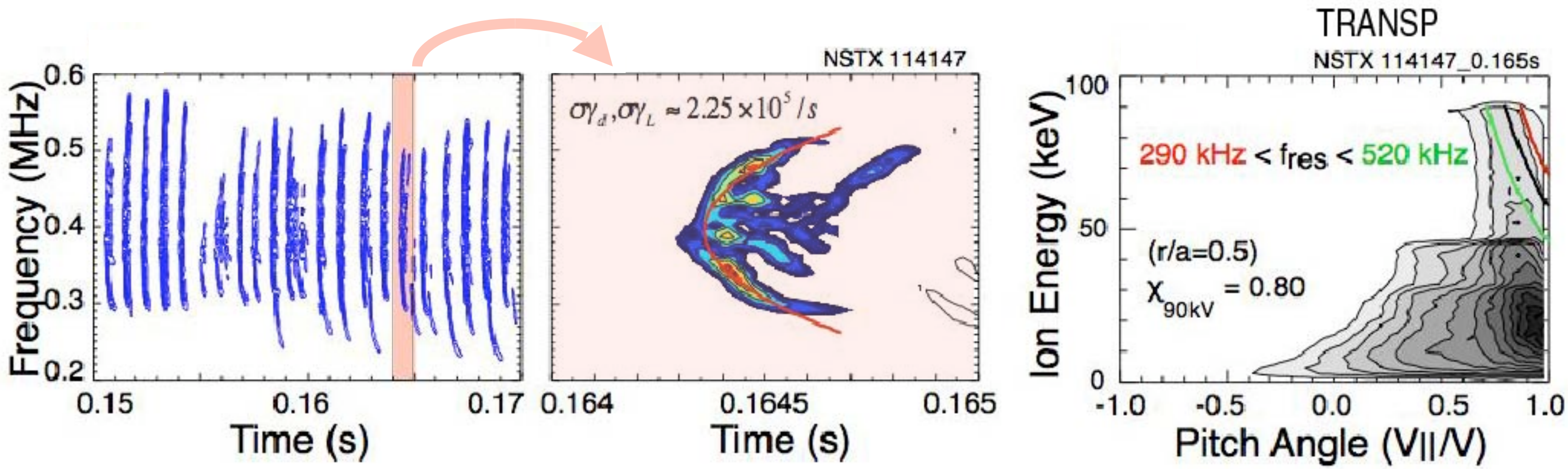
NSTX BAAEs, f=103kHz



NOVA on BAAE gap in NSTX



Compressional Alfvén Eigenmodes Create “Angelfish” Features in MHD Spectrum



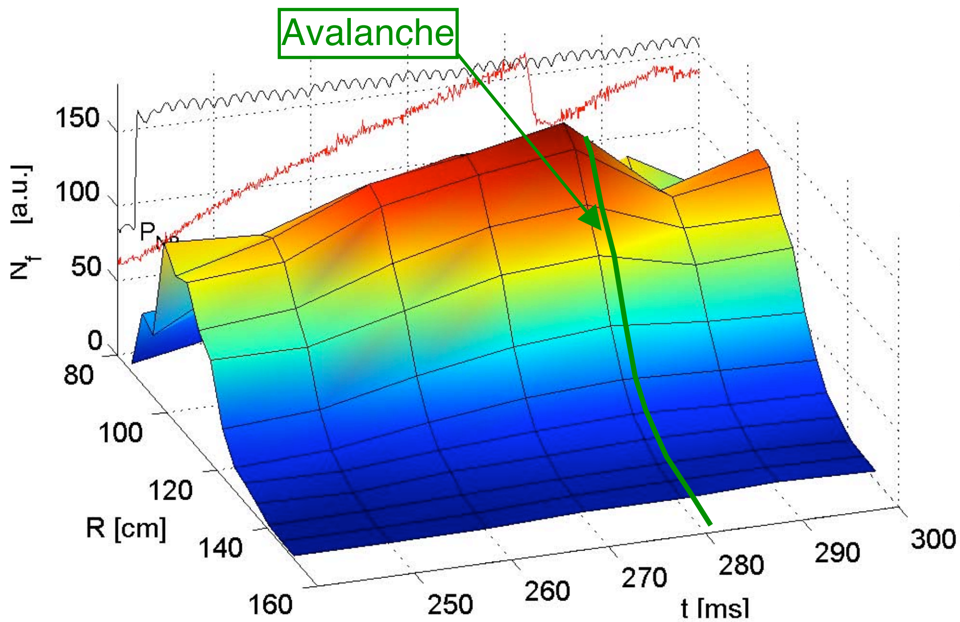
- Compressional Alfvén Eigenmode (CAE) satisfies Doppler-shifted resonance condition for calculated fast ion distribution ($\omega = \omega_c - k_{||}v_{beam}$)
  - Fast ions modelled with TRANSP code using classical slowing down
- Identified as form of “hole-clump”, consistent with theory
  - Expected growth rate in reasonable agreement with observation
- Controlling fast-ion phase space can suppress deleterious instabilities
  - “Angelfish” instability suppressed by addition of HHFW heating

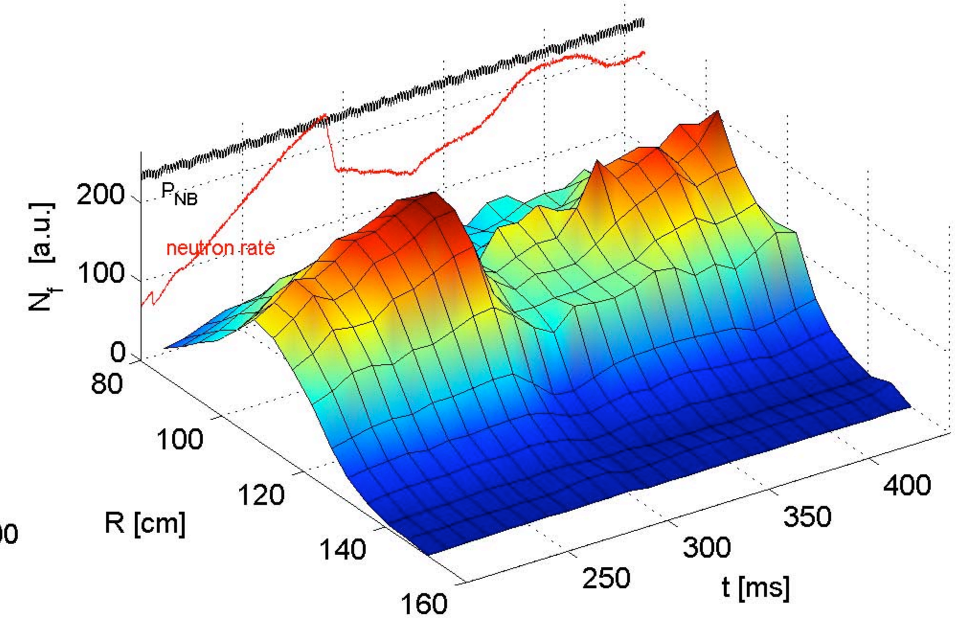
MHD Instabilities Affect Confinement of Fast Ions

- 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

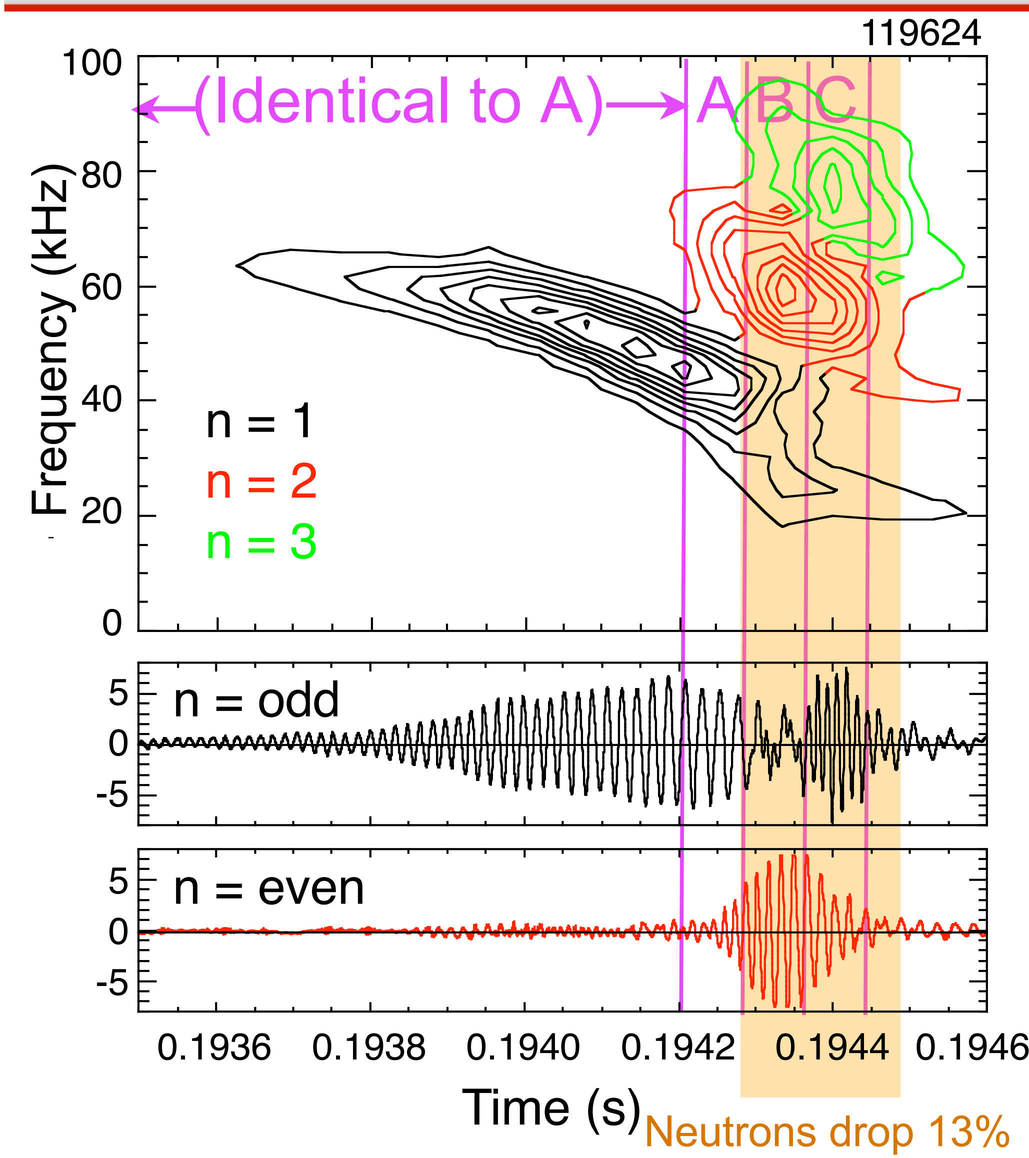
- During TAE avalanches, measured fast-ion losses up to 30%
  - Consistent with neutron rate drop
  - Profile remains peaked

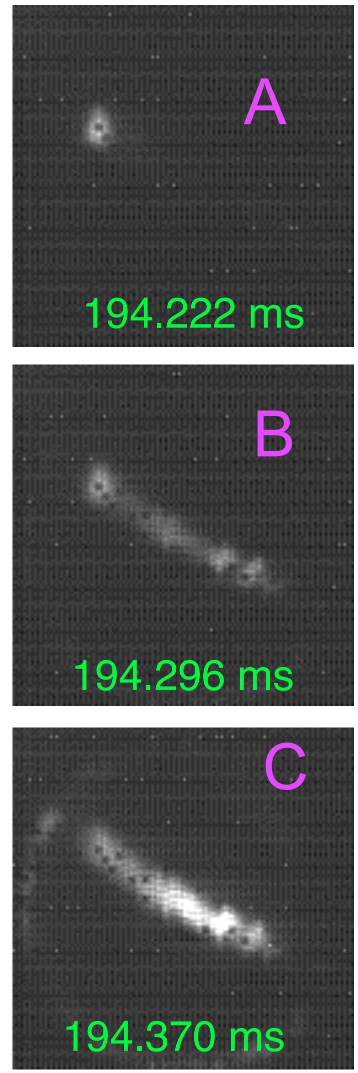
- Low-frequency (kink) activity redistributes fast ions outwards
  - Can destabilize Compressional Alfvén Eigenmodes (CAEs) in outboard midplane region





Energetic Particle Modes Cause NBI-Ion Loss Over Range in Pitch Angle When Multiple Toroidal Mode Numbers Present





Detector principle

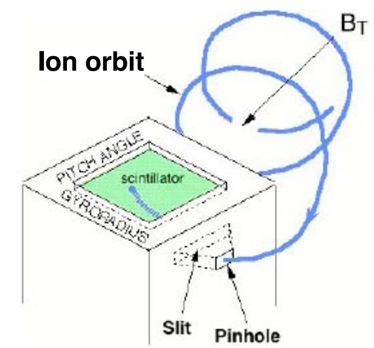
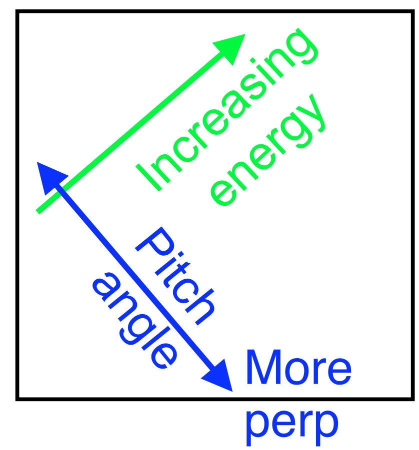


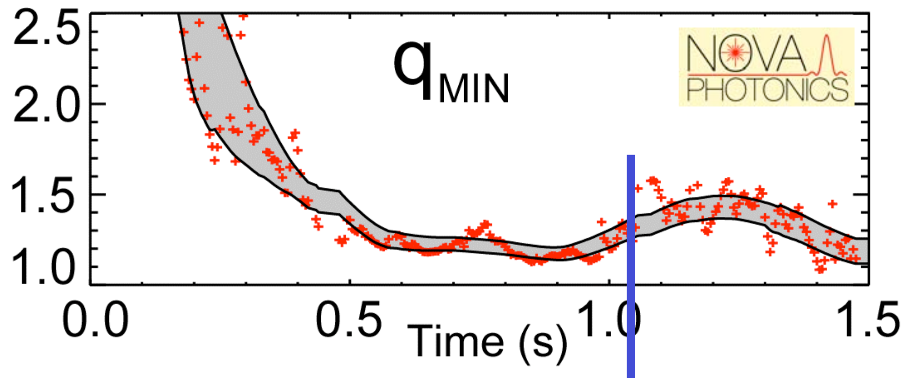
Image Interpretation



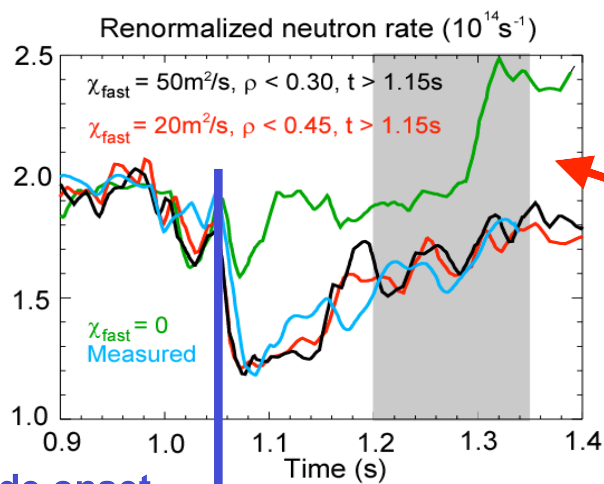
- Dominant loss close to injection energy

MHD-Induced Redistribution of NBI Current Drive Contributes to NSTX "Hybrid"-Like Scenario Proposed for ITER

q_{min}>1 for entire discharge, increases during late n=1 activity



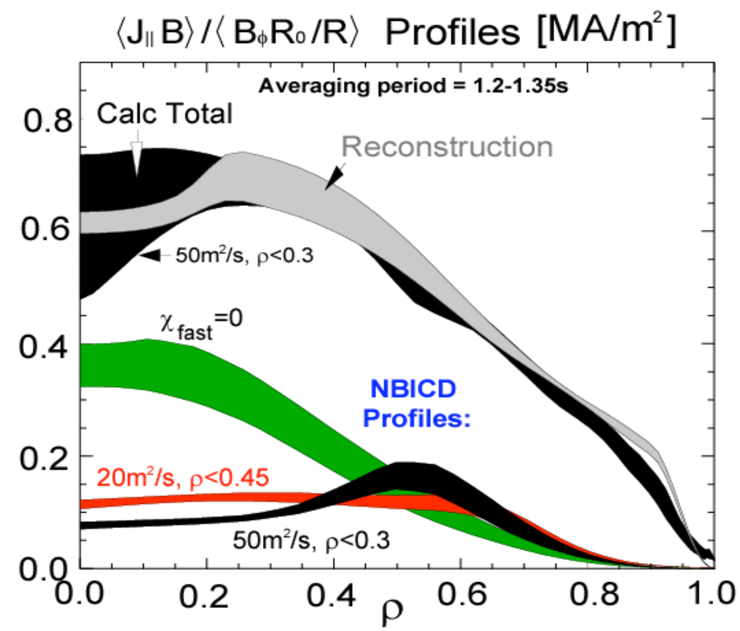
n=1 mode onset



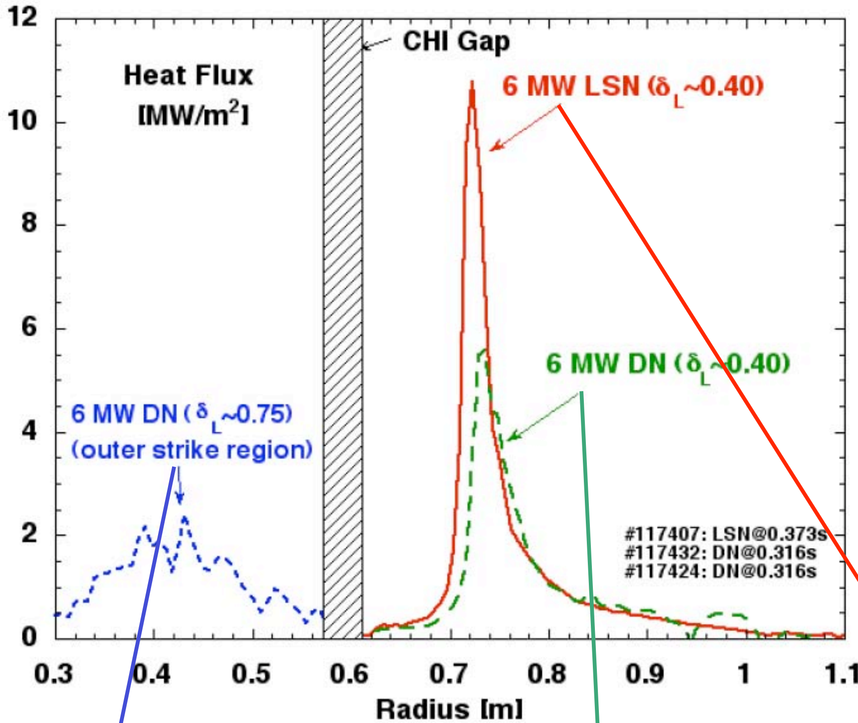
n=1 mode onset

- High anomalous fast ion transport needed to explain neutron rate discrepancy during *n*=1

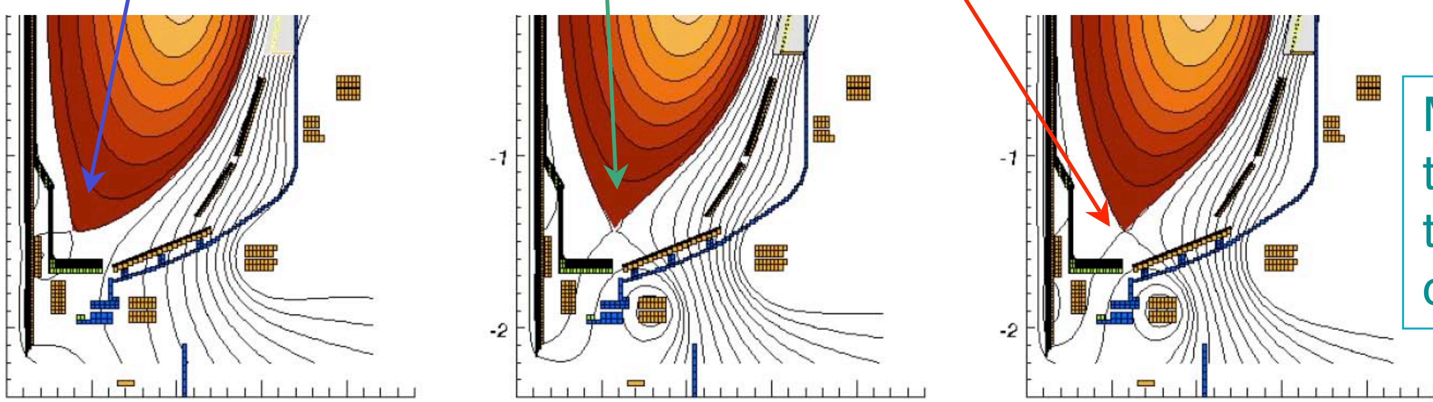
- Fast ion transport converts peaked J_{NBI} to flat or hollow profile
- Redistribution of NBICD makes predictions consistent with MSE



Plasma Shaping Reduces Peak Divertor Heat Flux: *Critical for ST Development*

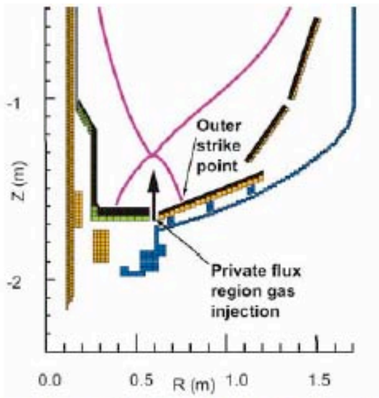


- Compare configurations with different triangularity at X-point δ_X
  - lower single-null (LSN), $\delta_X \approx 0.4$
  - double-null (DN), $\delta_X \approx 0.4$
  - high triangularity DN $\delta_X \approx 0.75$
- Flux expansion reduces heat flux
  1 : 0.5 : 0.2
- ELMs: Type I → Mixed → Type V
 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

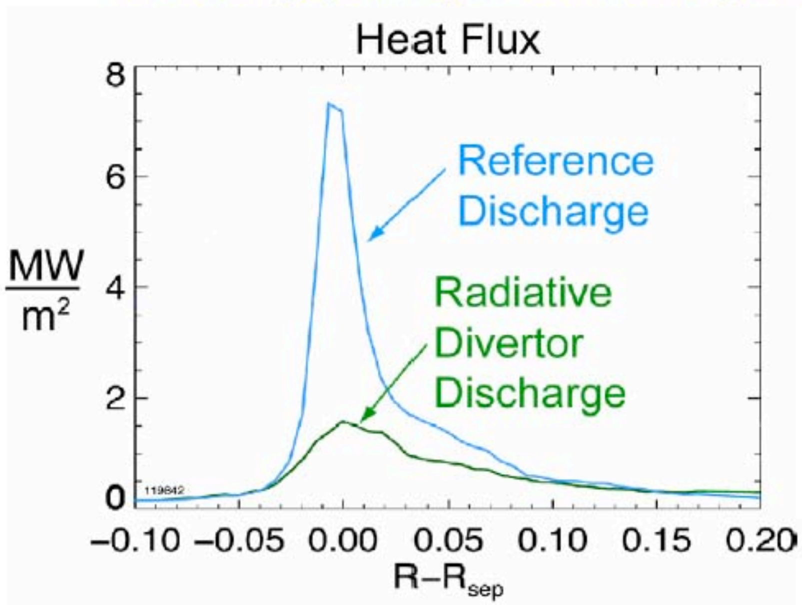


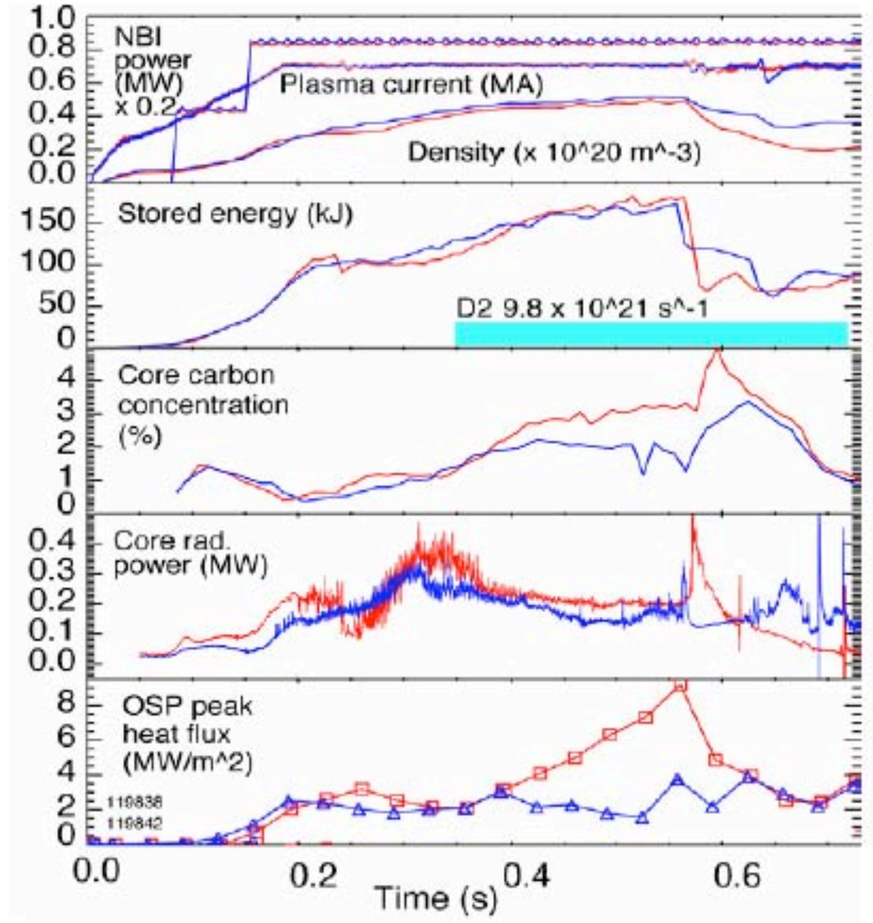
Measure heat flux to divertor with IR thermography of carbon tiles

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

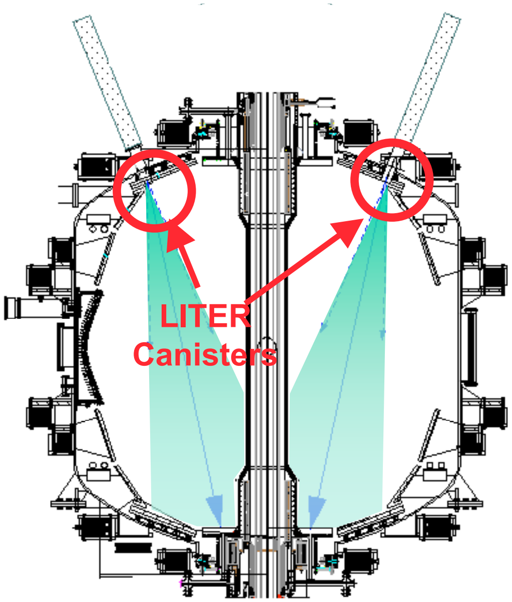
2005: Injected lithium pellets, 2 - 5 mg, into He discharges prior to D NBI shot

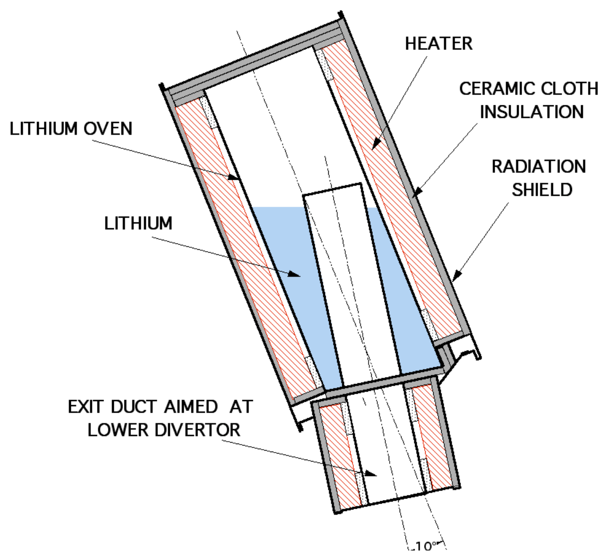
2006: LIThium EvaporatoR (LITER) deposited lithium on divertor between shots

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

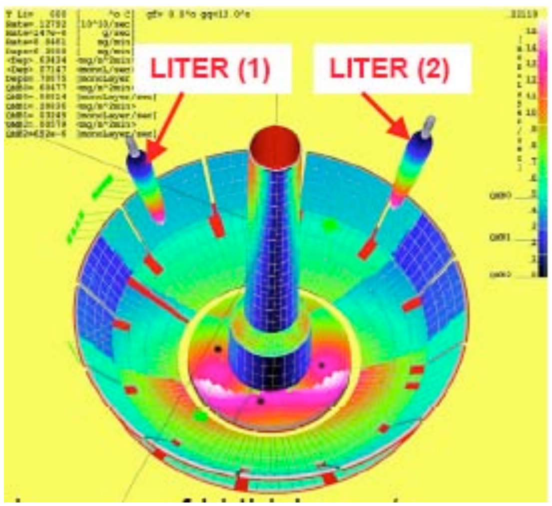
2008: Dual LITERs covered entire lower divertor; shutters interrupted lithium stream during plasmas; evaporated ~200g lithium (reloaded 3 times)

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

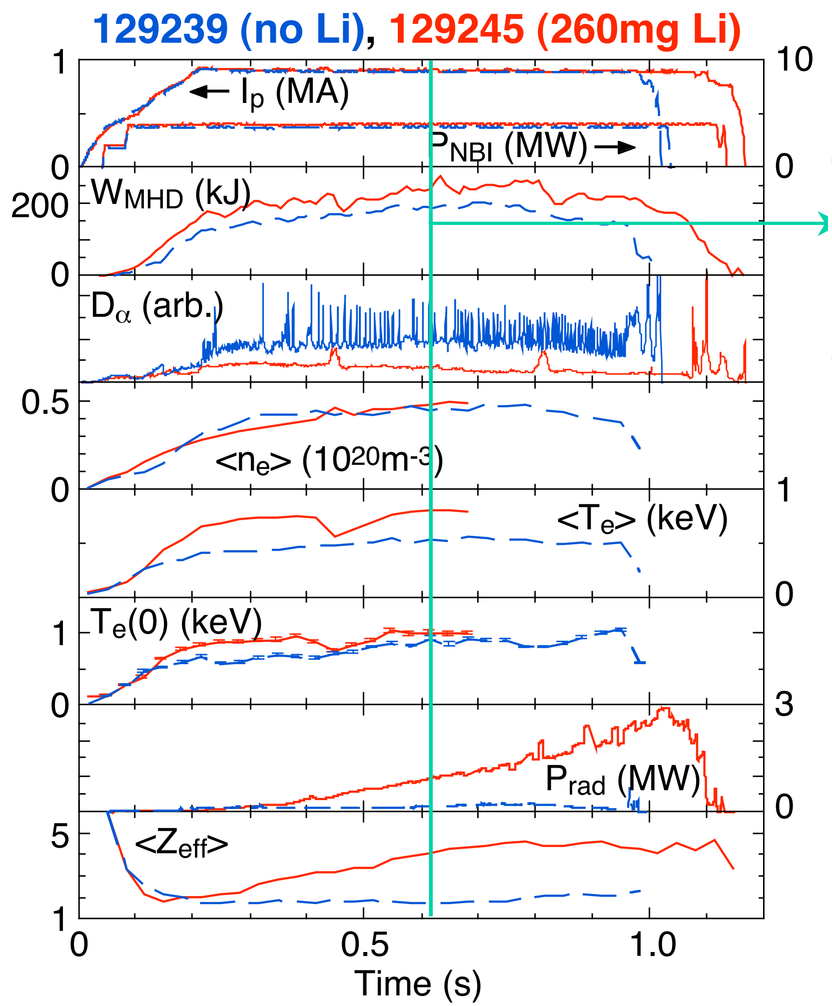


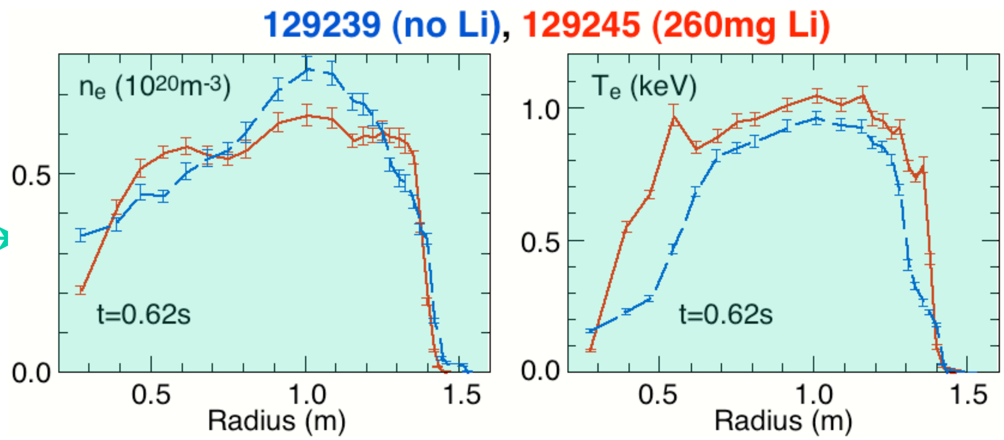


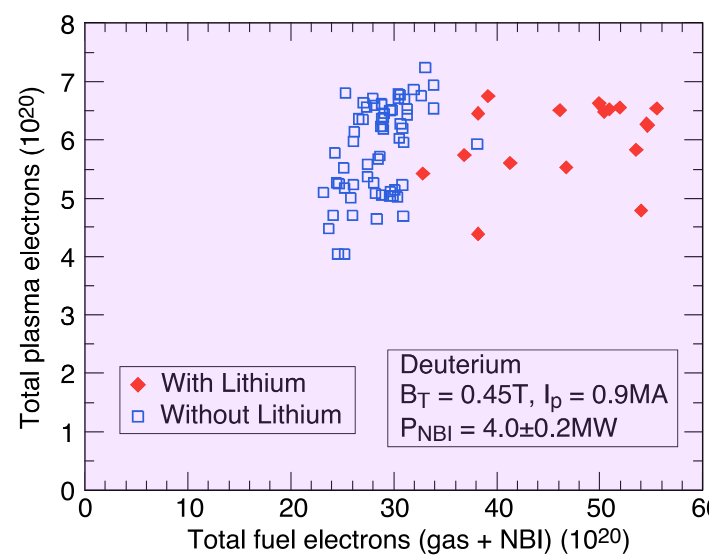
Modeled deposition pattern



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

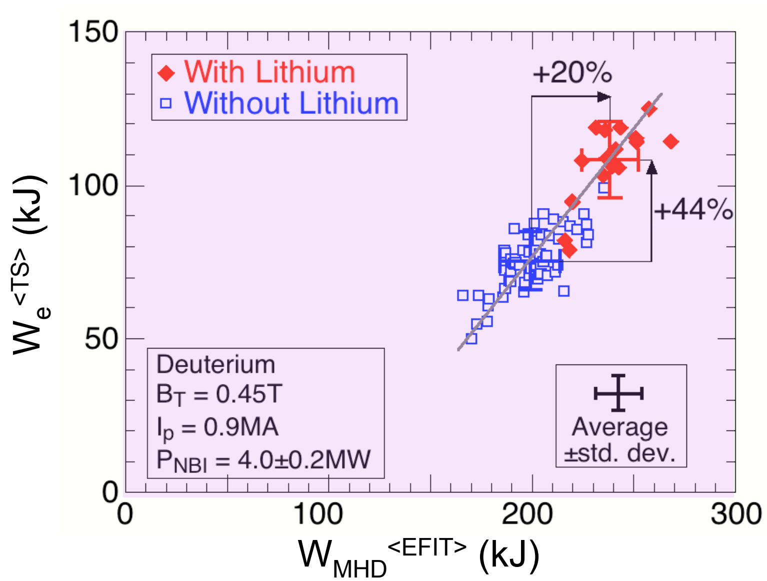


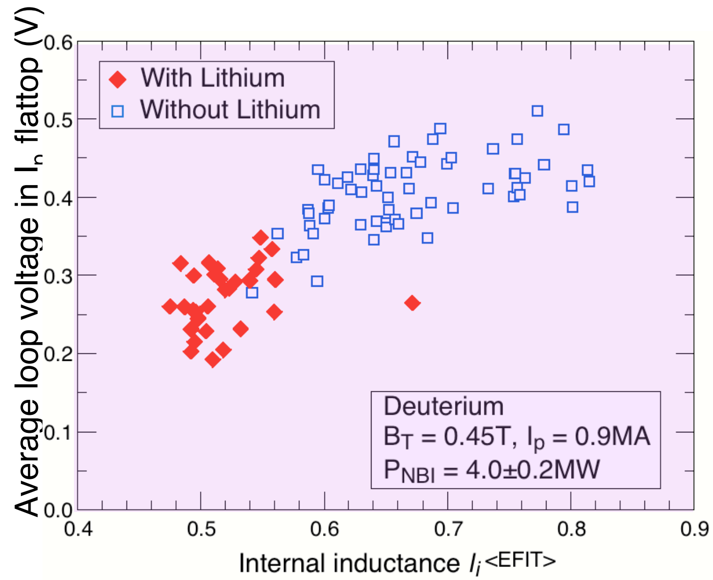


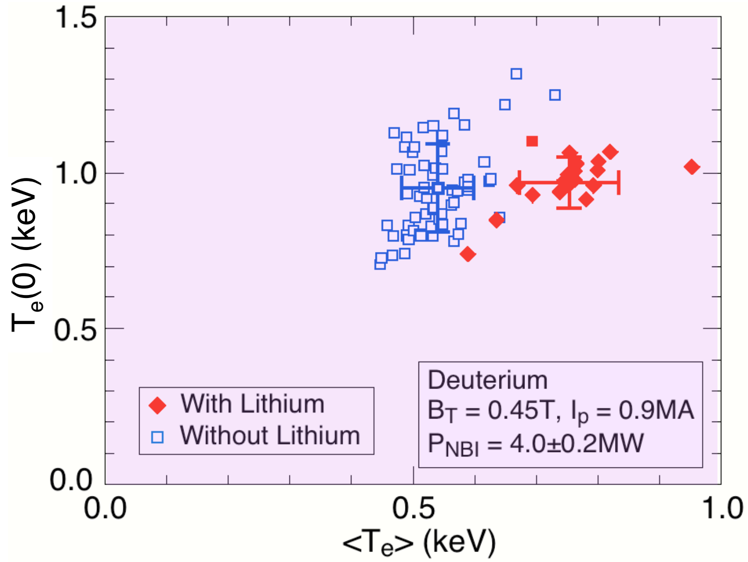


- Without ELMs, impurity accumulation increases P_{rad} and Z_{eff}

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

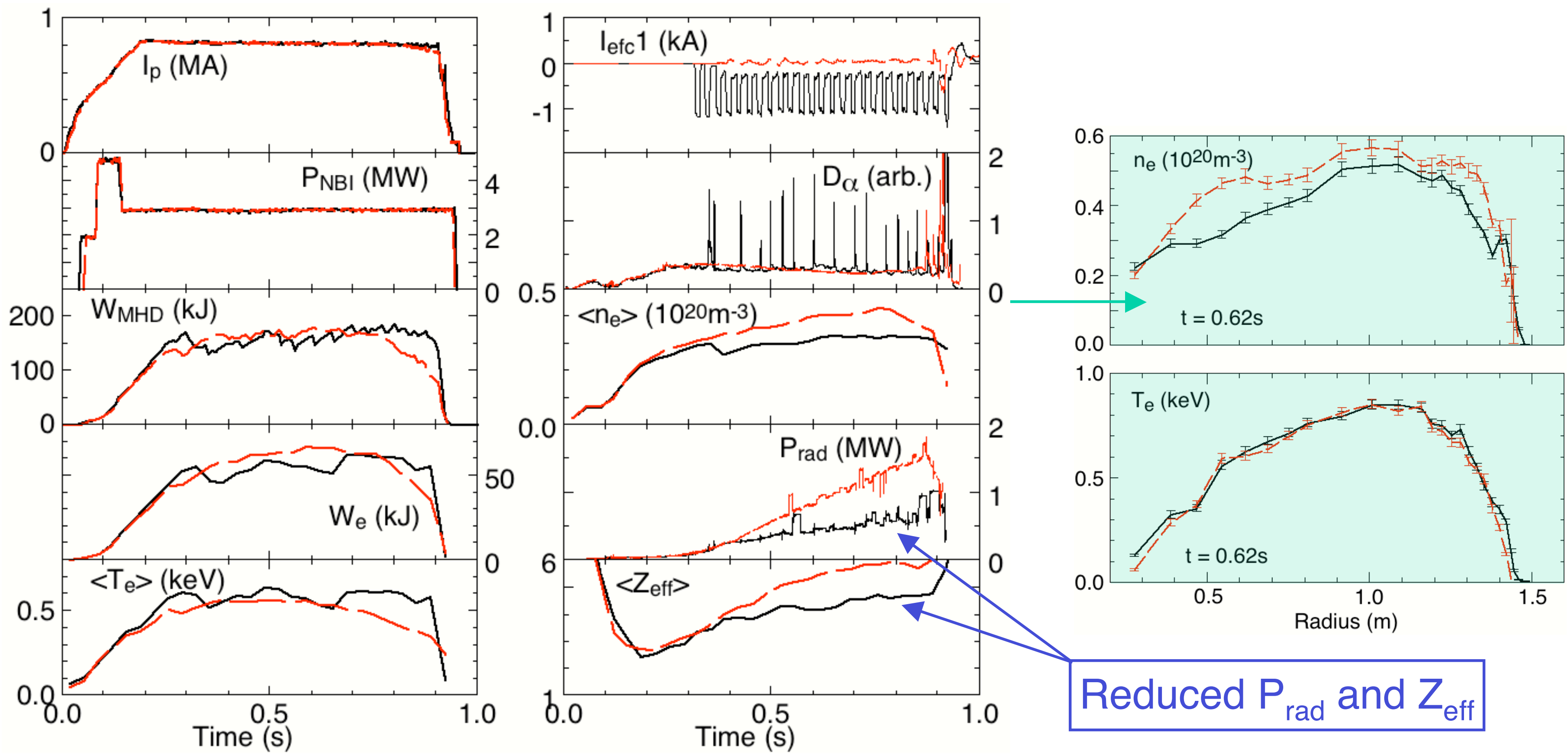






- Broader electron temperature profile reduces internal inductance l_i and inductive flux consumption in current flattop, despite higher Z_{eff}
- Lithium increases edge bootstrap current through higher p', lower collisionality

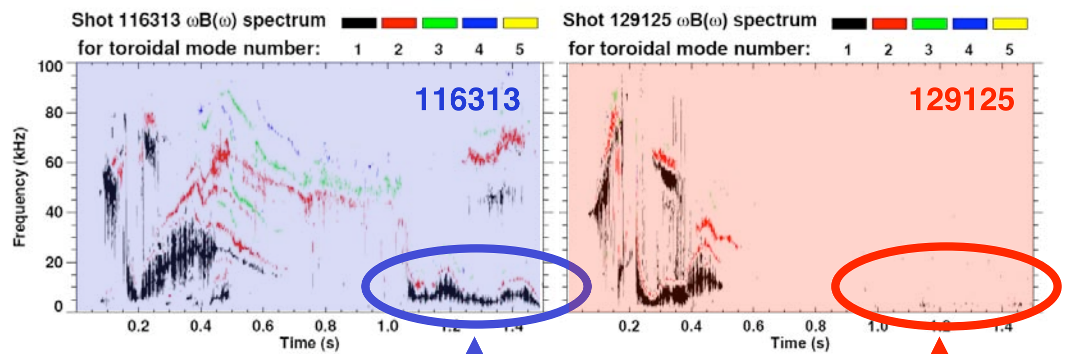
Non-Axisymmetric Midplane Coils Can Induce Repetitive ELMs in Lithium-Suppressed Plasmas

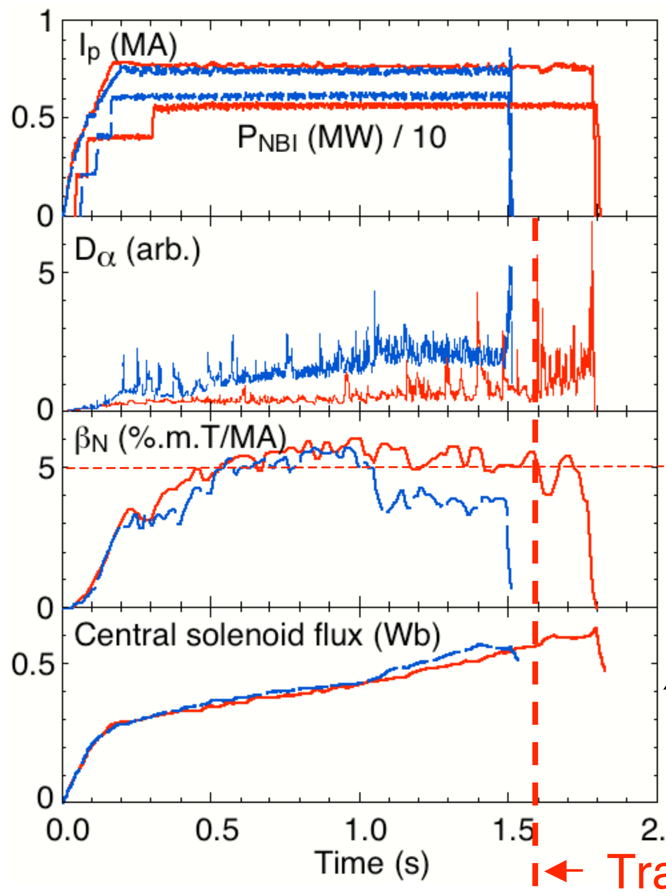


- n = 3 resonant magnetic perturbation applied
- 11ms duration pulse at 40Hz optimal for this shape (DN, κ=2.4, δ=0.8)
- RMPs have also modified ELM behavior in non-lithium ELMing plasmas

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}

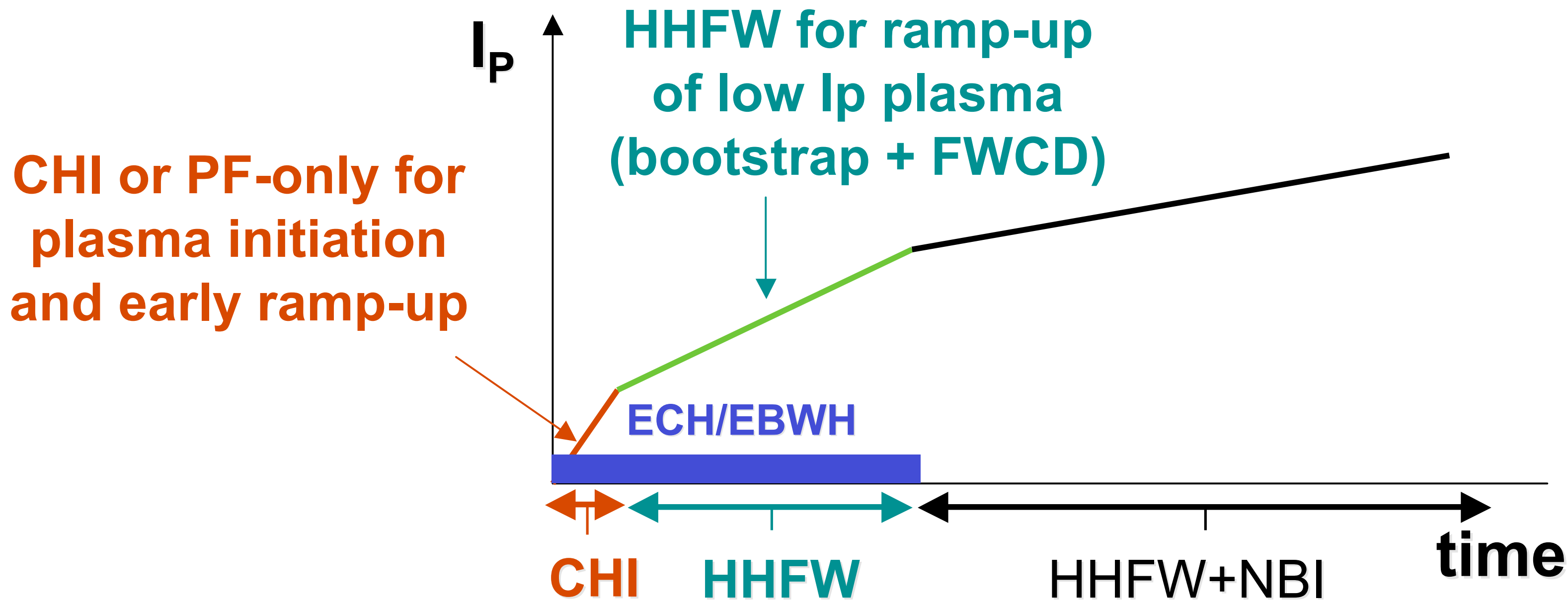
- EF/RWM control sustains rotation, high β

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

Initiating, Ramping-up and Sustaining Plasma Current without Reliance on Central Solenoid Critical for the ST



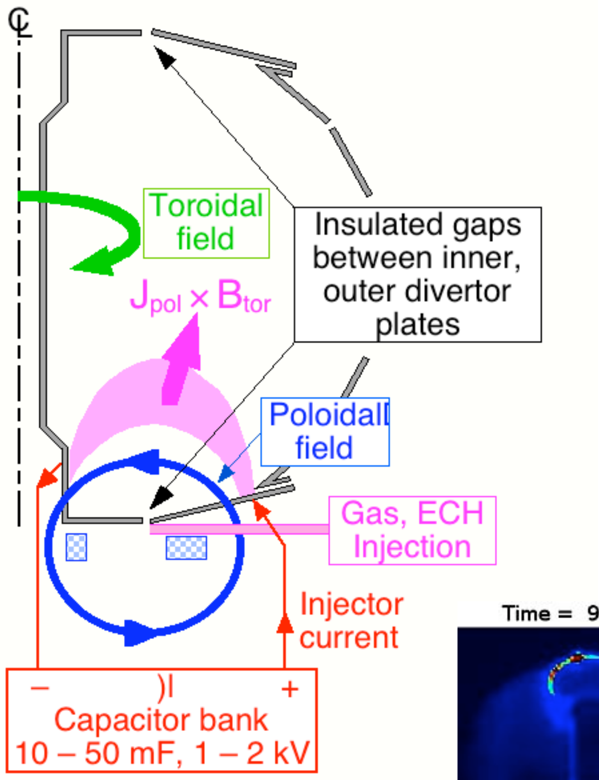
CHI: Co-Axial Helicity Injection

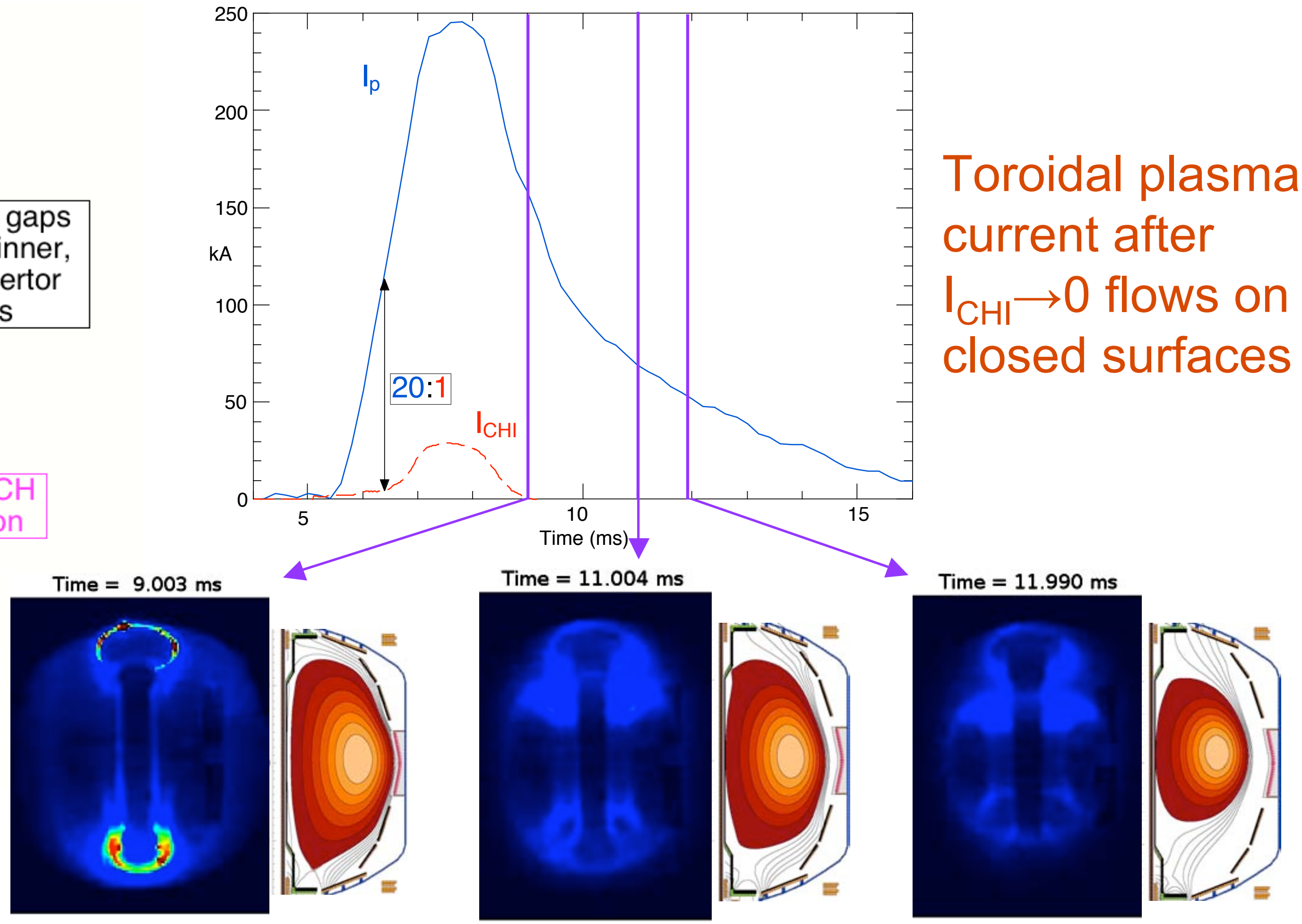
ECH/EBW: 28/15.3 GHz, 200 kW system planned

HHFW: 30 MHz (10 – 20^{th} D harmonic), 6 MW

NBI: effective with enough initial current to confine ions

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

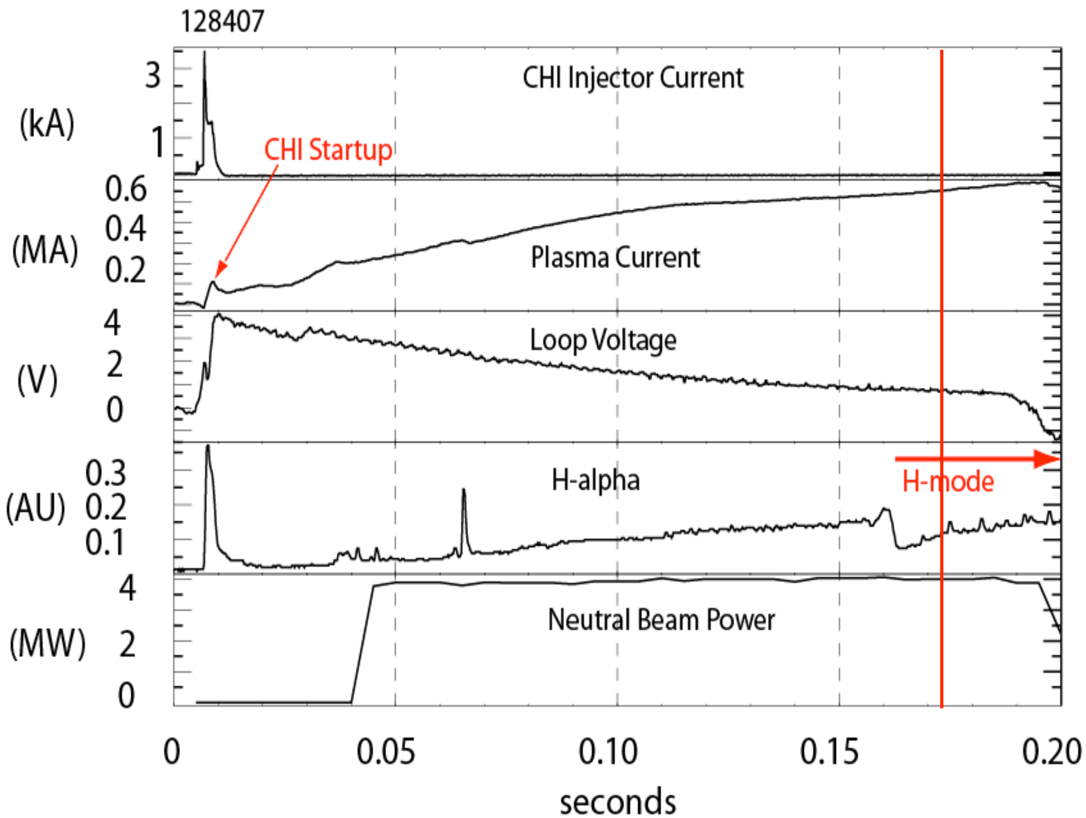


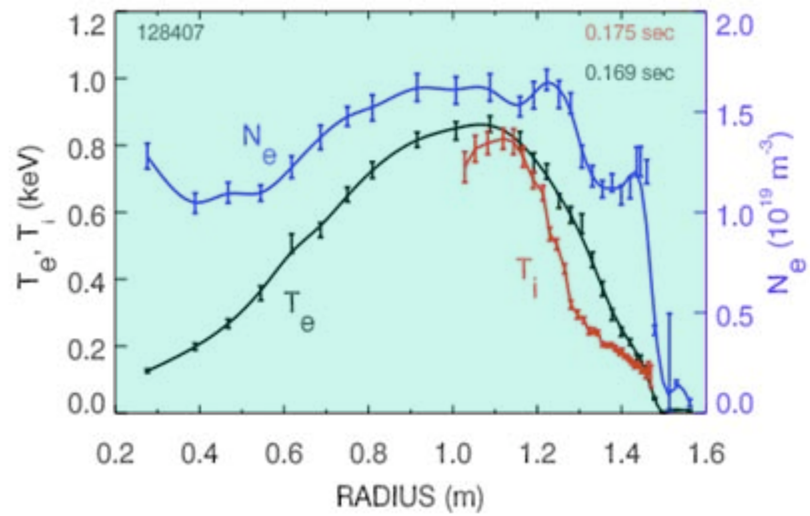


Toroidal plasma current after I_{CHI}→0 flows on closed surfaces

- After I_{CHI}→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





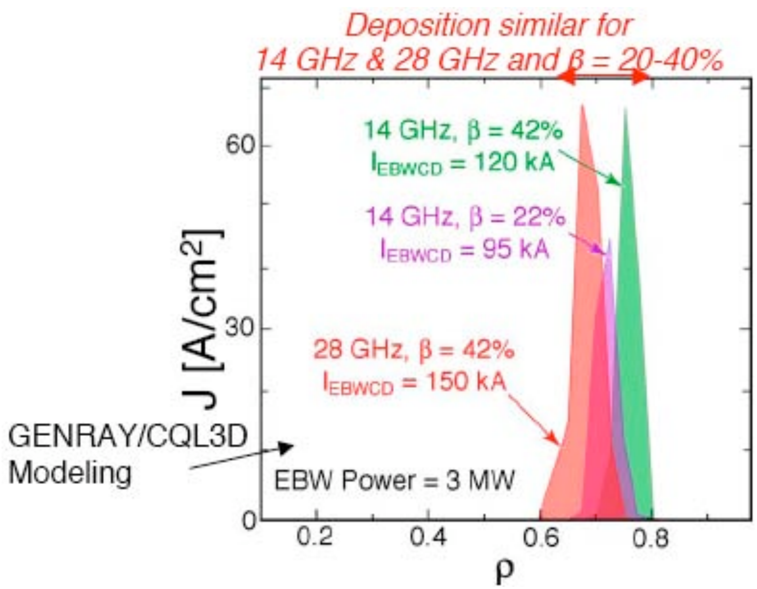
- Broad density profile during H-mode phase

- 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

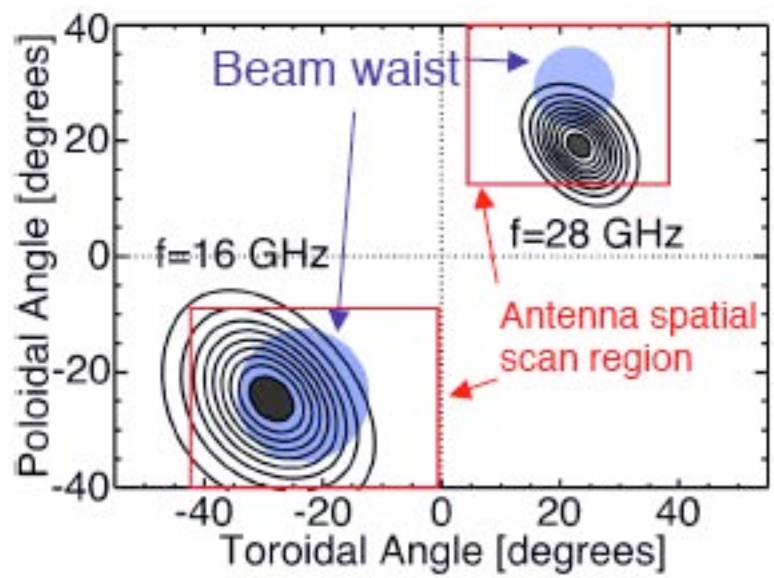
EBW Can Propagate in "Overdense" ST Plasma to Heat and Drive Current

- EBW-CD through the Ohkawa effect
  - Wave-driven diffusion of electrons across passing-trapped boundary
- Relies on mode conversion to EBW from externally launched e.m. waves
- Investigating physics of coupling to external antenna by measuring B-X-O mode conversion of thermal EBW in plasma

- EBW-CD can provide off-axis current needed to sustain high-β equilibrium



- Installed radiometers with scannable, obliquely viewing antennas on NSTX



Mode Conversion Efficiency of Thermal EBW from H-Mode Plasmas Increased with Lithium Deposition

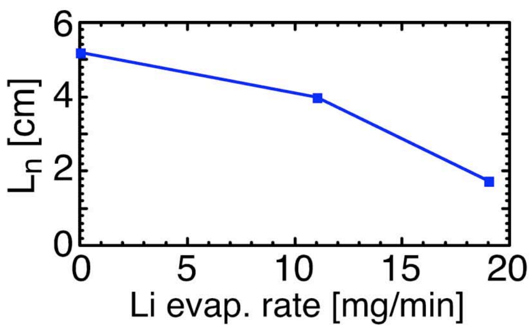
- Satisfactory coupling seen in L-mode but H-mode coupling initially low

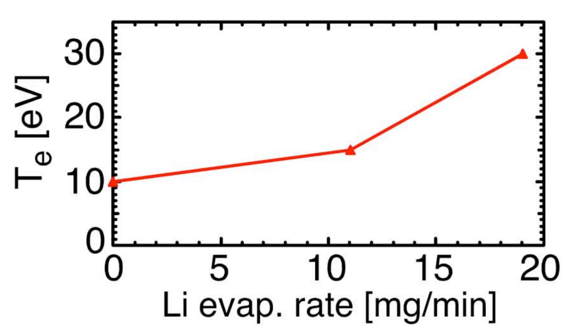
— 0 mg (0 mg/min) Li

····· 170mg (11 mg/min) Li

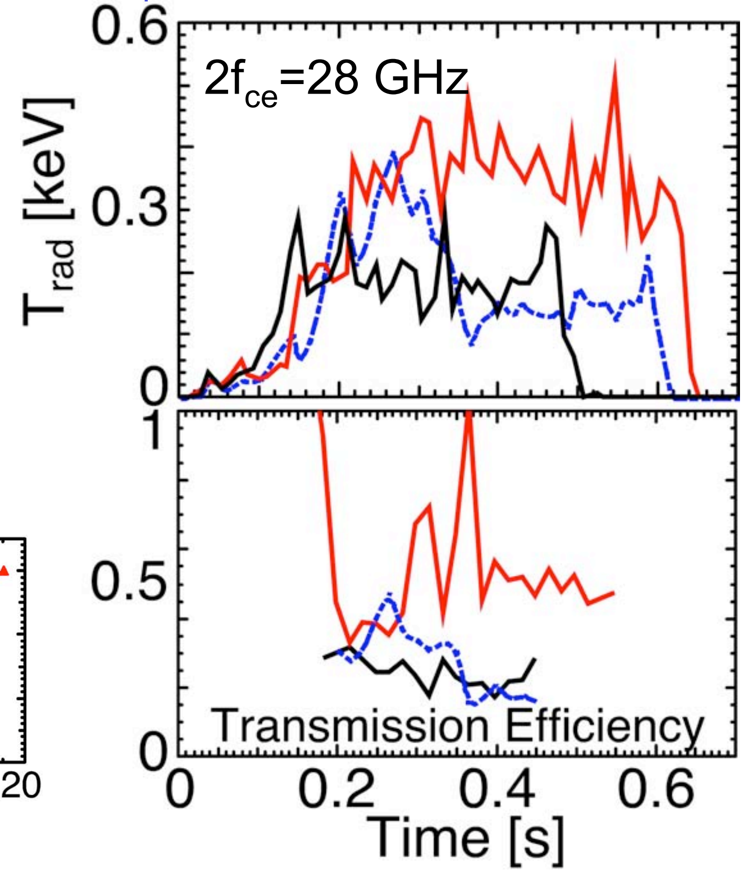
— 290mg (19 mg/min) Li

- T_{rad} increased from ~200eV to ~400eV
- Conversion efficiency increased:
  - 20% → 60% for f_{ce} = 18GHz
  - 20% → 50% for $2f_{ce}$ = 28GHz





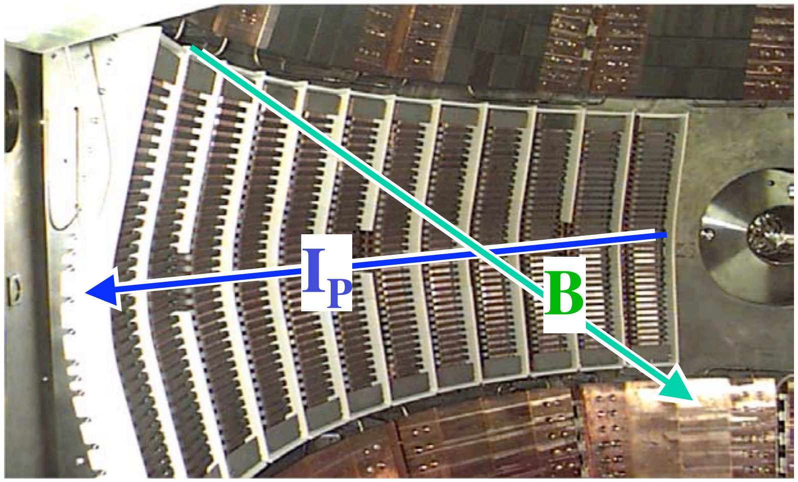
I_p = 0.8MA, $T_e(0)$ ~ 0.7keV

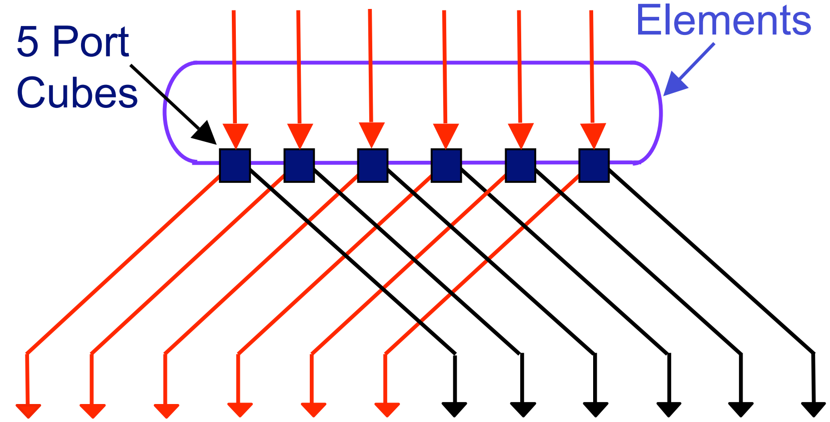


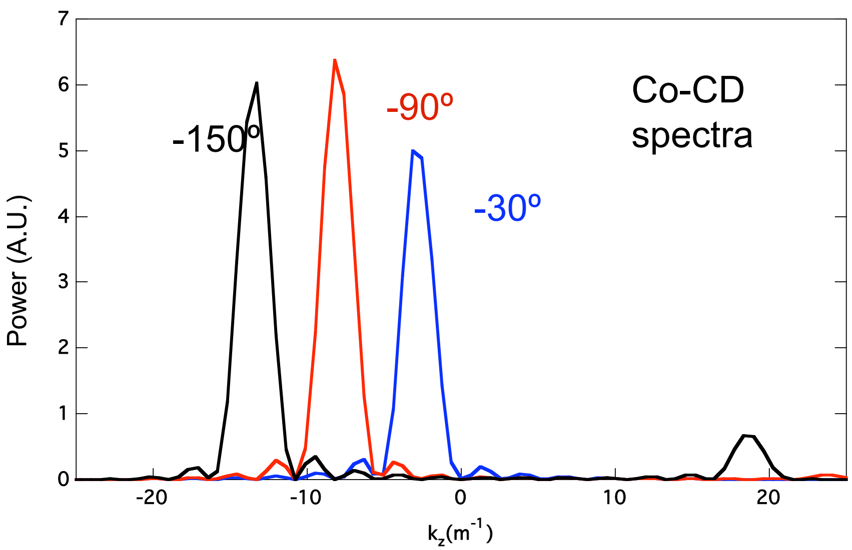
- Lithium increases T_e, reduces L_n near B-X-O mode conversion layer

NSTX 12-Element Antenna Array Produces Highly Directional Fast-Wave Spectrum at 30MHz

HHFW antenna extends toroidally 90°





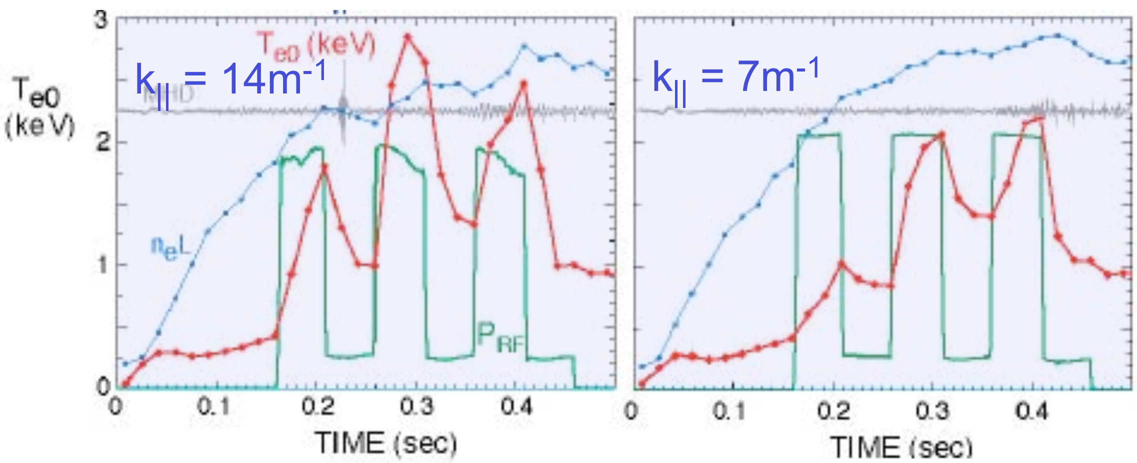


- Pair of straps for each source 180° out of phase
- Phase between adjacent loops adjustable in real-time 0 — 180°
- Full 12-element array operation for $\Delta\phi = \pm 30° (\pm 30°) \pm 180°$
- Large B pitch affects wave spectrum in plasma core

- Need directed waves with $k_{||} = 3.5 - 7 m^{-1}$ for HHFW-CD current drive

Heating Efficiency of HHFW Improves at High B_T and $k_{||}$

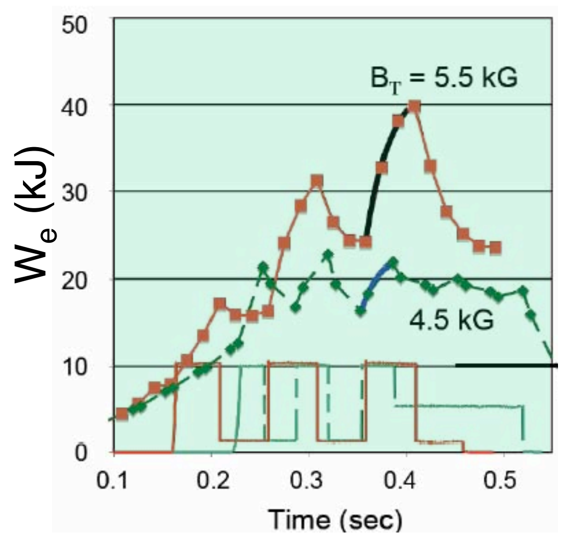
- Excitation of surface waves reduces power available for core heating
- Onset density for FW propagation $n \propto B k_{||}^2 / \omega$

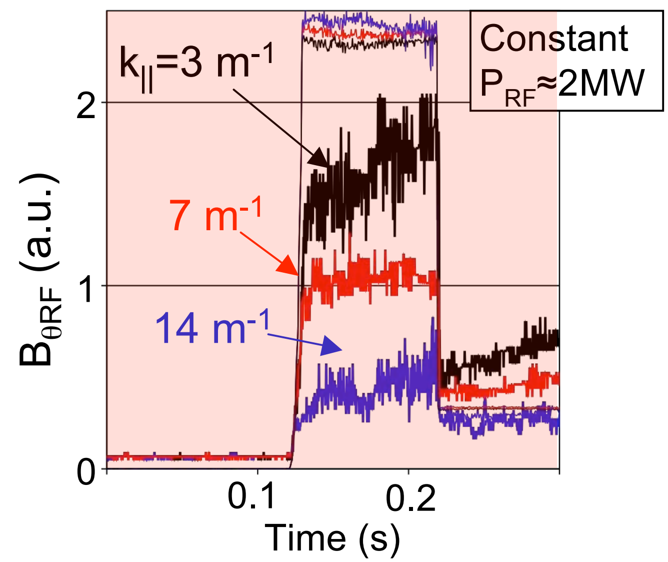


At fixed B_T = 0.45T, electron heating efficiency degrades at lower $k_{||}$ (higher v_{ph})

Magnetic probe at edge detects RF signal from Parametric Decay Instability

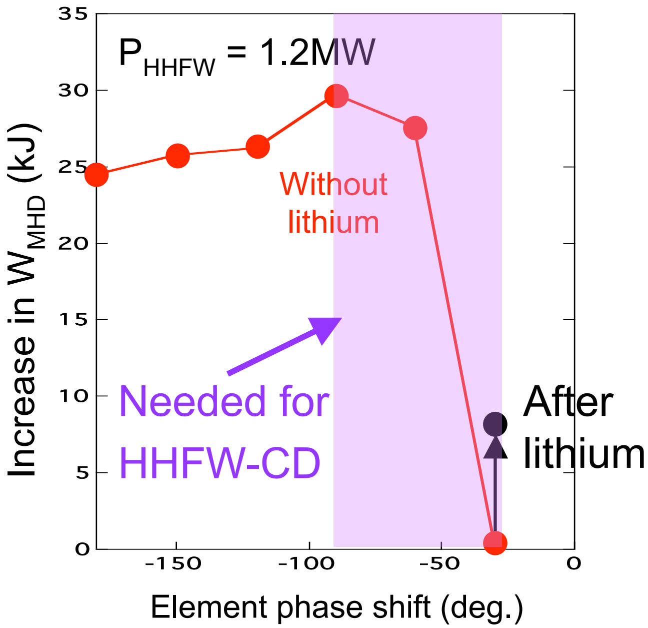
At fixed $k_{||}$ = 7m^{-1}, electron heating efficiency improves at higher B_T



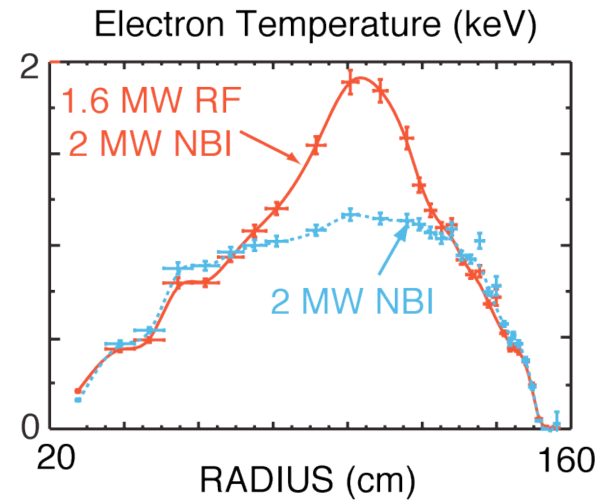


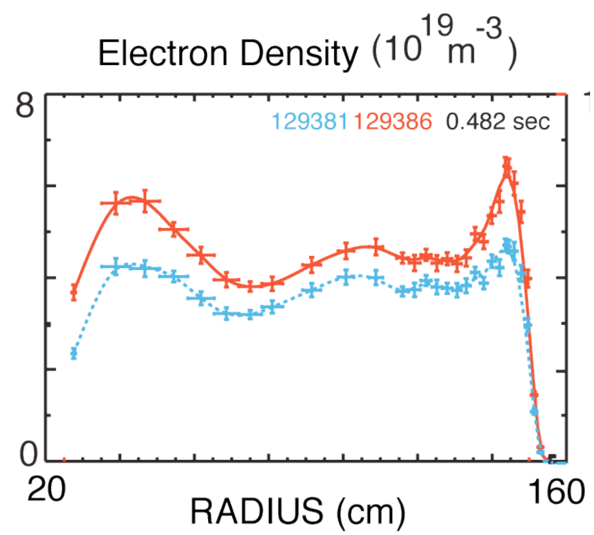
Lithium Coating Partially Restores HHFW Heating Efficiency at Low $k_{||}$ and in NBI H-mode Plasmas

Without lithium, increase in W_{MHD} during HHFW pulse vanishes for $\Delta\phi$ < 60°

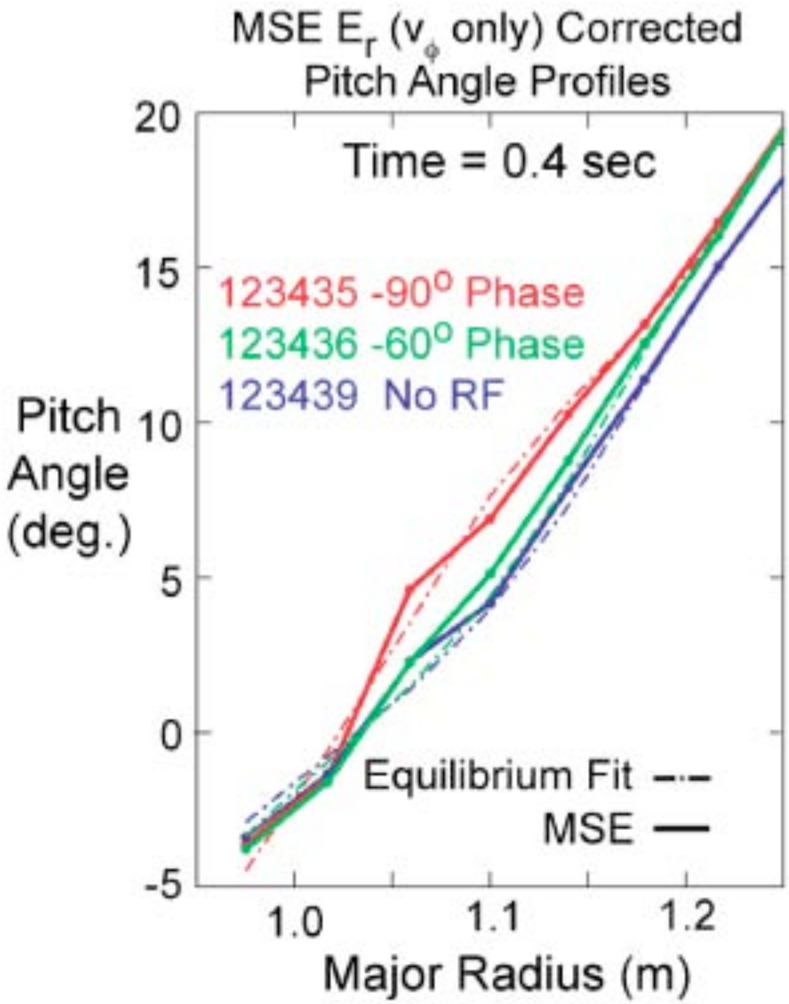


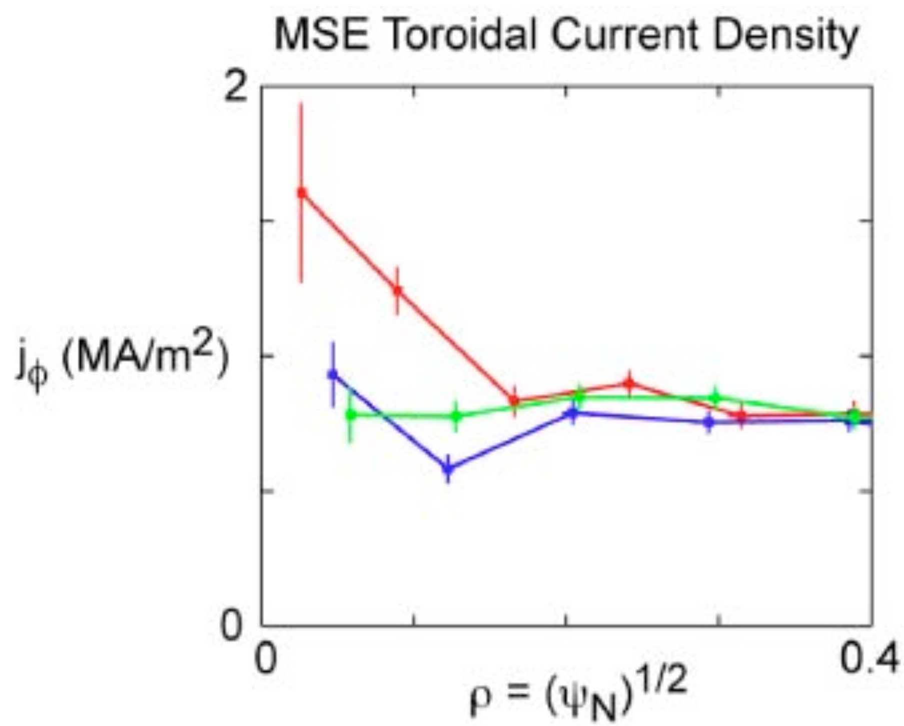
Core Electron Heating in Deuterium NBI H-Mode





MSE Shows Change in Core Field Pitch Angle for Current-Drive Antenna Phase





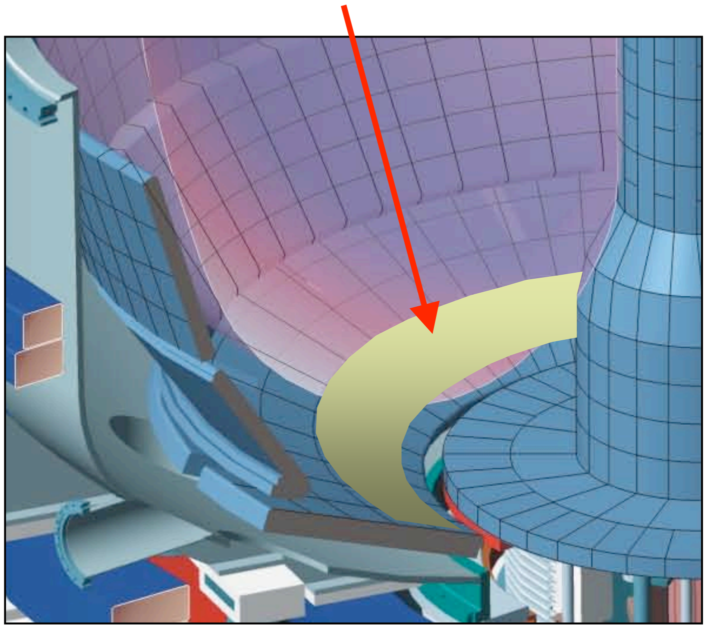
- j_ϕ obtained directly from MSE data using LRDFIT magnetic surfaces
- Integral over j_ϕ peak for -90° phase indicates ~15kA of HHFW-CD relative to no RF case inside R = 1.2 m

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
  - Investigating physics of RF current drive: EBW-CD, HHFW-CD

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

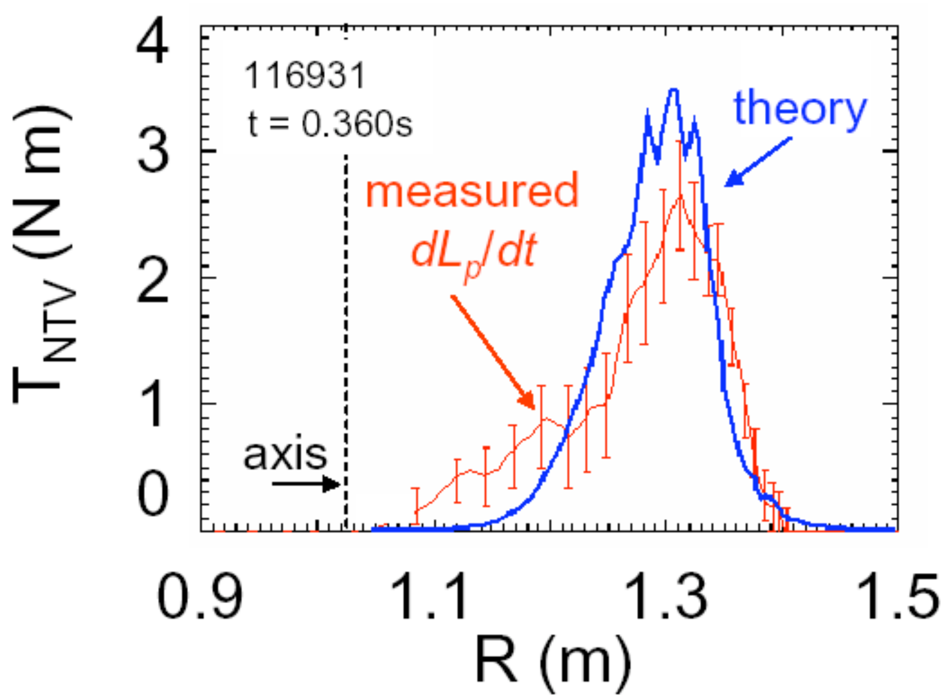
- Evaluate capability of liquid lithium to sustain deuterium pumping beyond capacity of solid film
- Upgrade to long-pulse capability will require method for core fueling
  - Compact Toroid injection or frozen deuterium pellets

NSTX Research Contributes to Fusion Energy Development, ITER Physics and Plasma Science

- Determine the physics principles of ST confinement
  - Limits, scaling, control, heating schemes, integration
  - Utilize low aspect ratio to address basic physics of toroidal confinement
- Support preparation for burning plasma research in ITER
  - Participate in the ITPA and USBPO
- Explore possibilities for a Plasma-Materials Test Facility or a Component Test Facility (CTF)
  - High heat flux or neutron fluence in a driven system

During Magnetic Braking, Rotation Profile Follows Neoclassical Toroidal Viscosity (NTV) Theory

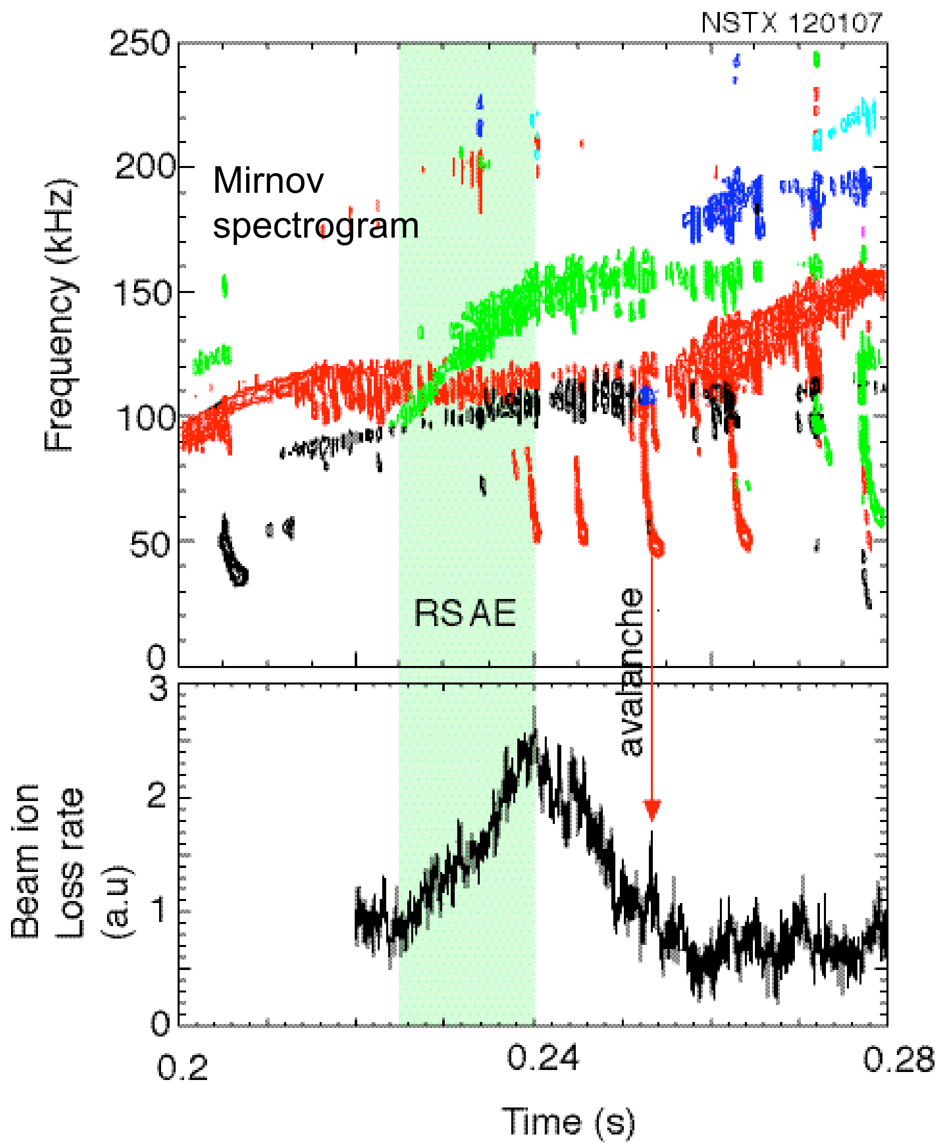
Magnetic braking due to applied n=3 field



- First quantitative agreement with NTV theory
  - Due to plasma flow through non-axisymmetric field
  - Trapped particles, 3-D field spectrum important
  - Computed using experimental equilibria
- Necessary physics for simulations of rotation dynamics in future devices (ITER, CTF)

W. Zhu et al., PRL 96 (2006) 225002

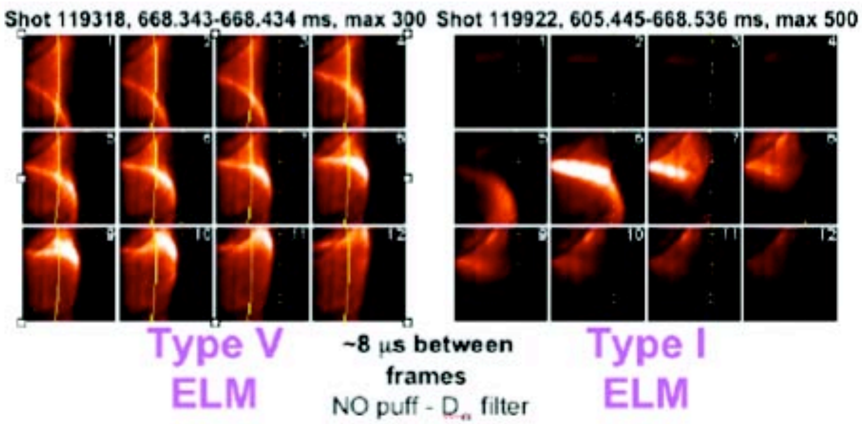
Quasi-Continuous RSAE and Bursting AE Avalanche Produce Characteristic Signatures in Ion Loss

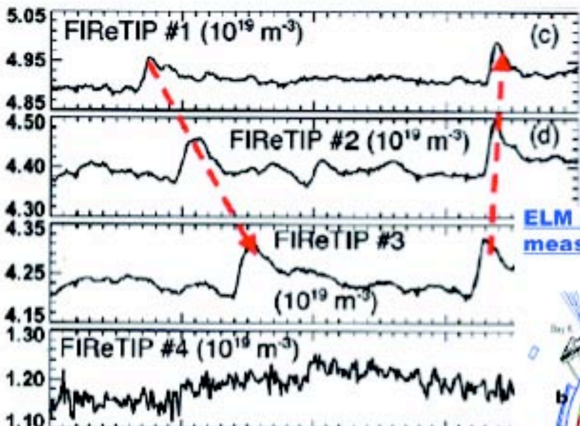


- Losses increase while RSAE frequency increases
- Avalanche also produces burst of loss

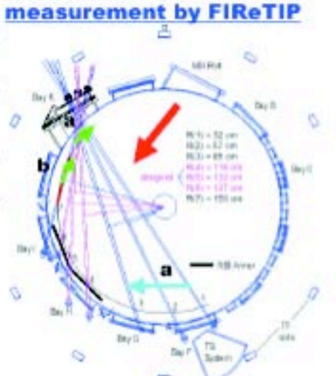
Imaging of Plasma Edge Contributing to Understanding Edge Turbulence Phenomena *(Blobs, ELMs)*

ELM dynamics and rotation measured

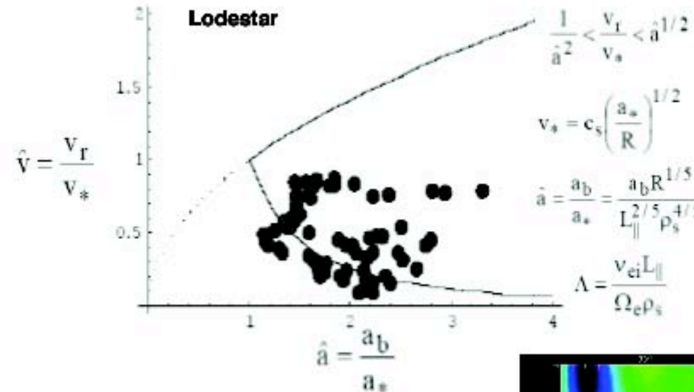


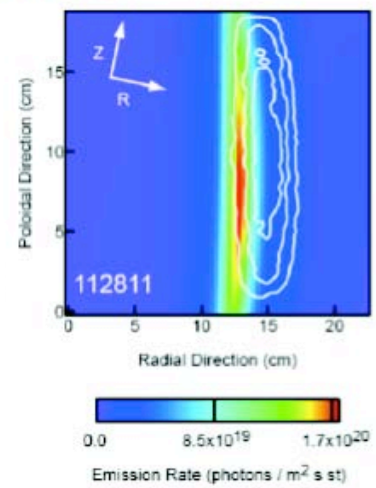


ELM rotation measurement by FIReTIP

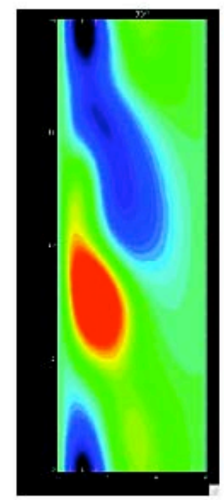


Measurements of "blob" propagation connect to evolving theory





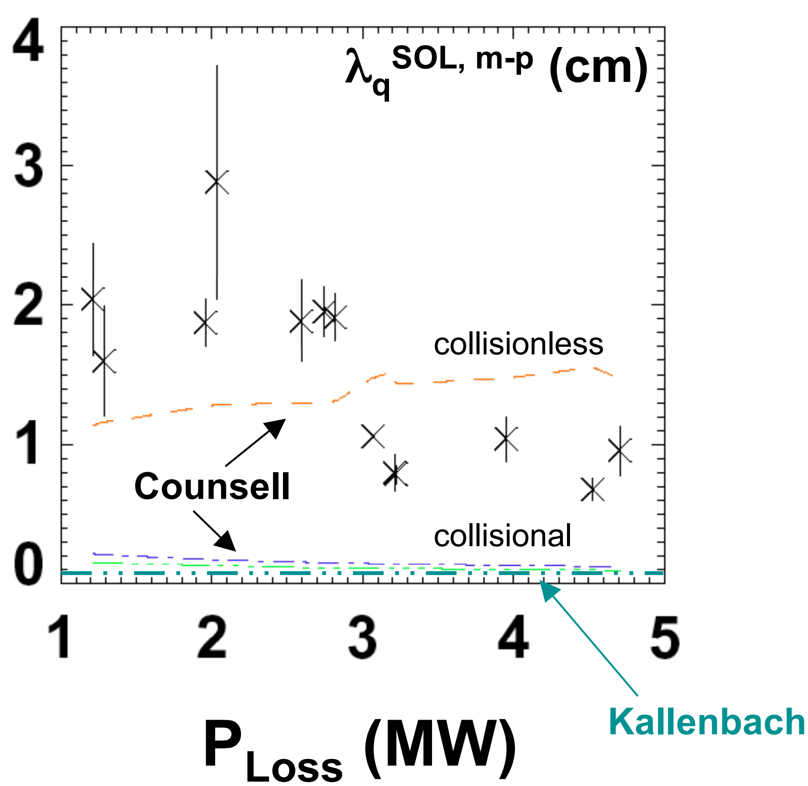
DEGAS 2 simulation of GPI diagnostic



edge n_e "blobs" from BOUT run for NSTX (LLNL)

Divertor Power Loading Critical Issue for the ST

Midplane heat flux SOL in NSTX broader than models predict



Peak heat flux increases with power as outer leg becomes connected