NSTX

Supported by U.S. DEPARTMENT OF ENERGY | Office of Science

NSTX Facility/Research Status and Plans

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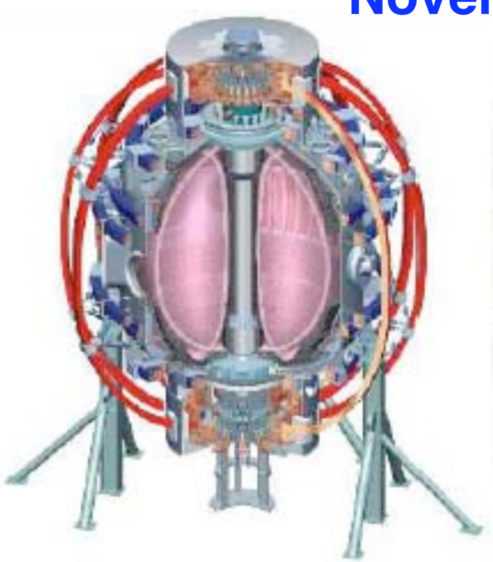
Masayuki Ono, PPPL

For the NSTX Team

APS - DPP Meeting
Dallas, Texas
November 17 - 21, 2008



Culham Sci Ctr
U St. Andrews
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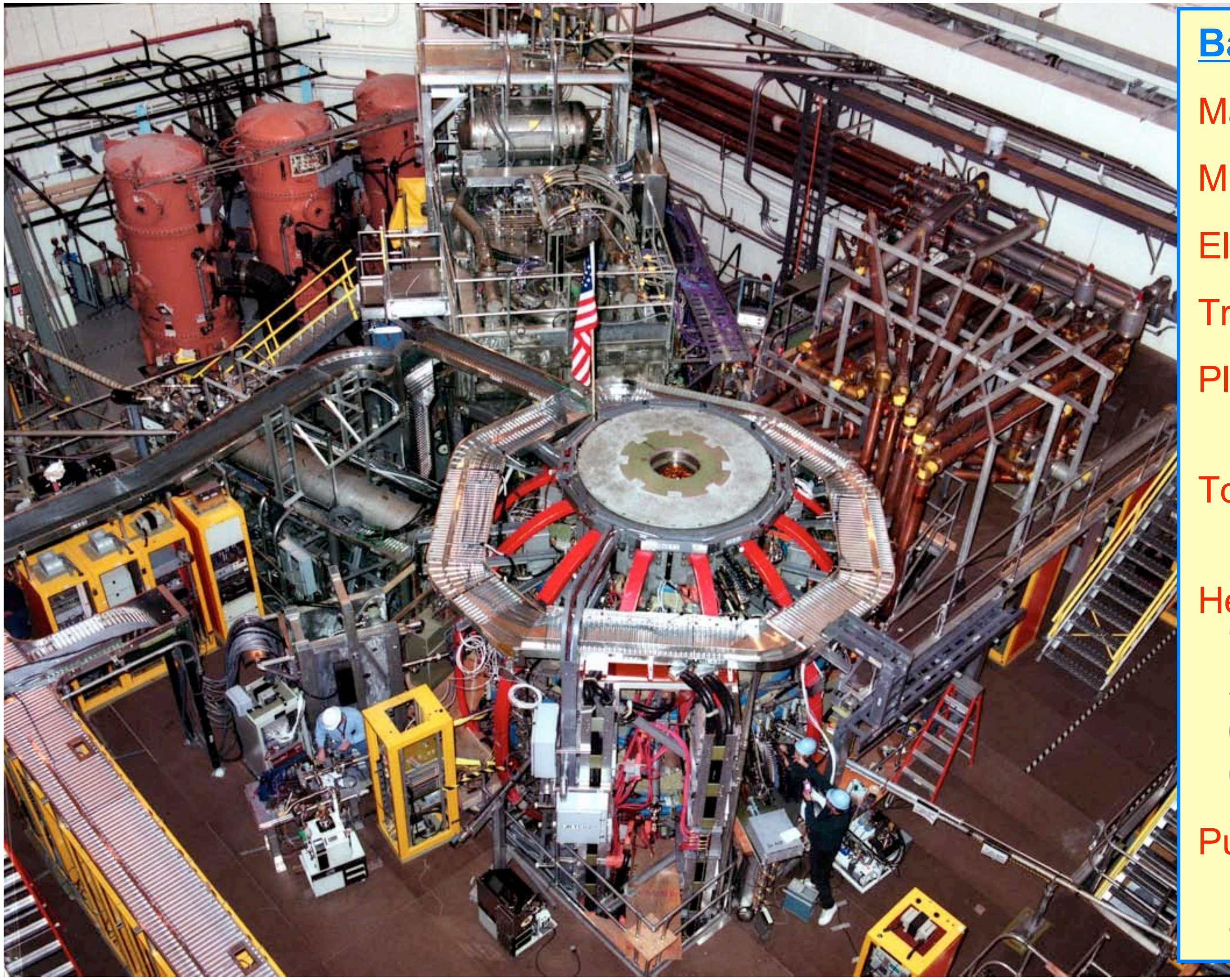
KBSI
KAIST
POSTECH
ASIPP
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
ASCR, Czech Rep
U Quebec

NSTX Facility Overview



Baseline Parameters

Major Radius 0.85 m

Minor Radius 0.68 m

Elongation 1.8 - 3.0

Triangularity 0.2 - 0.8

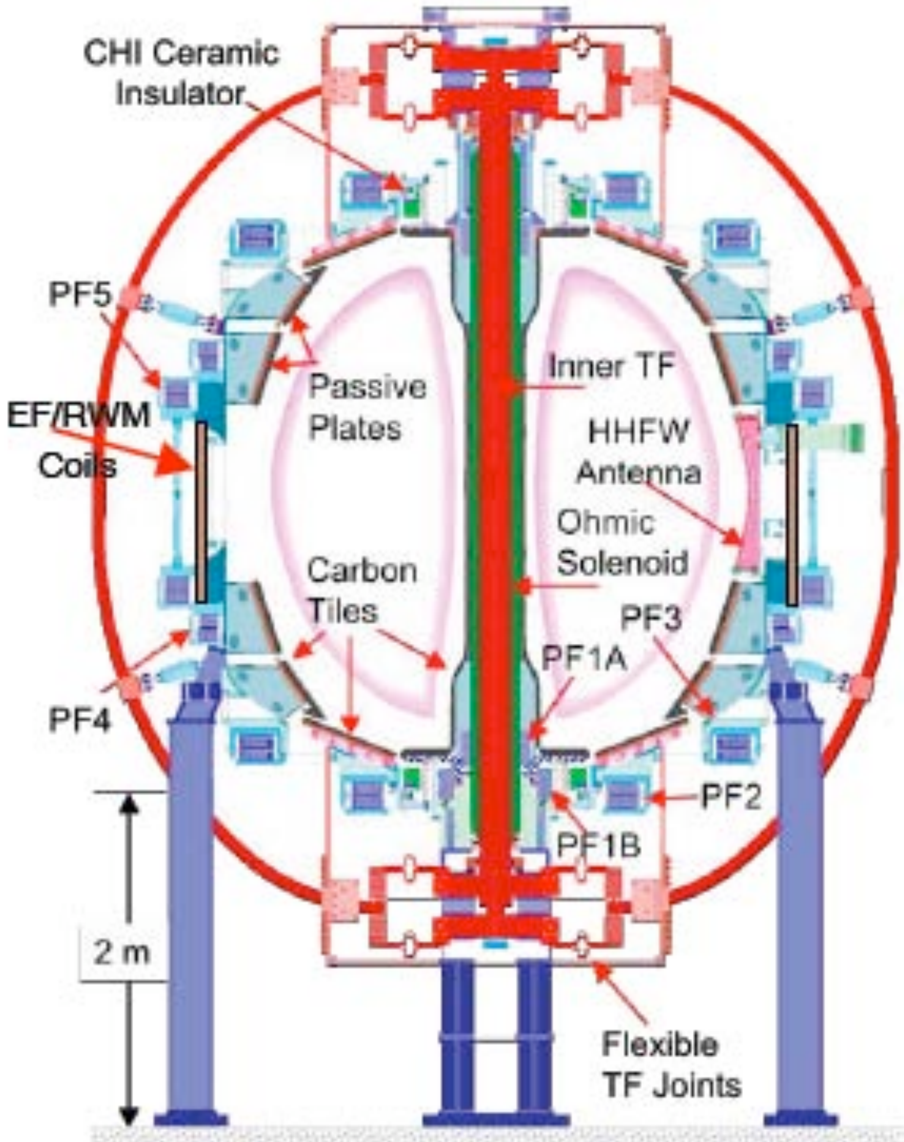
Plasma Current
1 MA (1.5 MA peak)

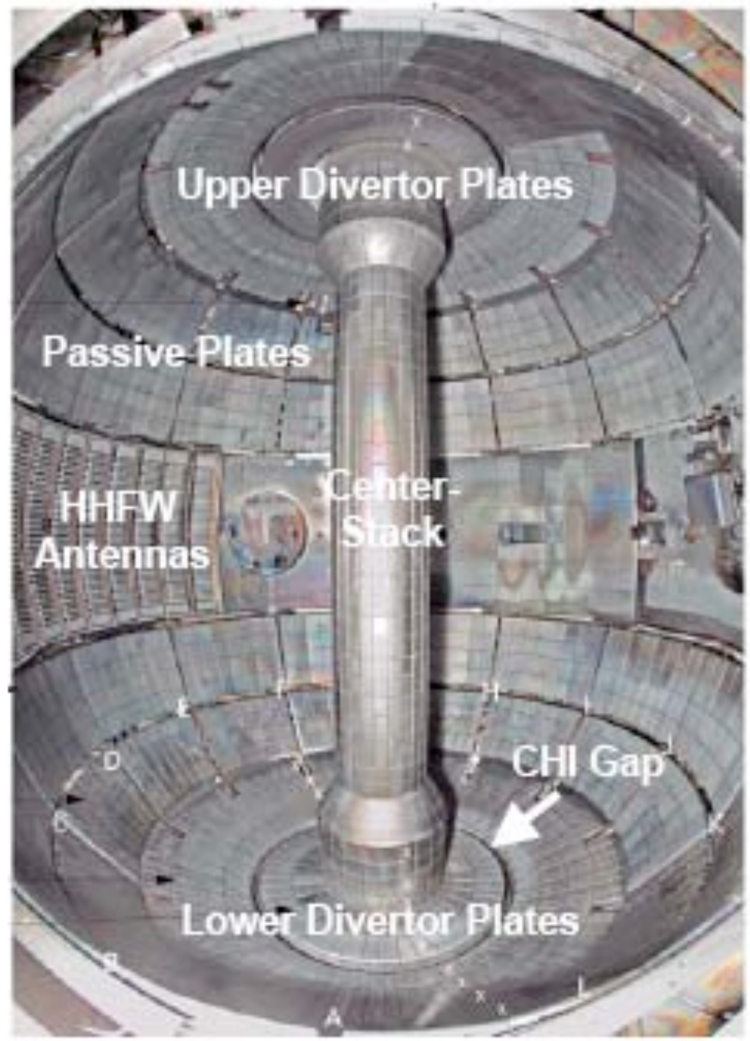
Toroidal Field
0.35 - 0.55 T

Heating and CD
7 MW NBI (2 sec)
5 MWNBI (5 sec)
6 MW HHFW (5 sec)
0.2 MA CHI

Pulse Length
~ 1 sec at 0.55 T
~ 2 sec at 0.38 T

NSTX Device Cross-Section and VV Internal Components
Removable Center-Stack Design

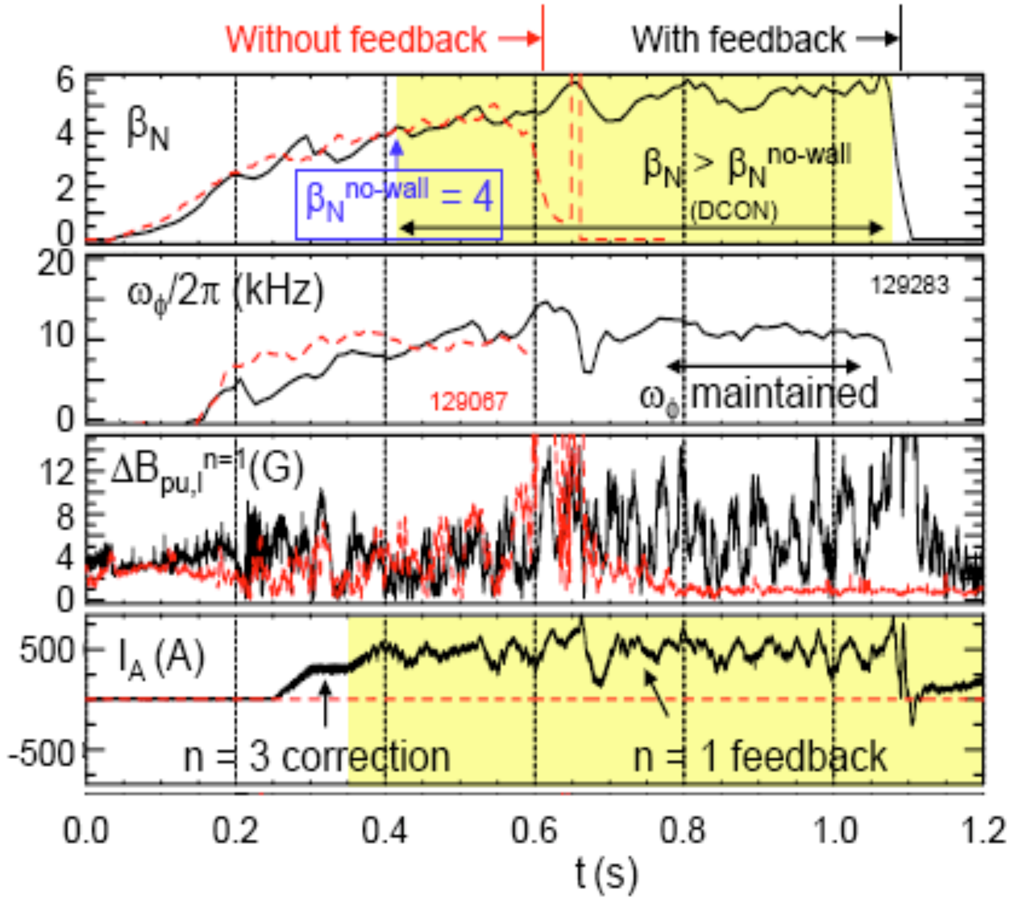




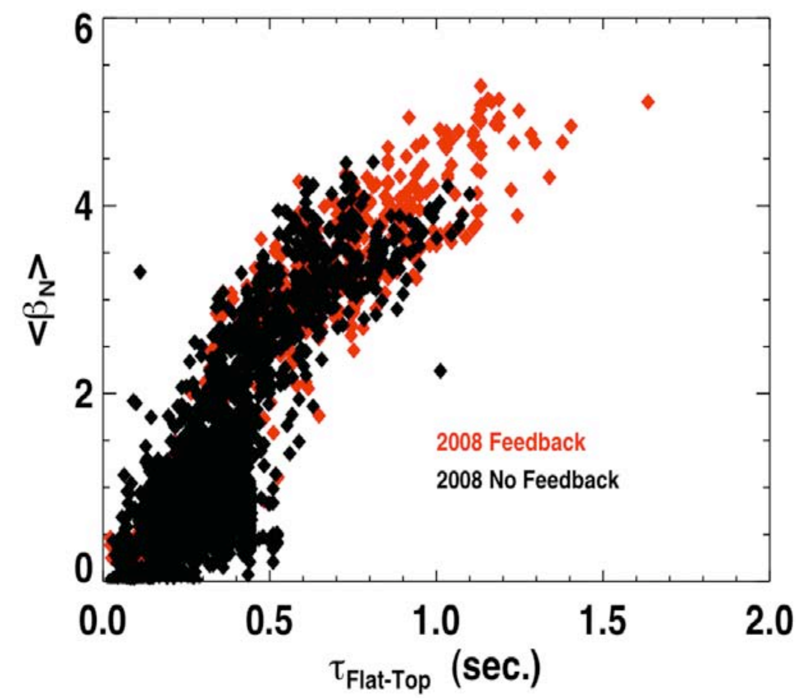
NSTX Completed Successful FY 2008 Run

- NSTX has completed 16.6 weeks of experimental operations meeting the FY 08 operational Joule milestone (out of our planned 15). Produced 2571 plasma shots in 16+ weeks which compares well with similar 2460 plasma shots in 2004 but it took 21 weeks.
- Dual LITER system has been working flawlessly. LITER also largely eliminated He-GDC which improved operational efficiency. Dual LITER were reloaded with lithium three times (total ~ 200g) during the operations.
- Lithium shaker was tested. It appears to reduce the density and impurity radiation during the long-pulse ELM-free H-mode discharges.
- The EF/RWM feedback control system are now routinely used as a tool for advanced long-pulse operation.
- The run concluded on July 14. Vent by late July, perform diagnostic calibrations, and then begin in-vessel activities in late August.

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

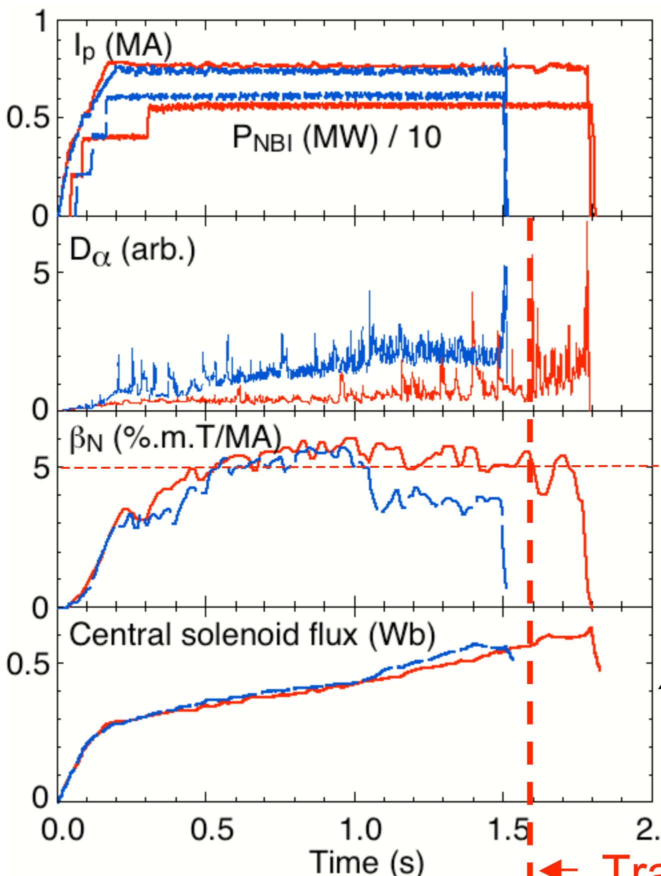


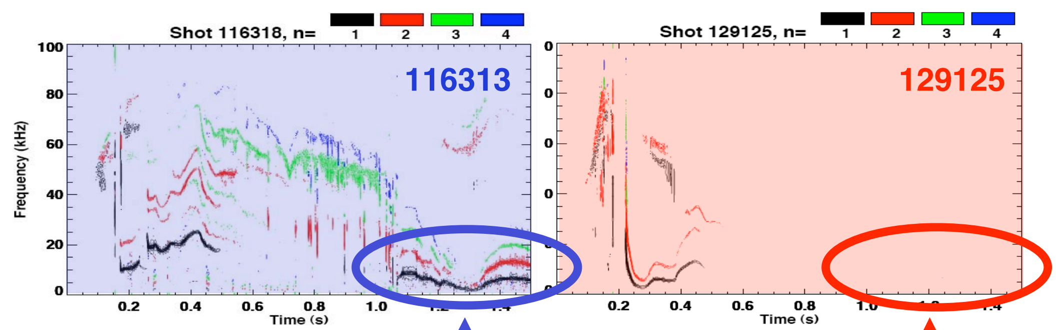
- **Correction of n = 3 intrinsic error field maintains toroidal rotation**
- **Resistive Wall Mode can develop at high normalized-β: terminates discharge**
- **Feedback on measured n = 1 mode reliably suppresses RWM growth**
  - **Limitations on time response and applied mode purity explored for ITER**

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

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

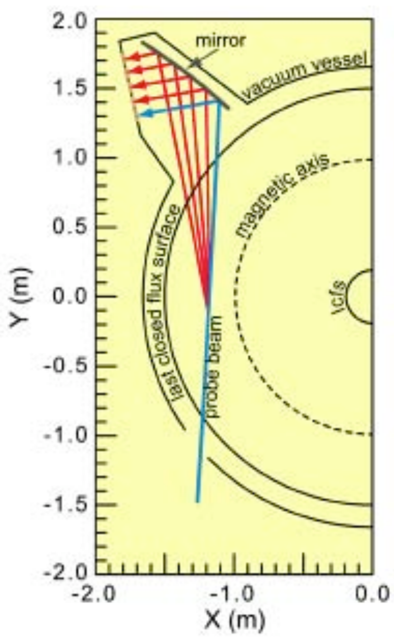
- High elongation κ = 2.4 increases bootstrap current fraction

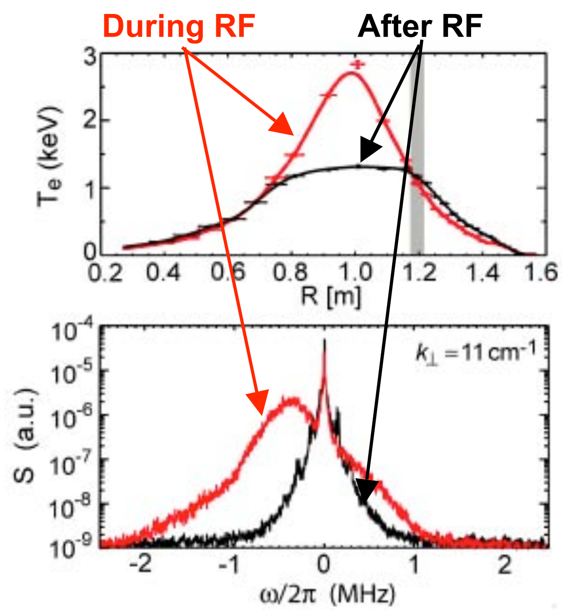
D. Gates-CO3.3, J. Menard-NP6.82

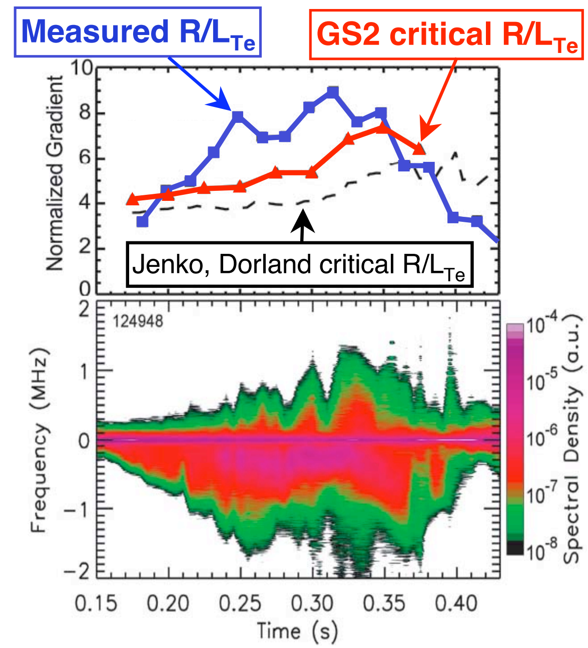
← Transition to phase with larger, more frequent ELMs

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

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



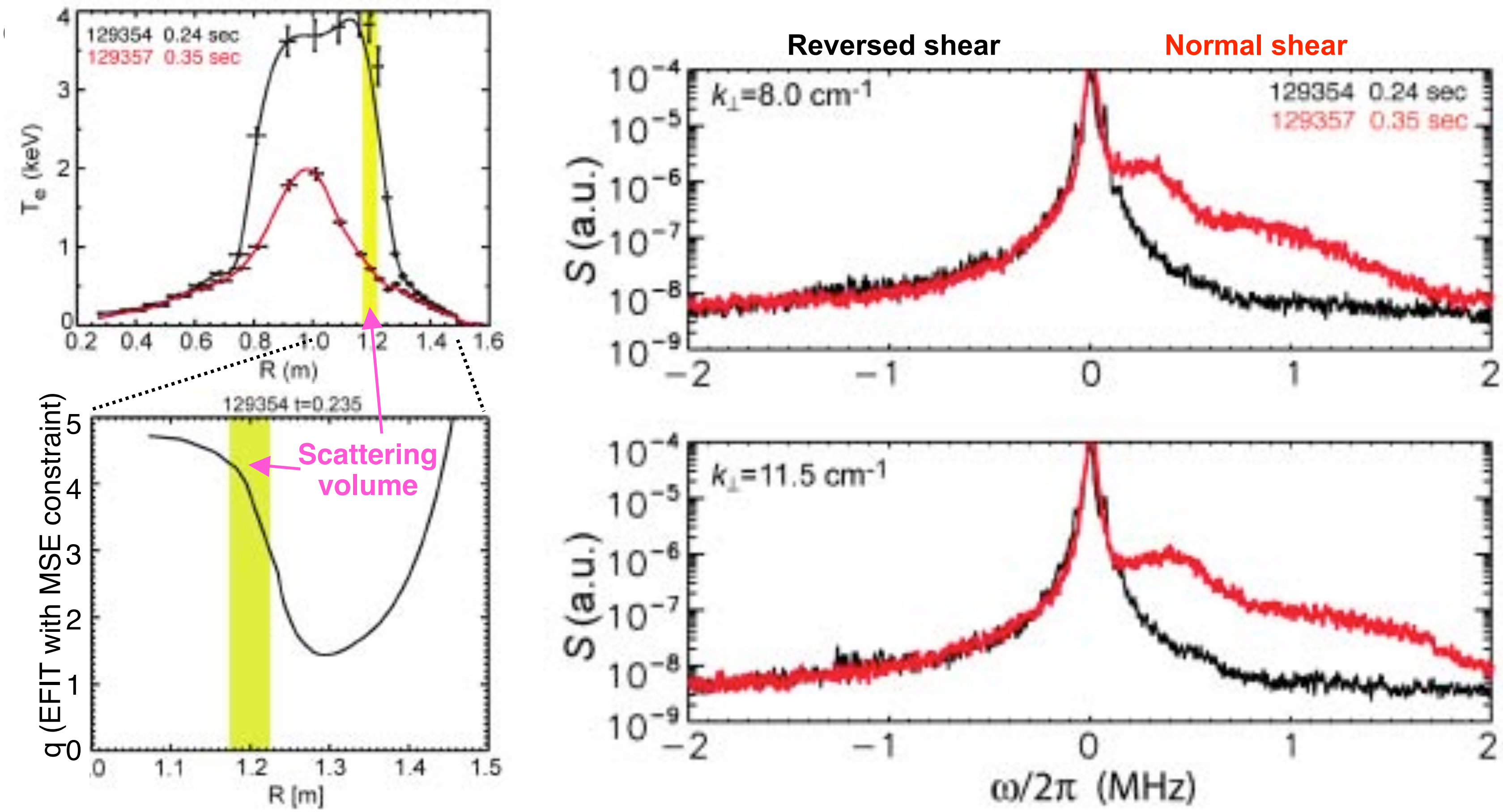




- **Detected fluctuations in range $k_\perp\rho_e$ = 0.1 – 0.4 ($k_\perp\rho_s$ = 8 – 16) propagate in electron diamagnetic drift direction**
  - **Rules out Ion Temperature Gradient mode ($k_\perp\rho_s$ ~ 1) as source of turbulence**
  - **Reasonable agreement with linear gyrokinetic code (GS2) for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

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

- Shear-reversal produced by early NB heating during plasma



- **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)**

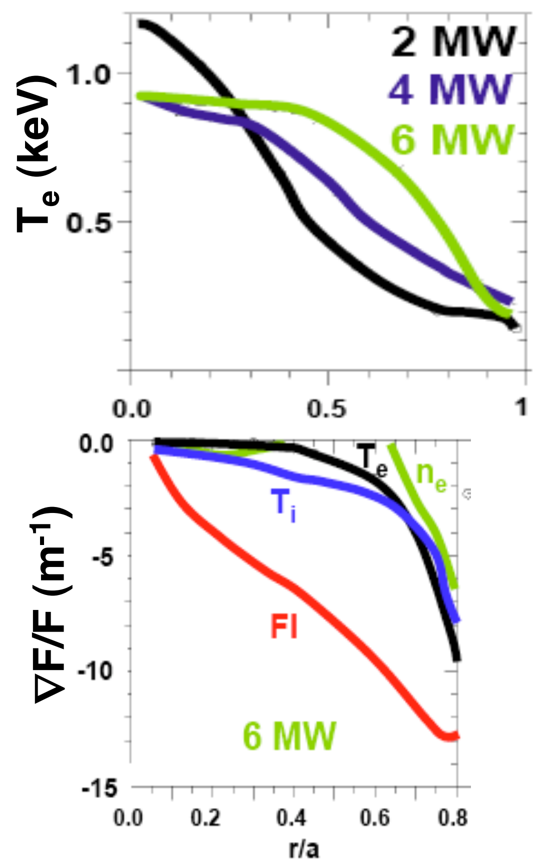
E. Mazzucato, H. Yuh

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

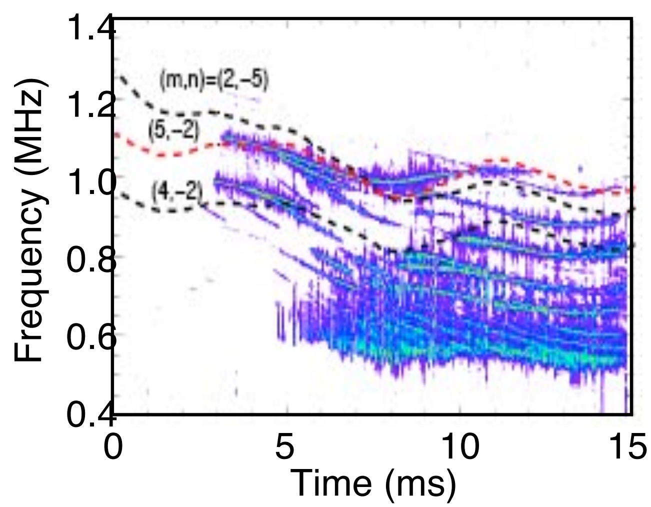
- **Observe "flat T_e" region in core of plasmas with high NBI power**

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

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

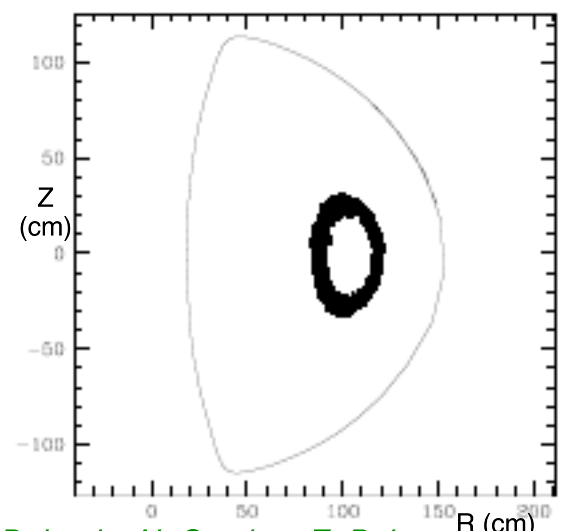


$$\omega_{GAE} \simeq v_{A0}(m - nq_0)/q_0 R.$$



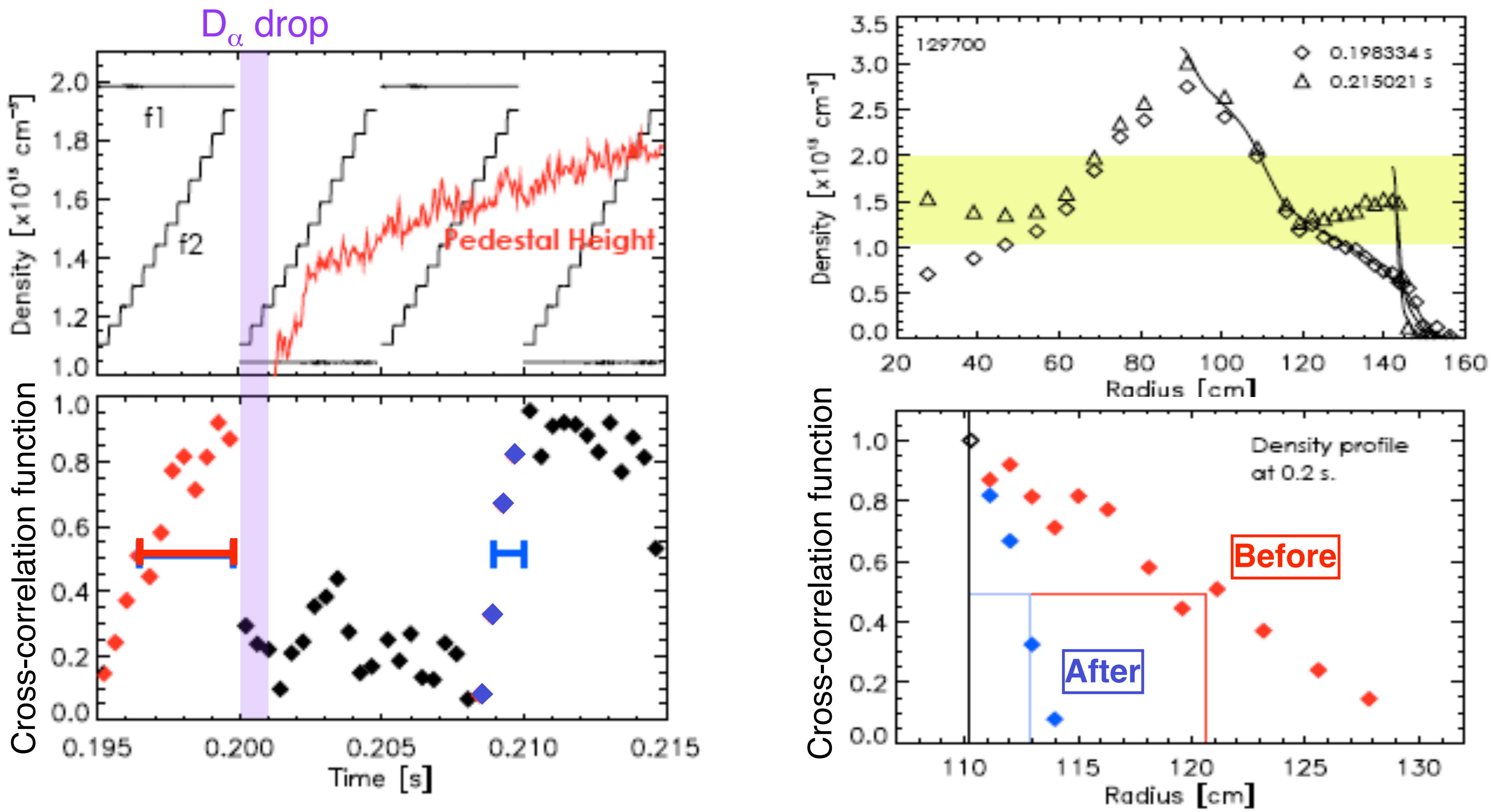
- **GAEs localized near center**
- **Radial width ∝ m^{-1}**
- **$f_{GAE} \sim f_{be}$ trapped electron bounce frequency**

- **ORBIT code modeling with GAE frequency and amplitude typical of NSTX**
- **After 3ms, see radial diffusion of electrons initially on a flux surface**



D. Stutman, N. Gorelenkov, L. Delgado, N. Crocker, E. Belova

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

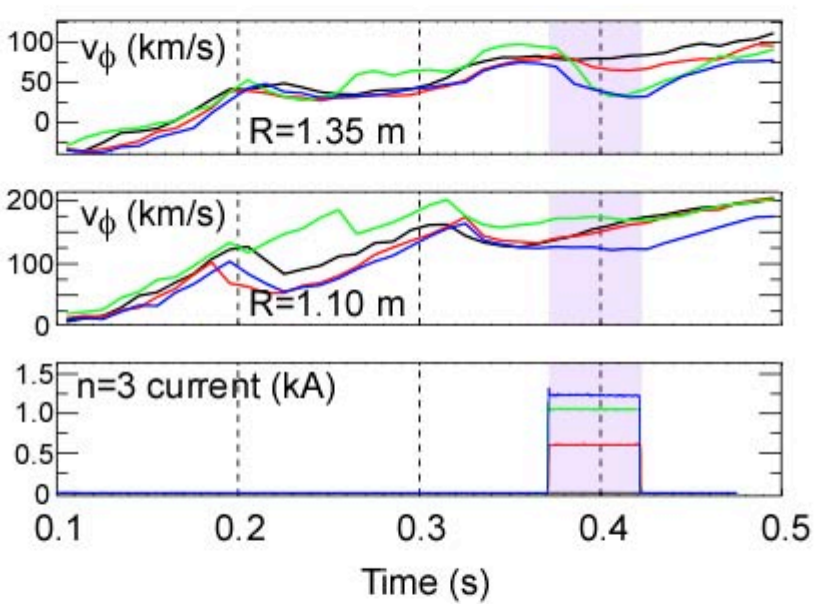


- Use fixed/swept frequency correlation reflectometer during period with monotonic density profile following H-mode transition
- Fluctuation characteristics change little except for a reduction in radial correlation length by factor 3 - 4

S. Kubota, C. Bush

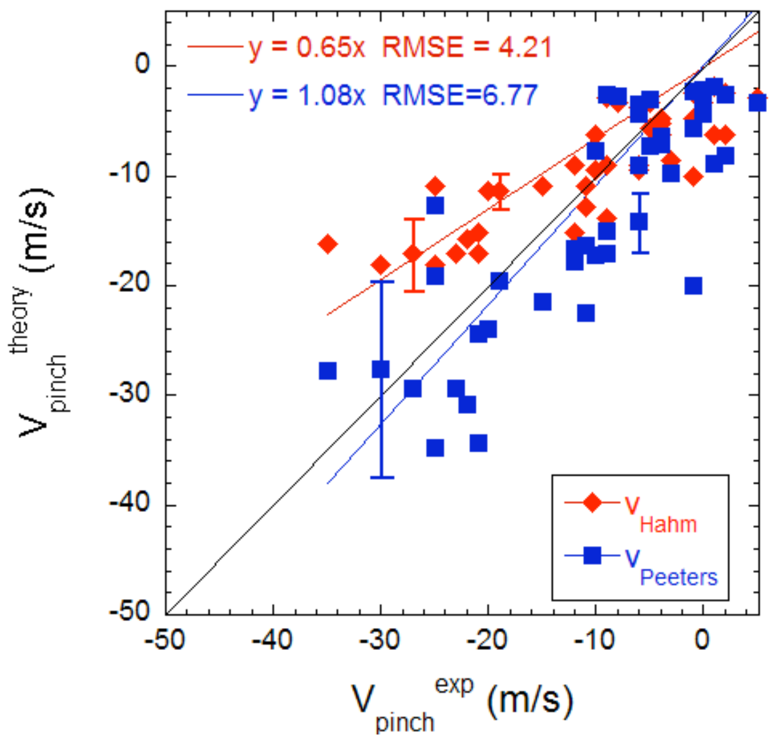
Investigated Momentum Transport Using Transient Perturbations to Separate Diffusivity and Pinch Terms

- **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**

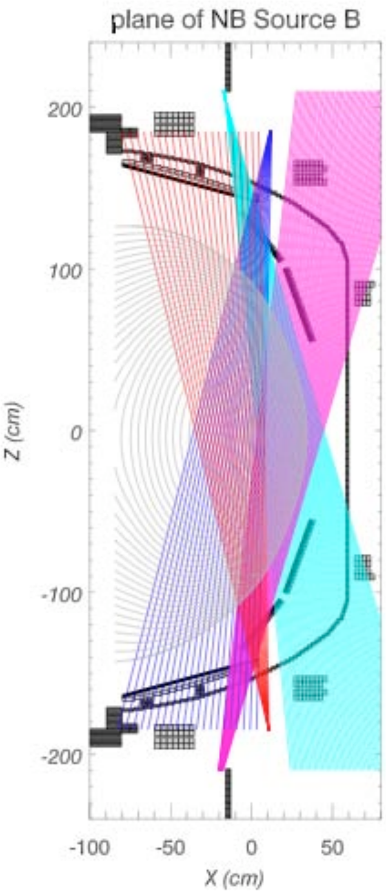


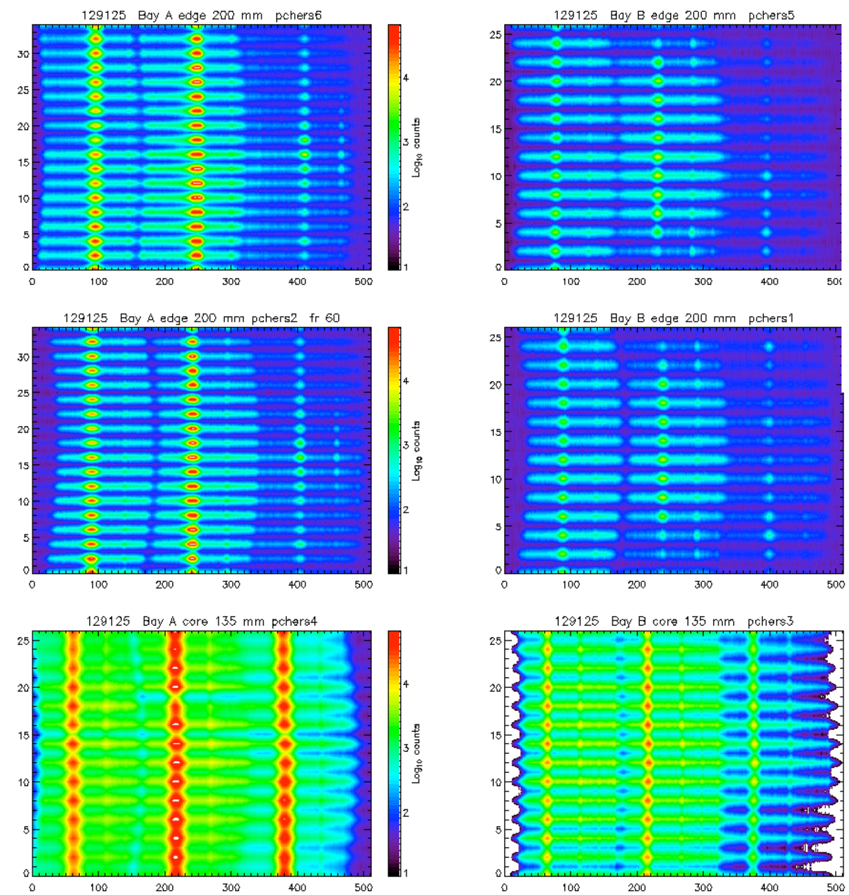
Peeters *et al.* (PRL, 2007)
Hahm *et al.* (PoP, 2007)

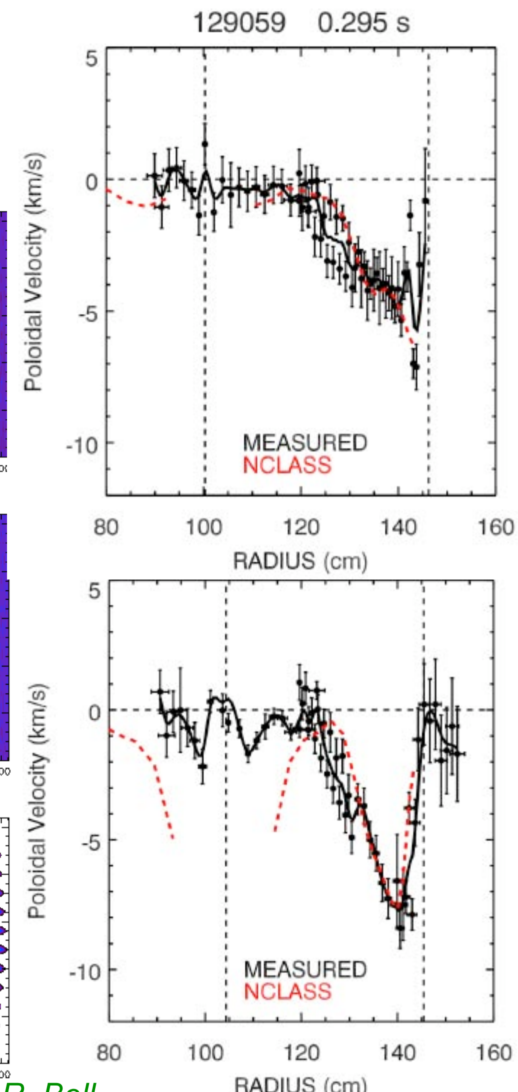
S. Kaye-NP6.88

Poloidal Charge-Exchange Recombination emission Spectroscopy achieved full spatial resolution and coverage.

– **Full system (75 ch active and 63 background ch, top & bottom symmetric views, 276 ch total) installed, commissioned and operated routinely for FY 08 run**
– **Yielded ion-gyro-radius scale poloidal flow structures**





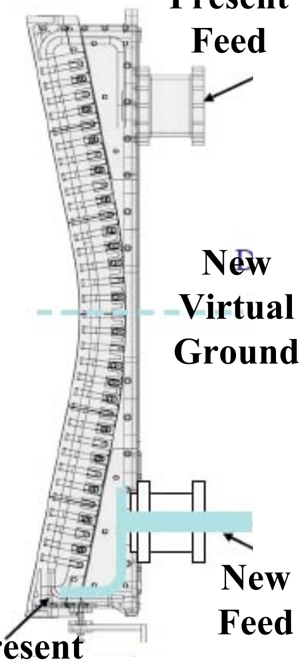


R. Bell

HHFW Antenna Upgrade Being Implemented

Upgraded Antenna Main Features:

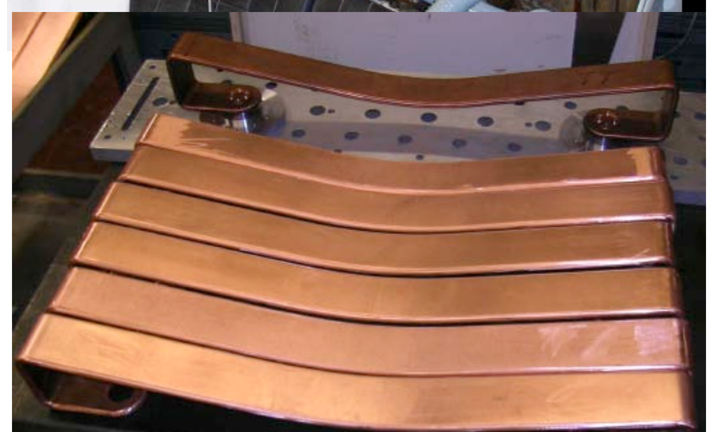
- Symmetric feed
- Virtual ground at antenna mid-plane
- Maximum radiation at mid-plane
- Voltage at feed-thru reduced by ~ 1.4
- Power capability should be up by ~ 2



HHFW Antenna Area Prepared

Antenna Feed-thrus

Feed-thru Adopters



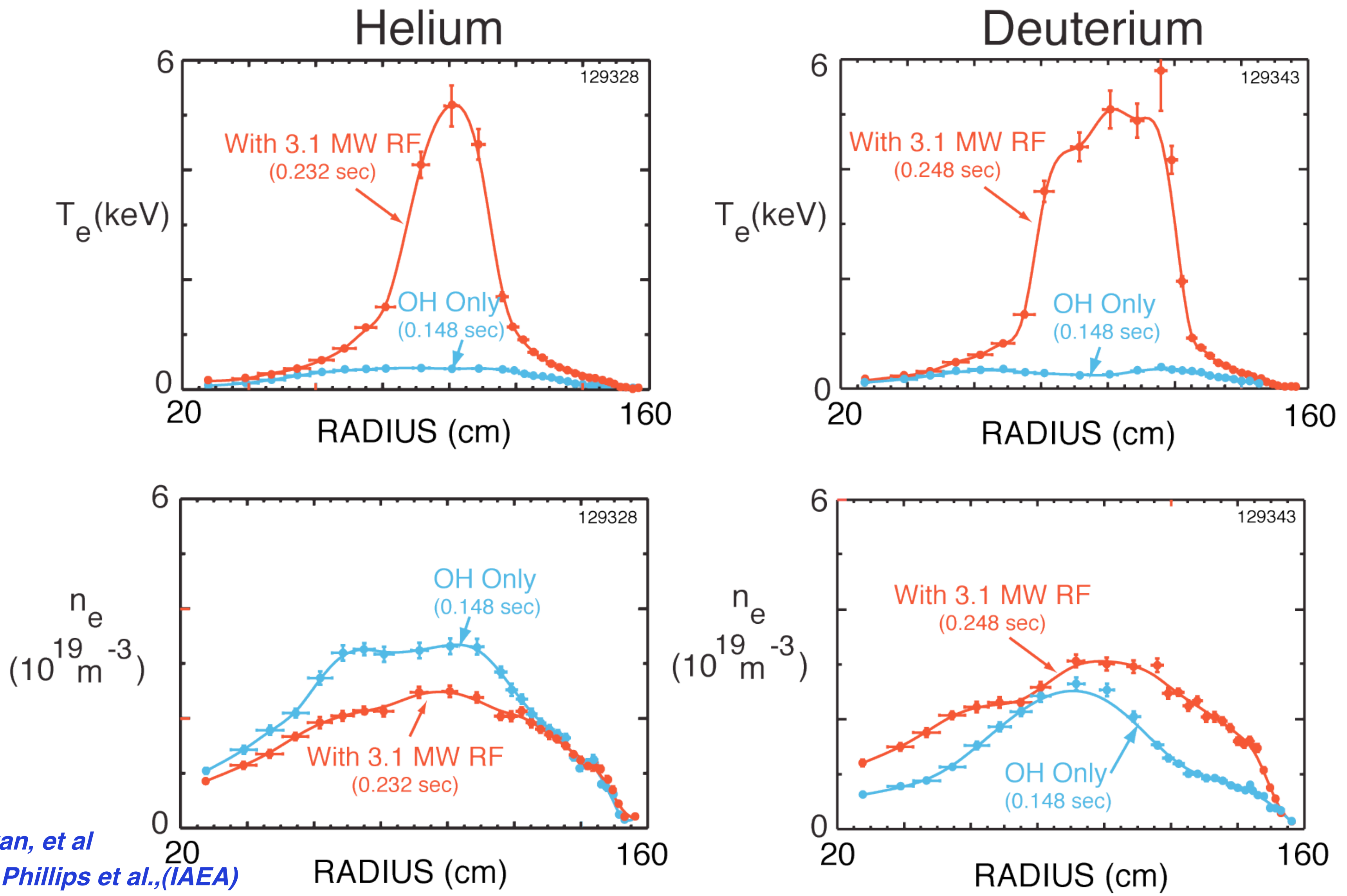
New antenna straps

Antenna Installation Scheduled in Mid-November

J. Hosea, R. Ellis

D, He Plasmas Heated to 5 keV with 3 MW HHFW at $k_{||}$ = 14 m^{-1}

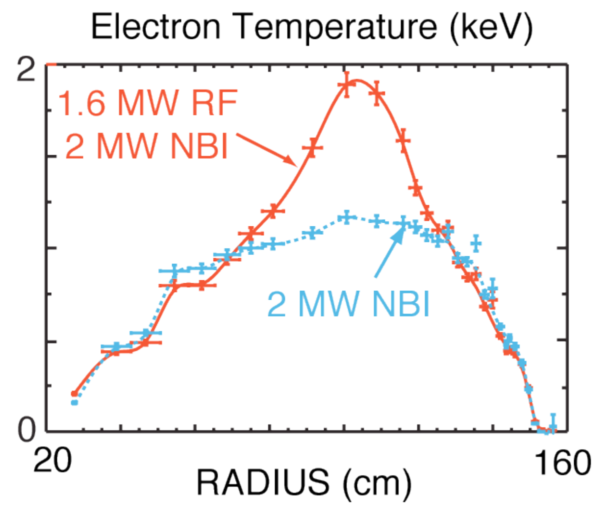
(Lithium has helped HHFW performance in deuterium, H-mode, and NBI)

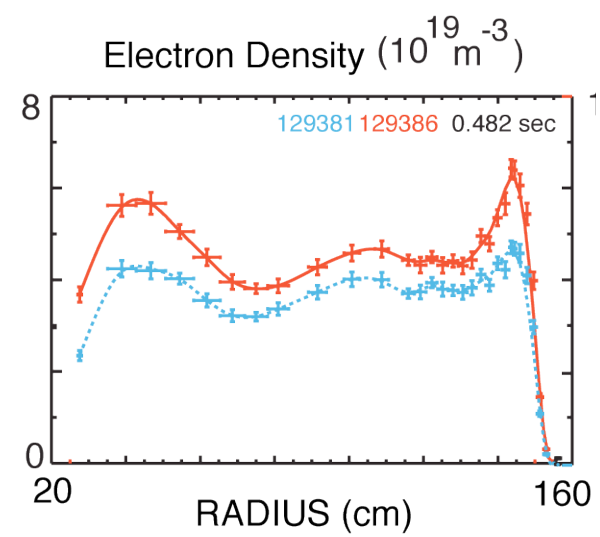


P. Ryan, et al
C. K. Phillips et al.,(IAEA)

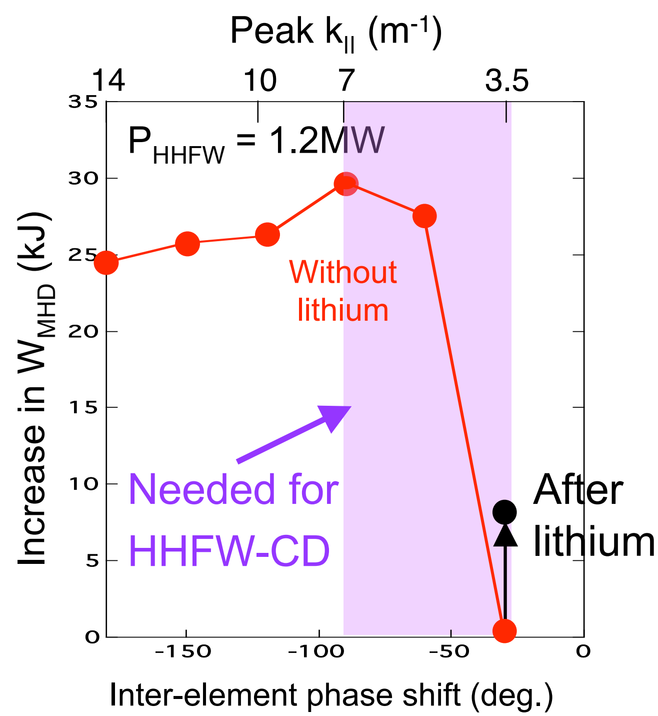
Lithium Coating Improves HHFW Heating Efficiency in NBI H-Modes and at Low $k_{||}$ for Current Drive

Core Electron Heating in Deuterium NBI H-Mode





Electron Heating by HHFW in Deuterium L-Mode

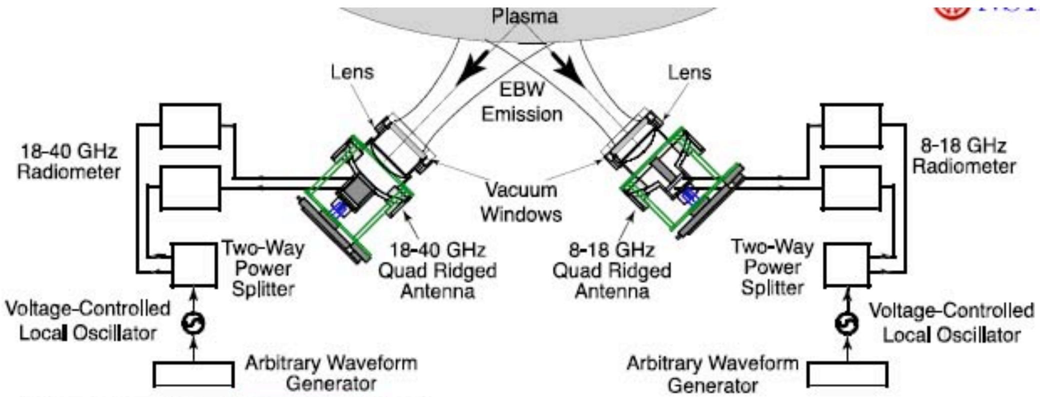


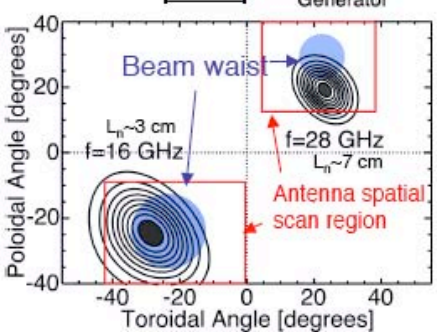
- **Without lithium, increase in W_{MHD} during HHFW vanishes for $\Delta\phi$ < 60º**
- **Reduction in edge density with lithium suppresses excitation of surface waves**

G. Taylor-CO3.10, P. Ryan-NP6.104, J. Hosea-NP6.105

LIThium EvaporatoR (LITER) provides PFC Conditioning Tool to Modify Plasma Edge

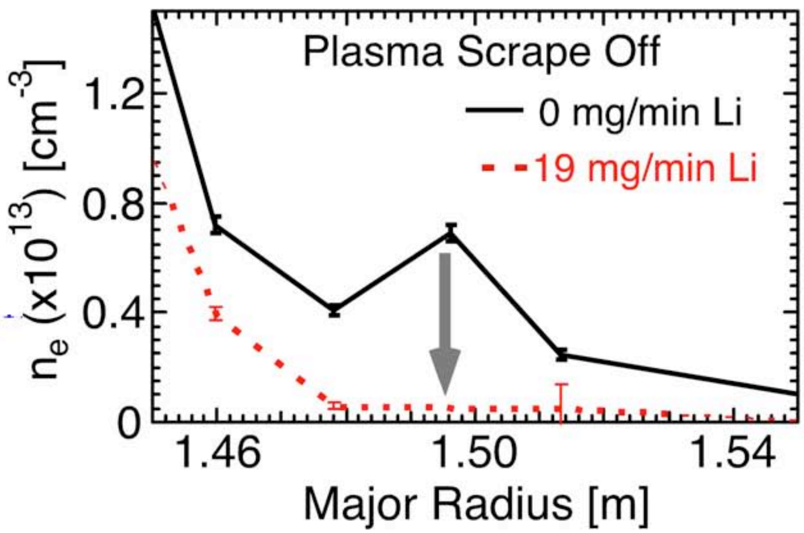
- B-X-O coupling depends on L_n and T_e
  - Li conditioning $T_e\uparrow$ & $n_e\downarrow$ near MC
- Reduction in edge n_e moves MC layer to LCFS where $T_e \sim 20$ eV

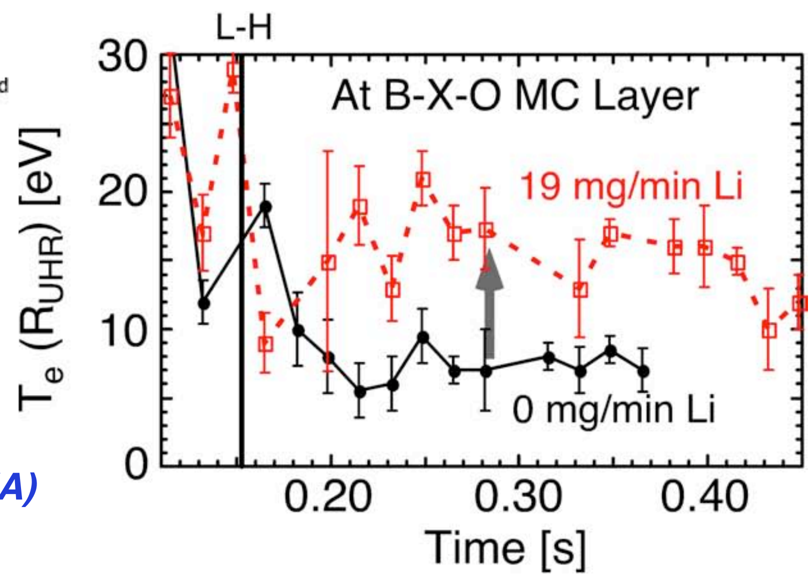




- ±10° scan in poloidal and toroidal directions between discharges
- Acceptance angle:
  - 8-18 GHz antenna ~ 22°
  - 18-40 GHz antenna ~14°

S. J. Diem, G. Taylor et al., (IAEA)
S. J. Diem PhD Thesis



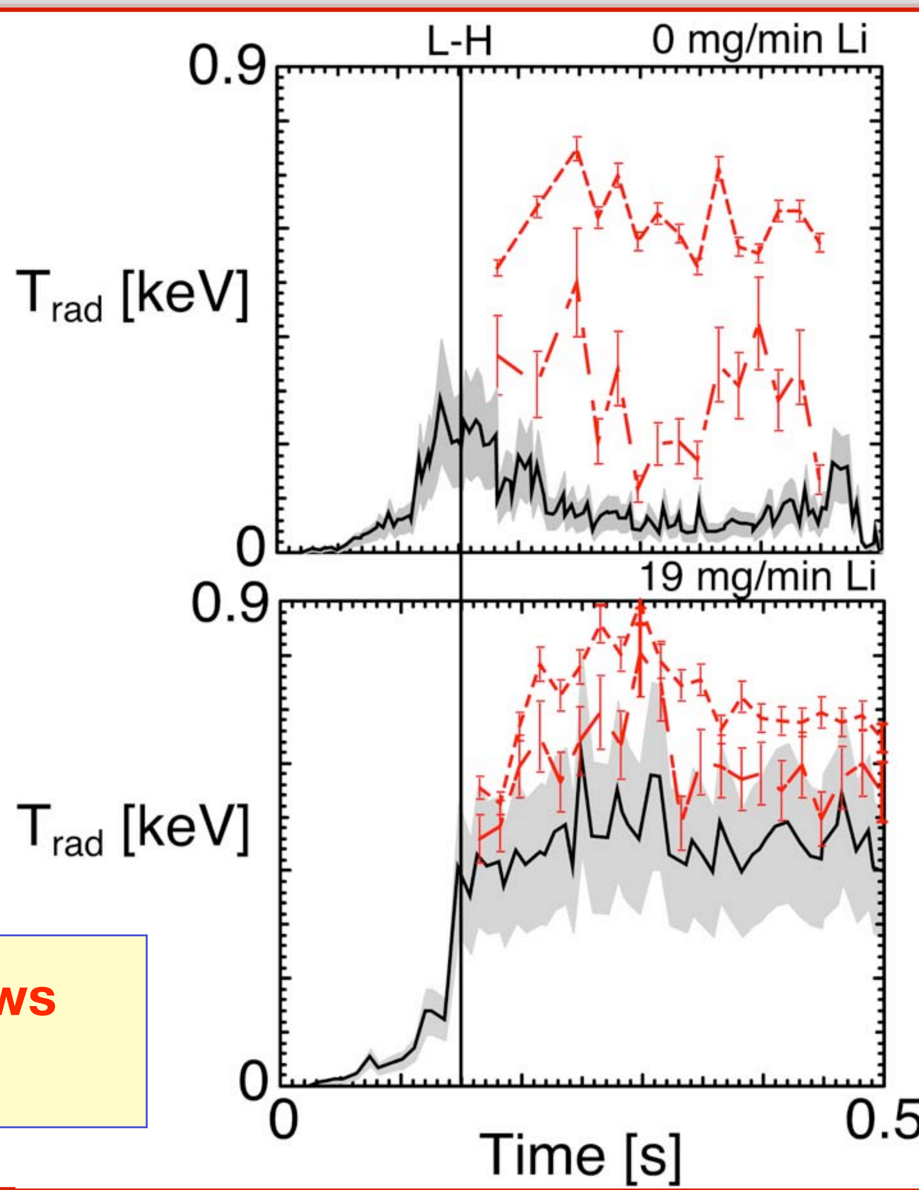


Better T_{rad} agreement with EBE simulation in Lithium conditioned plasma

—— T_{rad} (measured)
– – – T_{rad} (sim., no collisions)
– · – · T_{rad} (sim., with collisions)

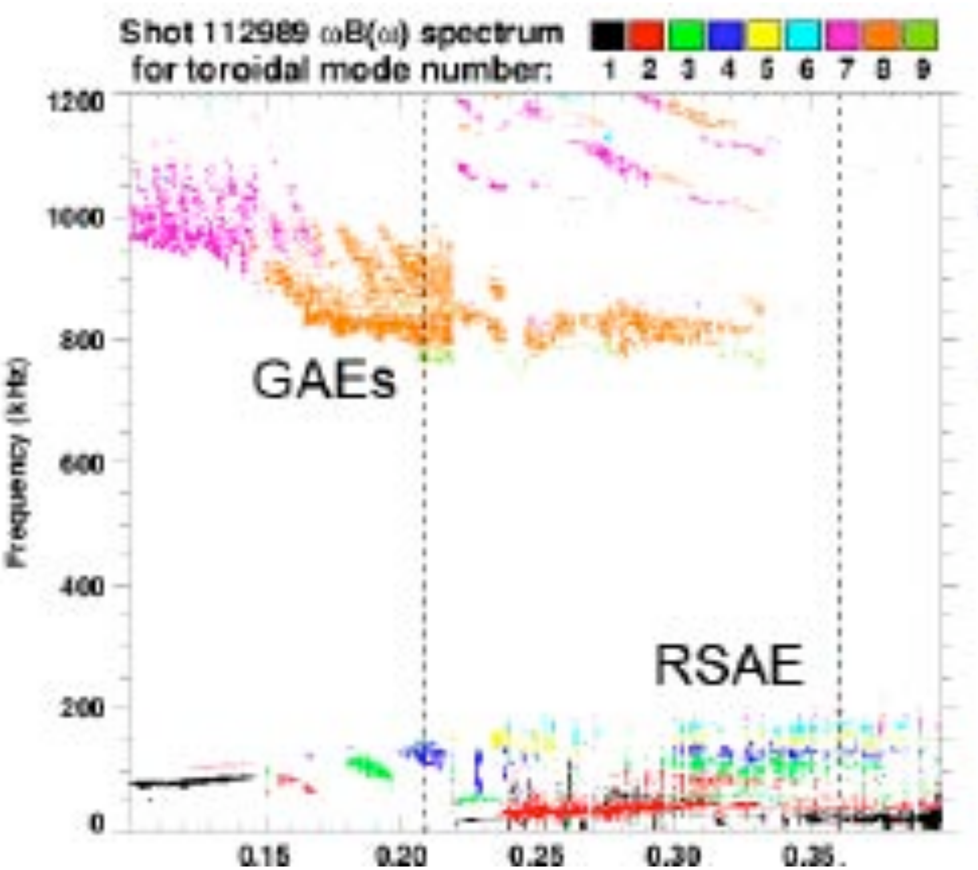
- **For highest Li evaporation mg/min:**
  - Measured T_{rad}~0.4 keV
  - Simulated T_{rad}~0.6 keV

- **For 0 mg/min:**
  - Measured T_{rad}~0.1 keV
  - Simulated T_{rad} ~0.4 keV

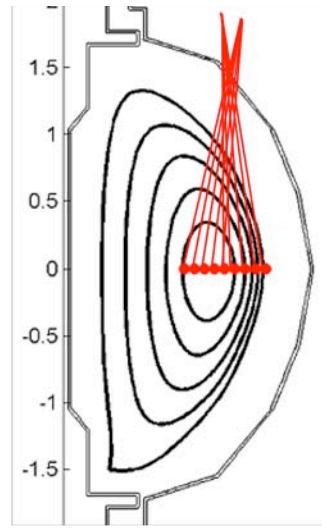


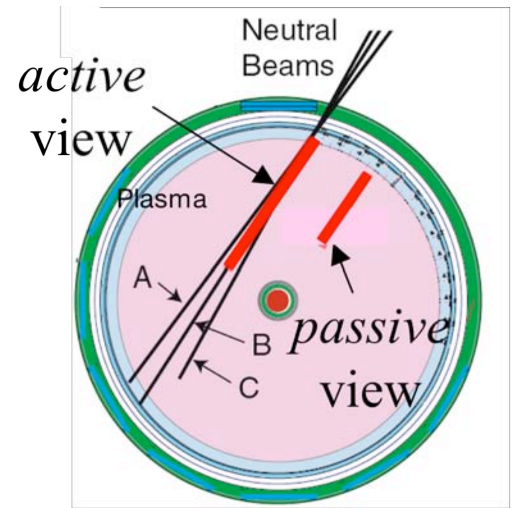
Control of edge conditions allows for good coupling to EBW

Extensive Energetic Particle Diagnostic Capability
Measures Fast Ion Properties



FIDA diagnostic on NSTX (2008)

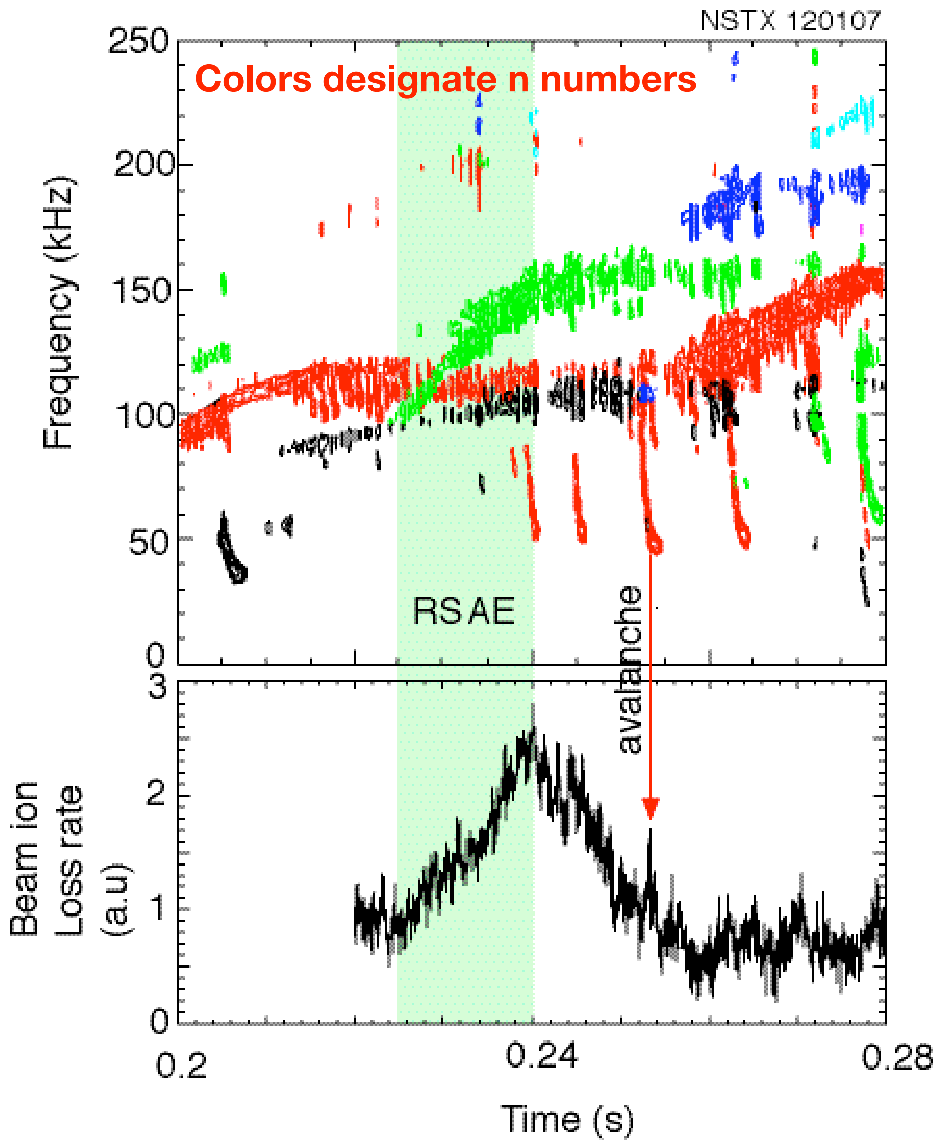




Collaboration contributions

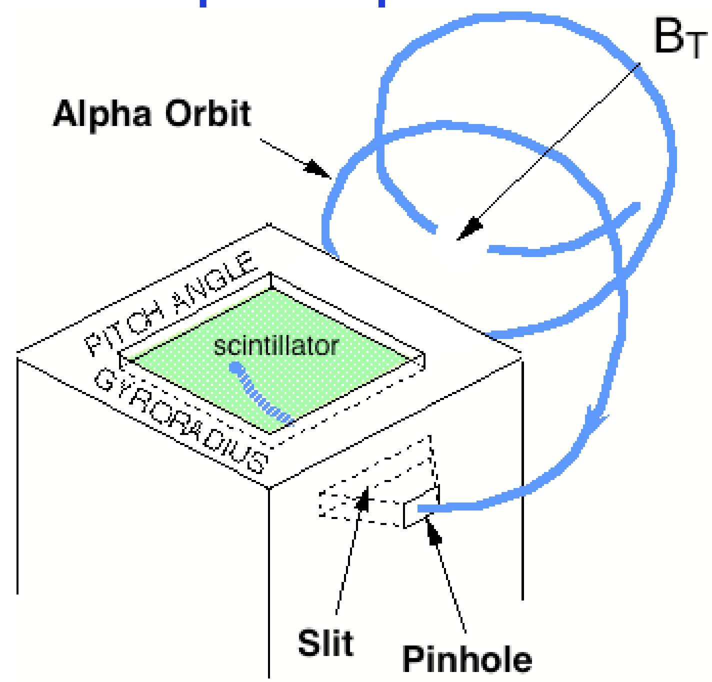
- Fast neutron rate monitors
- Scanning NPA;
- *ssNPA; 4-channel compact NPA*
- sFLIP; scintillator lost ion probe,
- iFLIP; Faraday cup lost ion probes
- *FIDA; spatial profile, energy resolved (2008)*

Quasi-Continuous RSAE and Bursting AE Avalanche Produce Ion Losses



- Losses increase while frequency still increasing
- Avalanche also produces burst of loss

s-FLIP Scintillator Detector Principle of Operation



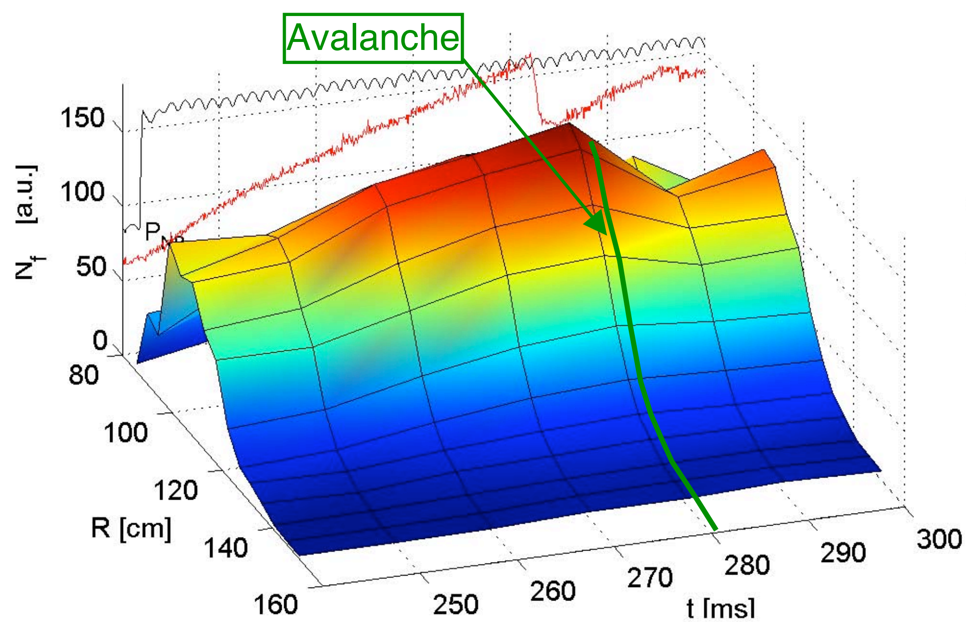
D. Darrow, E. Fredrickson

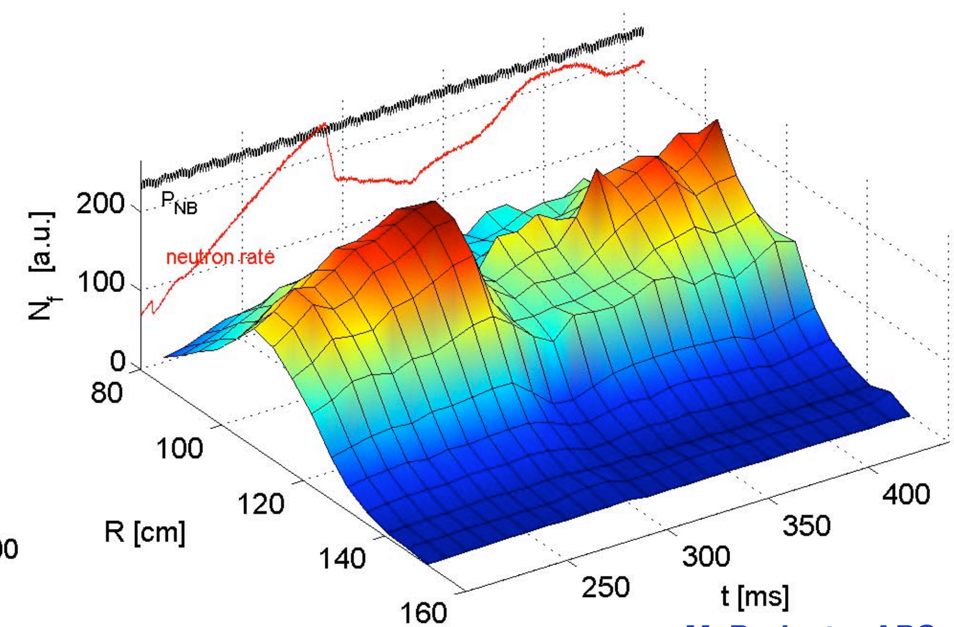
MHD Instabilities Affect Confinement of Fast Ions

- **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**





M. Podesta, APS

NSTX is Exploring and Developing Lithium-Coated Plasma Facing Components

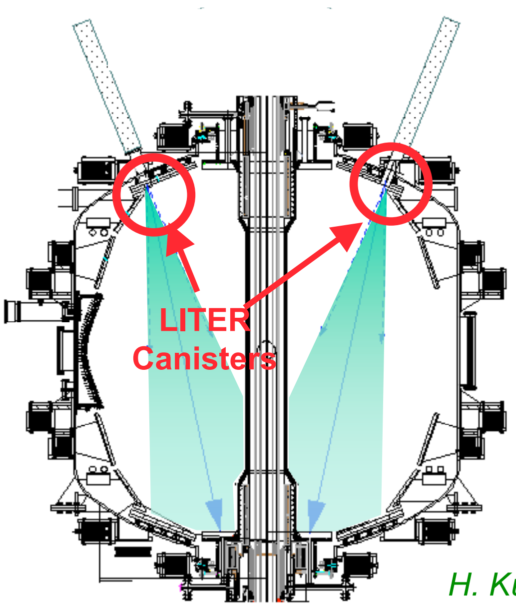
2005: Injected lithium pellets, 2 - 5 mg, into He discharges prior to D NBI shot

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

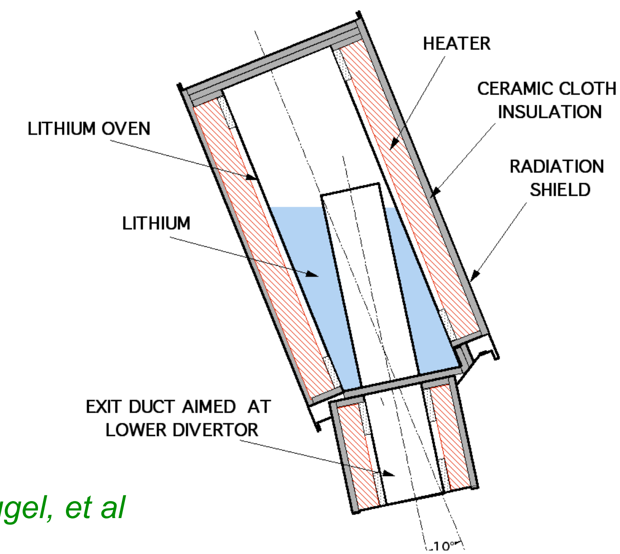
2007: Enlarged nozzle, re-aimed at lower divertor to increase deposition rate

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

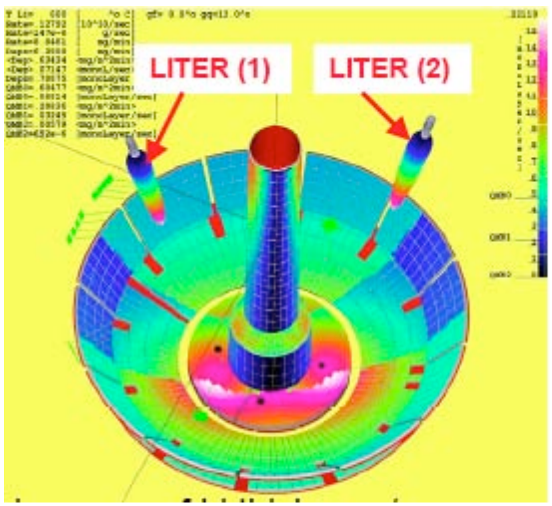
– Also used "lithium powder dropper" to introduce lithium through SOL



H. Kugel, et al

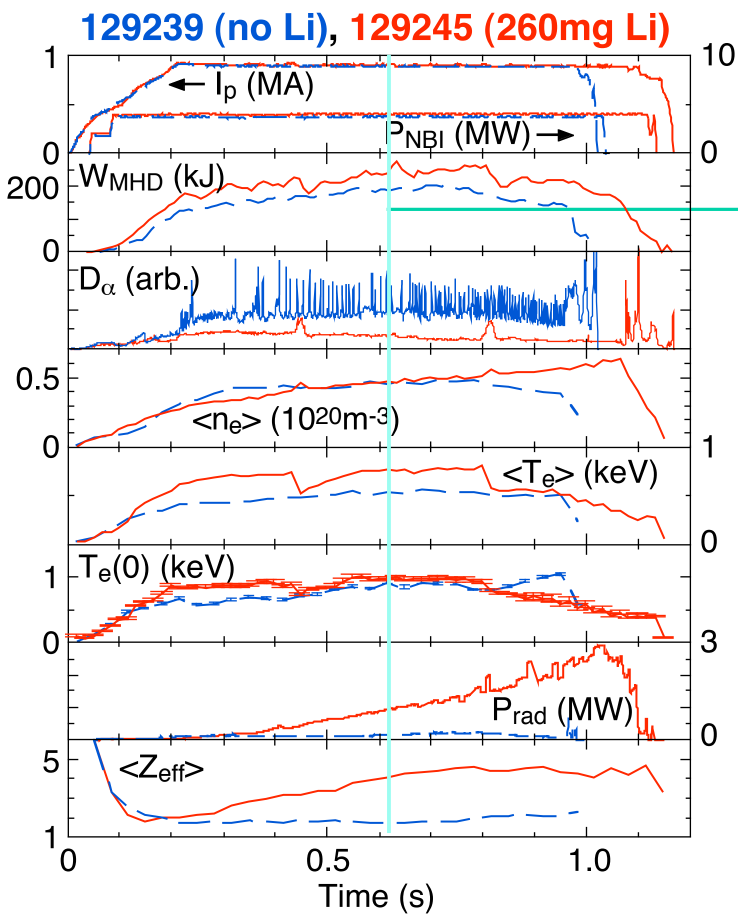


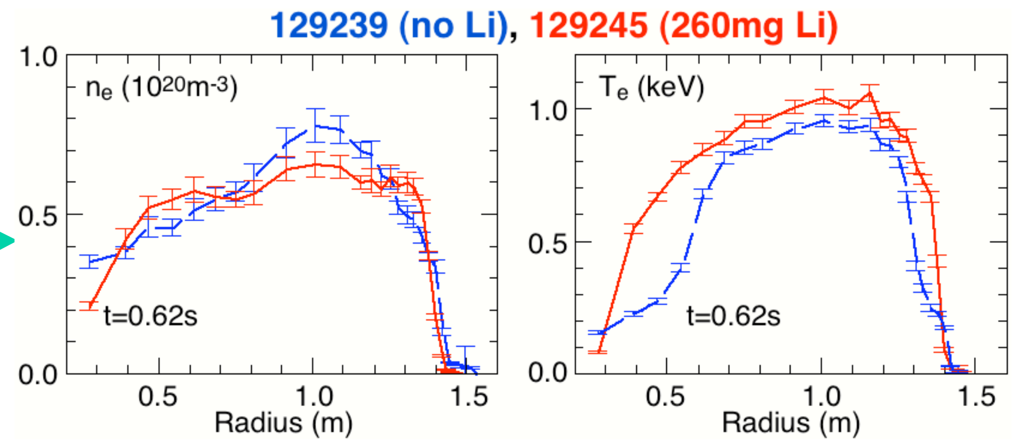
Modeled deposition pattern

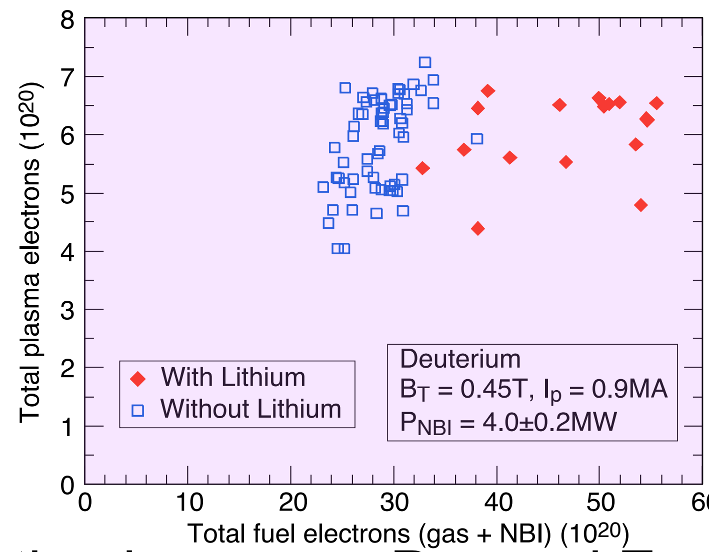


L. Zackharov

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



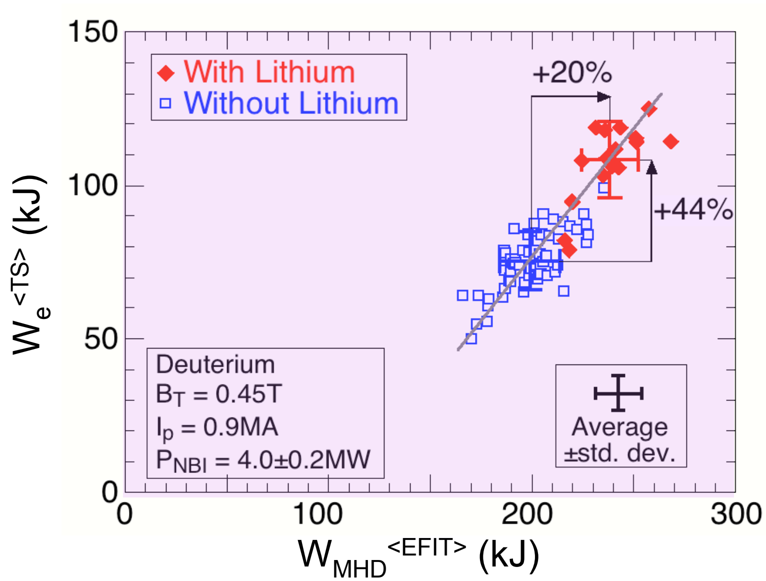


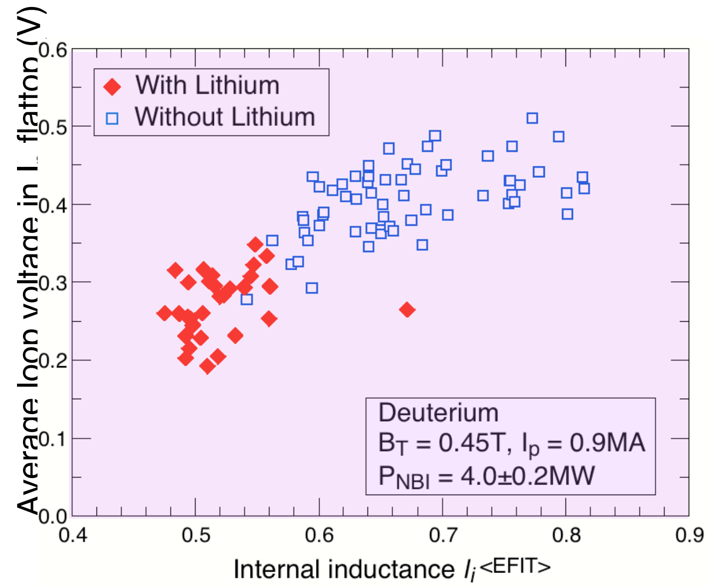


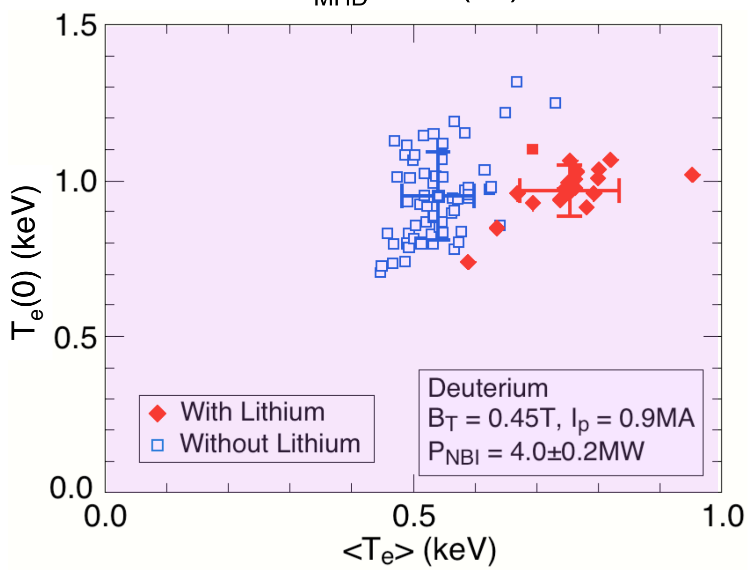
- Without ELMs, impurity accumulation increases P_{rad} and Z_{eff}

H. Kugel

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

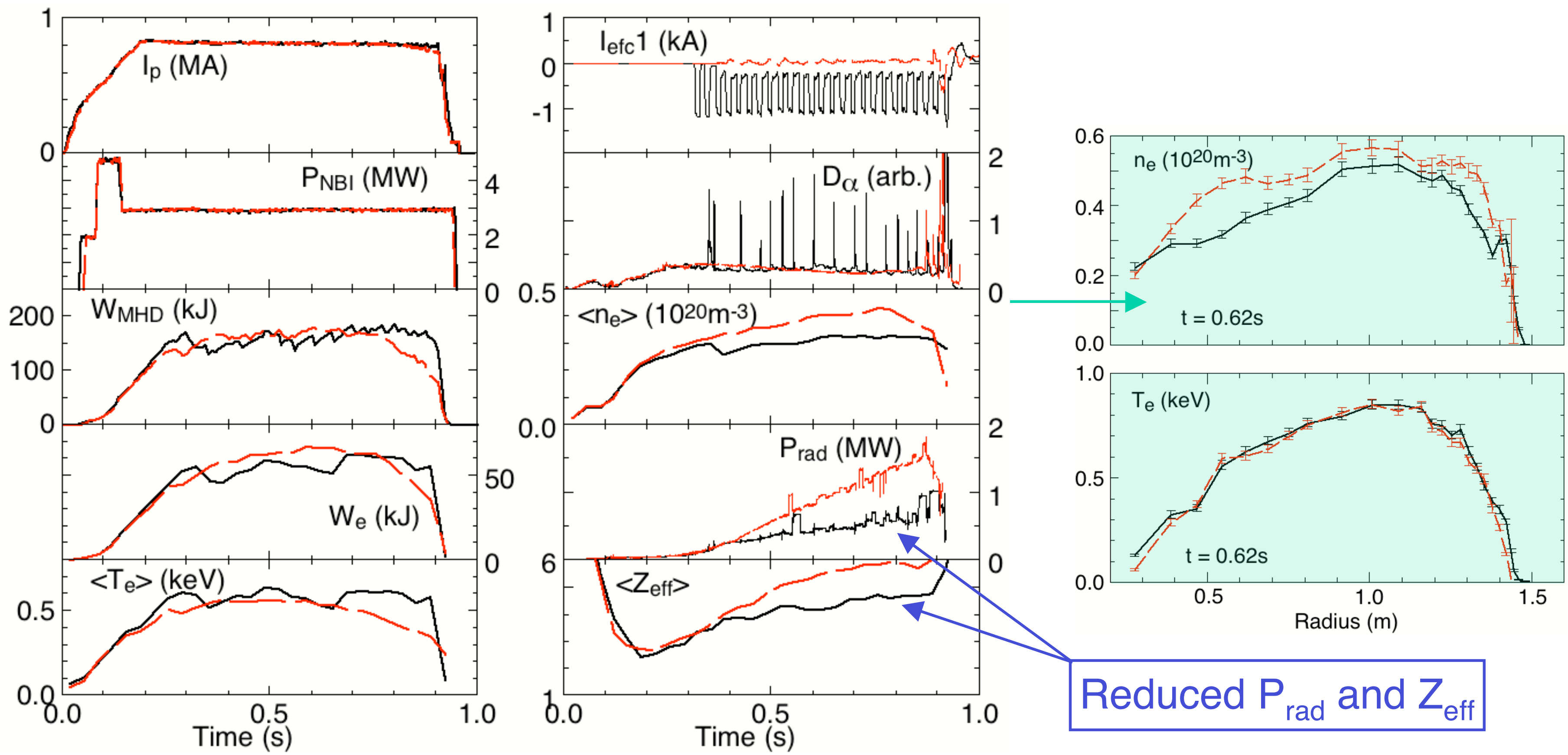






- **Broader electron temperature profile reduces internal inductance l_i and inductive flux consumption in current flattop, despite higher Z_{eff}**
- **Lithium increases edge bootstrap current through higher p', lower collisionality**

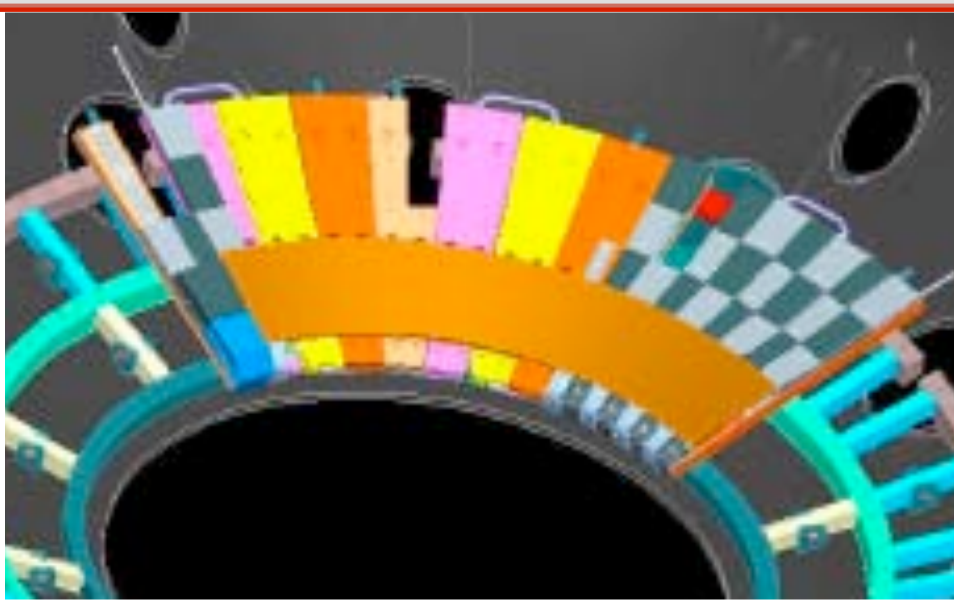
Midplane Radial-Field Control Coils Can *Induce* Repetitive ELMs in Lithium-Suppressed Plasmas



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

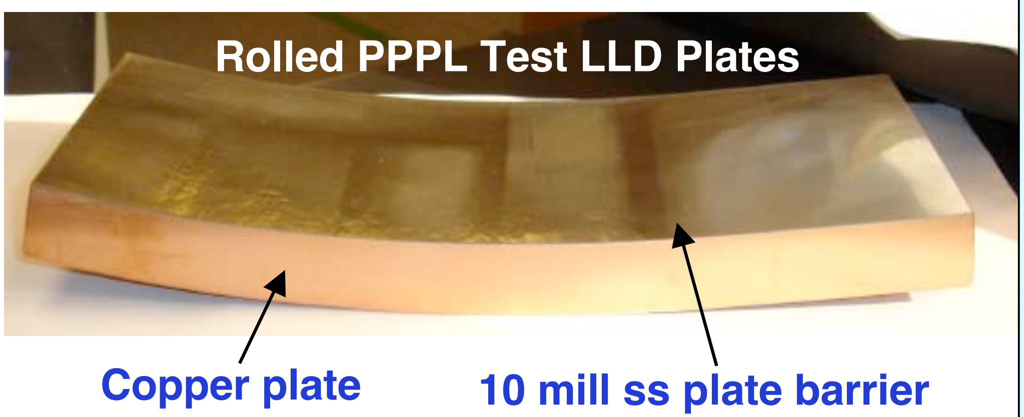
J. Canik

Liquid Lithium Divertor (LLD)



Liquid Lithium Divertor

- FDR for basic modules held 4/22/08
- SNL now procuring LLD Plates
- SNL preparing control system
- PPPL performing design, R&D and installation support
- PPPL preparing LLD diagnostics with university collaborations



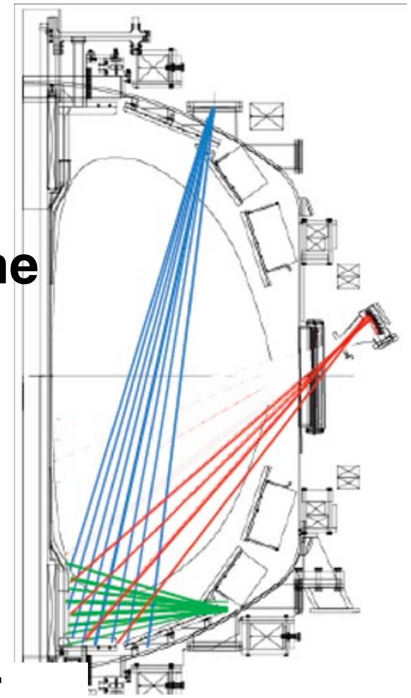
Issue: The delayed SNL LLD plate delivery schedule appears to match our mid-run schedule. However, there are some questions.

- NSTX is working on a back-up plan to manufacture them at PPPL
- LLD installation may shift toward summer time if delivery is delayed
- Perform LLD commissioning in September if the delivery is delayed

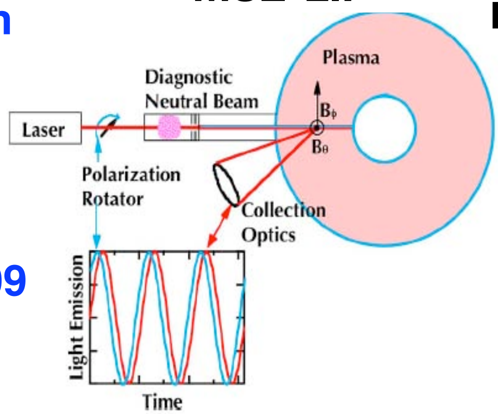
Diagnostic Upgrade Activities for FY 09

- **Divertor bolometer to strengthen divertor research**
  - Bay J upper installation to be installed in November
  - Full System should be ready for FY 09 Run
- **Edge Sample Probe to support FY 09 Joule Milestone**
  - Collaboration with Purdue University
  - The probe should be available for FY 09 Run
- **BES diagnostic**
  - BES viewing ports being installed / lens being procured
  - U. Wisconsin manufacturing detectors
  - Cable trays and diagnostic room being readied
  - Aiming to commission during the FY 09 run
- **MSE-LIF diagnostic**
  - MSE-LIF platform extension completed
  - PDR to held in Dec. 2008
  - Final installation planned in summer of 2009

Three-view divertor bolometer

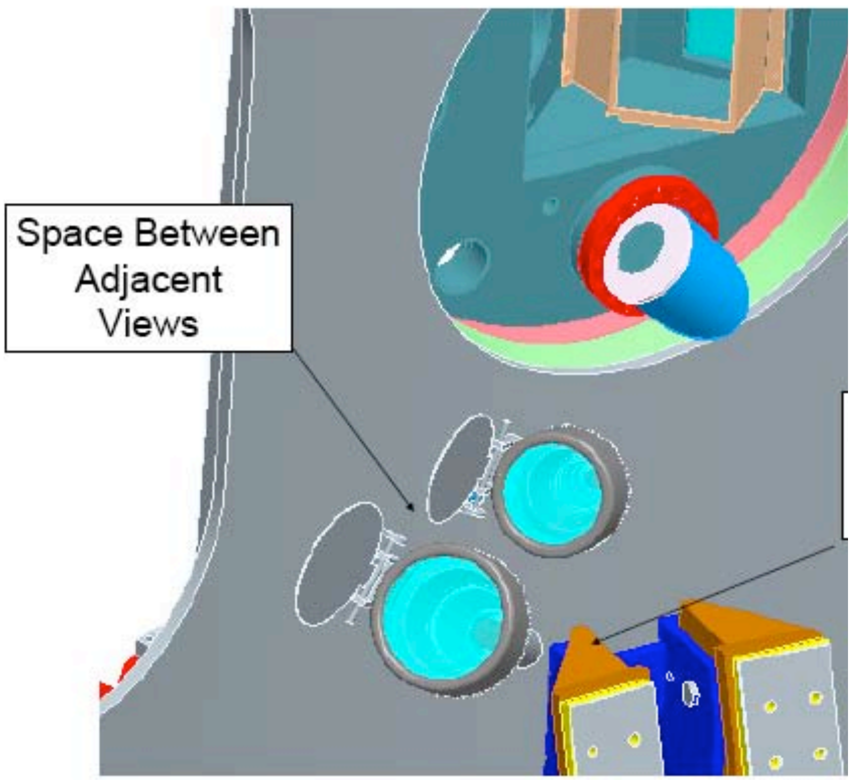


MSE-LIF



Platform Extension

Beam Emission Spectroscopy for FY 09

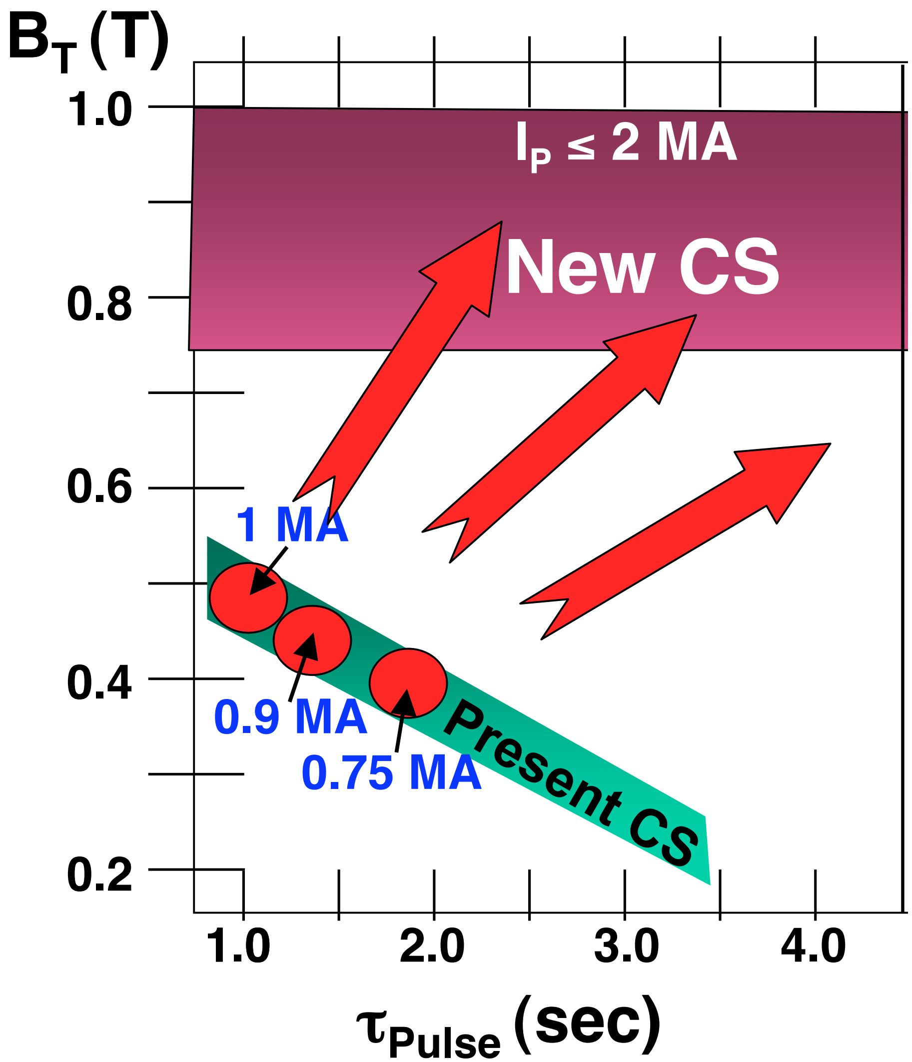


BES Ports Machining Set-up

BES diagnostic

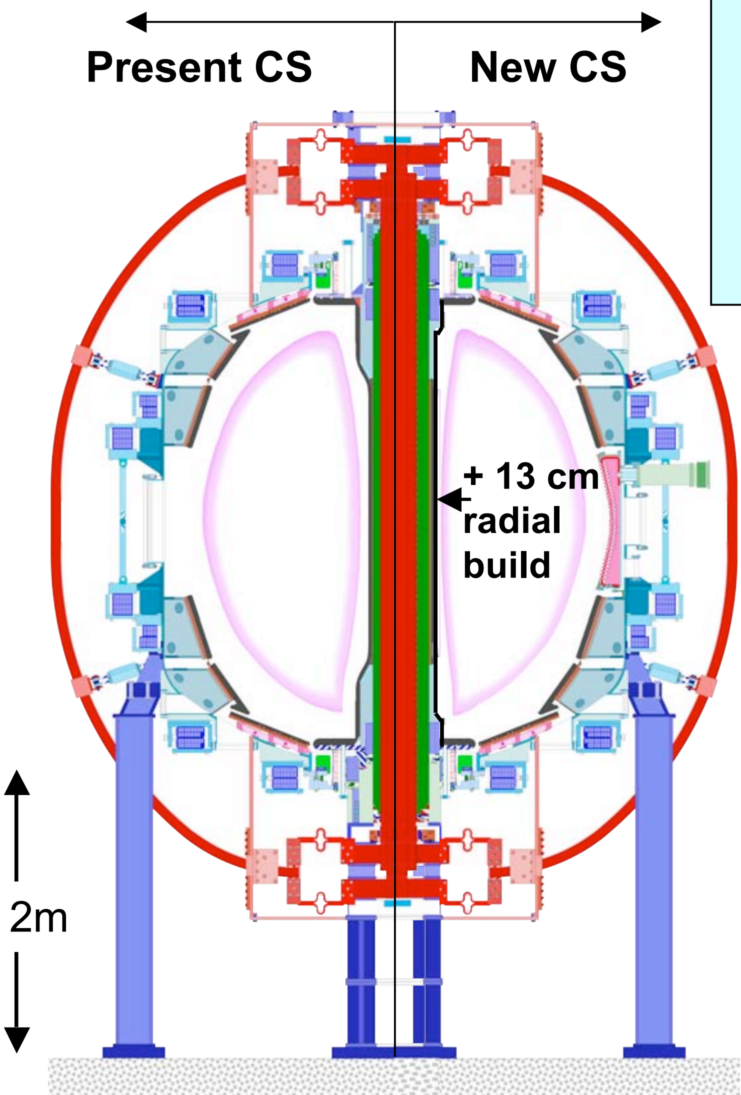
- BES viewing ports being installed / lens being procured
- U. Wisconsin manufacturing detectors
- Cable trays and diagnostic room being readied
- Aiming to commission in FY 09

New High-Performance Center-Stack will Expand Operational Space Toward Next-Step STs

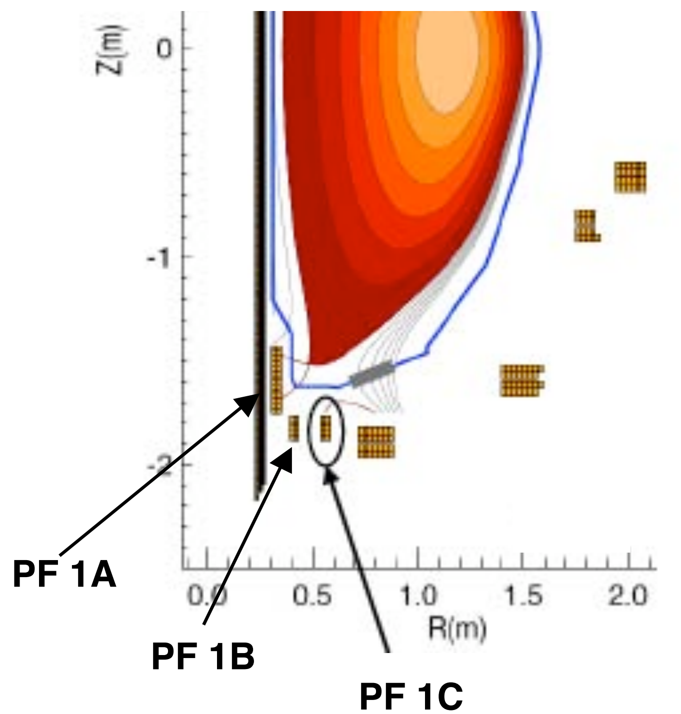


- Determine if the favorable ion and electron confinement scaling, and turbulence variation, observed in NSTX continues to higher magnetic fields and lower collisionality.
- Determine if the MHD stability of neoclassical tearing modes and resistive wall modes is favorable at lower collisionality and higher magnetic field.
- Using the higher magnetic field, which improves the efficiency of plasma heating and current drive both for RF and NBI, push further towards fully non-inductive start-up and current sustainment for long pulses.

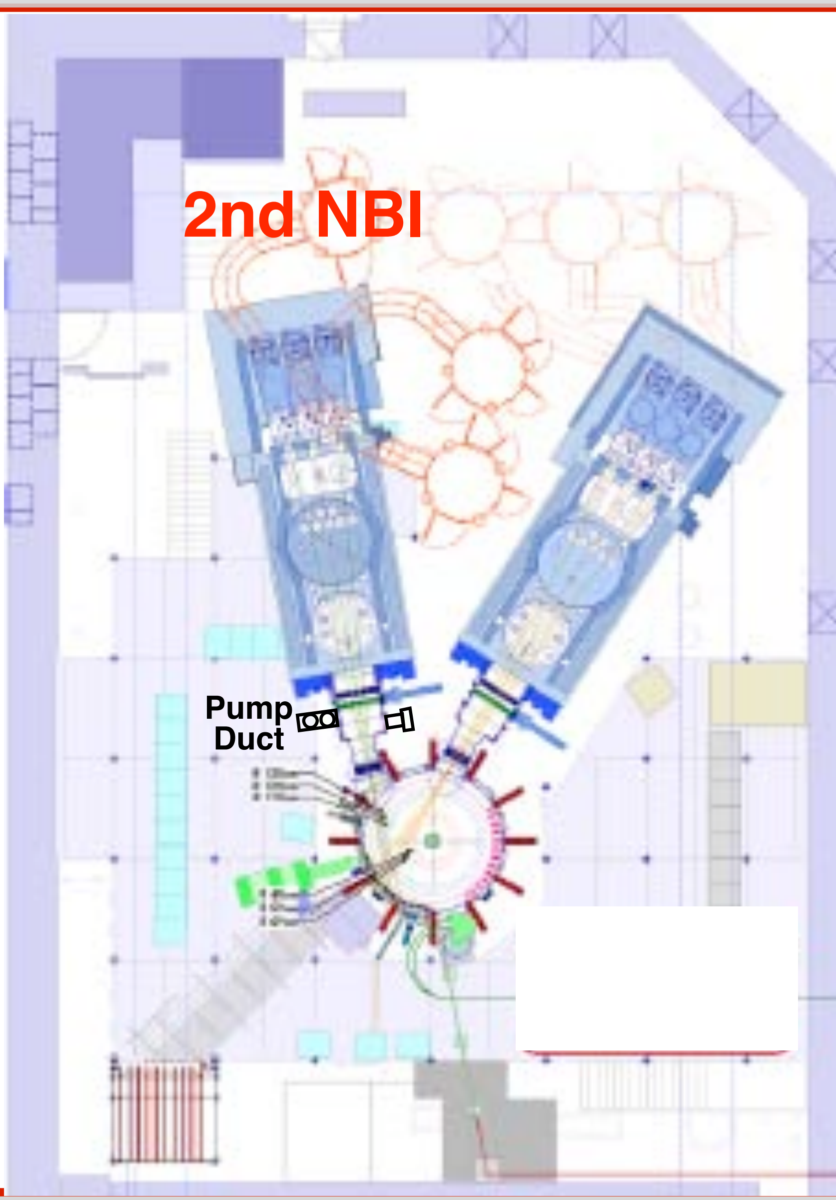
New Center Stack will Utilize Interchangeable Design but will Incorporate Additional Key Improvements



- Improved TF joint design to minimize lift off
- PF 1A, 1B, and 1C at both top and bottom for improved divertor control flexibility (e.g. very high expansion for X-divertor)
- Incorporate additional capabilities (e.g. pellet guide tube for inside launch)



Addition of Second NBI Will Produce Plasma Parameters Relevant for Next-Step STs

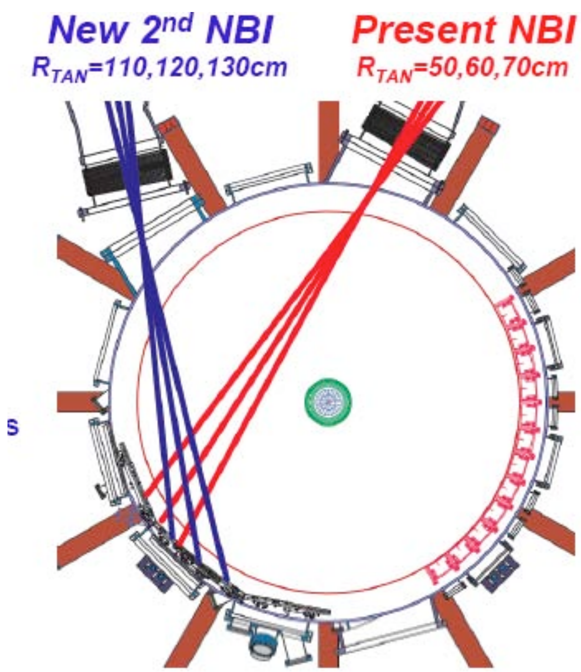


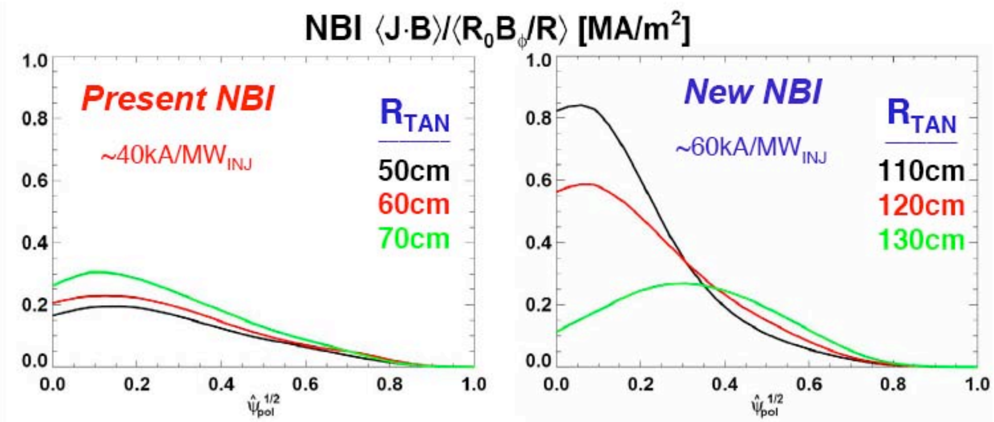
Greatly enhanced capabilities

- Doubles P_{NBI} from 7 to 14 MW (at 95 keV, 2s), 5 to 10 MW (at 80 keV, 5s)
- Higher CD Efficiency and j(r) control

- Extend Confinement scalings to higher power and plasma pressure, and lower collisionality, closer to next-step ST devices.
- Test Magneto-hydrodynamic stability at higher plasma pressure to explore the limits that could be encountered in future devices.
- Challenge the divertor in NSTX beyond the capabilities of any other device in the world (in terms of the scaling parameter, P/R)

More Tangential Injection Enables Profile Control and Fully-Non-Inductive Current-Drive Scenarios





P_{NBI}=2MW E_{NBI}=90keV, I_p=0.82MA, f_{GW}=0.58 $\overline{n}_e = 4.4 \times 10^{19} m^{-3}$, $\overline{T}_e$ = 1.2keV

- **Test predictions that more tangential injection increases beam current drive efficiency and can sustain a broadened and more MHD stable current profile.**
- **Increased Alfvén eigenmode activity and fast-ion redistribution/loss could result from more tangential injection and increased fast-ion pressure.**
- **Test plasma ramp-up using beam injection and demonstrate fully non-inductive sustainment to simulate the scenarios planned for future ST devices.**

NSTX is Assessing Potential of the ST for fusion

- FY 2008 run produced exciting results in all science topical areas:
  - EF/RWM feedback and Lithium produced record pulse length plasmas
  - High-k scattering revealed important ETG roles for electron transport
  - Progress made on momentum transport physics
  - Lithium impoved electron confinement, HHFW heating and EBW coupling
  - FIDA energetic particle diagnostic confirming energetic particle transport.
- NSTX is implementing cutting edge advanced diagnostics
  - 75 channel P-CHERS is yielding important results.
  - 32 channel BES system is being installed to complement high-k.
  - MSE-LIF will measure E_r and B_{total} for the first time.
- Upgrades will greatly expand the scientific capabilities of NSTX for next-Step STs:
  - Access and understand impact of reduced collisionality on ST physics at higher B_T and I_p with new center-stack
  - Access and understand impact of varied NBI deposition profile for fully non-inductive sustainment