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NSTX Recent Results and Plans

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Colorado Sch Mines
Columbia U
Comp-X
FIU
General Atomics
INL
Johns Hopkins U
Lehigh U
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LLNL
Lodestar
MIT
Nova Photonics
New York U
Old Dominion U
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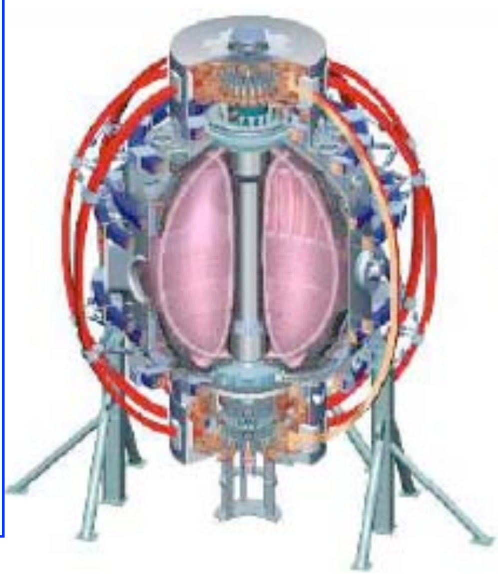
Think Tank, Inc.
UC Davis
UC Irvine
UCLA
UCSD
U Colorado
U Maryland
U Rochester
U Washington
U Wisconsin

Masayuki Ono and the NSTX Team

49th APS-DPP Annual Meeting
November 12 - 16, 2007
Orlando, Florida

Culham Sci Ctr
York U
Chubu U
Fukui U
Hiroshima U
Hyogo U
Kyoto U
Kyushu U
Kyushu Tokai U
NIFS
Niigata U
U Tokyo
JAEA
Ioffe Inst
RRC Kurchatov Inst
TRINITI
KBSI
KAIST
POSTECH
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
IPP AS CR



NSTX Addresses Key Issues for Plasma Science, Fusion Energy Development and ITER Physics

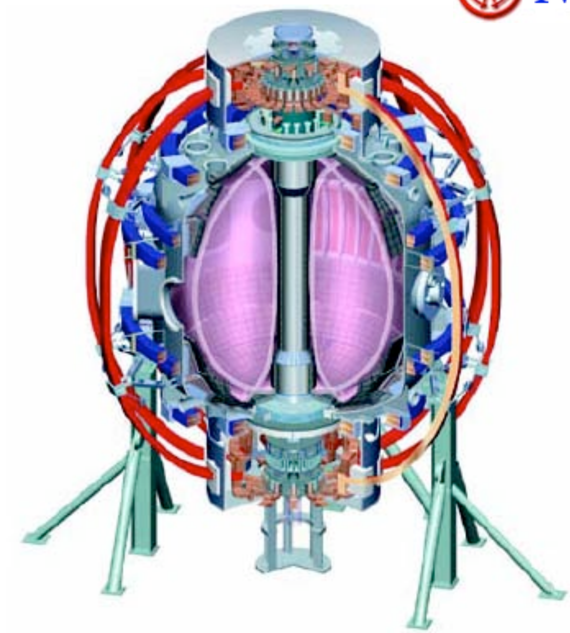
NSTX

- **Determine the physics principles of Spherical Torus (ST) confinement**

- **Complement and extend conventional aspect ratio tokamaks**

- **Explore attractive configurations for a Component Test Facility (CTF) and Demonstration Power Plant**

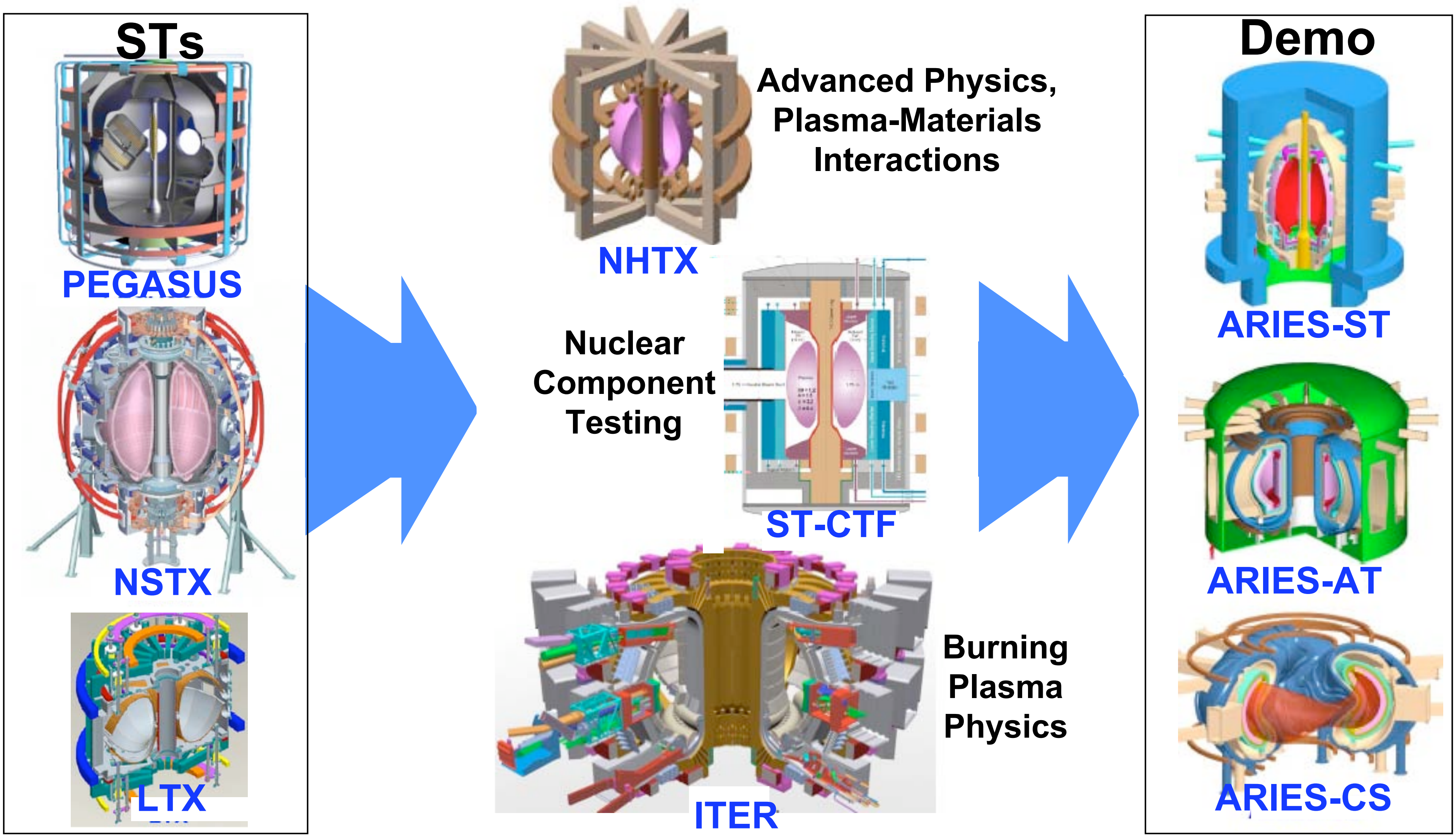
- **Support preparation of burning plasma research in ITER**
  - **Participate in the ITPA and USBPO**



Major Radius R_0	0.85 m
Aspect Ratio A	1.3
Elongation κ	2.8
Triangularity δ	0.8
Plasma Current I_p	1.5 MA
Toroidal Field B_T	0.55 T
Pulse Length	1.5 s
NB Heating (100 keV)	7 MW
$\beta_{T,tot}$	up to 40%

NSTX Research Program Contributes Strongly to US and World Fusion Development

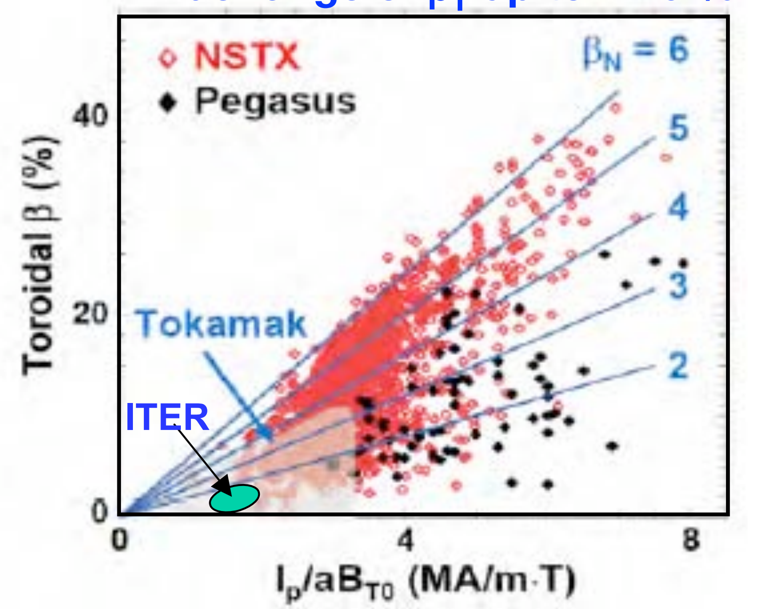
ST offers compact geometry + high β for attractive fusion applications



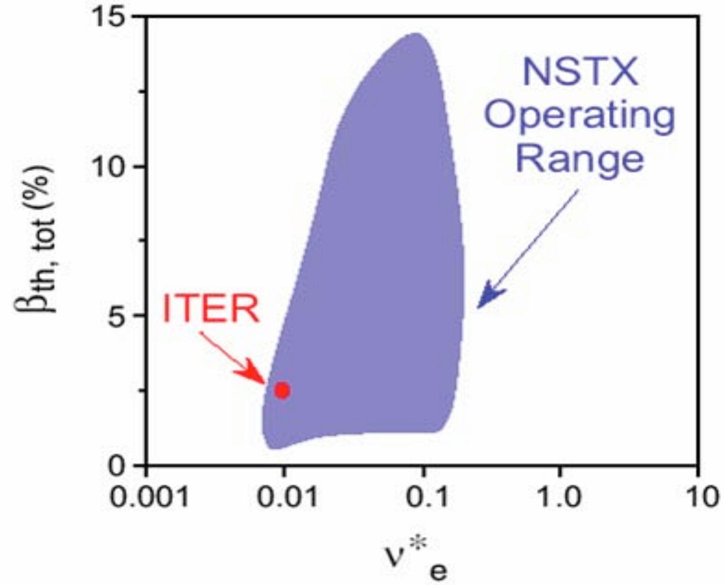
NSTX Offers Access to Wide Tokamak Plasma Regimes

NSTX

Wide range of β_T up to ~ 40 %

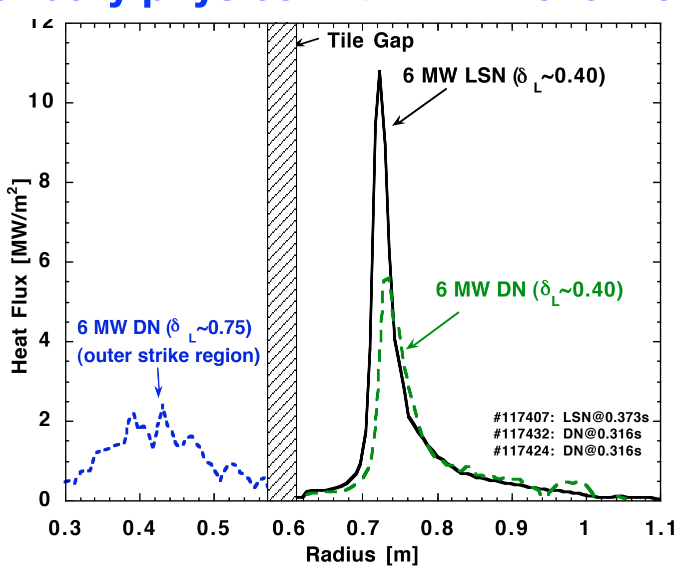


β Confinement Scaling, Electron Transport

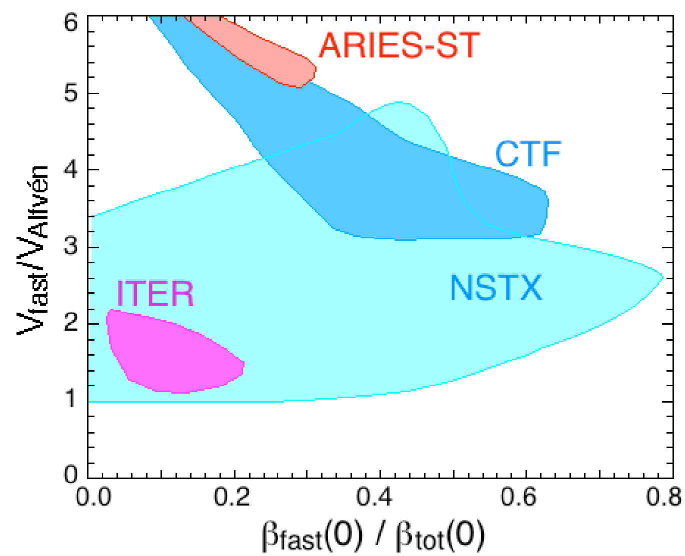


- Confinement scaling with wide range of β_T up to ~ 40 %

Boundary physics with ITER-level heat flux



Unique Energetic Particle Physics



- Full set of diagnostics: including MSE for j(r)

NSTX has Comprehensive and Powerful Set of Scientific Capabilities

NSTX

MHD : Passive stabilizers and Advanced EF/RWM mode stabilization tools and diagnostics

Multi-scale transport: High-k + MSE + $\chi_I \sim \chi_{i\text{-}neo} \rightarrow$unique opportunity for understanding transport & turbulence

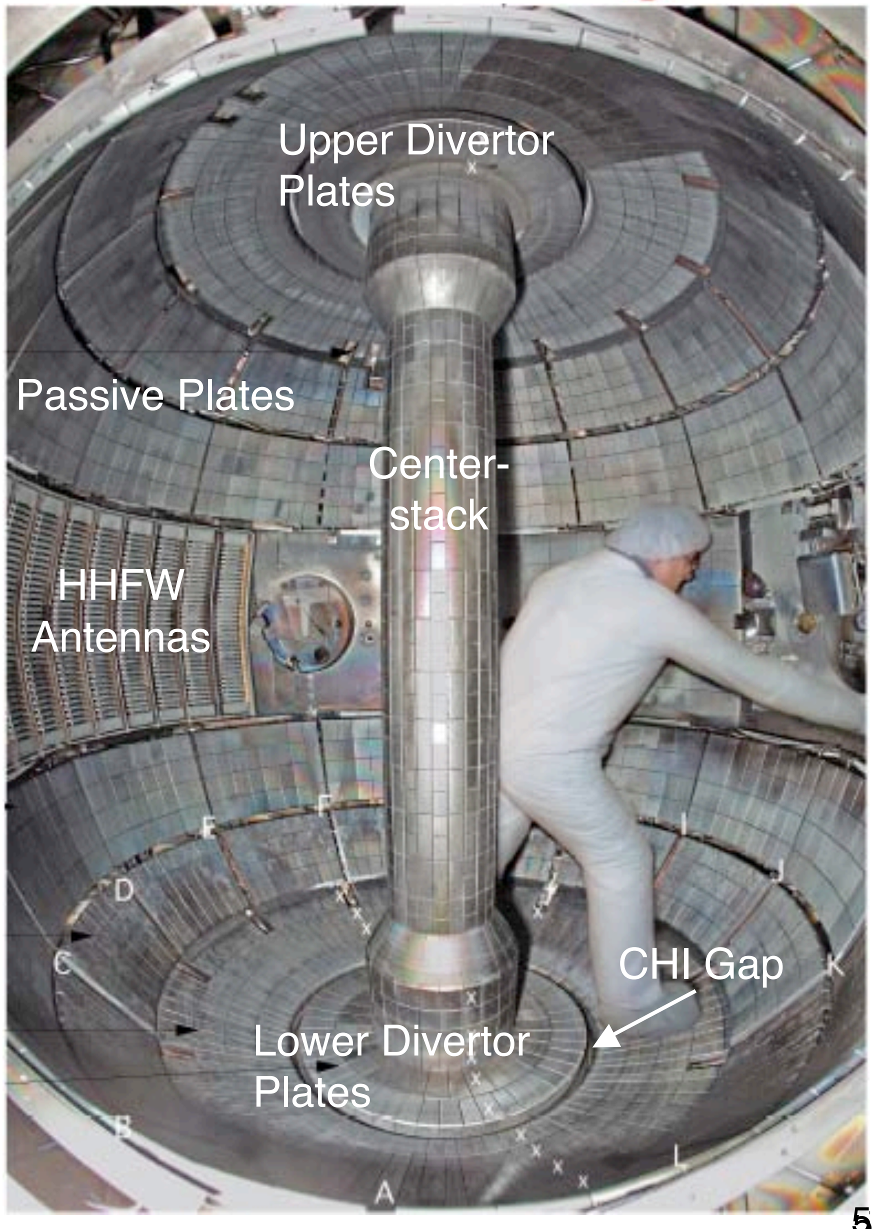
Waves: Developing unique HHFW and EBW heating and current drive tools essential for ST, useful for AT

Energetic Particles: Uniquely able to mimic multi-mode ITER fast-ion instability drive with full profile and energetic particle / mode diagnostics

Boundary Physics: High ITER-like power flux, Unique Li research,broad ITER and NHTX/ST-CTF-relevant boundary physics research

Integration: Most capable ST in world for developing high-non-inductive fraction, high β plasmas

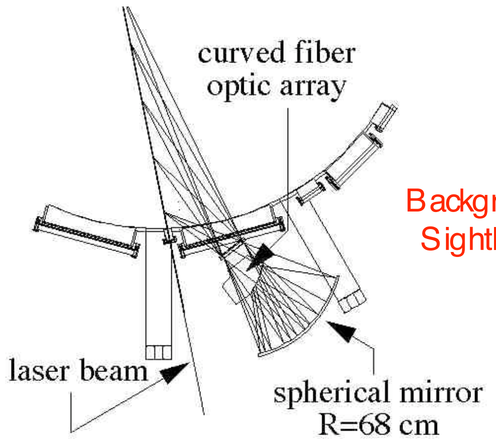
Solenoid-free Start-up Developing unique plasma start-up and ramp-up research crucial to ST concept, useful for AT



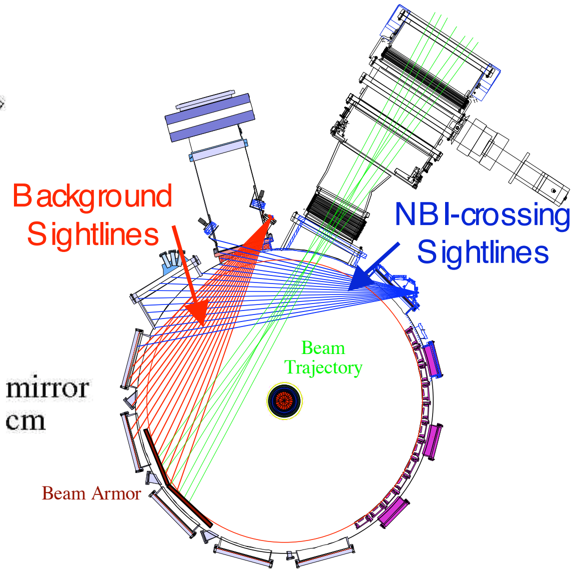
Highly Accessible Plasmas - Unique Diagnostics

NSTX

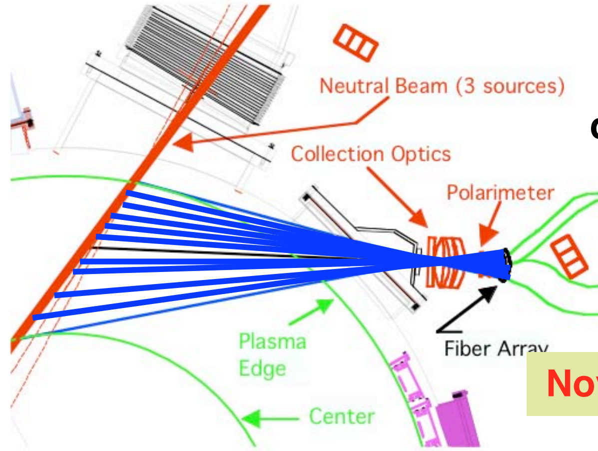
30 Ch, 60Hz MPTS for $T_e(r)$, $n_e(r)$



51 Ch CHERS for $T_i(r)$, $V_\phi(r)$

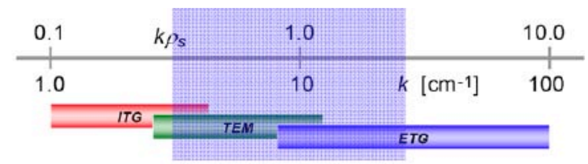


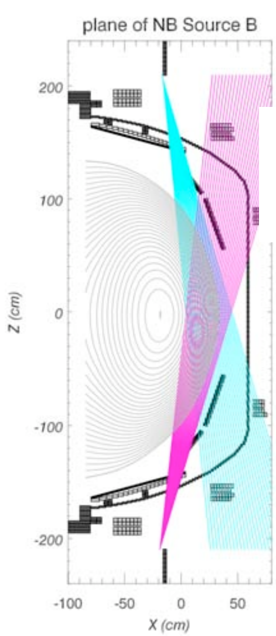
16 Ch MSE for q(r) (19 ch planned)



Innovative design enables MSE in kG range for the first time

Nova Photonics





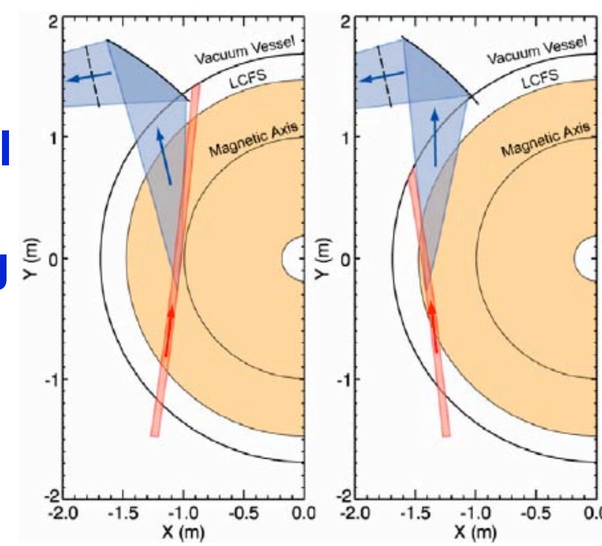
27 Ch (70 next year) Poloidal CHERS for $V_p(r)$

Fast Ion D-Alpha Camera using P-CHERS views

UC Irvine

Tangential High-k Scattering (3 MHz)

UC Davis

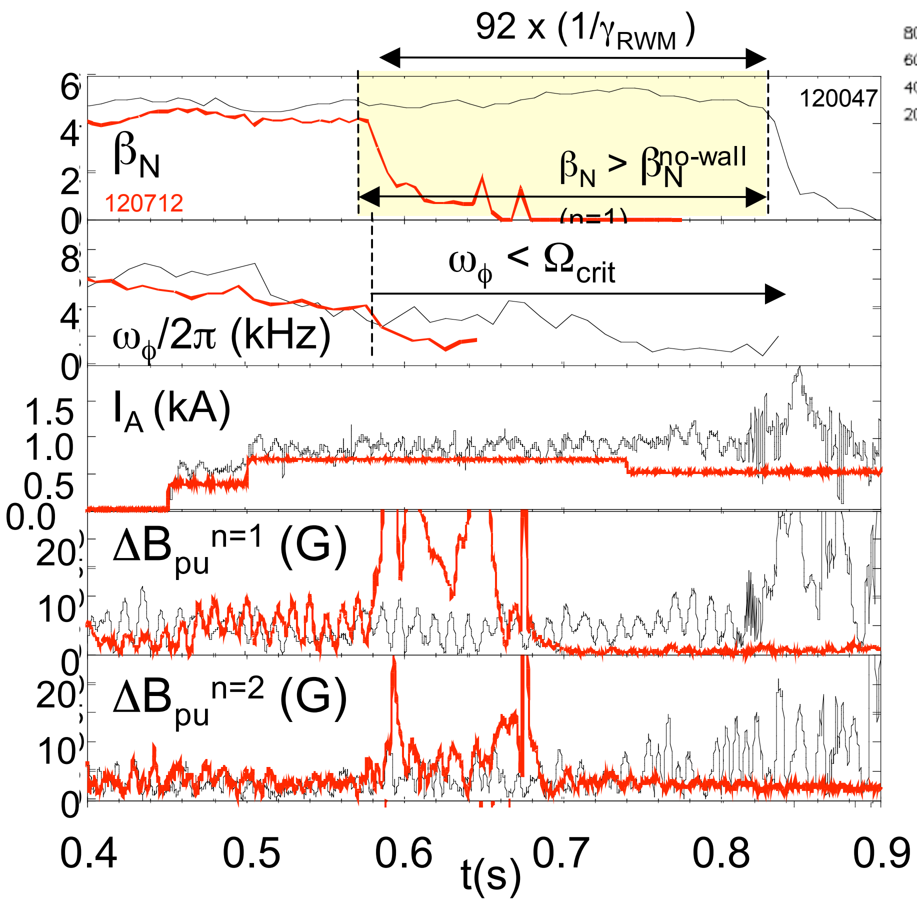


Significant Progress in All Science Areas

NSTX

- **MHD:** Demonstrated RWM feedback stabilization at low rotation at very high beta-N of 5.5 and discovered importance of n>1 error field for the first time.
- **T&T:** Measurements made on electron, particle, and momentum transport and electron scale turbulence.
- **Energetic Particles:** A complete power scan made on the AE stability and associated multi-mode burst fast ion redistribution, the beta dependence of the Alfvén Cascades/GAM coupling confirmed and "β-induced Alfvén-acoustic eigenmodes" at high β discovered.
- **Waves:** HHFW and EBW coupling efficiency improvements were obtained by controlling the edge plasma parameters.
- **Boundary Physics:** A lithium evaporator used to enhance confinement and particle pumping, improved understanding of the edge turbulence behavior through measurements and modeling obtained, and reduced and elucidated divertor heat flux thorough partial detachment demonstrated.
- **Solenoid-free Startup:** OH coupled to CHI generated plasmas for the first time.

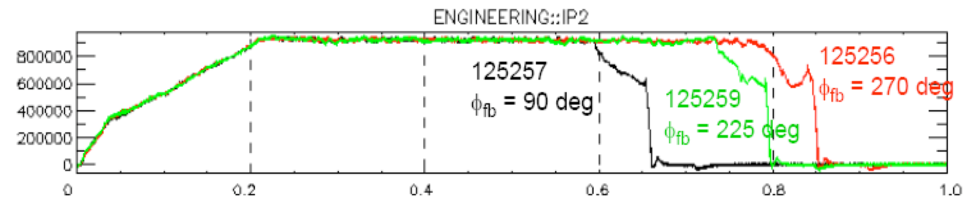
Low aspect ratio, high β provides high leverage to uncover key tokamak physics (e.g. RWM control, rotation damping, high elongation)



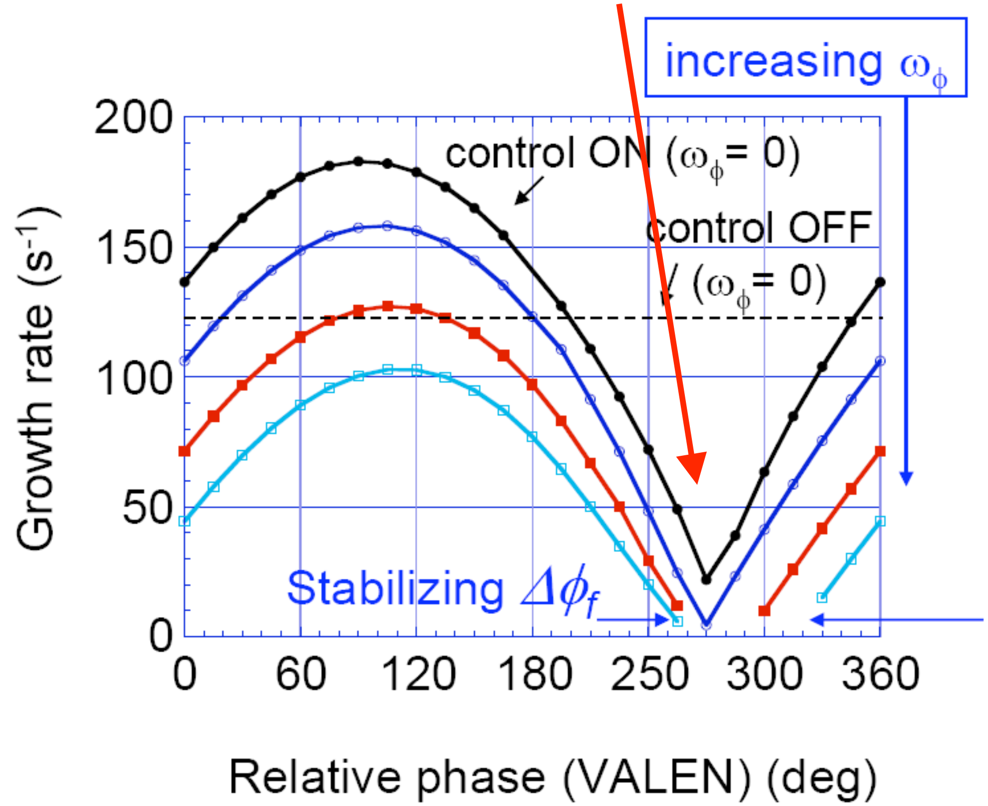
RWM actively stabilized at ITER-relevant rotation for ~ 90/γ_{RWM}

Columbia U

(S. Sabbagh, et al., CO3, APS)



•Optimal 270° phase difference between mode B_P and applied B_R consistent with **VALEN**

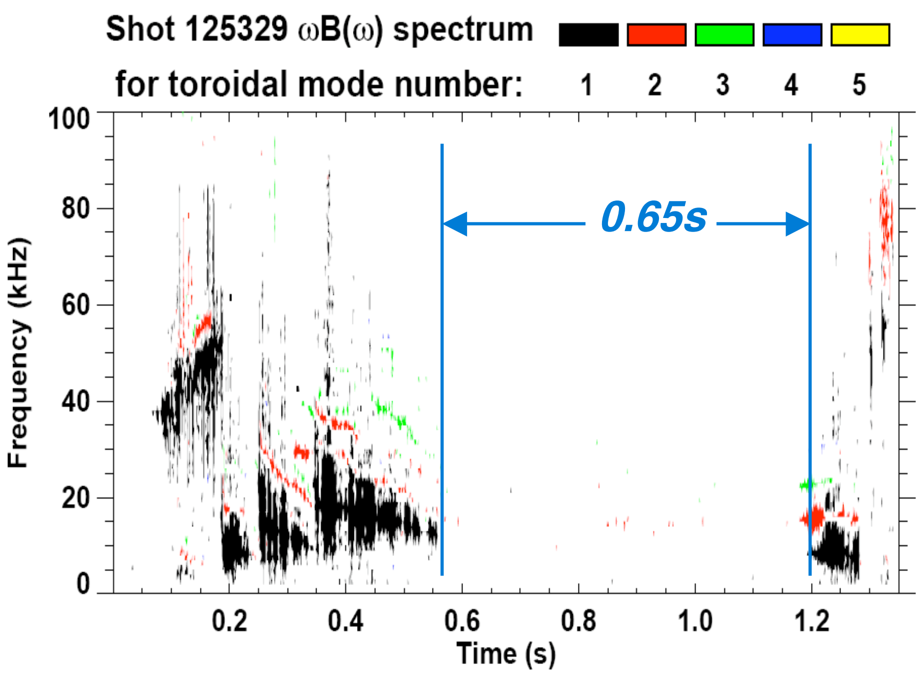


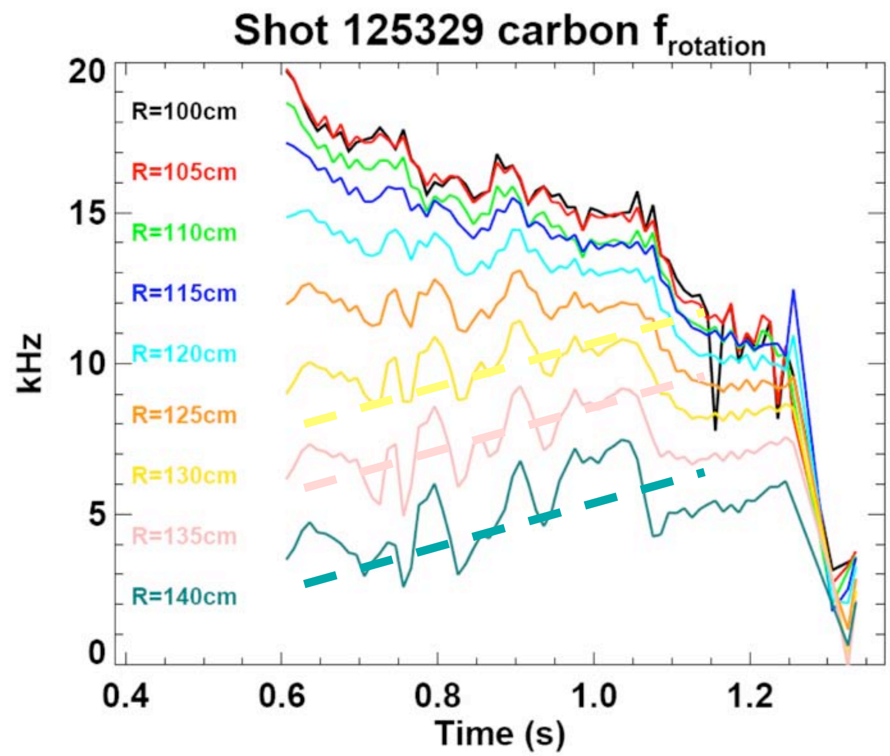
Simultaneous n=1 and n=3 Error Field Correction Reduce Low-f MHDs and Improves Plasma Performance

NSTX

Active feedback control of n=1 RFA + pre-programmed n=3 correction

- Long period free of core low-f MHD activity
- Plasma rotation sustained over same period
- Core rotation decreases with increasing density (fGW à 0.75), but…
- R > 1.2m rotation slowly increases until large ELM at t=1.1s
- A Record pulse-length at IP=900kA





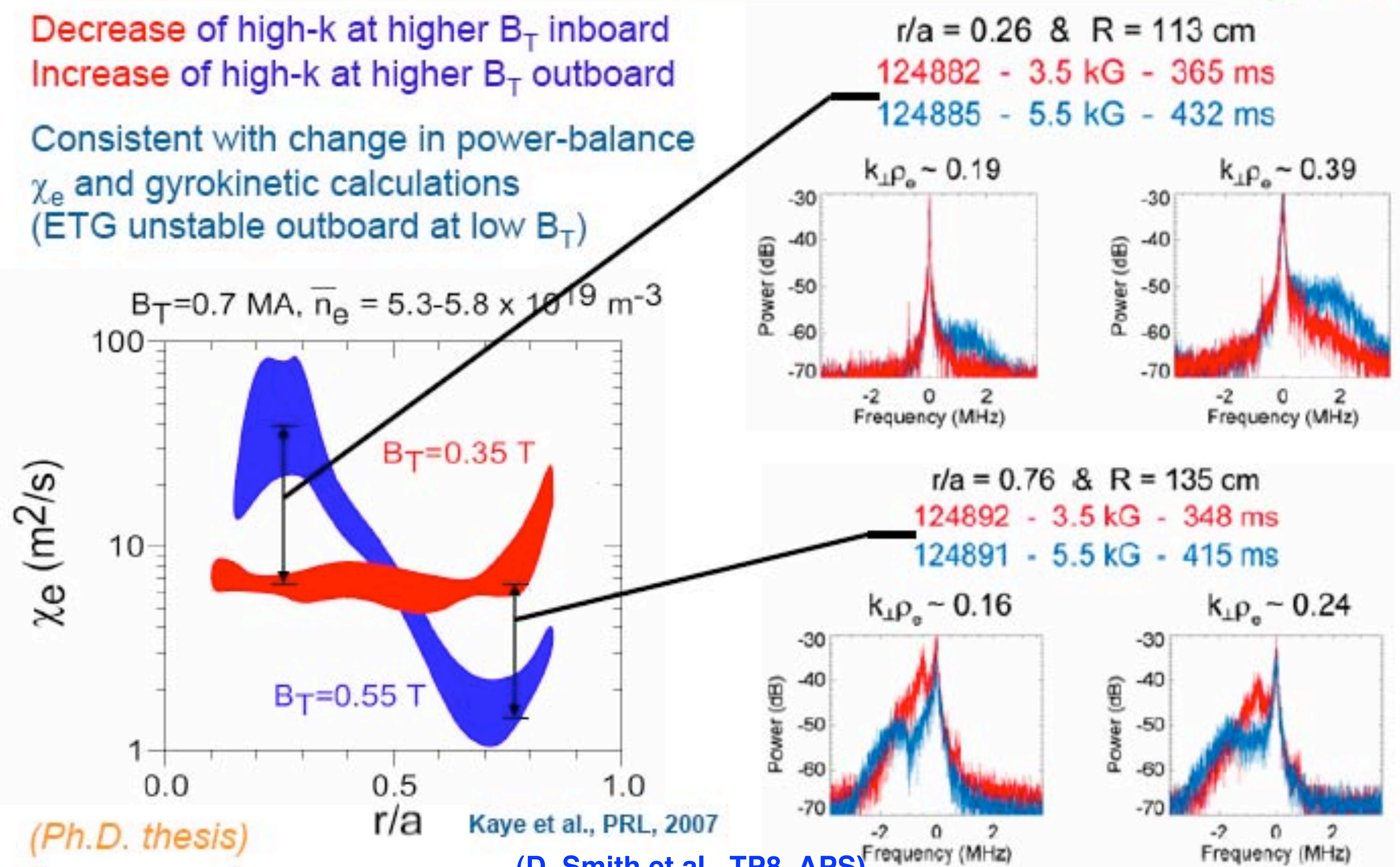
(J. Menard et al., UI1, J.K. Park, TP8, APS)

High-k Measurements to Elucidate Spatial Dependence of Strong Toroidal Field Scaling of Electron Transport in NSTX

NSTX

Decrease of high-k at higher B_T inboard
Increase of high-k at higher B_T outboard

Consistent with change in power-balance χ_e and gyrokinetic calculations (ETG unstable outboard at low B_T)

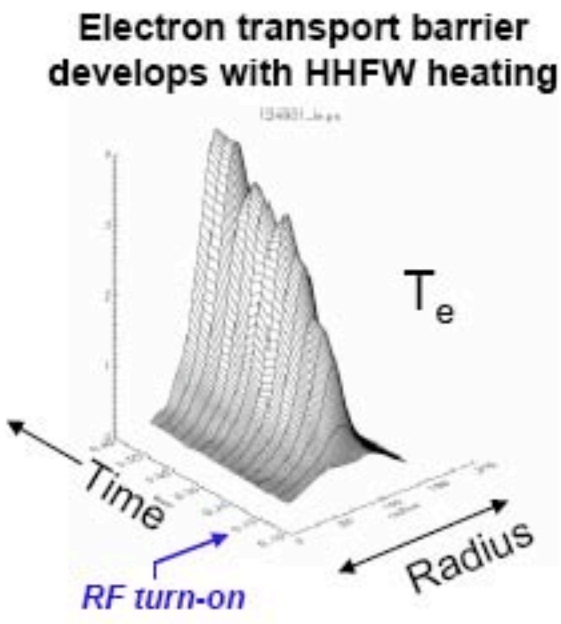


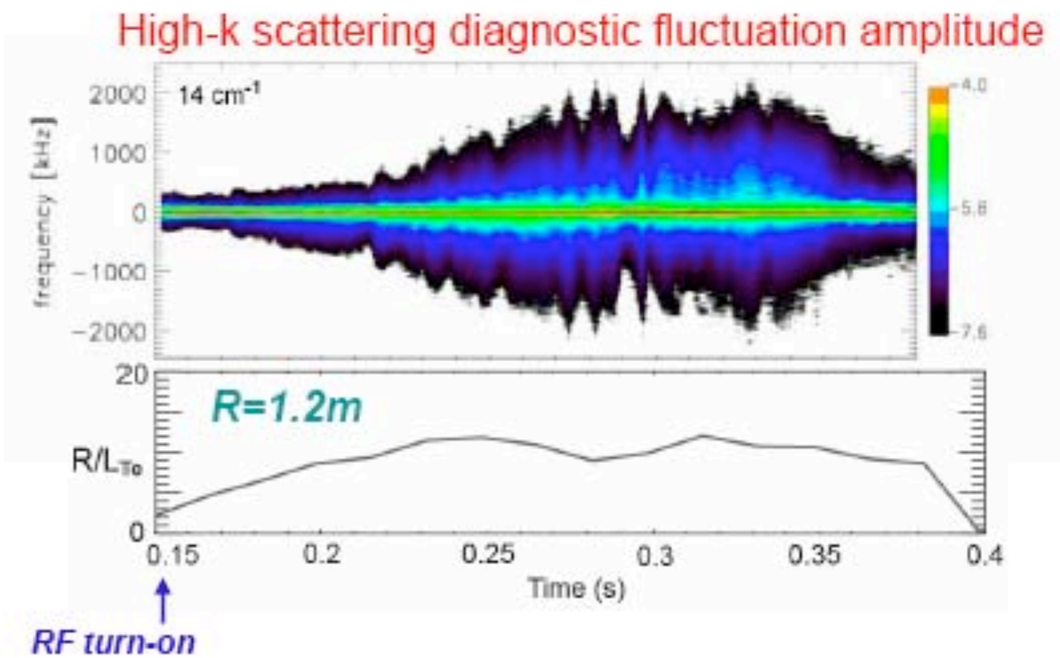
(Ph.D. thesis)

Kaye et al., PRL, 2007

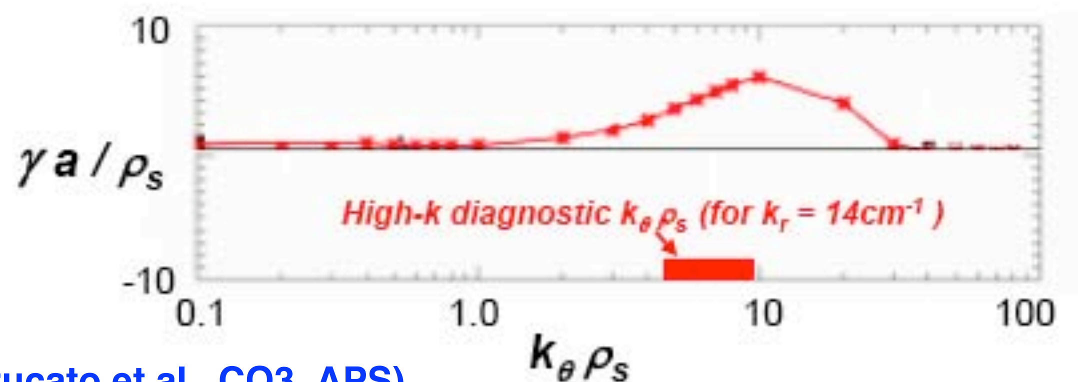
(D. Smith et al., TP8, APS)

Temporal Evoluation of High-k Scattering Measurements Exhibits Broadening of Fluctuation Spectrum with R/L_{Te}





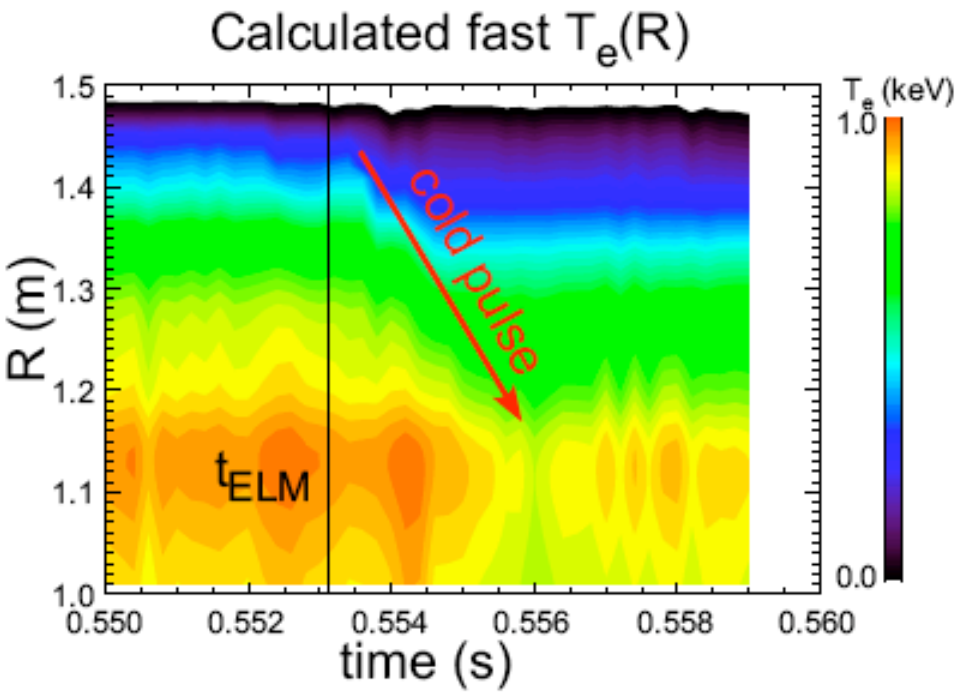
- Linear GS2 calculations indicate high-k mode (ETG) unstable at peak R/L_{Te}

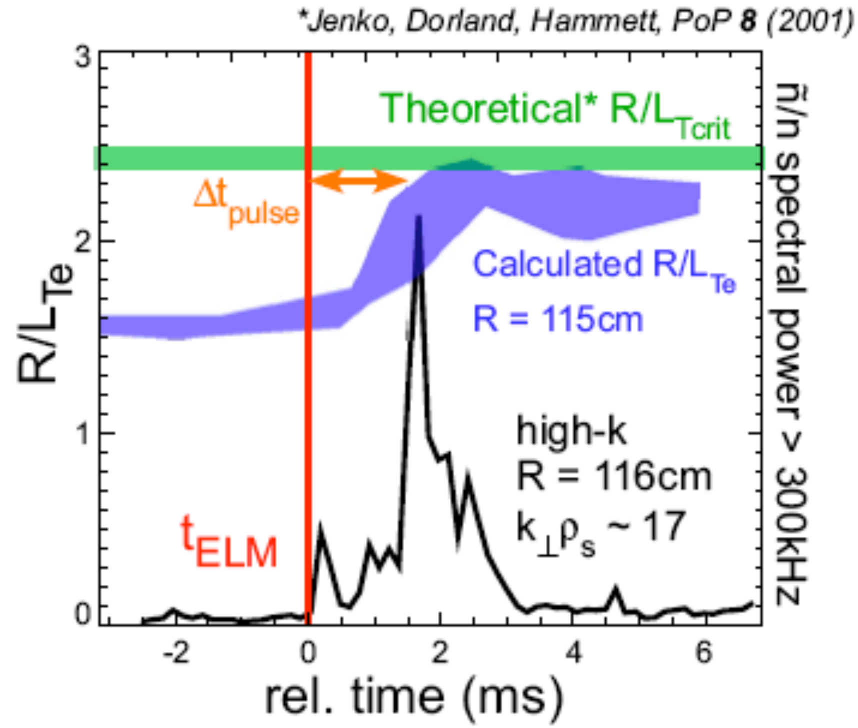


(E. Mazzucato et al., CO3, APS)

Core R/L_{Te} from ELM Induced Cold Pulse Can Reach R/L_{tcrit}

High-k Measurement and GS2 Code Support ETG Destabilization

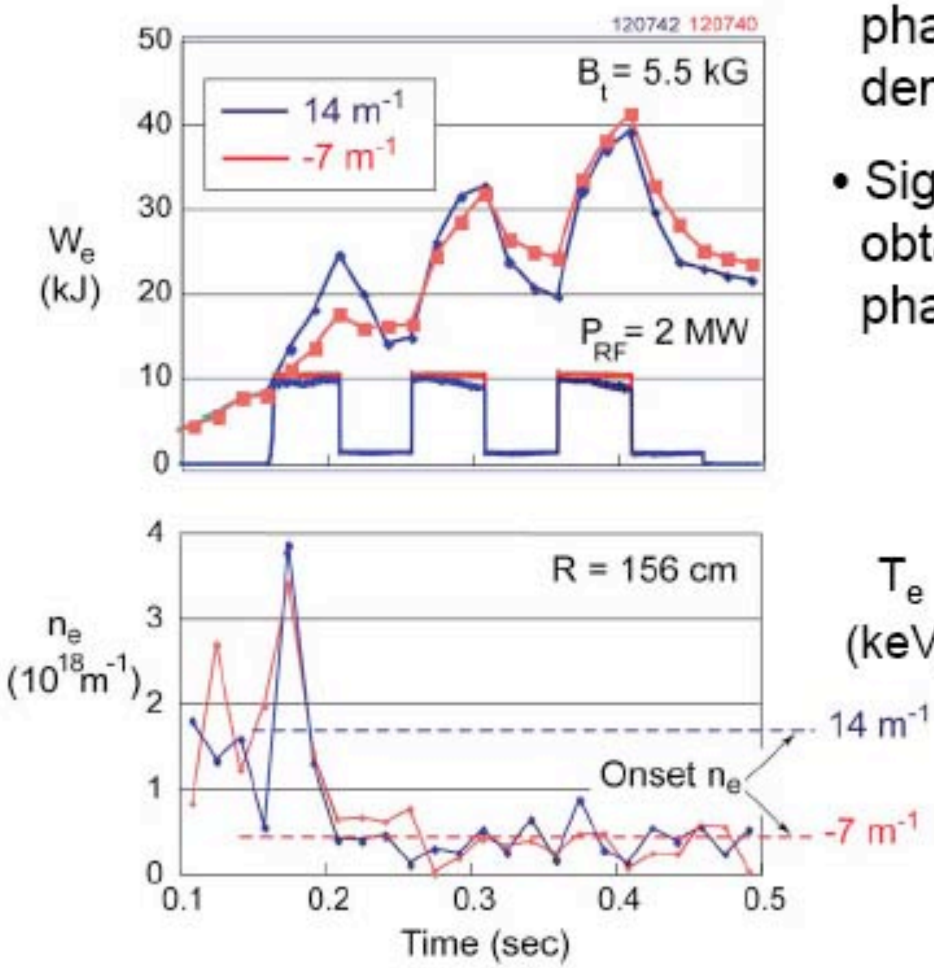




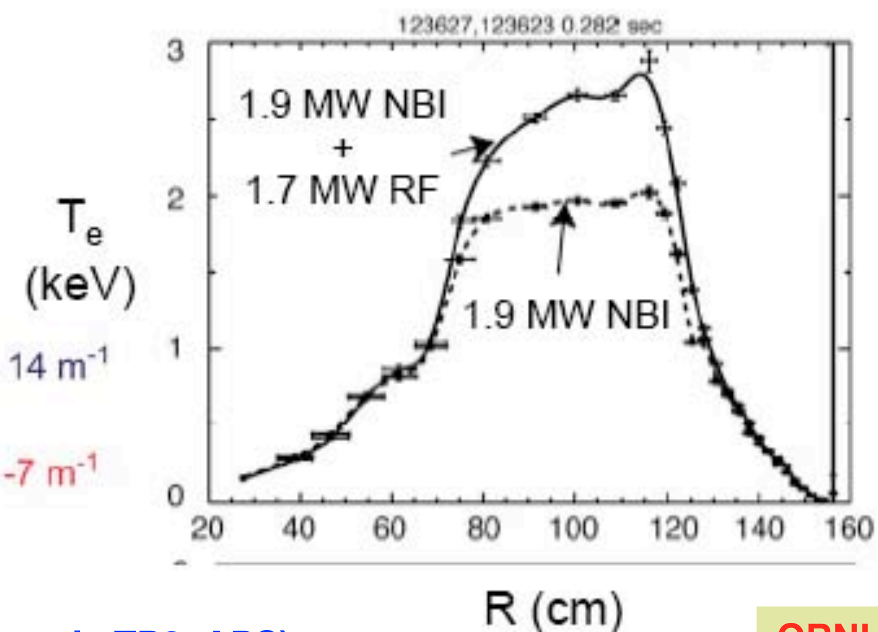
- Low steady-state Te gradient in core suggest stable ETG
- Core high-k measurements shows increased fluxtuations coincident with ELM induced cold pulse.
- Cold pulse increases Te gradient during core propagation
  - R/L_{Te} R/L_{Tcrit} supports ETG destabilization
  - Jenko et al. validated by GS2 $R/L_{tcrit\ calculation}$

Substantially Improved HHFW Coupling by Keeping Density Near Antenna Below Level Needed to Generate Surface Waves

NSTX



- Improved HHFW coupling for CD phasing obtained by lowering edge density **4.6 keV achieved with CD phase**
- Significant core electron heating now obtained in L-mode for CD antenna phasing during NBI at $B_t(0)$ = 5.5 kG

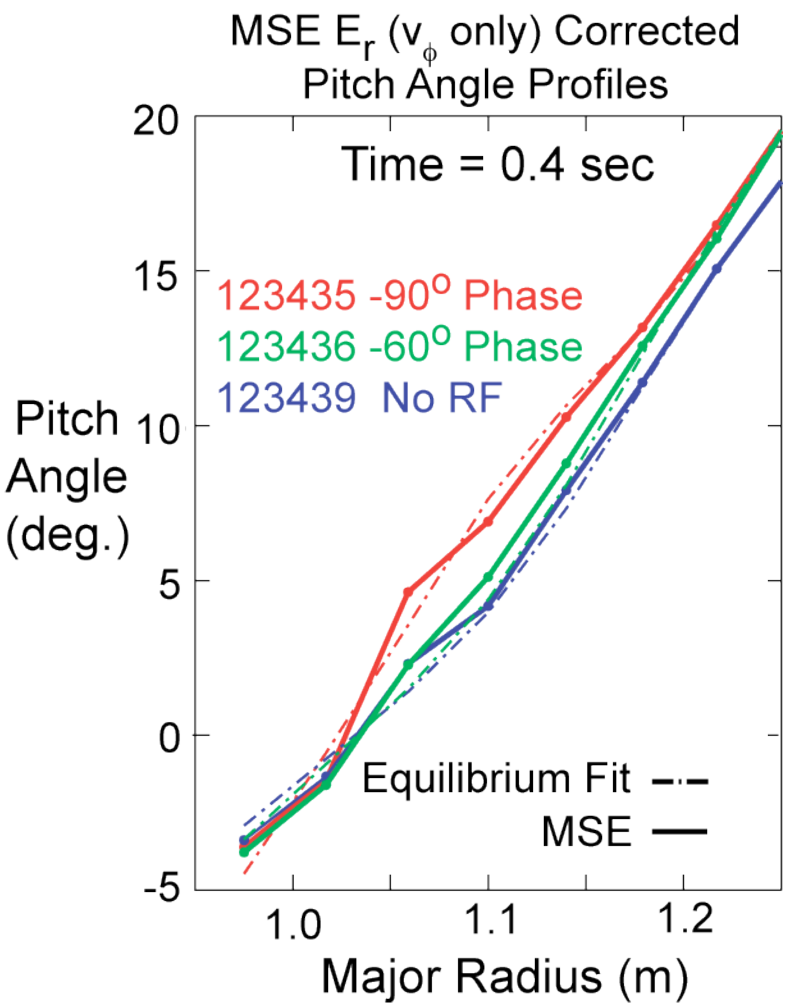


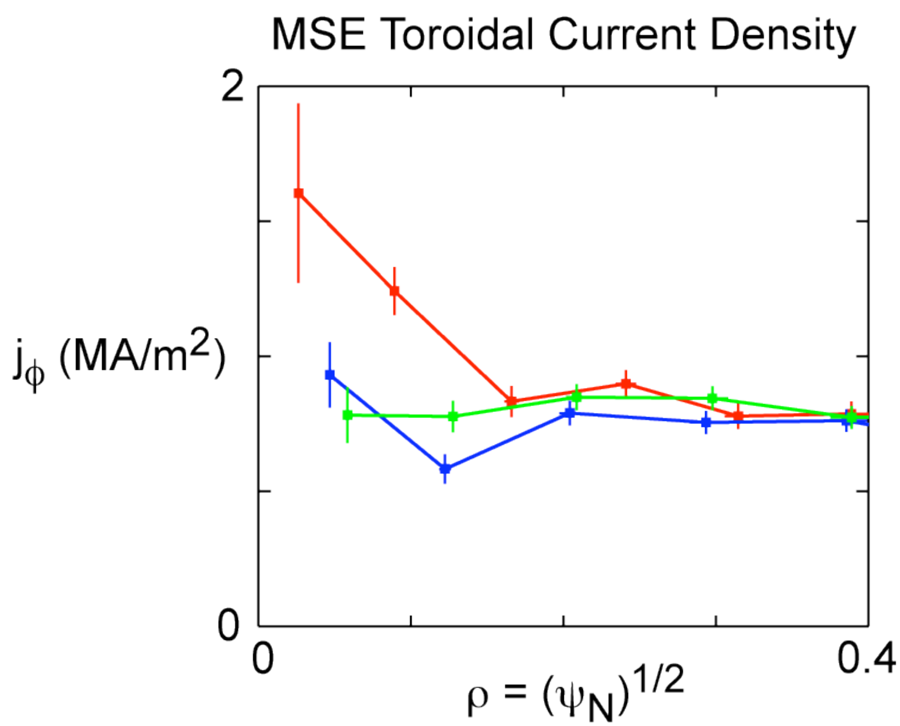
(J. Hosea et al., JI1, P. M. Ryan et al., TP8, APS)

ORNL

MSE Shows Clear Change in Core Field Pitch Angle for -90° Antenna Phase (k_ϕ = - 8 m^{-1})

NSTX





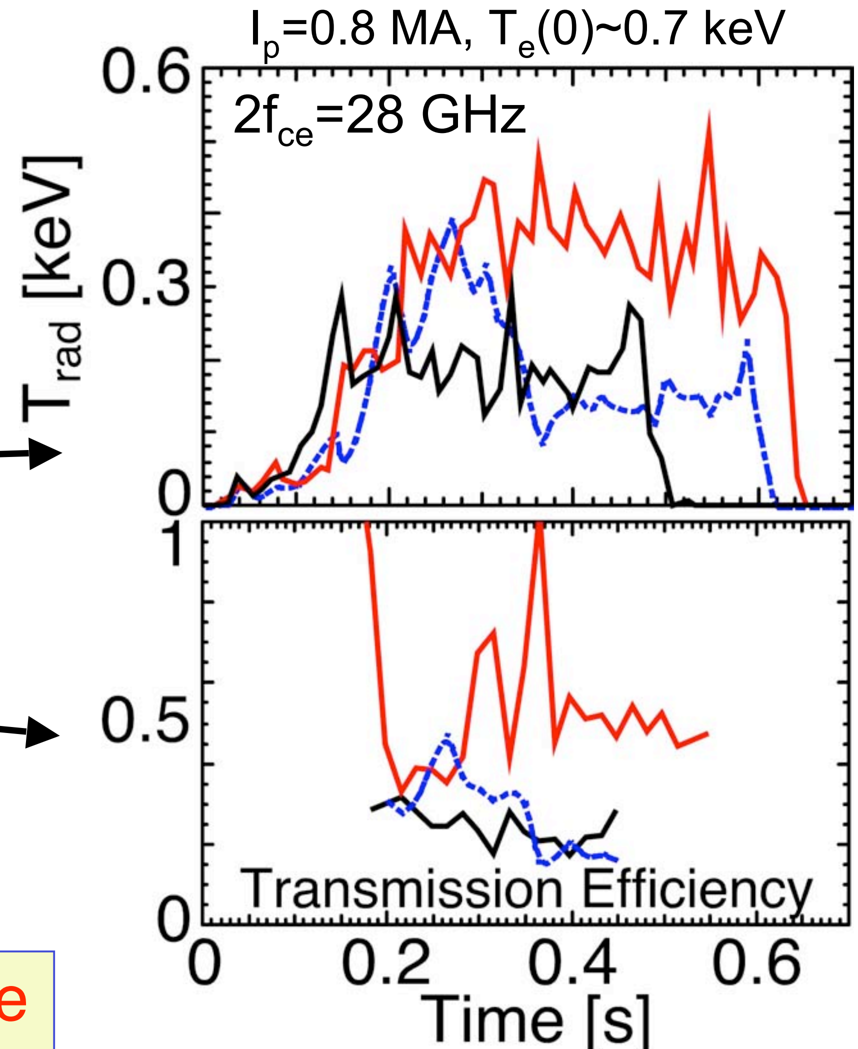
- **Difficult to fit equilibrium reconstruction curves to MSE fine structure in core**
- **j_ϕ obtained directly from the MSE pitch angles using LRDFIT magnetic surfaces**

- **Integral over j_ϕ peak for -90° phase indicates ~ 15 kA of RF CD relative to no RF case inside R = 1.2 m, ~ 5 kA relative to - 60° phase**
  - **- AORSA 2D predicts ~ 26 kA and TORIC predicts ~ 37 kA**

EBE transmission efficiency increased with lithium evaporation rate

NSTX

0 mg/min of Li (124284)
11 mg/min of Li (124290)
19 mg/min of Li (124309)



- **Measured T_{rad} increased from 200 eV to ~ 400 eV**
- **Transmission efficiency increased with Li conditioning:**
  - **From 20% → 60% for f_{ce}=18 GHz**
  - **From 20% → 50% for $2f_{ce}$=28 GHz**

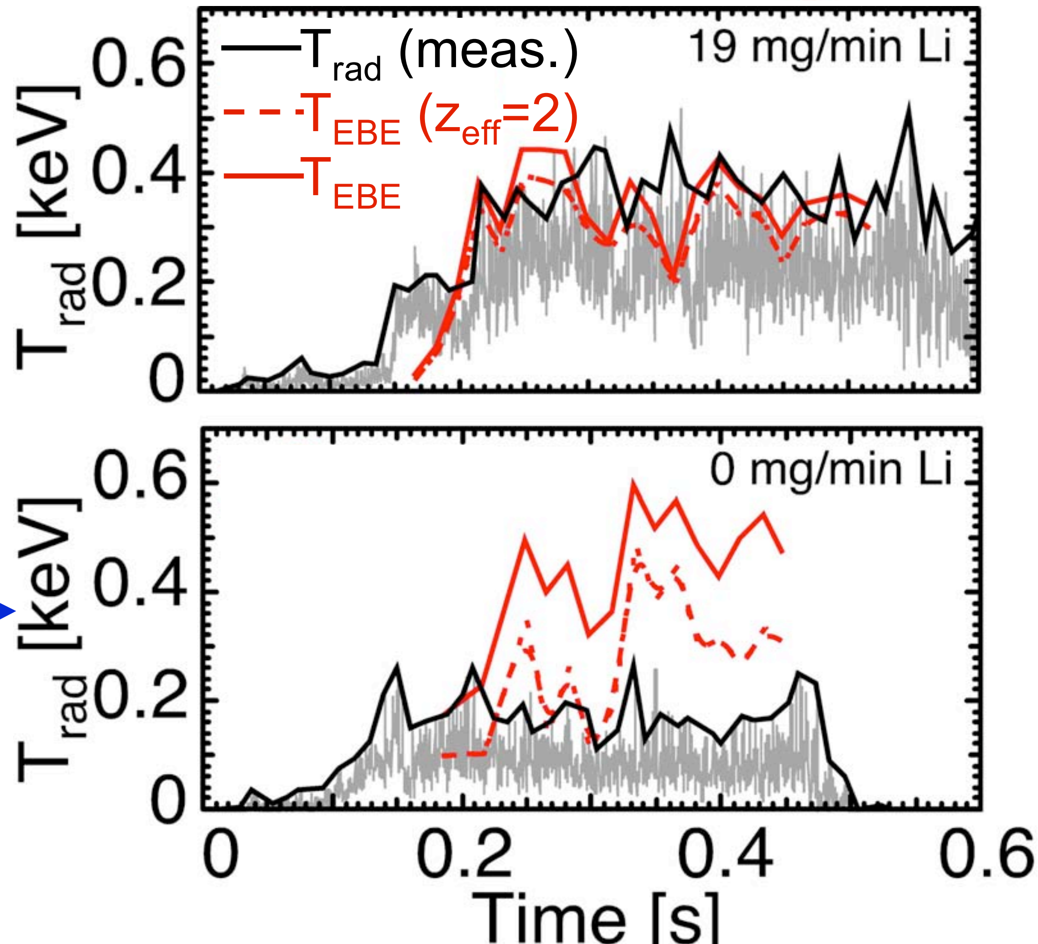
Li conditioning ↑ T_e & ↓ L_n near mode conversion layer

(S. Diem et al., CO3, APS)
(H. Kugel et al., TI2, APS)

Good T_{rad} Agreement with EBE Simulation in Highest Li evaporation Case for $2f_{ce}$=28 GHz

NSTX

- **For highest Li evaporation rate, 19 mg/min:**
  - **Measured and simulated T_{rad} agree**
- **For no Li, measured T_{rad} ~ 0.2 keV, simulated T_{rad} ~ 0.4 - 0.6 keV**



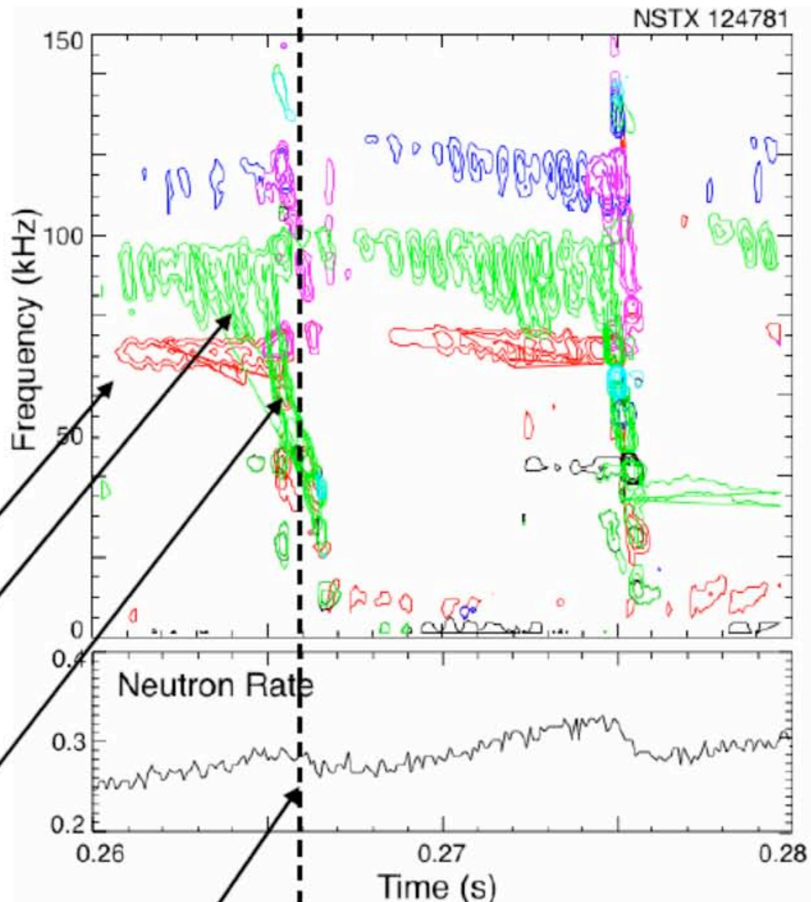
For 19 mg/min of Li conditioning, T_e near MC may be high enough to avoid EBW collisional damping before B-X-O conversion

(S. Diem et al., CO3, APS)

Fast Ion Loss on ITER Expected from Multiple Nonlinearly Interacting Modes, Currently being Studied on NSTX

NSTX

In 2007, entire AE stability space - from no AE modes to AE avalanche threshold – has been mapped and comprehensively diagnosed for the first time in NSTX.



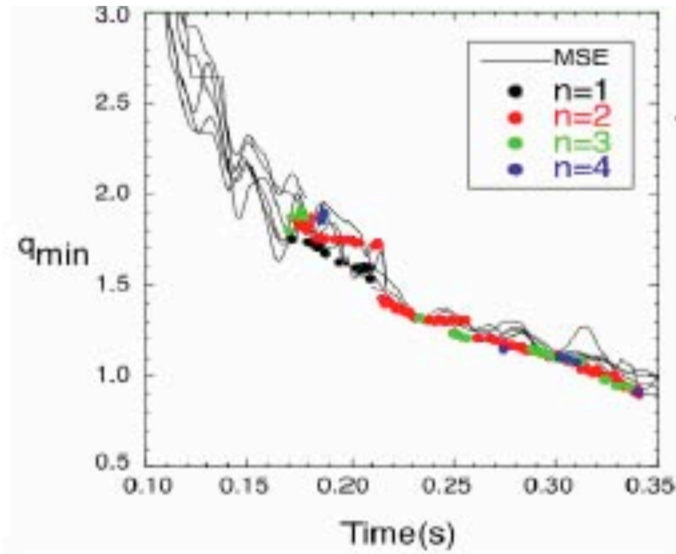
- As power is raised, first see TAE
  - then chirping TAE
  - then avalanches, multi-mode transport
- Avalanches are strong bursts of multiple TAE modes ($2 \leq n \leq 6$), with weak or no n=1 fishbone modes, and correlated with neutron drops

(N. A. Crocker et al., JI1, APS) UCLA

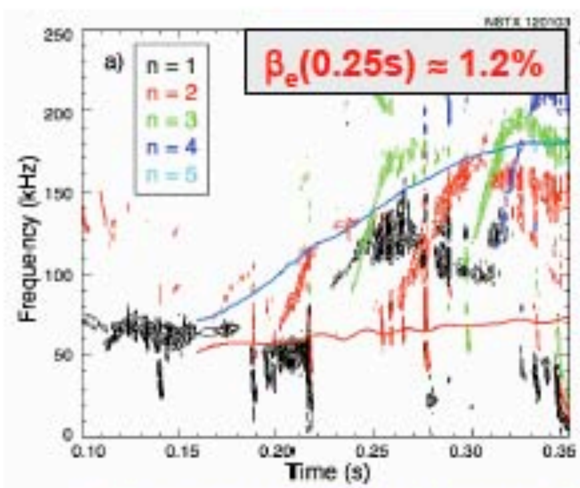
(E. Fredrickson et al., CO3, APS)

Beta-scan Supports Theoretical Models of Alfvén Cascades Mode-Coupling to Geodesic Acoustic Modes

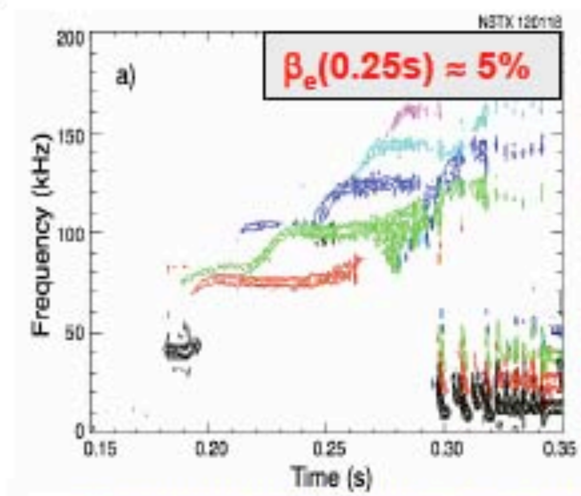
NSTX



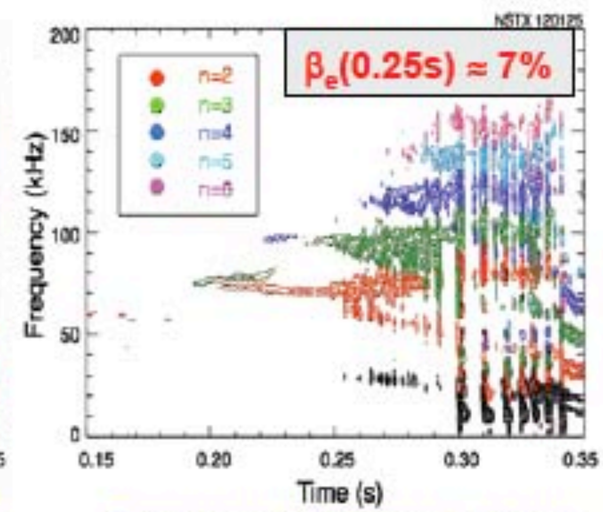
- MSE data agrees with q_{min} deduced from mode frequency sweeps
- Range of frequency sweep is reduced as β is raised, in agreement with theory
- Mode frequency evolution:
  - Onset near GAM frequency (lower red curve)
  - Frequency sweeps upwards
  - Saturates near TAE frequency (blue curve)



Largest frequency sweep



Frequency sweeps reduced

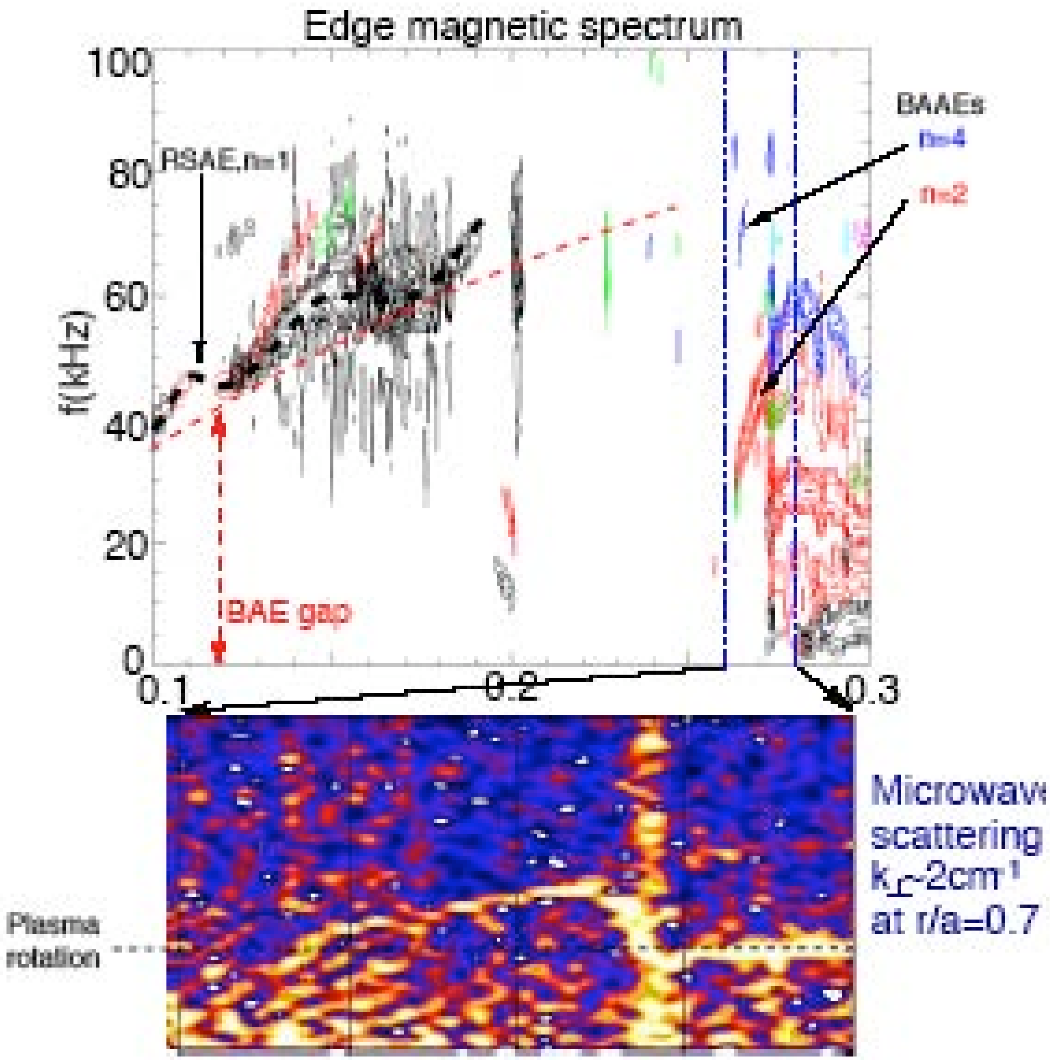


Frequency sweeps absent

β scan demonstrating AC/GAM coupling is first of its kind

Beta-induced Alfvén-Acoustic Eigenmodes
New global MHD eigenmode found at high beta

NSTX



- Beta-induced Alfvén-Acoustic Eigenmodes or BAAE found below the geodesic acoustic mode (GAM) frequency in gaps in the low frequency Alfvén - acoustic continuum.
- These new eigenmodes can explain observations of modes with frequencies well below the TAE frequency in NSTX

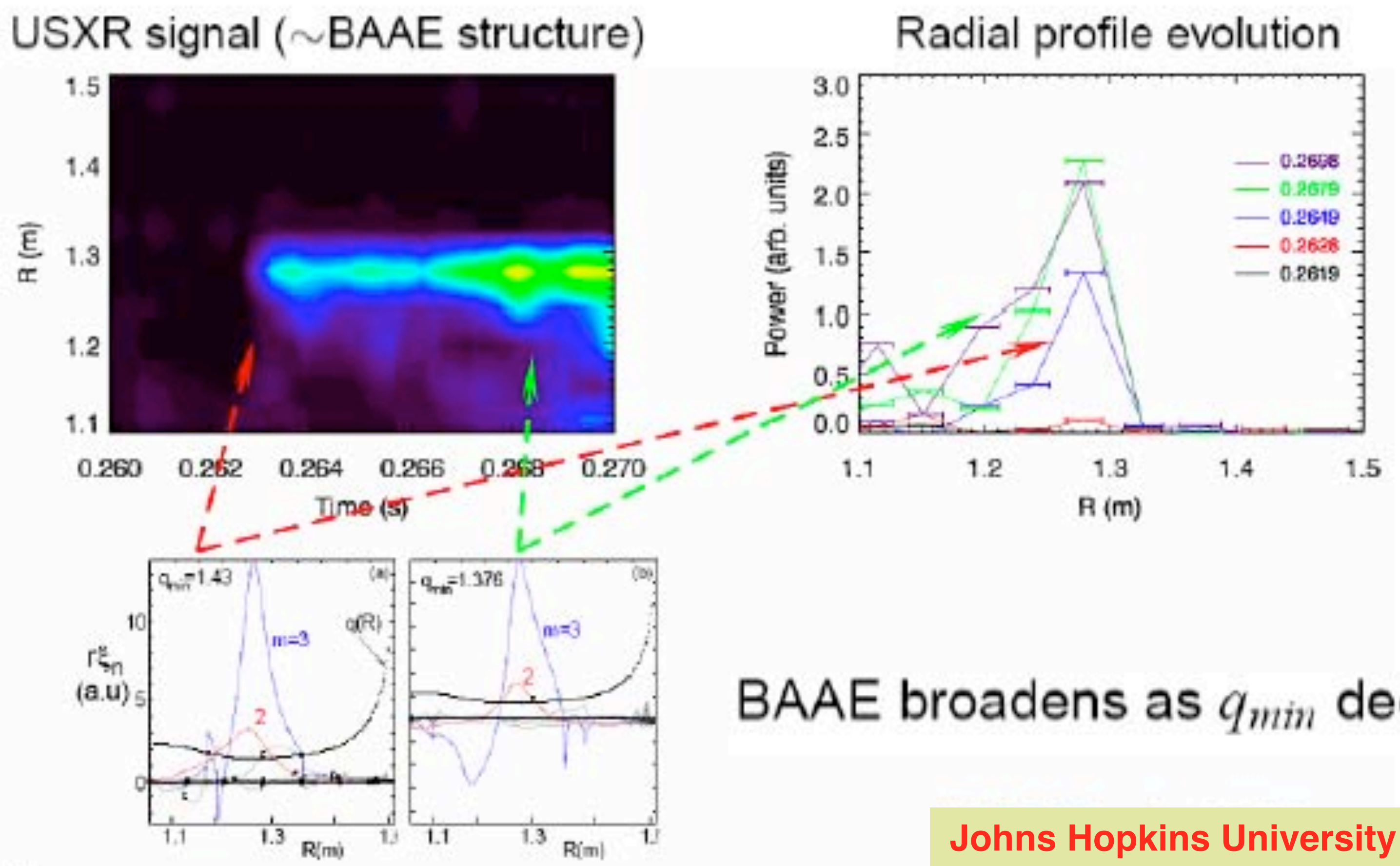
Conversion to short wavelength kinetic Alfvén waves observed with high-k scattering

(N. Gorelenkov et al., TP8, APS)

At high β (≥ 15%), Alfven Cascades are suppressed, and NBI can excite Beta-induced Alfven Acoustic Eigenmode (BAAE)

NSTX

- Coupling is due to geodesic curvature: between *m* Alfvénic and *m*±1 acoustic harmonics
- NOVA-K ω and eigenfunction evolution consistent with observation



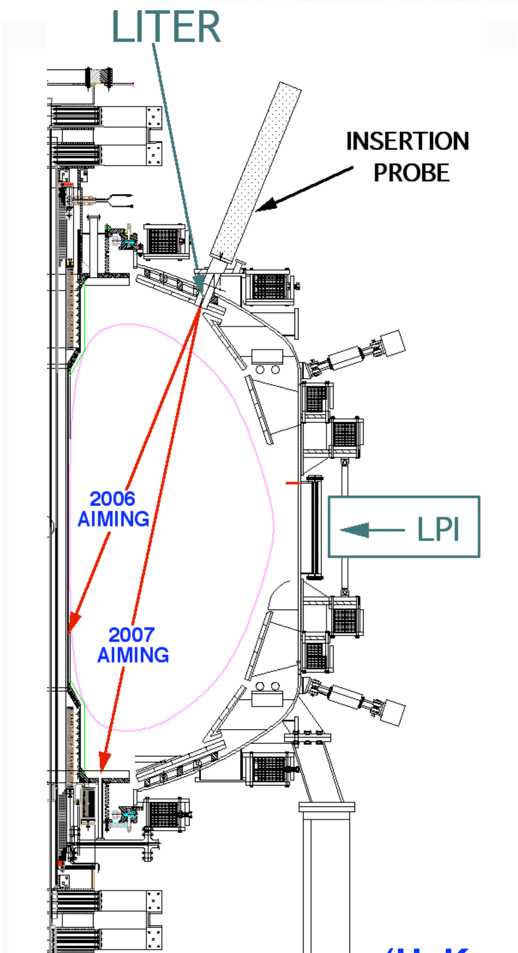
BAAE broadens as q_{min} decreases

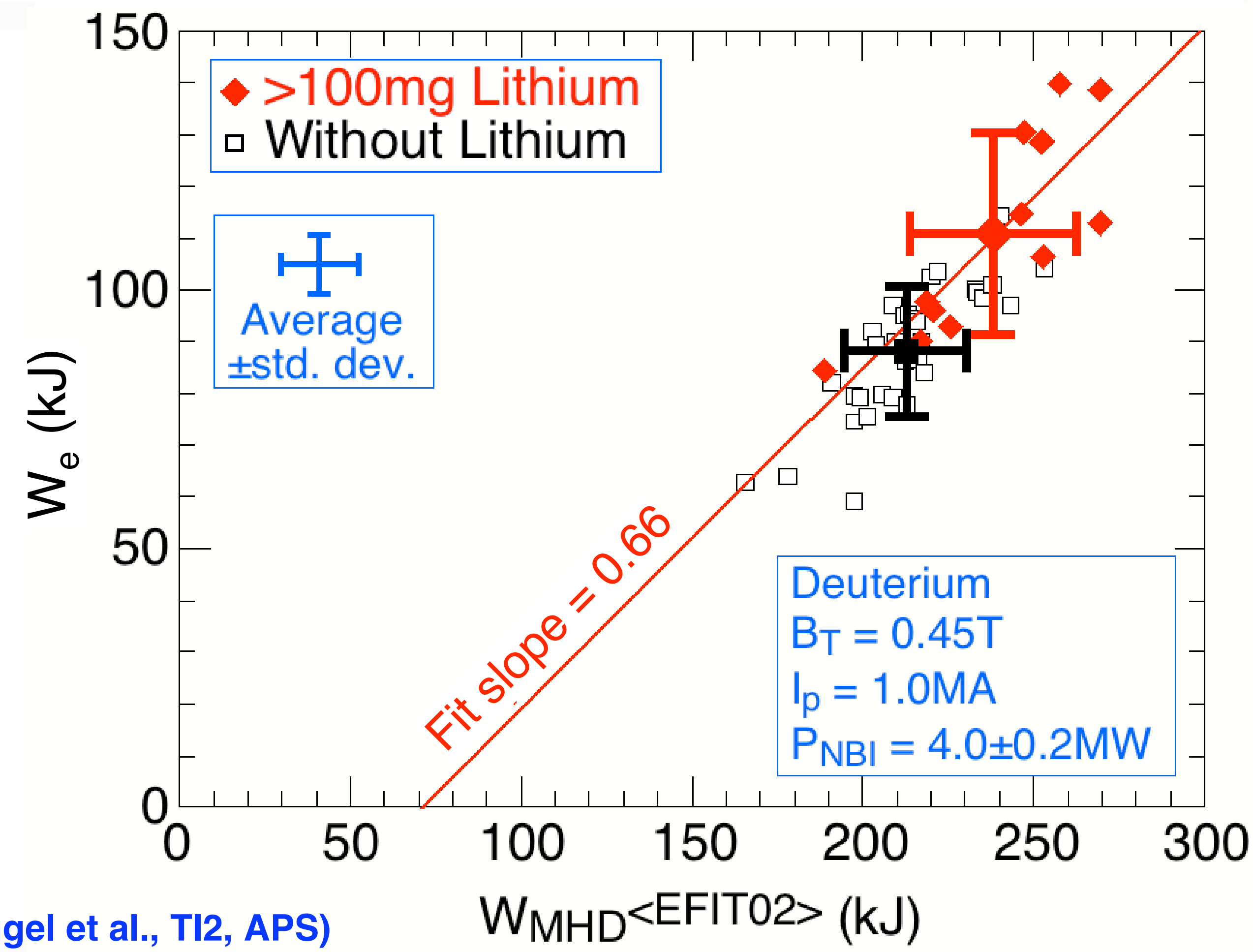
Johns Hopkins University

Lithium Evaporator (LITER) Re-aimed and Upgraded for Continuous Operation → Used in Many Experiments This Year

NSTX

- Improved energy confinement in H-mode plasmas **(10 - 15 %)**
- Much of increase in stored energy comes from electrons (broader T_e)



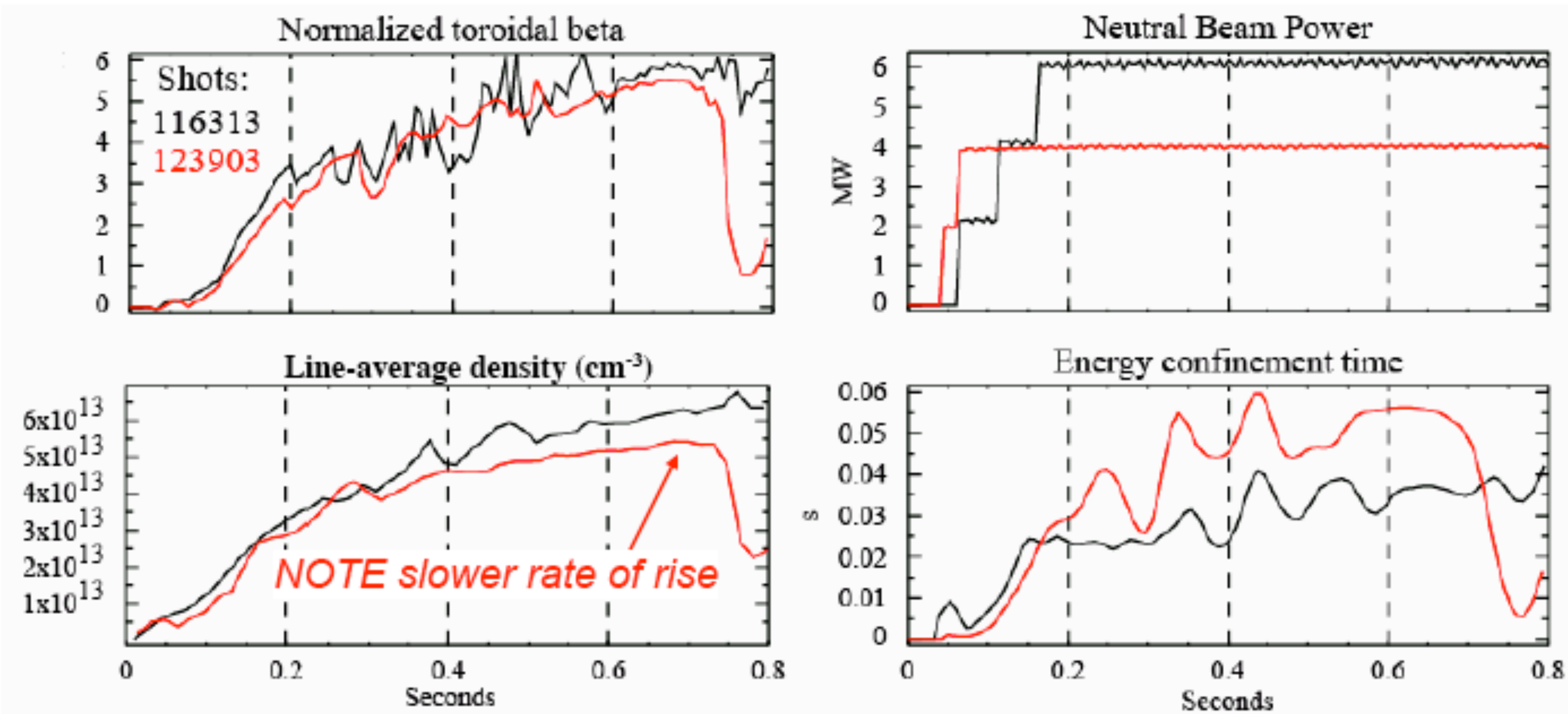


(H. Kugel et al., TI2, APS)

LITER-Conditioned Discharges can Achieve Same β_N as Previous Best Discharges with 1/3 Less NBI Power

NSTX

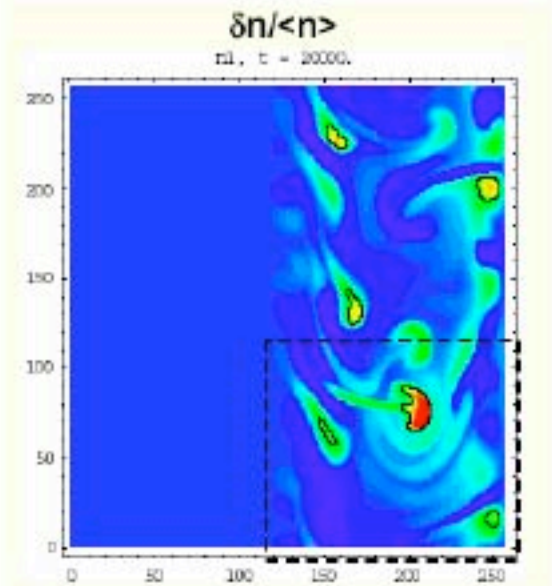
- Black → w/o LITER - 2005 long-pulse discharge at 750kA and 4.5kG
- Red → with LITER, same β_N → 5-5.5 with 2 sources → τ_E = 35ms → 55ms

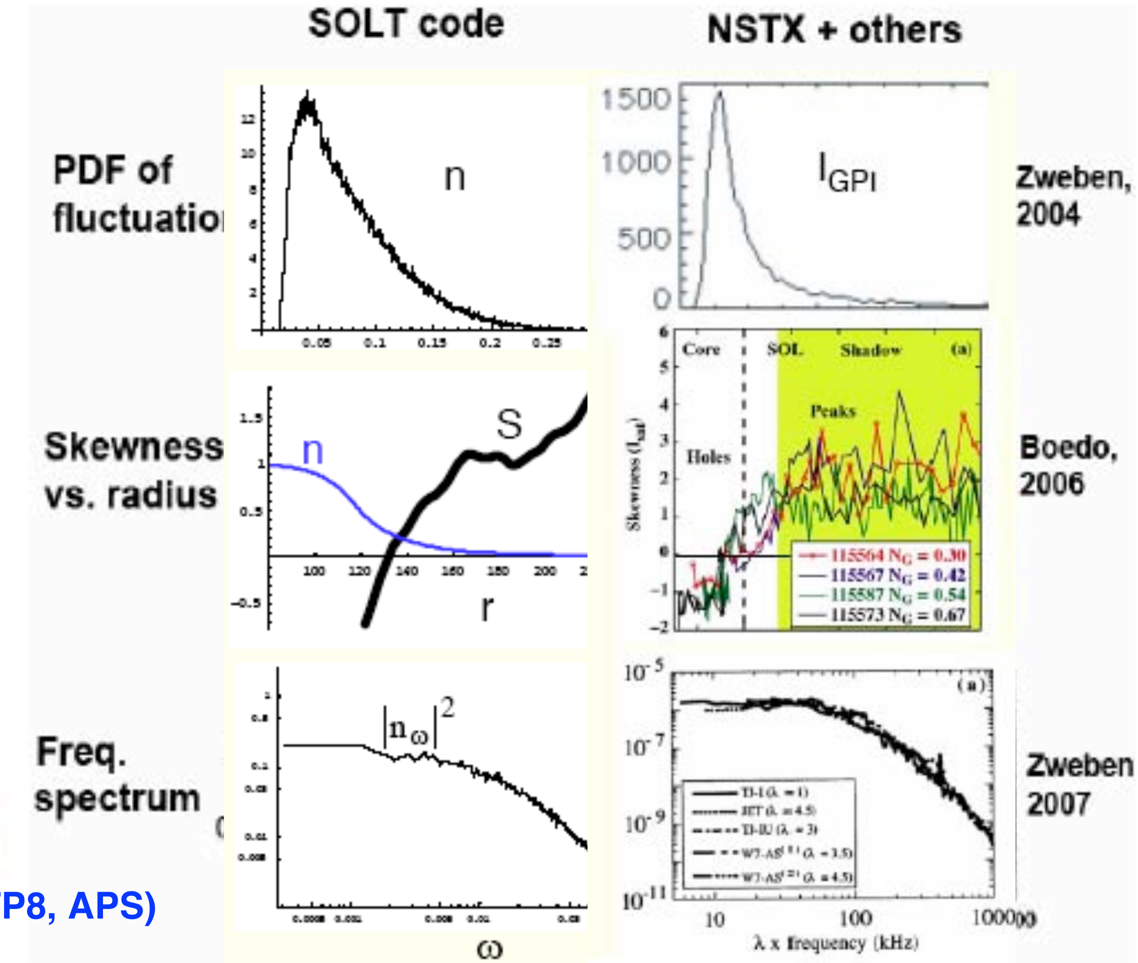


Edge Turbulence Code Shows "Blob" Formation and Ejection, Reproducing Many Features of Experimental Observations

NSTX

Validation and verification of code on several hierarchical levels





Working to resolve discrepancy between theory and exp't on blob acceleration when disconnected

Lodestar **(D.A. Russel, et al., TP8, APS)**

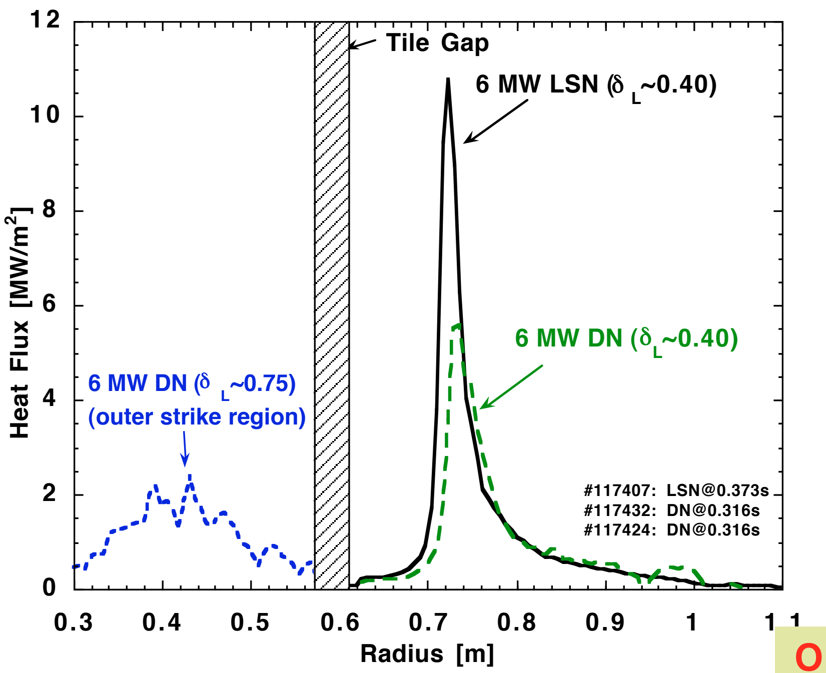
Analytic work on effect of parallel electron physics, e-s vs electromagnetic Effects in creating non-adiabatic fluctuations for driving blob formation

Studying Physics of Divertor and Detachment - Needed for NHTX and ST-CTF Design

NSTX

Power management through flux expansion and detachment

Boundary physics with ITER-level heat flux
Heat Flux Reduction with higher triangularity



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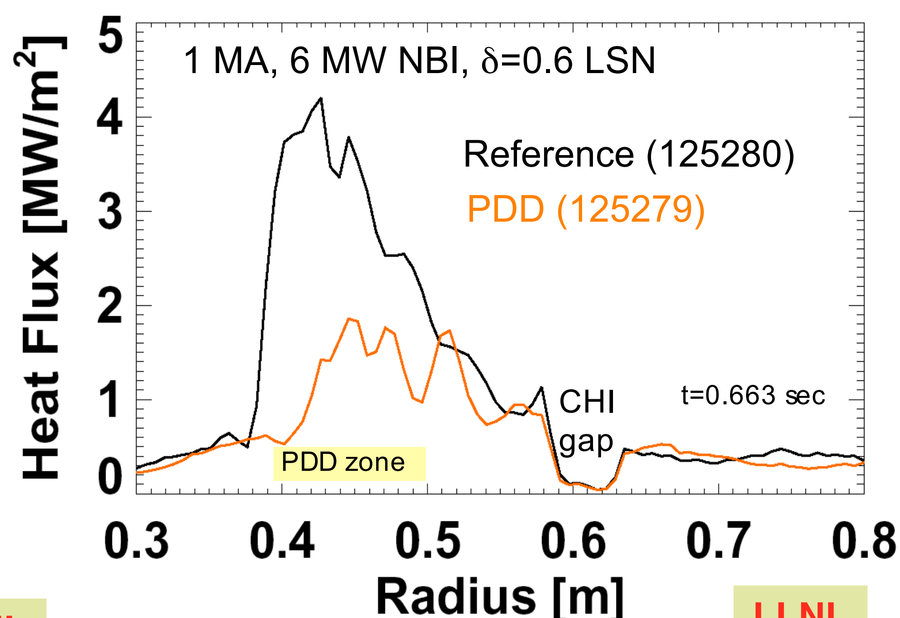
Partially Detached Divertor significantly reduce heat flux without reducing H-mode performance



LLNL

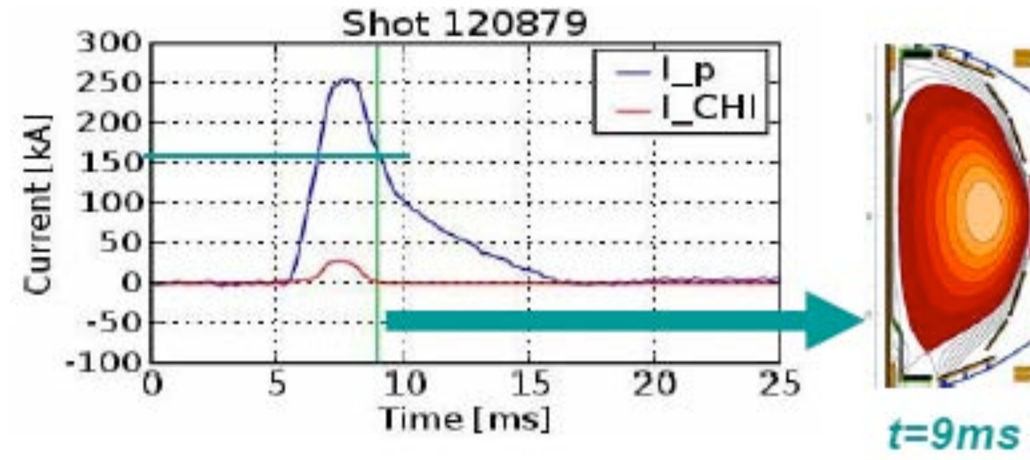
(V. Soukhanovskii et al., BI1, APS)

(J-W Ahn et al.,TP8, APS)

Coaxial Helicity Injection has convincingly demonstrated the formation of closed poloidal flux at high plasma current

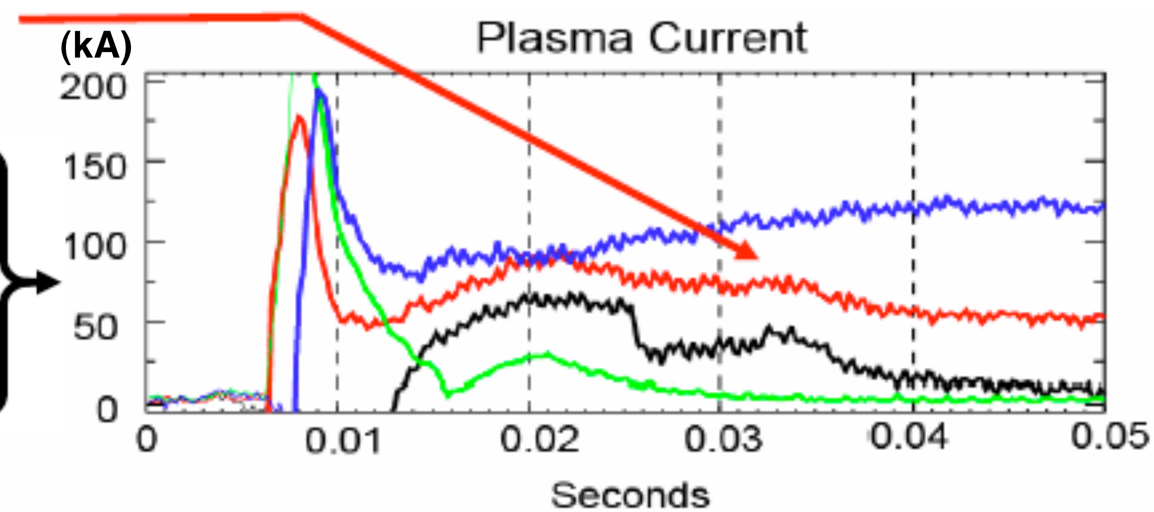
NSTX

160 kA closed flux current formed in FY 2006



Reduced OH flux consumption in FY 2006

CHI only
Induction only
CHI + induction
CHI + induction: I_p = 120kA
(Boronization + improved PF programming)



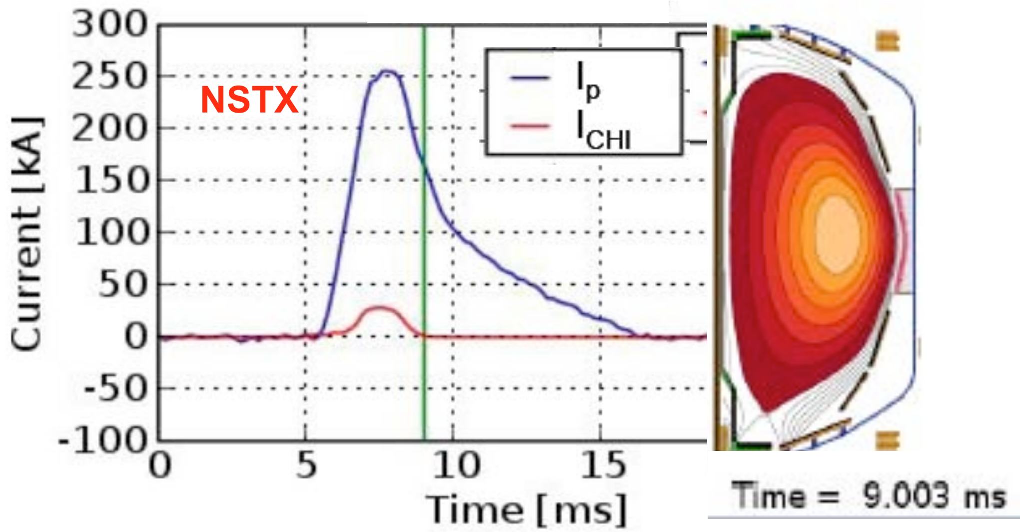
Univ. Washington

(R. Raman et al., CO3, APS)

Solenoid-free Startup for ST-CTF and Demo
A number of options being developed

NSTX

CHI drove 160 kA of closed-flux current



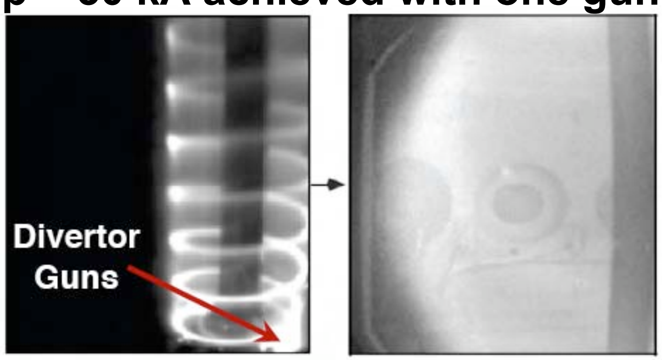
CHI to be optimized toward ~ 300 kA

Ip ~ 500 kA without OH

6 MW of HHFW Heating & CD

1 MW of ECH Preionization

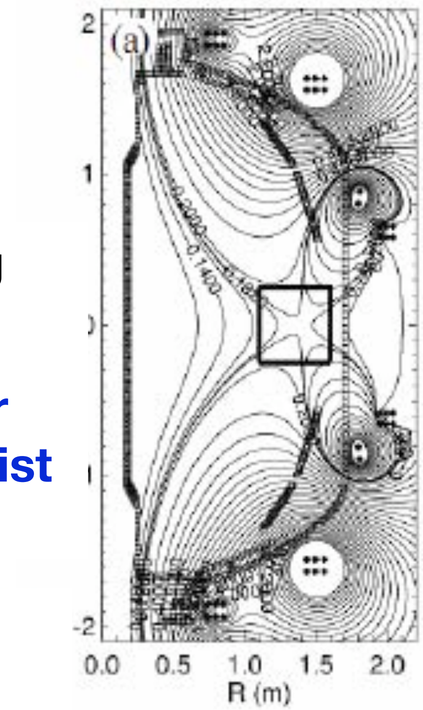
PEGASUS Gun Start-up
Ip ~ 30 kA achieved with one gun



Further improvements with improved/multiple guns

Start-up Utilizing Outer PF Flux

1MW ECH and/or Plasma Gun to assist the start-up



NSTX 5 Year Plan Mission Elements

NSTX

- To provide the physics basis for future ST-based devices, such as NHTX, ST-CTF and ST-Demo
- To broaden the physics basis for ITER, actively participating in ITPA and US BPO
- To advance the understanding of toroidal magnetic confinement.

NSTX/ST Strength:

- Exceptionally wide plasma parameter space
- High degree of facility flexibility
- Highly accessible plasmas - unique diagnostics

5 year goal: Achieve full NICD at high β and confinement while advancing startup/ramp-up research for NHTX/ST-CTF/DEMO

NSTX

- **Full non-inductive current drive strategy and method:**
  1. Increase BS current ↔ higher $\beta_{P\text{-}th}$ thru higher P_{HEAT} and/or H-factor
  2. Increase NBICD and P_{HEAT}, achieve J profile control ↔ 2nd NBI
  3. Control and improve confinement and stability ↔ J profile control
  4. $f_{GW} < 1$ & $\beta_N \sim 6$, n_e & J equilibration ↔ higher with longer flat-top
  5. Control n_e, increase confinement ↔ liquid lithium divertor (LLD)
  6. Sustain high τ_E, β_N by ELM/RWM/EF control ↔ off-midplane 3D coils

- **Plasma formation and ramp-up strategy and method:**
  1. Increase Coaxial Helicity Inj. (CHI) I_P ↔ higher ECH, V_{CHI}
  2. Optimize non-CHI start-up ↔ PF-only w/ ECH, plasma guns
  3. Increase early pre-ionization/heating power ↔ ECH/EBW system
  4. Extend long-pulse plasmas ↔ CHI/PF/Gun for ohmic flux savings
  5. Ramp-up I_P to full-NI target ↔ higher I_P for FW & NBI heating/CD

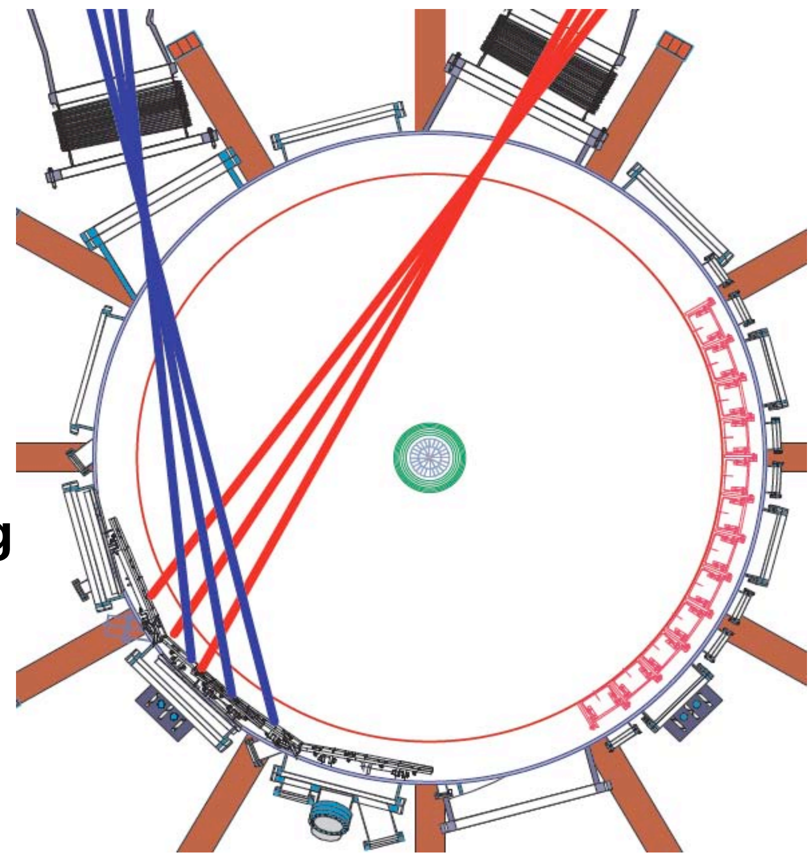
(J. Menard et al., Tokamak Workshop)

Addition of 2nd NBI Source with Increased Tangency Radius of Injection Offers Several Potential Advantages

- **Higher P_{HEAT} for higher β_P, f_{BS} at presently sustainable $H_{98y2} \leq 1.2$**
- **Increased NBICD from higher P_{NBI}**
  - And higher CD efficiency of large R_{TAN}
- **Increased control of *q* profile**
  - Optimize $q(\rho)$ for high τ_E, β, f_{NI}
- **Increased research flexibility by varying**
  - *q*-shear for transport & MHD physics
  - Heating, torque, rotation profiles
  - β at higher I_P and B_T
  - Fast-ion distribution and instabilities
  - Divertor P/R and pulse-length

New 2nd NBI
R_{TAN}=110,120,130cm

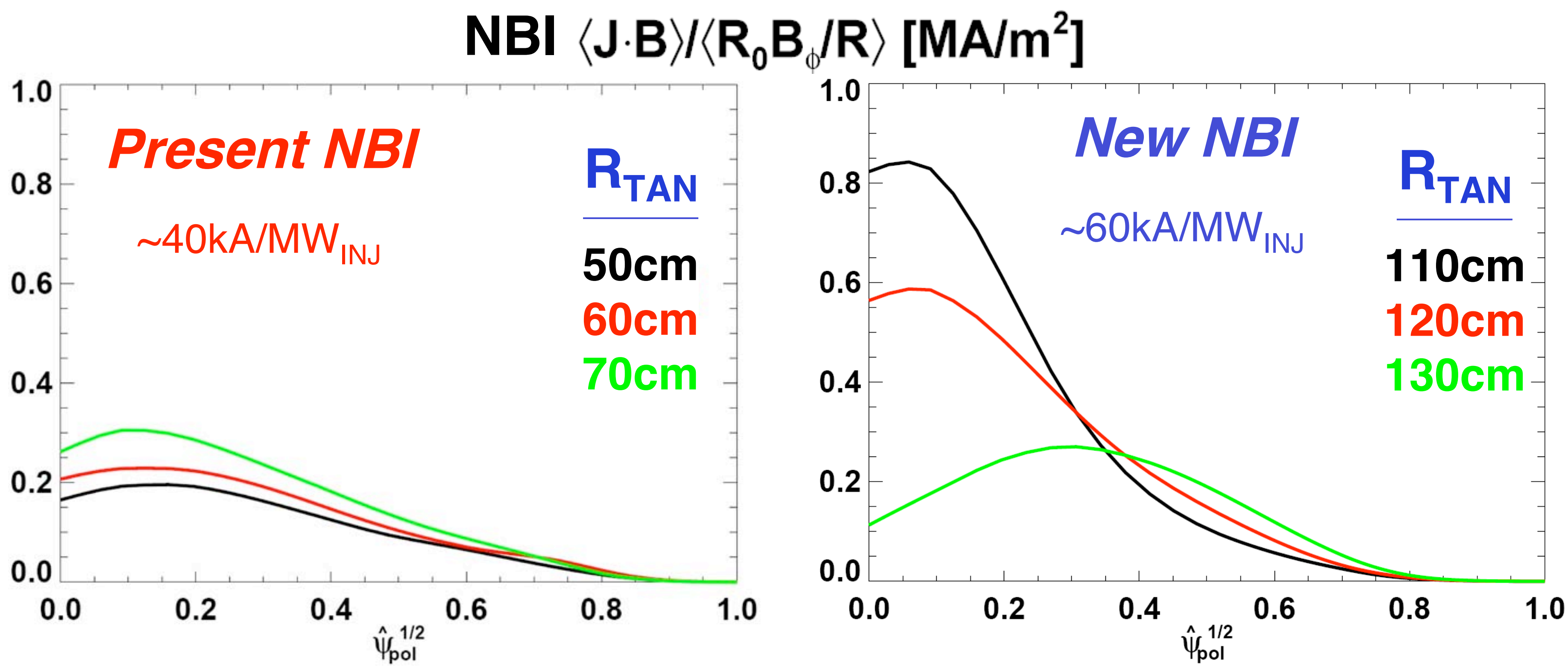
Present NBI
R_{TAN}=50,60,70cm



NBI upgrade operational mid-FY10

Increased R_{TAN} NBI provides 50% higher CD efficiency and much more control over NBICD $J_{||}$ profile than present NBI

NSTX

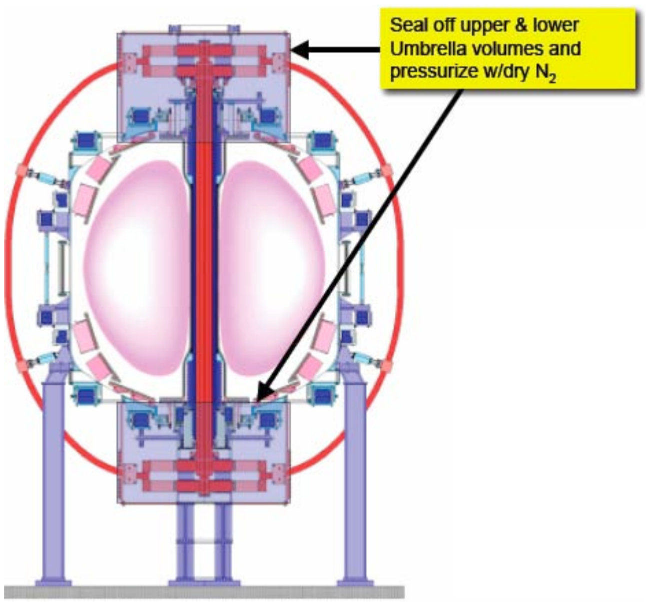


P_{NBI}=2MW E_{NBI}=90keV, I_p=0.82MA, f_{GW}=0.58 $\overline{n_e}$ = 4.4x10^{19}m^{-3}, $\overline{T_e}$ = 1.2keV

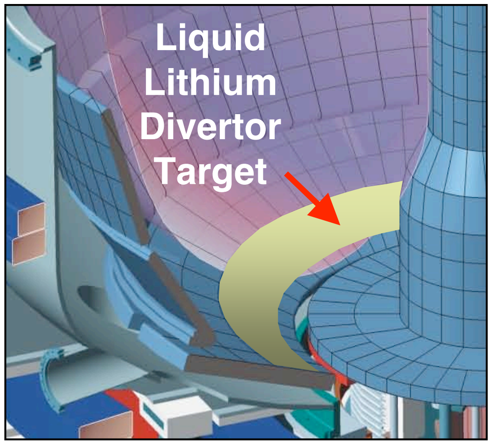
- Small R_{TAN} NBI provides little variation in NBI $J_{||}$ profile shape
- Large RTAN can vary NBI J||(0) by a factor of 8 → peaked to hollow J||

Long-pulse integrated scenarios benefit from extended TF and OH coil operation at full B_T, and require *sustained* density control

- **Sub-cooled OH and TF (-50°C-100°C) provide 2.5s flat-top at BT=0.55T**
  - Longer flat-top needed to reach density equilibration & J relaxation at higher Te
  - BT = 0.52-0.55T aids 700-750kA full-NI
  - Long-pulse OH à IP=1MA for 2.5s
    - Use increased NBICD of 2nd NBI source
- **Liquid Lithium Divertor for D pumping**
  - Designed to reduce density 25-50% depending on triangularity
  - Consistent with f_{GW} > 0.8 needed for fully-NI target scenarios
- **Long-pulse pumping and core fueling required for sustained density control**



Sub-cooling operational mid-FY10



Initial LLD operational FY09

Pumping upgrade in FY10

Implement core fueling FY10-12

NSTX achieved significant new results in all topical science areas during the 2007 campaign:

NSTX

- **MHD:** Demonstrated RWM feedback stabilization at low rotation and importance of n>1 error field
- **T&T:** Measured and characterized ion, electron, particle, and momentum transport and localized electron scale turbulence.
- **Fast-ion-driven instabilities:** Measured & modeled fast ion redistribution, TAE stability with power scan, AC/GAM coupling, BAAE
- **Wave heating and current drive:** Improved understanding of HHFW and EBW coupling efficiency vs. edge parameters.
- **Boundary physics:** Enhanced confinement and pumping with Li, reduced and elucidated divertor heat flux
- **Solenoid-free Startup:** Coaxial helicity injection coupled to OH

FY 2008 Plan: 70 channel P-CHERS, FIDA, Second LITER

FY 2009 Plan: Liquid Lithium Divertor, ECH/EBW heating

FY 2010-11Plan: Second NBI for improved j(r) control for fully NI operations.

NSTX Research Forum: Nov. 27 - 29, 2007 at PPPL