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Recent Physics Results from the National Spherical Torus Experiment (NSTX)

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Presented by:

Jonathan E. Menard, PPPL

For the NSTX Research Team

21st IAEA/Fusion 2006 Meeting

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8) General Atomics, San Diego, CA, USA
9) Nova Photonics Incorporated, Princeton, NJ, USA
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11) Lawrence Livermore National Laboratory, Livermore, CA, USA
12) Johns Hopkins University, Baltimore, MD, USA

NSTX is strongly contributing to fundamental toroidal confinement science in support of ITER and future ST's

- Integrated High Performance
- Macroscopic Stability
- Transport and Turbulence
- Boundary Physics
- Energetic Particle Physics
- Plasma Start-up and Ramp-up

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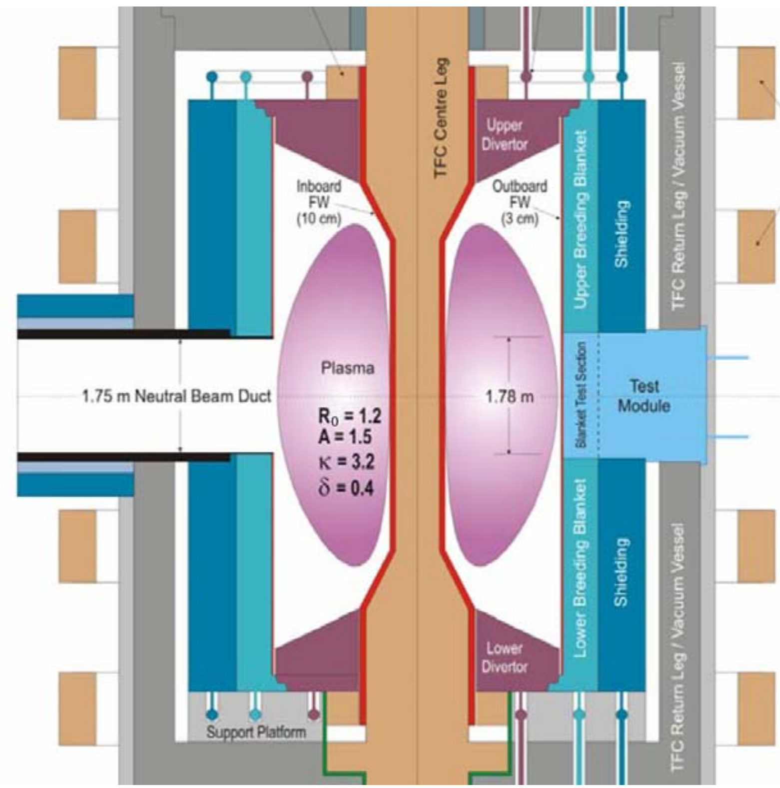
NSTX plasmas approach the normalized performance levels needed for a Spherical Torus - Component Test Facility (ST-CTF)

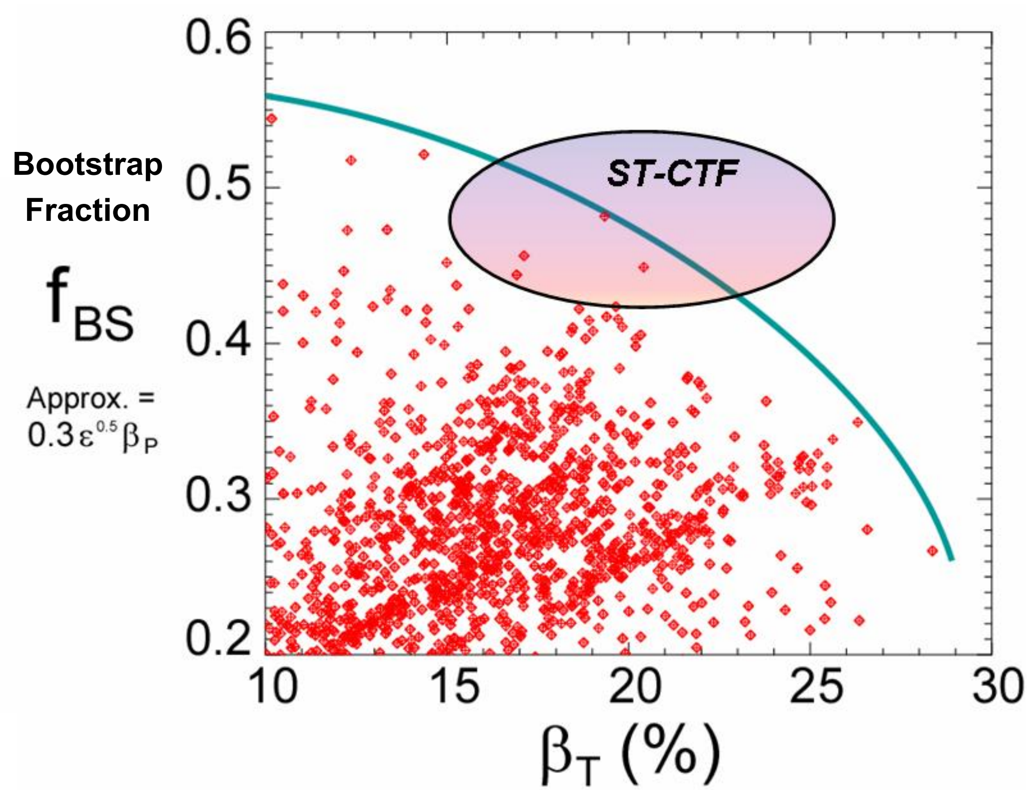
ST-CTF goal: neutron flux = 1-4MW/m²

A=1.5, κ = 3, R_0 = 1.2m, I_P= 8-12MA, β_N ~ 5, HH=1.3,

β_T = 15-25%, f_{BS}=45-50%



Peng et al, PPCF **47**, B263 (2005)



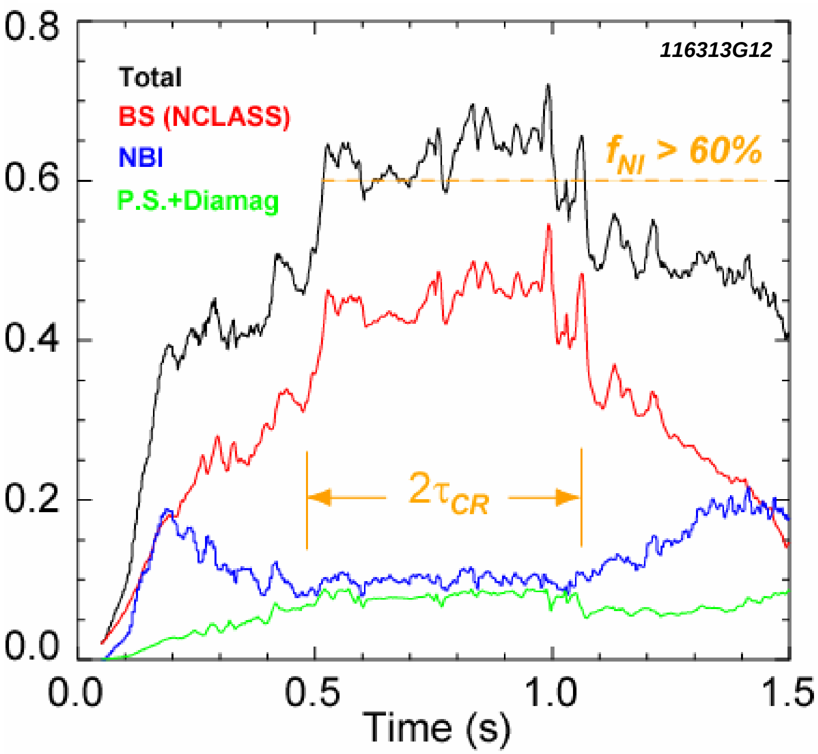
High performance can be sustained for several current redistribution times at high non-inductive current fraction

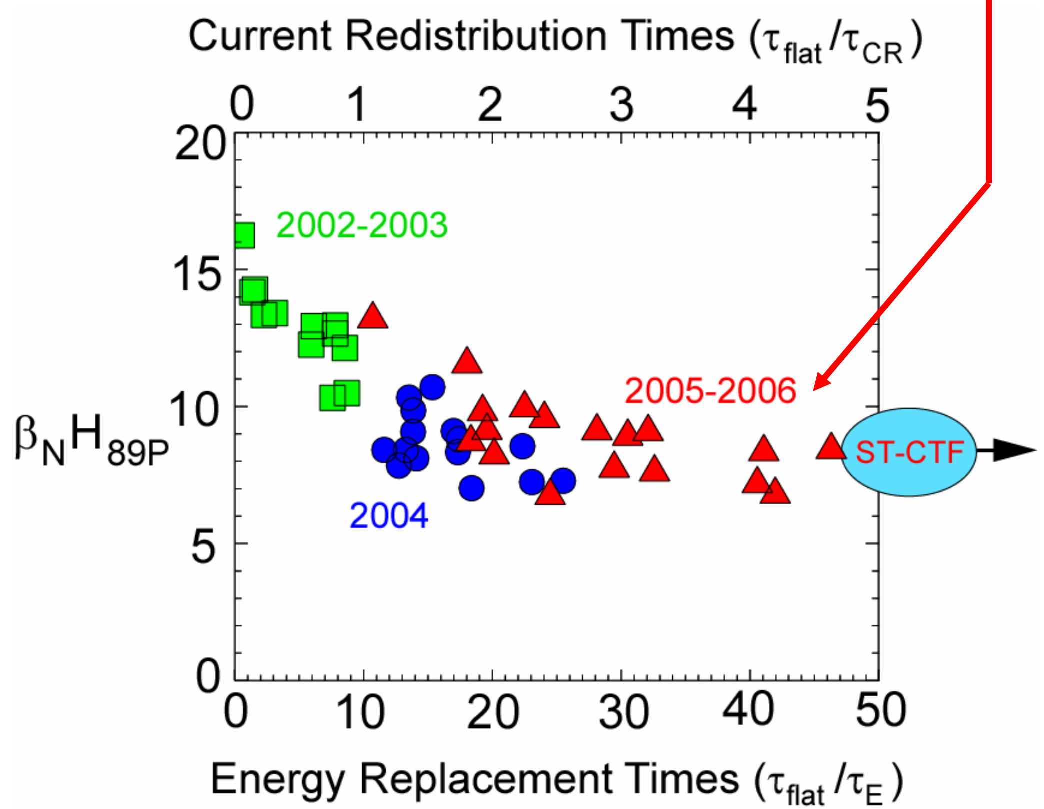
NSTX

- **∇p and NBI current drive provide up to 65% of plasma current →**

Relative to 2004, High $\beta_N \times H_{89P}$ **now sustained 2 × longer**

TRANSP non-inductive current fractions



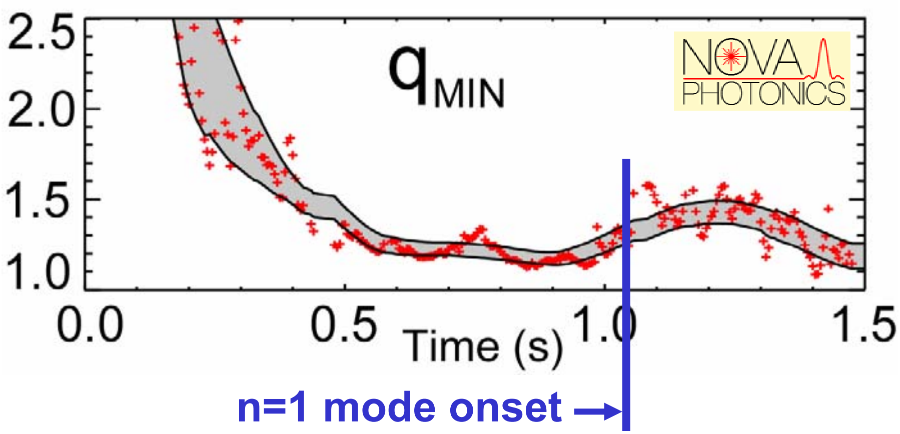


D. Gates, PoP **13**, 056122 (2006)

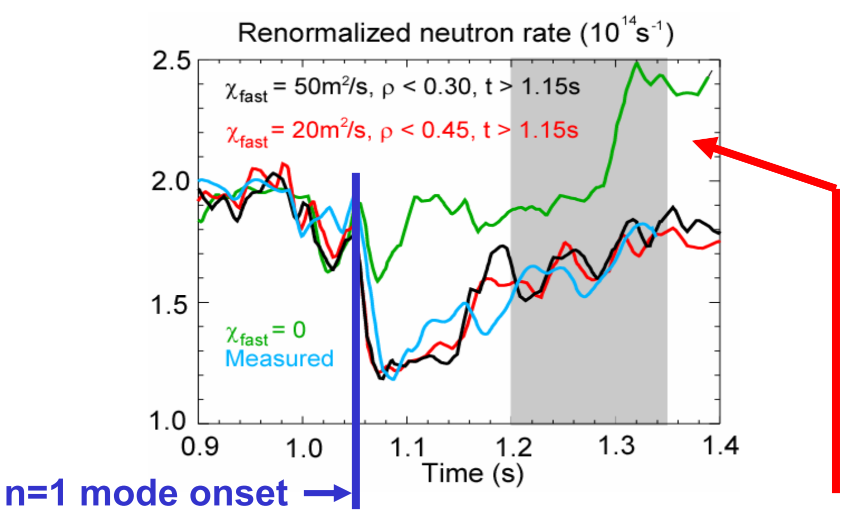
D. Gates – Poster EX/P1-3

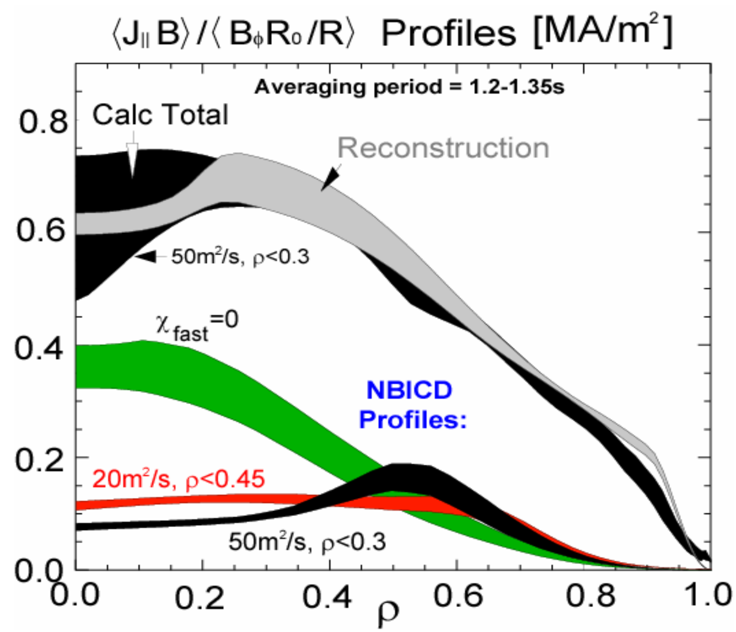
MHD-induced redistribution of NBI current drive contributes to NSTX "hybrid"-like scenario as proposed for ITER

- **q_{MIN} > 1 for entire discharge,** increases during late *n*=1 quasi-interchange activity



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





J. Menard, PRL **97**, 095002 (2006)

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

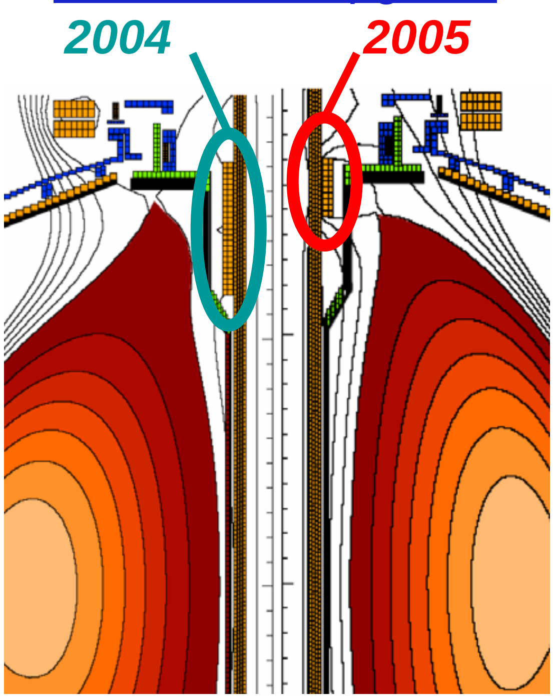
S. Medley – Poster EX/P6-13

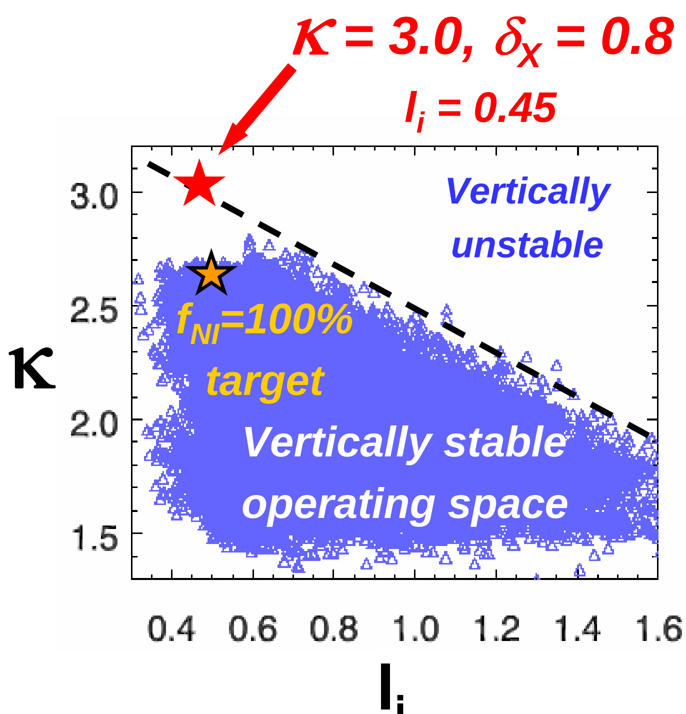
Very high elongation at low l_i opens possibility of higher β_P and f_{BS} operation at high β_T

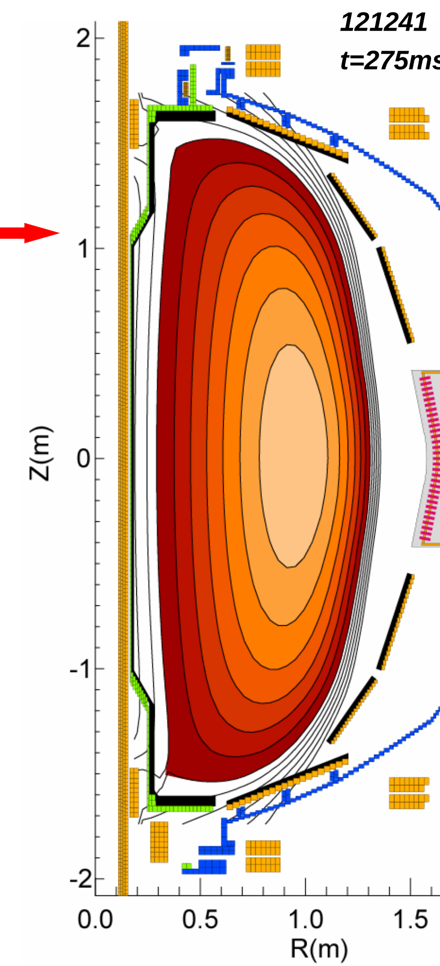
NSTX

- Sustained $\kappa \geq 2.8$ (reached $\kappa = 3$) for many τ_{WALL} using rtEFIT isoflux control
  - Allowed by divertor coil upgrade in 2005, **no** in-vessel vertical position control coils
- Stability analysis of new operational regime under investigation
- High κ research important for CTF design studies

Divertor coil upgrade







Gates, et al., PoP **13** (2006) 056122.
Gates, et al., NF **46** (2006) 17.

GENERAL ATOMICS

D. Gates – Poster EX/P1-3

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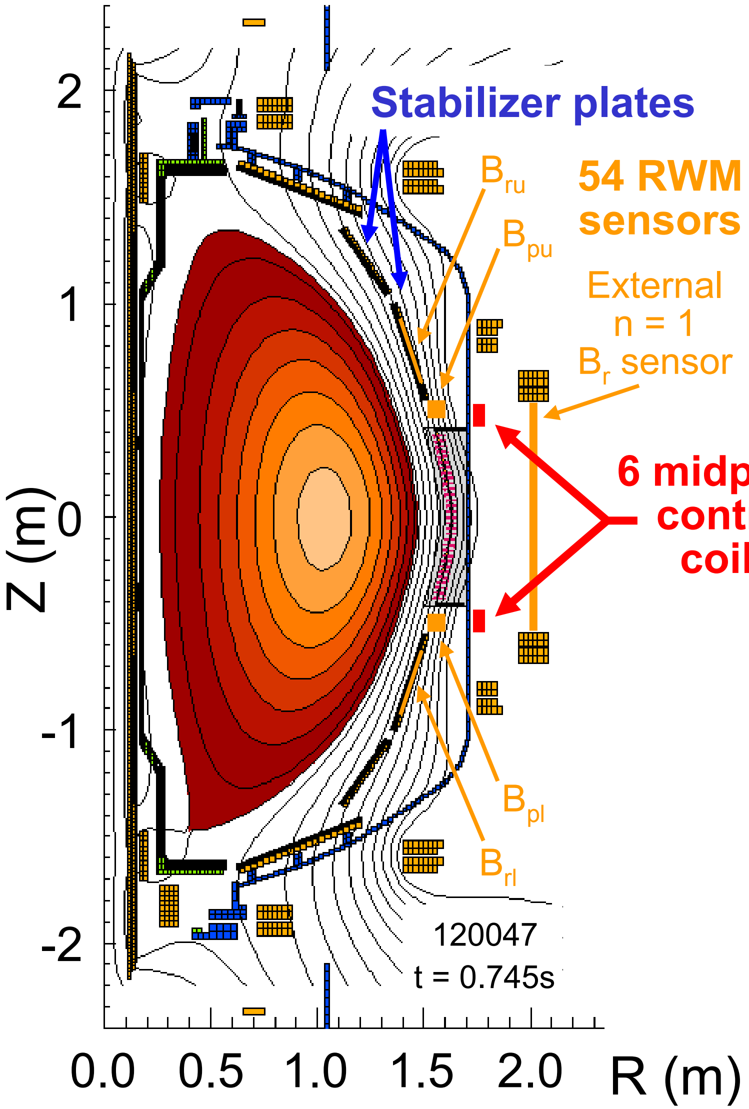
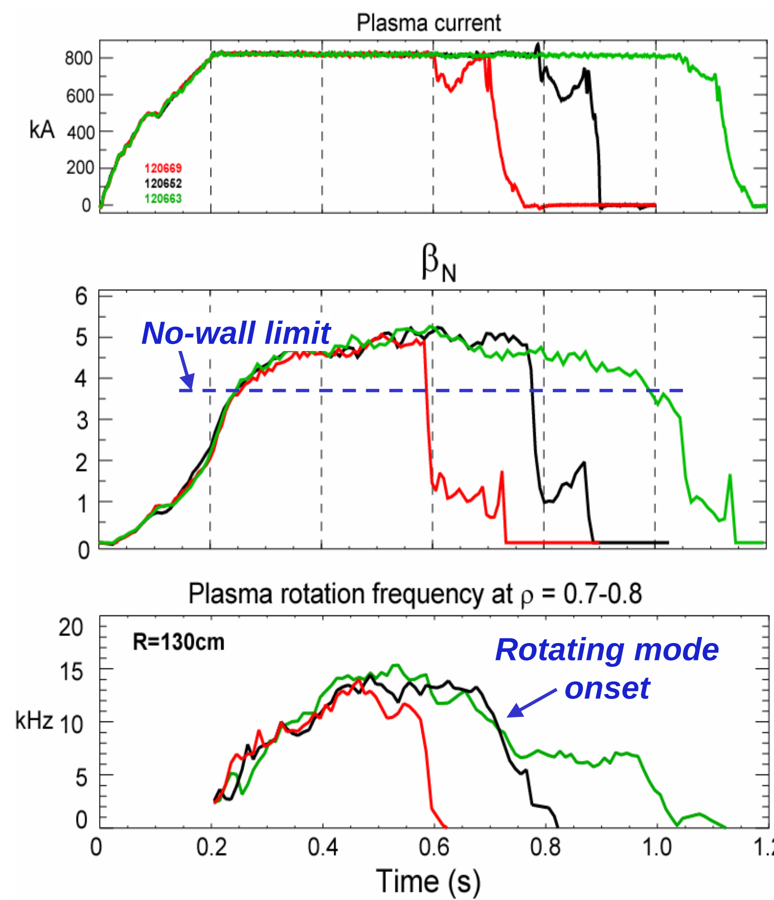
New mode control system enables error field and RWM research



- Dynamic error field correction (DEFC) increases pulse-length above no-wall limit
  - Maintains plasma rotation which stabilizes RWM

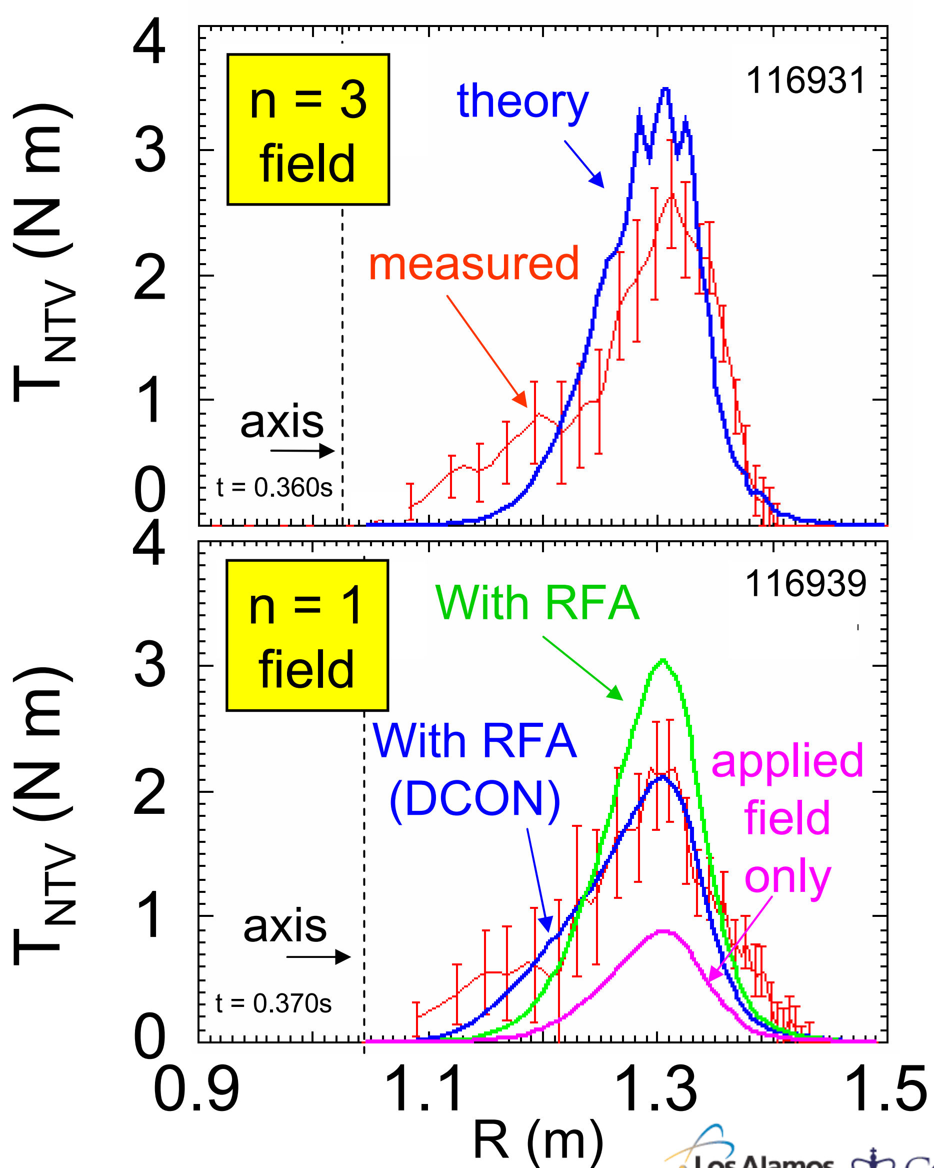
No error field correction at high β_N
Real-time correction of known error fields
Real-time EF correction + n=1 B_P feedback



- Low-frequency MHD spectroscopy used to diagnose Ω_ϕ-stabilized *n*=1 RWM as in DIII-D

Observed plasma rotation braking consistent with NTV theory

NSTX



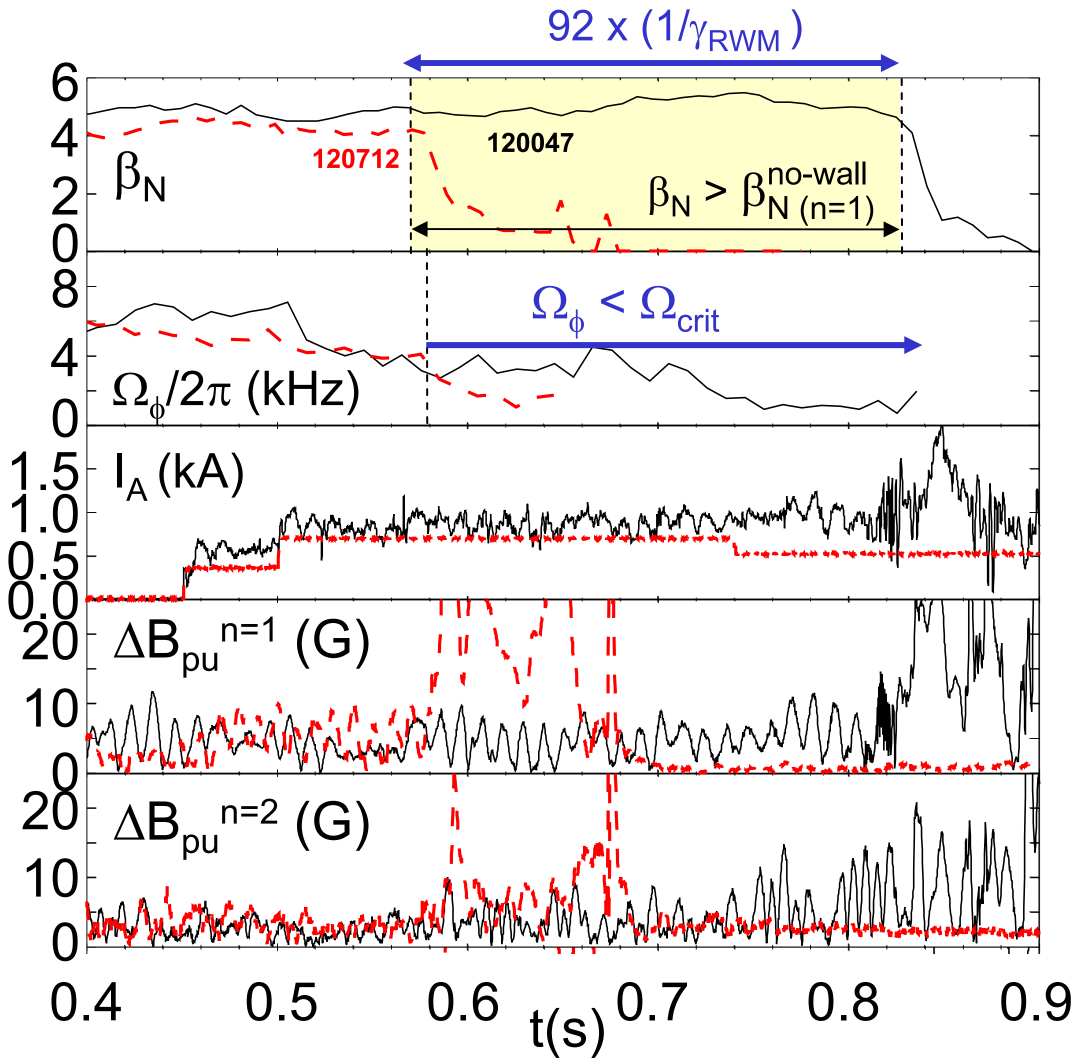
- First quantitative agreement using full *neoclassical toroidal viscosity* theory (NTV)
  - Due to plasma flow through non-axisymmetric field
  - Trapped particle effects, 3-D field spectrum important
- pressure-driven RFA increases damping at high-beta
  - Included in calculations
  - Based on applied field, or DCON computed mode spectrum
- Viable physics for simulations of plasma rotation in future devices (ITER, CTF, KSTAR)

Zhu, et al., PRL **96** (2006) 225002.
Columbia U. thesis dissertation

Los Alamos National Laboratory · Columbia University in the City of New York

A. Sontag – Oral EX/7-2Rb

RWM actively stabilized at ITER-relevant low rotation for $90/\gamma_{RWM}$



Sabbagh, et al., PRL **97** (2006) 045004.

- Plasma rotation Ω_ϕ reduced by non-resonant $n = 3$ magnetic braking
  - Non-resonant braking to accurately determine n=1 RWM critical rotation
- First demonstration of low-Ω_ϕ RWM control at low A
  - Exceeds DCON $\beta_N^{no\text{-}wall}$ for n = 1 and n = 2
  - n = 2 RWM amplitude increases, mode remains stable while n = 1 stabilized
  - n = 2 internal plasma mode seen in some cases

S. Sabbagh – Submitted post-deadline

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Dedicated H-mode confinement scaling experiments measure scaling trends that differ from high-A results

Stronger dependence on B_T:

$\tau_{E\text{-}98y,2} \propto B_T^{0.15}$ $\tau_{E\text{-}NSTX} \propto B_T^{0.85\text{-}0.9}$

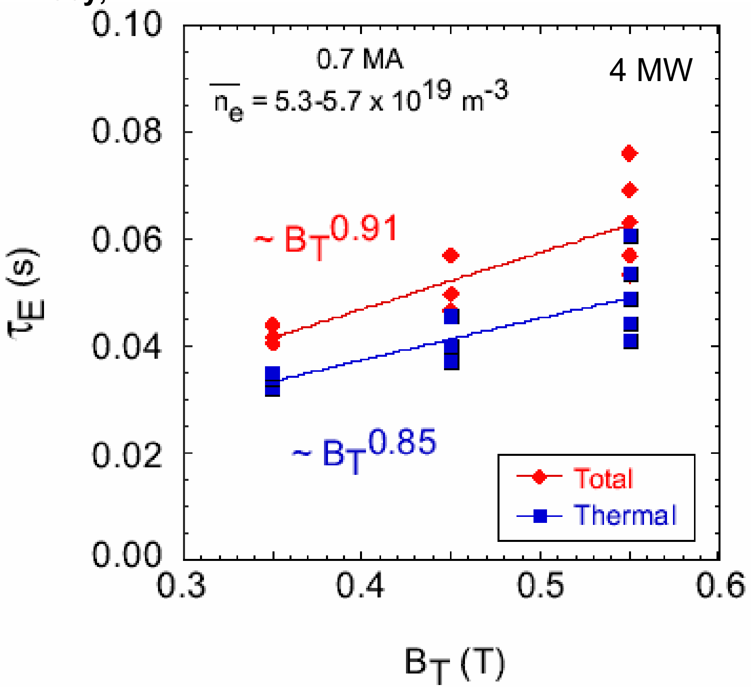
Electrons responsible for B_T dependence

Weaker dependence on I_P:

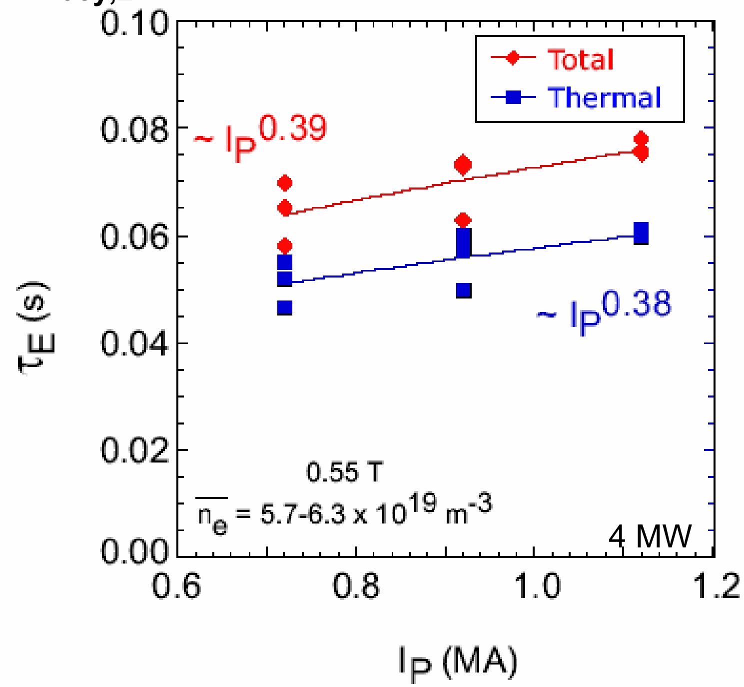
$\tau_{E\text{-}98y,2} \propto I_P^{0.93}$ $\tau_{E\text{-}NSTX} \propto I_P^{0.4}$

Ions responsible for I_P dependence

$H_{98y,2}$ ~ 0.9 → 1.1 → 1.4



$H_{98y,2}$ ~ 1.4 → 1.3 → 1.1



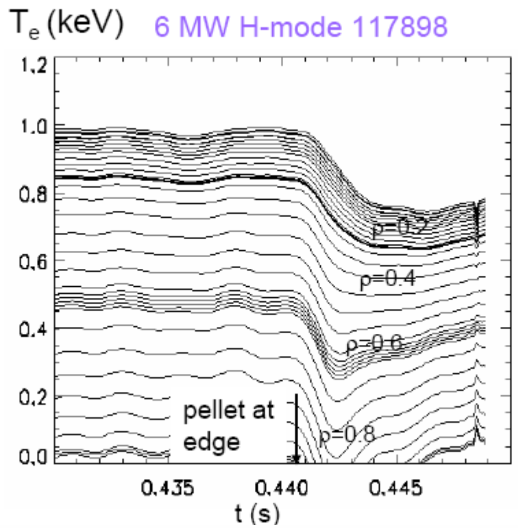
NSTX τ_E exhibits strong I_P scaling **at fixed q**:

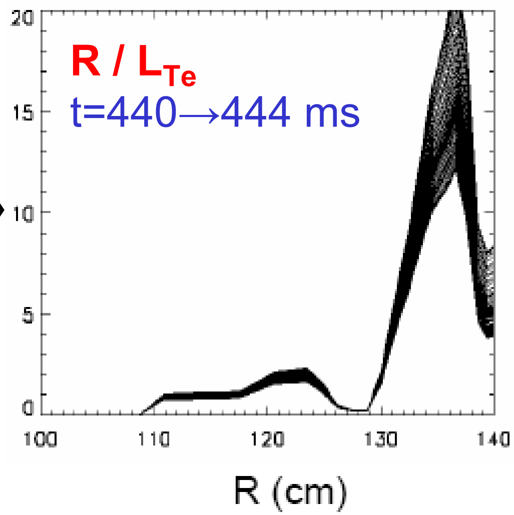
$\tau_{E\text{-}98y,2} \propto I_P^{1.1}$ $\tau_{E\text{-}NSTX} \propto I_P^{1.3\text{-}1.5}$

NSTX Transport Physics: S. Kaye – Oral EX/8-6

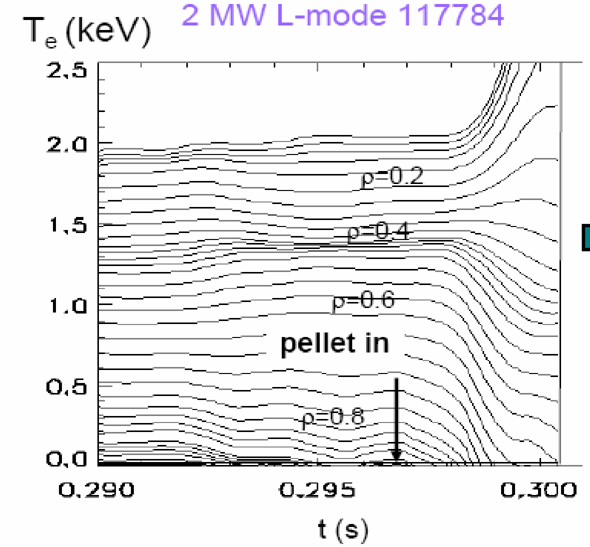
Pellet-induced temperature perturbations show that electron transport response depends strongly on equilibrium conditions

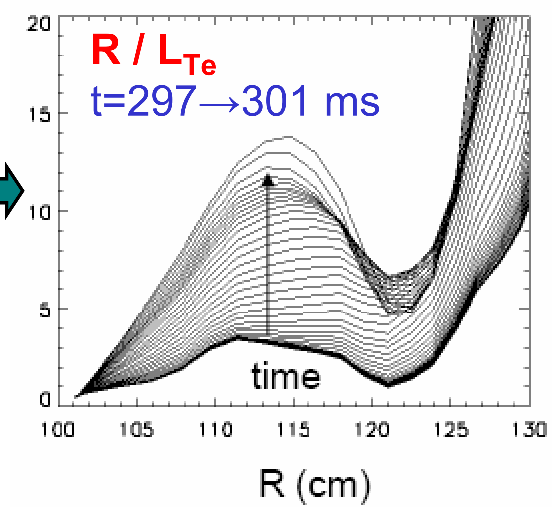
2-color soft X-ray array diagnoses fast T_e and ∇T_e response to lithium pellet injection





- **H-mode, monotonic q(ρ)**
  - Exhibits very stiff profile behavior →
  - **Critical T_e gradient**





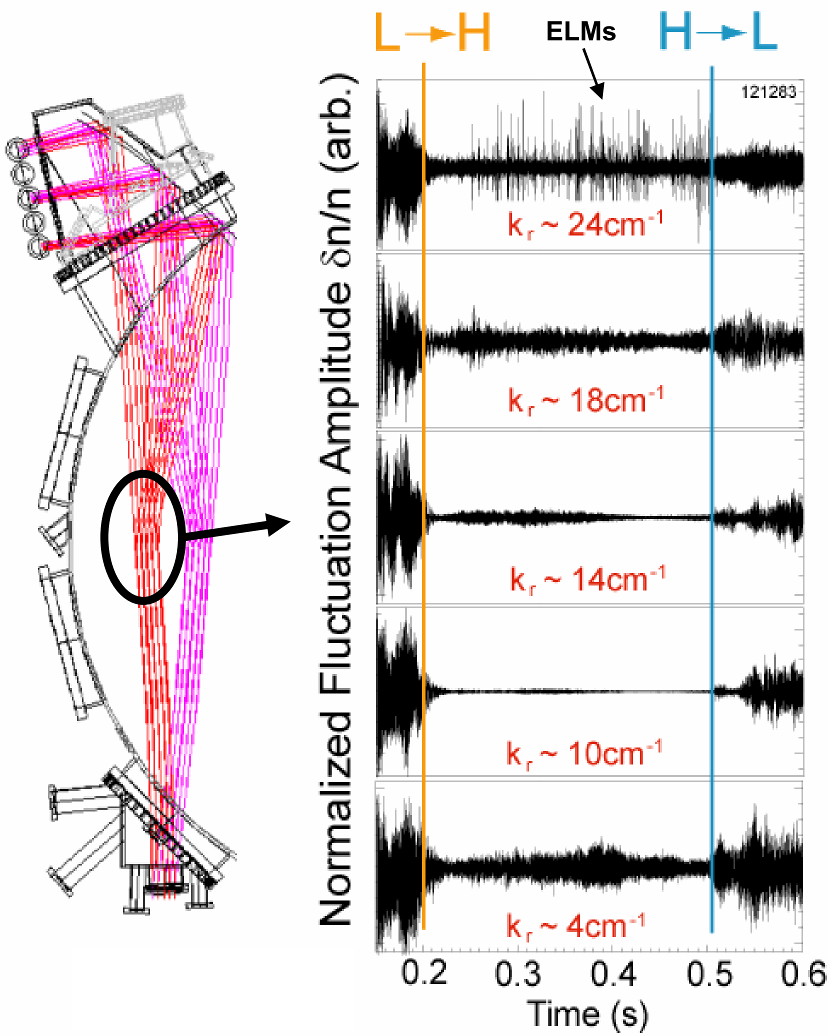
- **L-mode, reversed shear**
  - Core T_e increases while edge T_e decreases →
  - **No apparent critical temperature gradient**

Stutman, et al., to be published in PoP

Tangential microwave scattering system aiding in testing leading theories of anomalous electron transport

NSTX

Scattering system measures reduced $\delta n/n$ from upper ITG/TEM to ETG k_r ranges during H-mode

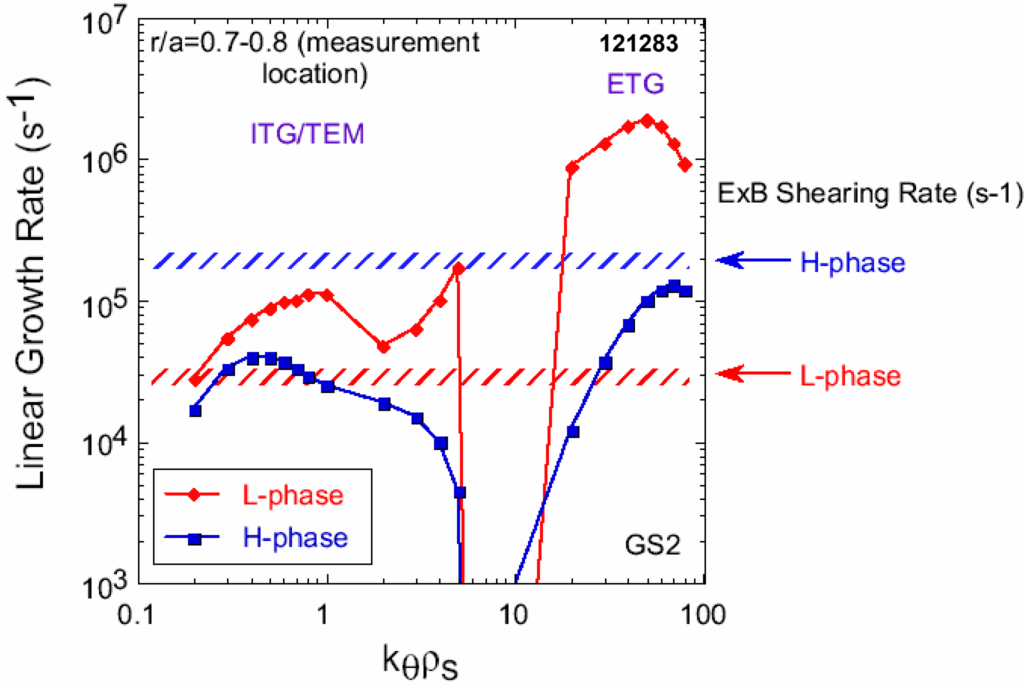


GS2 calculations indicate lower linear growth rates at all wavenumbers during H-mode: *ETG unstable*

$\gamma_{lin} >> \gamma_{ExB}$ during L-phase for all $k_\theta\rho_s$

$\gamma_{lin} << \gamma_{ExB}$ during H-phase for ITG/TEM

$\gamma_{lin} \sim \gamma_{ExB}$ during H-phase for ETG



Non-linear GTC → ITG *stable* during H-mode

χ_i at neoclassical level during H-mode

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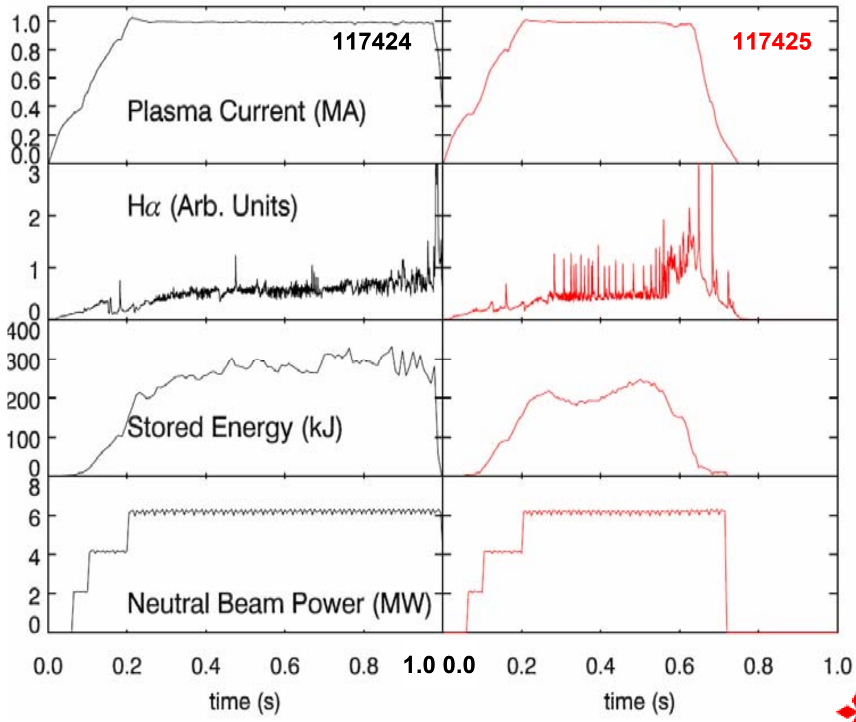
Experiments utilizing advanced shape control and parametric scans find ELM stability sensitive function of edge parameters

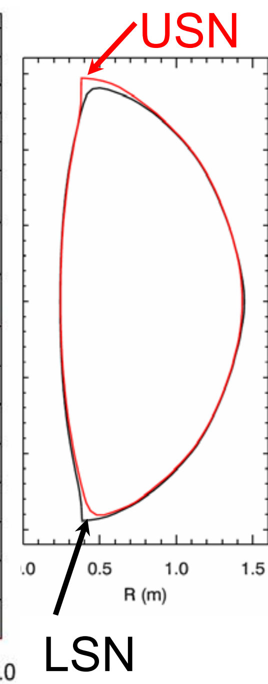
NSTX

- Control of ELM size critical issue for ITER
- Access to small-ELM regime sensitive function of magnetic topology

Lower Single Null (LSN) **Upper Single Null** (USN)



R. Maingi, Phys. Plasmas **13** (2006) 092510

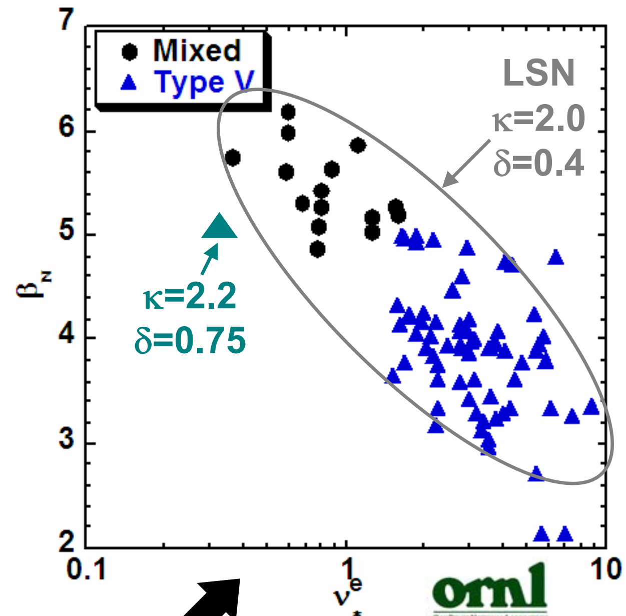


GENERAL ATOMICS

"Type V" = small ELM w/ ΔW/W < 1%

R. Maingi, Nucl. Fusion **45**, 1066 (2005)

I_P=0.6-0.9 MA, B_T=0.45T, P_{NBI} =2-6MW



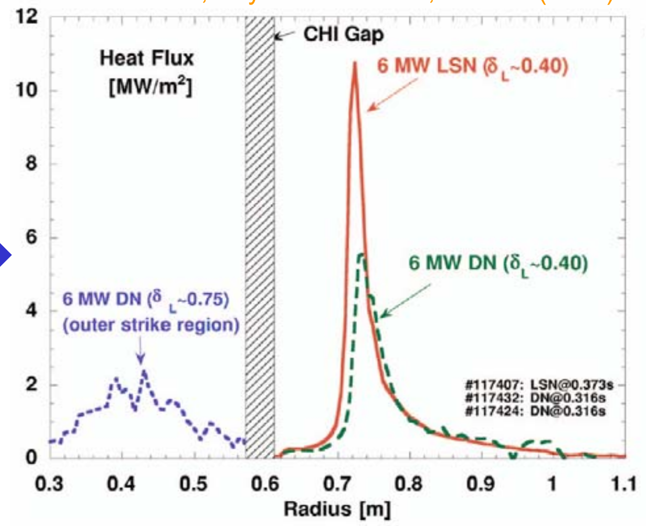
ornl

- ELM type also depends on global β_N & pedestal electron collisionality
  - Predicted to impact pedestal J_{BS}, access to ballooning second stability
  - Recent results find Type V also accessible at low ν_*^e via increased shaping

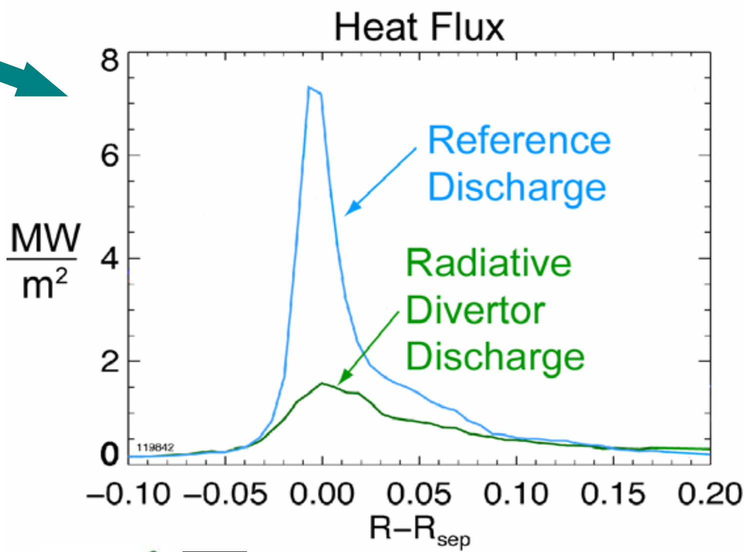
Divertor heat flux mitigation experiments achieved 5 × reduction in peak heat flux while remaining compatible with H-mode

- Steady-state divertor heat load mitigation critical for ST, ITER
  - NSTX: $q_{OUT} \leq 10$ MW/m^2, P/R < 9
  - Peak heat flux strongly shape-dependent in ST
  - NSTX divertor open, no active pumping
    - Inner strike point (ISP) is naturally detached
    - Outer SOL in high-recycling regime

D. Gates, Phys. Plasmas **13**, 056122 (2006)



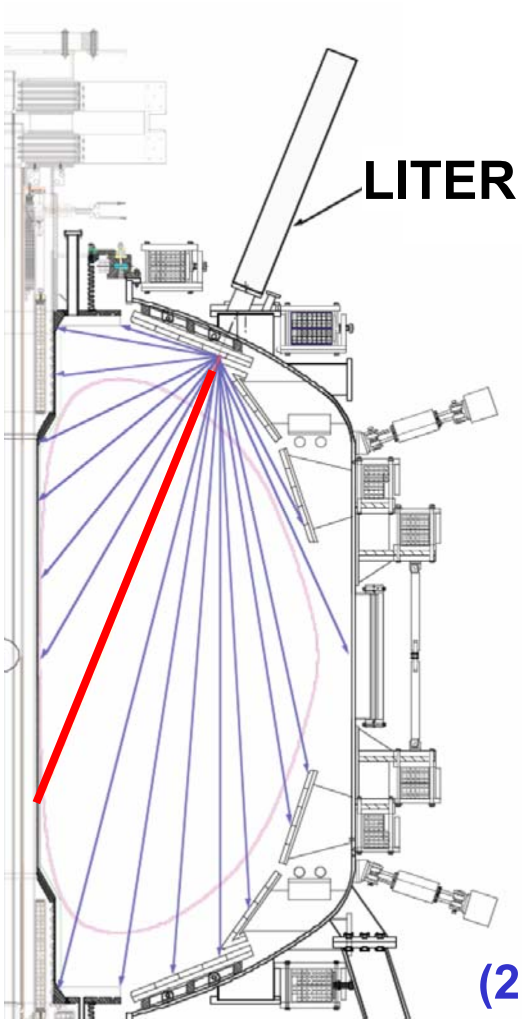
- Developed Radiative Divertor regime:
  - Outer SP (OSP) heat flux reduced by 4-5
  - No change in H-mode τ_E
  - Obtained by steady-state D_2 injection into private flux region or ISP

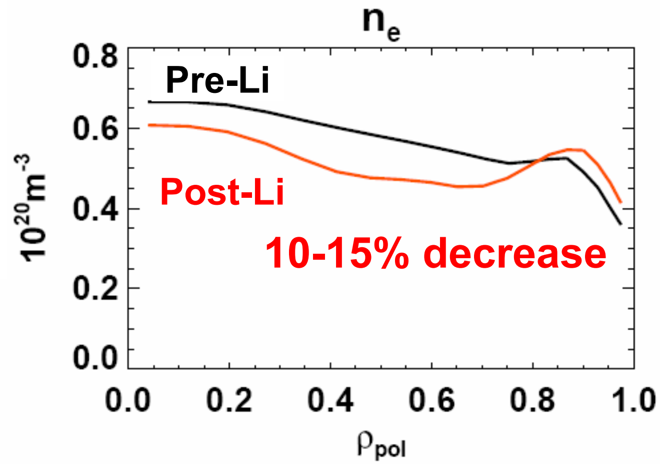


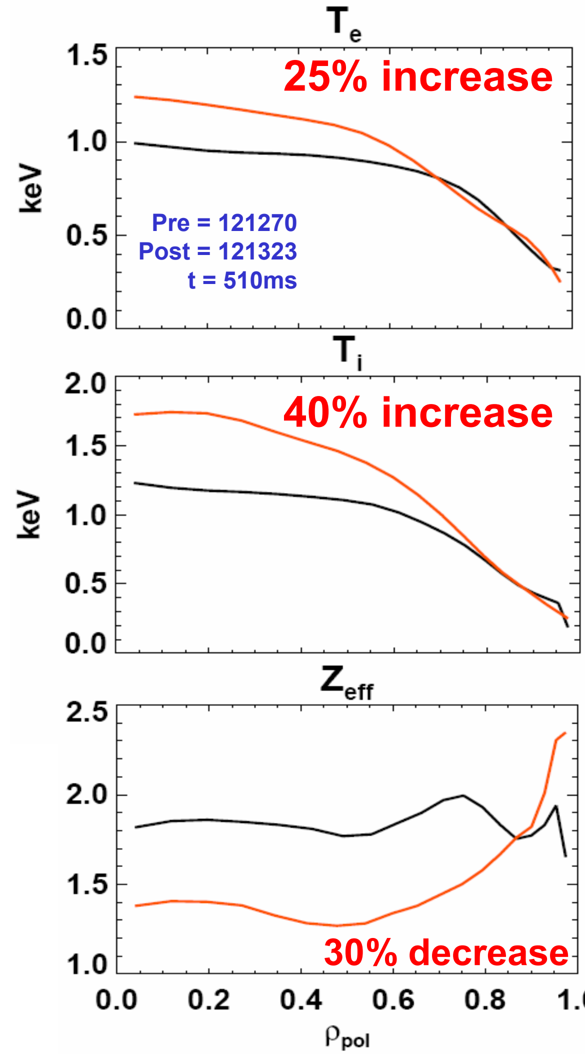
- Detached divertor regime also investigated
  - Induces H-L back transition, deleterious MHD

V. Soukhanovskii – Poster EX/P4-28

Initial Lithium Evaporator (LITER) experiments in H-mode exhibit improved particle pumping and energy confinement







TRANSP analysis:

W_{TOT} 20% higher post-Li

(reaches β-limit w/ same P_{NBI})

HH_{98y} = 1.1 → 1.3 post-Li

L-mode exhibits even larger (20-25%) relative density decrease

R. Majeski – Poster EX/P4-23

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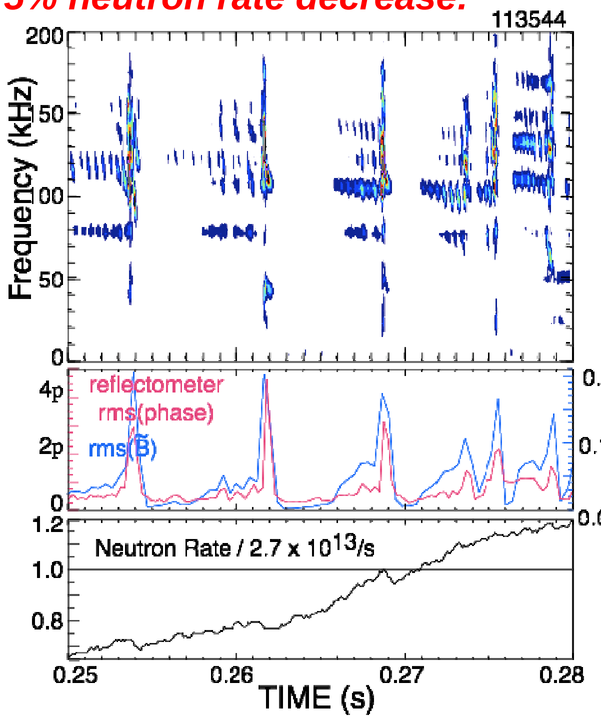
NSTX accesses ITER-relevant fast-ion phase-space island overlap regime with full diagnostic coverage – including MSE

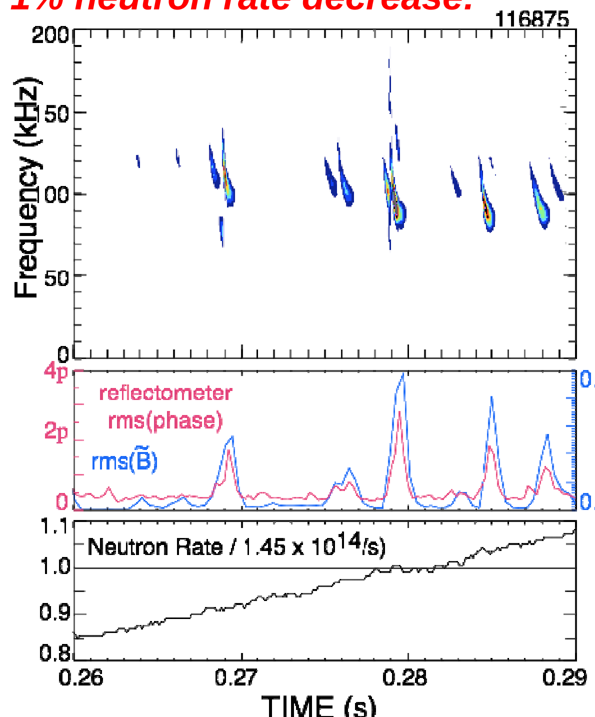
- **ITER** will operate in new, small ρ^* regime for fast ion transport
  - $k_\perp \rho \approx 1$ means "short" wavelength Alfvén modes
  - Fast ion transport expected from **interaction of many modes**
  - NSTX can access multi-mode regime via high $\beta_{fast} / \beta_{total}$ and v_{fast} / v_{Alfven}

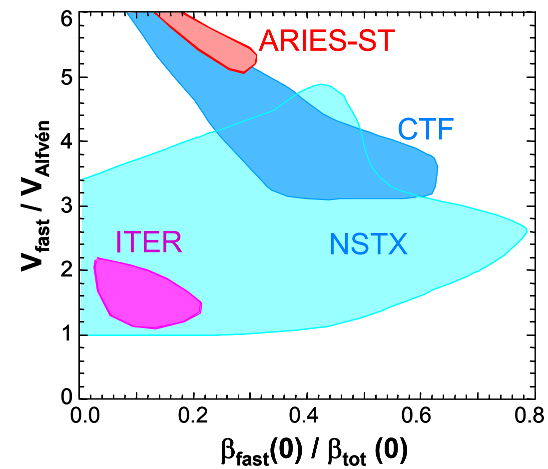
- **NSTX observes that multi-mode TAE bursts induce larger fast-ion losses than single-mode bursts:**

5% neutron rate decrease:



1% neutron rate decrease:





E. Fredrickson, Phys. Plasmas **13**, 056109 (2006)

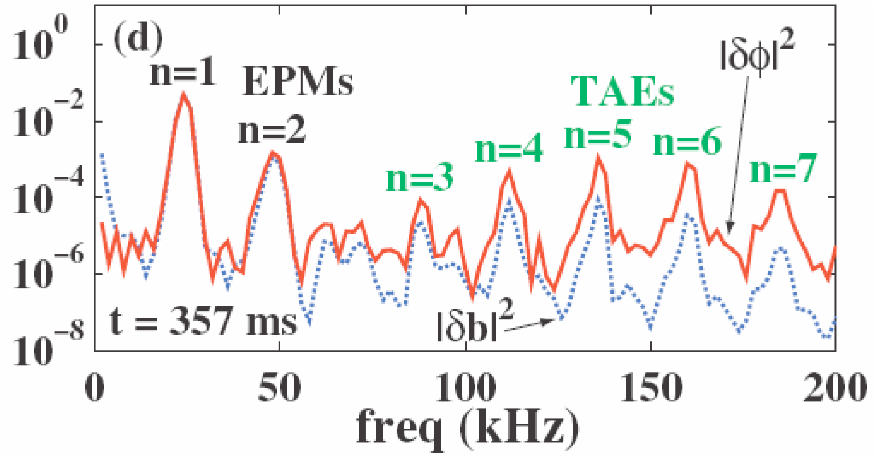
S. Medley – Poster EX/P6-13

Reflectometry data reveals 3-wave coupling of distinct fast-ion instabilities for first time

EPM ≡ Energetic Particle Mode

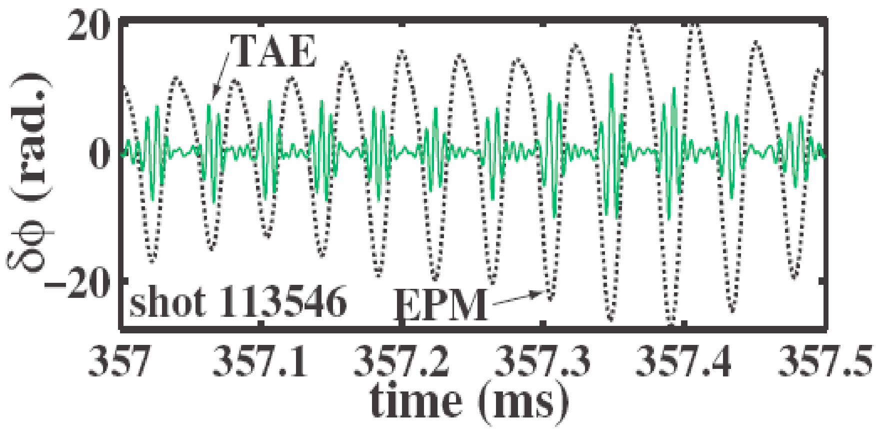
TAE ≡ Toroidal Alfven Eigenmode

- *Low-f EPMs co-exist with mid-f TAE modes*



Bi-coherence analysis reveals 3-wave coupling between 1 EPM and 2 TAE modes

- *Large EPM ➔TAE phase locks to EPM forming toroidally localized wave-packet*



N. Crocker, Phys. Rev. Lett. **97**, 045002 (2006)

Influence of toroidal localization of TAE mode energy on fast ion transport and EPM/TAE stability presently being investigated

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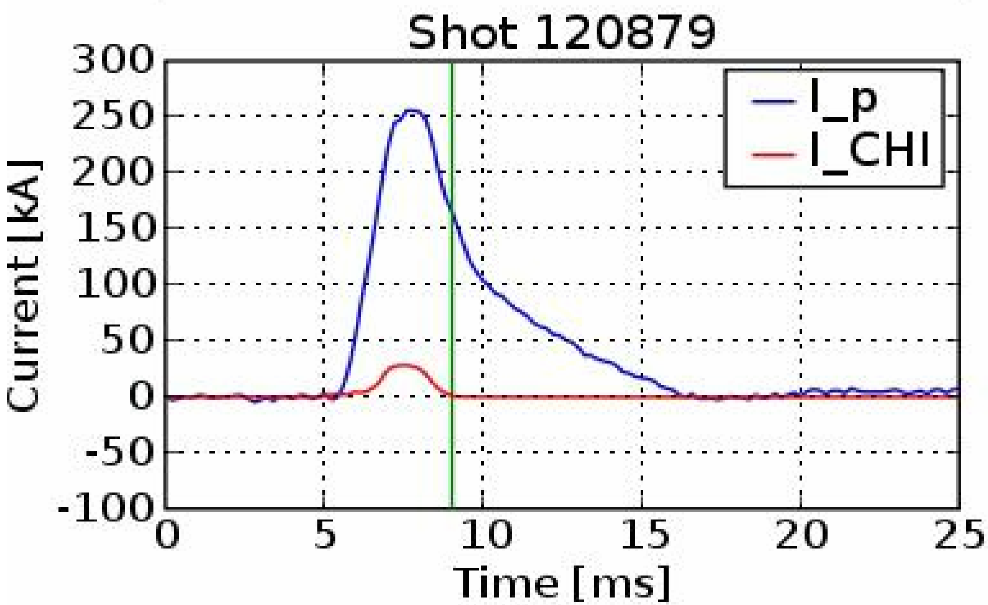
Coaxial Helicity Injection (CHI) has convincingly demonstrated the formation of closed poloidal flux at high plasma current

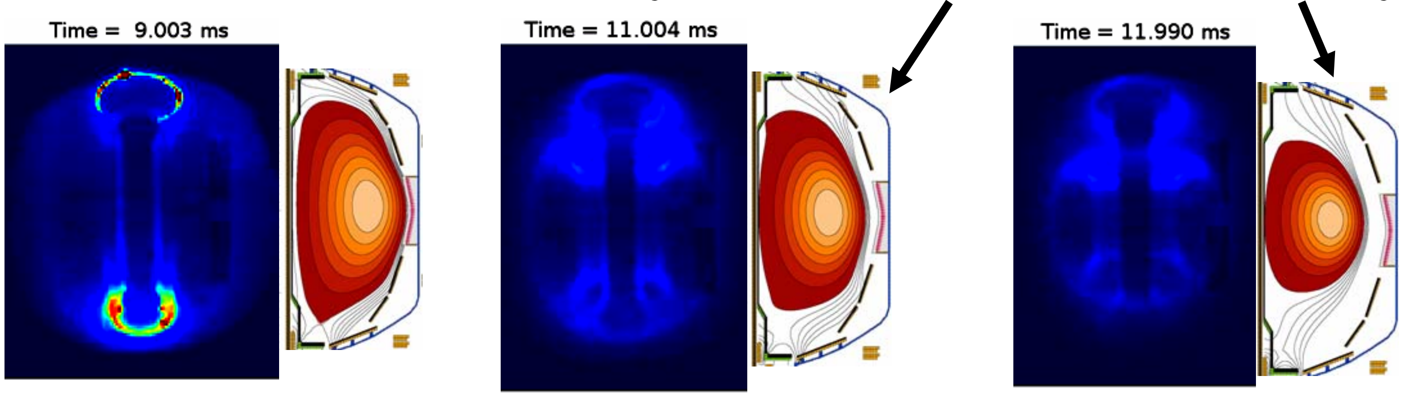
Evidence for high-I_P flux closure:

1. I_P=160kA remains after CHI injector current I_{CHI} → 0 at t=9ms



2. After t=9ms, plasma current decays away inductively

3. Once I_{INJ}→ 0, reconstructions track dynamics of detachment & decay



UWPS

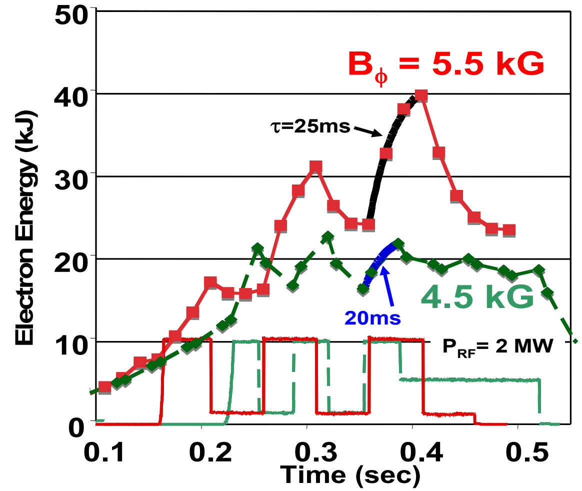
R. Raman, PRL (2006), accepted for publication

R. Raman – Poster EX/P8-16

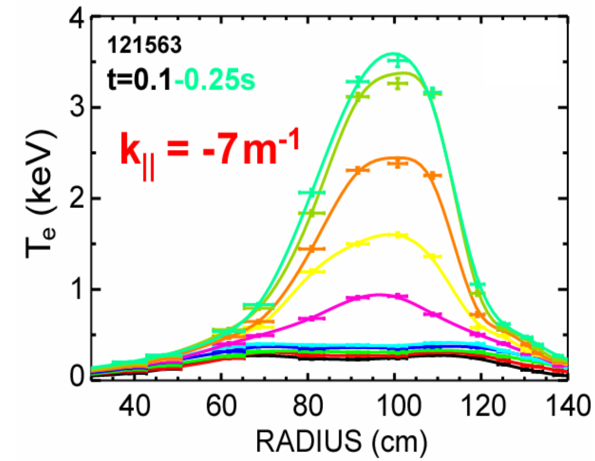
High-harmonic fast waves (HHFW) and electron Bernstein waves (EBW) being explored for low-I_P heating and I_P ramp-up

- **Goal: I_P ramp-up of CHI plasma with HHFW-CD & BS overdrive**

- Recent discovery: In CD phasing, electron heating efficiency doubled by increasing B_T=0.45T → 0.55T
  - Reduced parametric decay instabilities
  - Reduced surface wave excitation



- Achieved **high T_e=3.6keV** with HHFW in CD phasing for first time
  - Near NSTX record T_e of 4keV
  - Achieved at highest B_T = 5.5kG
  - **Can heat low-T_e = 200eV target plasma**



EBW emission measurements with steerable radiometer:

Measure up to 90% BXO conversion efficiency → Potential for efficient heating and CD

Highest in L-mode, poorer apparent coupling in H-mode

D. Gates – Poster EX/P1-3

NSTX is strongly contributing to fundamental toroidal confinement science in support of ITER and future ST's

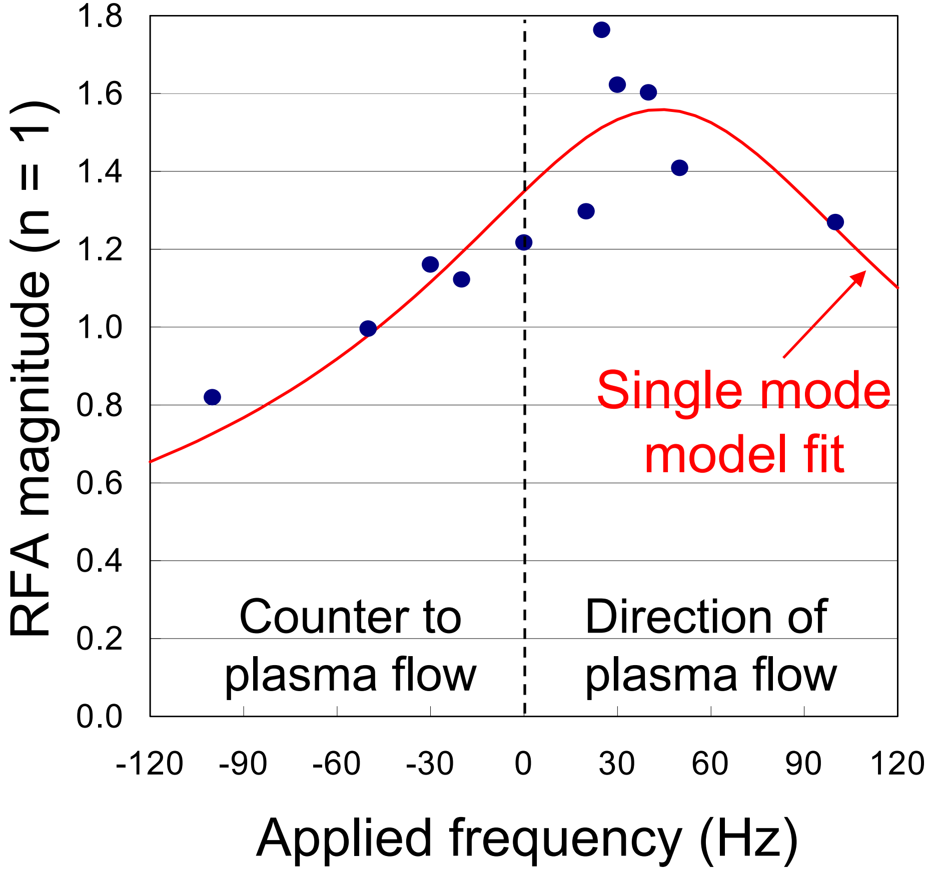
- NSTX normalized performance approaching ST-CTF level
  - D. Gates – Poster EX/P1-3
- Only ST in world with advanced mode stabilization tools and diagnostics
  - A. Sontag – Oral EX/7-2Rb, S. Sabbagh – post-deadline
- Unique tools for understanding core and edge transport and turbulence
  - S. Kaye – Oral EX/8-6, J. Myra – Poster TH/P6-21, J. Boedo – Poster EX/P4-2
- Developing understanding and unique tools for heat flux and particle control
  - V. Soukhanovskii – Poster EX/P4-28, R. Majeski – Poster EX/P4-23
- Uniquely able to mimic ITER fast-ion instability drive with full diagnostics
  - S. Medley – Poster EX/P6-13
- Demonstrated 160kA closed-flux plasma formation in NSTX using CHI
  - R. Raman – Poster EX/P8-16
- Improved understanding of HHFW and EBW coupling/heating efficiency
  - D. Gates – Poster EX/P1-3

ST offers compact geometry + high β attractive for CTF & reactor

Backup Viewgraphs

Low-frequency MHD spectroscopy used to diagnose stable RWM

$$RFA = \frac{\delta B_{measured}}{\delta B_{applied}}$$



- Toroidally propagating n = 1 fields used to examine resonant field amplification (RFA) of stable RWM
  - propagation frequency and direction scanned
  - RFA increases when applied field rotates with plasma flow
  - consistent with DIII-D results and theoretical expectations
- Single mode model of RWM fit to measured RFA data
  - peak in fit at 45 Hz in direction of plasma flow

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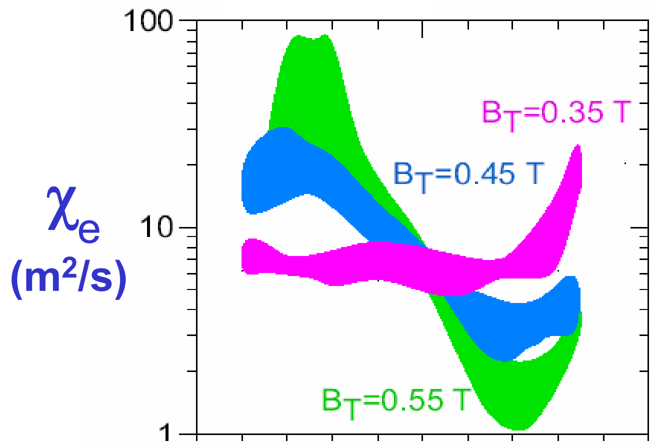
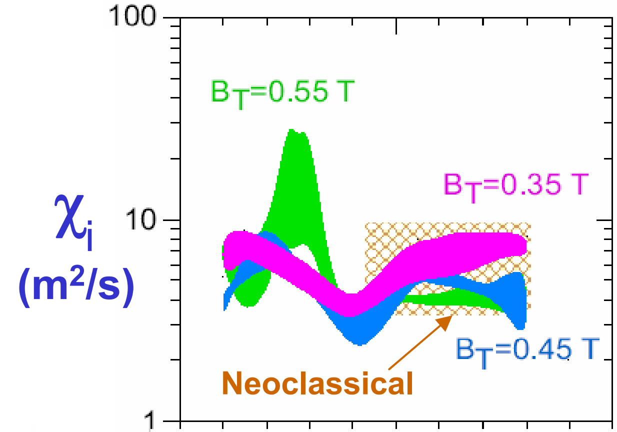
A. Sontag – Oral EX/7-2Rb

Thermal diffusivity profiles reveal source of confinement scalings

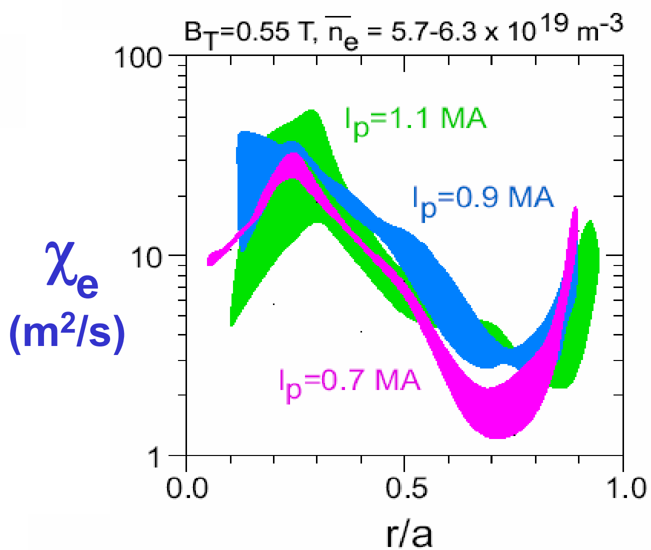
Broadening of T_e & reduction in χ_e outside r/a=0.5 with increasing B_T

Ion confinement outside r/a=0.5 consistent with neoclassical χ →

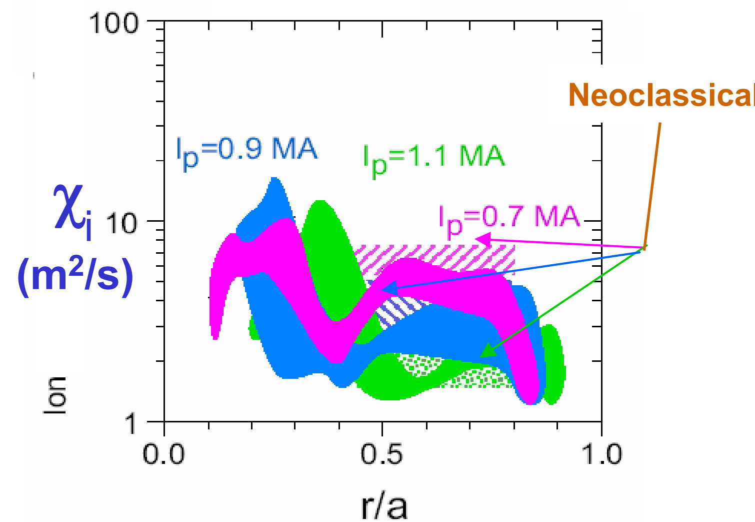




B_T Scan (fixed I_P)



I_P Scan (fixed B_T)



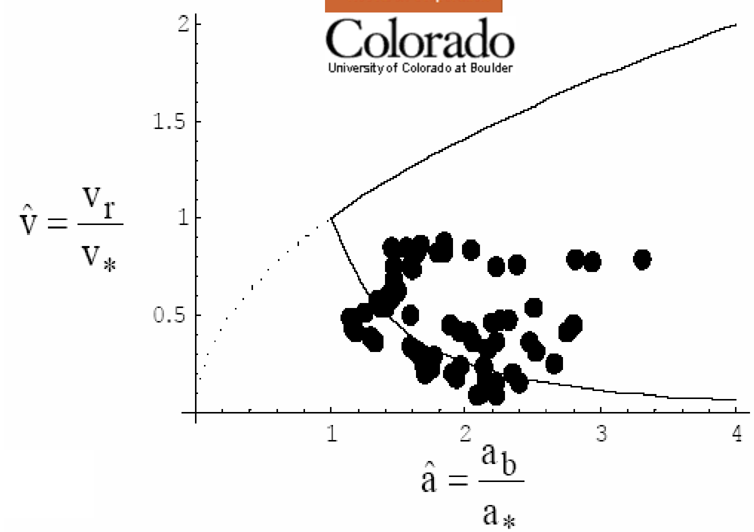
Electrons responsible for B_T dependence

Ions responsible for I_P dependence

Blob dynamics measured with gas-puff-imaging (GPI) and edge probe are being systematically compared to 2D transport theory

- Bounds on GPI-inferred blob radial velocities roughly consistent with 2D theory
  - blobs speed up with collisionality Λ
  - low Λ, small blobs fastest
  - large Λ, large blobs fastest

J. Myra – Poster TH/P6-21



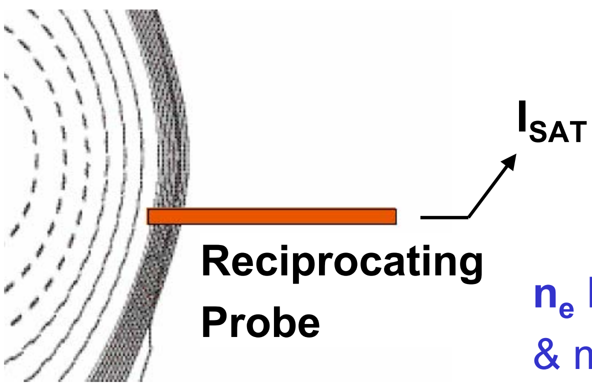
$$\frac{1}{\hat{a}^2} < \frac{v_r}{v_*} < \hat{a}^{1/2}$$

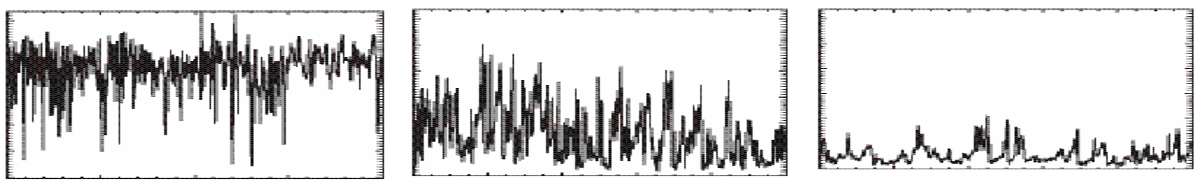
$$v_* = c_s\left(\frac{a_*}{R}\right)^{1/2}$$

$$\hat{a} = \frac{a_b}{a_*} = \frac{a_b R^{1/5}}{L_{\|}^{2/5}\rho_s^{4/5}}$$

$$\Lambda = \frac{\nu_{ei} L_{\|}}{\Omega_e \rho_s}$$

- Formation & dynamics of n_e holes & peaks being compared to theory

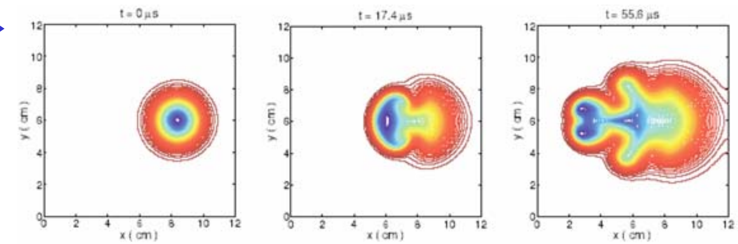




Holes: $R-R_{SEP} < -1$cm   Mixed: $-1 < R-R_{SEP} < 0$cm   Peaks: $R-R_{SEP} > 0$cm

n_e holes predicted

& measured to propagate inward in major radius

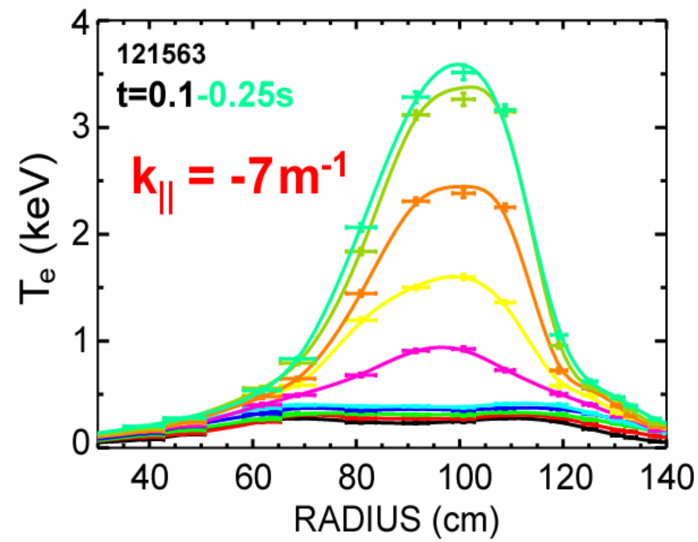


J. Boedo – Poster EX/P4-2

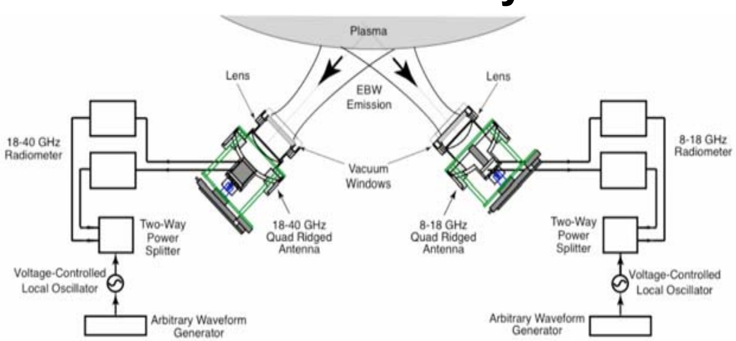
High-harmonic fast waves (HHFW) and electron Bernstein waves (EBW) being explored for low-I_P heating and I_P ramp-up

NSTX

- Achieved **high T_e=3.6keV** with HHFW in **CD phasing** for first time
  - Can heat 200eV target plasma
  - Achieved at highest B_T = 5.5kG
    - Reduced parametric decay instabilities
    - Reduced surface wave excitation
- Will attempt to ramp-up CHI plasma with HHFW-CD & BS overdrive



Dual-antenna remotely-steerable EBW radiometer system:



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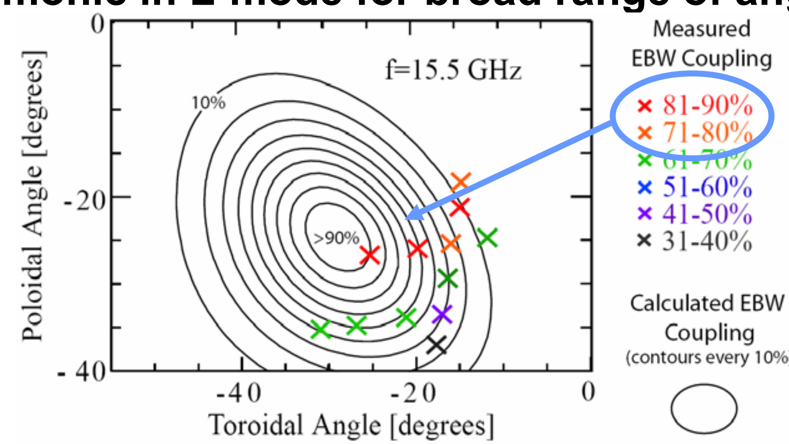
Measure up to 90% EBW coupling efficiency

1st harmonic in L-mode for broad range of angles



→ **Potential for efficient EBW heating and CD**