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NSTX Progress and Plans for
Wave-particle Interactions, Boundary Physics, Integrated Scenarios, and Solenoid-free Start-up

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Jonathan Menard
For the NSTX Research Team

Mid-term Review of Major MFE Facilities
Gaithersburg, MD
September 21, 2006

Culham Sci Ctr
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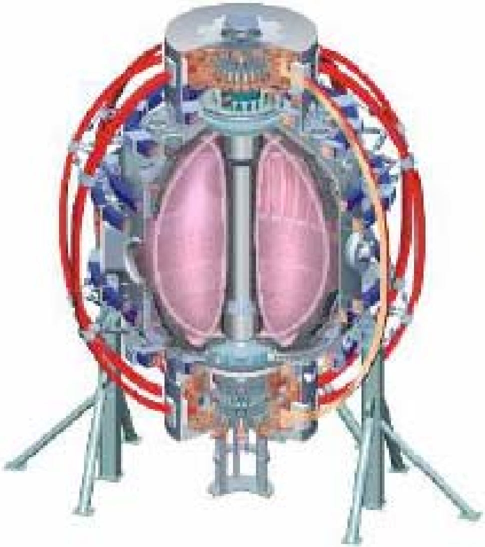
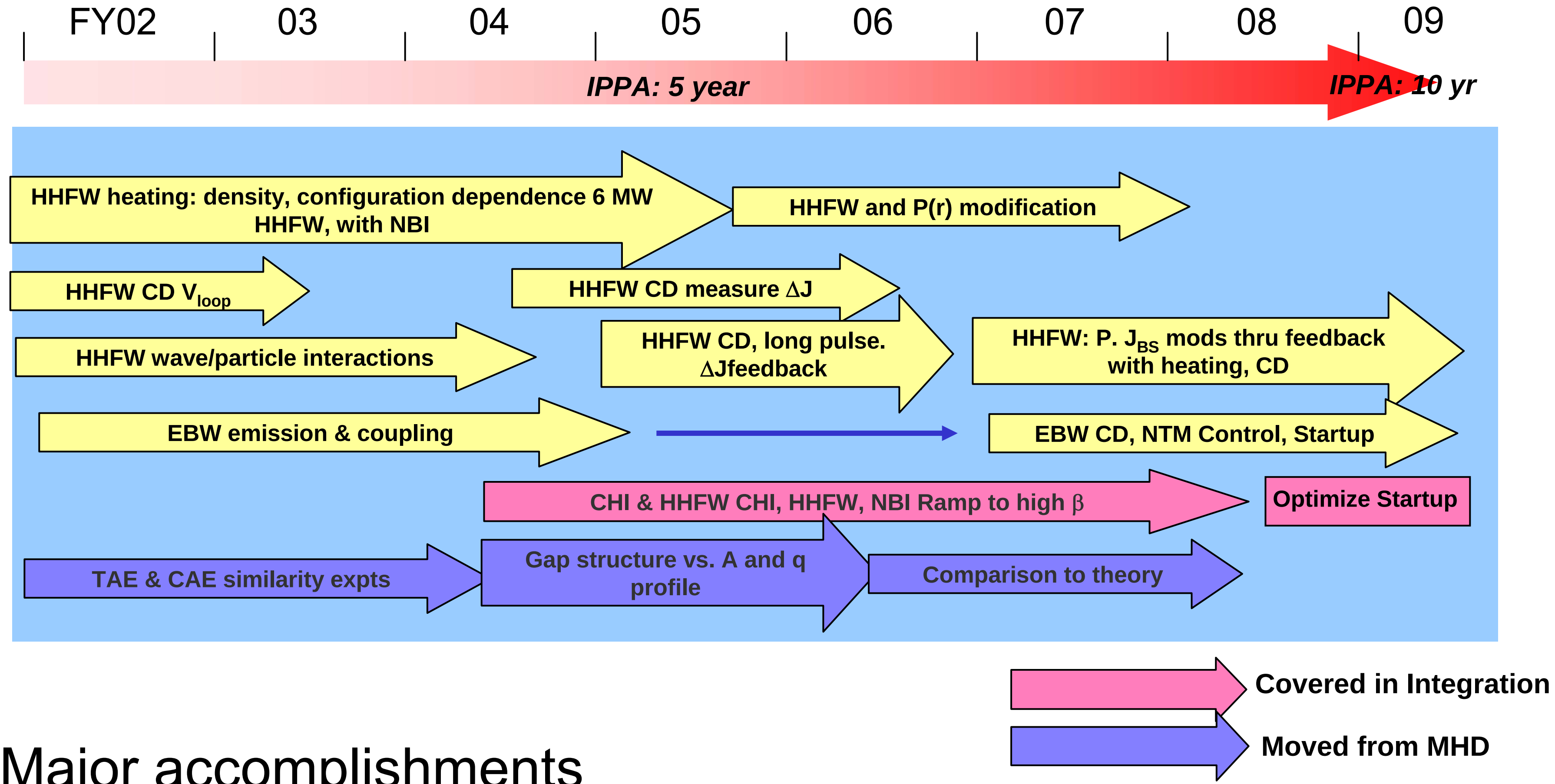


NSTX contributes broadly to fundamental toroidal confinement science in support of ITER and future ST's

- Wave-Particle Interactions
  - HHFW, EBW, fast-ion MHD
- Boundary Physics
- Integrated Scenarios + Solenoid-free Start-up

Wave-Particle Interaction Research



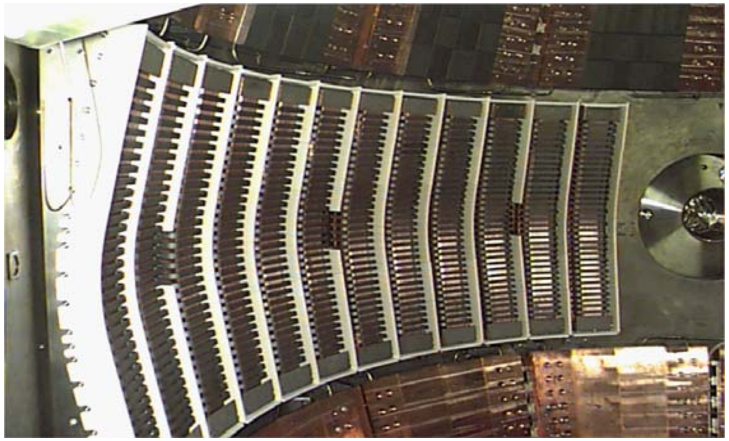
- Major accomplishments
  - Demonstration & understanding of HHFW core heating & current drive
  - Demonstrated possibility of high-power coupling to EBW
  - Discovered several new fast-ion-driven instabilities
  - Observe non-linear coupling of multiple fast-ion modes

NSTX is developing innovative wave heating and current drive techniques in a unique wave parameter regime

- High β → over-dense plasma ($\omega_{pe} > \Omega_{ce}$) with low v_A
  - – Lower Hybrid and Electron Cyclotron (EC) waves do not propagate
  - – Fast Alfvén Waves propagate with strong single-pass electron absorption
  - – Electron Bernstein Wave (EBW)→ no n_e limit + localized absorption
    - EBW current drive 2-4 × more efficient than Electron Cyclotron current drive
- Complementary NSTX characteristics
  - – Fast Wave also used for core current drive in AT plasmas of DIII-D
  - – Efficient off-axis Ohkawa current drive physics relevant to AT

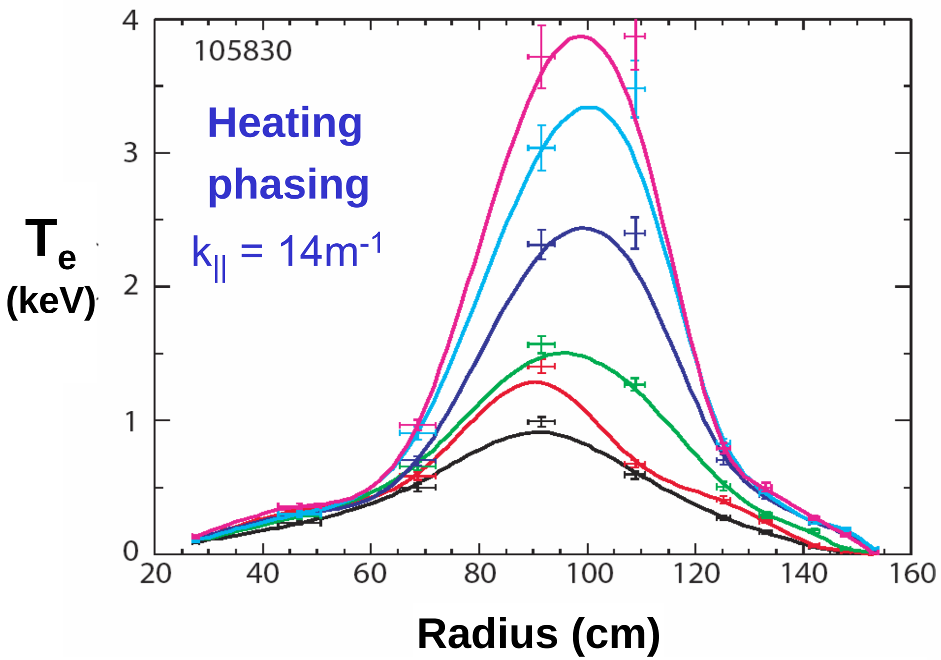
- ***NSTX High-Harmonic Fast Wave (HHFW) heating and current drive research utilizes world's most sophisticated ICRF launcher:***

- *12 strap antenna, 6MW capability*
- *6 independent transmitters*
- *Real-time control of launched $k_{||}$ from 0 to $14 m^{-1}$*



HHFW has successfully heated electrons and demonstrated core current drive in NSTX

Highest core electron temperatures on NSTX achieved with HHFW

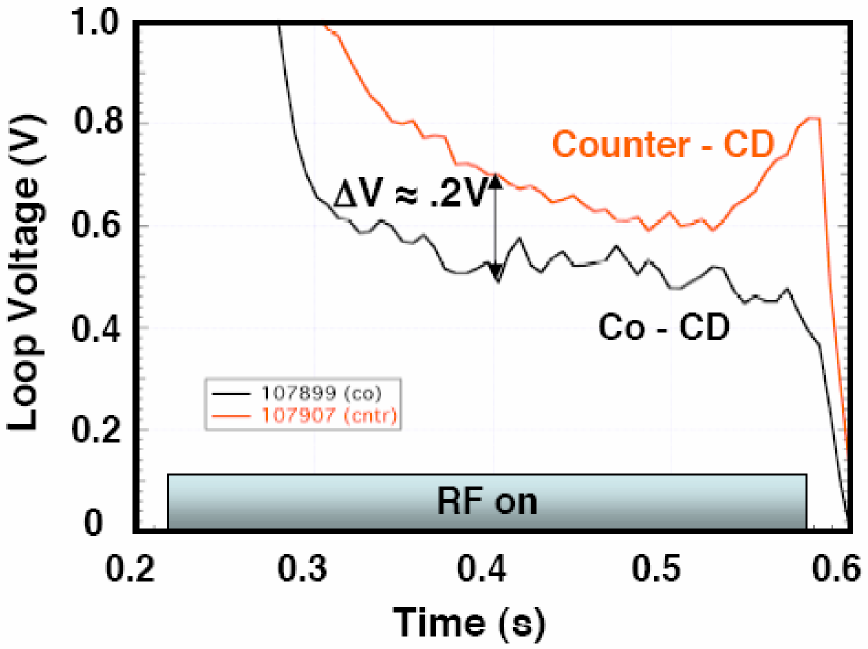


B. LeBlanc, Nucl. Fusion **44,** 513 (2004)

Co minus counter current drive

$\Delta I_{CD} = 180kA \ (I_P = 800kA)$

Consistent with theory predictions

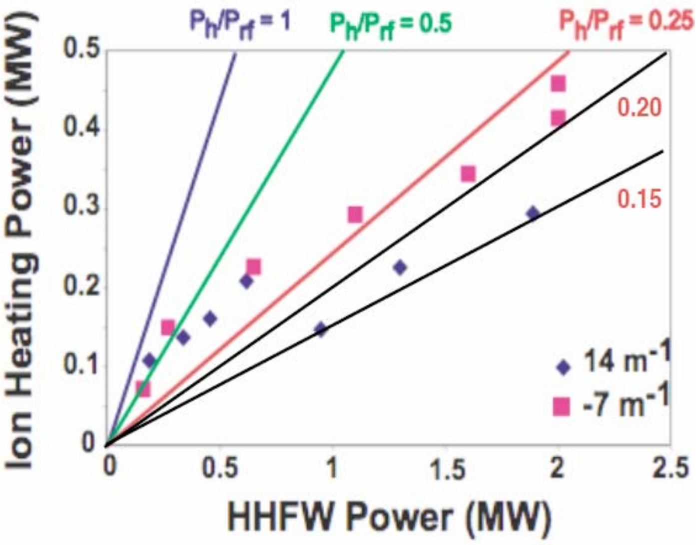


J.R. Wilson, Phys. Plasmas **10**, 1733 (2003)

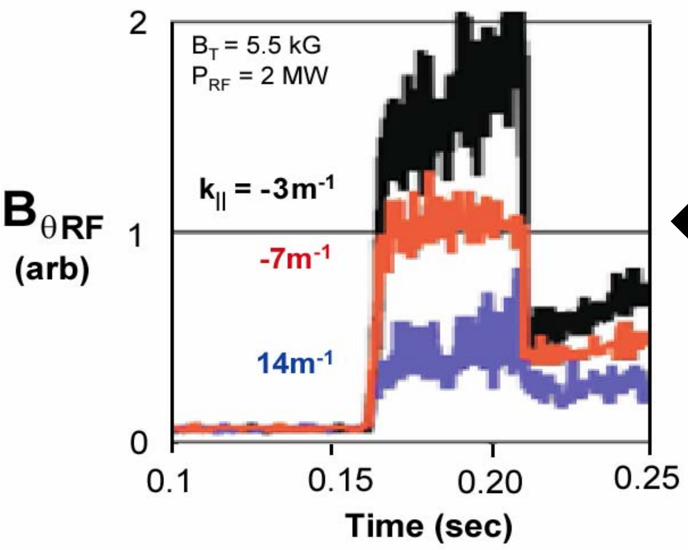
- **However, HHFW heating of core electrons is not always robust**
  - **Observe HHFW acceleration of NBI fast ions** A.L. Rosenberg, Phys. Plasmas **11**, 2441 (2004)

Improved understanding of HHFW edge interactions motivates changes to HHFW system for more efficient heating & CD

- Parametric Decay Instability (PDI) of HHFW → IBW → edge ion heating
  - PDI increases with lower $k_{||}$ and/or B_T
    - Low $k_{||}$ used for HHFW current drive
    - Low B_T needed for high β



T. Biewer, Phys. Plasmas **12**, 056108 (2005)



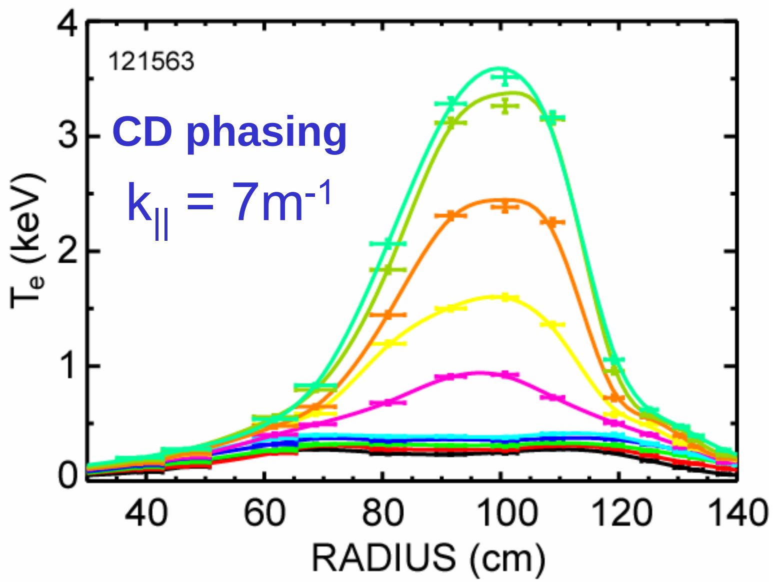
HHFW at low $k_{||}$ should begin propagating at much lower n_e → surface waves, wall interactions

- dB/dt probe data consistent with lower edge wave amplitude at high $k_{||}$

Both results imply higher $k_{||}$ should improve HHFW core electron heating

Key Research Results and Plans for HHFW

- Achieved high T_e=3.6keV in current drive phasing for first time using high B_T = 5.5kG
  - Improvement consistent with reduced PDI and surface waves expected at higher B_T
  - Expect similar improvements from **higher $k_{||}$**
    - Useful for HHFW-CD during ramp-up
    - Useful for HHFW heating at high-β



J. Menard, IAEA 2006

PLANS:

- Continue RF edge studies investigating causes of parasitic absorption (FY07-08)
  - Surface wave excitation damping + parametric decay instability ion heating
  - Additional RF probes to measure waves in plasma periphery
  - UCLA reflectometer upgrade to measure higher edge densities for RF studies

- HHFW antenna modification ⇒ directed spectra at 11m^{-1} for improved CD (FY-09)
  - High power operation capable of heating T_e ~ 50eV plasma with 28m^{-1}

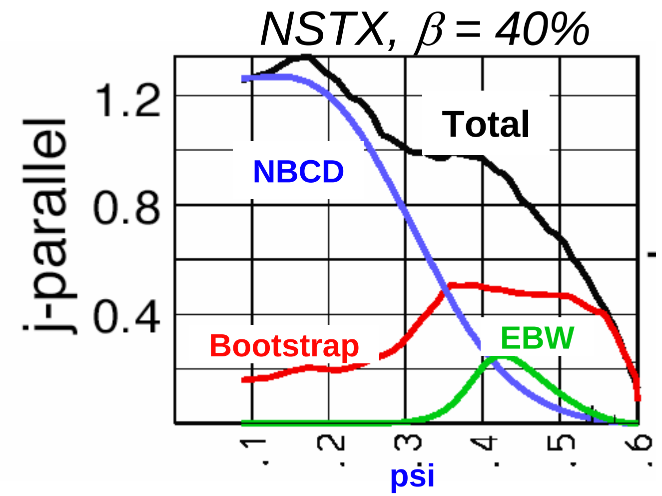
New physics understanding enabled by study of wave physics in over-dense plasmas

- Off-axis and efficient CD required for high β_T=40%, f_{NI} = 100% integrated scenarios.

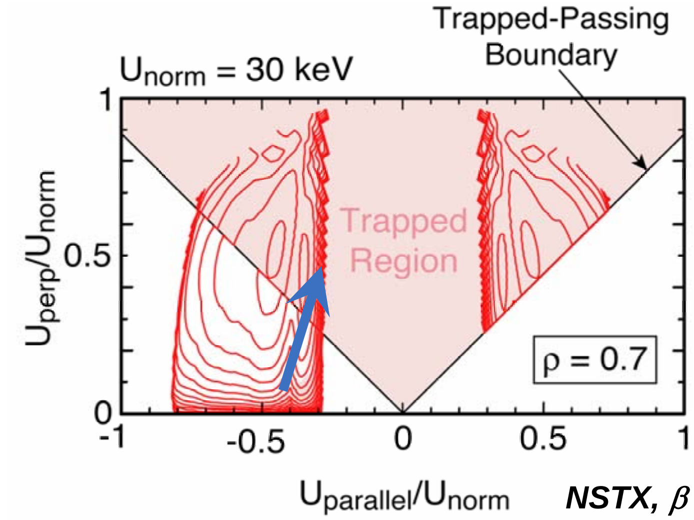
- EBW holds promise of taking advantage of unique, high trapping region: Ohkawa current drive:
  - **0.4 < ρ < 0.7 → $\zeta_{EBW\text{-}CD}$ = 0.4**
    - **2× more efficient than ECCD**
    - **8× more efficient than HHFW**

$$\zeta_{CD} \equiv 3.27 \times \frac{I_p(A) \times R(m) \times n_e\,(10^{19} m^{-3})}{P(W) \times T_e(keV)}$$

- For concept innovation: establish wave physics understanding for high beta fusion systems



C. Kessel, Nucl. Fusion **45** 814 (2005)



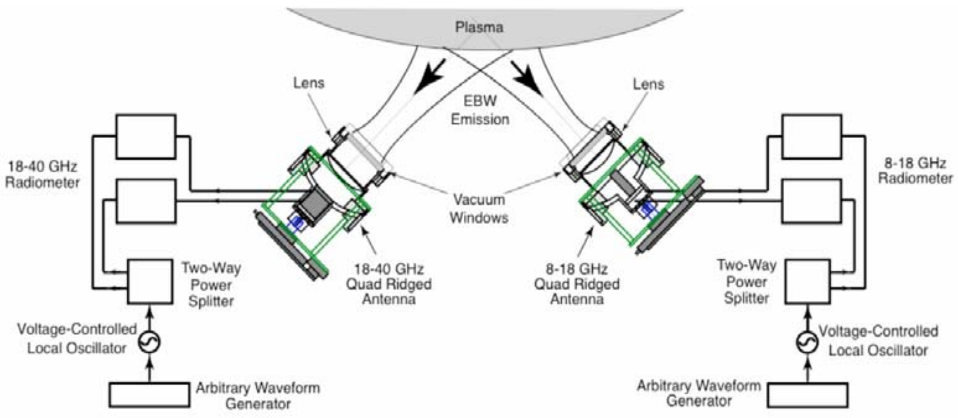
NSTX, β = 42%

CompX

G. Taylor, Phys. Plasmas **11** 4733 (2004), R. Harvey, Phys. Plasmas **12** 052509 (2005)

Initial measurements of B-X-O emission on NSTX confirm possibility of high-power coupling to EBW

Dual-antenna remotely-steerable EBW radiometer system:



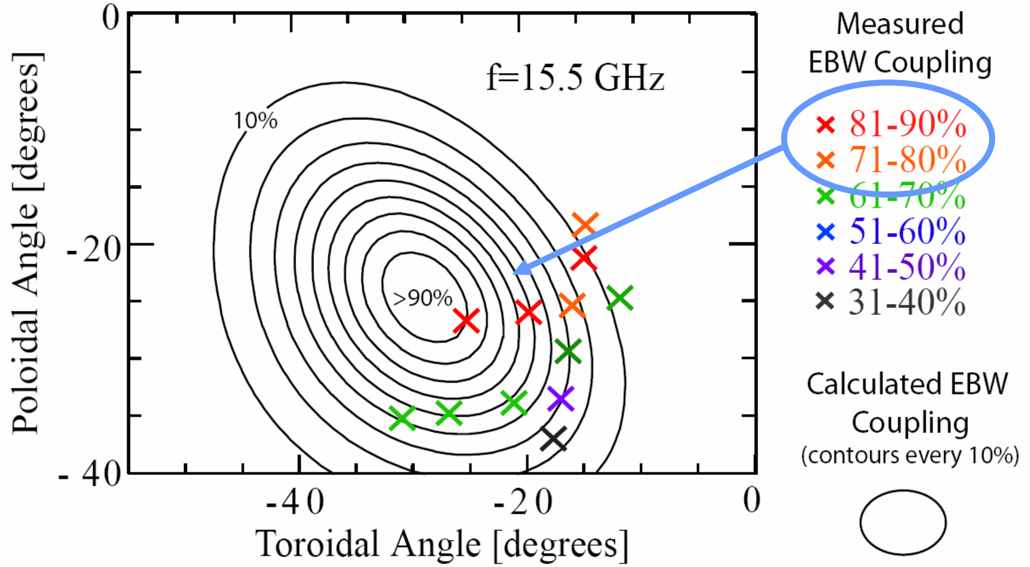
- Frequency range:
  - 1st & 2nd harmonic: 8-18GHz
  - 2nd & 3rd : 18-40 GHz
- Directionality:
  - ±10° steering in poloidal and toroidal directions
- Antenna acceptance angles:
  - 8-18GHz ~ 22°, 18-40GHz ~ 14°

- High EBW coupling efficiency for broad range of antenna pointing angles in L-mode:

G. Taylor, Phys. Plasmas **12** 052511 (2005)

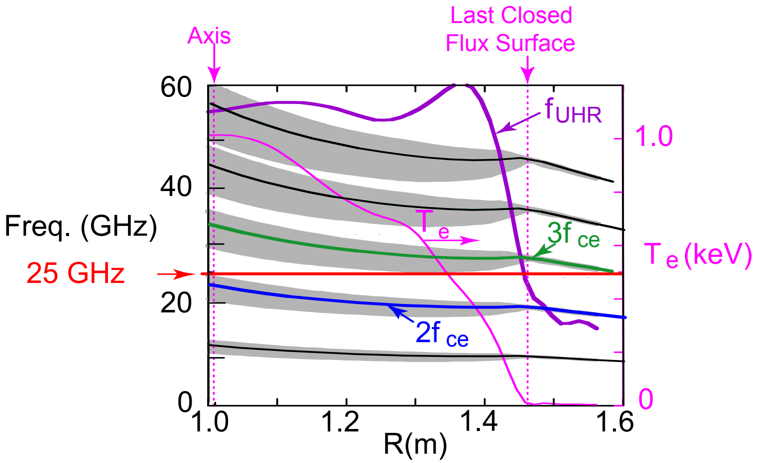
- But, poor apparent coupling efficiency (< 30%) observed in H-mode discharges

1st harmonic coupling efficiency vs. angle in L-Mode:



MAST MEGA-AMPERE SPHERICAL TOKAMAK UKAEA THE ACADEMY OF SCIENCES OF THE CZECH REPUBLIC ornl OAK RIDGE NATIONAL LABORATORY

Key Research Results and Plans for EBW



- 2005: Emission measurements in H-mode consistent with $3f_{ce}$ emission from large r/a
  - Evidence for collisional damping at f_{UHR} and possibility for $2f_{ce}$ overlap
- 2006: Angle/freq. scans confirm 2005 result:
  - Strong coupling in L-mode, poor in H-mode

PLANS:

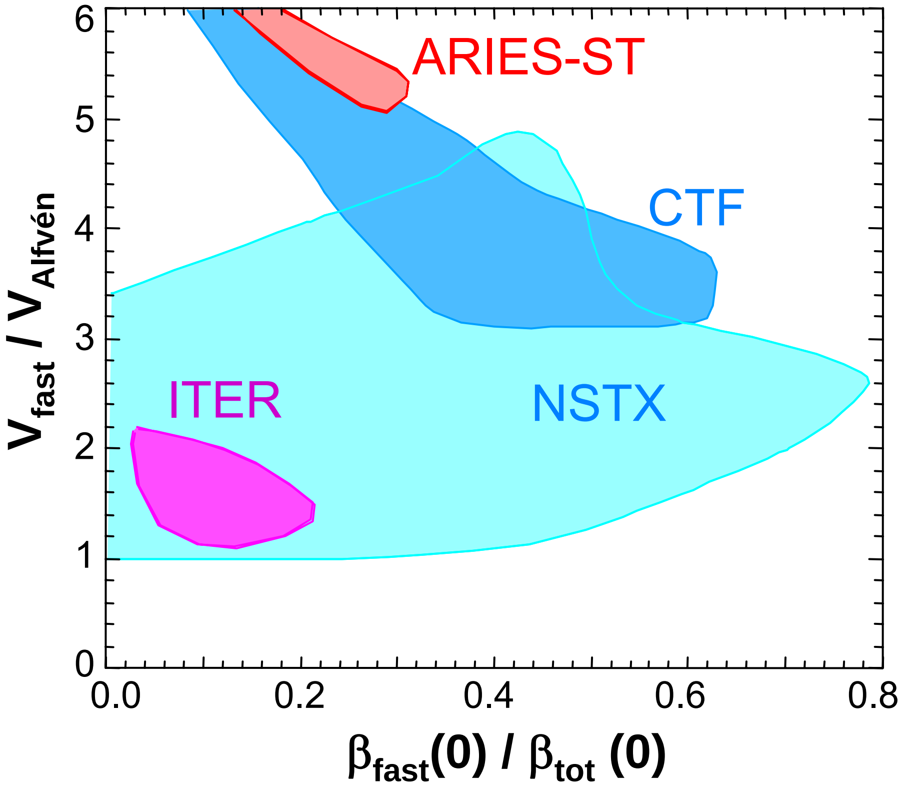
- Implement 100-200kW 15.3-28GHz EBW system w/ ORNL gyrotrons (FY08)
  - **EC pre-ionization & heating for CHI & PF-only startup plasmas (low n_e, T_e)**
  - **EBW coupling studies + initial electron heating experiments**

- Test EBW coupling models for L & H-mode plasmas (FY07-08) **(Ph.D. Thesis)**
  - Experiments to understand cause of apparent poor coupling in H-modes

- Enhanced understanding & modeling through collaboration (FY07-08)
  - MAST collaboration: 28GHz startup/ramp-up (FY-07), B-X-O (FY07-08)
  - Include EBW mode conversion in GENRAY, optimize EBWCD scenarios [MIT]
  - Radial transport, Ohkawa anti-pinch effect on BS - CQL3D/GENRAY [Comp-X]
    - Also EBE from non-thermal electrons – same model used for ECE on ITER

NSTX is an excellent test-bed for simulation and validation of critical fast ion physics for burning plasmas

- NSTX uniquely able to mimic ITER in v_{fast} / v_{Alfven} and β_{fast} while maintaining full diagnostic capability, in particular MSE
  - ρ^*_{fast} does not overlap with ITER
- NSTX shows nonlinear physics of wave-particle resonance overlap, similar to ITER, due to large β_{fast}
- Can also study fast ion physics expected for ST-based CTF



Many fast particle discoveries made on NSTX

- New discoveries a direct result of operating with $v_{fast} / v_{Alfven} > 1$ with full suite of diagnostics

References:

•NSTX fast particle mode physics:

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

• NSTX-motivated CAE work on DIII-D:

W. Heidbrink, Nucl. Fusion 46 324 (2006)

High-f modes: energy transport

Low-f modes: radial transport

Compressional Alfvén Eigenmode

Global Alfvén Eigenmode

Hole-clump pair

TAE & EPM

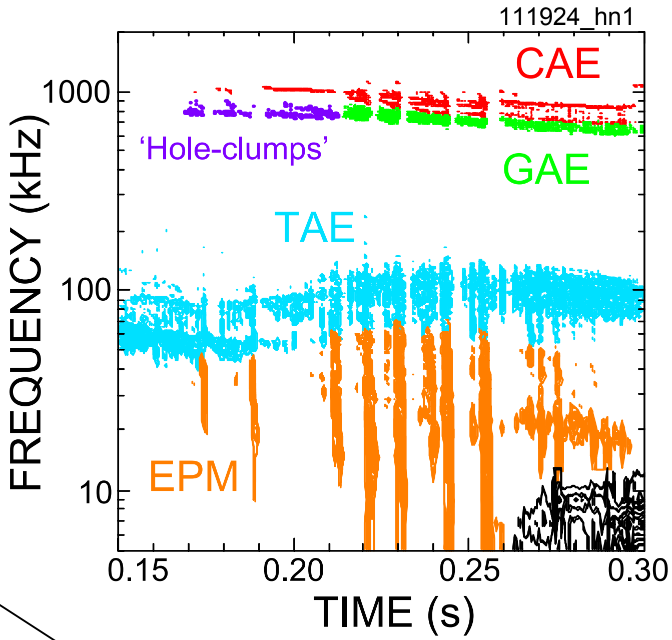
Bounce resonance fishbone

not present in f-spectrum shown above

New modes discovered on NSTX - **predicted to be present on ITER**

Multi-mode regime ITER relevant

New mode discovered - unique to NSTX

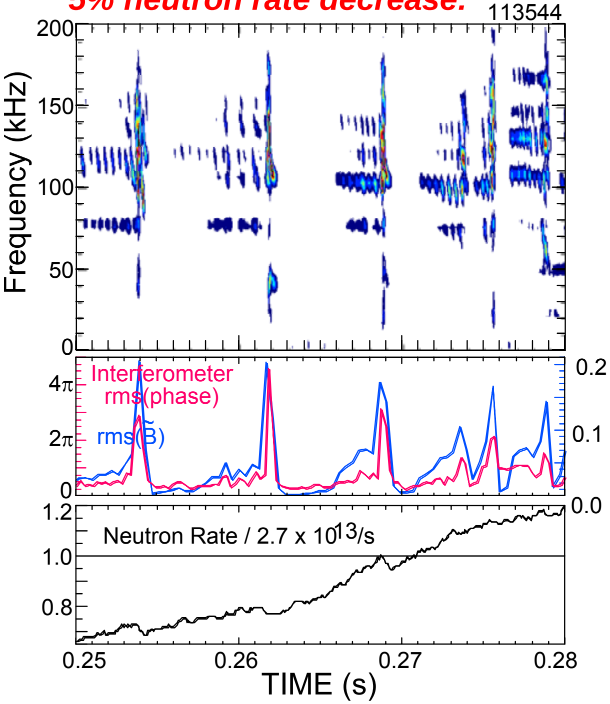


NSTX accesses ITER-relevant fast-ion phase-space island overlap regime with full diagnostic coverage

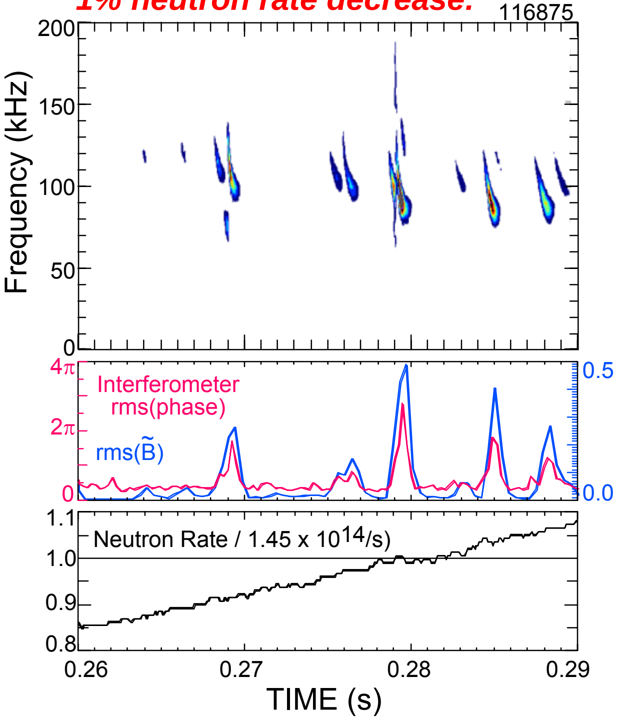
- **ITER** will operate in new, small ρ^* regime for fast ion transport
  - $k_\perp \rho \approx 1$ means "short" wavelength Alfvén modes
  - Fast ion transport expected from **interaction of many modes**
  - NSTX can study multi-mode regime while measuring MSE q profile

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

5% neutron rate decrease:



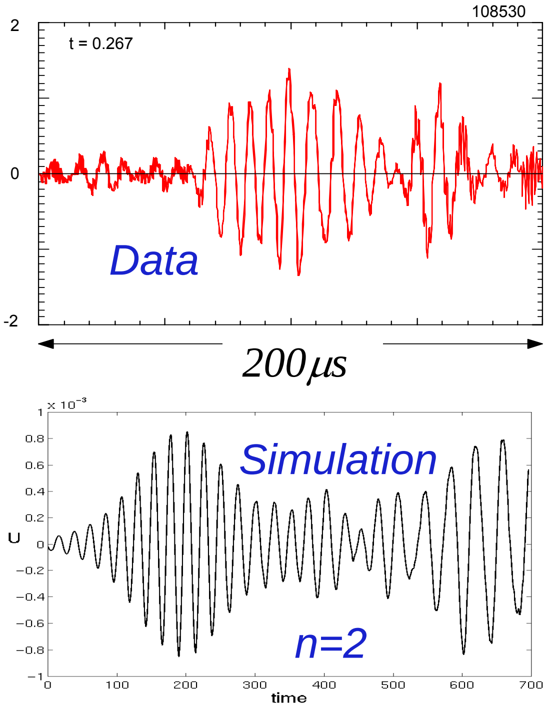
1% neutron rate decrease:



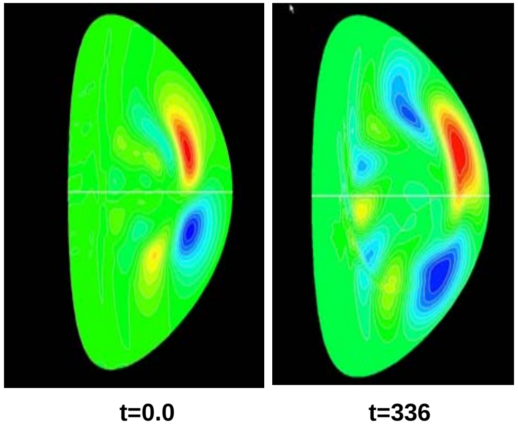
E. Fredrickson, Phys. Plasmas **13**, 056109 (2006)

Non-linear TAE simulations (single-*n*) reproduce many features observed in NSTX data

- M3D Nonlinear Hybrid simulations:
  - – Mode growth and decay times ≈ 50 - 100 μs
  - – Bursting/chirping behavior results from:
    - Non-linear modification of fast-ion distribution
    - Change in mode structure
    - Predicted to be present on ITER



Simulations → Mode moves radially outward during amplitude saturation

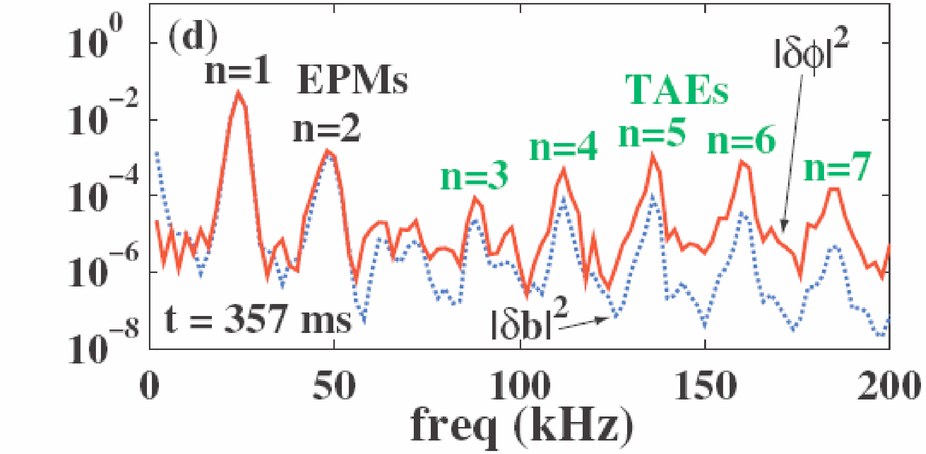


G.Y. Fu, IAEA FEC (2004)

- **New non-linear TAE simulations with multiple n's (not shown) predict:**
  - – Mode structure changes significantly due to non-linear evolution
  - – n=2 mode can be driven non-linearly by dominant n=1
- Comparisons to experiment just beginning…

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

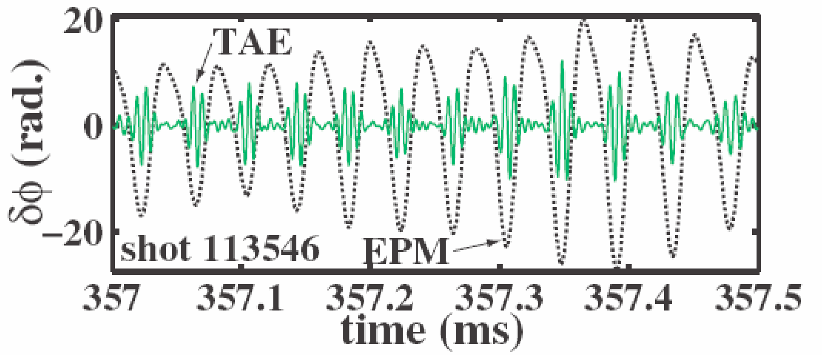
- *Low-f EPMs co-exist with mid-f TAE modes*



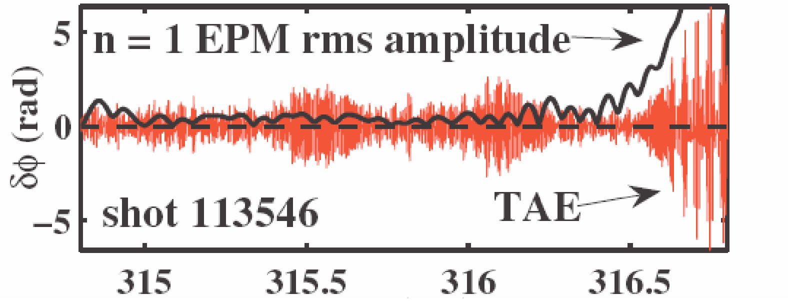
Bi-coherence analysis reveals 3-wave coupling between 1 EPM and 2 TAE modes

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

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

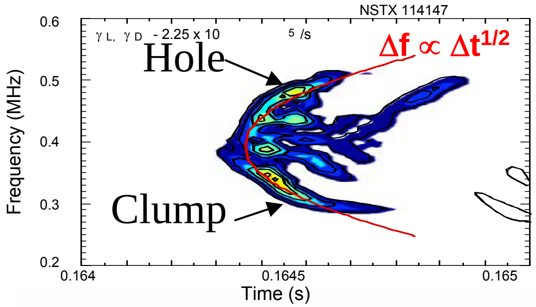


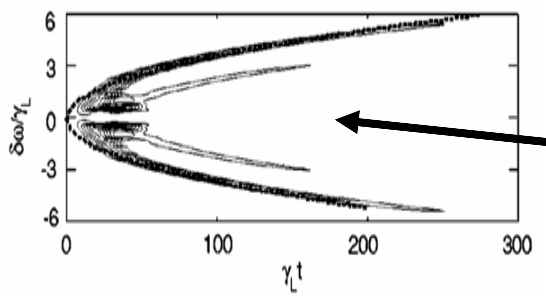
- *In absence of EPM, TAE modes do not form toroidally localized wave-packets*



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

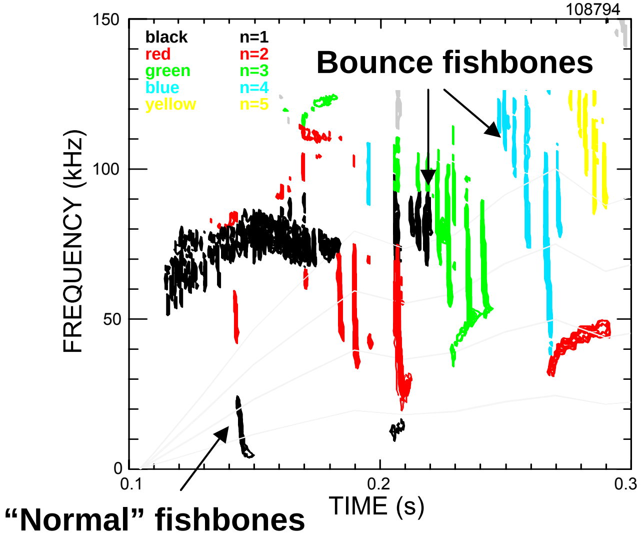
Hole-clump pair with GAE mode and bounce resonance fishbone discovered on NSTX





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

- High frequency (GAE) hole-clump pair mode observed driven by energetically inverted velocity space distribution
  - Hole-clump behavior more commonly observed for TAE modes
- Hole-clump mode frequency evolution $\Delta f \propto \Delta t^{1/2}$ prediction by Berk et al., (PoP, '99)



E. Fredrickson, Nucl. Fusion **43,** 1258 (2003)

- Bounce fishbones present at low aspect ratio where bounce frequency is low
- Modes identified by calculating bounce and precession frequency ranges and comparing to Doppler shifted mode frequencies
- High-n modes are bounce resonance, n=1 are regular precession resonance fishbone

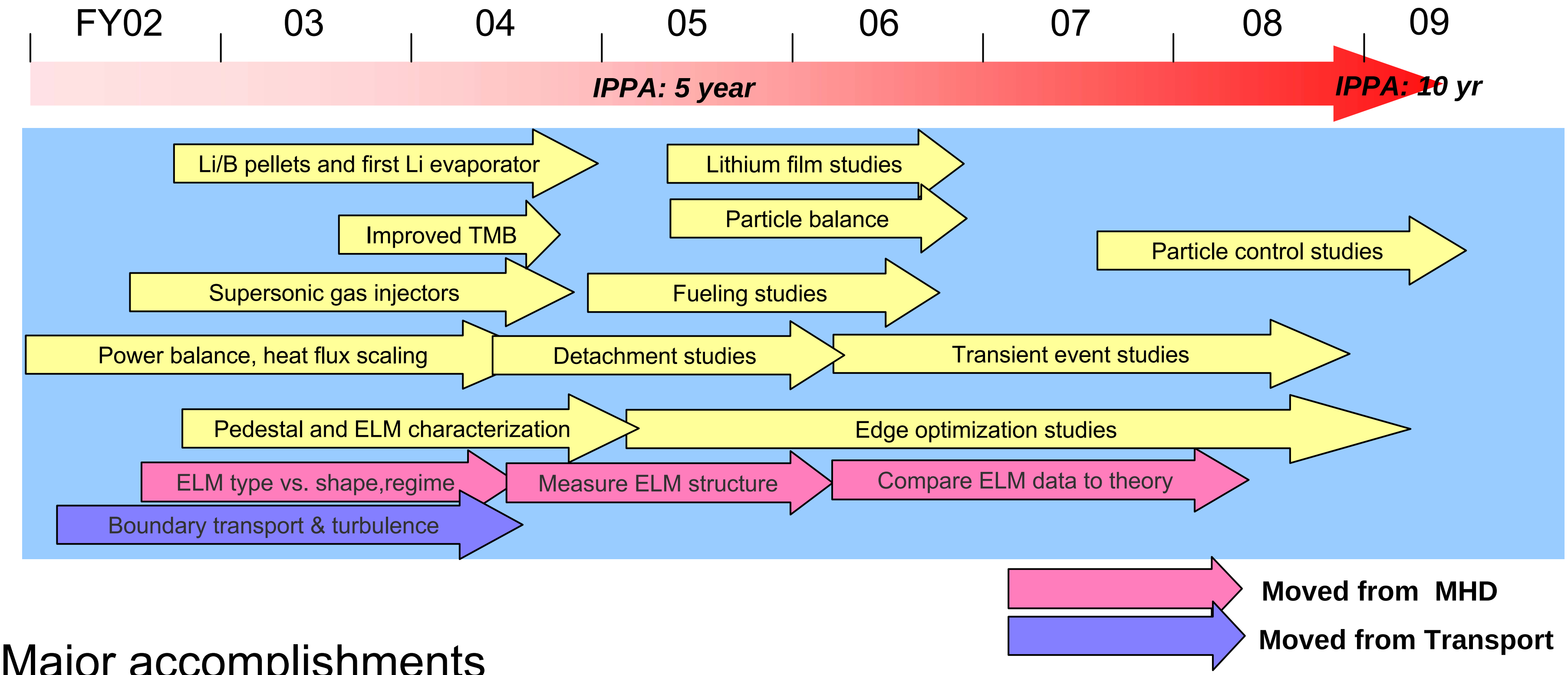
Research Plans for Energetic Particle Physics

- TAE avalanche threshold physics important for ITER (MDC-9)
  - Determine scaling of structure, stability, losses vs. *q* profile, v_{fast} / v_{Alfven} (FY07-08)
- Fast-ion MHD impact on NBICD important for ITER, CTF (SSO-2.2)
  - Validate/test bootstrap/beam-driven current models (TRANSP) (FY06-08)
    - Compare to J(r) evolution in plasmas with and w/o energetic particle MHD
- Comprehensive diagnosis of mode structure and fast-ion diffusion (MDC-9)
  - MSE measurement of current profile (FY07-08)
  - Mode structure: FIReTIP, reflectometer, δB polarization from Mirnovs (FY-07)
  - Fast ion loss: fast lost ion probe, solid-state & scanning E || B NPAs (FY06-08)
  - Fast ion $f(E,\rho)$: Fast Ion D-alpha (FIDA) diagnostic (FY-08)

NSTX contributes broadly to fundamental toroidal confinement science in support of ITER and future ST's

- Wave-Particle Interactions
- Boundary Physics
- Integrated Scenarios + Solenoid-free Start-up

Boundary Physics Research



FY02 03 04 05 06 07 08 09

IPPA: 5 year

IPPA: 10 yr

Li/B pellets and first Li evaporator

Lithium film studies

Improved TMB

Particle balance

Particle control studies

Supersonic gas injectors

Fueling studies

Power balance, heat flux scaling

Detachment studies

Transient event studies

Pedestal and ELM characterization

Edge optimization studies

ELM type vs. shape,regime

Measure ELM structure

Compare ELM data to theory

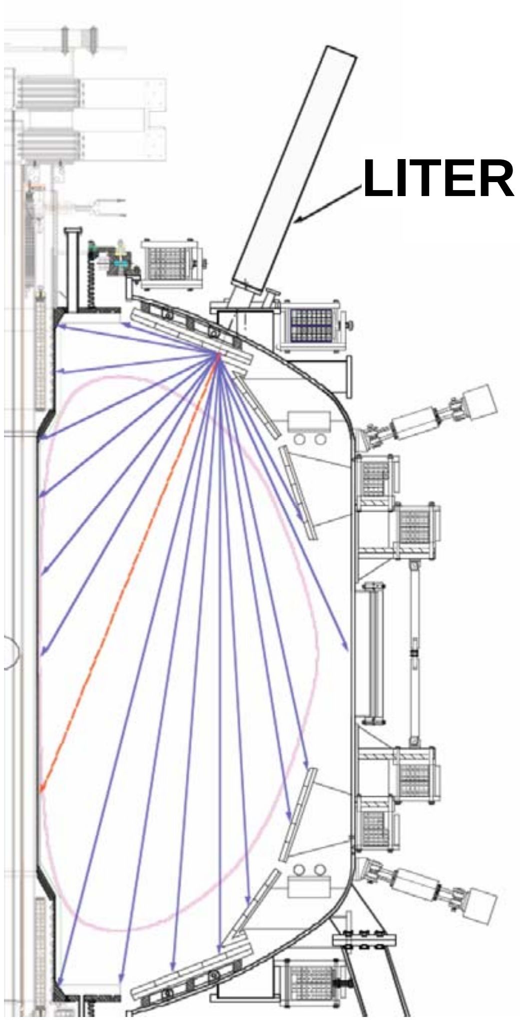
Boundary transport & turbulence

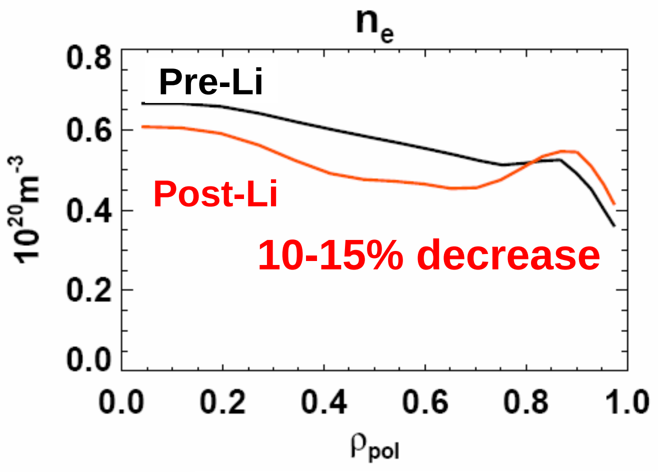
Moved from MHD

Moved from Transport

- Major accomplishments
  - Demonstrated particle pumping potential of Lithium conditioning
  - Demonstrated improved fueling efficiency of super-sonic gas injection
  - Characterized and controllably reduced divertor heat flux
  - Characterized ELM types, discovered small “type-V” ELM regime
  - Pursuing pedestal similarity experiments
  - Detailed comparisons of edge turbulence measurements to theory
  - Novel mass deposition measurements with quartz microbalance

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



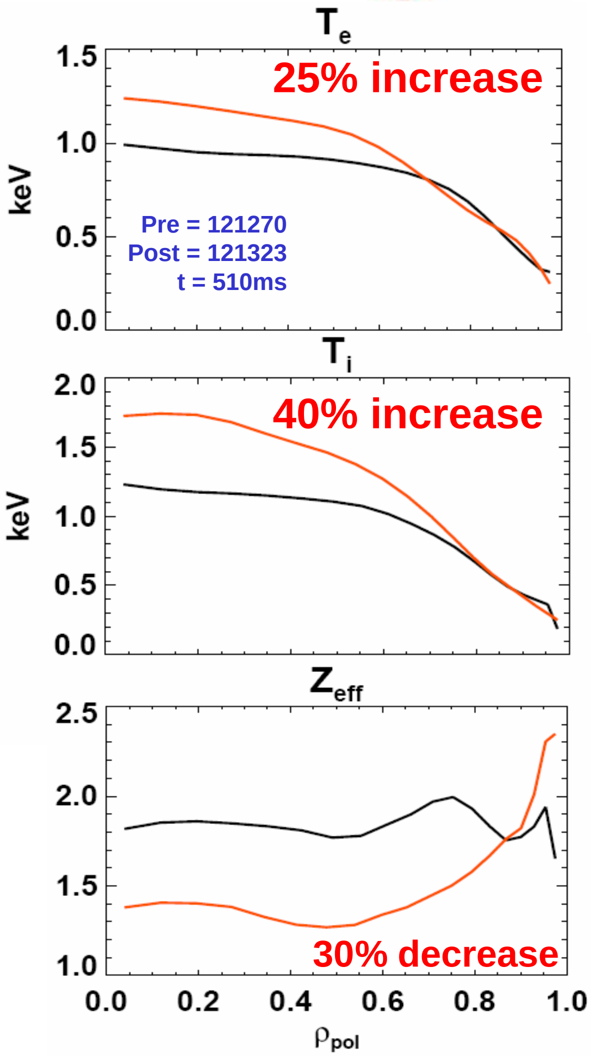


TRANSP analysis:

W_{TOT} 20% higher post-Li

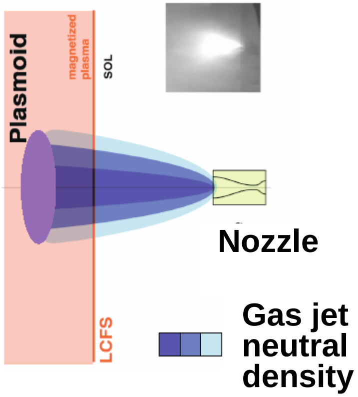
(reaches β-limit w/ same P_{NBI})

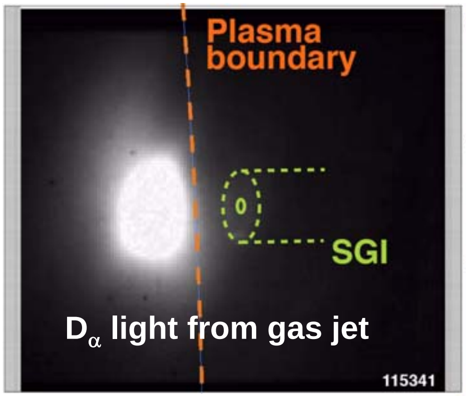
HH_{98y} = 1.07 → 1.25 post-Li

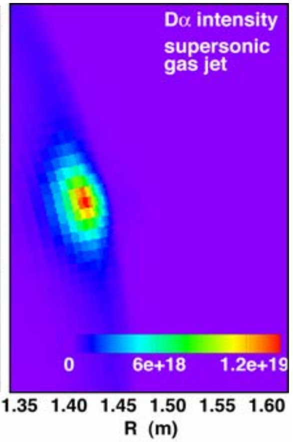


- **L-mode exhibits even larger (20-25%) relative density decrease**

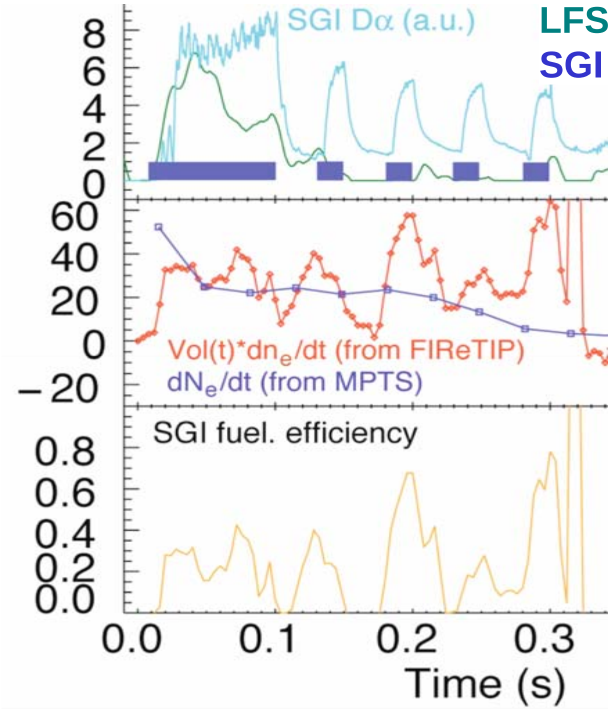
Supersonic Gas Injection (SGI) achieves up to 5 × higher fueling efficiency relative to standard low-field-side gas puff







DEGAS 2 Neutral transport modeling reproduces observed features



V.A. Soukhanovskii, et al. RSI **75**, 4320 (2004)

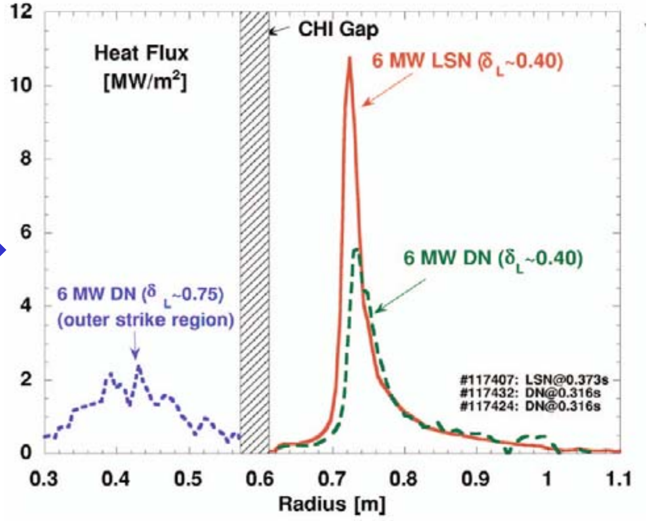
NBI-heated inner wall limited L-mode

- Pulsed SGI fueling
- Fueling efficiency = 0.1 - 0.5
  - Compare to LFS gas puff = 0.05-0.1

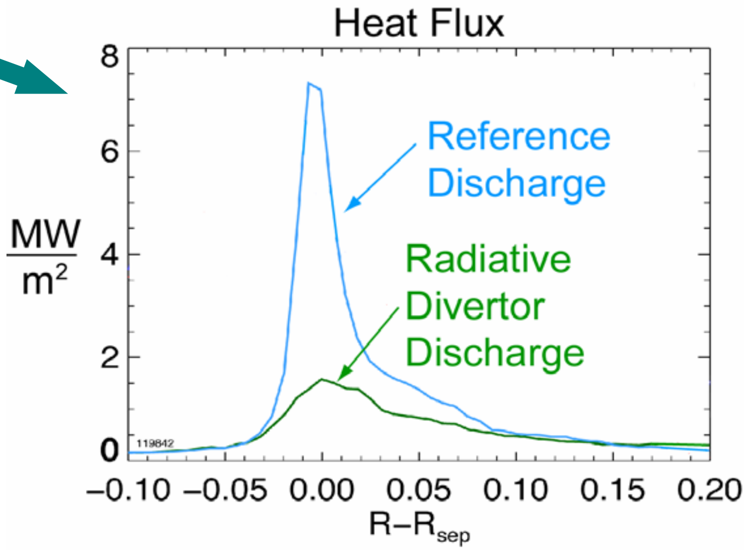
- H-mode scenarios:
  - SGI changes ELMs from mixed ELM regime (Type I+V) to Type III
  - SGI can replace HFS injector used for H-mode access while providing flow control
- **GOAL: Combine Li & SGI for n_e control**

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
- 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
  - ISP heat flux remains at detached levels
  - No clear signs of vol. recombination at OSP
- Detached divertor regime also investigated
  - Induces H-L back transition



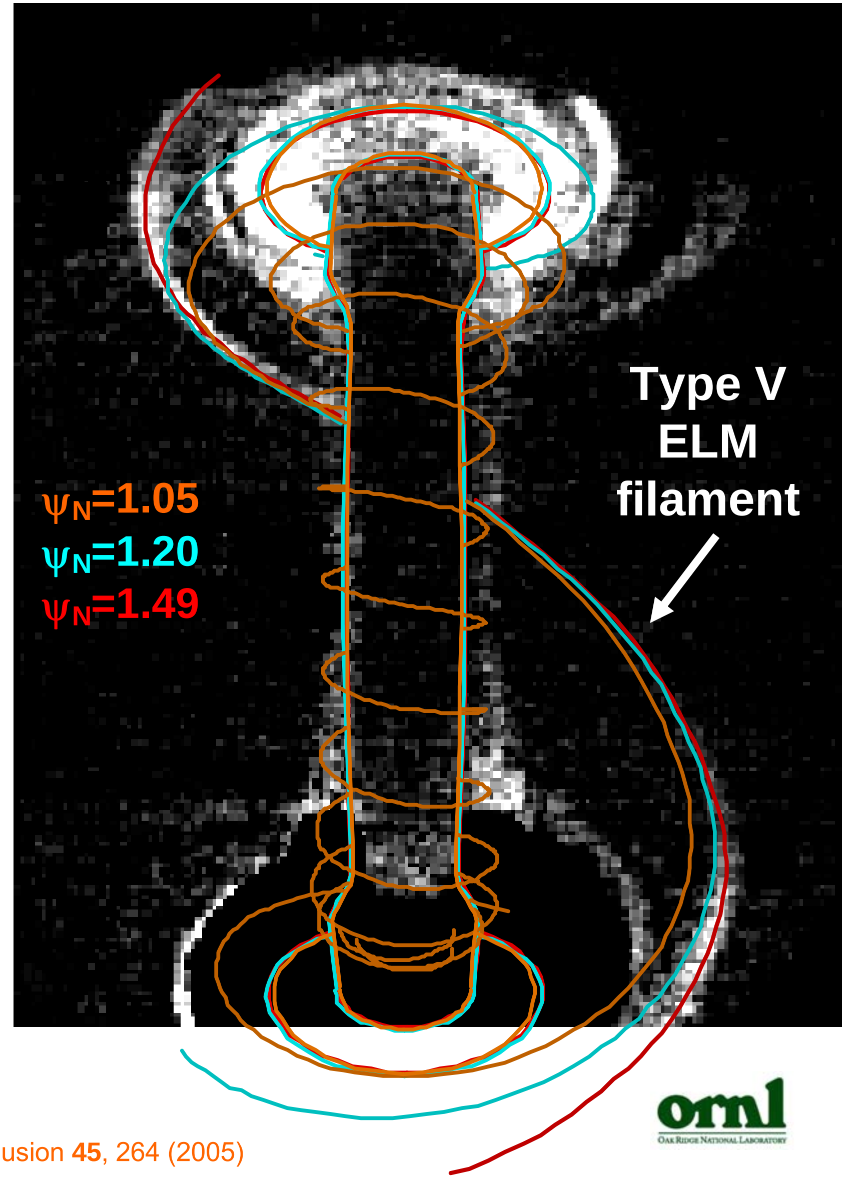
D. Gates, Phys. Plasmas **13**, 056122 (2006)



NSTX research on ELM formation and dynamics is unique and addresses fundamental issues for ITER

- ITER ELMs are predicted to be serious issue for divertor integrity
- Small ELMs are tolerable while exhausting particles/ash thus are ingredients of long pulse, high performance discharges. ITER/Demo/CTF relevant
- NSTX has characterized its ELMs, and also discovered a unique small ELM regime (Type V):

Type	Size	Threshold
V	**$\Delta W / W_{TOT} \leq 1\%$,**	**Wide P_{heat} range**
III	$\Delta W / W_{TOT} \sim 1\text{-}5\%$,	$P_{heat} \geq P_{L\text{-}H}$
I	$\Delta W / W_{TOT} \sim 3\text{-}15\%$,	$P_{heat} >> P_{L\text{-}H}$



R. Maingi, Nucl. Fusion **45**, 1066 (2005), Nucl. Fusion **45**, 264 (2005)

Comprehensive diagnostic set reveals Type-V ELMs are n=1 counter-propagating filaments that exist for < 1 toroidal transit

Interferometer

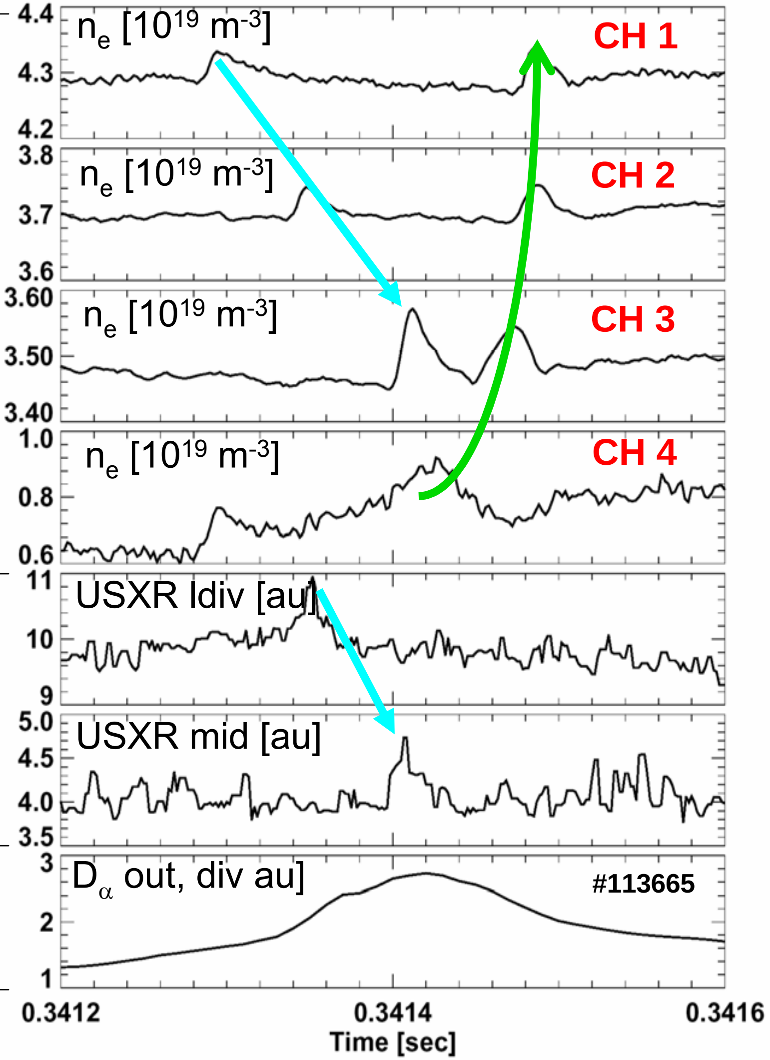
UCDAVIS UNIVERSITY OF CALIFORNIA

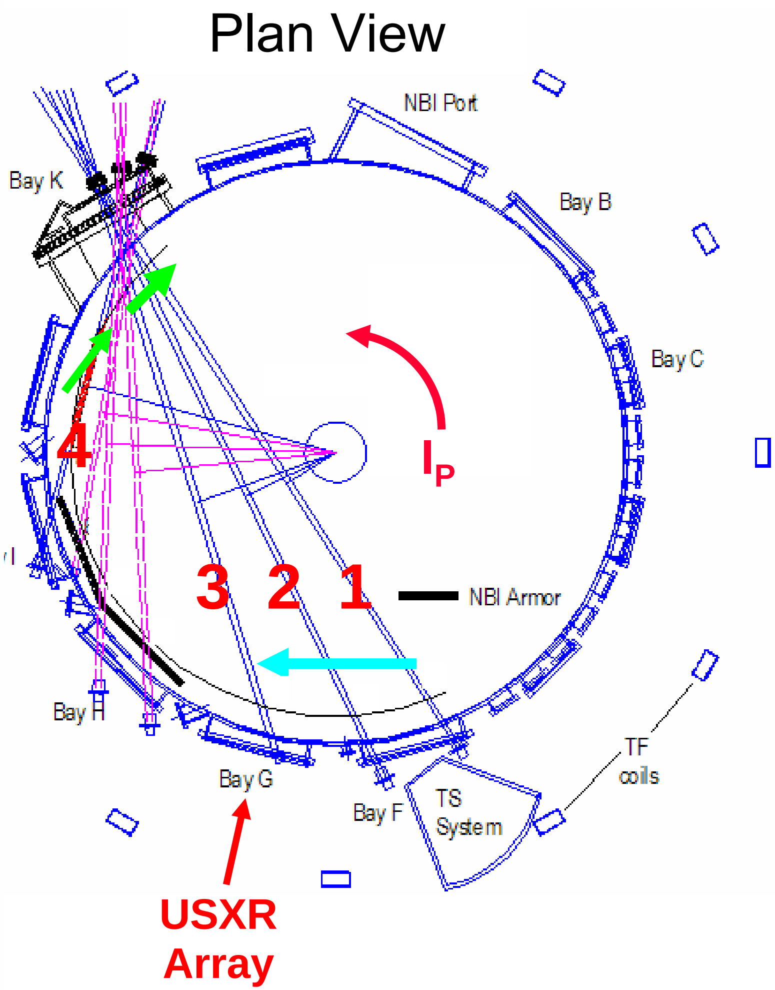
USXR

JOHNS HOPKINS UNIVERSITY

Divertor light

ornl Oak Ridge National Laboratory





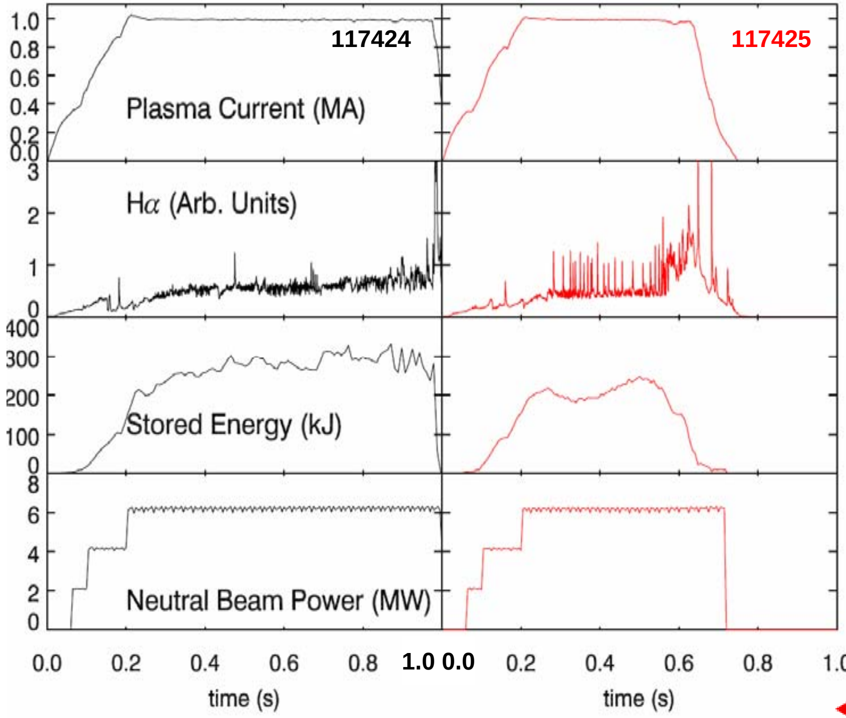
- **Mirnov data indicates ELM filament carries 400A current**

R. Maingi, Phys. Plasmas 2006, in press

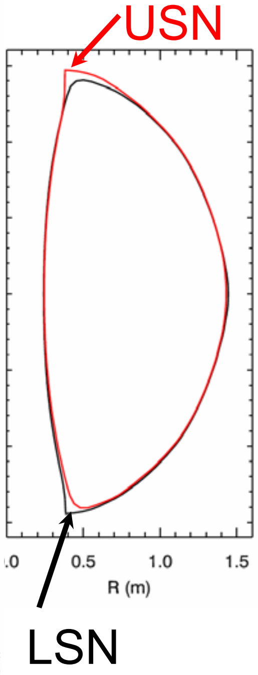
Experiments utilizing advanced shape control and parametric scans find ELM stability sensitive function of edge parameters

- ELM type and plasma performance sensitive function of magnetic topology

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

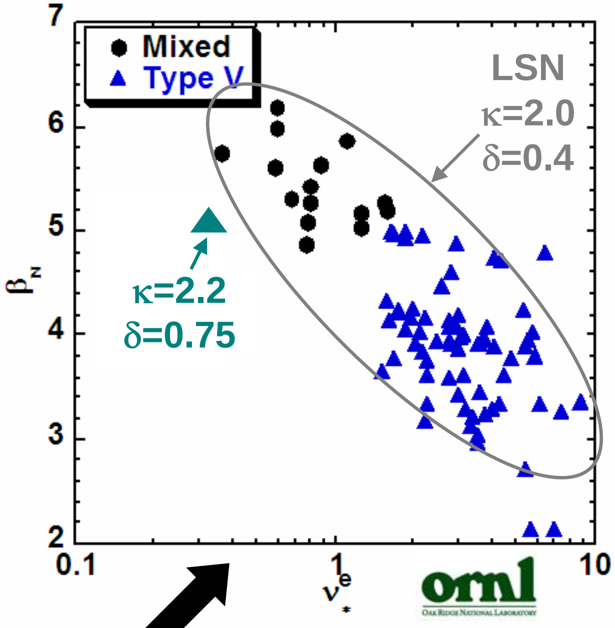


D. Gates, Phys. Plasmas **13**, 056122 (2006)



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

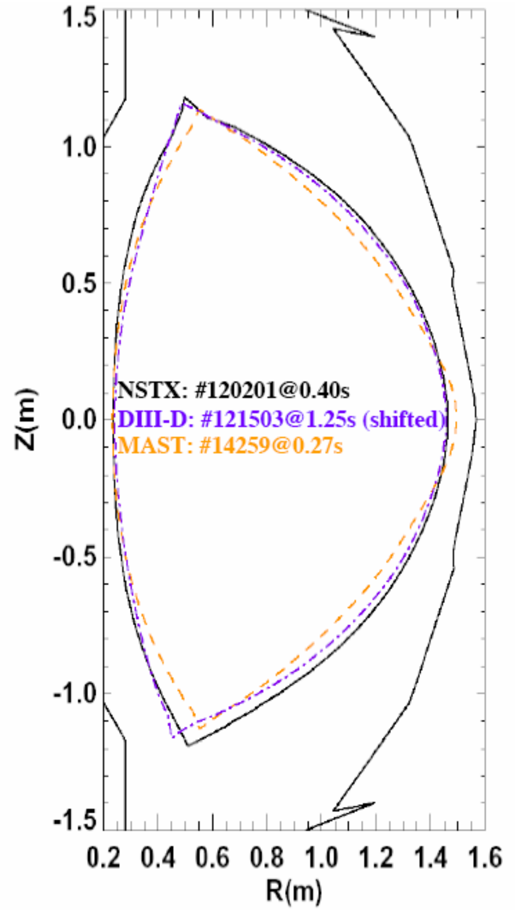
I_P=0.6-0.9 MA, B_T=0.45T, P_{NBI} =2-6MW

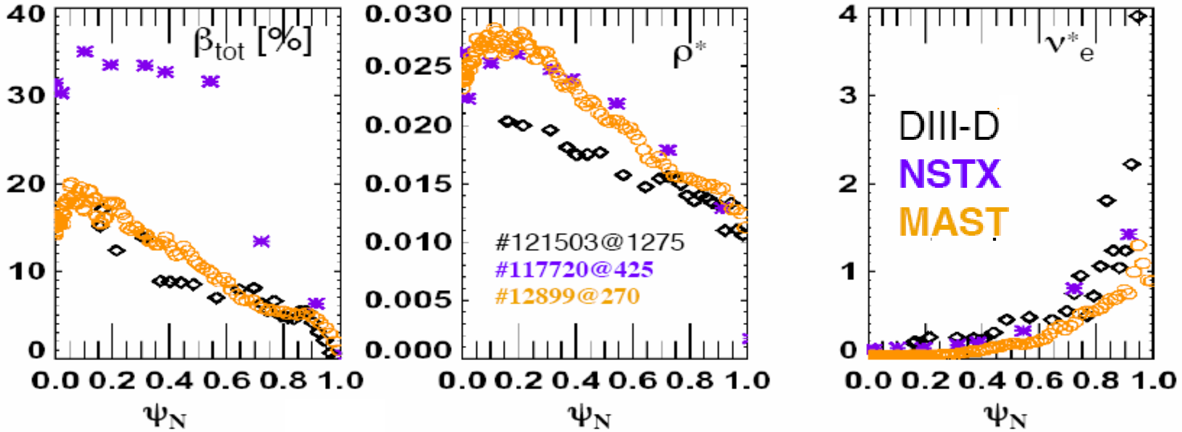


- ELM type also depends on global β_N & pedestal electron collisionality
  - Predicted to impact pedestal J_{BS}, access to ballooning second stability
  - Recent results find Type V also accessible at low ν_*^e via increased shaping

Pedestal similarity experiments will provide improved understanding of pedestal stability dependence on toroidicity

2005-2006 – Developed matched shapes for NSTX, MAST, DIII-D



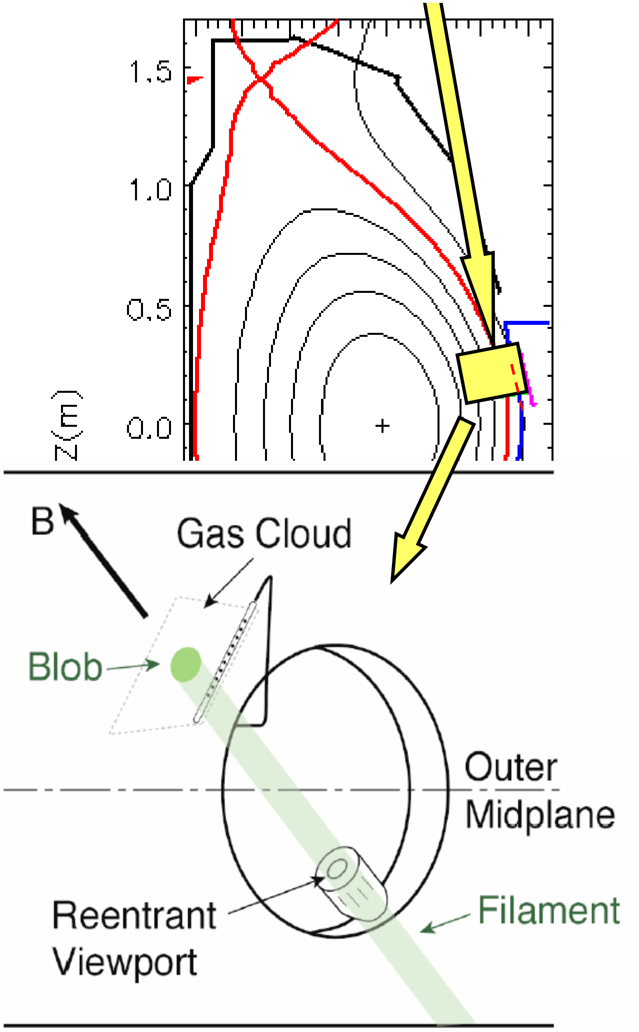


- Developed discharges with similar pedstal ρ^*, ν^*
- Also similar pedestal β (NSTX higher in core)
- 2006 – lower pedestal ν^*_e → 0.5 NSTX & MAST
  - NSTX: observe lower density/fueling/ν^*_e discharge was ELM-free → higher edge β limit
- Data/stability analysis ongoing for all 3 devices

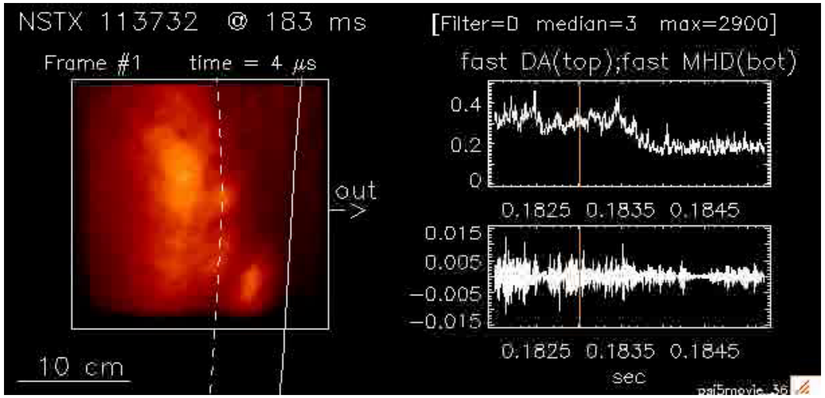
Predictive capability for ELM stability across wide range of plasma parameters **important for ITER and future ST devices**

Gas-puff imaging (GPI) diagnostic provides high-time-resolution diagnosis of near-edge transport phenomena and ELMs

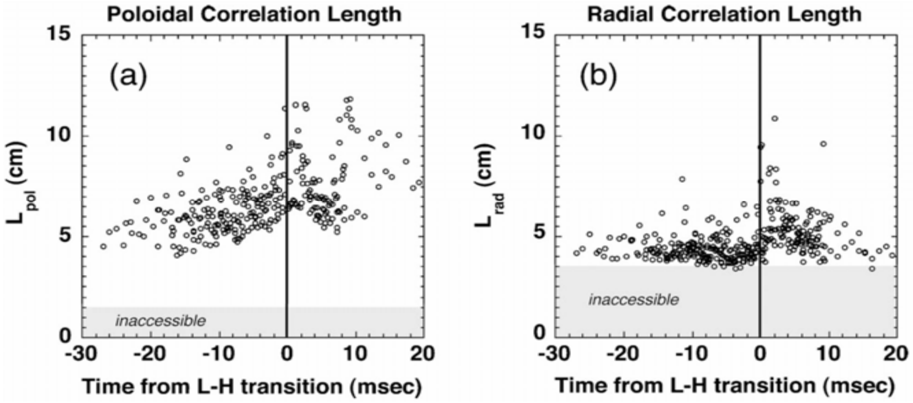
Viewing area just above midplane on outer edge



- Example: L → H transitions imaged with GPI



- Little change in correlation lengths at L→H transitions



- No change in poloidal flow shear of turbulence at L→H
- **Is change occurring radially inward of GPI signal?**

Zweben *et al.* Phys. Plasmas **13**, 056114 (2006)

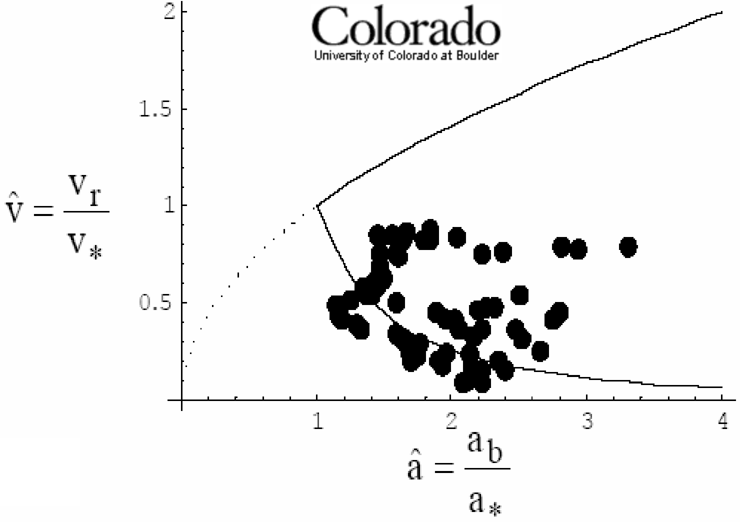
Blob dynamics measured with GPI are being systematically compared to 2D blob transport theory

- 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, Phys. Plasmas 2006, accepted

Lodestar Research Corporation

Colorado University of Colorado at Boulder



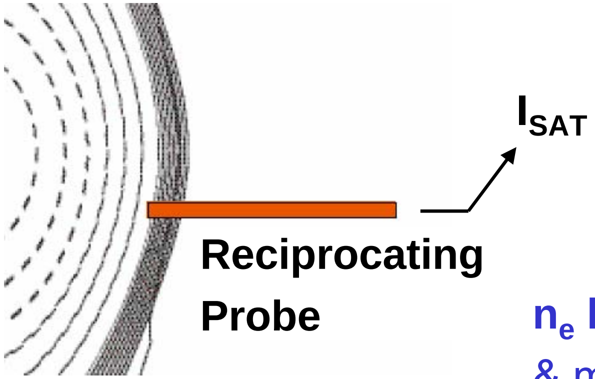
$$\frac{1}{\hat a^2} < \frac{v_r}{v_*} < \hat a^{1/2}$$

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

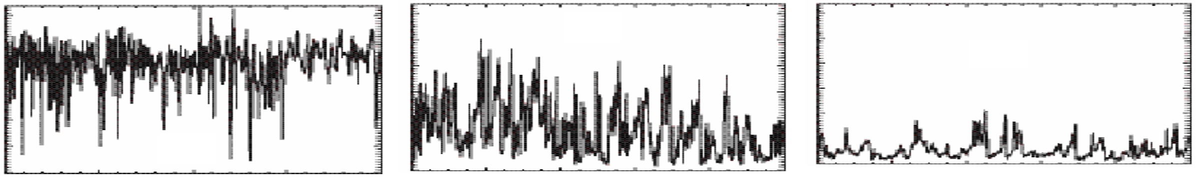
$$\hat a = \frac{a_b}{a_*} = \frac{a_b R^{1/5}}{L_{\parallel}^{2/5}\rho_s^{4/5}}$$

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

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



UCSD



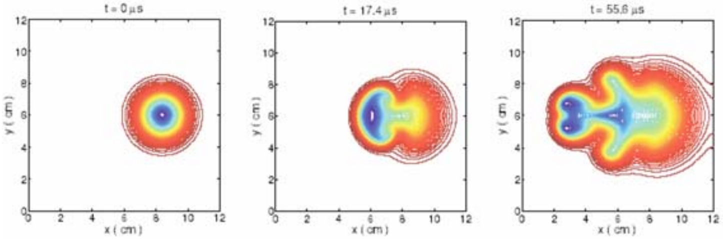
Holes: $R\text{-}R_{SEP} < -1$cm

Mixed: $-1 < R\text{-}R_{SEP} < 0$cm

Peaks: $R\text{-}R_{SEP} > 0$cm

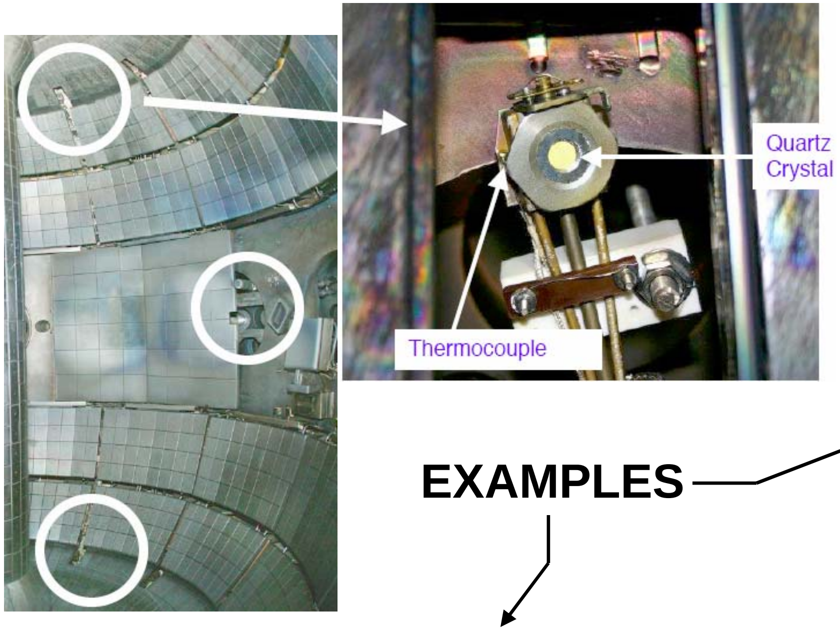
n_e holes predicted

& measured to propagate inward in major radius



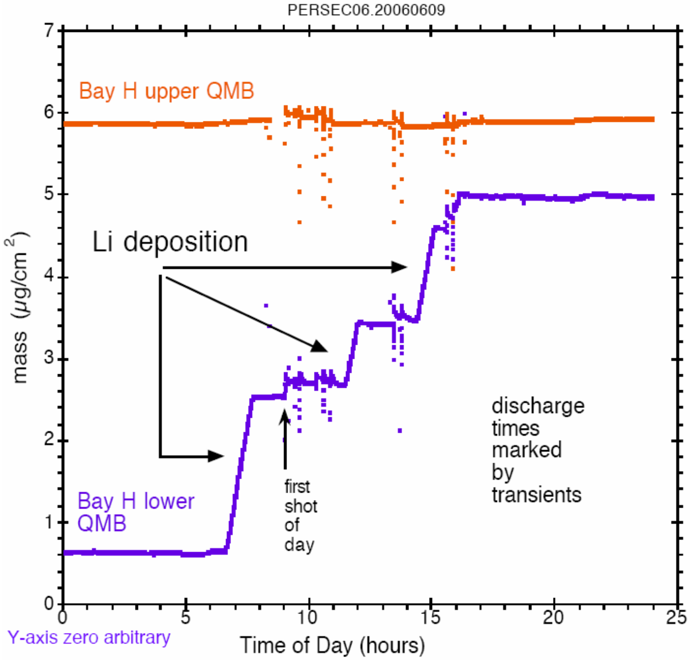
J. Boedo, IAEA 2006

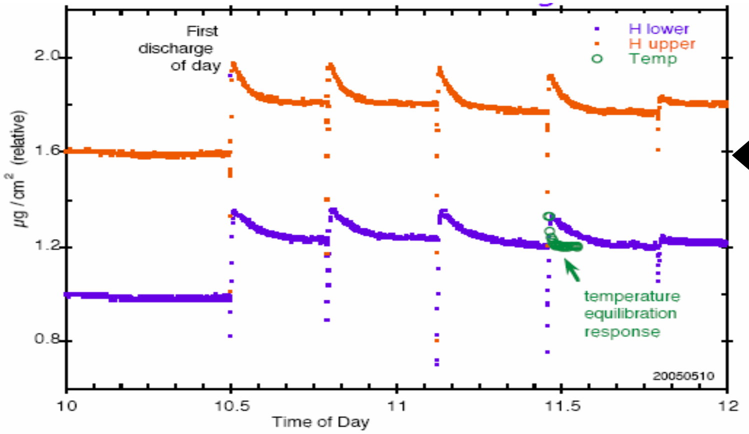
Quartz Microbalances (QMB) provide local, direct, and real-time measurement of mass deposition and erosion



EXAMPLES

Real-time measurements of Li deposition:





C. Skinner, Journal Nuc. Mat. **Vols. 337-339**, 129 (2005)

Real-time measurement of D_2 retention before and during a normal run-day

QMB potentially a powerful diagnostic for window coatings and Tritium retention – both critical issues for ITER

Research Plans for Boundary Physics

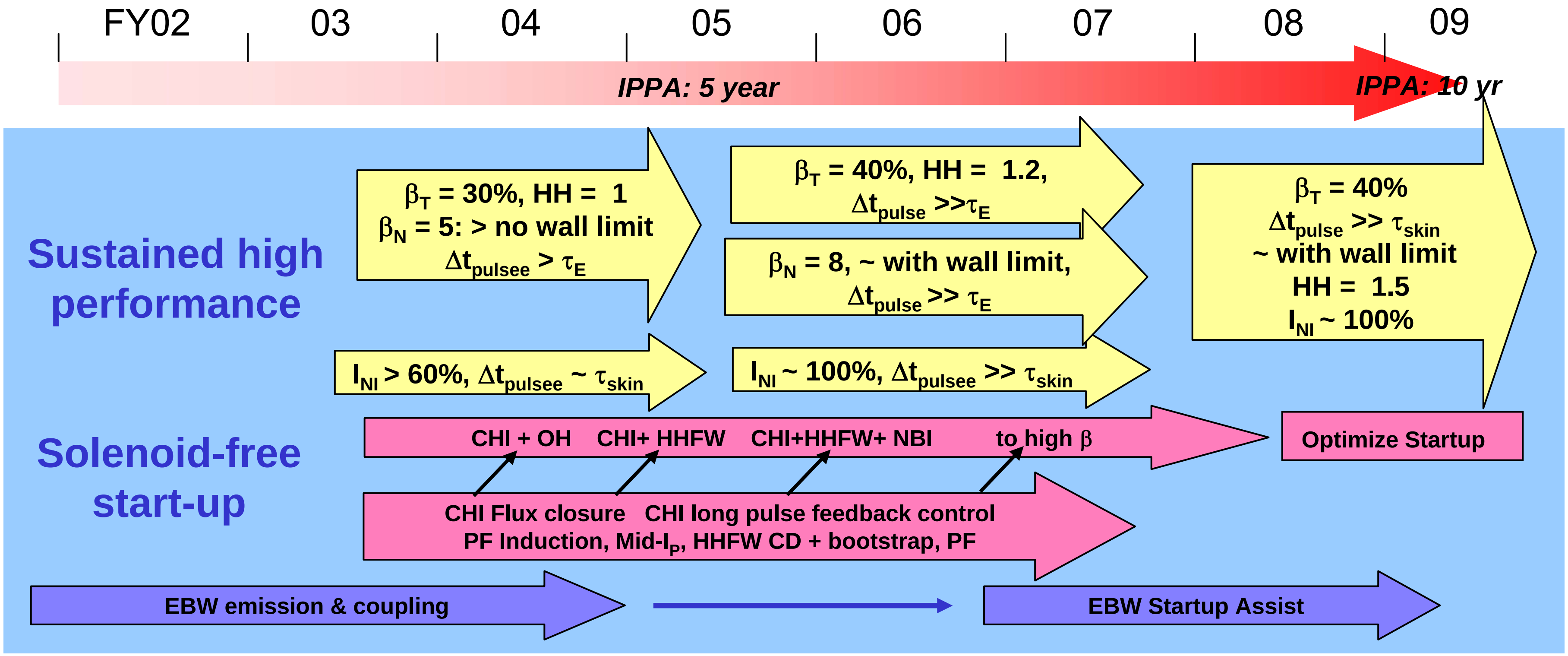
- **Enhanced particle pumping via liquid lithium divertor module** (FY08-09)
  - Enable advanced scenarios requiring n_e control, high H-factor

- Incorporate SGI fueling into long-pulse H-mode scenarios (FY07)
- Divertor heat load mitigation at high performance, low ν^* (FY07-08)
- Small ELM regime – cross-machine comparison (FY07-08) (PEP-16)
  - Dependence of small ELM regime access on proximity to double-null (FY07) (PEP-6)
  - Measure ELM radial penetration depth (FY07-08) (PEP-10)
- Use aspect ratio variation to understand pedestal physics (FY07) (PEP-9)
- Characterize H-mode pedestal with poloidal CHERs (FY08)
  - Poloidal rotation measurement for complete E_r (outboard coverage initially)
  - Study role of orbit squeezing effects, E_r shearing rates in pedestal transport
- Enhanced analysis and modeling of intermittent structures/blobs (FY07-08)
  - Analysis of 2-D turbulence velocity fields vs. time, motion of coherent structures
  - Comparisons with theory, simulation, and other experiments
- Characterize material migration vs. shape & pulse length (FY07-08) (DSOL-18)
  - Migration studies relevant to PFC integrity and tritium retention in ITER

NSTX contributes broadly to fundamental toroidal confinement science in support of ITER and future ST's

- Wave-Particle Interactions
- Boundary Physics
- Integrated Scenarios + Solenoid-free Start-up

Integrated Scenarios and Solenoid-Free Start-up



🟥 Moved from SFSU

🟦 Covered in WPI

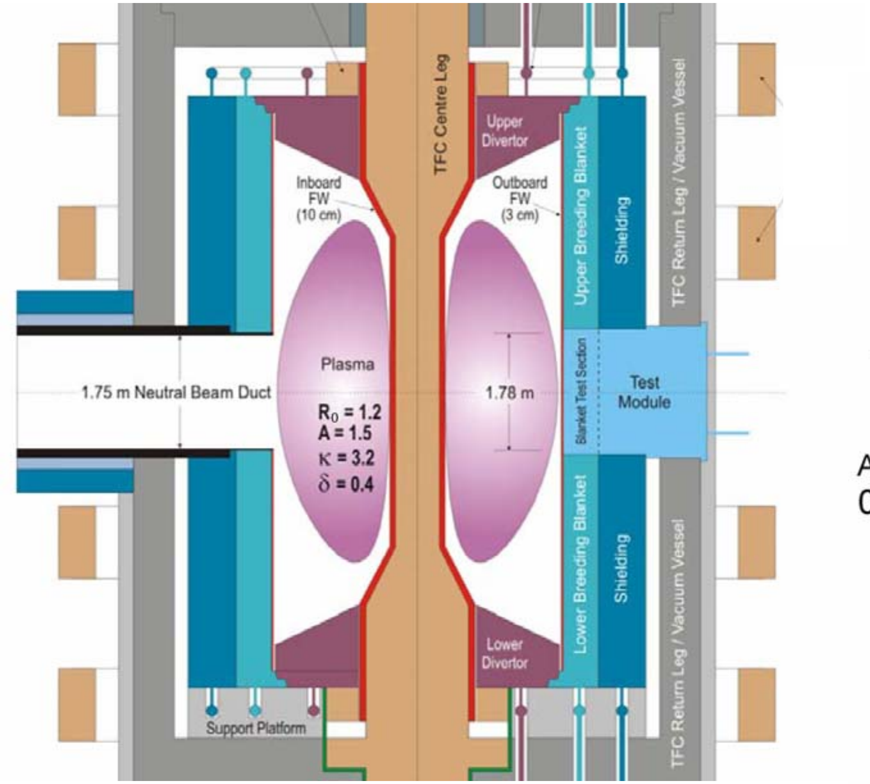
- Major accomplishments
  - – Demonstrated sustained f_{NI} = 65%, β_N above no-wall limit, HH=1.1
  - – Validated inductive and non-inductive CD models/diagnostics at low-A
  - – Observe current redistribution from MHD – relevant to ITER hybrid mode
  - – Produced 160kA closed-flux current using CHI start-up

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

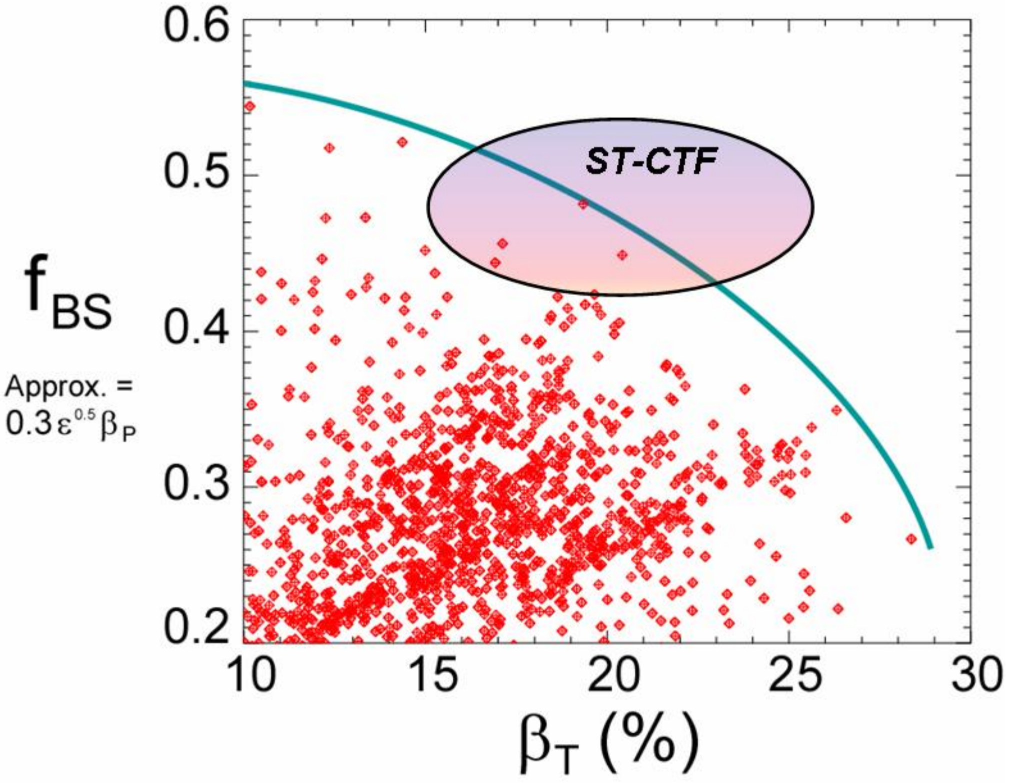
ST-CTF goal: neutron flux = 1-4MW/m^2

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%

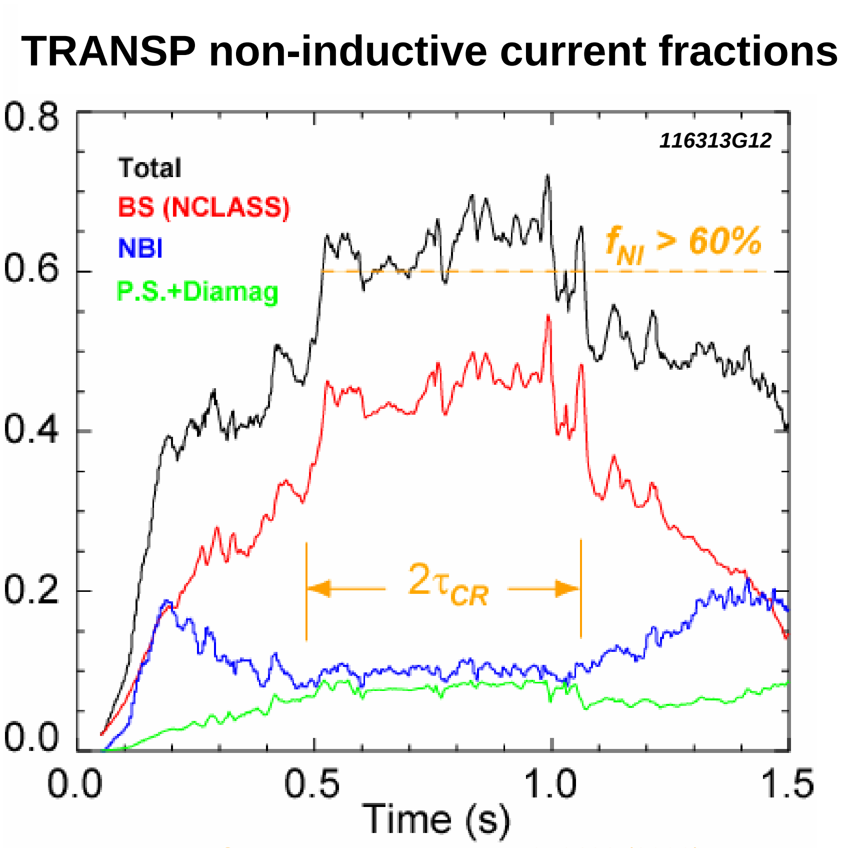


Peng et al, PPCF **47**, B263 (2005)



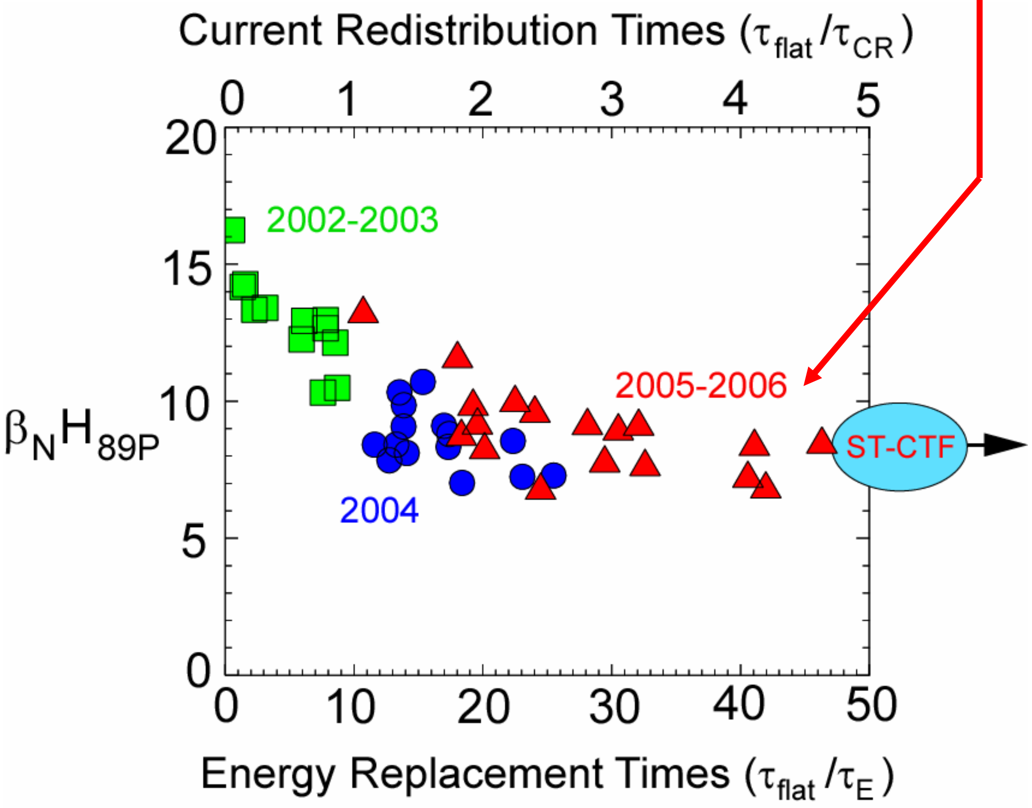
High performance can be sustained for several current redistribution times at high non-inductive current fraction

- **∇p and NBI current drive provide up to 65% of plasma current →**
  Relative to 2002-2003, High $\beta_N \times H_{89P}$ **now sustained 5 × longer**



TRANSP non-inductive current fractions

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

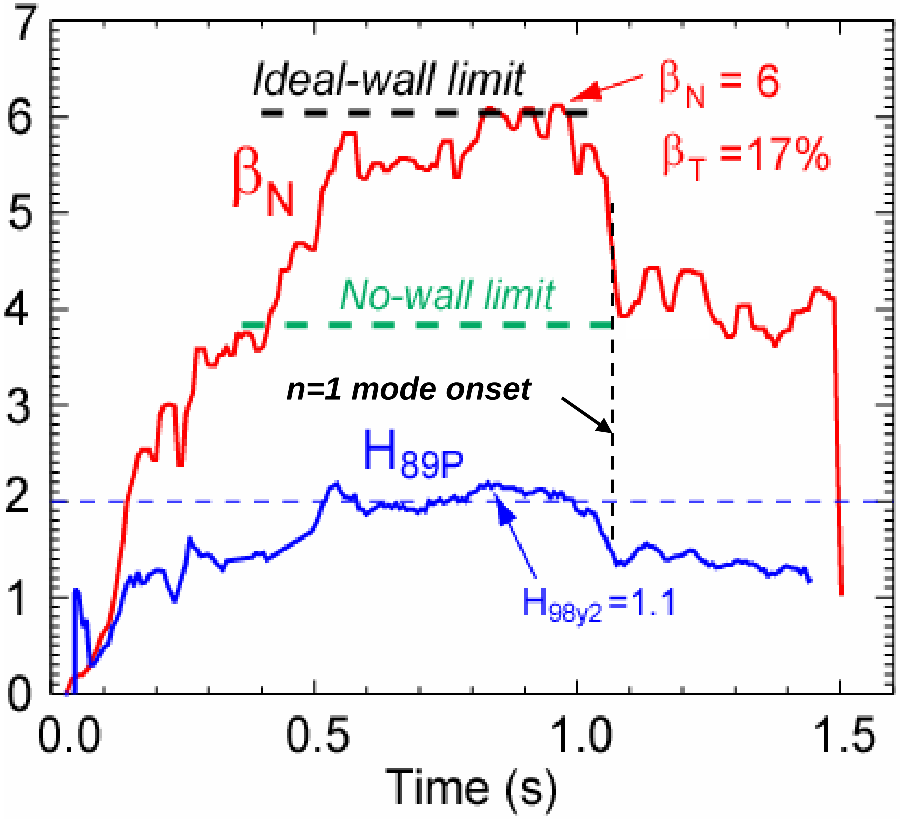


High beta phase of longest-pulse discharges is degraded by core n=1 “interchange-type” MHD activity

- Strong shaping (κ=2.4, δ_L= 0.7, LSN) improves global and edge stability

- MSE diagnostic enables accurate stability limit calculations:
  - Plasma β_N above n=1 no-wall limit
    - – Rotational stabilization of n=1 RWM
  - Repeated excursions above n=1 ideal-wall limit trigger core MHD

- Confinement reduced by core MHD
  - – Core MHD is n=1 continuous mode
  - → β_N decreases 30% after mode onset

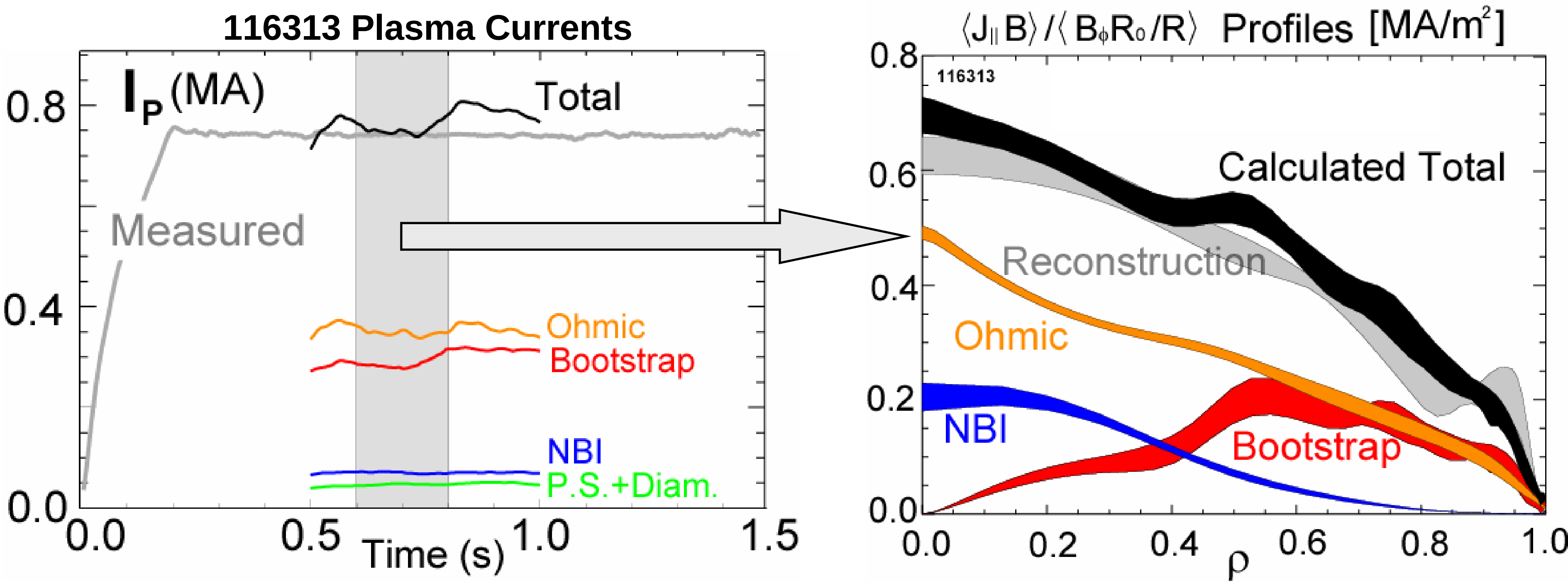


J. Menard, Phys. Rev. Lett. **97**, 095002 (2006)

MSE diagnostic has enabled validation of models of inductive and non-inductive current drive sources

- **Compute V_{LOOP} distribution/evolution directly from MSE-constrained fits**
  - **Long pulse-length and quiescent discharges needed for analysis**
- **Fit T, p, Z_{eff} to ψ, compute σ_{NC}, J_{OH} & J_{BS}, add TRANSP J_{NBI}**

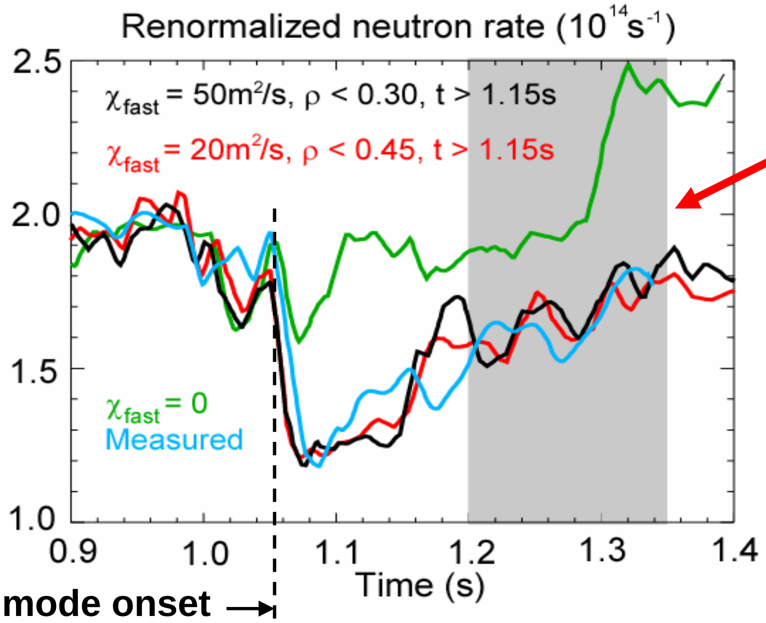
Sauter/NCLASS collisional NC models consistent with experimental I_P and $J_{||}$



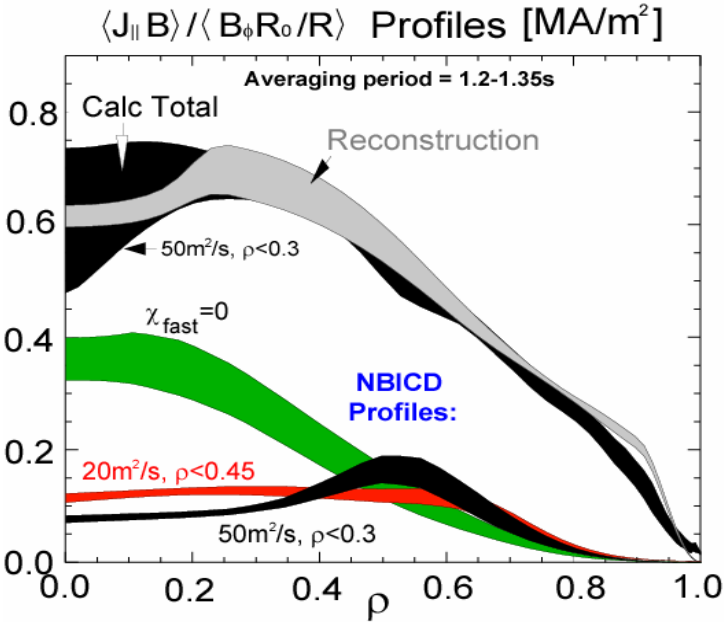
I_P=750kA, f_{NI} = 55-60%

Mode-induced fast ion diffusion necessary to explain neutron rate and $J_{||}(\rho)$ evolution during late n=1 interchange activity

- High core-localized anomalous fast ion diffusion can account for neutron rate deficit
- Core δB from mode estimated to be 100's of Gauss → large χ_{fast}



- Diffusion of fast ions can convert centrally peaked J_{NBI} to flat or hollow profile
- Redistribution of NBICD makes predictions consistent with MSE



MHD-induced NBICD diffusion may contribute to "hybrid" scenarios proposed for ITER

J. Menard, Phys. Rev. Lett. **97**, 095002 (2006)

Stable & fully non-inductive target scenario utilizing only NBI and BS current drive has been identified

Present high-f_{NI} long-pulse H-modes:

I_P = 750kA

$\beta_N < 5.6$, $\beta_P < 1.5$, $\beta_T < 17\%$

l_i = 0.6, q_{min}=1.3, B_T=4.5kG

κ = 2.3, $\delta_{X\text{-}L}$ = 0.75, q*=3.9

Target scenario:

I_P = 700kA

β_N = 6.7, β_P = 2.7, β_T =15%

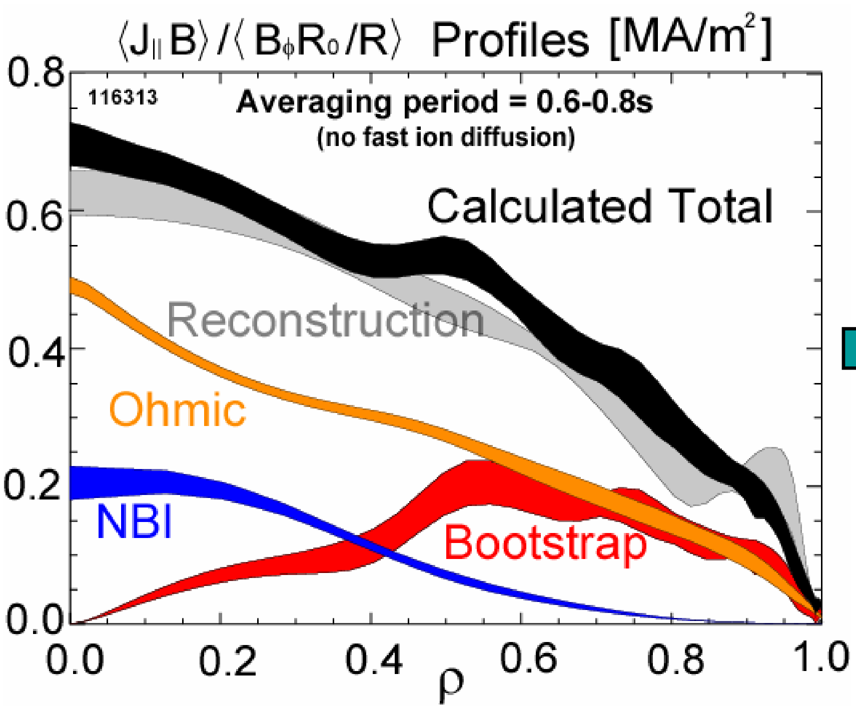
l_i = 0.5, q_{min} = 2.4, B_T=5.2kG

κ = 2.6, $\delta_{X\text{-}L}$ = 0.85, q*=5.6

Inductive current drive is replaced by:

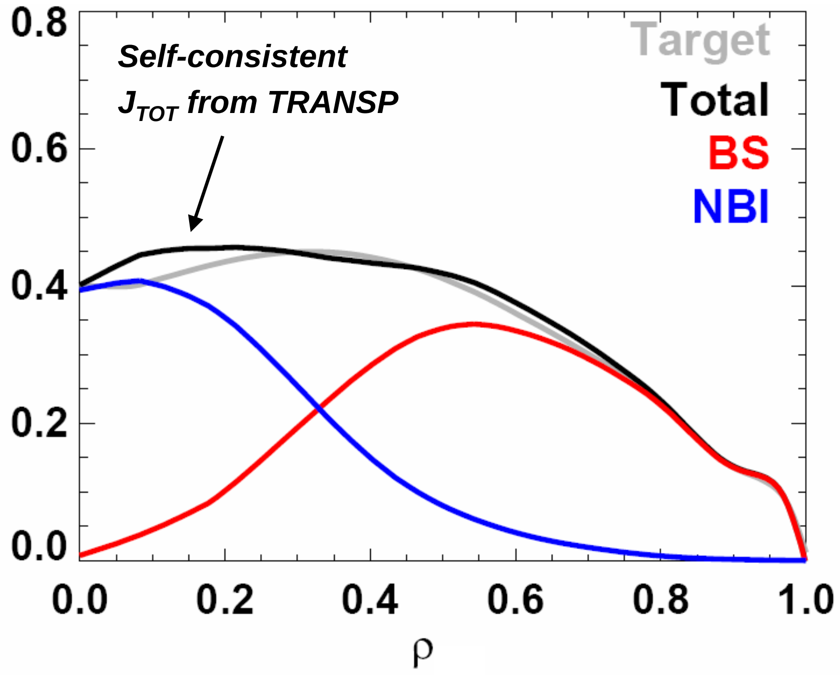
Higher J_{NBI} from higher T_e

Higher J_{BS} from higher $\beta_{P\text{-thermal}}$



$\langle J_{\parallel} B\rangle / \langle B_\phi R_0/R\rangle$ Profiles [MA/m^2]

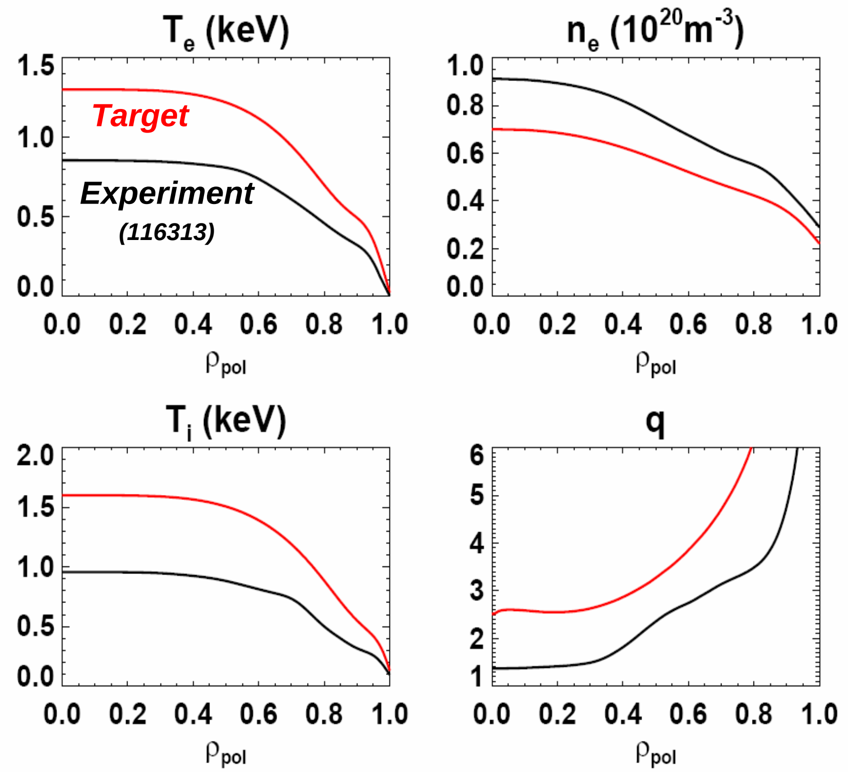
116313 Averaging period = 0.6-0.8s (no fast ion diffusion)



Self-consistent J_{TOT} from TRANSP

Fully non-inductive scenario requires higher confinement, higher *q*, strong plasma shaping

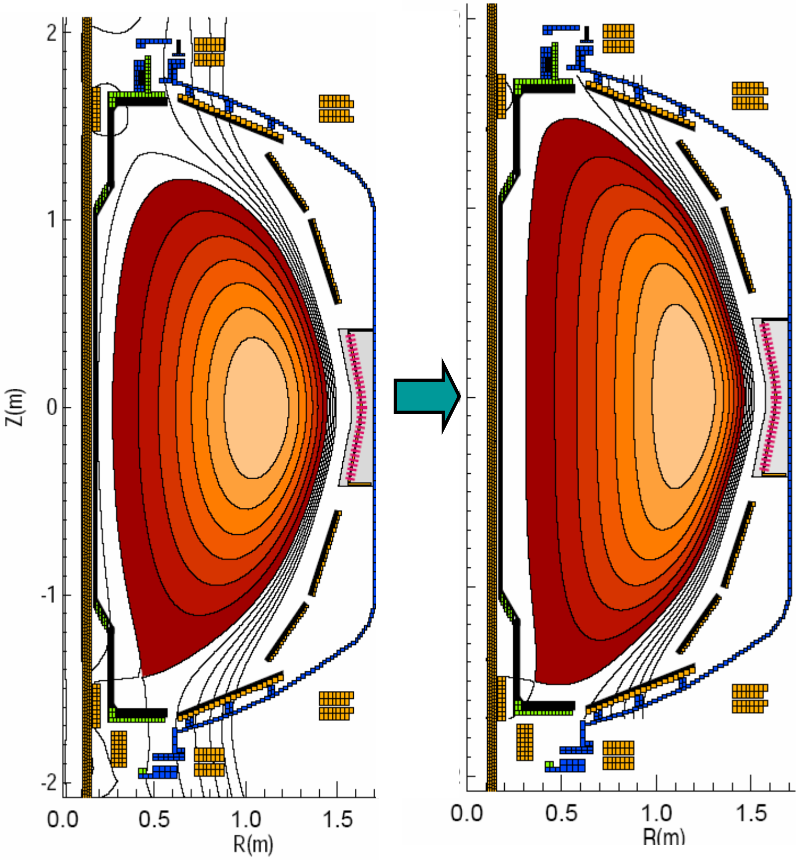
- Need 60% increase in T, 25% decrease in n_e
  - **Lithium for higher τ_E & density control?**
    - **20% increase in thermal confinement**
    - **30% increase in HH_{98}**
  - **Core HHFW heating**
- Want $q_0 \approx q_{min} \approx 2.4 \Rightarrow$ higher with-wall limit



- Higher κ for higher q, β_P, f_{BS}
- High δ for improved kink stability

κ= 2.3, $\delta_{X\text{-}L}$ = 0.75
δR_{SEP} = -1cm

κ= 2.6, $\delta_{X\text{-}L}$ = 0.85
δR_{SEP} = -2mm



Key Research Results and Plans for Scenario Integration

- Demonstrated sustained f_{NI} = 65%, β_N above no-wall limit, HH=1.1
- Validated CD models, measured current redistribution from MHD
  - Relevant to predicting performance of NSTX, future STs, and ITER
- Identified fully non-inductive targets extrapolated from existing discharges

PLANS:

- **Investigate long-pulse operation w/ n_e control from liquid-Li** (FY08-09)
  - **Liquid lithium target used to control density successfully on CDX-U**
  - Investigate effect of particle pumping on low density error fields/locked modes, H-mode access, ELMs, and thermal confinement

- Complete study of MHD effects on q(ρ)/hybrid scenarios (FY07) (SSO-2.1,2.2)
- Assess stability/confinement/CD for elevated-q/high f_{NI} target (FY07-08)
- Investigate current drive physics in CTF conditions (FY07-08)
  - Lower density plasmas with higher NBICD fraction and high total NI fraction
  - Demonstrate high f_{BS} at sustained κ = 2.8 with rtEFIT (control computer upgrade)

NSTX contributes broadly to fundamental toroidal confinement science in support of ITER and future ST's

- Wave-Particle Interactions
- Boundary Physics
- Integrated Scenarios + Solenoid-free Start-up

NSTX approach to developing non-solenoidal start-up: Divide problem into pieces, ultimately link pieces together

CHI for plasma initiation, early ramp (also PF-only ramp-up)

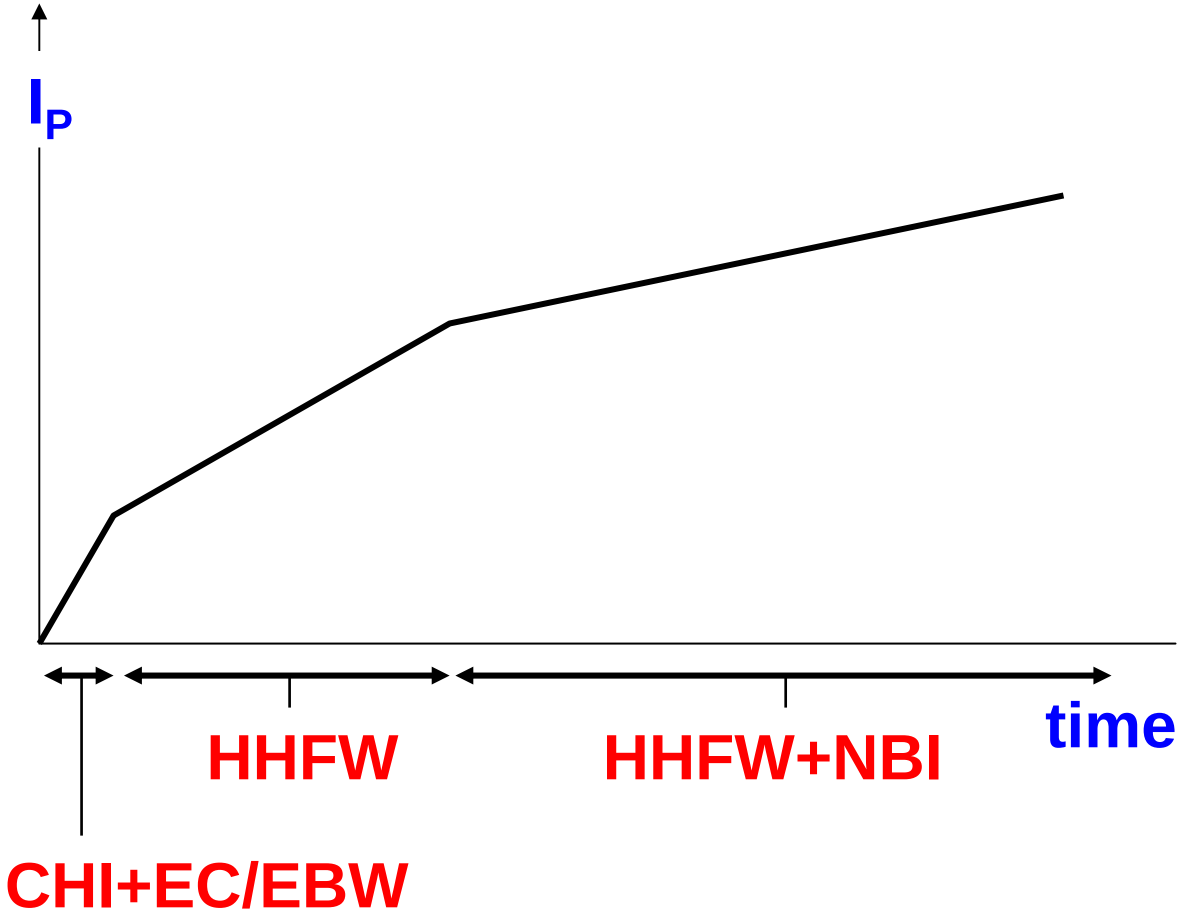
- High power EC pre-ioniz.
- EBW heating to T_e > 100eV

HHFW for ramp-up of low I_P CHI plasma

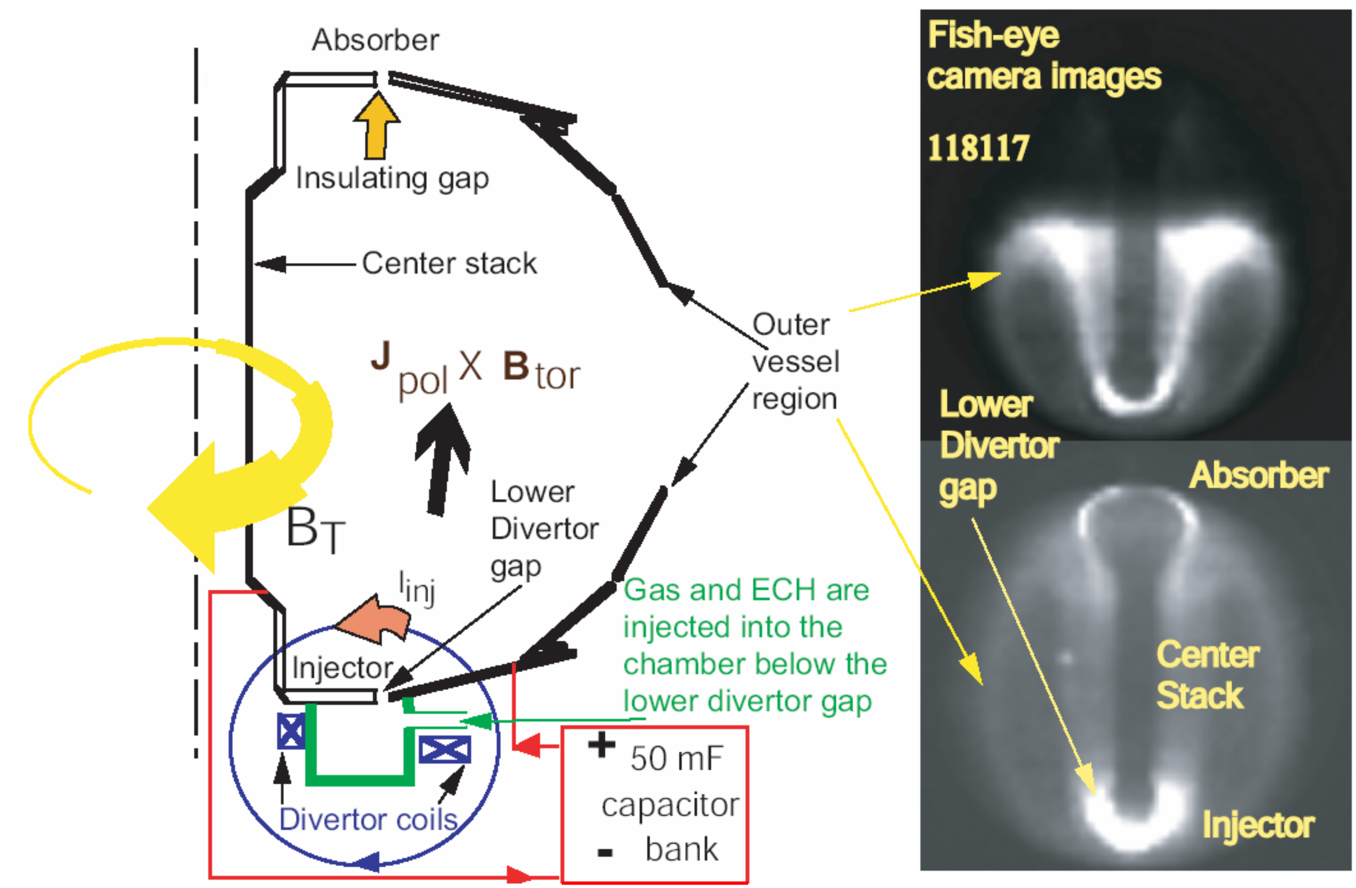
- Bootstrap + FWCD

NBI+HHFW for higher I_P ramp-up

- Bootstrap + FWCD + NBICD



Coaxial Helicity Injection (CHI) can generate toroidal plasma current with closed flux surfaces w/o a central solenoid → important for future ST and tokamak reactor concepts



Gas and ECH are injected into the chamber below the lower divertor gap

Expect axisymmetric reconnection at the injector to result in formation of closed flux surfaces

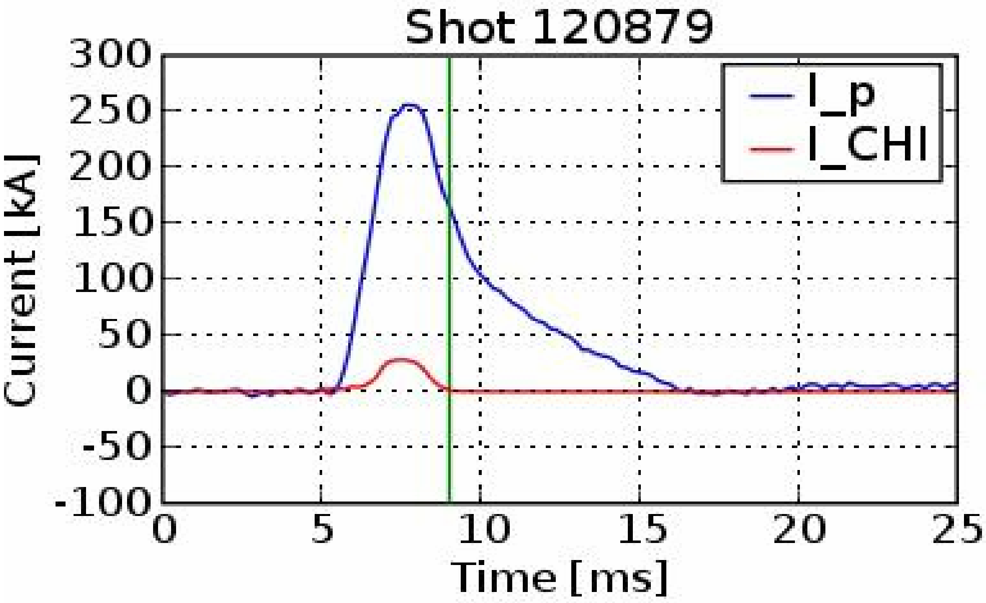
R. Raman, Nucl. Fusion **45** L15 (2005), X. Tang, Phys. Plasmas **12**, 042113 (2005)

Since 2003, CHI has convincingly demonstrated the formation of closed poloidal flux at high plasma current

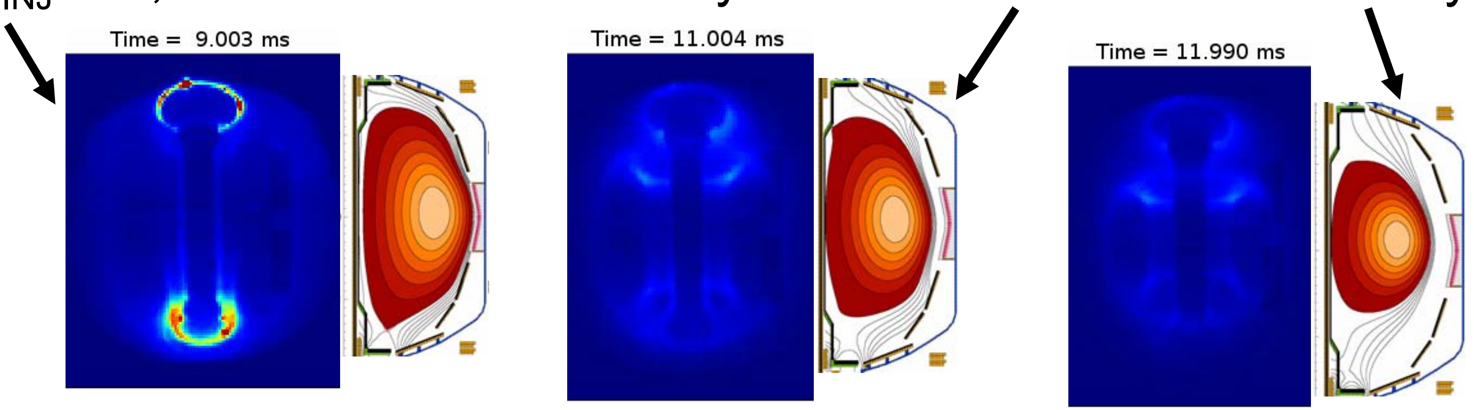
Evidence for high-I_P flux closure:

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

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



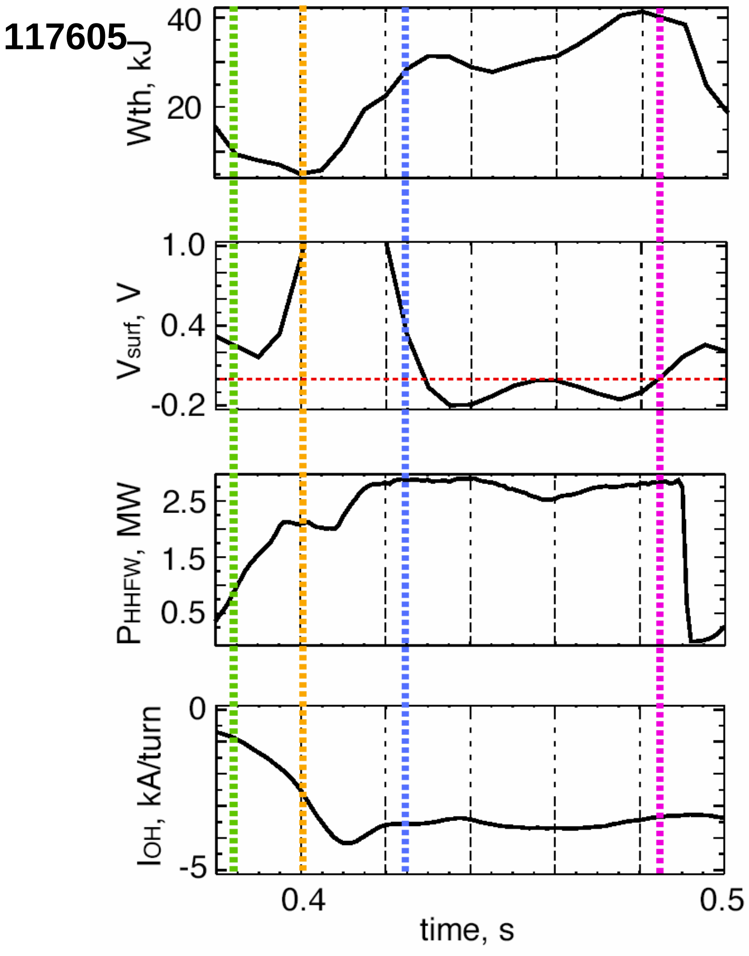
3. Once I_{INJ}→ 0, reconstructions track dynamics of detachment & decay



R. Raman, submitted to PRL

HHFW experiments at low I_P show HHFW heating can induce a high β_P H-mode and drive V_{SURF} and V_{LOOP} → 0

I_P = 250 kA, $k_{||}$ = 14 m^{-1} heating

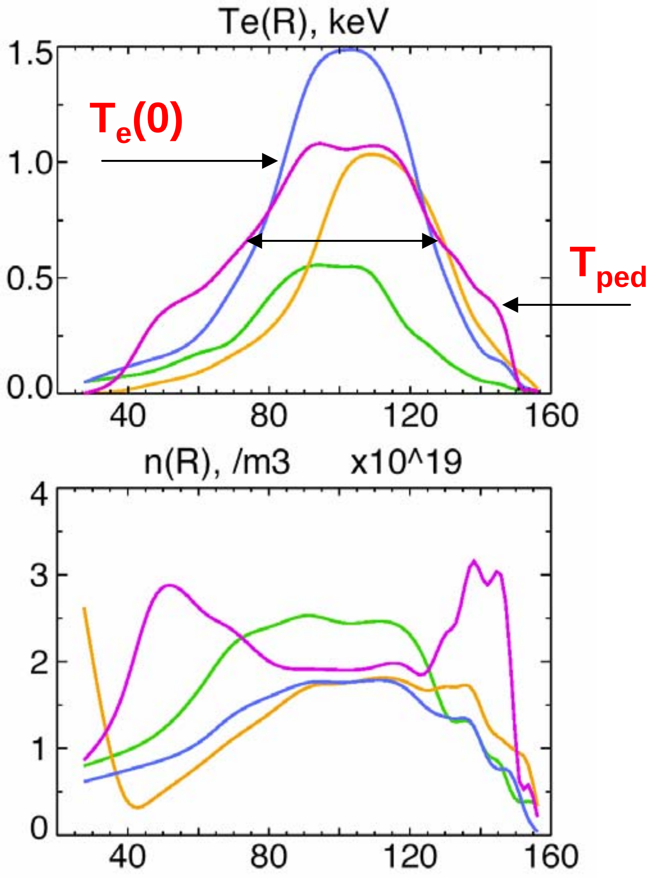


High $T_{ped,}$ broad T(ρ), and “not-too-high” $T_e(0)$ best for non-OH ramp-up

t = 0.385
0.400
0.425
0.485

β_P=1.8

f_{BS}=65-80%



C. Kessel, Phys. Plasmas **13**, 056108 (2006)

Key Research Results and Plans for Solenoid-Free Start-up

- CHI achieved > 160kA of closed flux current
  - Camera, magnetics clearly indicate detachment
- Low I_P=250kA HHFW heated plasma – drove surface and loop voltages to zero

PLANS:

- CHI development: (FY07-09)
  - **Heat CHI plasma w/ 200kW EC/EBW for burn-through → HHFW BS+FWCD** (FY08-09)
  - Increase V_{CHI} to 2 kV for higher I_P (FY07-08)
  - Couple transient CHI to OH ramp-up, study HHFW power coupling (FY07-08)
  - Diagnose w/ fast camera, SXR, Thomson, spectroscopy, bolometer, dynamo probe (FY07-09)

- Extend I_P=20kA PF-only start-up results from 2004-2005 to higher I_P: (FY08-09)
  - Assess higher power pre-ionization - 200kW EC/EBW (w/ ORNL), high $k_{||}$ HHFW
- Low I_P HHFW: Reduce HHFW trips caused by H-mode, extend pulse (FY09 or later)
  - Center-fed antenna straps to reduce strap voltage and trips, higher $k_{||}$ for low-I_P FWCD
- Mid I_P HHFW+NBI: complete NICD fraction assessment vs. I_P (FY07-08)
- Minimize OH flux used in I_P ramp to mimic small iron core in CTF (FY07-08)
  - Improve breakdown null, use early H-mode in more scenarios, earlier heating

NSTX will continue to contribute to fundamental toroidal confinement science in support of ITER and future ST's

- Only ST in world with advanced mode stabilization tools and diagnostics
  - RWM control at ITER-relevant rotation, dynamic EF control, NTV theory validation
- Unique opportunity for understanding transport and micro-turbulence
  - High-k scattering, MSE, neoclassical ion diffusivity → new understanding of e-transport
- Improved understanding of HHFW and EBW coupling efficiency
  - Developing heating and current drive tools essential for ST, useful for AT
- Uniquely able to mimic ITER fast-ion instability drive with full diagnostics
  - Measured fast ion diffusion/loss from multi-mode EPM/TAE bursts + 3-wave coupling
- Broad ITER and CTF-relevant boundary physics research program
  - Only major US facility studying Li for particle pumping and power handling
  - Addressing fueling, divertor, pedestal, ELM, edge turbulence, and deposition/erosion
- Moving rapidly toward fully non-inductive high performance scenarios
  - Enabled by J profile measurements + advanced scenario modeling applicable to ITER
- Demonstrated 160kA closed-flux plasma formation in NSTX using CHI
  - Plasma start-up and ramp-up research crucial to ST concept

- ST offers compact geometry + high β for attractive fusion applications:
  - Component Test Facility (CTF) for nuclear testing of reactor components
  - More attractive fusion reactor