Supported by Office of Science

National Spherical Torus Experiment

Facilities and Select Science Topical Areas

College W&M
Colorado Sch Mines
Columbia U
Comp-X
General Atomics
INEL
Johns Hopkins U
LANL
LLNL
Lodestar
MIT
Nova Photonics
New York U
Old Dominion U
ORNL
PPPL
PSI
Princeton U
SNL
Think Tank, Inc.
UC Davis
UC Irvine
UCLA
UCSD
U Colorado
U Maryland
U Rochester
U Washington
U Wisconsin

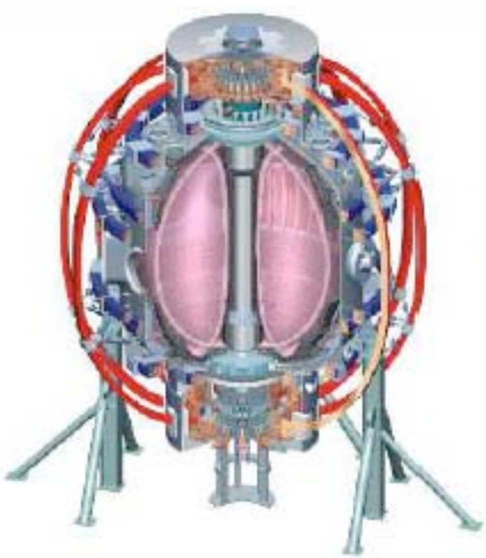
Masayuki Ono

For the NSTX Research Team

2006 48th DPP Americal Physics Society Meeting

October 30 - November 3, 2006

Philadelphia, Pennsylvania



Culham Sci Ctr
U St. Andrews
York U
Chubu U
Fukui U
Hiroshima U
Hyogo U
Kyoto U
Kyushu U
Kyushu Tokai U
NIFS
Niigata U
U Tokyo
JAERI
Hebrew U
Ioffe Inst
RRC Kurchatov Inst
TRINITI
KBSI
KAIST
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
ASCR, Czech Rep

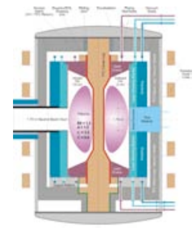
NSTX Strategy to Address Scientific Issues Important for ST-CTF, ITER, and Toroidal Fusion Plasmas

- Explore physics of Spherical Torus / Spherical Tokamak to provide basis for attractive U.S. Component Test Facility (CTF) and Demo.

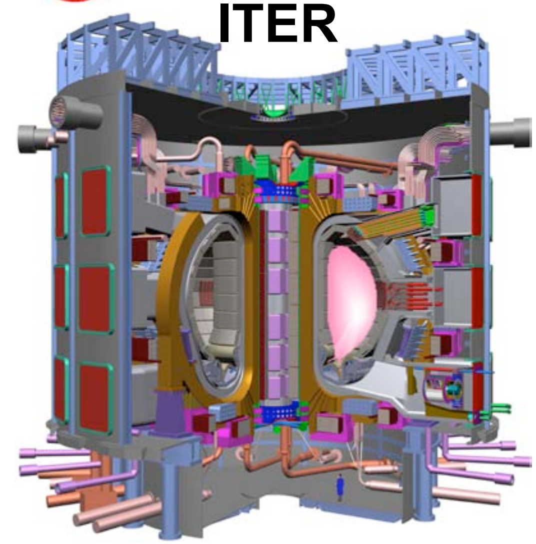
- Support preparation for burning plasma research in ITER using physics breadth provided by ST; support and benefit from "ITPA Specific" activities.

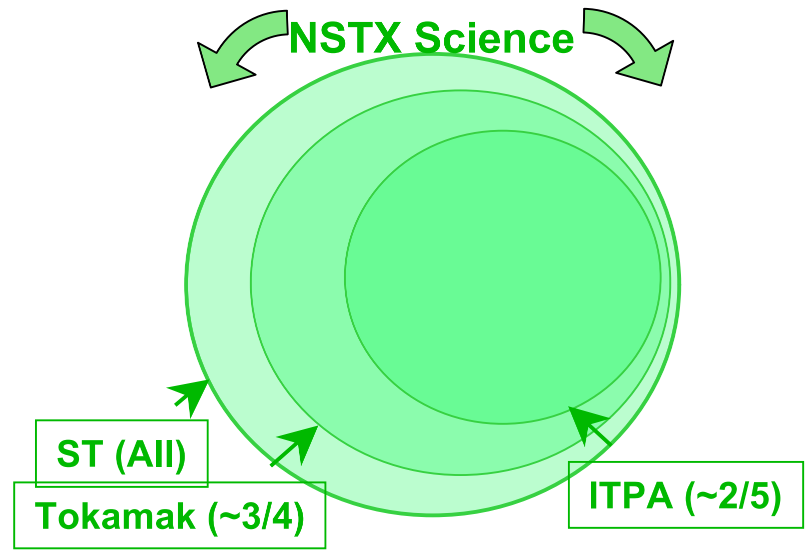
- Complement and extend tokamak physics experiments, maximizing synergy in investigating key scientific issues of toroidal fusion plasmas

ST CTF



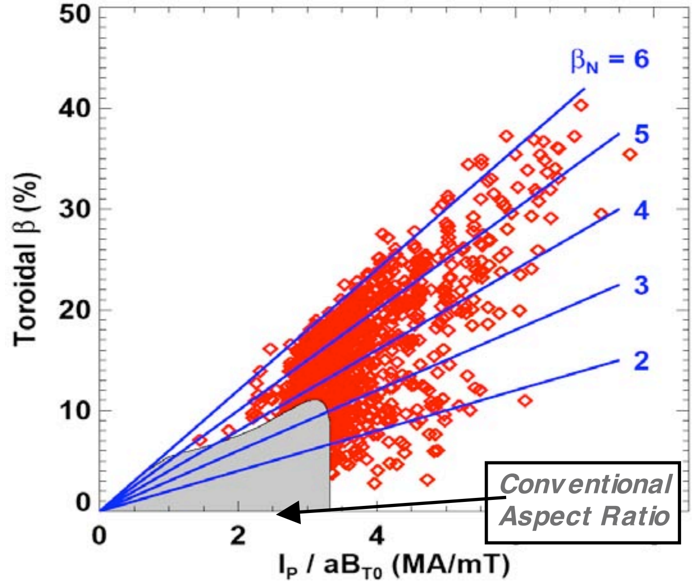
ITER



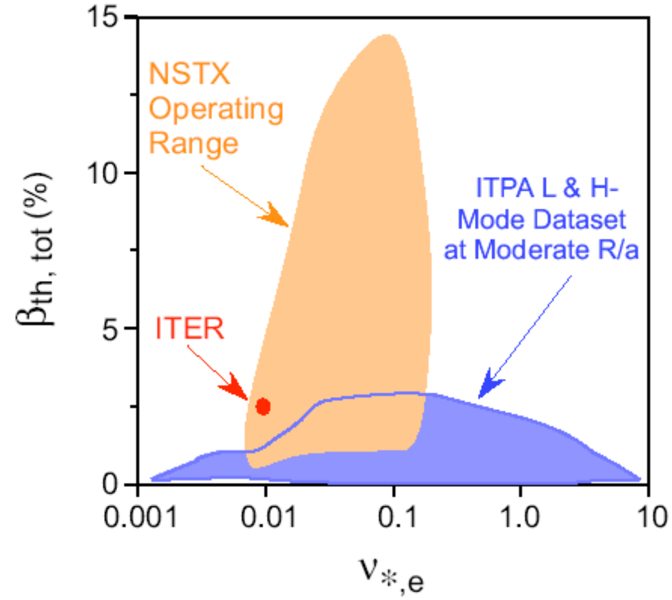


NSTX/ST Offers Access to Wide Tokamak Plasma Regimes

Wide range of β_T up to ~ 40 %.

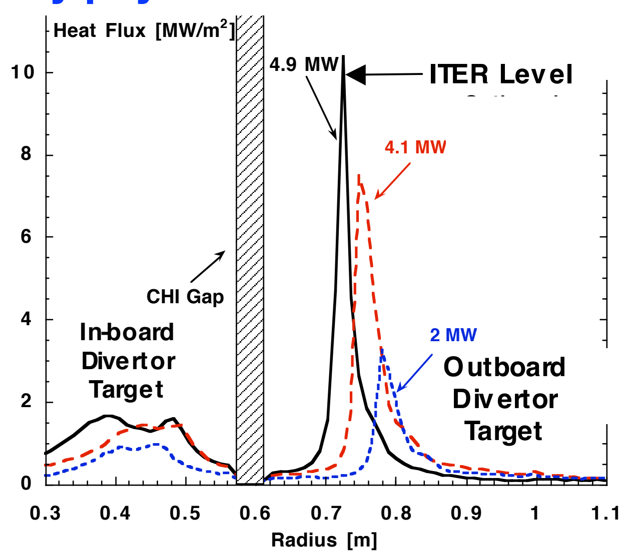


β Confinement Scaling, Electron Transport

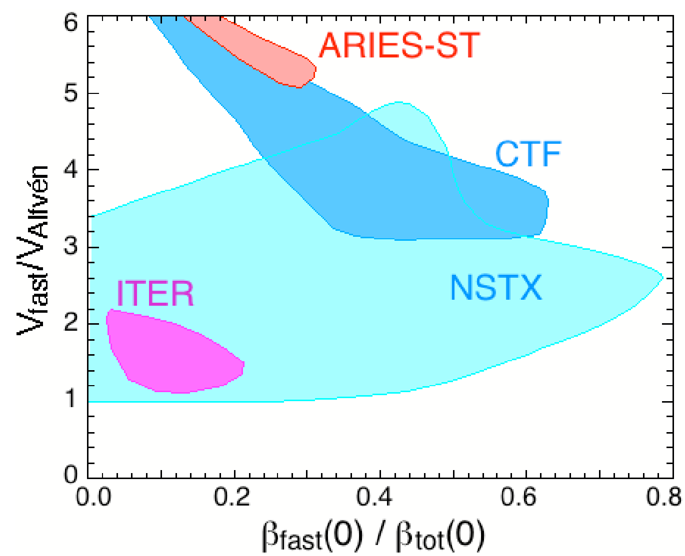


•Confinement scaling with wide range of β_T up to ~ 40 %

Boundary physics with ITER-level heat flux



Unique Energetic Particle Physics Capability

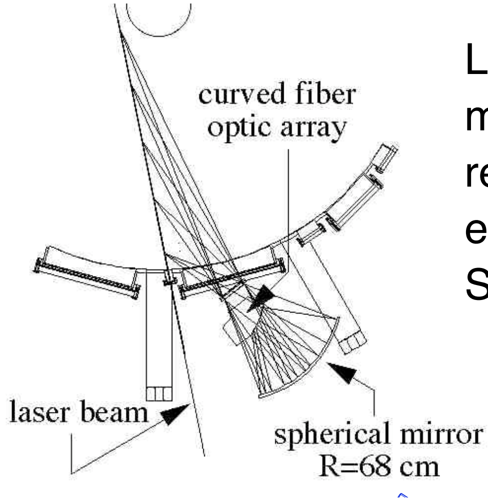


• Full set of diagnostics: including MSE for j(r)

State-of-the-Art Profile Diagnostics with Excellent Tangential Access Enable In-depth Research

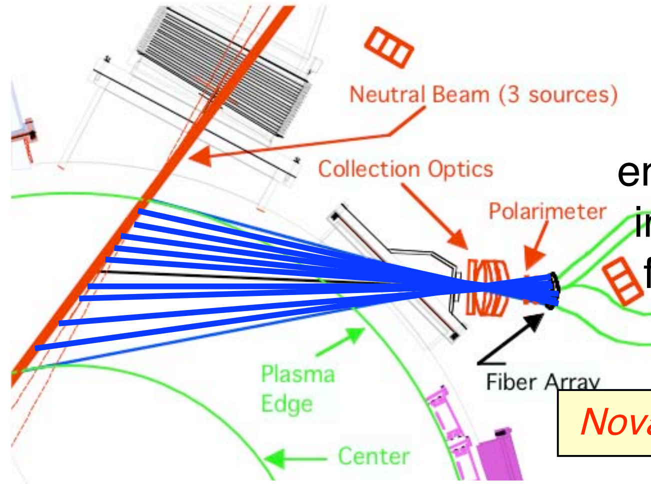
NSTX

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



Large collection mirror and low readout noise gives exceptionally high S/N ratio

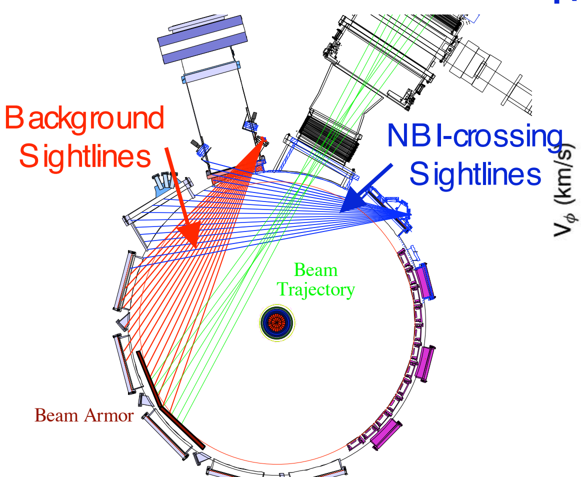
12 Ch MSE for q(r) (19 ch planned)



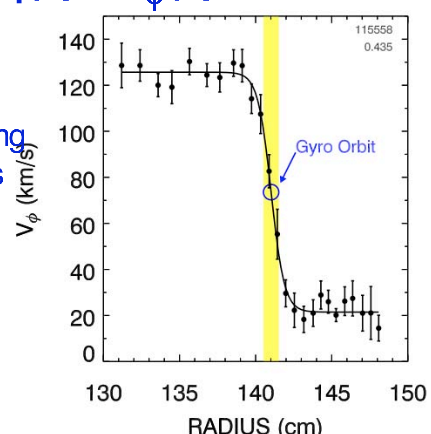
Innovative design enables MSE in kG range for the first time

Nova Photonics

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

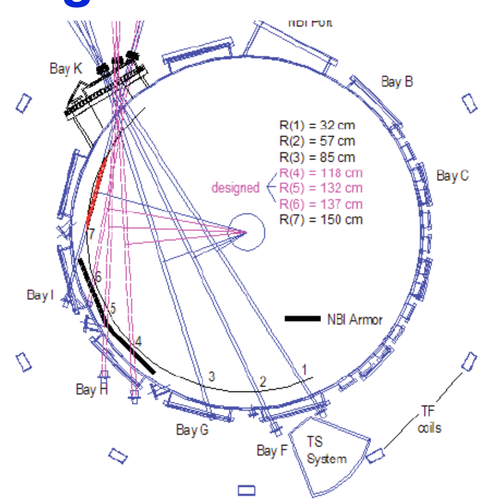


Poloidal CHERS planned



Resolves structure to ion gyro-radius

Tangential FIR Int-Pol (600 kHz)



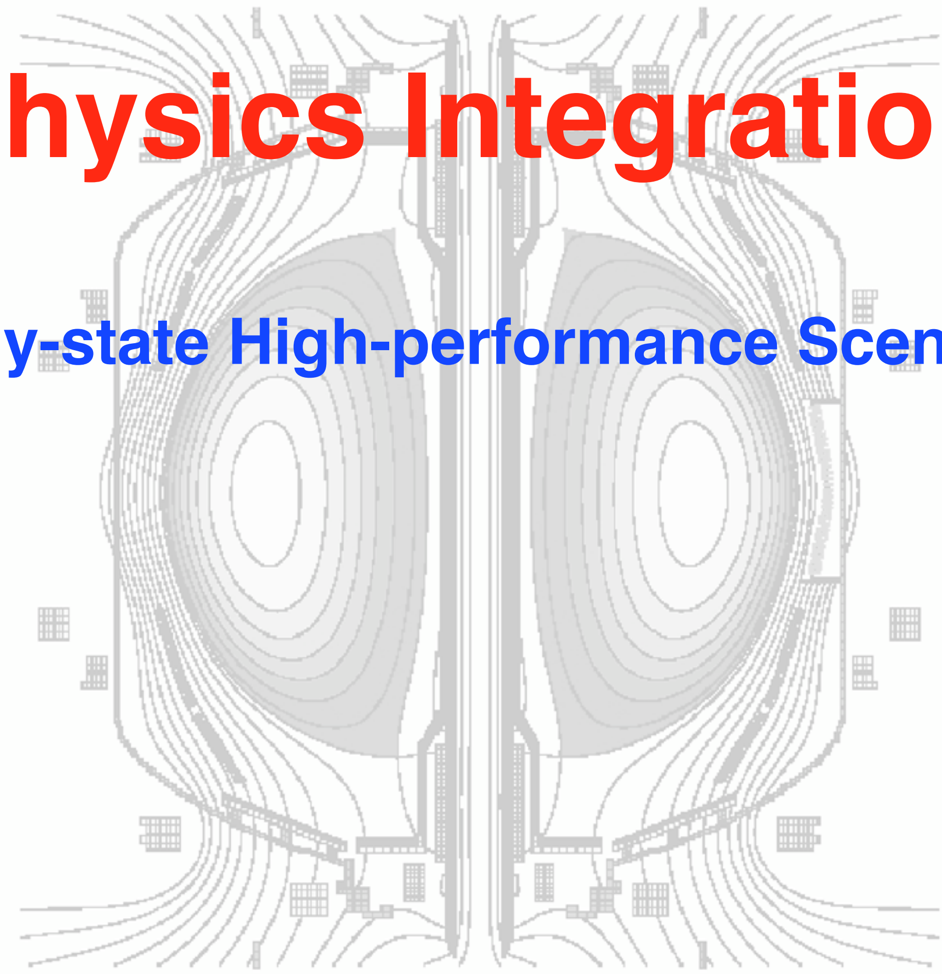
Installed 6 ch
7 ch, 2MHz planned
Spans plasma cross-section

UC Davis

UCD

Physics Integration

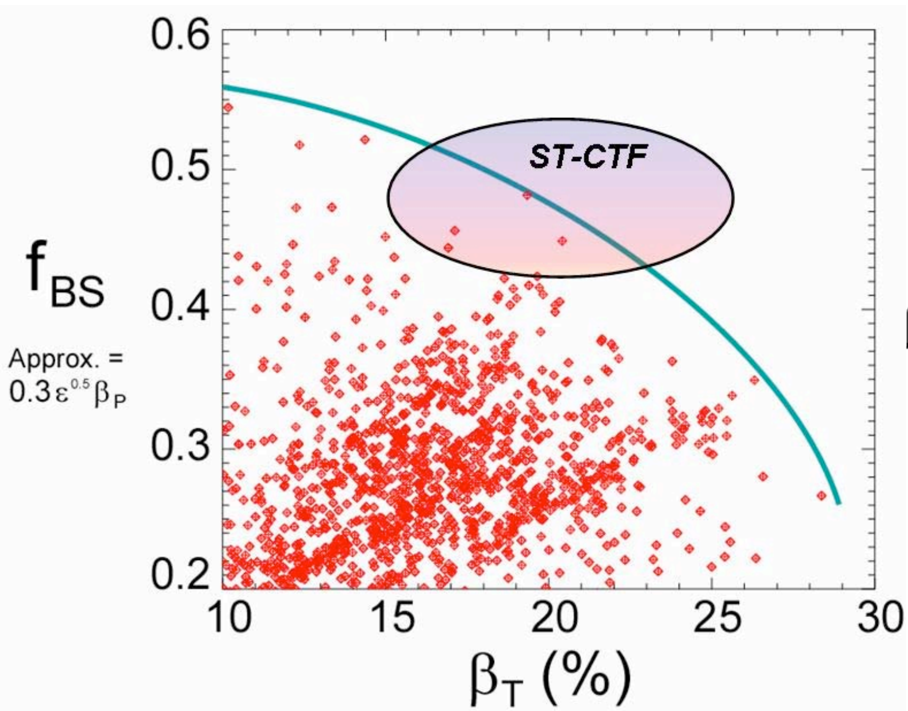
Steady-state High-performance Scenarios



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

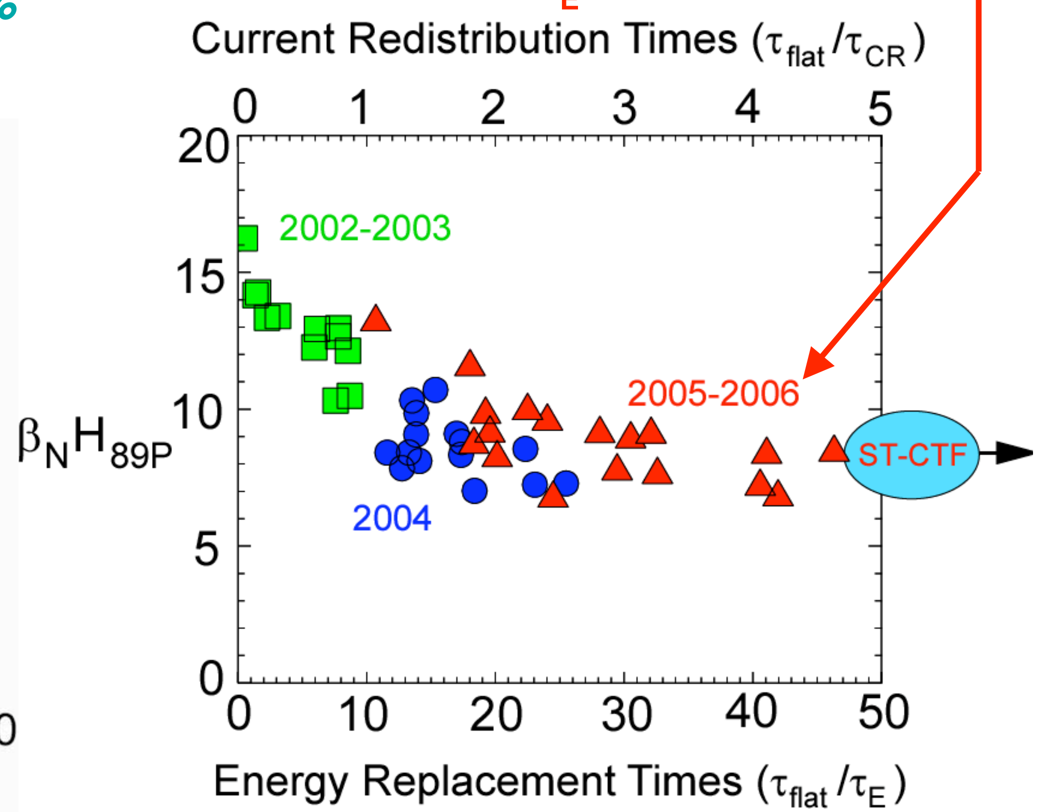
ST-CTF goal: neutron flux = 1-4MW/m²

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%



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

High $\beta_N \times H_{89P}$ ~ 9 **now sustained for ~ 50 τ_E**

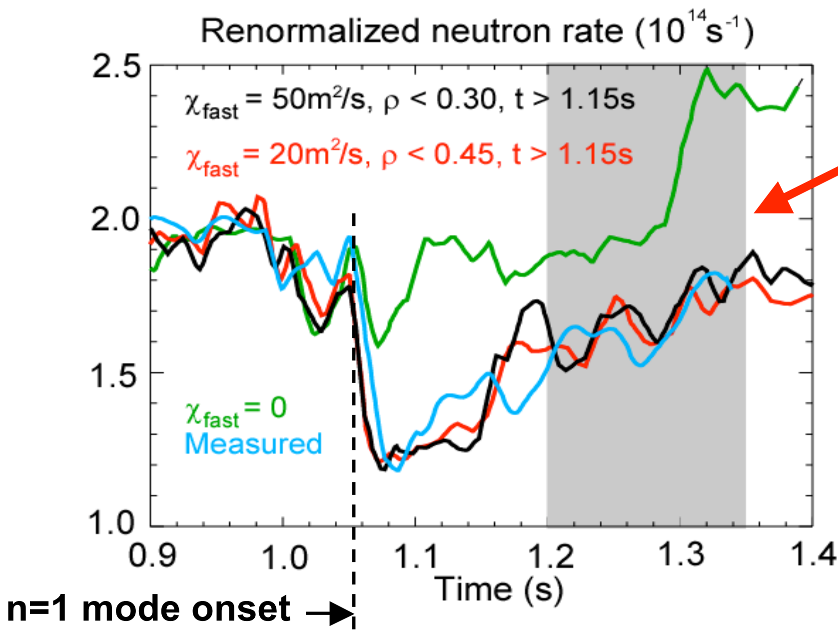


D. Gates, Phys. Plasmas 13, 056122 (2006)

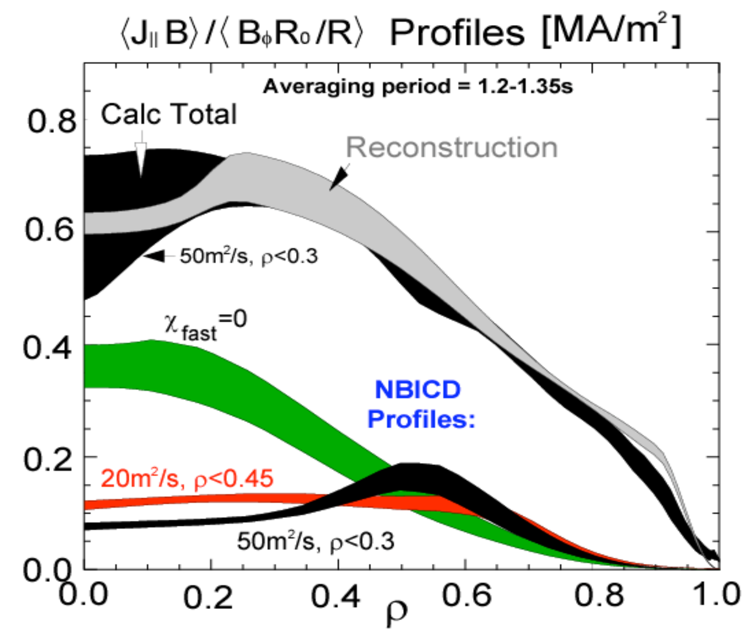
Mode-induced fast ion diffusion needed to explain neutron rate and $J_{||}(\rho)$ evolution during late n=1 interchange activity

NSTX

- 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

Nova Photonics

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

S. Medley QP1.19

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

NSTX

Need 60% increase in T, 25% decrease in n_e

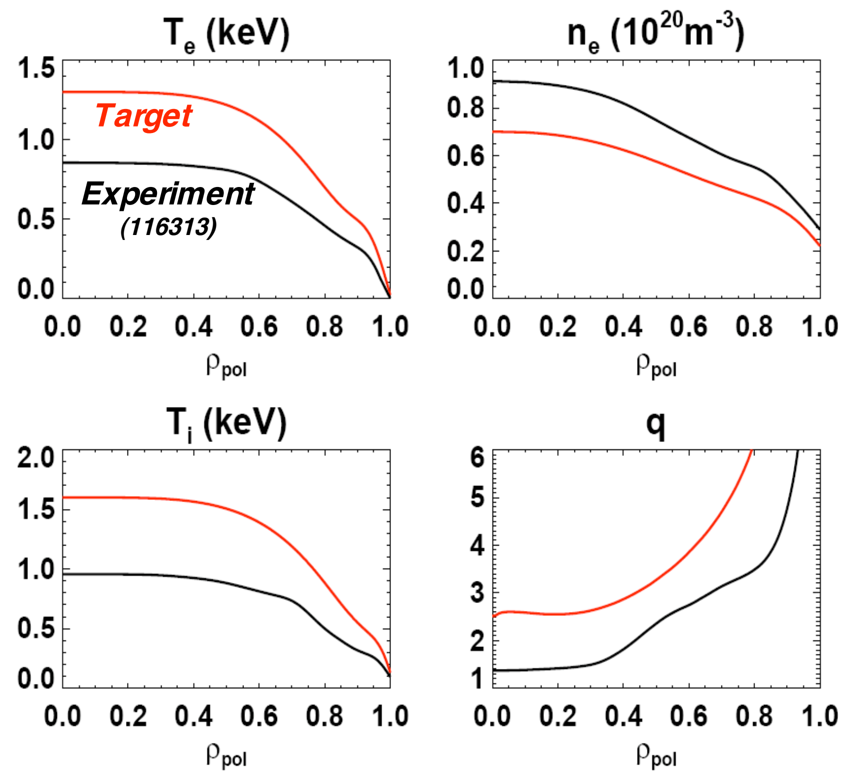
Lithium for higher τ_E & density control?

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

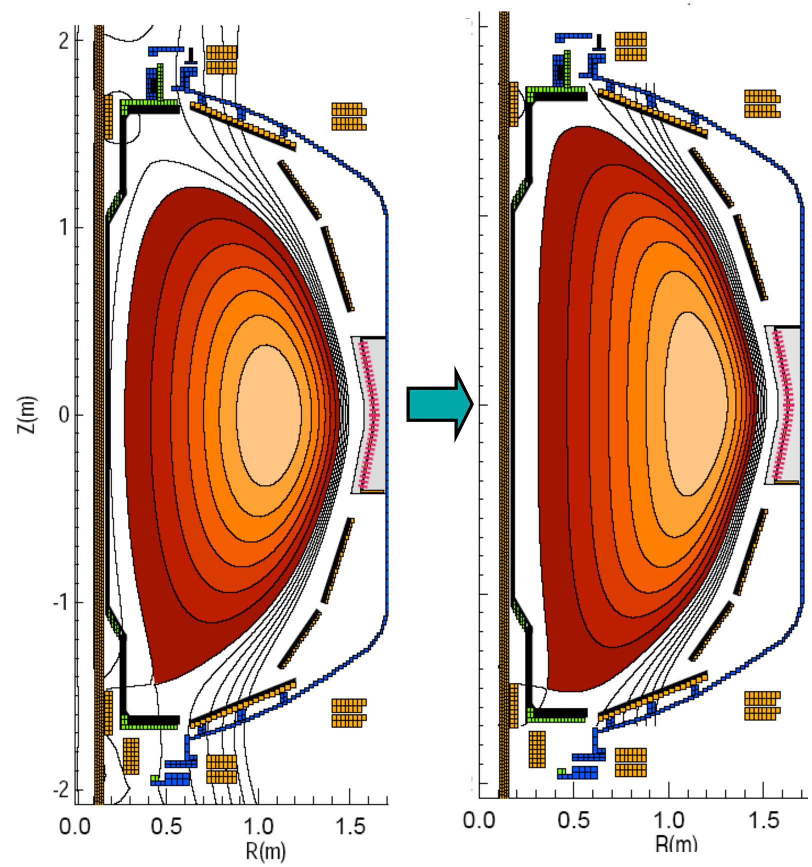


Higher κ for higher q, β_P, f_{BS}

High δ for improved kink stability

= 2.3, δ_{X-L} = 0.75
δR_{SEP} = -1cm

= 2.6, δ_{X-L} = 0.85
δR_{SEP} = -2mm



Macrostability (MHD)

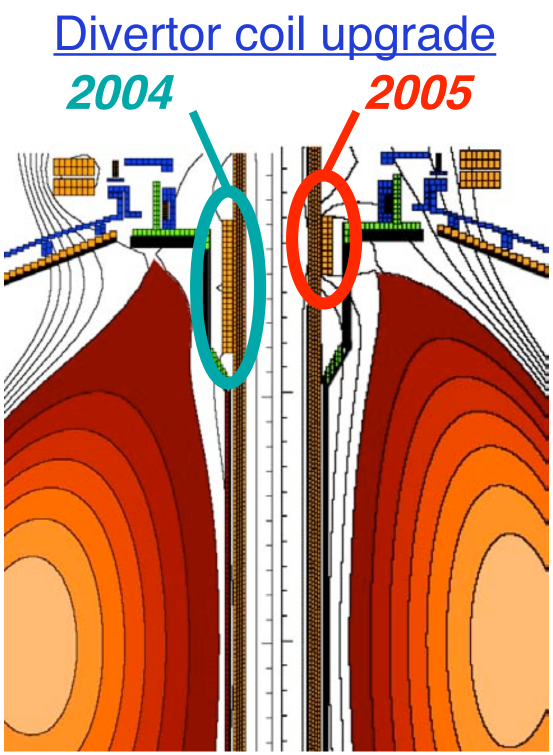
Low-Aspect-Ratio, High β Provides High Leverage to Uncover Key Tokamak Physics
(e.g., RWM Control, Rotation Damping, High Elongation)

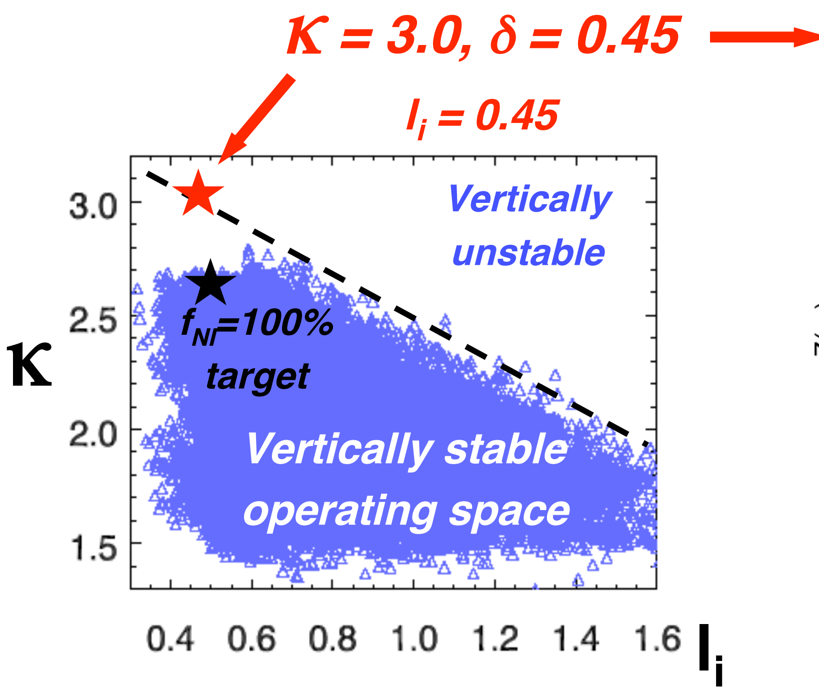
Extreme Elongation at Low l_i Opens Possibility of Higher β_P, f_{BS} Operation at High β_T

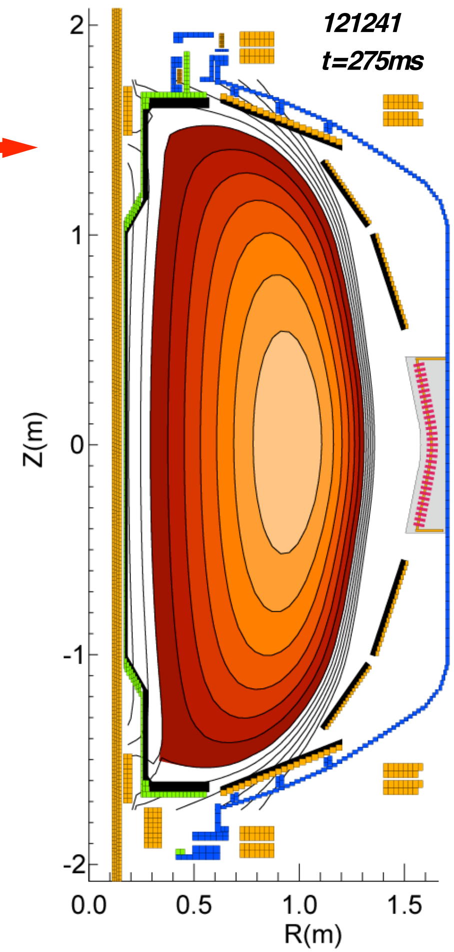
NSTX

GA

- Sustained $\kappa \geq 2.8$ for many τ_{WALL} using rtEFIT isoflux control
  - Allowed by divertor coil upgrade in 2005, **no** in-vessel vertical position control coils
- High κ research important for CTF and Advanced Tokamaks





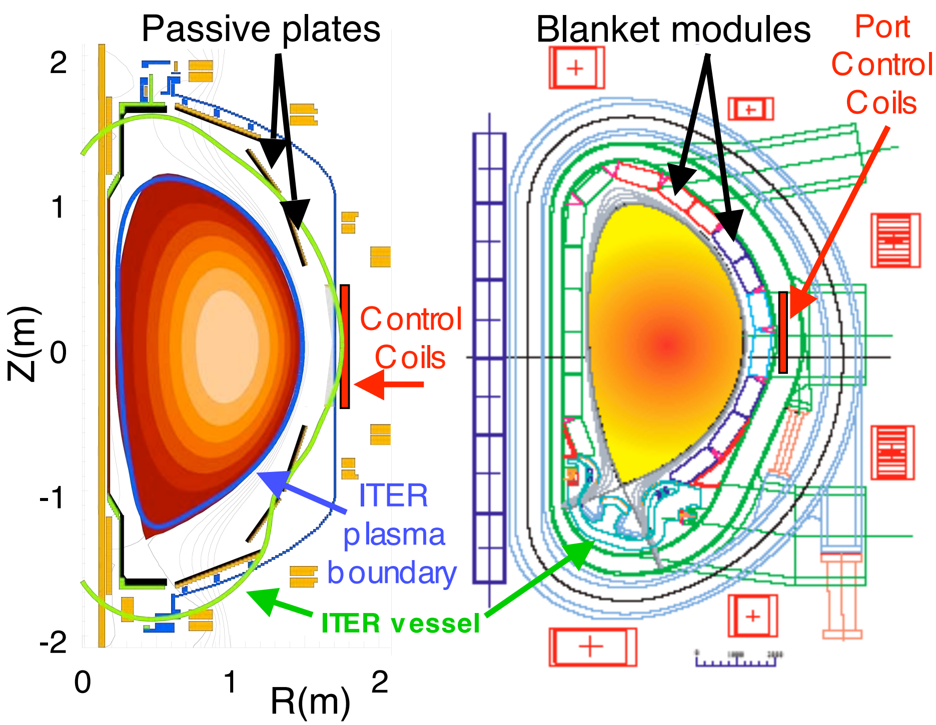


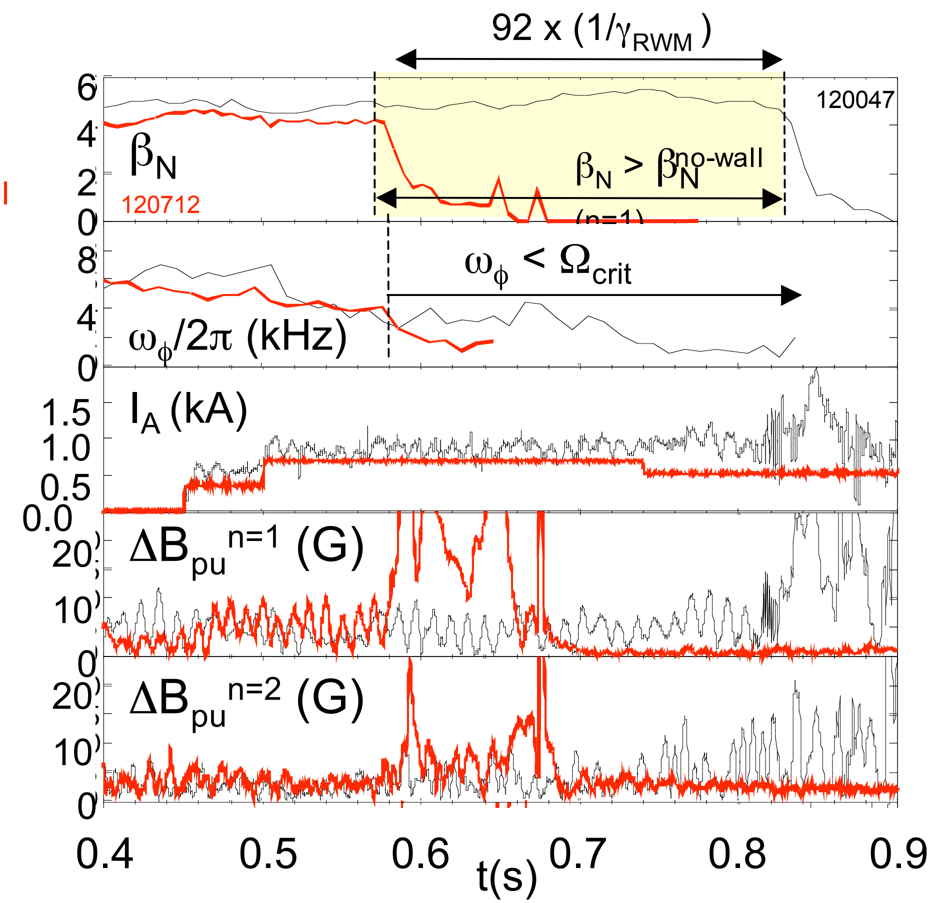
(Gates, et al., PoP **13** (2006) 056122.)

D. Gates NO1.6

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

NSTX / ITER RWM control





Addressing relevant physics for ITER, CTF, KSTAR

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

Columbia U

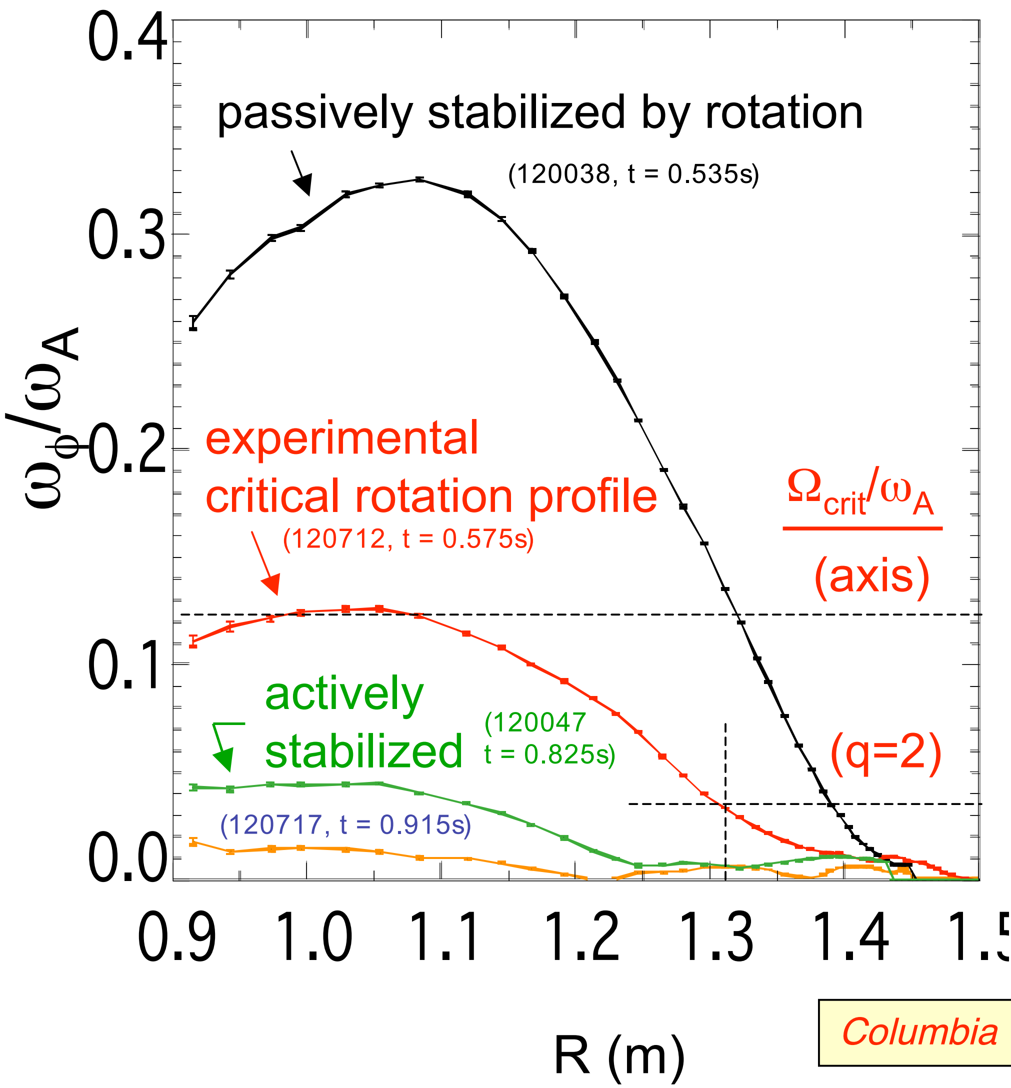
RWM actively stabilized at ITER-relevant rotation for ~ $90/\gamma_{RWM}$

S. Sabbagh VI2.1, D. Mueller QP1.4

Rotation reduced far below RWM critical rotation profile

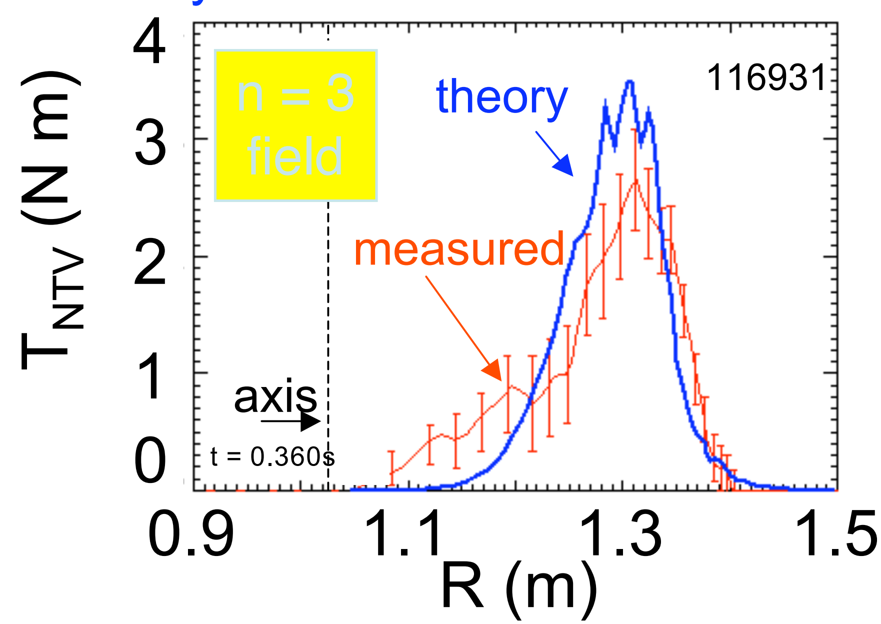
NSTX

Non-resonant n = 3 magnetic braking used to slow entire profile



Columbia U

First quantitative agreement with full neoclassical toroidal viscosity theory



Viable physics for simulations of plasma rotation in future devices (ITER, CTF, KSTAR)

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

A. Sontag NO1.8

Transport and Confinement

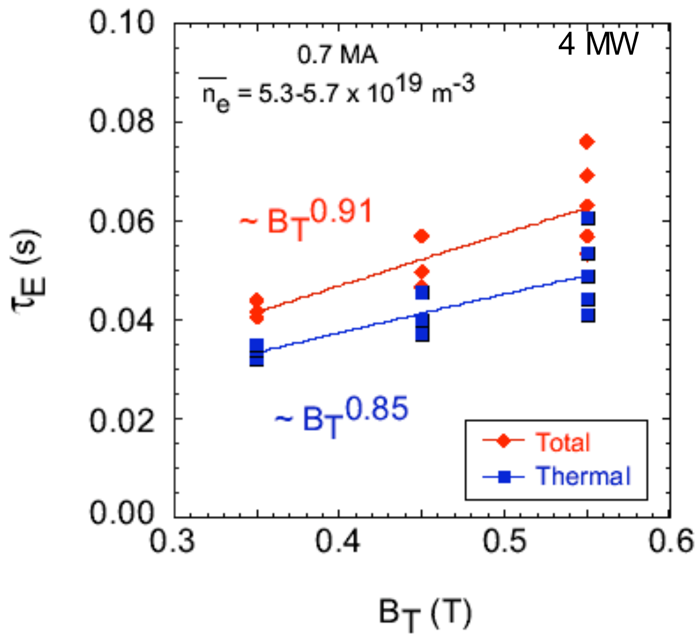
Measuring Transport and Associated Fluctuations to Gain Understanding of Electron Energy Transport

Dedicated H-mode Confinement Scaling Experiments Have Revealed Some Surprises

NSTX

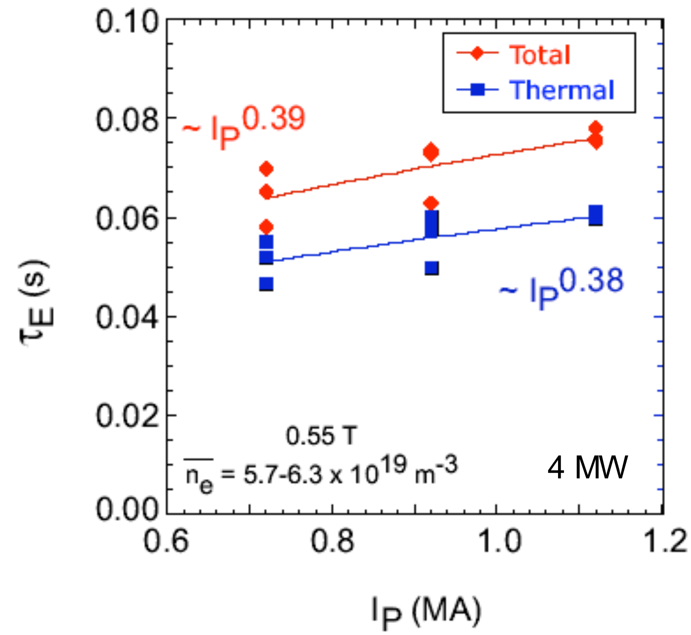
Strong dependence on B_T

$H_{98y,2}$ ~ 0.9 → 1.1 → 1.4



Weaker dependence on I_p

$H_{98y,2}$ ~ 1.4 → 1.3 → 1.1



$\tau_{E,98y,2} \sim B_T^{0.15}$

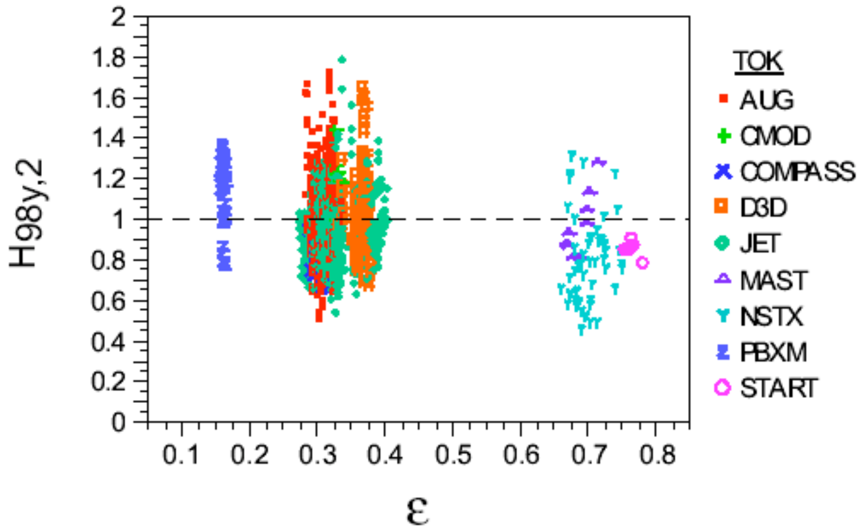
(Kaye et al, NF 46 [2006] 848)

$\tau_{E,98y,2} \sim I_p^{0.93}$

$\tau_E \sim I_p^{1.3-1.5}$ at fixed q **$\tau_{E,98y,2} \sim I_p^{1.1}$ at fixed q**

NSTX Addressing High-Priority ITPA Tasks in Confinement

ITER98PB(y,2) scaling deviates from experimental data at low A



NSTX data used in conjunction with ITPA database implies stronger ε (=a/R) scaling

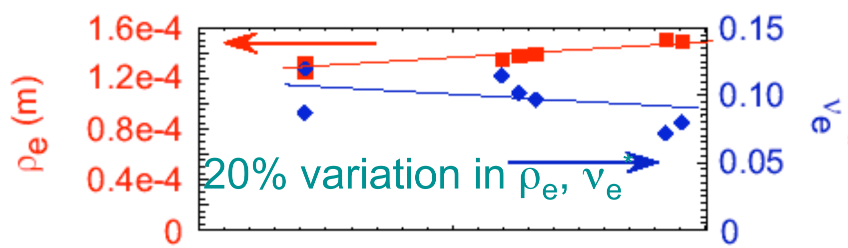
$$\tau_{98y2} \sim I_p^{0.93} B_T^{0.15} n_e^{0.41} P^{-0.69} R^{1.97} \varepsilon^{0.58} \ldots$$

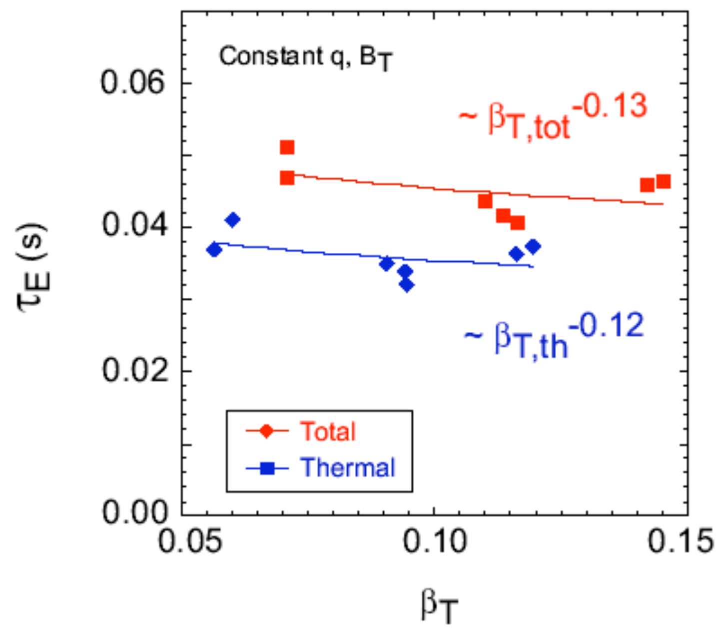
$$\tau_{new} \sim I_p^{0.73} B_T^{0.36} n_e^{0.39} P^{-0.62} R^{2.14} \varepsilon^{1.03}$$

[Kaye *et al.*, PPCF 48 (2006) A429]

Scan β by factor 2–2.5 at fixed ρ_e, ν_e^*

- β-dependence important to ITER advanced scenarios ($B\tau_{98y2} \sim \beta^{-0.9}$)
- Weak degradation of τ_E with β on NSTX



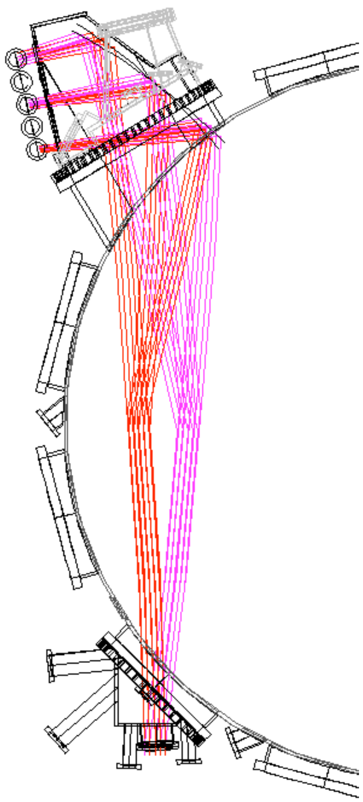


S. Kaye QP1.8

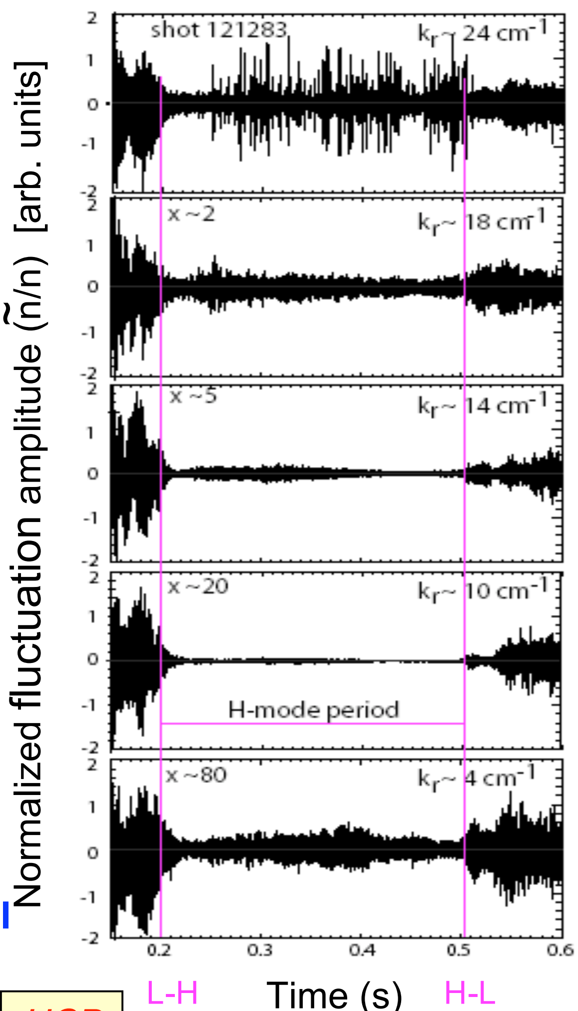
Detailed Transport and Turbulence Measurements during L-H Transition Reveals Important and Tantalizing Electron Transport Physics

NSTX

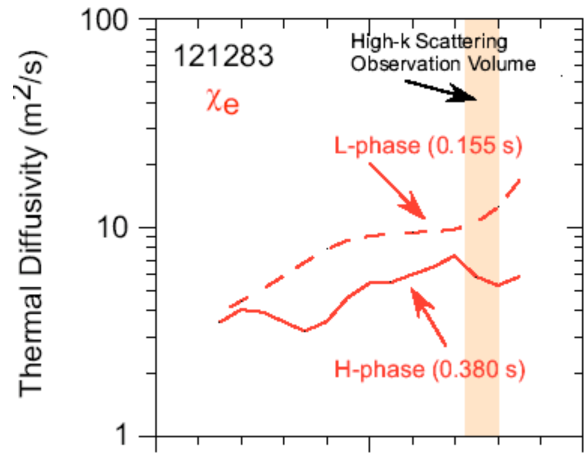
Tangential scattering system measures reduced fluctuations ($\tilde{n}/n$) in both ITG/TEM and ETG ranges during H-mode



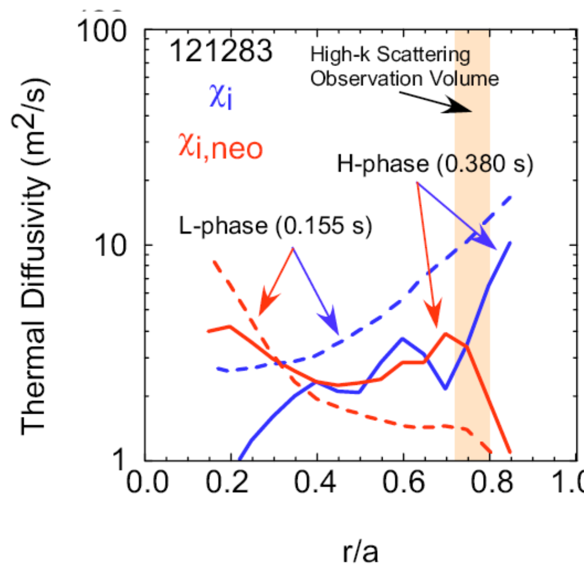
Unprecedented spatial resolution at high k



UCD



Electron transport reduced, but remains anomalous



Ion transport during H-phase at neoclassical level

H. Park NO1.3, D. Smith QP1.12

HHFW and EBW

Understanding HHFW Coupling Physics and Developing EBW CD for Profile Control for Advanced Operations

Solenoid-free Start-up

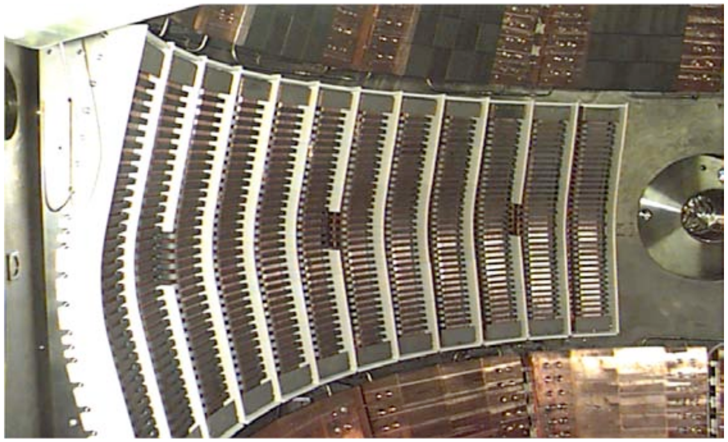
For Attractive ST-CTF andFusion Reactors

Energetic Particles

α–Particle Driven Instabilities and Associated Transport is a Critical Issue for ITER and Reactors

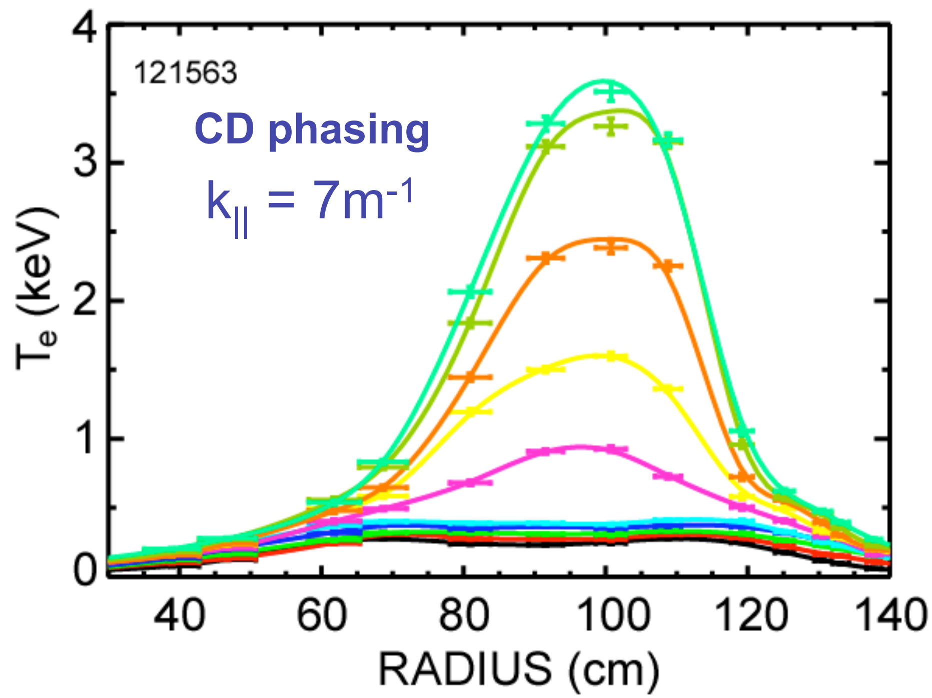
HHFW Heating Efficiency Improved with B_T

NSTX



- ***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 $14m^{-1}$***

- Achieved high T_e=3.6keV (nearly double the previous value) in current drive phasing for first time at B_T = 5.5kG
- Higher B_T and $k_{||}$ improved HHFW core electron heating - reduced edge parasitic loading



J. Hosea NO1.11, C.K. Phillips QP1.24

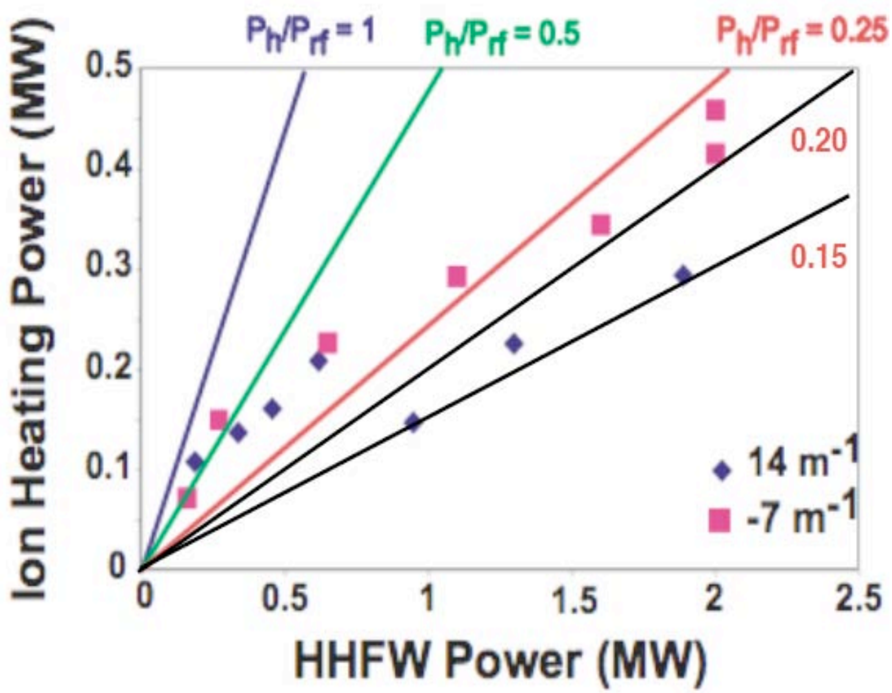
Improved Understanding of HHFW Edge Interactions Leads to More Efficient Heating & CD

Parametric Decay Instability (PDI) of HHFW → IBW → edge ion heating

PDI increases with lower $k_{||}$ and/or B_T

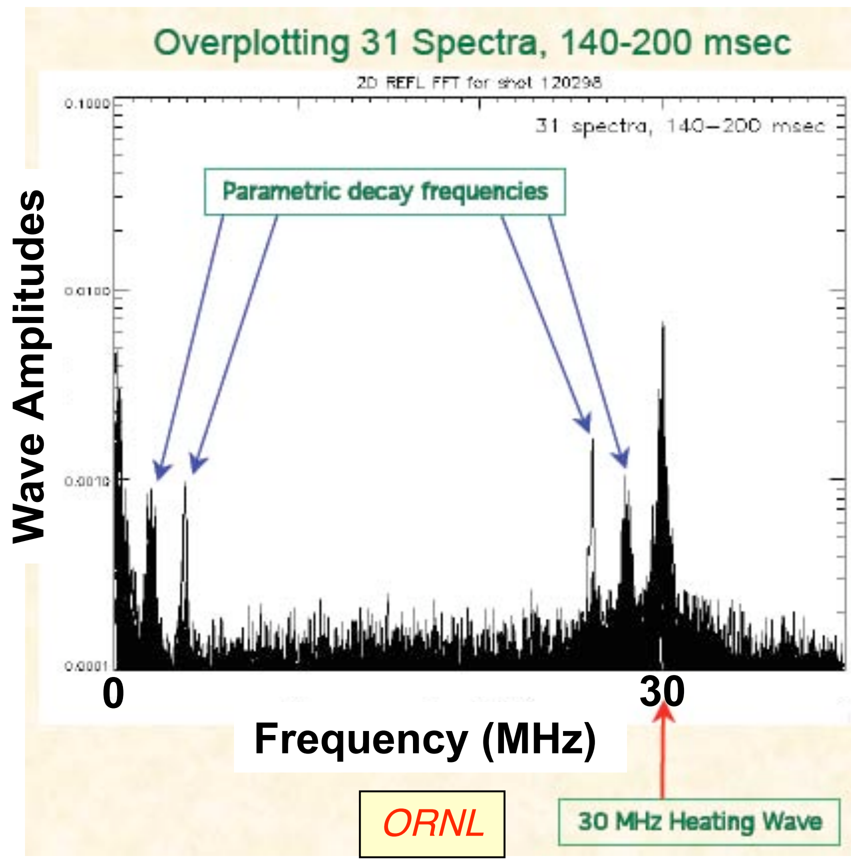
Low $k_{||}$ used for HHFW current drive

Low B_T needed for high β



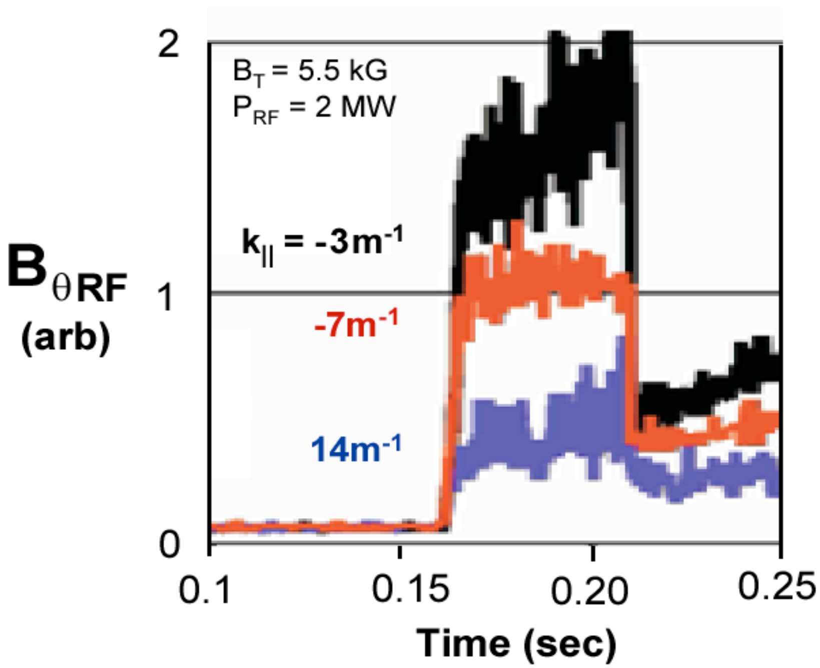
T. Biewer, Phys. Plasmas 12, 056108 (2005)

Edge 17.5 GHz Wave Reflectometer also shows phase dependence of PDI



Surface and Core HHWF Fluctuations Measured

Surface Wave Probe Data



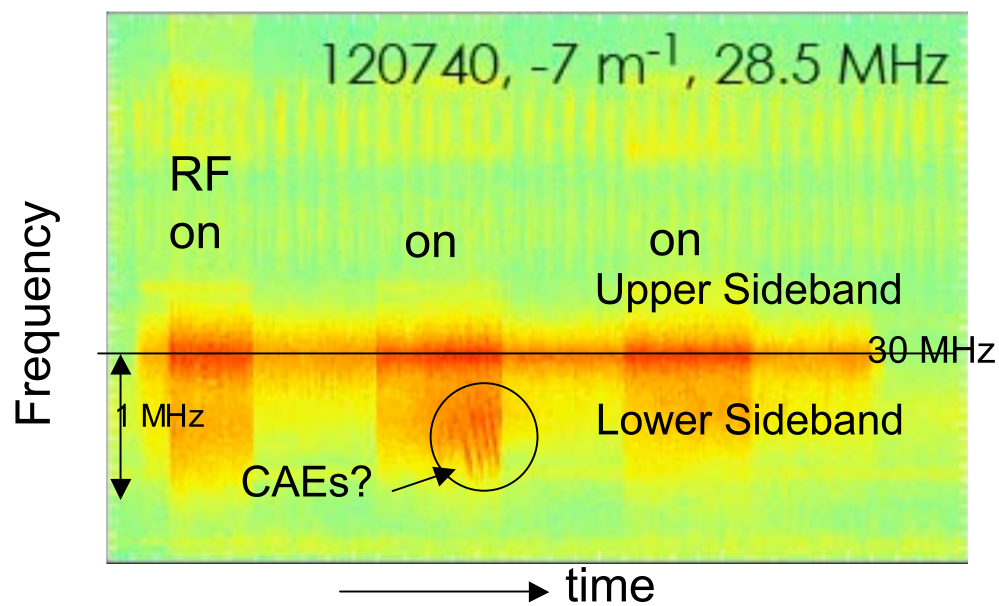
HHFW at low $k_{||}$ should begin propagating at much lower n_e

→ surface waves, wall interactions

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

New 47 Gz Wave Reflectometry Measurements on the HHFW fluctuations in the plasma core

- **Broad turbulence spectrum**
- **Typically asymmetric**
- **Coherent chirps**

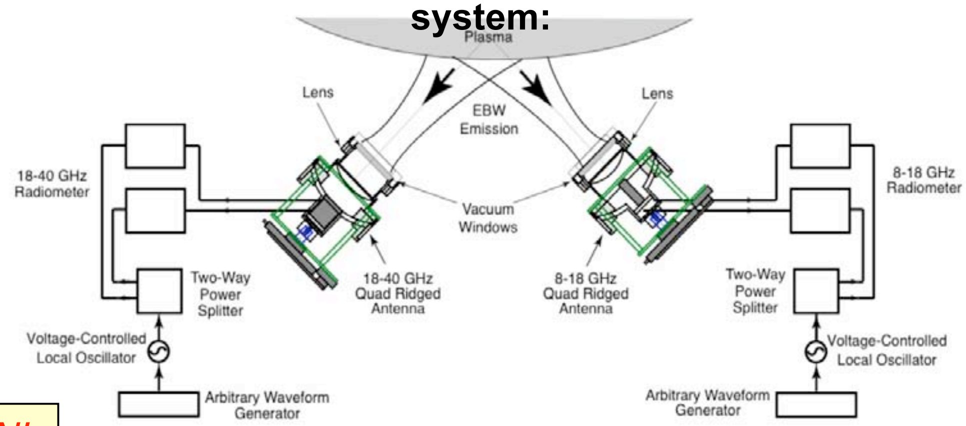


UCLA, Tokyo University

S. Kubota QP1.11

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

Dual-antenna remotely-steerable EBW radiometer system:



ORNL

Frequency range:

1st & 2nd harmonic: 8-18GHz

2nd & 3rd : 18-40 GHz

Directionality:

±10° steering in poloidal and toroidal directions

Antenna acceptance angles:

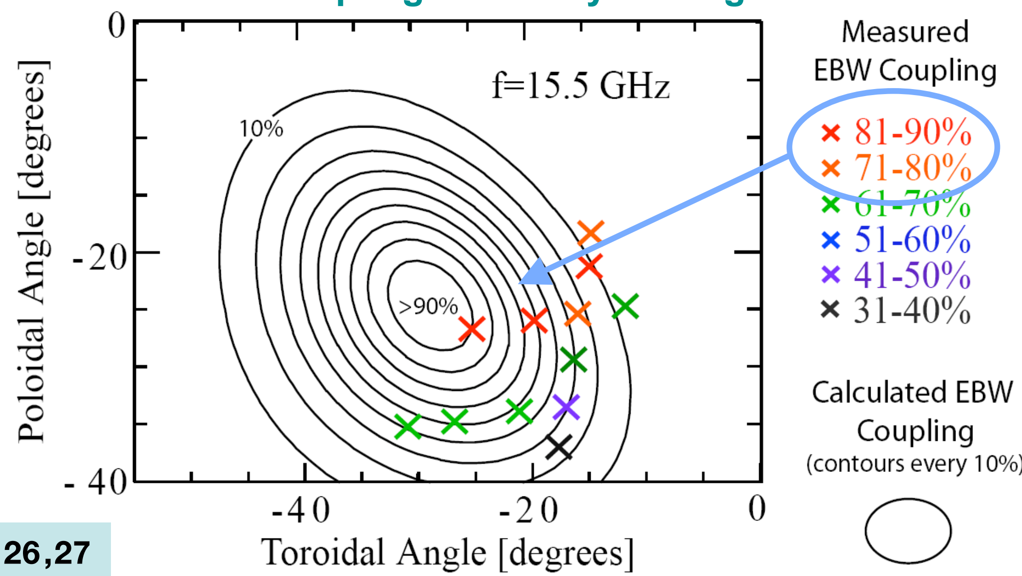
8-18GHz ~ 22°, 18-40GHz ~ 14°

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:



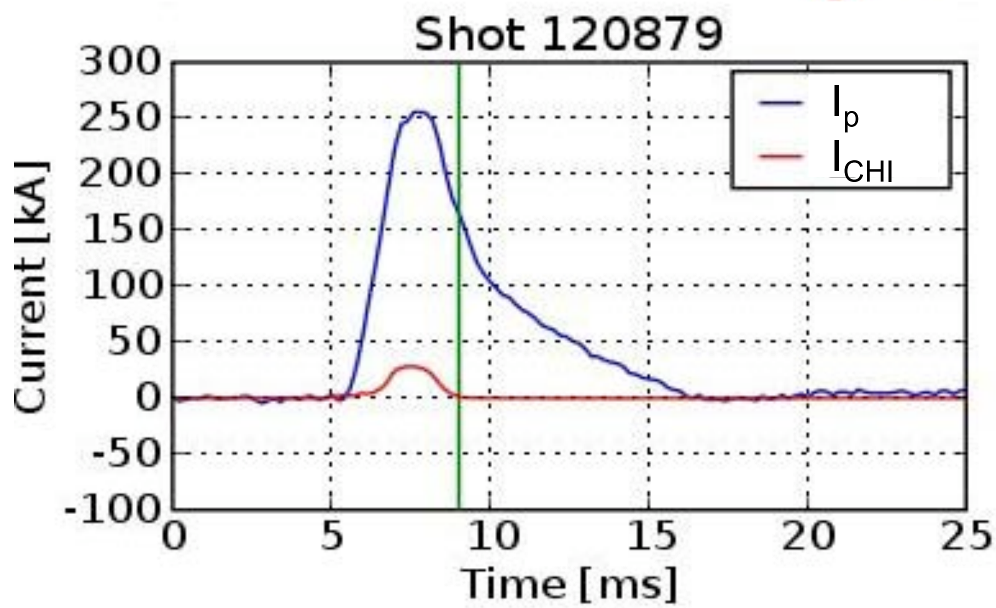
S. Diem NO1.12, G. Taylor, A. Ram, J. Urban QP1.25,26,27

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

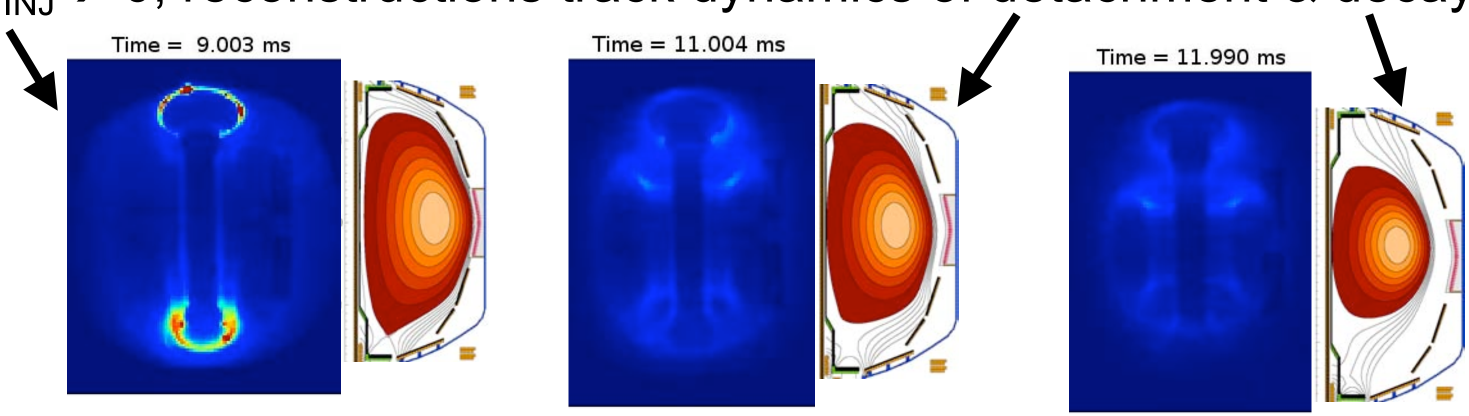
<u>Evidence for high-I_P flux closure:</u>

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

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



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



Univ. Washington

R. Raman, Phys. Rev. Lett. (2006)

R. Raman BI1.2, D. Mueller QP1.4

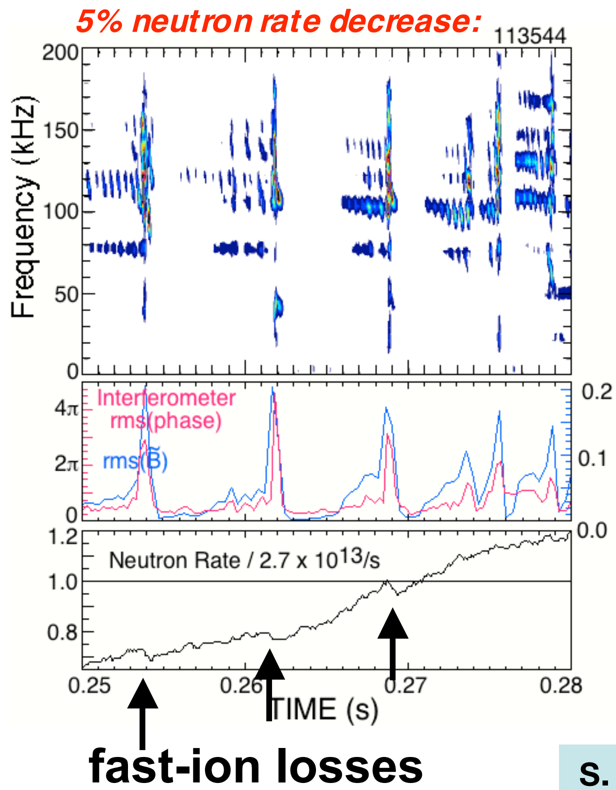
Clear Effect of Multi-Modes Observed for Super-Alfvénic, Fast Ion Population

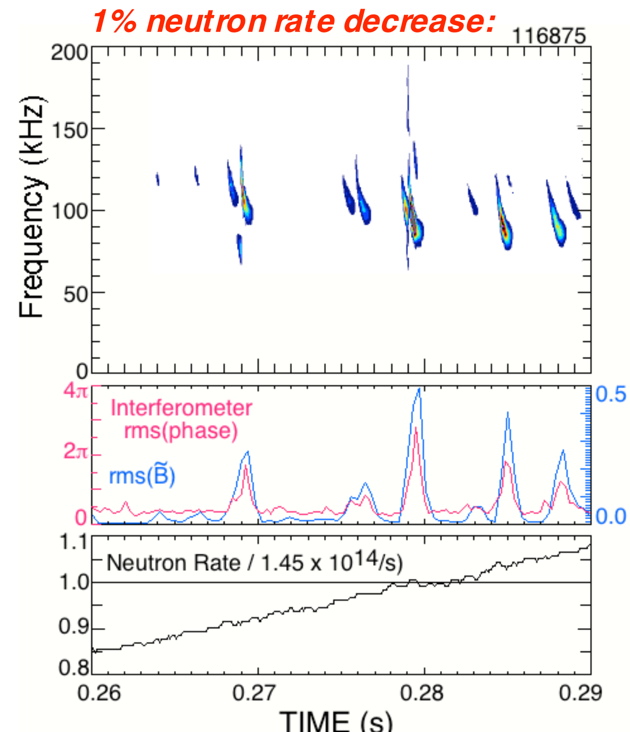
NSTX

ITER will operate in multi-modes regime for fast ion transport

- $k_{\perp}\rho \approx 1$ means "short" wavelength Alfvén modes
- Fast ion transport expected from <u>interaction of many modes</u>
- 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:





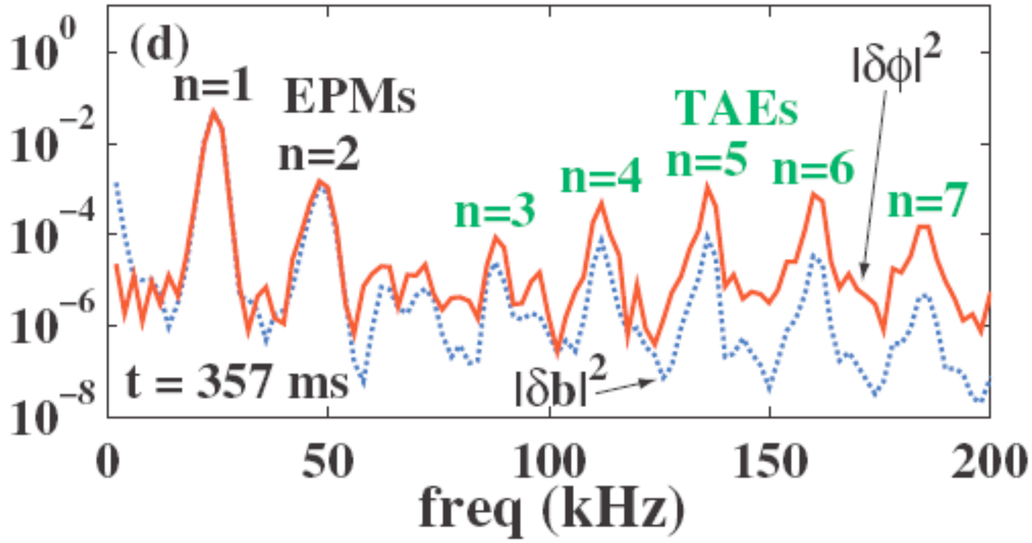
S. Medley QP1.19

UCI, UCLA

Reflectometry Data Reveals 3-wave Coupling of Distinct Fast-Ion Instabilities for First Time

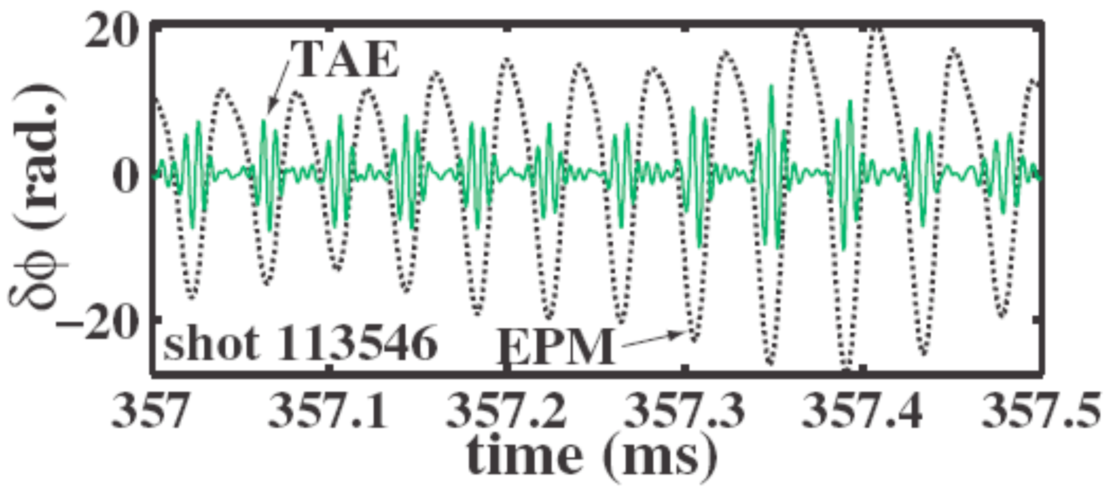
NSTX

Low-f Energetic Particle Modes (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***

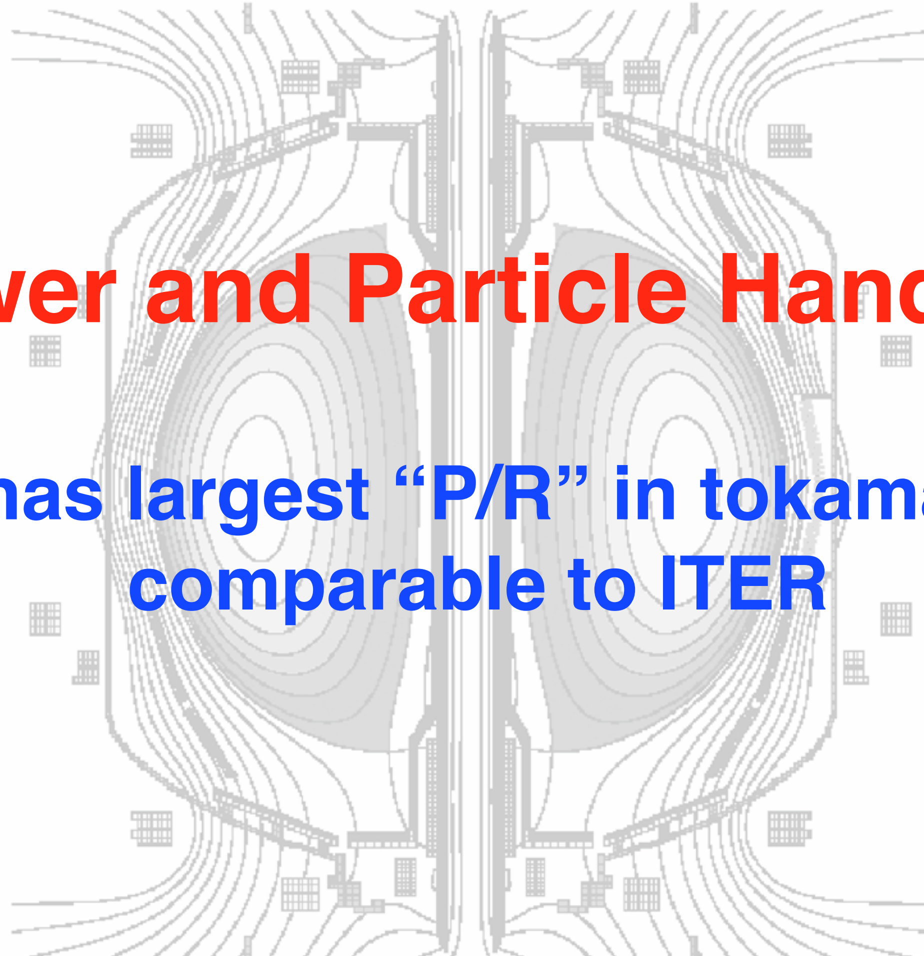
  forming toroidally localized wave-packet

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

N. Crocker QP1.23

UCLA

Power and Particle Handling

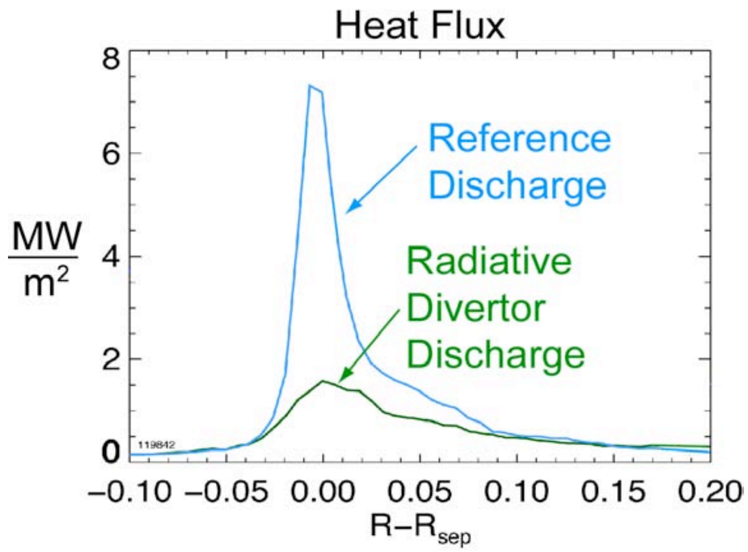


NSTX has largest “P/R” in tokamaks/STs comparable to ITER

Reduced Peak Heat Flux by Radiative Divertor and Utility of Supersonic Gas Injector for H-mode Access

NSTX

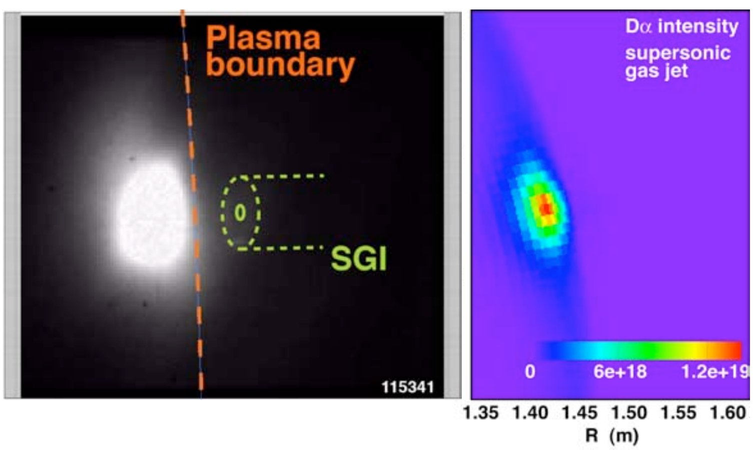
Developed Radiative Divertor regime: Obtained by steady-state D_2 injection into private flux region or ISP



– Outer SP (OSP) heat flux reduced by 4-5

– No change in H-mode τ_E

Supersonic Gas Injector (SGI) achieved up to 5 x higher fueling efficiency relative to standard low-field-side gas puff



DEGAS 2 Neutral transport modeling reproduces observed features

- 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: Increasing the SGI gas pressure, Combine Li & SGI for n_e control

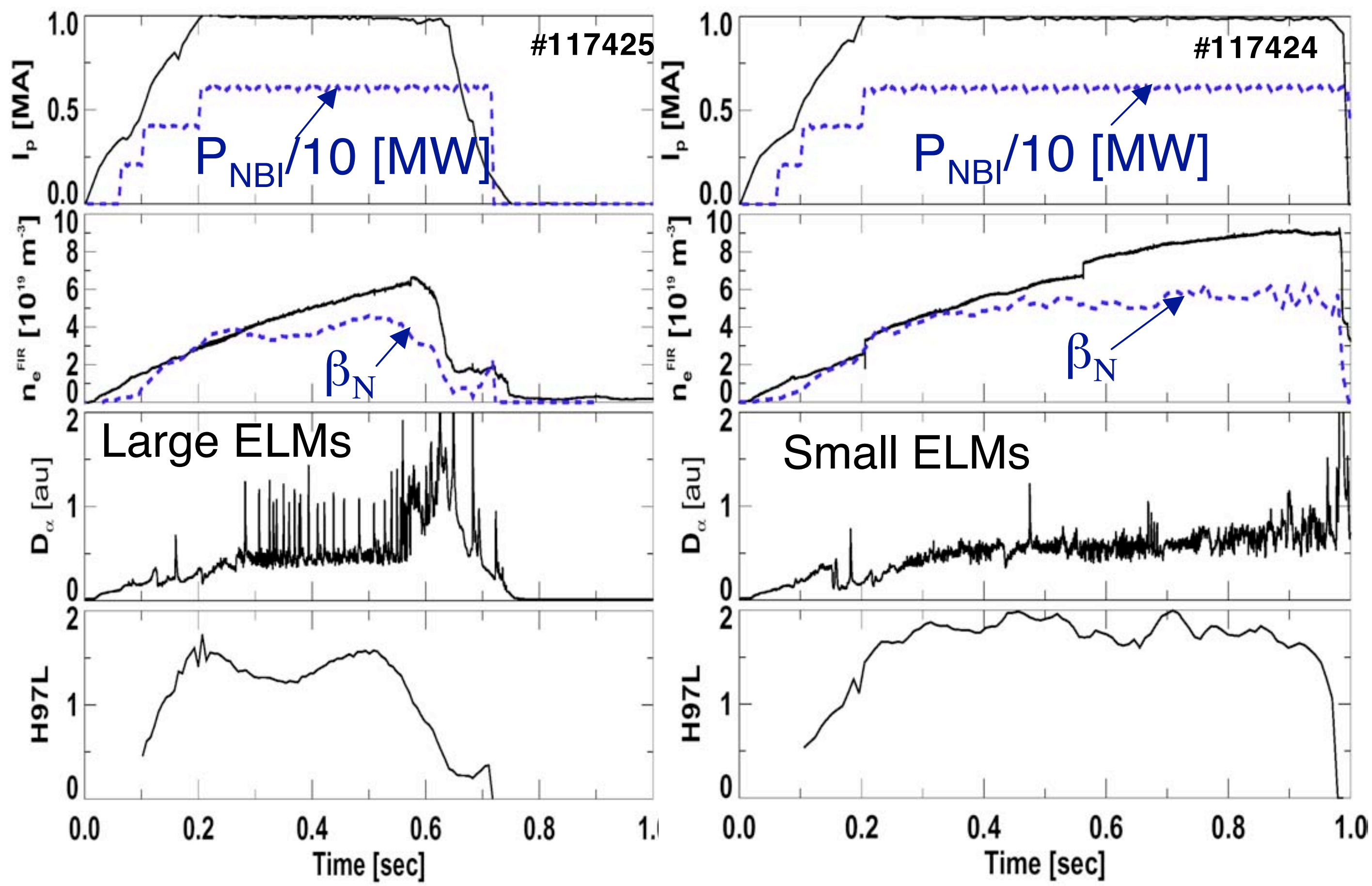
LLNL

V. Soukhanovskii NO1.14D. Stotler QP1.32

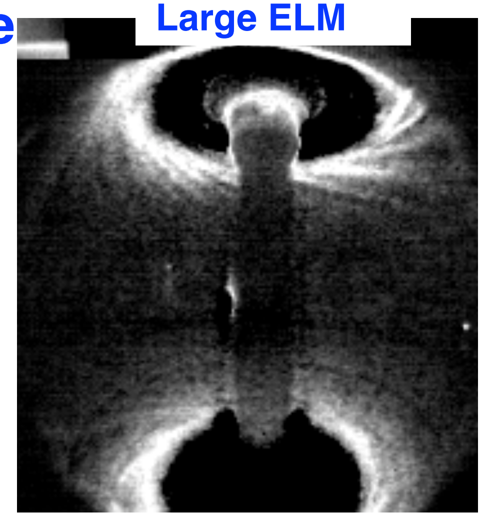
NSTX studying access conditions and structure of different ELM types

- **Small shape change leads to reduction of ELM size**

Balanced DN or biased slightly up | **Biased slightly down**



Large ELM

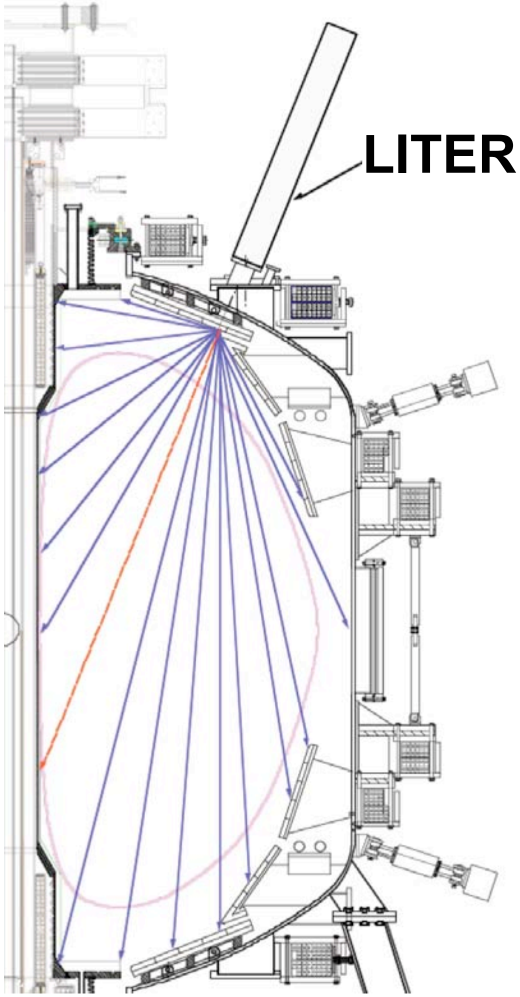


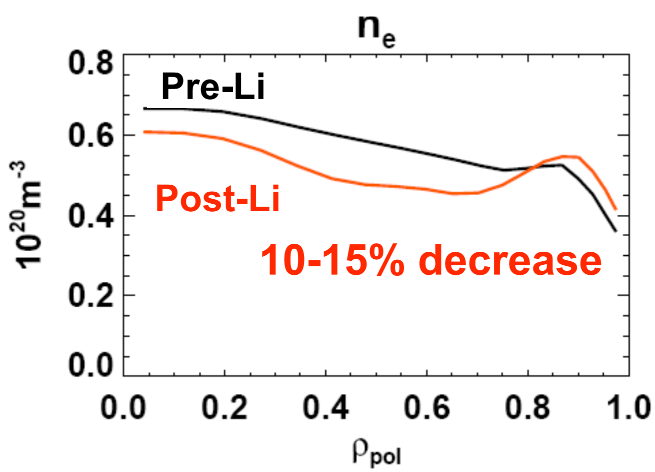
Small ELM

ORNL, Nova Photonics, Johns Hopkins, UCD

Maingi, POP 2006

In 2006, Lithium Evaporator (LITER) Experiments Improved Particle Pumping and Energy Confinement in H-mode



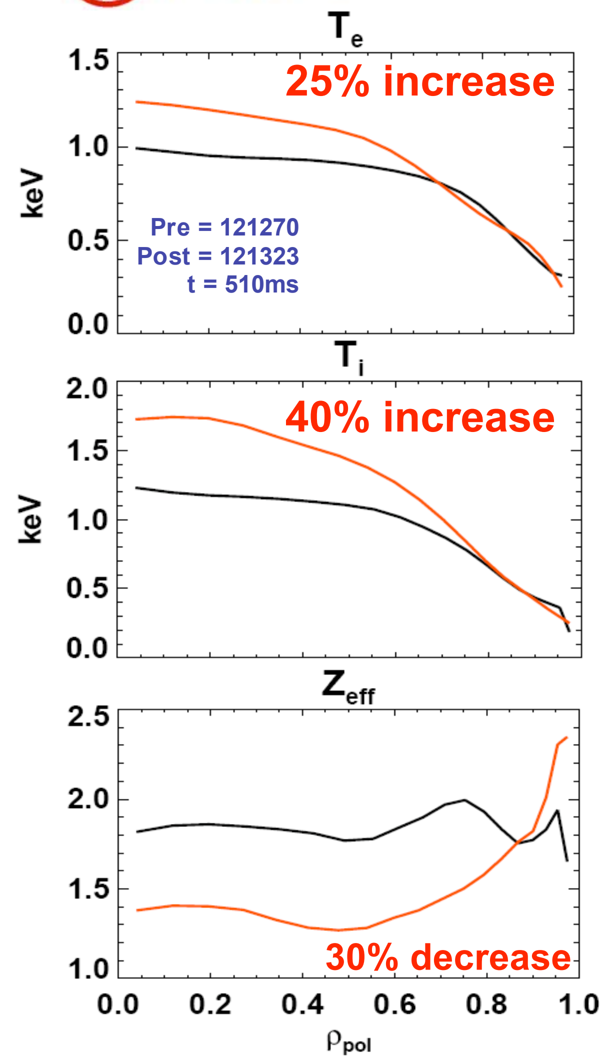


TRANSP analysis:

W_{TOT} 20% higher post-Li
(reaches β-limit w/ same P_{NBI})

HH_{98y} = 1.07 → 1.25 post-Li

Divertor D_α emission dropped by a factor of 3-4



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

D. Mansfield, H. Kugel QP1.5-6, M. Bell NO1.2

NSTX Facility/Diagnostic Improvements since 2005

Device Parameters

R = 85 cm

a = 65 cm [design]

κ = 1.7 - 3.0* [< 2.2]

δ = 0.3 - 0.8 [< 0.55]

B_T = 5.5 kG

I_p = 1.5 MA [1.0 MA]

V_p = 14 m^3 [12 m]

E_p ~ 430 kJ [200 kJ]

P_{NBI} = 7.4 MW [5MW]

P_{HHFW} = 6 MW

350°C bakeout

Passive Plates

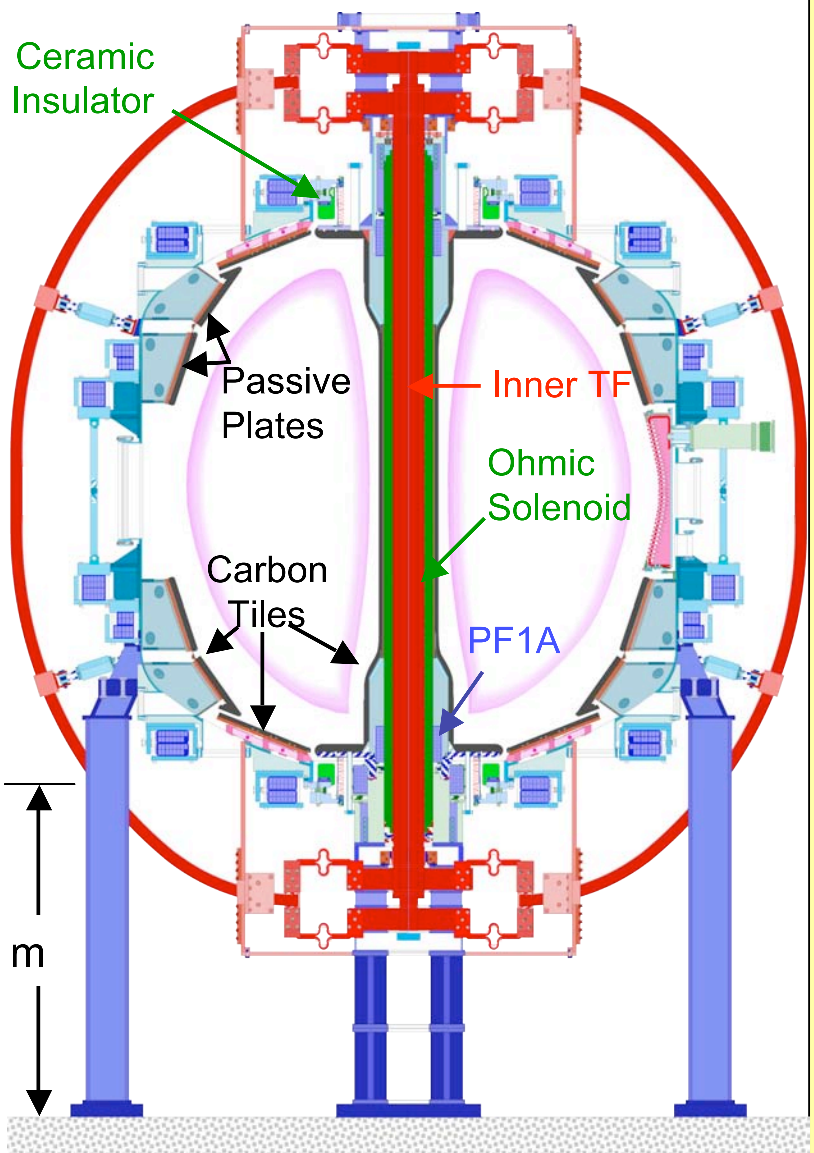
Active EF/ RWM Feedback*

I_{CHI} ~ 160 kA (I_{inj}=0)**

Lithium Evaporator

Wide tang. Access

RED - Since 2005



Major Diagnostic Systems - Confinement Studies-RED - Since 2005

- Magnetic equiplibrium reconstruction
- Diamagnetic flux measurement
- Multi-pulse Thomson scattering (30 ch)
- CHERS: $T_i(R)$ and $V_\phi(r)$ (51 ch)
- Neutal particle analyzer (2D scanning)
- Density Interferometer (1 mm, 1ch)
- Visible bremsstrahlung radiometer (1 ch)
- Midplane tangential bolometer array
- X-ray crystal spectrometer: $T_i(0)$, $T_e(0)$
- Multi-color USXR fast Te(r)
- MSE-CIF (12h)

MHD/Fluctuation/Waves

- High-n and high-frequency Mirnov arrays
- Ultra-soft x-ray arrays – tomography (4)
- Fast X-ray tangential camera (2μs)
- RF/TAE Wave reflectometers (edge/core)
- FIReTIP polarimeter (6 ch, 600 kHz)
- Tangential microwave scattering
- Dual Electron Bernstein wave radiometer
- Fast lost-ion probe (energy/pitch)
- Fast neutron measurement
- Locked-mode detectors
- RWM sensors (n = 1, 2, and 3)

Edge/divertor studies

- Reciprocating Langmuir probe
- Gas-puff Imaging (2μsec)
- Fixed Langmuir probes (24)
- Edge Rotation Diagnostics (T_i, V_ϕ, V_{pol})
- 1-D CCD H_α cameras (divertor, midplane)
- 2-D divertor fast visible camera
- Divertor bolometer (4 ch)
- IR cameras (30Hz) (3)
- Tile temperature thermocouple array
- Scrape-off layer reflectometer
- Edge neutral pressure gauges

Plasma Monitoring

- Fast visible cameras
- Visible survey spectrometer
- VUV survey spectrometer
- X-ray transmission grating spect.
- Fission chamber neutron measurement
- Visible filterscopes
- Wall coupon analysis
- Imaging X-ray crystal spect. (astrophys)

Planning medium power EBW/ECH upgrade

- Implement ~100 - 200 kW (15.3 - 28 GHz) EBW/ECH system for 2008 utilizing the existing ORNL equipment and the PPPL NBI power supply which can support 1.2 MW
  - Start EBW heating experiment
  - Heat CHI start-up plasma to ~ 50 - 100 eV enabling HHFW heating and CD
  - Assist PF-only start-up research

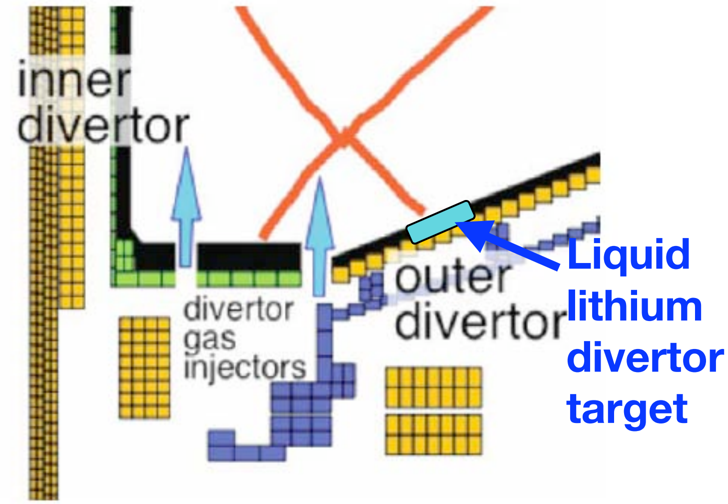
EBW/ECH Gyrotron source specification

- 28 GHz (4 ea.)
  - –200 kW CW
    (80 kV, 7A)
  - –350 kW pulsed
    ~ 500 ms
    (80 kV, 12A)
- TE02 output; high mode purity
- FC-75 cooled window

- EBW/ECH upgrade may be feasible with priority shift within NSTX and through collaborations
- Continue to work with MAST, PEGASUS and other ST experiments on EBW Physics

Now Investigating Liquid Lithium Divertor Target to Control Density in Long-Pulse, High Performance Discharges

- Lithium pellet injection reduced oxygen and particle recycling 2005.
- Lithium evaporation implemented in 2006 reduced oxygen level and hydrogen recycling.
- Continue to explore benefits of these techniques in forthcoming 2007 run



- Based on NSTX results and other lithium experiments (CDX-U, T–11), a liquid lithium divertor target is indicated to achieve effective particle control for long-pulse, high performance advanced plasmas
- Use lithium-filled tray or lithium-wetted mesh or porous material
- The liquid lithium divertor target could replace one row of graphite tiles Major radius R ~ 60 cm so modification is not extensive
  - Design and R&D in FY 07
  - Installation in FY 08 to be ready for the 2008 - 9 run

NSTX Contributes Strongly to Fundamental Toroidal Confinement Science in Support of Future ST's and ITER

- Unique ST facility with powerful heating systems, *advanced plasma control systems* and state-of-the-art plasma diagnostics
- Wide range of accessible tokamak plasma parameters in MHD, T&T, Boundary, and Energetic Particle research supported by full diagnostic set
- *Active EF/RWM feedback stabilization system demonstrated for a wide range of rotation speed including ITER relevant low rotation*
- Unique opportunity for understanding electron transport and micro-turbulence with high-k (electron scale) scattering system
- Uniquely able to mimic ITER fast-ion instability drive with full diagnostics
- Steady progress is being made on HHFW and EBW physics
- Broad ITER and CTF-relevant boundary physics research program
- *Rapid progress toward fully non-inductive high performance scenarios*
- *Solenoid-free 160kA closed-flux plasma formation in NSTX using CHI*