Supported by Office of Science

NSTX

National Spherical Torus Experiment

Facilities and Select Science Topical Areas

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For the NSTX Research Team

ISTW 2006

October 11-13, 2006

Chengdu, China

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

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
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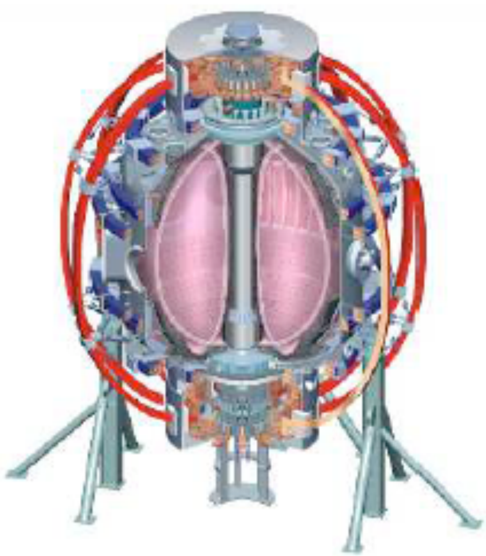
KBSI
KAIST
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
ASCR, Czech Rep



Talk Outline

- Introduction
- NSTX Facility/Diagnostic Overview
- Select NSTX Science Topical Areas*
  - Transport / Turbulence
  - HHFW / EBW
  - Energetic Particles
  - Boundary Physics
- Summary

* Plasma Control/ MHD/ Integration covered by D. Gates
CHI solenoid free start-up covered by R. Raman

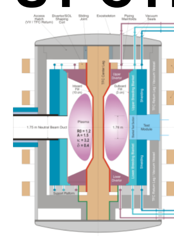
NSTX Strategy to Address Scientific Issues Important for ST-CTF, ITER, and Toroidal Fusion Plasmas

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

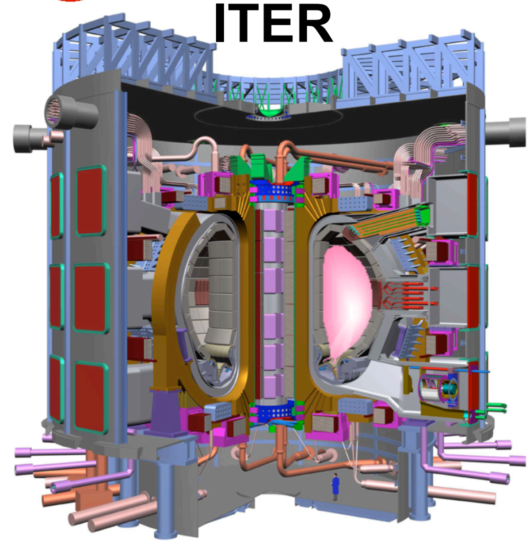
- **Support preparation for burning plasma research in ITER using physics breadth provided by ST; support and benefit from "ITPA Specific" activities.**

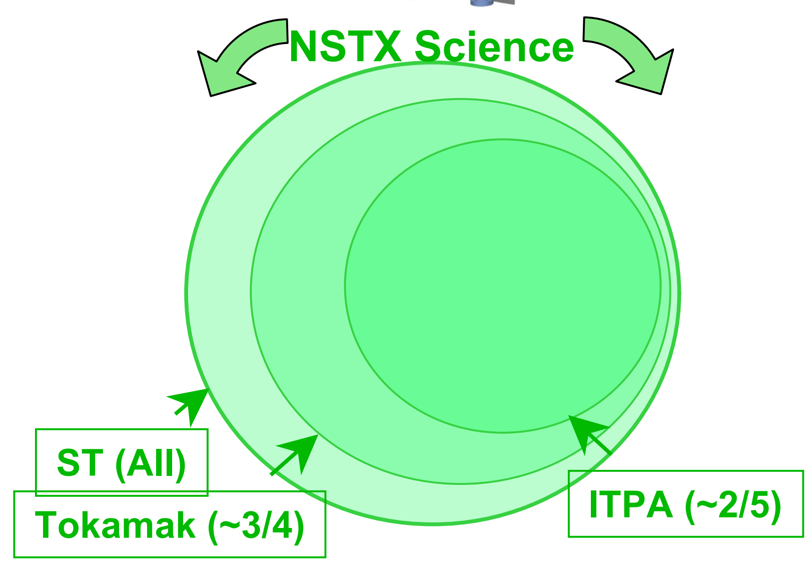
- **Complement and extend tokamak physics experiments, maximizing synergy in investigating key scientific issues of toroidal fusion plasmas**

ST CTF



ITER





NSTX 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)**

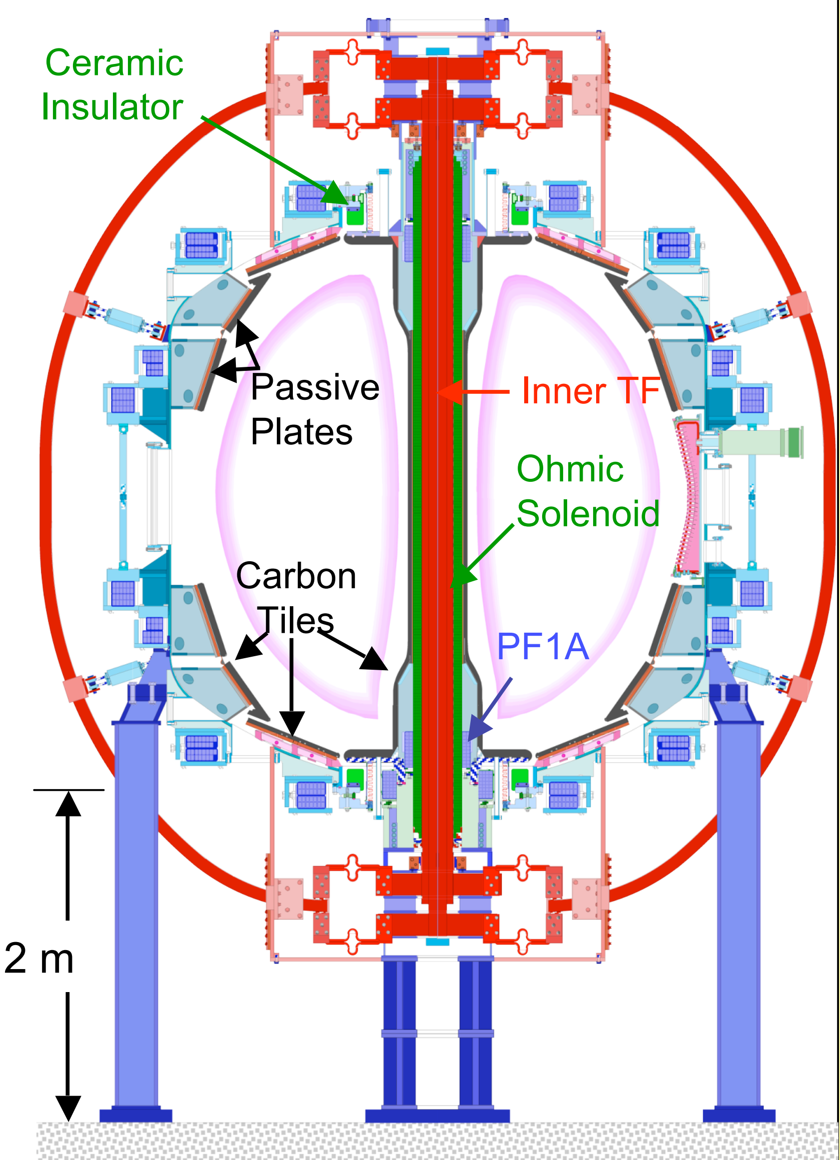
Lithium Evaporator

Wide tang. Access

RED - Since 2005

* Talk by D. Gates

** Talk by R. Raman



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)

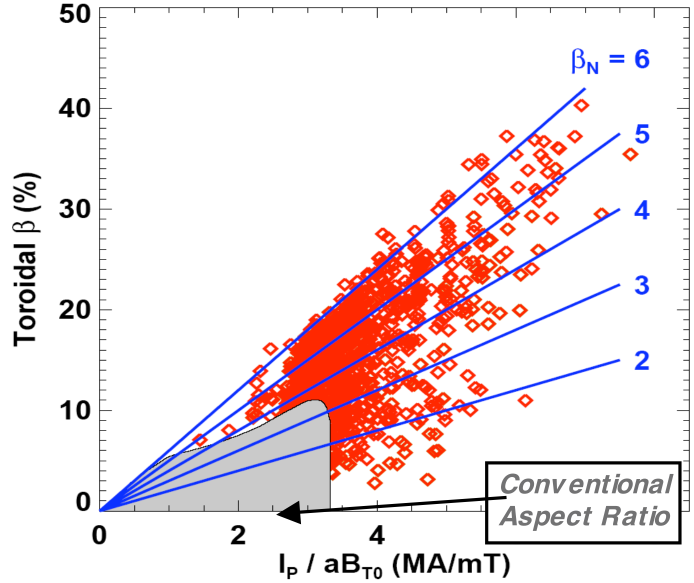
MHD/Fluctuation/Waves
- High-n and high-frequency Mirnov arrays
- Ultra-soft x-ray arrays – tomography (4)
- Fast X-ray tangential camera (2μs)
- RF/TAE Wave reflectometers (edge/core)
- FIReTIP polarimeter (6 ch, 600 kHz)
- Tangential microwave scattering
- Dual Electron B ernstein wave radiometer
- 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

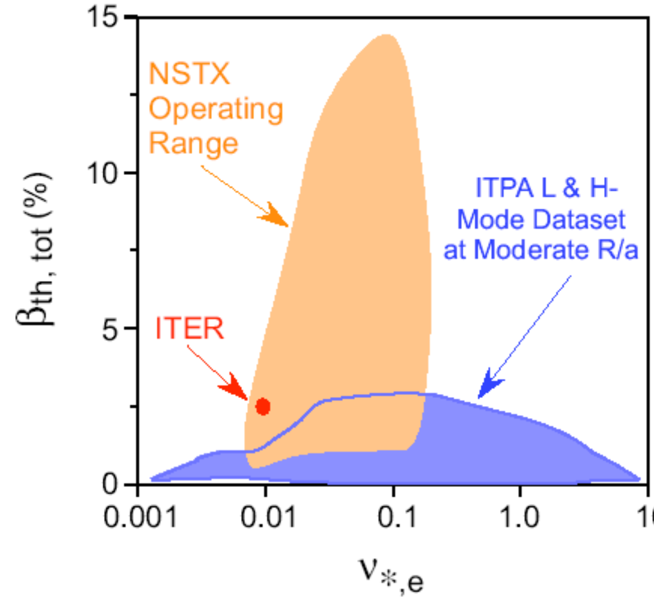
Plasma Monitoring
- Fast visible cameras
- Visible survey spectrometer
- VUV survey spectrometer
- X-ray transmission grating spect.
- Fission chamber neutron measurement
- Visible filterscopes
- Wall coupon analysis
- Imaging X-ray crystal spect. (astrophys)

NSTX/ST Offers Access to Wide Tokamak Plasma Regimes

Wide range of β_T up to ~ 40 %.

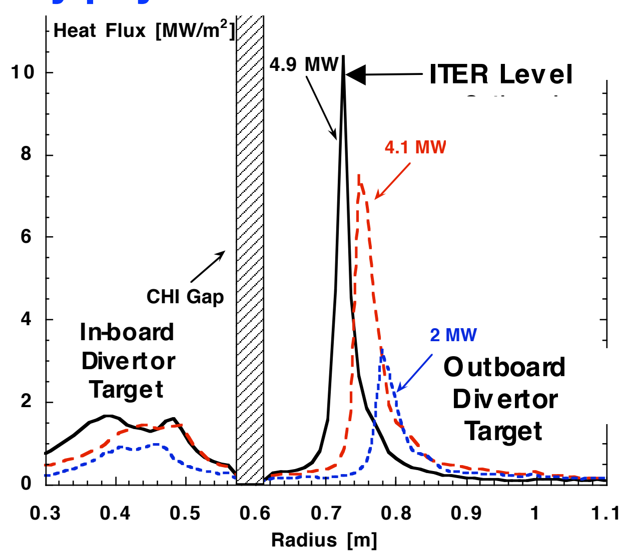


β Confinement Scaling, Electron Transport

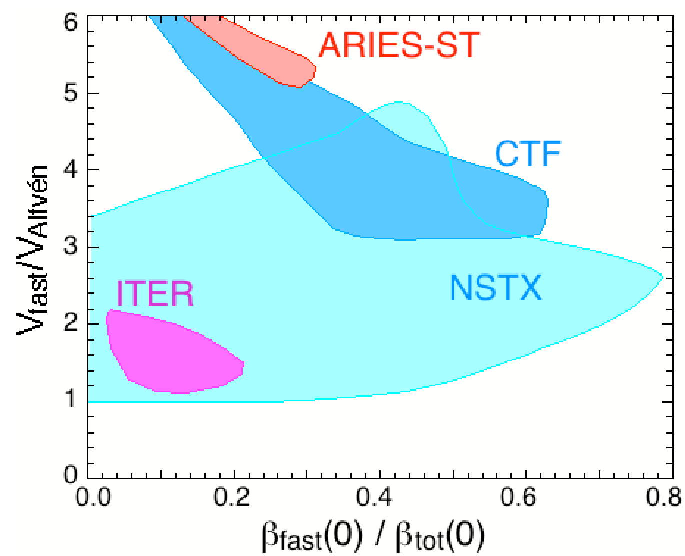


- Confinement scaling with wide range of β_T up to ~ 40 %

Boundary physics with ITER-level heat flux



Unique Energetic Particle Physics Capability

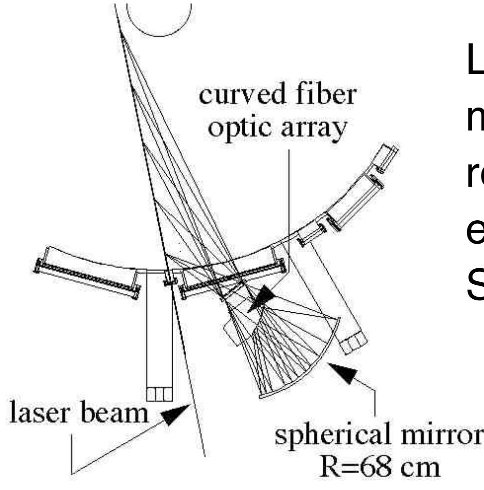


- Full set of diagnostics: including MSE for j(r)

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

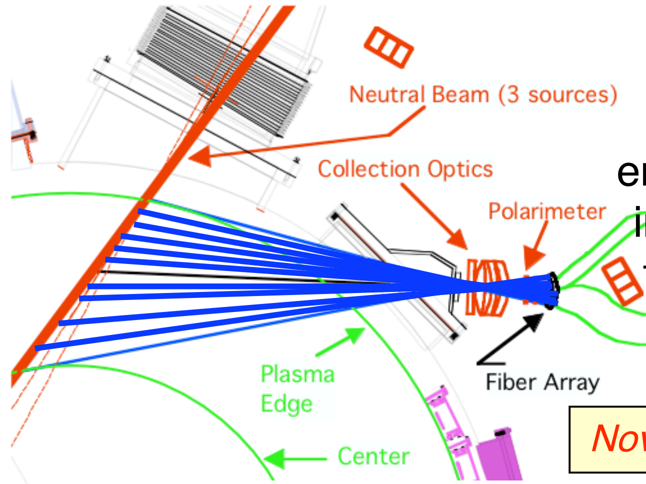
NSTX

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



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

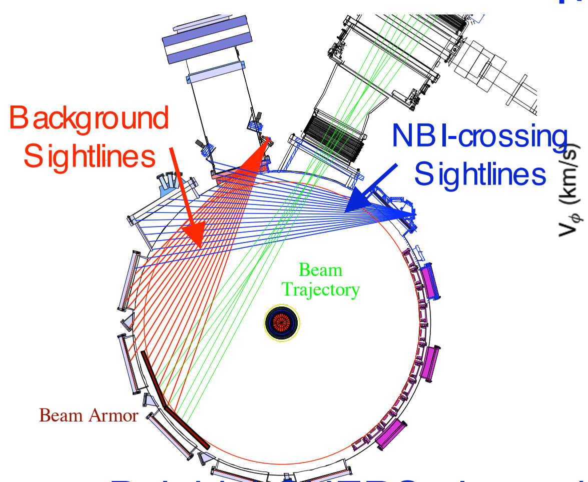
12 Ch MSE for q(r) (19 ch planned)



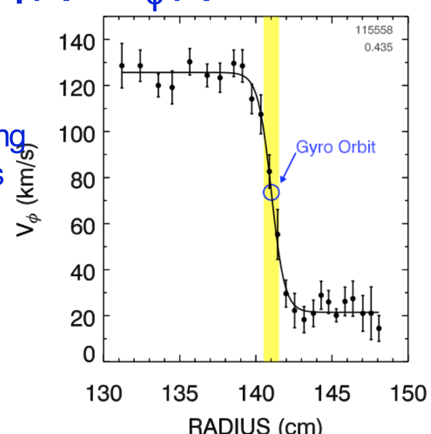
Innovative design enables MSE in kG range for the first time

Nova Photonics

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

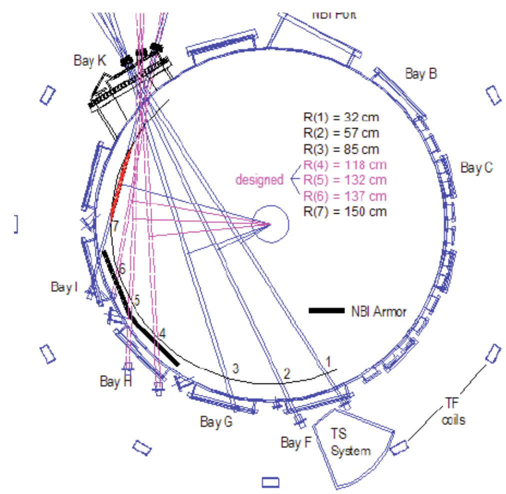


Poloidal CHERS planned



Resolves structure to ion gyro-radius

Tangential FIR Int-Pol (600 kHz)



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

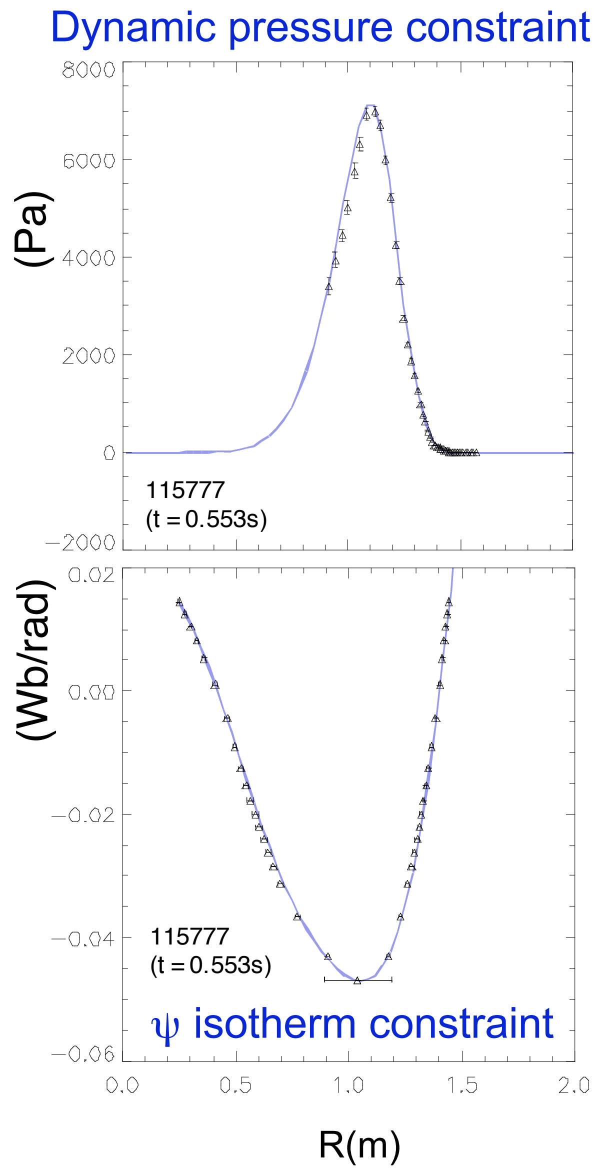
UC Davis

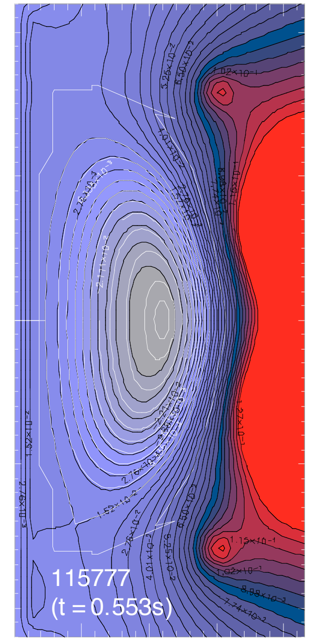
UCD

Unique Capability for Between-shots Plasma Equilibrium Reconstruction and Rapid Stability/Transport Analyses

NSTX

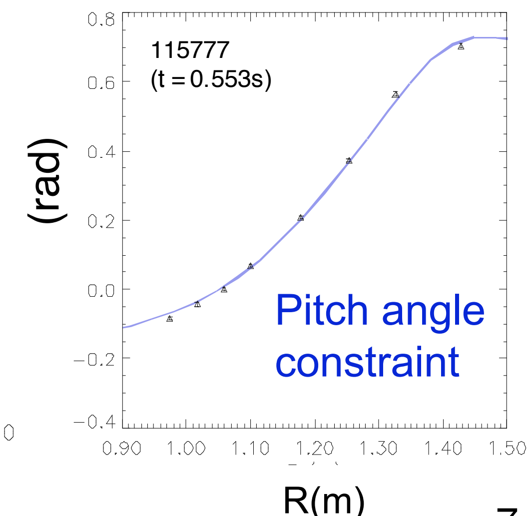
- NSTX EFIT ***(Columbia,GA,IPPCAS)***
- NSTX kinetic profiles and plasma rotation measured on the **mid-plane allowing direct input** for efficient between-shots analysis
- Flux surfaces constrained to be T_e isotherms at the midplane
- 12 channel MSE provides B field pitch angle to reconstruct q profile; $\delta\theta = 0.005$ rad ***(Nova)***
- Rapid (~20 minutes) MHD stability analyses using DCON ***(LANL)*** and transport analyses using TRANSP





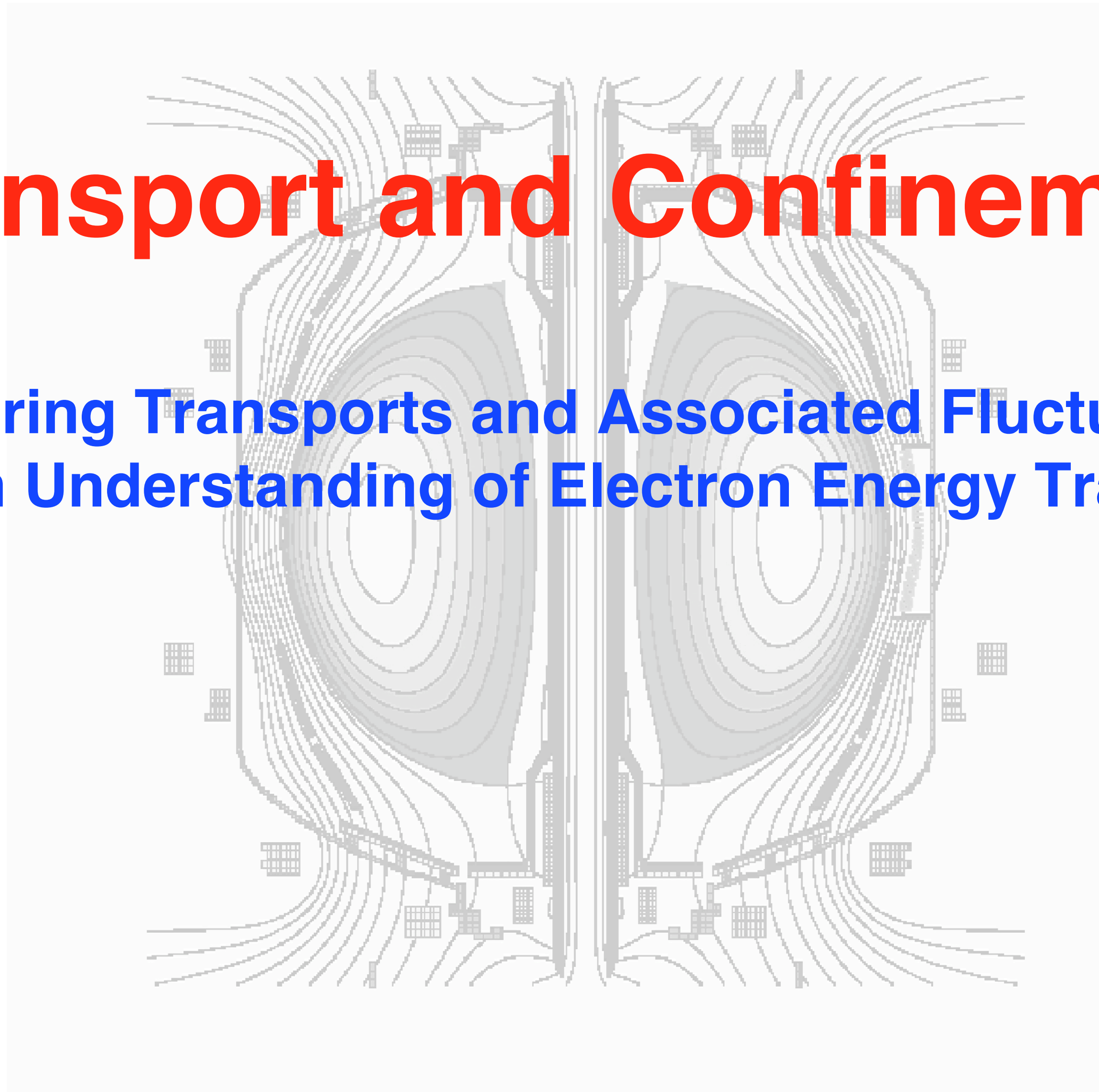
Poloidal flux (black)

Total pressure (white)



Transport and Confinement

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

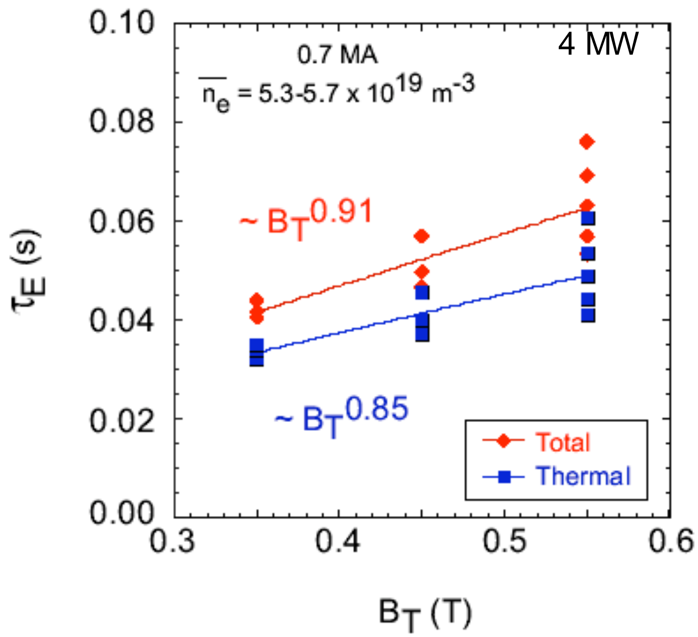


Dedicated H-mode Confinement Scaling Experiments Have Revealed Some Surprises

NSTX

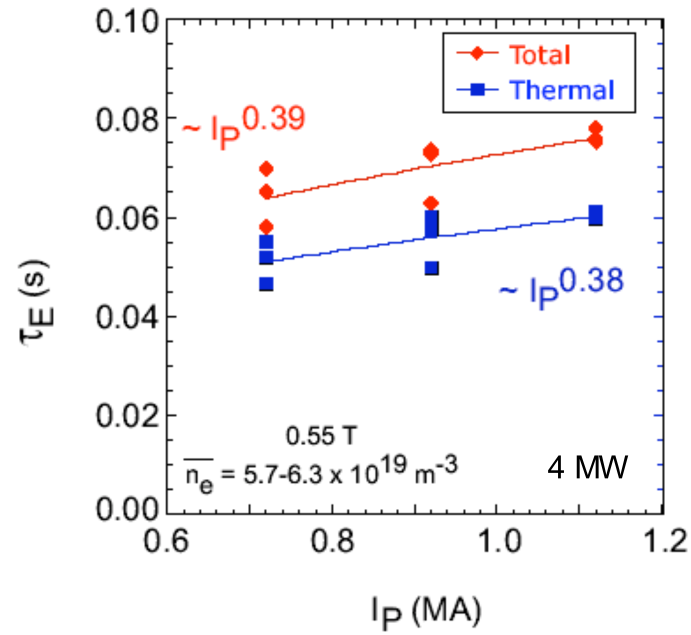
Strong dependence on B_T

$H_{98y,2}$ ~ 0.9 → 1.1 → 1.4



Weaker dependence on I_p

$H_{98y,2}$ ~ 1.4 → 1.3 → 1.1



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

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

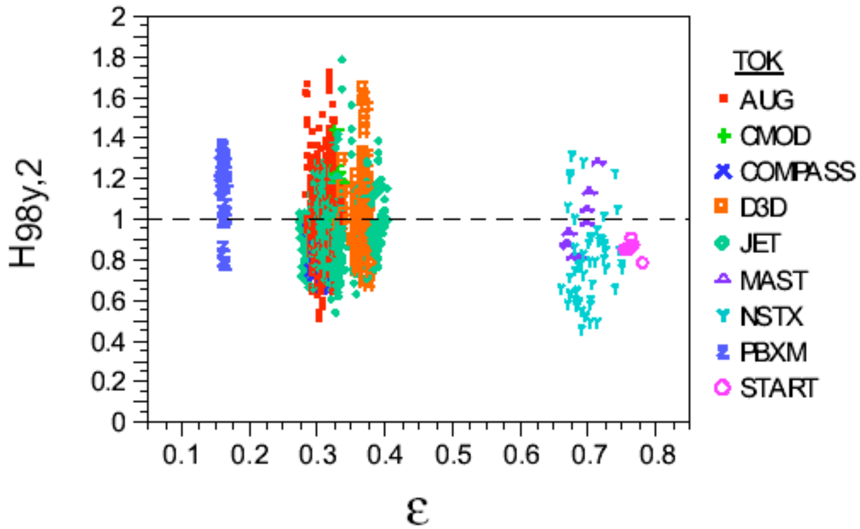
$\tau_{E,98y,2}$ ~ $I_p^{0.93}$

τ_E~$I_p^{1.3-1.5}$ at fixed q $\tau_{E,98y,2}$~$I_p^{1.1}$ at fixed q

NSTX Addressing High-Priority ITPA Tasks in Confinement

NSTX

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

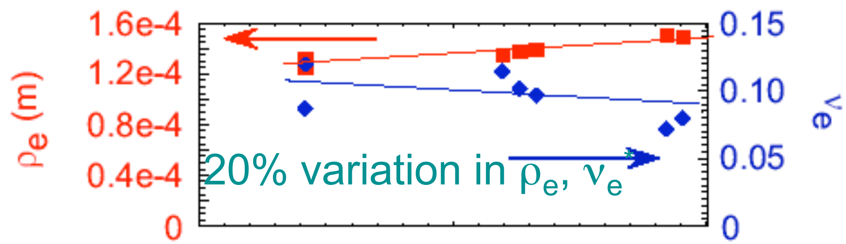
$$\tau_{98y2} \sim I_p^{0.93} B_T^{0.15} n_e^{0.41} P^{-0.69} R^{1.97} \varepsilon^{\mathbf{0.58}} \ldots$$

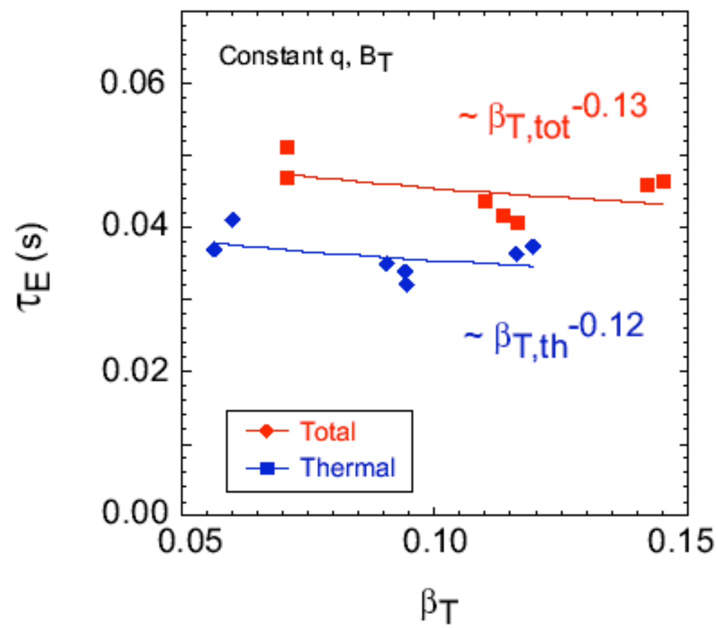
$$\tau_{new} \sim I_p^{0.73} B_T^{0.36} n_e^{0.39} P^{-0.62} R^{2.14} \varepsilon^{\mathbf{1.03}}$$

[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

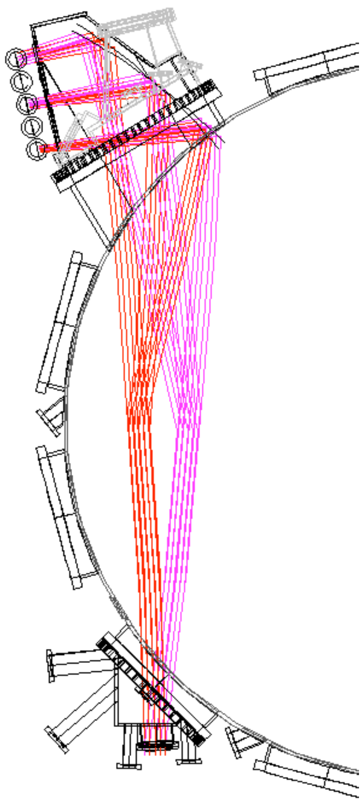




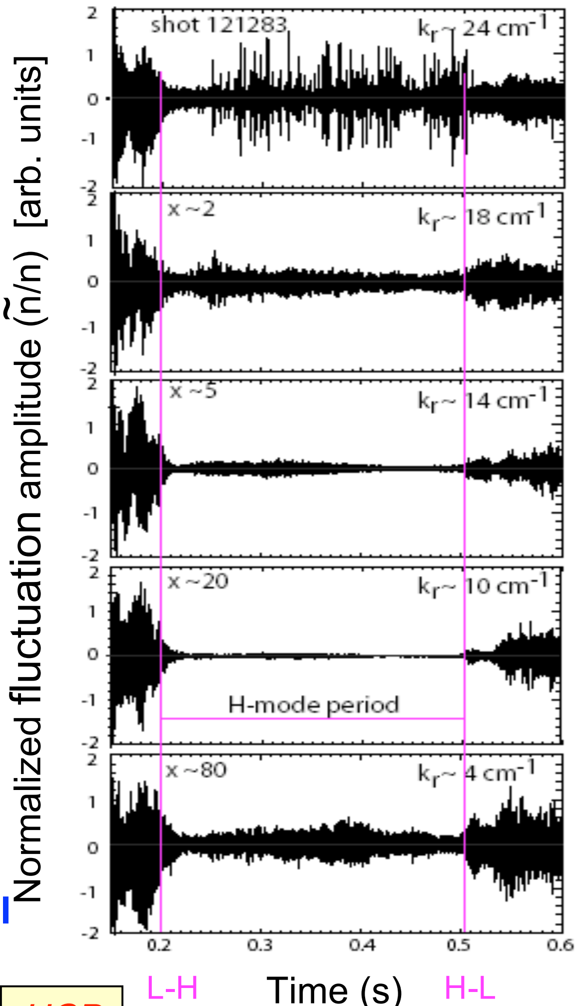
Detailed Transport and Turbulence Measurements during L-H Transition Reveals Important and Tantalizing Electron Transport Physics

NSTX

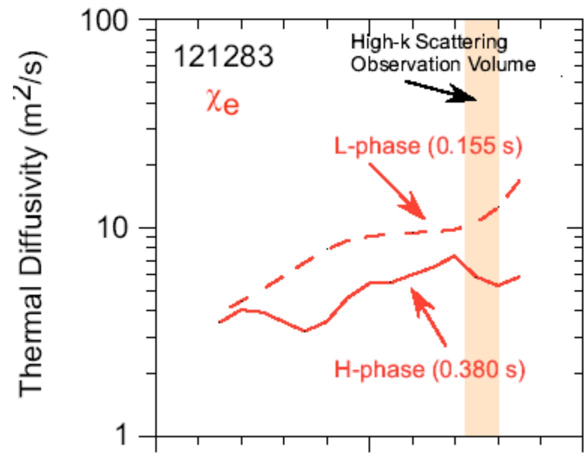
Tangential scattering system measures reduced fluctuations ($\tilde{n}/n$) in both ITG/TEM and ETG ranges during H-mode



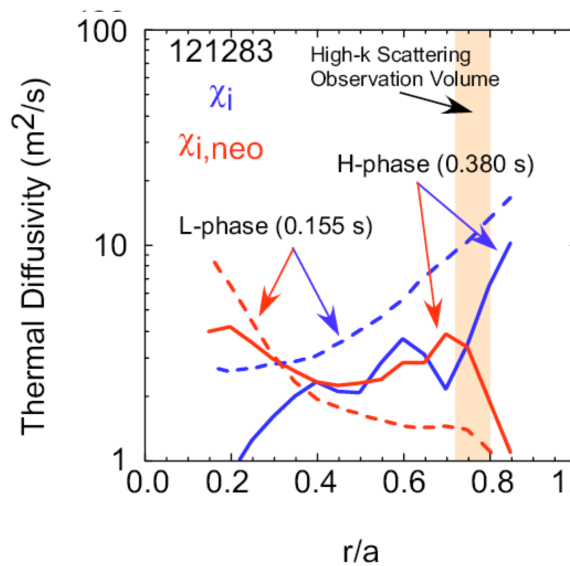
Unprecedented spatial resolution at high k



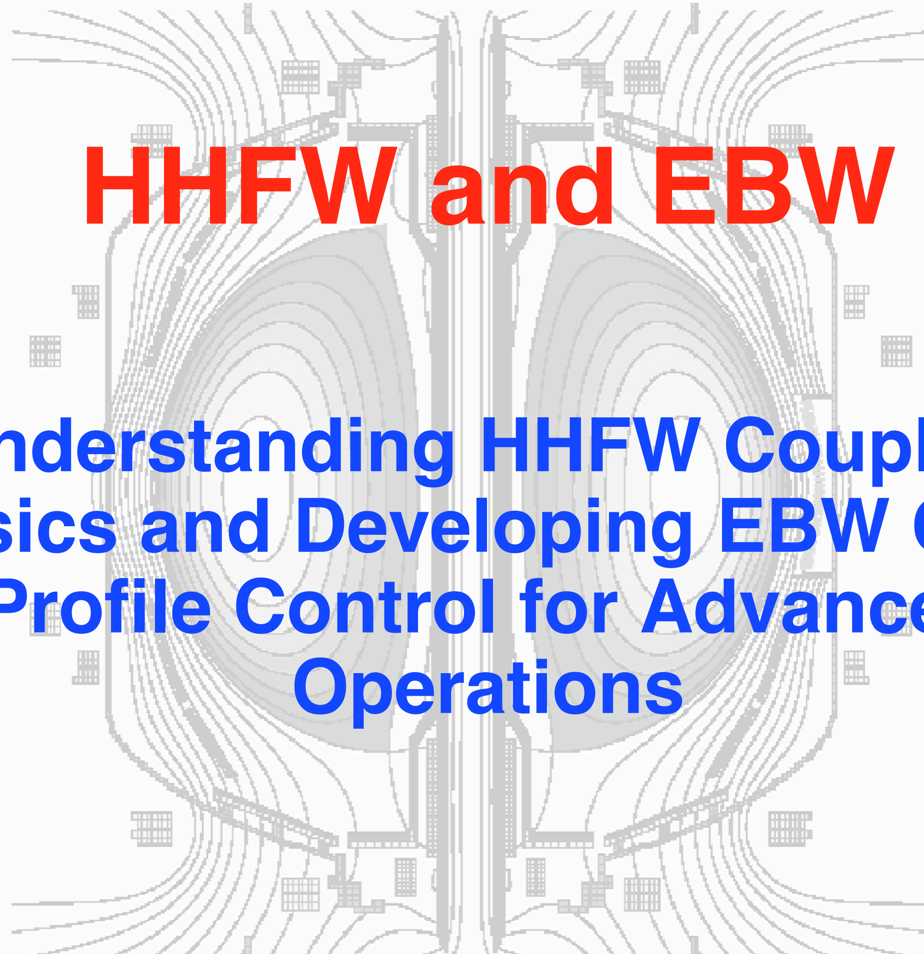
UCD



Electron transport reduced, but remains anomalous



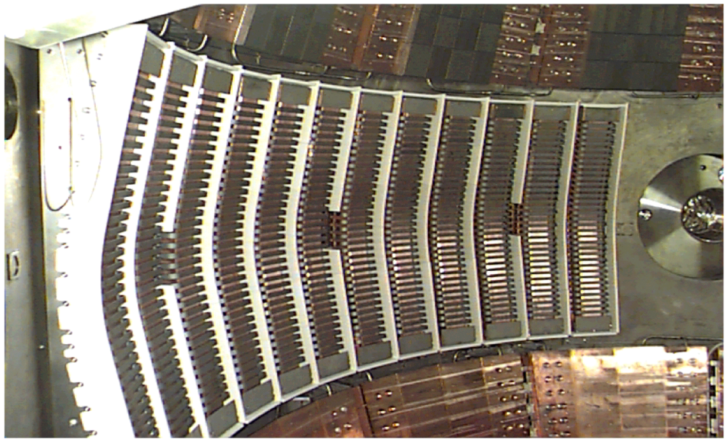
Ion transport during H-phase at neoclassical level



HHFW and EBW

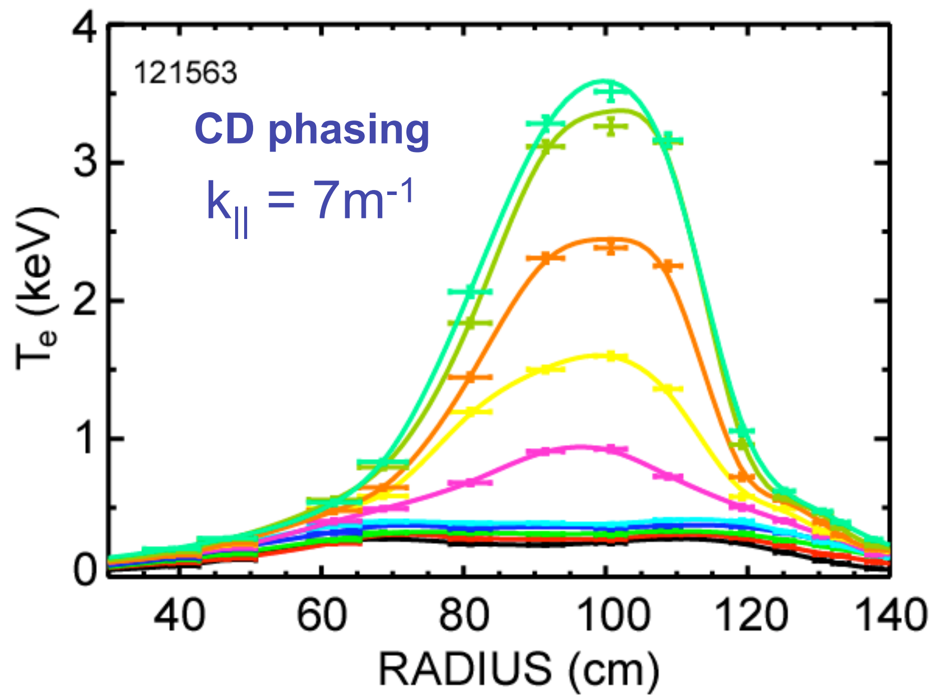
Understanding HHFW Coupling Physics and Developing EBW CD for Profile Control for Advanced Operations

HHFW Heating Efficiency Improved with B_T



- ***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. Menard, IAEA 2006

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

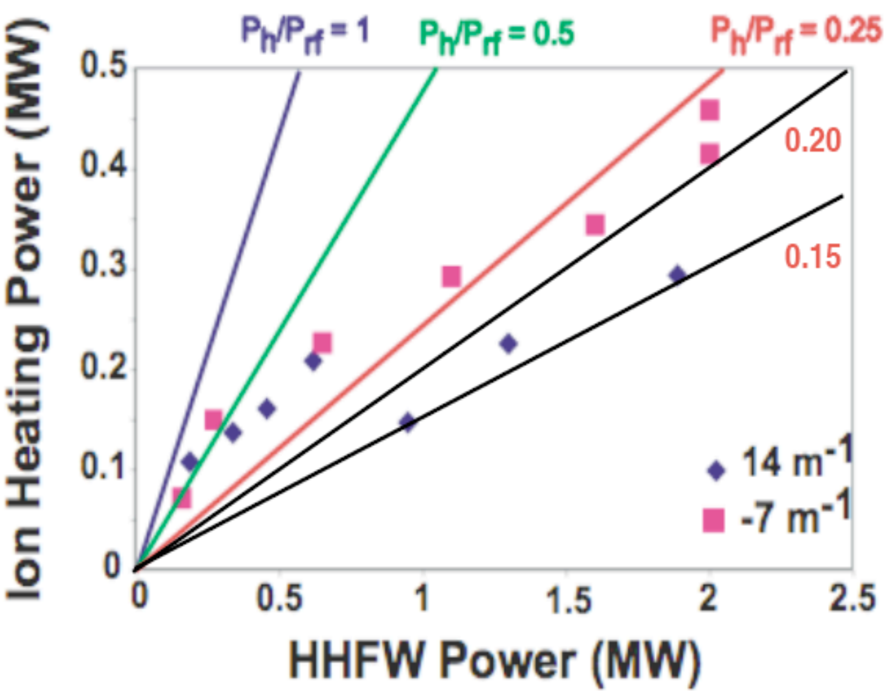
NSTX

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

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

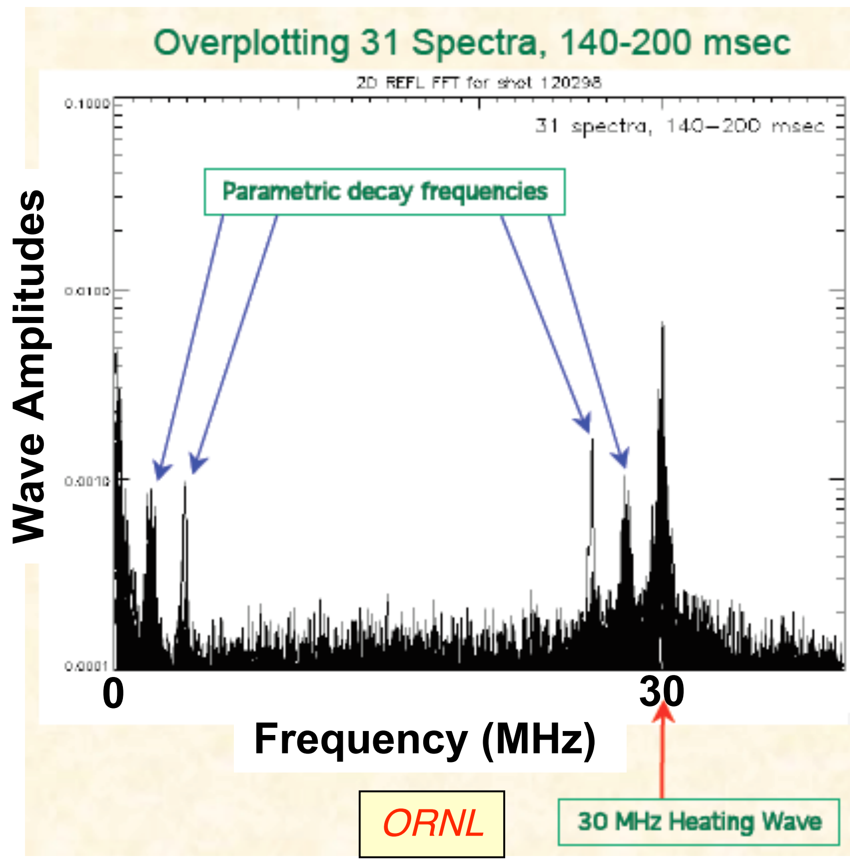
Low $k_{||}$ used for HHFW current drive

Low B_T needed for high β



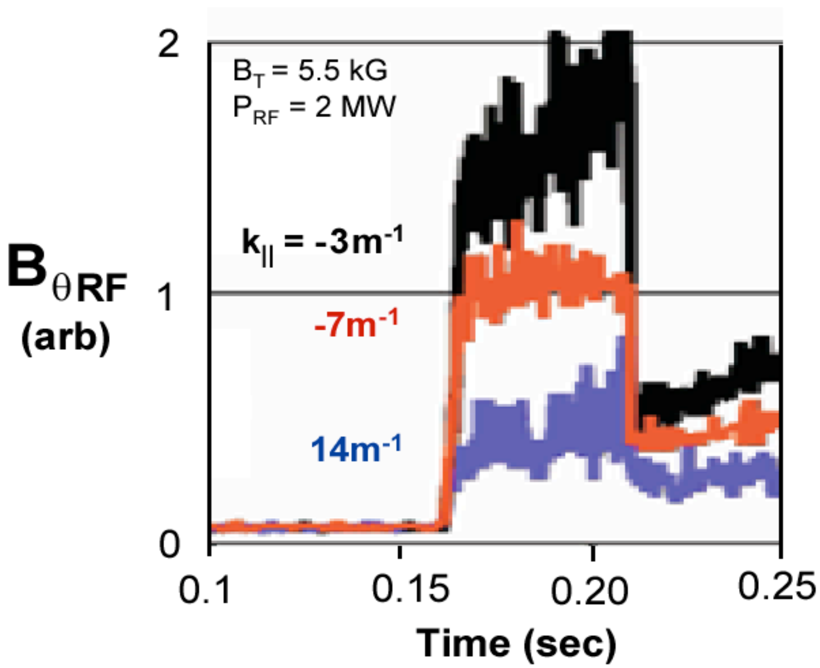
T. Biewer, Phys. Plasmas 12, 056108 (2005)

Edge 17.5 GHz Wave Reflectometer also shows phase dependence of PDI



Surface and Core HHWF Fluctuations Measured

Surface Wave Probe Data



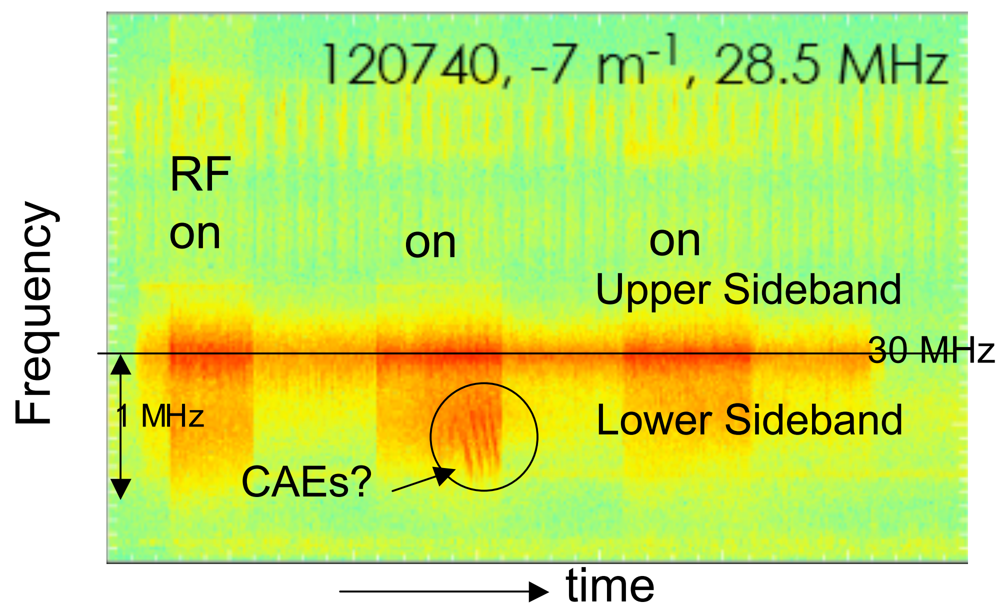
HHFW at low $k_{||}$ should begin propagating at much lower n_e

→ 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**

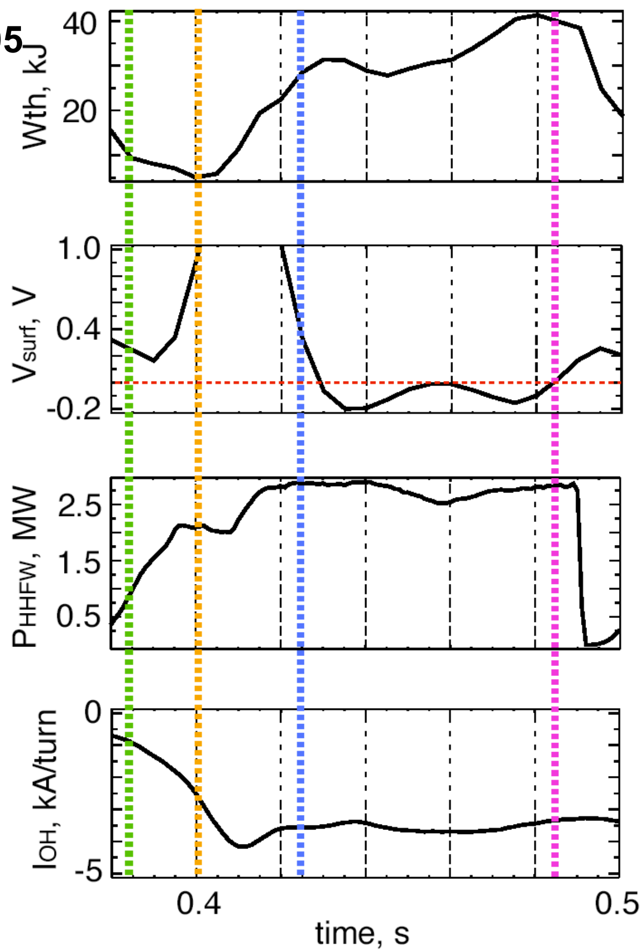


UCLA, Tokyo University

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

NSTX

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

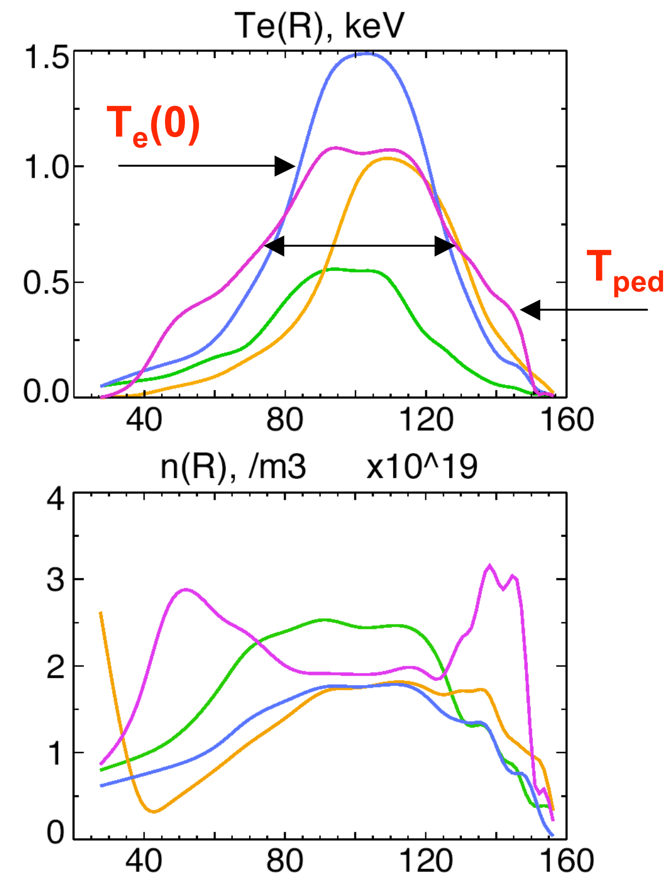


High $T_{ped,}$ broad $T(\rho)$, and "not-too-high" $T_e(0)$ best for non-OH ramp-up

t = 0.385
0.400
0.425
0.485

β_P=1.8

f_{BS}=65-80%

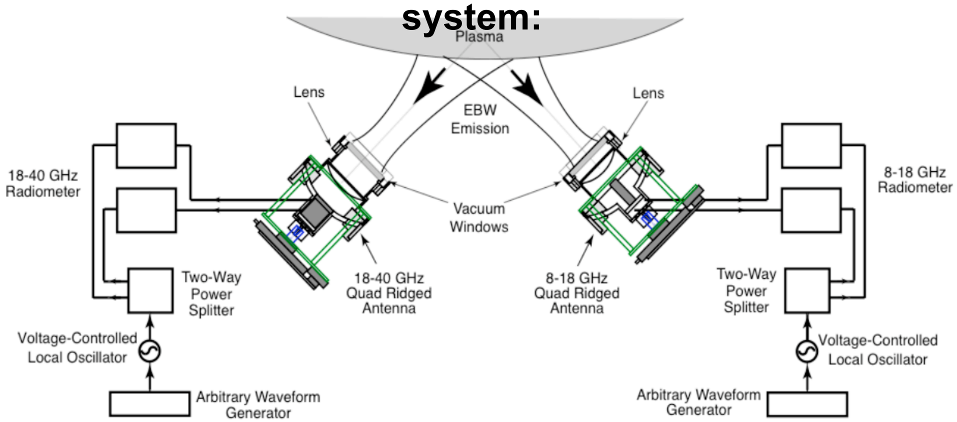


ORNL, UCSD, CompX,Columbia U

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

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:

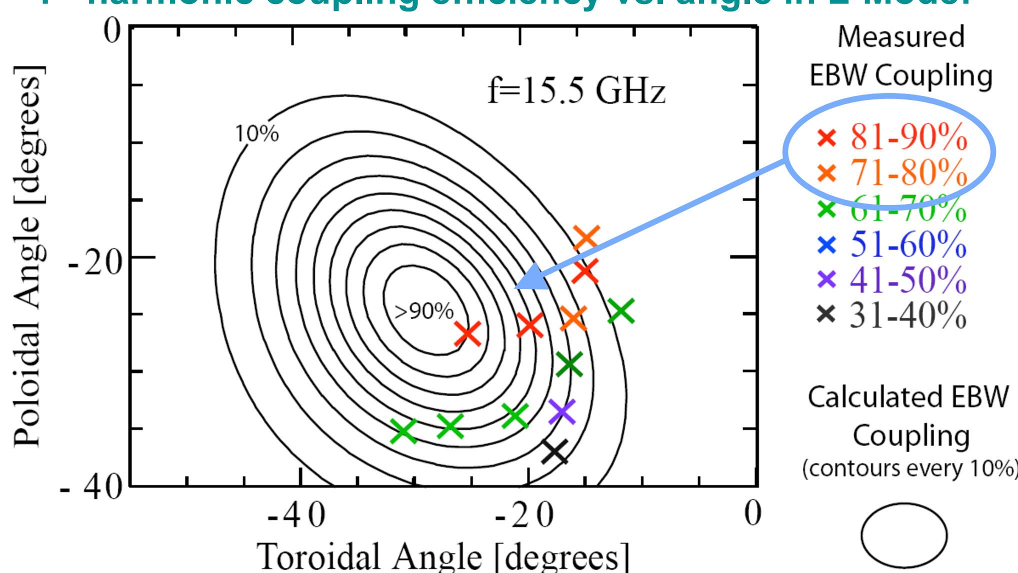
8-18GHz ~ 22°, 18-40GHz ~ 14°

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:



ORNL, MAST

Planning medium power EBW/ECH upgrade

NSTX

- 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 other ST experiments on EBW Physics

Energetic Particles

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

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

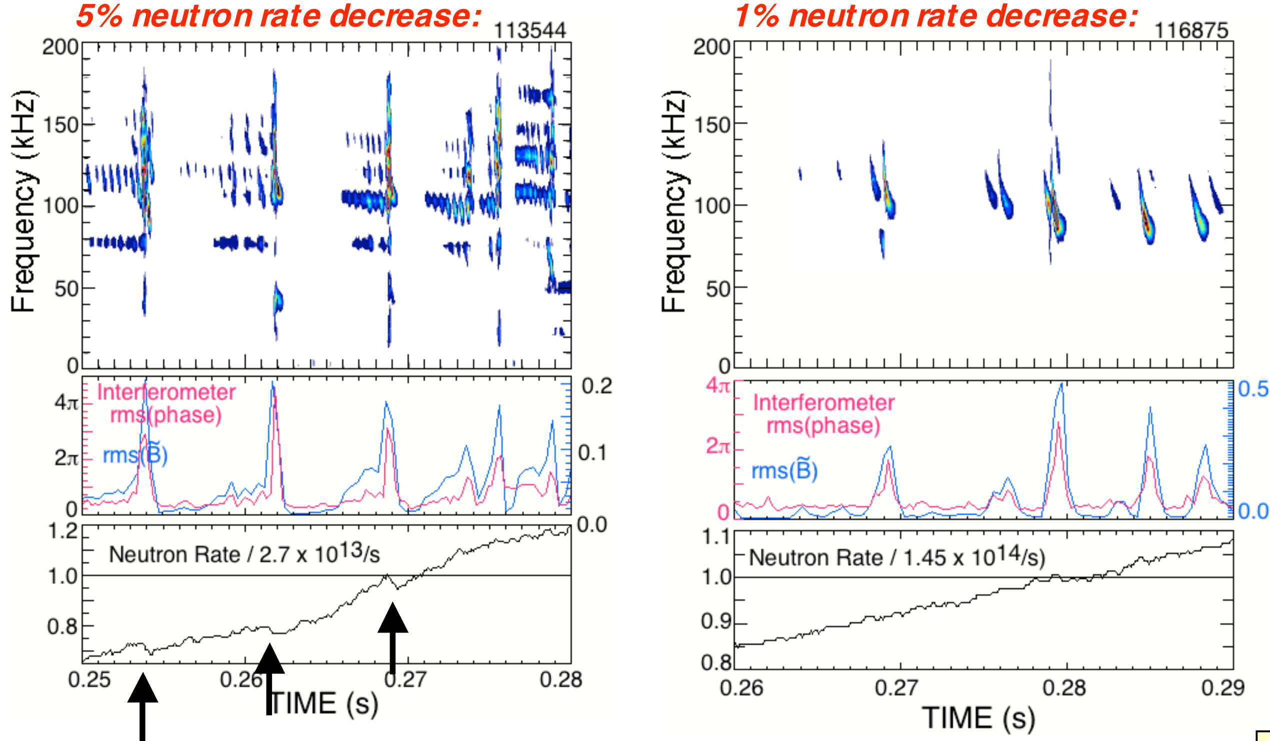
ITER will operate in multi-modes regime for fast ion transport

- $k_\perp \rho \approx 1$ means "short" wavelength Alfvén modes
- Fast ion transport expected from 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:



fast-ion losses

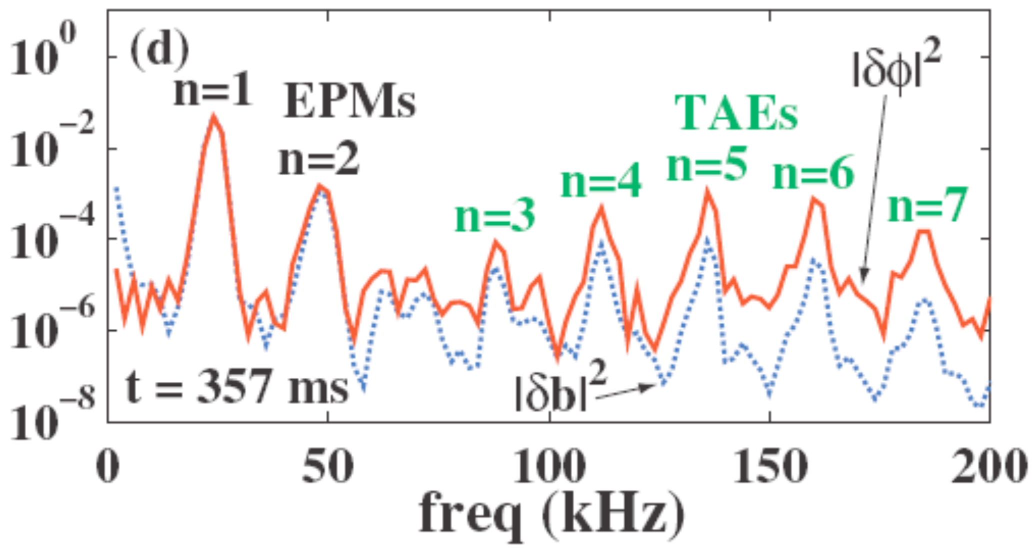
E. Fredrickson, Phys. Plasmas 13, 056109 (2006)

UCI, UCLA

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

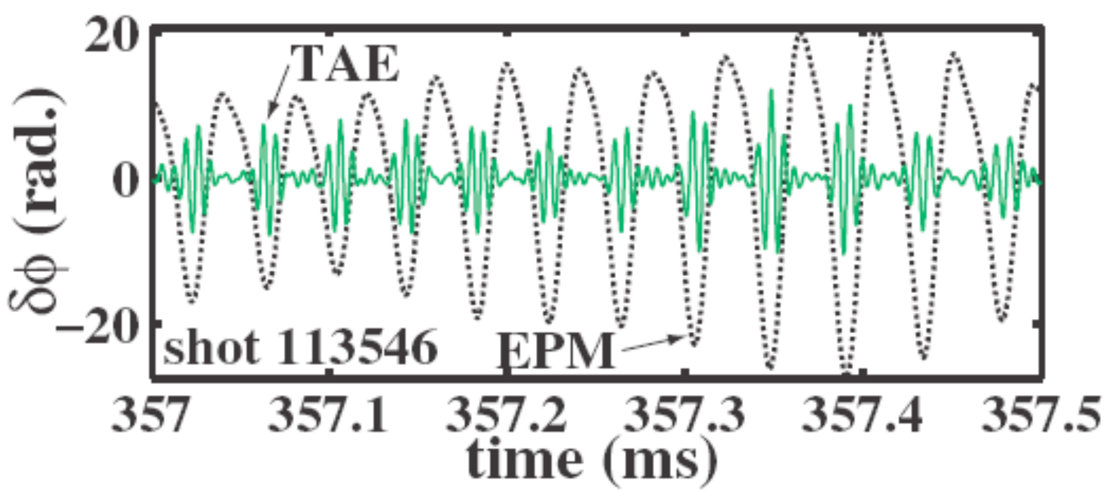
NSTX

Low-f Energetic Particle Modes (EPMs) co-exist with mid-f TAE modes



Bi-coherence analysis reveals 3-wave coupling between

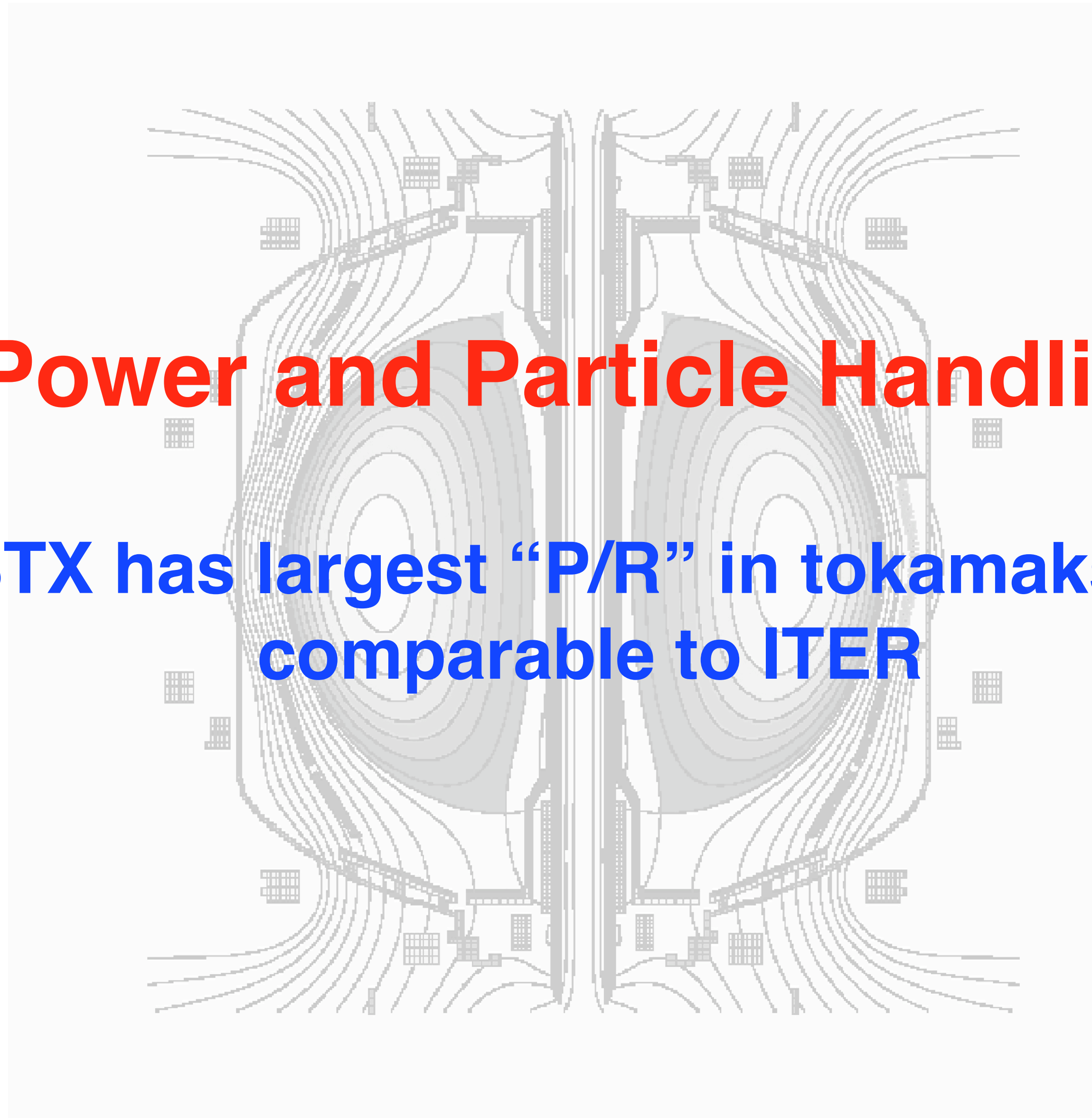
1 EPM and 2 TAE modes



- ***Large EPM → TAE phase locks to EPM***

forming toroidally localized wave-packet

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



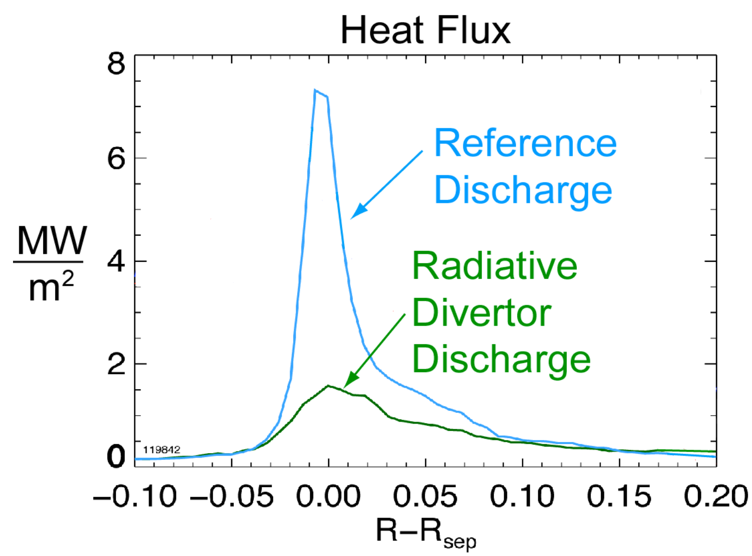
Power and Particle Handling

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

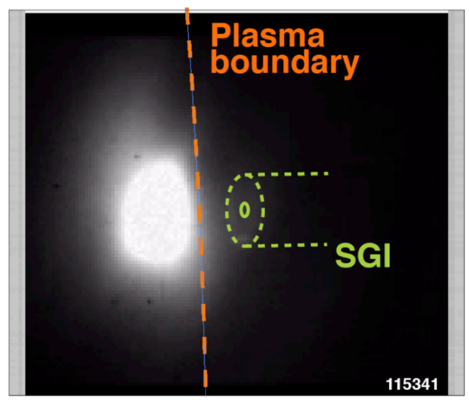
Developed Radiative Divertor regime: **Obtained by steady-state D_2 injection into private flux region or ISP**

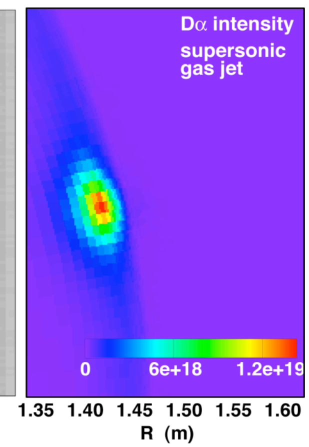


– Outer SP (OSP) heat flux reduced by 4-5

– 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



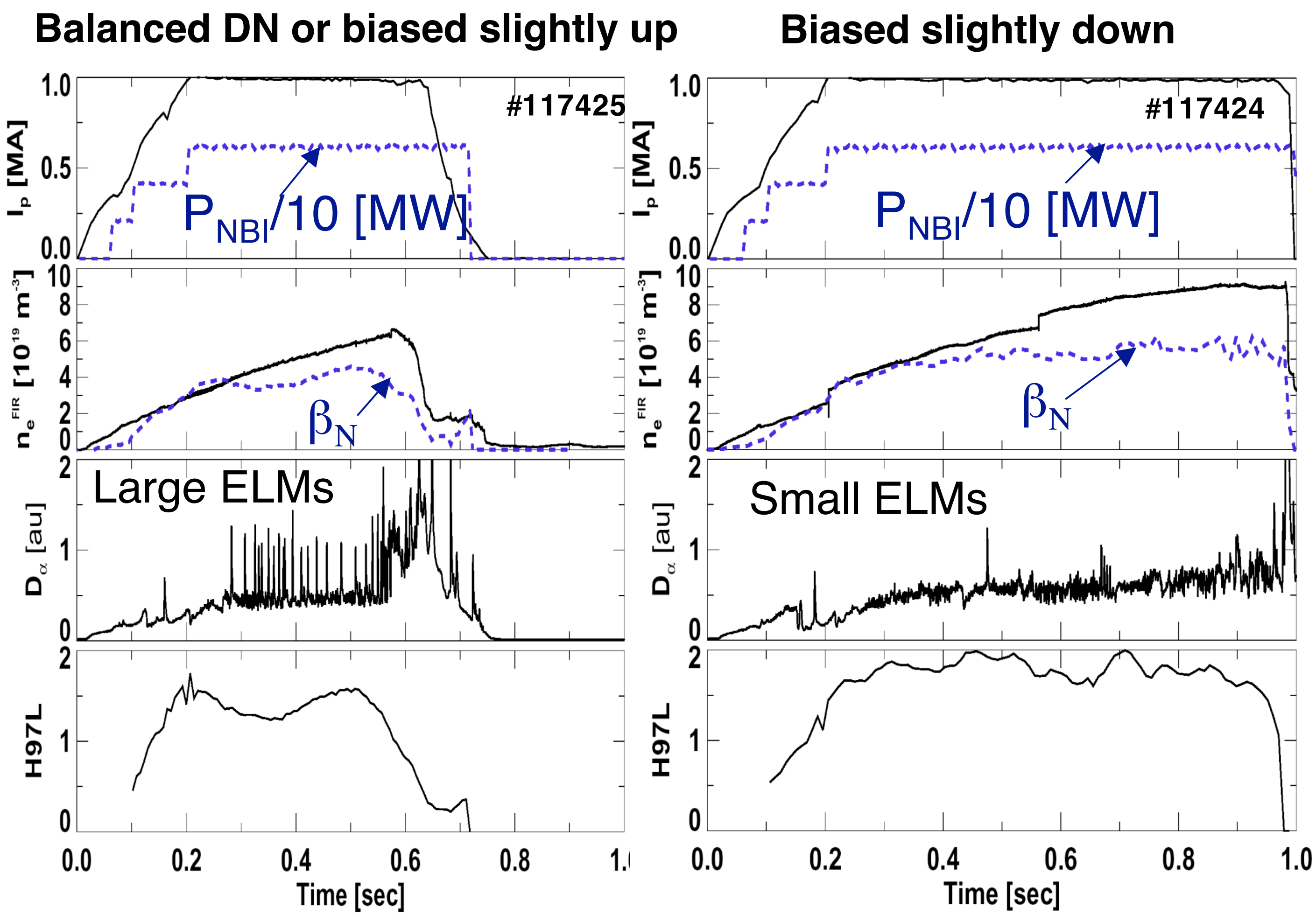


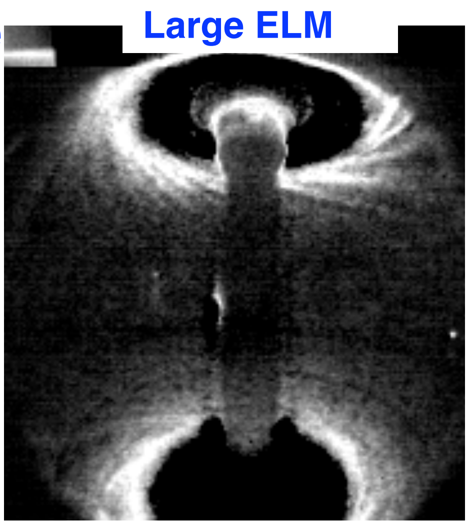
DEGAS 2 Neutral transport modeling reproduces observed features

- **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

NSTX studying access conditions and structure of different ELM types

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



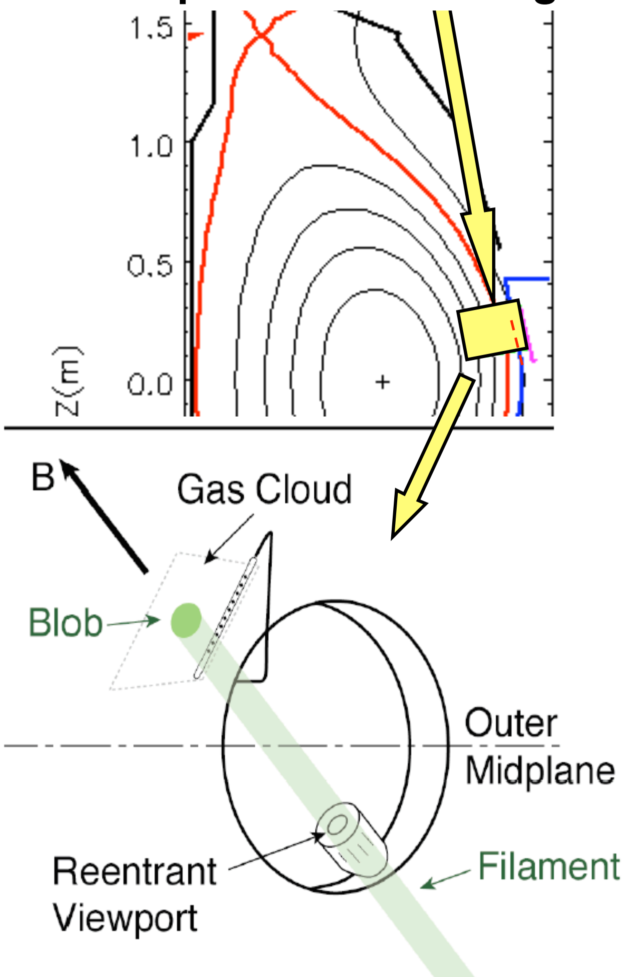


ORNL, Nova Photonics, Johns Hopkins, UCD

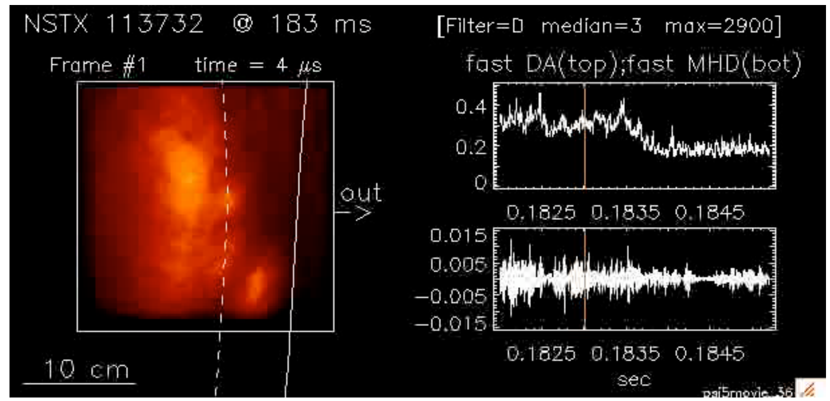
Maingi, POP 2006

Gas-Puff Imaging (GPI) Diagnostic Provides High Time-Resolution of Near-Edge Transport Phenomena and ELMs

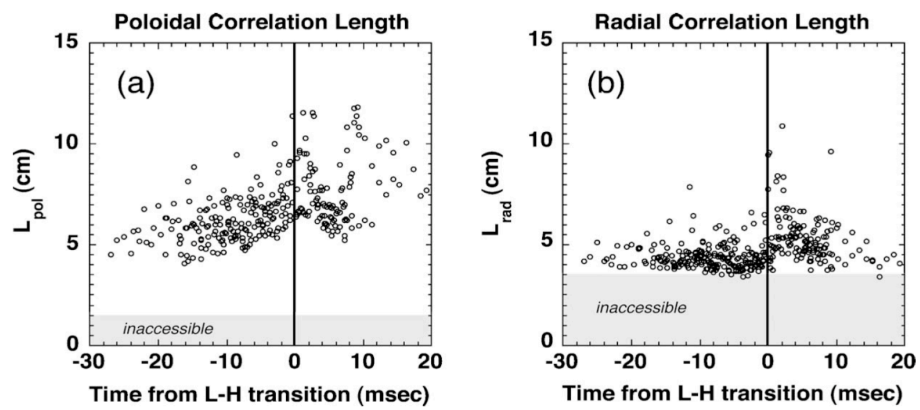
Viewing area just above midplane on outer edge



- Example: L → H transitions imaged with GPI

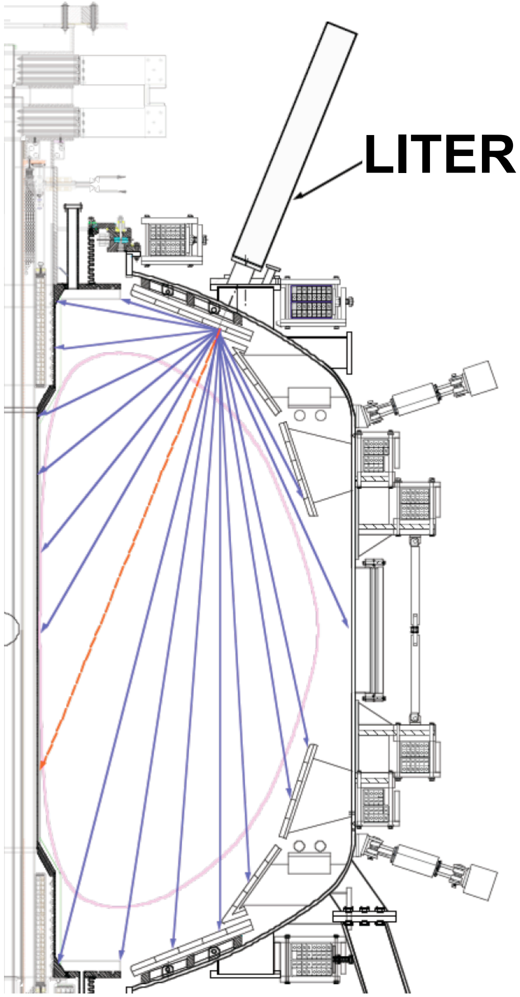


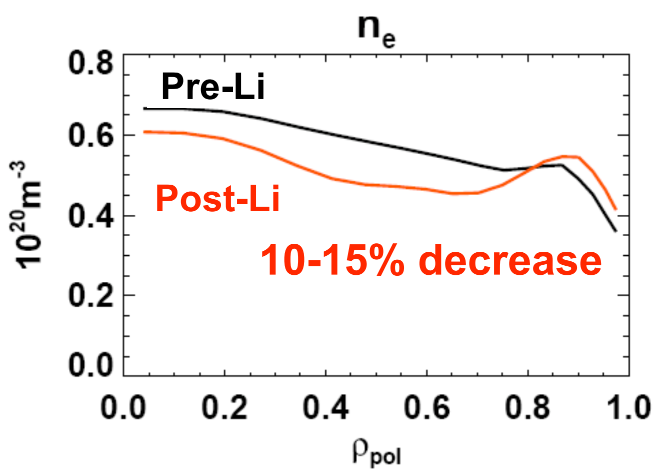
- Little change in correlation lengths at L→H transitions



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

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





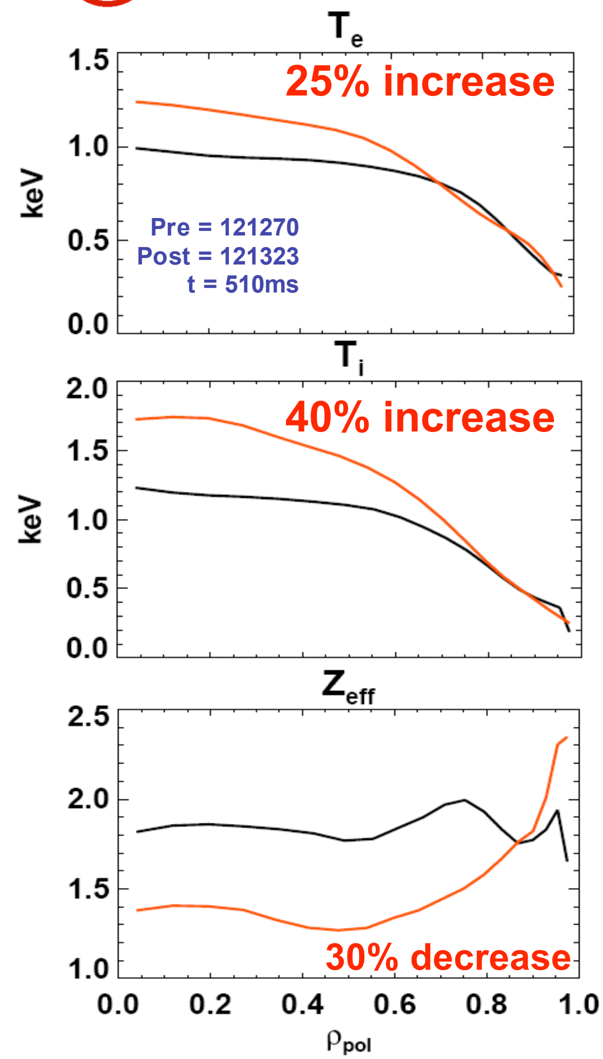
TRANSP analysis:

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

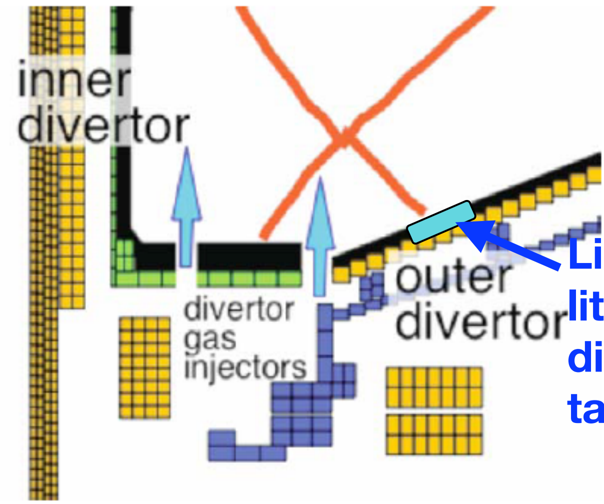


- L-mode exhibits even larger (20-25%) relative density decrease

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

NSTX

- 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 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
- Unique opportunity for understanding electron transport and micro-turbulence with high-k (electron scale) scattering system
- Steady progress is being made on HHFW and EBW physics
- Uniquely able to mimic ITER fast-ion instability drive with full diagnostics
- Broad ITER and CTF-relevant boundary physics research program
- *Active EF/RWM feedback stabilization system demonstrated for a wide range of rotation speed including ITER relevant low rotation (D Gates)*
- *Rapid progress toward fully non-inductive high performance scenarios (D. Gates)*
- *Soleonid-free 160kA closed-flux plasma formation in NSTX using CHI (R. Raman)*

Covered in details in other NSTX talks