Supported by

# Progress Towards High Performance Plasmas in the National Spherical Torus Experiment (NSTX)

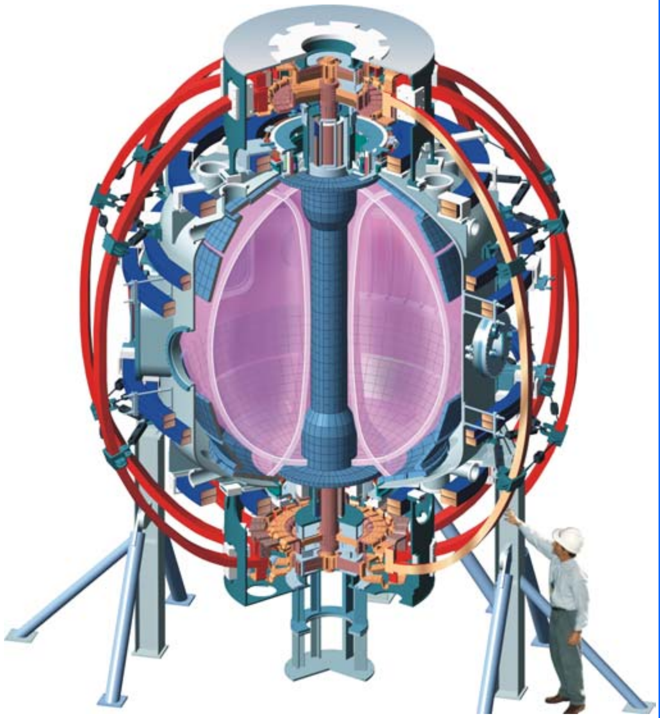

**Stanley M. Kaye**
**for the NSTX Research Team**
PPPL, Princeton University, U.S.A.


**20th IAEA Fusion Energy Conference**
**Vilamoura, Portugal**
November 2004

Columbia U
Comp-X
General Atomics
INEL
Johns Hopkins U
LANL
LLNL
Lodestar
MIT
Nova Photonics
NYU
ORNL
PPPL
PSI
SNL
UC Davis
UC Irvine
UCLA
UCSD
U Maryland
U New Mexico
U Rochester
U Washington
U Wisconsin
Culham Sci Ctr
Hiroshima U
HIST
Kyushu Tokai U
Niigata U
Tsukuba U
U Tokyo
JAERI
Ioffe Inst
TRINITI
KBSI
KAIST
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
U Quebec

# NSTX Is Designed To Study Toroidal Confinement Physics at Low Aspect Ratio and High $\beta_T$

Establish physics database for future Spherical Torus (ST) devices

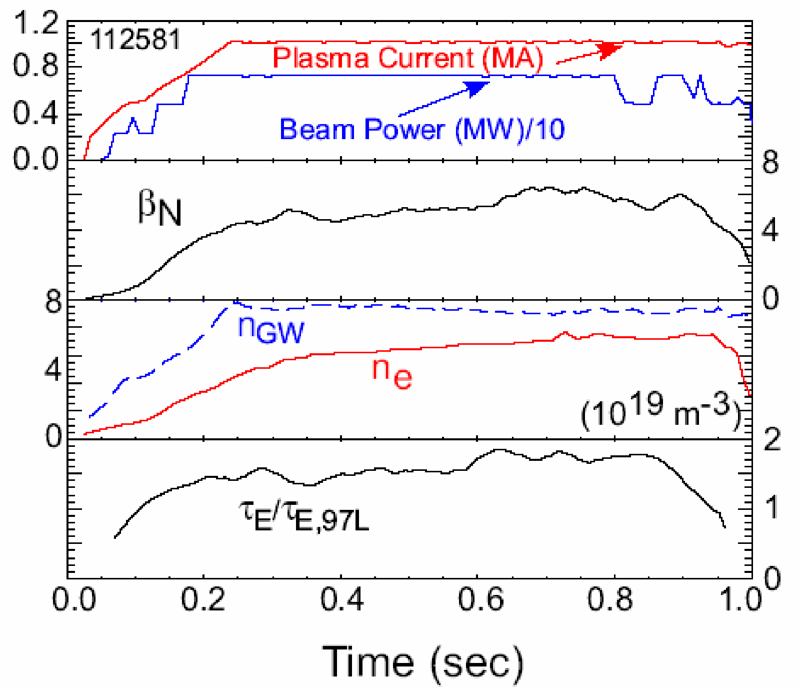


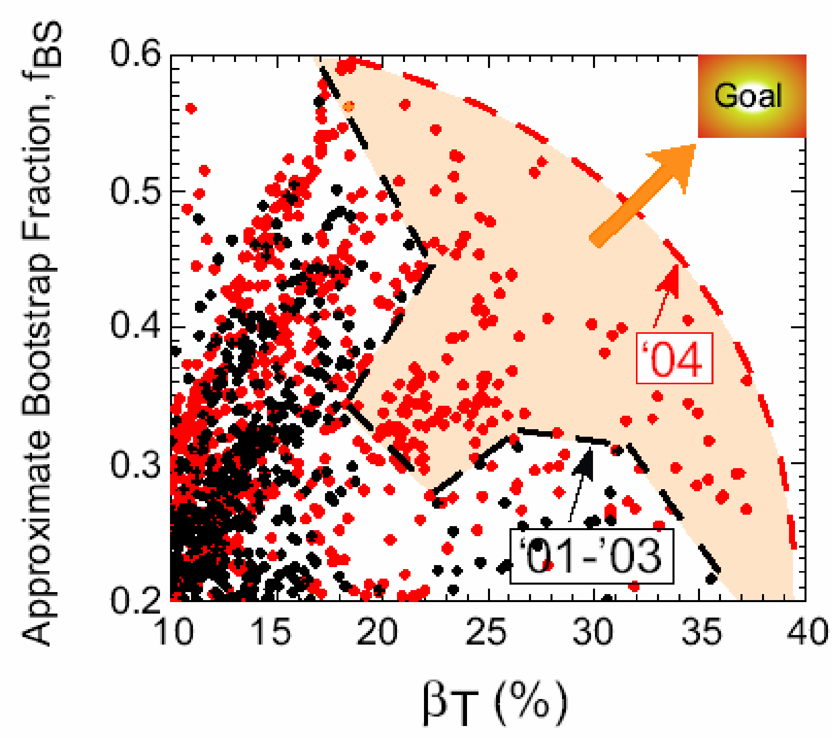
| | |
|---|---|
| Aspect ratio A | 1.27 |
| Elongation $\kappa$ | 2.5 |
| Triangularity $\delta$ | 0.8 |
| Major radius $R_0$ | 0.85m |
| Plasma Current $I_p$ | 1.5MA |
| Toroidal Field $B_{T0}$ | 0.6T |
| Pulse Length | 1s |
| Auxiliary heating: | |
| NBI (100kV) | 7 MW |
| RF (30MHz) | 6 MW |
| Central temperature | 1 – 3 keV |

Non-solenoidal current generation/sustainment key element of program

# Operational and Physics Advances Have Led to Significant Progress Towards Goal of High-$\beta_T$, Non-Inductive Operation

H-mode plasma




- $\tau_{Ip\ flattop} \sim 3.5\tau_{skin}$
- $\tau_{W\ flattop} \sim 10\ \tau_E$
- $\beta_T$>20%, $\beta_N$>5, $\tau_E/\tau_{E,L}$>1.5 for ~10 $\tau_E$
- $I_{BS}/I_p = 0.5$, $I_{Beam}/I_p = 0.1$

$$f_{BS} = I_{BS}/I_p = 0.5\ \varepsilon^{1/2}\ \beta_{pol}$$

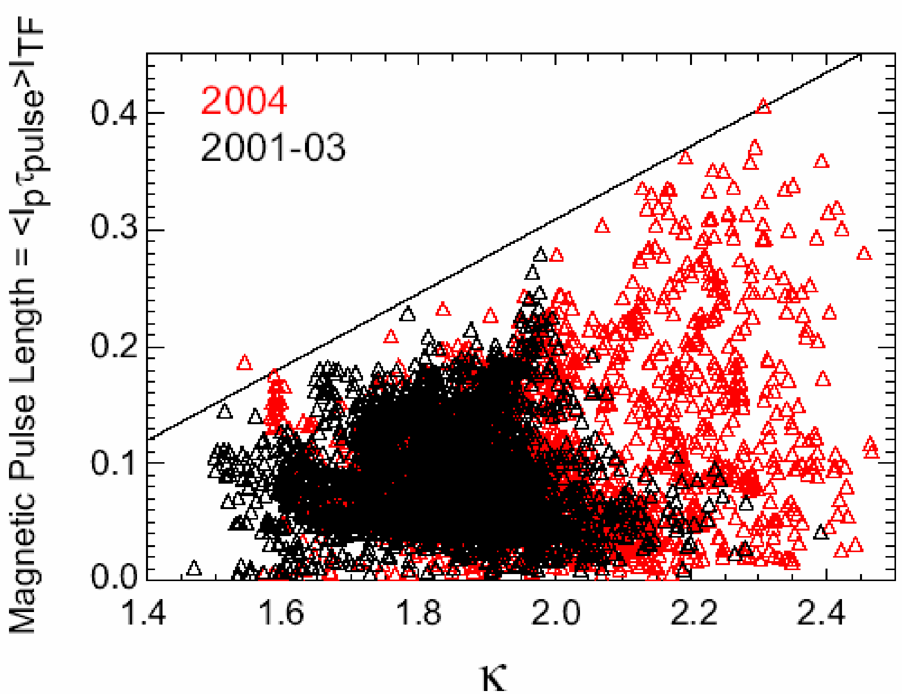
$$\beta_T = \langle p\rangle/(B_{T0}^2/2\mu_0)$$

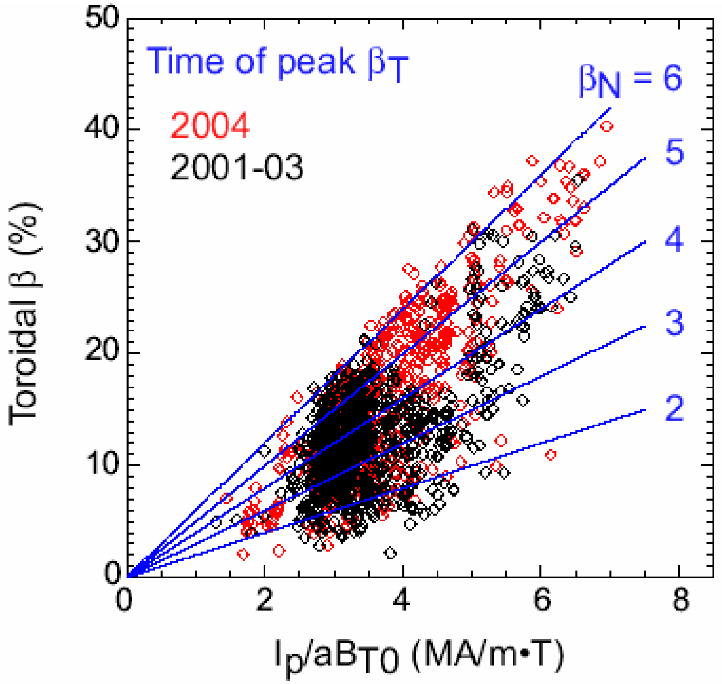
# Improved Plasma Control System Opened Operating Window During 2004 Campaign

Reduced latency improved vertical control at high-$\kappa$, high-$\beta_T$

More routine high $\kappa$, $\delta$
Longer current flattop duration
$\tau_{pulse} = \tau(>0.85\ I_{p,max})$

Capability for higher $\kappa$, $\delta$ allowed higher $I_P/aB_T$
Significantly more high-$\beta_T$
($\beta_N$=6.8 %·m·T/MA achieved)



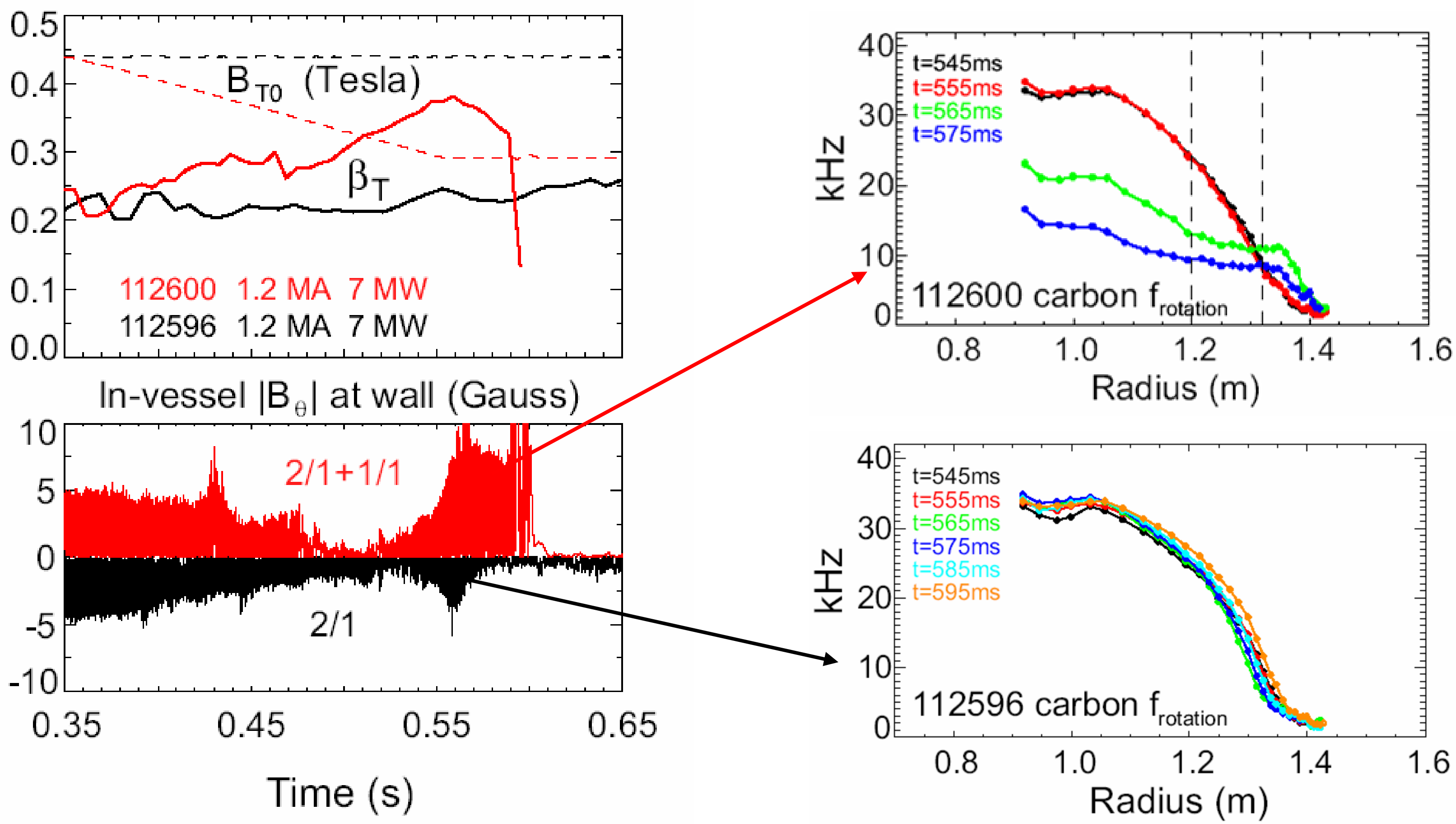






NSTX

# $\beta_T$ Can Be Limited by Internal Modes – Rotation Dynamics Important

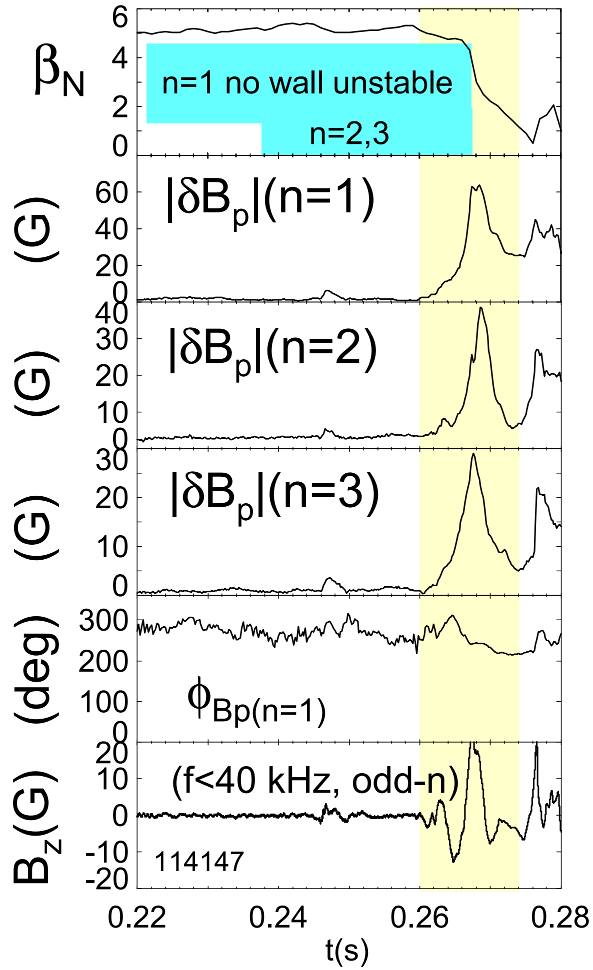
- Flow shear/diamagnetic effects slow internal mode growth
- Coupled 2/1, 1/1 modes eventually reduce rotation → $\beta_T$ collapse






Menard EX/P2-26

# Resistive Wall Modes Can Limit $\beta_T$ at Low q




Critical rotation frequency ~ $1/q^2$

10% above no-wall limit for many wall times ($\tau_{wall}$ ~ 5 msec)

n=1-3 components measured by new internal magnetic sensors
- first observation of n>1

Newly installed active coils for error field/RWM control will provide means to stabilize external modes

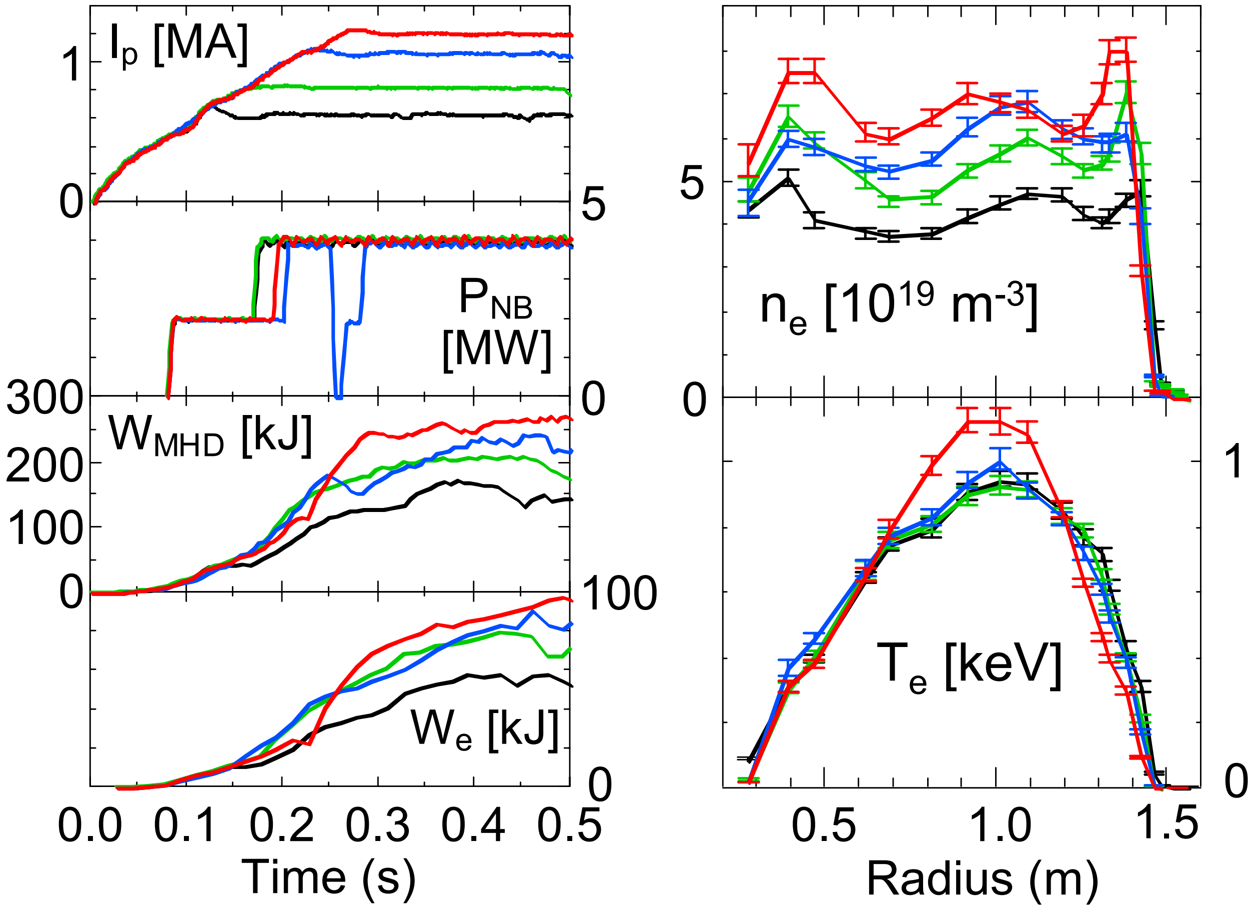
Sabbagh EX/3-2

NSTX exhibits a broad spectrum of instabilities driven by fast ion resonance

Fredrickson EX 5-3

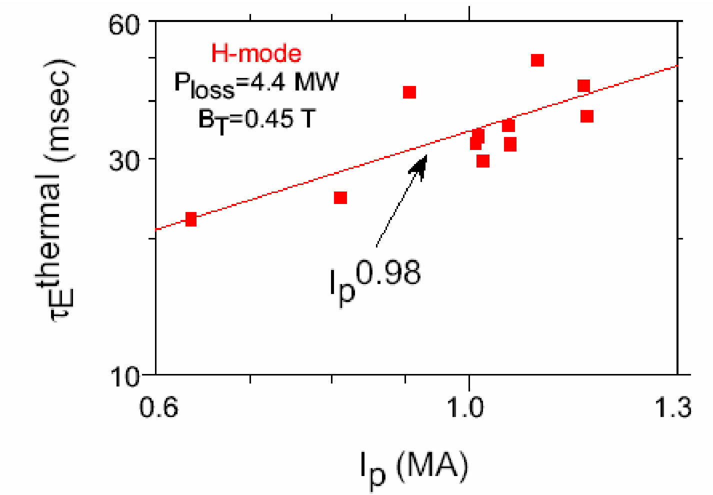
# Systematic Scans Reveal Stored Energy Increases With Plasma Current in NBI Discharges

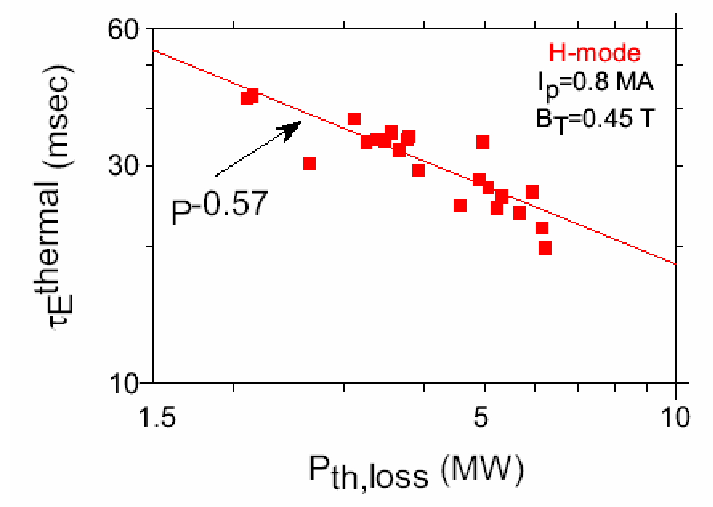
~ Linear dependence at fixed $B_T$, $P_{inj}$



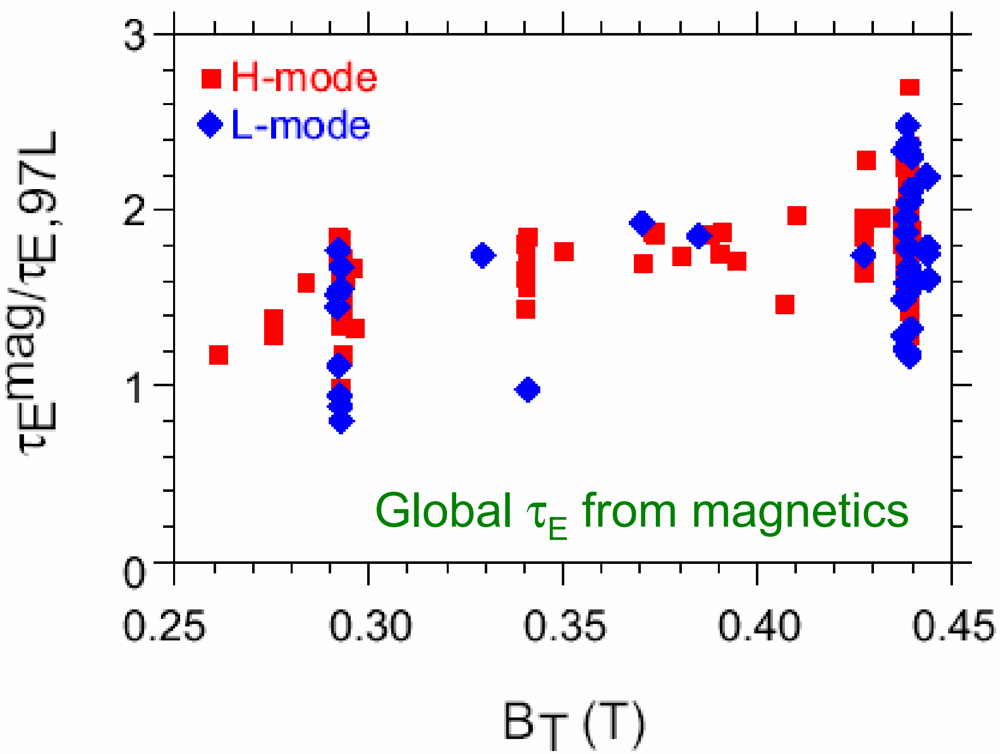
# Parametric Dependences of NSTX Energy Confinement Time Established

Some tokamak trends reproduced in thermal and global $\tau_E$'s




- $\tau_E$ exceeds tokamak scalings
- L~H; L more transient
- $B_T$ dependence observed

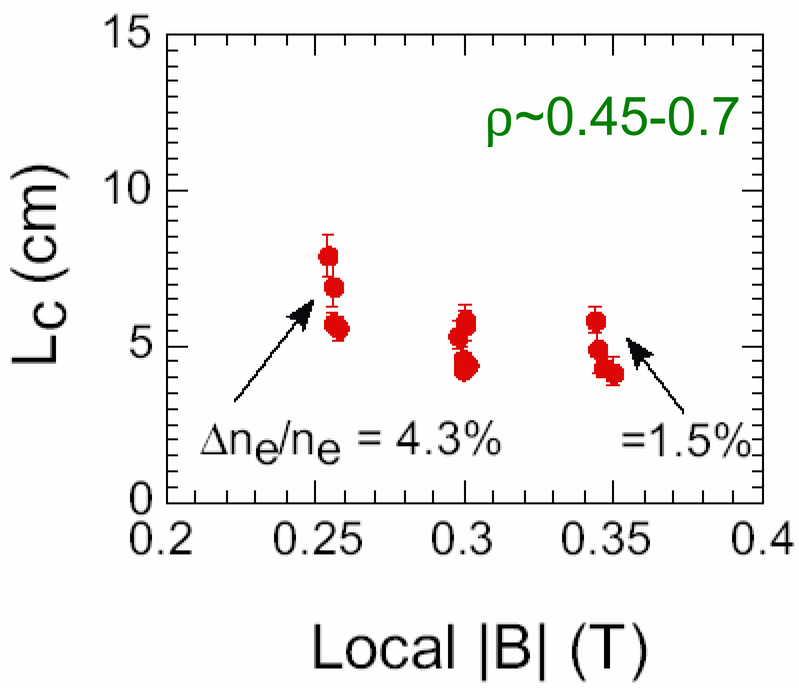



$\tau_{E,th}/\tau_{pby2}$ = 0.5 to 1.4

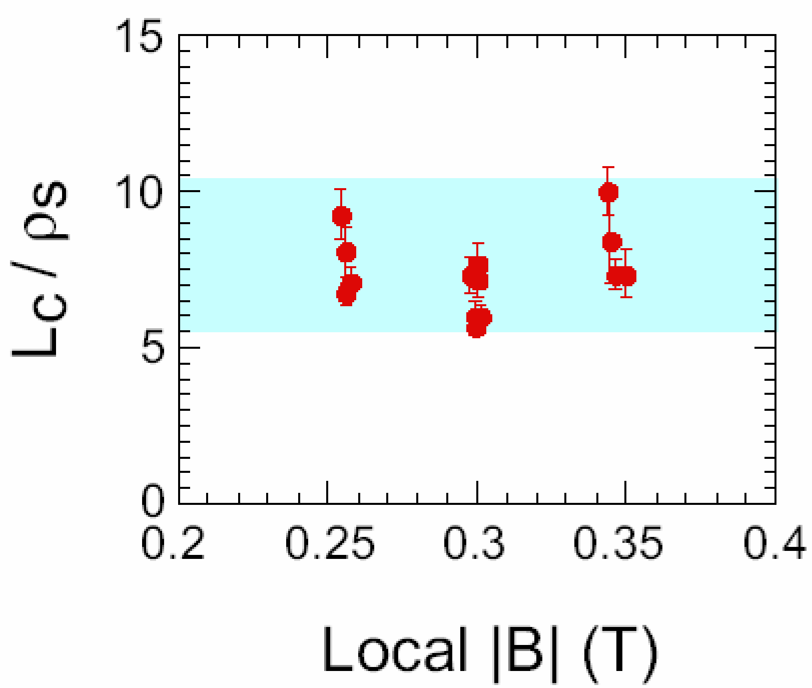
# Long-Wavelength Turbulence Measured in Core for First Time in an ST Through Correlation Reflectometery

Core density fluctuations influenced strongly by magnetic fluctuations – radial correlation lengths long

$L_c$, $\Delta n_e/n_e$ larger at lower $B_T$

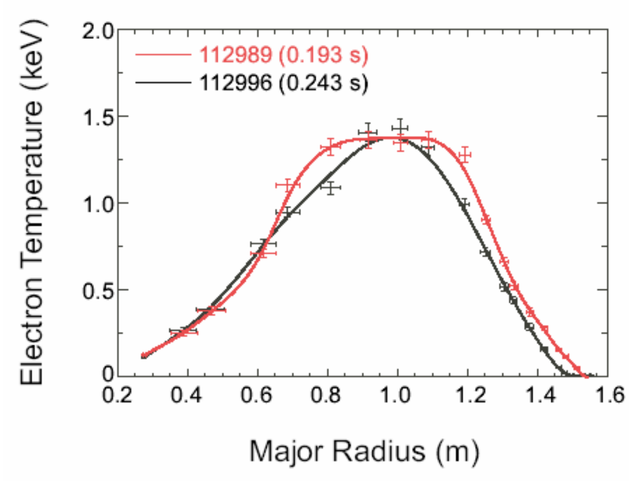


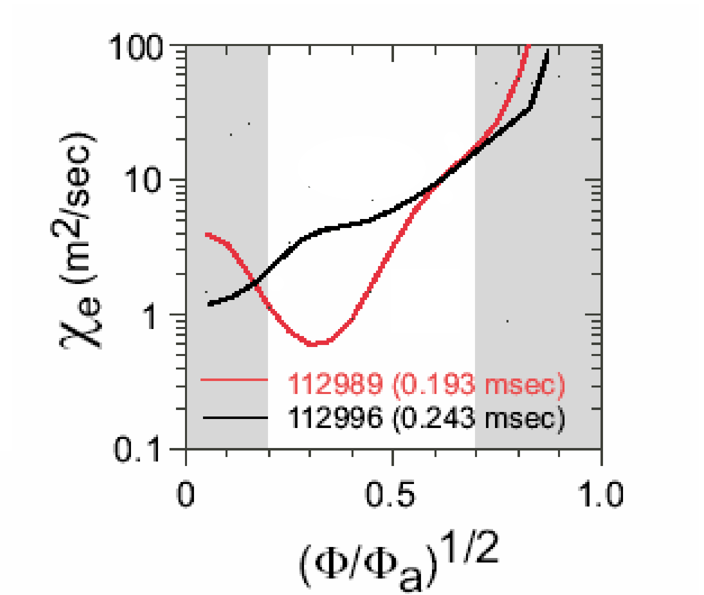

$L_c$ scales as $\rho_s$

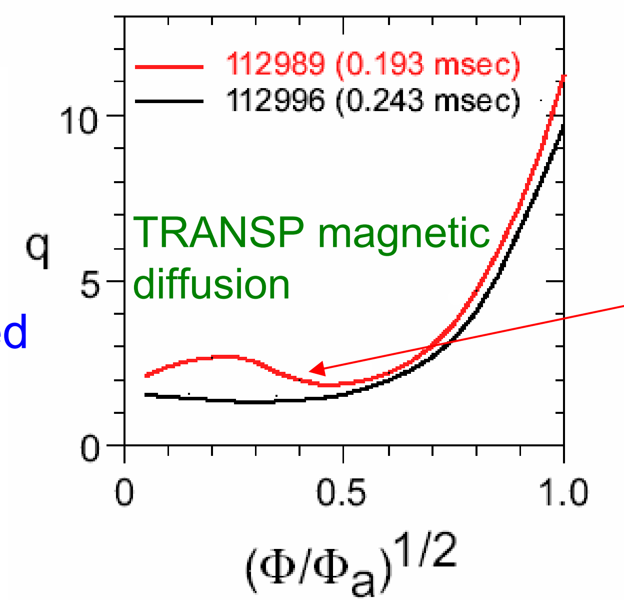


# NSTX Has Investigated Regimes of Reduced Electron Transport

- Electron transport generally dominant ($\chi_{neo} \leq \chi_i << \chi_e$ in H-mode)
- Produced electron ITBs using fast current ramp, early NBI in low density ($n_{e0} \sim 2 \cdot 10^{19}$ m$^{-3}$) L-modes




Reverse shear corroborated by observation of double-tearing modes

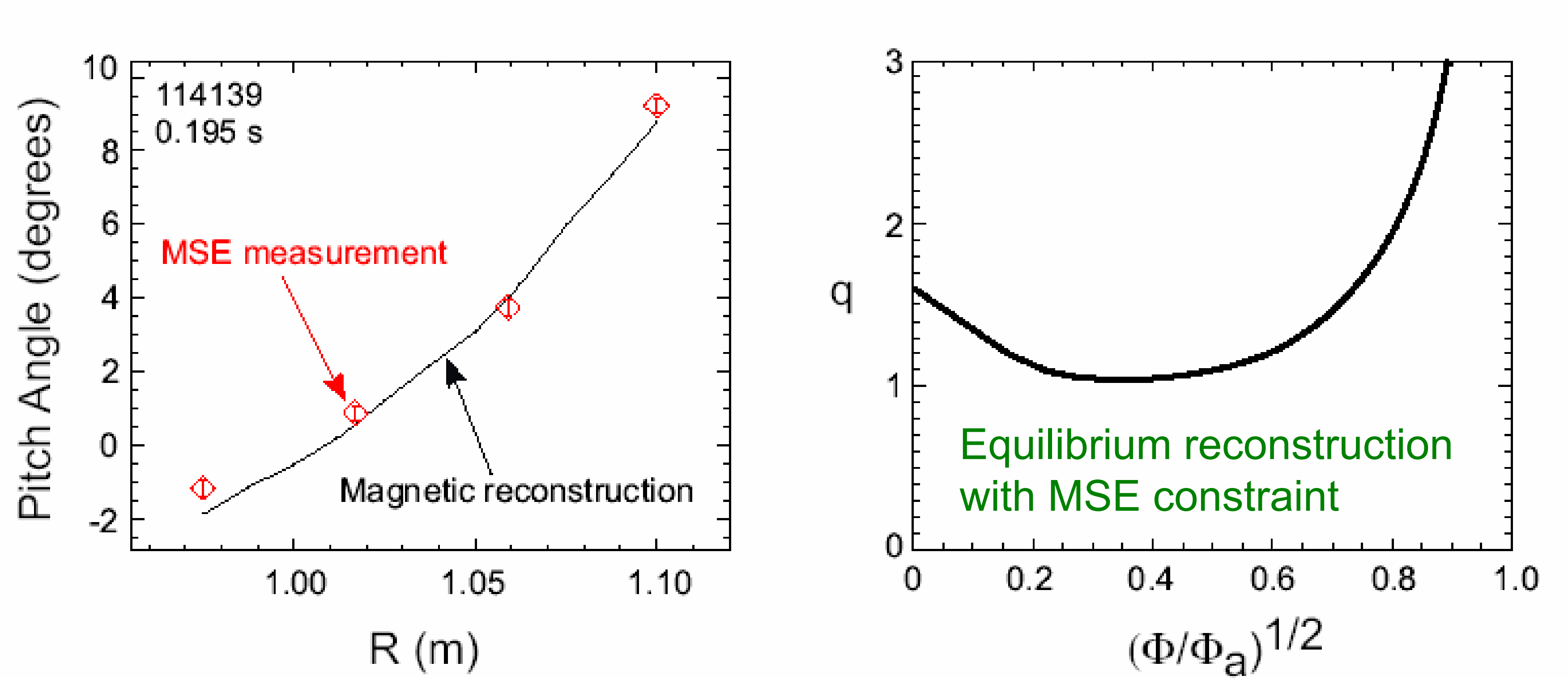
ETG modes predicted to be linearly stable in region of reversed shear (gyrokinetic calculations)



Stutman EX/P2-8

# NSTX Has Developed MSE for Current Profile Measurements at Low $B_T$

- Preliminary reconstructions performed
- Agreement with TRANSP modeling good

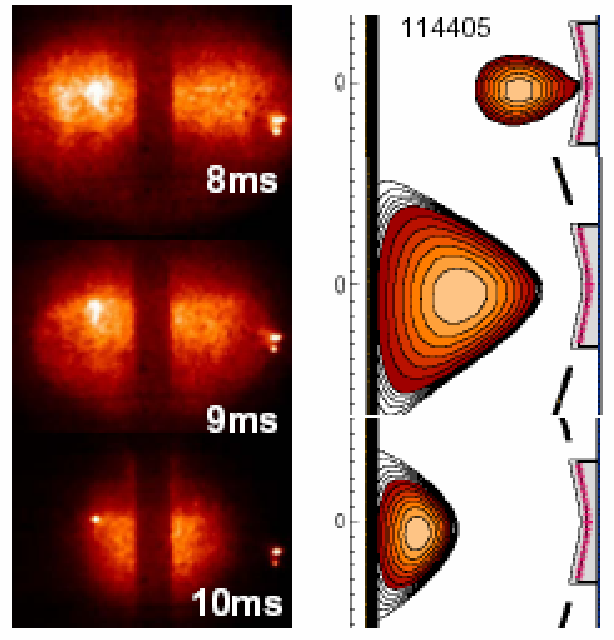


# Toroidal Current Generated Without a Solenoid

Non-solenoidal current generation/sustainment essential in future ST

## 1) PF-only startup

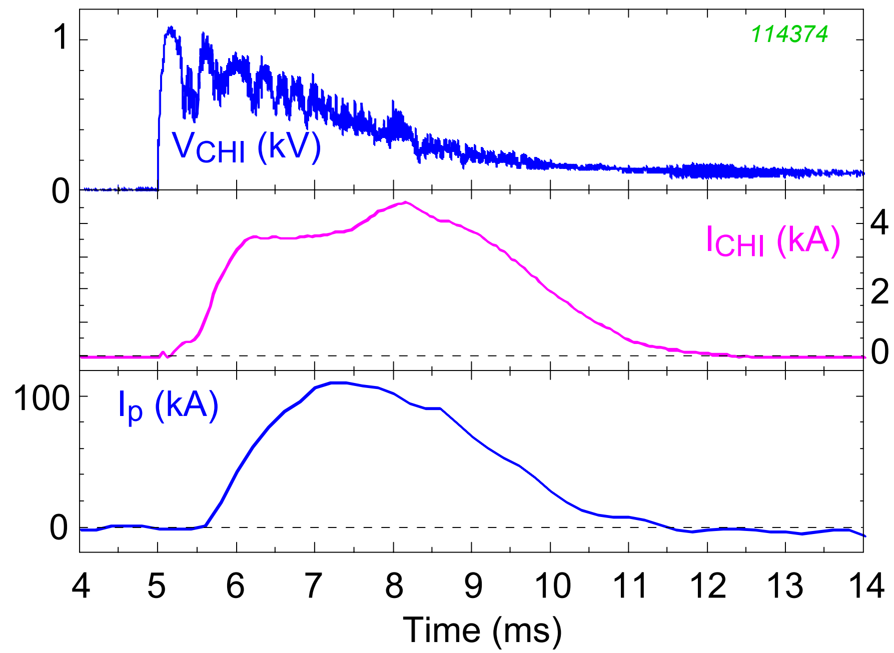
- 20 kA generated




Goal is to maintain plasma on outside where $V_{loop}$ is high

## 2) Transient Co-Axial Helicity Injection

- $I_p$ up to 140 kA, $I_p/I_{injector}$ up to 40




Goal is to extend $I_p$ beyond duration of $I_{injector}$

# New Diagnostics/Experiments Leading to Better Understanding of HHFW Absorption

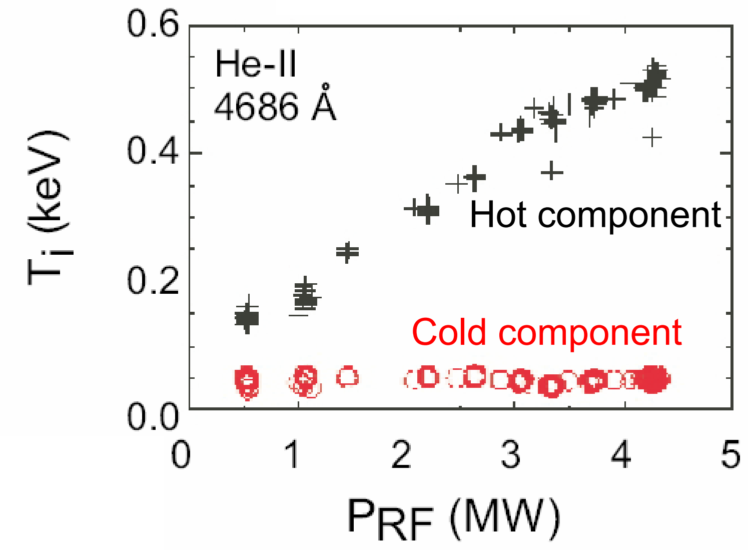
Absorption deficit observed during HHFW heating

- Dependent on wave phase

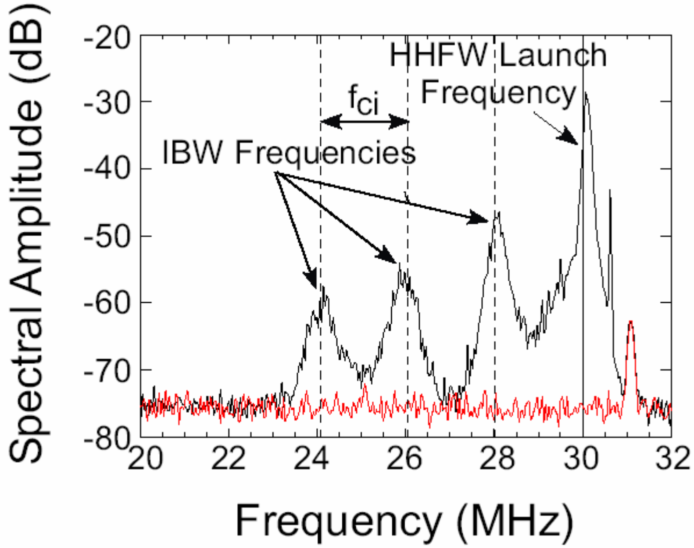
% Absorption

| | | |
|---|---|---|
| $k_{\|\|}$=14 $m^{-1}$ | | 80% |
| 7 $m^{-1}$ | (ctr) | 70% |
| -7 $m^{-1}$ | (co) | 40% |
| -3 $m^{-1}$ | | ~10% |

Edge ion heating observed during HHFW




Edge ion heating associated with parametric decay of HHFW into IBW



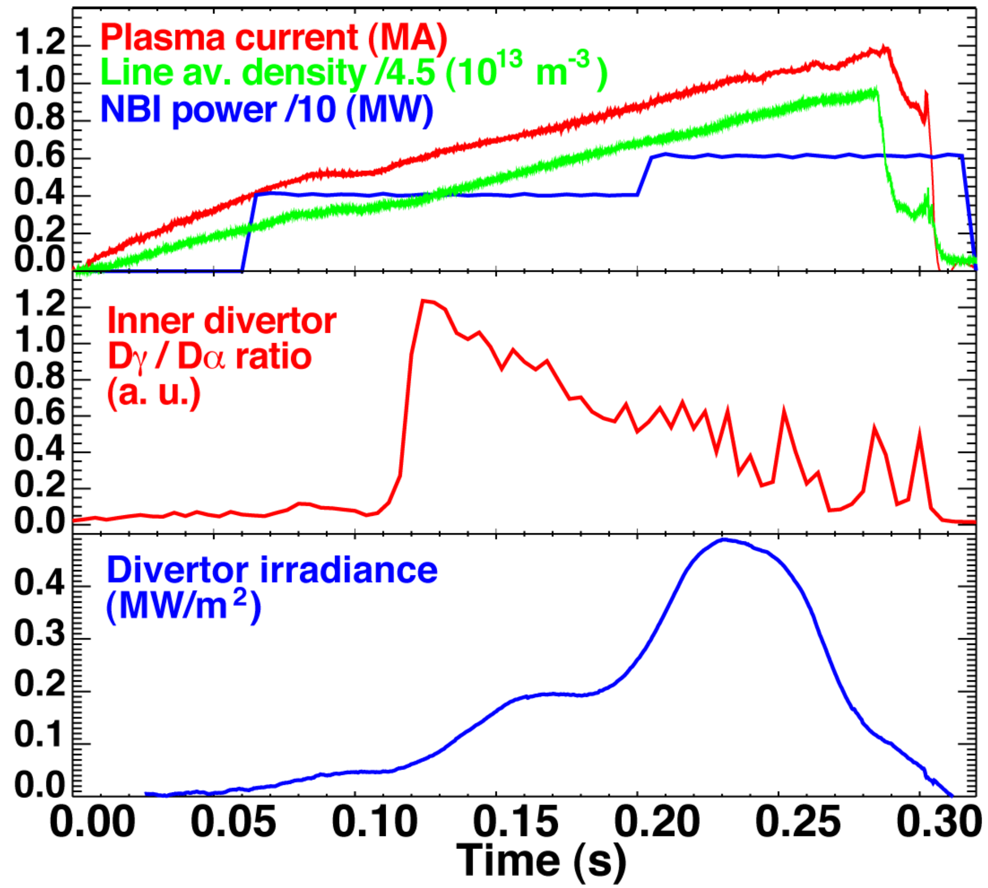

Impact of edge heating on HHFW absorption being studied



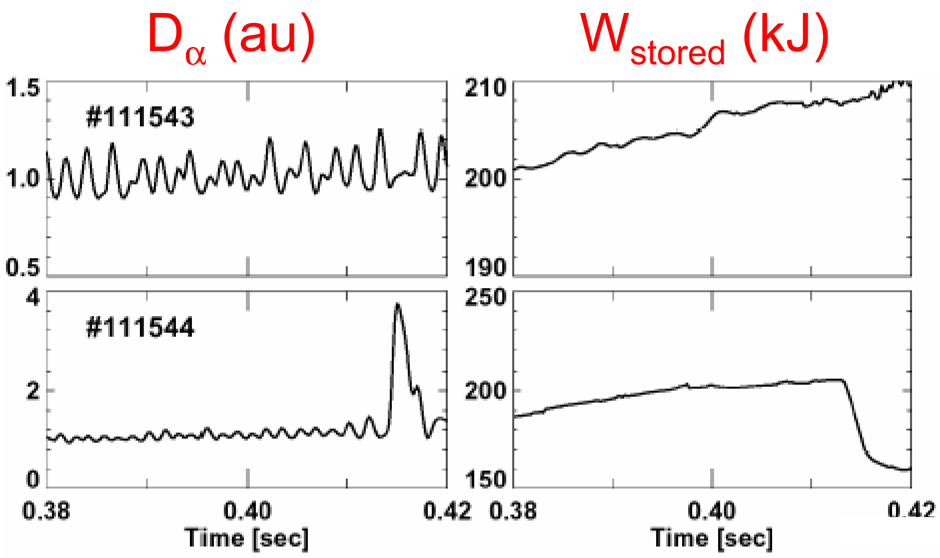
NSTX

# 70 to 90% of Power Accounted for in NBI Discharges

- Most power to divertor plates (35%)
- Inner divertor detachment for $n_e \geq 2{\cdot}10^{19}$ m$^{-3}$
  - Reduced heat flux: 1 MW/m$^2$
- Outer divertor always attached
  - $q_{heat}$ up to 10 MW/m$^2$
  - Attempt to detach with higher $n_{edge}$ &/or $P_{rad,div}$



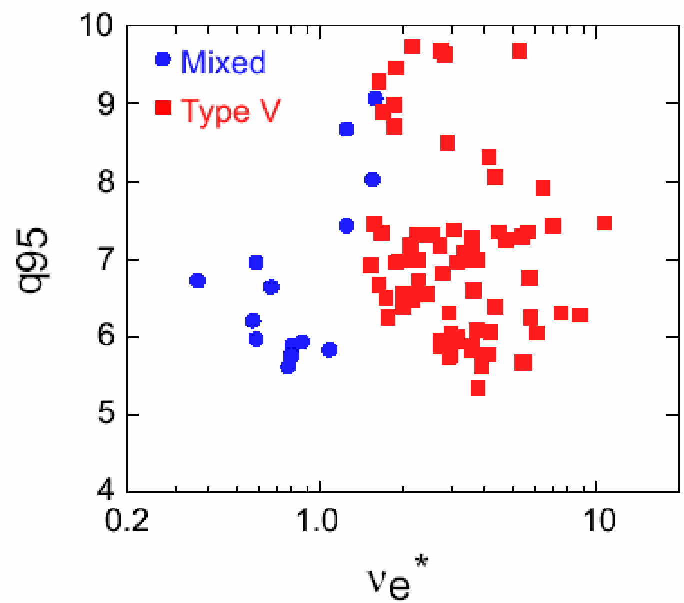
# A New Type of ELM With Minimal Energy Loss/Power Loading Has Been Observed




Type “V”

Mixed Type I + Type “V”

Different ELMs reside in different regimes




SMK – IAEA ‘04

Maingi EX/2-2

NSTX

# Significant Progress Made in Addressing ST Physics Goals and in Increasing Our Understanding of Toroidal Confinement Physics

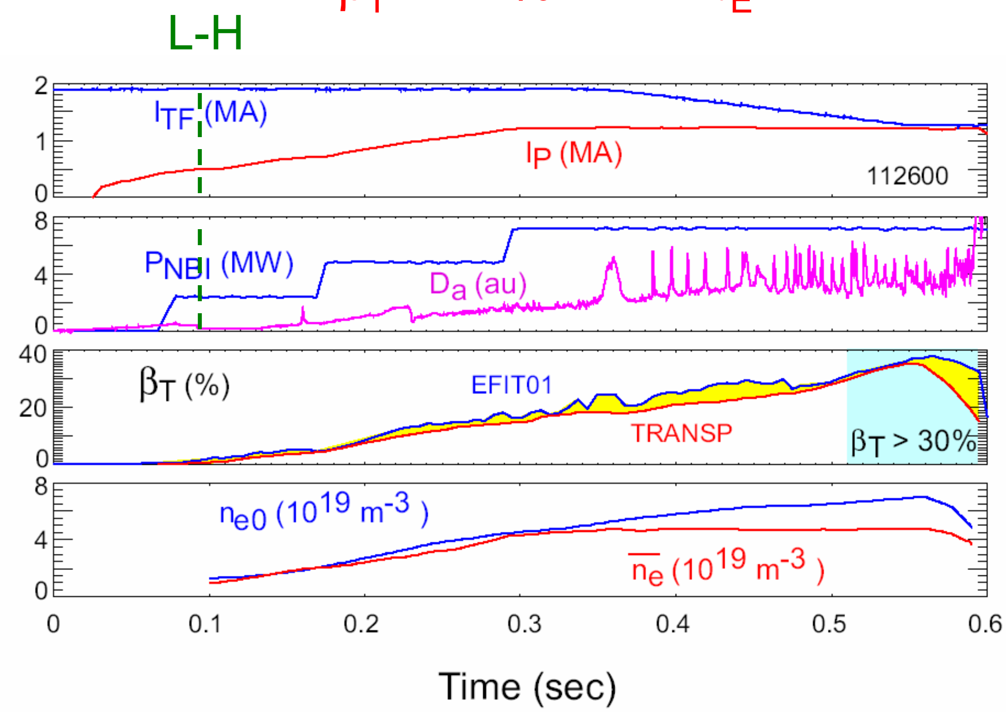
- Improved plasma control and routine high elongation
- High $\beta_T$ and enhanced confinement for long duration (several $\tau_E$)
  - $\beta_T$ up to ~40%, $\beta_N$ up to 6.8 %·m ·T/MA
  - Developing understanding of β-limits and methods to control MHD modes
  - Developing integrated understanding of plasma transport and methods to reduce transport
- Non-solenoidal plasma startup
- Regimes of reduced power loading
- Current flattops for several current relaxation times
  - Significant sustained non-inductive current at high-$\beta_T$ (60% of total)

- Integration of achievements form basis for moving forward with ST concept
  - Many NSTX accomplishments consistent with requirements for ST Component Test Facility (Wilson FT/3-1a,b)

# Backup

# Longer Duration High-$\beta_T$ Achieved With Edge Density Control

$\beta_T$ >30 % for ~$2\tau_E$




- He pre-conditioning to control recycling
- Early NBI and pause in $I_p$ ramp trigger early H-mode
- $\beta_T$ max at $I_P/I_{TF}$ ~ 1

Large flow shear and strong gradients observed at time of peak $\beta_T$ →