Supported by

NSTX Overview

Masayuki Ono
On Behalf of NSTX Team

2nd IAEA TCM on Spherical Tori
& 7th International Spherical Torus Workshop

Aug. 1 - 3, 2001
S. J. Campos, Brazil

NSTX Team Members

M. Ono, M. Bell, R. E. Bell, M. Bitter, C. Bourdelle, D. Darrow, D. Gates, J. Hosea, S. M. Kaye, R. Kaita, H. Kugel, D. Johnson,, B. LeBlanc, R. Majeski, J. Menard, D. Mueller, H. Park, S. Paul, C. Skinner, V. Soukhanovskii, E. Synakowski, G. Taylor, J.R. Wilson , P. Efthimion, R. Goldston, L. Grisham, S. C. Jardin,, R. Hawryluck, K. Hill, H. Ji, R. Majeski, E. Mazzucato, C.K. Phillips, B. Stratton, S. Zweben, W. Blanchard, J. Chrzanowski, W. Davis, L. Dudek, R. Ellis, E. Fredd, T. Gibney, R. E. Hatcher, M. Kalish, McCormack, R. Marsala, C. Neumeyer, G. Oliaro, R. Parsells, E. Perry, G. Pearson, S. Ramakrishnan,, J. Robinson, P. Roney, L. Roquemore, P. Sichta, T. Stevenson, A. Von Halle, M. Williams, *Princeton Plasma Physics Laboratory, Princeton, NJ 08543, USA*

Y-K.M. Peng, R. Maingi, R.E. Barry , T. Bigelow, M. D. Carter, M.M. Menon , P. Ryan, D. Swain,J. Wilgen, *Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA,*

S. Sabbagh, F. Paoletti, J. Bialek, W. Zhu, *Columbia University, New York, N.Y., USA*

R. Raman, T. Jarboe, B. A. Nelson, *University of Washington, Seattle, Washington, USA*

R. Maqueda, G. Wurden, *Los Alamos National Laboratory, New Mexico, USA*

R. Pinsker, M. Schaffer, J. Ferron, L. Lao,. *General Atomics, Calif. USA*

D. Stutman, M. Finkenthal, *Johns Hopkins University, Maryland, USA*

W. R. Wampler, *Sandia National Laboratory, New Mexico, USA*

S. Kubota, M. Gilmore, T. Peebles, E. Doyle, L. Zeng, *UC Los Angeles, Calif. USA*

T. K. Mau, *UC San Diego, Calif, USA*

K.C. Lee, N.C. Luhmann, *UC Davis, Calif, USA*

P. Bonoli, A. Bers, A.K. Ram, *MIT, Massachusetts, USA*

R. Ackers, EURATOM/UKEA. Culham, UK

J. G. Yang, Korea Basic Science Institute, *Taejeon, Korea*

Y. Takase, A. Ejiri, S. Shiraiwa, *Univ. Tokyo, Tokyo, Japan*

N. Nishino, Hiroshima Univ., *Hiroshima, Japan*

O. Mitarai, Kyushu Tokai Univ., *Kumamoto, Japan*

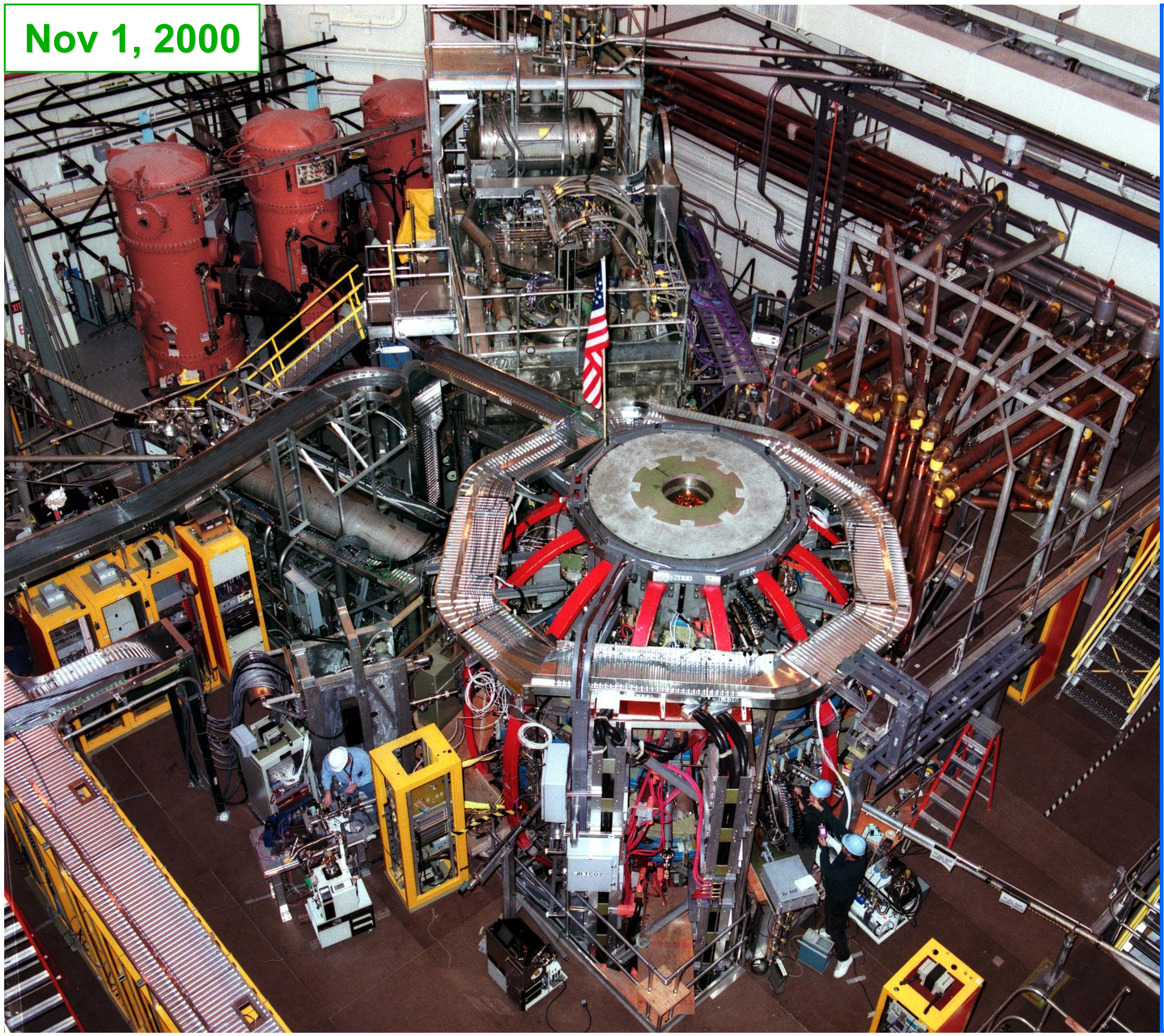
M. Nagata, Himeji Inst. Technology, *Okayama, Japan*

NSTX Overview Talk Outline

- **Device Highlights** (Diagnostics will be covered in M. Bell talk.)
- **Plasma Capability Improvements**
- **NBI Heating Results**
  - Plasma Confinement (C. Bourdelle at this conference)
  - MHD Stability
  - High frequency modes
- **High Harmonic Fast Wave Heating**
  - Strong electron heating regime
  - Energetic particle interaction
- **Coaxial Helicity Injection** (B. Nelson at this conference.)
- **Facility Plans**
- **Summary**

NSTX Facility Has Continued Rapid Progress in Operational and Experimental Capabilities

Nov 1, 2000



Baseline Parameters
(Achieved)

Major Radius 0.85 m

Minor Radius 0.68 m

Elongation = 2.2 (2.5)

Triangularity = 0.6 (0.5)

Plasma Current
1 MA (1.4 MA)

Toroidal Field
0.3 to 0.6 T (≤0.45 T)

Heating and CD
5 MW NBI (5 MW)
6 MW HHFW (4.2 MW)
0.5 MA CHI (0.26 MA)

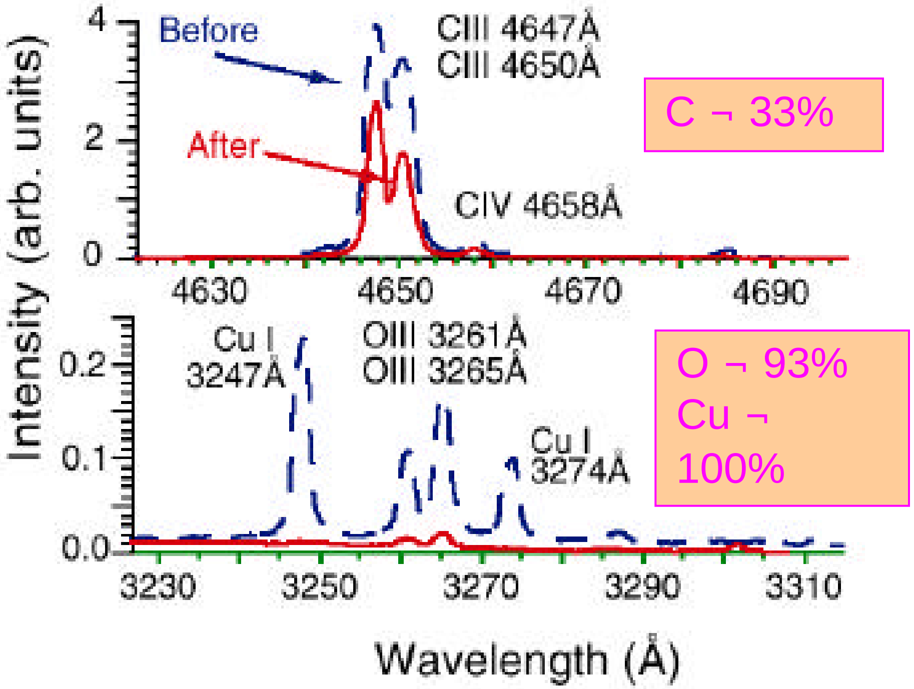
Pulse Length
= 5 sec (0.5 sec)

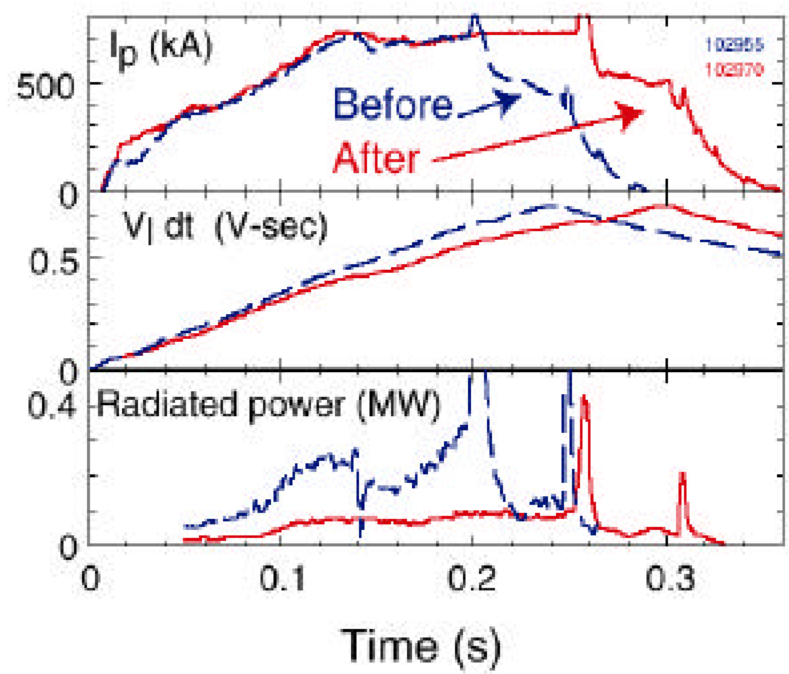
NSTX Facility Highlights

- **CHI 50 kA Injection Power Supply (July 00)**
- **Between-shots He Glow (Sept. 00)**
- **TMB Gas Boronization (Sept. 00) (MAST Technique)**
- **NBI System became operational (Sept. 00)**
- **6 kG Toroidal Field Test Performed (Nov. 00)**
- **HHFW System reached 4 MW (Dec. 00)**
- **Center Stack coil removed for repair (Feb. - Apr. 01)**
- **Skybolt II Plasma Control Computer (May 01)**
- **NBI System reached 5 MW (June 01)**
- **Plasma Boronization (July 01)**
- **Real Time Phasing Control (July 01)**
- **HHFW System reached 6 MW (July 01)**

Boronization Reduces Impurities and Ohmic Flux Consumption

NSTX

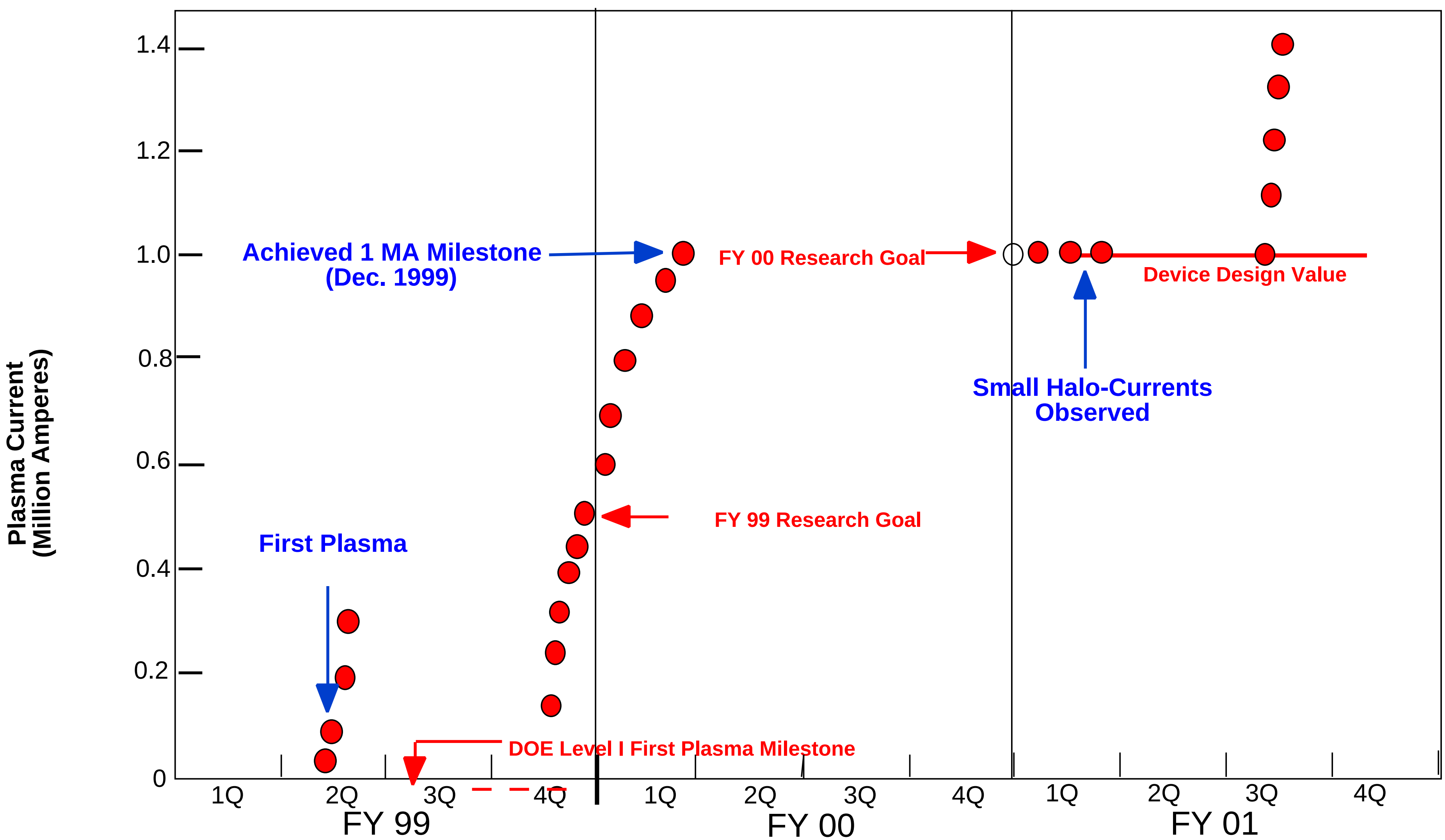




Reduced MHD activity after boronization (TMs, REs)

Plasma Current Exceeded Device Design Value

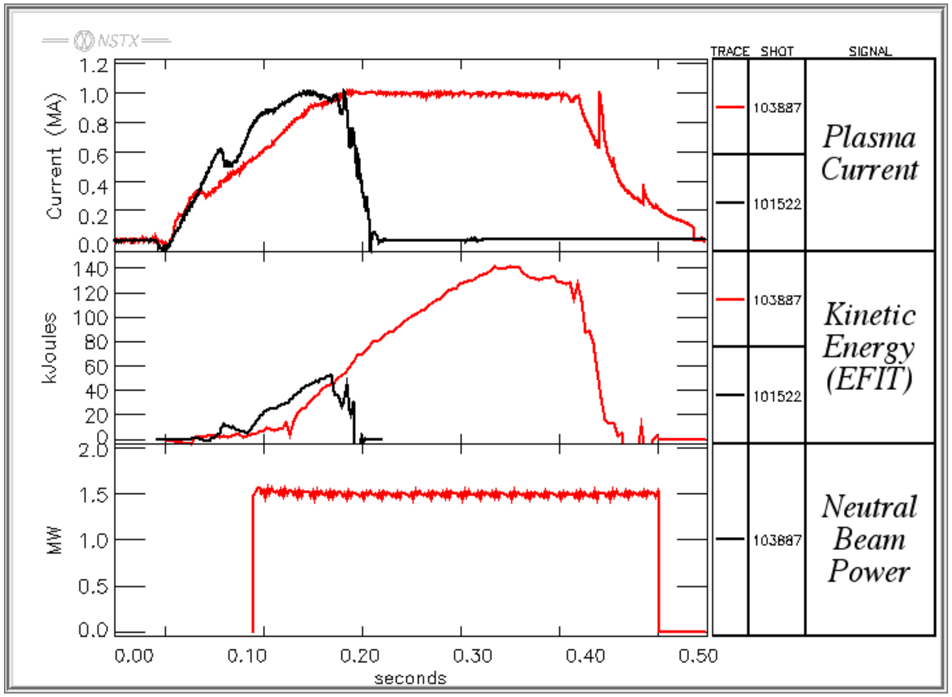
NSTX



NSTX Plasma Operations Greatly Improved!

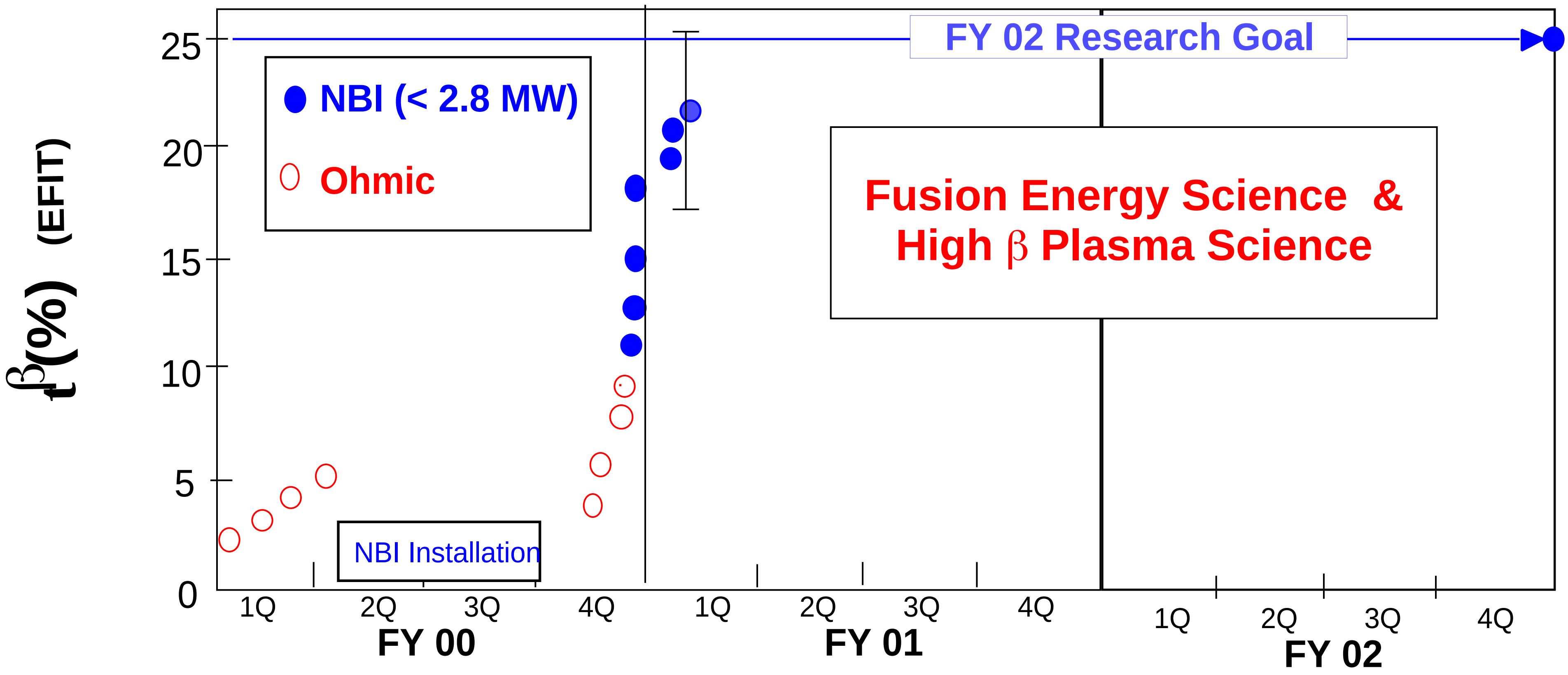
- Significant progress in pulse length and reproducibility in a year
  - 1 MA routine; design rating
  - Tools in place: NBI (5 MW), HHFW heating (**ORNL**; 6 MW), shape control (**GA**), wall preparation techniques

- Towards even longer pulse more control, current, and heating tools
  - Being developed: CHI (**UWash**), HHFW CD (**ORNL**), real-time EFIT (**Columbia, GA**)
  - To be assessed: active mode stabilization (**Columbia, GA**)



Collaborative research a key element

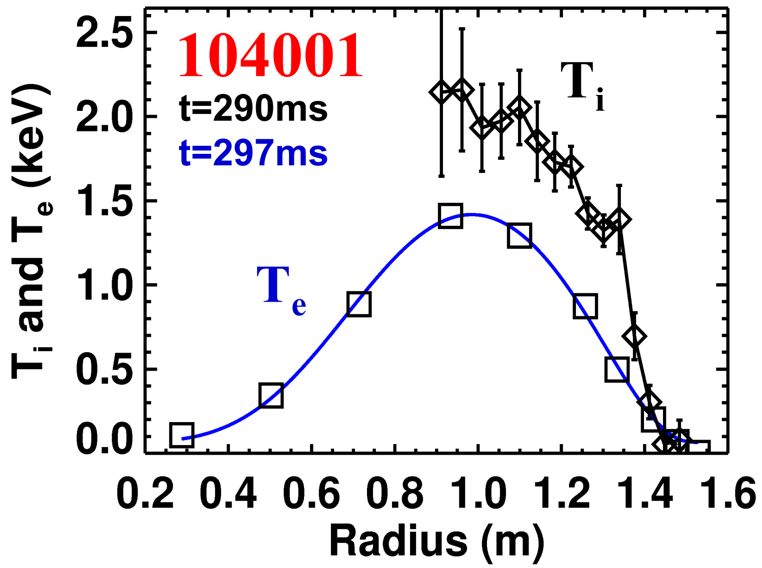
NSTX Produced High Temperature - High β Plasmas Ahead of Schedule

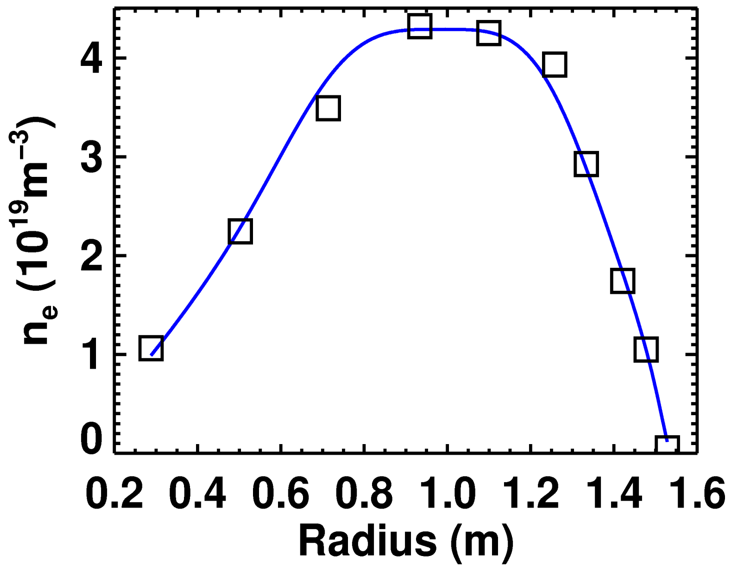


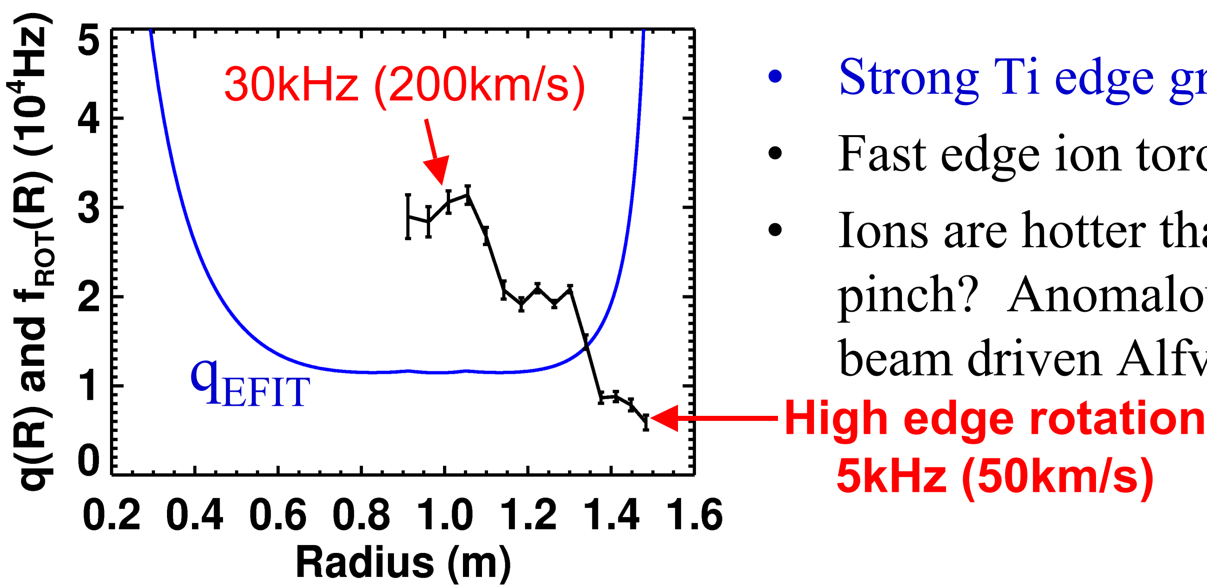
(From magnetic reconstruction)

Kinetic profiles for non H-mode shot 104001

(I_P = 1MA, B_{t0} = 4.5kG, β_{t0}=9%, W_{TOT}=150kJ, P_{NBI}=1.5MW)



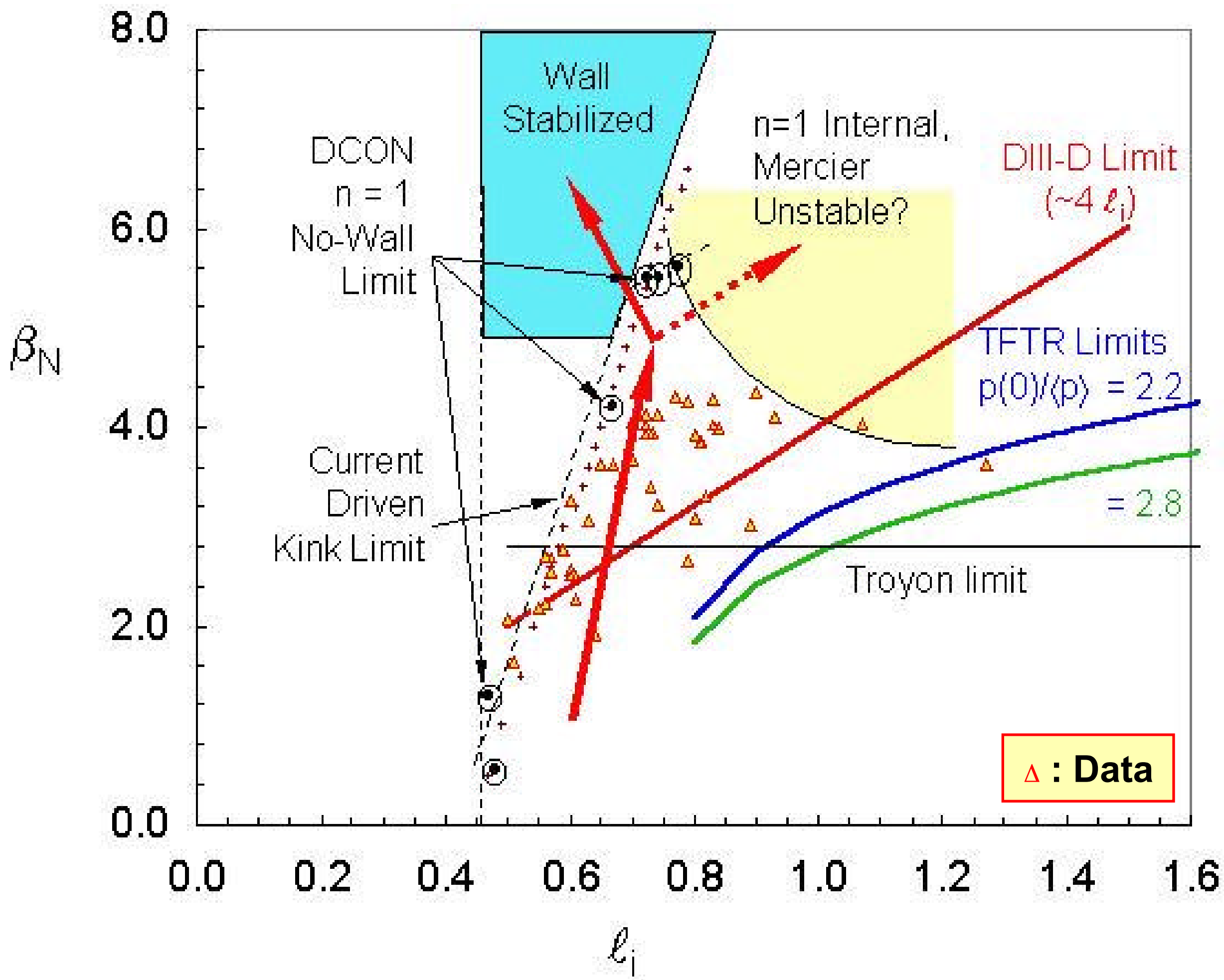




- Strong Ti edge gradient (barrier)
- Fast edge ion toroidal rotation.
- Ions are hotter than expected. Ion heat pinch? Anomalous ion heating via NBI beam driven Alfven modes?

Present Data and Analysis Suggests New Scenarios to Test Instabilities at Even Higher β_N

NSTX

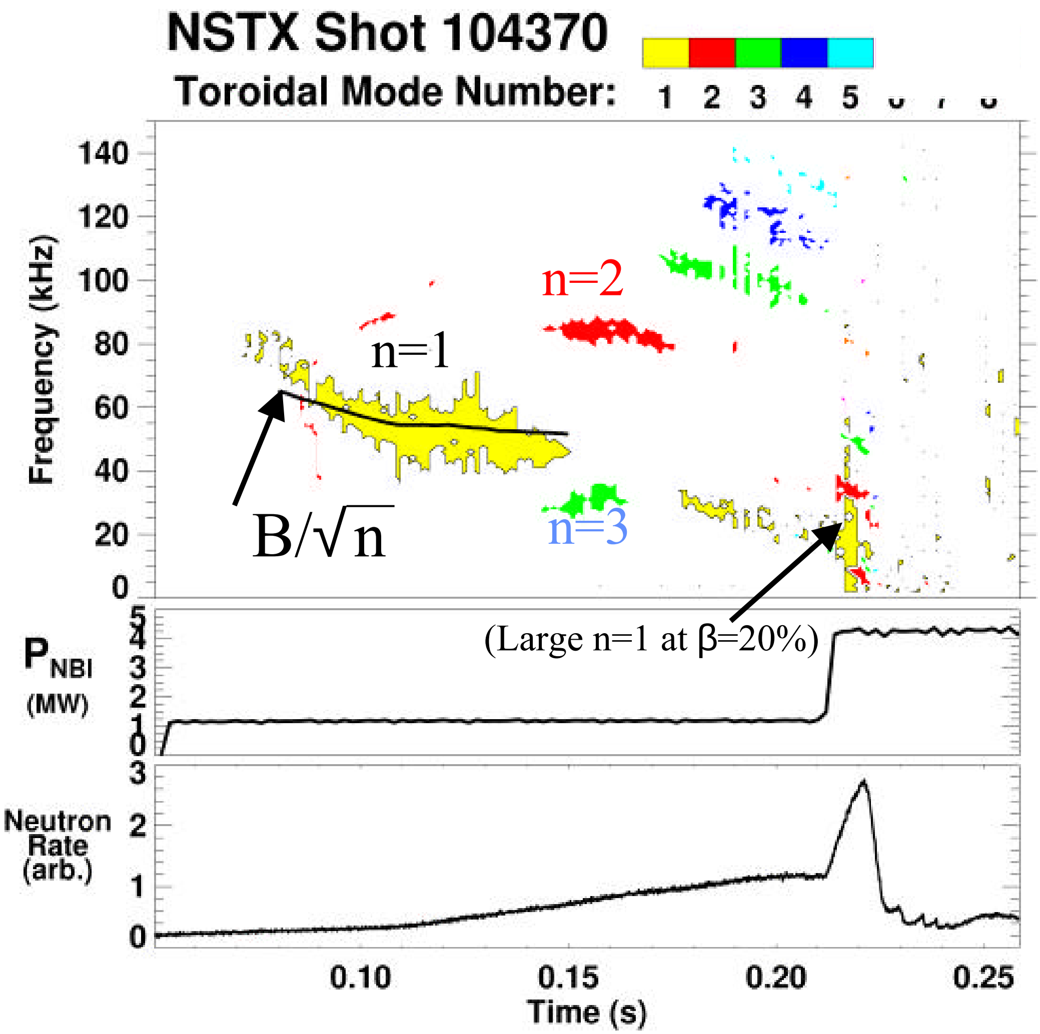


- Raise β_N 5+ while increasing ℓ_i to avoid current-driven kink modes
- Raise β_N 6+ but lower ℓ_i to couple mode to wall
- Stabilize mode for $\beta_N > 6$
- Option: higher ℓ_i to test unstable Mercier modes (no need for wall stabilization)?
- DIII-D mode control data encouraging

Beam-driven MHD activity observed in many discharges

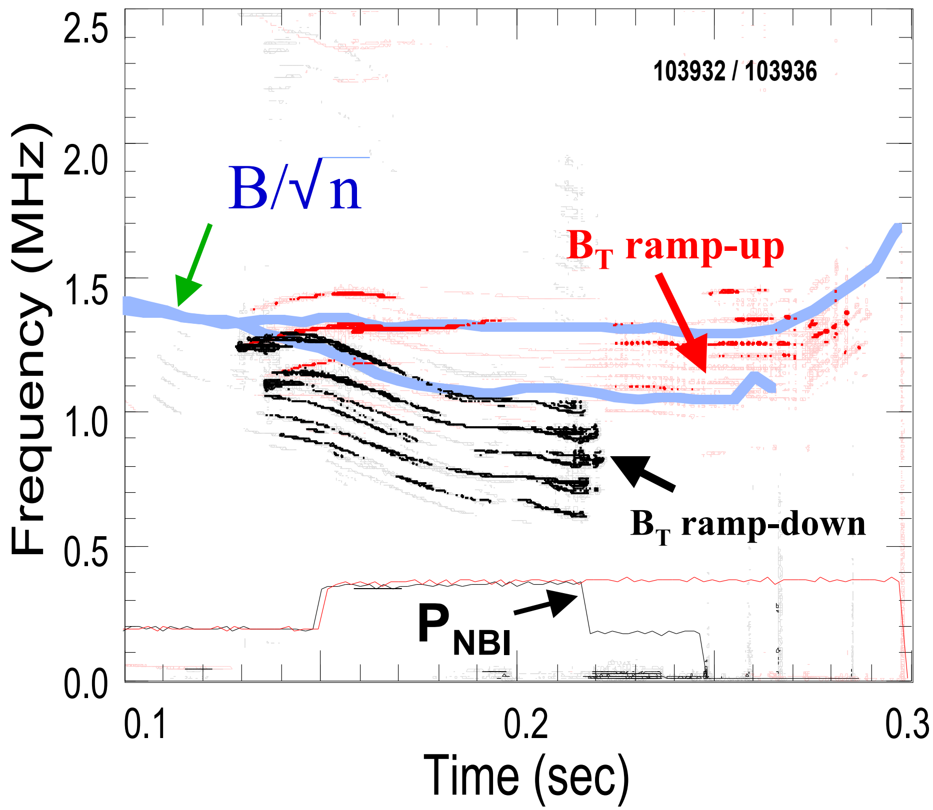
In NSTX V_{Beam} ~ 4 V_{Alfven}

⇒ Stronger velocity space instability drive



- TAE-like modes observed:
  - Frequency scales as V_{Alfven}
  - n=1 disappears at t=150ms
    - q(0) crosses 1
    - Continuum damping?
  - n=1 re-appears at lower frequency for q(0) < 0
- 0.5-2kHz amplitude bursting observed
  - Early q(0) > 1
    - Not 1/1 fishbone
    - Possibly 2/1 fishbone
    - Over-driven TAE?
    - **Fast ion losses modest**

NBI also excites high-frequency MHD activity



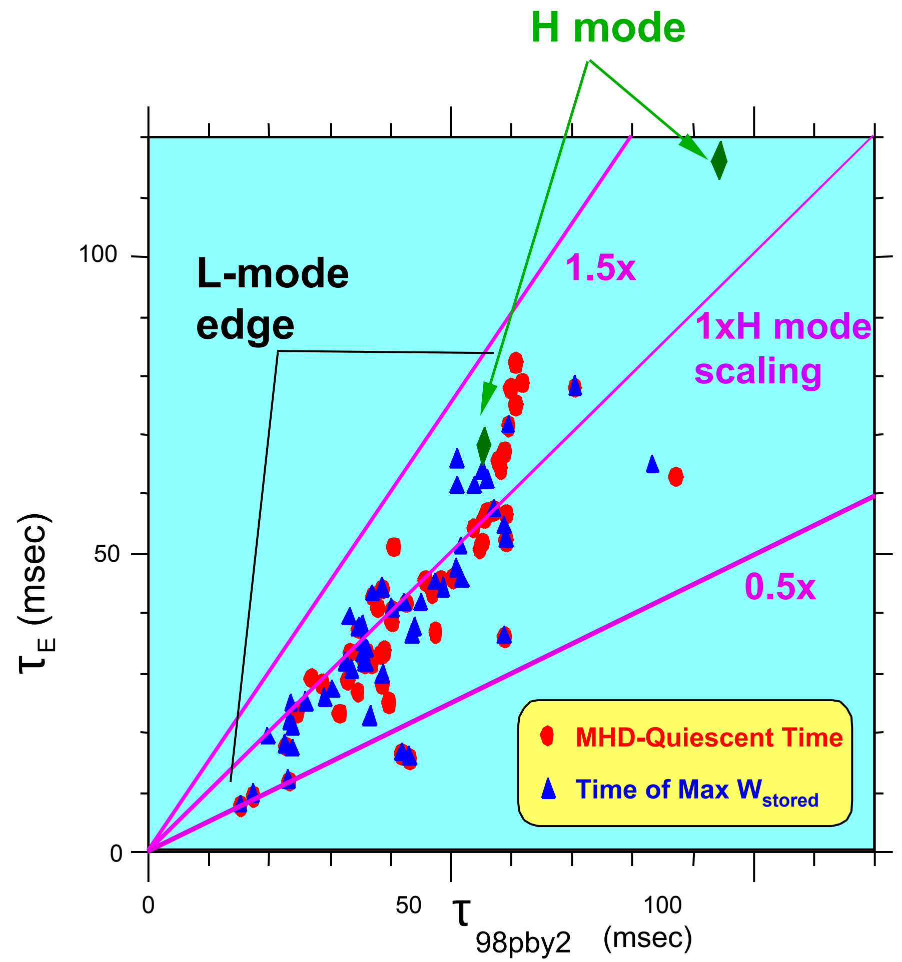
- For NSTX parameters:
  - $k_{||}$ 2-4m^{-1} weak electron and ion Landau damping

- Observed Characteristics:
  - f = 0.5-1.5 MHz
  - ω Alfven speed
  - ω depends on fast particle source

- Compressional Alfven Eigenmodes (N. Gorelenkov - Nuclear Fusion '95):
  - Compressional ω k V_{Alfven}
  - Perpendicular resonance with beams: ω Ω_D - $k_{||}V_{||\text{-BEAM}}$
  - Discrete frequencies different poloidal m-numbers
    - Observed splitting (100-200kHz) similar to model predictions

Early Confinement Studies Reveal Exciting Trends with Different Operating Regimes

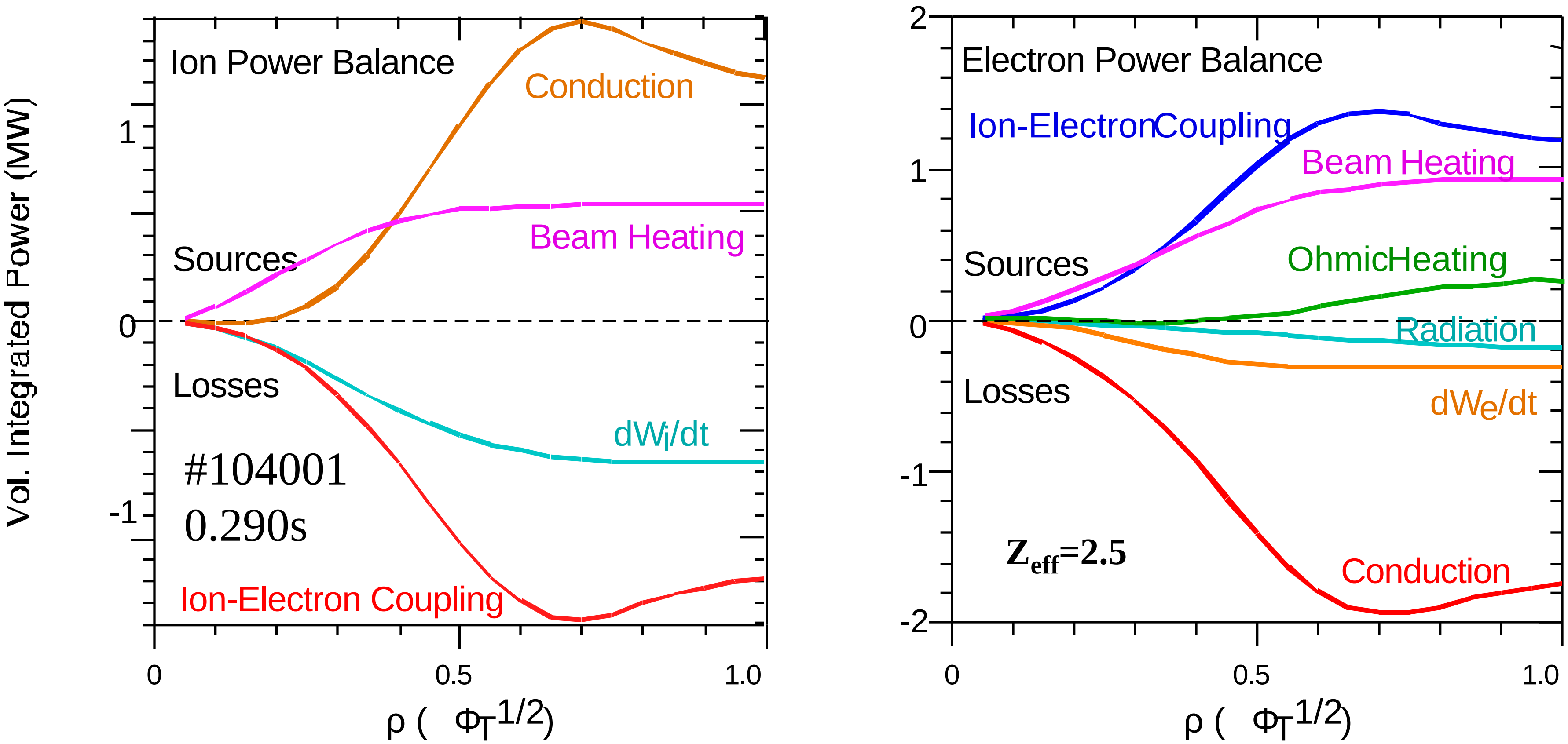
- Good confinement without transition to H-mode
- H-mode-level τ_E with L-mode edge (NBI)
- H-mode transition (NBI)
  - Steep edge n_e
  - Broadening pressure profile
  - Large ρ_i^* could help discriminate among pedestal theories
- HHFW heated plasma
  - Broadening n_e & pressure profiles
- Ohmic shows pressure peaking at constant I_p



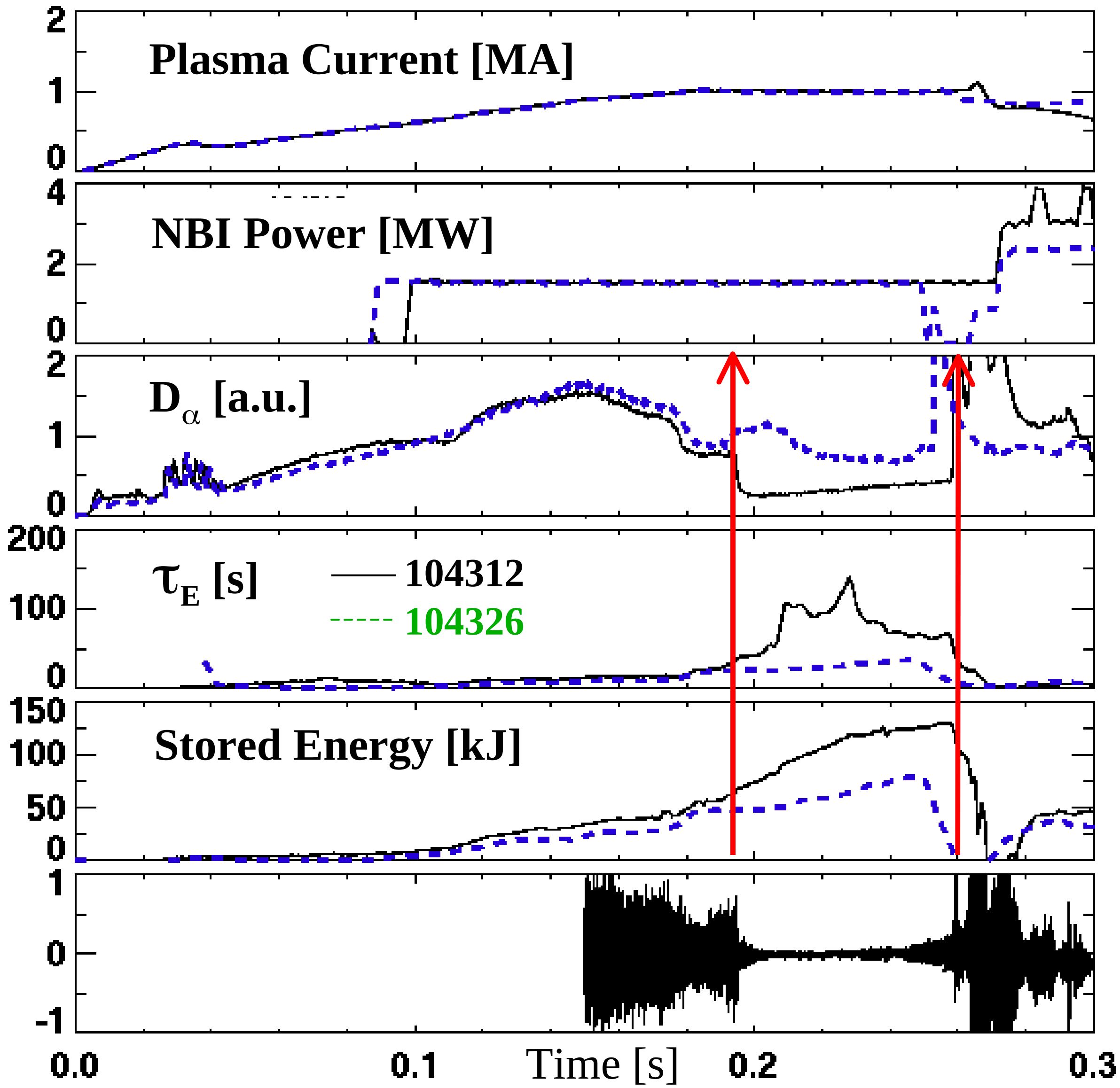
Power balance analysis reveals puzzles

-With NBI: apparent anomalous source of heat to ions, or a heat pinch

- -Diagnostic issue? Heating physics?
- -If correct *important implications*

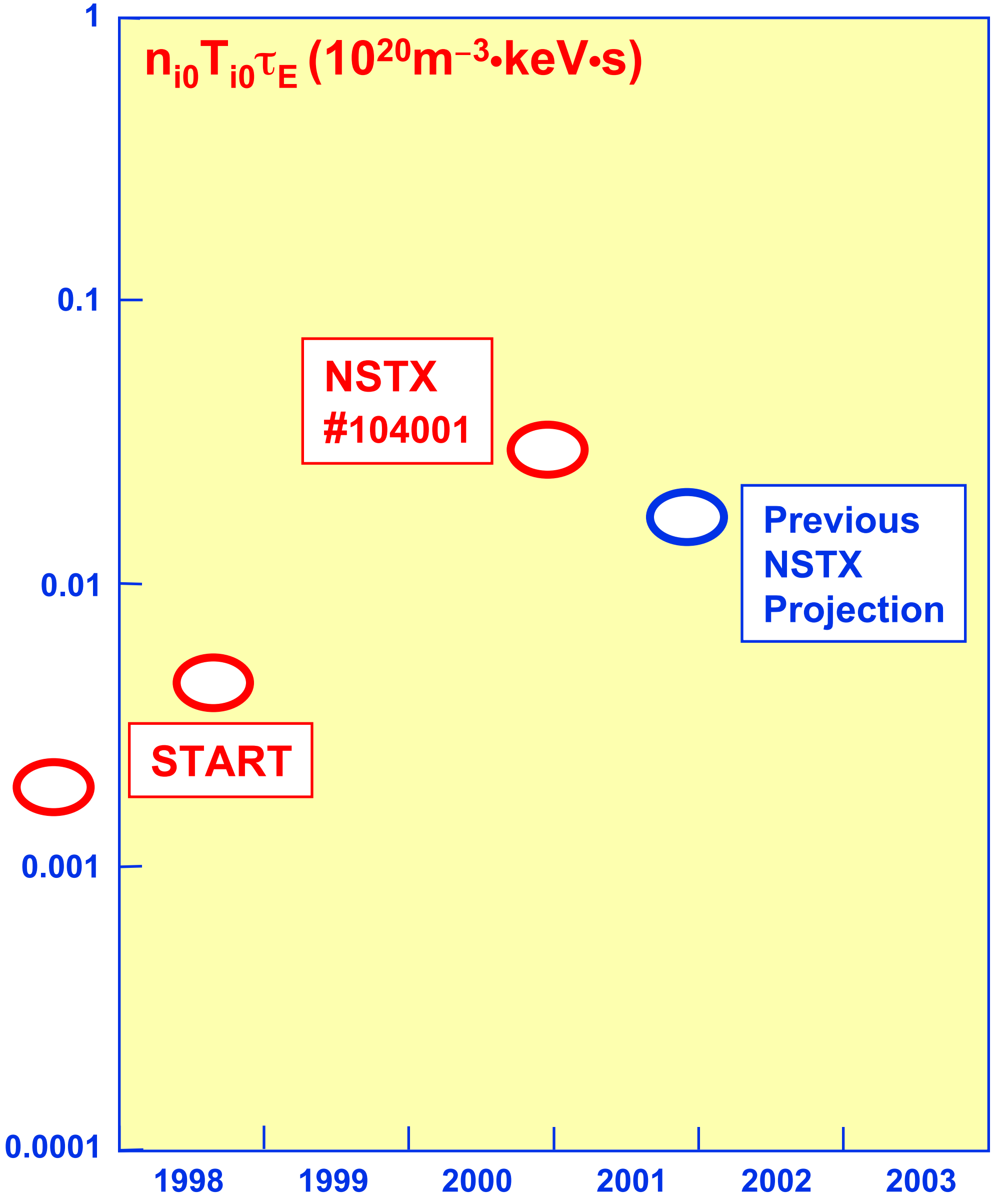


H−mode τ_E increases to 100ms prior to ELM



- Same I_P
- Early NBI
- D_α drop in H-mode
- τ_E increases to ~ 100ms
- Stored energy ↑ 60%
- Mirnov fluctuations reduced

Early Confinement Results Have Been Encouraging



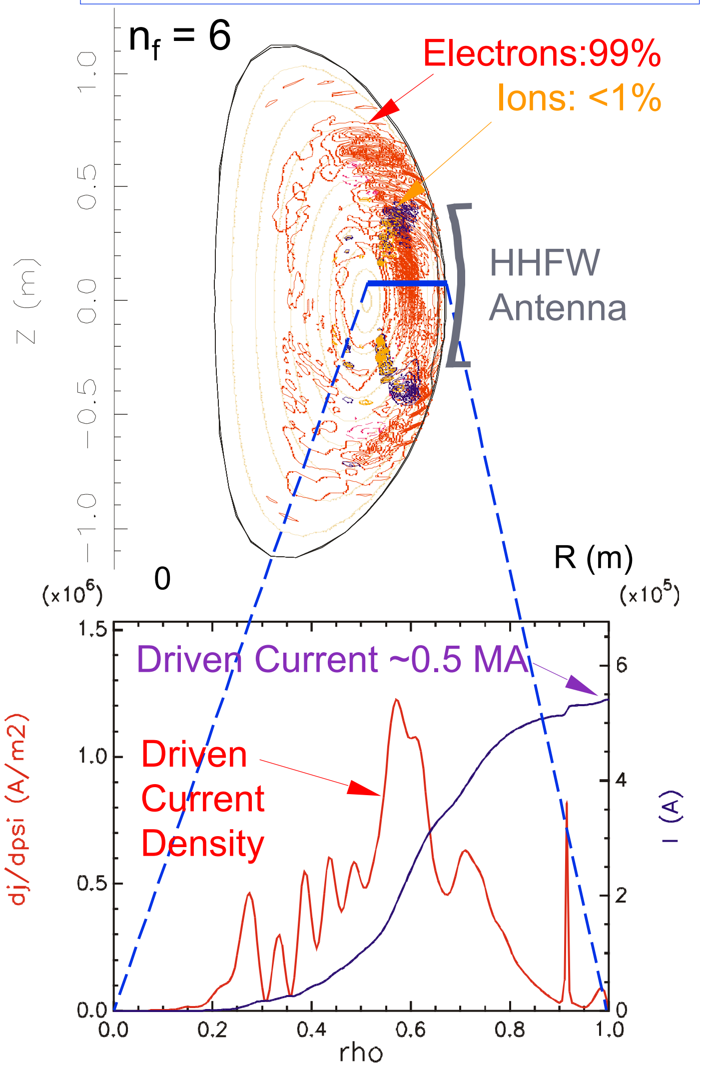
- **Laser Thomson Scattering (MPTS)**
  - $n_{e0} \sim 0.4\times10^{20}m^{-3}$
  - Varied $n_e(R)$ profiles, sensitive to MHD
- **Magnetic Reconstruction (EFIT)**
  - $P_{NBI} \sim 3$ MW
  - $W_p \sim 125$ kJ
  - $\tau_E \sim 0.07$ s
  - H_H(98pby2) ~ 1.4
- **Impurity Spectroscopy**
  - Zeff ~ 2

    $n_{i0} \sim 0.3x10^{20}m^{-3}$
- **First Charge Exchange Spectroscopy (CHERS)**
  - $T_{i0} \sim 2$ keV
  - Broad T_i profile

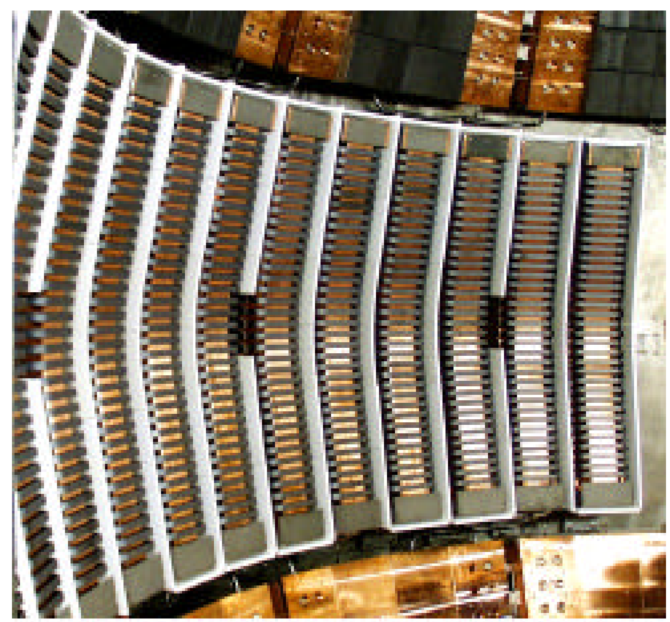
High Harmonic Fast Wave Utilizes High Dielectric ε (~100) in ST for Efficient Heating & Current Drive

NSTX

Contours of HHFW Absorption



- Provide Heating Power to Plasma
- Explore the Physics of HHFW Heating
- Drive Current to Extend Pulse Length
- Provide a Tool for Discharge Modification



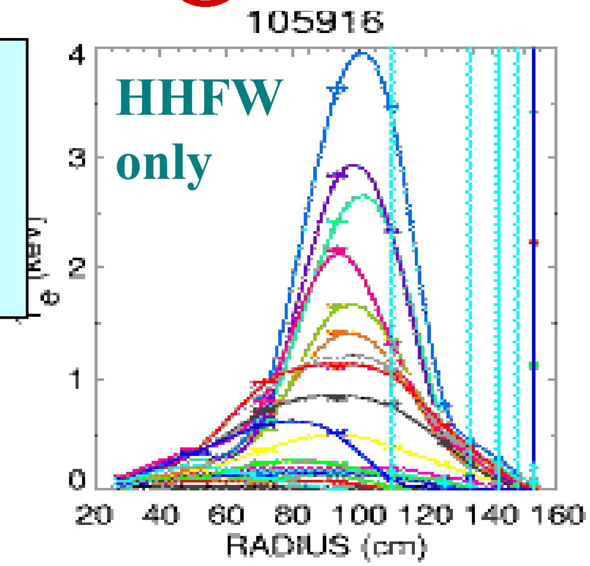
12 HHFW ANTENNA

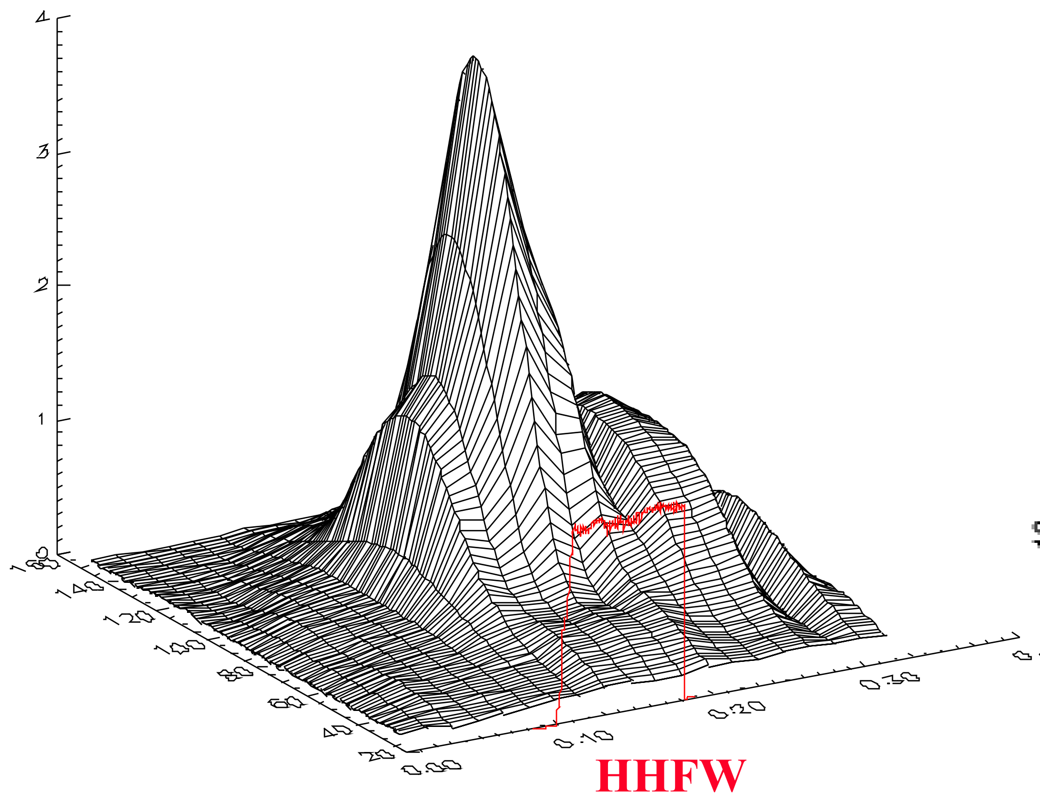
HHFW produce record central T_{eo} and P_{eo}
T_{e0} heated from 200 eV to nearly 4 keV!

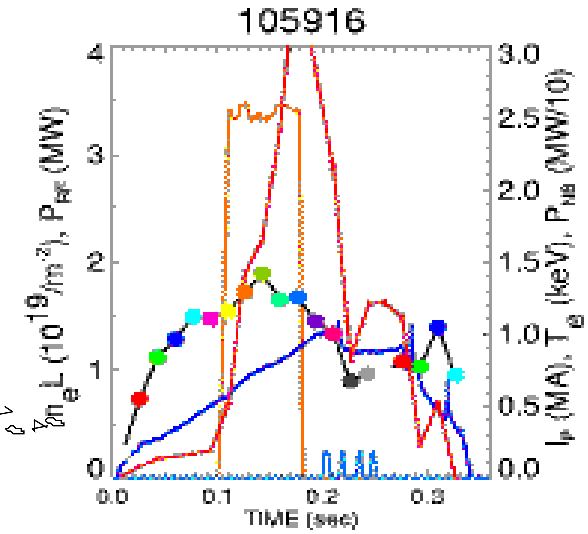
NSTX

However, heating is sensitive on plasma edge:

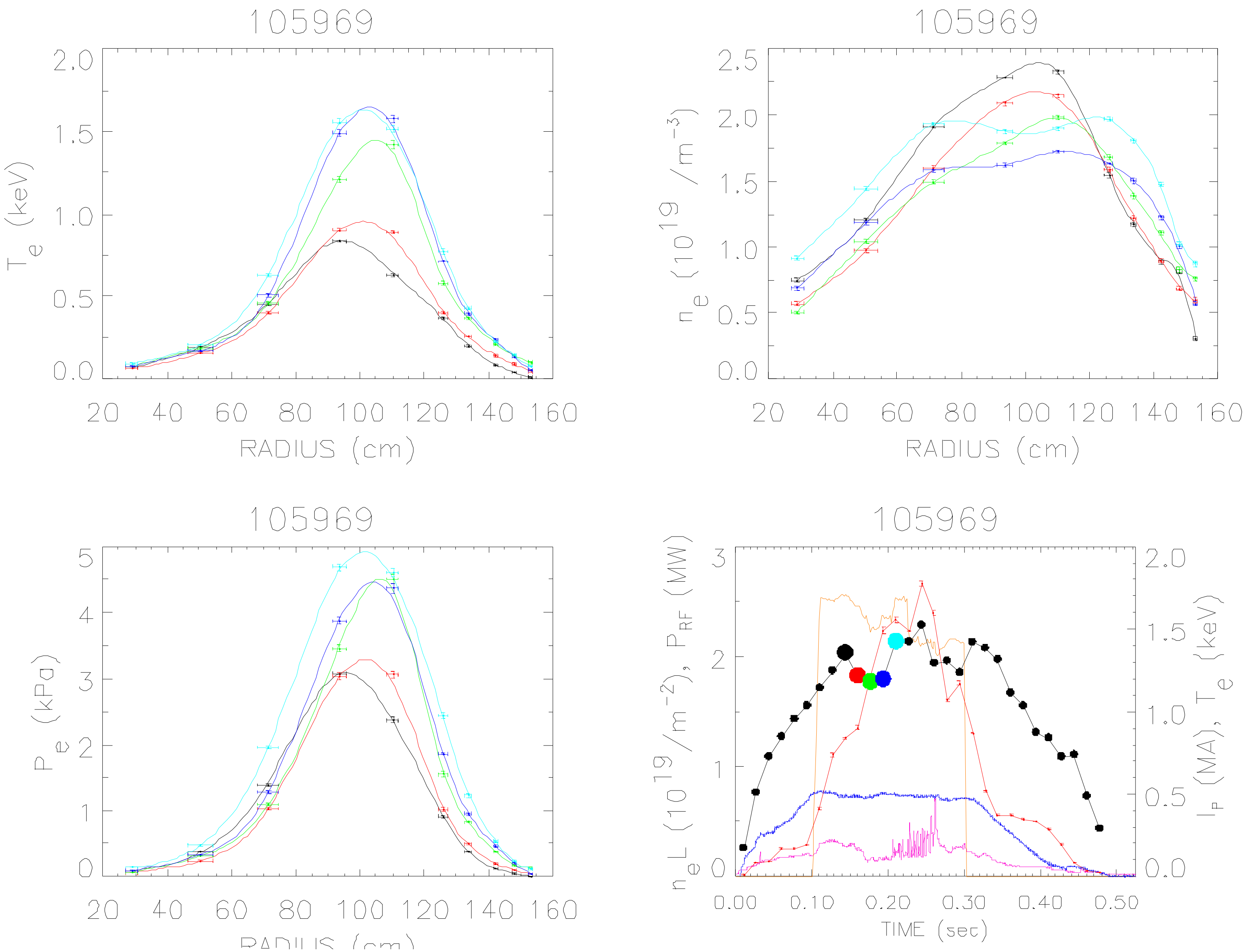
- **Diverted discharges show better heating than limiter discharges.**
- **Now the difference between D and He is gone**







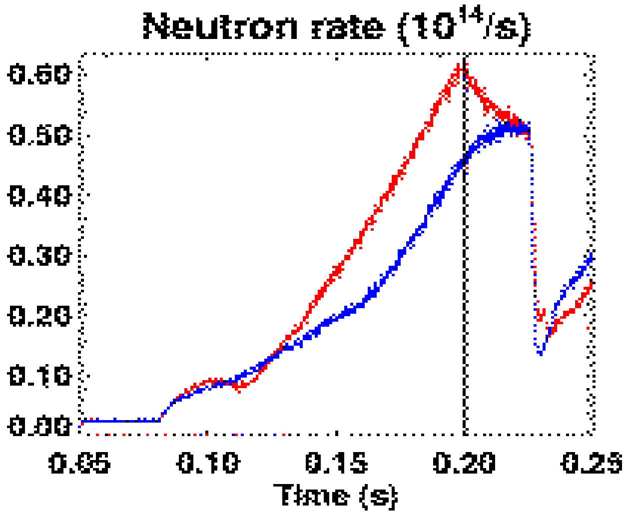
HHFW Only H-Mode Produced!

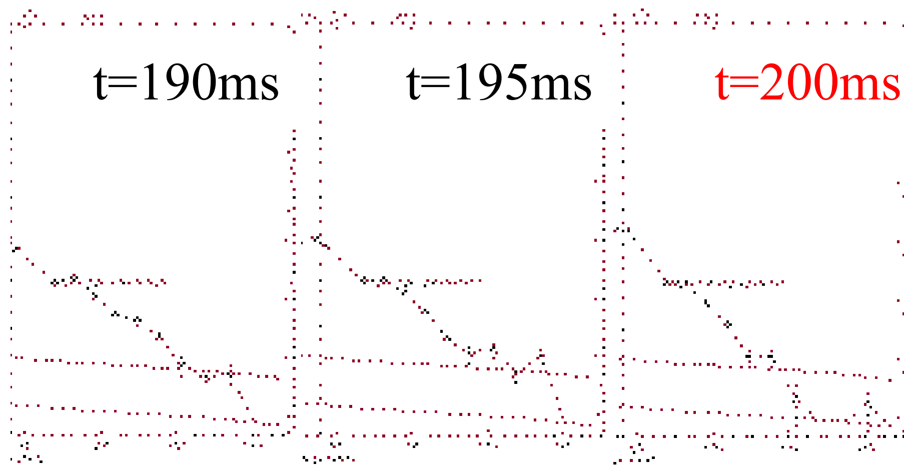


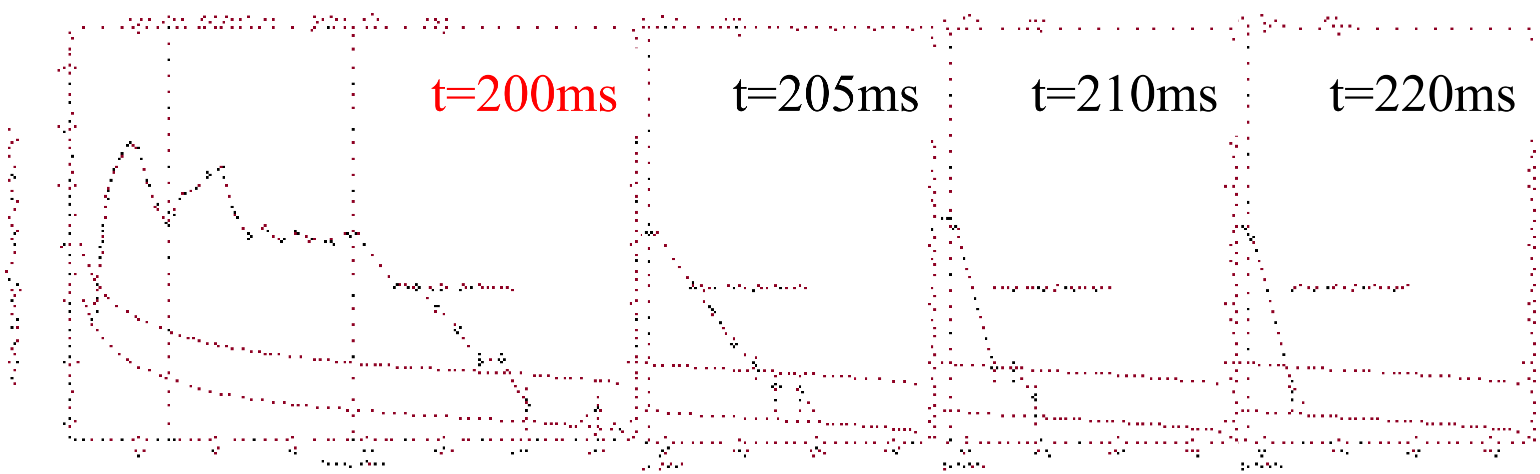
NPA shows fast ion tail build-up and decay

- HHFW turns off at t=200ms
- NBI Source A on throughout

- D^+ tail extends to 140keV
- Tail saturates in time during HHFW

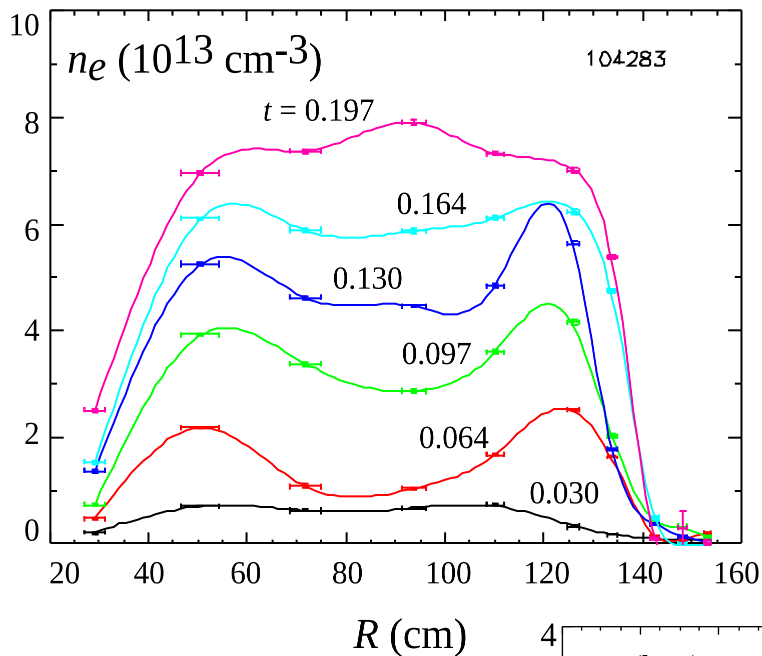




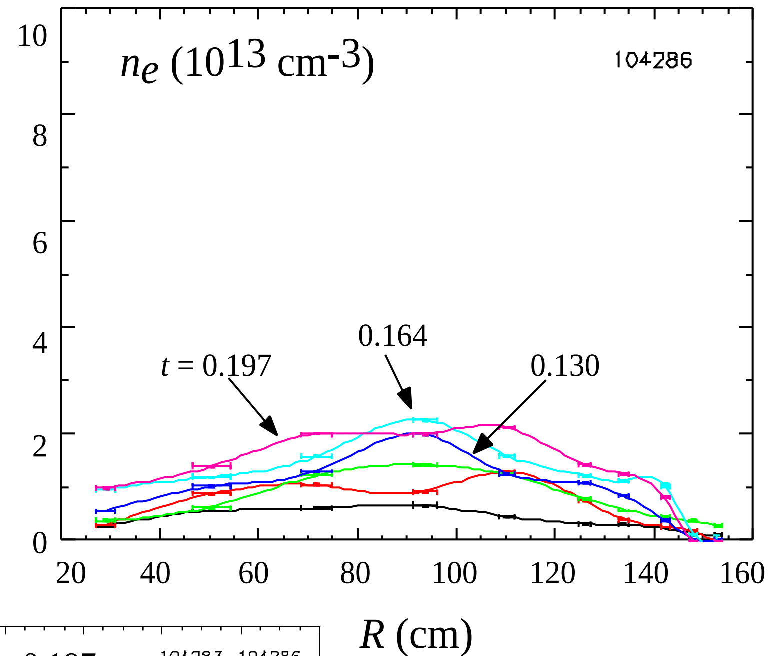


Early HHFW Heating Produced Broad Density and Current Profiles with H-mode like Edge Gradient

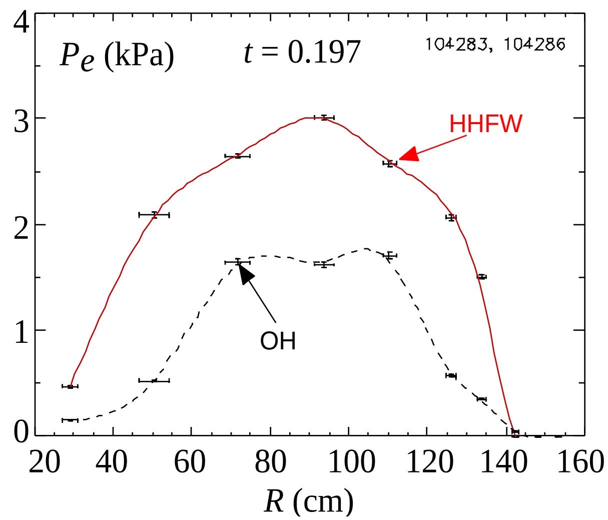
HHFW ON



NO HHFW

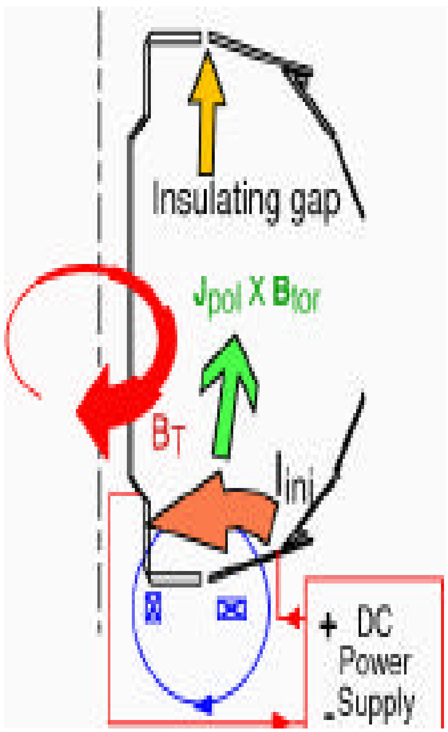


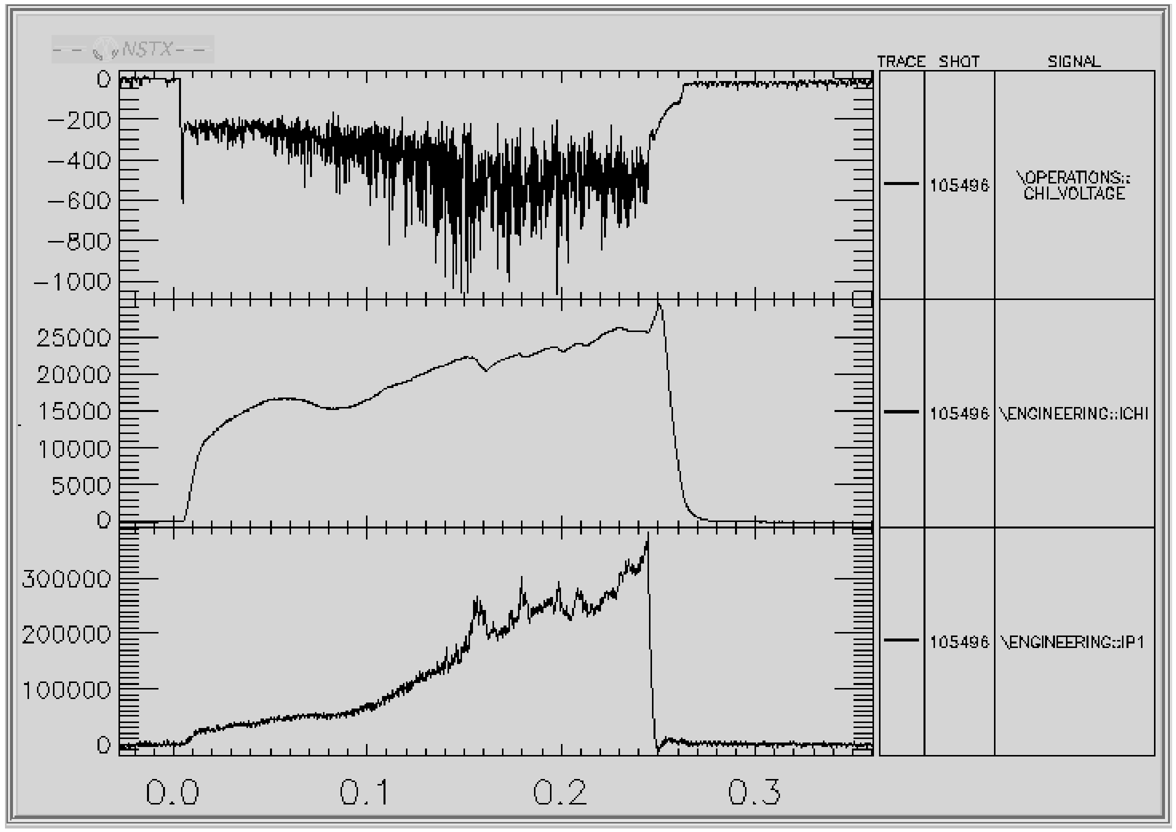
Pressure increases.



360 kA toroidal current achieved with only 26 kA of Coaxial Helicity injection current - Current Multiplication of 14!

NSTX





- **Highest toroidal current achieved with highest multiplication factor.**
- **Hopeful signs of flux closure.**
  - **- EFIT reconstruction**
  - **- Centrally peaked T_e profile**
  - **- Strong n=1 activities**

(B. Nelson, et al., at this conference.)

NSTX Plans to Study Physics of Progressively More Non-Inductive ST Plasmas

NSTX

Present Plan: *Decrease reliance on solenoid induction; Carry out longer-pulse physics studies.*

Phase	I	II	III
Rnwks	13	41	40

Exp. Operation Capabilities	Inductive	Non-inductive Assisted	Non-inductive Sustained
Toroidal Beta, β_T		→ 25%	→ 40%
Bootstrap Current		→ 40%	→ 70%
Current	→ 0.5 MA	→ 1 MA	~ 1 MA
Pulse	→ 0.5 s	→ 1 s	→ 5 s
HHFW Power	→ 4 MW	→ 6 MW	~ 6 MW
NBI Power		→ 5 MW	~ 5 MW
EBW Power	→ 30 kW	~ 30 kW	→ 0.4 MW (proposed)
CHI Startup	→ 0.2 MA	→ 0.5 MA	~ 0.5 MA
Control	current, R, shape	heating, density	flows, profiles, modes
Measure	$T_e(r)$, $n_e(r)$	$j(r)$, $T_i(r)$, flow, edge, modes	turbulence

Future Prospect: *Decrease next-step device complexity & size; Carry out longer-pulse technology R&D.*

Summary

- NSTX Facility has been rapidly ramping up.
- Facility achieved high availability and utilization since the last ST meeting.
- Research program is proceeding on schedule and the initial results look very encouraging and interesting:
  - High beta ($\beta_T \approx 20\%$) achieved at high temperature (T_{io}, $T_{eo} \approx 1$ - 2 keV) and high confinement (τ_E up to 1.4 x τ_E (ITER 98 pby2).)
  - H-mode with good confinement ($\tau_E \approx 100$ msec) observed at lowest R/a.
  - Good progress on ST tool development:
    - HHFW heated electrons to T_{eo} up to 3.7 keV from 0.4 keV.
    - Coaxial Helicity Injection drove 360 kA toroidal currents.
  - Diagnostic systems are maturing. (M. Bell)
- Exciting Research Program is planned toward Advanced Spherical Torus plasma regimes.