Supported by

Physics Results from the National Spherical Torus Experiment

Stanley M. Kaye
for the National Spherical Torus Experiment Research Team

NSTX Team Members

M. Bell, R. E. Bell, M. Bitter, D. Darrow, P. Efthimion, E. Fredrickson, D. Gates, L. Grisham, K. Hill, J. Hosea, S. C. Jardin, H. Ji, D. Johnson, R. Kaita, S. M. Kaye, H. Kugel, B. LeBlanc, R. Majeski, J. Manickam, E. Mazzucato, J. Menard, D. Mueller, M. Ono, H. Park, S. Paul, C.K. Phillips, C. H. Skinner, D. Stotler, B. Stratton, E. Synakowski, G. Taylor, J.R. Wilson, S. Zweben Princeton Plasma Physics Laboratory, Princeton, NJ 08543
T. Bigelow, M. D. Carter, R. Maingi, M. Menon, Y-K.M. Peng, P. Ryan, D. Swain, J. Wilgen Oak Ridge National Laboratory, Oak Ridge, TN 37831
J. Bialek, F. Paoletti, S. Sabbagh, W. Zhu Columbia University, New York, N.Y.
T. Jarboe, B. A. Nelson, R. Raman University of Washington, Seattle, Washington
R. Maqueda, G. Wurden Los Alamos National Laboratory, Los Alamos, New Mexico
J. Ferron, L. Lao, R. Pinsker, M. Schaffer General Atomics, San Diego, Calif.
M. Finkenthal, D. Stutman Johns Hopkins University, Baltimore, Md.
R. Nygren, M. Ulrickson, W. R. Wampler, Sandia National Laboratory, Albuquerque, New Mexico
E. Doyle, S. Kubota, T. Peebles, L. Zeng, UC Los Angeles, L.A., Calif
T. K. Mau, UC San Diego, San Diego, Calif.
B. Deng, C. Domier, K.C. Lee, N.C. Luhmann, UC Davis, Calif.
A. Bers, P. Bonoli, A.K. Ram, MIT, Cambridge, Mass.
G. Porter, M. Rensink, T. Rognlien, X.Q. Xu Lawrence Livermore National Laboratory, Livermore, Calif.
J. G. Yang, Korea Basic Science Institute, Taejeon, Korea
Y. Takase, H. Hayashiya, 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

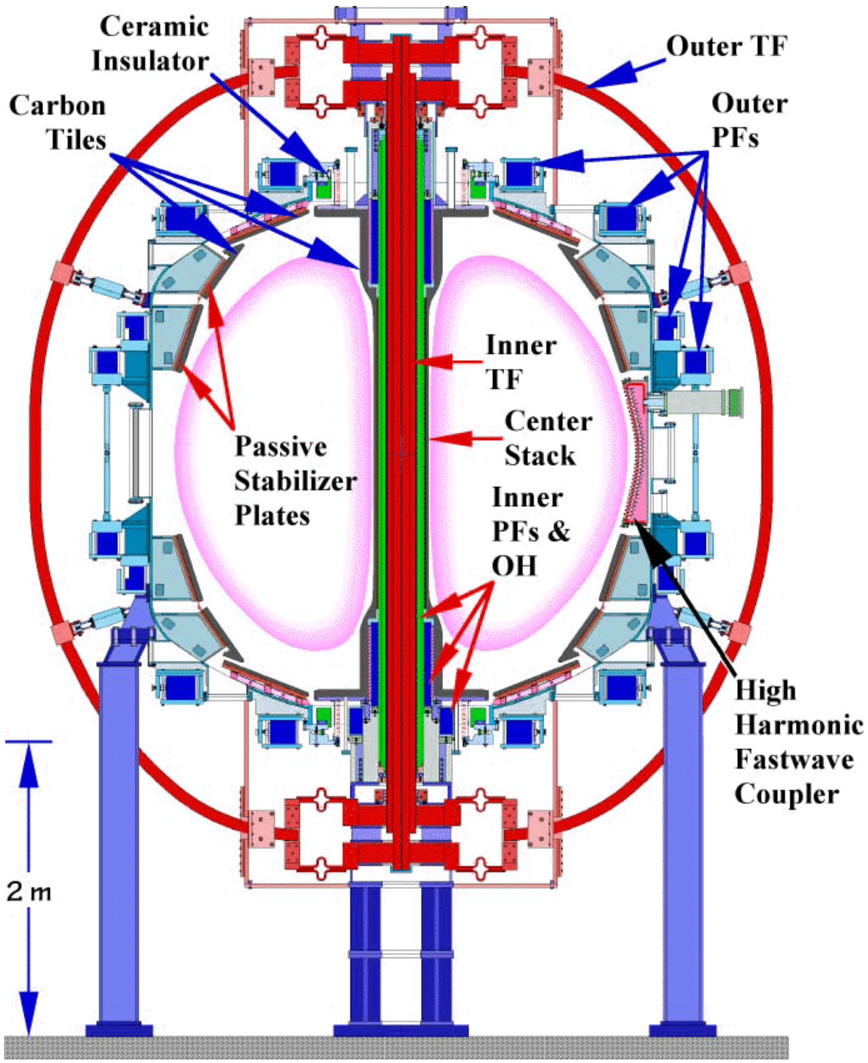
NSTX Mission

NSTX

- ➔ Extend the understanding of toroidal physics to high-β, low-collisionality regimes at low aspect ratio ($R/a \leq 1.4$)
- ➔ Develop technologies necessary for a Spherical Torus (ST) power plant

- Essential elements of mission
  - High-β_t (≤ 40%), large bootstrap current fraction ($f_{bs} \leq 0.7$)
  - Non-inductive current generation and sustainment
  - Adequate power and particle handling
  - Integration of individual elements in long-pulse discharges

National Spherical Torus Experiment (NSTX)



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 (1.07 MA)

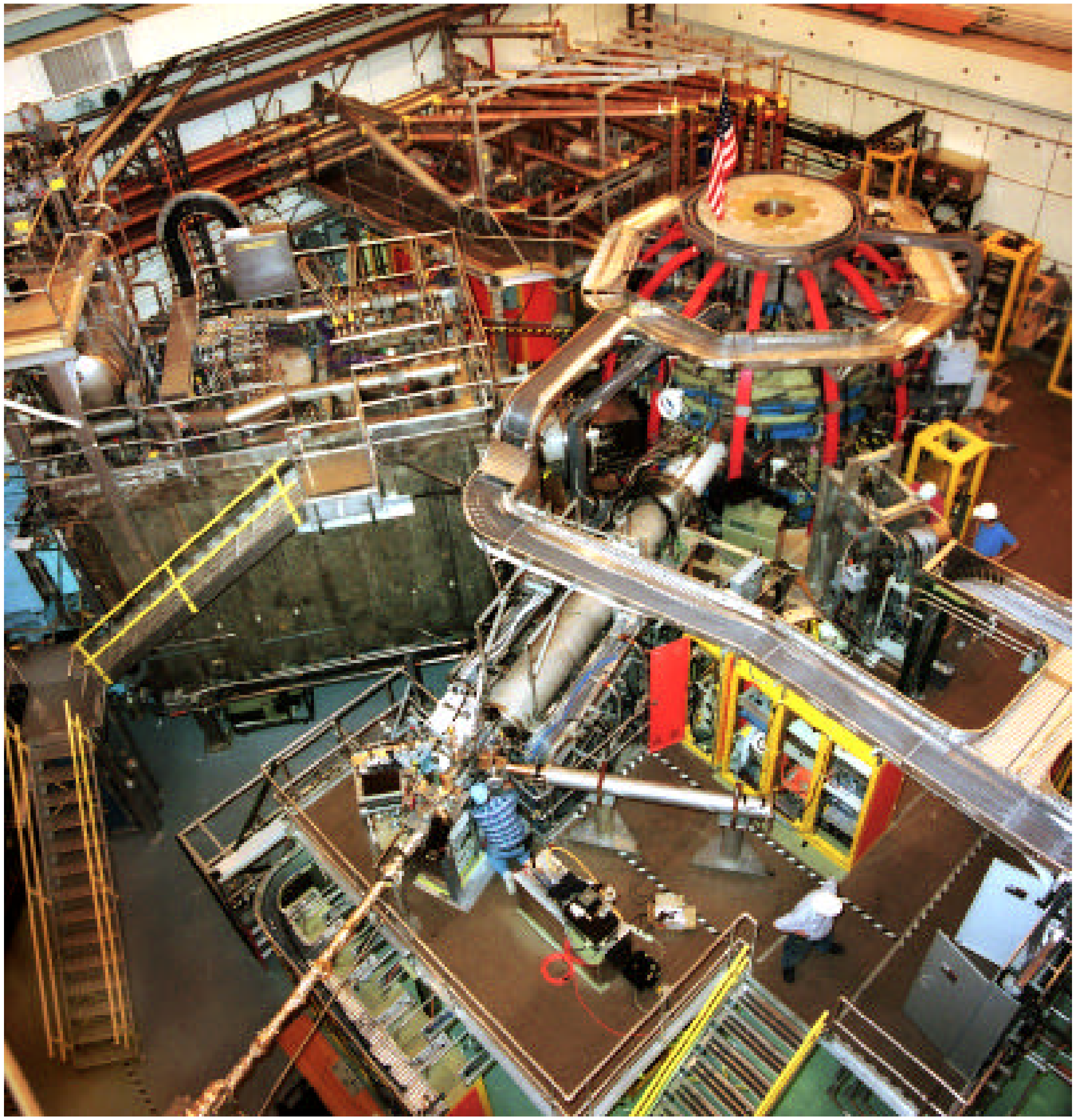
Toroidal Field
0.3 to 0.6 T (≤0.45 T)

Heating and CD
5 MW NBI (3.2 MW)
6 MW HHFW (4.2 MW)
CHI

Pulse Length
≤ 5 sec (0.5 sec)

Ono (MP1.134)

National Spherical Torus Experiment (NSTX)



Ono (MP1.134)

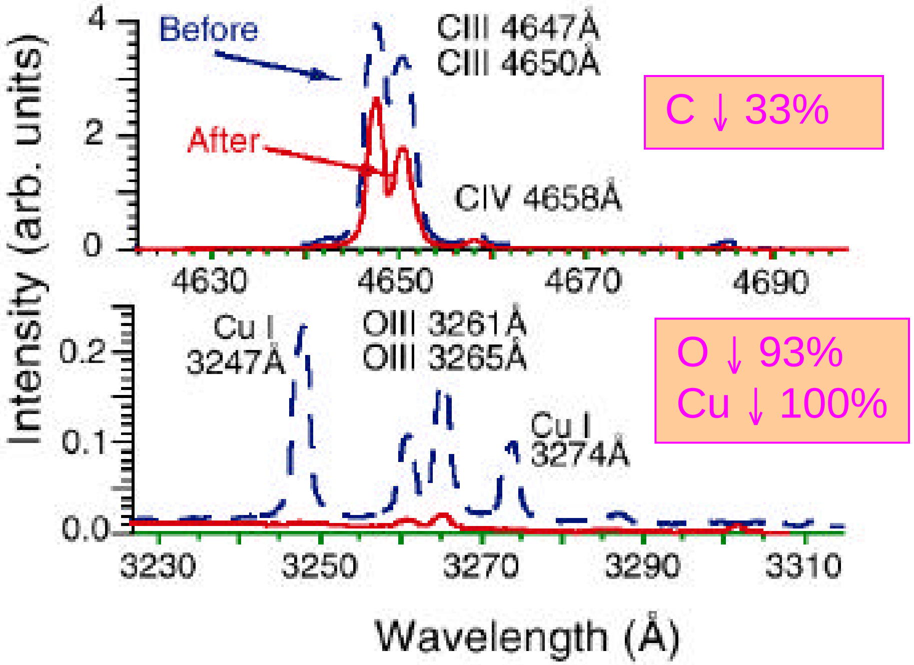
Significant Progress Made During Initial Operating Period

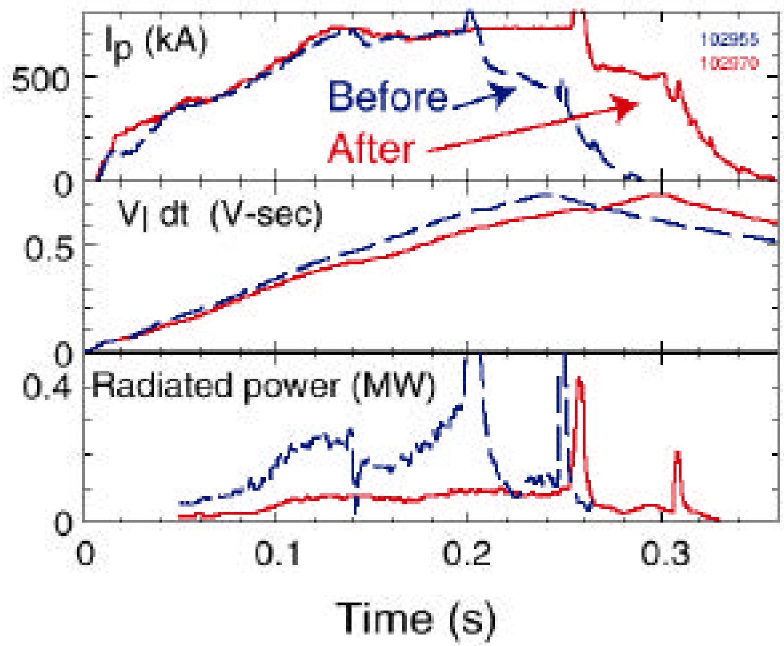
NSTX

- Explored OH operations space
  - Established target equilibria
  - Studied confinement trends, operating limits, and limiting mechanisms
- High Harmonic Fast Waves (HHFW) used for electron heating
  - Significant increase in $T_e(0)$
- Non-inductive startup using Co-Axial Helicity Injection (CHI)
  - Significant toroidal currents generated
- Achieved $\langle\beta_t\rangle$=21% with Neutral Beam Injection (NBI)

Boronization Reduces Impurities and Ohmic Flux Consumption

NSTX





Reduced MHD activity after boronization (TMs, REs)

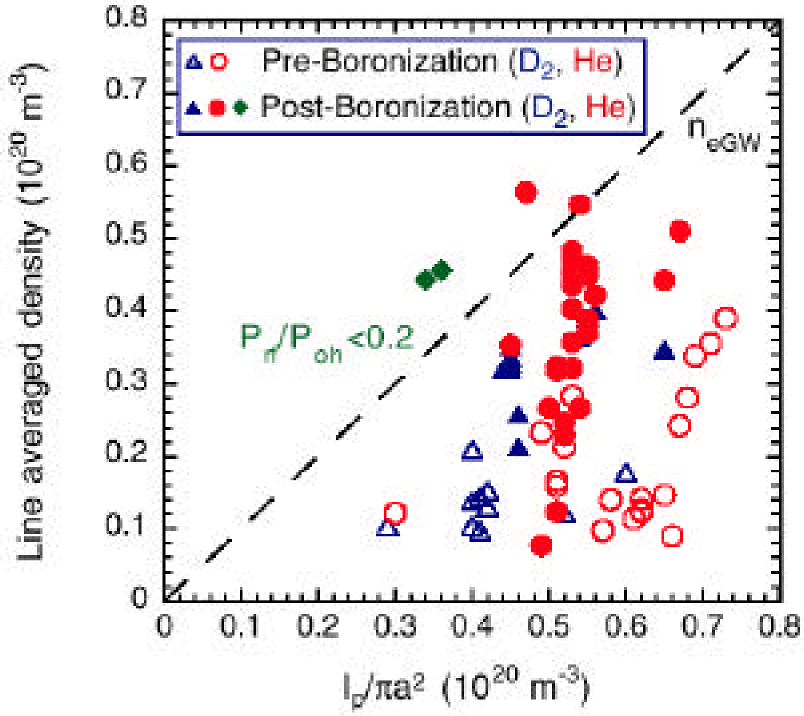
Menard (BO1.001), Maingi (BO1.006), Kugel (MP1.145)

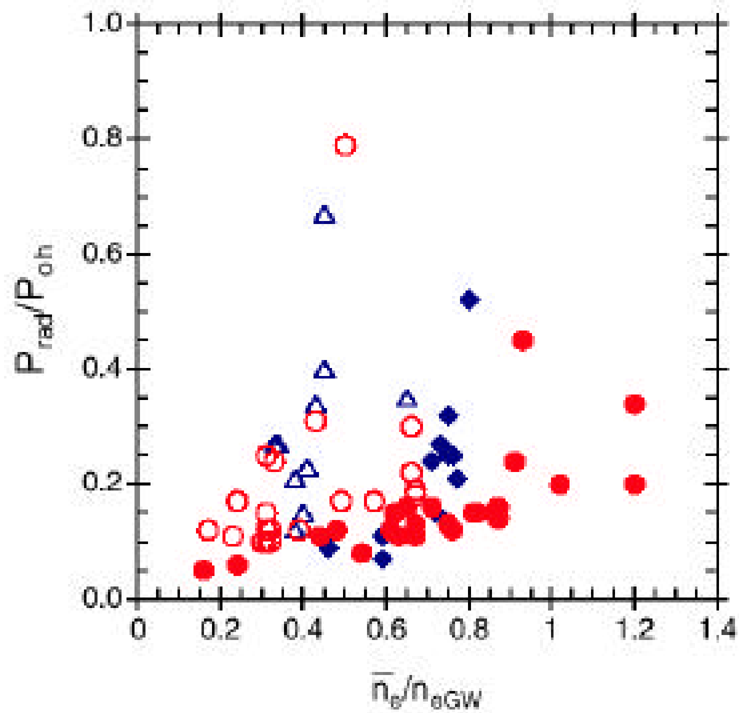
Achieved Ohmic Densities Above Greenwald Limit

NSTX

Boronization extends accessible n_e range

P_{rad}/P_{oh} increases, but still low (≤0.40) at high density



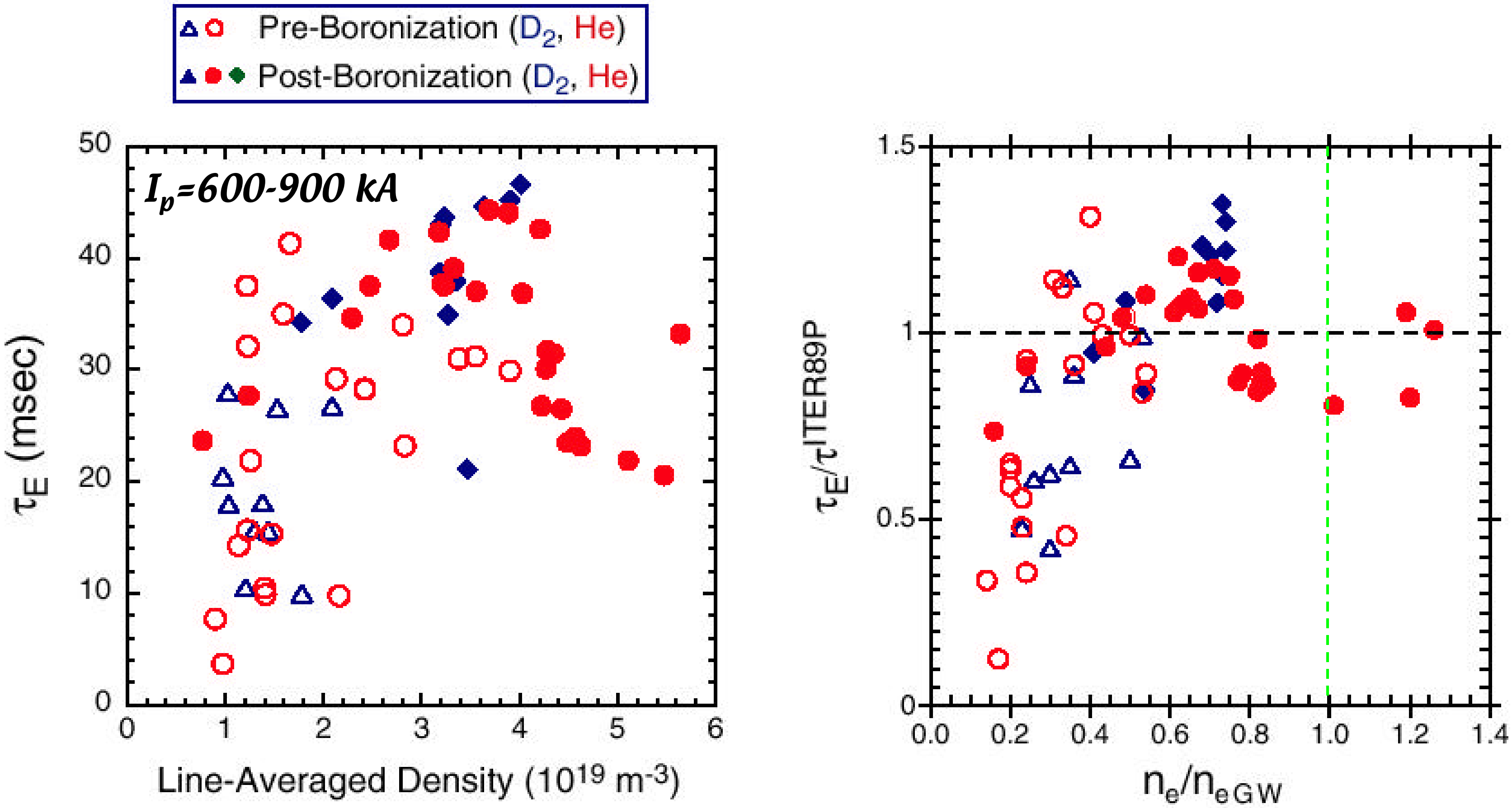


Maximum n_e appears to be set by fueling limitations

Kaye (MP1.137)

Ohmic Confinement Trends Similar to Those at Conventional R/a

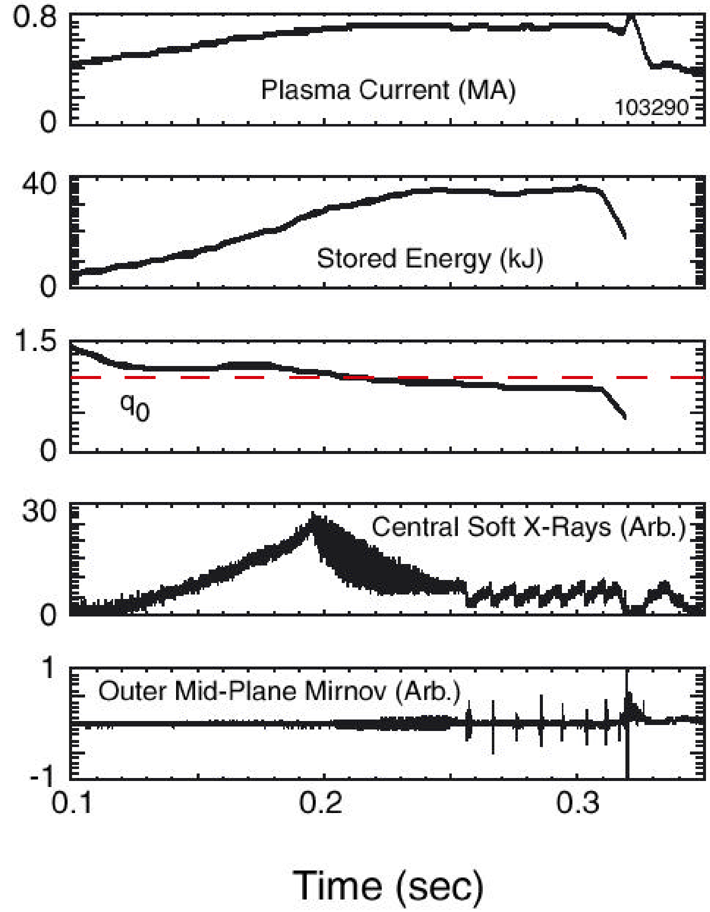
NSTX

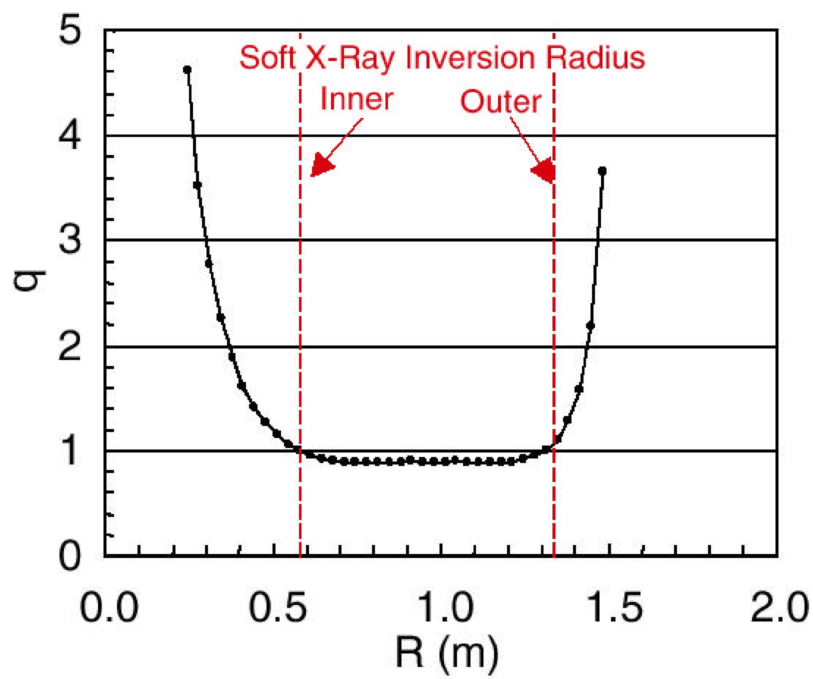


Kaye (MP1.137)

Plasma Performance Can Be Limited by MHD

- **Large m=1/n=1 mode, sawteeth**
  - **Extended region of low shear with q≤1**

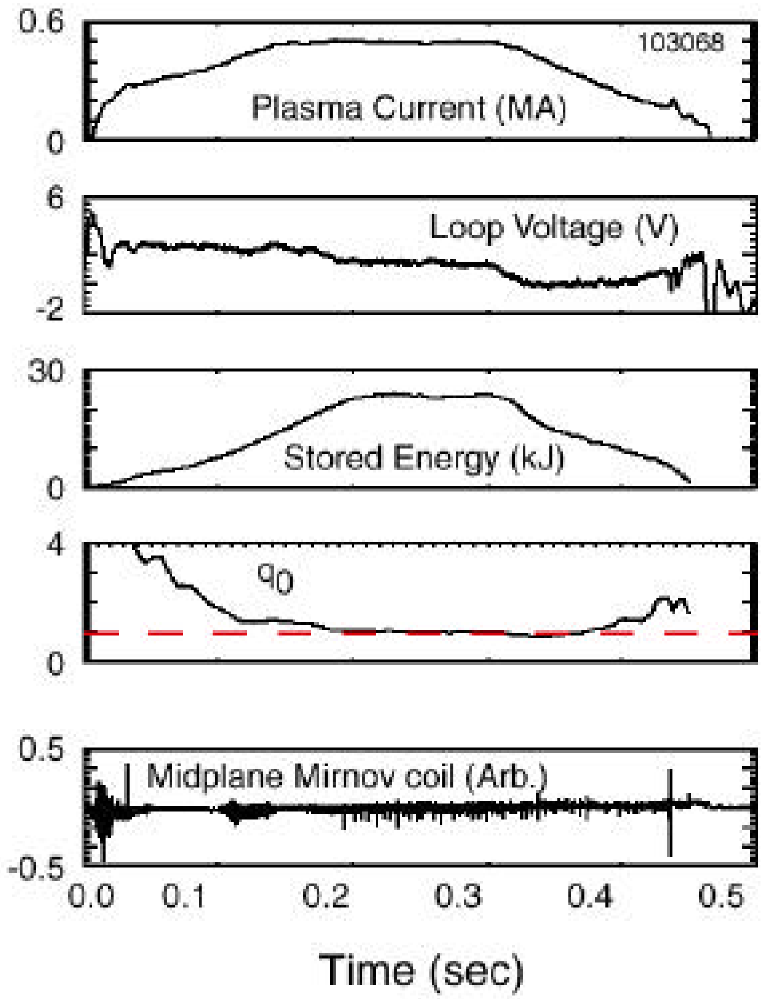


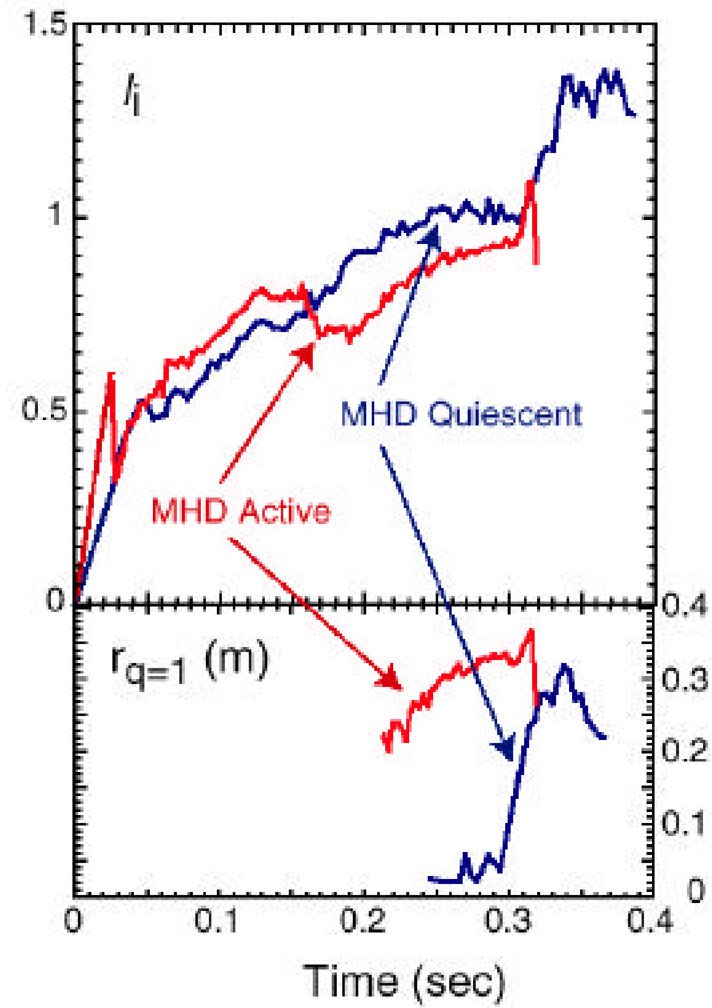


Fredrickson (MP1.138)
Stutman (MP1.144)

MHD Free Discharges Can Be Produced With Control of q-profile

NSTX

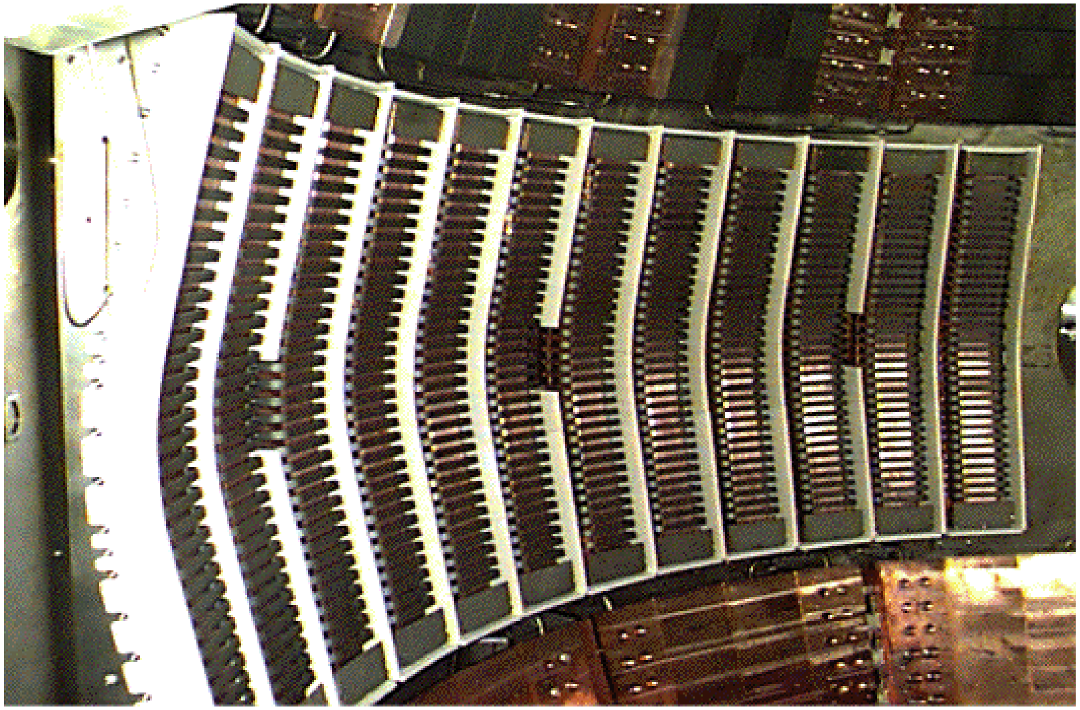




High Harmonic Fast Waves (HHFW) Can Provide Heating and Current Drive

NSTX

- $\varepsilon=(\omega_{pe}/\Omega_{ce})^2$~10-100 with high n_e, low B_T (~1 at conventional R/a)
- Strong electron absorption with HHFW

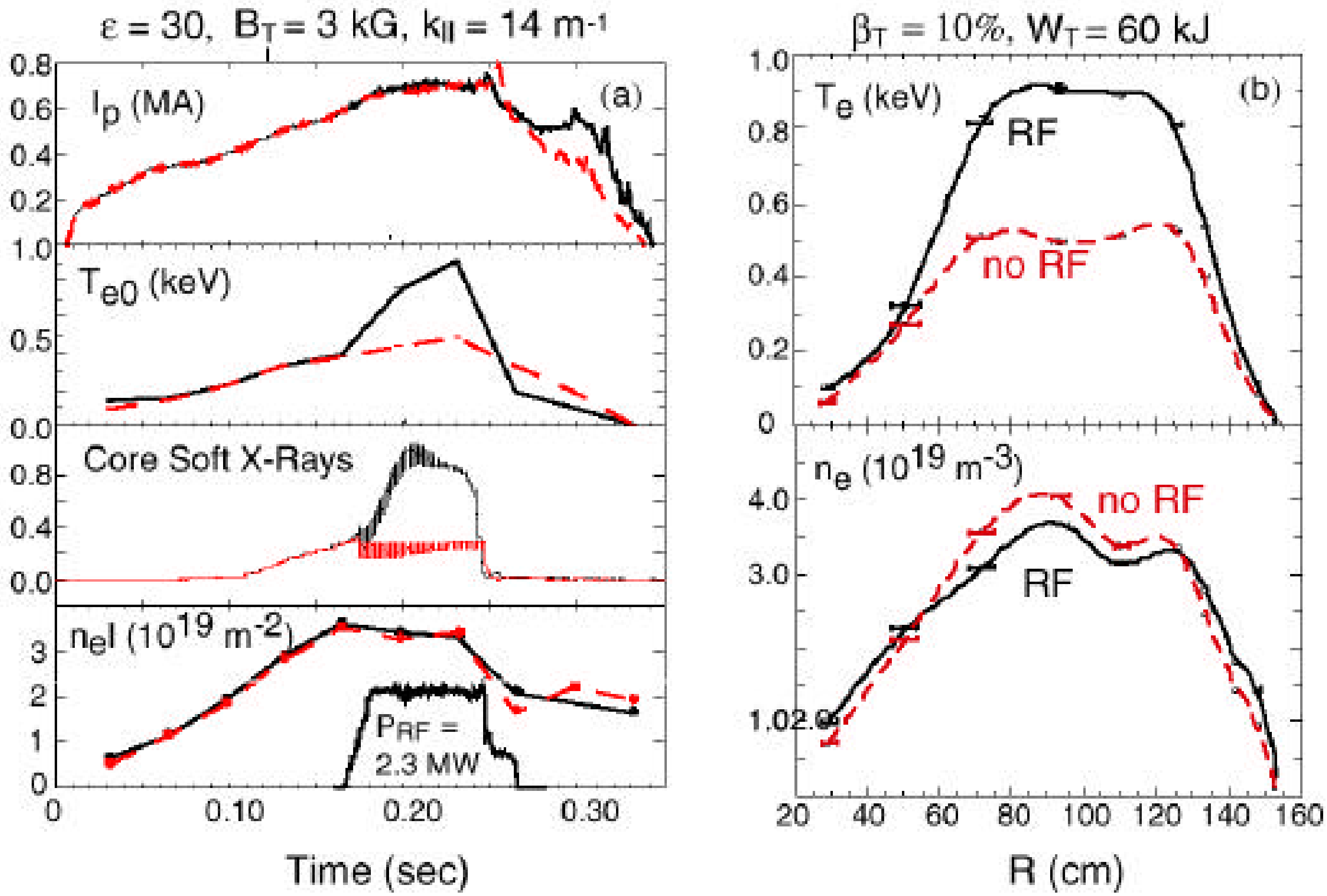


12 strap antenna with flexible phasing

- 30 MHz, 6 MW, 5 sec, $k_{||}$=4-14 m^{-1}
- Over 4 MW coupled to plasma

Hosea (BO1.005)
Ryan (MP1.151)

Significant Electron Heating with HHFW On- and Off-Axis

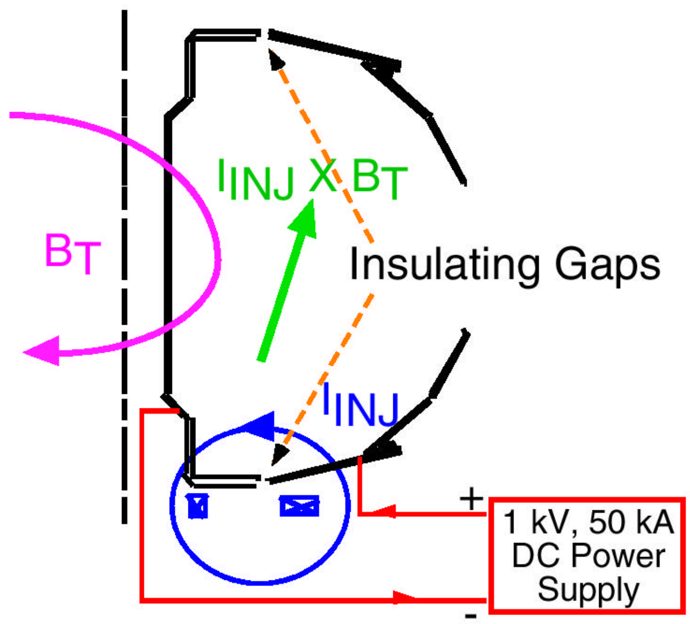


T_{e0}>1 keV achieved

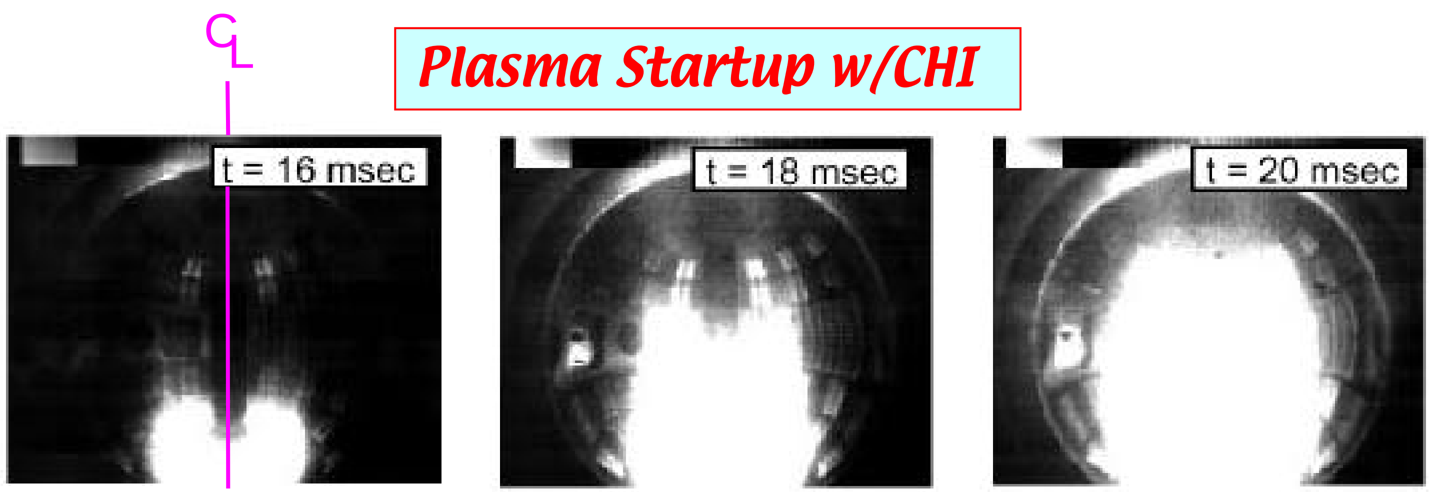
Co-Axial Helicity Injection (CHI) Generates Toroidal Current Non-Inductively

NSTX

- Inject poloidal current on open field lines in lower divertor
- Plasma moves up into main chamber
- Toroidal current develops to maintain force-free configuration
- Flux surfaces may close through magnetic reconnection



Plasma Startup w/CHI

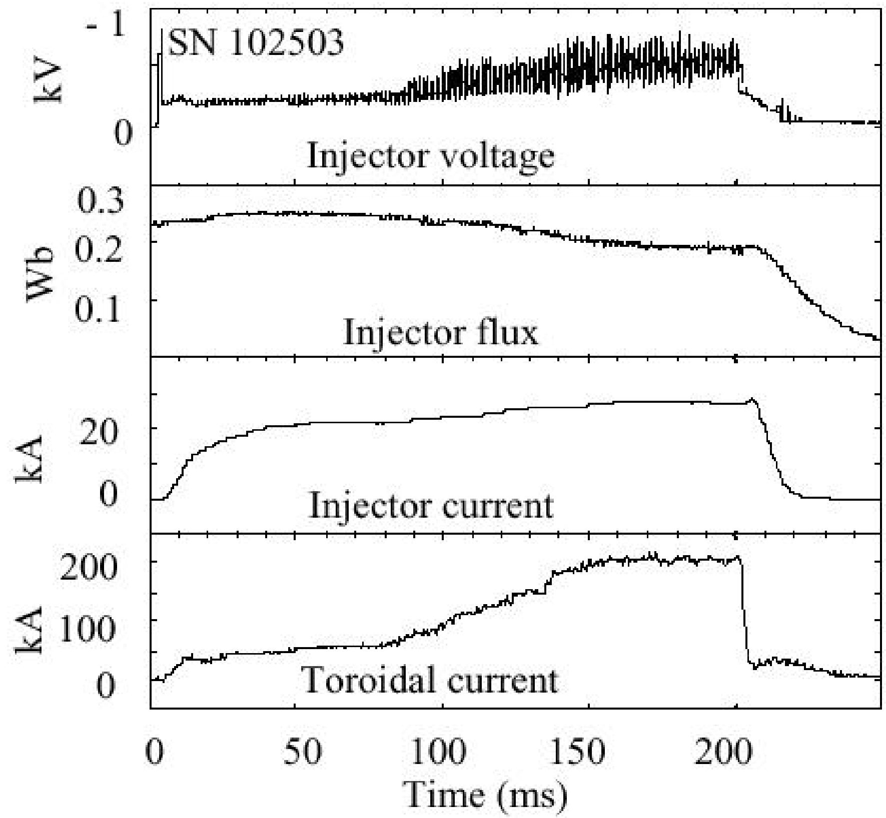


Raman (BO1.004)

Significant Toroidal Currents, Pulse Durations Achieved With CHI

NSTX

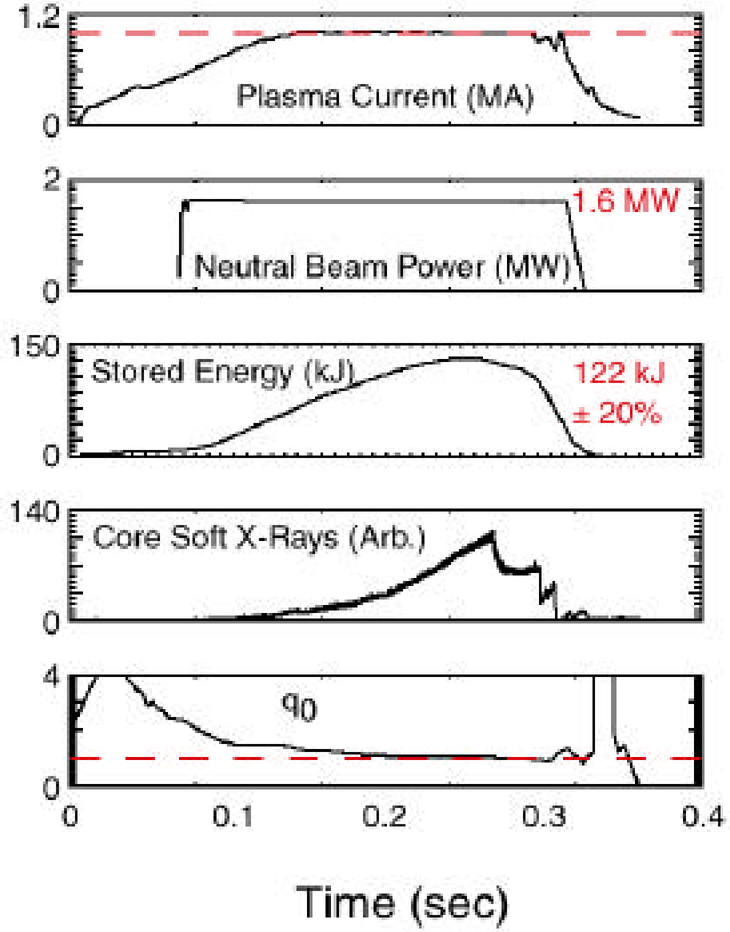
- No OH flux used
- 200 kA in 200 msec discharge
- Up to 270 kA transiently
- Practically all injector flux fills confinement region
- 0.2 Pa prefill (compatible with OH operation)

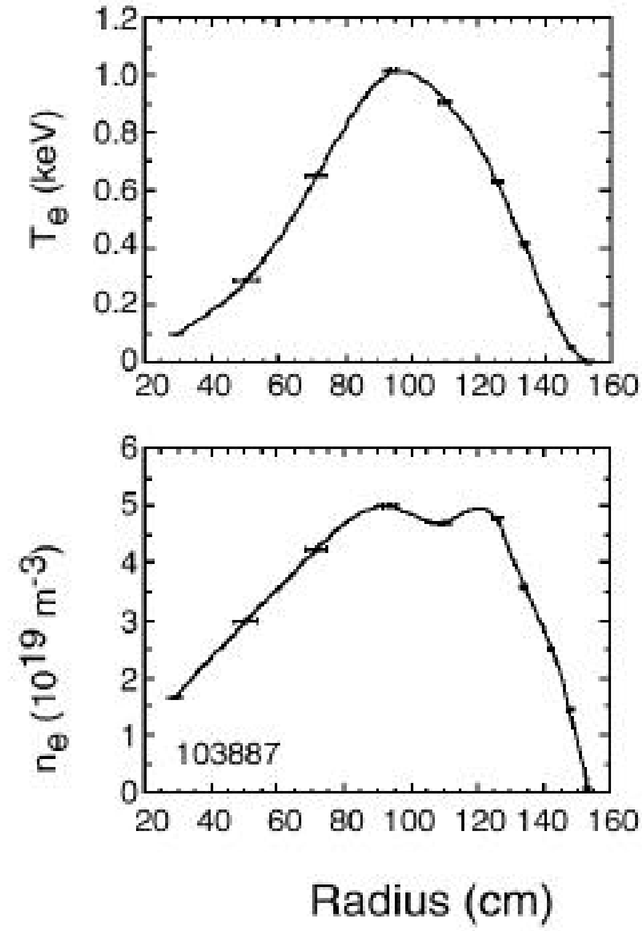


High T_e, Stored Energy, Pulse Duration Achieved With NBI

NSTX

B_0=0.4 T



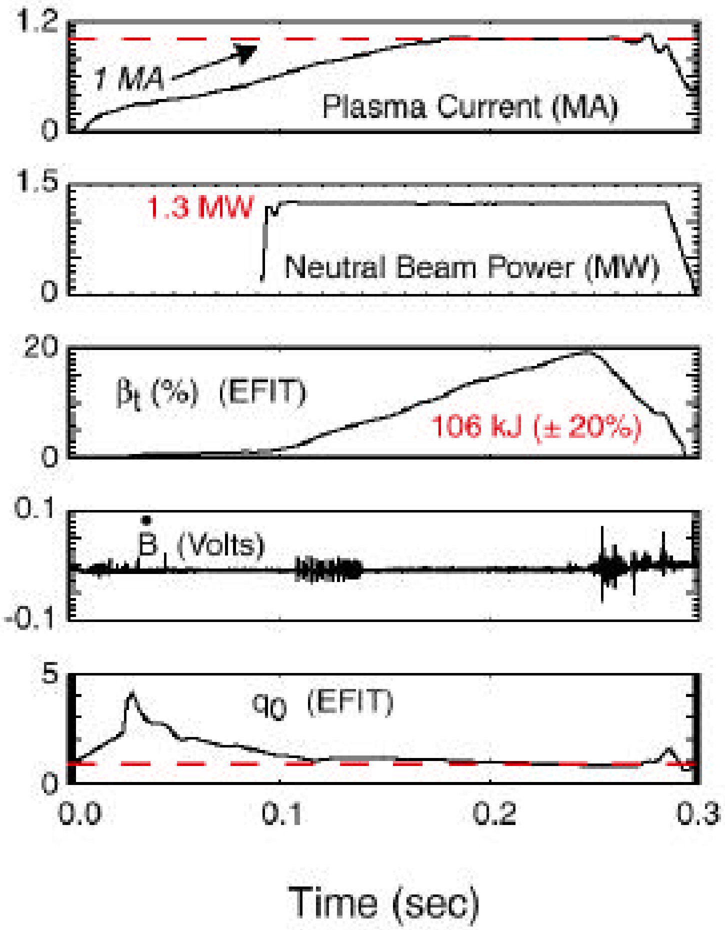


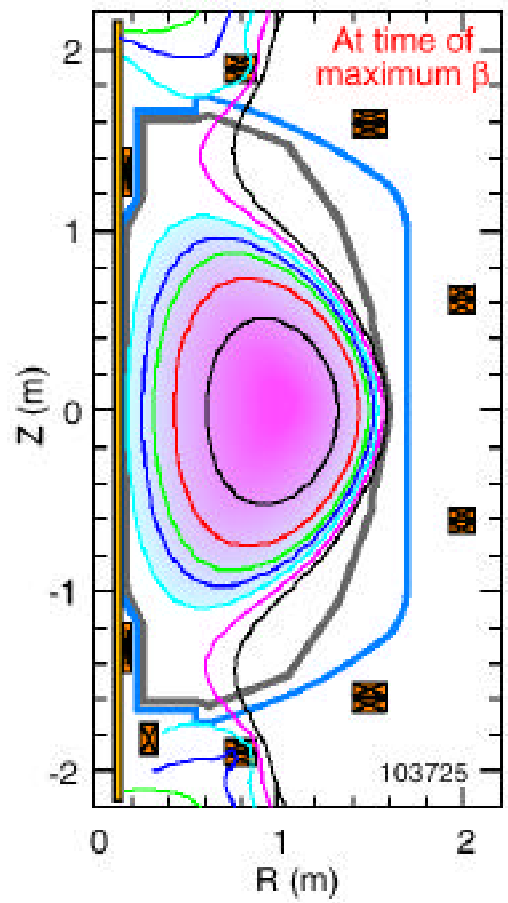
185 msec current flattop at 1 MA

High-β_t Achieved With NBI

NSTX

$\beta_t = 2\mu_0\langle p\rangle/B_0^2 = 19.7\%$, $\beta_n = 3.9$, $B_0 = 0.3$ T, $q_\psi = 7.5$





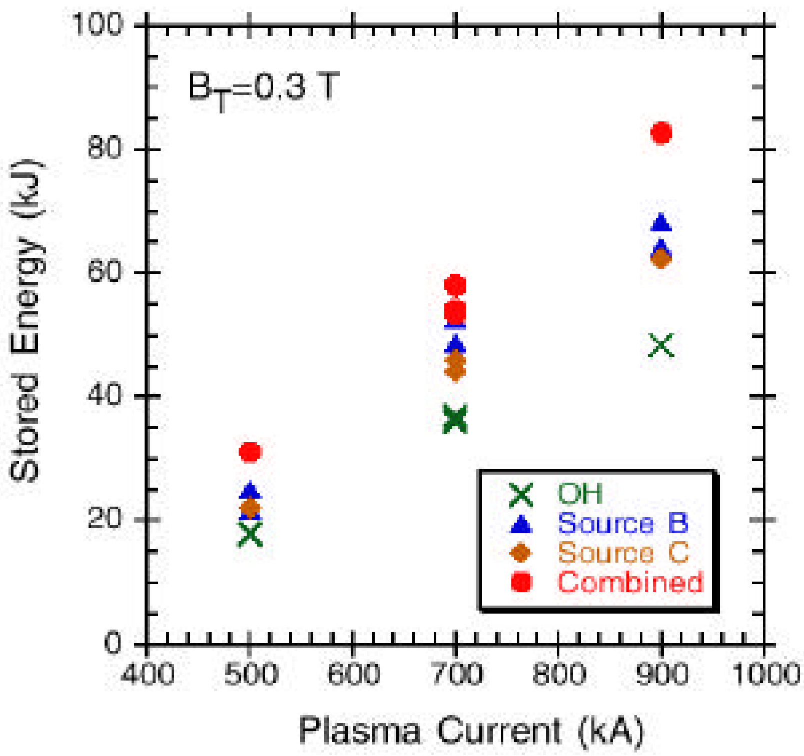
τ_E *(uncorrected)= 40 msec,* $\sim 1.35\tau_E^{89P}$, $0.95\text{-}1.1\tau_E^{ELMy}$

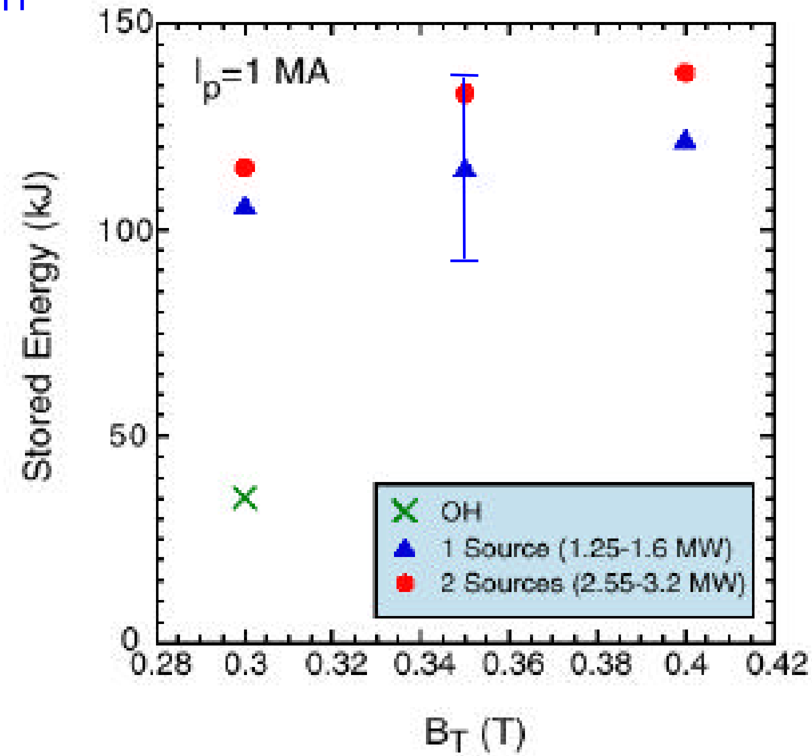
Initial NBI Experiments Studied Heating Efficiency

NSTX

Only two sources currently available

EFIT



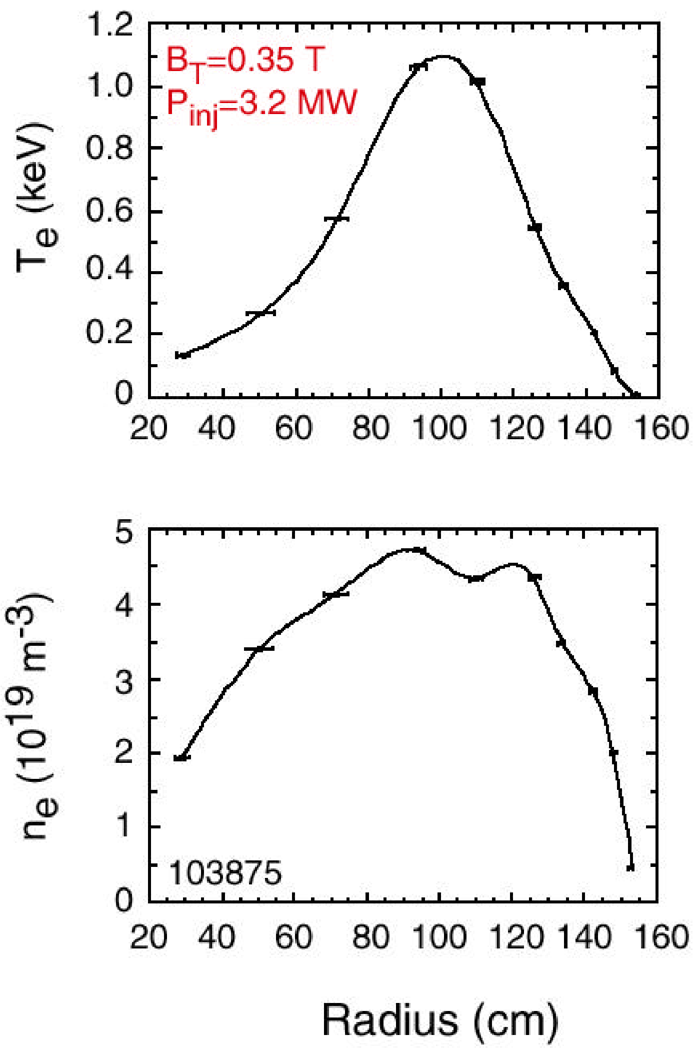


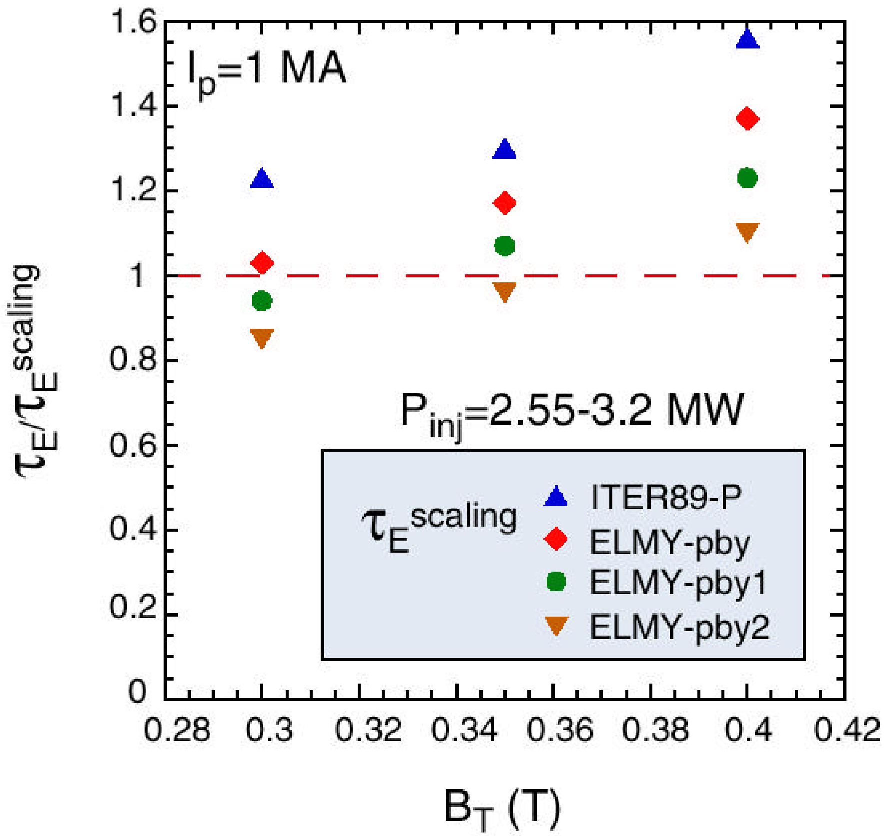
Preliminary diamagnetic measurements show agreement with EFIT

Gates (BO1.007)
Darrow (MP1.147)

High T_e, Energy Confinement Achieved With NBI

NSTX





Summary

NSTX

- Initial performance goals met or exceeded
  - A full range of shapes and configurations produced
- Wall conditioning/discharge tailoring crucial to attaining high-β_t, high stored energy, long pulse length
  - High-n_e, high τ_E, reduced V-sec consumption in OH
  - β_t=19.7% (β_n=3.9), 105 kJ with 1.3 MW of NBI @0.3T (21% max)
  - $\leq$140 kJ; $\tau_E \leq$50 msec, $\leq 1.6\tau_E^{89P}$, 0.9-1.4τ_E^{ELMy}
  - $\leq$ 200 msec current flattop duration at 1 MA
- HHFW effective in heating electrons
- CHI generated $\leq$270 kA of toroidal current non-inductively

=> Control of MHD activity (q-profile) is essential

Near Term Plans

- Auxiliary systems to full capability
  - HHFW to 6 MW
  - NBI to 5 MW (up to 8 MW)
  - CHI to 500 kA start-up current
- High temperature bake, between shots GDC for further wall conditioning
- Commission additional profile and fluctuation diagnostics for local transport and MHD studies
- Study wall stabilization techniques (passive, assess need for active) in q_0~1, β_t~25% plasmas
- Continue development of non-inductive current drive techniques (HHFW, CHI, bootstrap)

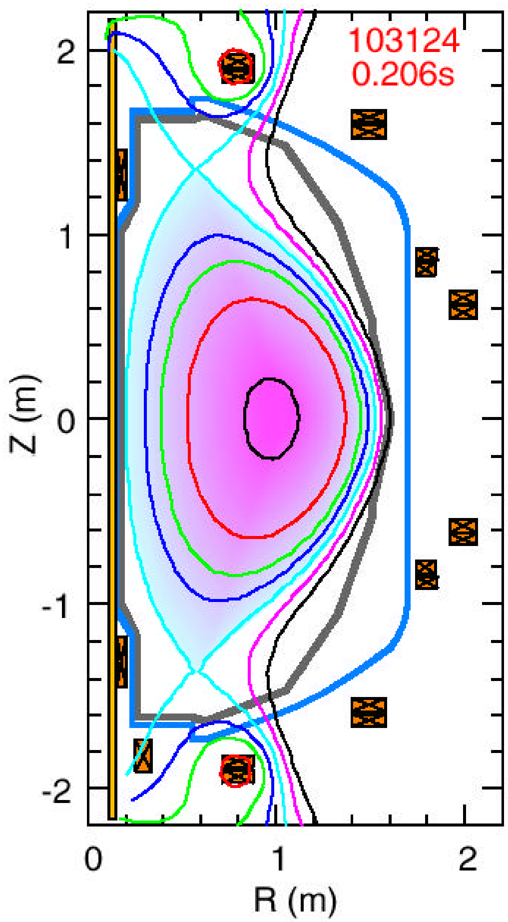
Other NSTX Presentations

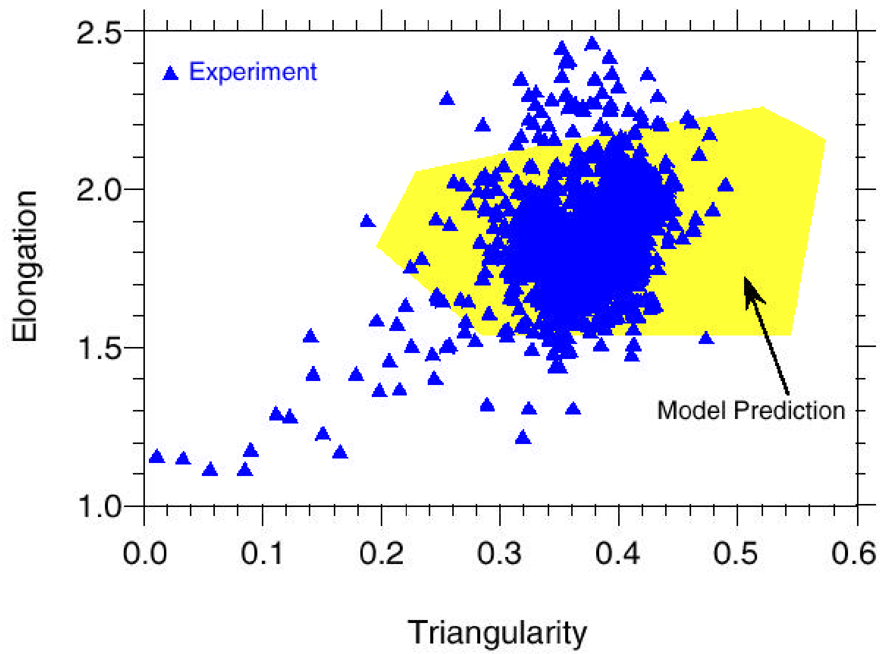
Oral Session (B01): Monday morning

Poster Session (MP1.134-164): Wednesday morning

Additional Vugraphs Follow

A Range of Equilibria Has Been Developed



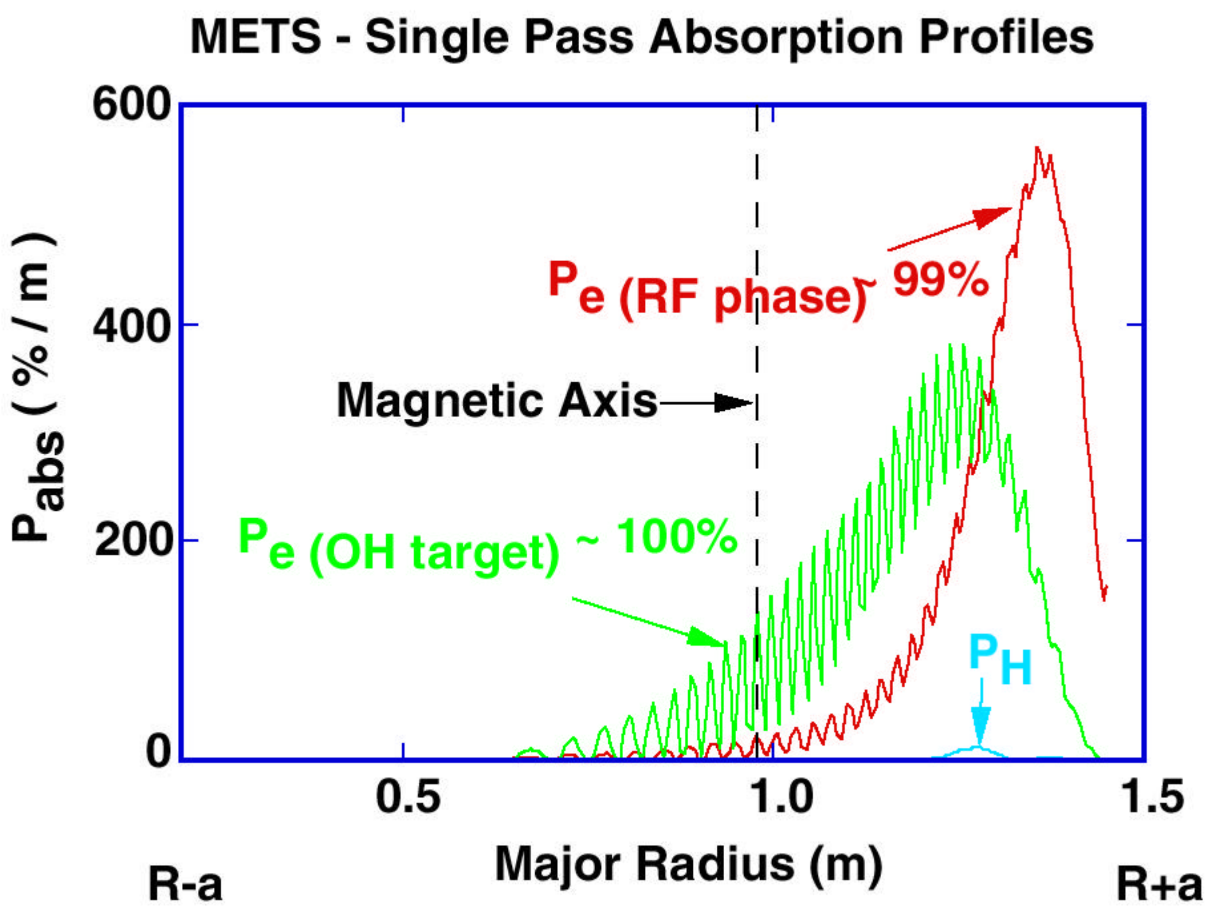


Inner Wall Limited, Double and Single Null Divertor Configurations Created

Sabbagh (BO1.001)

HHFW Modeling Indicates Strong Single Pass Absorption in Both Target and RF Phases

NSTX



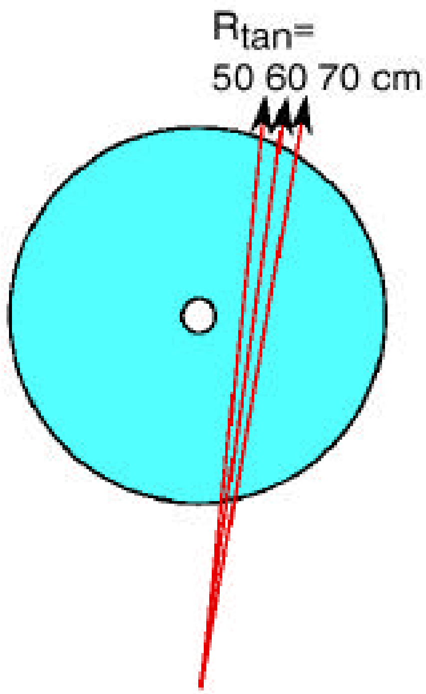
TORIC, CURRAY results similar

Phillips (MP1.152)
Spaleta (MP1.153)
Mau (MP1.154)

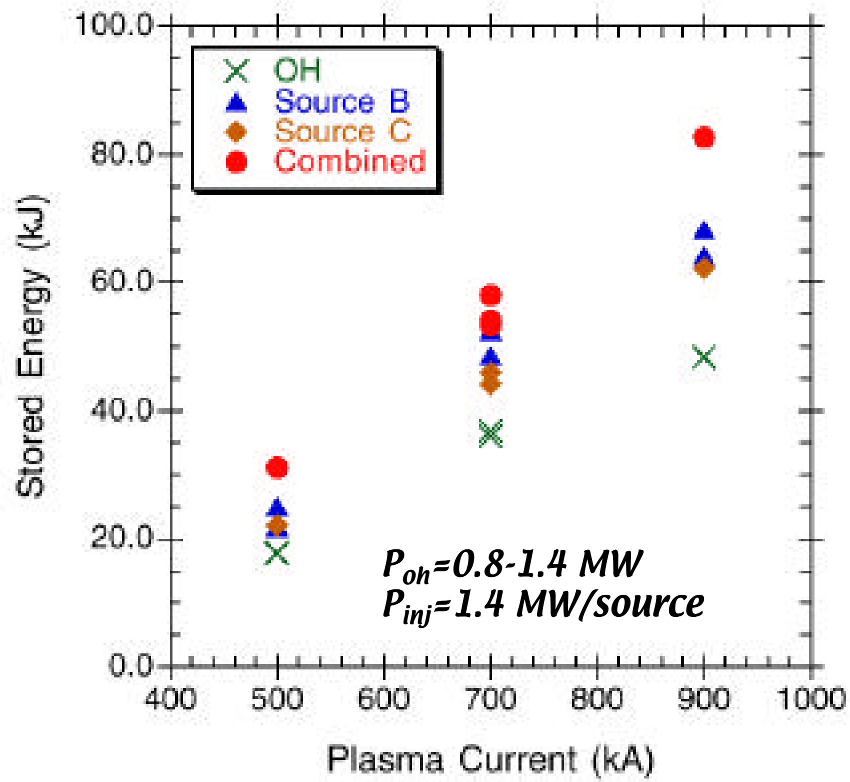
Absorption profiles indicate potential for current profile control

Initial NBI Experiments Studied Heating Efficiency

Only two innermost sources currently available



~Linear increase of stored energy with plasma current



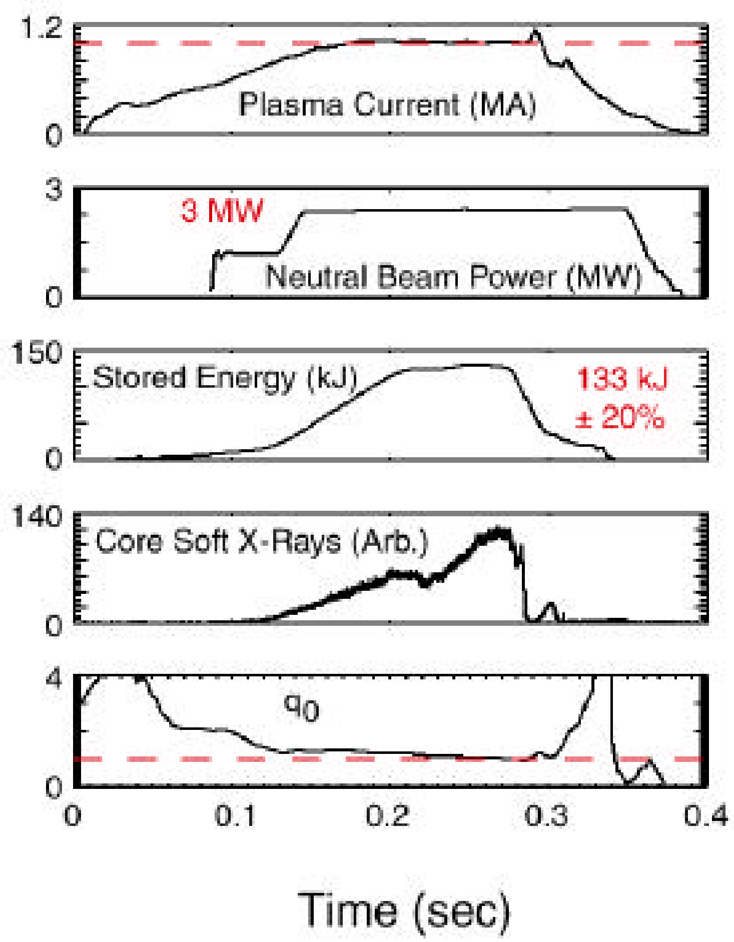
Gates (BO1.007)
Darrow (MP1.147)

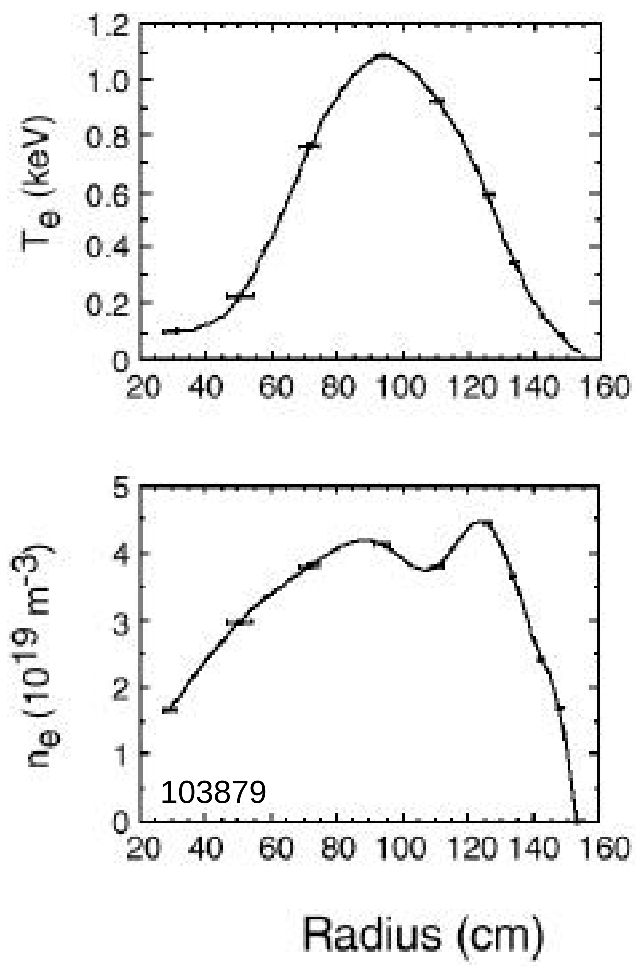
Reduced heating efficiency with innermost sources due to larger prompt orbit loss - consistent with modeling

High Stored Energy Achieved With NBI

NSTX

B_0=0.35 T

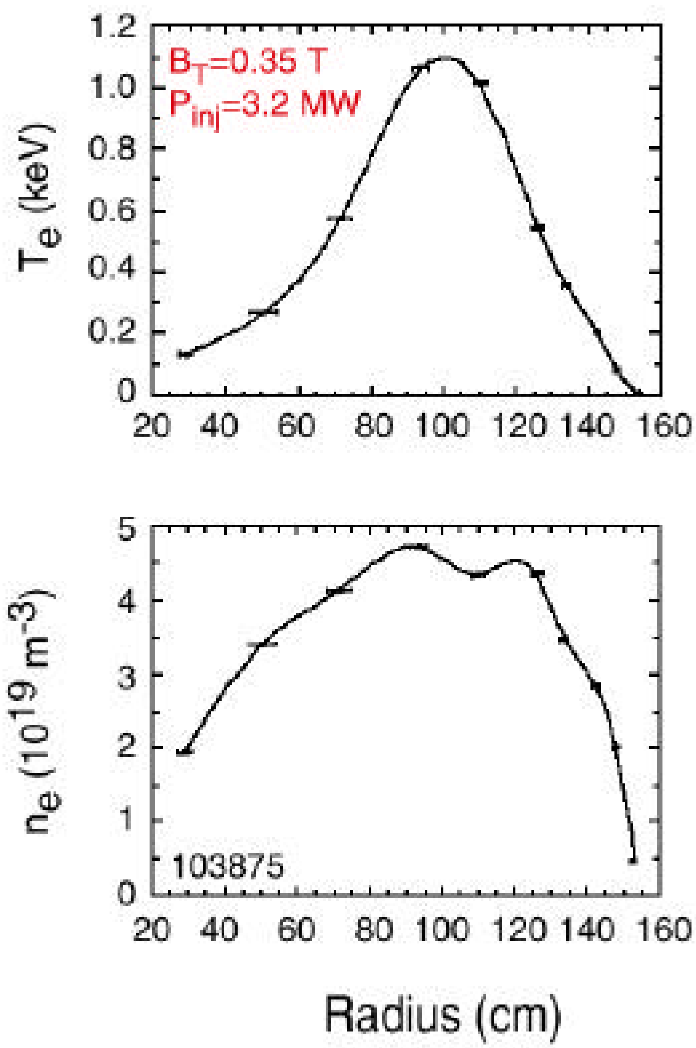


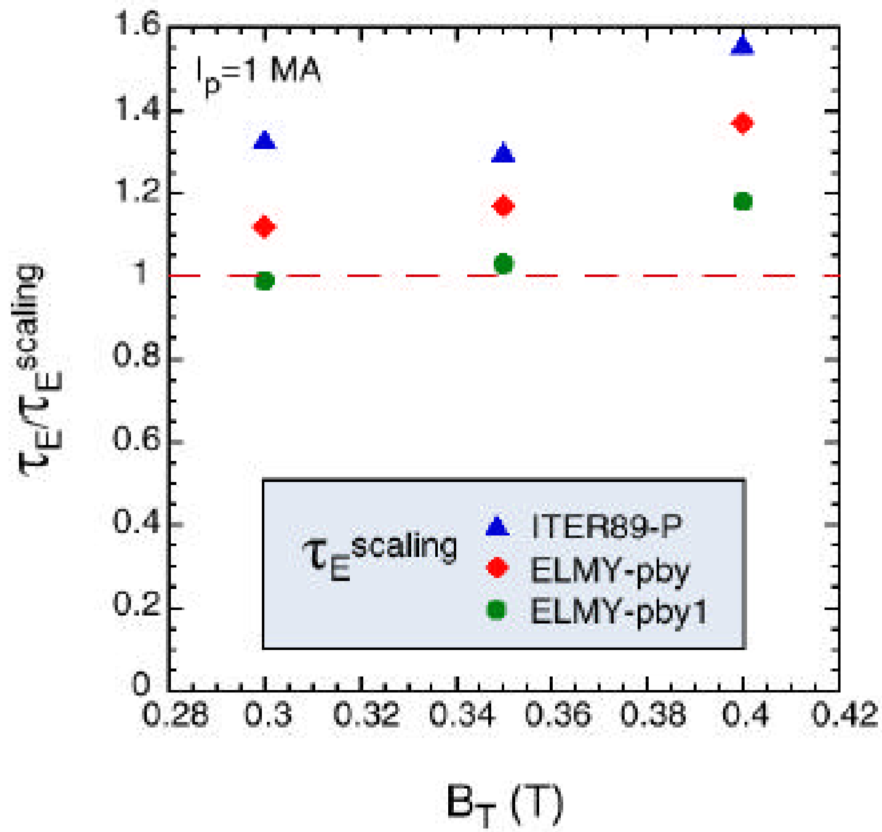


τ_E (uncorrected)= 31 msec, ~1.3τ_E^{89P}, ~1.0-1.2τ_E^{ELMy}

High T_e, Energy Confinement Achieved With NBI

NSTX





Summary

- Initial performance goals met or exceeded
- Wall conditioning/discharge tailoring crucial to attaining high-β_t target
  - High-n_e, high τ_E, reduced V-sec consumption in OH
  - β_t=21% (β_n=4.1), 115 kJ with 2.55 MW of NBI
  - [β_t=19.7% (β_n=3.9), 105 kJ with 1.3 MW of NBI]
- HHFW effective in heating electrons
- CHI generated ≤270 kA of toroidal current non-inductively

=> Control of MHD activity is essential