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Overview of the Initial NSTX Experimental Results

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Columbia University Seminar, Nov. 3, 2000

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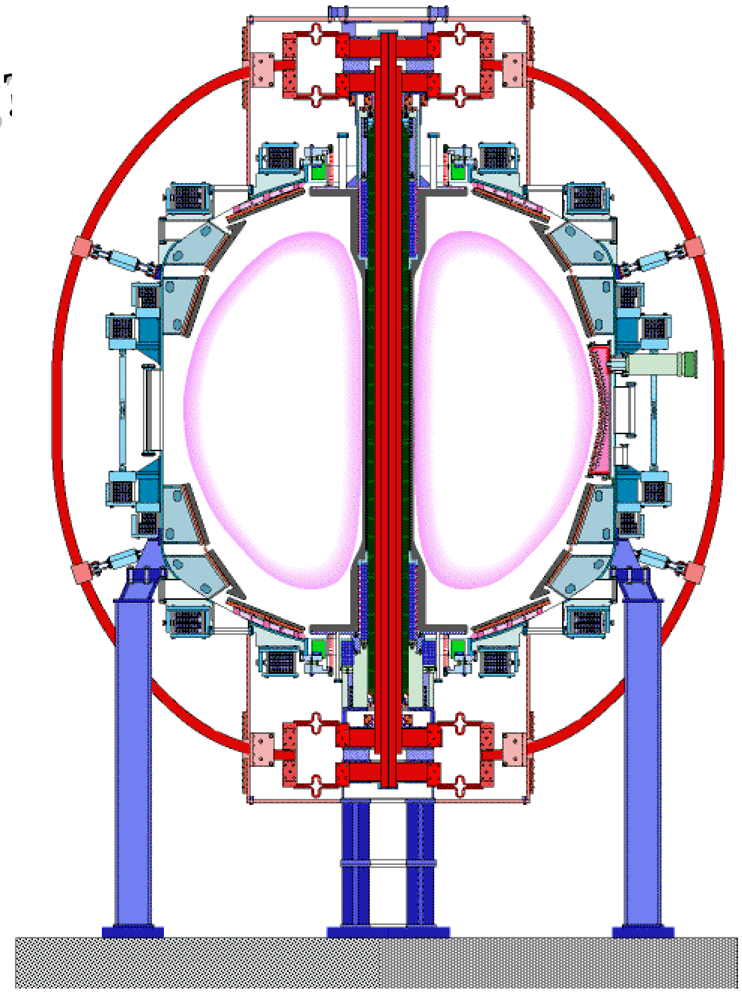
NSTX Overview Outline

- What is ST and why is it interesting?
- NSTX Facility Status
- Summary of Ohmic Operations
- Status of Tool Development:
  - CHI (Coaxial Helicity Injection)
  - HHFW (High Harmonic Fast Wave)
  - NBI (Neutral Beam Injection)
- Summary and Future Plan

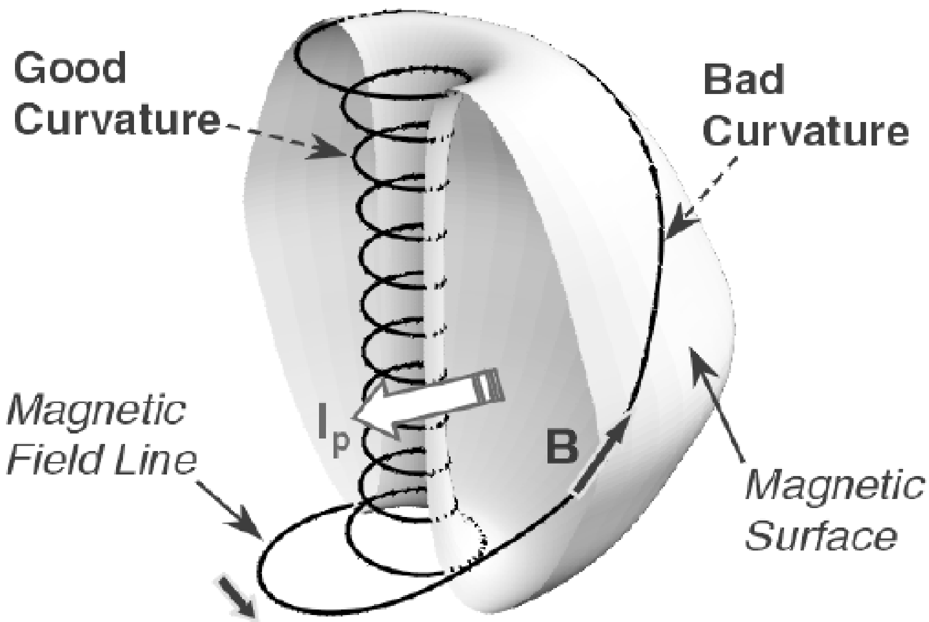


What is Spherical Torus and why is it interesting?

NSTX

- Spherical Torus (ST) is a low-aspect-ratio tokamak.

  - A circular cross section conventional aspect-ratio tokamak become spherical shape as R/a is reduced toward one. (Natural elongation κ ≈ 2 and triangularity δ ≈ 0.3.)



Why is ST interesting?

- Strong toroidicity
- Strong shaping (high κ and δ)
- Maximizes field line length in the good curvature region
- Absolute minimum B well.
- Strong sheared flow
- Larger trapped particle fraction

Basic Property of Spherical Torus?

- ST can sustain high current even at high q(a) ≈ 10:

$$I_p \approx \frac{1+\kappa^2}{2} \quad \frac{R_0 \; B_0}{q(a)} \quad \frac{A\,(1.22\;A - 0.68)}{(A^2-1)^2} \qquad where\ A \equiv R_0\ /\ a$$

- ST can sustain high toroidal beta (β_N tends to increase in ST):

$$\beta_T \equiv \frac{2\,\mu_0 \langle p \rangle}{B_0^2} \qquad \beta_N \quad \frac{I_p}{a\;B_0}$$

- ST can be made to produce high fusion power:

$$P_{fusion} \qquad Vol\ \ (nT)^2\ \frac{\langle \sigma v \rangle}{T^2} \qquad \beta_N^2\ \kappa\,(1+\kappa^2)^2\ \frac{R_0^3\;B_0^4}{q(a)^2}\ \frac{A^2\,(1.22\;A-0.68)^2}{(A^2-1)^4}$$

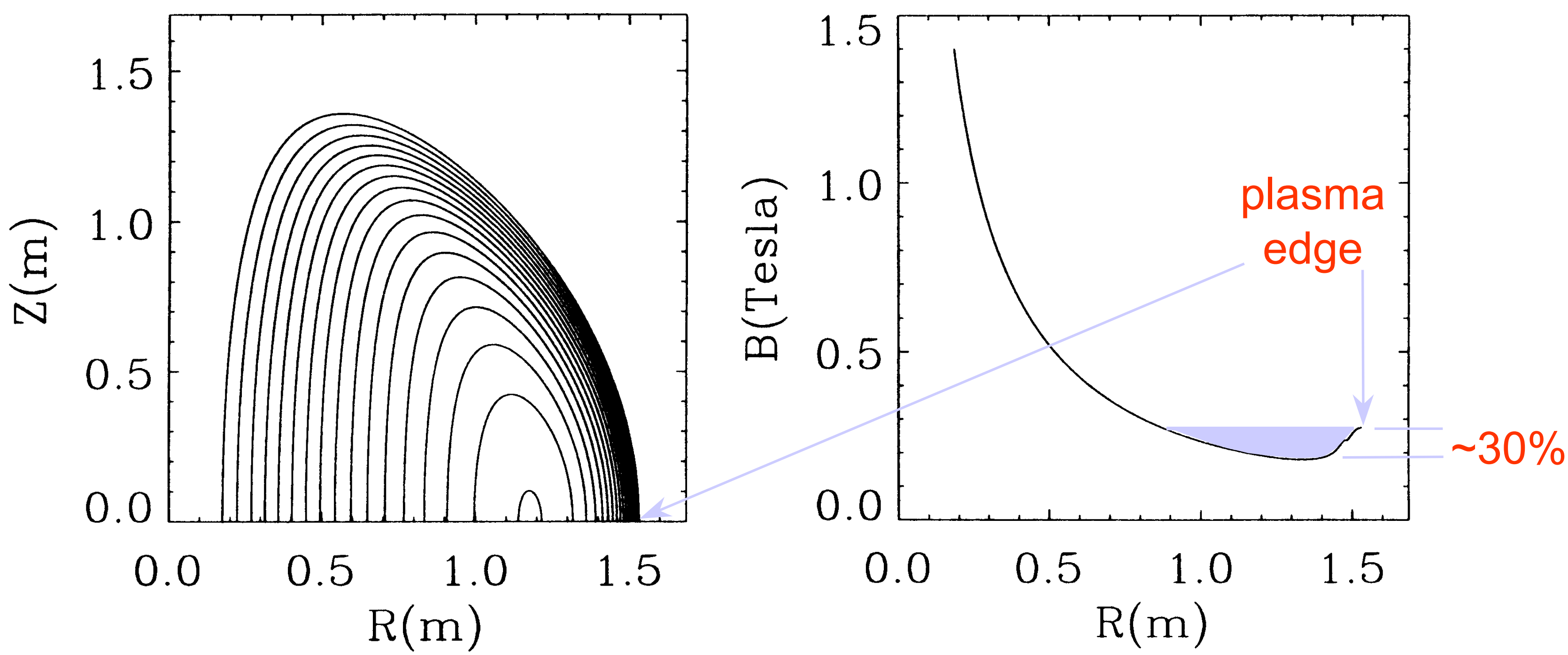
- ST can be made to be self-sustaining by pressure driven current.

Combination of high β_T, high κ, and high q(a) leads to a large j_{BS}

MHD Stable, High Beta (β_t = 40%) Plasmas with Strong Well (~30%) in NSTX Are Calculated (Menard)

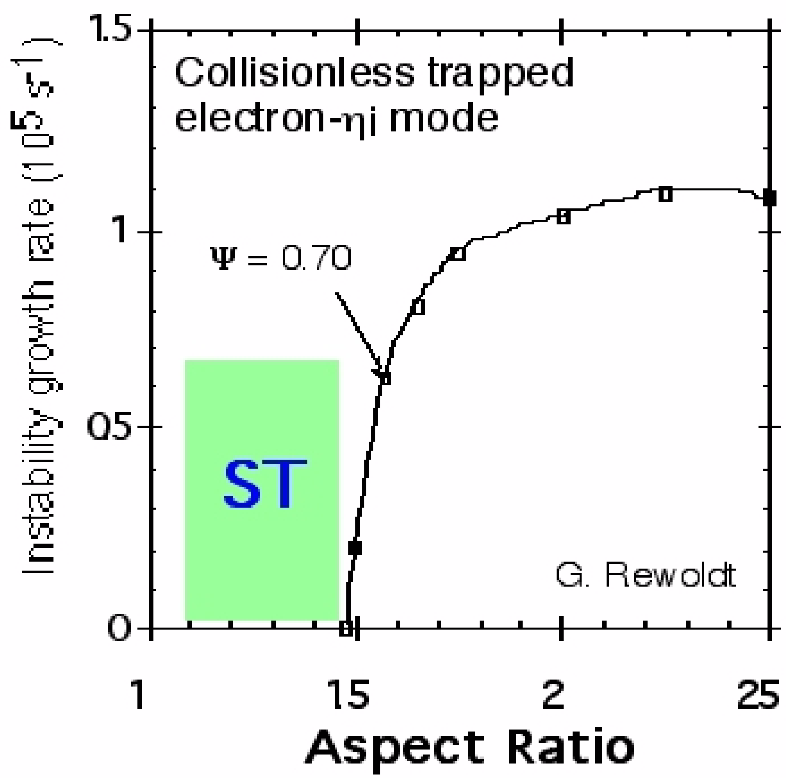
MHD Equilibrium
Flux Surfaces

Magnetic Well (~30%)
on Mid-plane

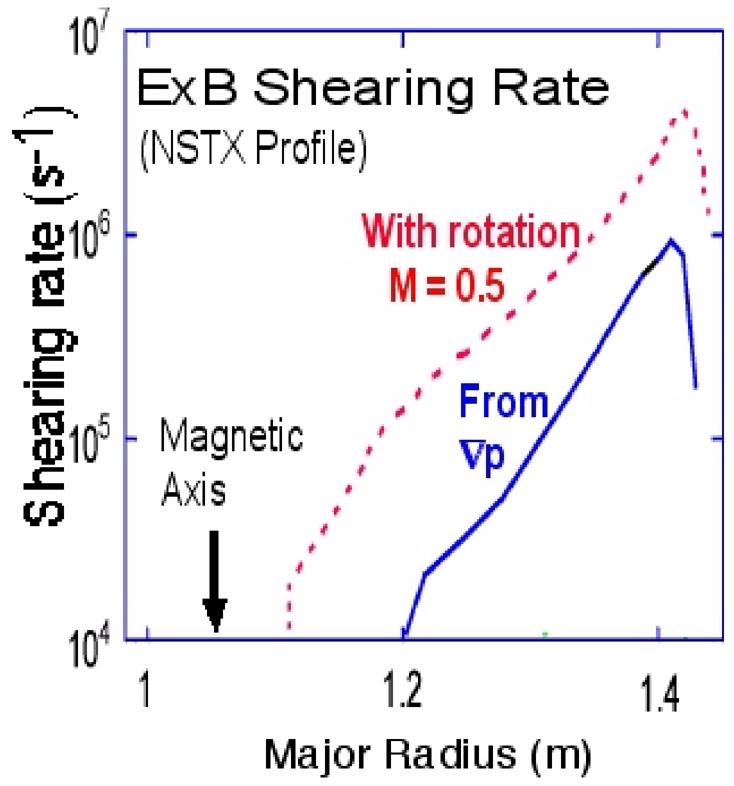


Prospect of Good Confinement in ST

Decreased instability drive



Increased stabilization



High β, high confinement, self-sustaining fusion system.

Motivation and Objectives of NSTX

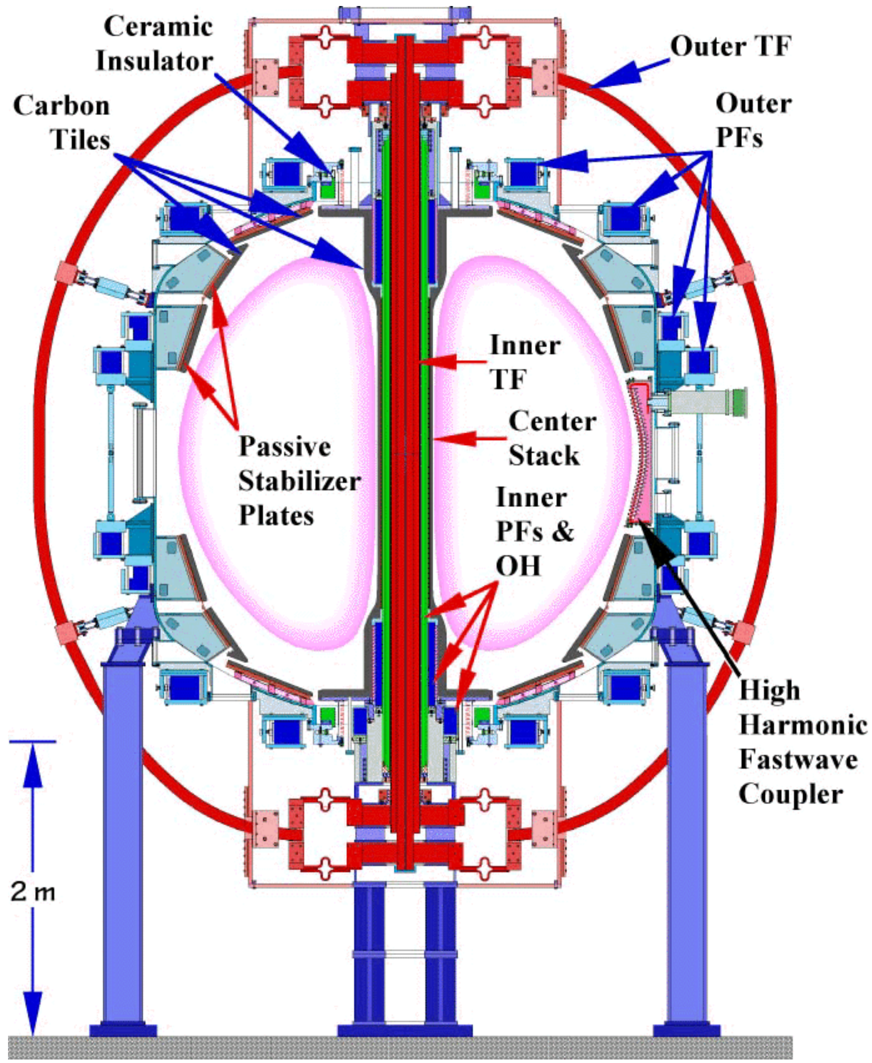
- Extend the understanding of toroidal plasmas to new regimes.
  - High β_T (up to 40 %)   [Note: $\beta_T = 2\,\mu_0 < p > / B_{T0}^2$]
  - High j-boot fraction (up to 70%).
  - Strong toroidicity and shaping ($R/a \geq 1.26$, $\kappa \leq 2.2$, $\delta \leq 0.6$).
  - Fully relaxed, low collisionality regimes.

- Develop "tools" needed for attractive ST power plant.
  - Non-inductive start-up, current sustainment, profile control
  - MHD mode-control
  - Confinement improvement
  - Power and particle handling

- Contribute to general science of high β / high temp. plasmas.

National Spherical Torus Experiment (NSTX)

NSTX



Baseline Parameters
(Achieved)

Major Radius 0.85 m

Minor Radius 0.68 m

Elongation ≤ 2.2 (2.5)

Triangularity ≤ 0.6 (0.5)

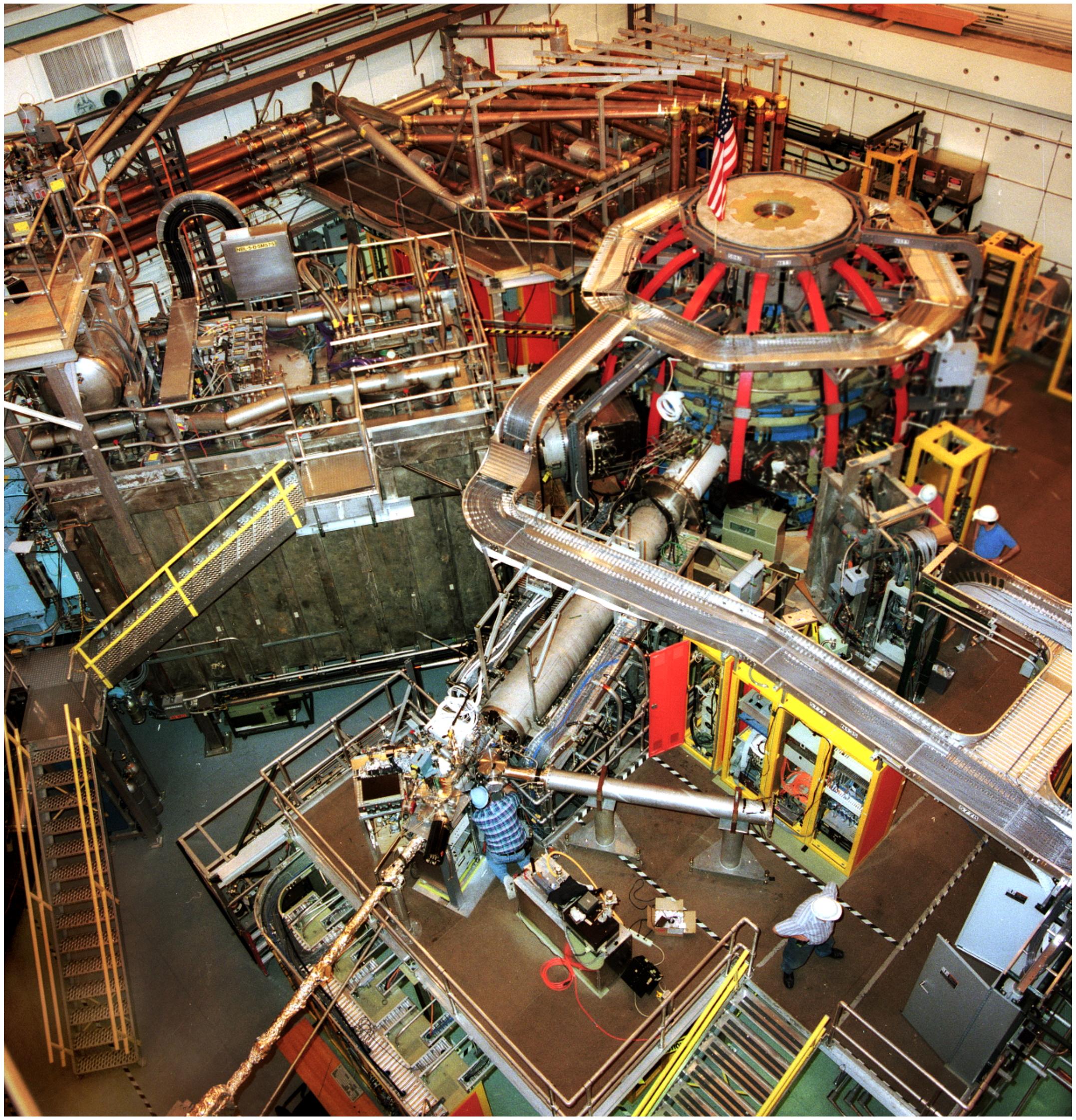
Plasma Current
1 MA (1.07 MA)

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)

NSTX facility ramping up quickly



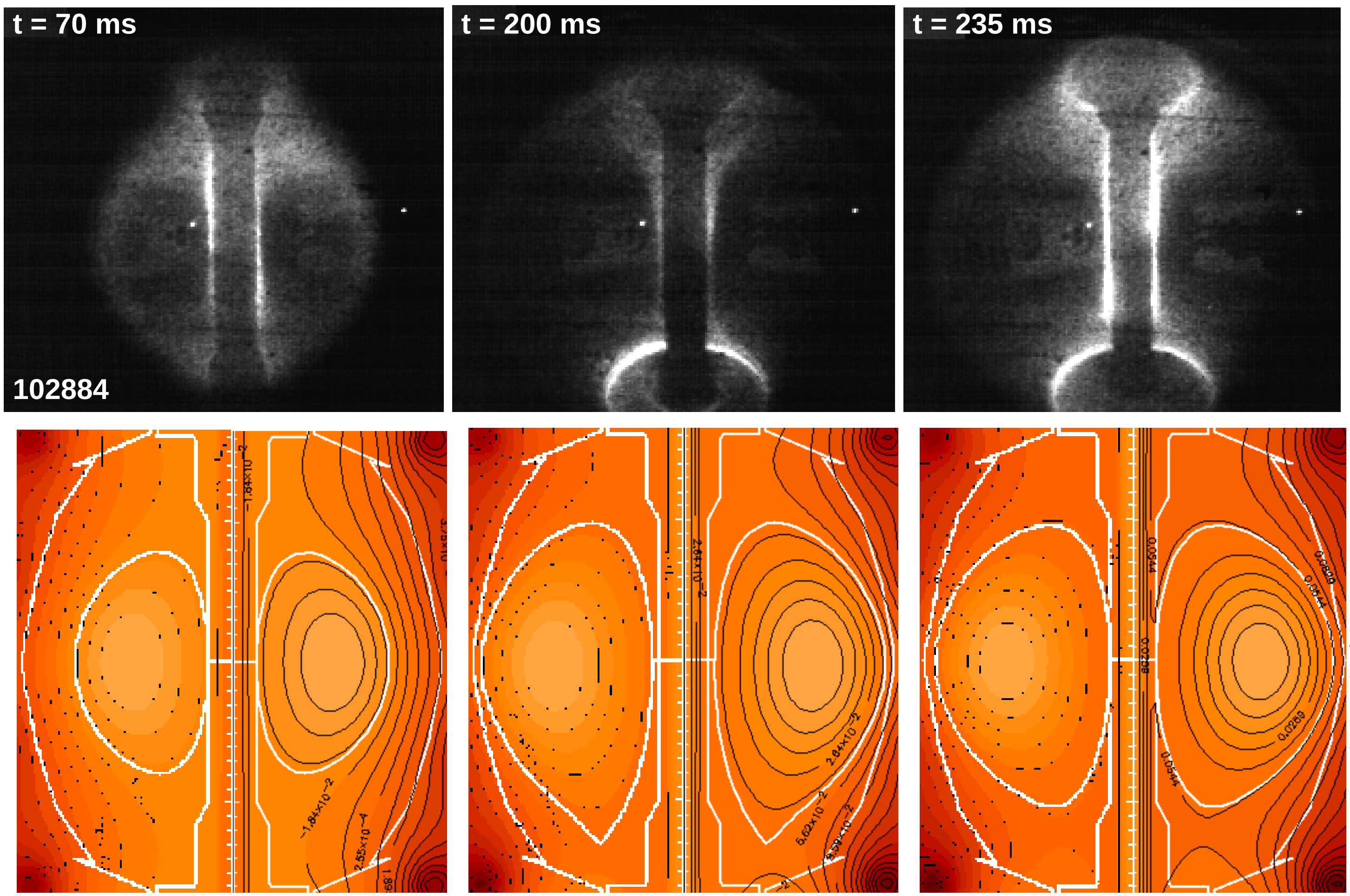
Sept. 2000

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)

Ohmic Operations Made Good Progress



Fast Camera
(1ms)

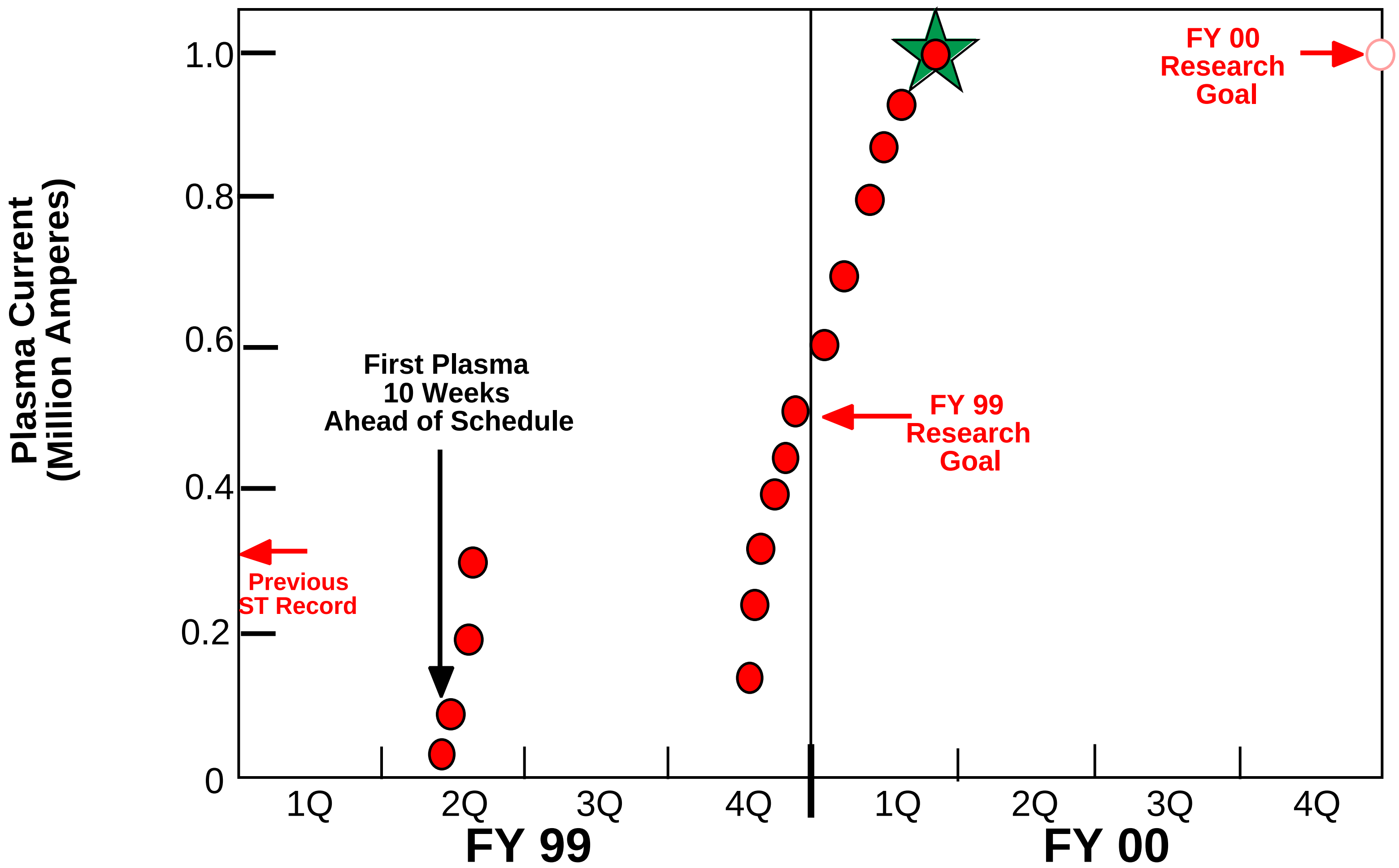
EFIT
Reconstruction
(1ms)

- EFIT Reconstruction agrees well with the Fast Camera.

Steve Sabbagh et al., IAEA EX3/6

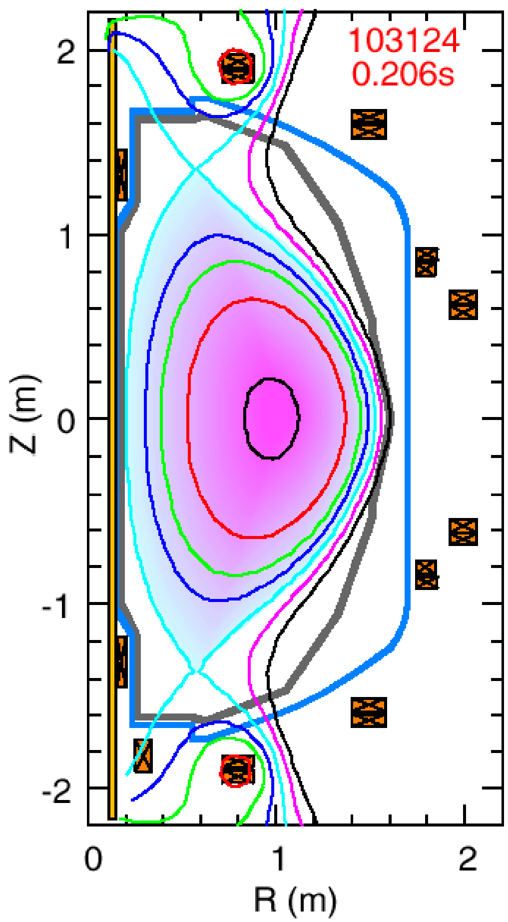
One Million Amperes Achieved on NSTX
– Nine Months Ahead of Schedule! –

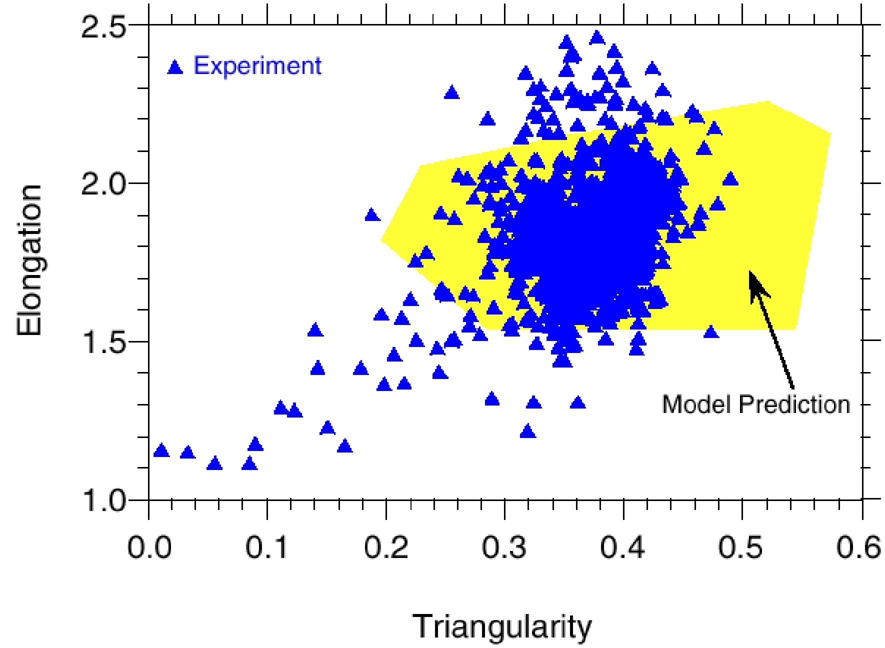
NSTX



A Range of Equilibria Has Been Developed

NSTX



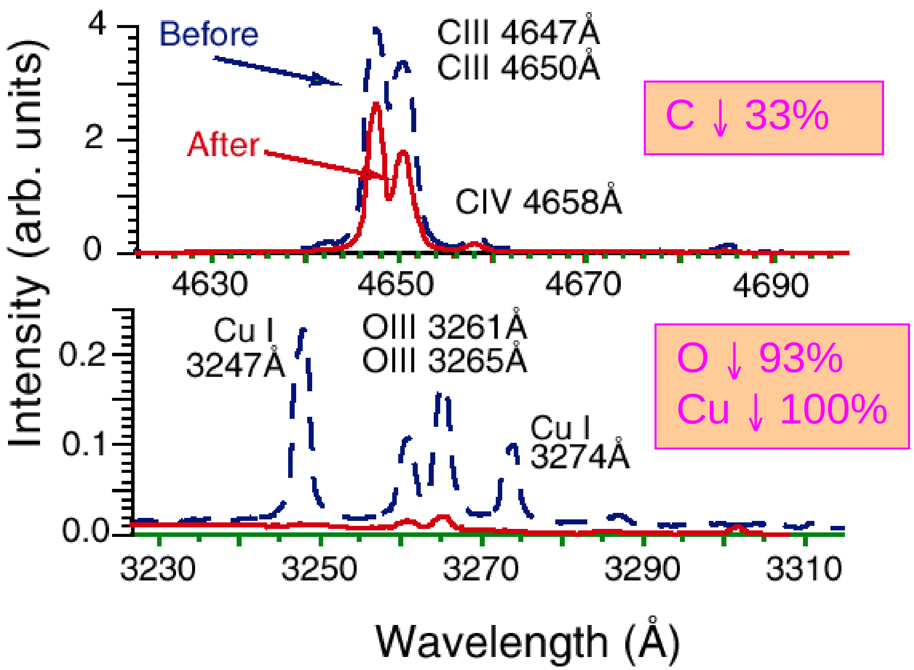


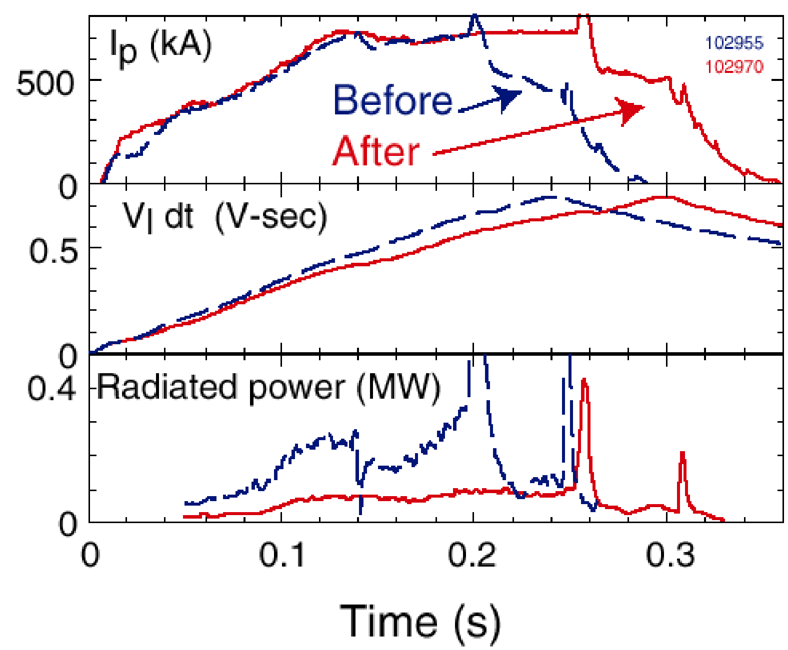
Inner Wall Limited, Double and Single Null Divertor Configurations Created

Sabbagh (BO1.001)

Boronization Reduces Impurities and Ohmic Flux Consumption

NSTX



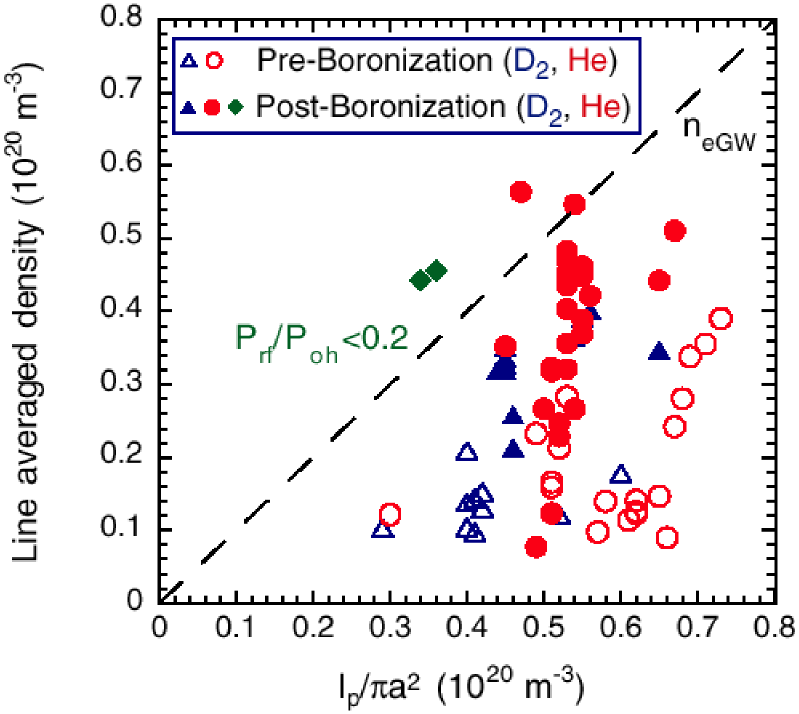


Reduced MHD activity after boronization (TMs, REs)

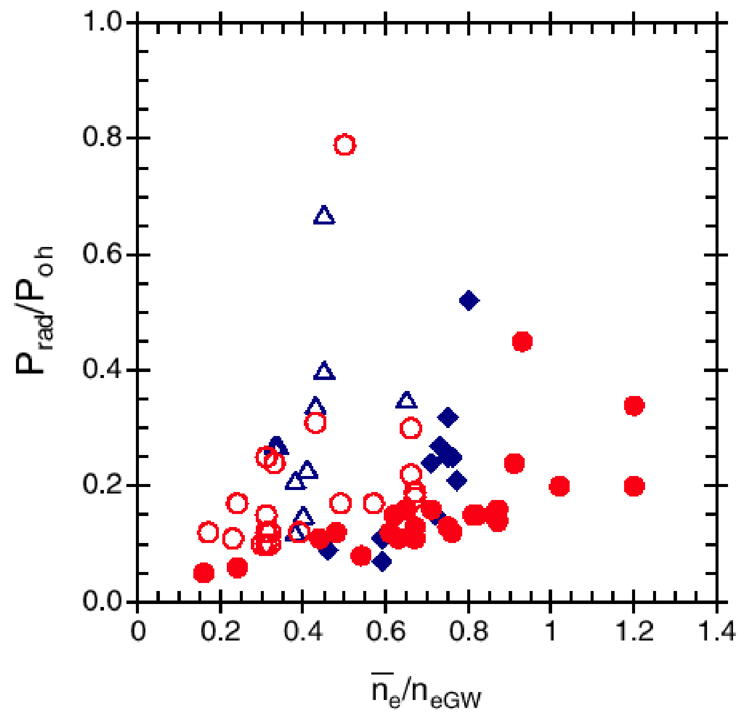
Menard (BO1.001), Maingi (BO1.006), Kugel (MP1.145)

Achieved Ohmic Densities Above Greenwald Limit

Boronization extends accessible n_e range



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

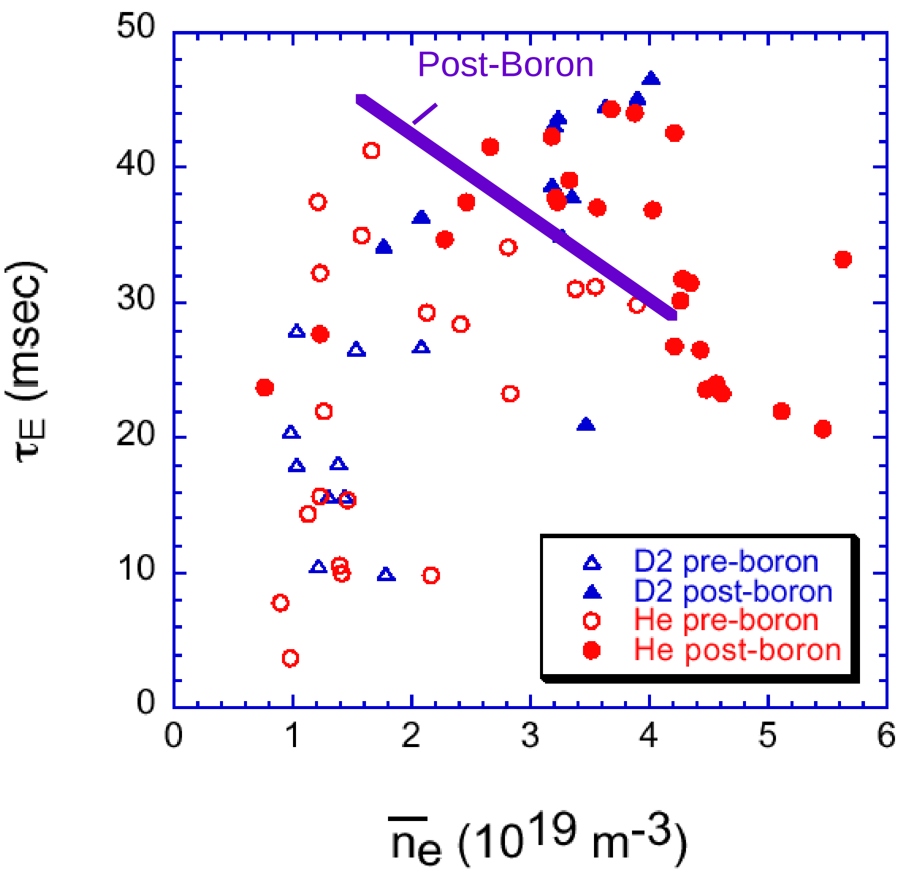


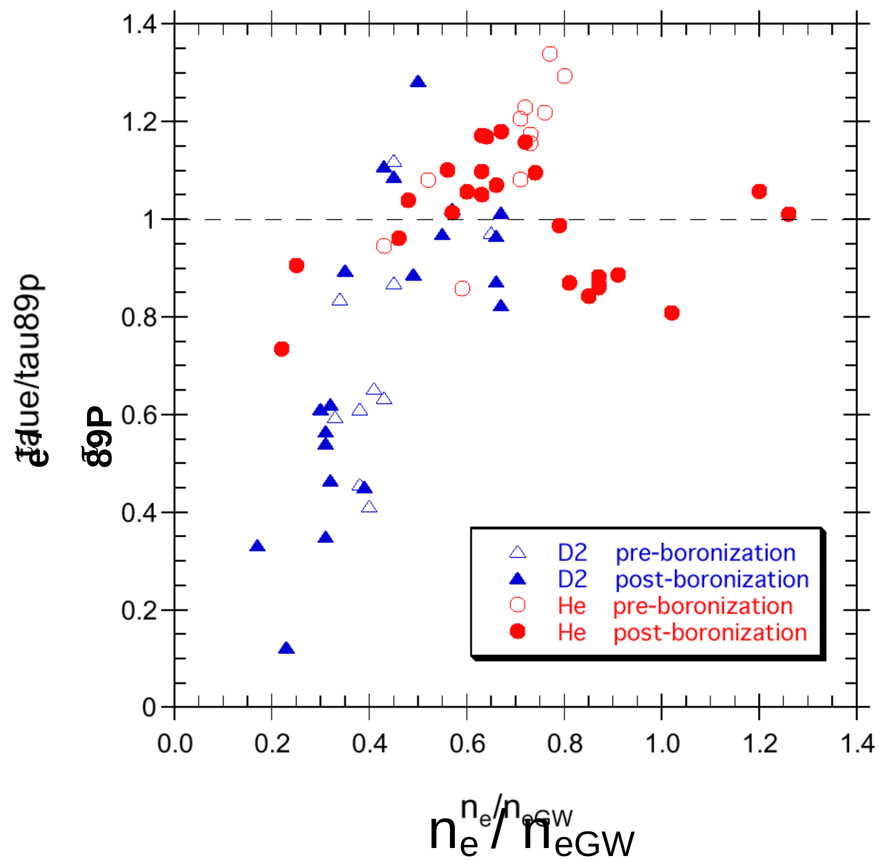
Maximum n_e appears to be set by fueling limitations

Kaye (MP1.137)

Ohmic n_e and τ_e trends similar to those at conventional R/a

- Boronization extended range of achievable densities.
- τ_E scales linearly with n_e up to 0.8 n_{GW} .

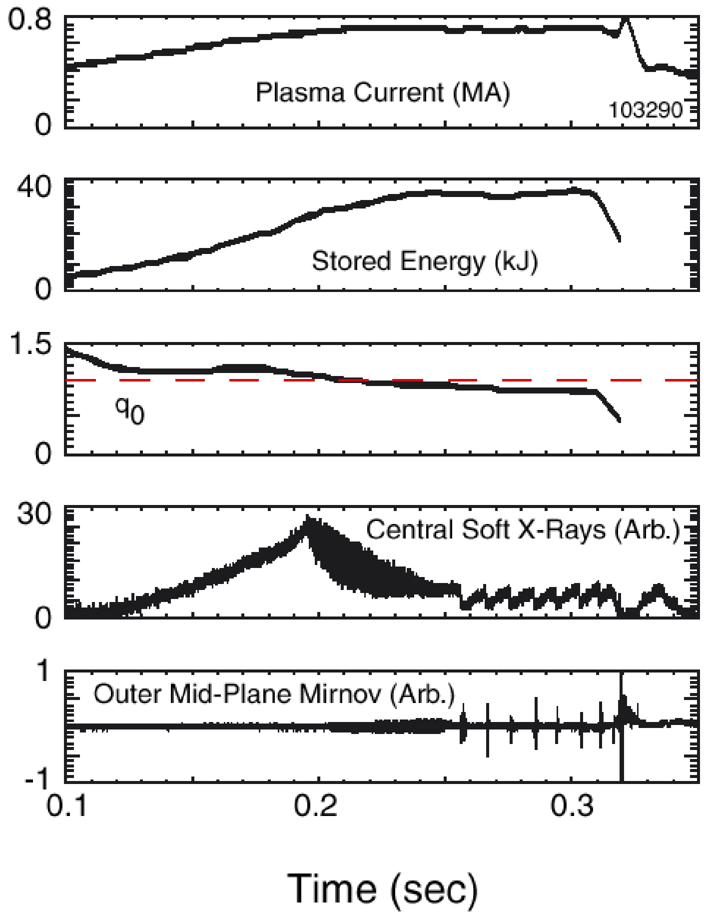


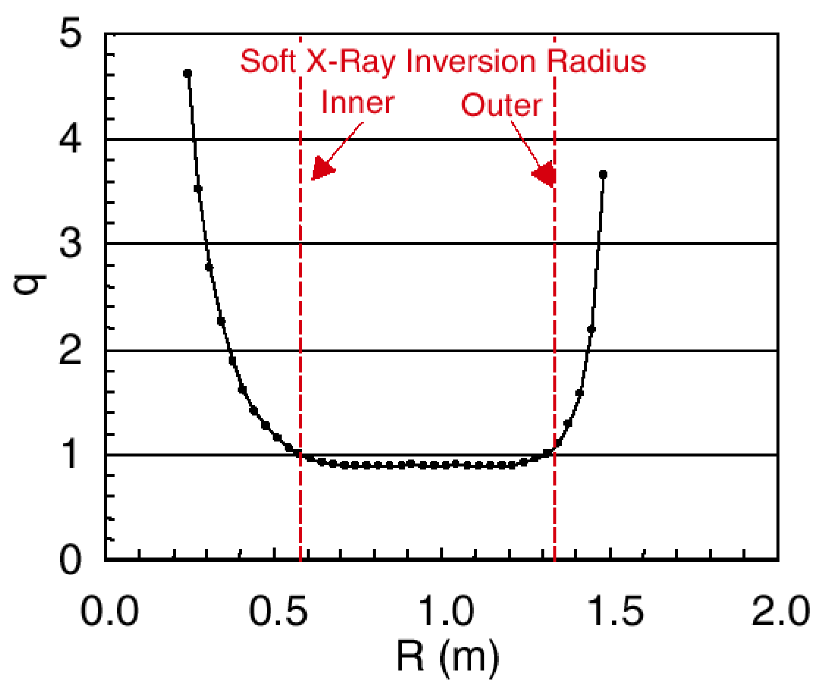


Plasma Performance Can Be Limited by MHD

NSTX

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





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

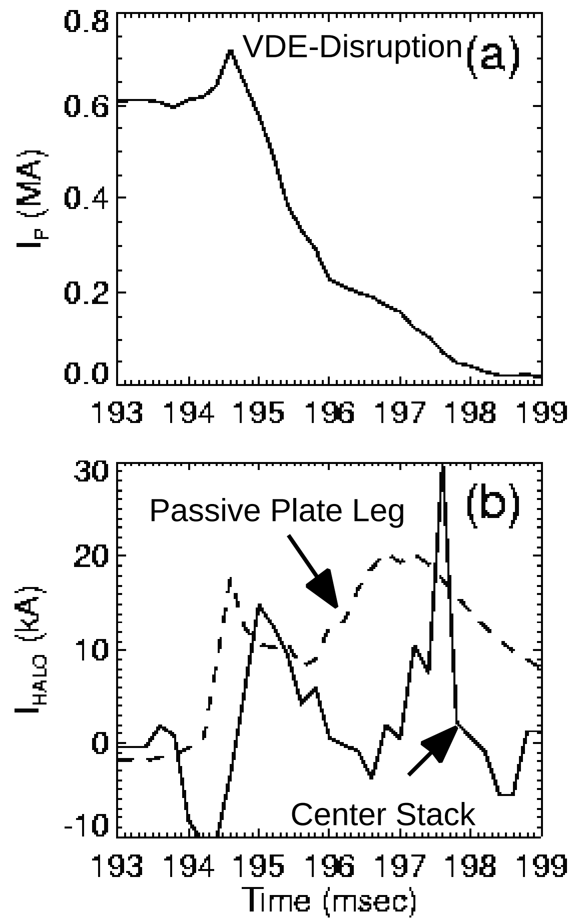
Small Disruption-induced Wall Halo-Currents

• Plasma Disruption / halo-current / j x B force

→ Design Challenge

• Vertical Displacement Events (VDEs) result in fast disruptions.
dIp/dt ≤ - 400 MA/sec.

• Observed halo-currents are modest, ≤ 5 % of Ip. I-halo ≤ 0.03 MA for Ip ≤ 1.1 MA.



Observation of small halo-current in NSTX is consistent with the results from CDX-U (M. Ono, IAEA 96), START/MAST (A. Sykes, et al., IAEA 00)

Why Non-Ohmic Start-up?

NSTX

- Essential for ST to eliminate OH solenoid.

  - Valuable real estate. [For example, if NSTX can replace the region occupied by OH solenoid by toroidal field magnet, the toroidal field can double. For proportional current and beta, the plasma performance (fusion power) can increase by 2^4 or 16,]

  - OH solenoid with insulation material is not compatible with the neutron environment expected in the ST Power Plant.
  - OH solenoid is highly stressed and engineered. (Costly!)
  - OH current profile is not compatible with high q(0) operation.

- Number of possible options:

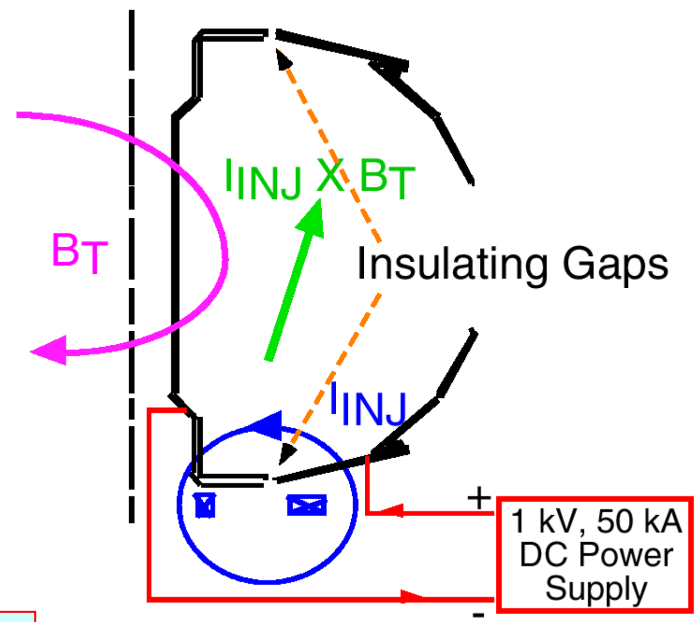
  - For more steady-state device(such as future ST reactor), there are other options including rf-current drive and bootstrap current over-drive.
  - Non-Ohmic coils (helical per A. Boozer, PF coil optimization.)

  - For NSTX, CHI is pursued due to the relatively quick and efficient current ramp up.

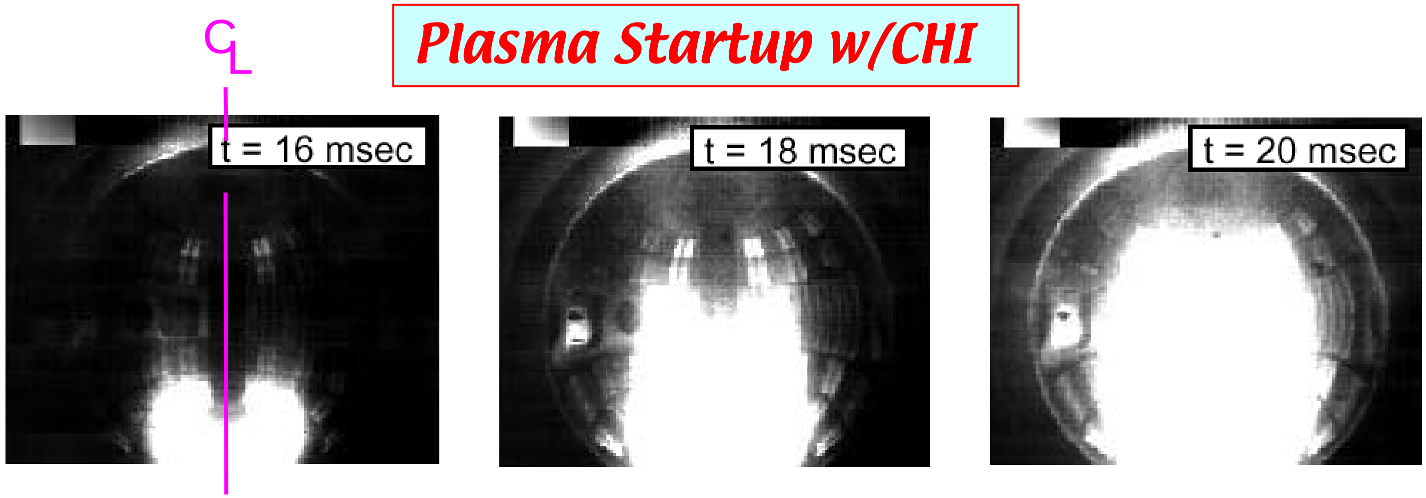
Co-Axial Helicity Injection (CHI) Generates Toroidal Current Non-Inductively

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

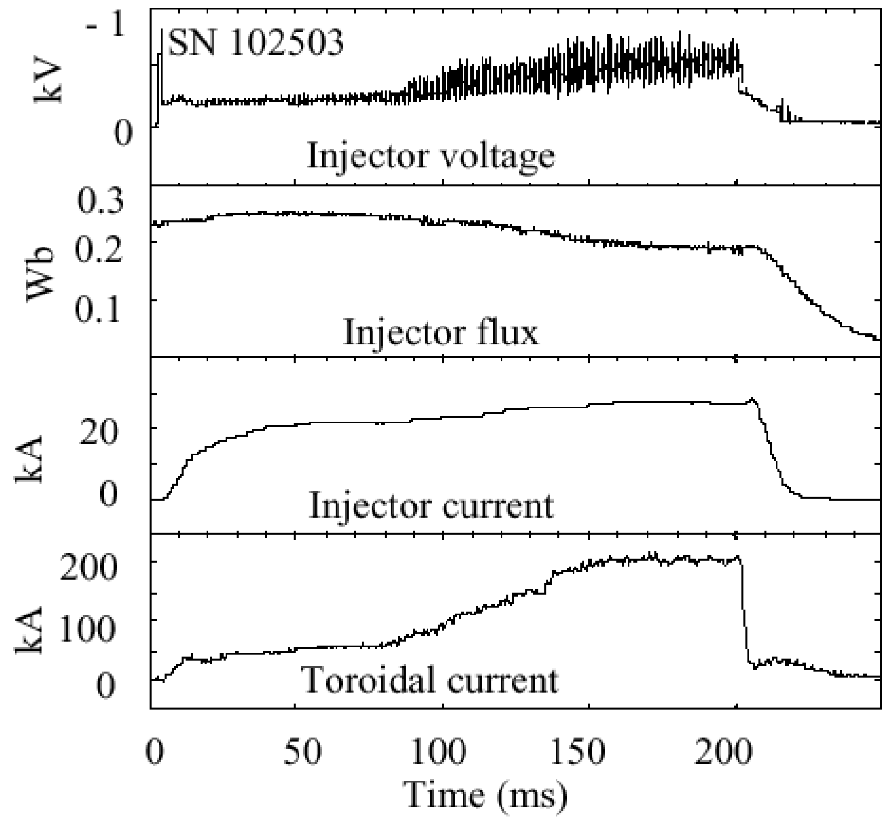


Raman (BO1.004)

Significant Toroidal Currents, Pulse Durations Achieved With CHI

NSTX

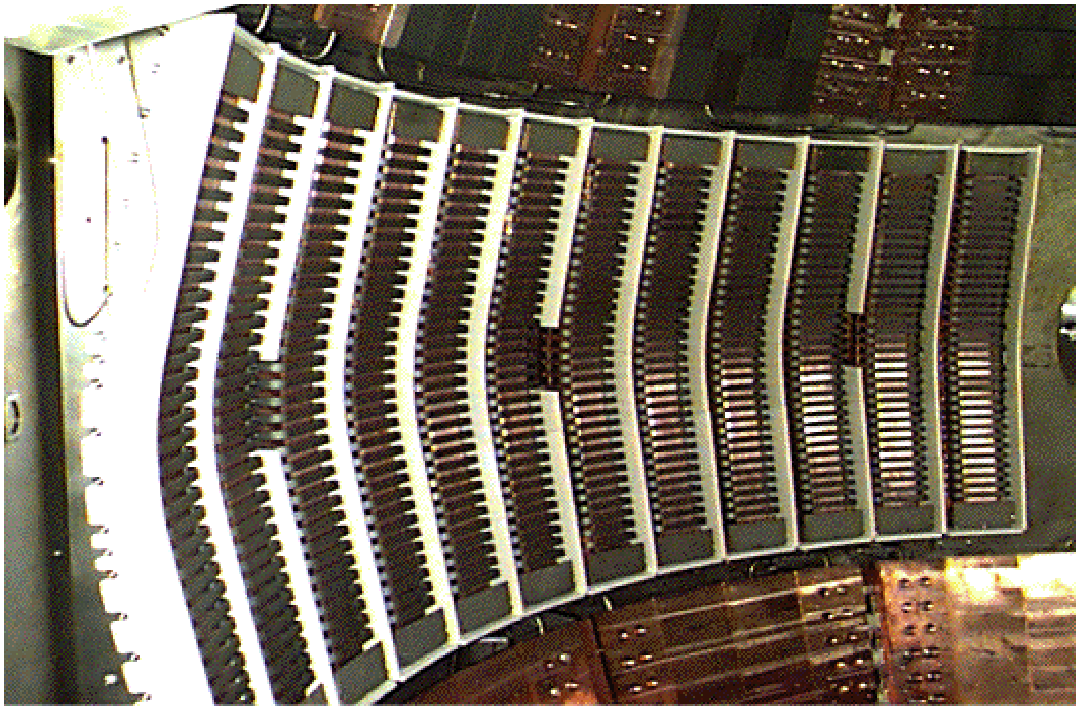
- No OH flux used
- 200 kA in 200 msec discharge
- Up to 270 kA transiently
- Practically all injector flux fills confinement region
- 0.2 Pa prefill (compatible with OH operation)



High 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



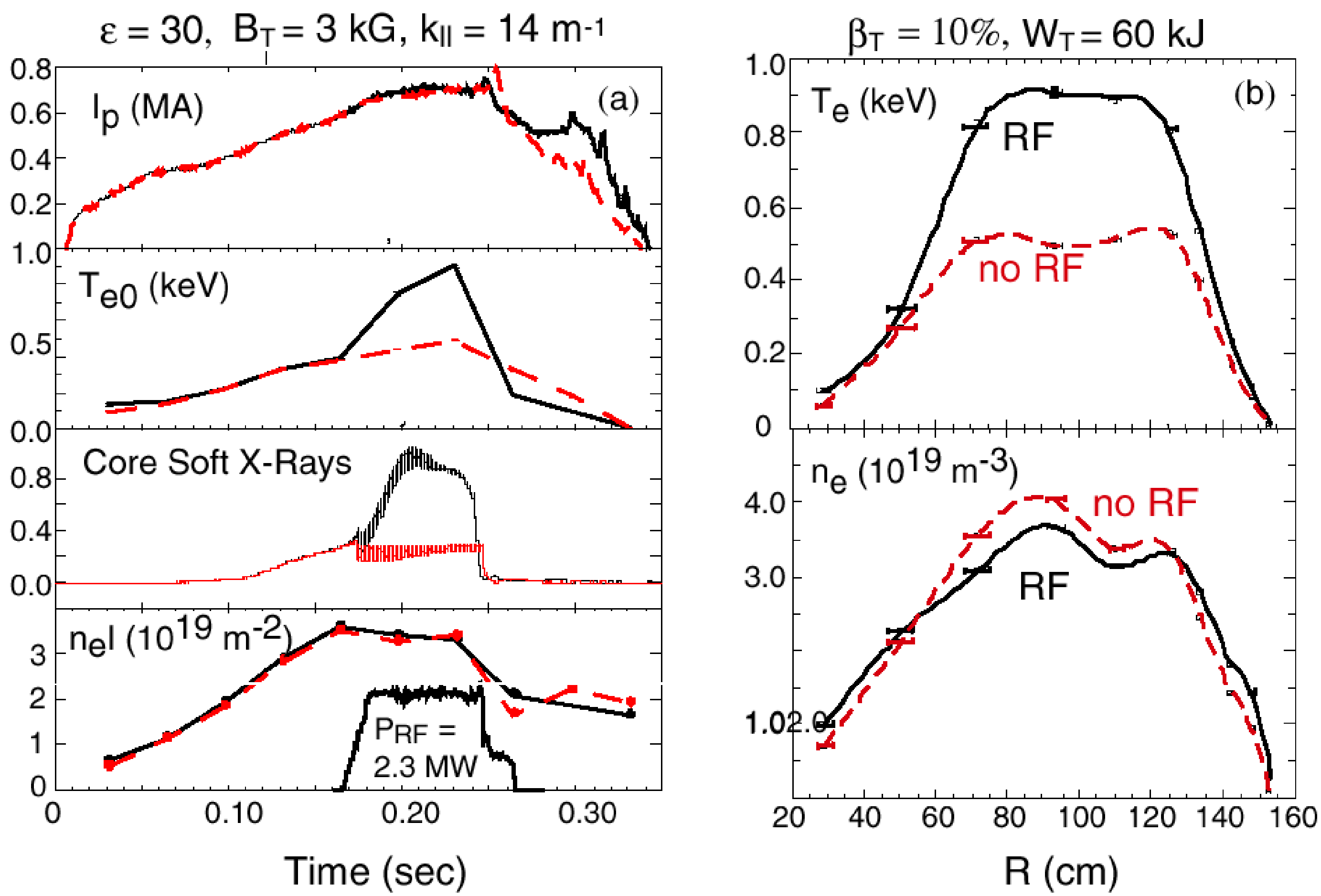
12 strap antenna with flexible phasing

- 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

NSTX

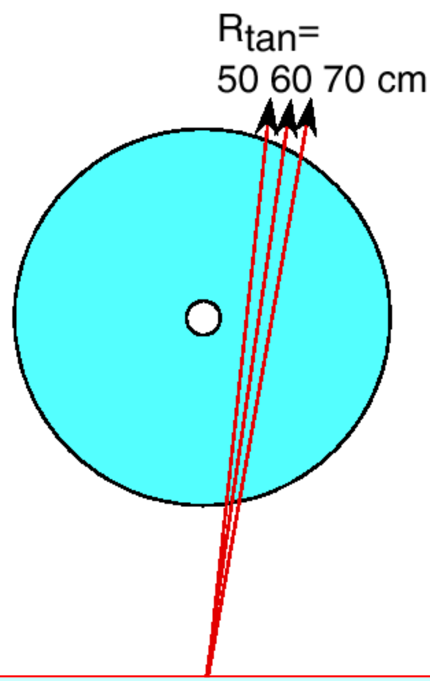


T_{e0}>1 keV achieved

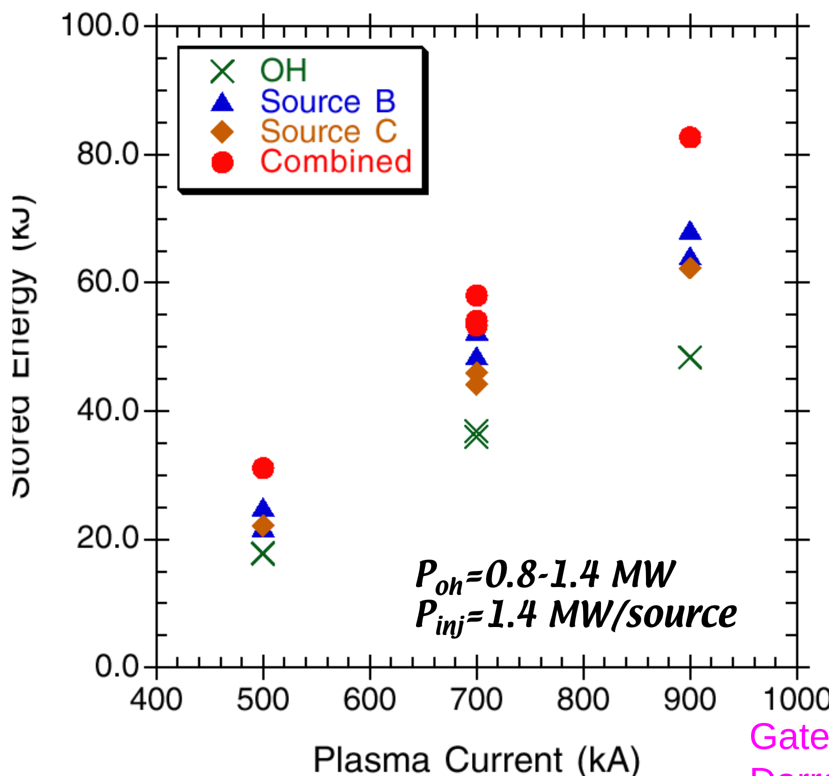
NBI Injection Started!

NBI System : from TFTR, 80 keV, Source B and C

New heting regime: $V_{Ti} \leq V_{Alfv} < V_{NBI} < V_{Te}$



Only two innermost sources currently available



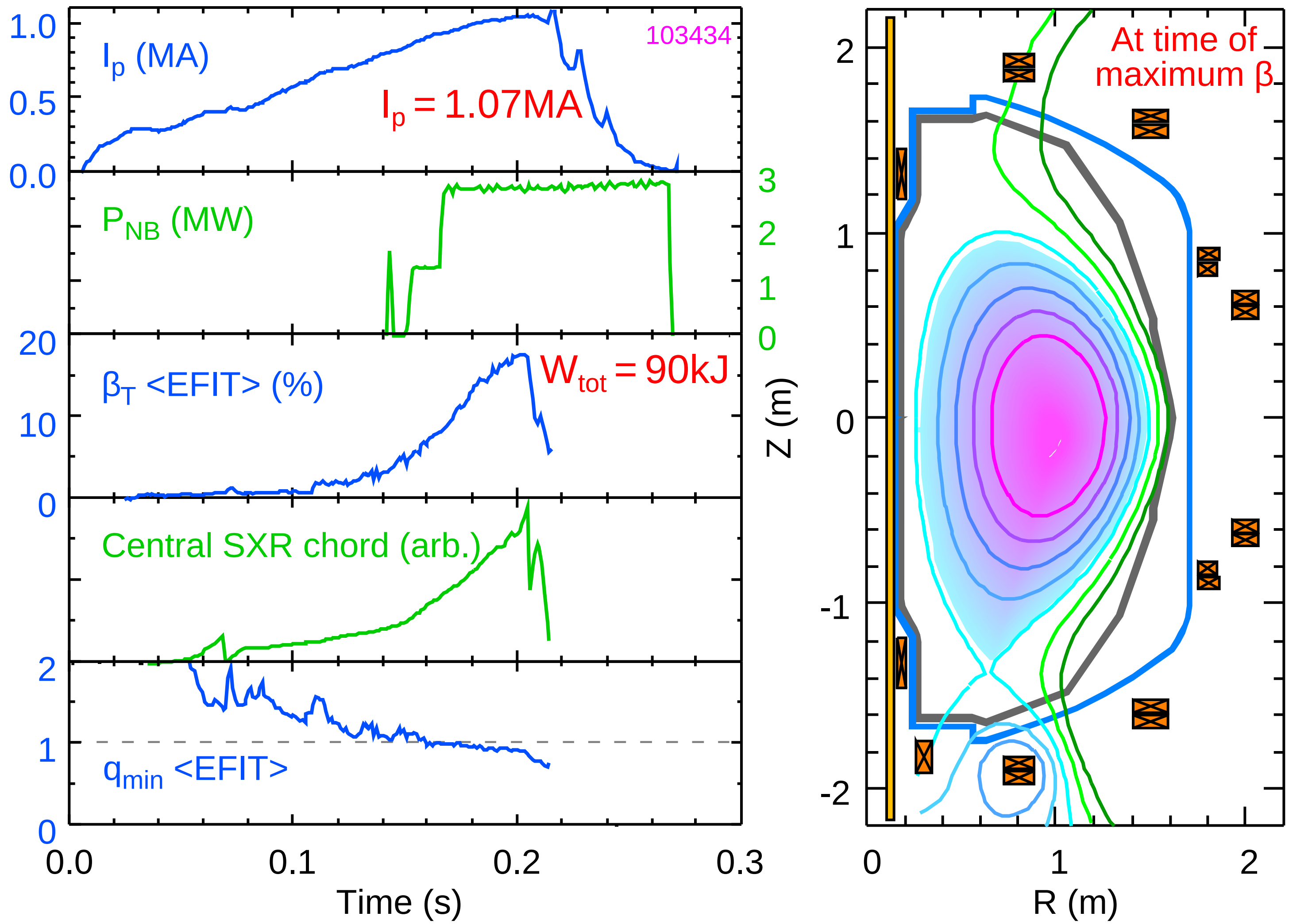
Gates (BO1.007)
Darrow (MP1.147)

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

β_T = 18% Achieved with 2.8MW NBI Heating

NSTX

- $\beta_T = 2\mu_0\langle p\rangle/B_{T0}^2$; B_{T0} = vacuum toroidal field at center = 0.3T

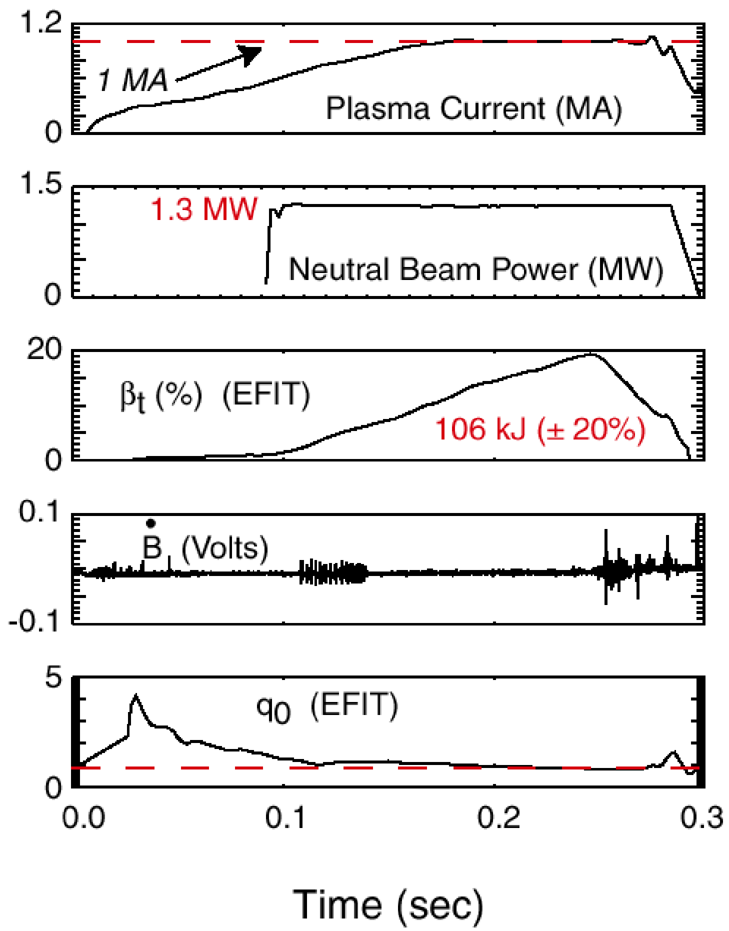


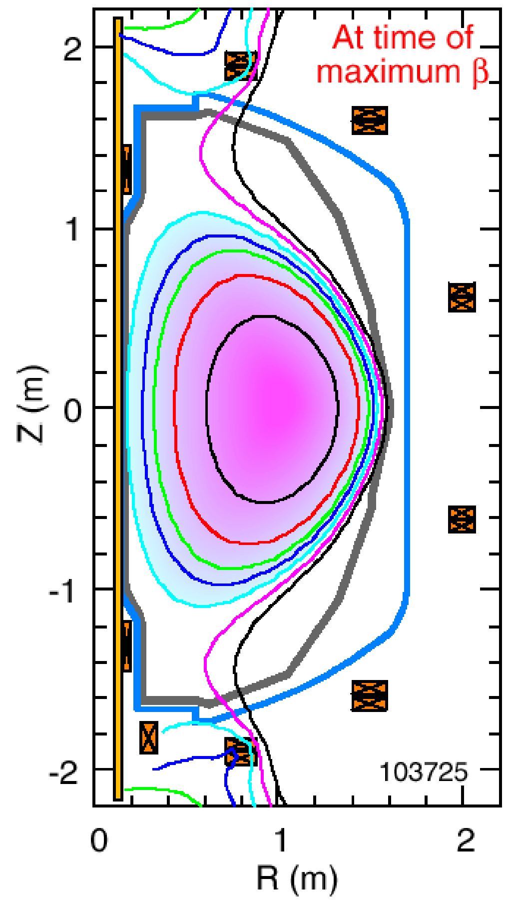
- Onset of mode at q_{min}=1 confirms importance of current profile control

High-β_t With Good Confinement Obtained

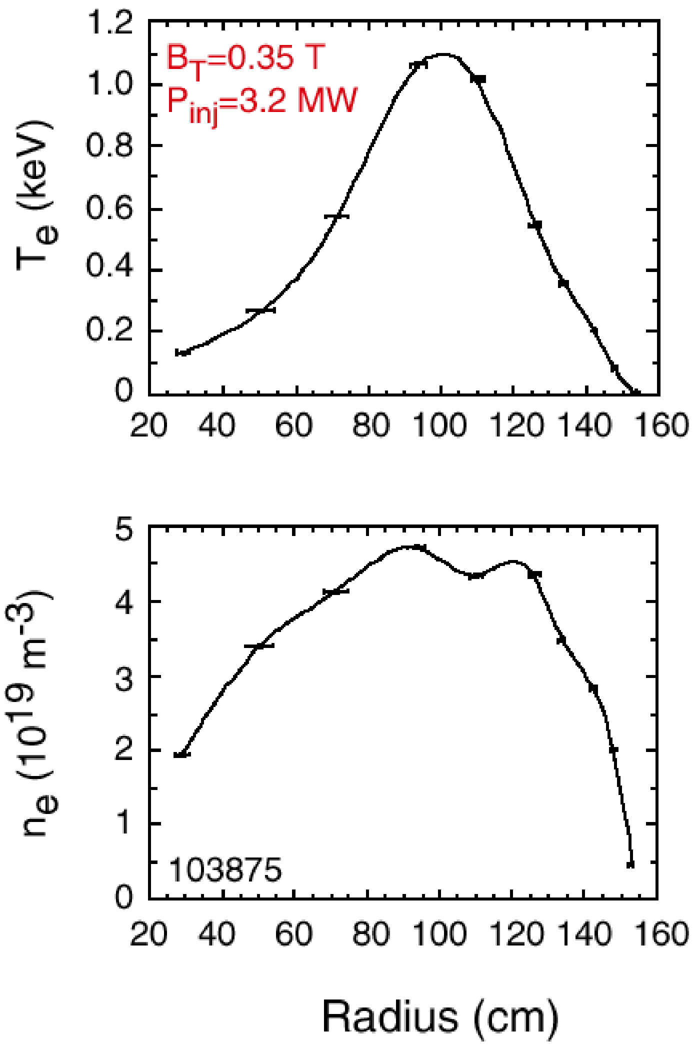
NSTX

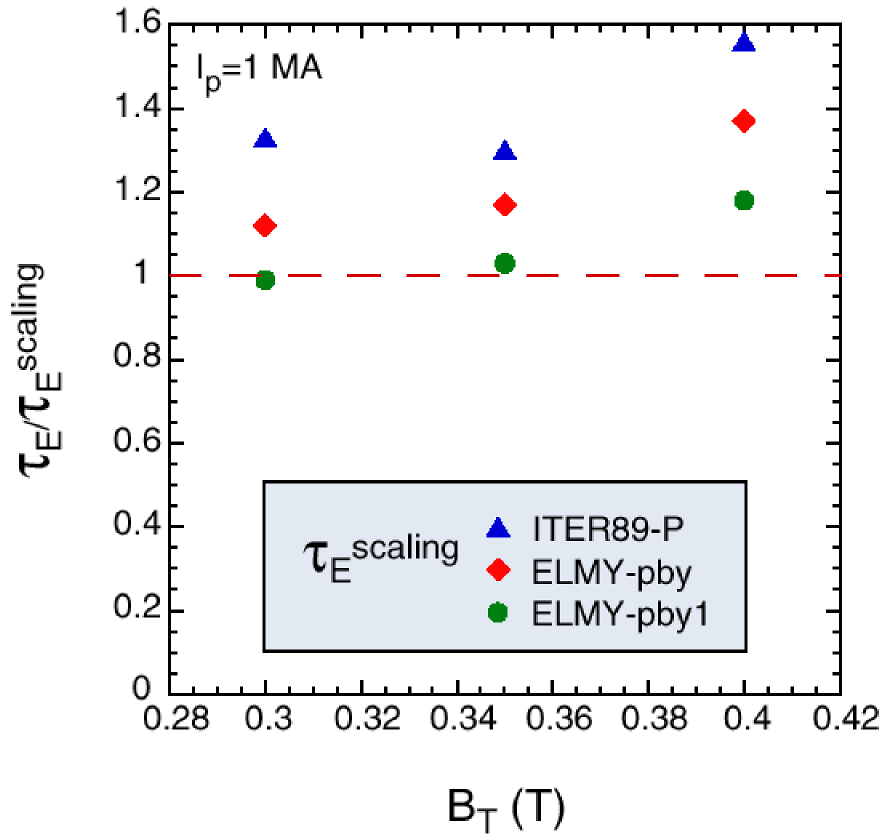
$\beta_t = 2\mu_0\langle p\rangle / B_0^2 = 19.7\%$, $\beta_n = 3.9$, $B_0 = 0.3$ T, $q_\psi = 7.5$



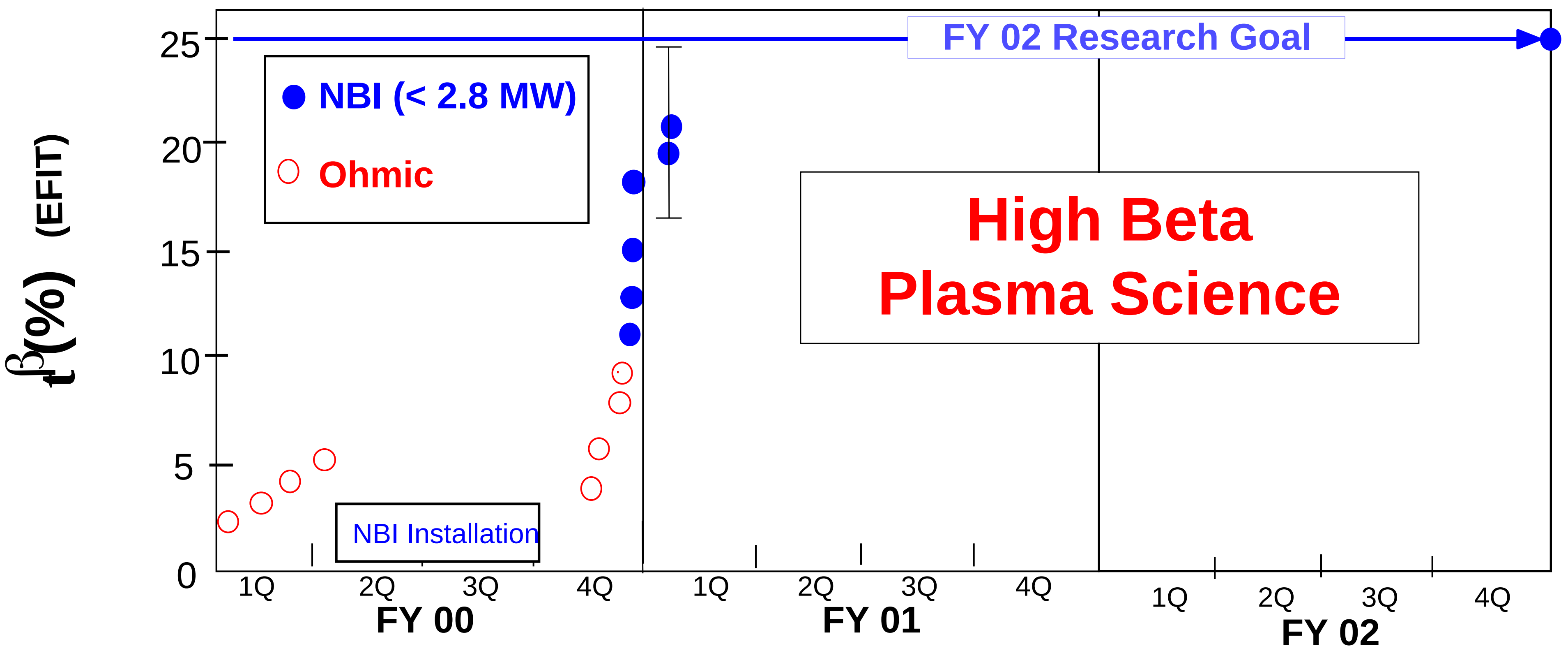


High T_e, Energy Confinement Achieved With NBI





NSTX has Already Exceeded 2/3 of Its Plasma Energy Goal for Oct 1, 2002!



(Kinetic data not yet available)

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)
  - ≤140 kJ; τ_E ≤50 msec, ≤1.6τ_E^{89P}, 0.9-1.4τ_E^{ELMy}
  - ≤ 200 msec current flattop duration at 1 MA
  - NBI heated discharges appear to have excellent confinement

- **HHFW effective in heating electrons**

- **CHI generated ≤270 kA of toroidal current non-inductively**

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

Near Term Plans

- Study wall stabilization techniques (passive, assess need for active) in q_0~1, β_t~25% plasmas with auxiliary systems at full capability
  - HHFW to 6 MW
  - NBI to 5 MW (up to 8 MW)
  - CHI to 500 kA start-up current

- Explore local transport and MHD studies with additional profile and fluctuation diagnostics.

- Continue development of non-inductive current drive techniques (HHFW, CHI, bootstrap)

- Establish physics foundation to explore advanced ST regimes with β_t ~ 40% and f_{bs} ~ 70%.
  - Current/Pressure profile control for core MHD mode stability
  - Wall-mode stabilization for n=1 kink (Columbia-GA-PPPL)