Supported by

NSTX

New NSTX Results and Research Plans

Martin Peng
ORNL (on assignment at PPPL)
On Behalf of **NSTX National Team**

UKAEA Fusion Colloquium
May 16, 2001

Abingdon, United Kingdom

U.S. National NSTX Research Team and International Research Cooperation

M. Ono, E. Synakowski, S. Kaye, M. Bell, R. E. Bell, S. Bernabei, M. Bitter,* C. Bourdelle, R. Budny, D. Darrow, P. Efthimion, D. Ernst, G. Fu, D. Gates, L. Grisham, N. Gorelenkov, R. Kaita, H. Kugel, K. Hill, J. Hosea, H. Ji, S. Jardin, D. Johnson, B. LeBlanc, Z. Lin, R. Majeski, J. Manickam, E. Mazzucato, S. Medley, J. Menard, D. Mueller, M. Okabayashi, H. Park, S. Paul, C.K. Phillips, N. Pomphrey, M. Redi, G. Rewoldt, A. Rosenberg, C. Skinner, V. Soukhanovskii, D. Stotler, B. Stratton, H. Takahashi, G. Taylor, R. White, J. Wilson, M. Yamada, S. Zweben, *Princeton Plasma Physics Laboratory, USA*
M. Peng, R. Maingi, T. Bigelow, C. Bush, W. Houlberg, M. Menon,* D. Rasmussen,* P. Mioduszewski, P. Ryan, P. Strand, D. Swain, J. Wilgen, *Oak Ridge National Laboratory, USA*
R. Raman, T. Jarboe, B. A. Nelson, A. Redd, D. Orvis, E. Ewig, *University of Washington, USA*
S. Sabbagh, F. Paoletti, J. Bialek, G. Navratil, W. Zhu, *Columbia University, USA*
J. Ferron, R. Pinsker, M. Schaffer, L. Lao, B. Penaflor, D. Piglowski, *General Atomics, USA*
D. Stutman, M. Finkenthal, B. Blagojevic, R. Vero, *Johns Hopkins University, USA*
G. Wurden, R. Maqueda, A. Glasser,* *Los Alamos National Laboratory, USA*
G. Porter, M. Rensink, X. Xu, P. Beiersdorfer,* G. Brown,* *Lawrence Livermore National Laboratory, USA*
T. Mau, J. Boedo, S. Luckhardt, A. Pigarov,* S. Krasheninnikov,* *UC San Diego, USA*
N. Luhmann, K. Lee, B. Deng, B. Nathan, H. Lu, *UC Davis, USA*
S. Kubota, T. Peebles, M. Gilmore, *UC Los Angeles, USA*
F. Levinton, J. Foley, *Nova Photonics, USA*
P. Bonoli, A. Bers, A. Ram, *MIT, USA*
W. Heidbrink, *UC Irvine, USA*
M. Ulrickson,* R. Nygren,* W. Wampler,* *Sandia National Laboratory, USA*
J. Lowrance,* S. von Goeler,* *Princeton Scientific Instruments, USA*
J. Myra,* D. D'Ippolito,* *Lodestar, USA*
C. Cheng,* *NYU, USA*
R. Akers, S. Fielding, A. Sykes, M. Nightingale, etc., *EURATOM/UKEA. Culham, UK*
Y. Takase, H. Hayashiya, Y. Ono, S. Shiraiwa, *Univ. Tokyo*.; O. Mitarai, *Kyushu Tokai Univ*.; M. Nagata, *Himeji Inst. Technology*; N. Nishino, *Hiroshima Univ.*, A. Ishida, *Niigata Univ.*, T. Tamano, *Tsukuba Univ., Japan*
V. Gusev, A. Detch, E. Mukhin, M. Petrov, Y. Petrov, N. Sakharov, S. Tolstyakov, Dyachenko, *Ioffe Inst.;* A. Alexeev, Krasilinikov, S. Mirnov, I. Semenov, *TRINITI;* V. Belyakov, *Efremov Inst., Russia*
N. Na, *KBSI, Korea*

*In cooperation with DOE OFES Theory, OFES Technology, Astrophysics, or SBIR programs

NSTX Has Begun to Investigate New Plasma Properties in the Very Low Aspect Ratio Regime

- Why ST and NSTX?
- Exciting results– first 7 run-weeks with strong heating
  - Coaxial Helicity Injection (CHI)
  - Macroscopic modes at high toroidal beta β_T
  - Heating and energy containment efficiency
  - Effects of energetic NBI ions
  - Edge fluctuations
- Research plan

Tokamak Theory in Early 1980's Showed Maximum Stable β_T Increased with Lowered Aspect Ratio (A)

- A. Sykes et al. (1983); F. Troyon et al. (1984) on maximum stable toroidal beta β_T:

$$\beta_{Tmax} \approx \beta_N I_p / a B_T \approx 5 \beta_N \kappa / A q_j$$

where

β_N ~ constant (~ 3 %m·T/MA)

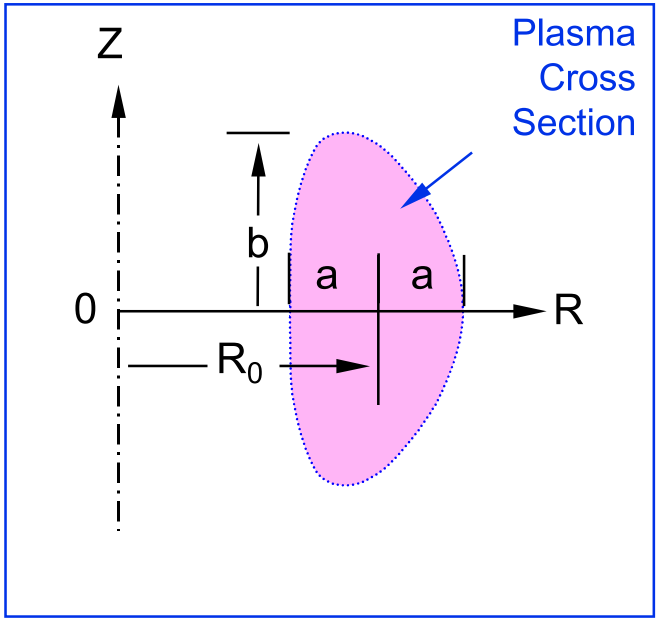
κ = b/a = elongation

A = R_0/a = aspect ratio

$q_j \approx$ edge safety factor

I_p = toroidal plasma current

$B_T \approx$ applied toroidal field at R_0

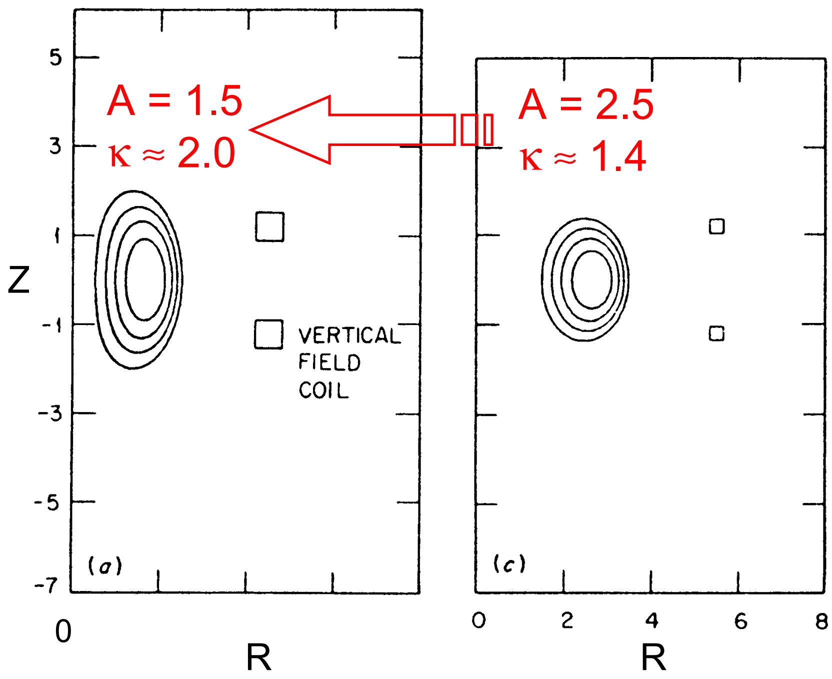


- Peng & Strickler (1986):

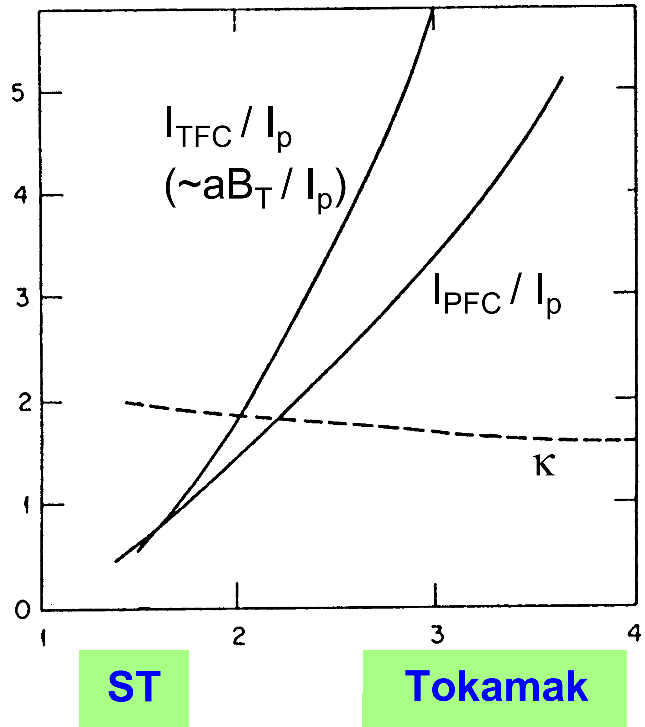
What would happen to tokamak equilibrium as A → 1?

Spherical Torus Plasma Elongates Naturally, Uses Less Coil Currents, and Increases I_p/aB_T & β_{Tmax}

Natural Elongation

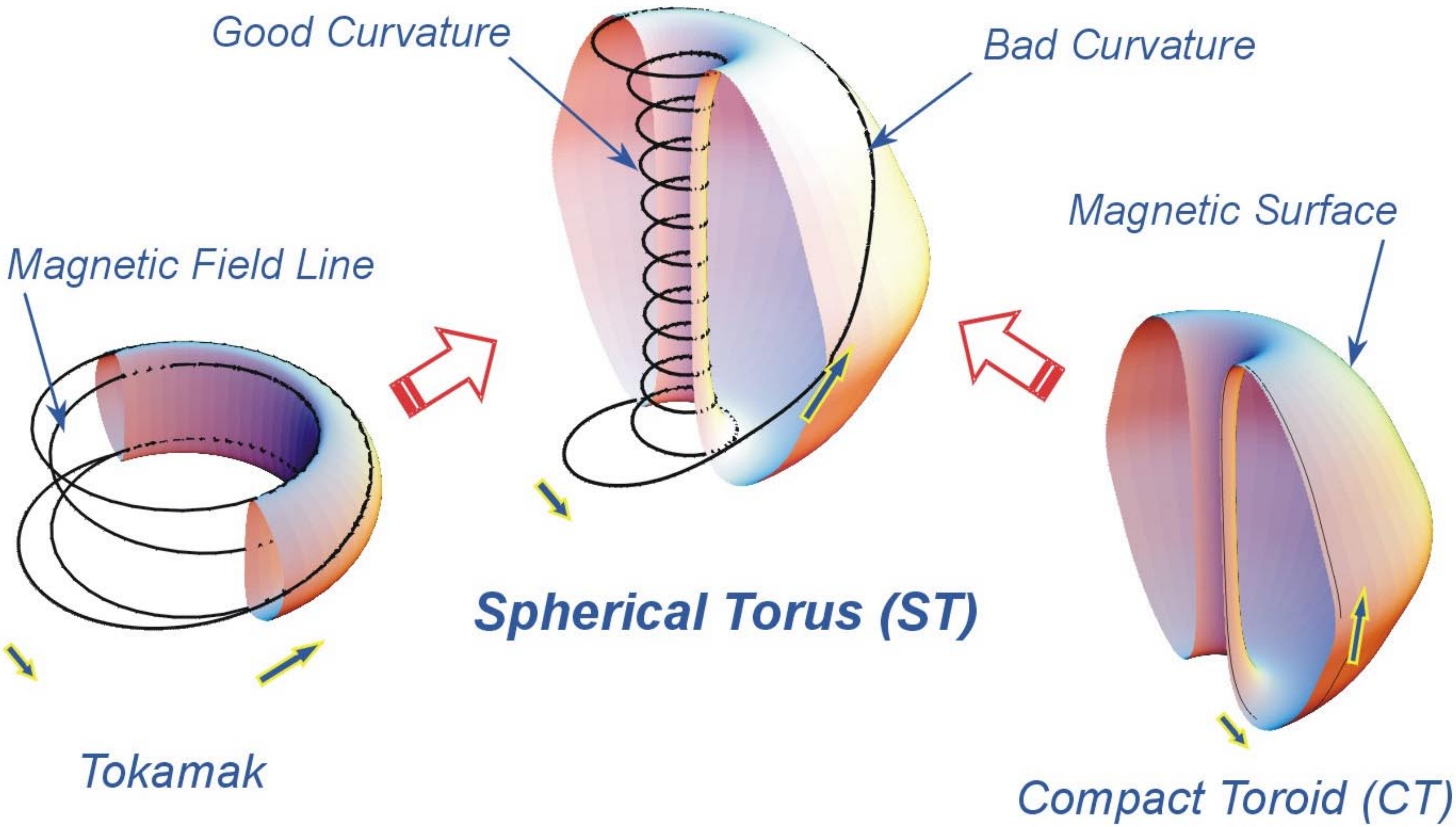


Coil Currents/I_p (q_{edge}~2.5)



- Elongates naturally to $\kappa \sim 2$; $I_{TFC} < I_p$, $I_{PFC} < I_p$
- $I_p/aB_T \sim 7$ MA/m·T $\Rightarrow$ **$\beta_{Tmax} \sim 20\%$, if $\beta_N \sim 3$**
- Basic relationship exceeded by **START** (U.K., 1989-1998)!

Minimizing Tokamak Aspect Ratio Maximizes Field Line Length in Good Curvature

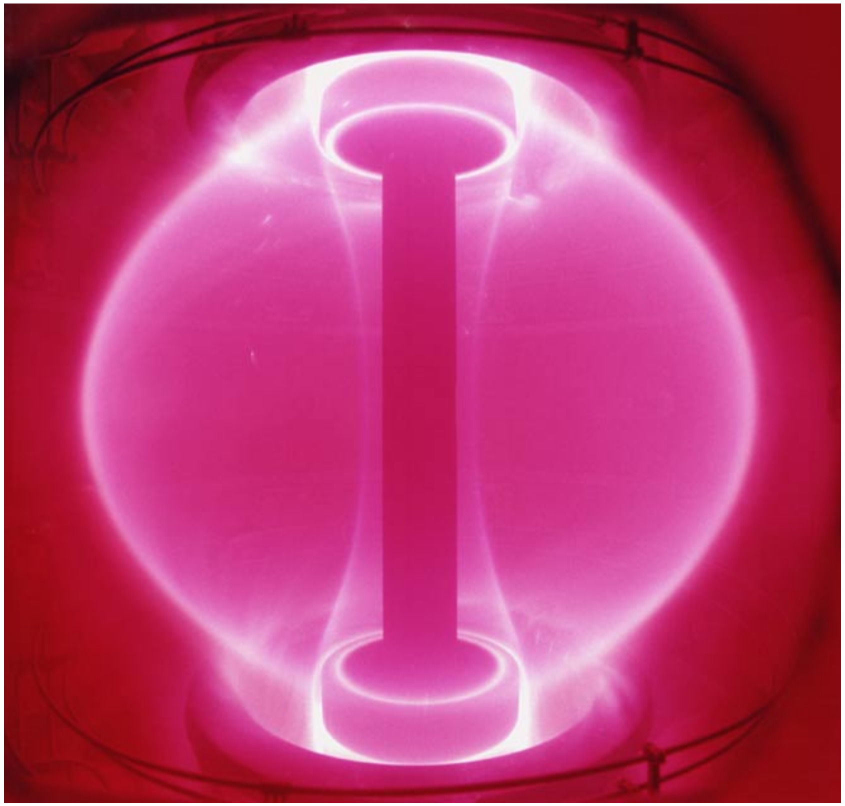


The outboard field lines are closer to CT.

Record High β_T (~40%) was Achieved by START (U.K.) in 1998

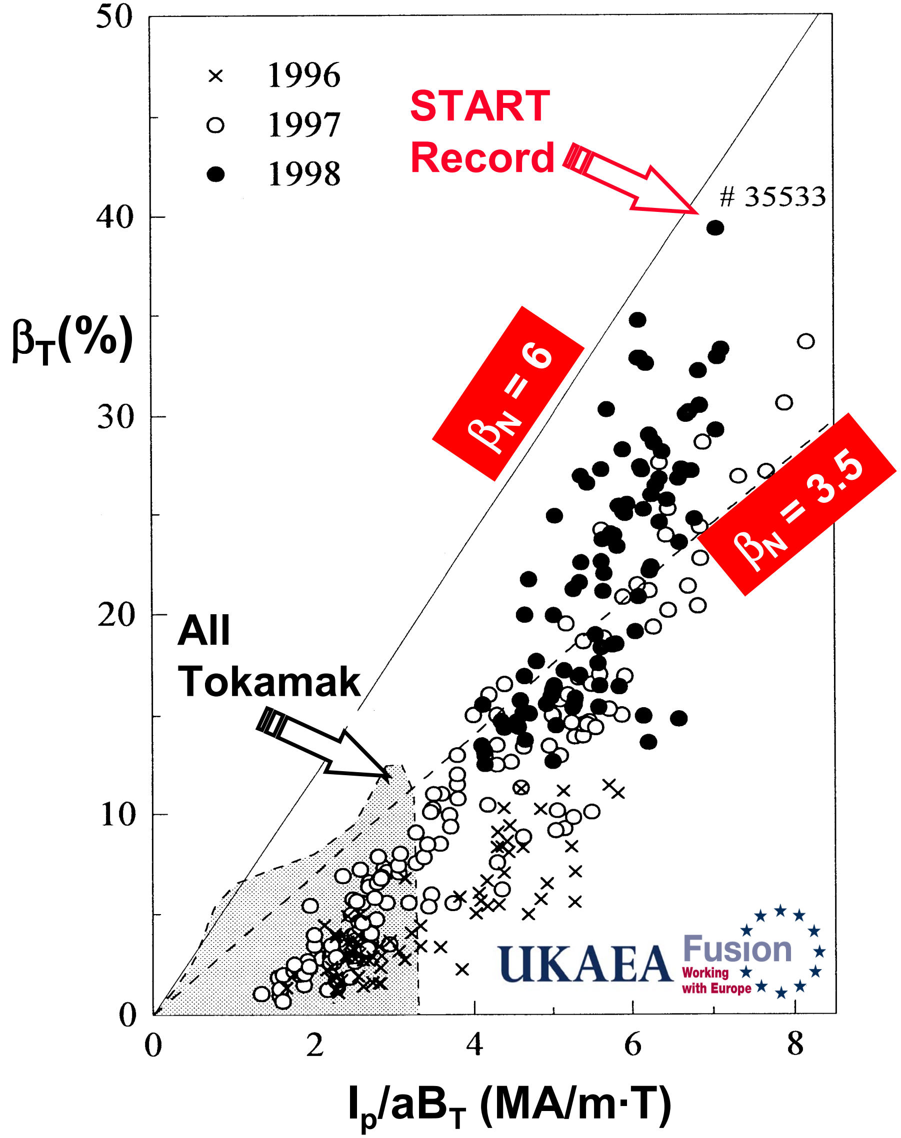
START

(Courtesy of A. Sykes & START Team, U.K.)

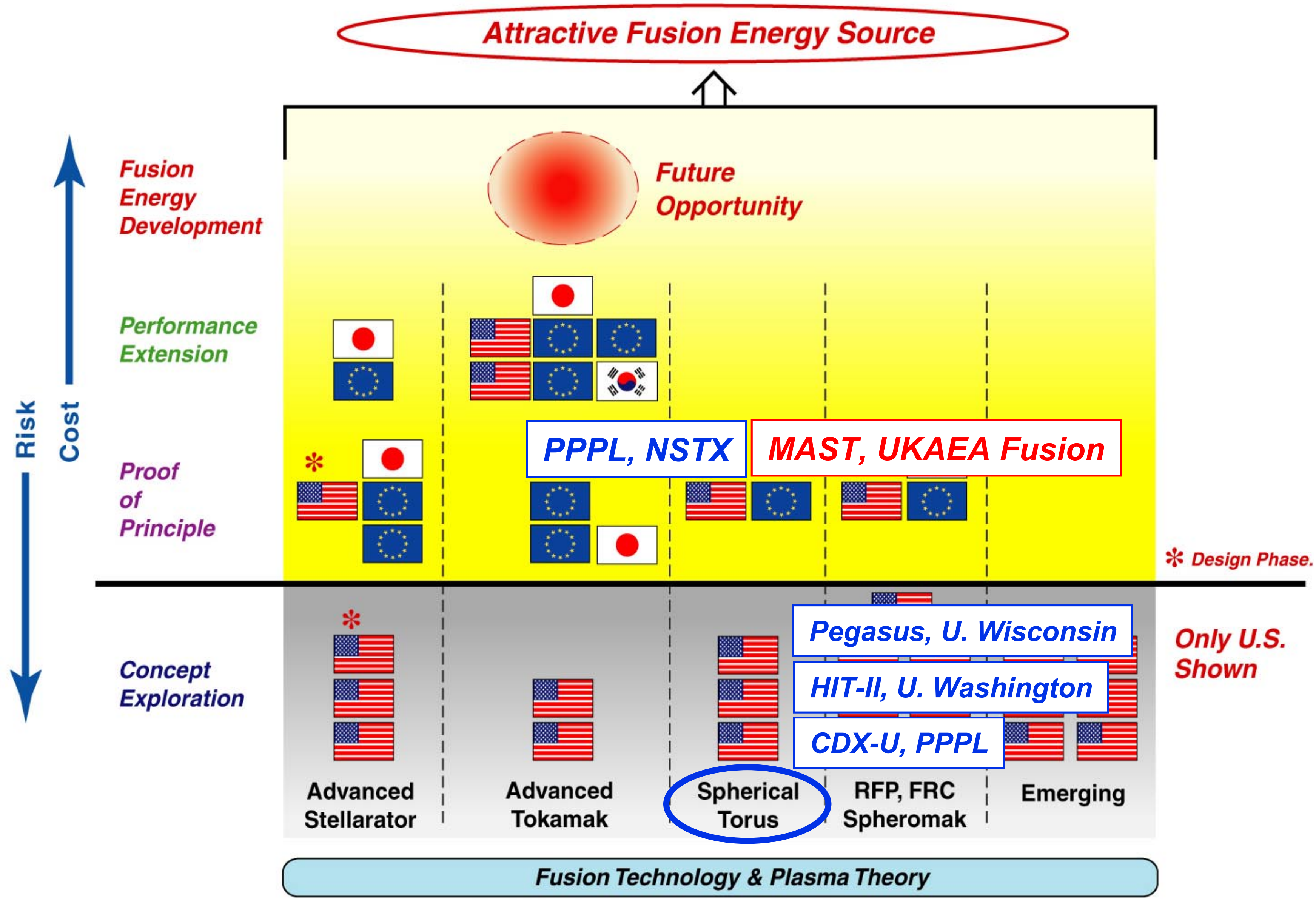


1 m

- I_p ~ 250 kA, $\langle\beta\rangle \rightarrow$ 15%, for ~10 ms
- Low q_{95} ~ 3, κ ~ 1.8, no nearby wall
- β_N can be higher than 3!



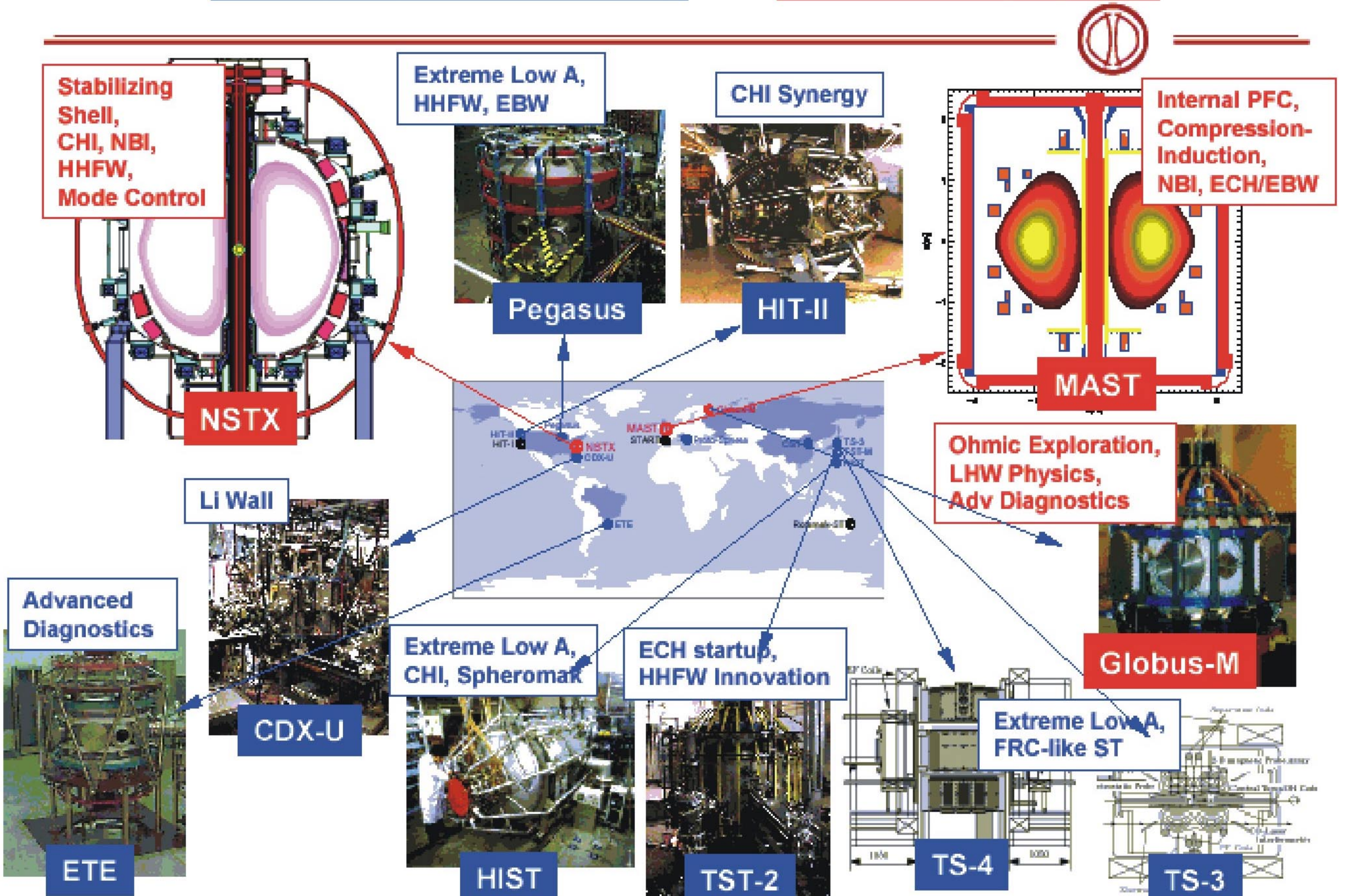
Spherical Torus Became A Component in U.S. Fusion Portfolio, & NSTX A Proof of Principle Experiment



Facilities both operating and under construction.

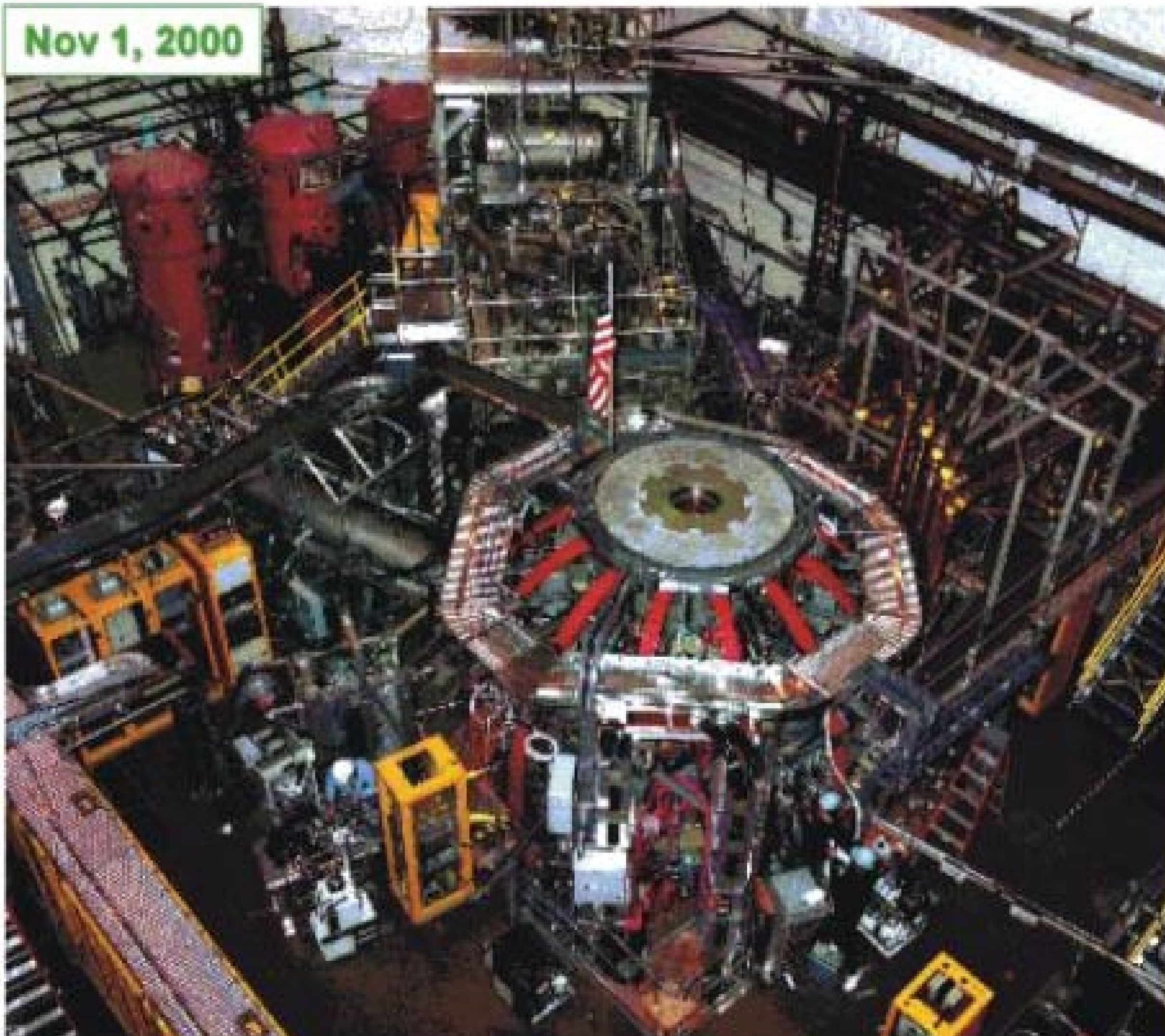
NSTX Is Part of Growing US & Worldwide ST Research

Concept Exploration (~0.3 MA) | Proof of Principle (~MA)



NSTX Facility Has Continued Great Progress in Operational and Experimental Capabilities

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 ($\leq$0.45 T)

Heating and CD
5 MW NBI (4.5 MW)
6 MW HHFW (4.2 MW)
0.5 MA CHI (0.26 MA)

Pulse Length
= 5 sec (0.5 sec)

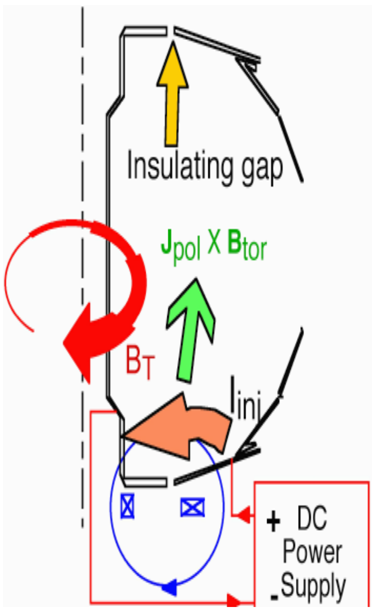
NSTX Is To Prove the Science Principles for Practical Fusion Energy

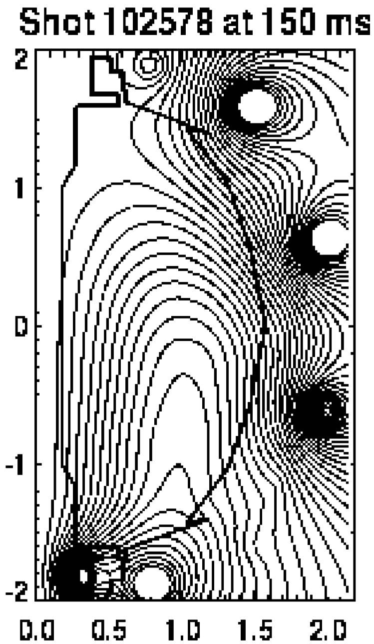
NSTX

Spherical Torus Scientific Principles for	→	Benefits to Fusion Energy
Startup & sustainment with minimal or no solenoid magnet?	→	Simplified magnets & design
High toroidal beta & order-unity central beta?	→	Lower magnet and device costs
Reduce turbulence & improve containment efficiency?	→	Small unit size for sustained burn
Disperse plasma heat and particle fluxes over large area?	→	Survivable plasma facing components
Copious supra-Alfvénic energetic ions (NBI, fusion α)?	→	Efficient fusion self heating?

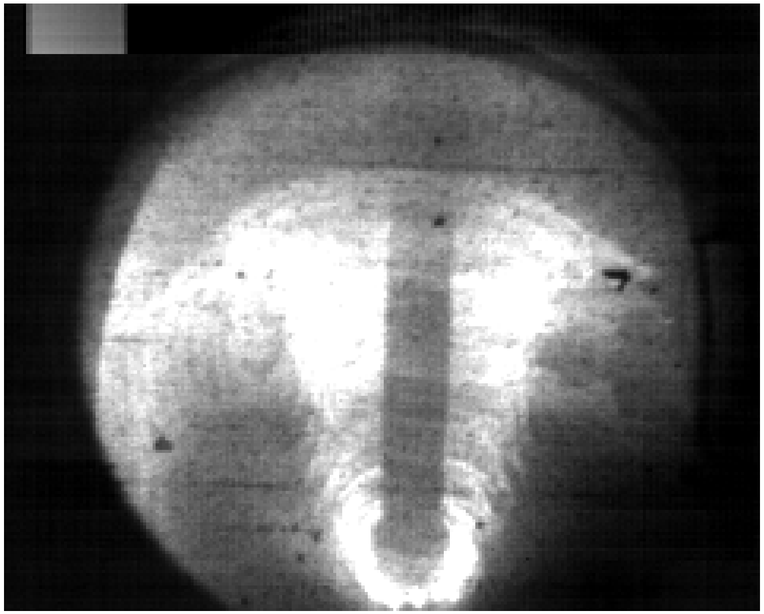
NSTX Contributes both to toroidal science & development of the ST concept.

CHI Converts DC Voltage and Current into Plenty of Toroidal Current Without Solenoid Induction

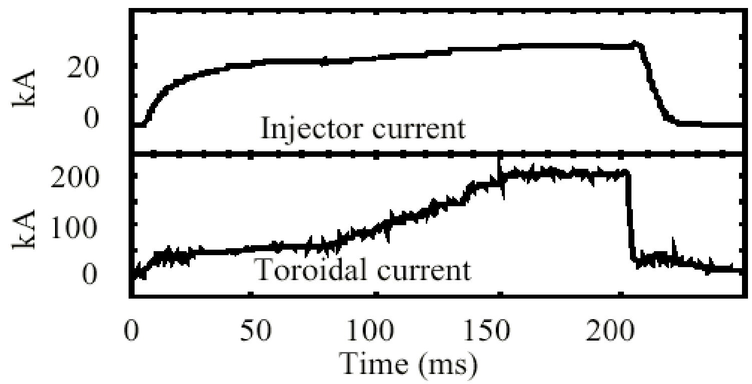




(MFIT, M. Schaffer, GA)


Fast Camera (R. Maqueda, LANL)

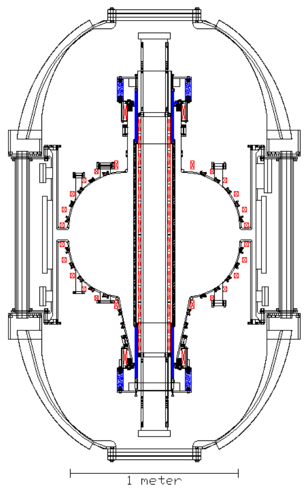
- **No Closed Flux Surface:** Effects of induction, B_T ,poloidal shaping, instabilities, electron flow on reconnection and flux closure?
- Plasma control and unwanted arcs?
- Compare with HIT-II, HIST (Japan)?



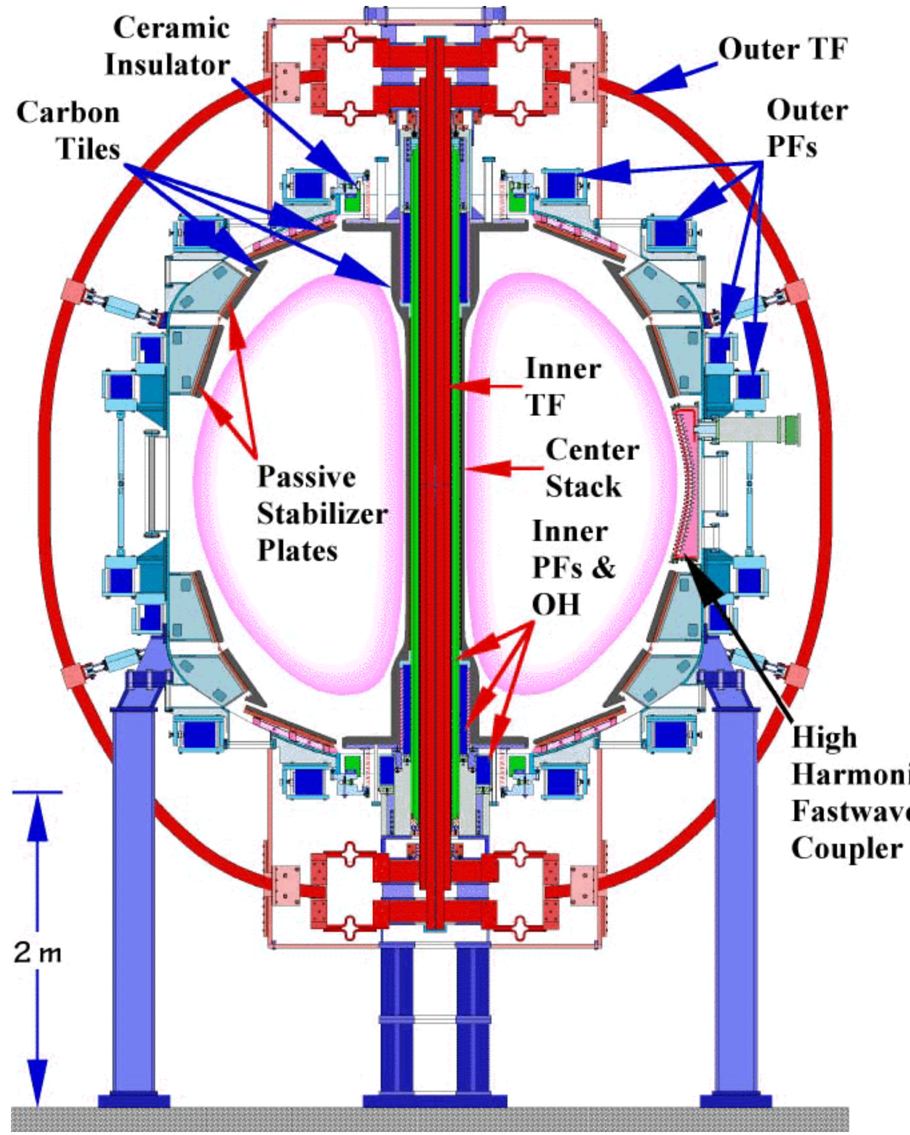
(R. Raman, R. Nelson, T. Jarboe, U. Wash; D Mueller, D. Gates, PPPL)

Close Cooperation Between HIT-II (U Wash.) and NSTX Are Crucial to CHI Research

HIT-II, U. Wash.



- ⇑ Closed flux surfaces observed
- ⇑ Long insulator on center post
- ⇑ Many close-by fast PF coils
- ⇒ Flux surface not yet closed
- ⇒ 30 × volume
- ⇒ 20 × pulse length
- ⇒ Lower density



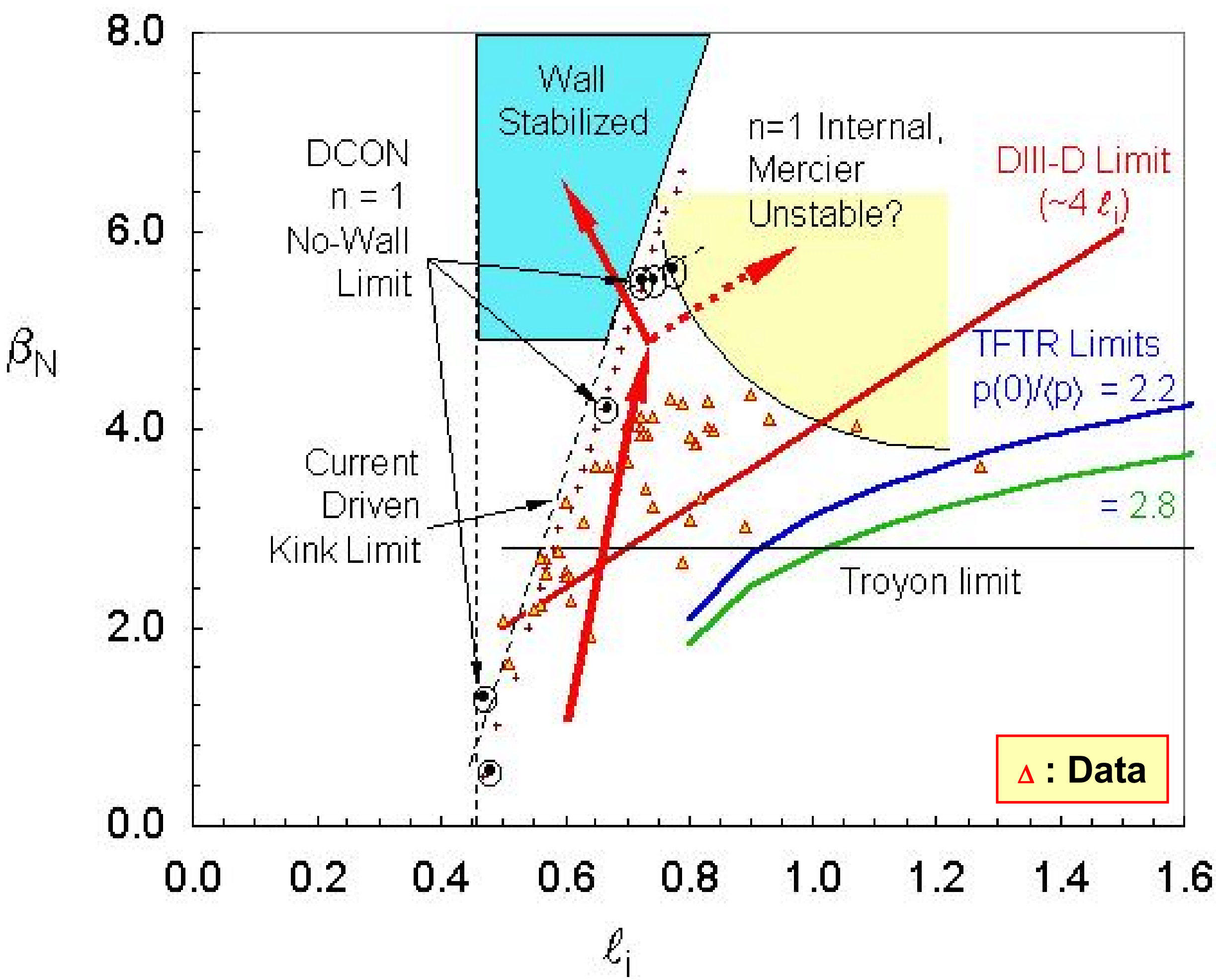
Several Instabilities Have Been Observed or Are Expected for β_T in the 10-20% (β_N ~ 2-4) Range

NSTX

Instability	Free Energy
• Current-driven kinks	$j'(r)$, q_{edge} = integer
• Ideal low-*n* kink/ballooning (?)	∇p
• Resistive wall modes (?)	∇p
• Tearing modes (neoclassical?)	∇p
• Sawteeth	$j'(r)$, $q < 1$
• Fast reconnection events	$j'(r)$, high η_{edge}
• High frequency Alfvén(?) modes	energetic particles, etc.

(ET2 leaders: S. Sabbagh, Columbia U., J. Menard, PPPL)

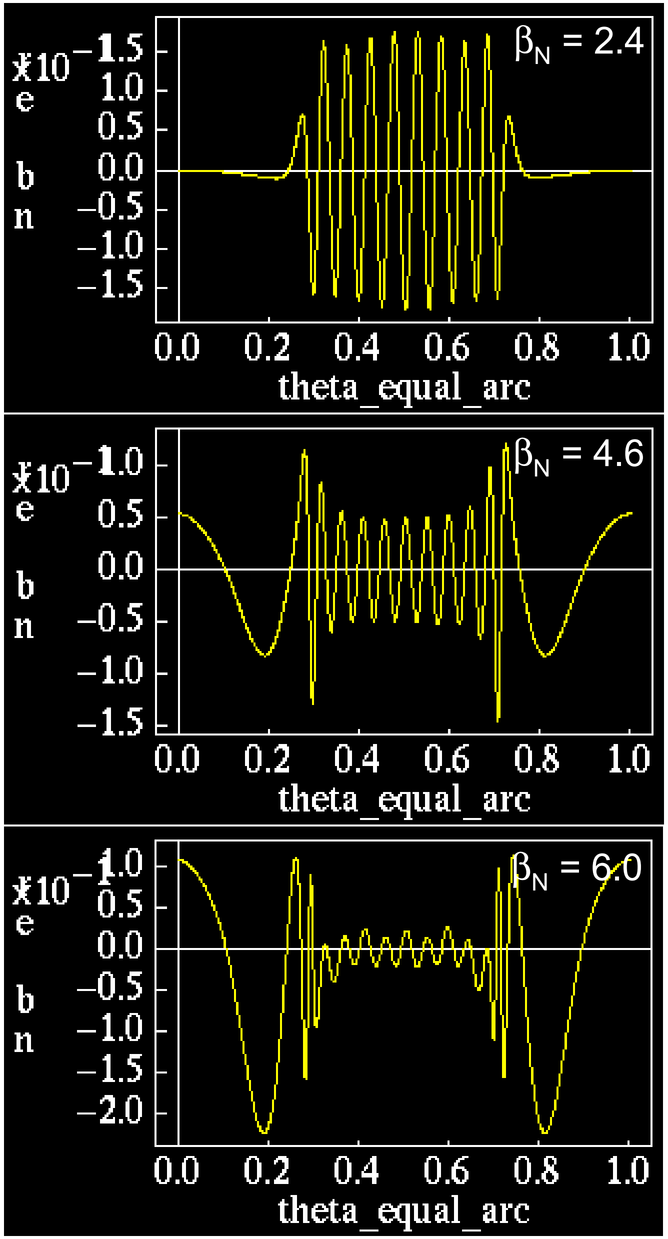
Present Data and Analysis Suggests New Scenarios to Test Instabilities at Even Higher β_N



(S. Sabbagh, F. Paoletti, Columbia U; Jon Menard, PPPL)

- Raise $\beta_N \Rightarrow$ 5+ while increasing ℓ_i to avoid current-driven kink modes
- Raise $\beta_N \Rightarrow$ 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

(II) Pressure Driven MHD Modes Couple to Outboard Conductor Only at High $\beta_N \Rightarrow$ RWM Control

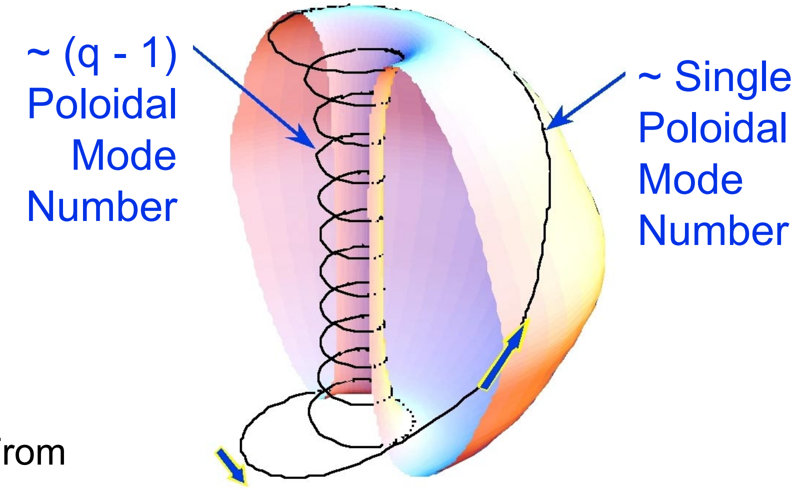


Profiles From #104403

Calculated Mode Structure of Edge δB_{norm} vs. Poloidal Angle

(Bialek, Paoletti, Sabbagh, Columbia U; Manickam, PPPL)

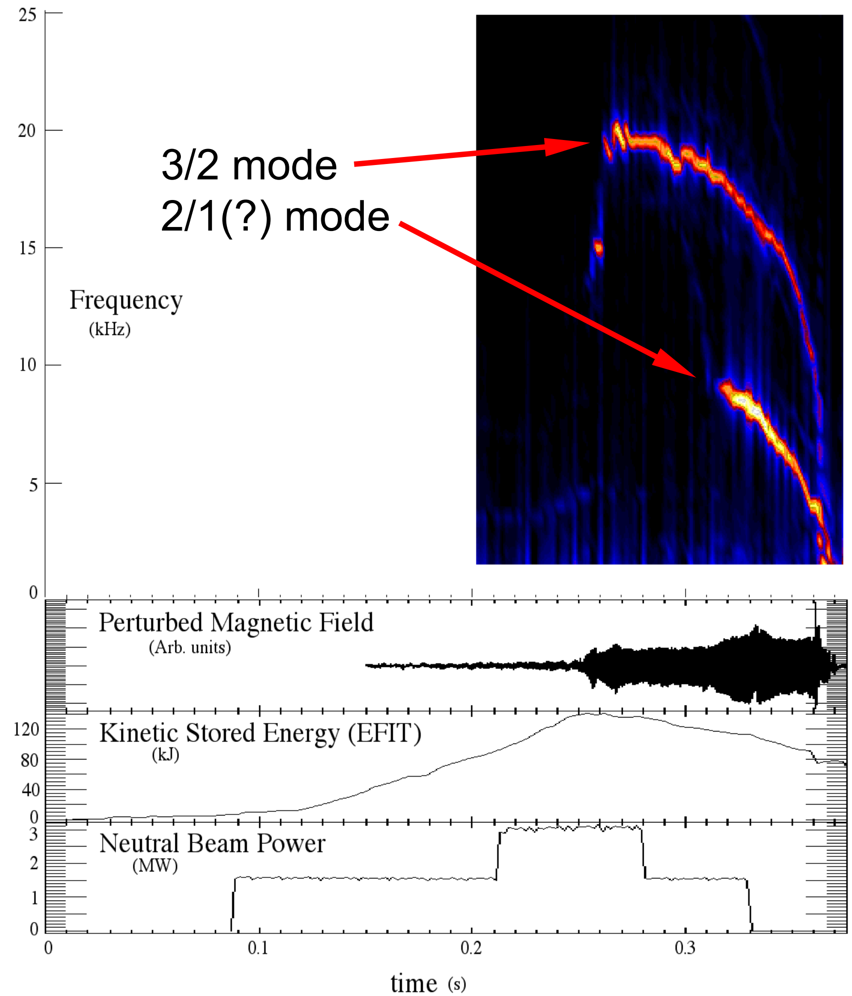
- **At low β_N:**
  - Max. amplitude on inboard
  - Short poloidal wavelength
- **At high β_N:**
  - Max. amplitude on outboard
  - Long poloidal wavelength



β-Limiting MHD Mode Identification Has Begun

- Expect different β-limiting modes in different regimes:
  - RWM, NTM, …
  - Improve magnetics, SXR diagnostics
- Identify beta-limiting modes to determine strategy for mode control
- Start feedback system design near end of FY '02
  - Active magnetic coils,
  - Reduce error fields to encourage plasma rotation, and/or
  - EBW CD for tearing modes?

Possible Tearing Modes, #104162



(D. Gates, PPPL)

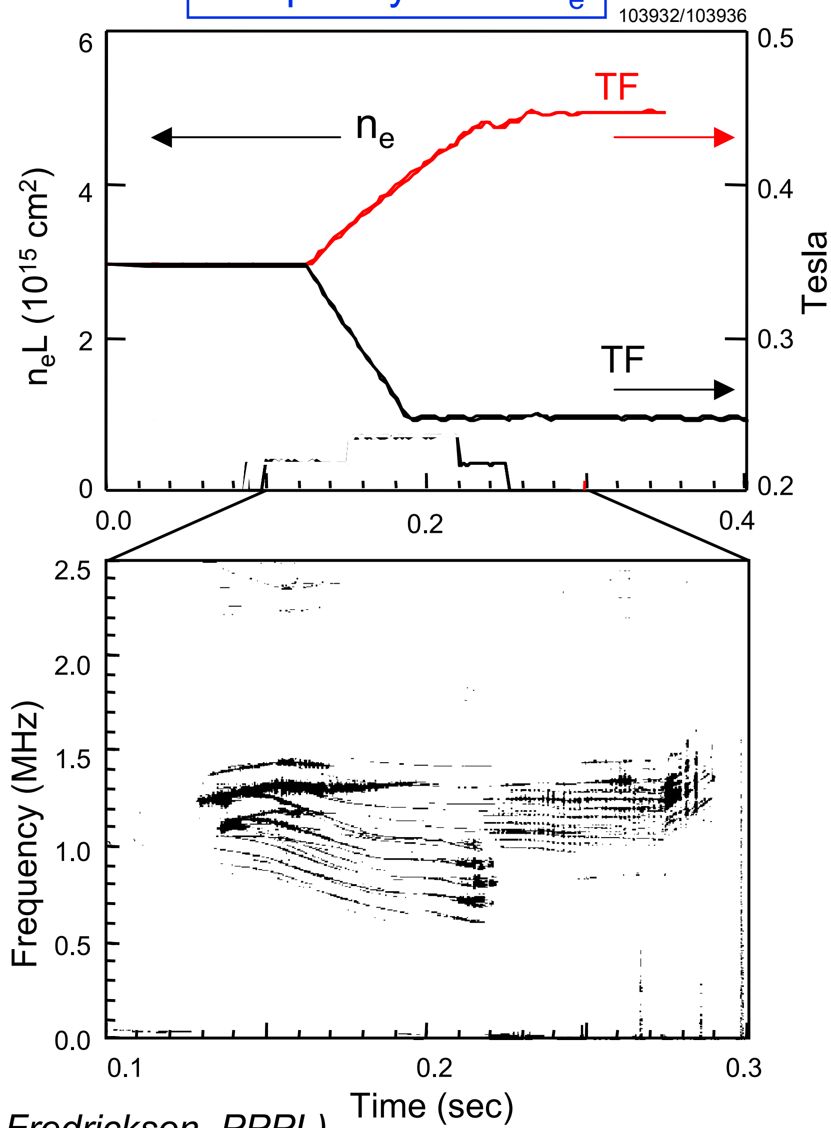
New Energetic Ion-Induced MHD Data Speaks to New Science

NSTX

- **Rich variety of modes**
  - Likely Compressional Alfven Eigenmodes (AE's)
  - Multiple bands
  - Measure effects on fast ions (TRINITI)
- **New physics regime?**
  - $V_{beam} >> V_{Alfven}$
  - $V_{th} \sim V_{Alfven}$ at high beta
- **New theory**
- **DIII-D/NSTX comparison should be revealing**
  - Role of aspect ratio (UC Irvine)
  - Different gap structure at low A

(D. Darrow, N. Gorelenkov, PPPL; W. Heidbrink, UC Irvine; A. Krasilnikov, A. Alekseyev, D. Portonov, TRINITI)

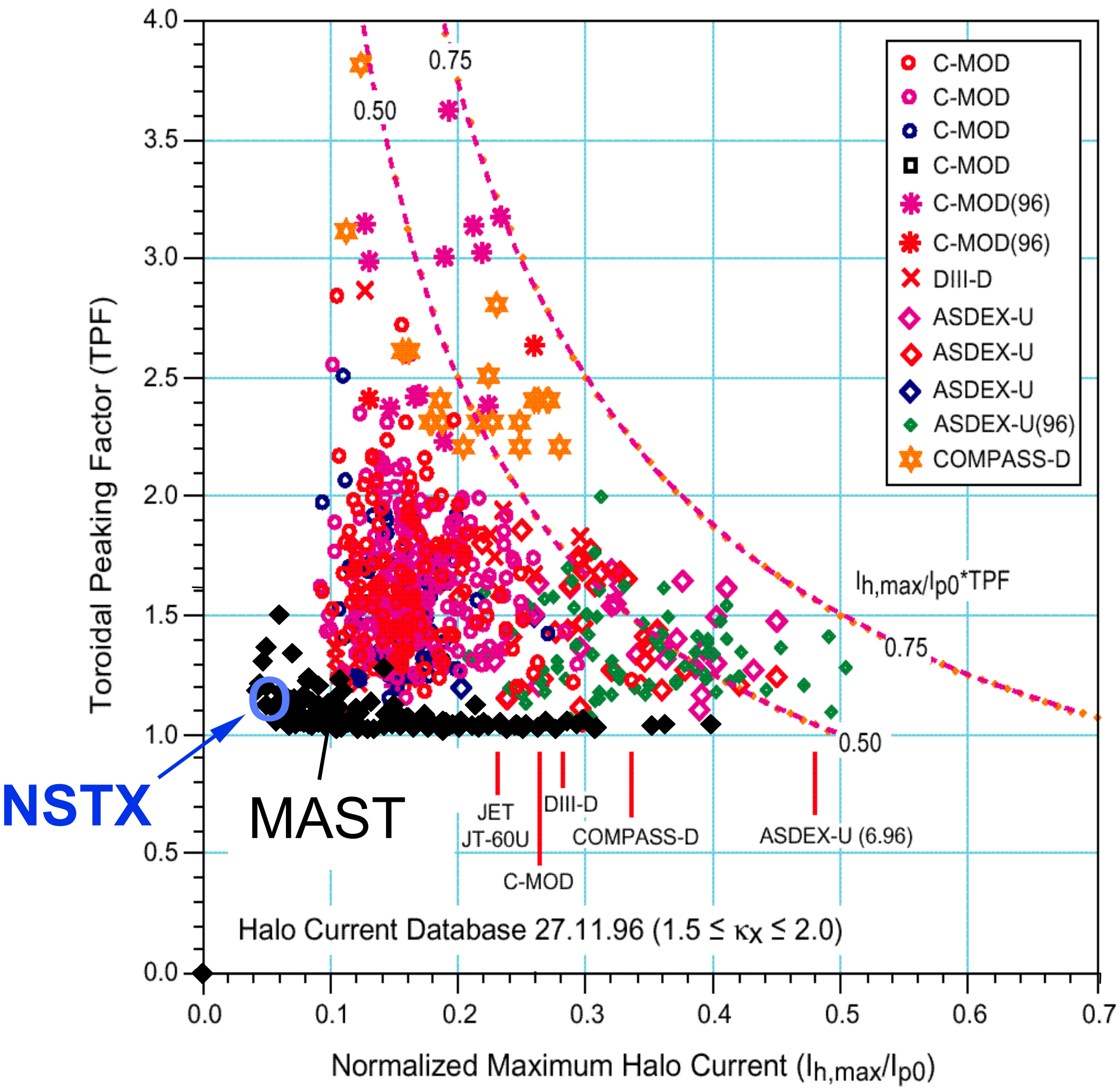
Frequency $\propto B^{1/2}/n_e$



(E. Fredrickson, PPPL)

Halo Currents in MAST & NSTX Have Been Very Modest

UKAEA Fusion Working with Europe



*(ITER Physics Basis, Nuclear Fusion **39** (1999) 2137)*

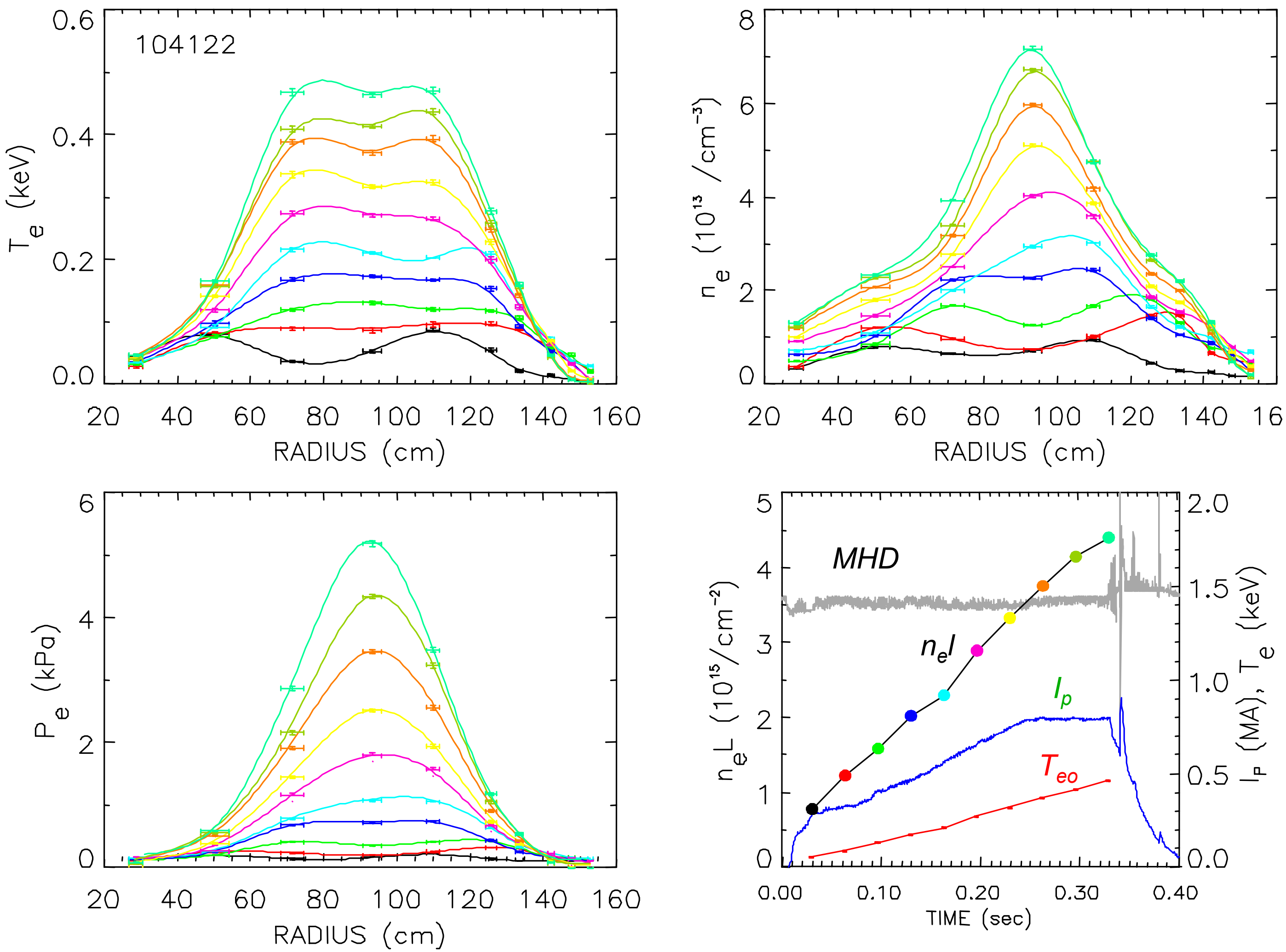
- **Lower and more symmetric halo currents anticipated in ST than in tokamak**
- **Scientific Understanding Important**

- POMPHREY, N, BIALEK, J M & PARK, W, Nuclear Fusion **38** (1998) 449.
- CALOUTSIS, A and GIMBLETT, C G, Nuclear Fusion **38** (1999) 1487.

MHD-Quiescent Ohmic Plasmas Points to Existence of Pressure Peaking or Internal Barrier Formation

NSTX

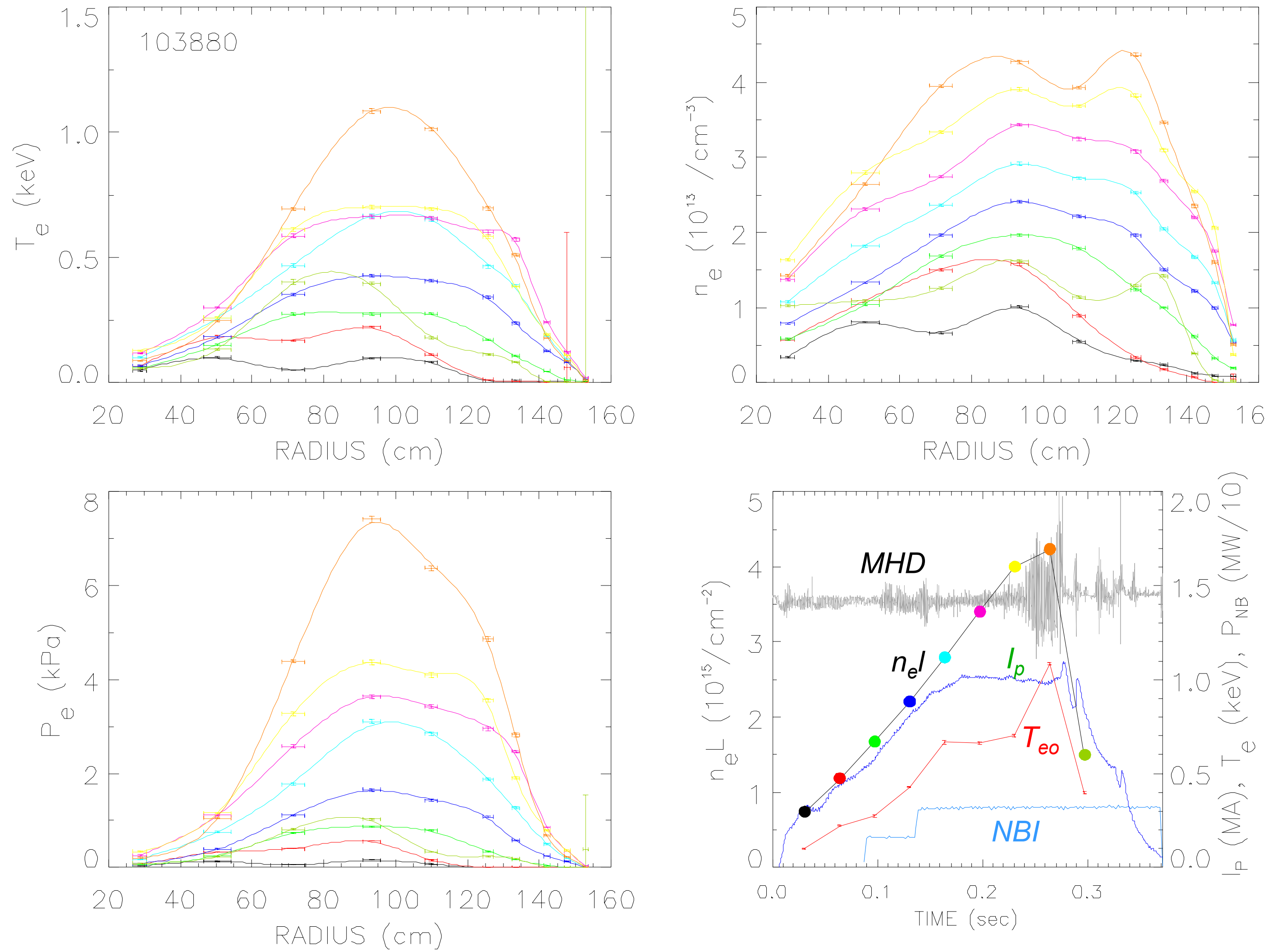
Increasing central T_e and n_e at constant current!



(B. LeBlanc, R. Bell, PPPL)

A Late Te Increase in Some Cases Suggests Core Transport Barrier

No H mode transition

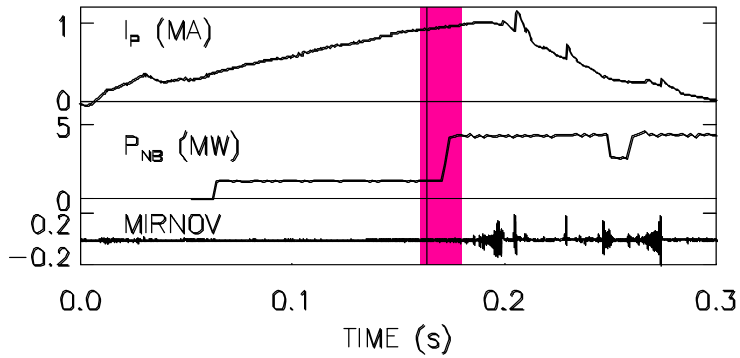


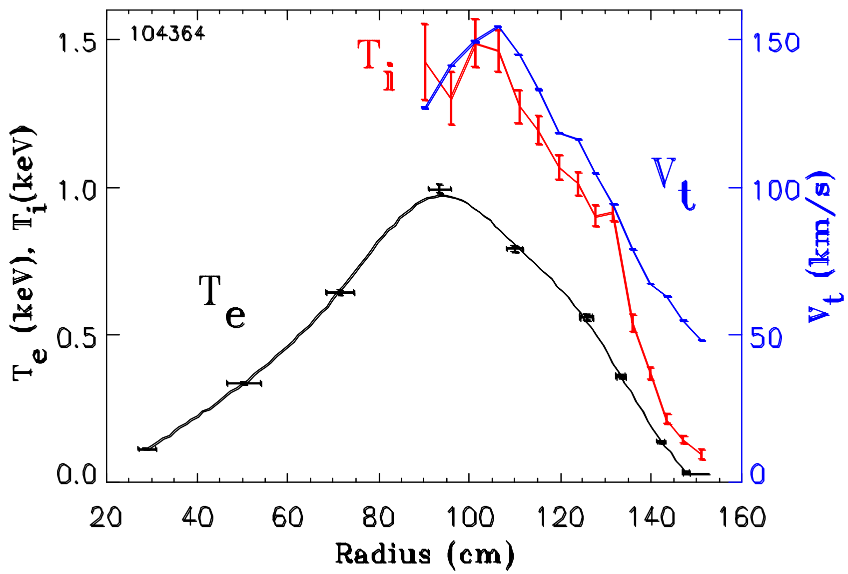
(B. LeBlanc, R. Bell, PPPL)

Charge Exchange Recombination Spectroscopy Reveals Very Strong Ion Heating by NBI & High Edge Rotation

- Preliminary CHERS data
- Interim system, 17 spatial channels
- C-VI, n=8-7, 5290 Å, 20-ms window
- Present analysis done at NBI power step-up points.
- Power balance issues to resolve:
  - (T_i -T_e) much larger than expected
  - D vs. C rotation speeds
  - Exotic mechanisms (related to: supra-Alfven beam ions; non-adiabaticity of beam ion orbit; large Alfven Mach number; large ρ_{NBi}*, ρ_i*?)

$n_e \sim 4\times10^{19}$ m^{-3}, no H mode transition

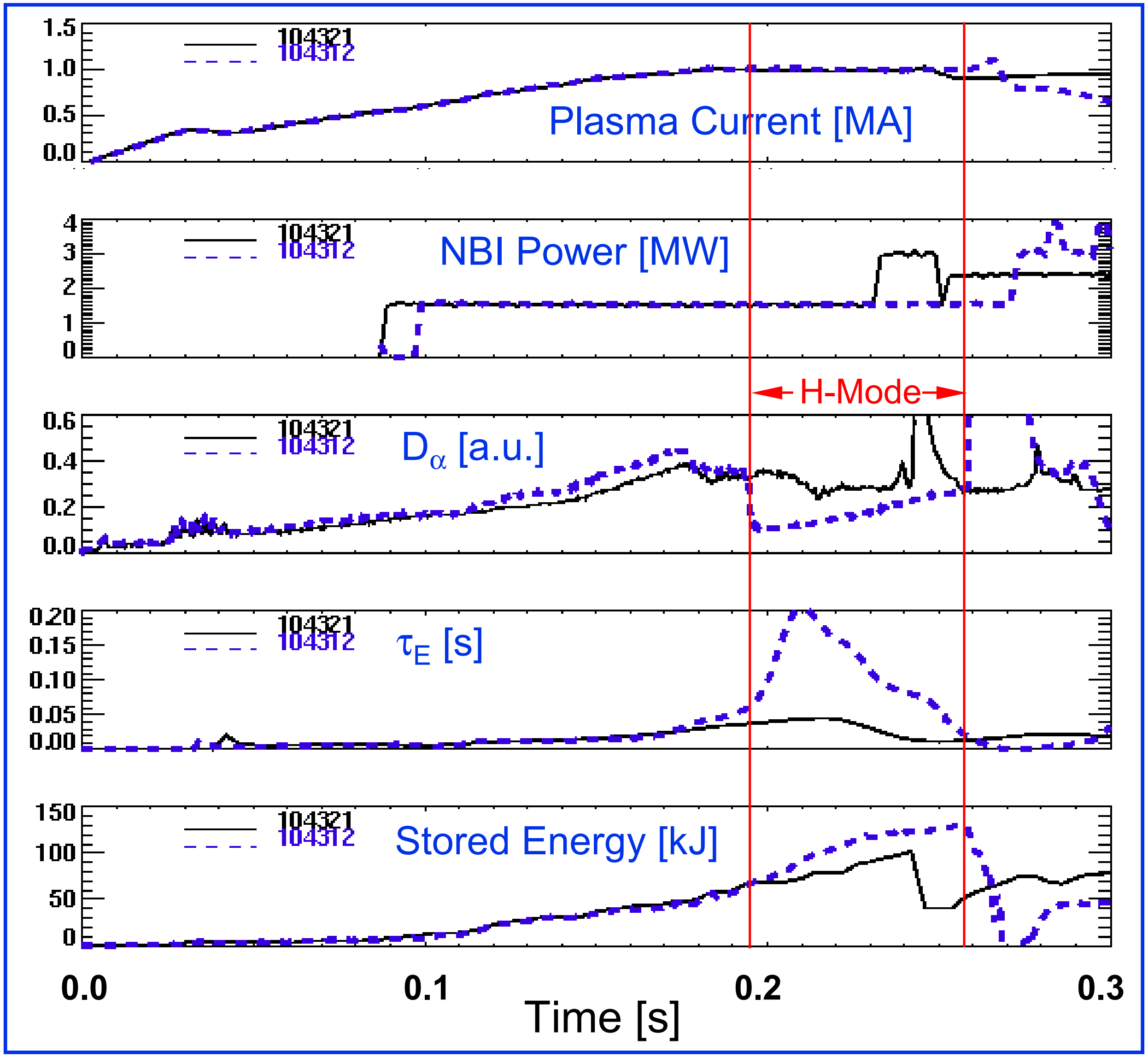




(R. Bell, PPPL)

(ET1: S. Kaye, B. LeBlanc, PPPL; Th: Z. Lin, PPPL, W. Houlberg, ORNL)

Short Duration H Mode Transitions Observed



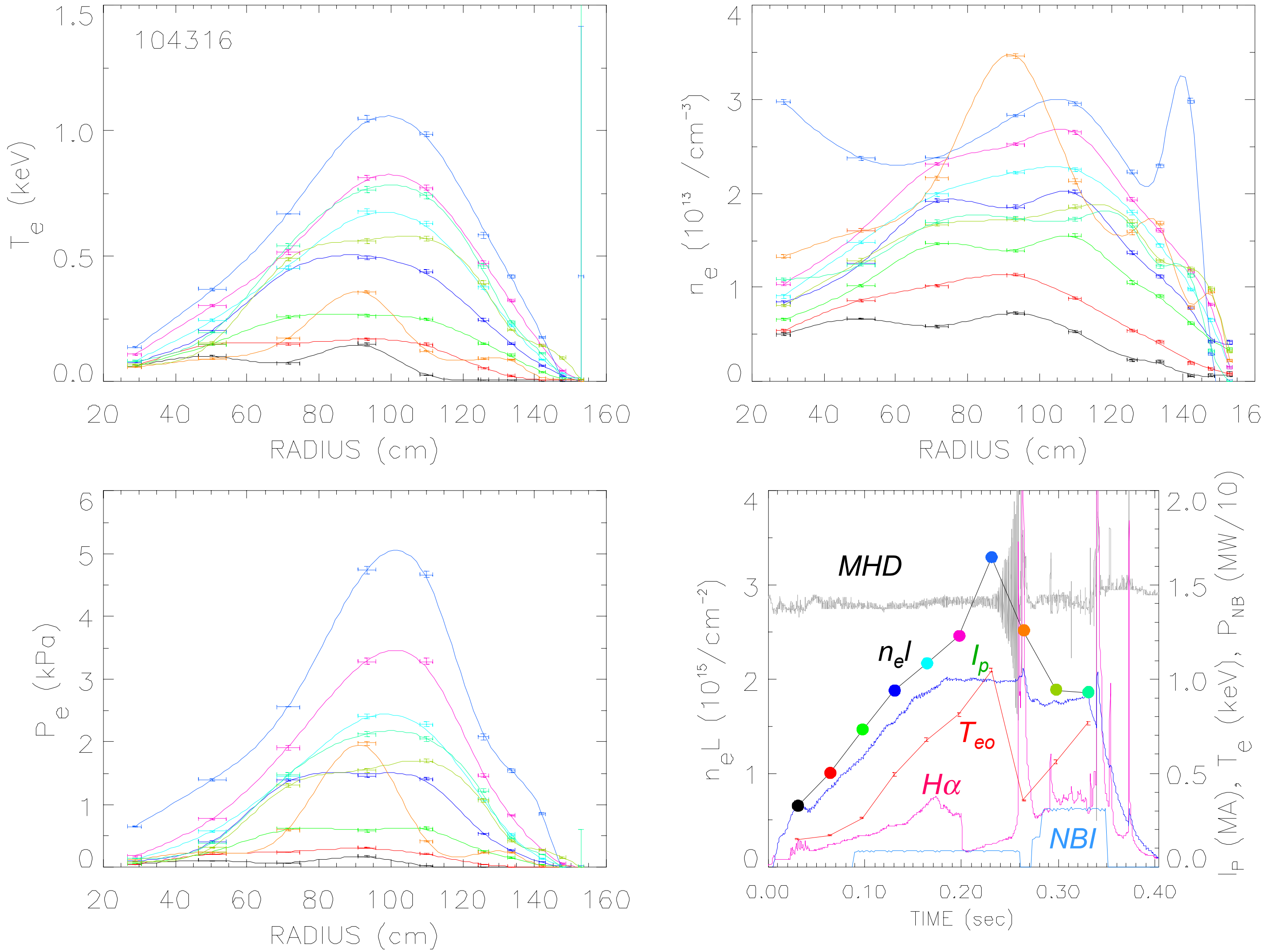
- **Same I_p**
- **Early NBI**
- **D_a drop in H-mode**
- **τ_E improves (EFIT)**
- **Stored energy increases 25% (EFIT)**

(R. Maingi, ORNL, S. Sabbagh, Columbia U.)

H Mode Transition Has Been in Some Cases Clearly Seen in Electron Density and Pressure Profiles

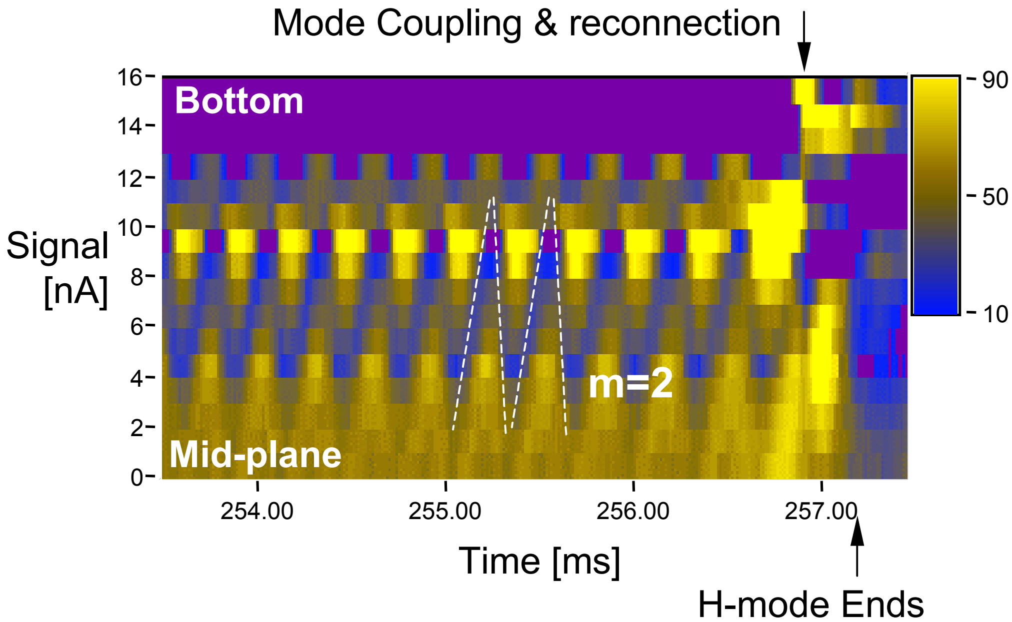
NSTX

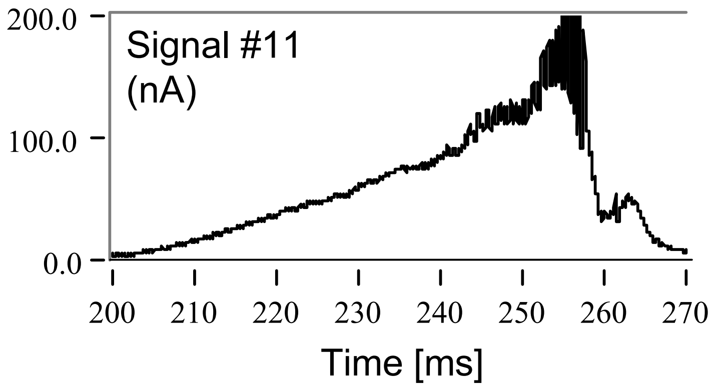
MHD activities usually terminated the H Mode



(R. Maingi, ORNL, B. Leblanc, R. Bell, PPPL)

m/n=2/1 Precursor Observed Prior to H-Mode Termination (E > 0.6 keV Emission, 0.5-100 kHz Band)



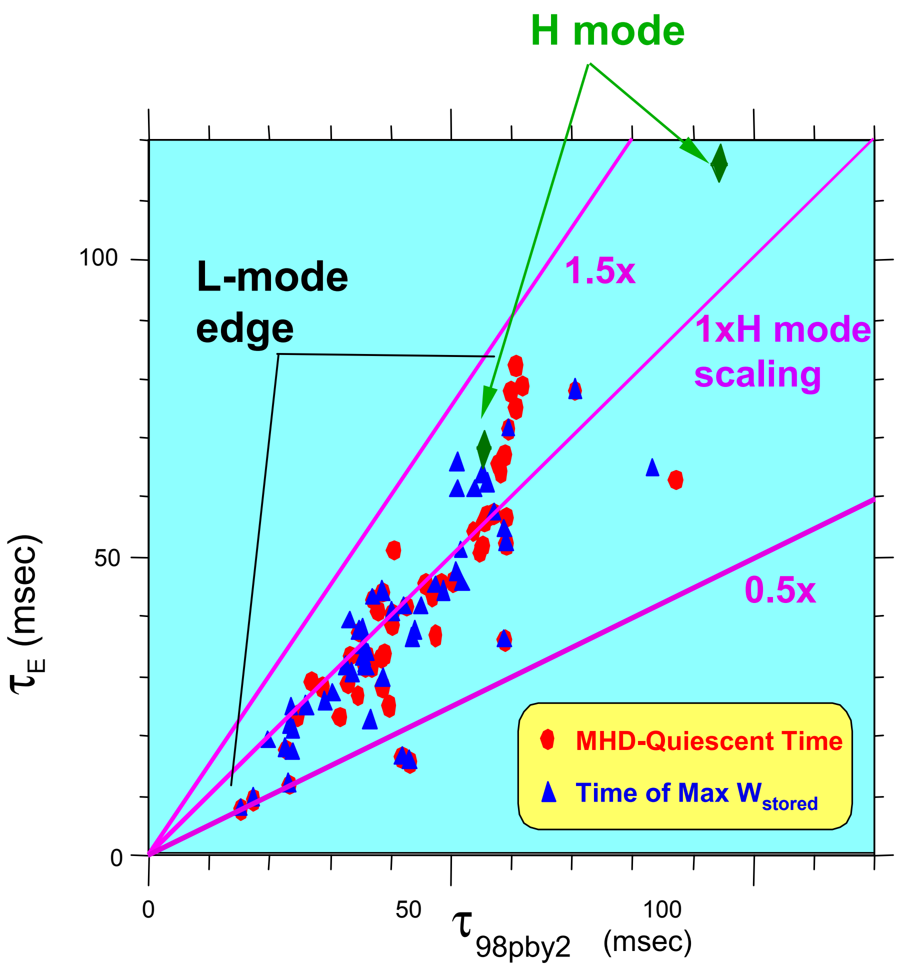


- Magnetic reconnection at the periphery
- *Process following L-H transition:*
  - *→ edge confinement improves*
  - *→ impurity accumulates*
  - *→ edge plasma cools*
  - *→ current redistributes*
  - *→ islands appear*
  - *→ islands couple*
  - *→ field line reconnects*
- Improve impurity control?
- Inducing ELMs to avoid impurity accumulation?

(D. Stutman, M. Finkenthal, JOHNS HOPKINS UNIVERSITY*)*

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

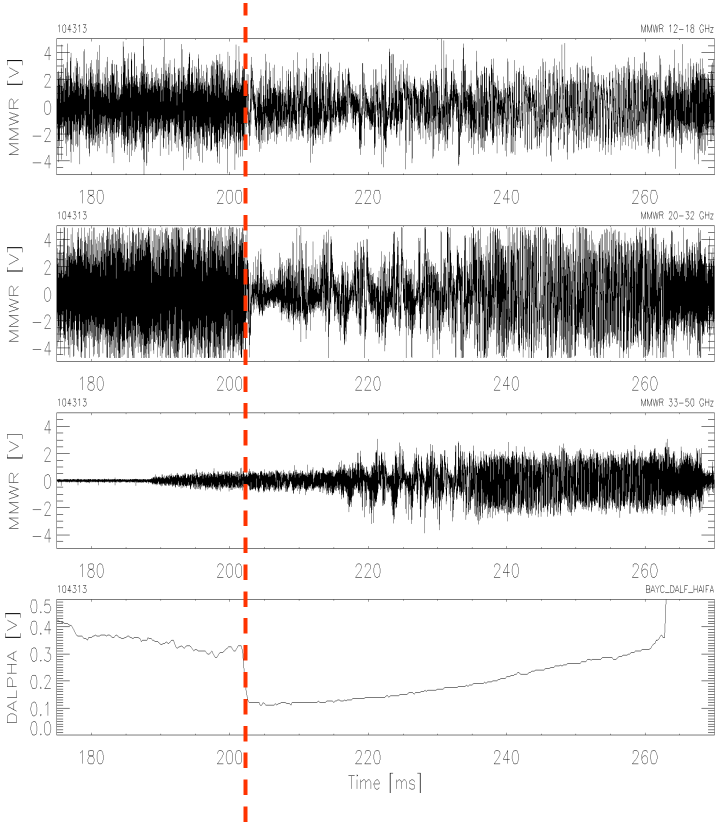


(S. Kaye, PPPL)

Measurements of EBW Emission and Reflectometry Confirm Steepened Gradients & Reduced Fluctuations

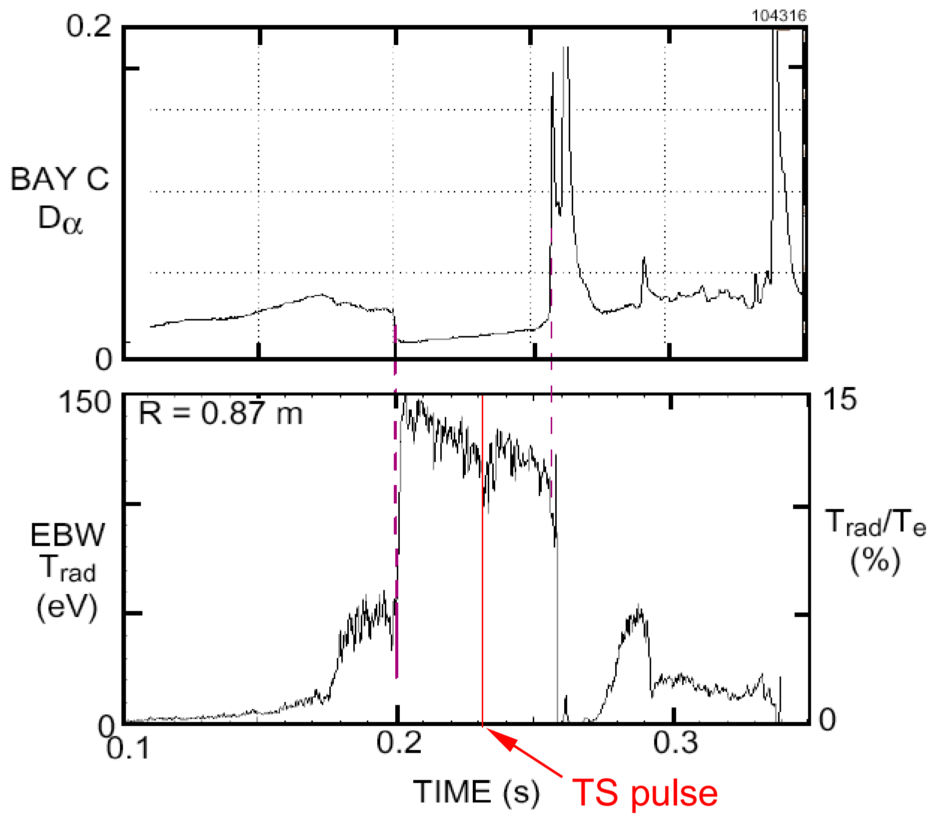
NSTX

Scattered rf power reduced at L-H transition



(T. Peebles, S. Kubota, UCLA)

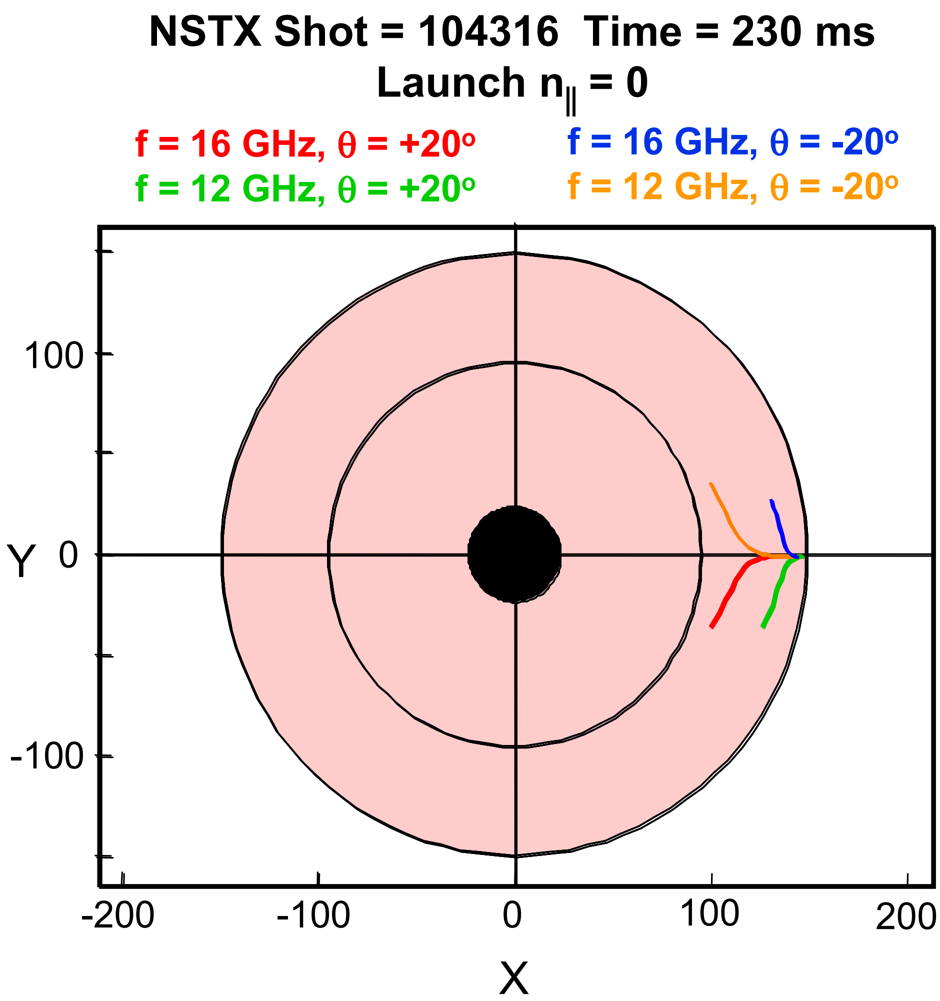
Increased EBW radiation temperature with decreased n_e scale to ~2 cm, consistent with theory



(Exp: Bigelow, ORNL, Taylor, Efthimion, PPPL)
(Th: Bers, Ram, MIT)

EBW Current Drive Is Potentially Efficient and Localized

GEBRAY Calculation



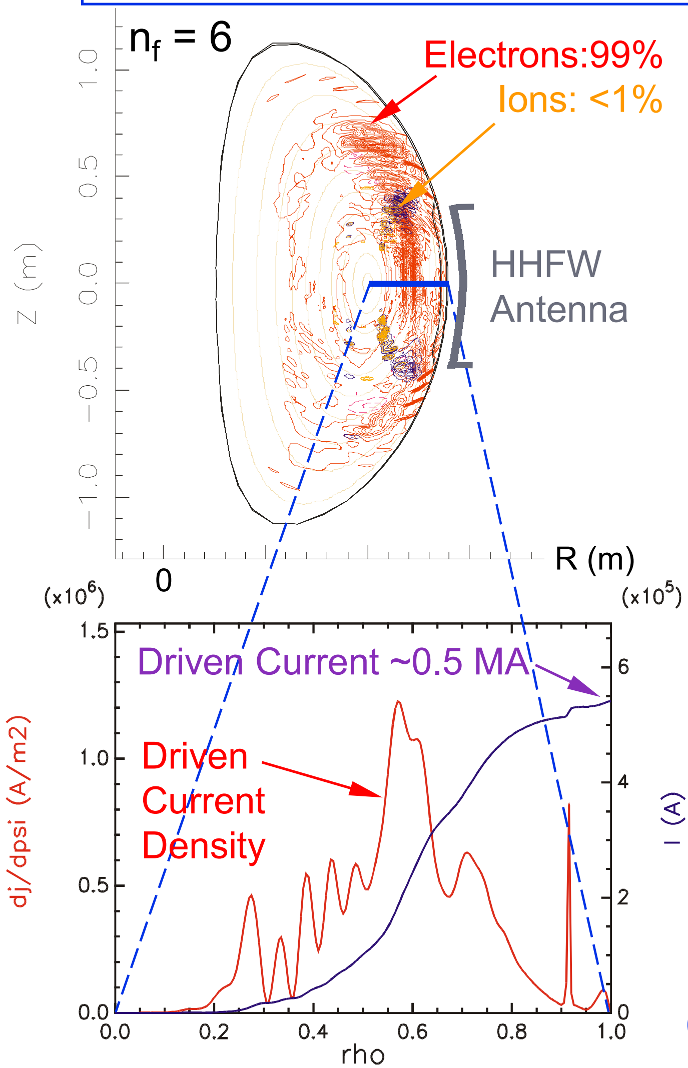
- Power launched +/- 20° off mid-plane bends co/counter to current.
- Large absorption rate very near resonance ensures localized, tailored CD.
- Local limiter to create density gradient for highly efficient ECH-EBW conversion (>50%).
- Current drive efficiencies and dependences are being calculated.

(P. Efthimion, G. Taylor, J. Wilson, PPPL, R. Harvey)

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

NSTX

Contours of HHFW Absorption

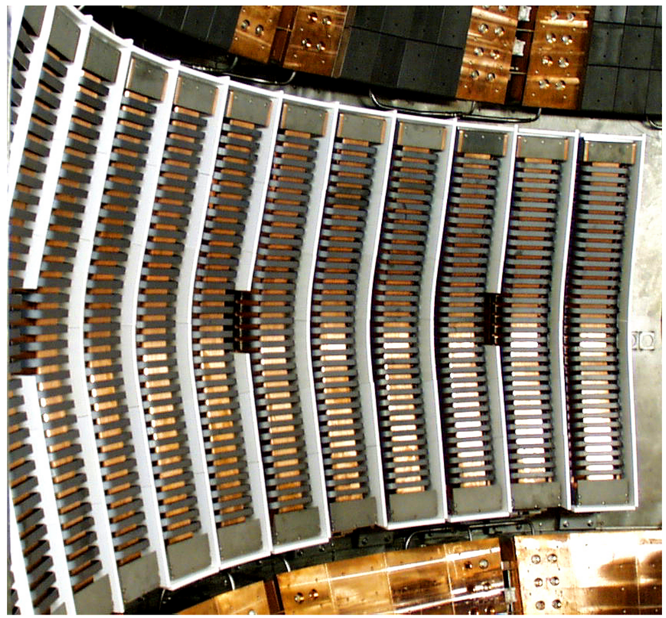


M. Ono (1995): Fast wave decay (absorption) rate:

$$k_{\perp im} \sim n_e / B^3 \sim \varepsilon / B,$$

$$\varepsilon = \omega_{pe}^2 / \omega_{ce}^2 \sim 10^2$$

(J. Wilson, et al., PPPL, D. Swain, et al. ORNL)



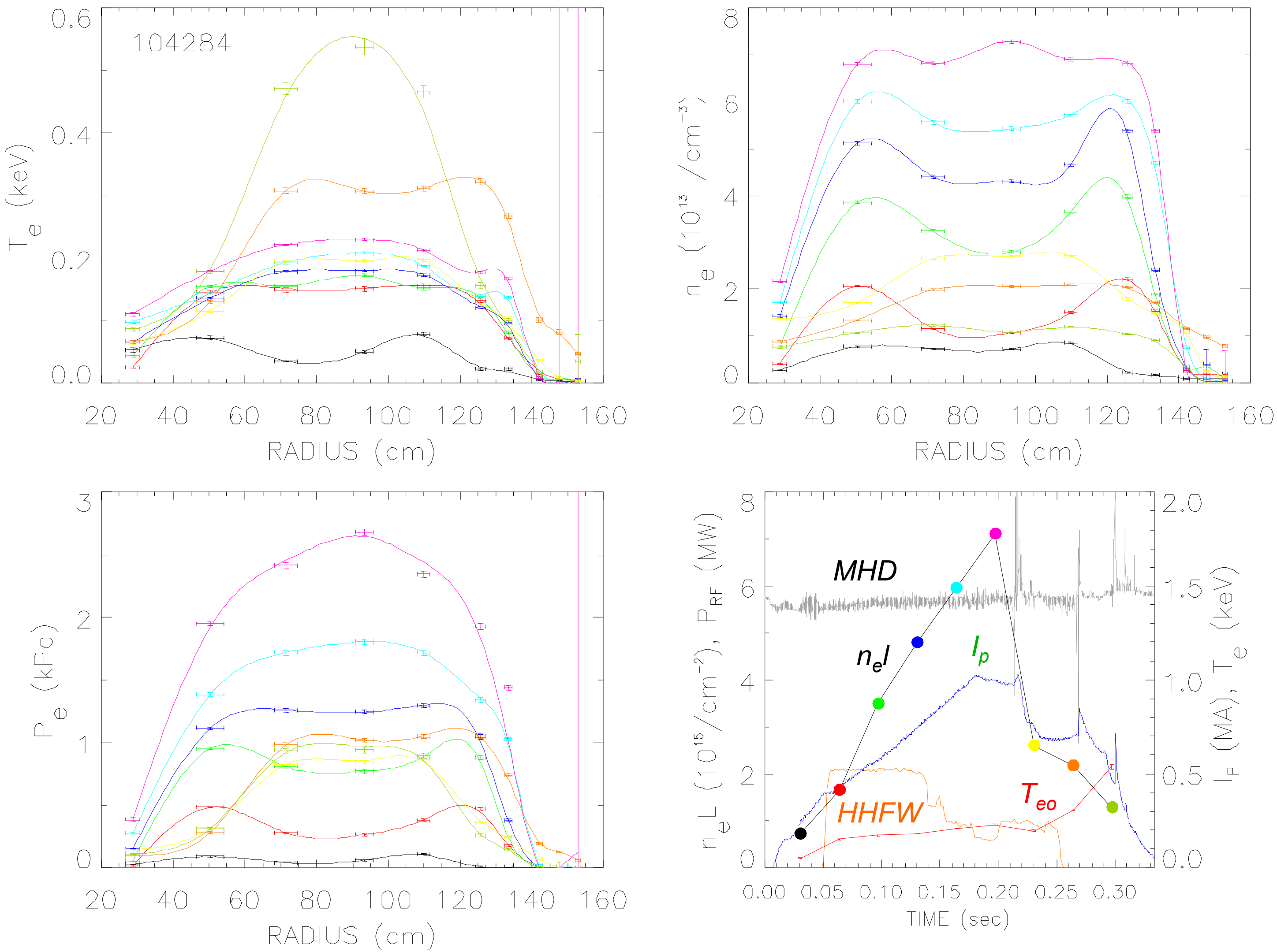
12 HHFW ANTENNA

(PICES & RANT codes, F. Jaeger & M. Carter, ORNL)

With Early HHFW Heating, Substantial Density and Pressure Broadening is Observed

NSTX

$T_e(0)$ reached >1 keV by HHFW heating alone.

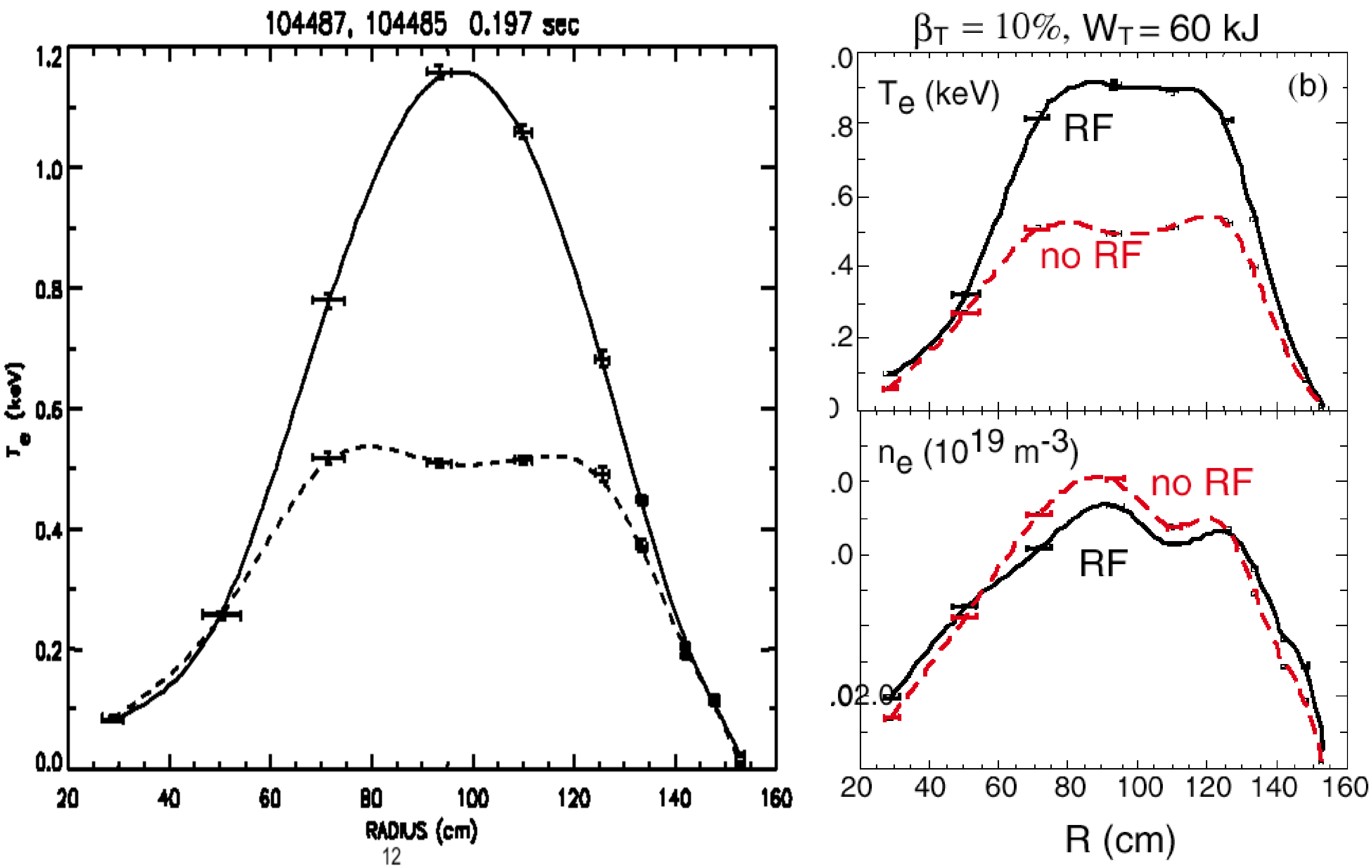


(MPTS Group: B. LeBlanc, R. Bell, PPPL)

Highest T_e Obtained with On-Axis HHFW Heating

NSTX

No MHD, Peaked temperature profile, Te(0) ≤ 1.2 keV

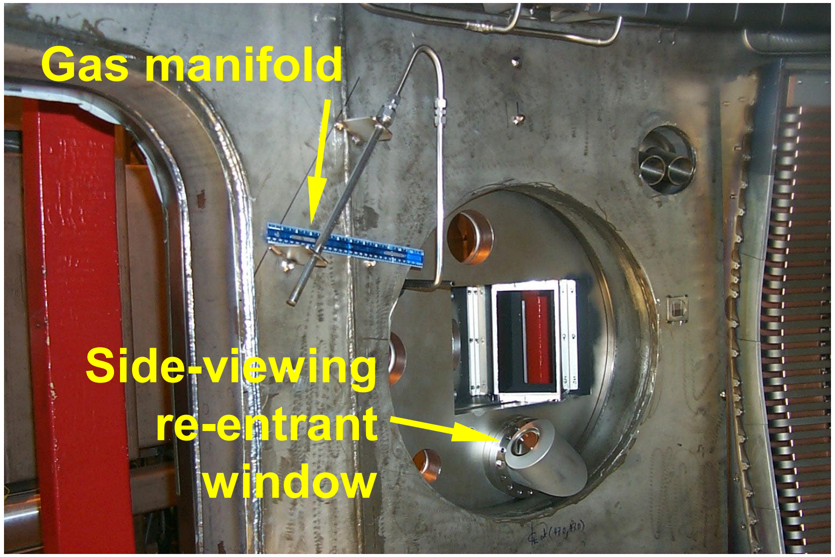


(ET3: Wilson, Hosea, Phillips, PPPL; Swain, Ryan, ORNL; R. Pinsker, GA, etc.)

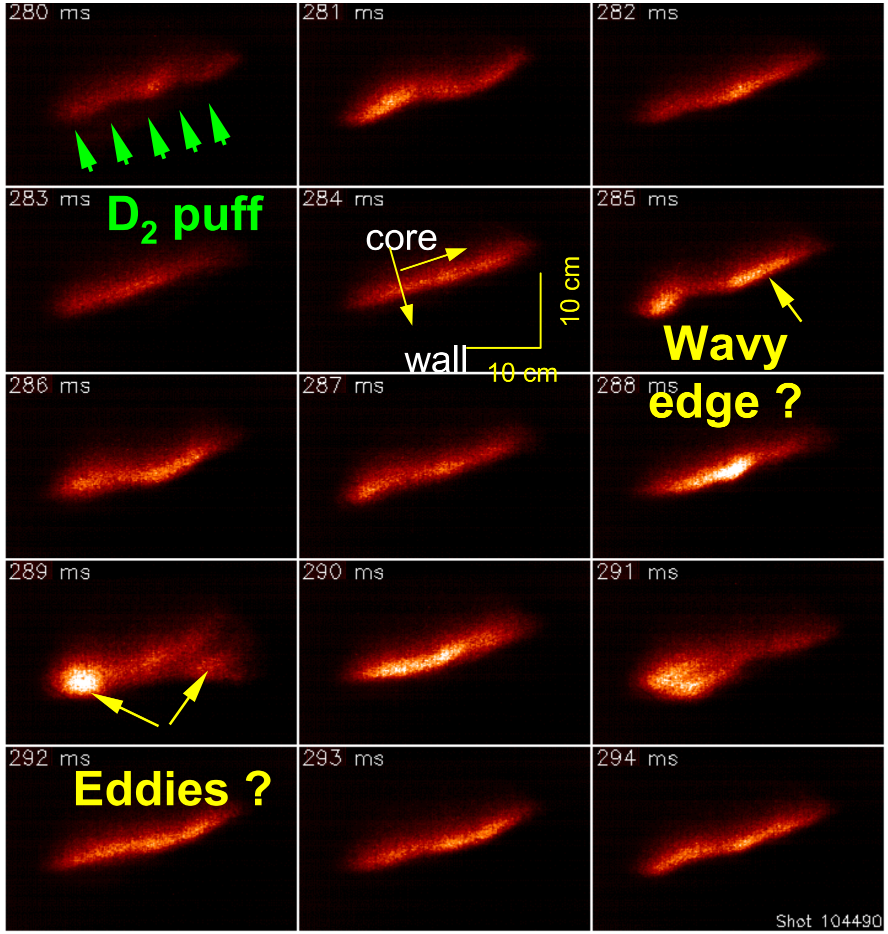
Emission from GPI Image Reveals Wavy Structures & Some Evidence of Eddies

NSTX

Radial vs. poloidal imaging



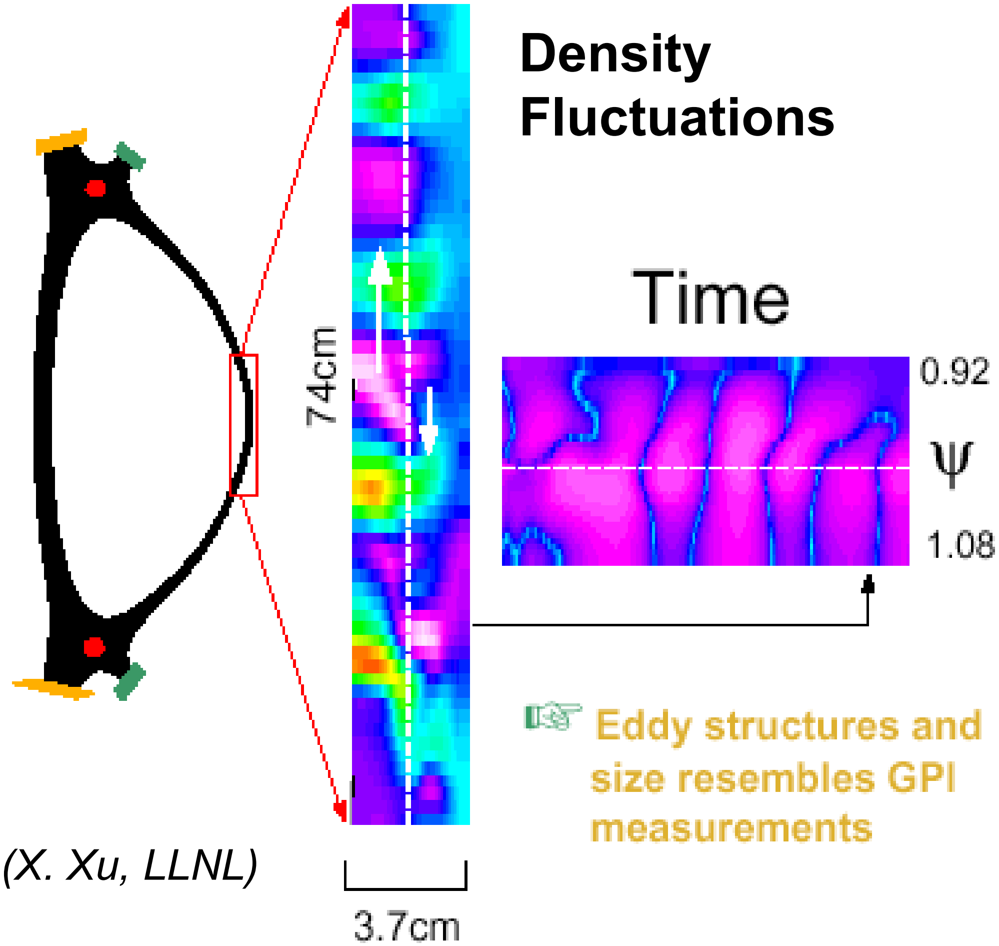
D_2 puff in He discharge
10 μs exposures @ 1000 Hz



Los Alamos NATIONAL LABORATORY

(S. Zweben, PPPL; R. Maqueda, G. Wurden, LANL)

BOUT Calculations of NSTX Edge Suggest Sheared Poloidal Flow & Radial Streamers Across Separatrix



(X. Xu, LLNL)

☞ Eddy structures and size resembles GPI measurements

- EFIT equilibrium for 104312, at 250 ms.
- Edge: $T_i = T_e = 26$ eV, $n_i = 2.3\times10^{18}$ m^{-3}
- ψ=0.9: $T_i = T_e = 51$ eV, $n_i = 4.4\times10^{18}$ m^{-3}
- Radial streamers (~10 cm) of filaments (~10 m) along field line
- Effects on
  - SOL cross-field transport?
  - H-mode?
  - Core confinement?

Spherical Torus Plasma and Magnetic Features That Could Affect Physics Properties Are Better Identified

NSTX

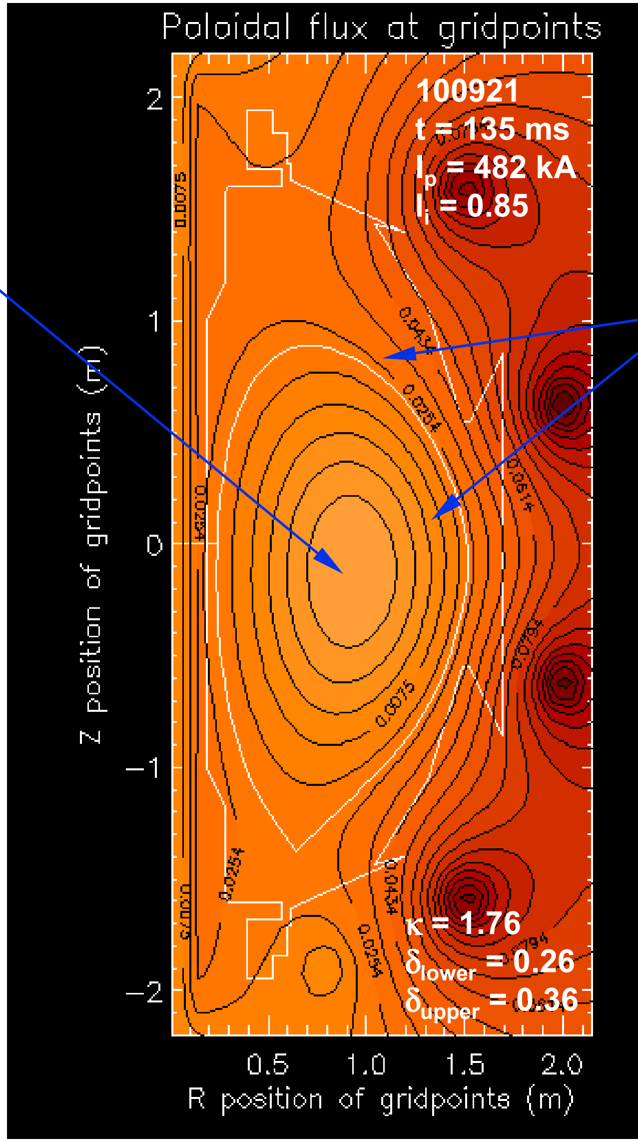
Single-Null Divertor

Central Region

- ~1/2+ minor radius, ~1/3 volume
- Flat q profile
  - $q_0 \sim 1$ ($\beta_0 \sim 0.4$)
  - $q_0 > 2$ ($\beta_0 \sim 1$)
- |B| profile
  - Flat ($\beta_0 \sim 0.4$)
  - Well ($\beta_0 \sim 1$)

Both Regions

- Large ρ_i^* & $\rho_{\theta i}^*$ (~0.02)
- Large ρ_{NBI}^* & $\rho_{\theta NBI}^*$ (~0.2)
- $v_{NBI} >> v_{Alfvén}$
- Large $\omega_{pe}^2/\omega_{ce}^2$ (~100)



Outer & Edge Regions

- ~1/2- minor radius, ~2/3 volume
- Steep q profile and q shear, but small outboard local magnetic shear
- $B_p > B_t$ outboard
- $B_p << B_t$ inboard
- Large β gradient, diamagnetic flow
- Compressed banana width
- Strong |B| variation along flux surface (up to 4-to-1)
- Large SOL flux tube expansion

(EFIT by S. Sabbagh Columbia University)

The Research Program Will Investigate the Physics of Special ST Plasma and Magnetic Features

NSTX

FY	2001	2002	2003	2004 - 2006
	Noninductive Assisted			Noninductive Sustained
Rnwks	15	13	13	40

ST MHD & Transport Physics of $\tau_{skin} \gg \tau_{pulse} \gg \tau_E$

Tools, Capabilities

- NBI & HHFW Heating, B/S, EP, Diagnostics
- CHI, HHFWCD, NBCD, SOL, Diagnostics

ST Current Drive & Edge Physics for $\tau_{skin} \gg \tau_{pulse} \gg \tau_E$

Physics of $\tau_{pulse} \geq \tau_{skin}$ ST

Research Milestones (Implementation Approaches)

- Study τ_E
- Heat with HHFW
- Study MHD modes (no feedback)
- Assess effects of high β_T & flow on χ
- Demonstrate CHI startup
- Assess HHFW current drive efficiency
- Study SOL fluxes
- Integrate high β_T & high τ_E for ~$5\tau_E$
- Extend startup & sustainment to ~1s

2004 – 2006 Program Areas

- Noninductive startup & sustainment
- Heating, CD, profile control
- MHD mode control
- Turbulence suppression
- Energetic ion effects
- Multi-state interface control

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

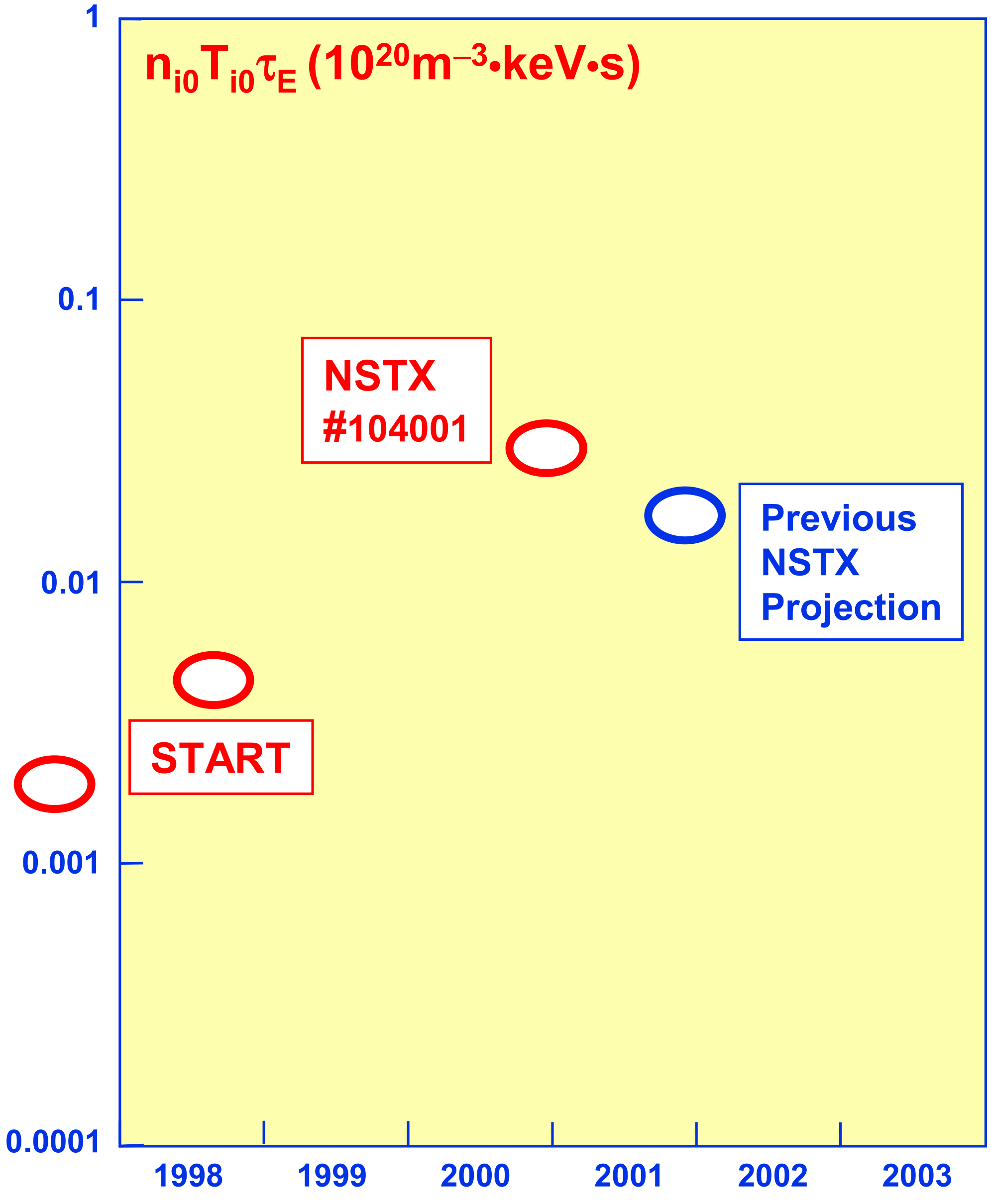
NSTX

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.*

Early Confinement Results Have Been Encouraging

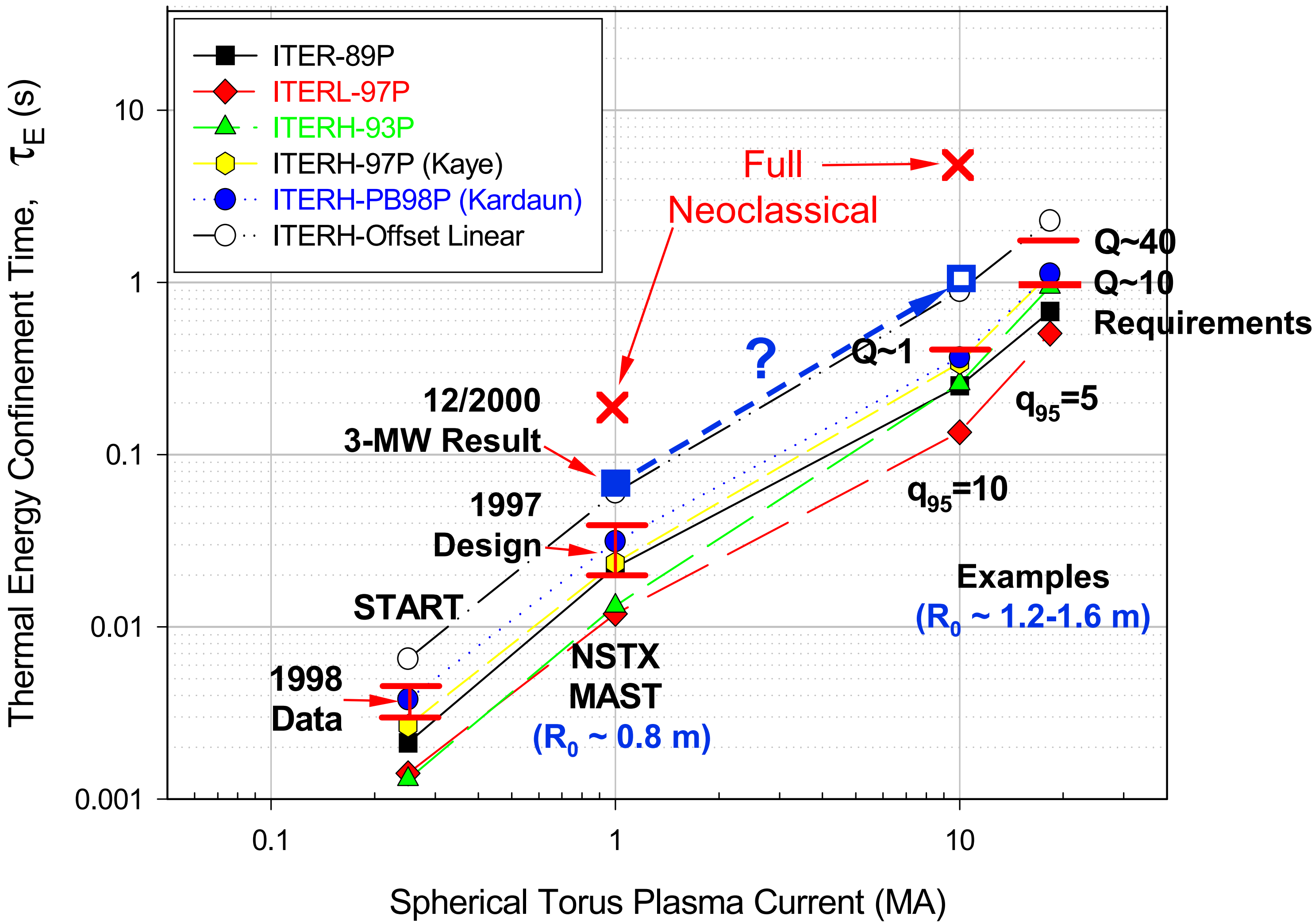


- **Laser Thomson Scattering (MPTS)**
  - $n_{e0} \sim 0.4\times10^{20}m^{-3}$
  - Varied $n_e(R)$ profiles, sensitive to MHD
- **Magnetic Reconstruction (EFIT)**
  - $P_{NBI} \sim 3$ MW
  - $W_p \sim 125$ kJ
  - $\tau_E \sim 0.07$ s
  - H_H(98pby2) ~ 1.4
- **Impurity Spectroscopy**
  - Zeff ~ 2

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

Do Enhanced Confinement Properties on NSTX Project to High Performance in Future ST Devices?

Assuming Tokamak-like scaling dependence



NSTX Has Begun to Investigate New Plasma Properties in the q > 1, Very Low Aspect Ratio Regime

- **Spherical Torus concept was motivated by potential high β_T**
- **NSTX is to prove science principles for practical fusion energy**
- **Initial results are exciting and enticing, in all scientific topical areas**
- **ST plasma and magnetic features are identified for the upcoming research program**
- **Rough projections of confinement performance of future devices are encouraging**