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Transport Issues and ITB Results on NSTX

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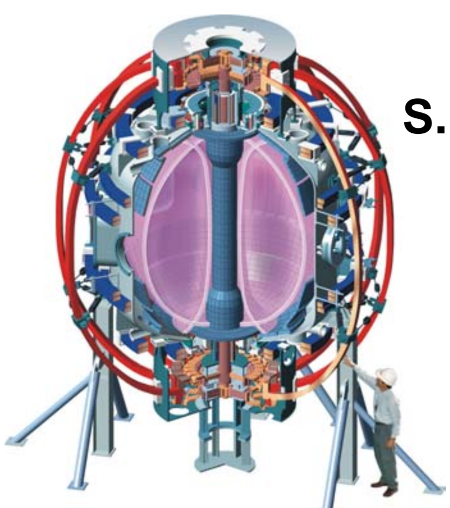


4th Meetings of ITPA Topical Groups on Transport and ITB Physics (T & ITB) & Confinement Database and Modeling (CDBM)
8-12 April, 2003, Scientific Educational Center
Ioffe Institute, St. Petersburg, Russia

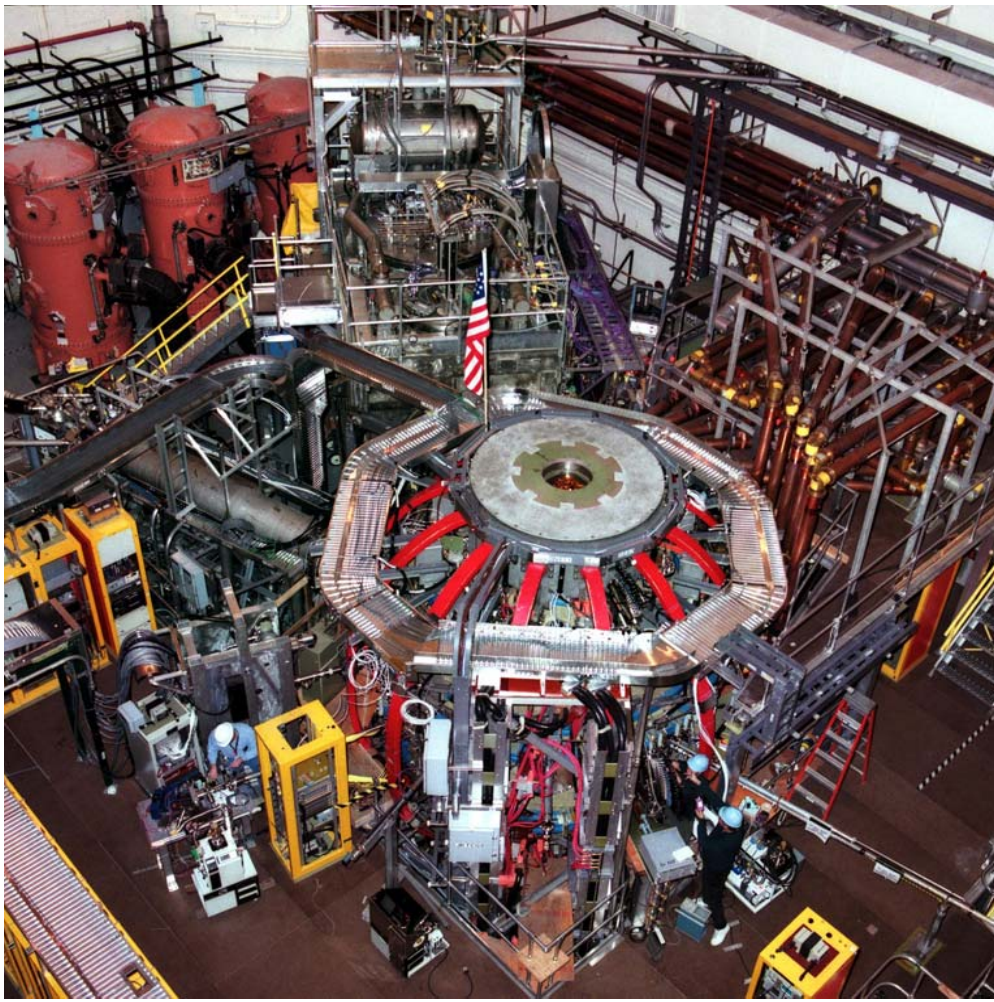
NSTX Produces Plasmas That Help Clarify Key Issues of Transport & ITB

- Features and Status of NSTX
- Ion ITB properties in $T_i > T_e$ plasmas with higher β and lower A (issue identified by ITPA leaders)
- Possible electron ITB in $T_e > T_i$ (HHFW) plasmas (potential contribution)
- Other physics issues of potential interest

Please note:

- *new results of on-going NSTX Team research*
- *look to ITPA for discussion & expert feedback*
- *participate in and contribute to T&ITB TG*

NSTX Facility Has Since 9/99 Made Rapid Progress in Capability to Produce MA and keV Level Plasmas



Parameters	Design	Achieved
Major Radius	0.85m	}⇒A≥1.27
Minor Radius	0.68m	
Elongation	2.2	2.5
Triangularity	0.6	0.8
Plasma Current	1MA	1.5MA
Toroidal Field	0.6T	0.6T
Heating and Current Drive		
Induction	0.7Vs	0.7Vs
NBI (100keV)	5MW	7MW
HHFW (30MHz)	6MW	6MW
CHI	0.5MA	0.4MA
Pulse Length	5s	1.1s

NSTX Has Built up Basic and Modern Diagnostic Capabilities to Support Research

Core Plasma Diagnostics

- Thomson scattering (20 ch., 60Hz)
- Charge Exchange Recomb. Spect. (CHERS): T_i & v_ϕ (51 ch.)
- VB detector (single chord)
- Soft x-ray arrays (4) [JHU]
- Bolometer array (midplane tangential)
- X-ray crystal spectrometer (T_i (0), T_e(0))
- Edge rotation spectroscopy
- Electron Bernstein wave radiometer
- FIReTIP interf'r/polarim'r (4 ch) [UCD]
- PICXIS Fast 2D X-ray camera [Frascati, JHU]
- Tang. X-ray pin hole camera [U. Wisconsin]

Magnetics and MHD

- Magnetics for equilibrium reconstruction
- Diamagnetic flux measurement
- High-n and high-frequency Mirnov arrays
- Locked mode coils
- 1mm interferometer [UCLA]

Turbulence

- Edge reflectometer [UCLA]
- Edge fluctuation imaging [LANL, PSI]

Plasma Monitoring

- Fast visible camera [LANL]
- VIPS: Visible spectrometer
- SPRED: UV spectrometer
- Transmission grating spectrometer [JHU]
- EFIT (Columbia University)

Boundary Physics

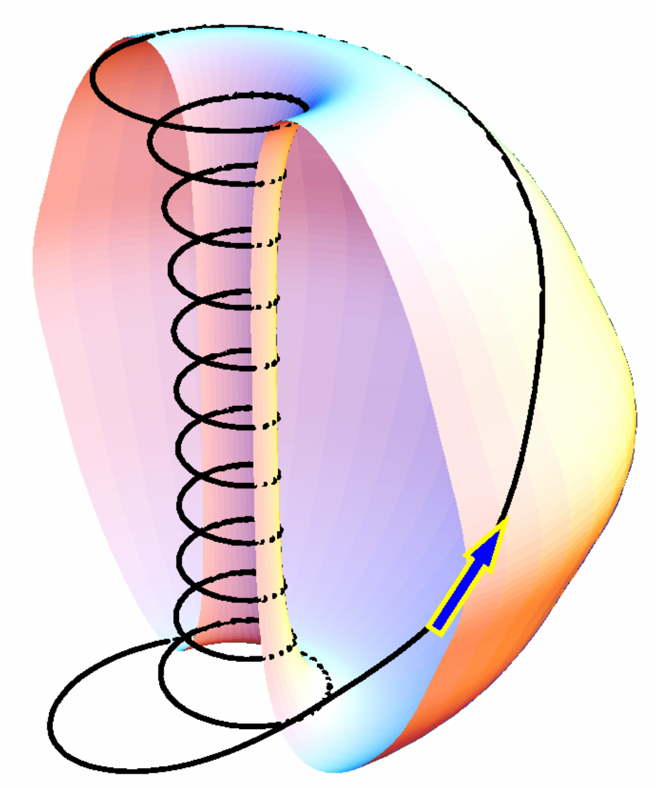
- Divertor Bolometer
- Fast probe [UCSD]
- Infrared Camera (2) [ORNL]
- Fast Ion Gauge [University of Wash]
- Divertor fast camera [Hiroshima Univ.]
- Divertor tile Langmuire probe array
- 1-D CCD H_α camera (2) [ORNL]
- Visible filterscopes (H_α, OII, CII) [ORNL]
- Scrape-off layer reflectometer [ORNL]
- Fast camera (PSI)

Energetic Particles

- Fission chamber neutron measurement
- Fast neutron measurement
- Neutral particle analyzer (scanning)
- Fast ion loss probe

Extending β, Shaping, and q Provide New Opportunities to Contribute to Resolving Key ITPA Issues

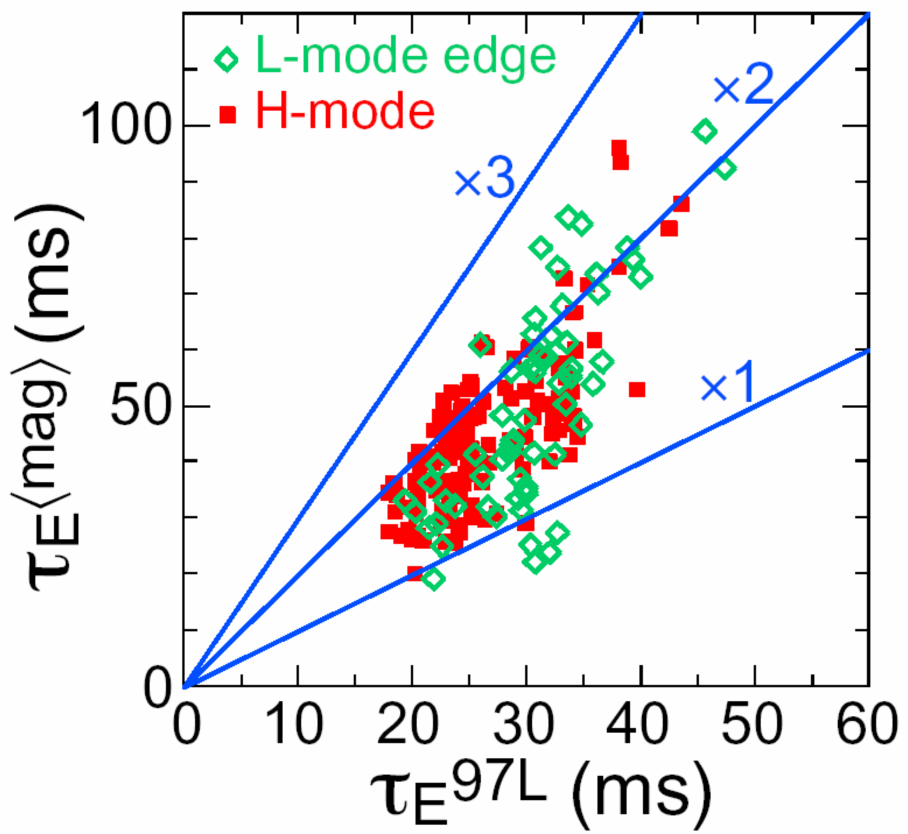
NSTX: A ~ 1.3 – 1.5



Parameters on NSTX that affect MHD, turbulence, and other physics:

- Bigger $\beta_T \leq 40\%$, $\beta_0 \sim 1$, |B|-well ~ 30%
- Stronger plasma shaping & self fields ($A \geq 1.27$, $\kappa \leq 2.5$, $B_p/B_t \sim 1$, $q_{edge} \sim 10$)
- Large plasma flow ($V_{rotation}/V_A \sim 0.3$)
- Large flow shearing rate ($\gamma_{ExB} > 10^5$/s)
- Large B-mirror in edge magnetic field
- Supra-Alfvénic fast ions ($V_{fast}/V_A \sim 4$–5)
- High dielectric constant ($\varepsilon \sim 30$–100)
- Reduced internal inductance (ℓ_i) & magnetic stored energy ($\propto \ell_i R I_p^2$)

Plasmas with NBI Heating Show Favorable Energy Confinement Compared to Scaling Predictions



Kaye, Sabbagh

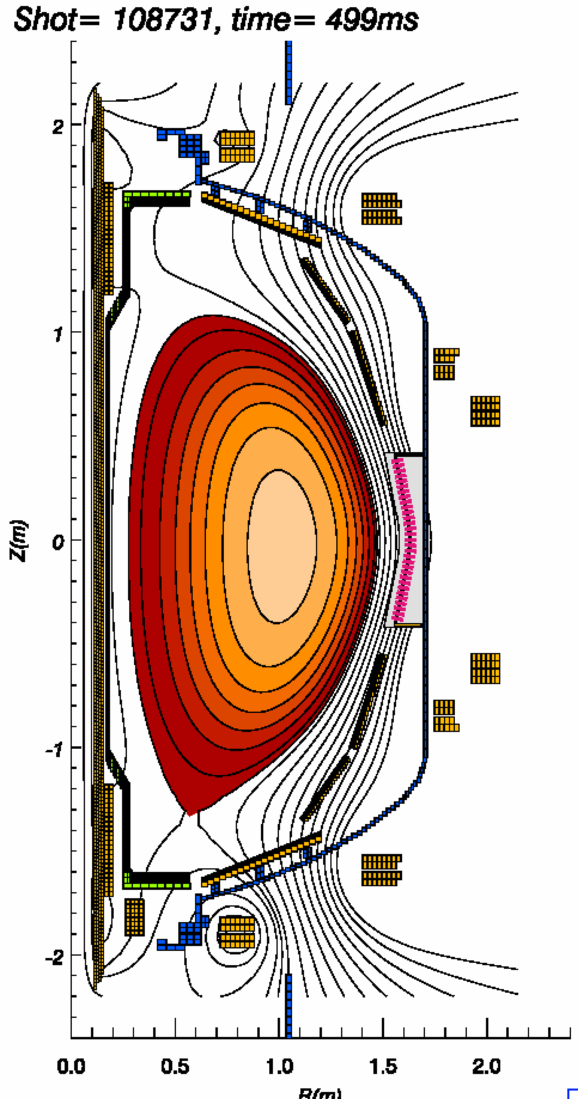
- Similar H-factors vs. 97L
- Typically
  - L: low-χ_i core; H: flat-T_i core
  - $T_i \sim 2\ T_e$; relatively stiff T_e
  - rising $n \leq n_{GW}$

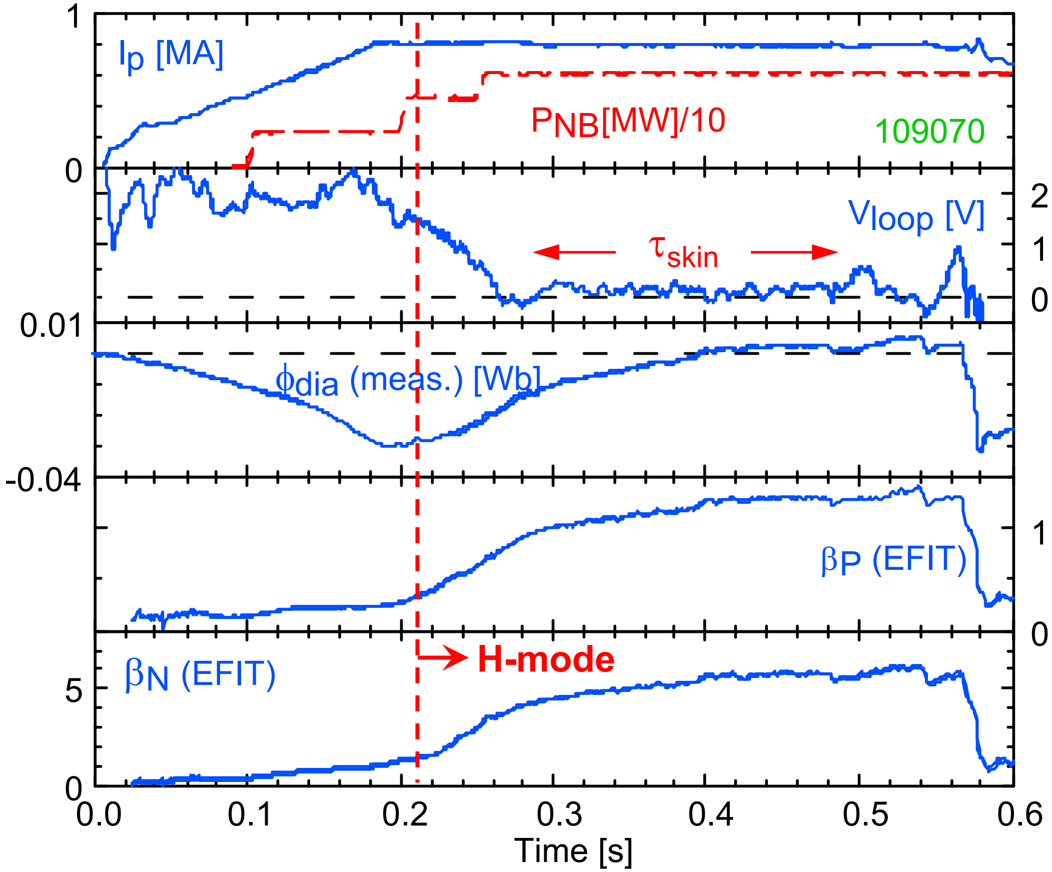
Different H Mode Features

	Sustained	Inductive
β_p	~1.2	~0.5
ℓ_i, q_{95}	~0.5, ~10	~1, ~5
β_T	≤20%	≤35%
β_N	~6	~5
V_L (V)	~0.1-0.2	~0.7

Focus on H-mode high β plasmas

NBI-Heated, High-β_p Nearly Sustained H-Mode Plasmas Provide Good Vehicles for ITB Studies

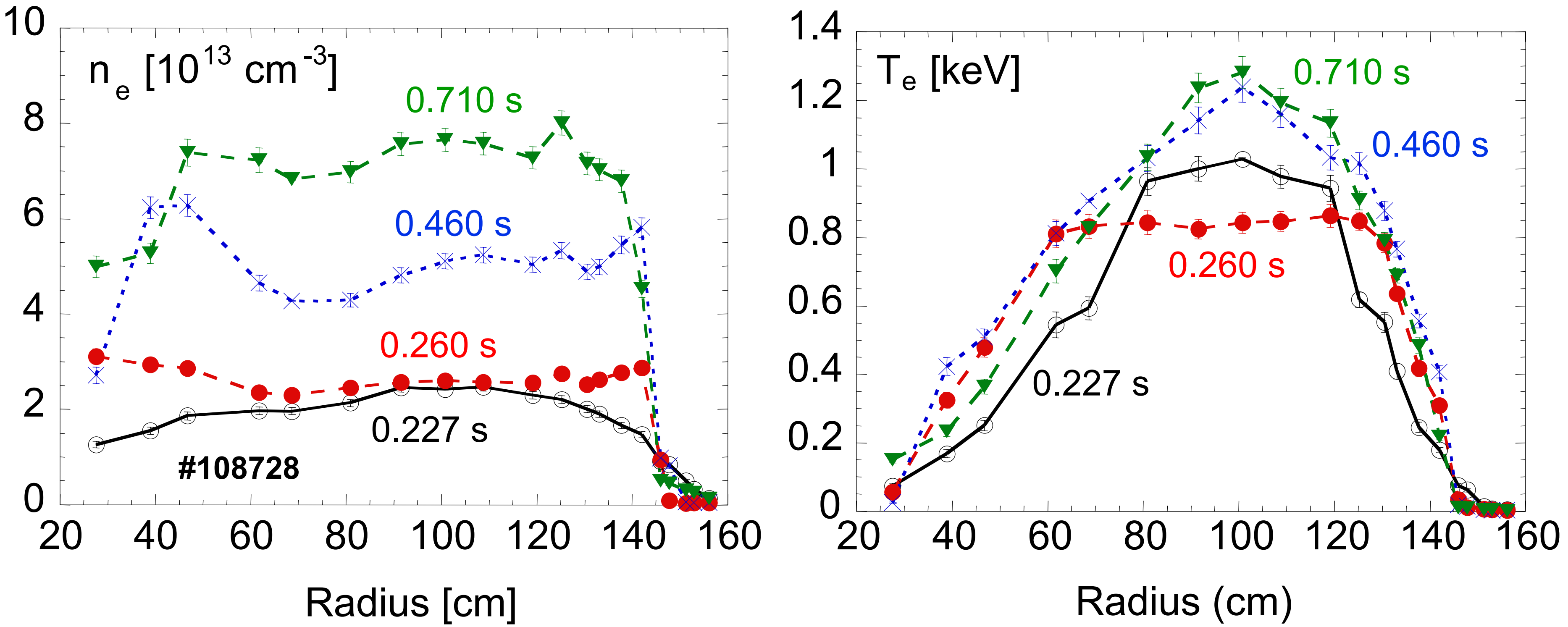




$f_{BS} \sim 0.5$; $f_{NBI} \sim 0.1$; $V_L \sim 0.1$ V for $\geq \tau_{Skin}$

Gates, Menard, Sabbagh

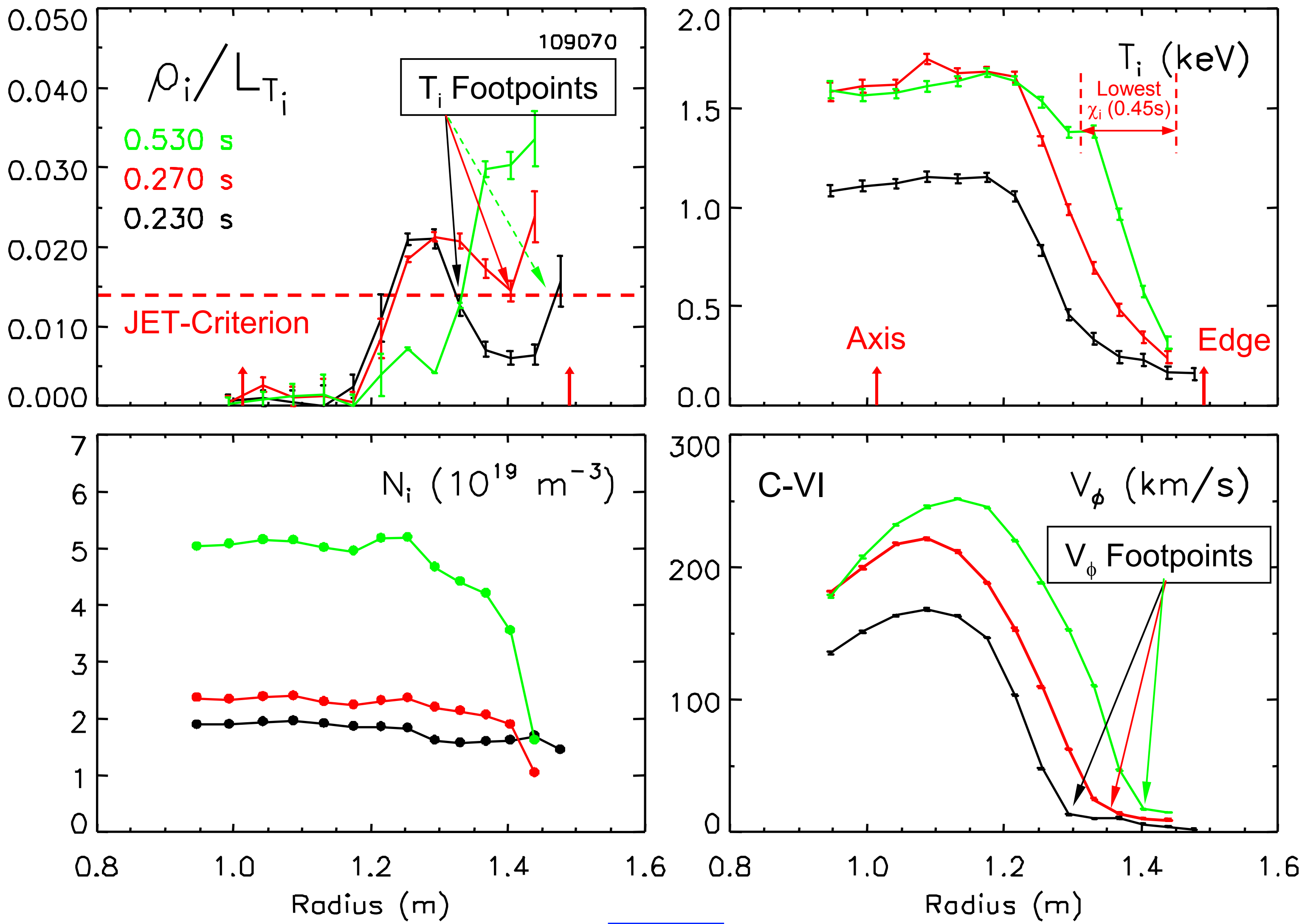
n_e and T_e Profiles Evolve Differently During Long H-mode



- n_e profile hollow after transition and fills in 300-500 ms
- T_e profile flattens initially and peaks later in time
- $p_{e\text{-}ped} \sim 0.7\ p_{e0}$!

LeBlanc

NSTX T_i and V_ϕ Profiles Evolve in Accordance with JET ITB Criterion ($\rho_{Ti}^* = \rho_i/L_{Ti} > 0.014$) for ITG

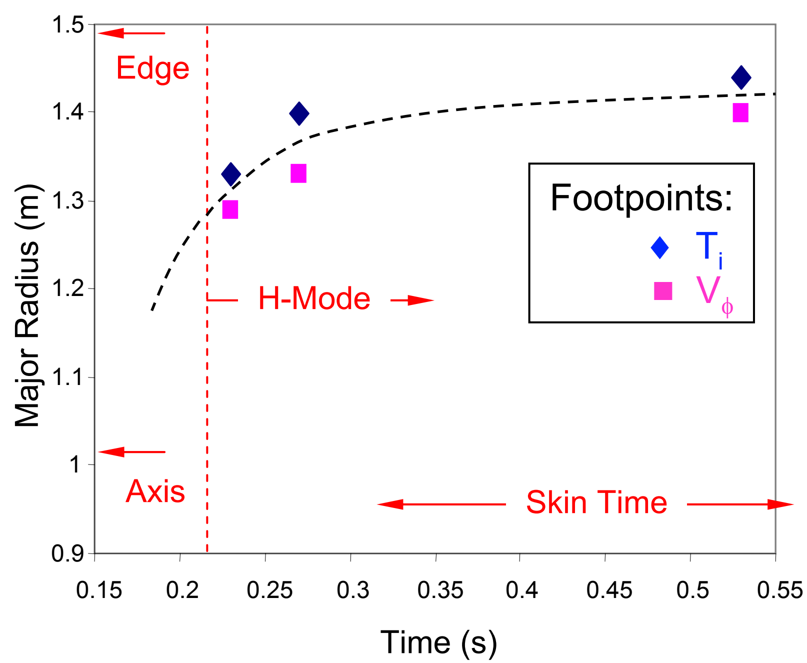


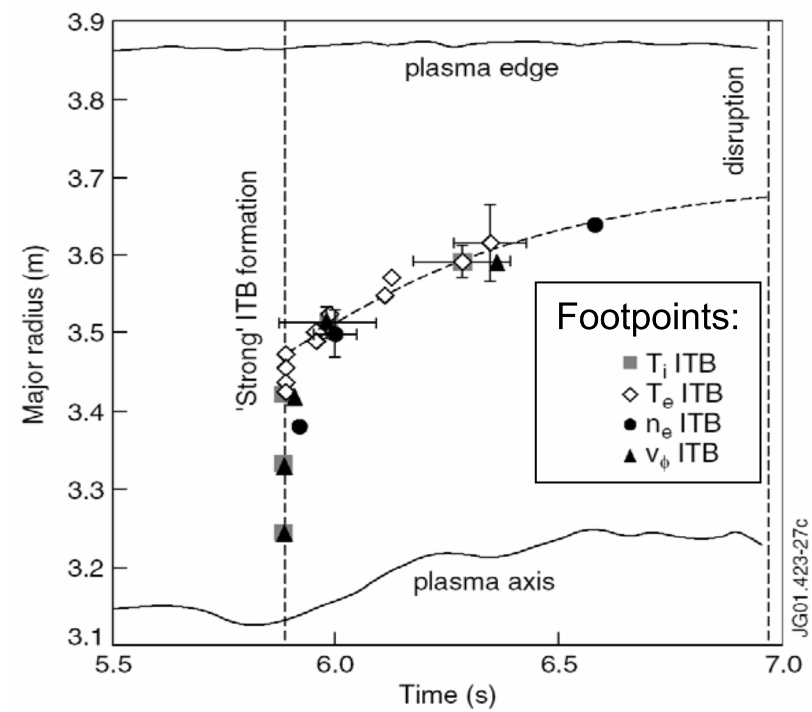
R. Bell

NSTX H-Mode Plasmas Show Similar Footpoint Evolution of T_i and V_ϕ Profiles

- **No apparent transition to "ITB"**
- **n and T_e profiles evolve differently**
- **Absence of active particle control**

- **High performance ITB in JET**
- **Negative core magnetic shear**
- **LHCD prelude** (Challis et al, PPCF 2002)

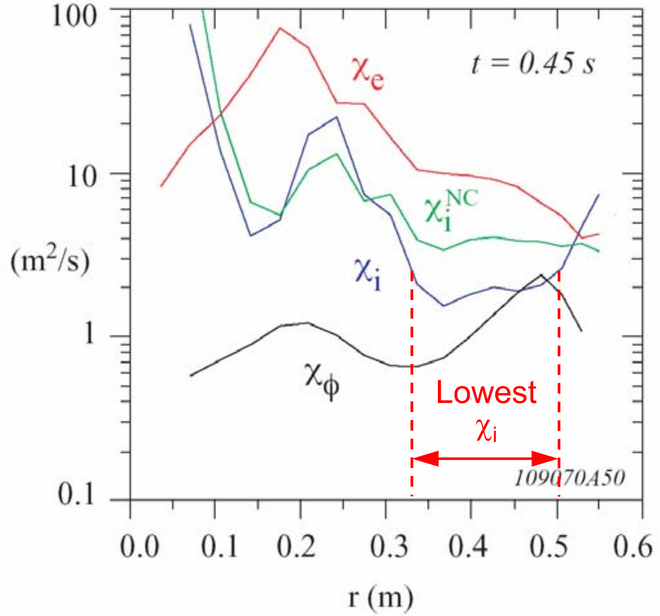


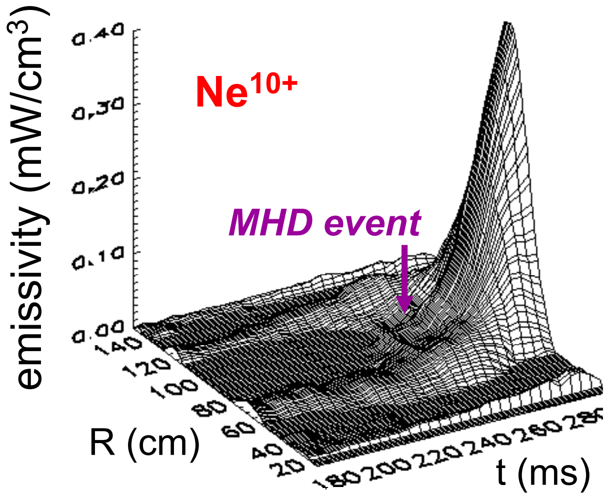


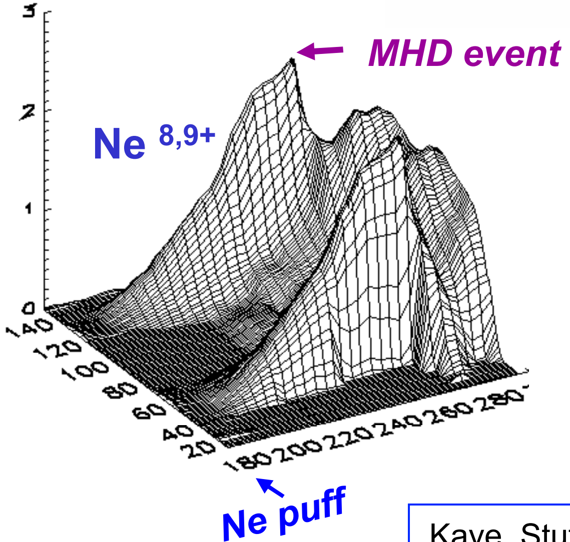
- *New data; no apparent ITB transition; large r/a; broad ITB-like zone*
- *To be resolved: Is this ITB? What q-dependence? Why not n & T_e?*

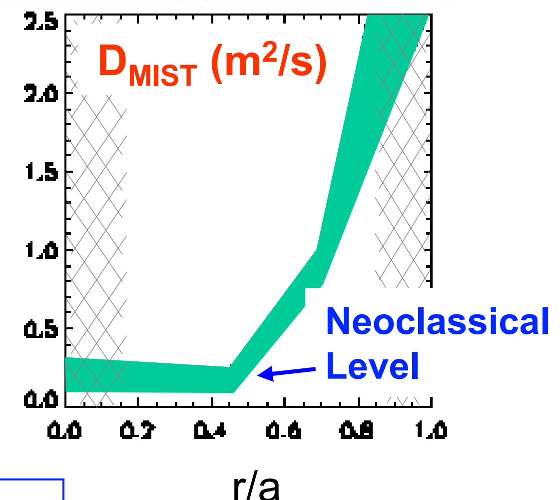
Under NBI Heating, Ion Energy and Particle Diffusivities are Very Low – over Sizable Zone

Transport Physics	NSTX Results Suggest
Thermal Conductivity	• $\chi_{ion} \leq \chi_{neoclassical}$ • $\chi_{elec} >> \chi_{ion}$
Impurity Diffusivity	• $D_{imp} \sim D_{neoclassical}$



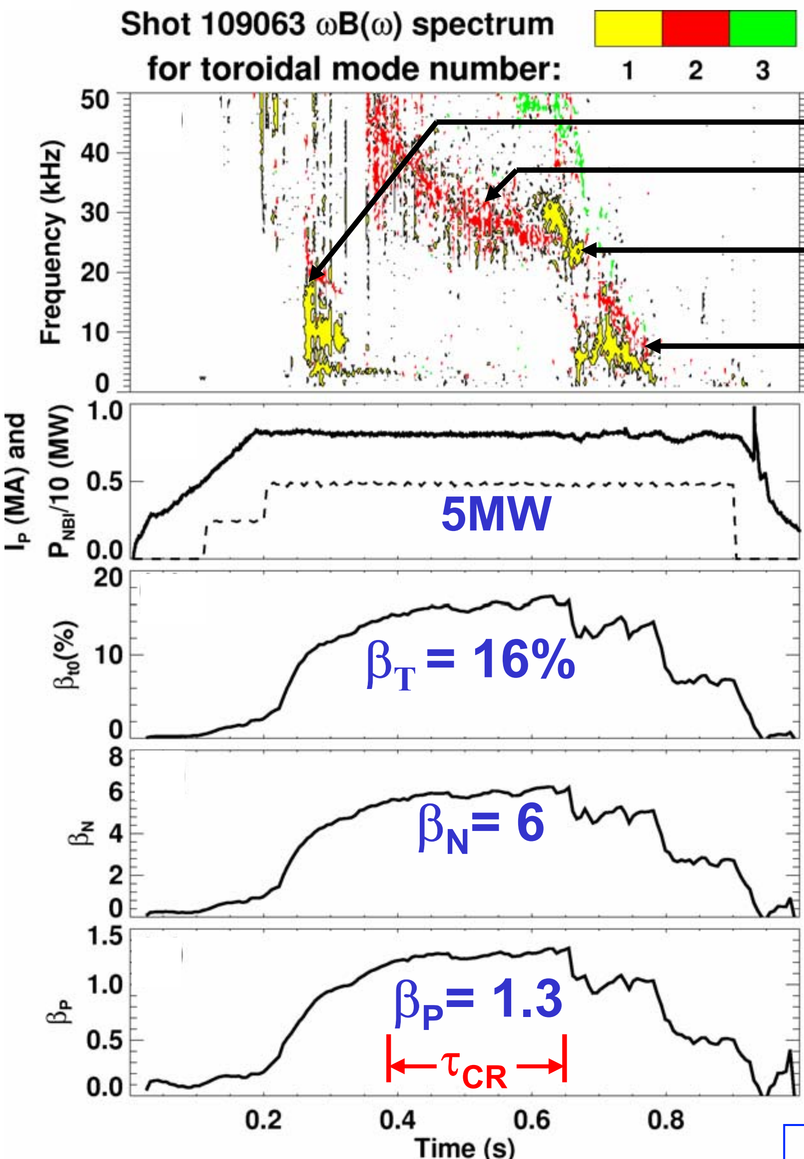






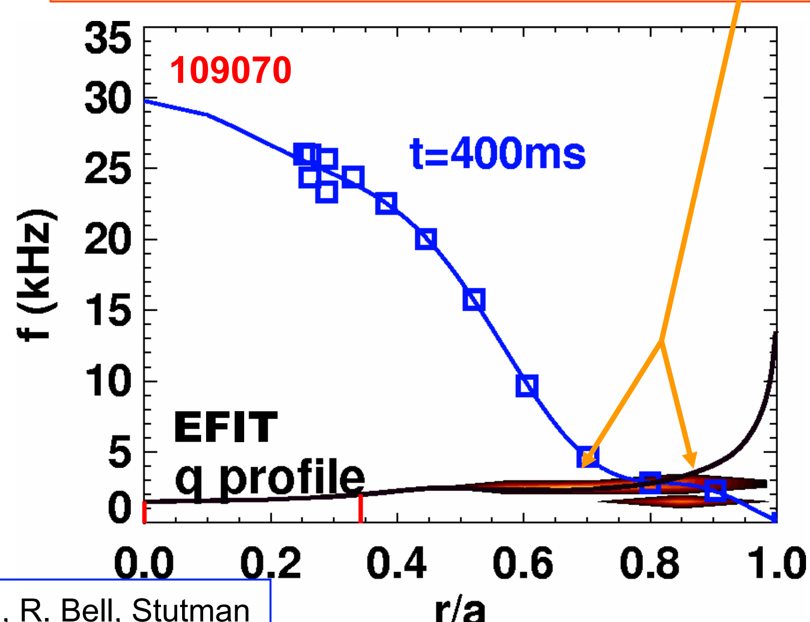
Kaye, Stutman

Such Plasmas Can Coexist with Tearing Modes but not with Internal MHD Reconnections



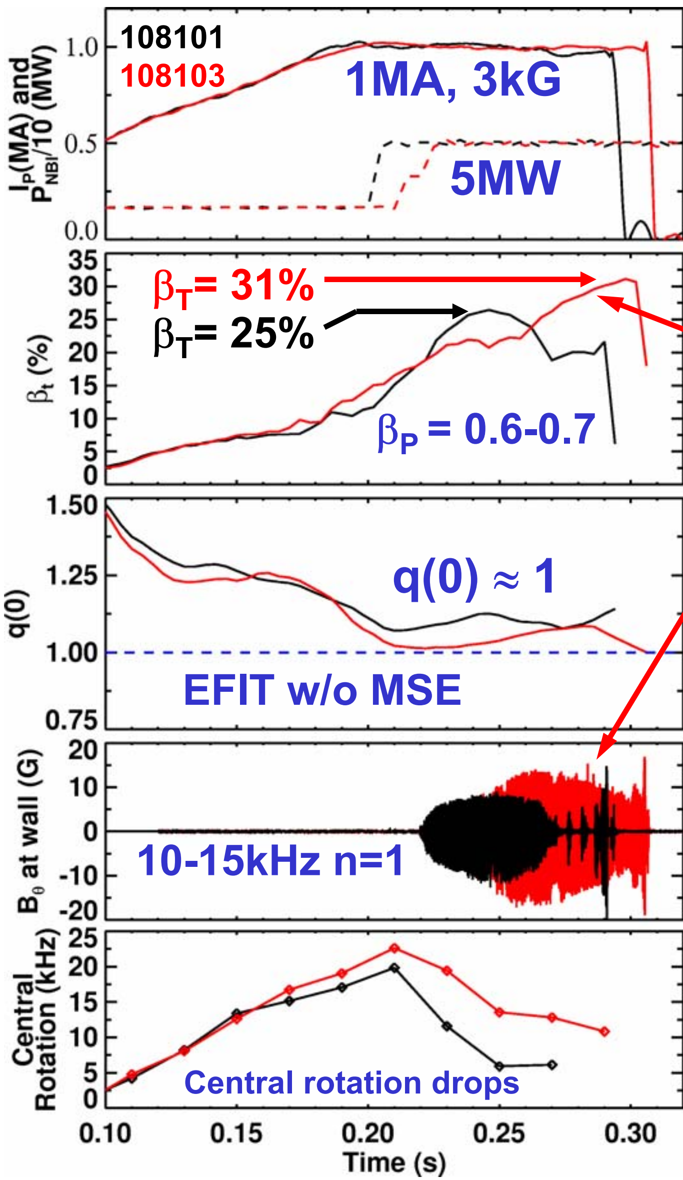
- early n=1, transient
- long-lived n=2 mode in flat-top, NTM?
- fast n=1 internal mode disrupts β
- residual n=1,2 rotating modes, NTMs?

Prior to internal collapses, SXR shows only edge 2/1 or 3/1

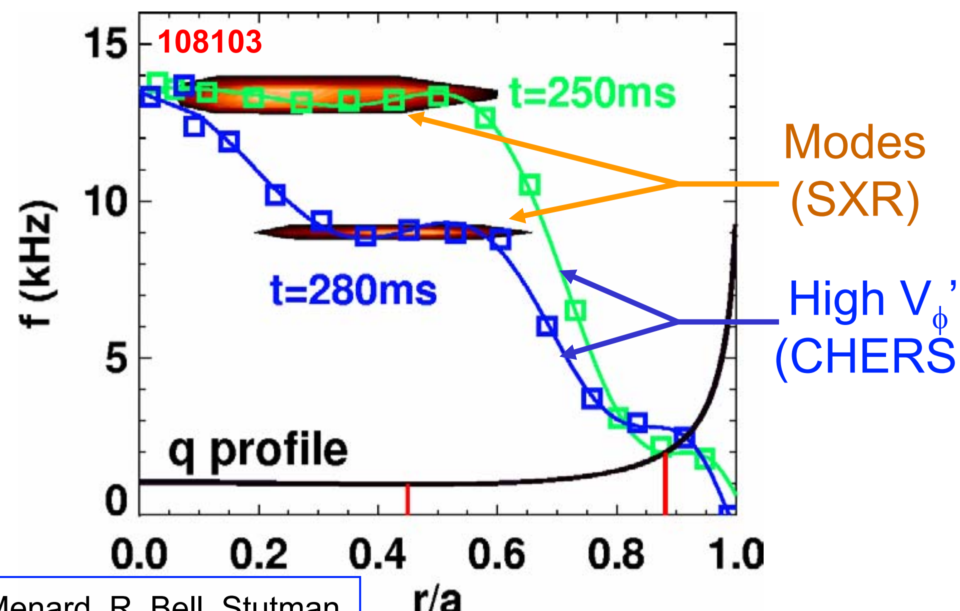


Menard, R. Bell, Stutman

ITB-Like High β_T Is Limited by 1/1 Modes

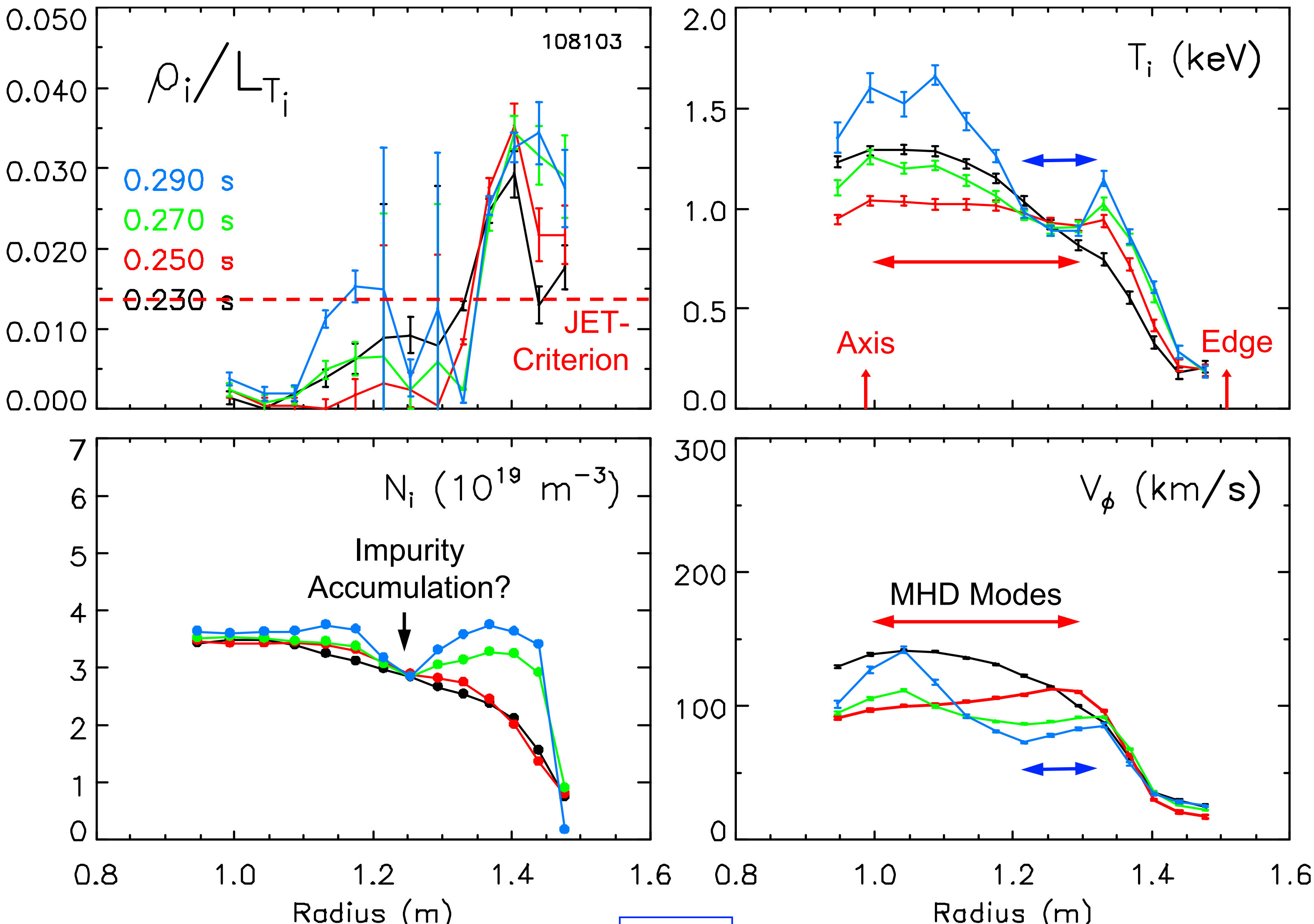


- Core becomes n=1 kink unstable
- 1/1 mode degrades β & rotation, slows, locks, large $r_{q=1}$ → disruption
- Neoclassical drive possible, but…
  - Modes can decay as β rises
  - Rotation evolution dominates ITB



Menard, R. Bell, Stutman

ITB-Like Zone (ρ_i/L_{Ti} > 0.014) Can Persist and Revive Away from MHD Modes



R. Bell

High Harmonic Fast Wave Tests Heating and Current Drive Efficiency in High ε (~100) Plasmas

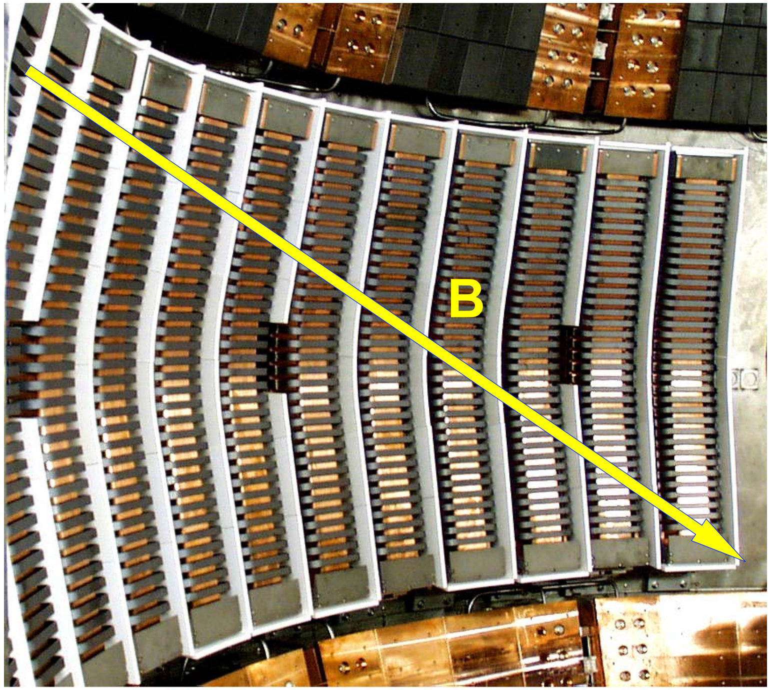
NSTX

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

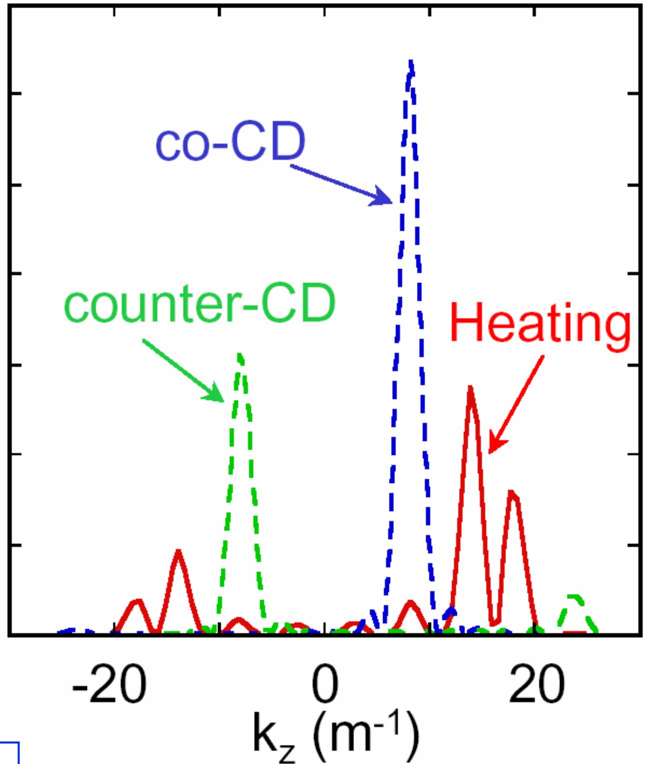
$$k_{\perp im} \sim n_e / B^3 \sim \varepsilon / B,$$

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

- 6 transmitters and phase controls
- Flexible spectrum



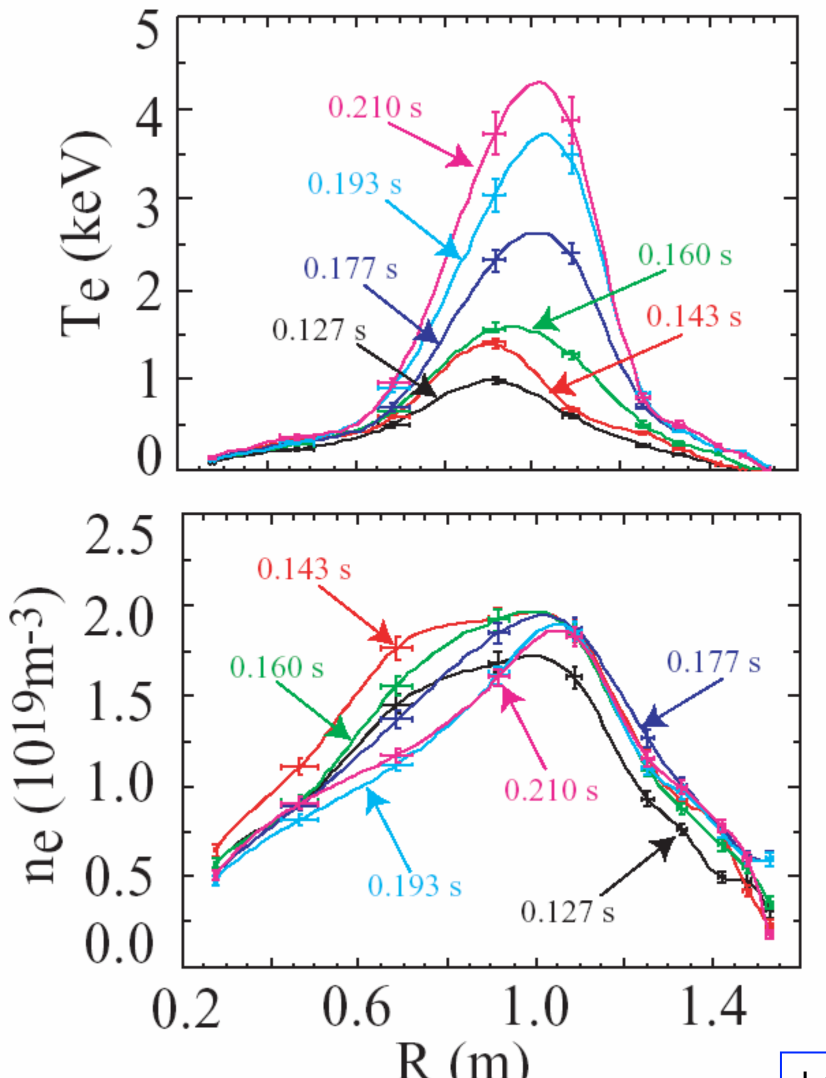
12 HHFW ANTENNA



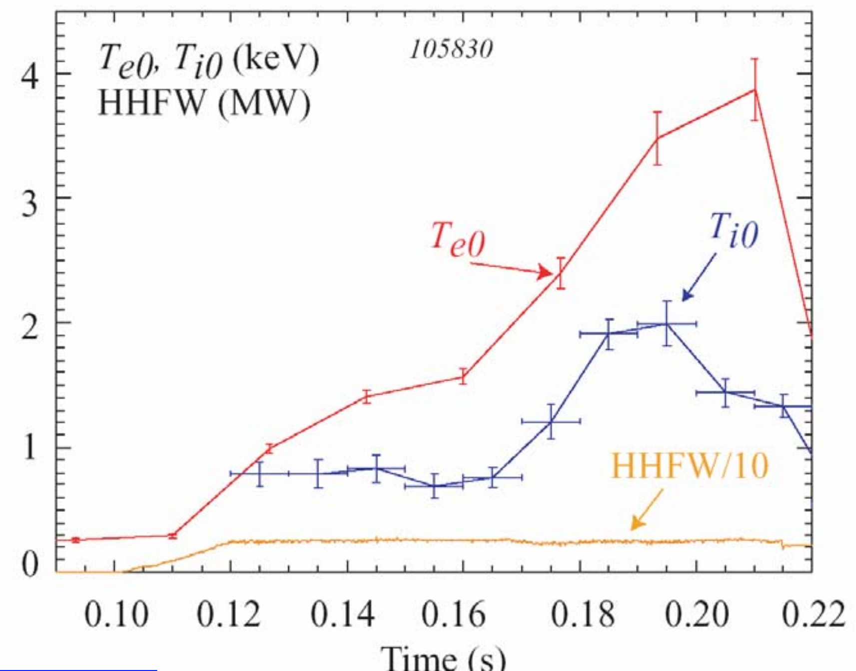
Wilson, Phillips

HHFW Heats Electrons Strongly When Coupled to the Plasma – $T_e \sim 2T_i$

NSTX

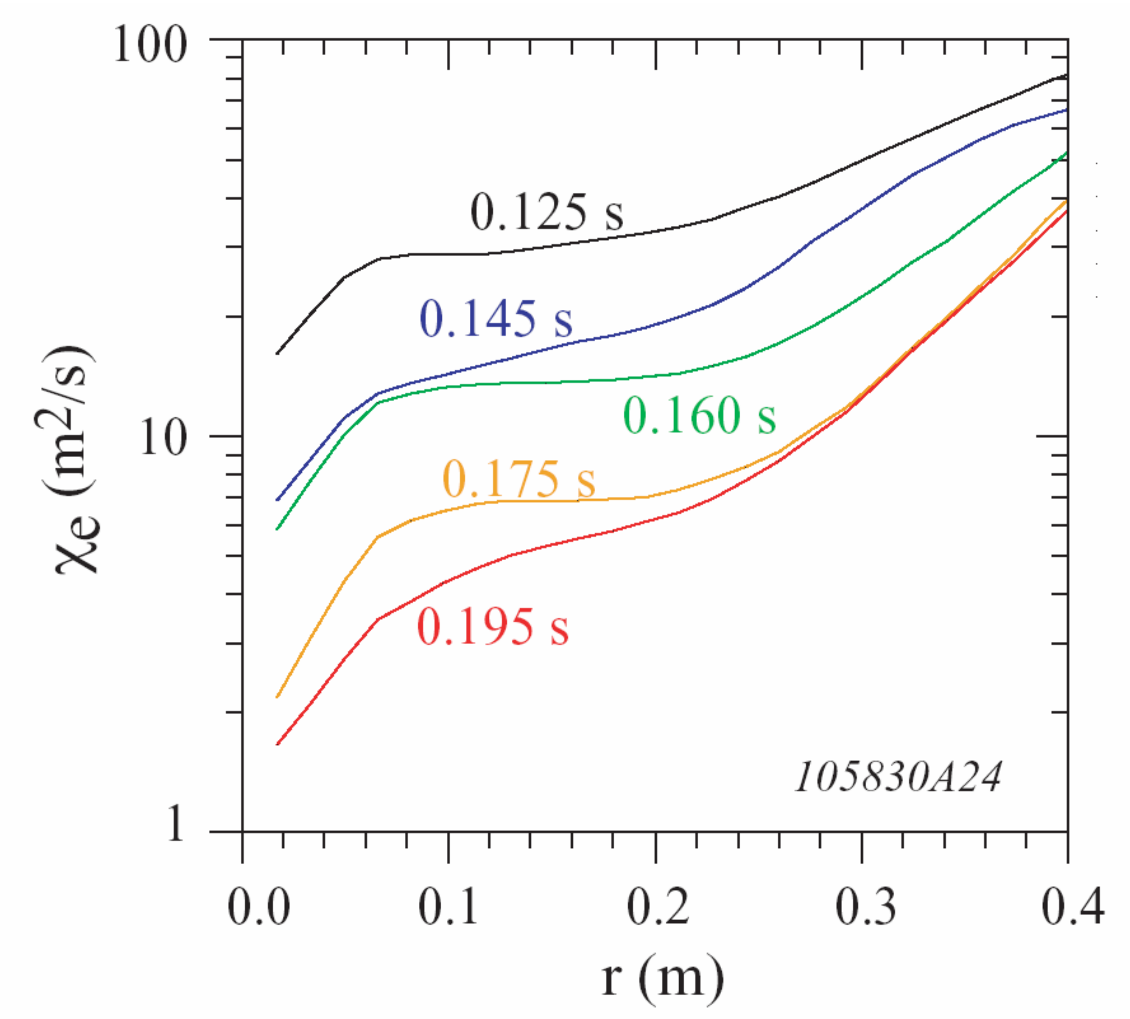


- Deuterium, 0.8 MA, 0.45 T, $n_e(0) \sim 2\text{x}10^{13}/\text{cm}^3$
- P_{HHFW} = 2.5 MW; $\mathbf{k}_{||}$ = 14 m^{-1} (heating phasing)



LeBlanc, Bitter

TRANSP Analysis Suggests Formation of Electron ITB



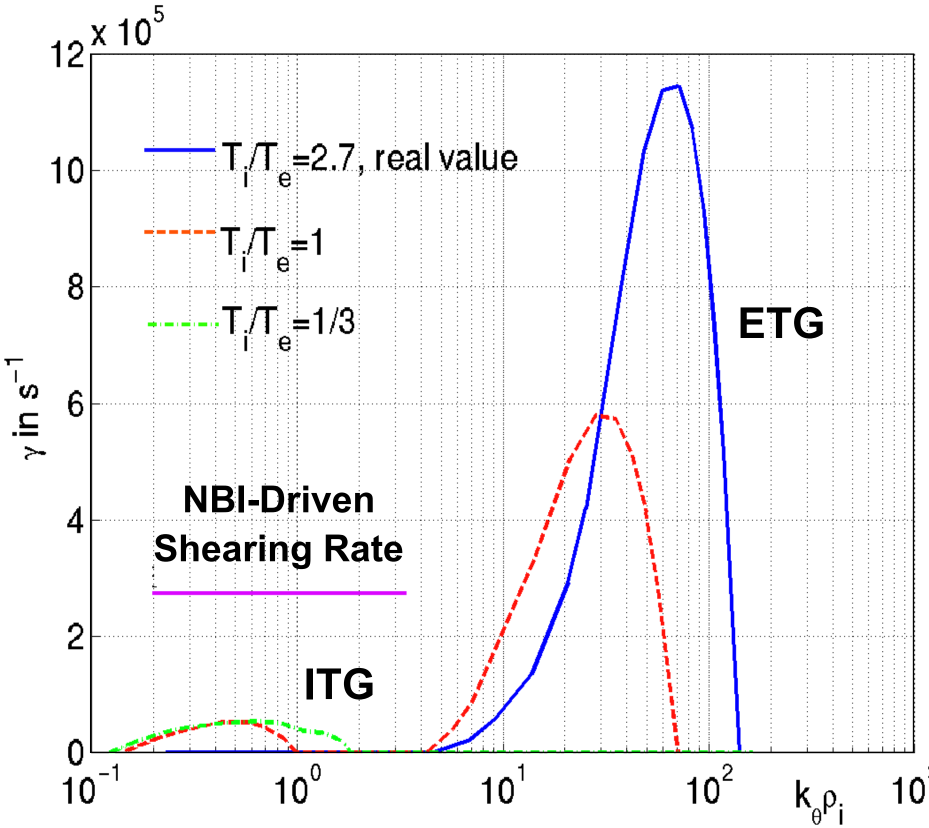
- Small n_e profile changes
- Provide a T_e/T_i "knob" for ITG and ETG studies
- VB: Z_{eff} = 3 – 4.5
- TRANSP:
  - Factor of 10 reduction of χ_e during heat up
  - Reversed q in core?
  - Heating profile?

LeBlanc

Gyrokinetic Microinstability Calculations Indicate Suppression of Weak ITG by Flow Shear

- NBI-driven flow shearing rate >> ITG growth rate ($T_i \sim 2T_e$)
- Virulence of ETG depends strongly on T_i/T_e
  - not likely stabilized by flow shearing for $T_e \leq T_i$
- Other physics under exploration
  - effects of β'
  - stabilization by negative magnetic shear

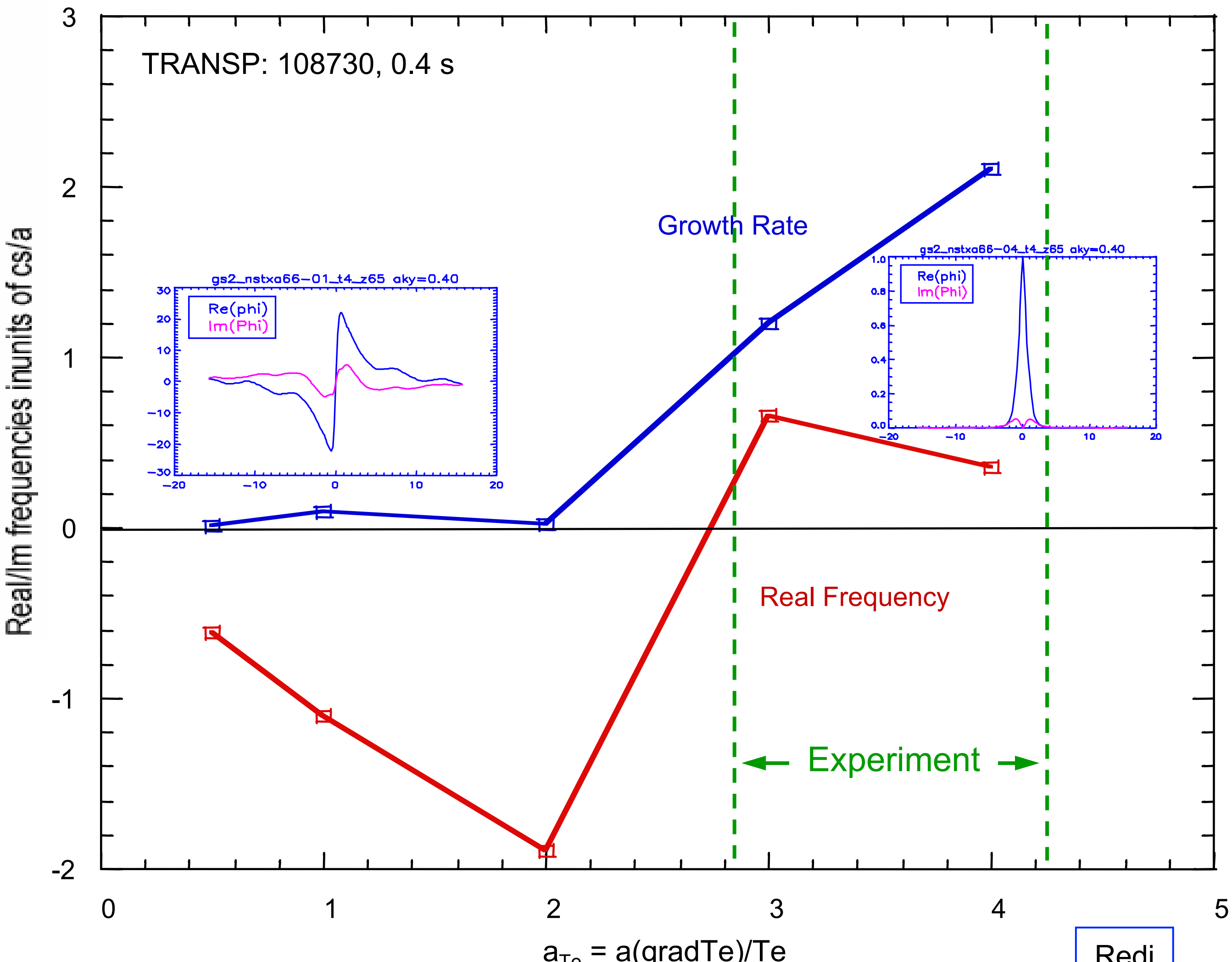
Gyrokinetic Microinstability Growth Rates



Bourdelle

Microinstability Changes from Tearing (ETG) to Ballooning (ITG-TEM) as a_{Te} Increases (r/a=0.65)

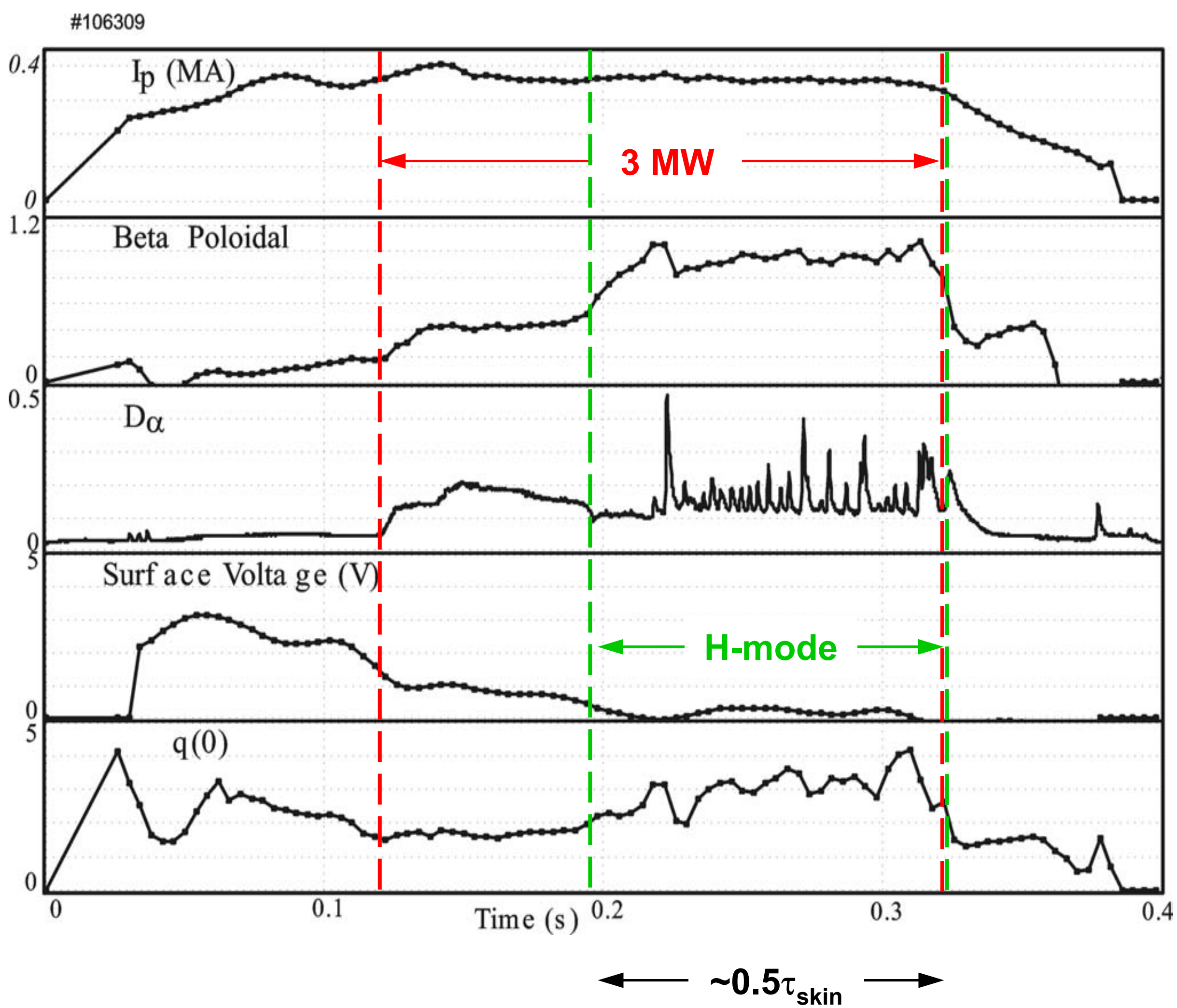
Mode unchanged even if a_n and a_{Ti} = 0



- **Micro-tearing seen so far only in ST calculations**
- **Mechanism?**
  - β
  - β'
  - q'
  - J'
  - |B|-well
  - other?

Redi

H-Mode Sustained Plasmas Using HHFW Alone May Shed Additional Light on H-Mode Mechanisms

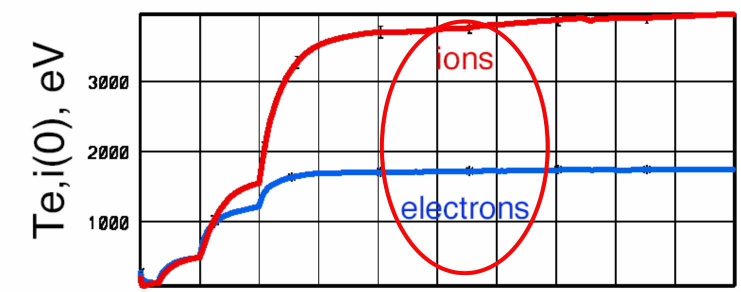


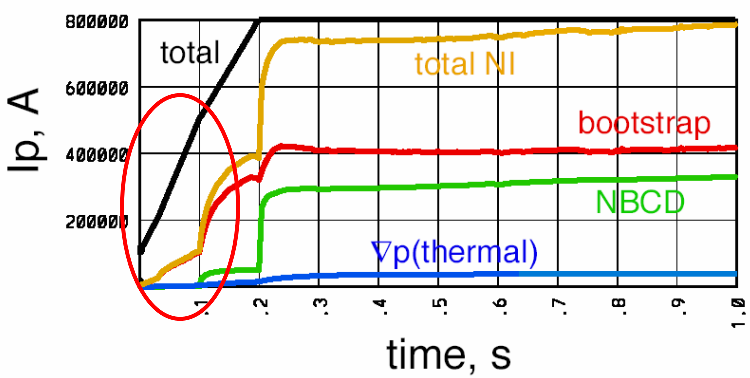
- **Moderate plasma current**
- **High β_p ~ 1**
- **H-mode with Edge-Localized Modes**
- **Induction voltage reduced to <0.5 V**
- **lower ℓ_i ~ 0.9**

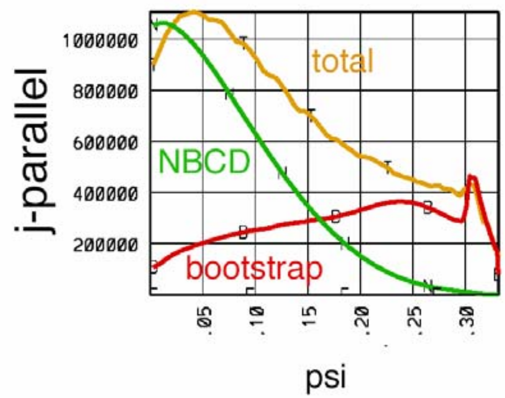
Wilson

Simulations of J_{NI} = 100% Plasmas Motivate Important Research Topics and Identify Scenarios

Identified Scenarios to Achieve Long Pulse Sustainment

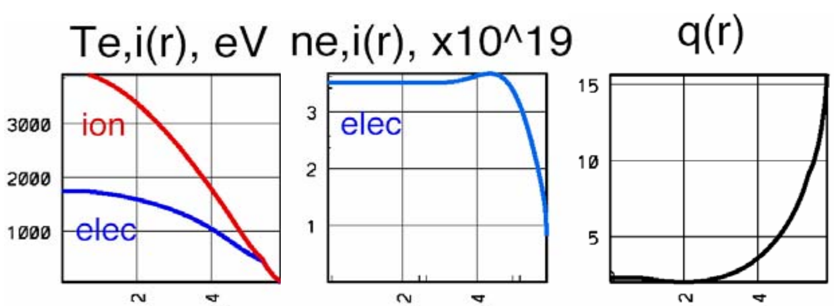






<u>Assume #109070 plus χ_e, $\chi_i \propto P^{-0.5}$:</u>
κ = 2.6, $H_{98(y,2)}$ = 1.1,
β_N = 7.0, β_T = 20%,
Stable to n = 1 & ∞

Kessel, Synakowski

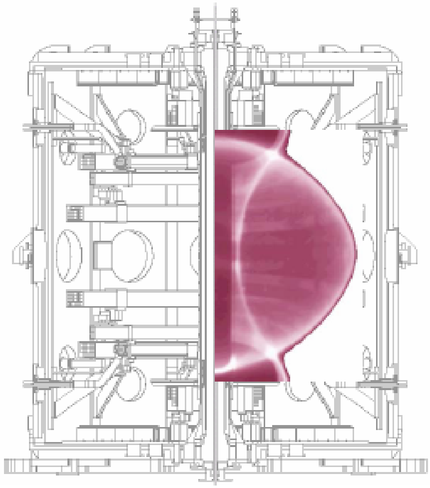


- **ST research topics**
  - Effects of large V_ϕ and V_ϕ shear on stability & transport
  - Scaling of χ_e, χ_i with $T_i \sim 2T_e$
  - HHFW heating in presence of NBI
  - Bootstrap J at low A
- **Scenario elements**
  - Active particle control
  - CHI or EBW I_p initiation
  - Non-inductive I_p ramp-up
- **Relevance: sustained burning plasma**

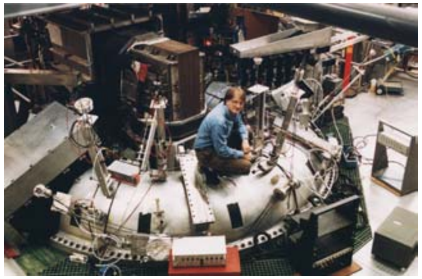
Extended Physics Parameters of NSTX Has Led to Broadened Collaborations

- **Began participation in ITPA (ITER)**
  - A and β effects: H-mode, ITB, ELM's & pedestal, SOL, RWM, and NTM
- **DIII-D & C-Mod collaboration**
  - Joint experiments on RWM, Fast ion MHD, pedestal, core confinement, edge turbulence
- **Merging database with MAST, U.K.**
  - NBI H-mode, transport, τ_E
  - EBW H&CD (1 MW, 60 GHz), FY03
  - Divertor heat flux studies, FY03-04
  - NTM, ELM characterization
- **Exploratory ST's in Japan**
  - **TST-2**: ECW-EBW initiation
  - **TS-3,4**: FRC-like β~1 ST plasmas
  - **HIST**: helicity injection physics
  - **LATE**: solenoid-free physics
- **MST:** electromagnetic turbulence, EBW

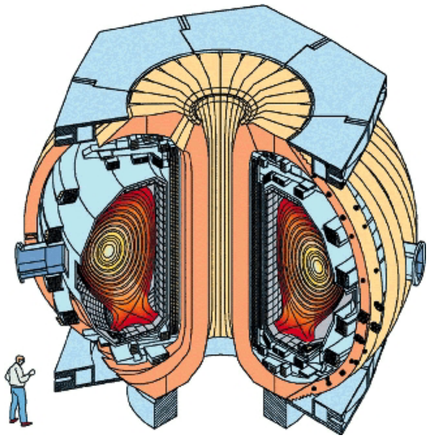
MAST (U.K.)



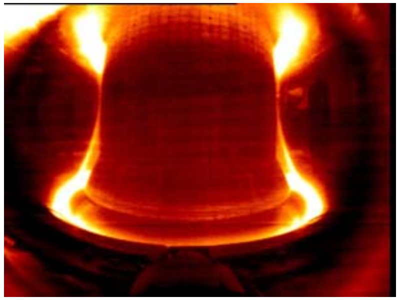
MST (U.S.)



DIII-D (U.S.)



C-Mod (U.S.)



NSTX Plans to Participate in ITPA Strongly

- Continued progress in research capabilities & results
- Results of interest: large ρ_i/L_{Ti} zone & r/a at footpoint, some tolerance to MHD
  - Mechanisms related to β, A
  - Similarities and differences
    - Does NSTX have ITB? Why not apparent in n_e, T_e?
    - What should be its definition (local χ reduction, ρ_T*, etc.)?
    - What affects strength, locations, evolution (V_ϕ', MHD modes, q, β, fueling, Zeff, etc.)?
    - What measurements needed for modeling comparisons?
- Investigate ITB physics by adding HHFW H&CD
- Extensive work just begun – plans to install MSE, low and high k fluctuations diagnostics in 2004-5
- Contribution in other topics