Stability and Confinement Properties of Auxiliary Heated NSTX Plasmas

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for the NSTX Team

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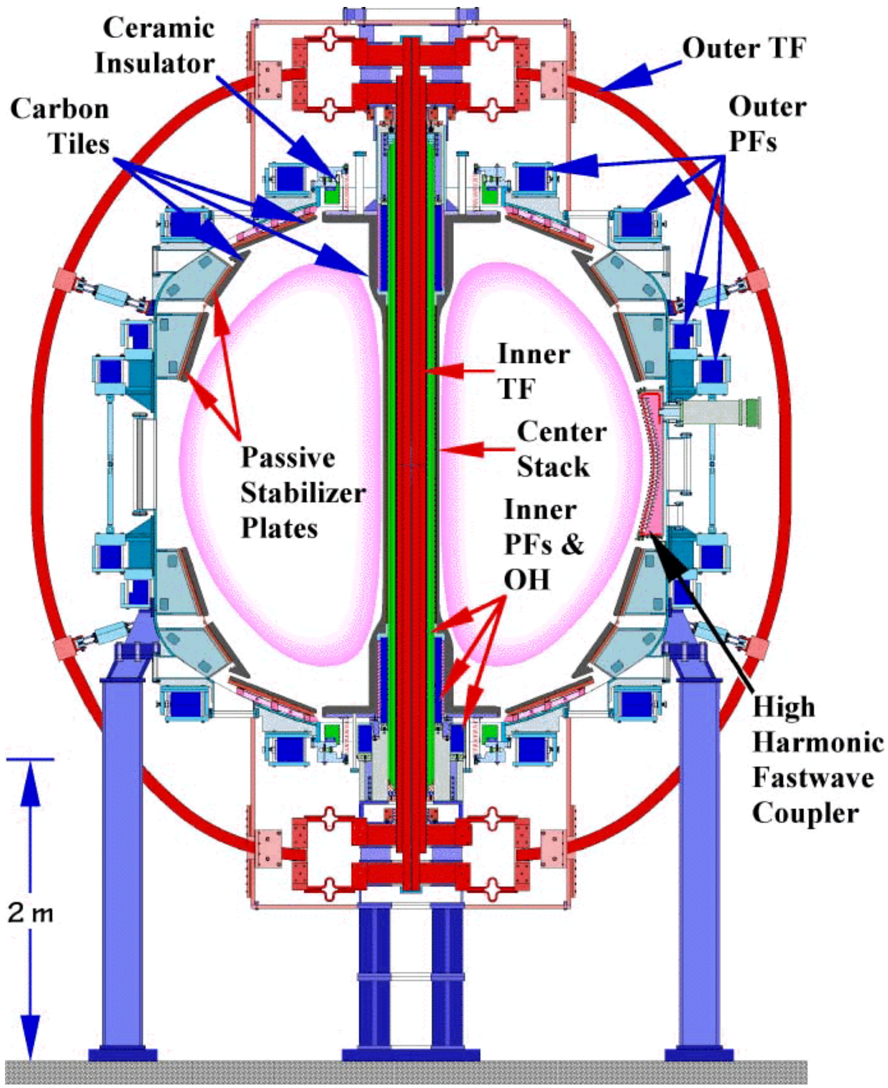
NSTX is a MA-class Spherical Tokamak



Baseline Parameter ***(Achieved)***

Aspect Ratio ≥ 1.28

Major Radius = **0.85 m**

Minor Radius = **0.68 m**

Elongation = 2.2 ***(2.5)***

Triangularity = 0.5 ***(0.6)***

Plasma Current = 1 MA ***(1.4 MA)***

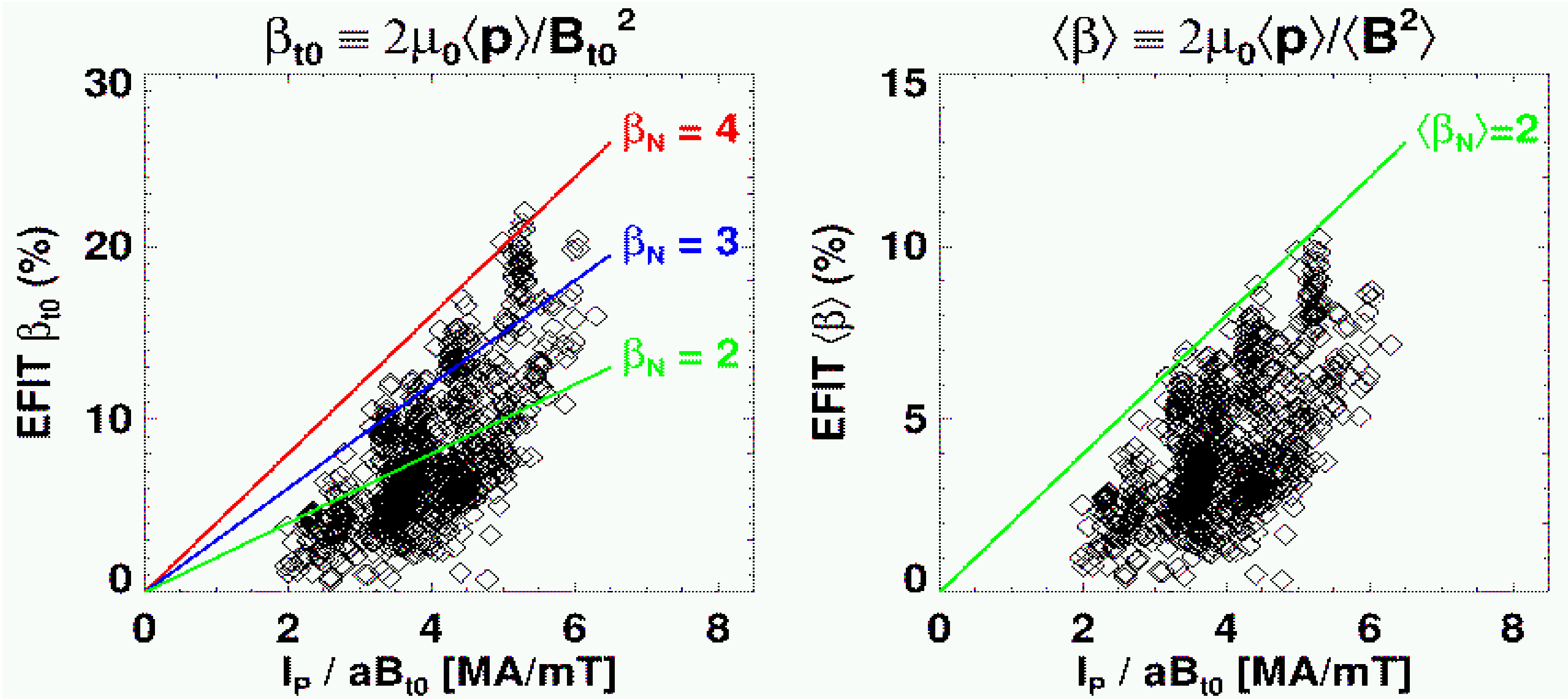
Toroidal Field
0.3 to 0.6 T ***(≤ 0.45 T)***

Heating and CD
5 MW NBI ***(5.0 MW)***
6 MW HHFW ***(4.2 MW)***
0.5 MA CHI ***(0.26 MA)***

Pulse Length = 5 sec ***(0.5 sec)***

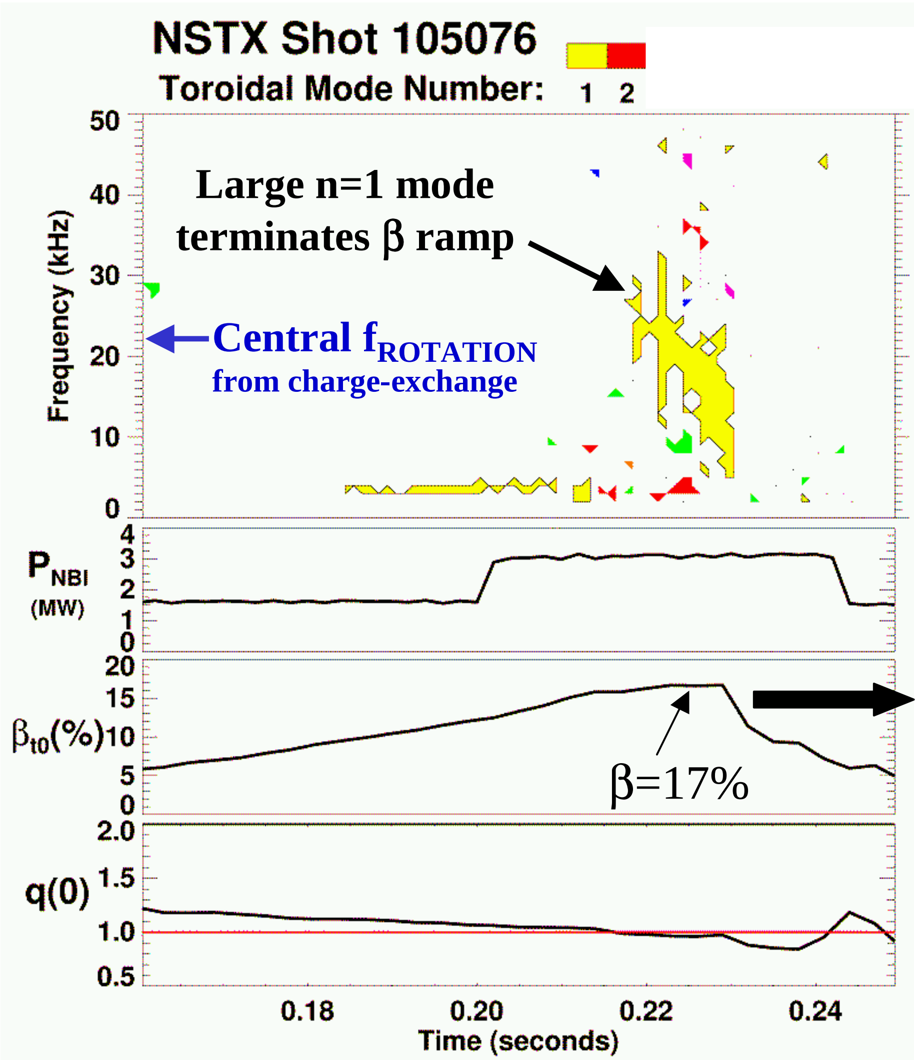
NSTX has achieved β_{t0}~20% plasmas

- **Data shown below:**
  - **EFIT reconstructions using external magnetics only**
- $\beta_N \leq$ 3-4 ***at peak*** W_{TOT}
- I_P/aB_{t0} = 2-6
- $\beta_P \leq 0.55 \Rightarrow$ paramagnetic
- Original Troyon definition of β better fit to present data

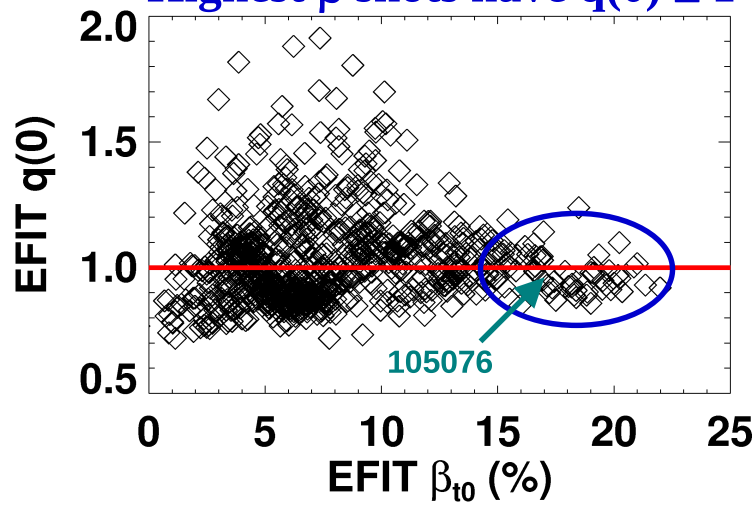


EFIT - S. Sabbagh

Highest β shots experience fast β collapses



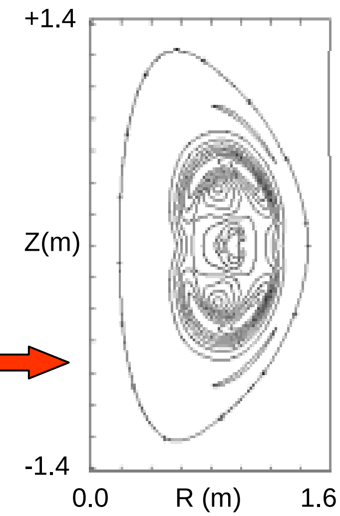
Highest β shots have q(0) ≤ 1



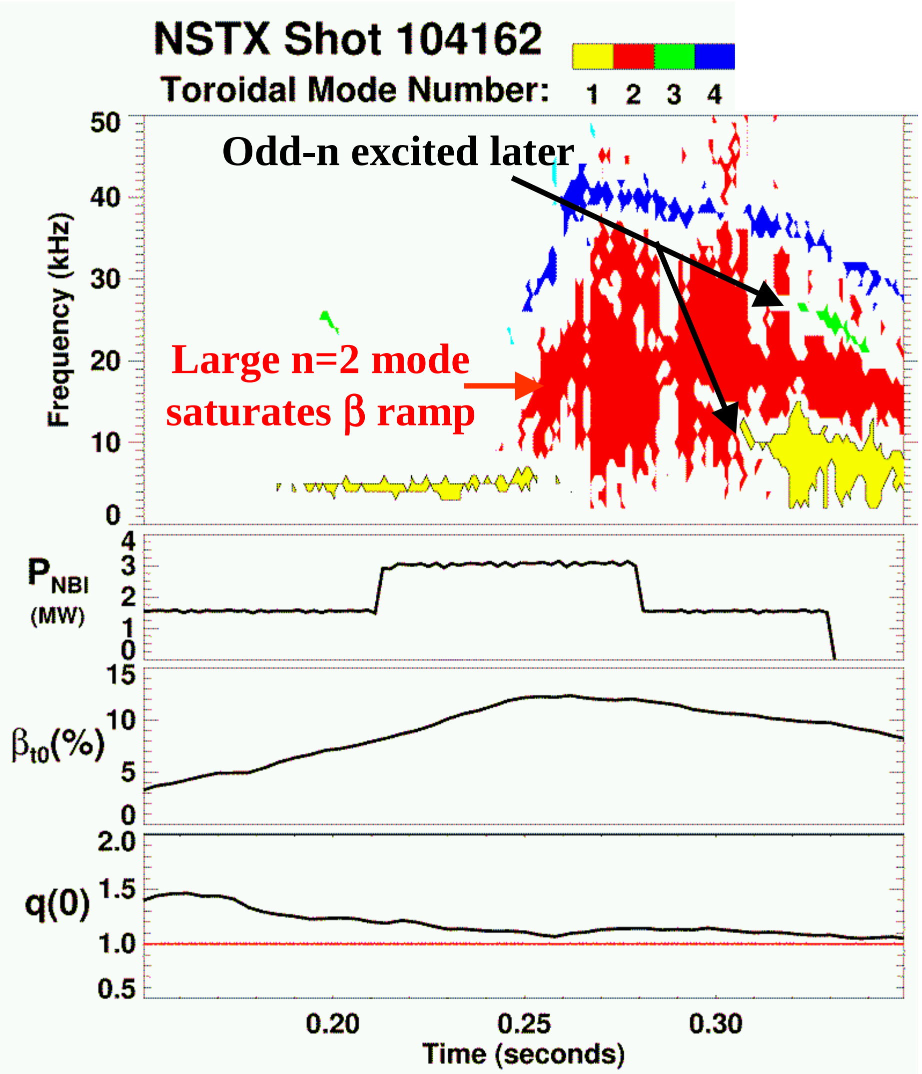
At t=226ms,

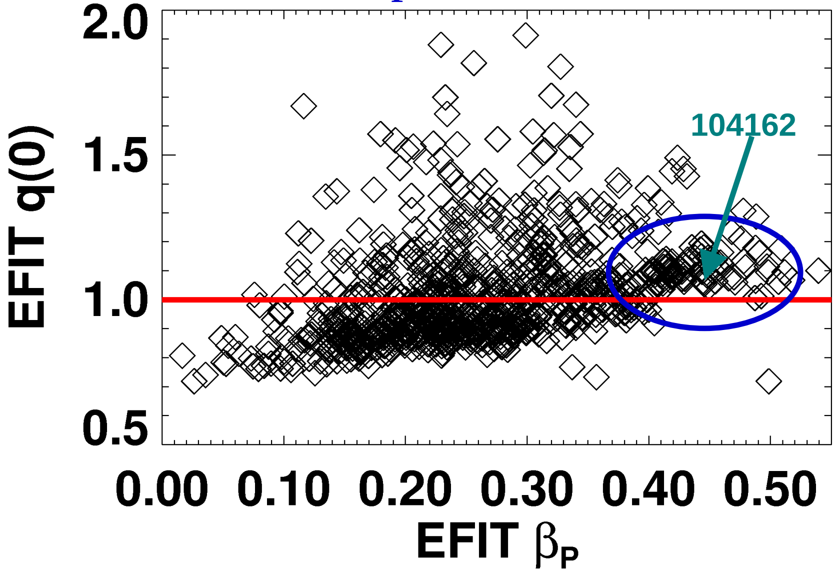
- DCON finds n=1,2 unstable internal kinks
- PEST-I finds n=1 mode inside q(0) = 1 radius spans most of core

$|v|^2$ contours



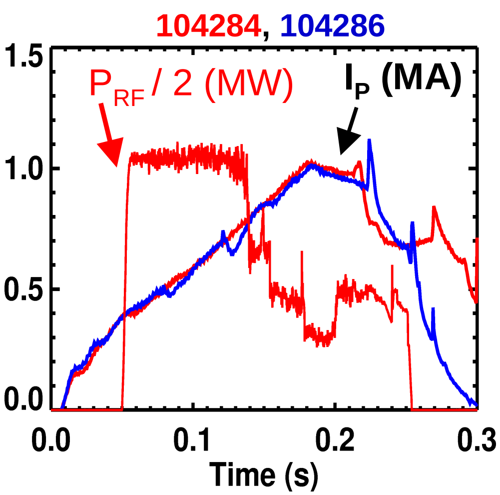
Highest β_P shots often exhibit saturation

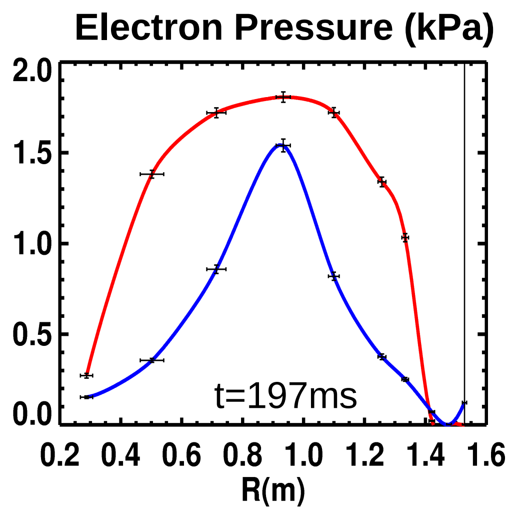




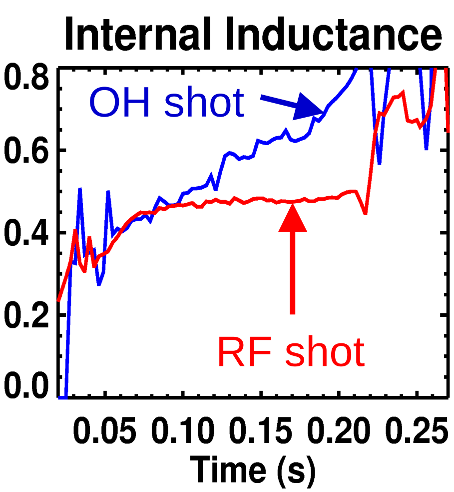
- **Possible evidence for NTM**
- But, preliminary kinetic EFITs suggest lower q(0) at higher β_P
- **Many shots have n=1 activity**

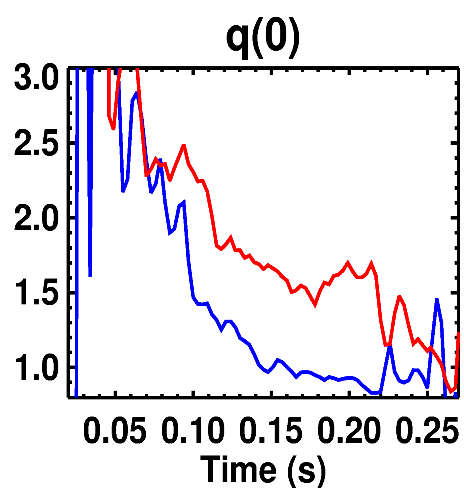
RF heating during I_P ramp can lower $p(0)/\langle p \rangle$, raise q(0)

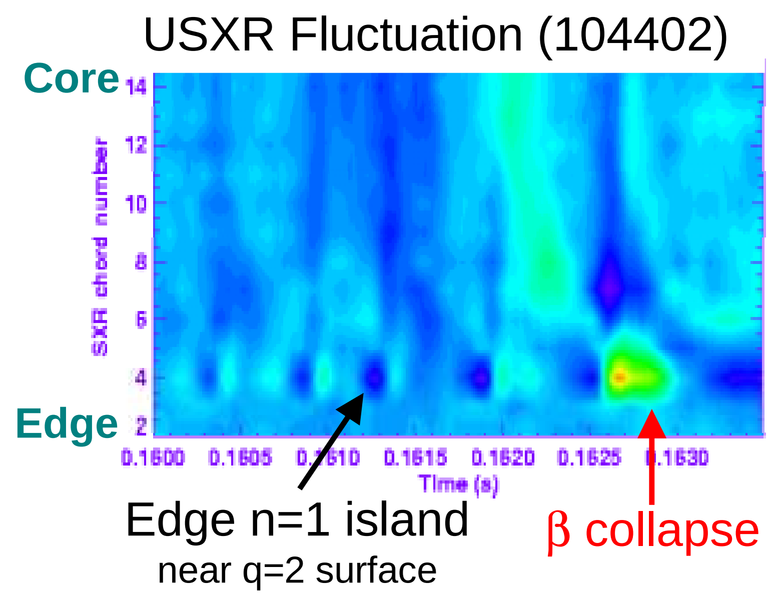




- Achieved β=15% at low-li ~ 0.5-0.6 using early RF+NBI
- β-collapse caused by **edge** MHD
- Possibly useful for "AT" regimes





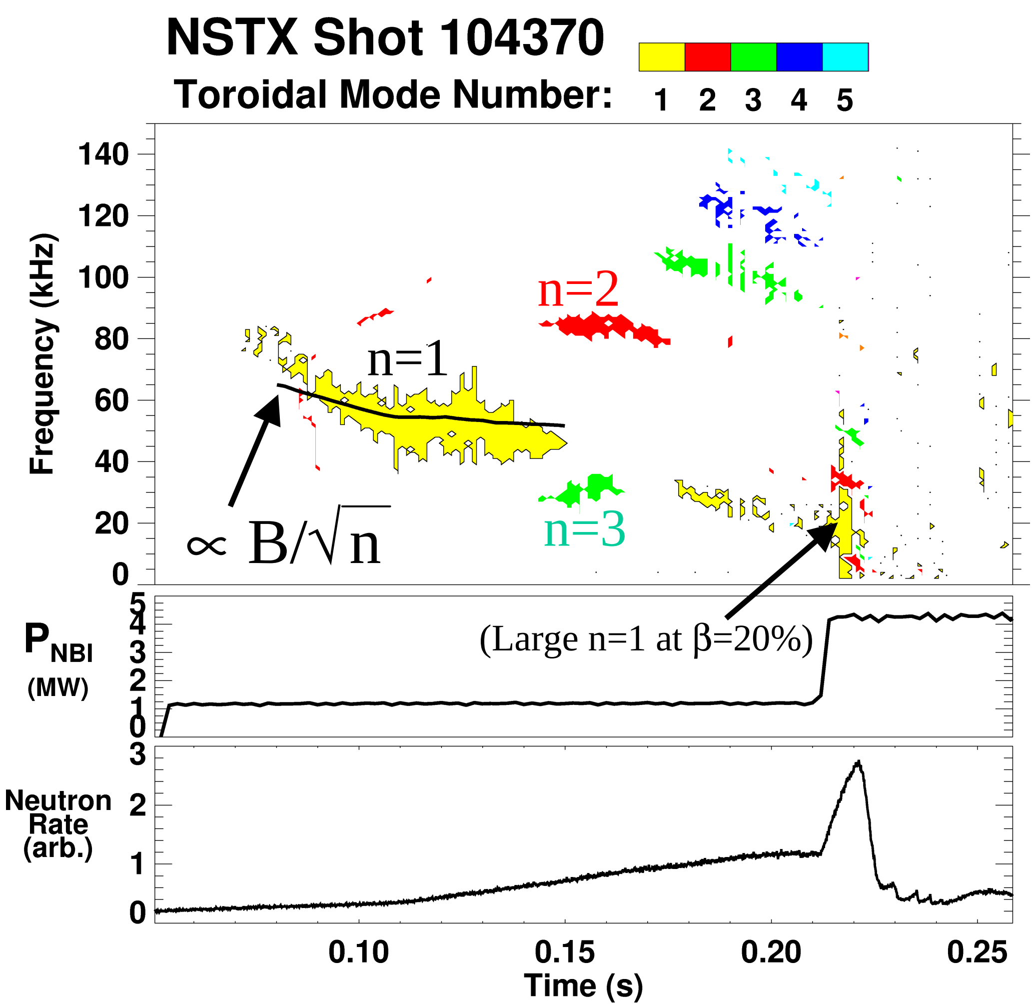


XP025,016 - J. Menard
XP017 - S. Sabbagh

Beam-driven MHD activity observed in many discharges

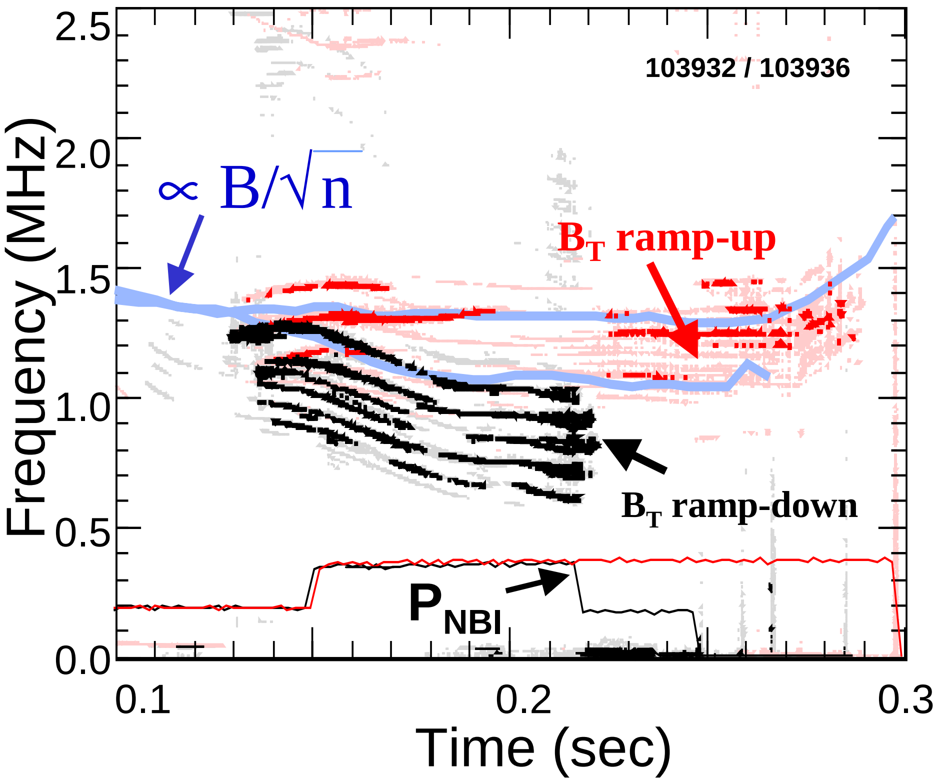
In NSTX V_{Beam} ~ 4 V_{Alfven}

⇒ 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



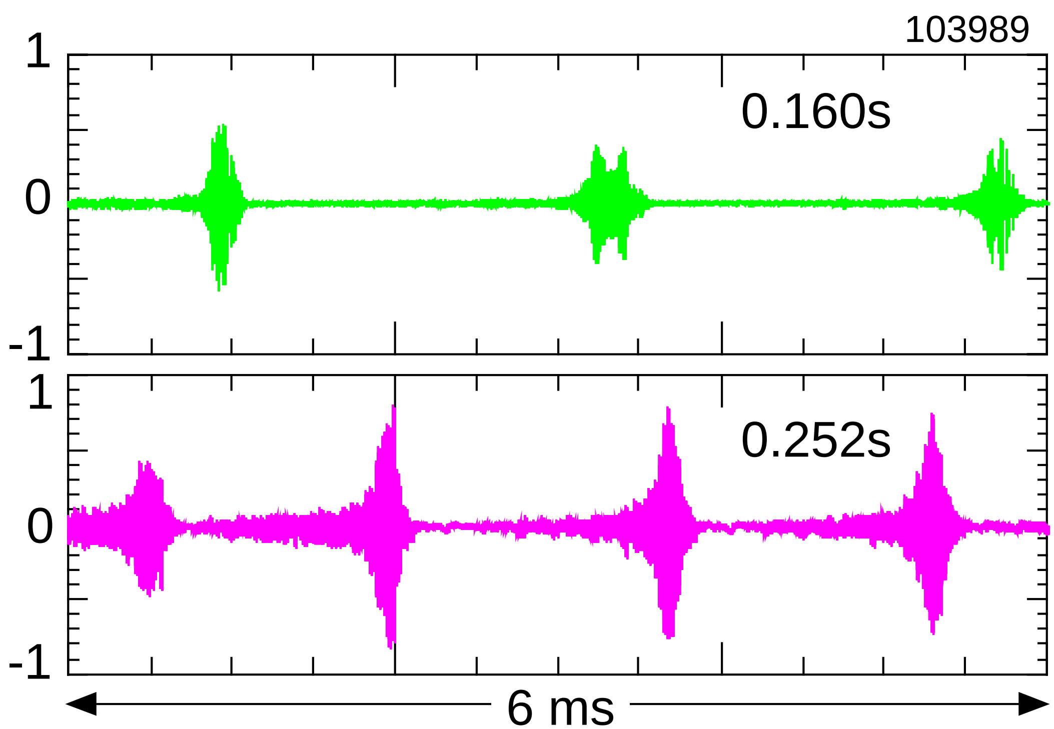
- For NSTX parameters:
  - $k_{\|} \sim$ 2-4m^{-1} ⇒ weak electron and ion Landau damping

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

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

CAE modes can be quasi-continuous or bursting in character

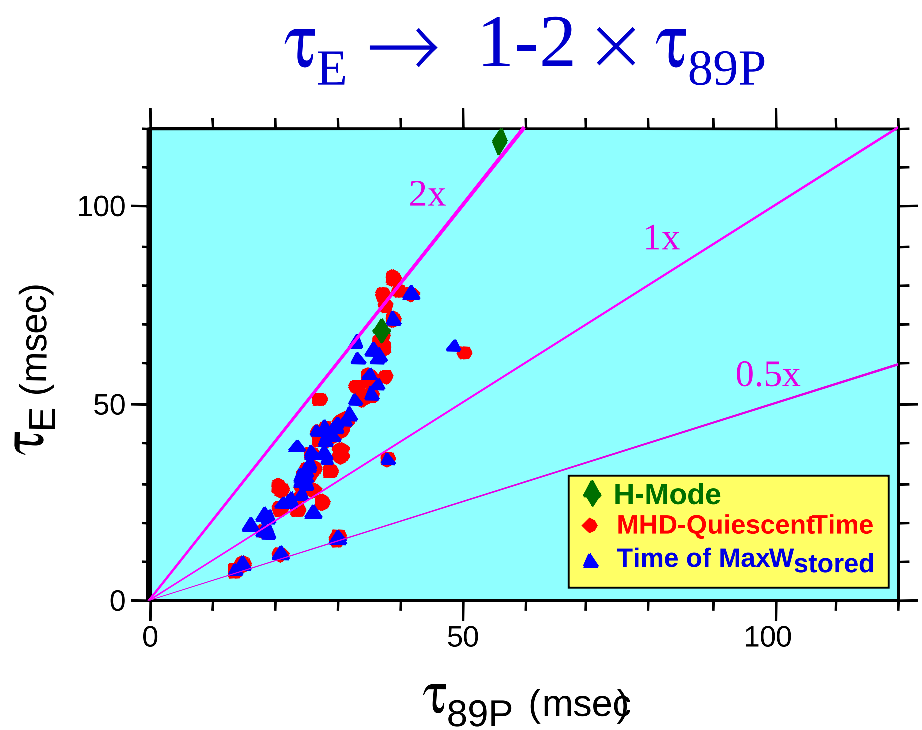
- Bursts yield growth/damping rates 10^4/s or γ/ω 0.15%.
- All modes grow/damp together.

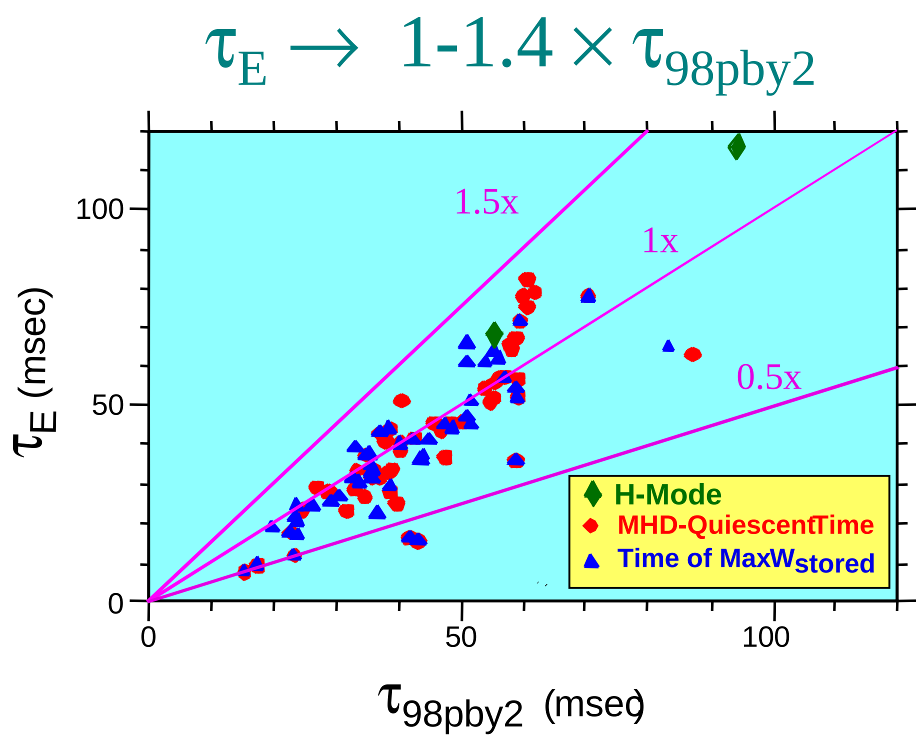


Peak rms fluctuation level (0.5-2.0 MHz) at probes is
- 10-15mG

NSTX confinement exceeds L-mode scaling

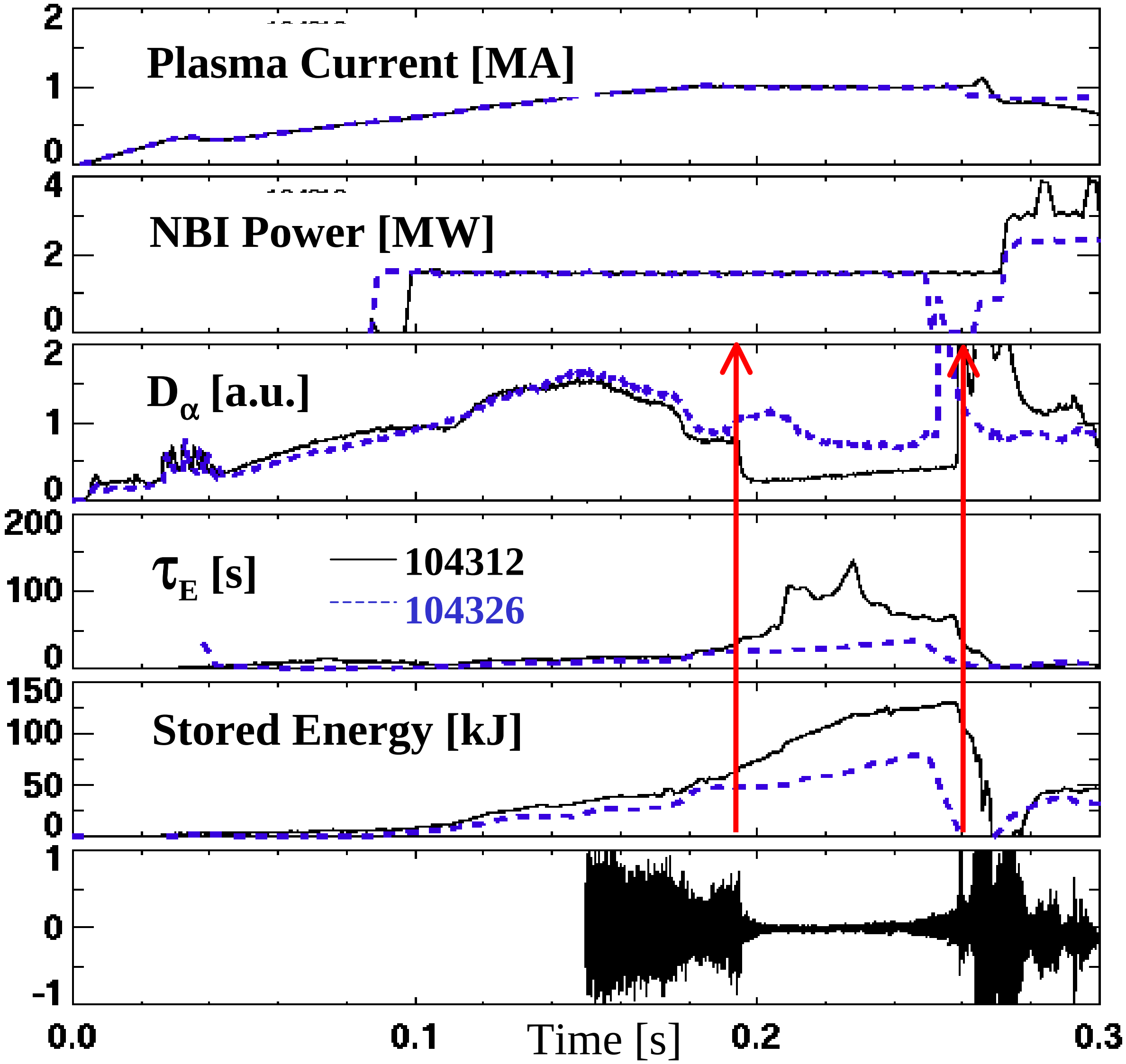
- NSTX confinement best fit by H-mode scaling





- **Plasmas w/ and w/o H-mode transitions have similar H-factors**
- Good confinement has allowed rapid access to β limit

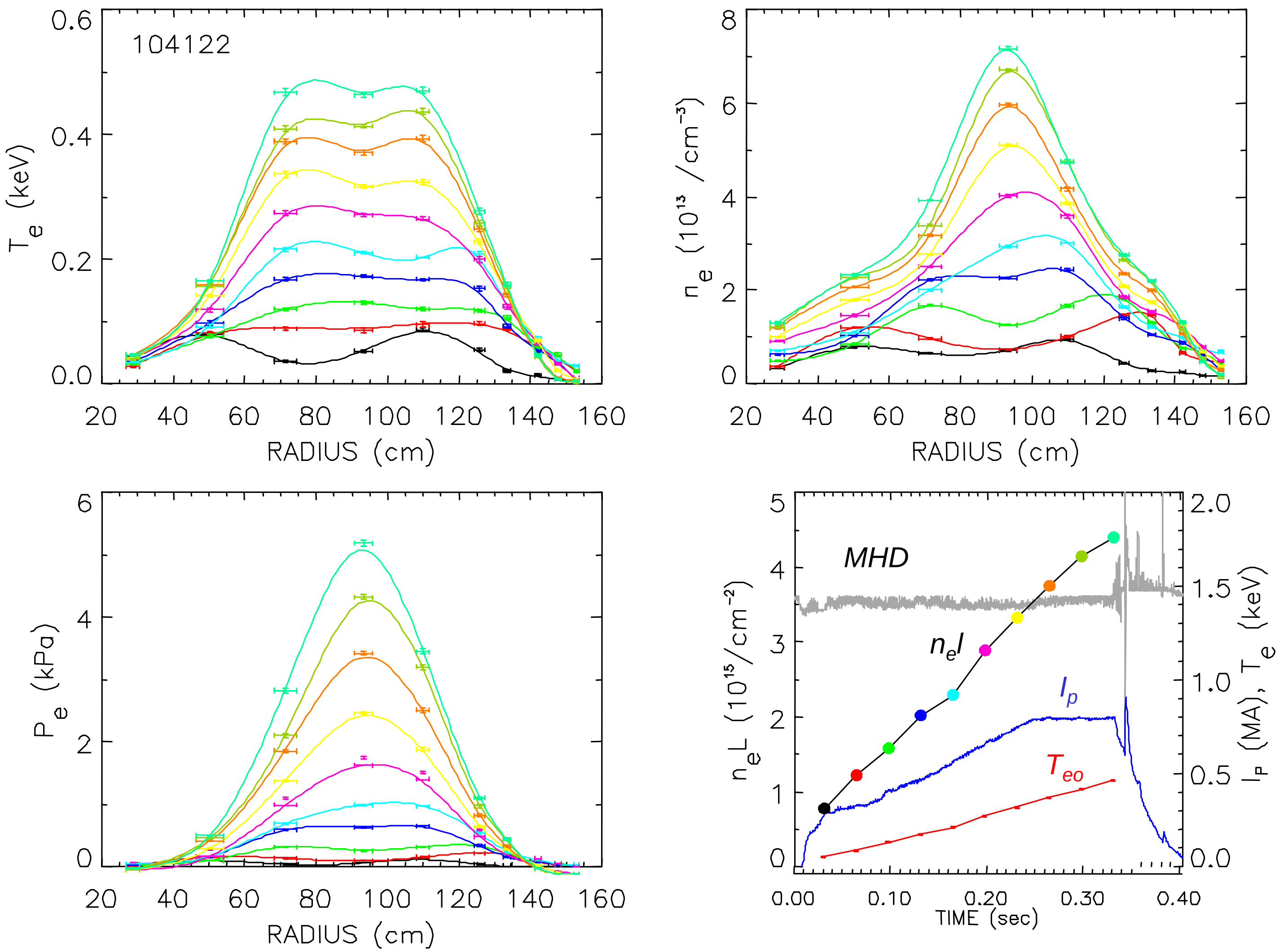
H–mode τ_E increases to ~ 100ms prior to ELM



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

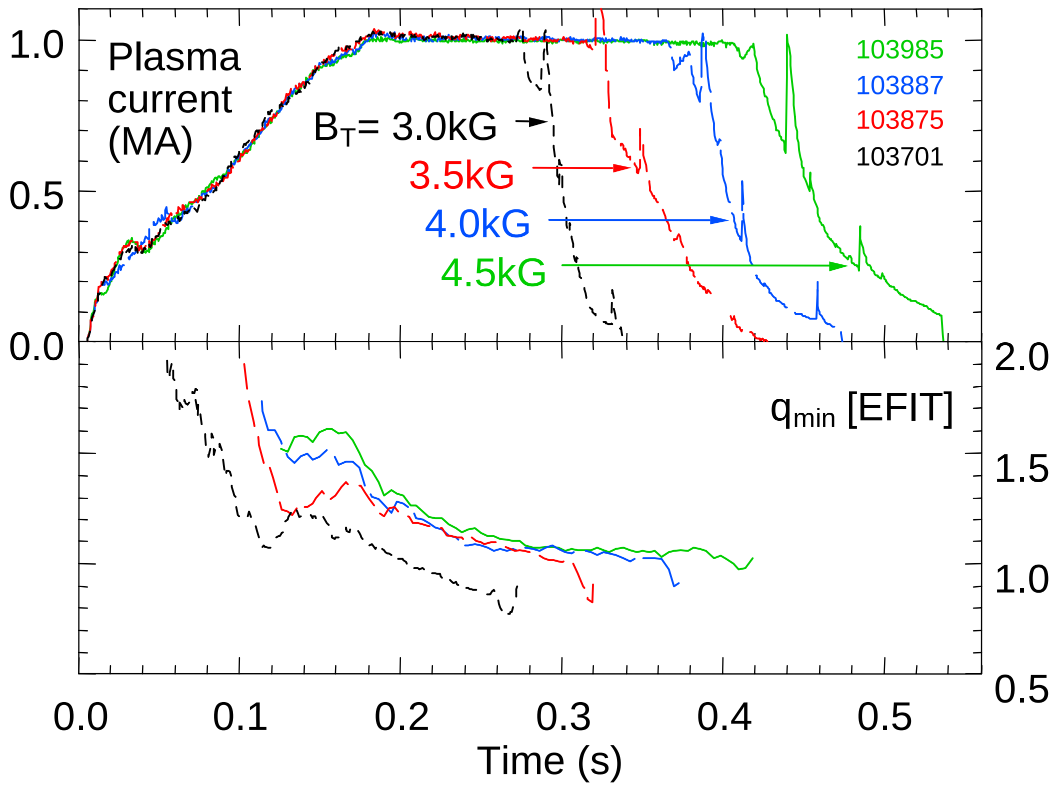
Some MHD-quiescent ohmic plasmas point to the existence of a particle pinch

- B_T=4.5kG
- I_P=800kA



B. LeBlanc, R. Bell, J. Menard

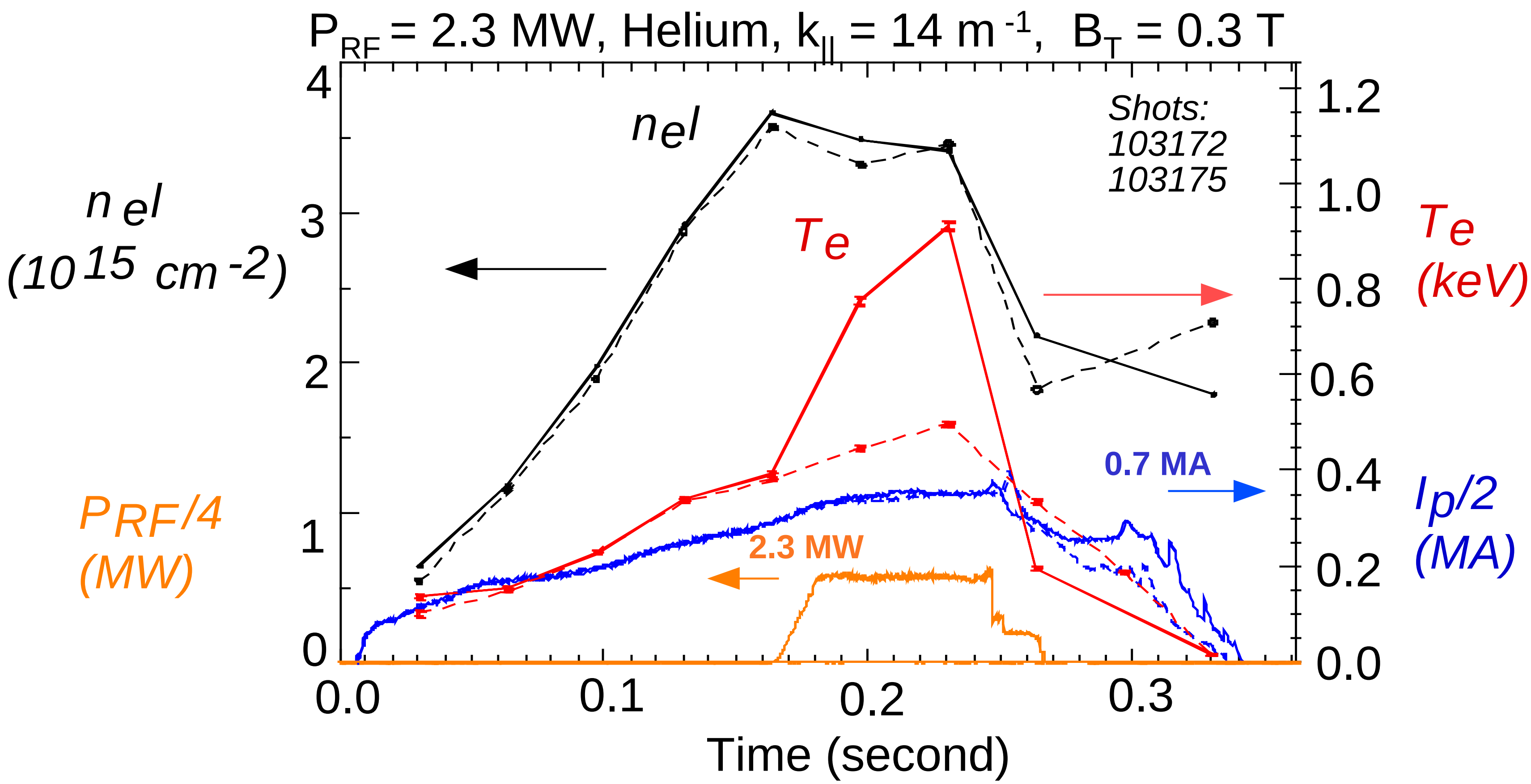
Raising B_T increases discharge duration



- Raising B_ϕ dramatically increases pulse length
- Effect is **not** due to increase of T_e with B_ϕ
- Final **pulse length determined by MHD** in all cases shown
- Maximum pulse length exceeds 0.5 seconds
- Further increases to B_ϕ may lead to longer pulses

- Beam injection starts at t=90ms for discharges shown
- P_{NBI} = 1.2-2.5 MW

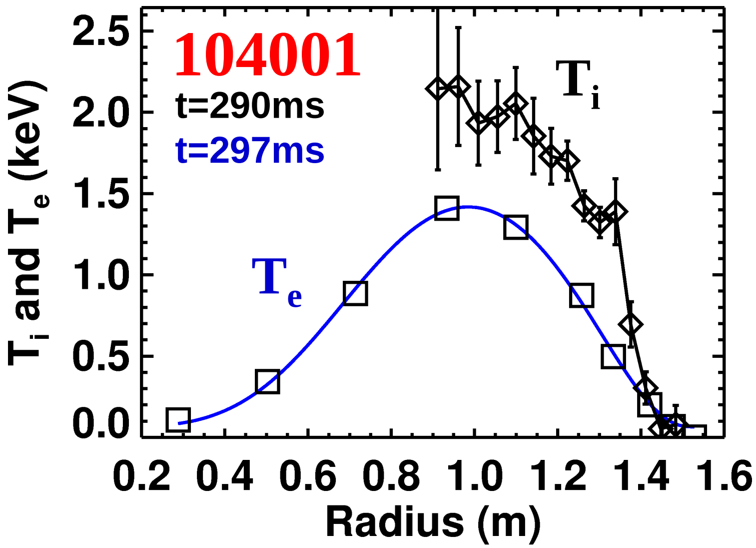
Strong electron heating observed with HHFW

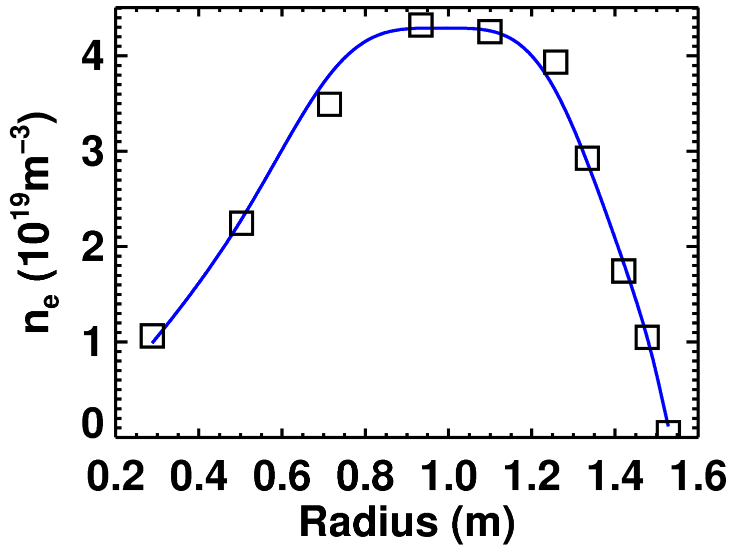


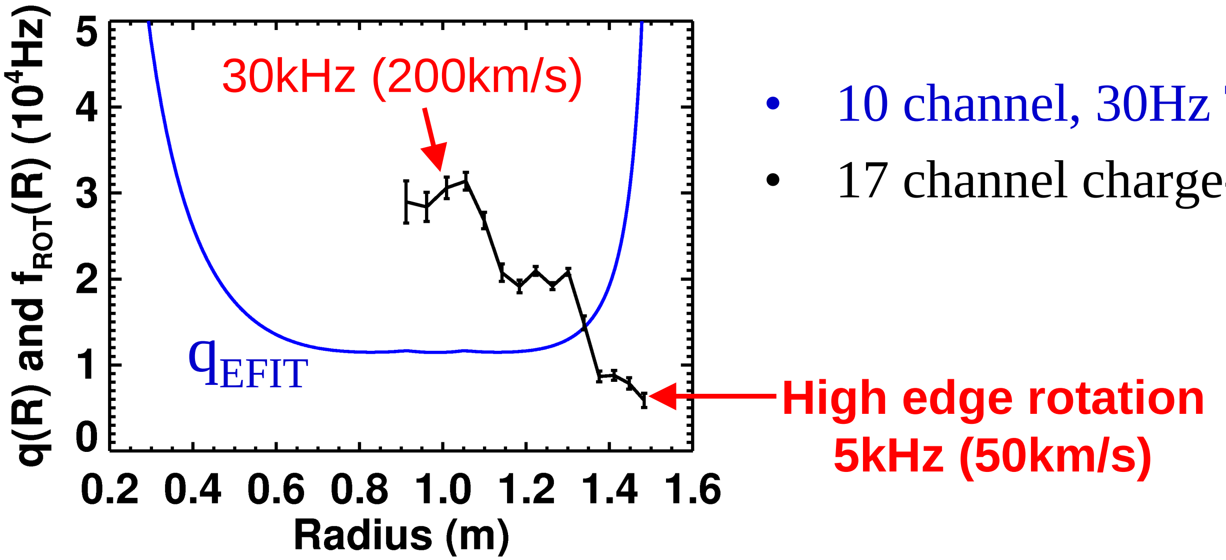
- $T_e(0)$ increases to ~ 900 eV in helium plasma at P_{RF} = 2.3 MW
- No density increase with RF and V_{loop} decreases by ~ 30 %
- Stored energy increases to 58 kJ (magnetic): β_T = 10%, β_N = 2.7

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)





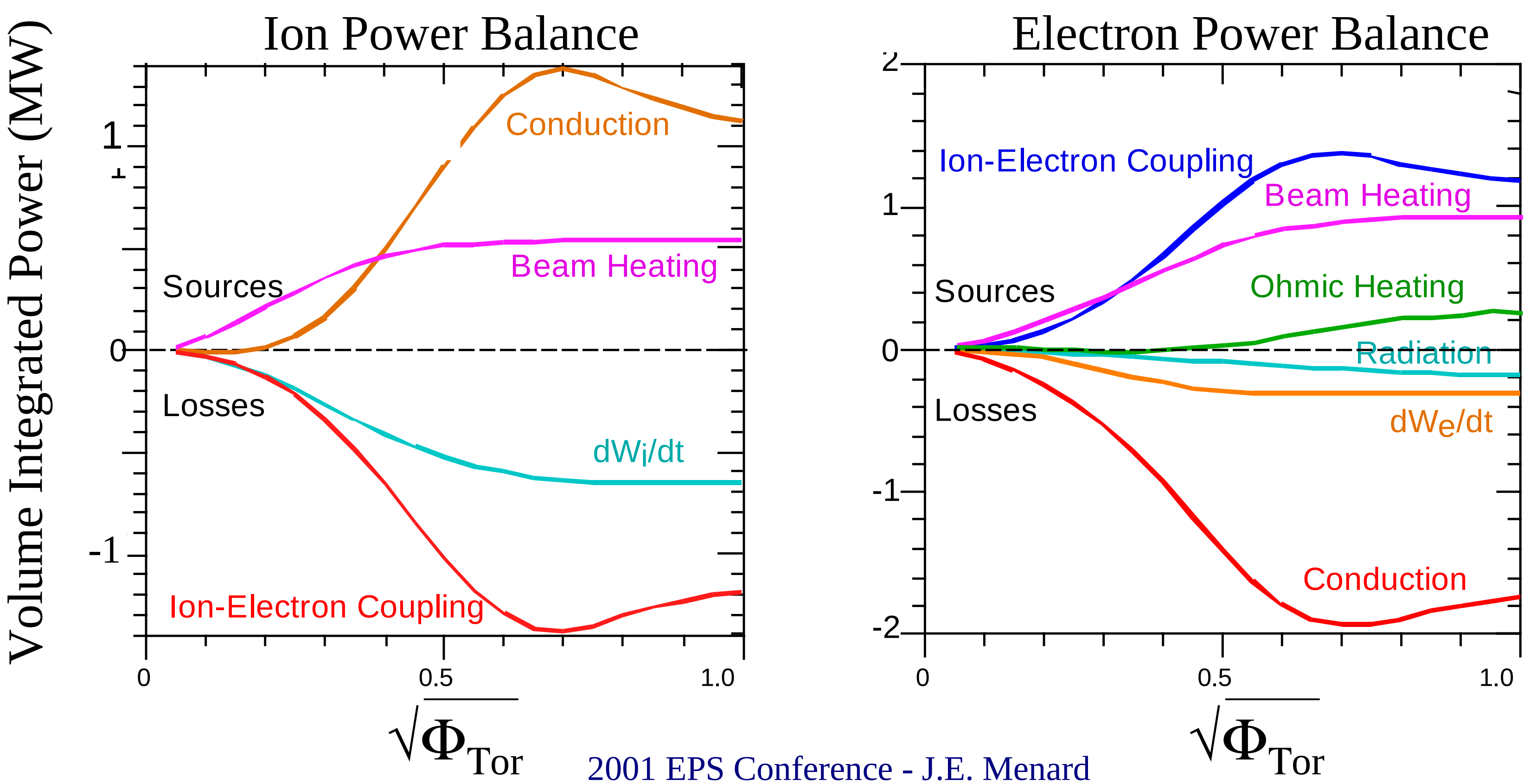


- 10 channel, 30Hz Thomson scattering
- 17 channel charge-exchange (CHERS)

D. Gates, R. Bell,
B. LeBlanc, S. Sabbagh

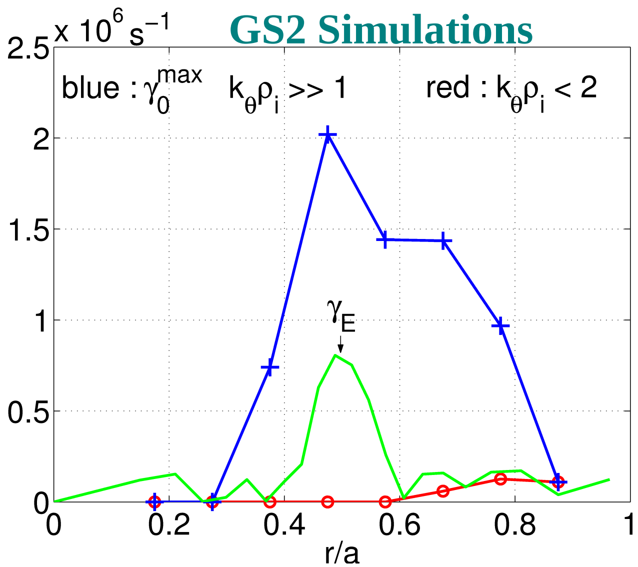
Power balance for 104001 not yet understood

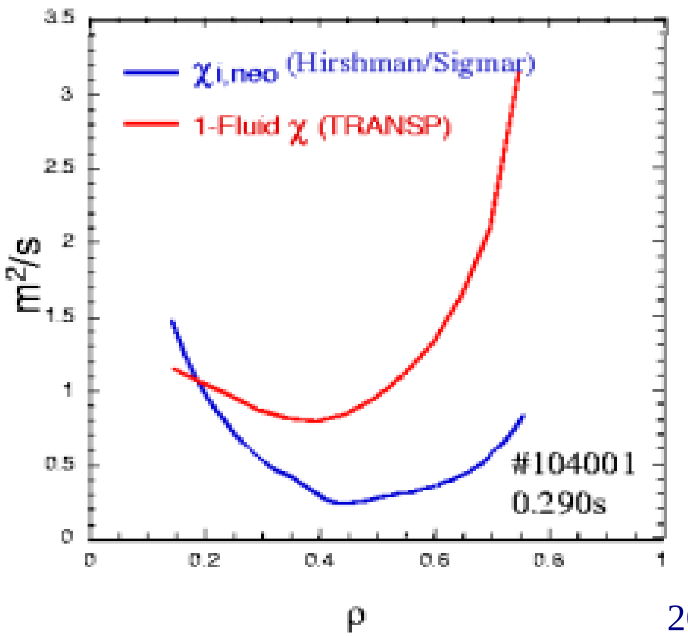
- electron-ion coupling term dominates power balance
- Ion conduction term appears as <u>source</u> ⇒ **unusual**
- Diagnostic calibration problems unlikely:
  - Thomson Z_{eff} =2 for He plasmas, CHERs T_i = Thomson T_e for ohmic shots



S. Kaye

Comments on power balance for 104001





- Linear gyrokinetic simulations (C. Bourdelle):
  - ETG growth-rate >> ExB shearing rate
  - ITG+TEM growth-rate ≤ ExB shearing rate
  - 1-Fluid χ (TRANSP) is found to be few times χ_i-neoclassical *(see lower left)*
- Finite-amplitude wave simulations (R. White)
  - Large numbers of CAE modes may cause **stochastic ion heating** below Ω_D (Gates, White, Gorelenkov)
- But, for 104001, even if **all** NBI power went directly to ions, ion conduction is still ≤ 0 assuming classical electron-ion coupling
- Final resolution might involve
  - ion-electron coupling corrections
  - anomalous ion heating mechanisms (CAE/TAE)
  - other ion transport effects ?

Summary

- Beta limit encountered in NSTX for $\beta_N \leq$ 3-4, $\langle\beta_N\rangle \leq 2$
  - Internal kink and possibly NTM presently limit performance
  - Attempting to push to higher I/aB and β_{t0}
  - RF $\Rightarrow$ NBI targets with higher q(0) and broader p-profiles
- TAE & CAE activity observed $\rightarrow$ small fast ion losses
- Confinement is twice L-mode, follows 98pby2 scaling
  - H-modes have $\tau_E \sim$ 100ms confinement until first ELM
  - No ELMy H-mode yet, and power threshold is 0.8-1.2MW
- Power balance indicates **negative** ion conduction
  - classical ion-electron coupling wrong?
  - anomalous ion heating from CAE/TAE?
  - other ion transport effects?