High β, Long Pulse, Bootstrap Sustained Scenarios ons NSTX

Presented by David Gates (PPPL)
For the NSTX National Research Team
at the 44th Annual of the meeting APS-DPP
Orlando, Florida
November 11, 2002

Outline

- Machine improvements
- High β_t
- β limiting instabilities
- Long pulse - high β_p
- Summary

Facility Upgrades broaden operating regime

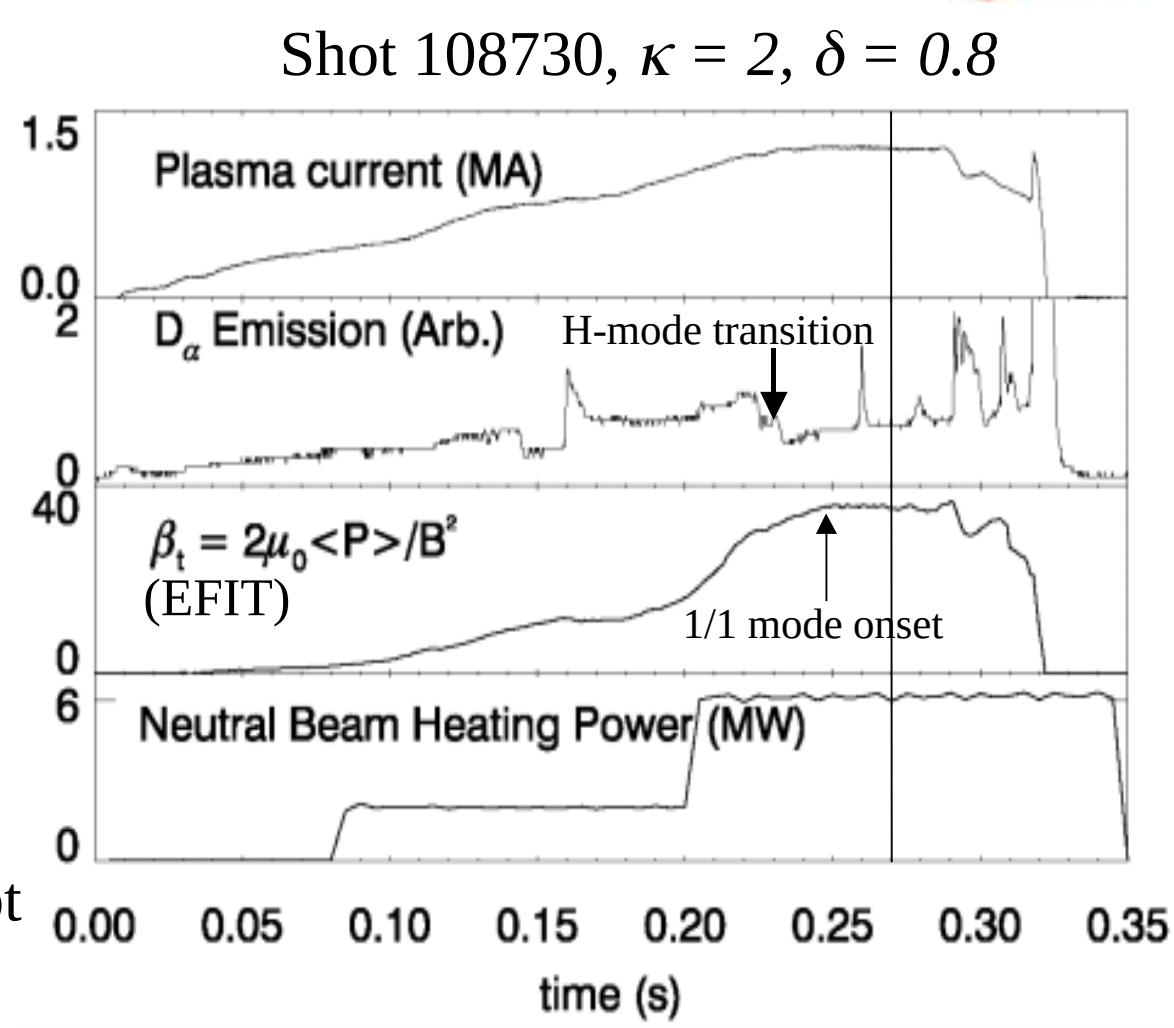
- Error field reduction - fewer IREs
- Shaping field pwr supply improvements - high δ
- Full TF operation (6kGauss) - wider q range
- 100keV neutral beam - higher stored energy
- Better H-mode access

  $\Rightarrow$350°C bakeout capability

  $\Rightarrow$Center stack gas puff

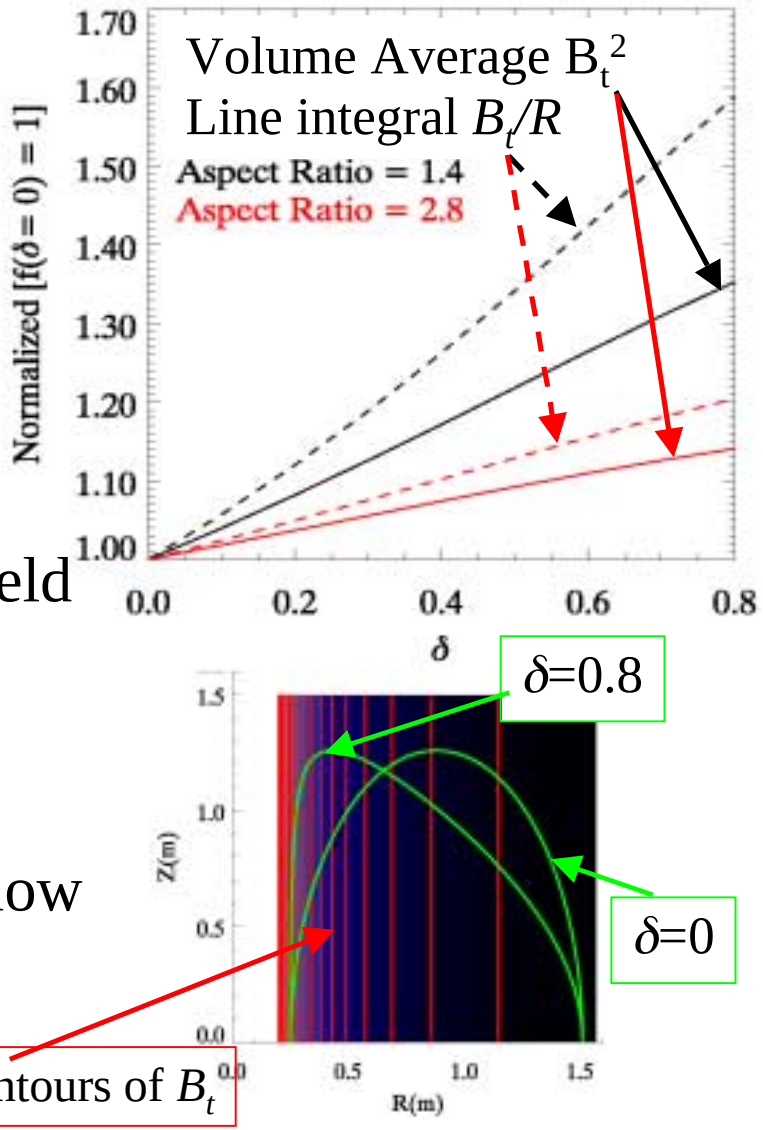
β_t = 35% achieved on NSTX

- β_t ($\equiv 2\mu_0 \langle P \rangle / B^2_{t0}$) ~ 35% achieved in high triangularity double null H-mode discharge
  - β_N ~ 5.5
  - l_i ~ 0.6
  - I_p = 1.2MA
  - B_t = 0.3T
  - P_{NBI} = 6MW
- Neutral beam preheat aids startup
- Plasma does not disrupt until ramp down

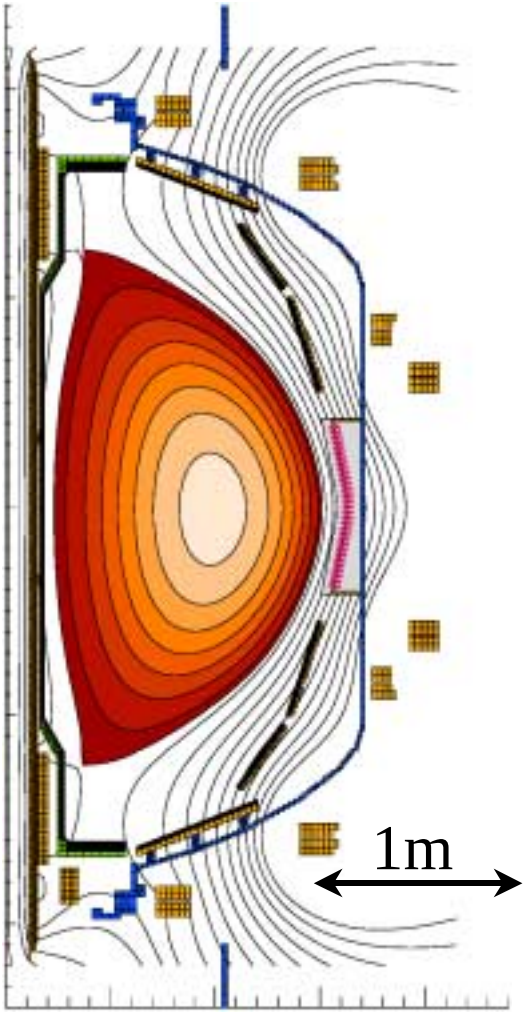


Shaping particularly important at low A

- High δ raises magnetic pressure for fixed B_{axis}
  - Higher pressure
- High δ and elongation raises edge q for fixed current, toroidal field
  - Higher I/aB
  - Also allows more rapid I_p ramp
- Effect stronger at low aspect ratio



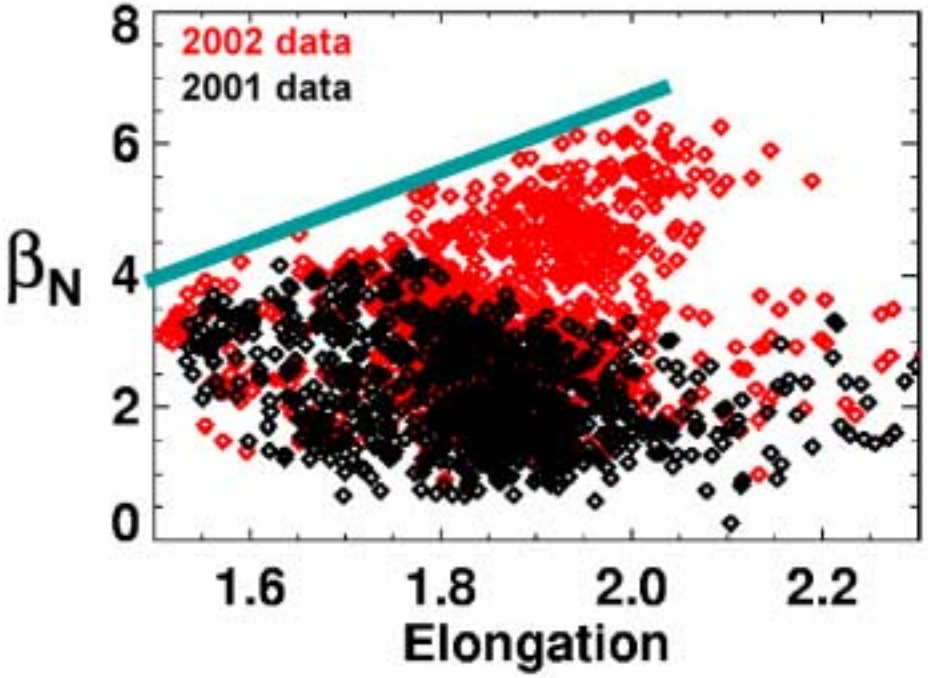
High β shot 108989
κ=2, δ =0.8, A=1.4



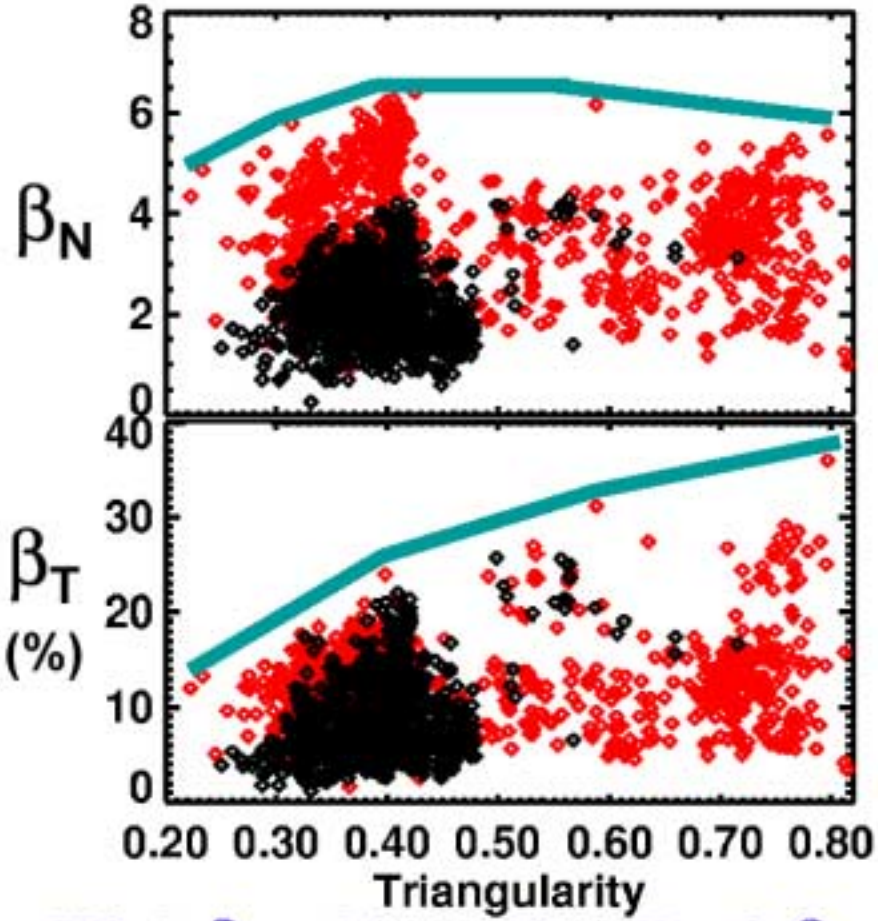
High β obtained with high κ and δ

NSTX

- β_N increases with increasing elongation
  - β_N degraded for $\kappa > 1.8$ in previous run year

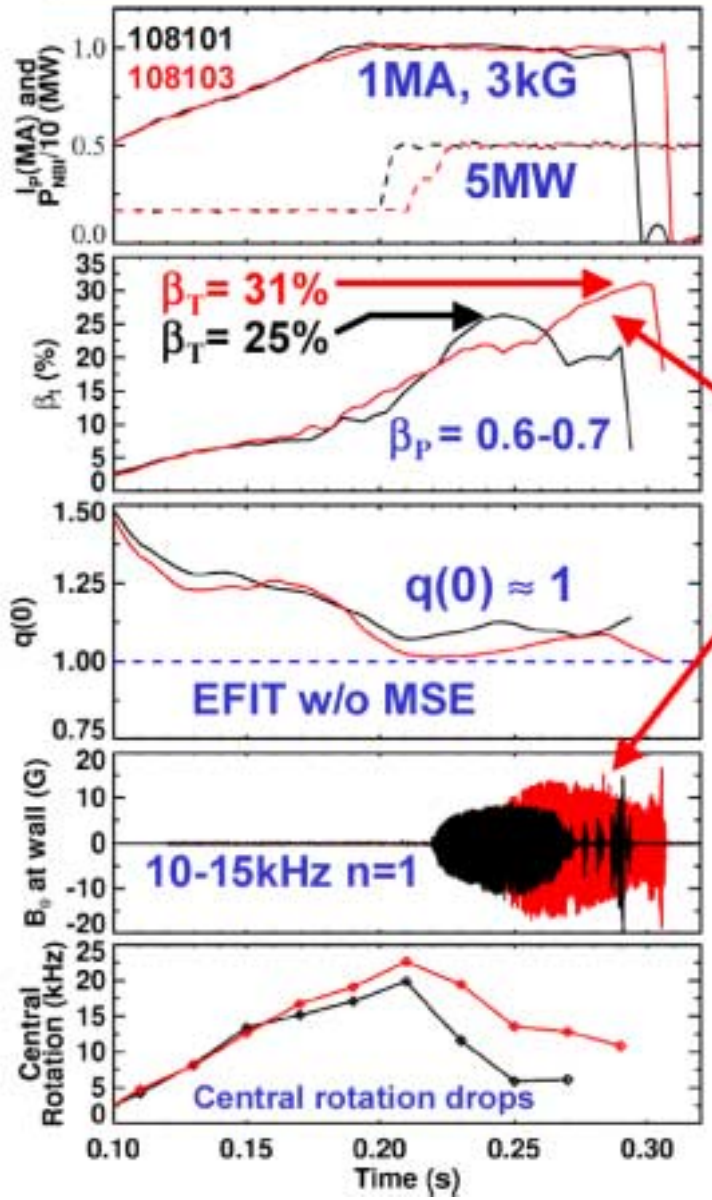


β_N weak function of δ for $\delta > 0.4$

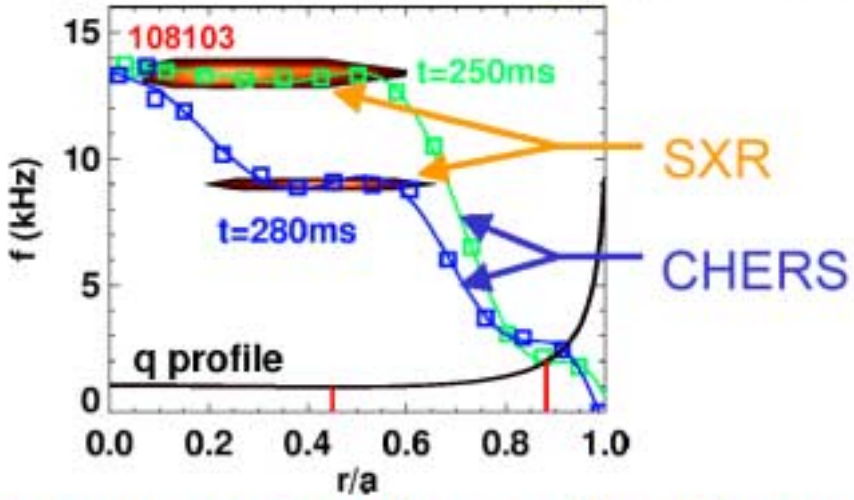


High $\delta \rightarrow$ higher I_p/aB_{t0} & β_T

Highest β_T discharges limited by 1/1 modes



- Core becomes n=1 kink unstable
- 1/1 mode degrades β & rotation, slows, locks → disruption
- Neoclassical drive possible, but…
  - Modes can decay as β rises
  - **Rotation evolution may dominate:**



Very large q=1 radius → fast disruption

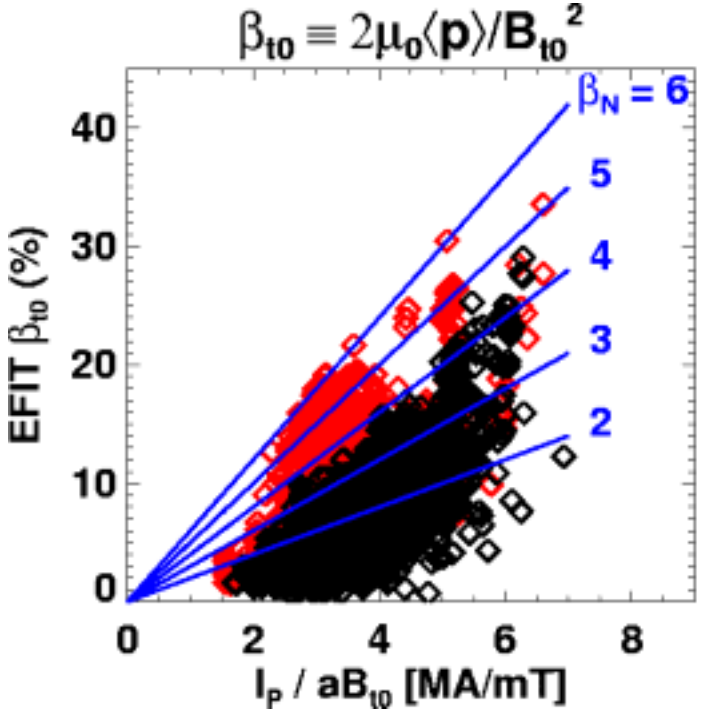
Troyon limit routinely exceeded

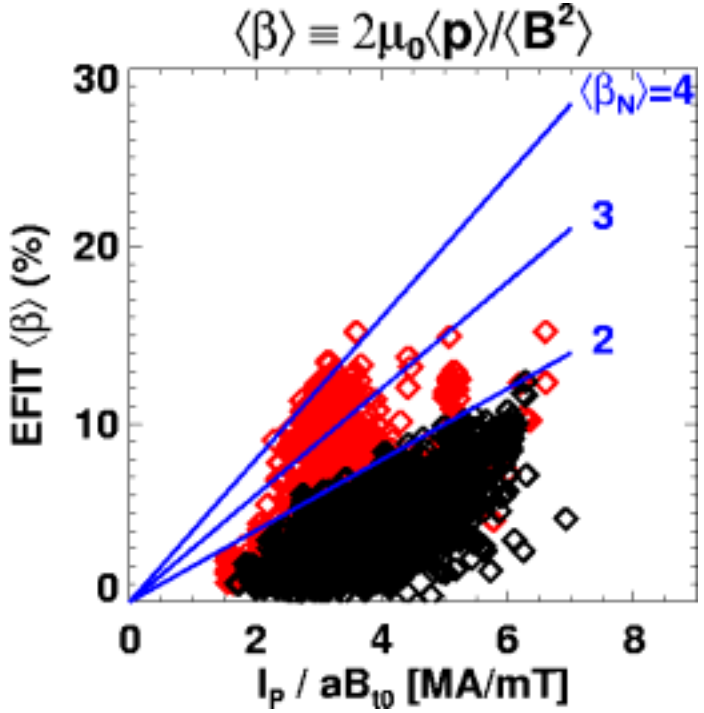
- $\beta_{N,max} \sim 6.3$
- $\beta_P \leq 1.5 \Rightarrow$ slightly diamagnetic
- $W_{MAX} \sim 390$kJ
- Kinetic data confirms β

Black data $\Rightarrow$ previous year's run

- Last year limited to $\langle \beta_N \rangle \leq 2$
- After machine improvements, at or above theoretical no-wall limit of $\langle \beta_N \rangle = 3$

Red data $\Rightarrow$ PF coil alignment + bake

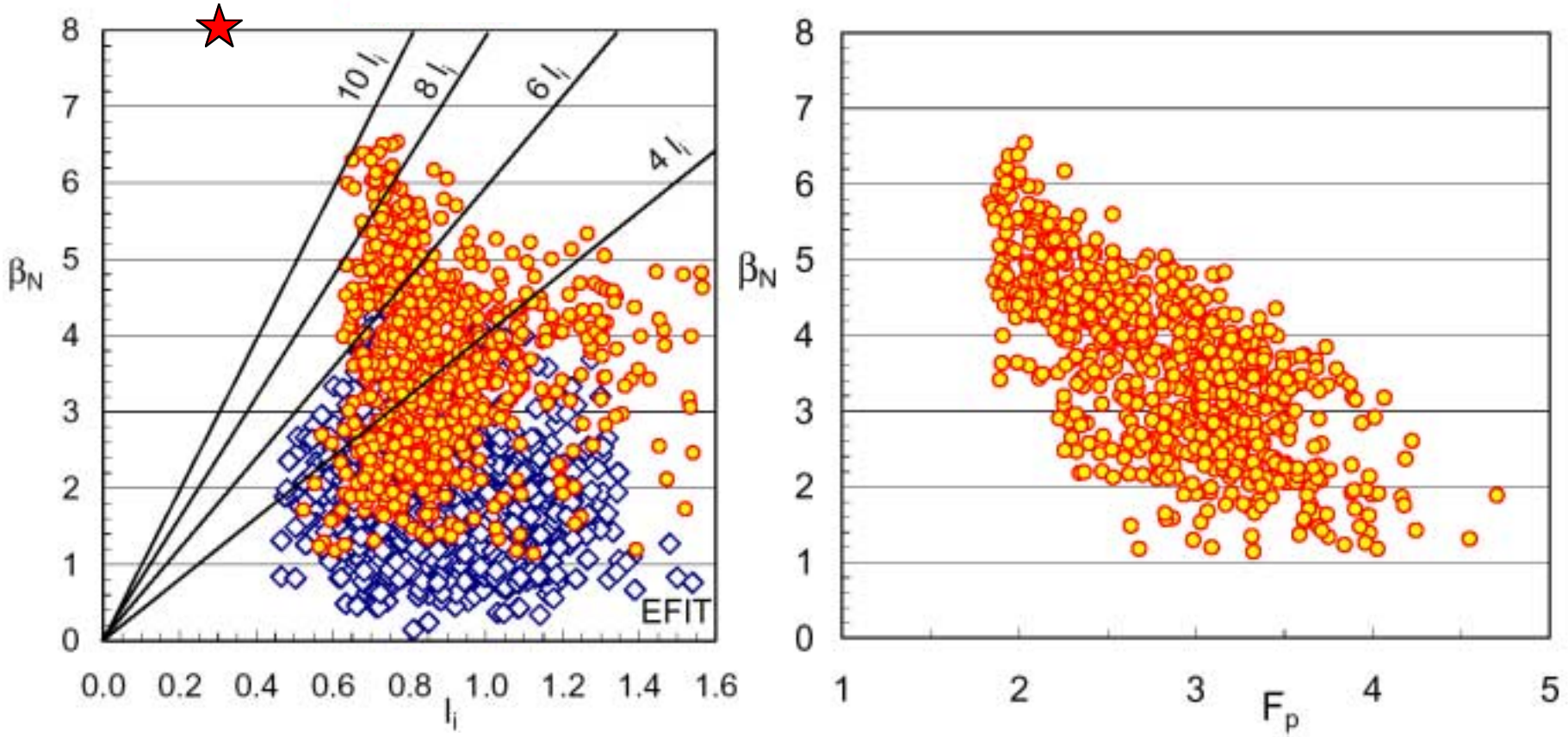




J. Menard

High β_N attained with low pressure peaking

NSTX target, J. Menard, Nucl. Fusion (1997)



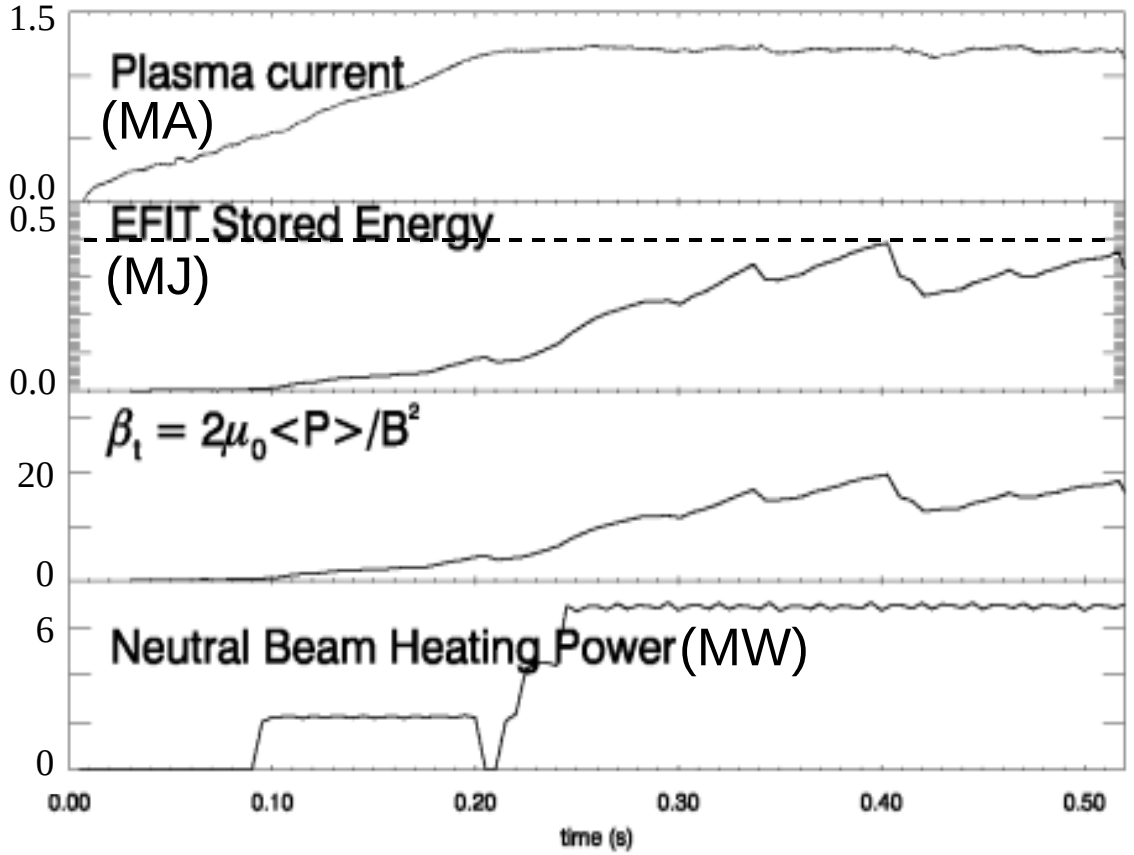
- Lowest $F_p = p(0)/\langle p \rangle$ in H-mode
- Normalized beta, $\beta_N > 6$, $\beta_N / l_i \sim 10$

S. A. Sabbagh, CO1.003,
Monday afternoon, 14:24, Salon 1-2

High toroidal field gives highest stored energy

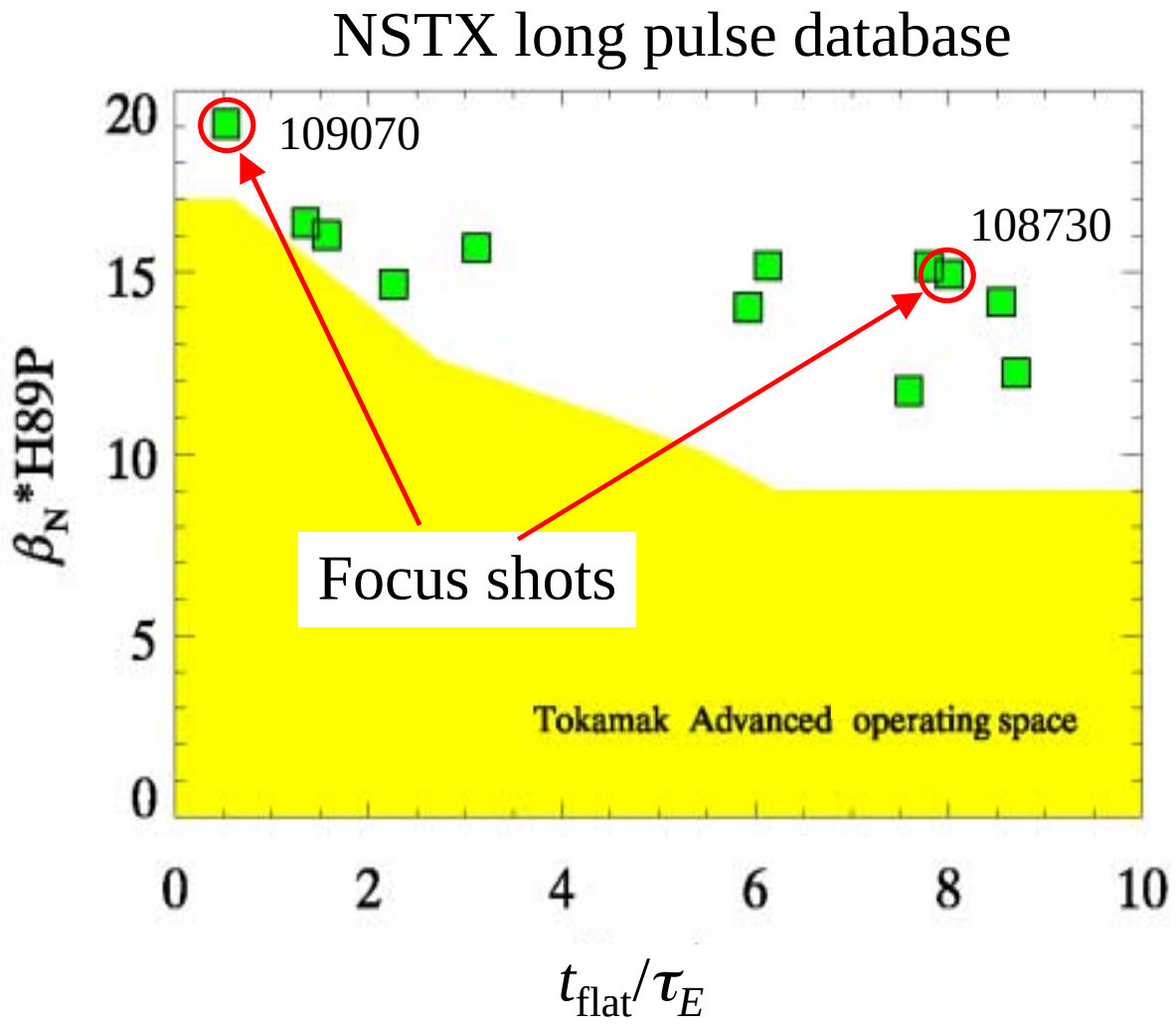
- Reached 20% β_t ($\beta_N \sim 5.5$) at 5.5kGauss
- 7MW injected power (100keV)
- I_p = 1.2MA
- ~0.4MJ stored energy (confirmed with kinetics)
- Record ST neutron rate 5x10^{14}/s and yield (1.7x10^{14})
- β collapses due to internal modes

Shot 108819, $\delta = 0.8$, $\kappa = 2.0$



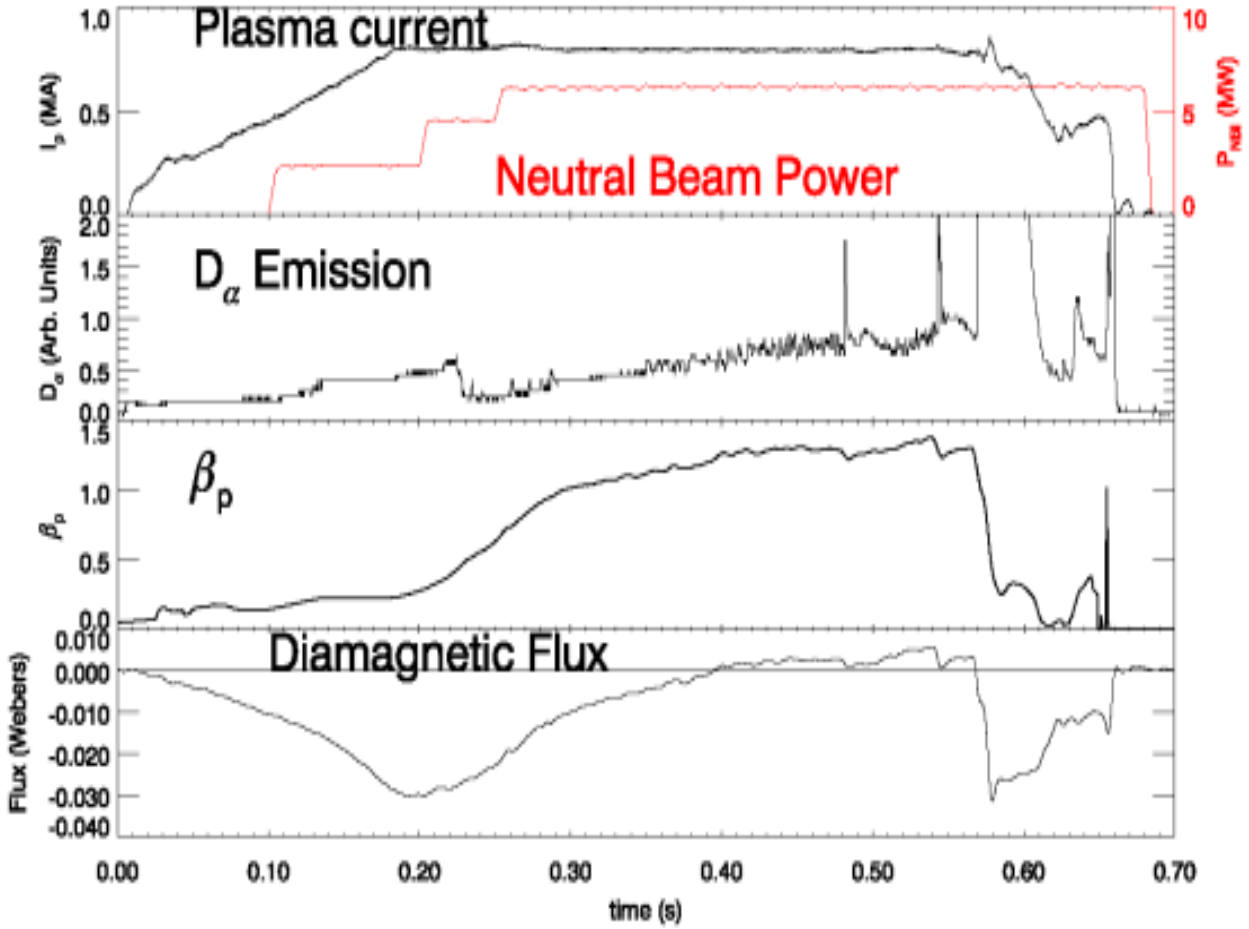
Long pulse plasmas achieved on NSTX

- Plasmas with β_N*H89P ~15 have been created for t_{flat} ~ 8*τ_E (= 0.4s)
- Timescale also long when compared to current diffusion time 8*τ_E ~ 1.7*τ_{CR}
- Pulse length up to 1s
- Comparison to tokamak is for reference only ⇒ need R/a independent physics scalings



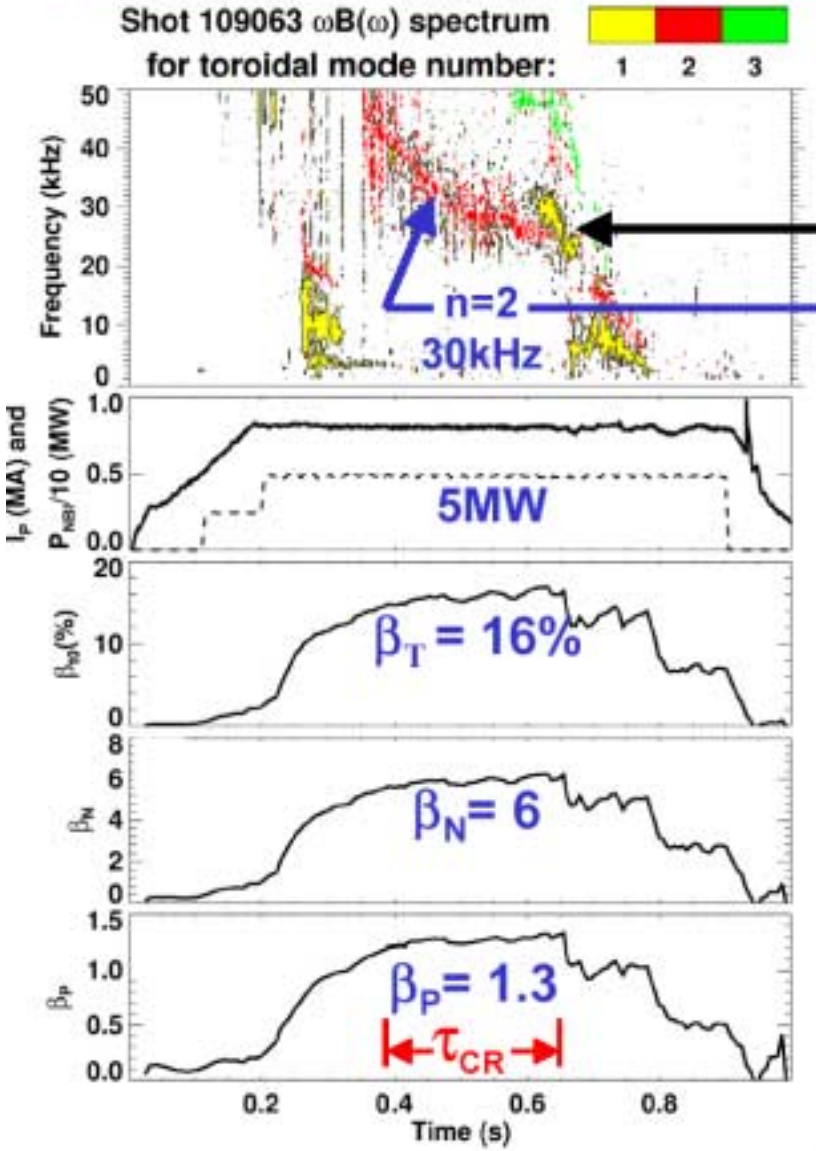
Highest $\beta_N * H_{89P}$ discharge is diamagnetic

- Achieved in a plasma with $\varepsilon\beta_p \sim 0.9$
- Max. local $\beta \sim 1$
- $\beta_N \sim 6.3$
- $f_{bs} = 50\%$
- *60%* non-inductive current (~10% NBI current drive)



See J. Menard, CO1.002, Monday afternoon, 14:12, Salon 1-2

High β_P discharges avoid 1/1 modes

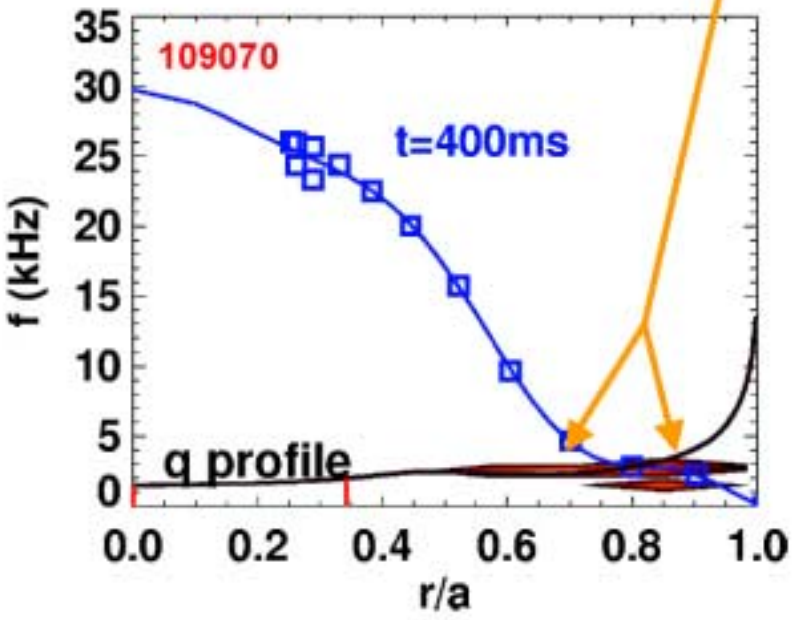


- 800kA, 5kG → q(0) >> 1
- 1sec NBI H-mode discharge

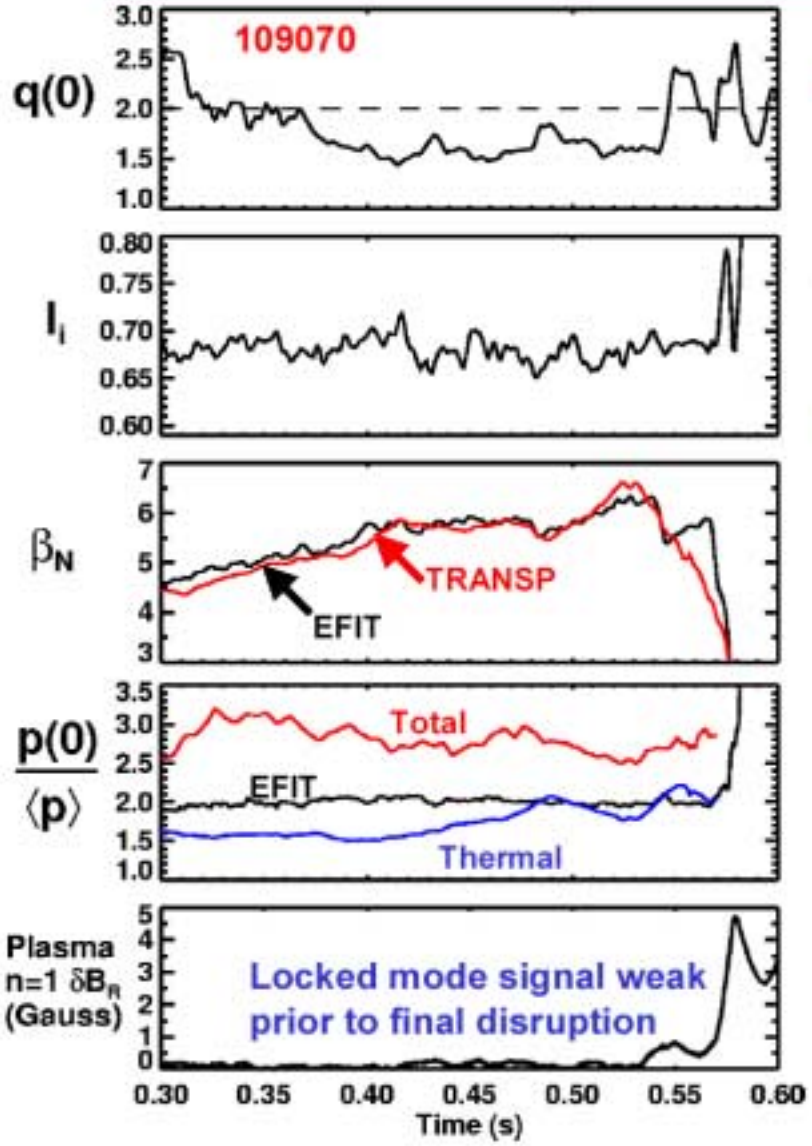
n=1 internal disruptions

Mirnovs show possible 3/2 mode

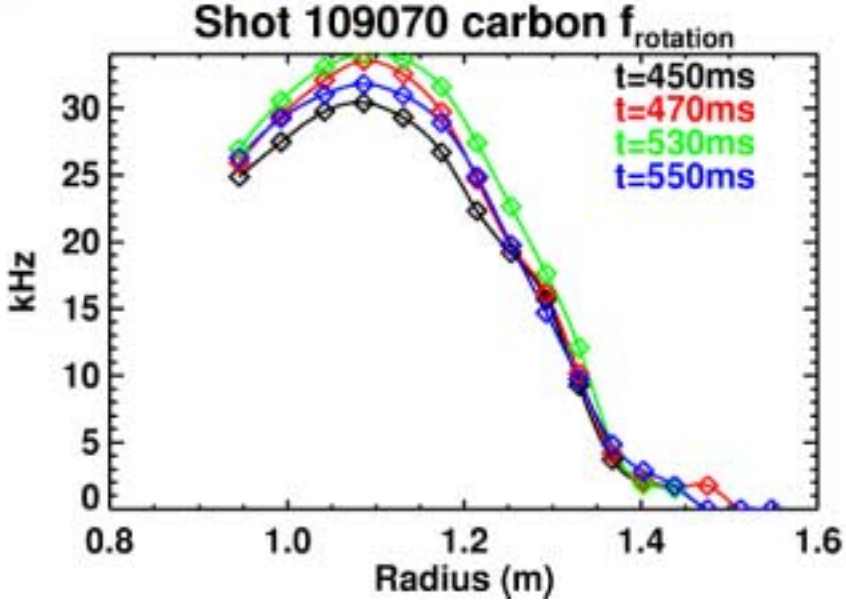
Only mode on SXR is 2/1 or 3/1



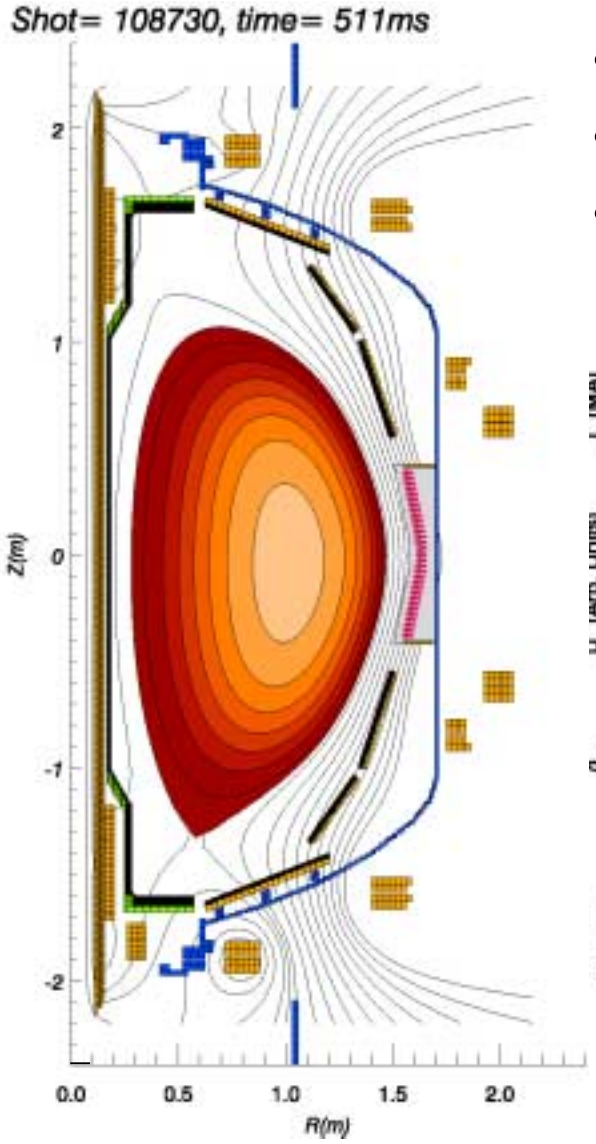
Highest β_P cases disrupted by ideal modes



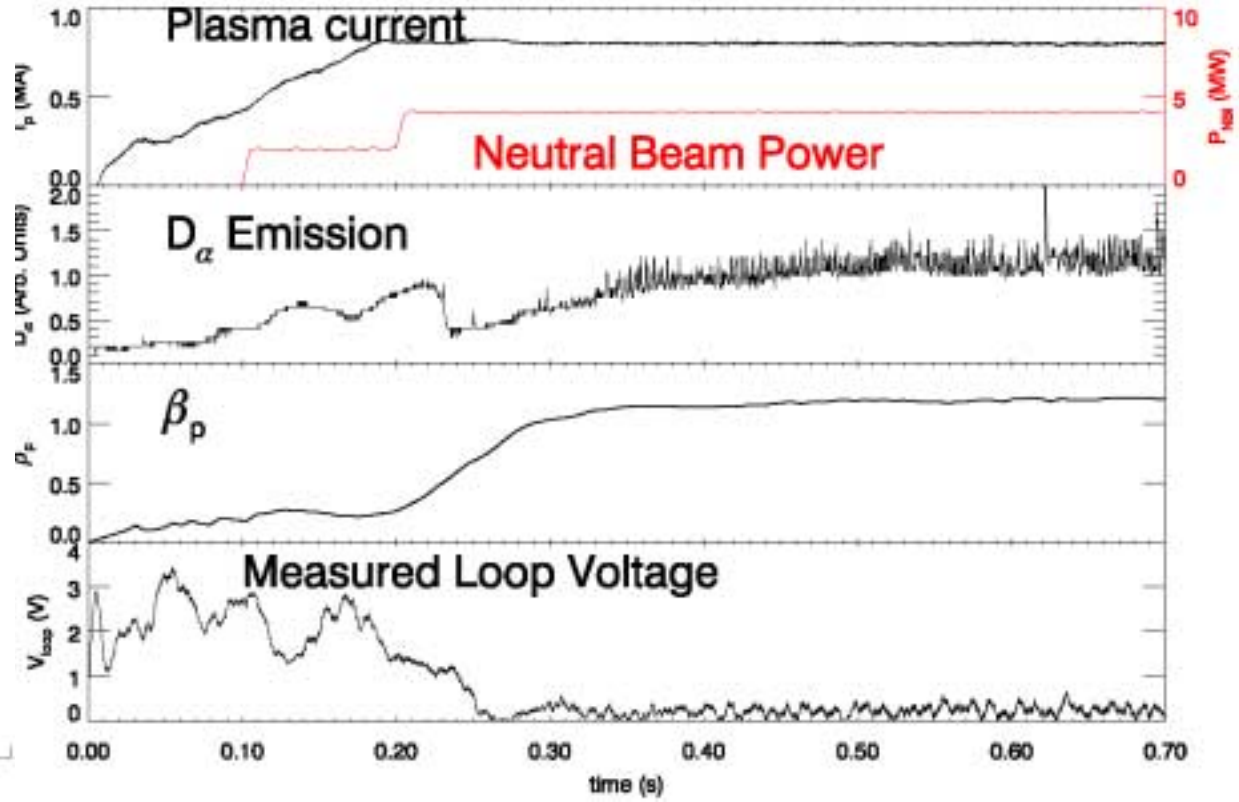
- **P_{NBI}=6MW, $\beta_N \approx 6.3$, $\beta_P \approx 1.4$**
  - $q(0) \approx 1.5$, $l_i = 0.65$-0.7
- $p(0)/\langle p \rangle$ and β_N evolve slowly
- Rotation decay not observed preceding disruption phase:



Long pulse, High β_p attained in lower single null

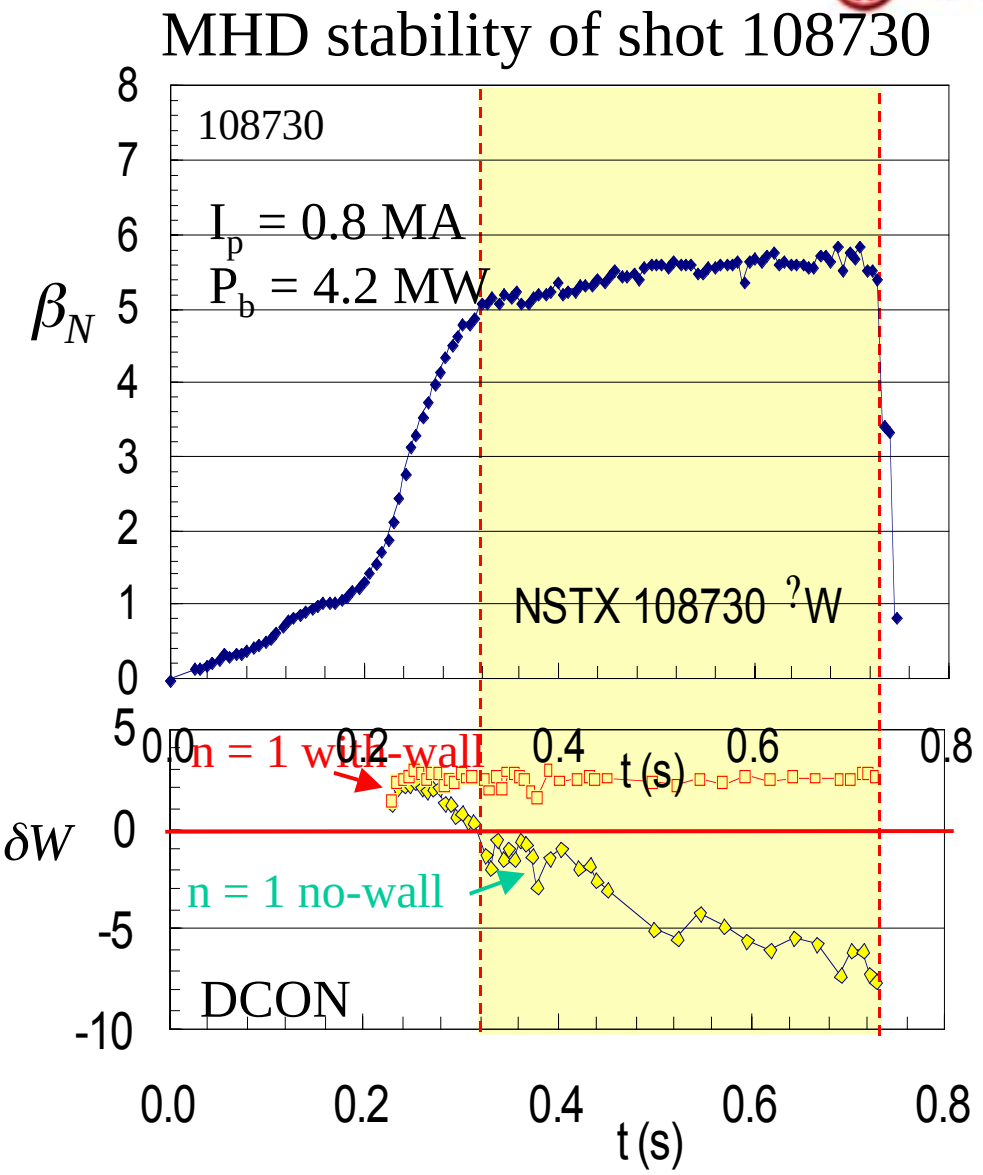


- Single null offers easier H-mode access
- Loop voltage < 200mV for > 0.4s
- Bootstrap current ~40%



No-wall limit exceeded for many wall times

- No evidence of non-rotating MHD modes
- *H89P ~ 2.7*
  $\Rightarrow$ typical H factor
  $\Rightarrow \tau_E \sim 54$ms
- $\beta_N \sim 5.6$
- $< \beta_N > \sim 4$, ~20% above the ideal no-wall β-limit for ~20 τ_{wall}



S. Sabbagh

NSTX has pushed the ST into exciting new physics regimes

- Attained 35% β_t
  - $\Rightarrow$ 0.4MJ stored energy - 20% β_t at ~ maximum TF
- Achieved long pulse operation with high bootstrap fraction and good confinement
  - $\Rightarrow$ $\beta_N * H89P = 15$ *for* $8*\tau_E$
  - $\Rightarrow$ $<\beta_N>$ 30% above no-wall ideal MHD β-limit
  - $\Rightarrow$ Diamagnetic plasmas created with $\beta_{local} \sim 1$
  - $\Rightarrow$ Up to 60% non-inductive current (~10% neutral beam)
- Highest β_t limited by 1/1 modes
- Highest β_p limited by internal modes
  - $\Rightarrow$ with wall limit?

Future research

- Increase shaping: $\Uparrow \kappa \Rightarrow \Uparrow \beta_p \Rightarrow \Uparrow f_{bs}$
  - Improve vertical position control system
- Lower l_i and raise current $\Rightarrow \Uparrow \beta_t * \beta_p$
  - Increase current/shape ramp rate
- Non-axisymmetric feedback (RWM coils)
  - Install coil-set, power supplies
- Couple to non-inductive current drive tools
  - CHI, HHFW, EBW (as they become available)