MHD stability of high-β and long-pulse NSTX spherical torus plasmas

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for the NSTX Research Team

April Meeting of the American Physical Society

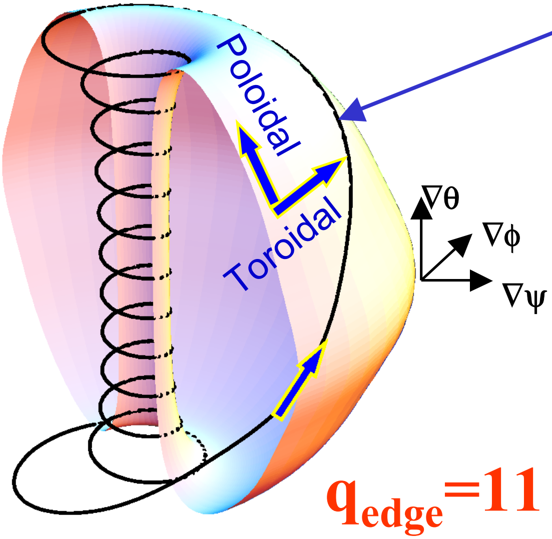
Saturday, April 5, 2003

Washington B, Loews Philadelphia Hotel

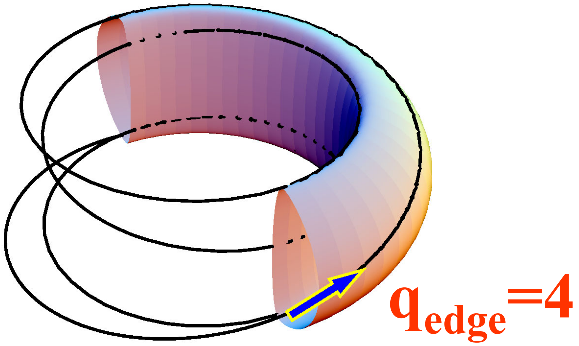
Philadelphia, PA

How does low aspect ratio change stability?

Spherical torus
($A = R_0/a \leq 1.6$)



Tokamak ($A > 2.5$)



- **Primarily through safety factor "q"**

  q is # ***toroidal transits / # poloidal transits*** of a magnetic field-line on a magnetic surface

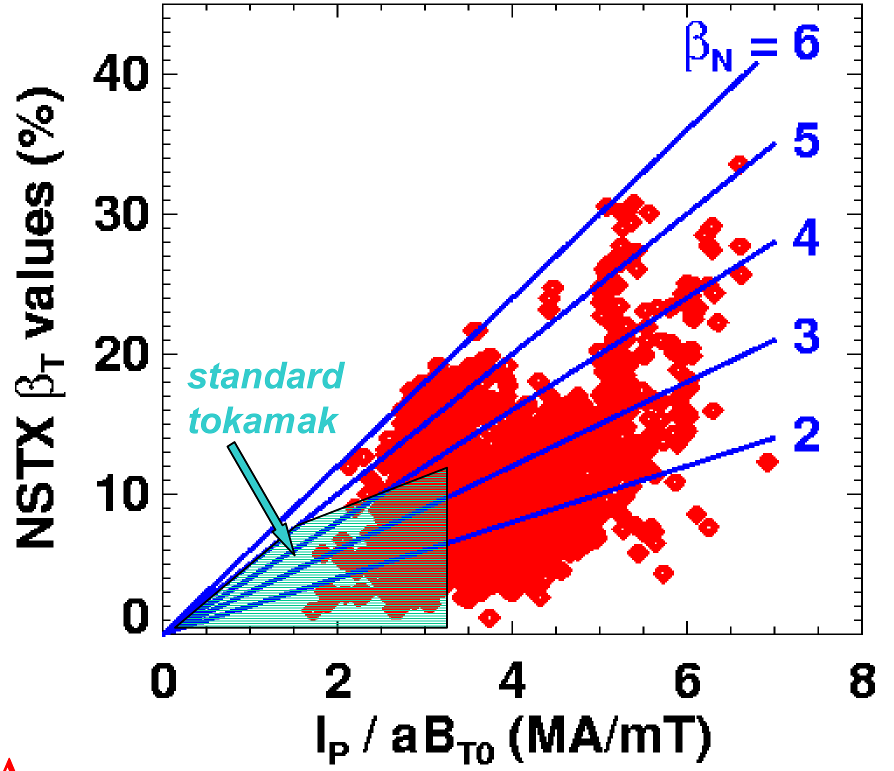
  - **MHD instabilities try to satisfy $\mathbf{k} \cdot \mathbf{B} = 0$**
    - Instability wave-vector $\mathbf{k} = n\nabla\phi - m\nabla\theta$
    - Occurs on resonant rational $q = m/n$ surface
    - n = toroidal mode number (integer)
    - m = poloidal mode number (integer)
  - High q and shear in q profile stabilizing
    - Field-line bending energetically unfavorable

- $q \propto (1+\kappa^2)\, a\, B_T / I_P\, A$
  - Higher q for given $I_P / a\, B_T$ at low A
  - Increased shear in q profile at low A

MHD stability improved at low A

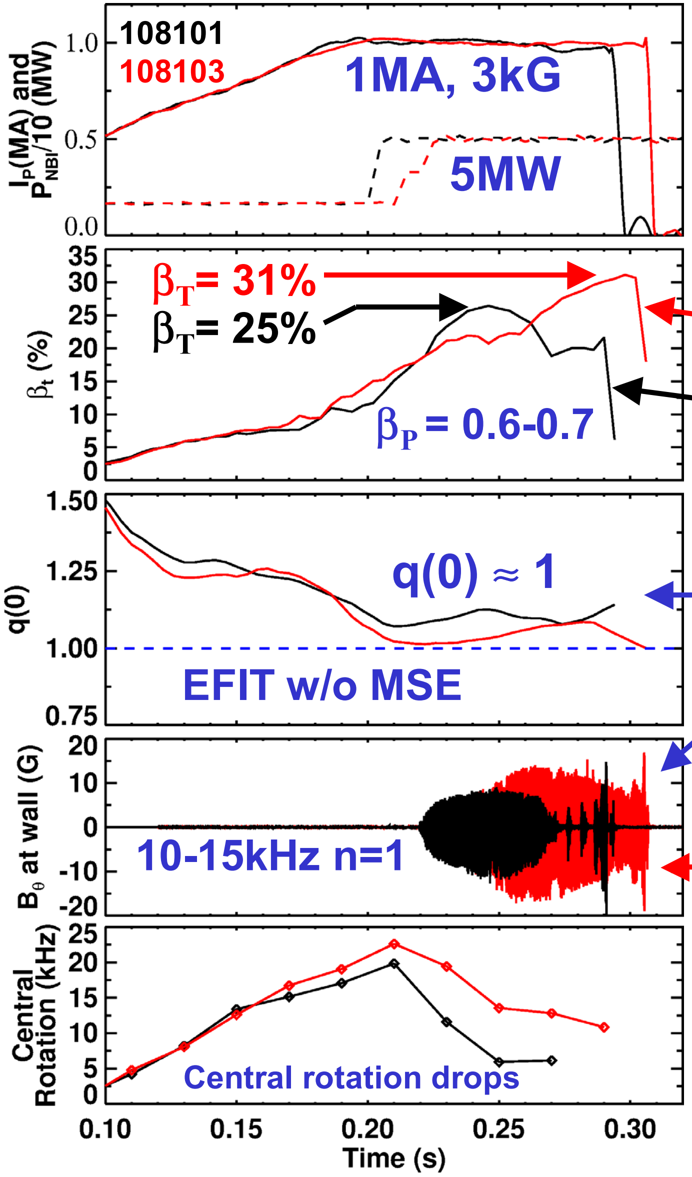
- Efficient reactor needs high toroidal β
  - β = kinetic pressure / magnetic pressure
  - Generating toroidal field (TF) is costly
- Theory and experiment show →
  - MAX(β_T) ∝ I_P / a B_T
  - $\beta_N \equiv \beta_T(\%)\, a\, B_T / I_P(\mathrm{MA}) \le C \approx 3\text{-}6$
- β_N increases at low A
  - β_N up to 6 at low A
  - β_N = 3-4 in standard tokamak
- $I_P / a\, B_T \propto (1+\kappa^2) / A\, q \Rightarrow$
  - Stable $I_P / a\, B_T$ increased at low A

$\beta_T \equiv 2\mu_0\langle p\rangle / B_T^2$



Higher β_N and $I_P / a\, B_T$ at low A result in β_T up to 35%

Highest β_T discharges limited by m/n=1/1 modes



- I_P=1MA, B_T=0.3T, P_{NBI}=5MW
  - Both discharges terminate rapidly
- Before rapid termination….

Sometimes, β rises throughout discharge

Most times, β saturates, then drops

When q(0) is near 1 and β_T > 20%, 10-15kHz n=1 instability appears

n=1 mode larger in high β shot (!)

How is drop in β avoided?

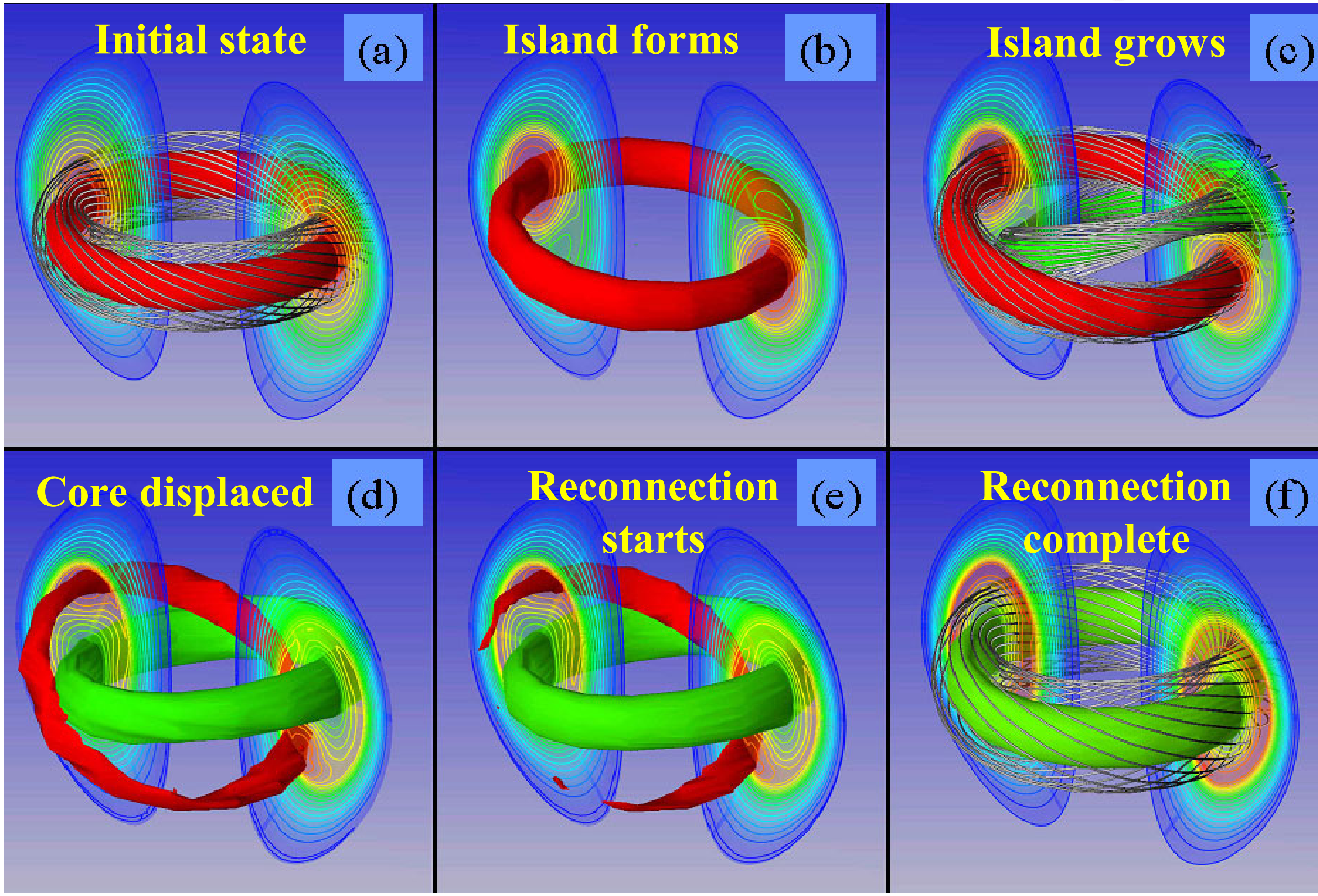
Difference appears to be ***sustained rotation***

Instability dynamics from non-linear simulations

(from Wonchull Park, M3D code, PPPL)

Simulation without rotation ⇒

B-field lines
Hot core
Cold island

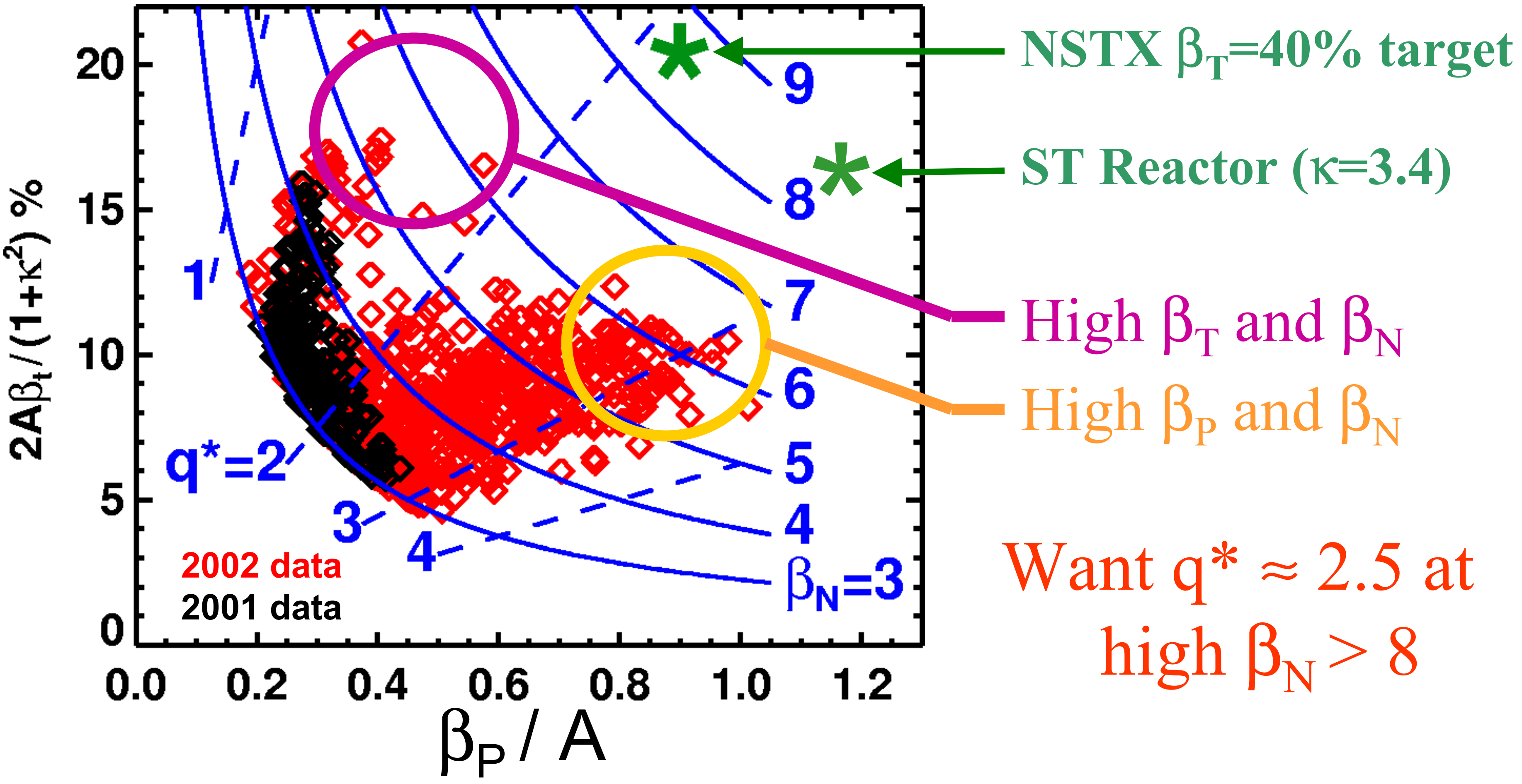


With sufficient rotational flow and shear, reconnection can be interrupted

May explain long-lived 1/1 modes in high β_T NSTX discharges

Steady-state ST also requires high β_P

- Self-driven current fraction $\propto \beta_P \equiv 2\mu_0\langle p\rangle / B_P^2$
- $\beta_T \propto \beta_N^2 / \beta_P \Rightarrow$ Need very high β_N for steady state



NSTX β_T=40% target

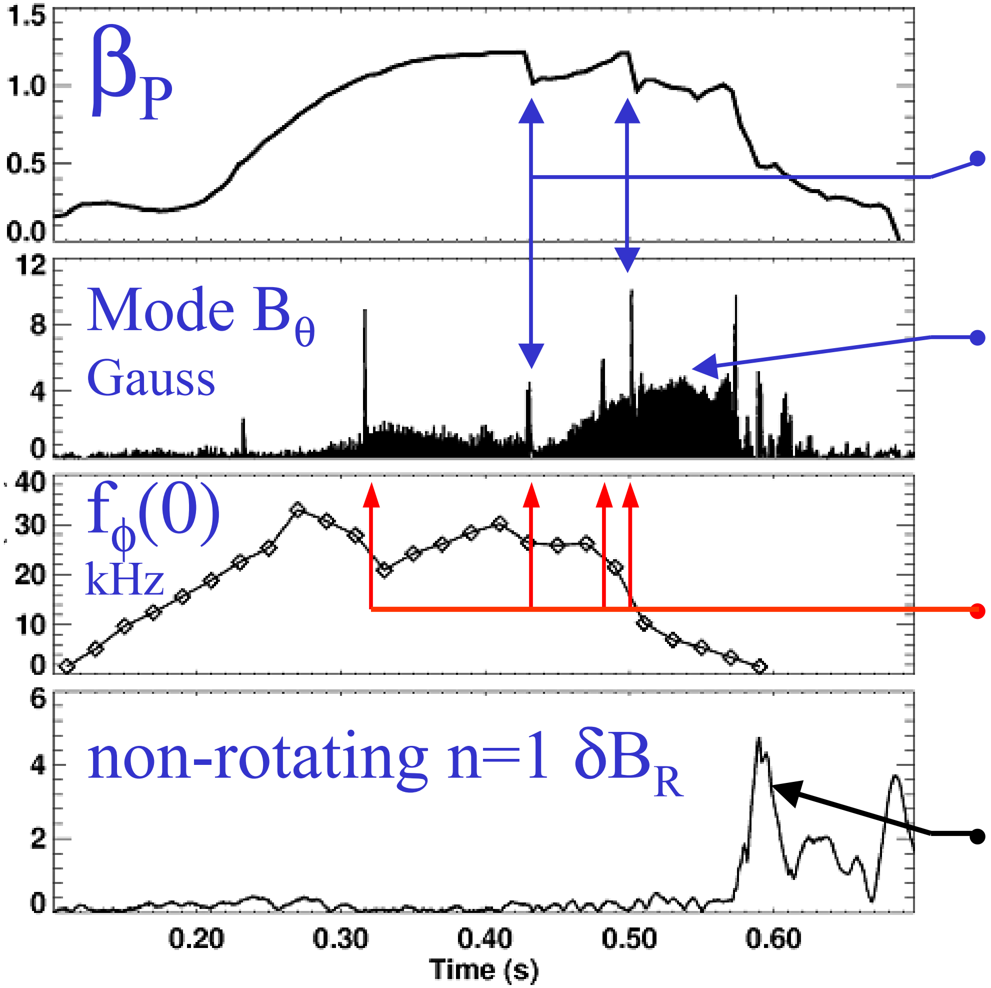
ST Reactor (κ=3.4)

High β_T and β_N

High β_P and β_N

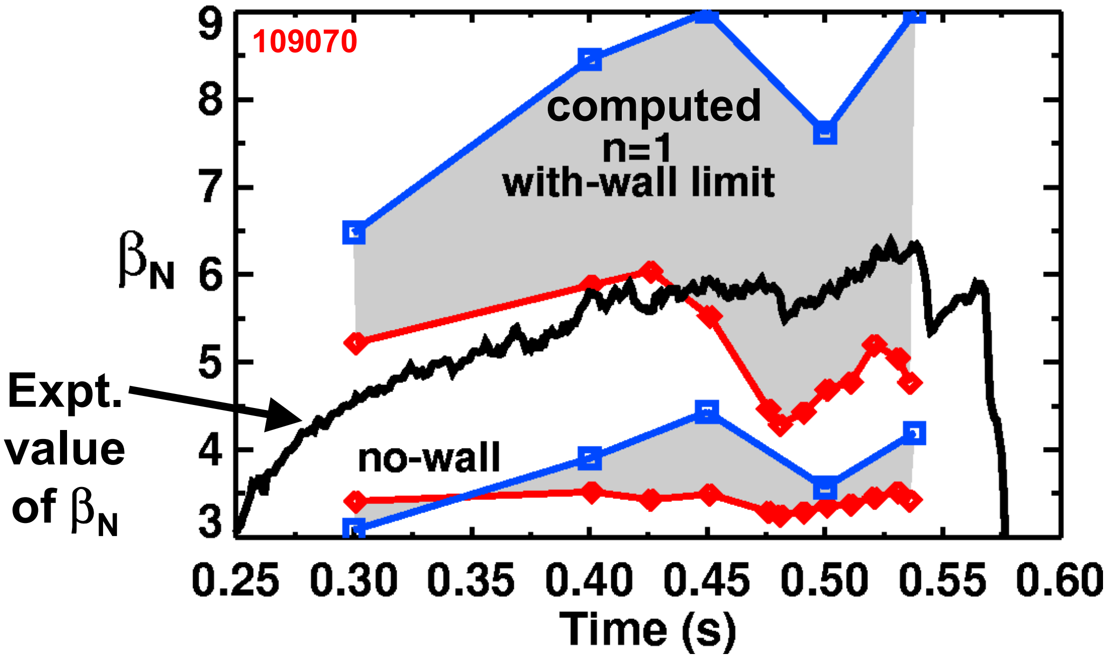
Want $q^* \approx 2.5$ at high $\beta_N > 8$

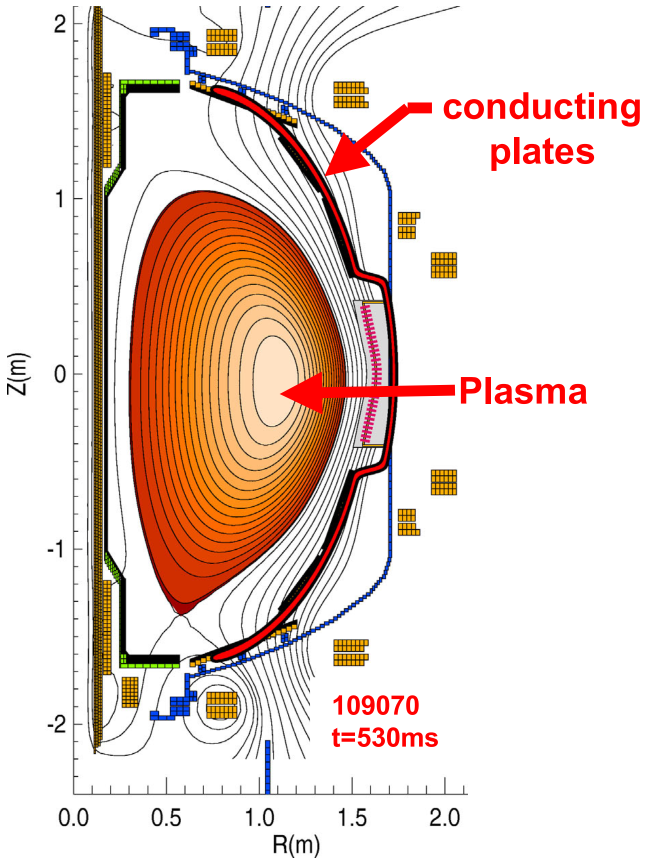
High β_P discharges limited by “bursting” n=1



- Rapid n=1 bursts cause β drops
  - β can recover between bursts
- Continuous modes degrade β?
- Each n=1 burst reduces rotation
  - Also triggers continuous modes?
- ***Non-rotating*** n=1 becomes unstable once rotation is low
  - Causes final collapse of plasma β

High β_P shots operate above no-wall limit





Theory and other experiments (DIII-D):

⇒ resistive wall and plasma rotation can stabilize "resistive wall mode"

NSTX high β_P shots may be hitting <u>with-wall</u> limit

Stability increases at low A

- Low A ⇒ high I_P / a B_T and β_N ⇒ high $\beta_T \leq 35\%$
  - High β_T discharges limited by ***long-lived*** n=1 modes

- High β_P and high β_N needed for steady-state ST
  - High β_P discharges limited by ***bursting*** n=1 modes

- Highest β_P discharges are above stability limits w/o wall
  - Rotational stabilization of resistive wall mode