Toroidal Magnetic Plasma Confinement at the Limit: the *National Spherical Torus Experiment*

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for the

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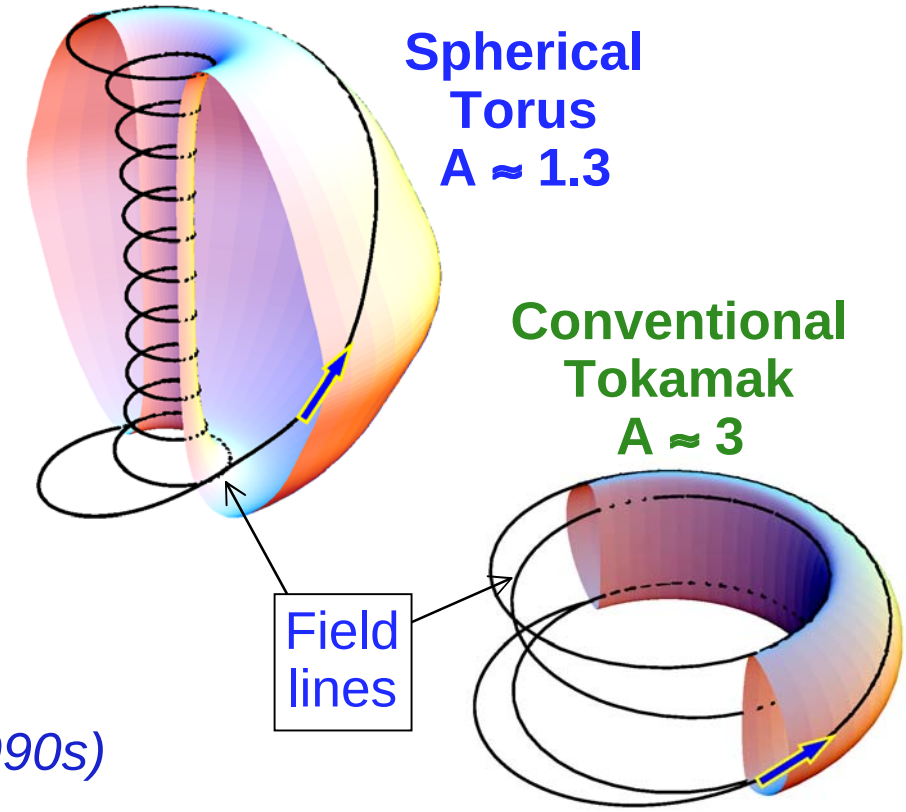
"Spherical Torus" Extends Tokamak to Extreme Toroidicity

- Motivated by potential for increased β *(Peng & Strickler, 1980s)*

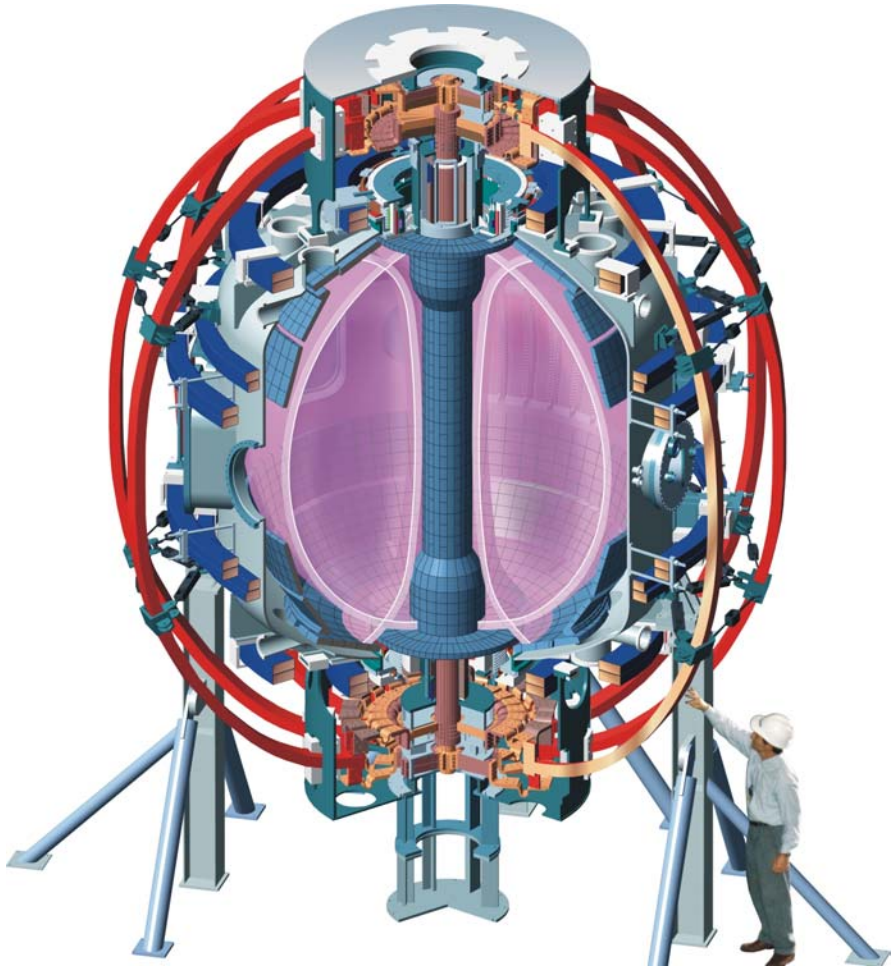
$$\beta_{max}\ (= 2\mu_0\langle p\rangle/B_T^2) \;=\; C\cdot I_p/aB_T \;\propto\; C\cdot\kappa/Aq$$

B_T: toroidal magnetic field on axis;
$\langle p\rangle$: average plasma pressure;
I_p: plasma current;
a: minor radius;
κ: elongation of cross-section;
A: aspect ratio (= R/a);
q: MHD "safety factor" (> 2)
C: Coefficient ~3%·m·T/MA
(Troyon, Sykes - early 1980s)

- Born out by experiments
  - $\beta_{max} \approx 40\%$ *(START - UK, 1990s)*



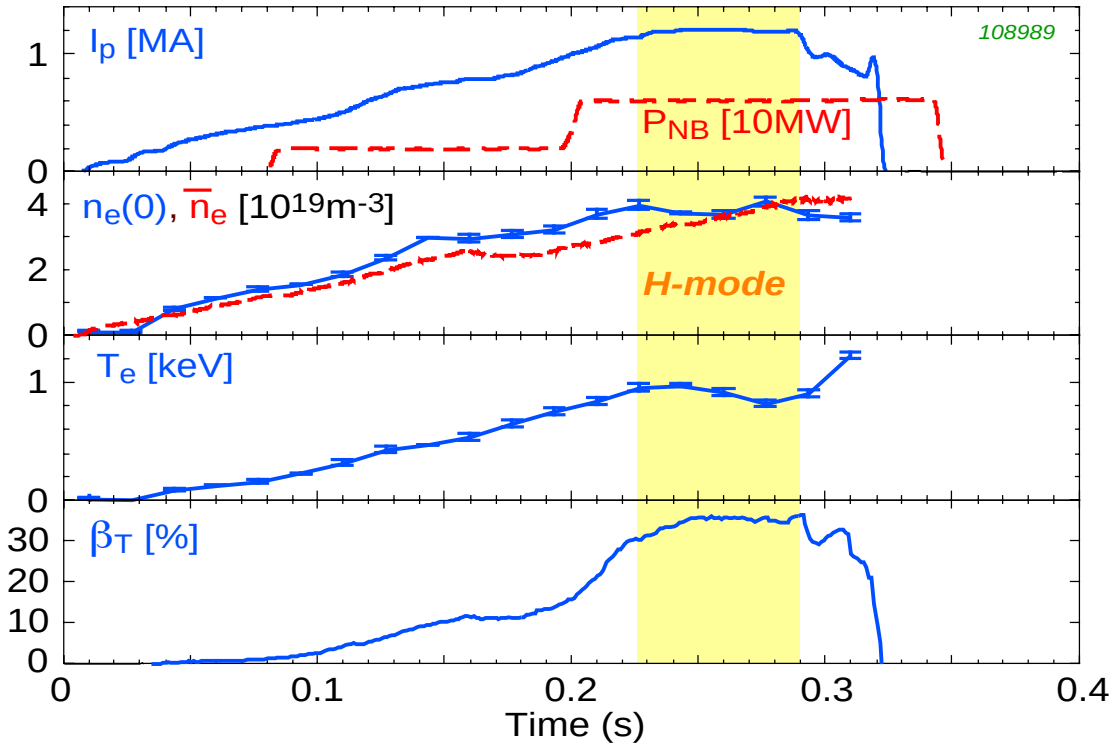
NSTX Designed to Study High-Temperature Toroidal Plasmas at Low Aspect-Ratio

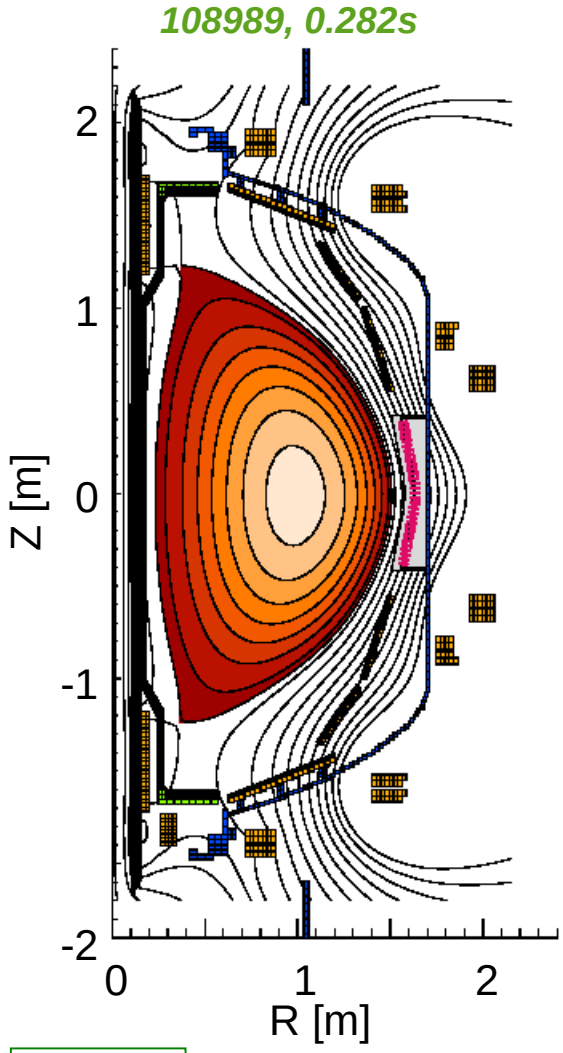


Experiments started in Sep. 99

Aspect ratio A	1.27
Elongation κ	2.5
Triangularity δ	0.8
Major radius R_0	0.85m
Plasma Current I_p	1.5MA
Toroidal Field B_{T0}	0.6T
Pulse Length	1s
Auxiliary heating:	
NBI (100kV)	7 MW
RF (30MHz)	6 MW
Central temperature	1 – 3 keV

NSTX Has Achieved Good Progress in β_T





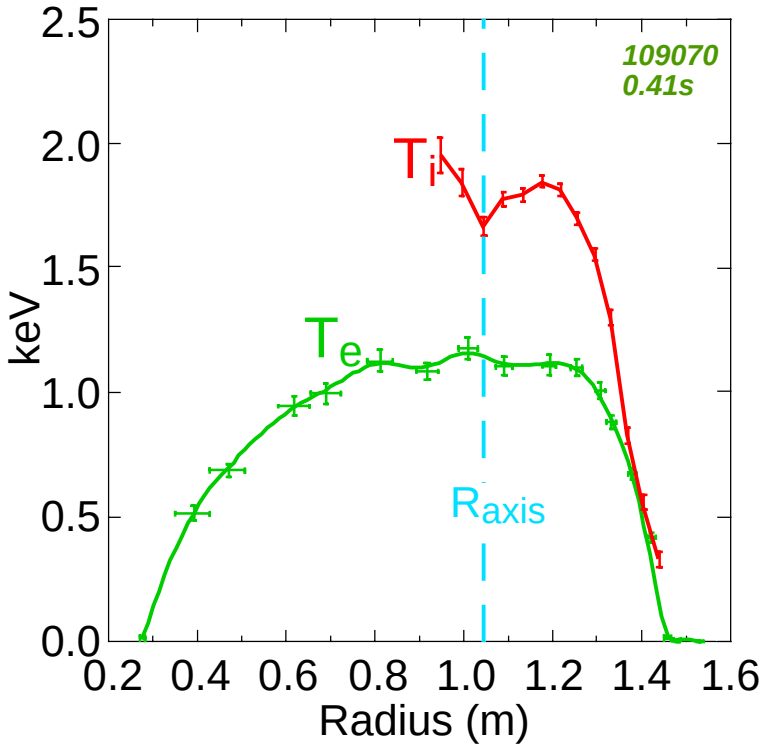
- β_T = 35% determined by magnetic analysis
- B_T = 0.3T, A = 1.4, κ = 2.0, δ = 0.8
- High confinement (H) mode (*c.f.* standard tokamaks) broadens pressure profile

D. Gates

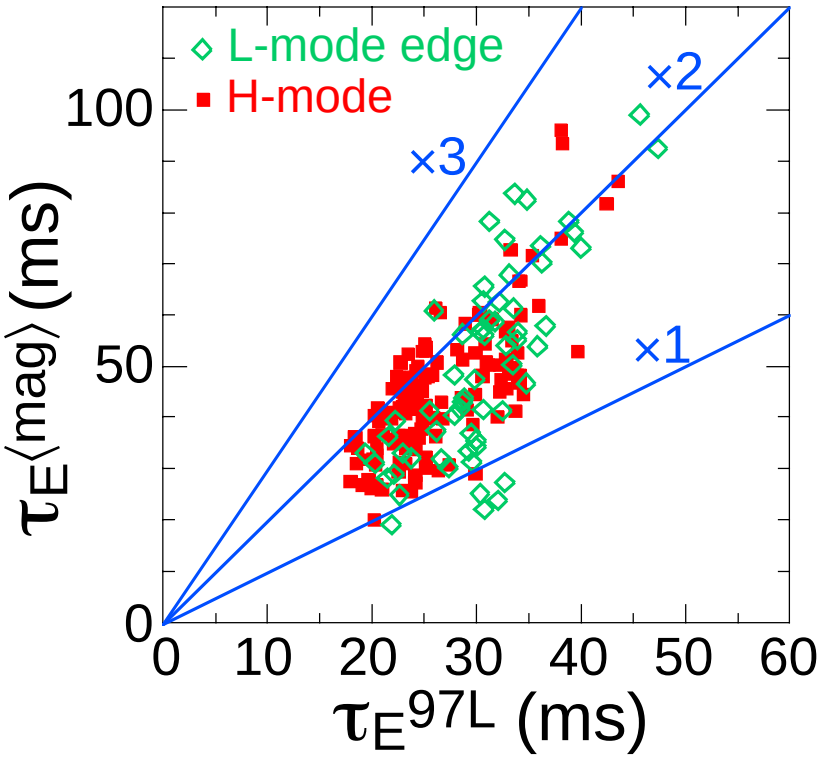
In Addition to High β, New Physics Regimes Are Expected at Low Aspect Ratio

- Intrinsic cross-section shaping (B_P/B_T ~1)
- Large gyro-radius (a/ρ_i ~ 30–50)
- Large fraction of trapped particles (~$\sqrt{(r/R)}$)
- Large bootstrap current (up to 70% of total)
- Large plasma flow & flow shear (M ~ 0.5)
- Supra-Alfvénic fast ions ($v_{NBI}/v_{Alfvén}$ ~4)
- High dielectric constant (ε ~ 30–100)

With NBI Heating, Ions Are Well Confined & Global Confinement Exceeds Predictions



- $T_i > T_e$ although for NBI $P_{b,i}/P_{b,e} \approx 0.7$
- Both thermal and *fast* ions are well confined

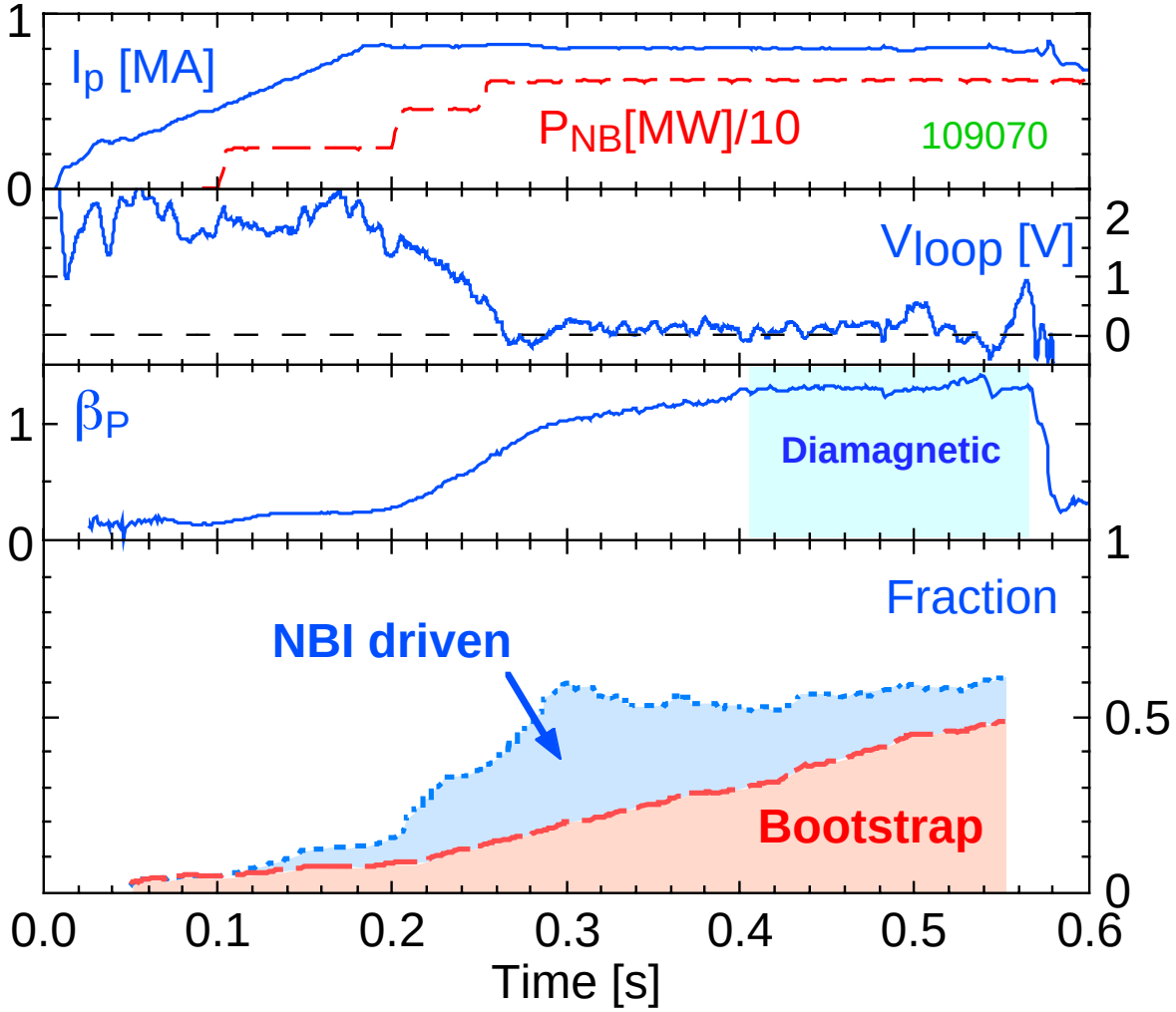


- Confirmed by analysis based on profiles of T_i, T_e, n_e
- Both L & H -mode plasmas exceed ITER-97L scaling

Exploring Additional Methods for Generating and Sustaining Toroidal Plasma Current

- STs need non-inductive current
  - space for transformer solenoid in center is very limited
- Exploit the neoclassical "bootstrap" current at high β
  - effect of toroidicity in a collisionless plasma
- RF waves at high harmonics of the ion cyclotron frequency can heat and drive current
  - *details in talk C10.003 by C. Phillips*
- Coaxial Helicity Injection (CHI) can initiate toroidal plasma current
  - Create linked toroidal and poloidal magnetic flux (helicity) by injecting poloidal current which relaxes to form closed magnetic surfaces
  - *Demonstrated on the HIT-II experiment at U. of Washington, Seattle*

Neoclassical Bootstrap Effect Drives Substantial Fraction of Plasma Current

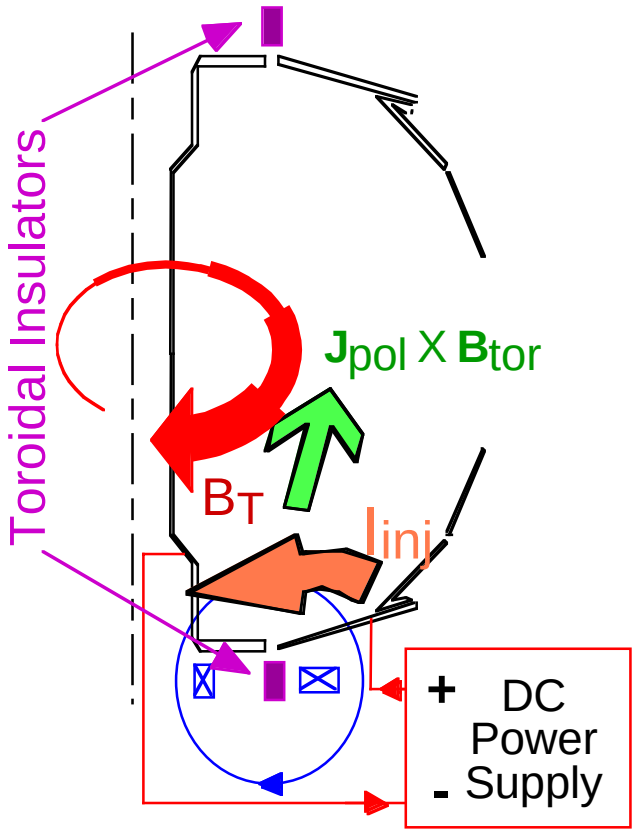


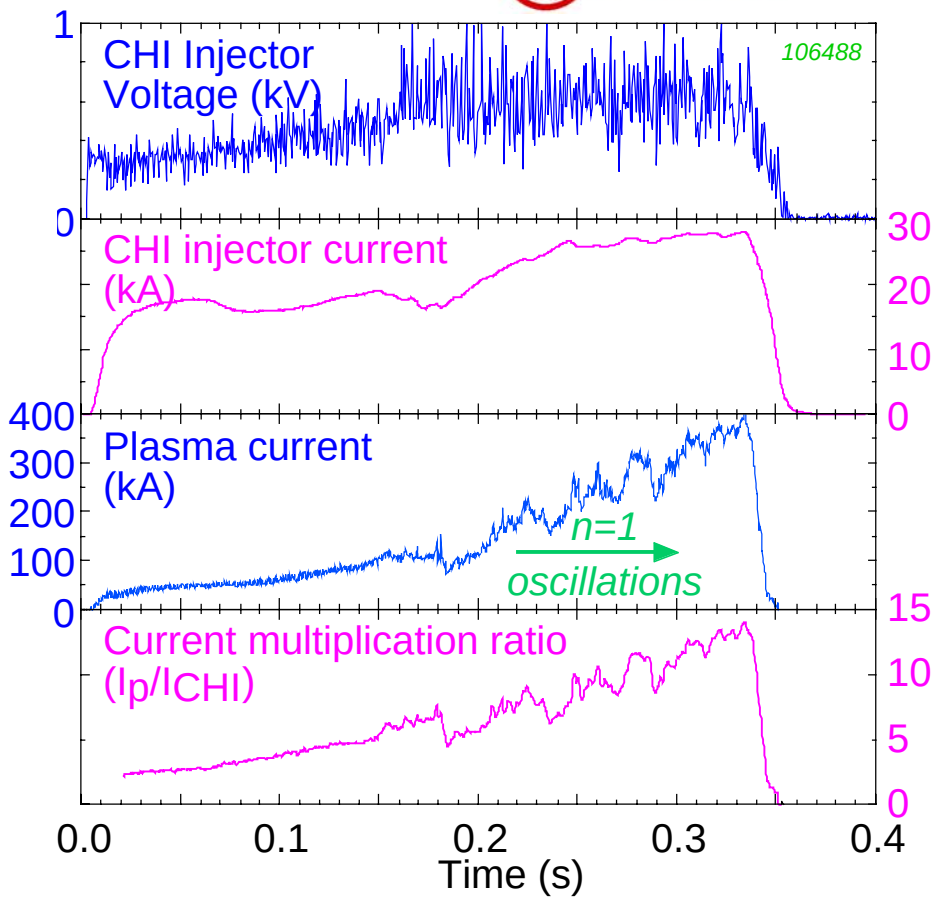
- $V_{loop} \approx 0.1V$ for ~0.3s
- Control profiles of pressure & current to maximize stability & bootstrap current

NSTX Explores Plasma Confinement in a Unique Toroidal Configuration

- Potential for high β already demonstrated
- Confinement with NBI heating exceeds expectations
  - Ions are well confined
  - Combined NBI-driven and bootstrap current up to 60% of total
- Challenge is to achieve favorable characteristics simultaneously with non-inductive current drive
  - Self-consistent bootstrap current
  - Current sustainment by RF waves
  - Current initiation by coaxial helicity injection

CHI Has Generated Significant Toroidal Current Without Transformer Induction





- Goal to control discharge evolution to promote reconnection of toroidal current onto closed flux surfaces