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Latest Results from the U.S. National Spherical Torus Experiment

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For NSTX National Team

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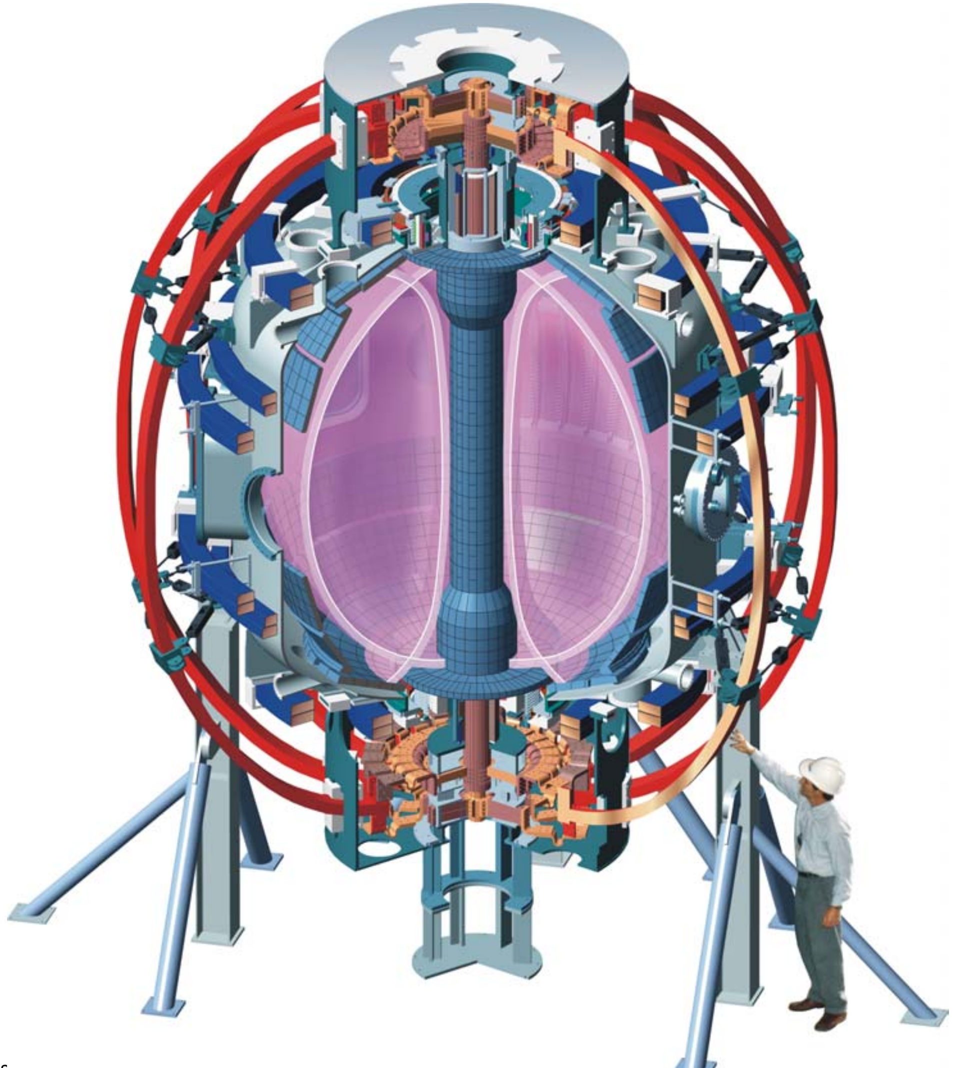
NSTX is a New Magnetic Fusion Energy Sciences Experiment in the U.S.

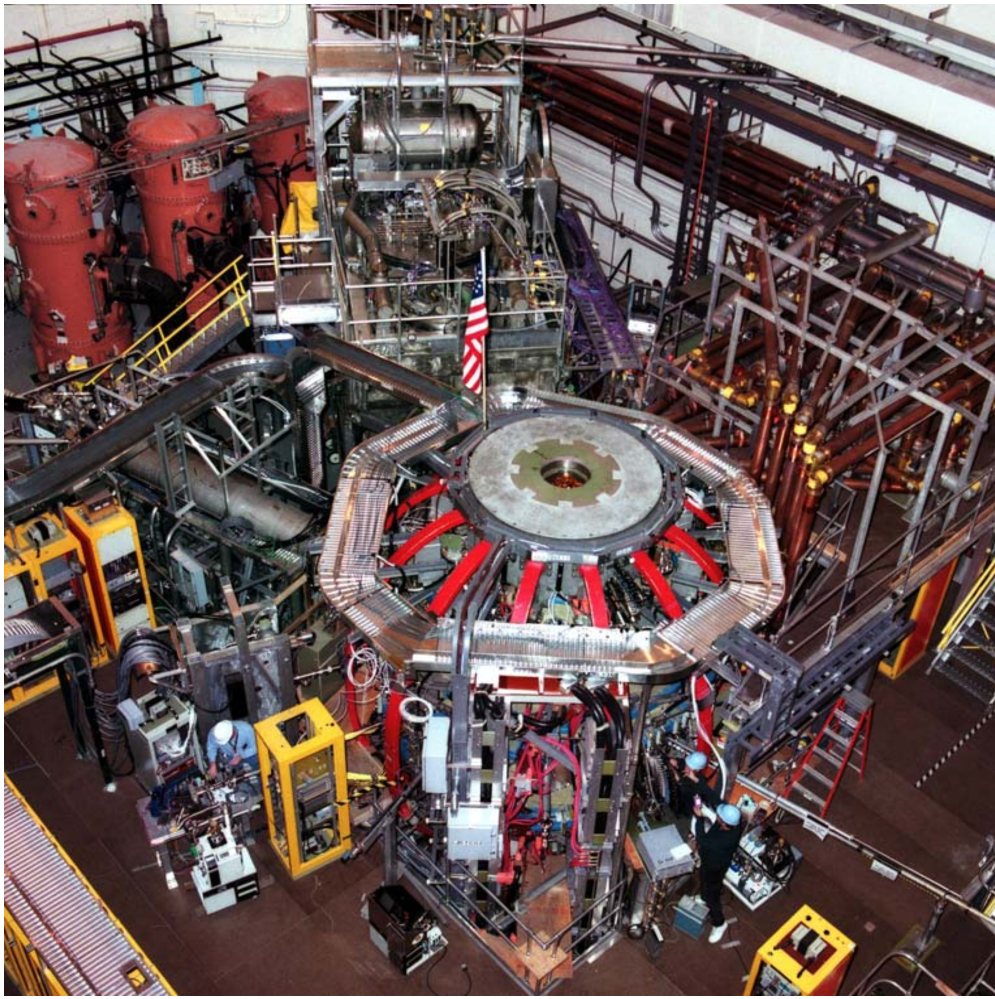
National Spherical Torus Experiment



New results are expanding the parameter space of toroidal plasma science

- Capabilities; research goals in science and fusion energy
- Solenoid-free startup – **magnetic reconnection**
- Energy confinement - **turbulence**
- Stability at beta (pressure/field^2) $\rightarrow$ order unity - **MHD**
- Heating & current drive - **wave-fast ions-plasma interactions**
- Plasma heat & particle fluxes – **plasma edge physics**
- Sustainment without induction – **self-organization**

NSTX Facility Has Made Rapid Progress in Capability Since Start of Operation in 9/99



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 (90keV)	5MW	7MW
HHFW (30MHz)	6MW	6MW
CHI	0.5MA	0.4MA
Pulse Length	≤5s	1.1s

Spherical Torus Permits Studies of High β Plasmas with Strong Shaping & Toroidal Rotational Transform (q ~ 10)

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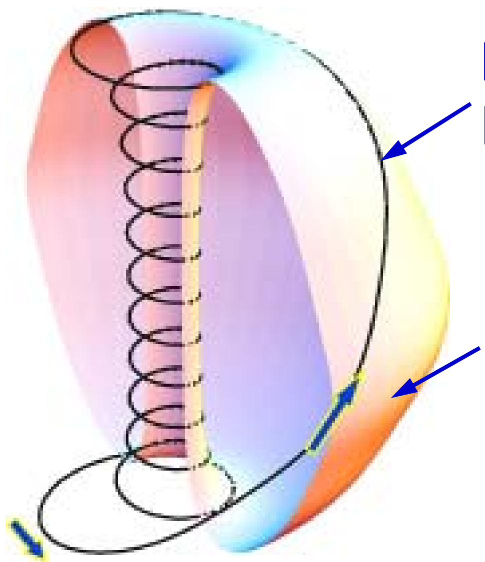
Spherical Torus



Definitions:

- A = aspect ratio
- $\beta_T = 2\mu_0\langle p\rangle/B_{T0}^2$
- q = toroidal rotational transform

Expanded plasma parameter space:

- Strong plasma shaping ($A \geq 1.27$, $\kappa \leq 2.5$, $B_p/B_t \sim 1$, $q_{edge} \sim 10$)
- Stability with hollow current (low internal inductance, l_i)
- High β_T ($\leq$ 40%) & central β_0 (~100%)
- Large plasma flow ($V_{rotation}/V_A \sim 0.25$)
- Large flow shearing rate ($\gamma_{ExB} > 10^5$/s)
- Supra-Alfvénic fast ions ($V_{fast}/V_A \sim 4$–5)
- High dielectric constant ($\varepsilon \sim 30$–100)
- Large curvature in edge magnetic field

Expanded Plasma Parameter Space Potentially Also Lead to Attractive Fusion Energy Devices

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Plasma Science of Expanded Parameter Space	$\Rightarrow$	Attractive Energy Development Steps
• Solenoid-free Startup	$\Rightarrow$	Simplified design, reduced operating cost
• Reduced turbulence	$\Rightarrow$	Smaller unit size for sustained fusion burn
• Stable high β_T & β_0	$\Rightarrow$	Lowered magnetic field and device costs
• Strong wave-energetic particle-plasma interaction	$\Rightarrow$	Efficient fusion α particle, neutral beam, & RF heating
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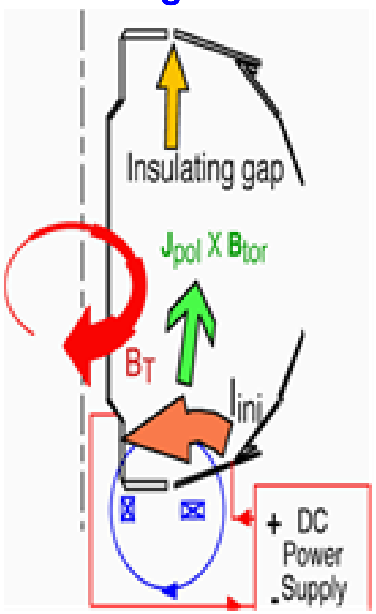
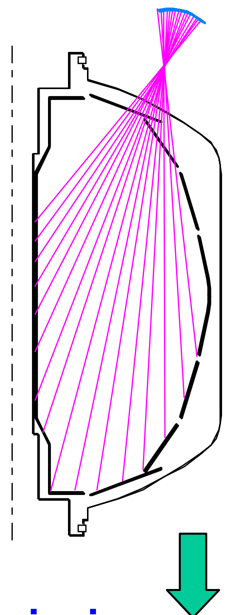
Obtained 390 kA Toroidal Current by Coaxial Helicity Injection (Helicity =ÚA∑B dV)

n=1 oscillations related to reconnection mechanisms

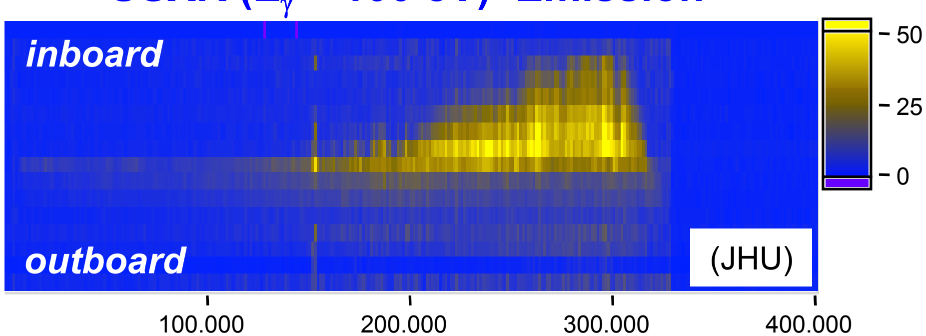
Injection Configuration

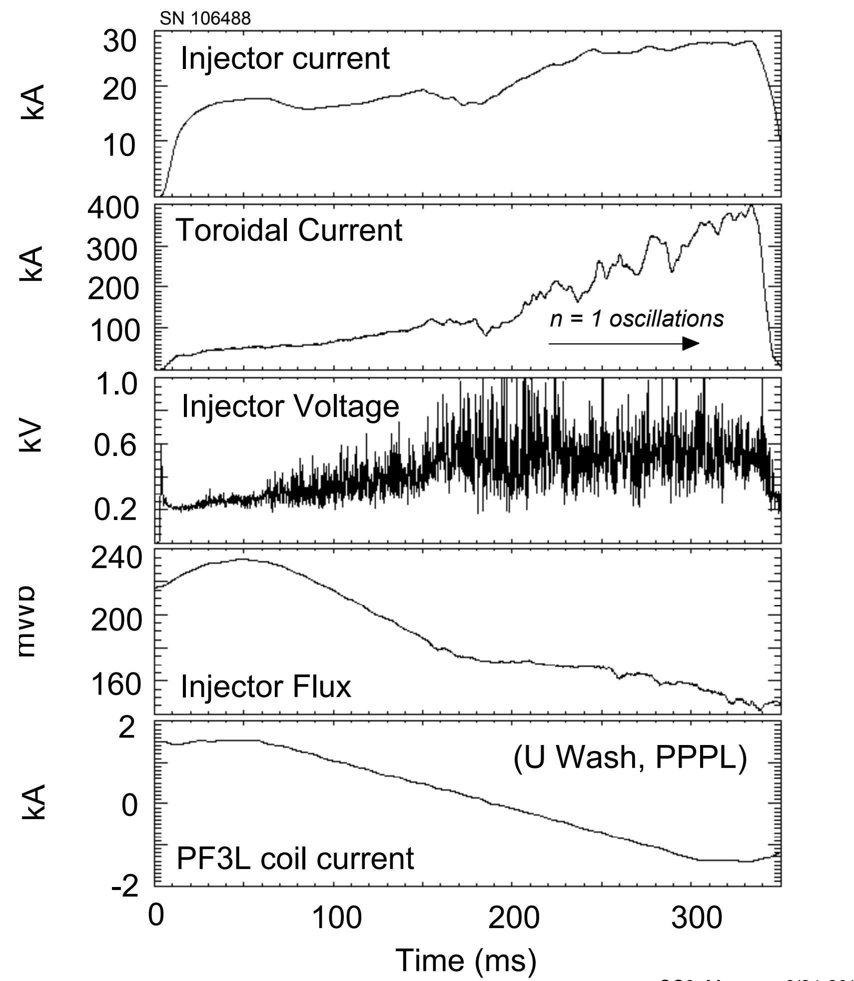


USXR Detectors



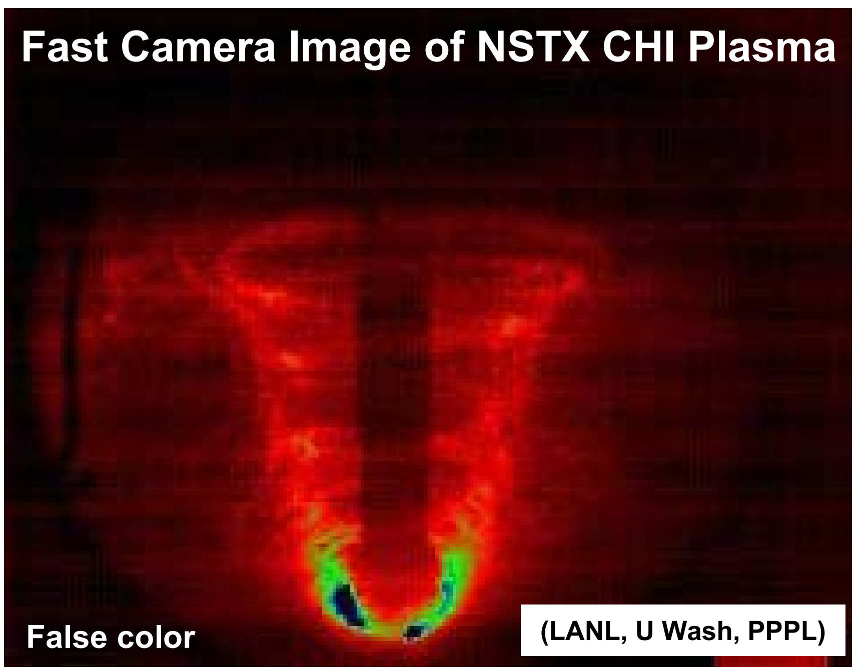
USXR (E_γ > 100 eV) Emission

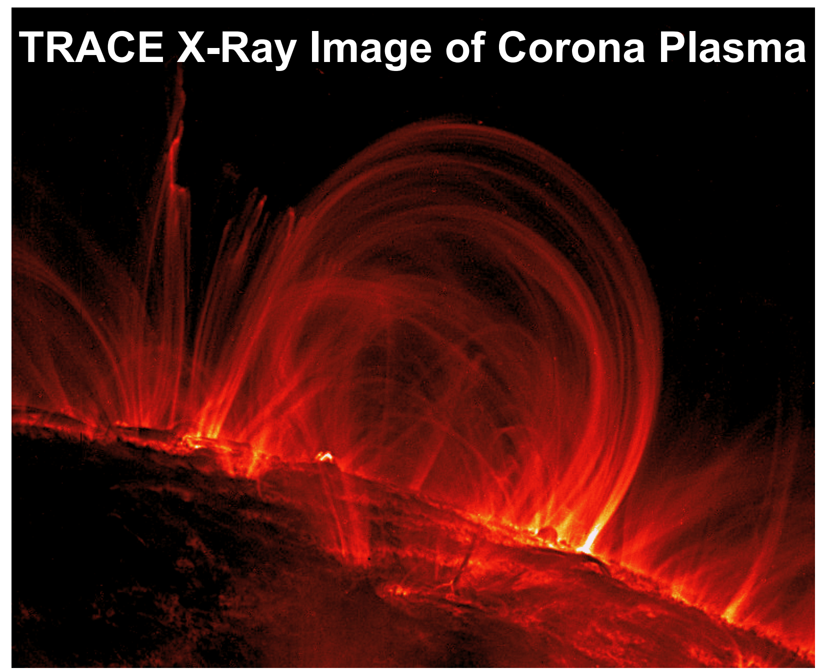




This Enables Studies of Reconnection Needed to Form Nearly Closed Magnetic Surfaces

- Flux surface closure important to solenoid-free startup
- Need effective coupling to solenoid induction and RF heating
- Lundquist No. *S*(CHI) ~ 10^4 – 10^6 vs. *S*(corona) ~ 10^{10} – 10^{12}
- Laboratory investigation of interest to space plasma studies





← 2 m →

← 3×10^7 m →

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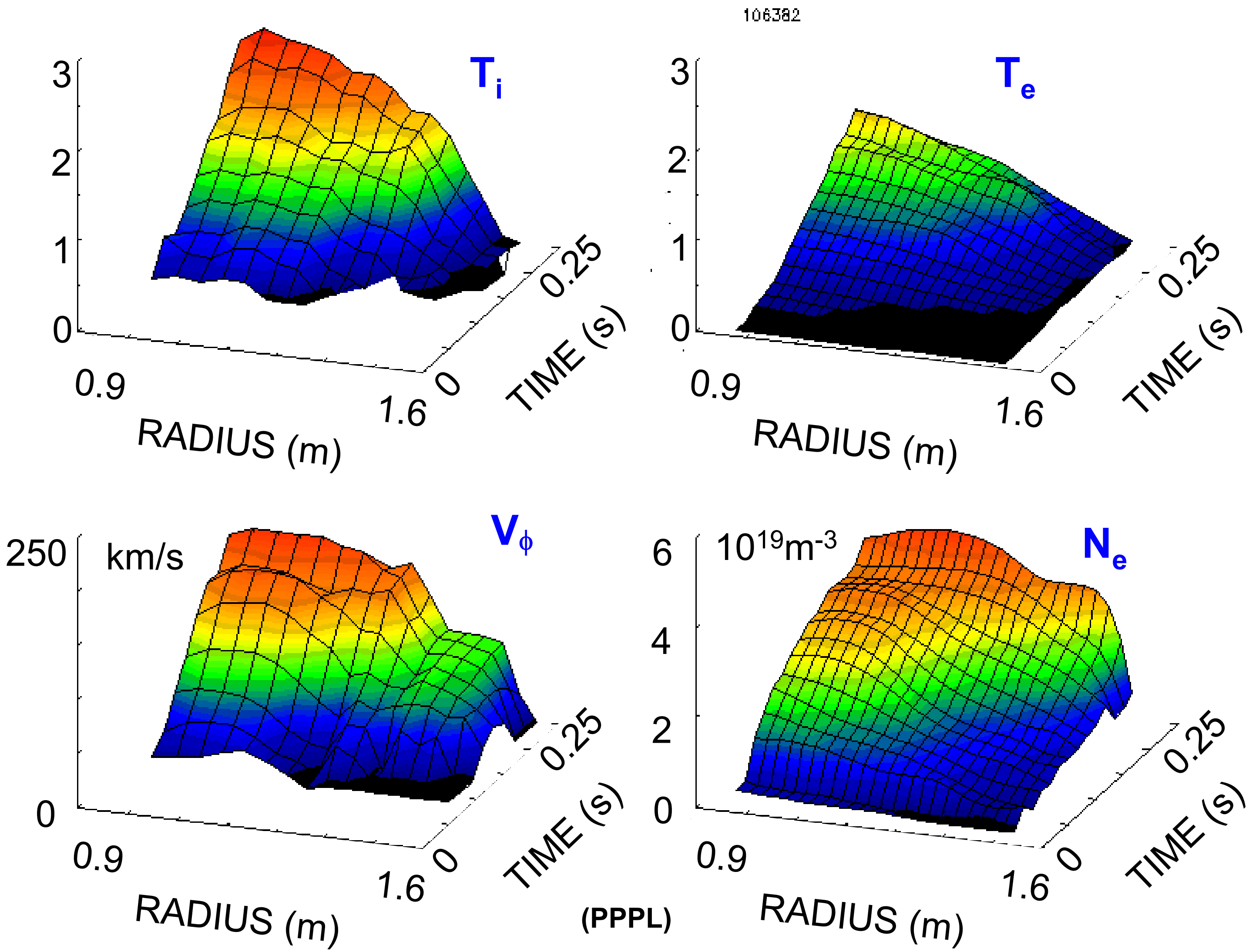
Neutral Beam Heating Yields High Ion Temperatures with Strong Plasma Rotation

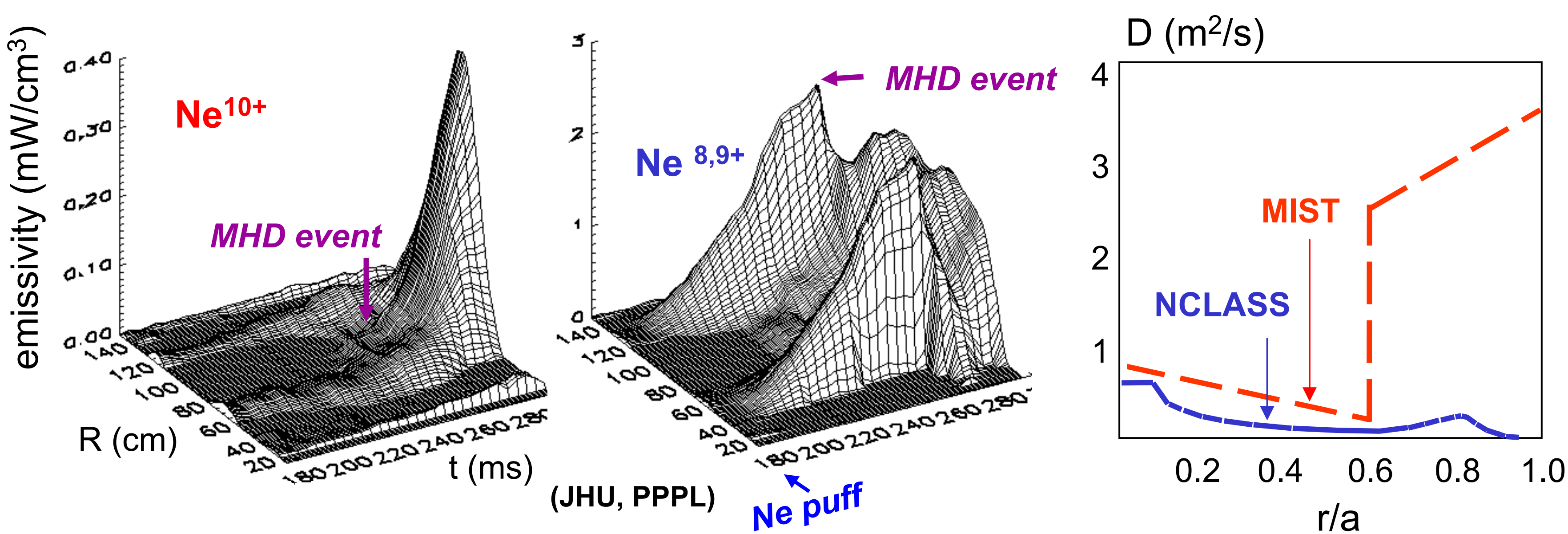


#106382

- Ip ~ 1.2 MA
- Bt ~ 0.33 T
- P(NBI) ~ 4.8 MW
- T_i ~ 2.5 keV
- T_e ~ 1.5 keV
- T_i broader
- V_ϕ ~ 200km/s Core
- V_ϕ ~ 50km/s pedestal

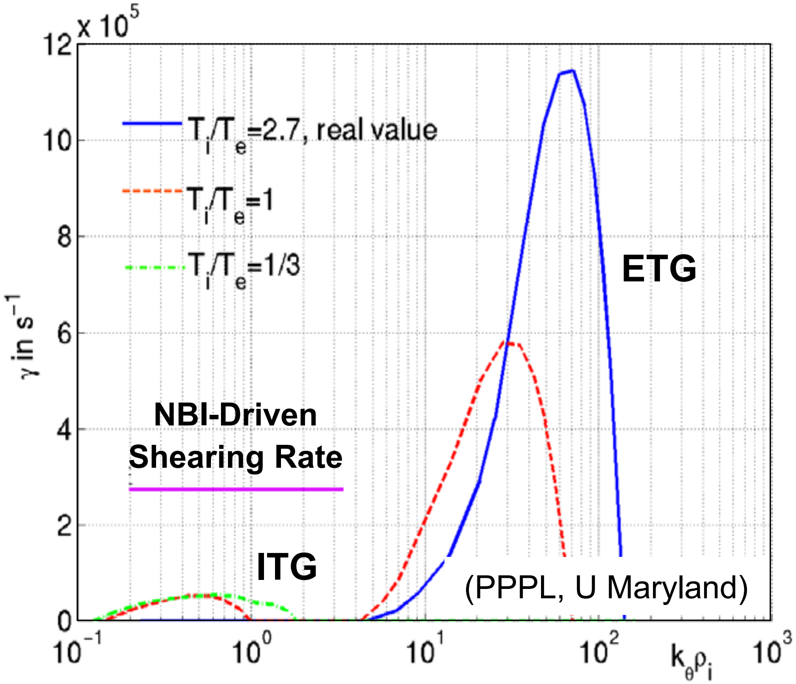
Neon Particle Diffusion Rates Measured to be ~2X the Neoclassical limit

- Almost no Neon penetrates into center until MHD event
- Estimated diffusion (MIST) is in the neoclassical range (NCLASS), for r/a < 0.6



Gyrokinetic Theory on Fluctuation Growth Rates Indicates Strong Dependence on T_i/T_e

Gyrokinetic Fluctuation Growth Rates



ETG: electron temperature gradient

ITG: ion temperature gradient

ρ_i: ion gyroradius

- **Interpretation**
  - ITG stabilized
  - ETG strongly unstable
- **Questions**
  - High β' $\rightarrow$ diamagnetic flow?
  - High β $\rightarrow$ magneto-sonic effects?
  - Strong shearing + $T_i \leq T_e$ $\rightarrow$ stabilize both ITG & ETG?
- **Need direct measurement of large-k fluctuations**
  - High β $\rightarrow$ stronger electromagnetic fluctuations
  - Larger ρ_e $\rightarrow$ eases ETG measurement

Laboratory High-β (~1) Turbulence Has Interesting Scientific Link with Astrophysics

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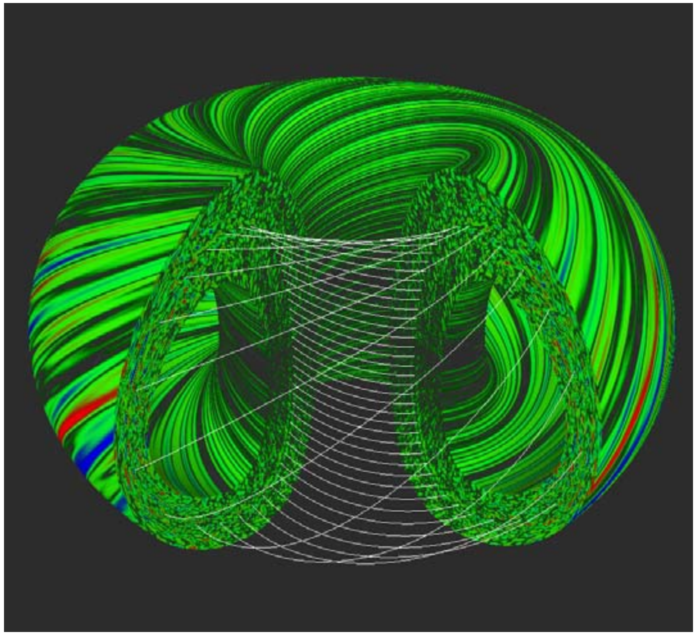
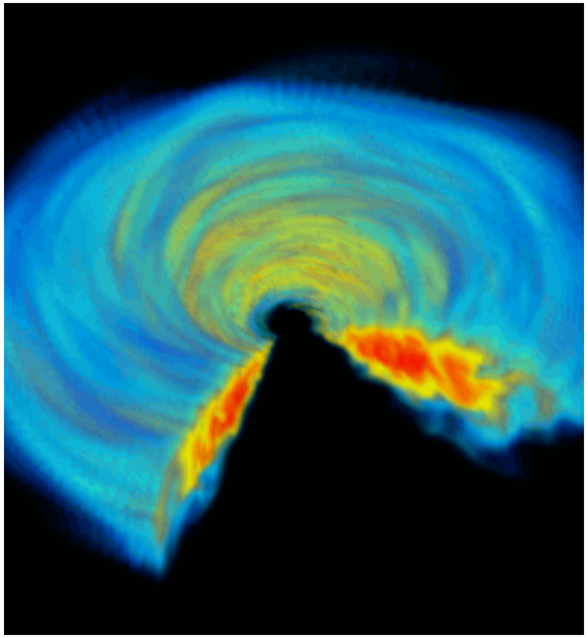
NSTX Simulation



(GA, LLNL)

Accretion Disk Simulation

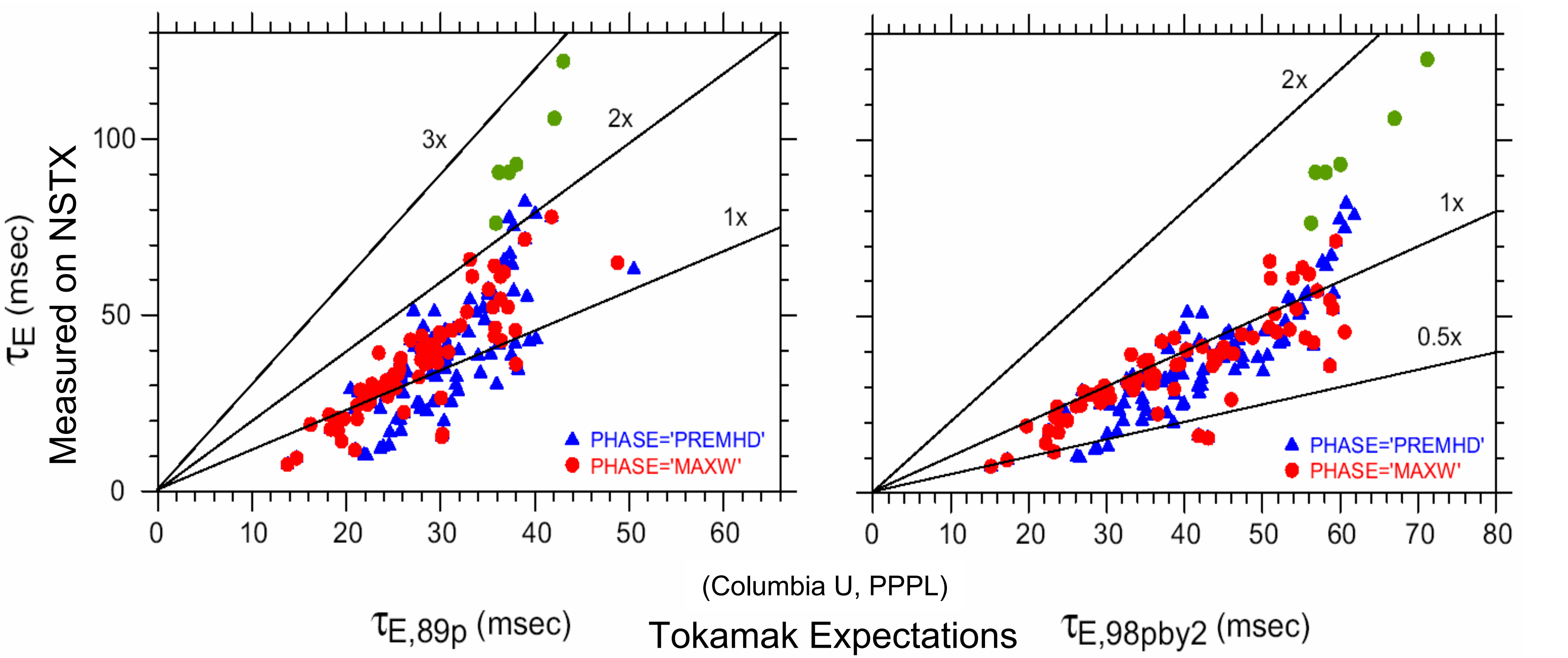


(Hawley, Balbus, Univ. Virginia)

- Turbulent momentum transport is needed to fuel black holes.
- Cascades to small eddies that heat electrons and ions.
- High-β laboratory plasmas acquires magnetic turbulence features.
- Benchmark turbulence codes in NSTX high-β plasmas contributes.

Plasmas with Beam Heating Can Surpass "High-Confinement Mode" Level Without Edge Barrier

- Confinement time better than expectations based on Tokamak data
- Encouraging indications for future small fusion energy devices



Expanded Plasma Parameter Space Potentially Can Also Lead to Attractive Fusion Energy Devices

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Plasma Science of Expanded Parameter Space		Attractive Energy Development Steps
• Solenoid-free Startup	⇒	Simplified design, reduced operating cost
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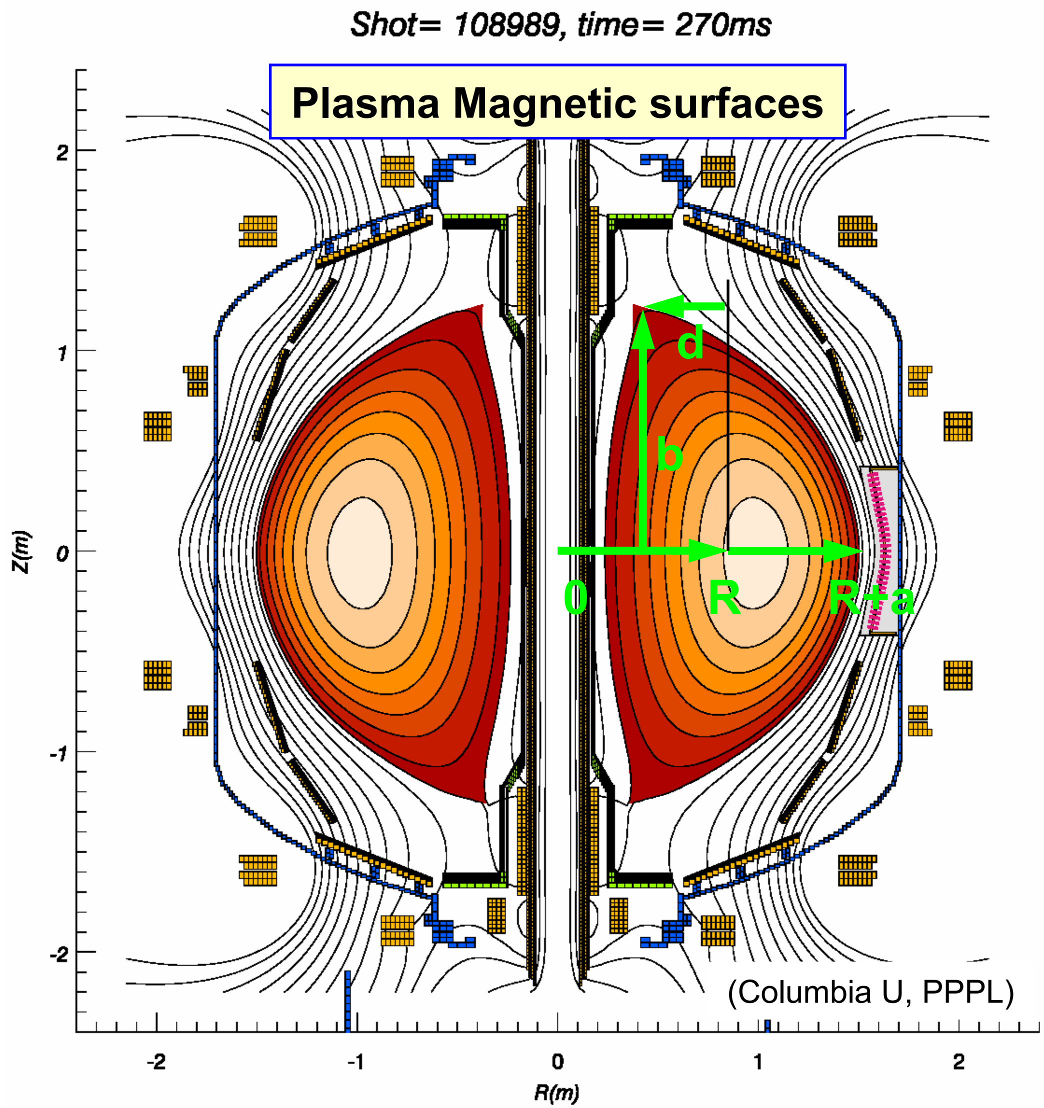
Strong Plasma Shaping Increases Stable β

- **Strong shaping:**
  - Small A = R/a ~ 1.4
  - Large κ = b/a ~ 2.0
  - Large δ = d/a ~ 0.8
- **Raises edge q** for fixed plasma current and toroidal field
- **Higher I_p/aB_{t0}**: utilization of size and applied field:
- **Increased stability** during fast I_p ramp up



Troyon Scaling ($\beta_{t0} = \beta_N I_p / aB_{t0}$) Continues to be Obeyed

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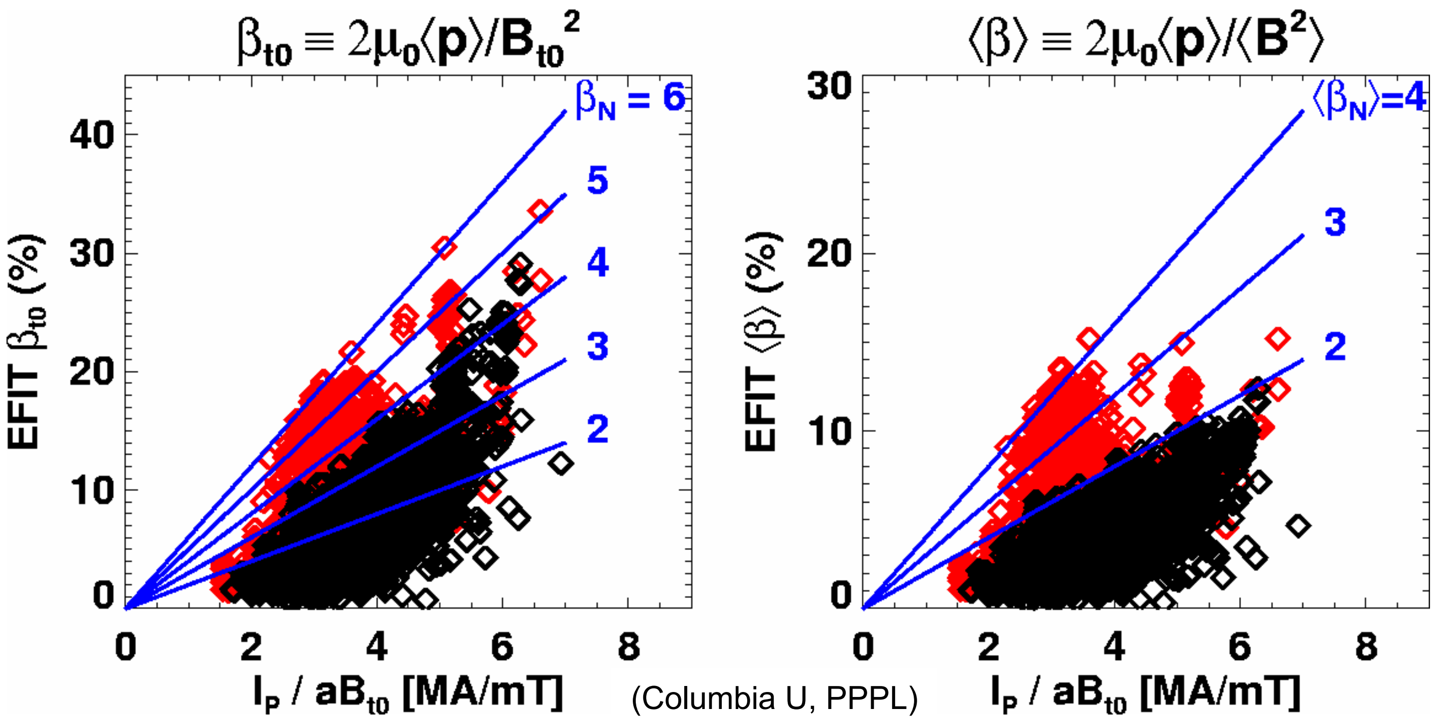
- $\beta_{N,max}$ ~ 6.3, W_{MAX} ~ 390kJ
- $\beta_P \leq 1.5 \Rightarrow$ first indication of diamagnetic current that lowers B_t
- Improved field axisymmetry and wall cleanliness $\Rightarrow$ higher β

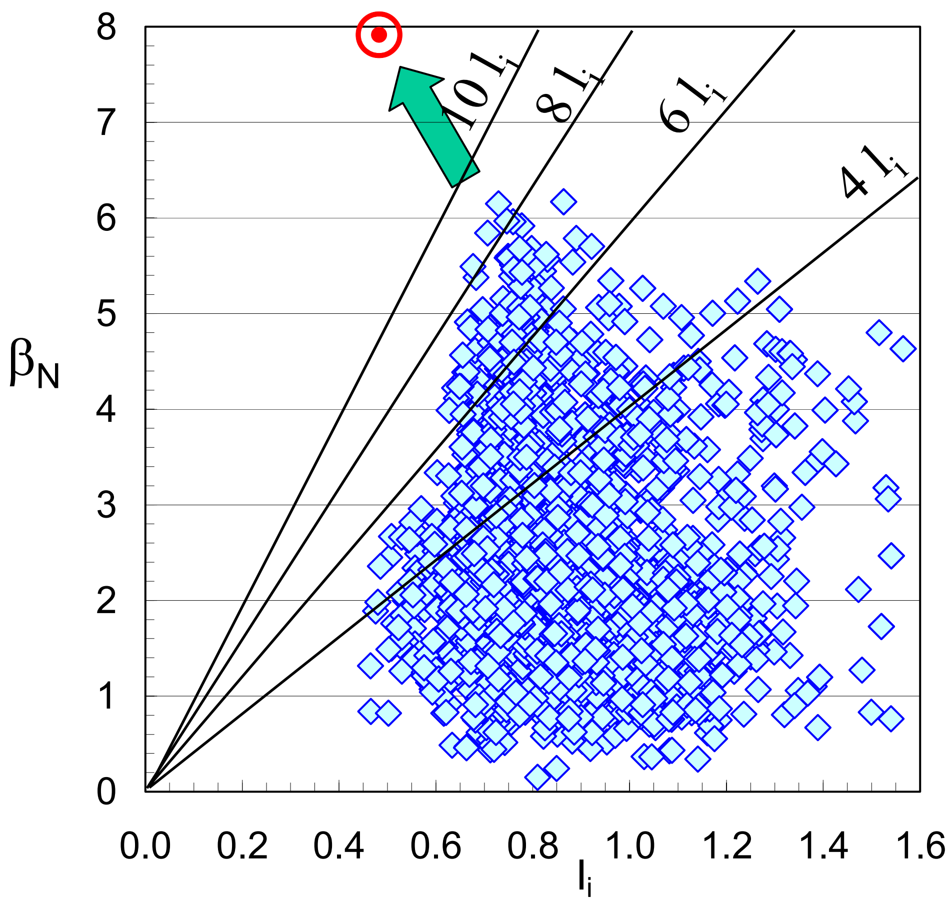


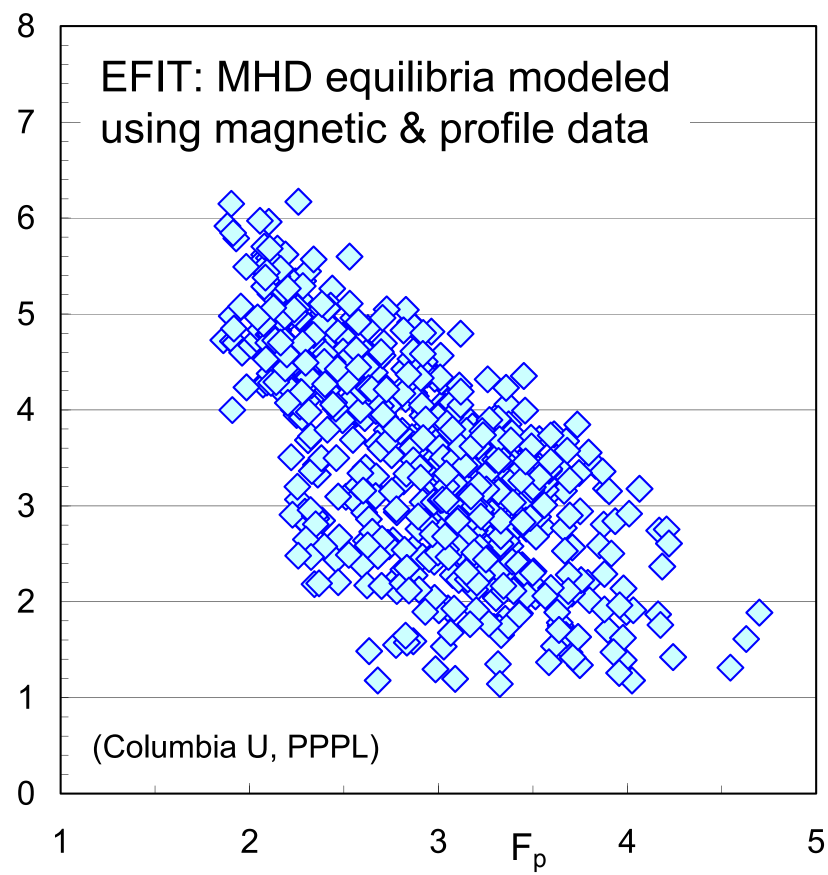
(Columbia U, PPPL)

(Black $\Rightarrow$ 2001 data   Red $\Rightarrow$ 2002 data, coil alignment + bake to 300 ^{o}C)

High β_N Attained With Low Pressure Peaking F_p & Internal Inductance l_i, as Suggested by Theory

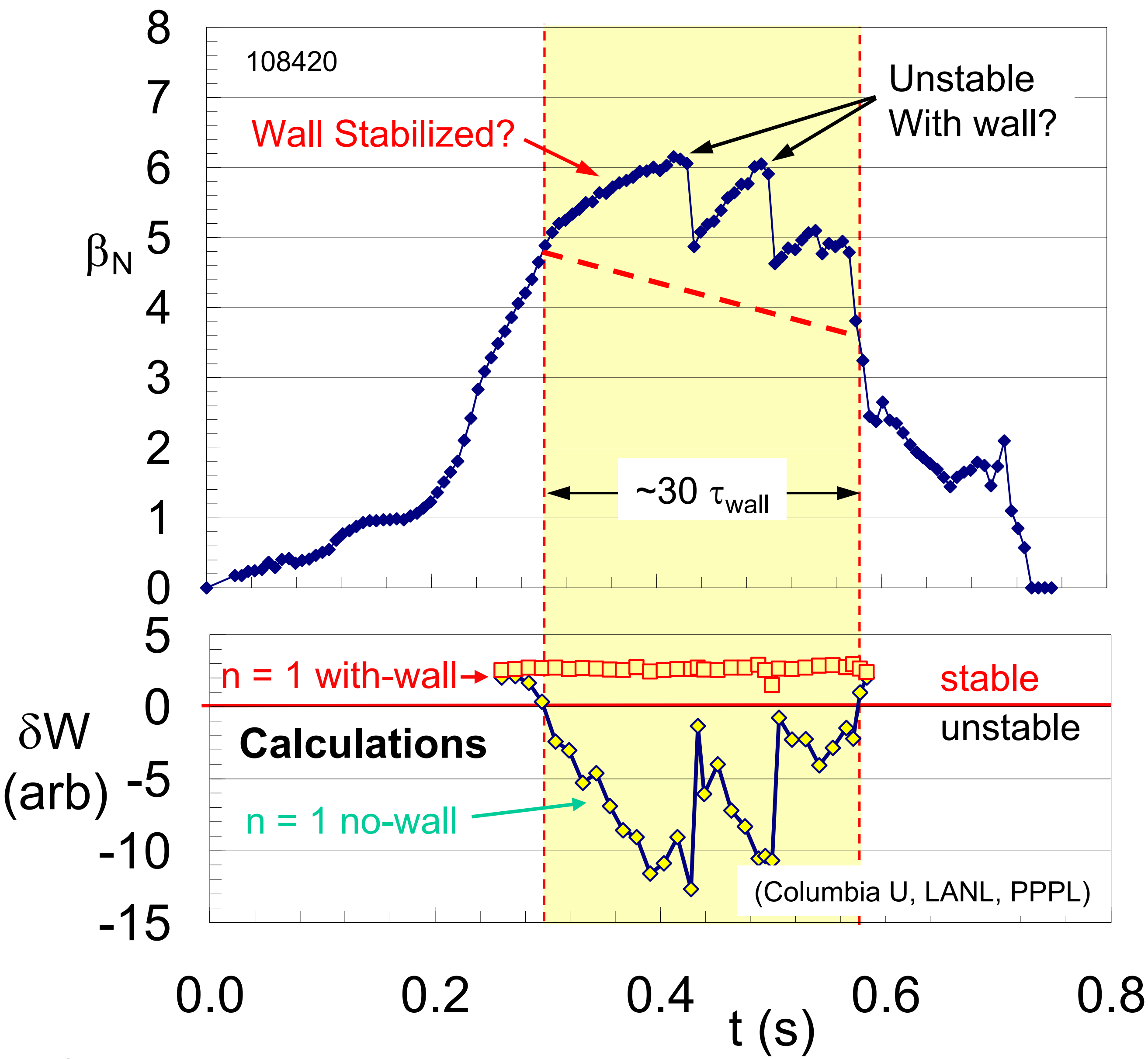
NSTX





- Toroidal beta has reached 34% toward target of 40%
- The effects of nearby conducting wall & plasma rotation important

Evidence for Wall Stabilization Is Under Examination



- Also suggested by theory
- Strong experimental evidence from DIII-D tokamak (GA, U.S.)
- Ideal no-wall limit violated for many τ_{wall}?
- Plasma rotation stabilizing
- Subject to mode, field error, & rotation control
- Crucial to $\beta_T \rightarrow 40\%$

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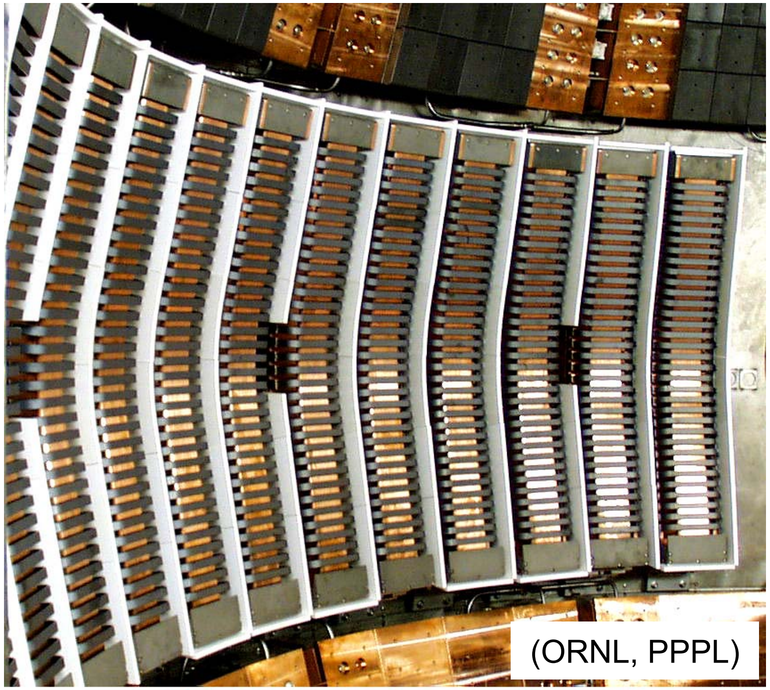
High Harmonic Fast Wave Utilizes High ε (~100) in ST for Efficient Heating and Current Drive

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

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

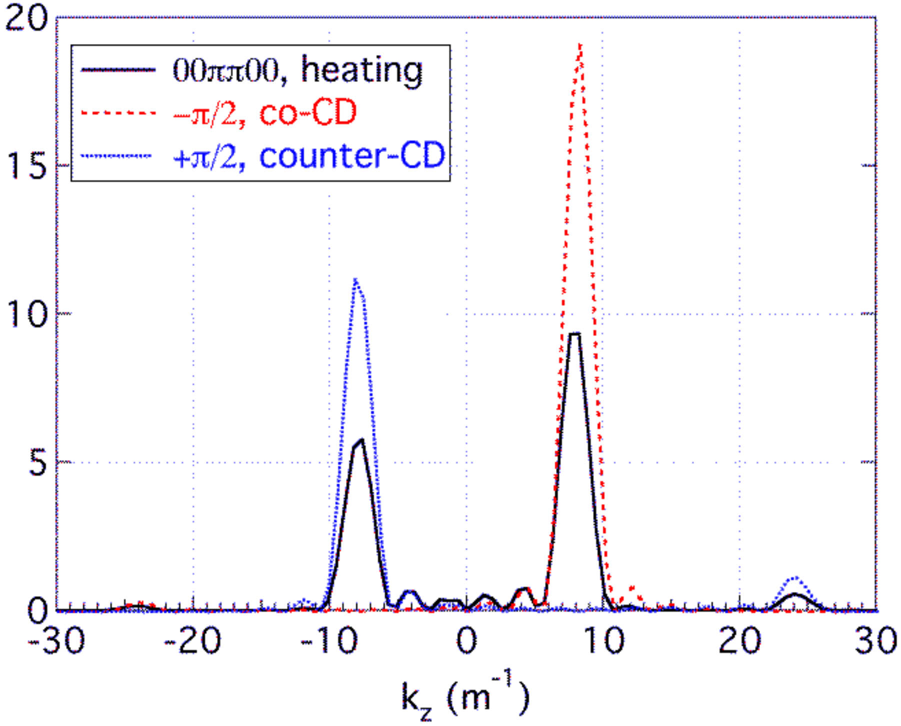
$$\varepsilon = \omega_{pe}^2 / \omega_{ce}^2 \sim 10^2$$

- 6 transmitters and phase controls
- Flexible spectrum

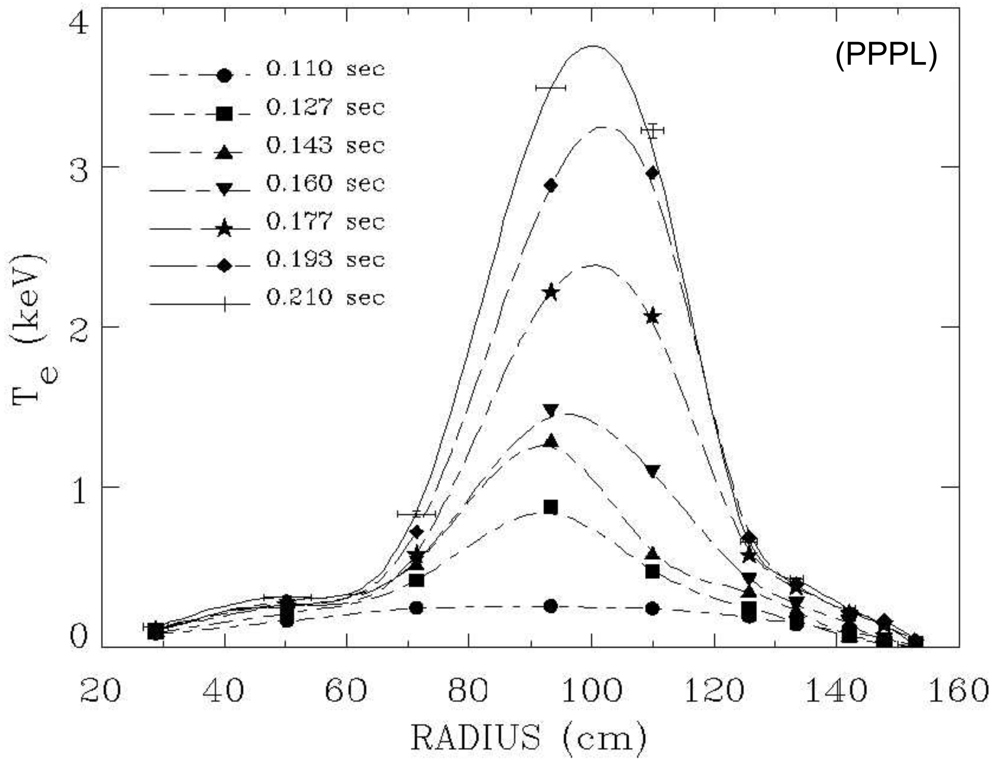


12 HHFW ANTENNA

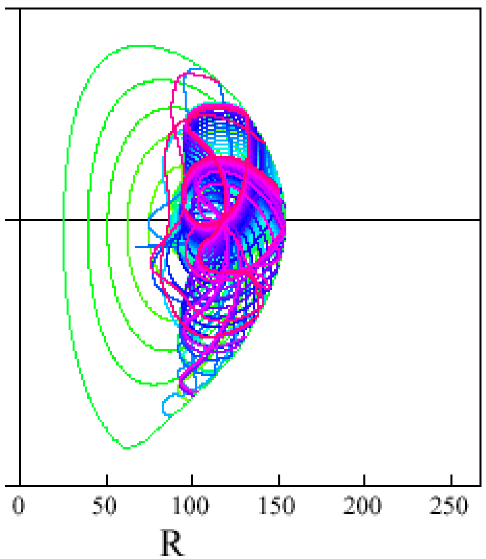
GLOSI/RANT3D calculations



HHFW (A Magnetosonic Wave at High Harmonics) Can Interact Strongly with Electrons



Laser Thomson Scattering



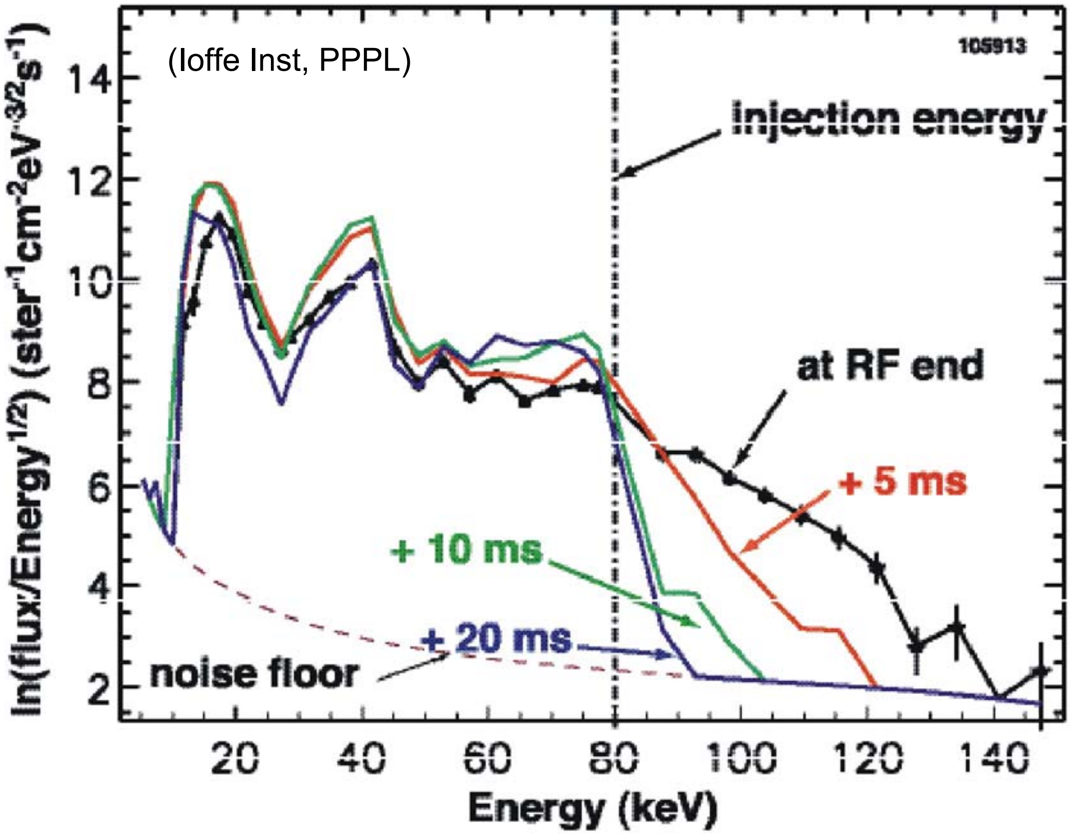
GENRAY Code

(CompX)

- 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)

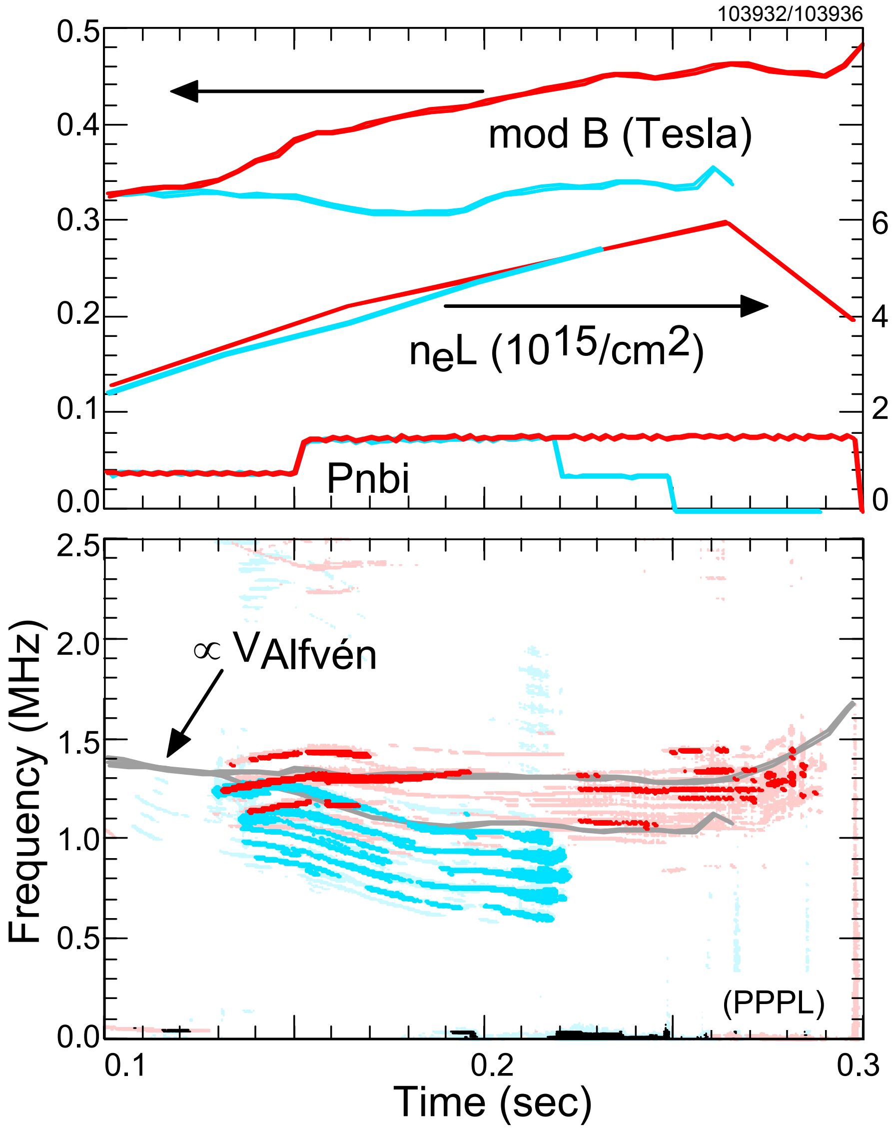
HHFW Also Interacts Readily with Supra-Alfvénic Neutral Beam Injected Ions

- Data from Neutral Particle Analyzer
- P_{RF} = 3 MW
  P_{NBI} = 1.5 MW
  $T_e(0)$ = 1.0 - 0.4 keV
  $n_e(0) \approx 3 \times 10^{19} m^{-3}$
- Ions accelerated to higher multiples of $V_{Alfvén}$



NBI Ions Excite Magnetosonic Oscillations, or Compressional Alfven Eigenmodes (CAE's)

NSTX



- Mode identified to be Alfvénic
  - Red: B_T ramp-up
  - Blue: B_T ramp-down
- Fit CAE theory: broad spectra away from ion cyclotron frequencies
- Correlates well with increasing NBI energy - **consistent with large V_{fast}/V_{Alfven} ~ 4**
- Could impact ion heating and ion-electron power balance
- Important for future devices with **V_α/V_{Alfven} ~ 4 or higher**

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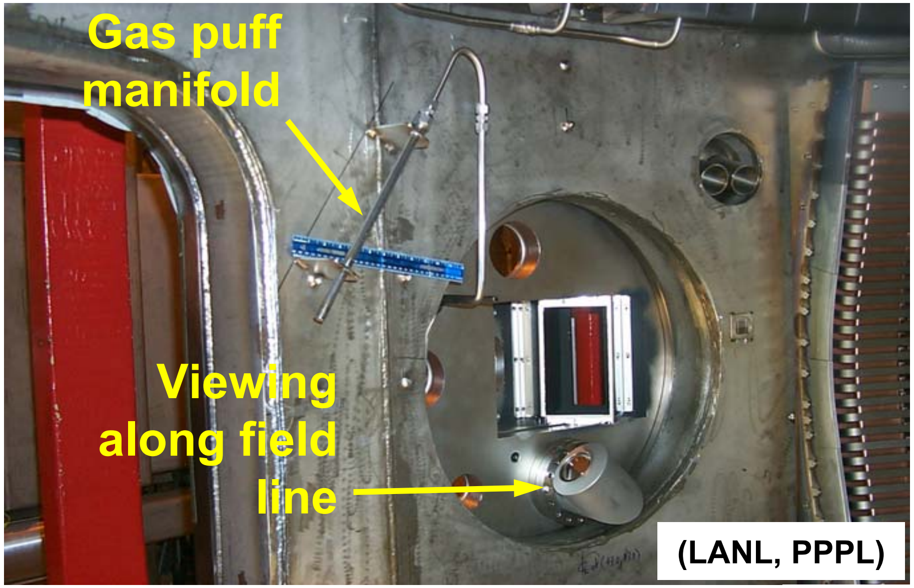
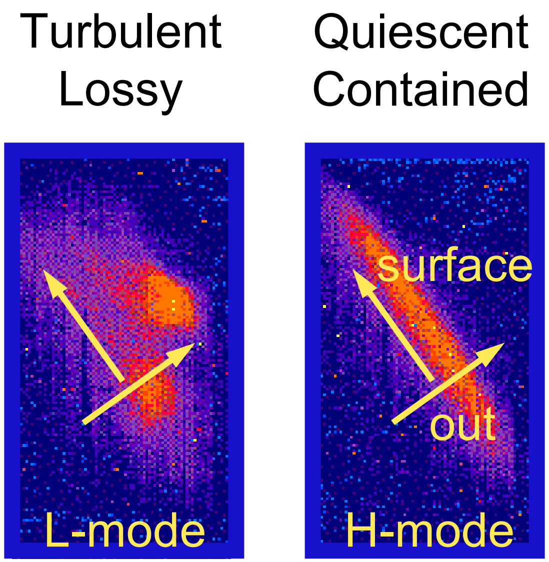
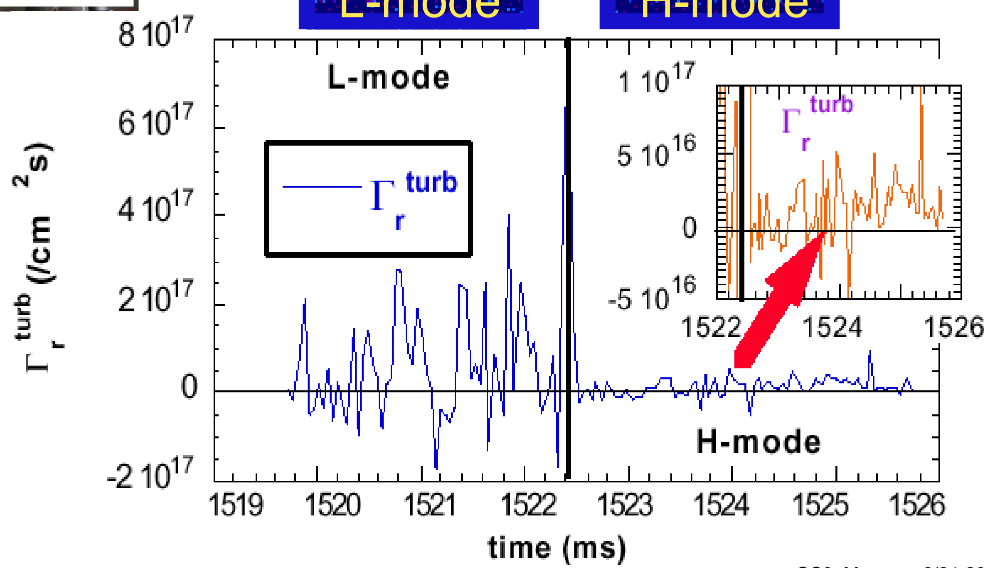
Emission from Gas Puff Imaging Reveals Ejected "Filaments" Leading to Large Edge Plasma Loss

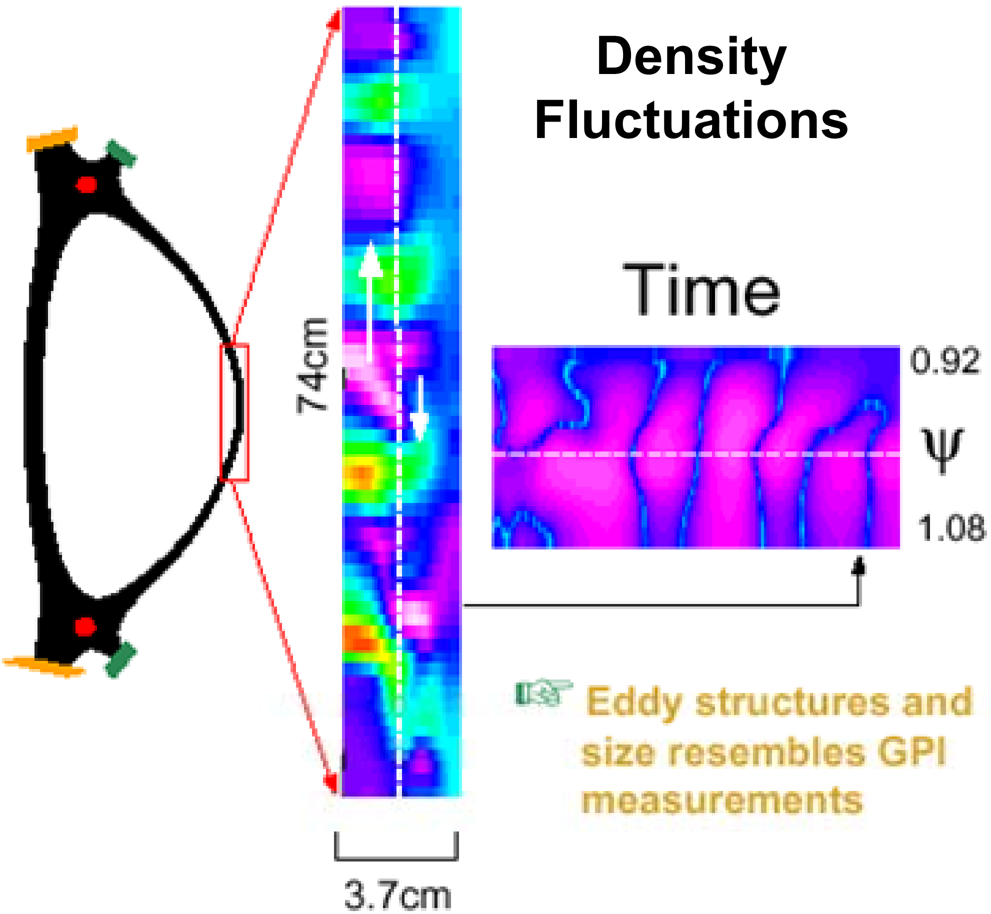




- Also in C-Mod Tokamak (MIT)
- He puff in D_2 discharge
- 10 μs exposures @ 100 kHz
- Several cm in cross section
- Moves at a few hundred m/s
- Coincidental with "Low-Mode"
- Absent or rare in "High-Mode"



Simulations Confirms Theory: Sheared Flow Reduces Fluctuations & Improves Edge Confinement



BOUT Fluid Simulation code (LLNL)

- EFIT equilibrium for 104312, at 250 ms.
- Edge: $T_i = T_e = 26$ eV, $n_i = 2.3\times10^{18}$ m^{-3}
- ψ=0.9: $T_i = T_e = 51$ eV, $n_i = 4.4\times10^{18}$ m^{-3}
- Driven by edge pressure gradient in bad field line curvature, but reduced by sheared flow
- Kinetic and boundary effects important
- **Impacts plasma flux dispersion**

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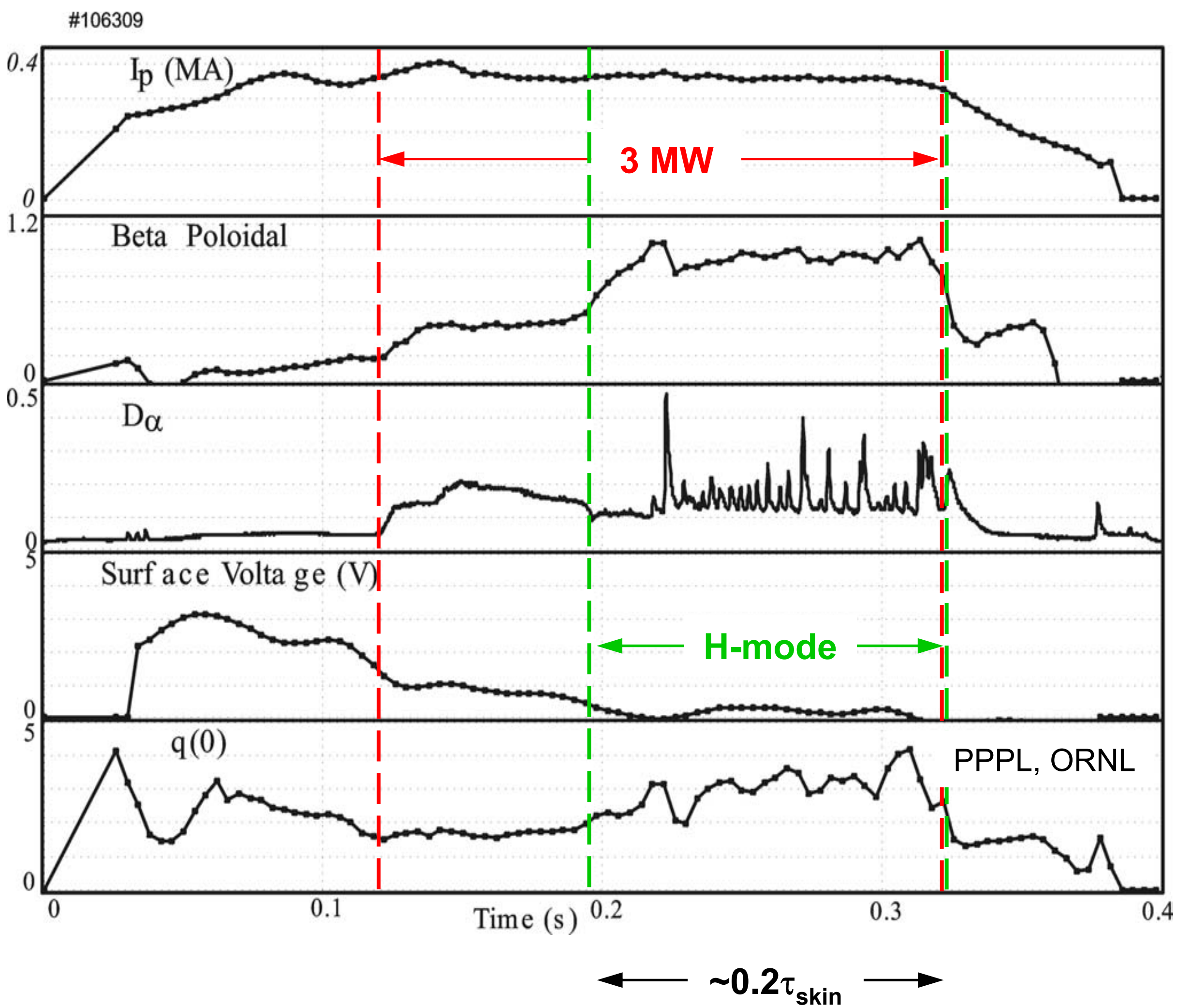
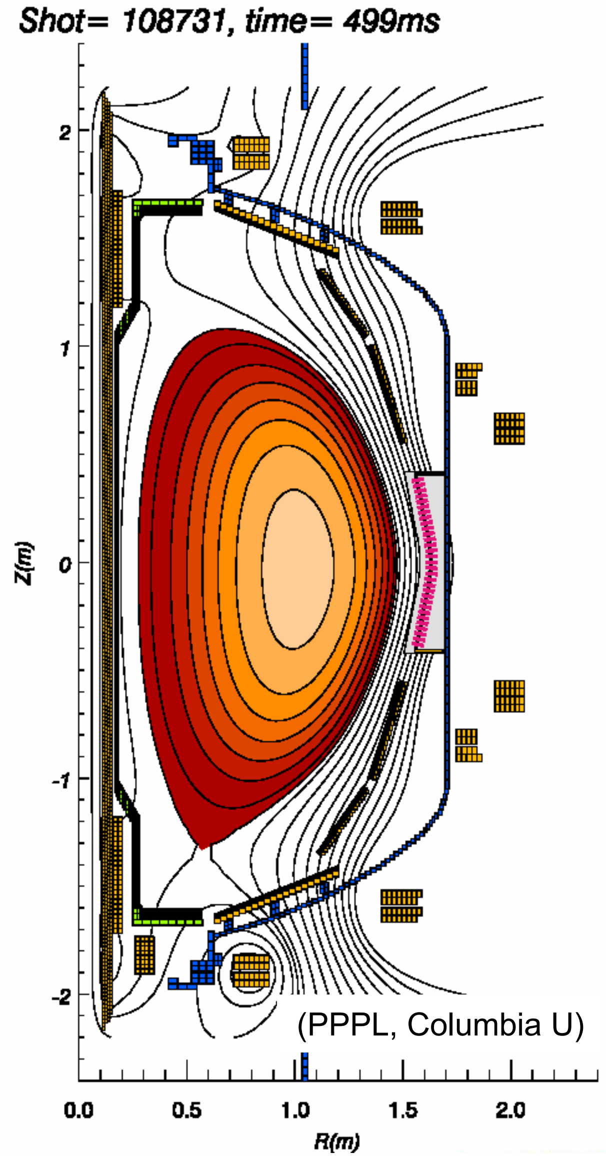
First Indications of HHFW-Heated Plasmas with Reduced Inductive Requirements

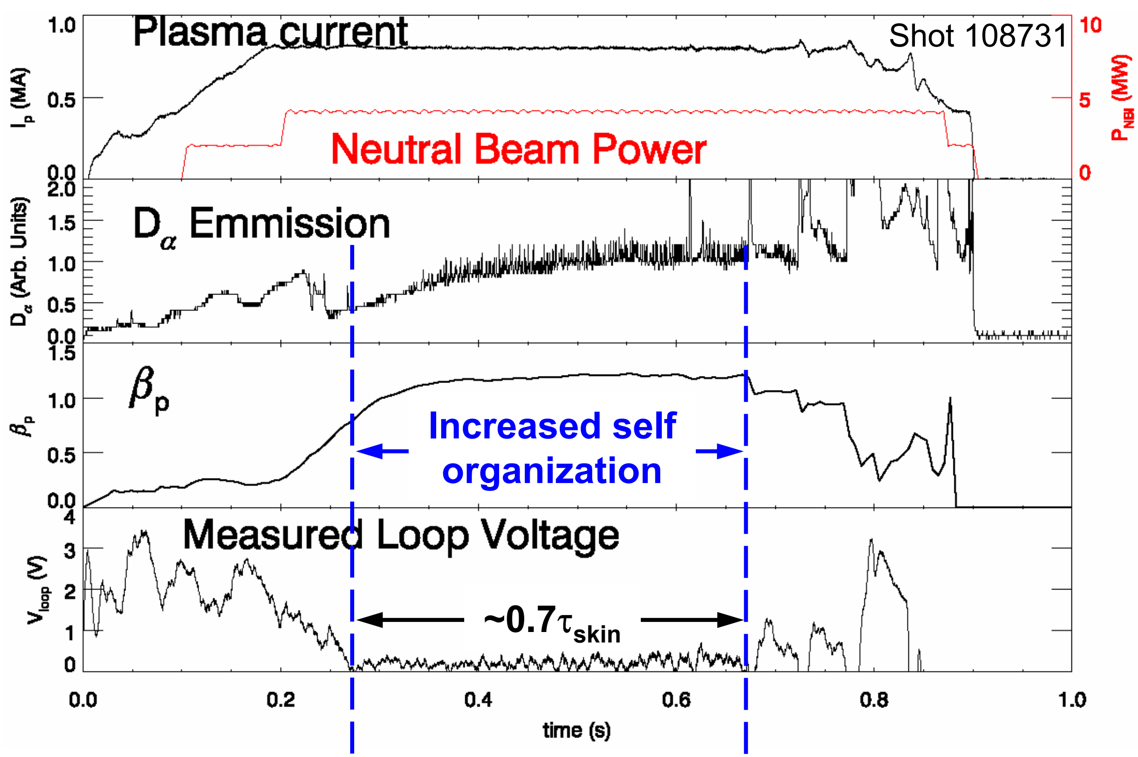


- **Moderate plasma current**
- **High β_p ~ 1**
- **H-mode with Edge-Localized Modes**
- **Induction voltage reduced to <0.5 V**
- **Low internal inductance l_i ~ 0.9**

Stronger Indications of NBI-Heated Self-Organized Plasma Nearly Sustained without Induction



- Edge turbulence largely quieted – H-mode
- β_p ($\propto$ pressure/I_p^2) ~ 1.2 $\Rightarrow$ high self-driven current (pressure gradient, "thermo-electric")
- Neutral beam also drives substantial current
- Inductive voltage reduced to <0.2V for > 0.4s



New NSTX Results Are Expanding the Parameter Space of Toroidal Plasma Science

NSTX

- Great progress
  - Magnetic reconnection – solenoid-free start-up
  - Reduced turbulence – suppressed ion turbulence
  - MHD stability – β_T reached 34%, exceeded no-wall limit?
  - Wave-fast ion-plasma interactions – rich magnetosonic properties
  - Edge physics – ejected plasma filaments imaged
  - Self-organization – initial encouraging indications
- Links to astrophysics and solar plasma physics
- Strong contributions to toroidal plasma science & fusion energy development

In parallel with a burning plasma such as ITER, ST science will point the way to cost-effective and practical fusion energy

NSTX offers unique scientific research opportunities

In toroidal plasma physics