Supported by

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

M.G. Bell

Princeton Plasma Physics Laboratory

for the

NSTX Research Team

presented at the

4th General Scientific Assembly of the
Asia Plasma & Fusion Association,
Hangzhou, China, Oct 13 – 16, 2003

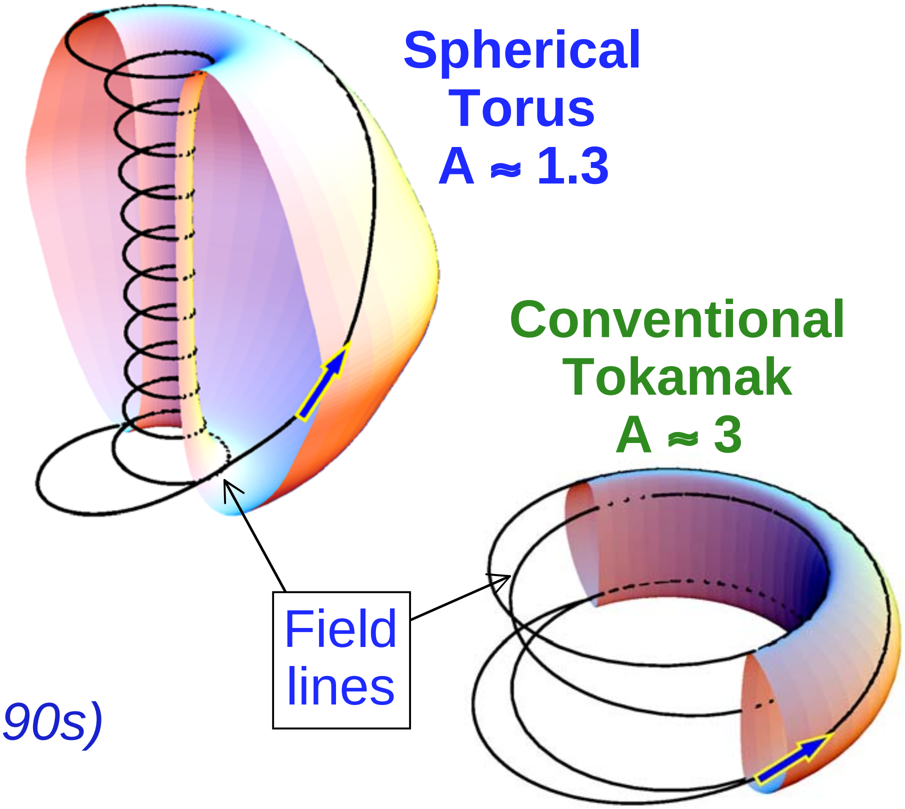
Columbia U
Comp-X
General Atomics
INEL
Johns Hopkins U
LANL
LLNL
Lodestar
MIT
Nova Photonics
NYU
ORNL
PPPL
PSI
SNL
UC Davis
UC Irvine
UCLA
UCSD
U Maryland
U New Mexico
U Rochester
U Washington
U Wisconsin
Culham Sci Ctr
Hiroshima U
HIST
Kyushu Tokai U
Niigata U
Tsukuba U
U Tokyo
Ioffe Inst
TRINITI
KBSI
KAIST
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
U Quebec

“Spherical Torus” Extends Tokamak to Extreme Toroidicity

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

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

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: Constant ~3%·m·T/MA
(Troyon, Sykes - early 1980s)



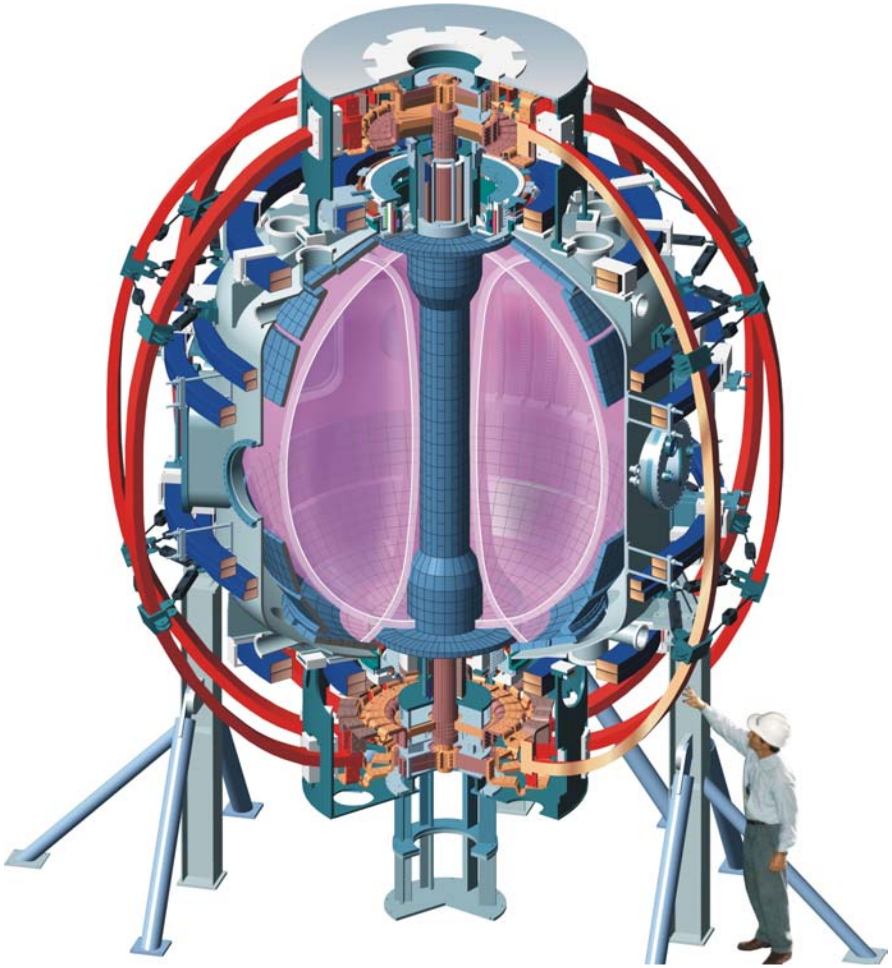
Spherical Torus
A ≈ 1.3

Conventional Tokamak
A ≈ 3

Field lines

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

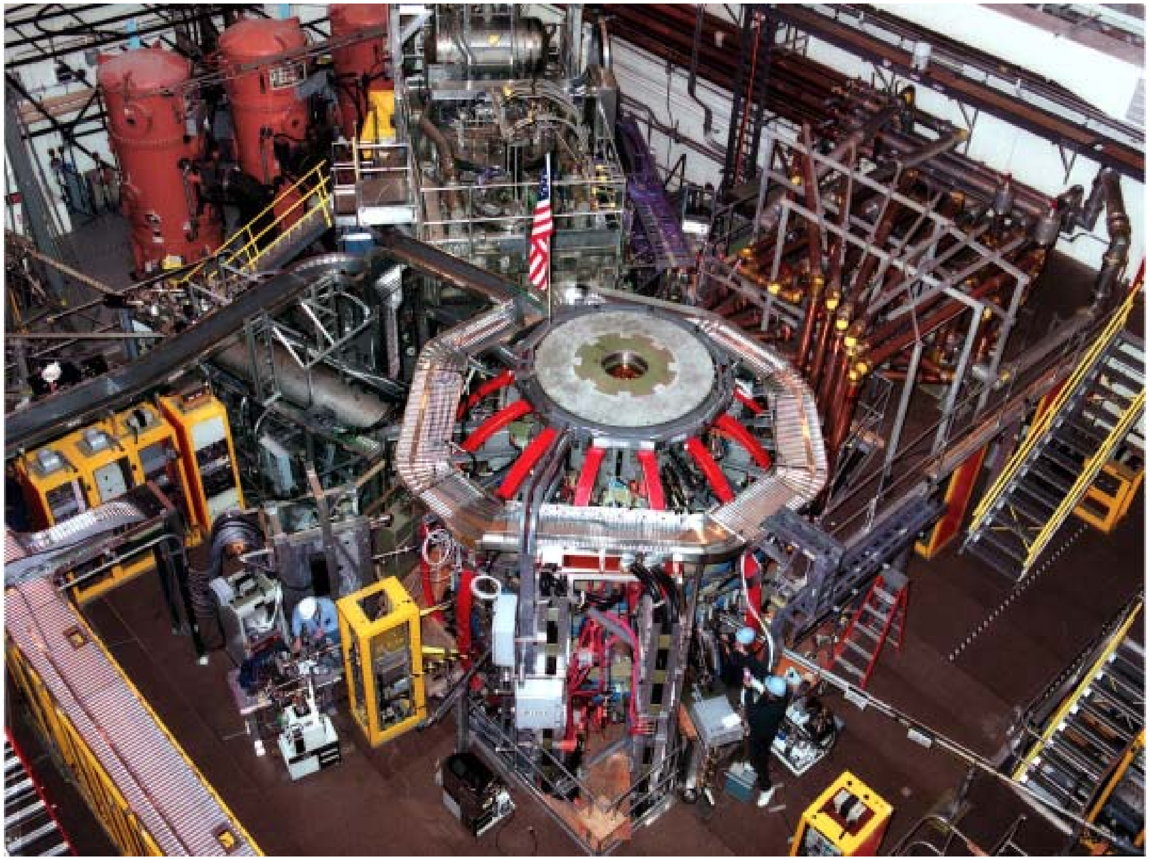
NSTX Designed to Study High-Temperature Toroidal Plasmas at Low Aspect-Ratio



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

View of NSTX, Heating Systems and Diagnostics

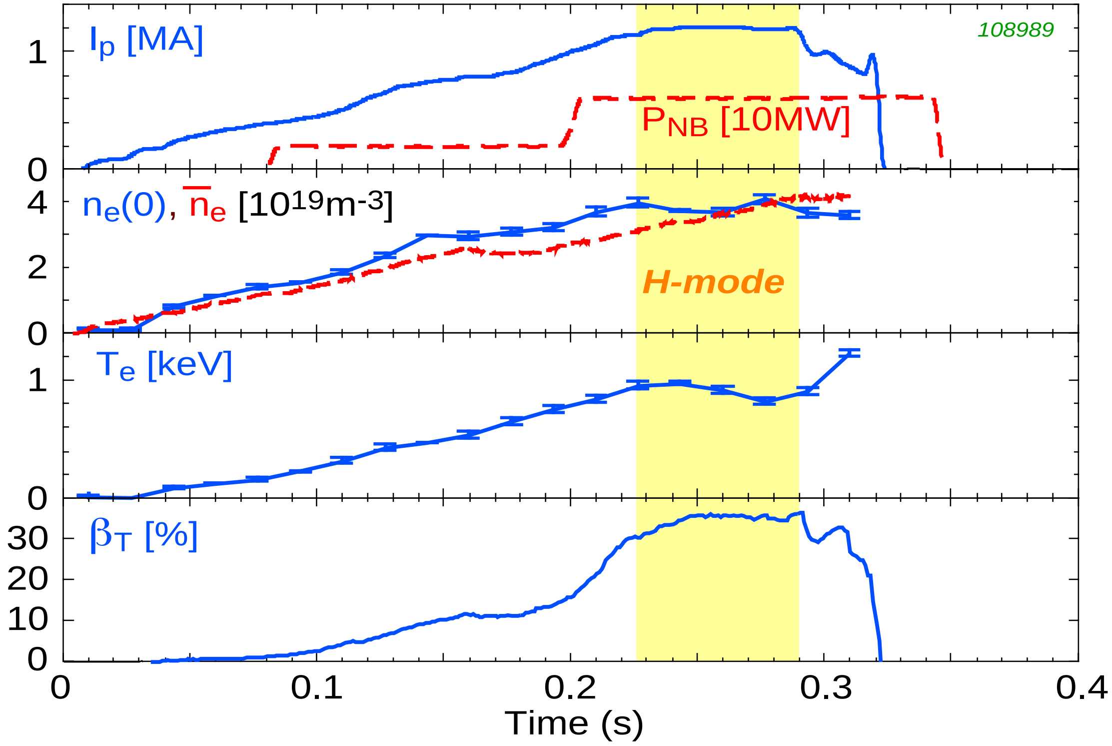


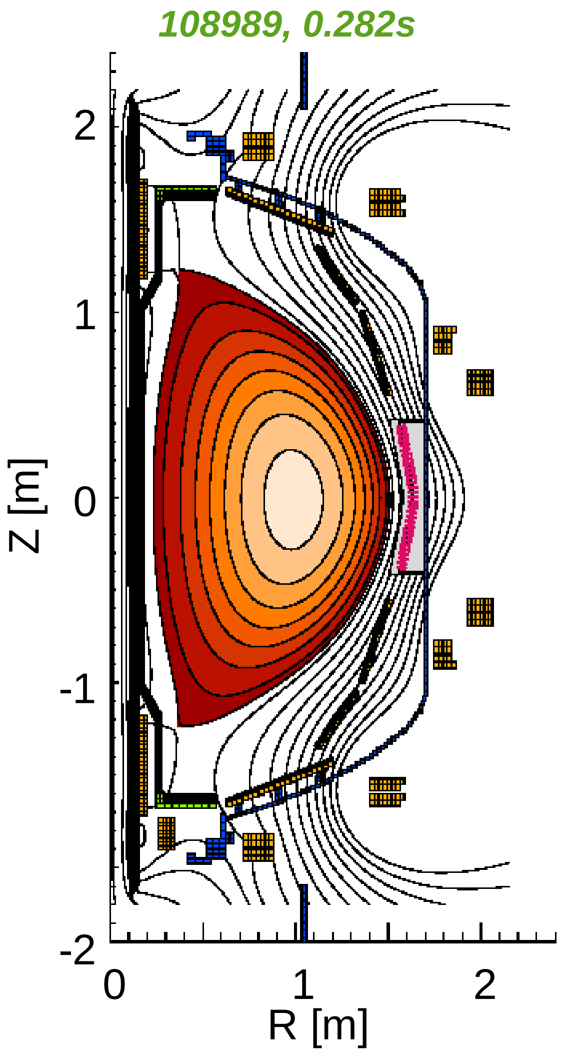
- Currently constructing a new center bundle for TF coil
  - Original damaged by a joint failure in February 2003

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

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

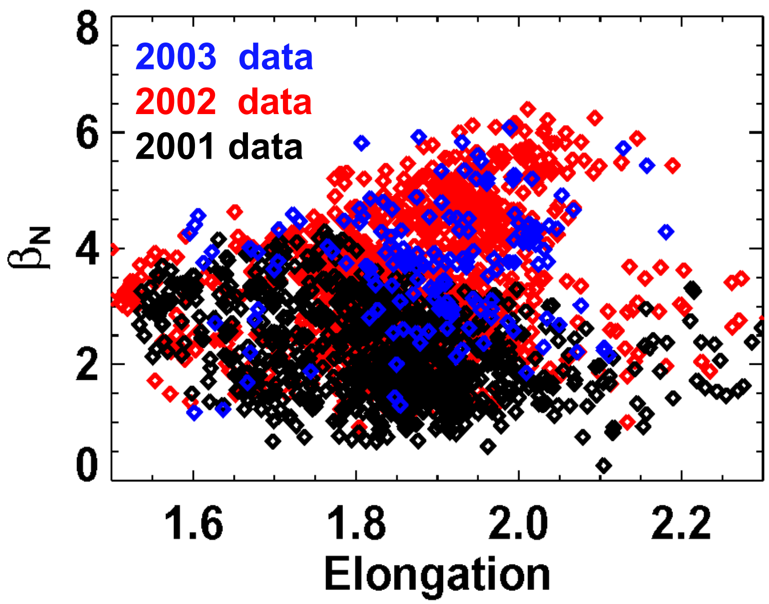
NSTX Has Achieved Good Progress in β_T

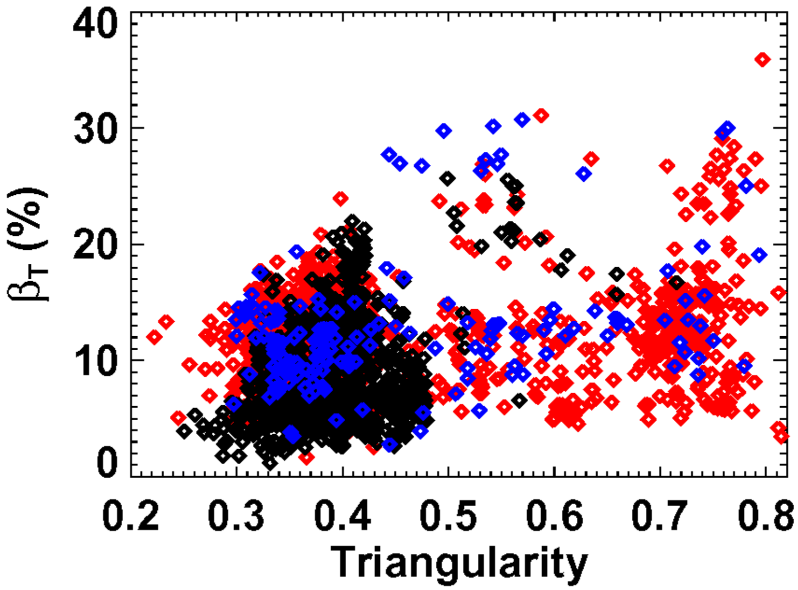




- β_T = 35% determined by magnetic analysis
- B_T = 0.3T, A = 1.4, κ = 2.0, δ = 0.8
- High confinement (H) mode (*c.f.* standard tokamaks) broadens pressure profile

Measured Dependence of Beta-Limit Motivates Shaping Enhancements



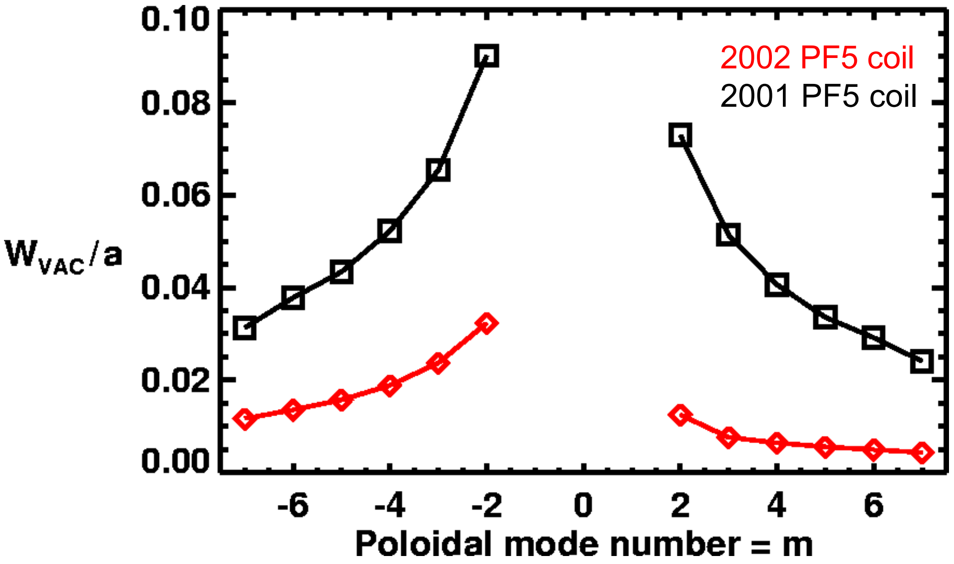


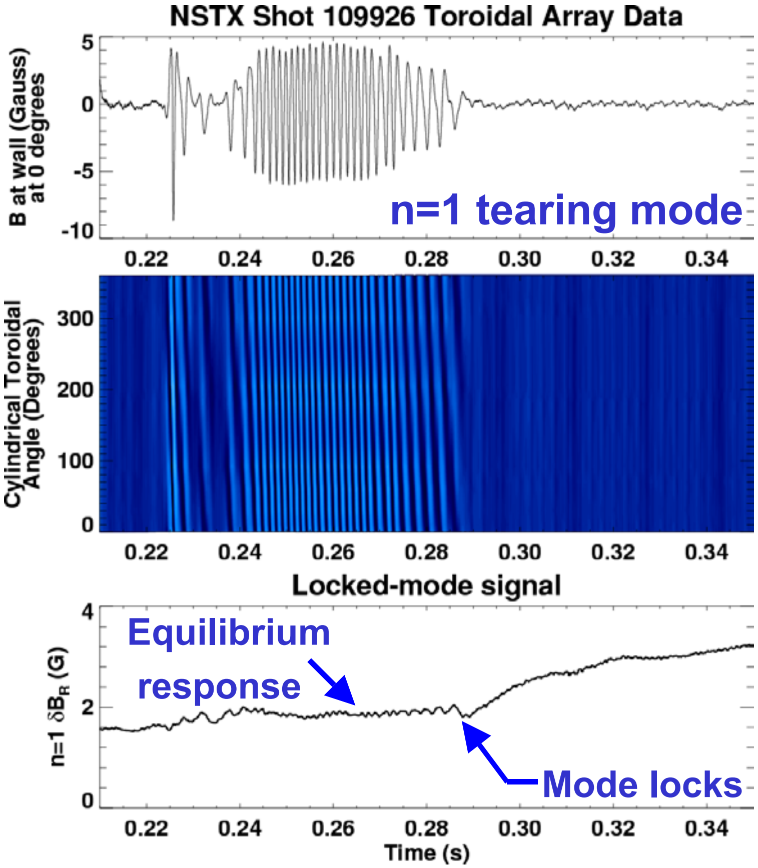
- Reducing error fields and routine H-modes improved performance in ‘02
- Improving feedback control of vertical position to increase elongation

- Capability for higher I_p at high δ contributes to strong dependence
- Planning to modify inboard PF coils to increase δ at higher κ

Reduction of Error Fields from PF Coils Reduced Occurrence of Locked Modes

- PF5 (vertical field) coils found to generate large n=1 field perturbation
- Re-shaped prior to '02 run
- Vacuum islands ***reduced to < 1cm***





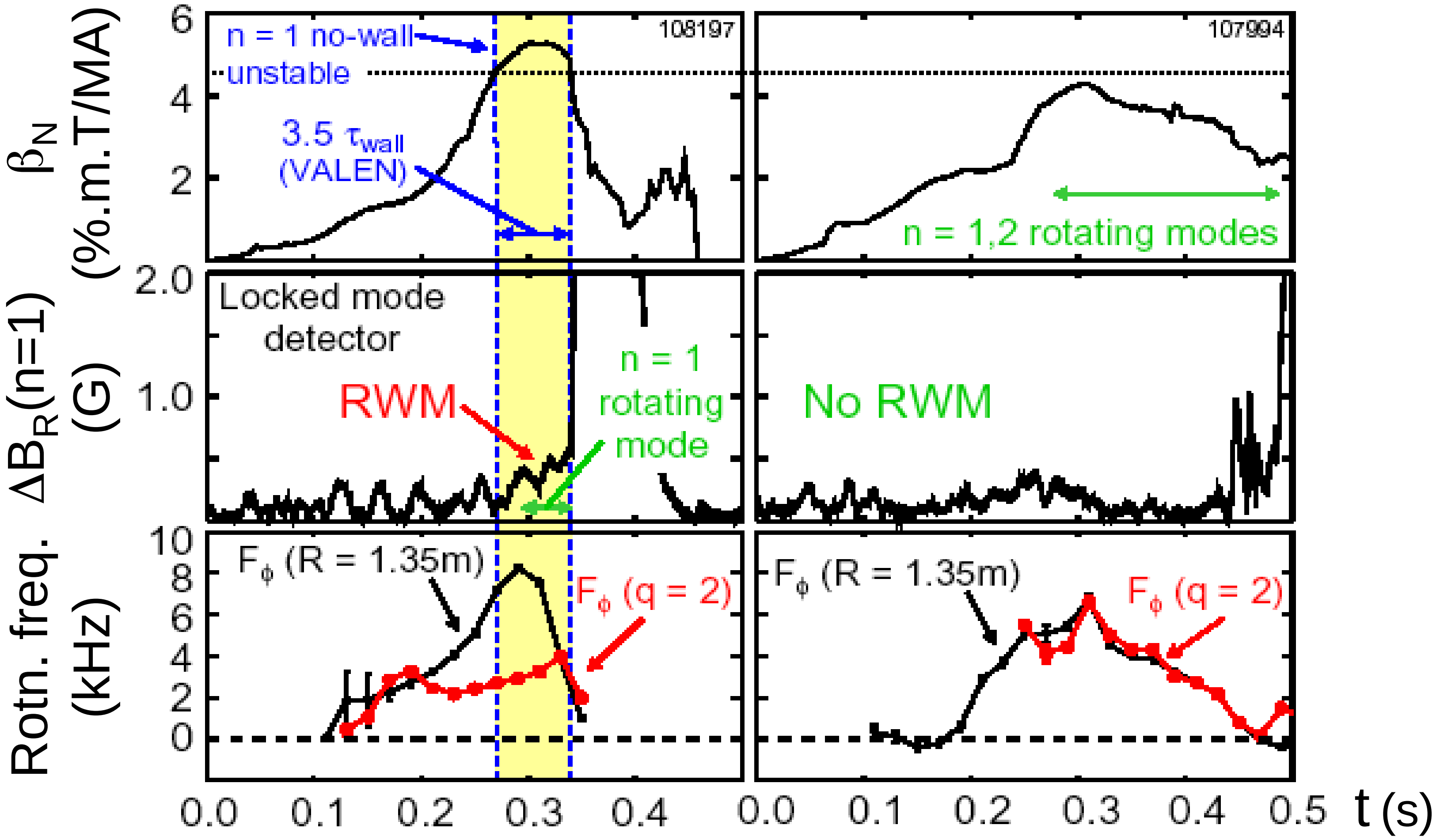
n=1 tearing mode

Equilibrium response

Mode locks

- With OH, mode locking now only occurs at low density
- With NBI, mode locking occurs more readily: torque opposes rotation

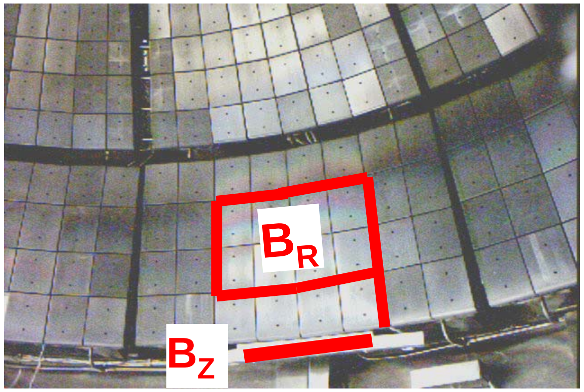
Observed Growth of Resistive Wall Modes When Normalized-β Exceeds No-Wall Limit



- Global rotation damping ~ 6 times larger when $\beta_N > \beta_N^{<\text{no-wall}>}$

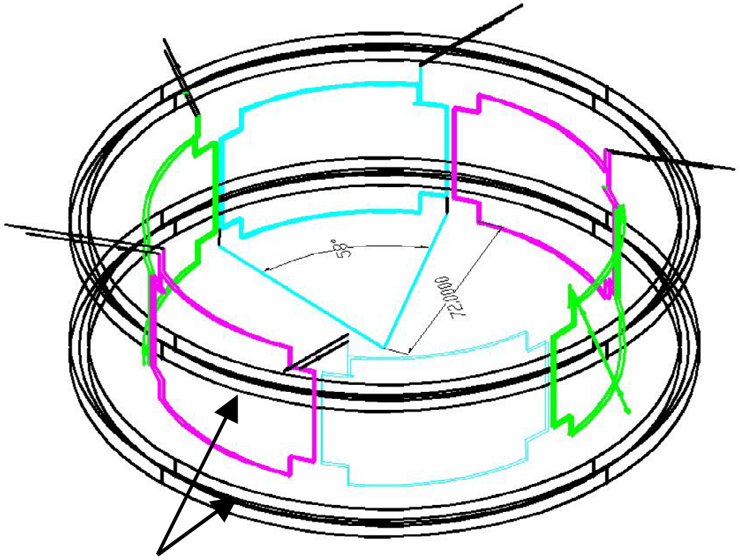
Developing Capability for Active Control of Resistive Wall Modes

- 24 each large-area internal B_R, B_Z coils installed before '03 run
  - Mounted on passive stabilizers
  - Symmetric about midplane



Internal RWM/EF sensors

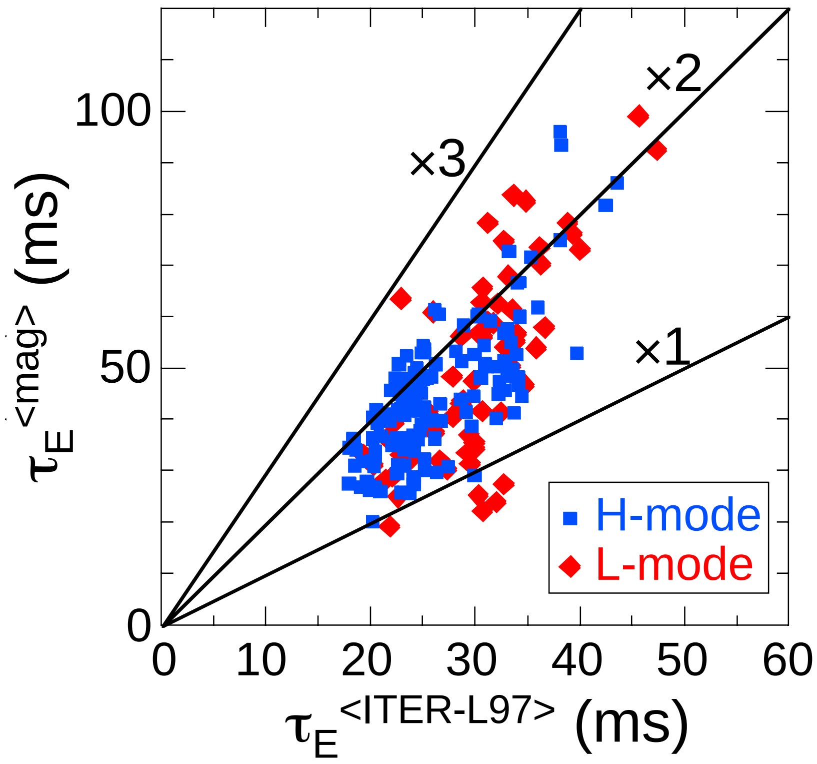
- 6 external correction coils in '04
  - Operate as 3 opposing pairs
  - Counteract error field amplification

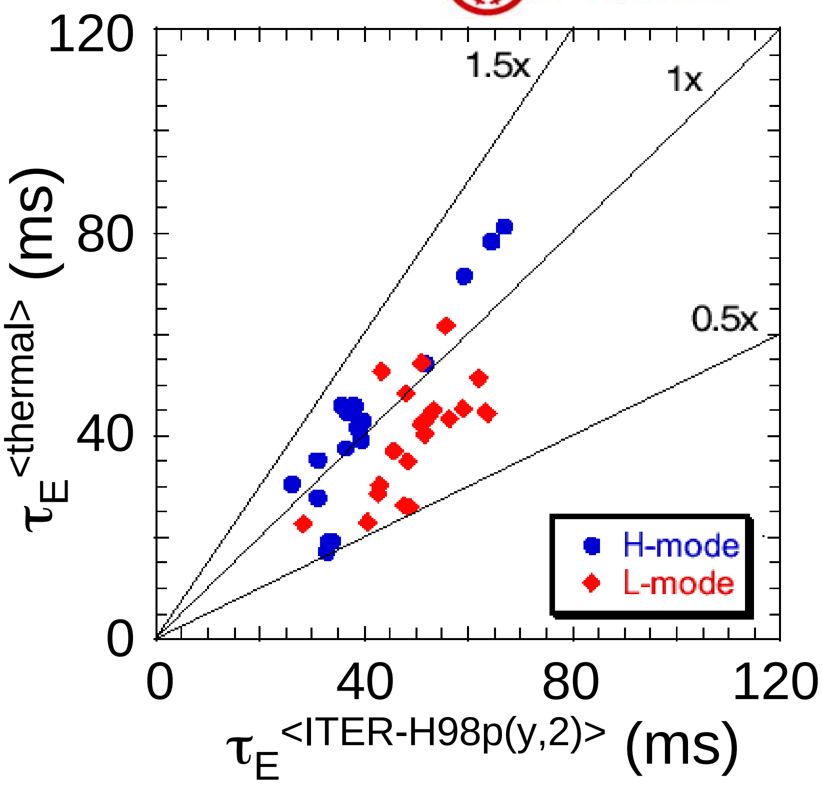


PF5 coils (main vertical field)

- Process sensor data in real-time through plasma control system for eventual feedback control

With NBI Heating, Global Confinement Exceeds Standard ITER Scalings

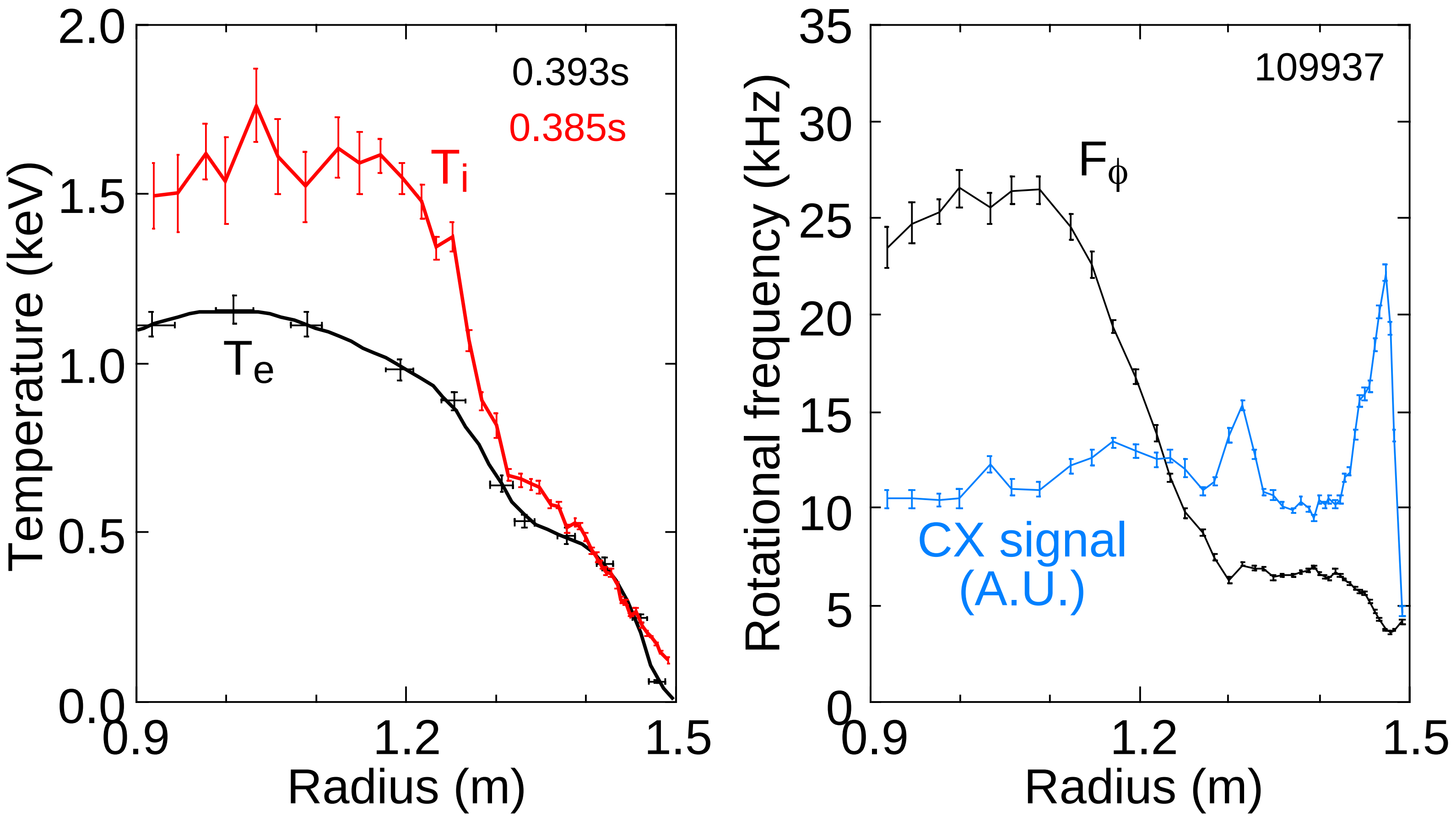




- Both L & H -mode plasmas exceed ITER-L97 scaling for total confinement (EFIT)

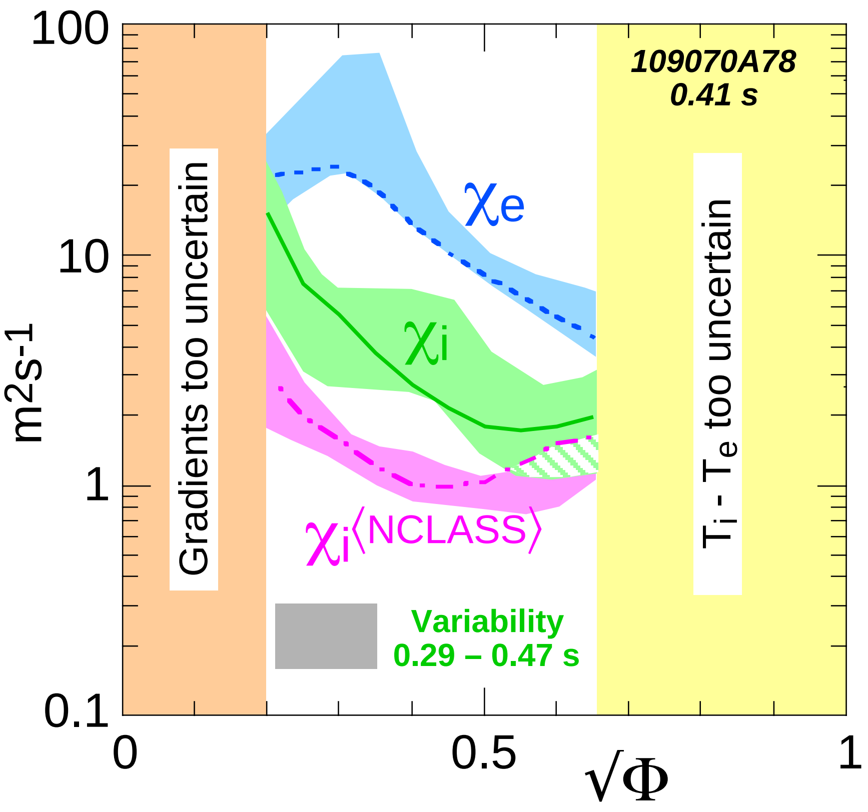
- Many plasmas also exceed ITER-H98p(y,2) scaling for thermal confinement (TRANSP)
  - L-modes are more transient

During NBI, $T_i > T_e$ in Center Although Most Heating Power Flows to Electrons



- “Flat spot” appears to be associated with 2/1 MHD island

Power Balance During NBI Heating Shows Ions Have Low Transport

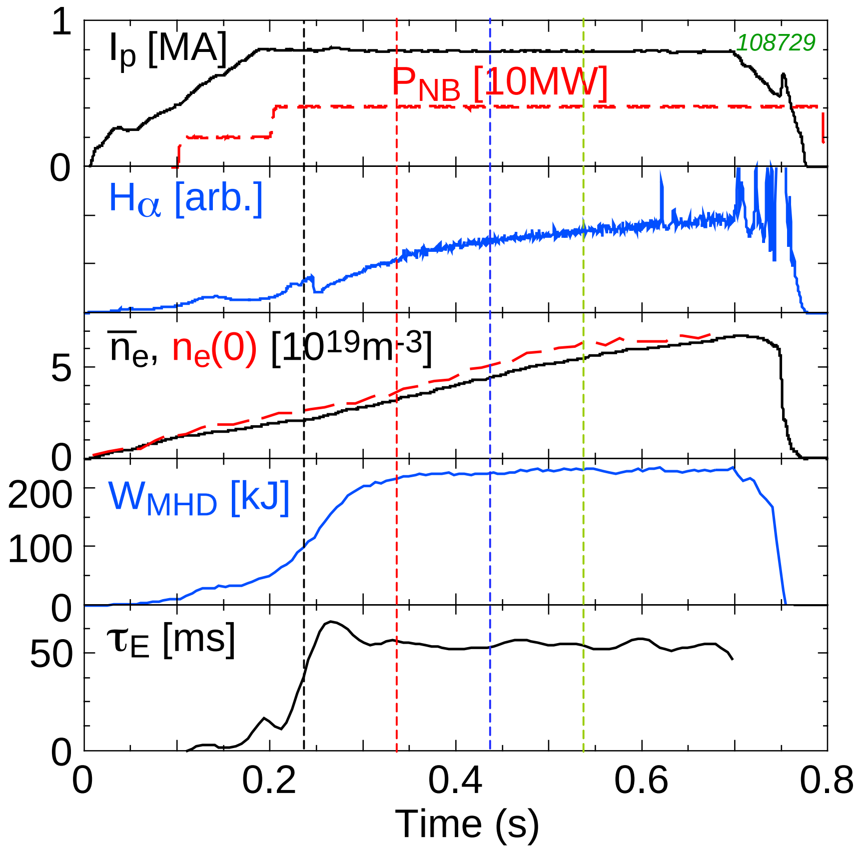


- Analyze power balance with TRANSP code
  - Use measured profiles of T_e, T_i, n_e, n_{imp}, P_{rad}
  - Monte-Carlo calculation of NBI deposition and thermalization
- $\chi_i^{<NC>} < \chi_i < \chi_e$

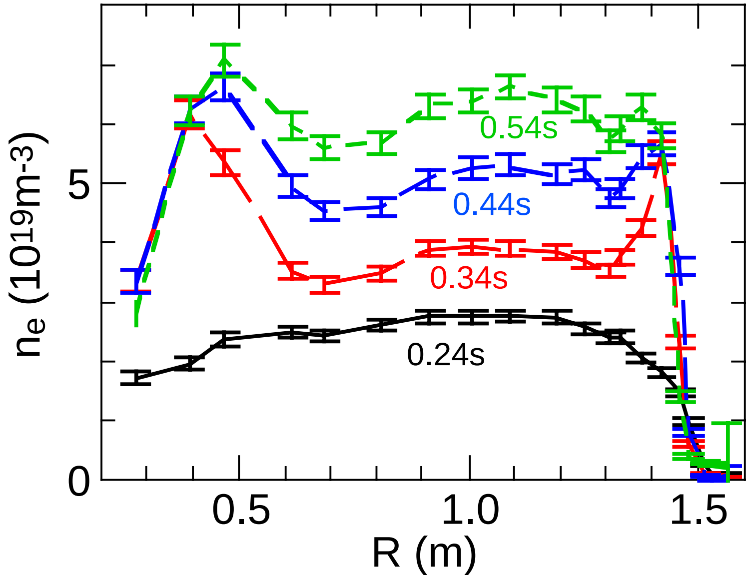
- Some shots show anomalously high T_i in region r/a ~ 0.6 – 0.8, yielding $\chi_i < \chi_i^{<NC>}$

High-Field-Side Gas Injection Improves Both Reproducibility and Duration of H-mode

- Consistent with effects of neoclassical viscosity
- Low-field-side fueling with similar rate delays H-mode transition



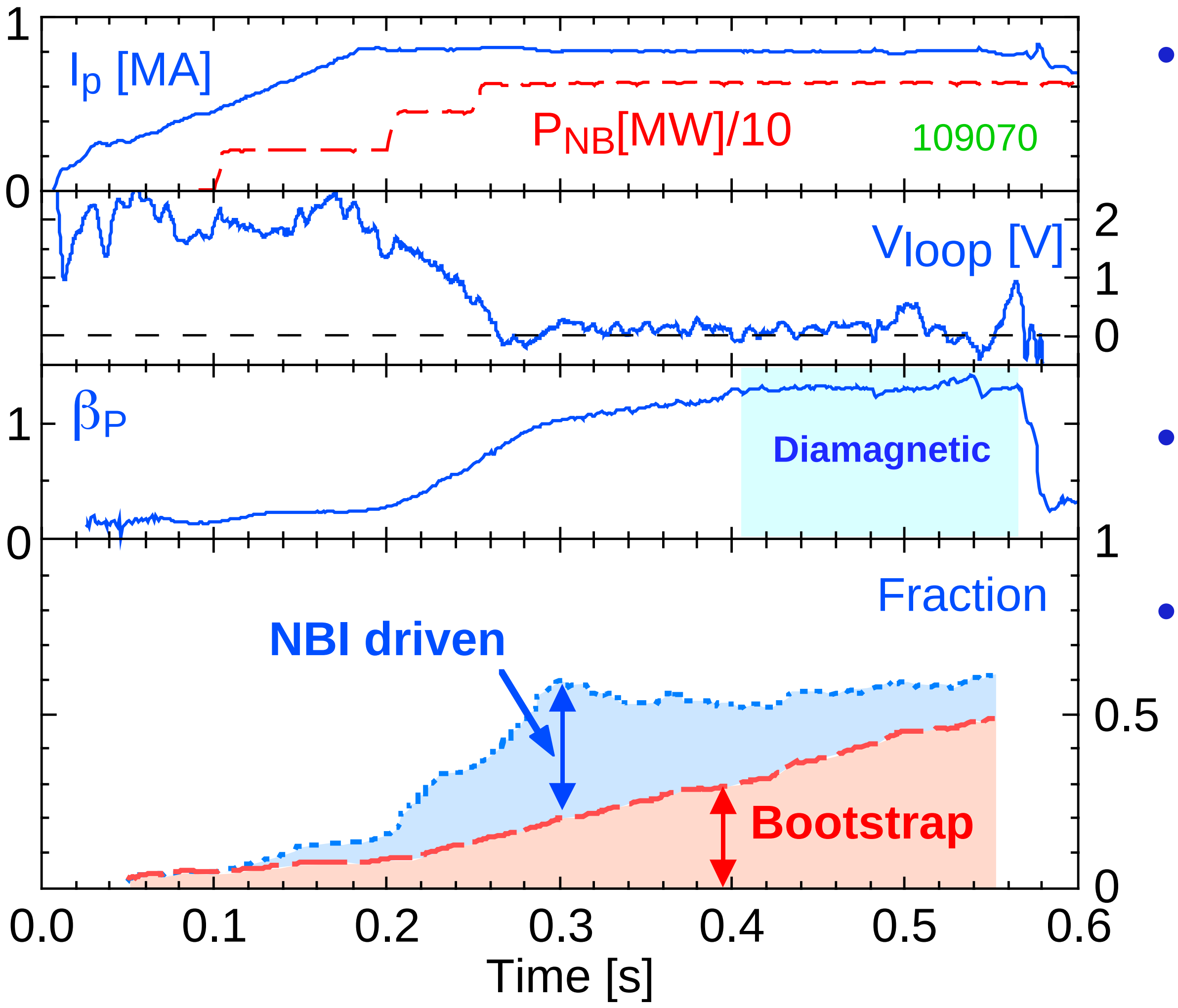
- Rapid density build up indicates effective edge transport barrier



Exploring Methods for Generating and Sustaining Toroidal Plasma Current

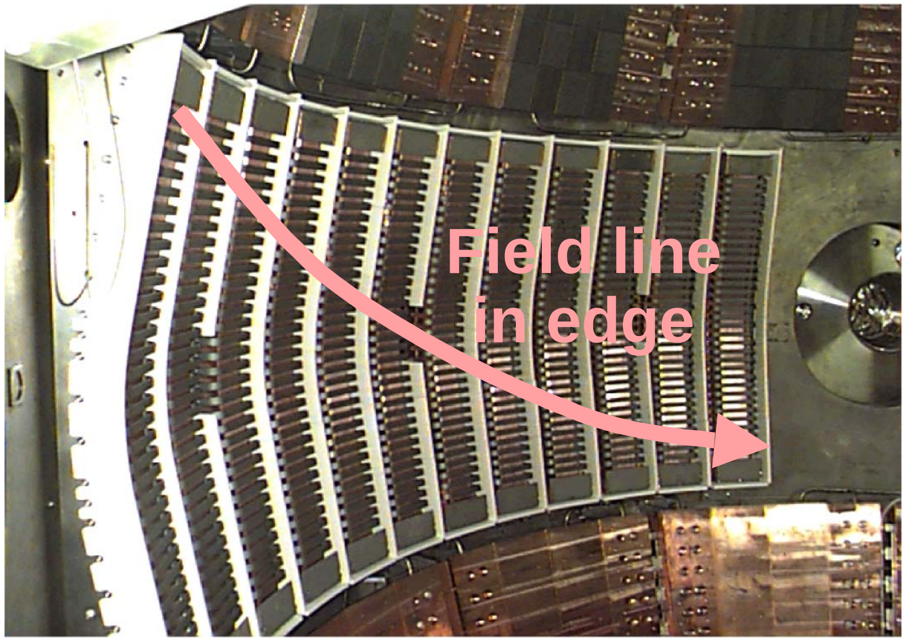
- STs need non-inductive current
  - space for transformer solenoid in center is very limited
- Exploit the neoclassical “bootstrap” current at high β
  - effect of toroidicity in a collisionless plasma
- Use RF waves which interact with the electrons
  - Fast waves at high harmonics of ion cyclotron frequency (**HHFW**)
  - Electron Bernstein Waves (**EBW**) at low harmonics of electron cyclotron frequency
- Coaxial Helicity Injection (**CHI**) can initiate toroidal current
  - Create linked toroidal and poloidal magnetic flux (helicity) by injecting poloidal current which relaxes to form closed magnetic surfaces

Neoclassical Bootstrap Effect Drives Substantial Fraction of Plasma Current



- Achieved substantial fraction of NBI-driven and bootstrap current for ~ skin time in diamagnetic plasma
- $V_{loop} \approx 0.1$V for ~0.3s
- Control of profiles of pressure & current needed to maximize stability & bootstrap current together

High-Harmonic Fast-Waves Can Provide Both Heating & Current Drive

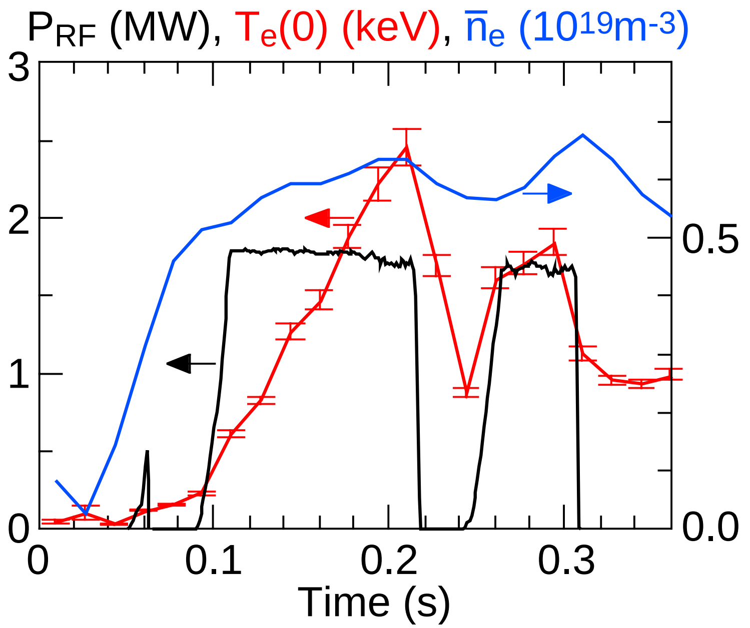


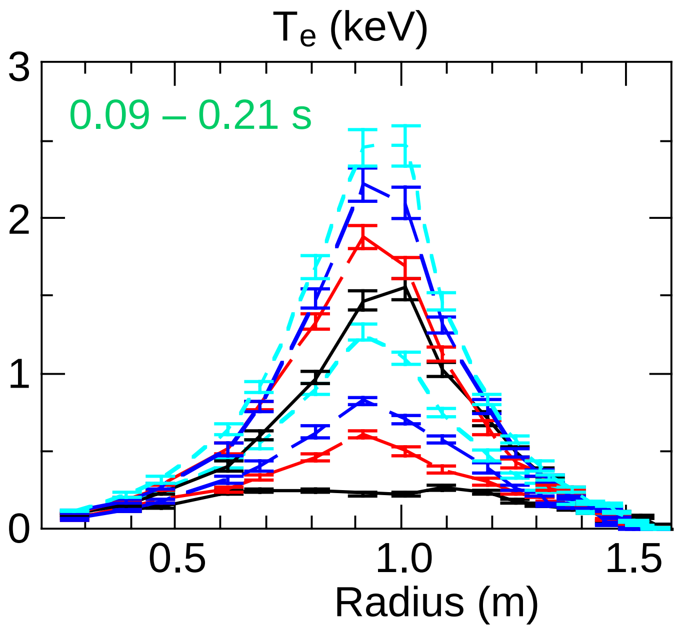
- 6 MW at f = 30 MHz
  - Pulse length up to 5 s
- 12 Element antenna
  - Active phase control between elements
  - $k_T = \pm (3\text{-}14)\ \mathrm{m}^{-1}$

- $\omega/\Omega_D = 9 - 13$
- Expect little direct wave absorption on thermal ions
- Wave velocity matched to thermal velocity of electrons

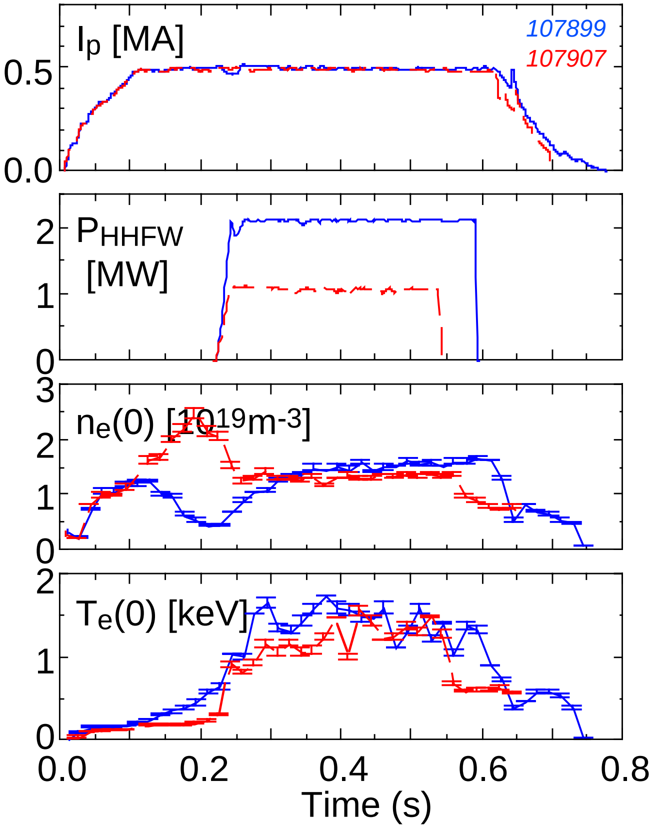
HHFW Effectively Heats Electrons

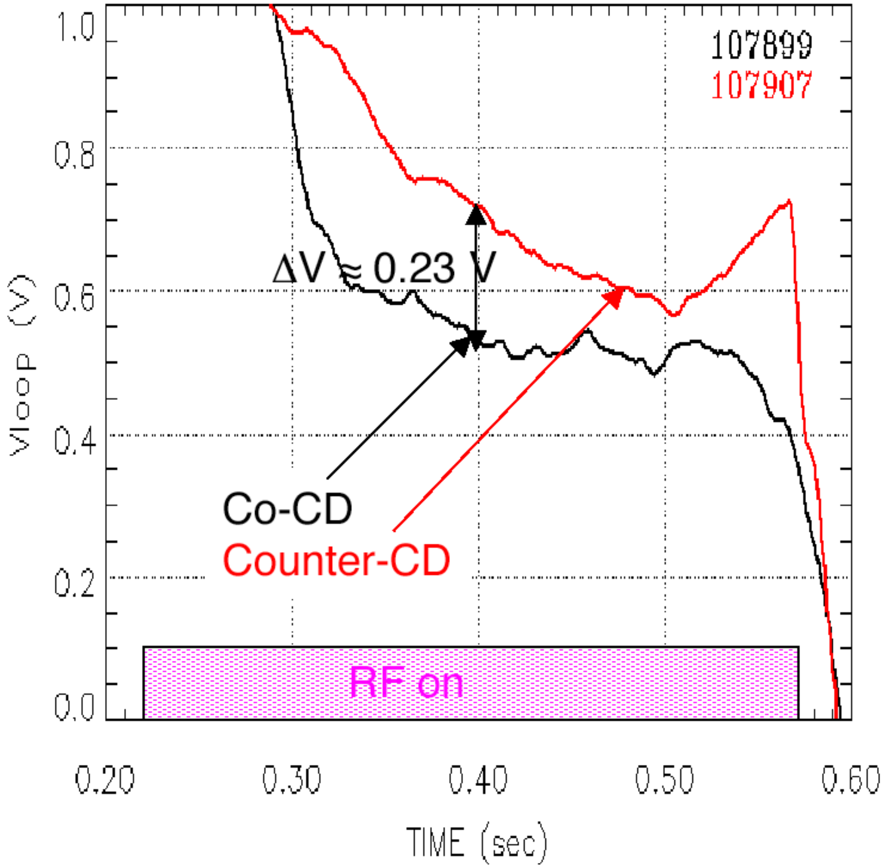
- Coupled power to 6MW, energy 1.6MJ
- Good electron heating observed at low density with early HHFW
  - Antenna operated in phasing for slowest waves: $k_T \approx 14 m^{-1}$
  - Improved density control by helium pre-conditioning shots





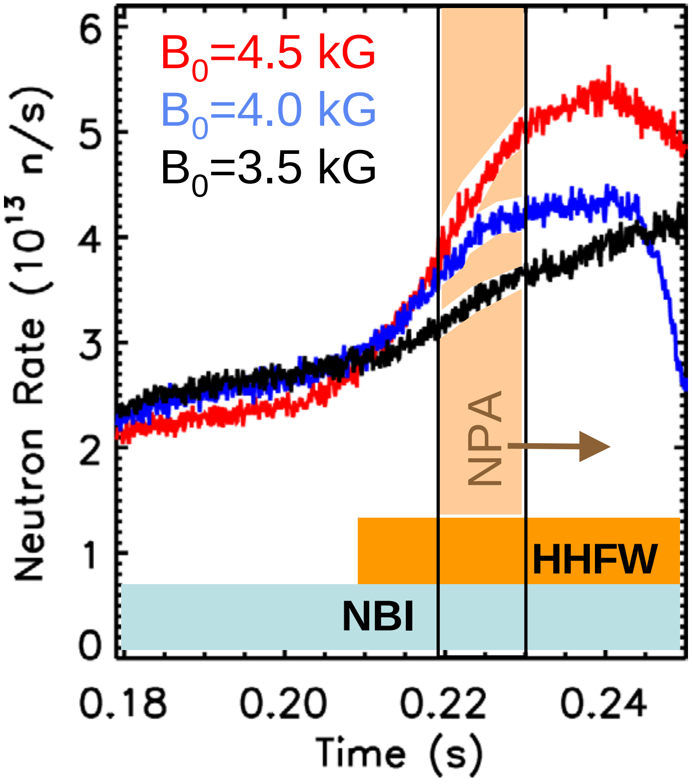
Evidence for Current Drive by HHFW in Plasmas with Co and Counter CD Phasing

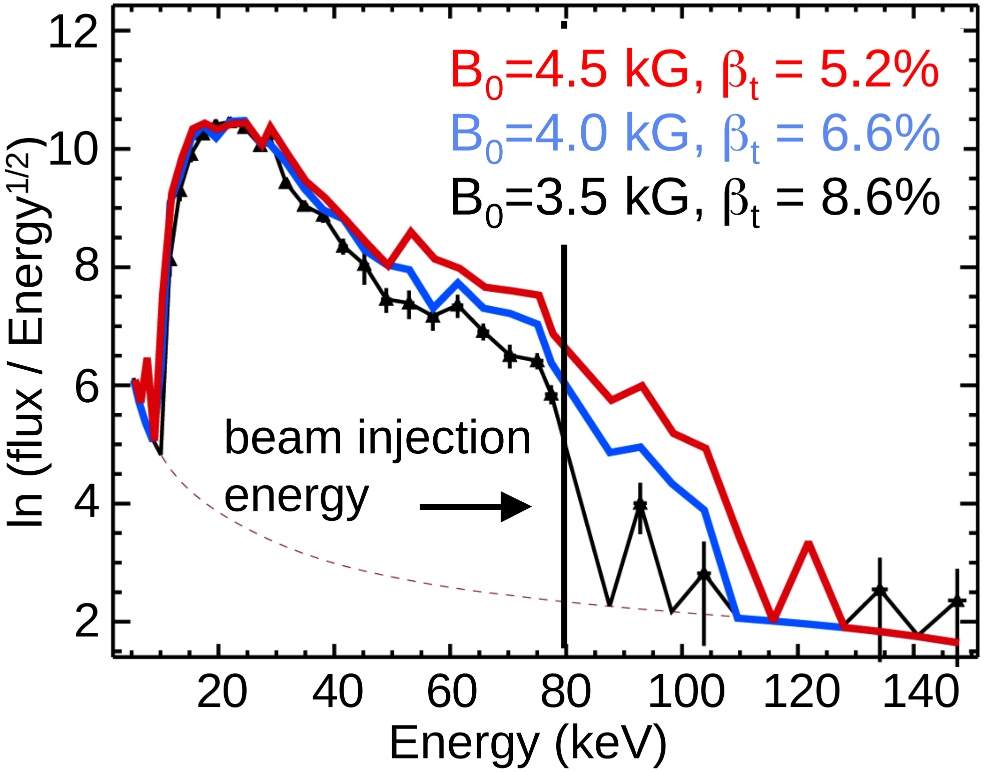




- 150 kA driven current from simple circuit analysis
- Modeling codes calculate 90 – 230 kA driven by waves

Neutral Particle Analyzer Shows Interaction of HHFW with Energetic Ions Produced by NBI

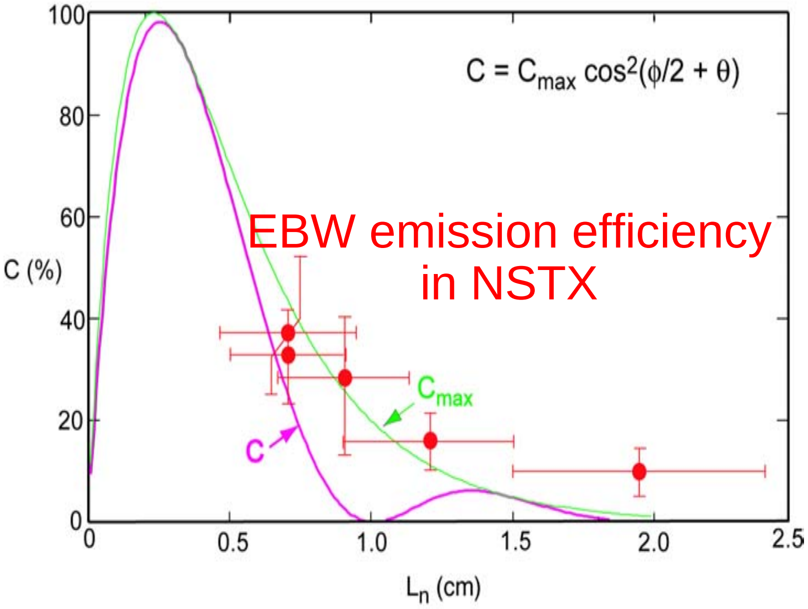




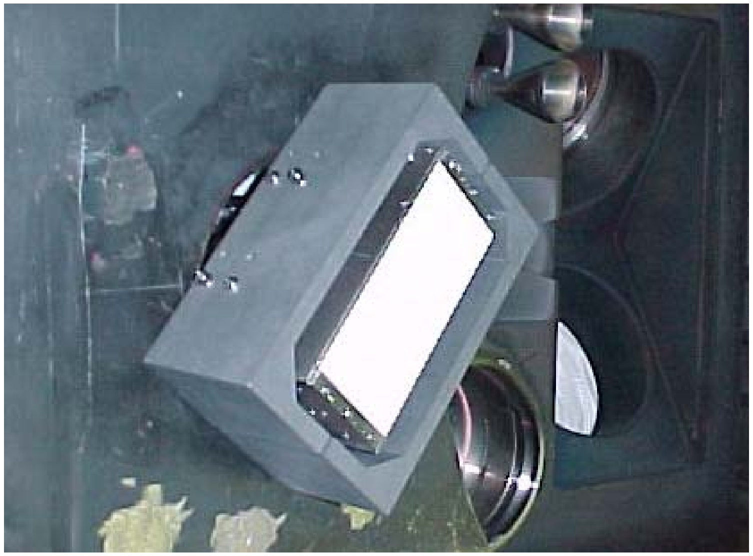
- Ion “tail” above NB injection energy enhances DD neutron rate
- Tail reduced at lower B:
  - Higher β promotes greater off-axis electron absorption reducing power available to central fast-ion population

Detecting Emission of Thermal EBW to Measure Efficiency of Wave Coupling to Antenna

- Black-body EBW is mode-converted to propagating EM wave at Upper-Hybrid resonance layer in plasma edge
- Requires small density scale-length L_n for efficient conversion
  - – Antenna includes movable limiters to steepen edge locally

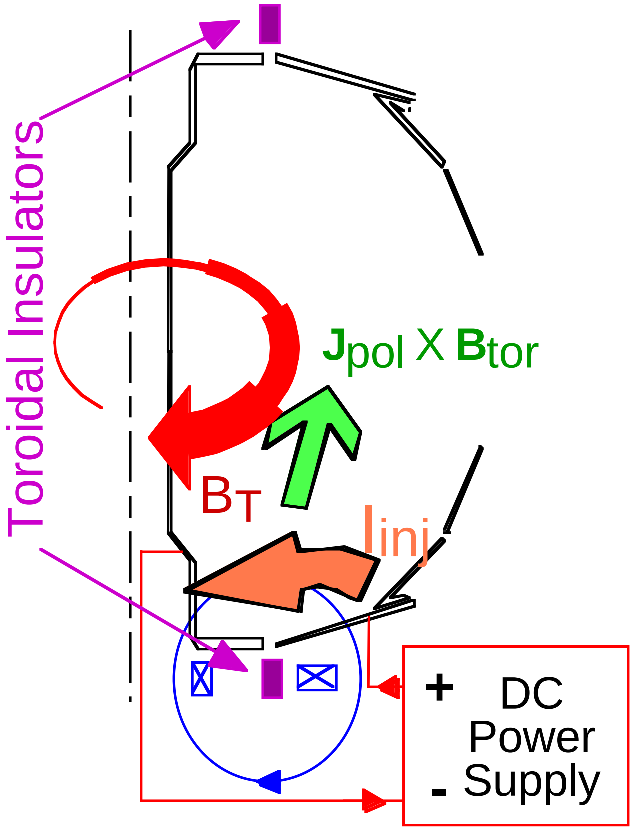


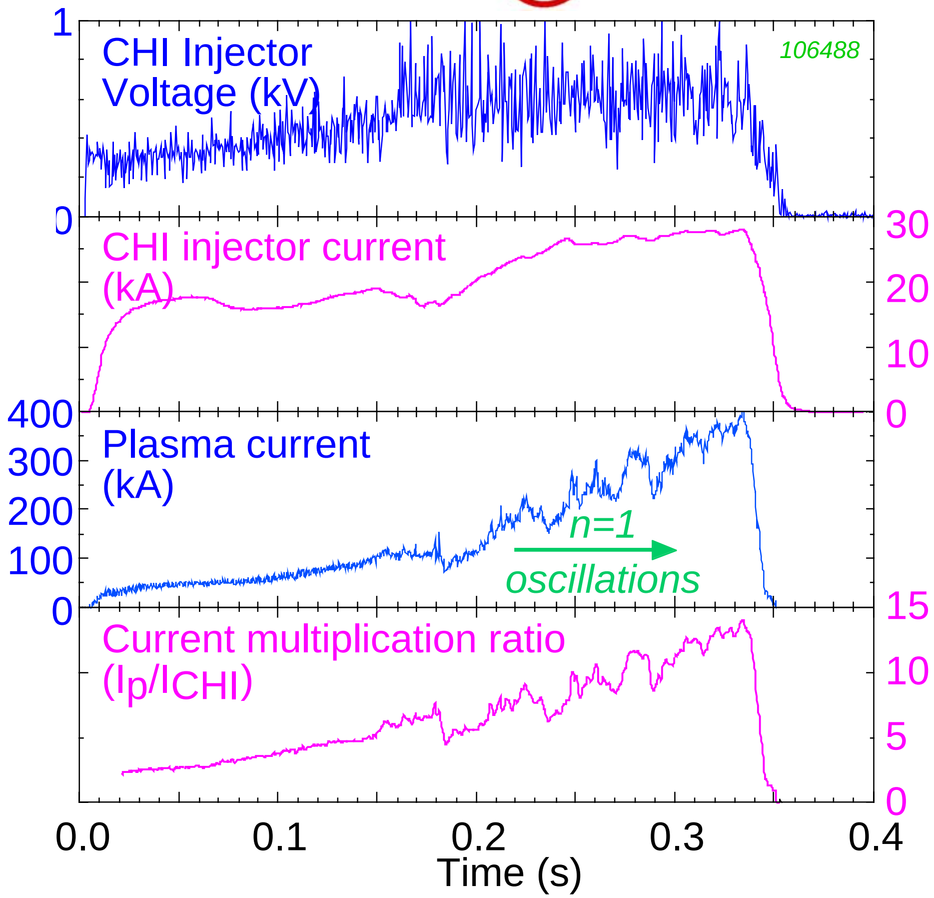
EBW emission efficiency in NSTX



- Planning 3MW EBW system for localized current drive
  - – ~15GHz for f_{ce} and Doppler-shifted $2f_{ce}$ absorption

CHI Has Generated Significant Toroidal Current Without Transformer Induction





- Goal to produce reconnection of current onto closed flux surfaces
  - *Demonstrated on HIT-II experiment at U. of Washington, Seattle*

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