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Overview of NSTX Research and Plans

M.G. Bell

Princeton Plasma Physics Laboratory

for the

NSTX Research Team

9th ST Workshop, September 15–17, 2003
Culham Science Centre, Abingdon, UK

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Hiroshima U
HIST
Kyushu Tokai U
Niigata U
Tsukuba U
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KBSI
KAIST
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
U Quebec

Topics

- Review of operation in 2002 - 3
- Results from experiments in 2003
- Continuing analysis of data from 2002
- Upgrades for the 2004 experiments
- Major elements of the future research plan
  - Guided by the Five-Year Plan developed over the past year and reviewed in June 2003

Calendar and Highlights of Operation

2002

- Start '02 operation
- End '02 operation
- ST workshop 02

I_p = 1.5MA, B_T = 0.6T, P_{NBI} = 7MW,
β_T = 35%, β_N = 6.2%mT/MA, RWM, HHFW-CD

New absorber insulator & nulling coils,
RF antenna mods, Add'l gas injectors,
RWM det'n coils, 51-ch CHERS, Edge rot'n

2003

- Start '03 operation
- TF coil failure
- Review of Five-Year Plan

P_{HHFW} = 5MW, CHI recommissioning,
implement rt-EFIT plasma control

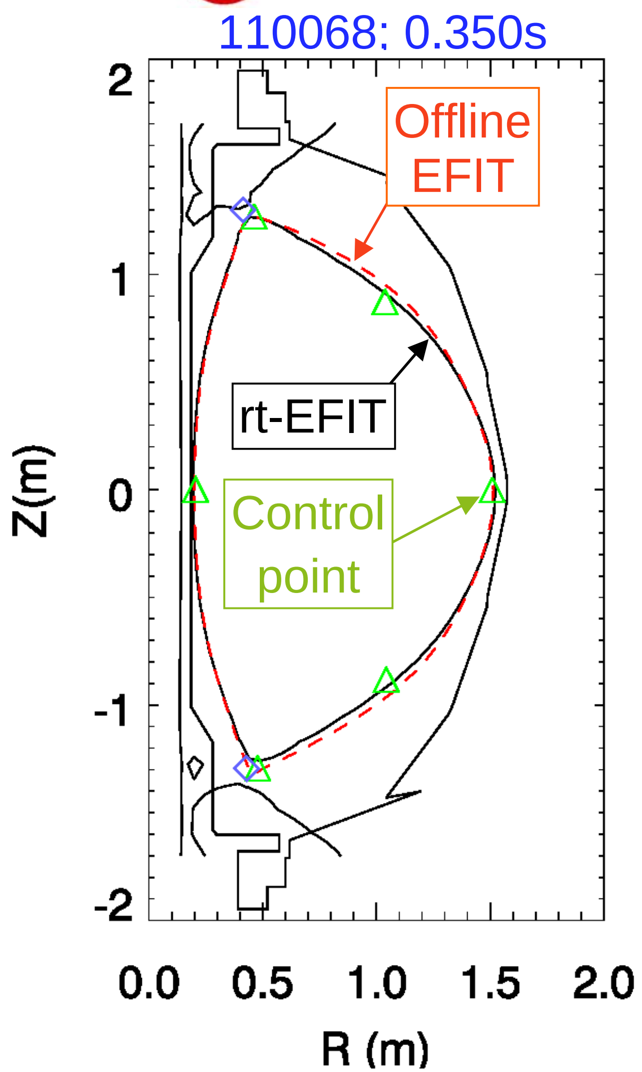
TF coil repair, NB bellows repair,
Solid pellet injector, RWM control,
Diagnostic upgrades incl. MSE

2004

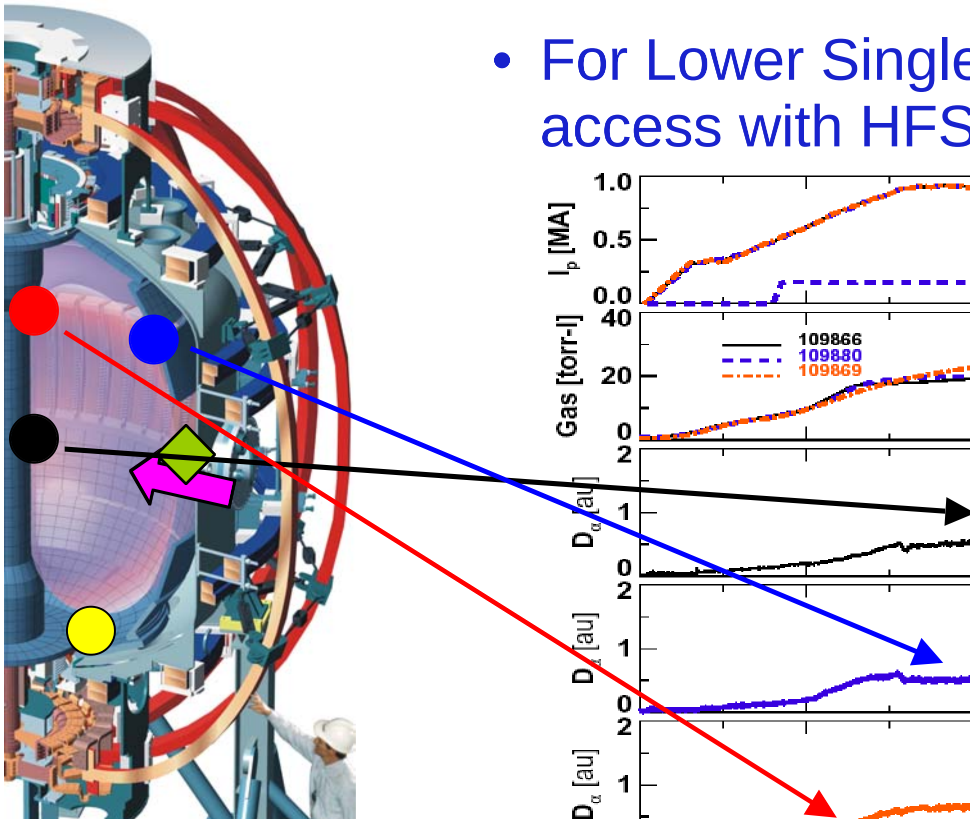
- Start '04 operation

Developed Feedback Control of Plasma Equilibrium Based on rt-EFIT Analysis

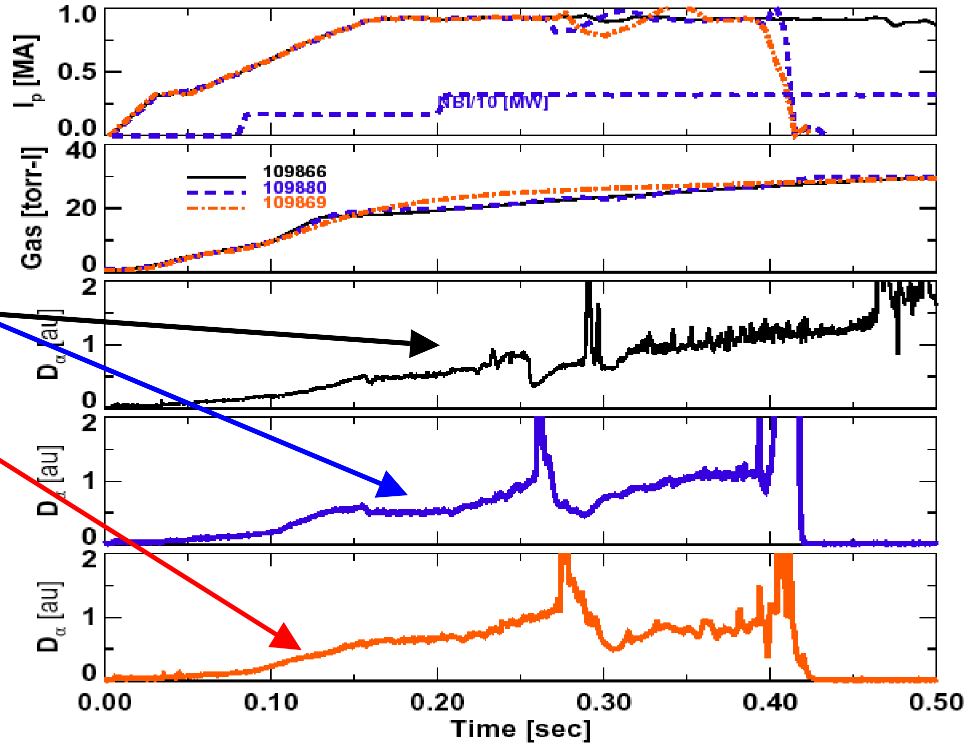
- Real-time analysis on 8 G4 processors
  - Data acquisition at 5kHz
    - 75 magnetic data points,
    - 11 coil currents,
    - 8 loop voltages (⇒ vessel eddy currents)
  - Reconstruction every 12ms
  - Currents calculated on grid every 0.4ms
- Controlled boundary at 6 points using all PF coil currents for I_p flattop (~300ms)



Started Investigating Dependence of H-mode on Poloidal Location of Fueling



- For Lower Single Null divertor, easiest access with HFS midplane injector



- Gas injectors (03)
- Supersonic gas (04)
- Solid pellets (04)

- For Double Null divertor, HFS midplane and upper injectors give similar response

Solid Pellets and Supersonic Gas Injection Will Augment Fueling Capabilities

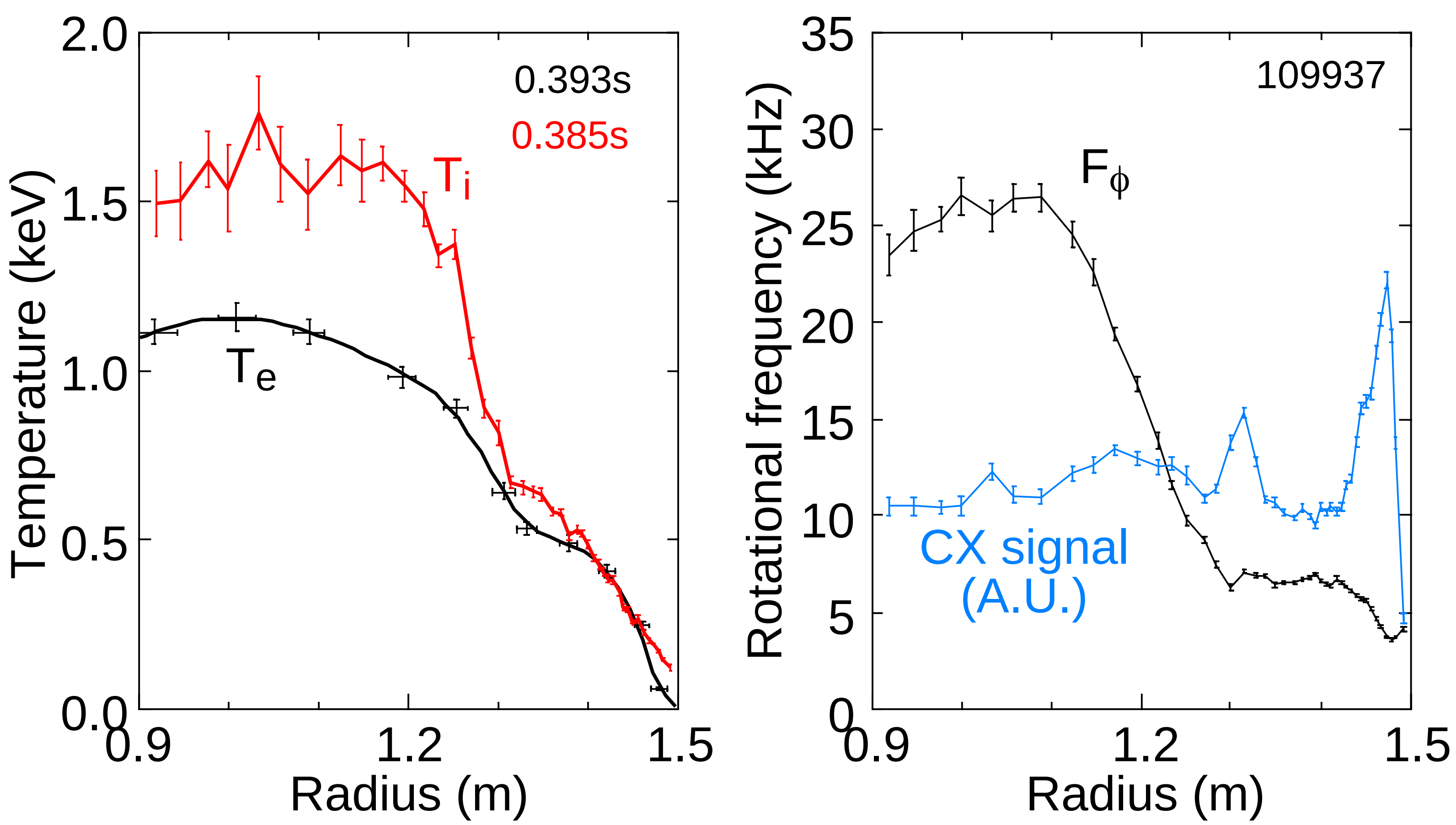
NSTX

- Lithium, boron, carbon as pellets or micro-pellet ensembles
  - Pellets accelerated by gas in vespel sabot: 20 – >100 m/s
    - Pellets up to 2mmØ × 6mm (~10mg for lithium, ~10^{21} Li)
    - Minimal accompanying gas: < 4 Torr.l in 2s (<5% addition)
  - Inject up to 8 pellets/shot from 400 barrel turret
  - Now in final testing before installation
- Supersonic gas injector being developed with CDX-U for installation in '04
  - Laval nozzle made of graphite for close proximity to plasma
  - Inject gas at ~1.8km/s (Mach 8 at final gas temperature)
  - Up to 6 × 10^{21} D in 300ms

Recent Diagnostic Upgrades

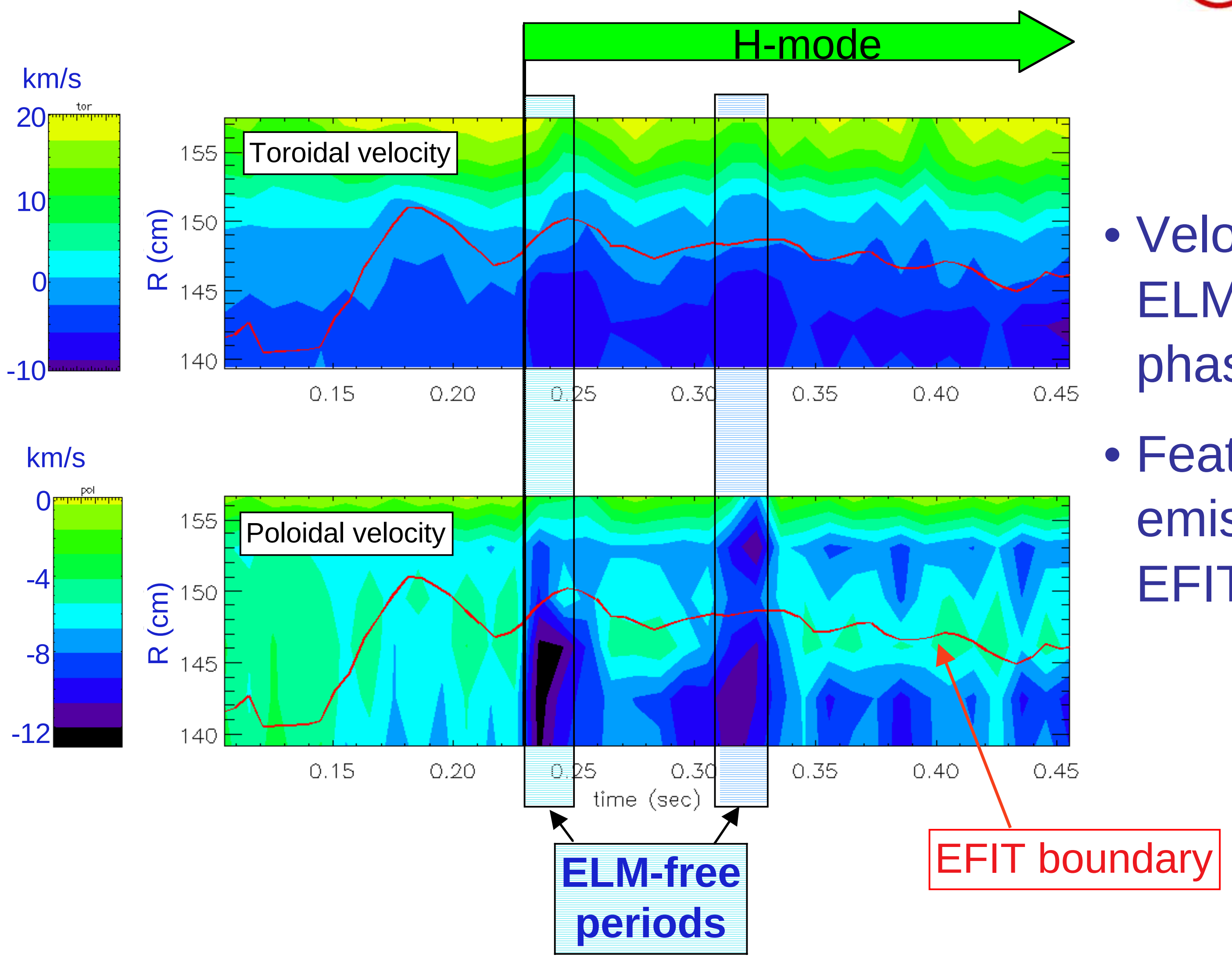
- 51-channel **CHERS** system for T_i, v_{tor}, (n_C)
- **Edge Rotation Diagnostic** for instrinsic CIII, CIV, HeII emission
  - – 7 toroidal, 6 poloidal sightlines, 1.4 – 1.58 m at outboard midplane
- Collection optics for **10-channel MSE** installed
  - – Analyzers now being assembled for installation during next run
- $\mathbf{B_r}$ and $\mathbf{B_p}$ **measurements** for Resistive Wall Mode identification
- **Edge deposition monitor** with mass sensitive quartz crystal
- Scintillator **analyzer for fast ions on lost orbits** (pitch, energy)
- **EBW emission antenna** with local limiter for edge gradient control
- **Edge Turbulence Imaging** optical throughput increased ×10, 300 frame camera (‘04)

High Resolution CHERS Diagnostic Shows Additional Structures in Ion Profiles



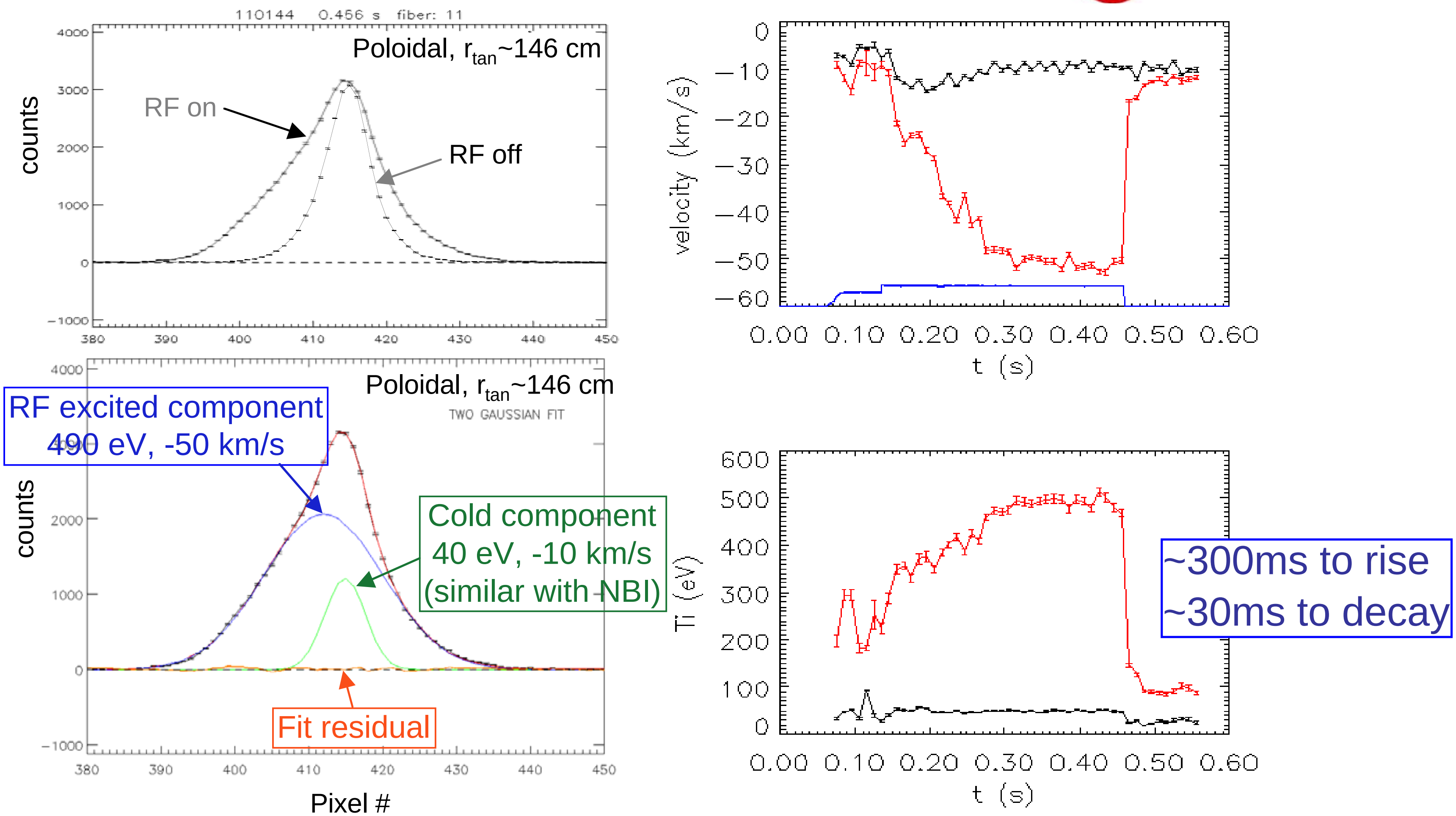
- “Flat spot” appears to be associated with 2/1 MHD island

Features of Flow in H-mode Edge Revealed in C III Emission



- Velocities change in ELM-free H-mode phases
- Features in CIII emission track EFIT boundary

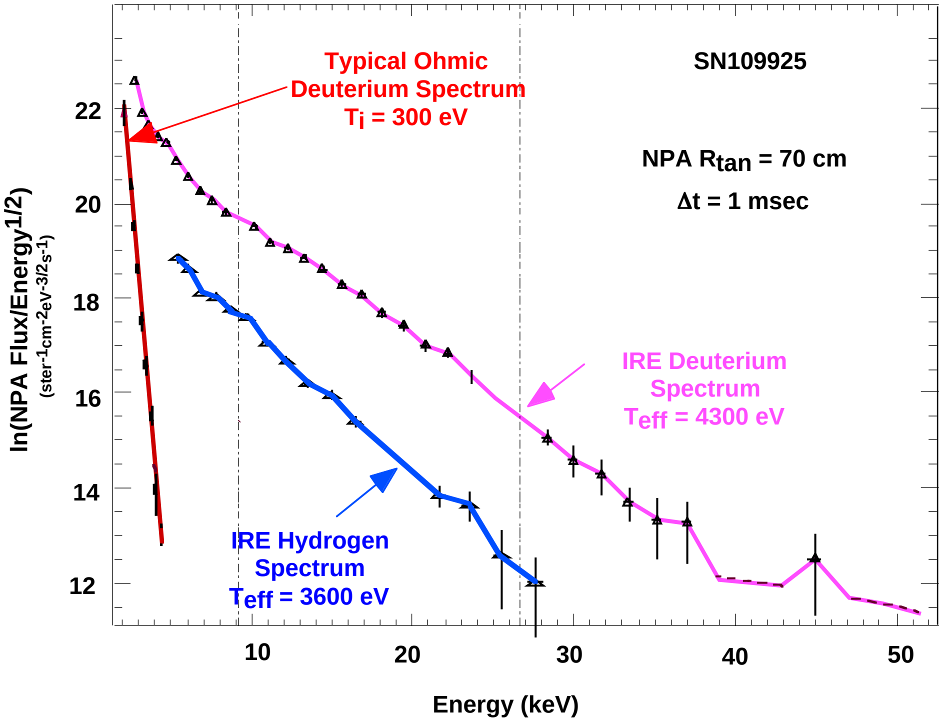
He II (Majority) Ions Develop Hot Component During HHFW Heating



• Possible indication of parametric decay of RF waves
  - launched waves do not interact directly with ions

Neutral Particle Analyzer Reveals Ion Heating Following Reconnection Events

- Maxwellian tails for both D (majority) and H (minority)

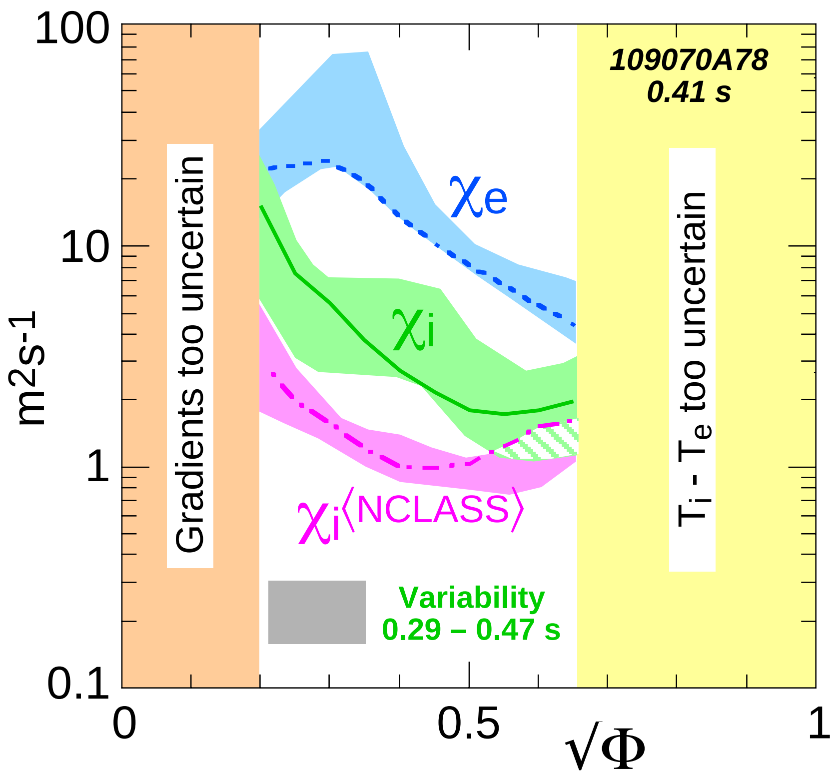


- Decay of tail consistent with classical slowing
- H/D ~ 2 - 5 %
- Heating also seen in NB heated plasmas
  - Complicated by possible spatial redistribution of energetic ions

- Similar to MAST observations and consistent with theory of Helander *et al.* [Phys. Rev. Lett. **89**, (2002)]

Anomalies in Power Balance Reduced By Renanalysis of CHERS: $\chi_i^{<NC>} < \chi_i < \chi_e$

- Intrinsic emission from edge complicates T_i measurement
- Inclusion of atomic fine structure effects reduced T_i by ~5%



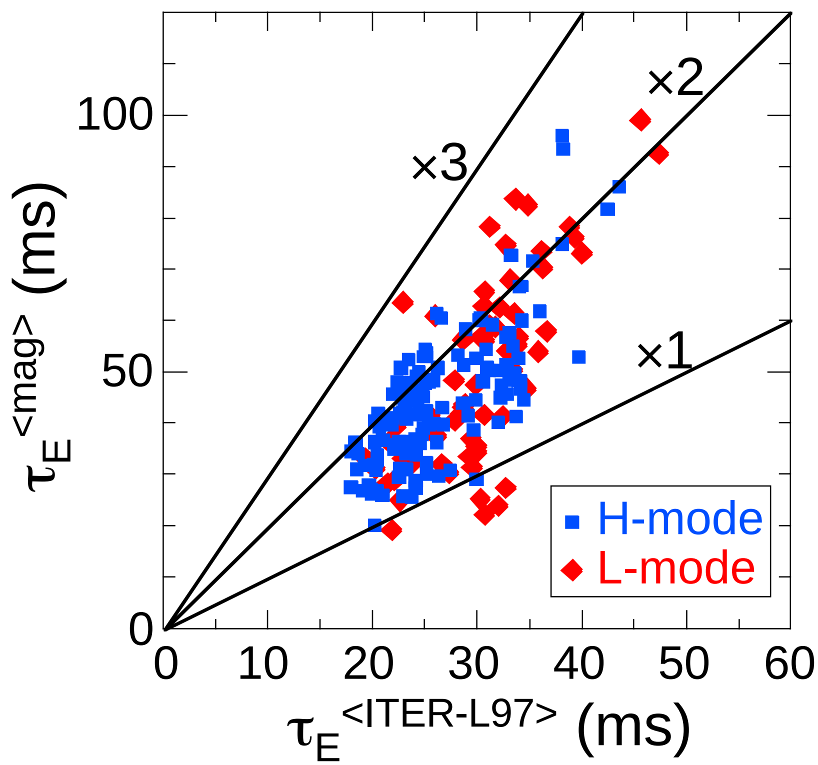
- Most previous anomalies in TRANSP power balance resolved

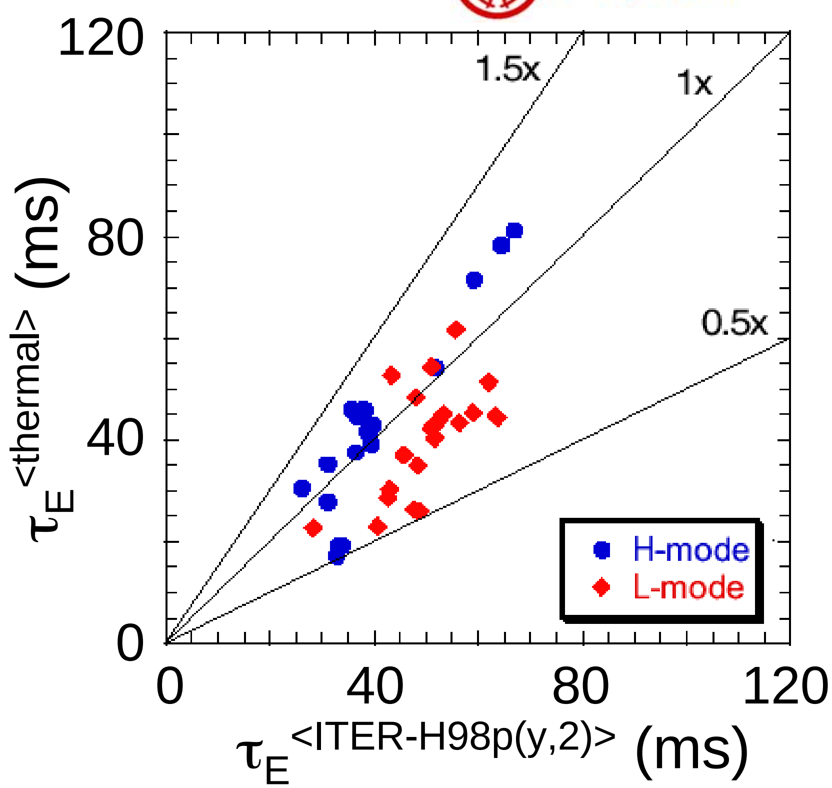
but

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

- Investigating effects of large trapped particle population
  - Can lead to anisotropy in apparent ion temperature

With NBI Heating, Global Confinement Continues to Exceed Standard ITER Scalings



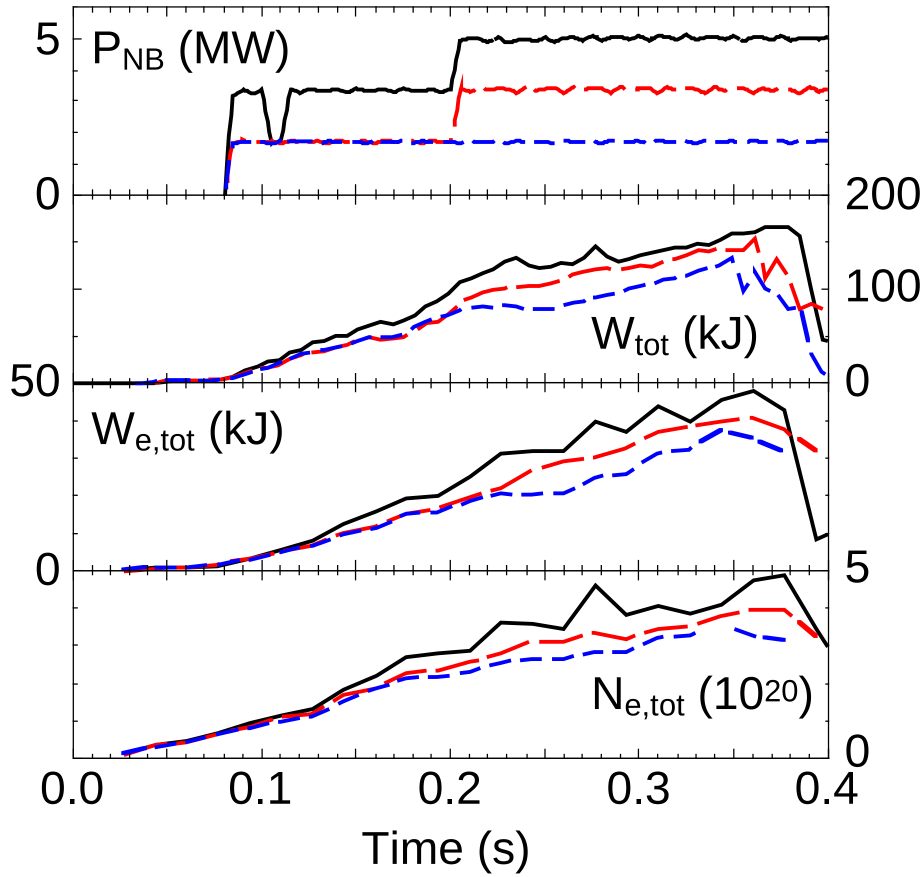


- Both L & H -mode plasmas generally exceed ITER-L97 scaling for total confinement (EFIT)

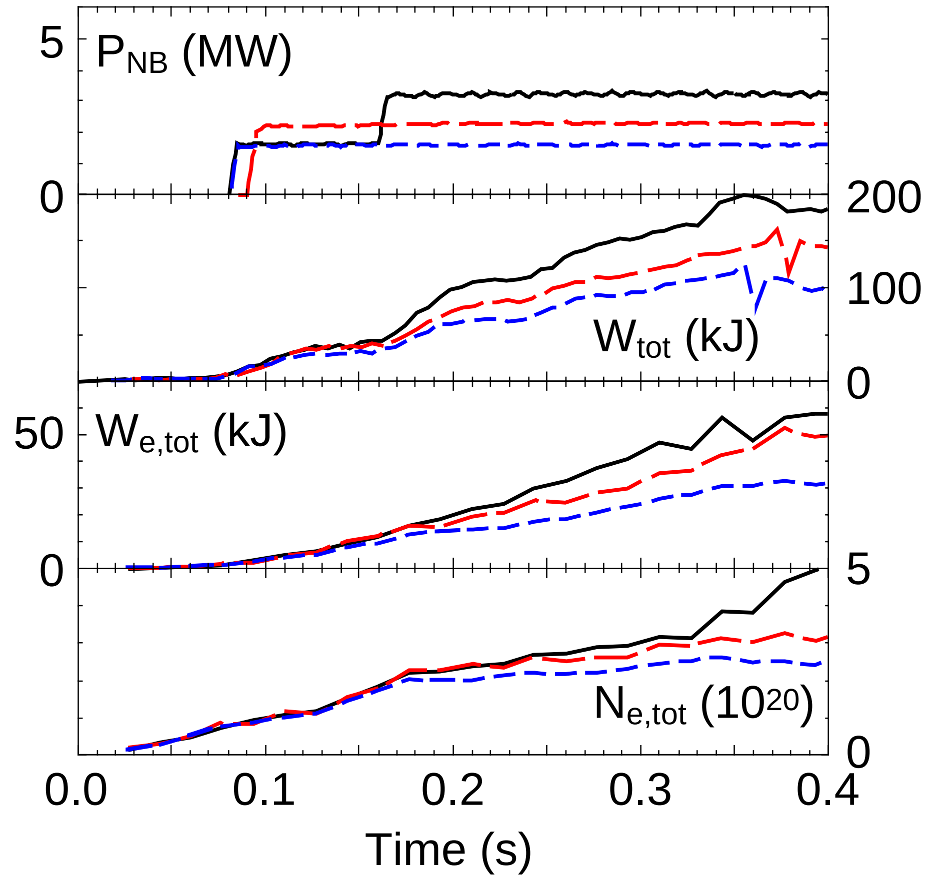
- Many plasmas also exceed ITER-H98p(y,2) scaling for thermal confinement (TRANSP)
  - L-modes are more transient

Power Scans Reveal Complex Dependence of Confinement on Toroidal Field

B_T = 0.45T: τ_E degrades

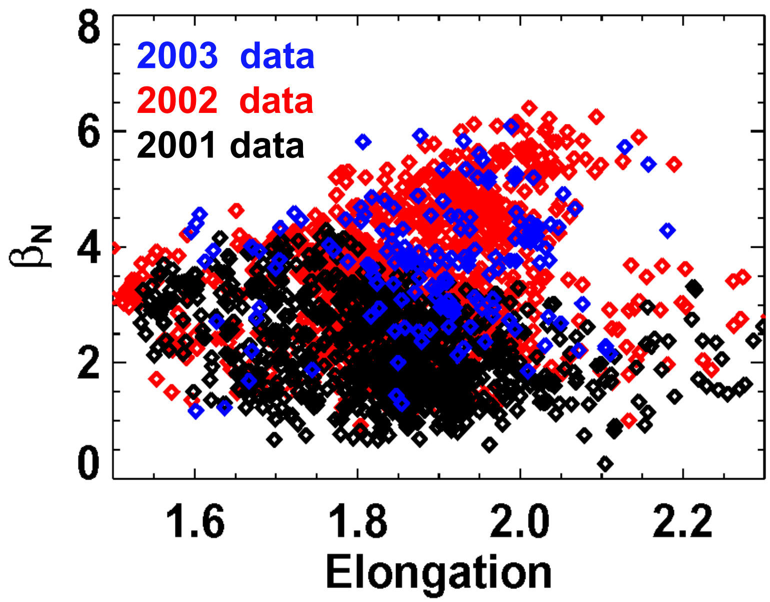


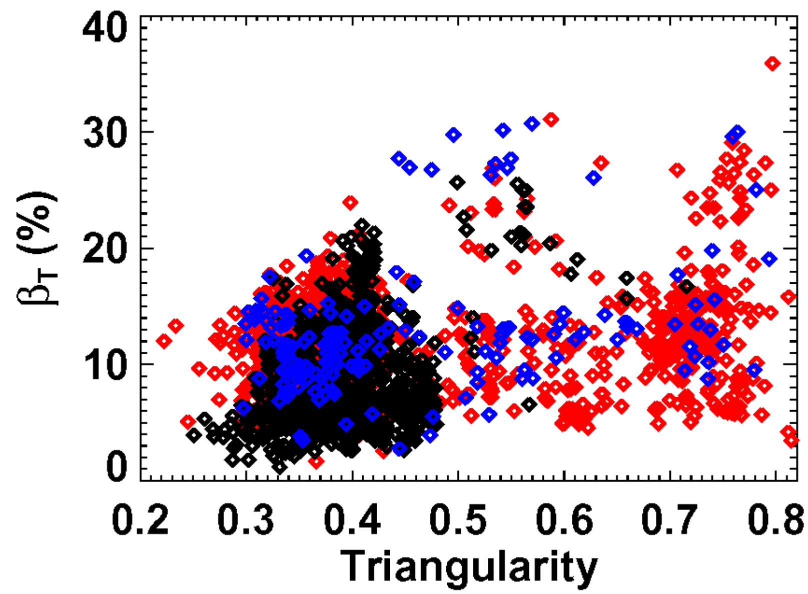
B_T = 0.6T: small τ_E degradation



- Scaling cannot be described by a simple power law

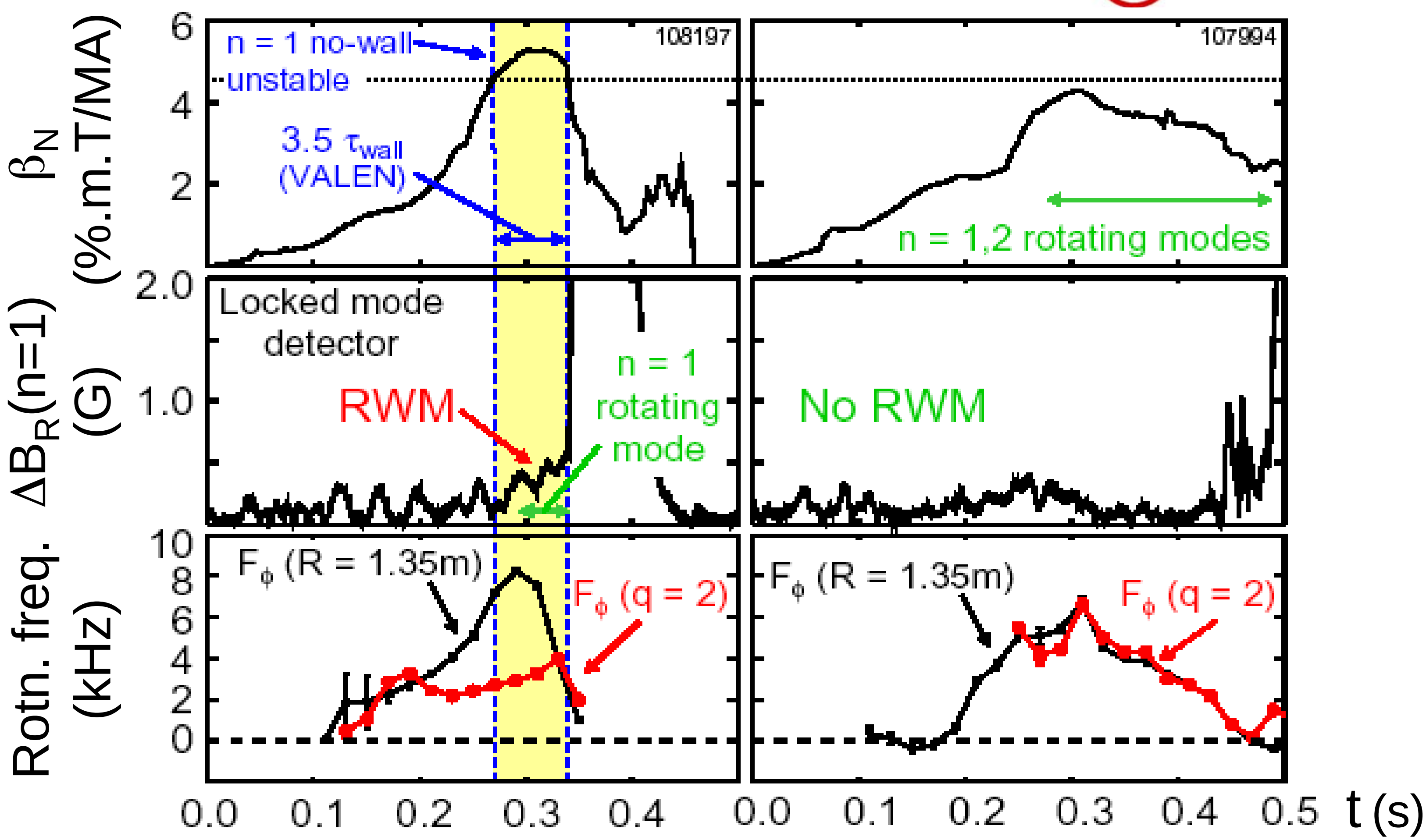
Measured Dependence of Beta-Limit Motivates Shaping Enhancements





- Reducing error fields and routine H-modes improved performance in ‘02
- Reducing latency in vertical position control loop to increase elongation in ‘04
- Capability for higher I_p at high δ contributes to strong dependence
- Investigating modification to inboard PF coils to increase δ at higher κ

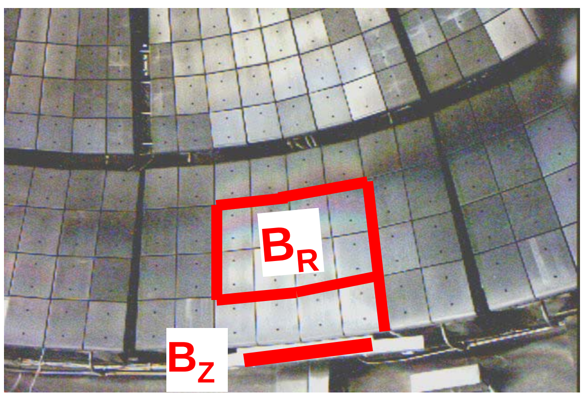
Observed Growth of Resistive Wall Modes When β_N Exceeds No-Wall Limit



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

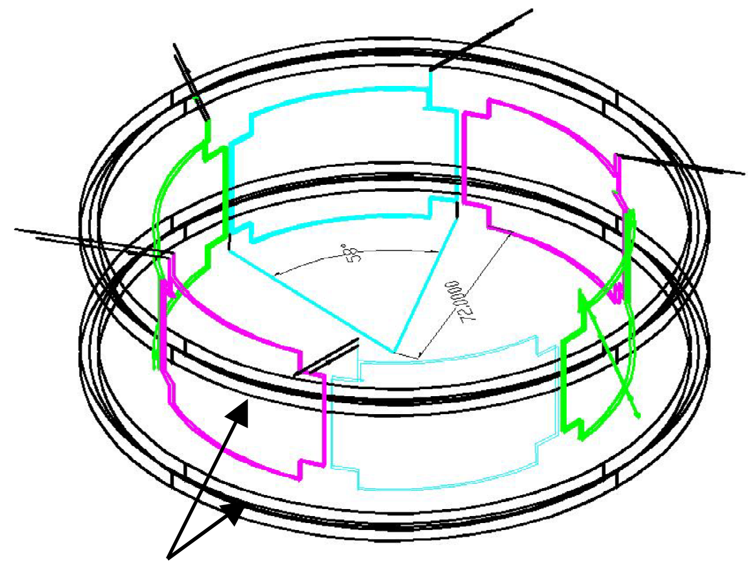
Developing Capability for Active Control of Resistive Wall Modes

- 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

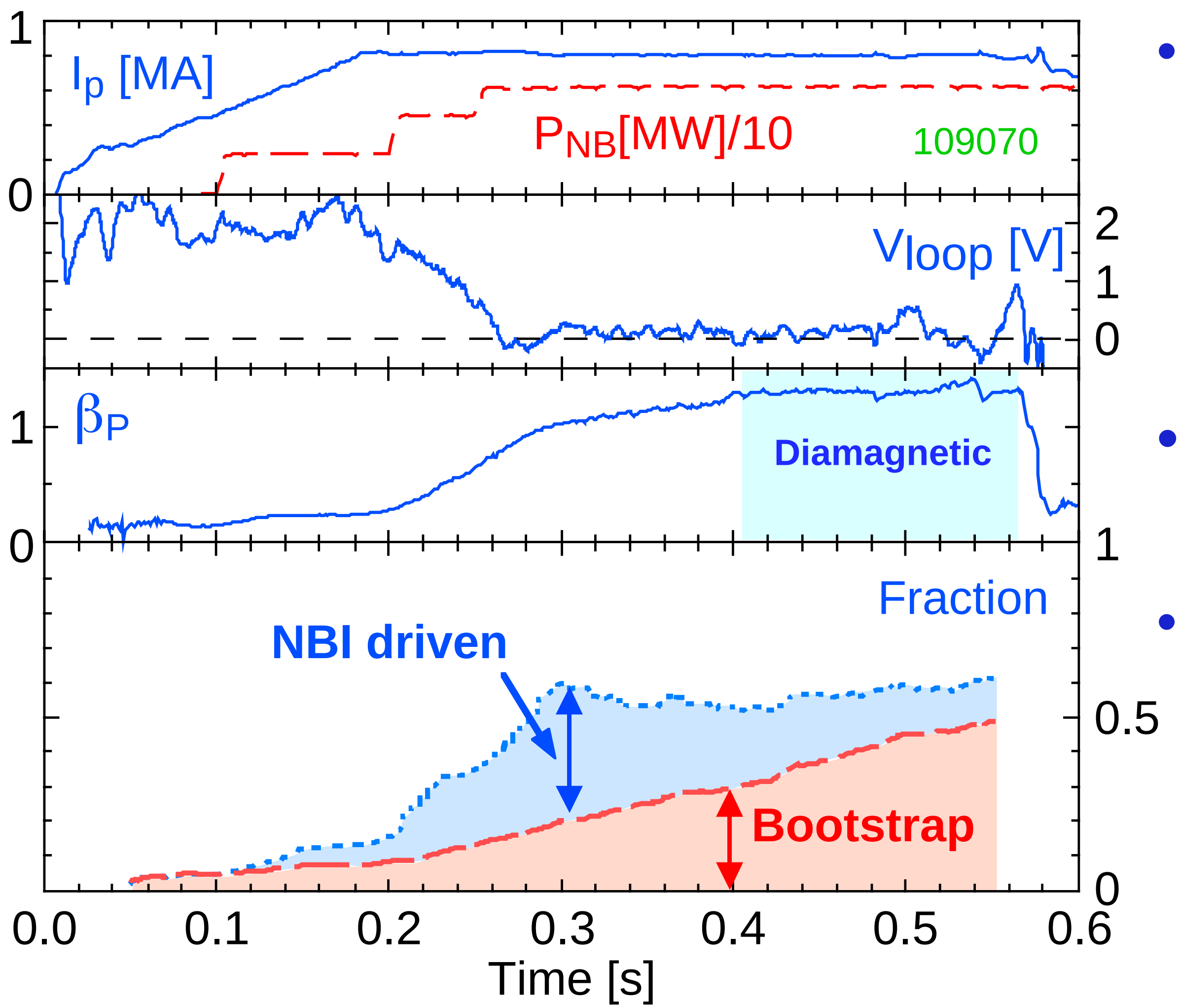
- 6 external correction coils in '04
  - Operate as 3 opposing pairs
  - Counteract error field amplification



PF5 coils (main vertical field)

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

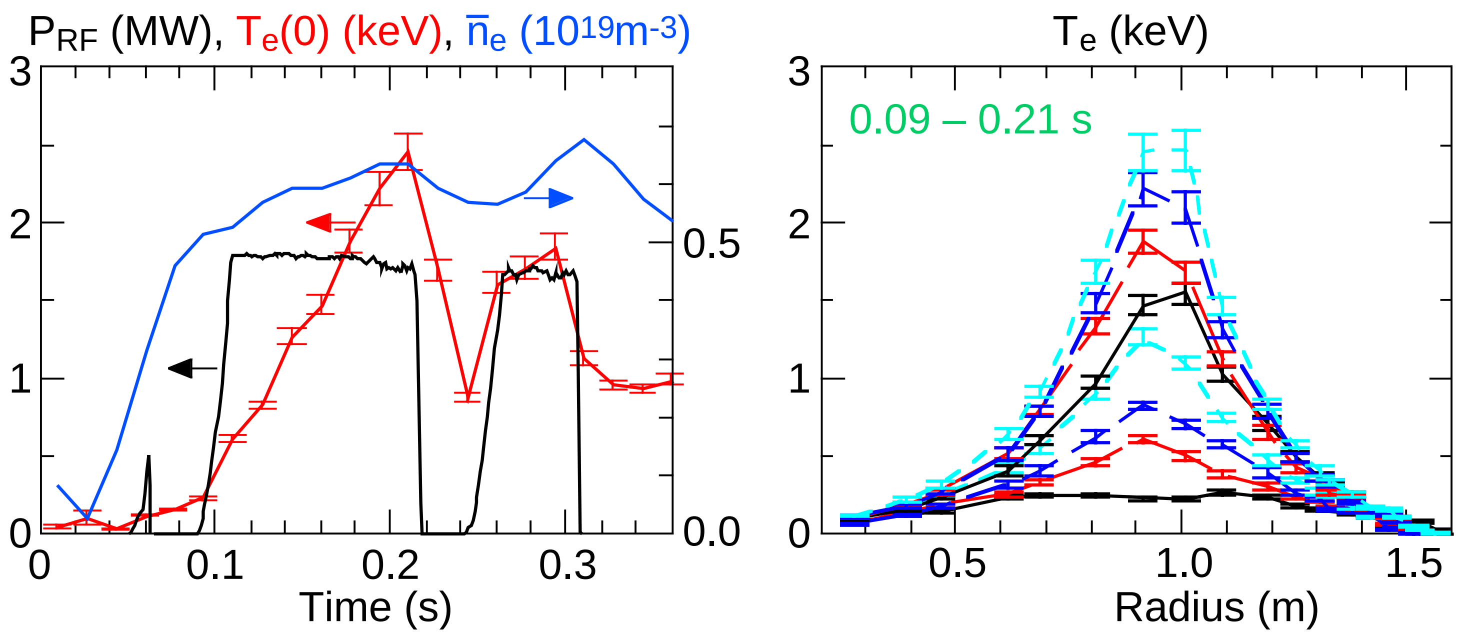
Non-Inductive Current Drive Vital to Achieving Goals for Pulse Duration



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

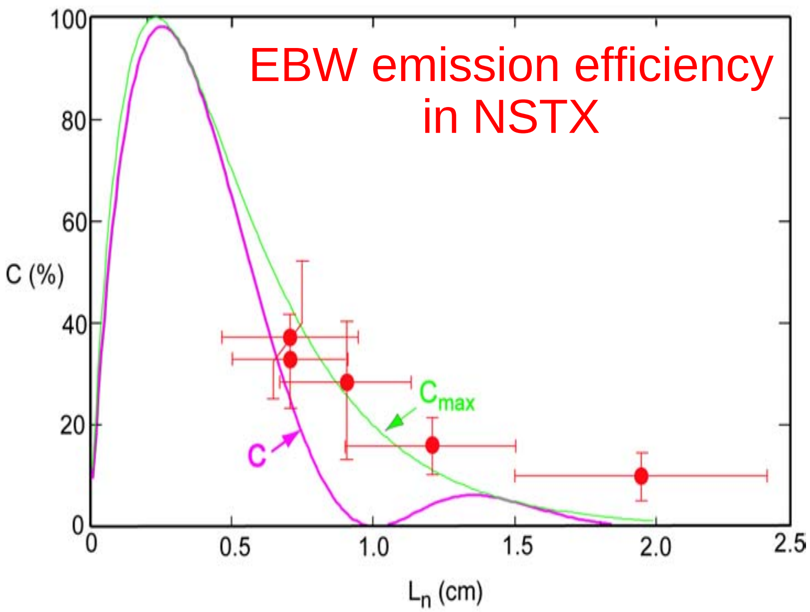
Achieved Reliable Operation of High-Harmonic Fast-Wave Antenna for Heating & CD

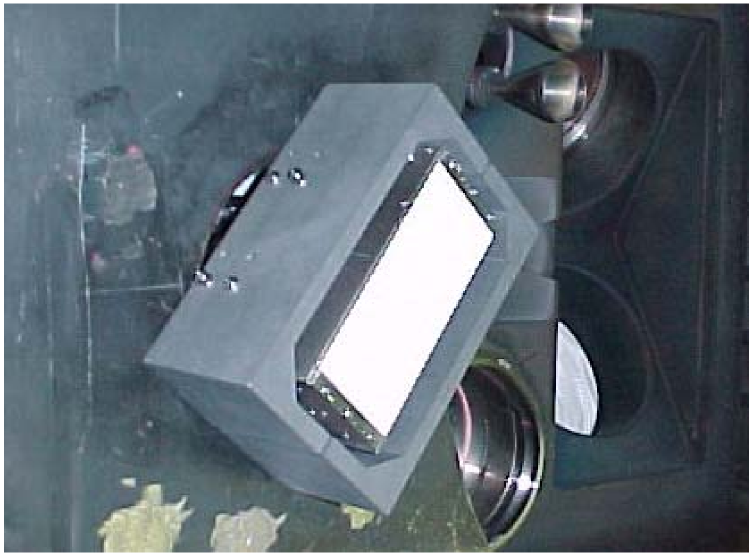
- Modified feedthroughs in 2002 opening to reduce voltage stress
- Quickly raised power in 2003 experiments
  - Antenna voltages to 15 kV, coupled power to 5.1MW, energy 1.6MJ
- Good electron heating observed at low density with early HHFW
  - Obtained improved density control by helium pre-conditioning shots



Planning 3MW Electron Bernstein Wave System for Localized Current Drive in Advanced Regimes

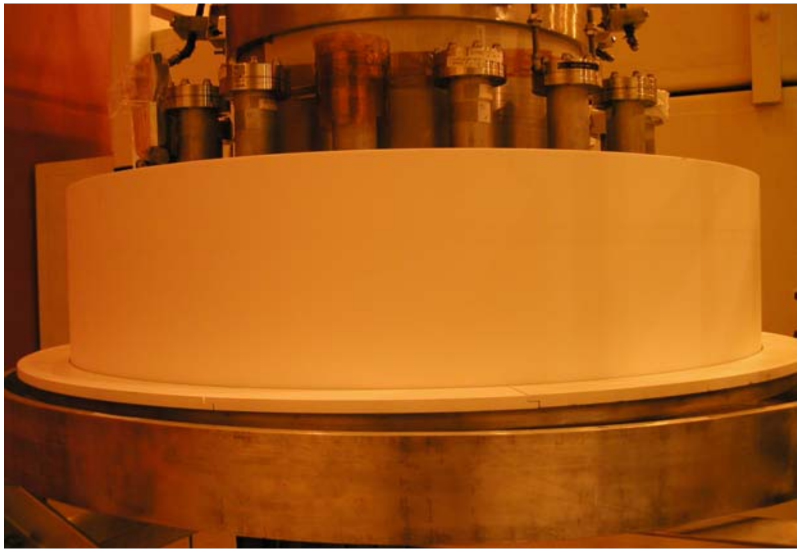
- ~15GHz for f_{ce} and Doppler-shifted $2f_{ce}$ absorption
- Develop ~1MW gyrotron sources ’04 – 5, install ‘06 – 7
- Requires small L_n for mode-conversion of EM wave to EBW
- Investigating with emission measurements in NSTX
  - New antenna includes movable limiters to steepen edge locally

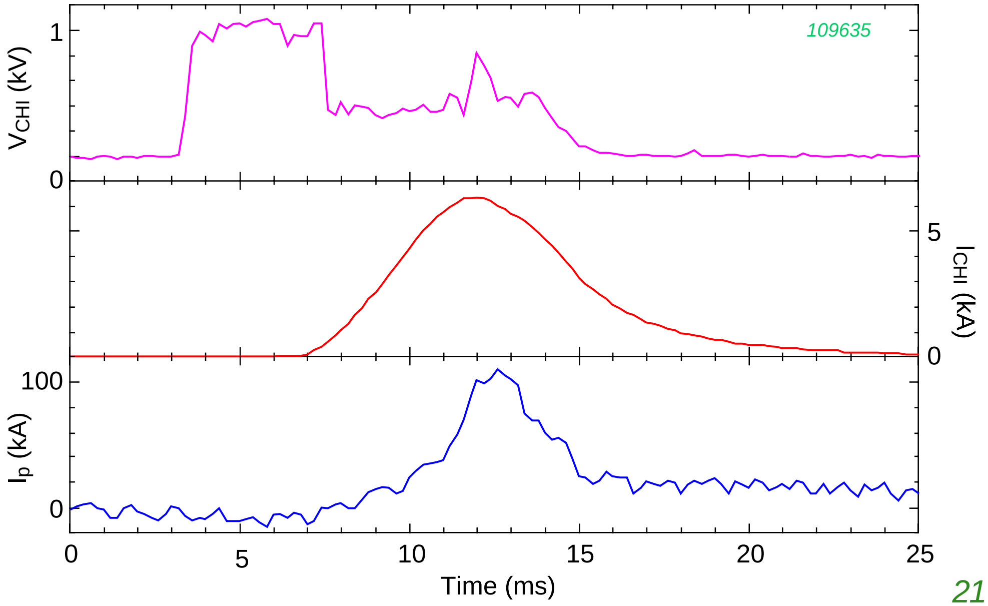




In Near Term, CHI Experiments Will Focus On Transient CHI Scenario

- Transient CHI developed on HIT-II (U. Wash.) in 2002
  - Closed flux develops as brief (few ms) CHI pulse is terminated
  - Apply induction to ramp up current
- Reliably produced highest currents obtained in HIT-II
- Initiated experiments with transient CHI in NSTX in ‘03
  - New absorber insulator does appear more resistant to arcs

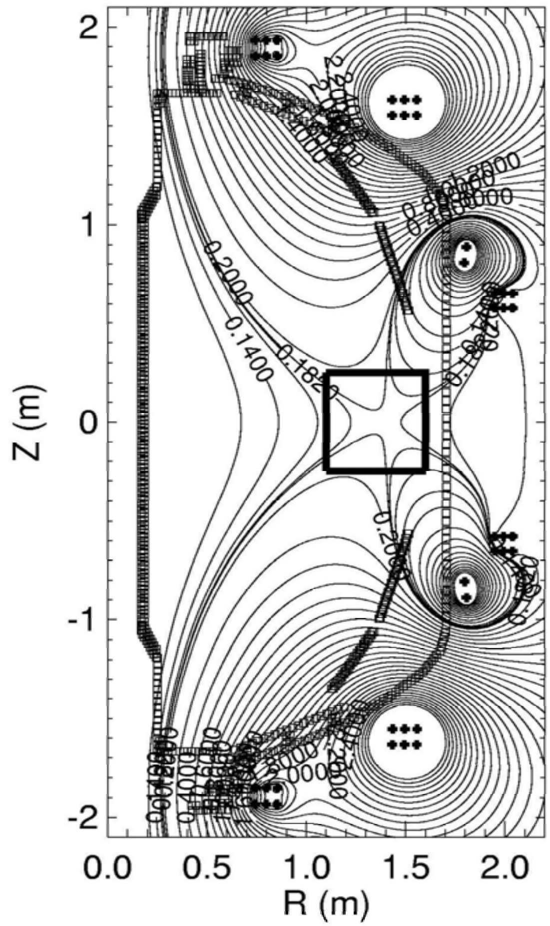




Alternative Scheme for Non-Solenoid Startup will be Investigated Using Outer PF Coils

- Use existing PF5, PF4, PF3, PF2 coils to get poloidal flux *and* poloidal field null
  - ~0.15Wb available at ~1m radius
    - Possibility for > 100kA
  - Meets conventional requirements for breakdown with adequate preionization
  - Provide power supply for PF4 coils (FY'04)
  - Reverse PF5 supply for initial tests
- Also investigate JT-60U non-solenoid scheme

Poloidal flux contours at time of breakdown



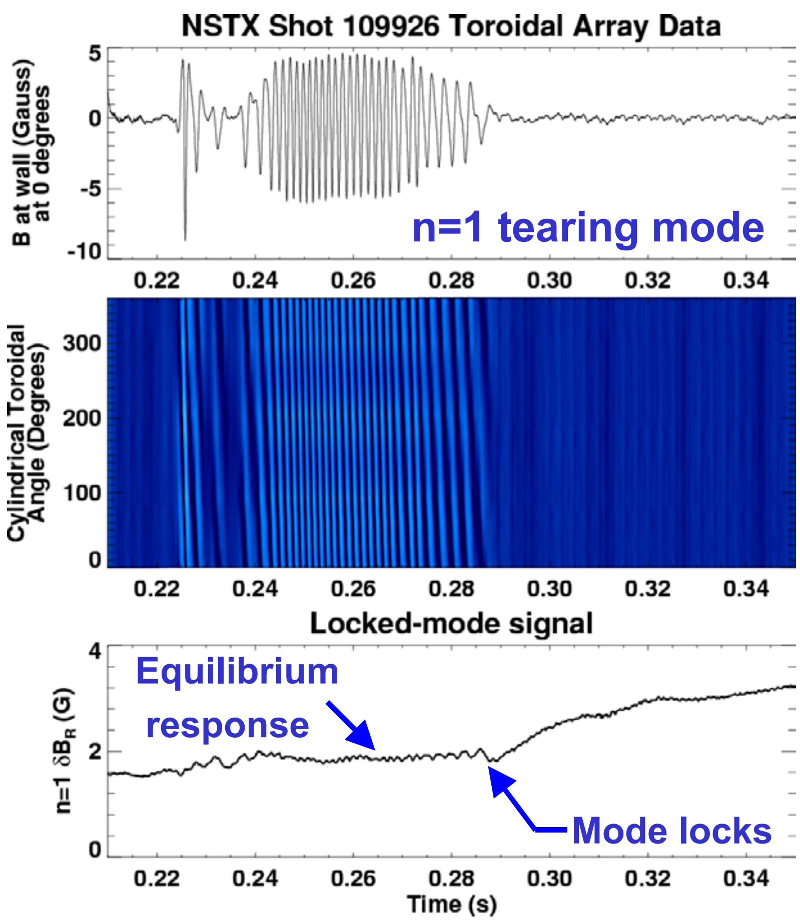
Planning Additional Methods for Controling Recycling

- Density control will be a major issue for long pulses in “advanced” operating modes combining
  - Edge transport barriers (H-mode)
  - Possible internal transport barriers (indications with HHFW)
  - High fraction of bootstrap current (dominated by density gradient)
  - RF current drive to maintain stability (dependent on T_e)
- Effects of “mini” boronization between shots in ‘04
- Lithium pellet conditioning in ‘04
- Lithium evaporator in ‘05 (CDX-U development)
- Cryo-pump installation in ‘05
- Lithium surface module in ‘07

Results Have Encouraged Development of an Ambitious Research Plan for NSTX

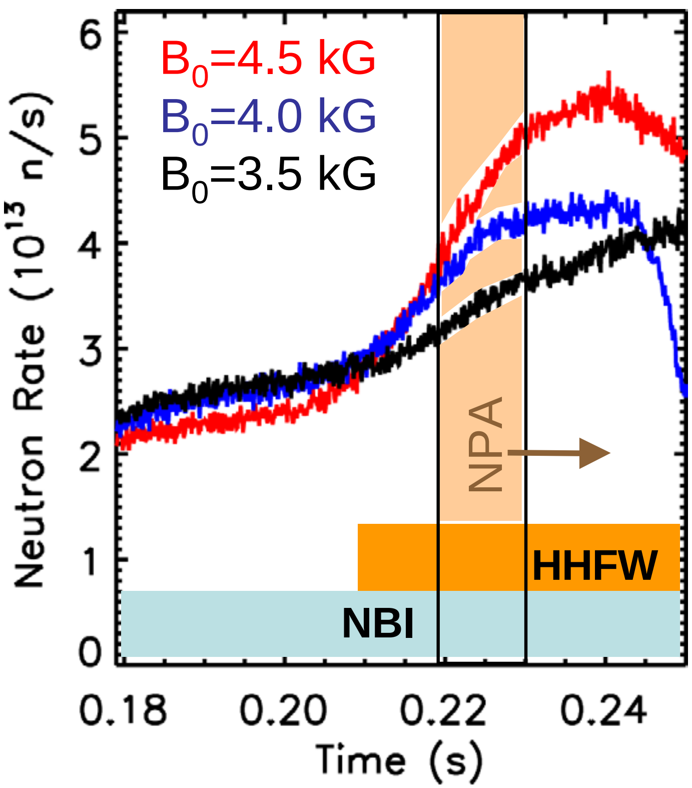
- Potential for high β already demonstrated
  - Expand boundaries by additional shaping and active control
- Confinement with NBI heating exceeds expectations
  - Ions are well confined and contribute to good total confinement
  - Combined NBI-driven and bootstrap current up to 60% of total
- Challenge is to achieve these favorable characteristics simultaneously with non-inductive current drive
  - Self-consistent bootstrap current
  - Current sustainment by RF waves
  - Current initiation by coaxial helicity injection and other novel means
- TF joint failure has delayed but not deterred research
  - Fabrication of new TF center bundle is well advanced

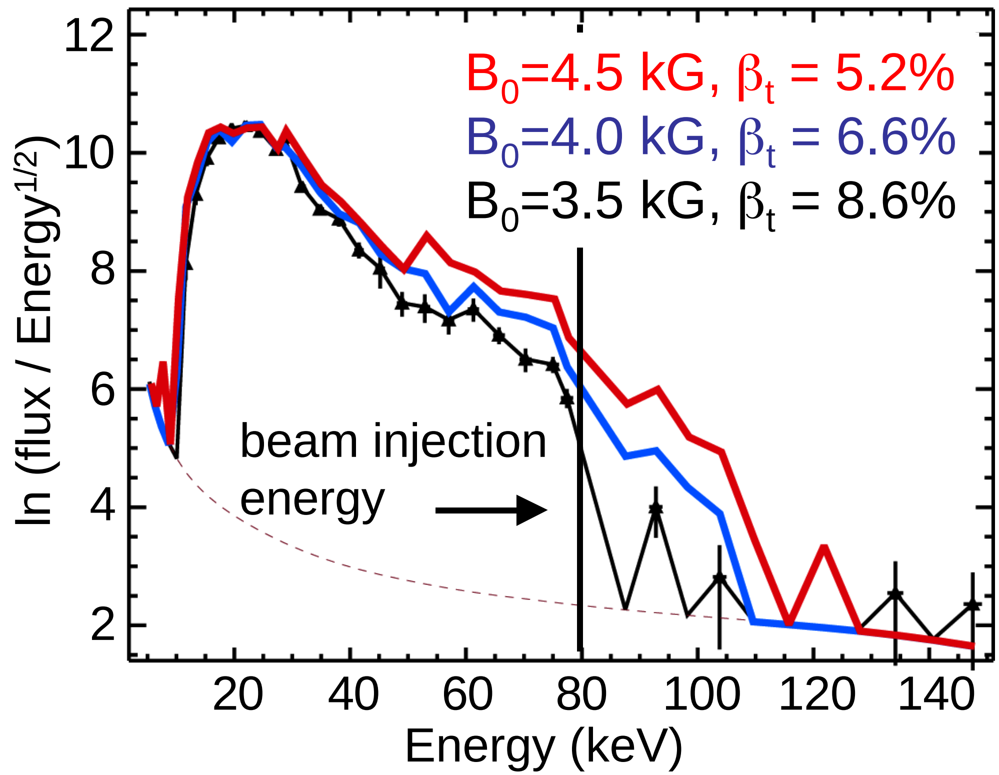
Appendix 1: Since Coil Realignment, Mode-locking Now Only Observed at Low $n_{e,}$ B_T



- In ohmically heated plasma, reducing density by 5% can cause rotating mode to lock
  - Modes lock to preferred locations
- Intrinsic mode rotation in electron diamagnetic drift direction
- With NBI, mode locking occurs more readily
  - NB torque opposes rotation

Appendix 2: Evidence Seen for HHFW Interactions with Energetic Beam Ions





- Tail reduced at lower B:
  - Higher β promotes greater off-axis electron absorption reducing power available to central fast-ion population