FY2004 Research Results

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PPPL, Princeton Univ.

NSTX PAC-16 Meeting
Princeton, N.J.
9-10 September 2004

Outline

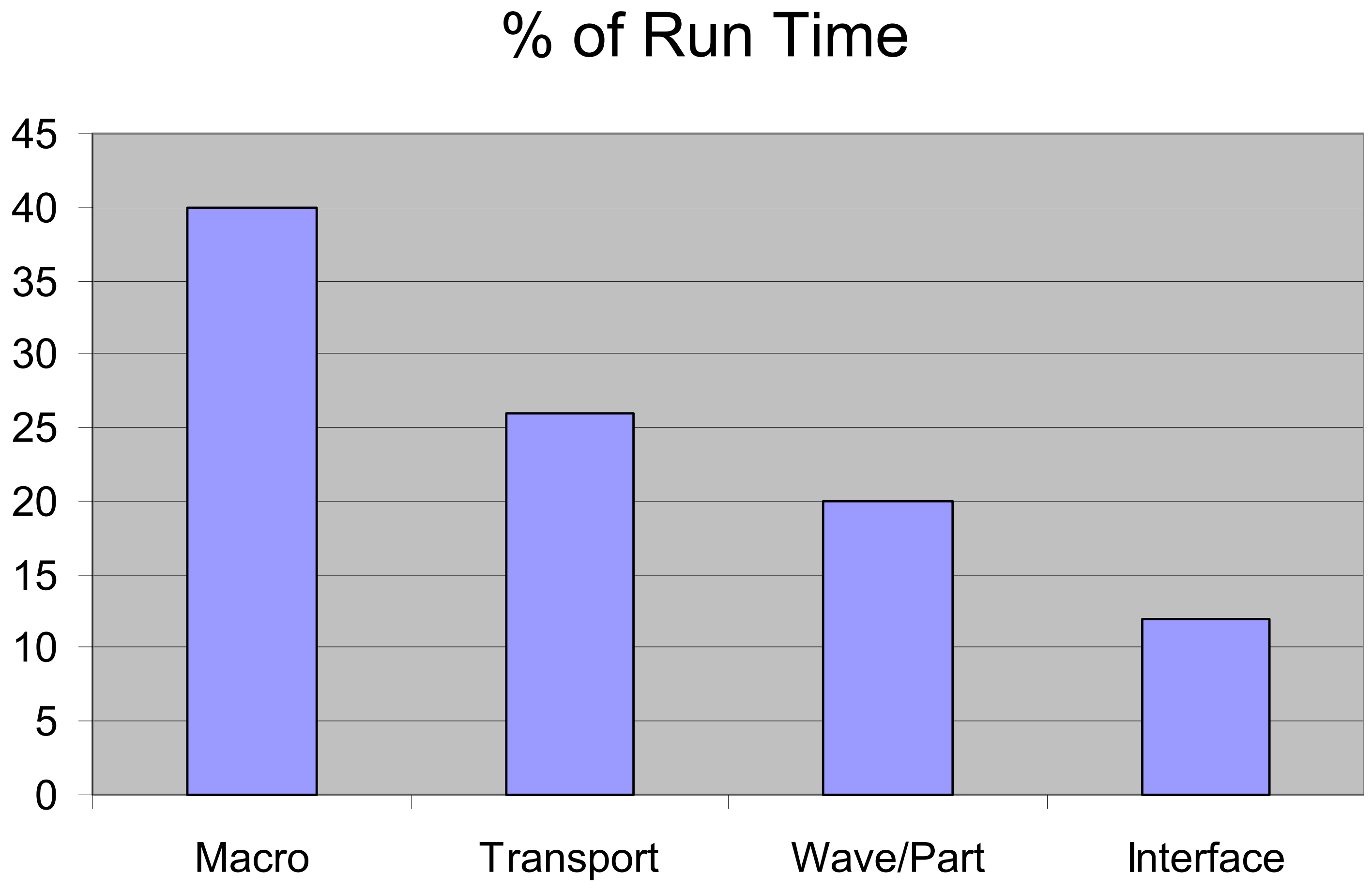
- Science issues addressed
- Run statistics
- New capabilities in FY04
- Results highlights
- Wrap-up

A Significant Amount of High-Quality Data That Addresses the FESAC Science Goals Was Obtained During the FY04 Run

- Understand the role of magnetic structure on plasma confinement and the limits to plasma pressure in sustained magnetic configurations (Macro)
- Understand and control the physical processes that govern the confinement of heat, momentum and particles in plasmas (Transport)
- Learn to use energetic particles and electromagnetic waves to sustain and control high temperature plasmas (Part/Waves)
- Learn to control the interface between a 100 million degree plasma and the room temperature surroundings (Interface)

Anaylysis underway for upcoming meetings

21 Run Weeks Allowed For Comprehensive Research in all Areas



New Capabilities in FY04

- Control system upgrade for higher elongation (All areas)
  - Reduced latency (<1 msec)
  - rtEFIT
- MSE – up to 8 channels (All areas)
- Divertor Mirnov arrays, internal RWM sensors (Macro)
- 2 external EF/RWM control coils (Macro)
- USXR, FIRETIP upgrades (Macro, Transport)
- PF4 commissioning – July '04 (Macro)
- CHI capacitor bank – July '04 (Macro)
- HHFW antenna increased voltage/power limit (Wave/Part)
- RF Probe (Wave/Part)
- 51 channel CHERS (Transport, Macro)
- Scanning NPA (Transport, Macro, Wave/Part)
- Edge rotation diagnostic to measure edge T_i, $v_{\phi,\theta}$, E_r (Transport, Wave/Part)
- Upgraded correlation reflectometry – long λ turbulence (Transport)
- Li pellet injector – July '04 (Interface)
- Supersonic gas injector – July '04 (Interface)
- Improved boronization schemes (Interface)
- Fast camera (Transport, Interface)

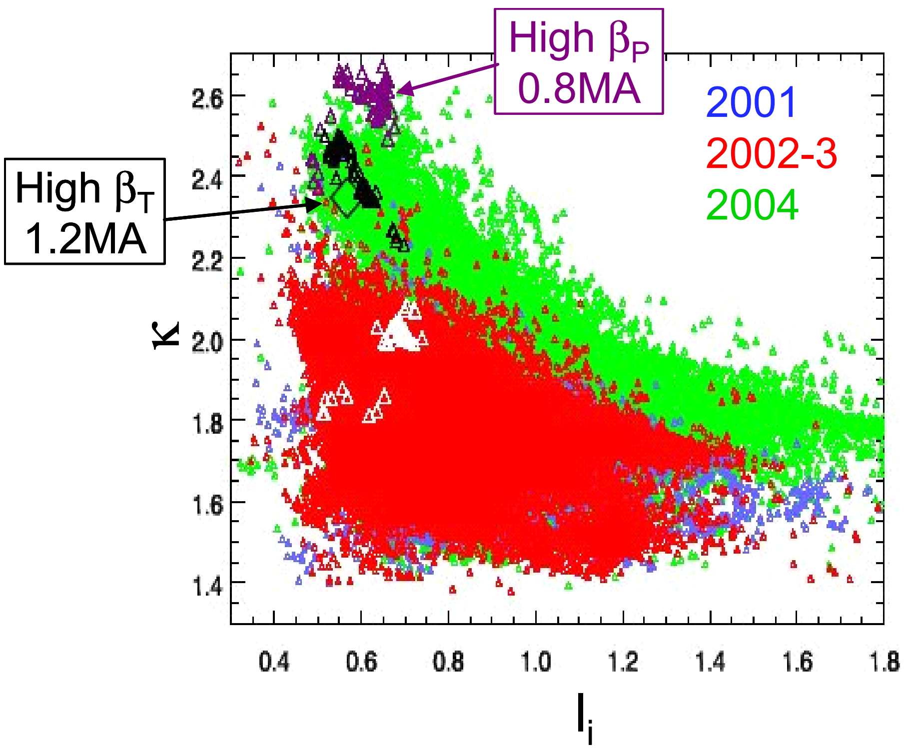
Macroscopic Plasma Behavior

- Plasma control development
  - rtEFIT (Gates, Ferron-GA)
  - Vertical stability control (Mueller, GA)
- High β_T, β_{pol} (Gates, Menard, Sabbagh)
- Locked mode thresholds w & w/o active coil (Menard)
- RWM Physics (Sabbagh, Zhu, Sontag)*
  - Passive stabilization, rotation damping, dissipation physics, active control coil studies
- NTM Physics (Fredrickson)
- Long pulse LSN/DND development (Menard/Gates)
- Solenoid-free plasma initiation
  - PF-only startup (Menard, Ono, Takase)
  - Co-axial helicity injection (Raman)

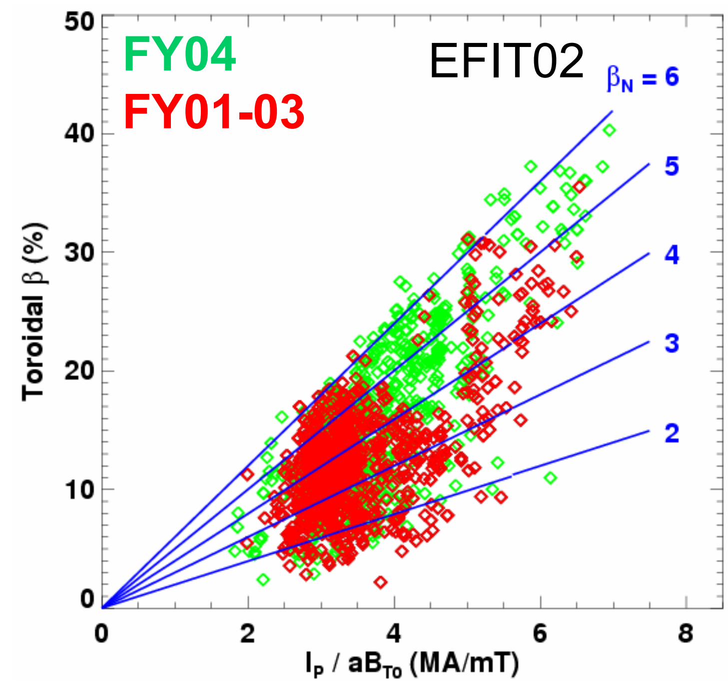
* Details given by S. Sabbagh

Improved Vertical Position Control & Early H-modes Opened Operating Window This Year

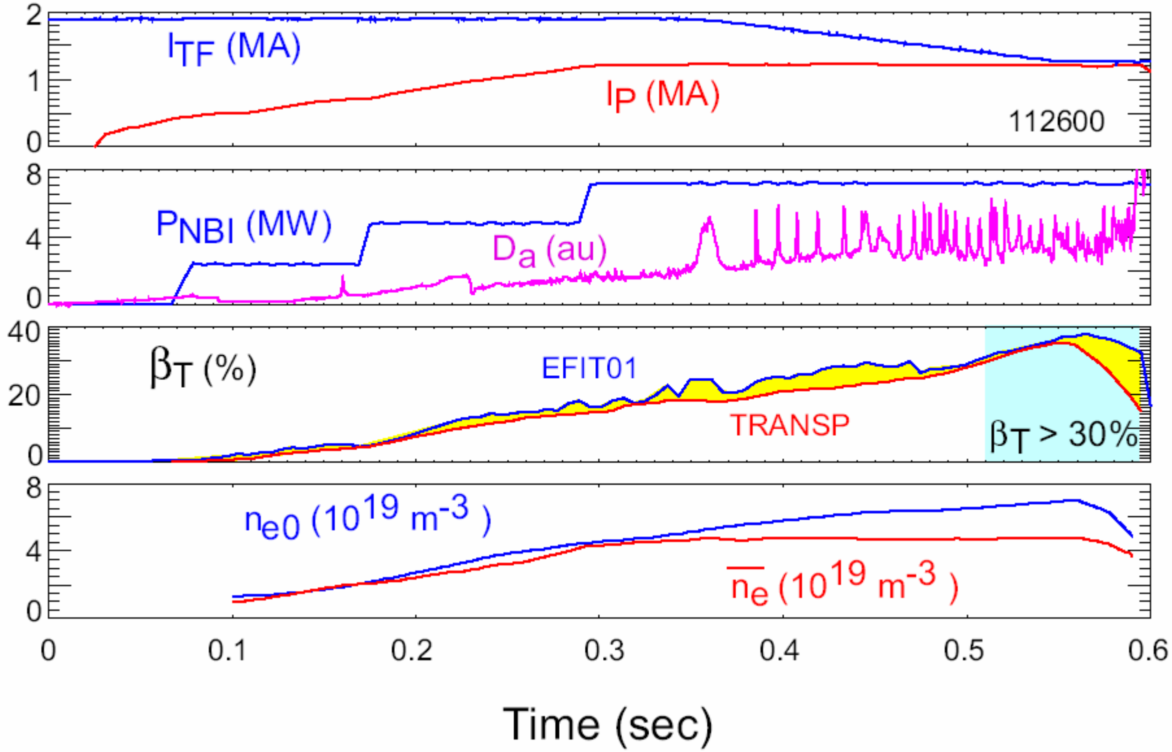
- Latency in digital control system reduced to < 1 msec
- Lower internal inductance in H-mode allowed higher elongation
- Capability for higher κ, δ allowed higher I_P/aB_T



Significantly more high-β_T shots during FY04 run than previously



Longer Duration High-β_T Achieved With Edge Density Control



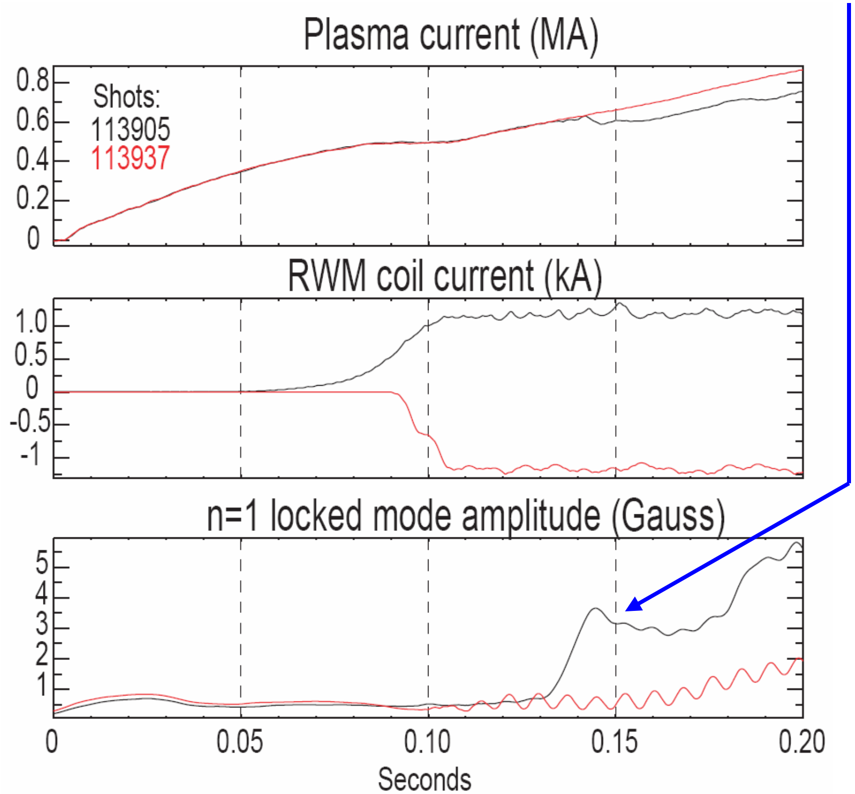
- He pre-conditioning to control recycling
- Initiate plasma at high B_T ($\propto I_t$) for most quiescent ramp-up
- Early NBI and pause in I_p ramp trigger early H-mode
- Reduce B_T to increase β_T
- ELMs develop as B_T falls

β_T >30 % for ~$2\tau_E$

Active Control Coil Pair Has Expanded Operating Space by Reducing Locked Mode Threshold

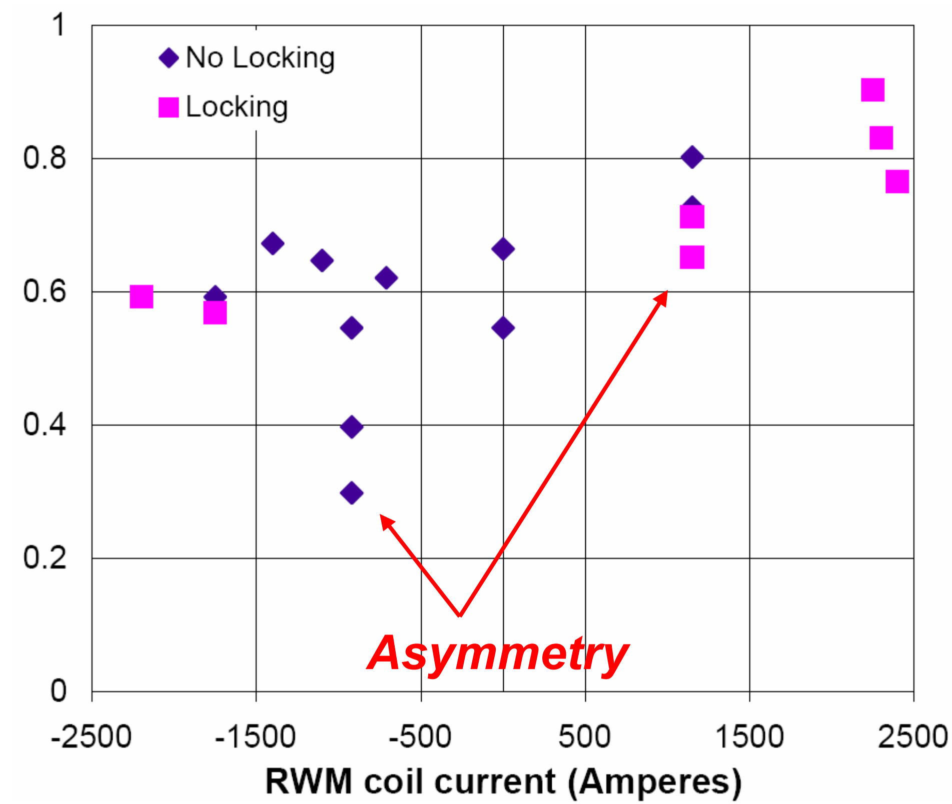
Mode locking density threshold during I_p ramp depends on sign of applied external field

Typical 2/1 locked mode signatures during I_p ramp w/ RWM coil current on

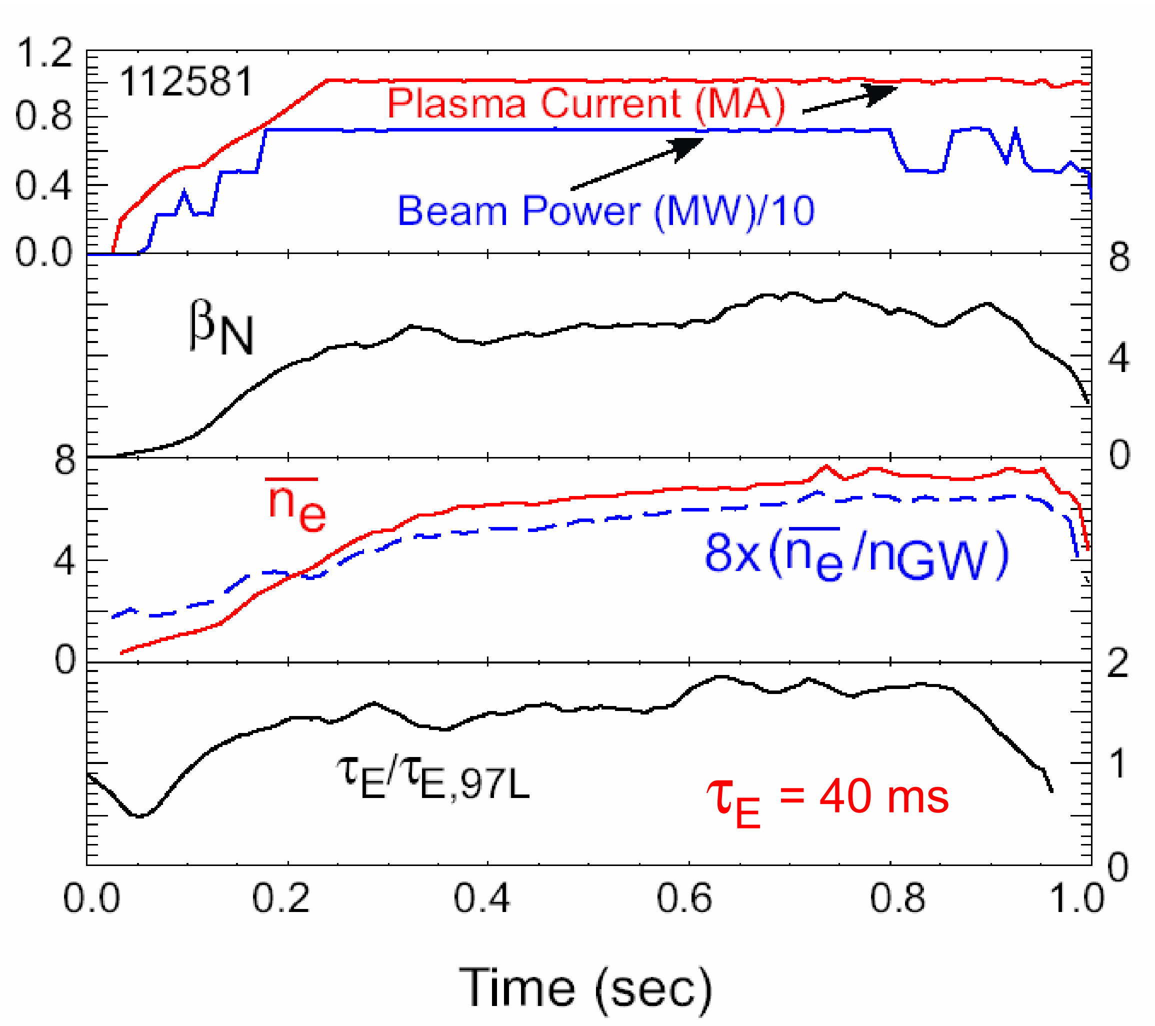


Density threshold vs. RWM coil current

$\overline{n}_e(20) \times q_{95}^{0.8}$ (DIII-D scaling)



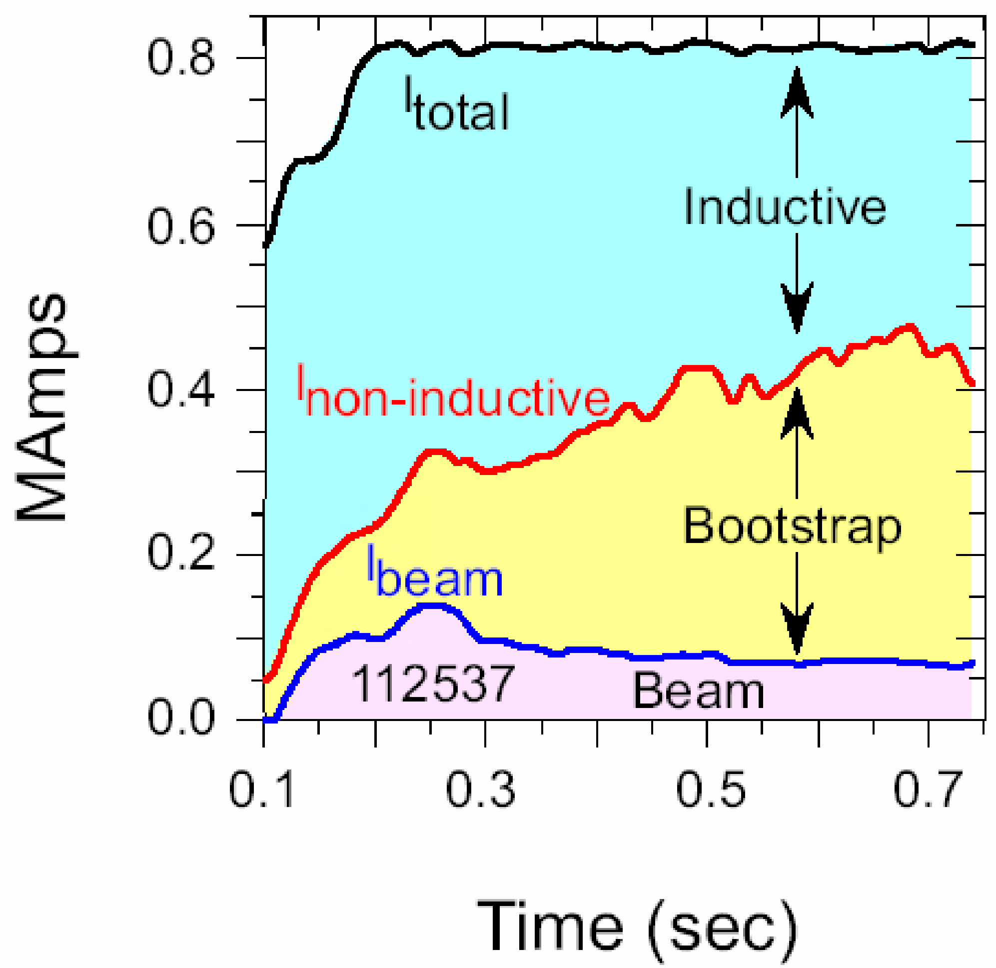
Long Pulse Discharges Developed With Simultaneous High β_N, τ_E



- $\tau_{flattop} >> \tau_E$
- τ_E high at high n_e/n_{GW}

Discharge Sustainment by Non-Inductive Current Drive is a Key Component of the NSTX Program

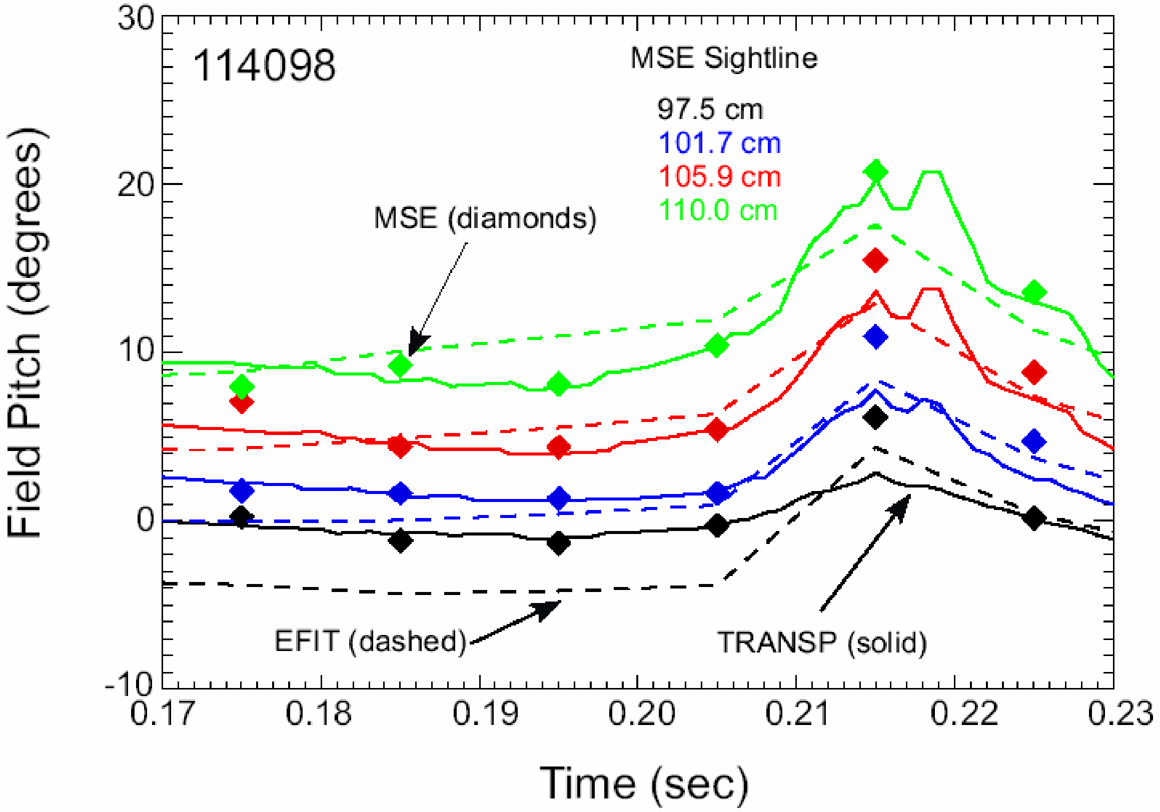
- Significant amount of non-inductive current driven by beams and bootstrap



Initial Measurements of Current Profile Made with MSE

Good agreement between MSE And TRANSP current profiles when R_{mag}'s shifted to coincide

(ΔR_{mag} = 4 to 6 cm; δR_{MPTS} ~ 4 to 5 cm, δR_{MSE} ~ 2 cm)

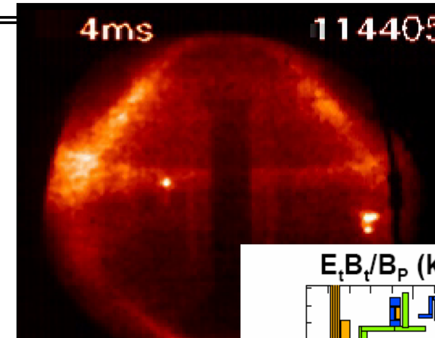


Details given by F. Levinton

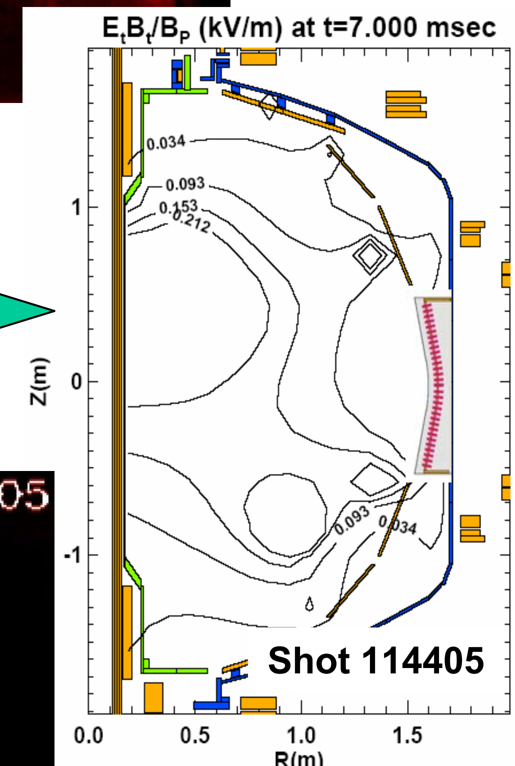
Non-Solenoidal Startup is a Major Element of the NSTX Program

PF-only startup

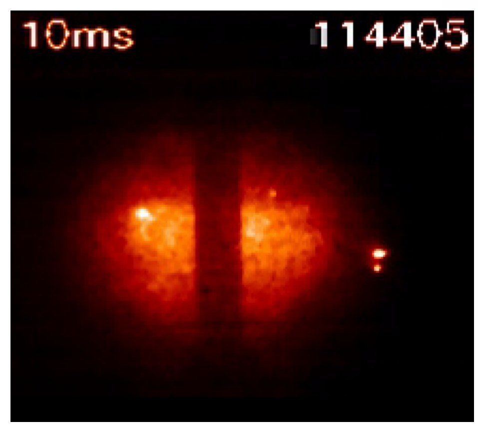
1. Pre-ionize plasma near RF antenna with ECH + HHFW



2. Create high-quality field-null with 5-15 loop-volts at antenna
   - *Require $E_\phi B_\phi / B_P > 0.1$kV/m over substantial plasma volume*

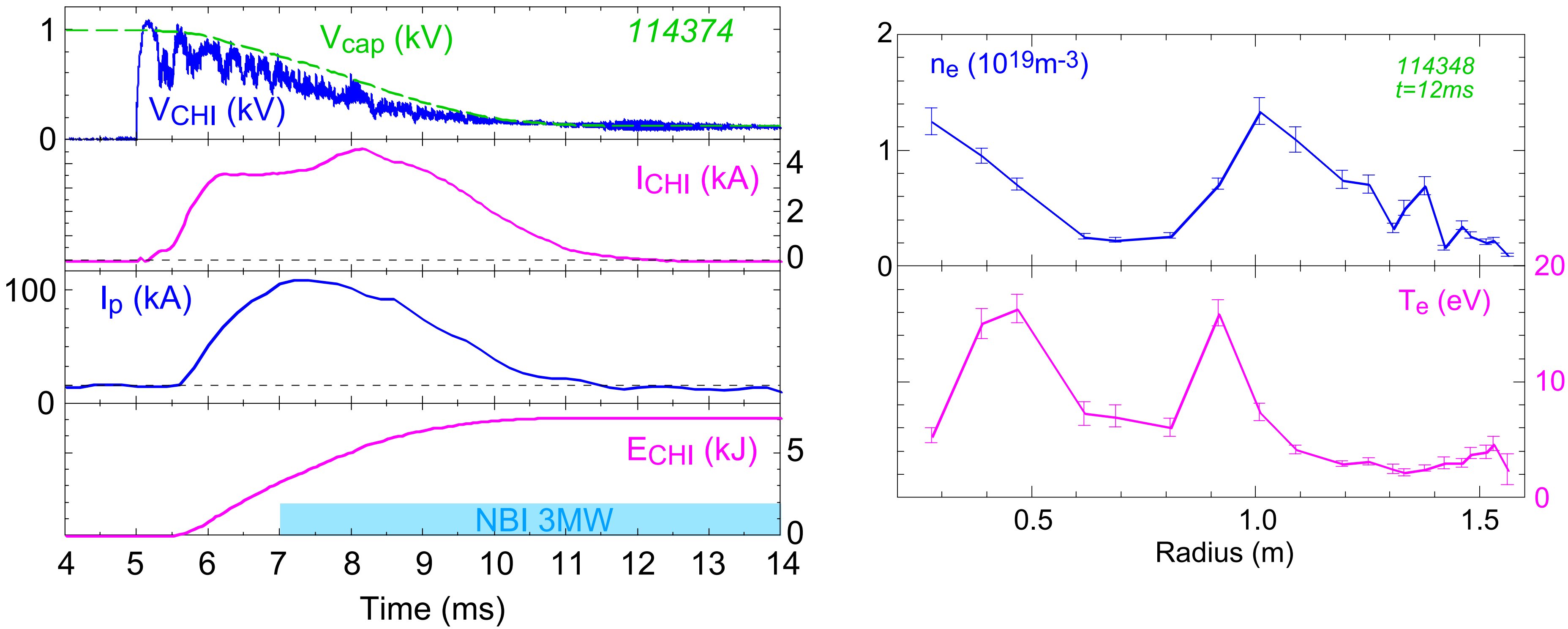


3. Have created 20kA plasmas that terminate near center-stack



Goal is to increase available flux swing further to ramp plasma current

Significant Toroidal Current Generated With Transient CHI Startup

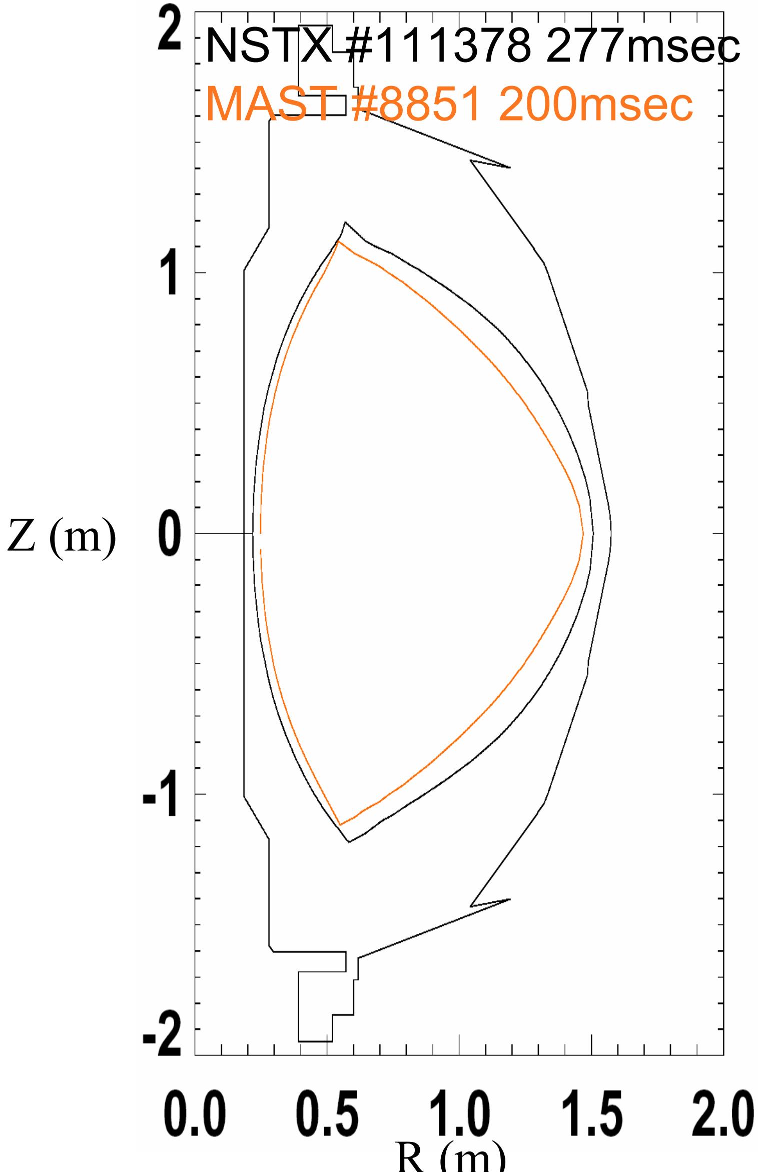


- Up to 7 capacitors used
- Absorber arc not fatal
- Up to 20 eV T_e
- $I_p \geq 140$ kA with amplification factors (I_p/I_{CHI}) up to 40
- Exploring possibility of closed flux surfaces (EFIT)

Multi-Scale Transport Behavior

- L-H Thresholds (Maingi, Meyer-MAST)
  - Shape and fueling
- H-mode confinement scaling (Kaye, Akers-MAST)
- Internal transport barriers
  - Electron (Stutman)
  - Ion (Peng, Field-MAST)
- Core turbulence in low n_e L-mode (Peebles)

L-H Threshold Probed as Part of NSTX/MAST Identity Experiment



Objective is to identify underlying physics at low aspect ratio
- NSTX, MAST have different device configurations

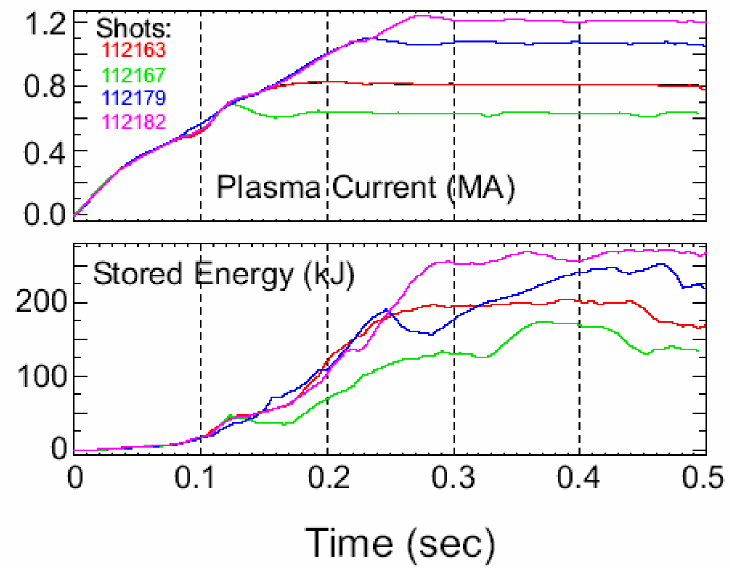
Develop similar plasmas, probe L-H threshold vs configuration (DN vs SN)
Vary Δ_r^{sep} to study P_{LH} vs configuration

rtEFIT crucial for fine Δ_r^{sep} control

P_{LH} in double-null (Δ_r^{sep}<1 mm) comparable
350 kW @ 0.5 MA, 0.45 T
P_{LH} significantly higher for $|\Delta_r^{sep}|$>1 mm

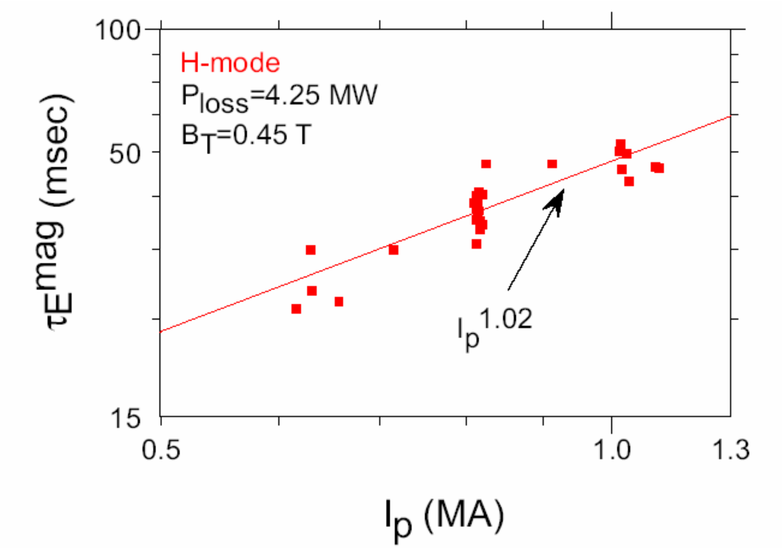
L-H transition physics similar

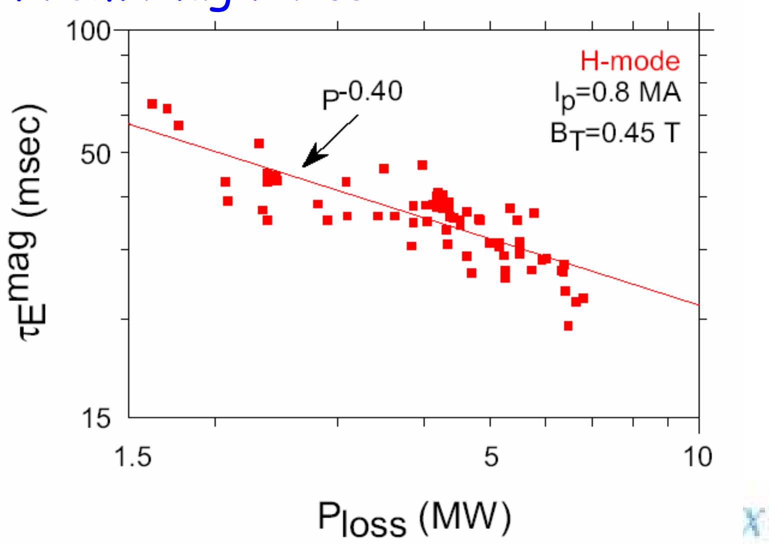
Confinement Trends in NSTX Similar to Those in Conventional Tokamaks



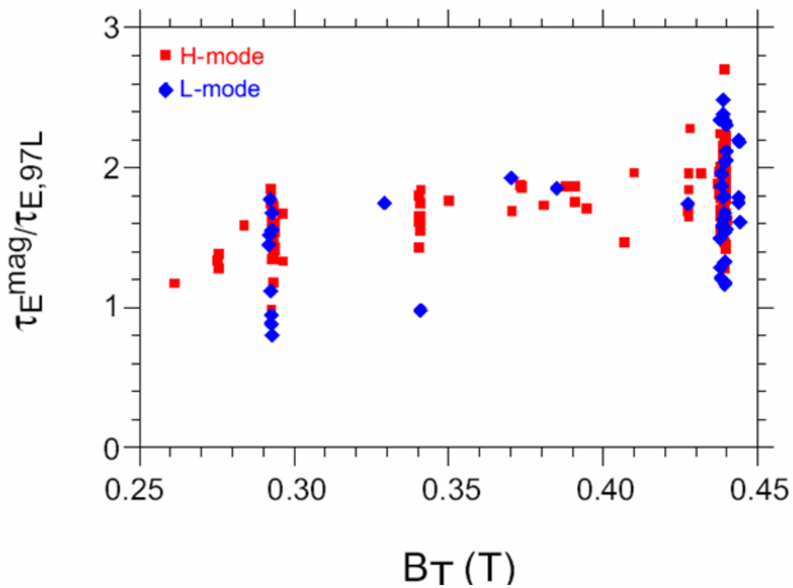
NSTX portion of NSTX/MAST identity comparison

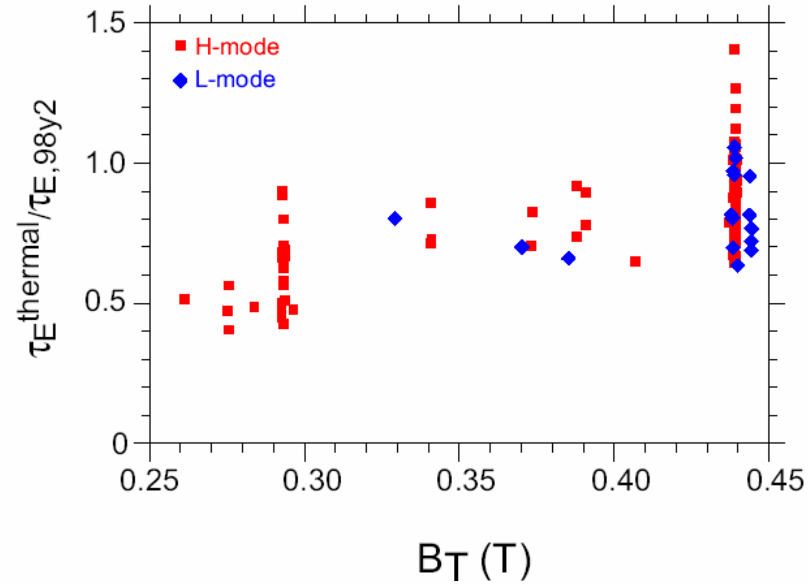
Global Confinement From Magnetics

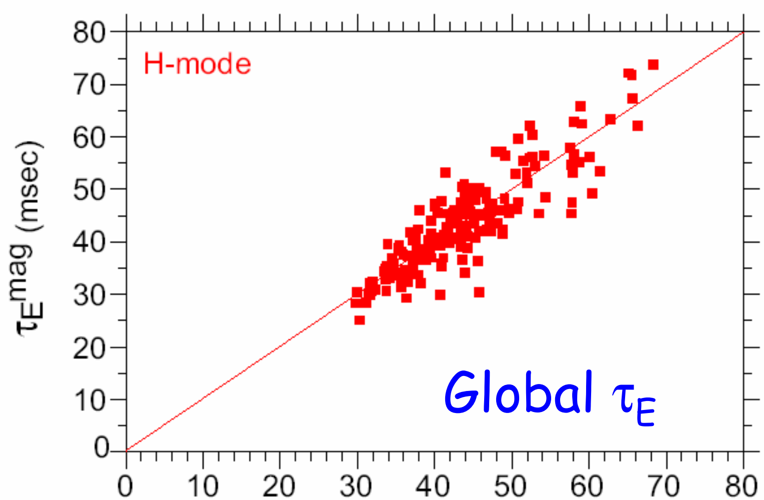


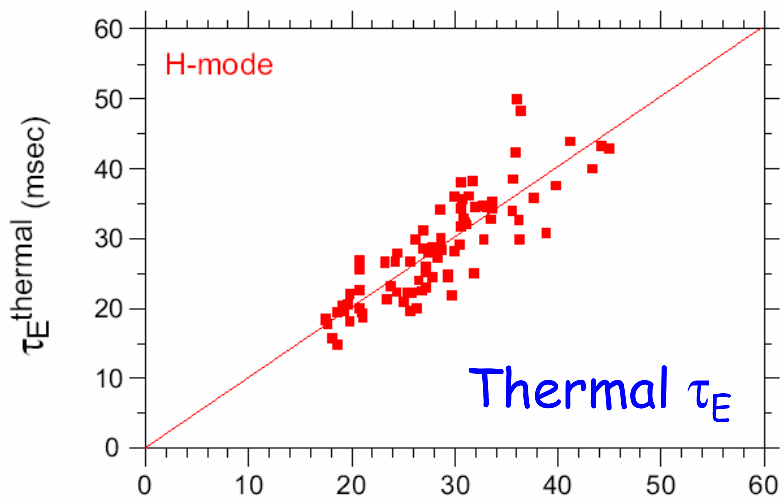


Strong B_T Dependence Observed ⇒ Need to Sort Out Effects of MHD



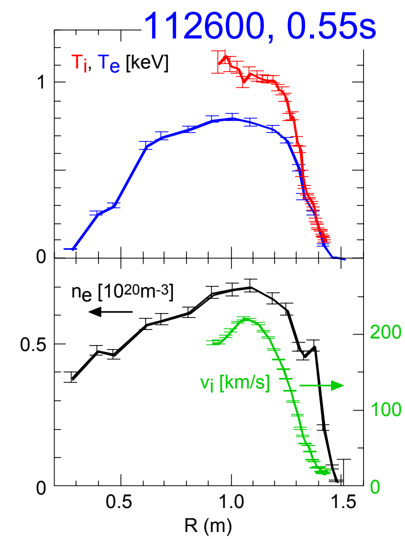


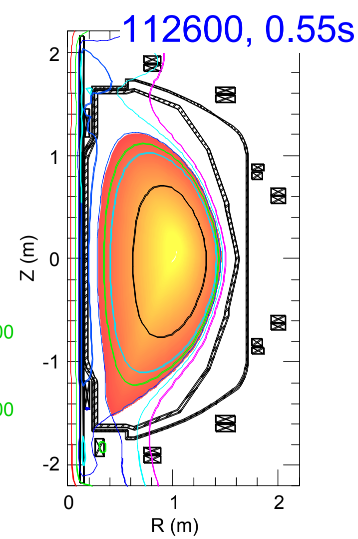




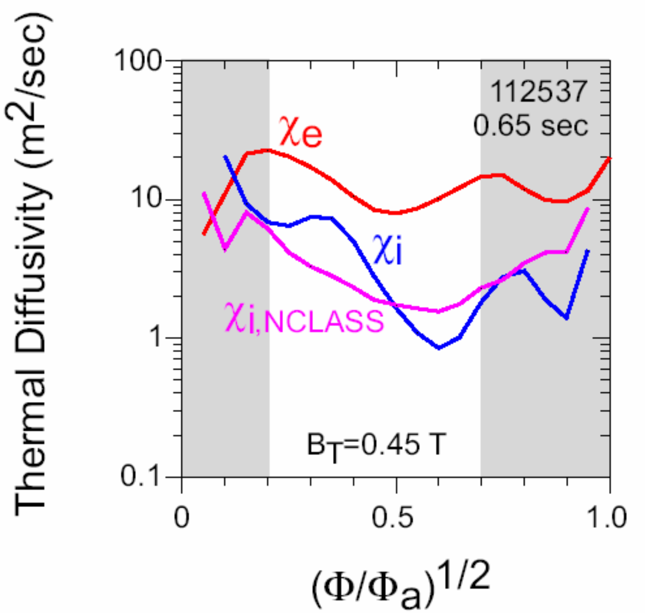
Local Transport Properties Calculated by TRANSP

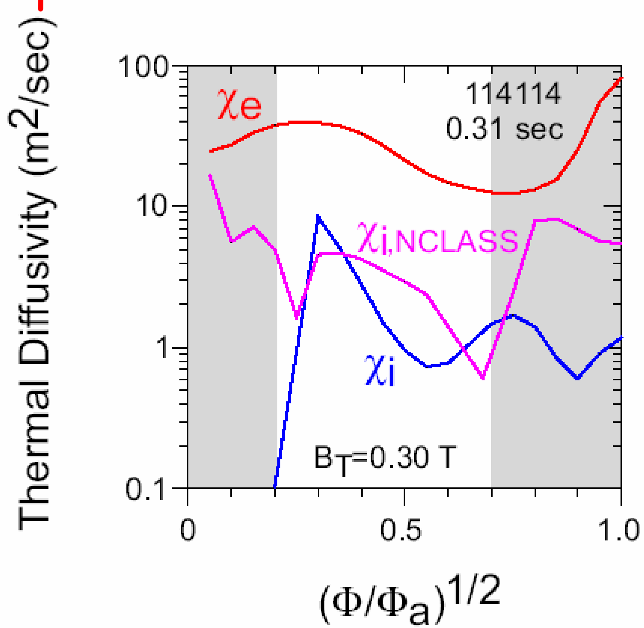
High-resolution Charge-Exchange Spectroscopy measures high rotation & large gradients in T_i, v_ϕ





Electrons dominate transport loss in most H-modes



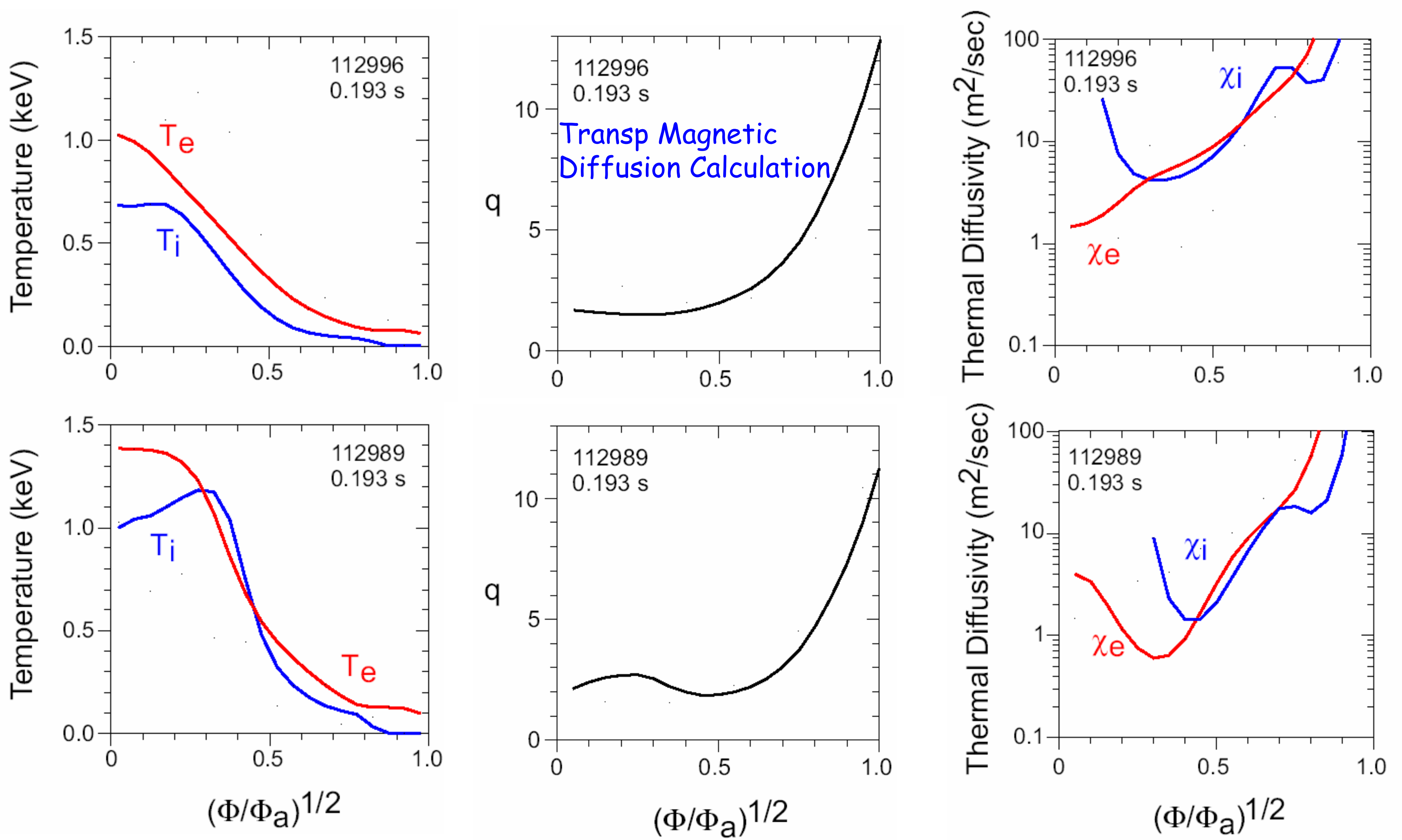


126 Discharges Analyzed with TRANSP

$\chi_i \sim \chi_e$ in L-mode

CHERS data calibration continuing

Reduced Thermal Diffusivity in Regions of Possible Reversed Magnetic Shear

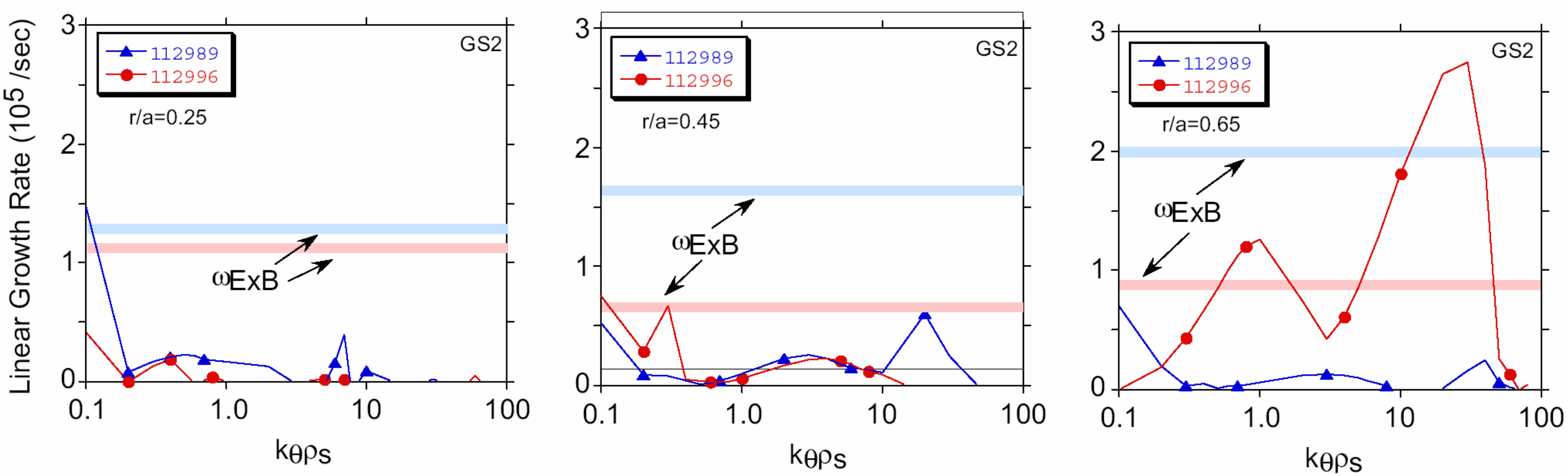


Gyrokinetic Calculations Indicate Linear Growth Rates Small Over Most of the Plasma

Study role of electron vs ion modes and associated transport

Non "reverse-shear" discharge shows significant growth rates in outer part of plasma for all $k_\theta \rho_s$

t=.193 sec



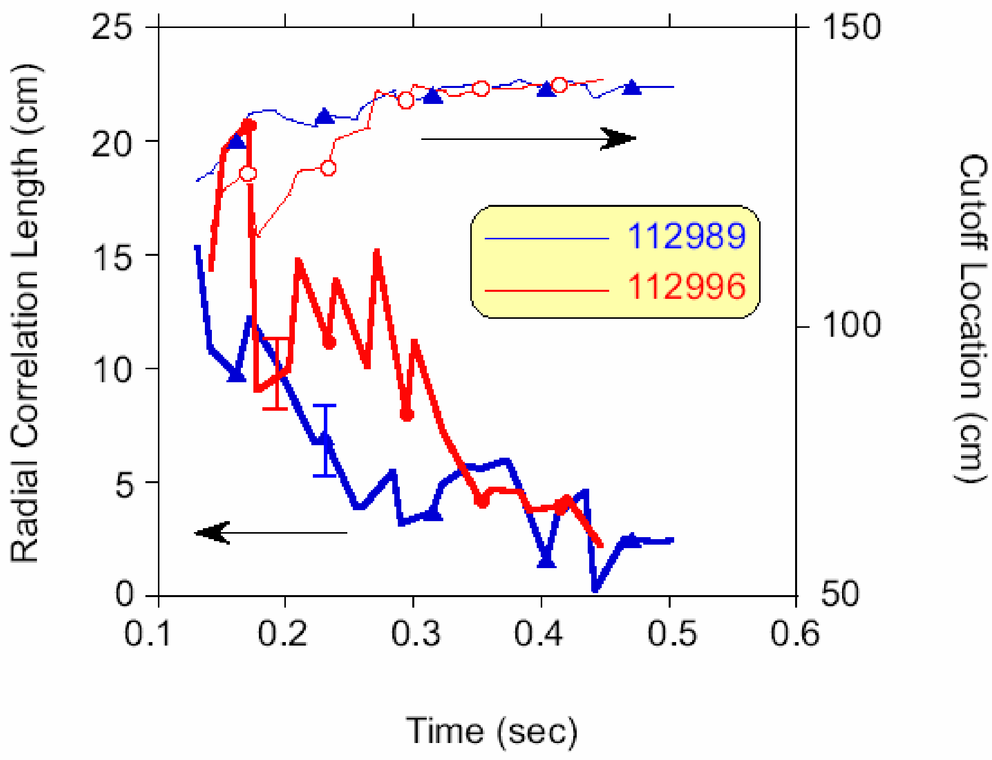
Linear analysis underway for other times

Non-linear analysis also underway

Core Turbulence Measured in Low Density L-modes

Turbulence measured for r/a ~ 0.2 to 0.65

Long-λ turbulence correlation lengths generally larger in non-reversed shear discharge (112996)

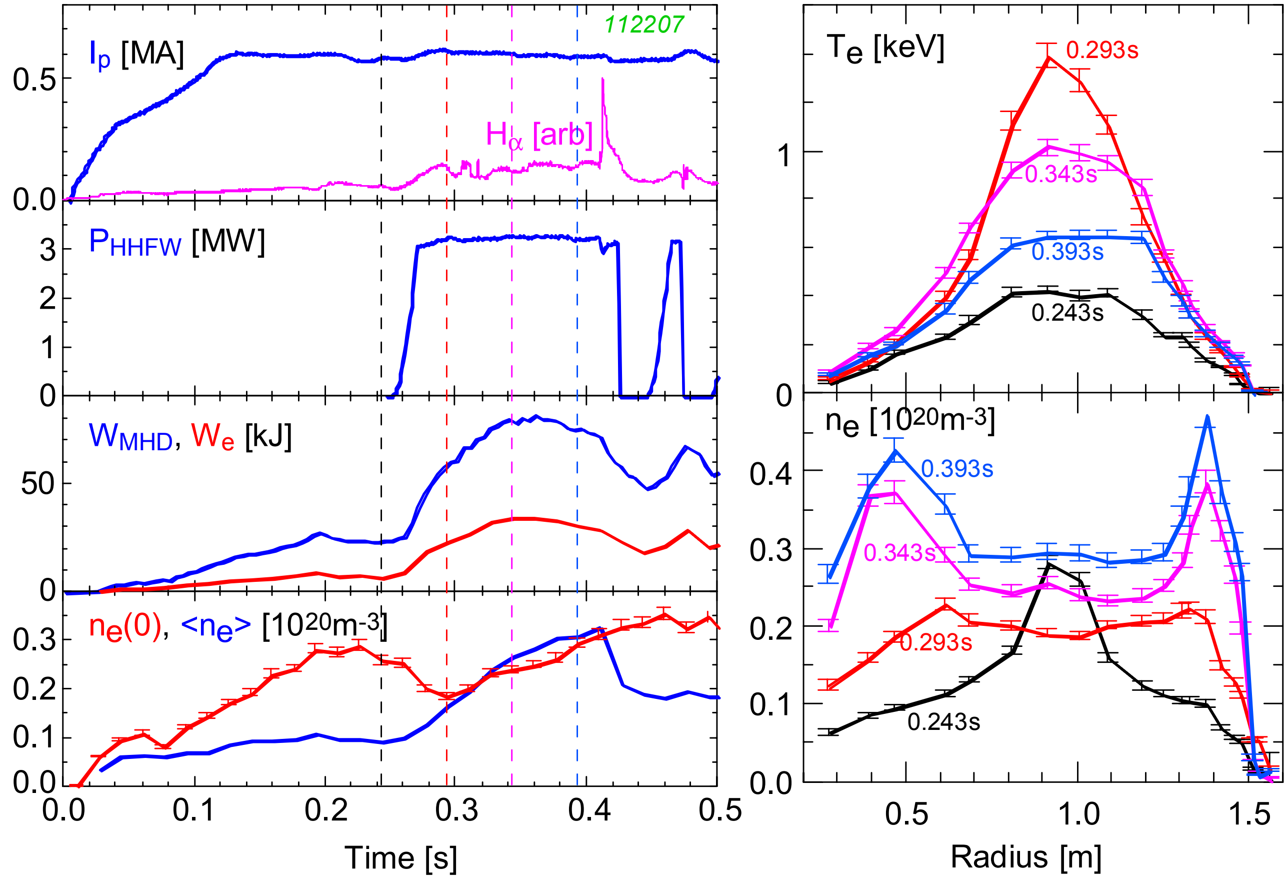


Details given by T. Peebles

Waves and Energetic Particles

- HHFW heating
  - H-mode (LeBlanc)
  - HHFW+NBI compatibility (LeBlanc)
- HHFW Deposition (Wilson)
  - Edge coupling effects (Biewer)
- HHFW Current Drive (Ryan)
- EBW emission assessment (Taylor)
- Energetic particle confinement (Medley)
- Energetic particle modes
  - Collective fast ions (Fredrickson)
  - Stabilization of chirping modes with RF (Heidbrink)

H-mode Operation Regime Extended to Higher Current During FY04 run (500 → 800 kA)



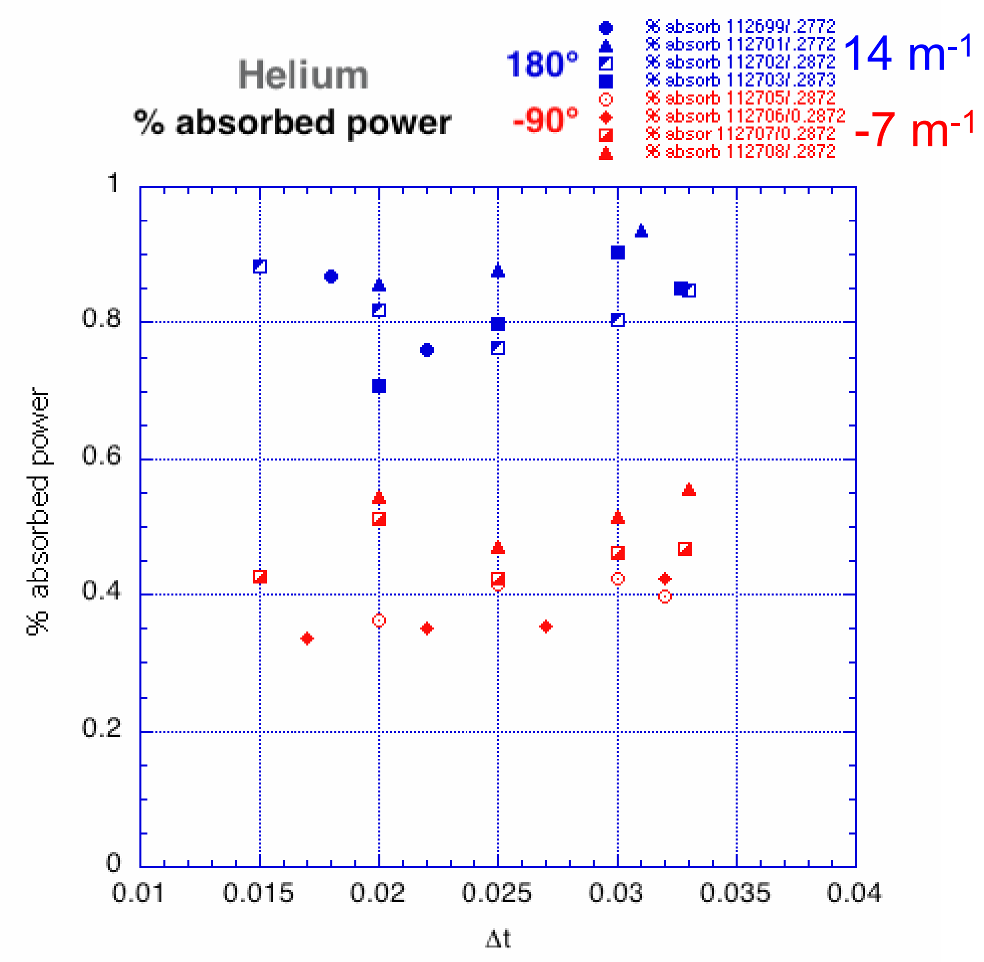
$k_{||}=14\ m^{-1}$

Confinement near L-mode scaling value assuming 100% absorption

NSTX

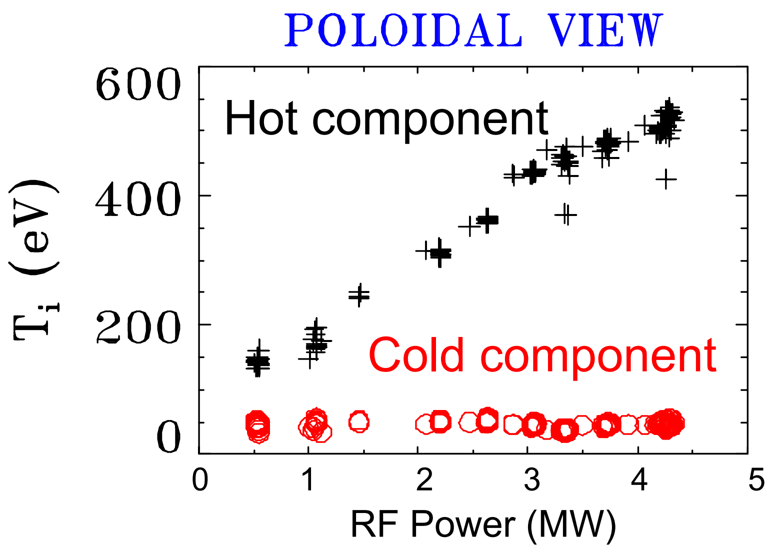
Degree of Absorption Assessed by Performing HHFW Modulation Exp'ts

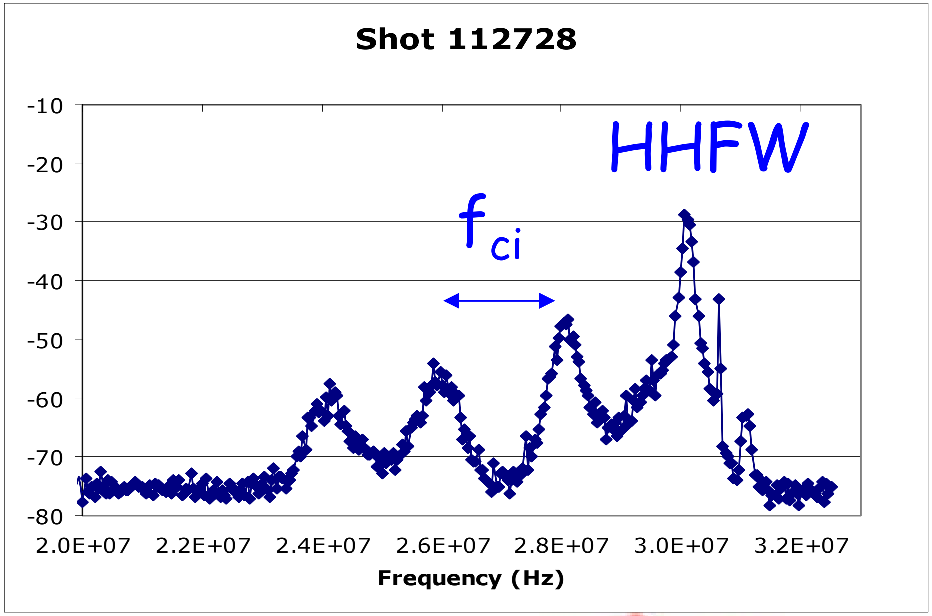
- Heating efficiency decreases with $k_{||}$
- +90° (counter CD) is more efficient than –90° (co-CD)
- -30° does not produce any heating
- Strong absorption by fast ions when NBI on



Parametric Decay of HHFW and Edge Thermal Ion Heating May Account for Reduced Core Absorption

- Edge ion heating observed with ERD during HHFW
- Waves, believed to be parametric decay of the HHFW wave, were observed with RF probe
- Strong qualitative correlation between probe signals and edge heating
- Analysis underway to understand connections among parametric decay, edge heating and power absorption

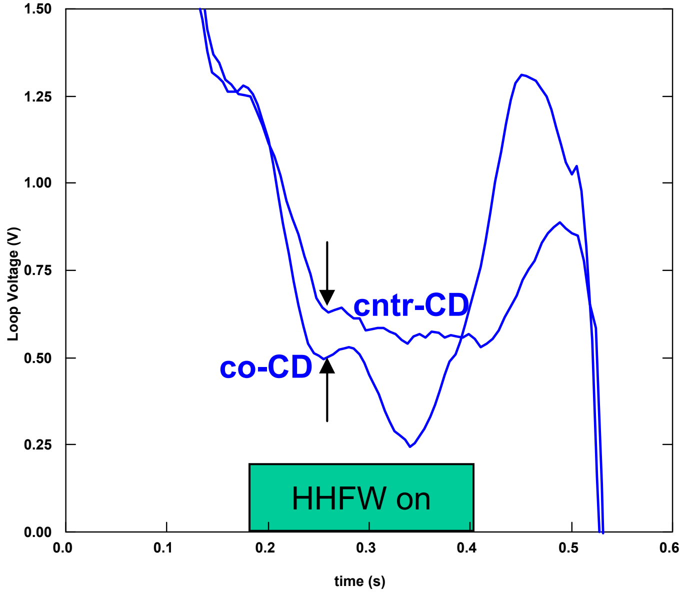




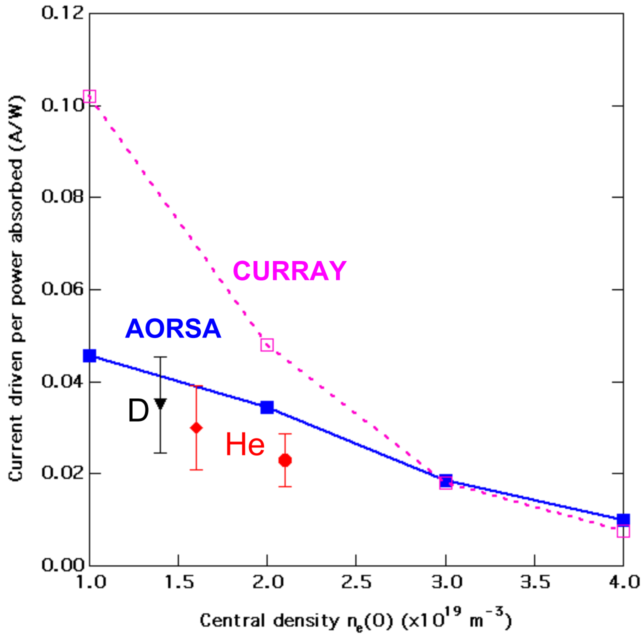
HHFW Tested as Tool to Drive Non-Inductive Current

- ΔI_{CD} ~ 100 kA for ΔP = 4.2 MW (2.7 MW co-CD, 1.5 MW cntr-CD).
  - $T_e(0)$ = 1.7 keV, $n_e(0) = 2.1 \times 10^{19}$ m^{-3}, He, double-null diverted, I_p = 0.5 MA, 0.45 T
  - 30% higher density operation for HHFW CD in FY04
- CD efficiency consistent with value from AORSA full-wave code, assuming 100% absorption

V_{loop} comparison at I_p = 0.5 MA for 112309 (2.7 MW, co-CD) and 112320 (1.5 MW, cntr-CD)

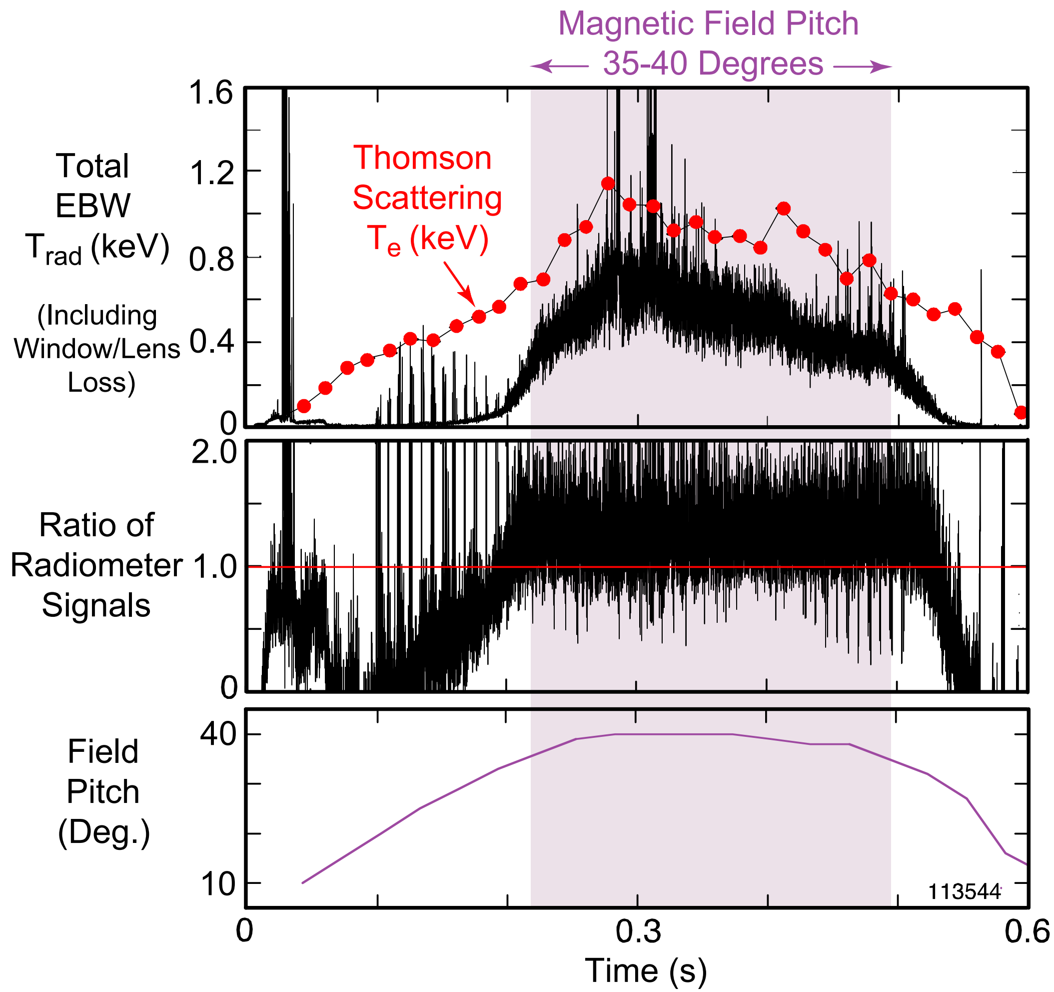


Measured HHFW CD lower than predicted



EBW Being Assessed for Heating and Non-Inductive Current Drive

- 80-90% conversion efficiency required
  - Circular polarization maximizes conversion efficiency
  - Data confirms modeling results and supports the conversion efficiency requirement
- Details and plans covered by G. Taylor

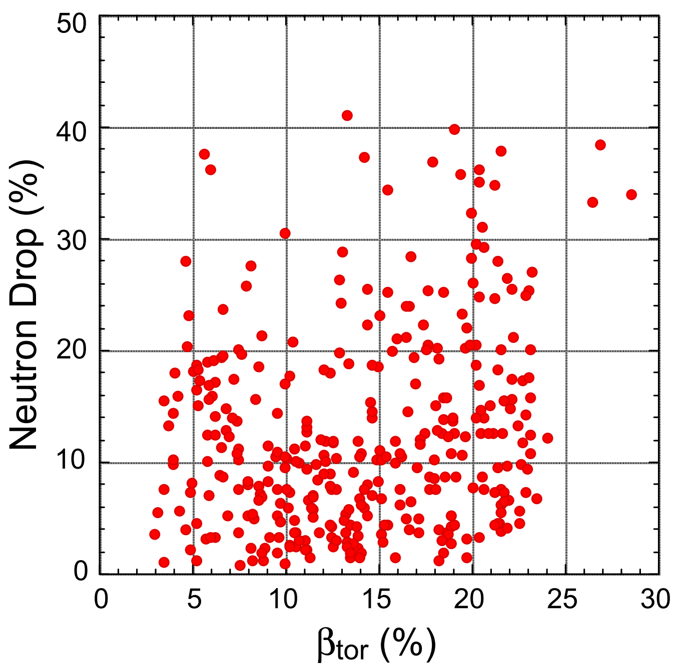


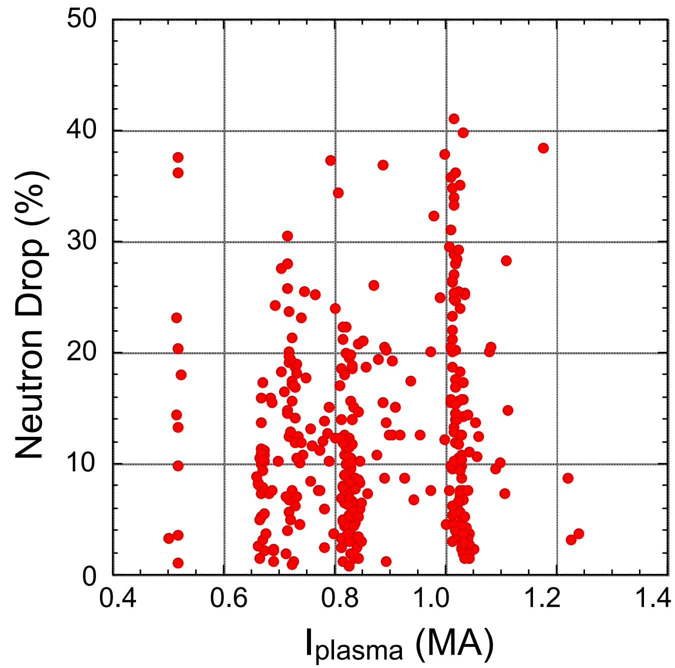
Emission Data Frequency = 16.5 GHz

Experimental Tests of Theories Indicate No Scaling of Fast Ion Loss with Plasma Current or β

- Both TAE and chirping modes (fishbones, rTAE) seen at <u>all</u> β
- **Thermal ion Landau damping** expected to stabilize TAE at high β
- **Precession drift reversal** expected to stabilize chirping modes at high β
- Reduced loss at high current expected (**smaller** ρ_{pol}*)

- Both TAE and chirping modes contribute to fast ion losses in these events





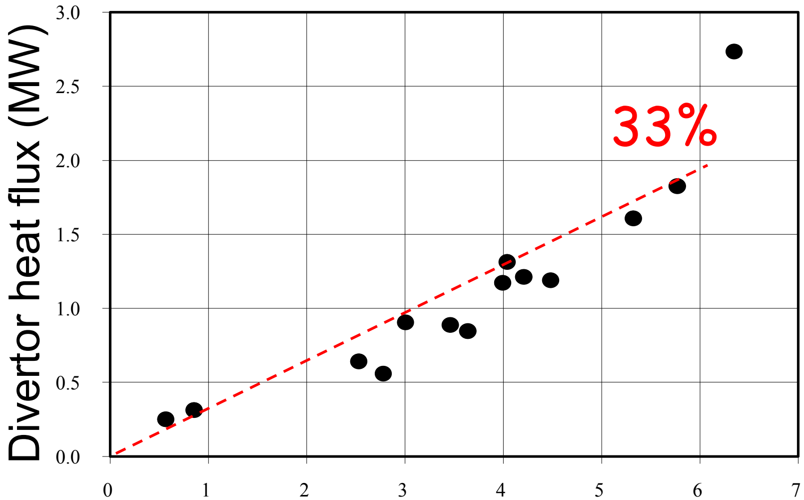
Possible impact on ITER needs to be studied

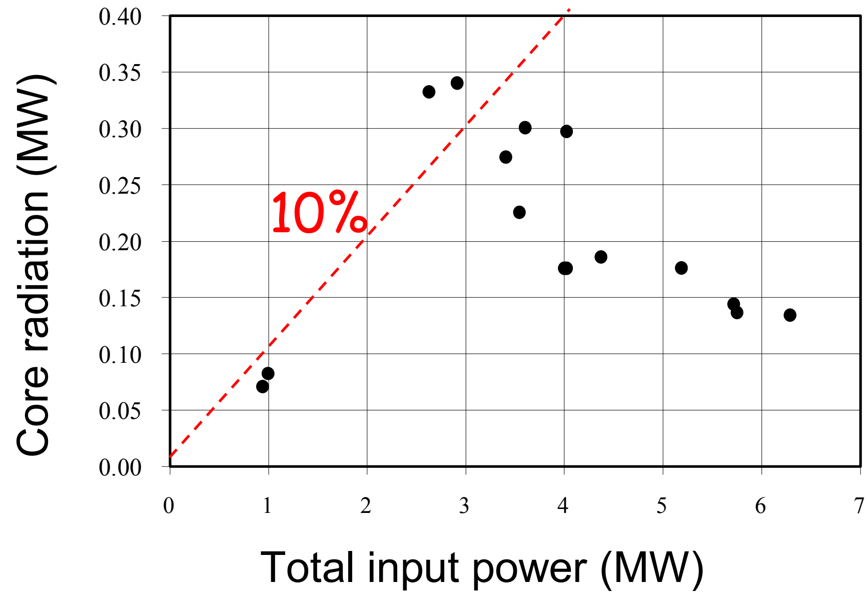
Plasma Boundary Interface

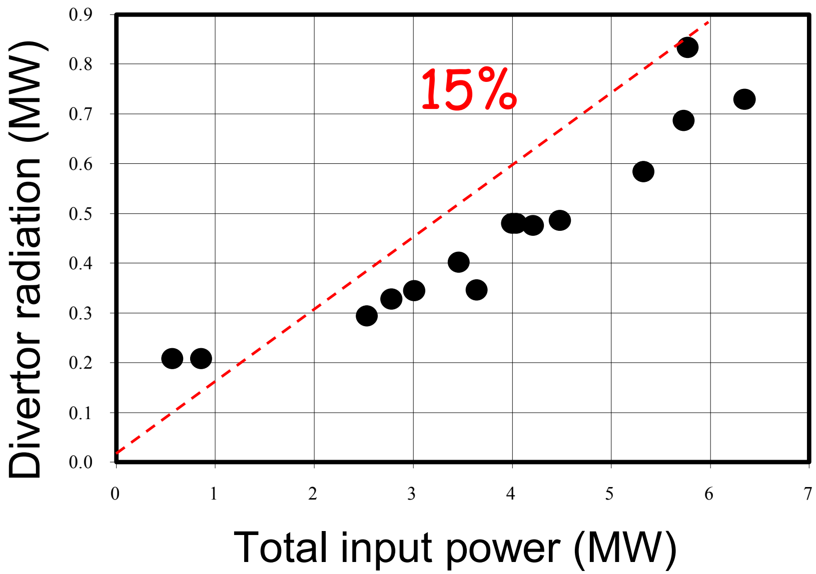
- Power and particle control
  - Morning/Between-shot boronization (Kugel)
    - Morning boronization restored/maintained good conditions
  - Li pellet injection (Kugel)
    - Injection into OH, L- and H-mode plasmas
    - Good penetration in OH
  - Supersonic gas injection (Soukhanovskii)
    - Initial operation – small inventory injected
    - Highly collimated, s-s gas jet observed
  - Divertor detachment (Soukhanovskii)
- Edge characterization
  - Power accounting (Paul)
  - Edge flows vs plasma configuration (Biewer)
- Edge turbulence (Boedo, Zweben, Nishino)
- ELM studies
  - Characterization (Maingi)
  - Shape dependence/Mitigation (Kaye)

Movie of Li pellet injection

60-80% Power Accountability in LSN-NBI Discharges



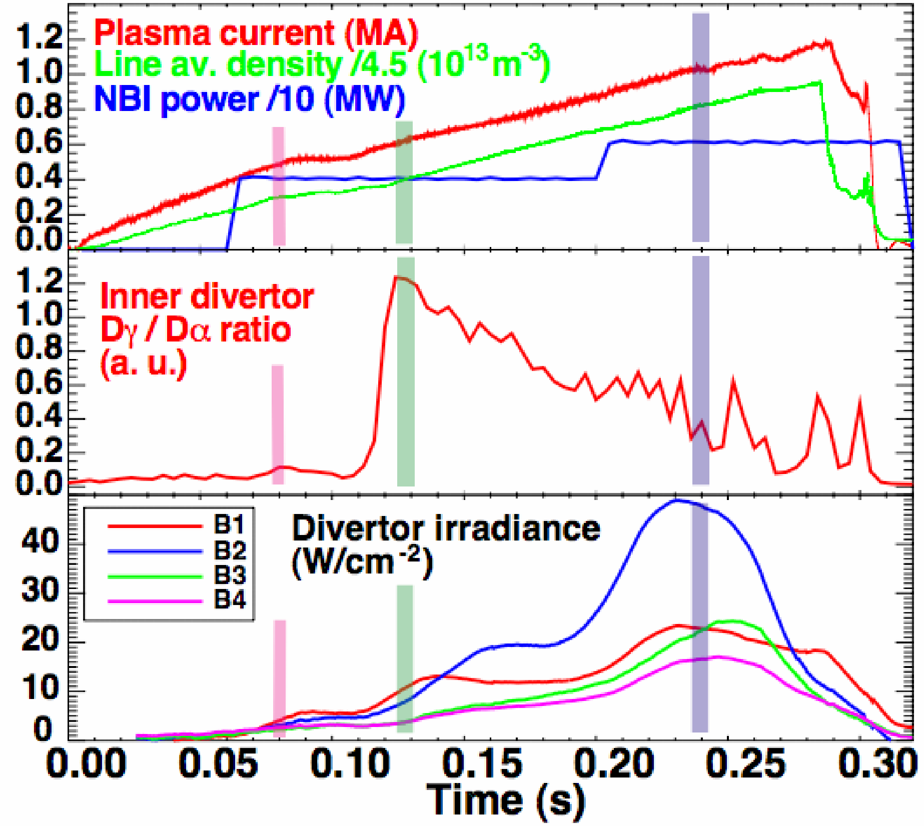




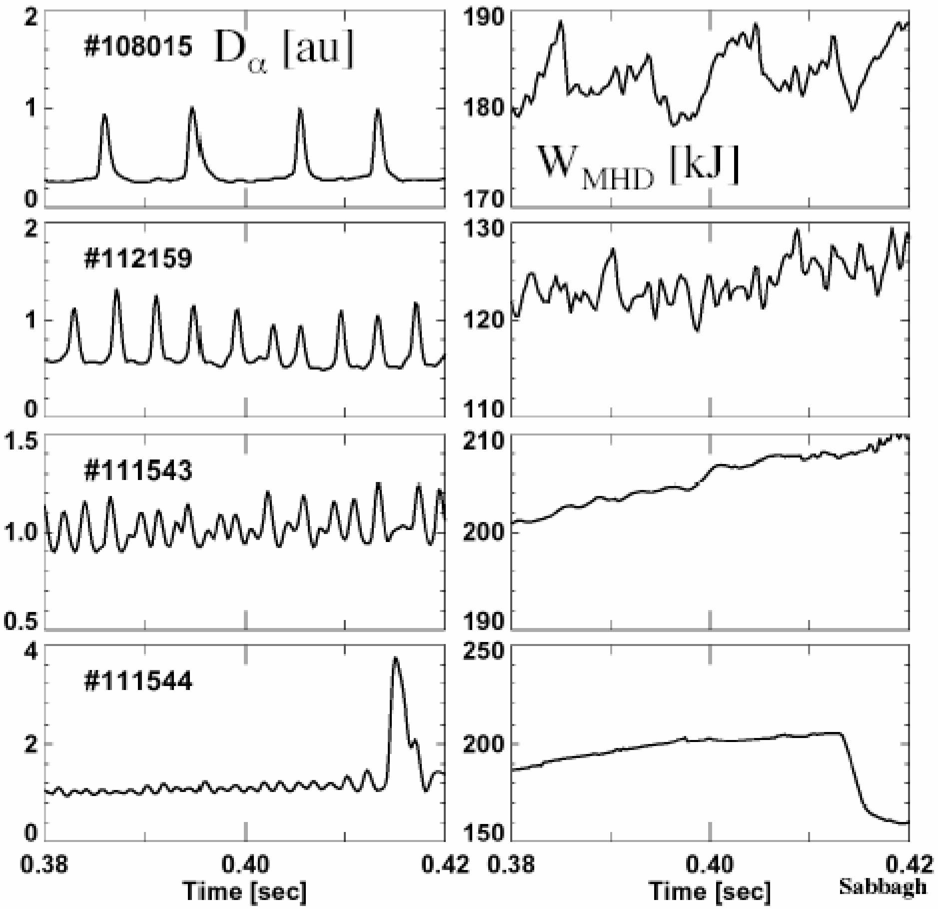
- 20% fast ion loss (calculated)
- 85-90% accountability in DND

Detached Inner Divertor Leads to Low Heat Flux

- $q_{heat} < 1\ MW/m^2$
- High D_γ/D_α, Stark broadened Balmer series lines on inner divertor indicate high n_e, low T_e region
  - Detachment
- Outer divertor always attached
  - $q_{heat} < 10\ MW/m^2$
- Challenge is to develop scenarios for outer divertor detachment



A Variety of ELMs Observed on NSTX



Type I - Mid ΔW_{MHD}
No magnetic pre-cursor
$P_{heat} >> P_{L\text{-}H}$

Type III - Small ΔW_{MHD}
Magnetic signature
And low frequency pre-cursor

NEW, type V
Tiny(?) ΔW_{MHD}
Magnetic signature n=1
No clear pre-cursor

Mixed Type V + 'Giant ELM'
(couples to core mode?)
Large ΔW_{MHD}

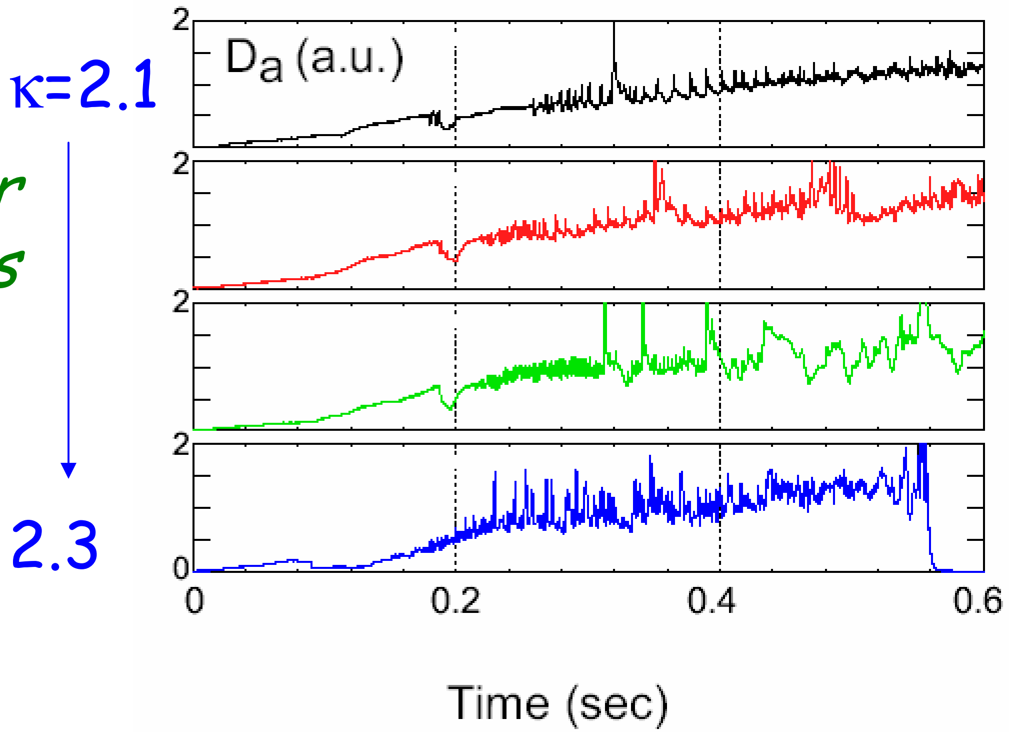
ELM control critical to optimizing performance

Movie of Type I ELM from GPI, Type V/I from Divertor Camera, L-H Transition

ELM Severity Found to Depend Sensitively on Plasma Elongation

- No dependence on X-point position
- Attempts to isolate triangularity, squareness indicate more (operational) development work needed
- ELMs less severe at higher I_p

Understanding ELM stability will require higher resolution edge diagnostics
MPTS
MSE
CHERS



NSTX Addressed a Broad Spectrum of Scientific Issues During Successful FY04 Run

- Experiments addressed FESAC priority science issues and added to our understanding of fundamental toroidal physics
- Experimental proposals took advantage of significant new facility and diagnostic capabilities
- 21 run weeks allowed us to develop and carry out a comprehensive science program
- Key results included
  - Improved plasma control and routine high elongation
  - High β_T for long duration (several τ_E)
  - Expanded operating range to low density with EF/RWM control coil
    - Initial Error Field Amplification experiments performed
  - Confinement and transport scaling
    - Effect of strong sheared flow
    - Relation to core turbulence
    - Relation to gyrokinetic calculations (linear and non-linear)
  - Current profile measurements
    - Will expand our analysis capabilities