Heating and Current Drive Topical Science Area

by
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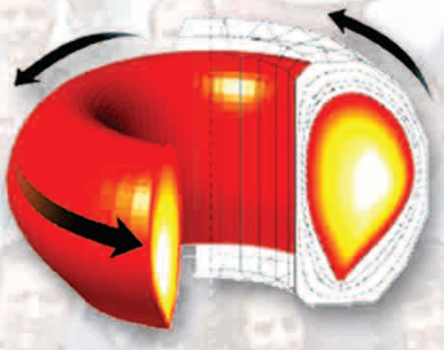
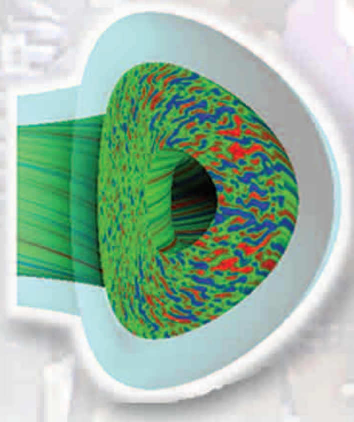
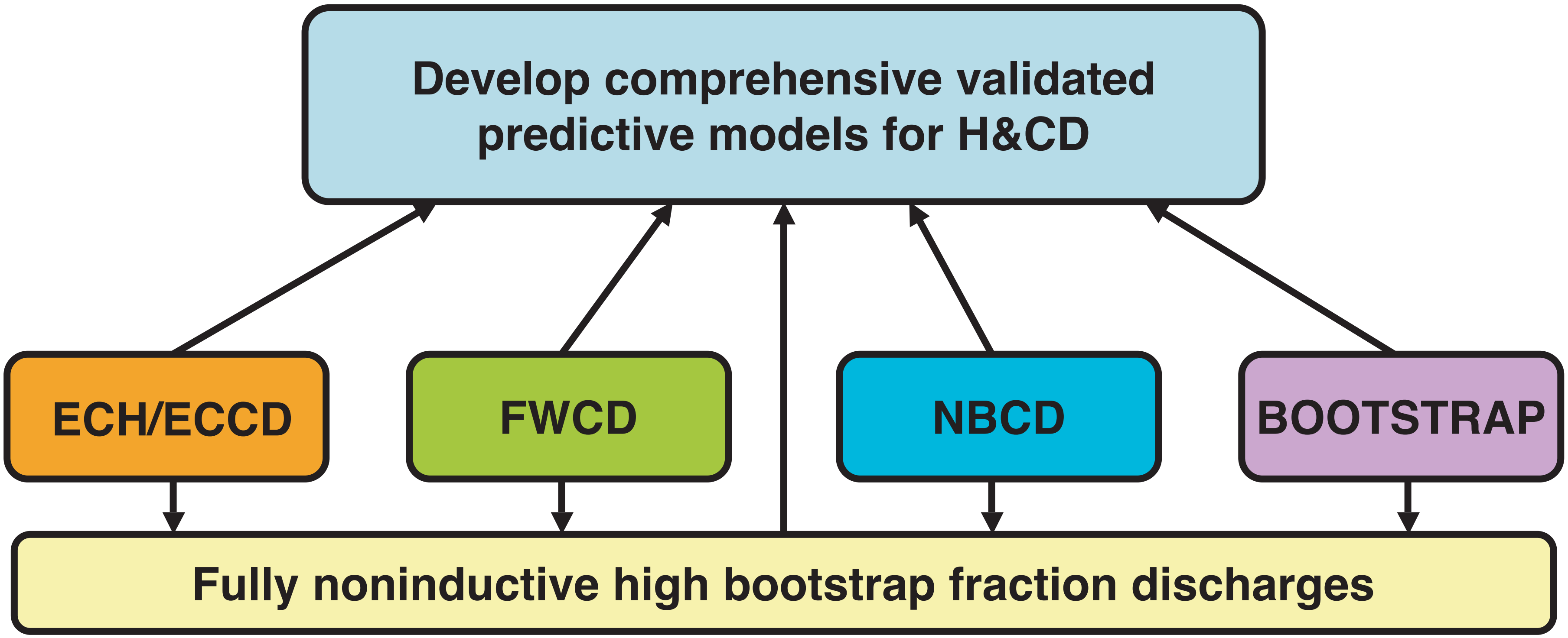


Presented to
DIII–D Program
Advisory Committee



January 31– February 2, 2006

Heating and Current Drive Topical Science Area: Goals



Predictive Understanding of H&CD is Important for ITER

- H&CD systems must be designed and fully implemented long before experiments are begun, and changes will be expensive, lengthy, and difficult
- Development of reliable predictive models in advance of the ITER final design is extremely cost-effective
- The H&CD program on DIII–D is well focused on testing of models

New Tools Are Available for H&CD in 2006–7

- **Higher ECH power with long pulses and all fully steerable antennas provides great flexibility and improved S/N for ECCD experiments**
- **Reversed neutral beam provides new capabilities**
  - Ability to distinguish NBCD from bootstrap current
  - Quantitative evaluation of NBCD and bootstrap current
  - New MSE and CER views for unambiguous measurement of E_r and improved reconstruction of equilibria
- **Lower high triangularity pump provides improved control of density for larger CD effects**
- **New tetrode (2007) and refurbished FWCD antenna provide improved performance of FWCD systems**
- **New diagnostics, like array of fast ion distribution measurements and new MSE and CER views, provide vital new information**

Theory and Modeling Tools Support H&CD Experiments

- **Traditional codes – TORAY-GA, CURRAY, GENRAY, CQL3D – are consistently being extended and improved**
  - Easily coupled to DIII–D modeling

- **New ORBIT-RF code provides very valuable insight into FW physics where nonMaxwellian distribution functions and ion orbit effects are required**

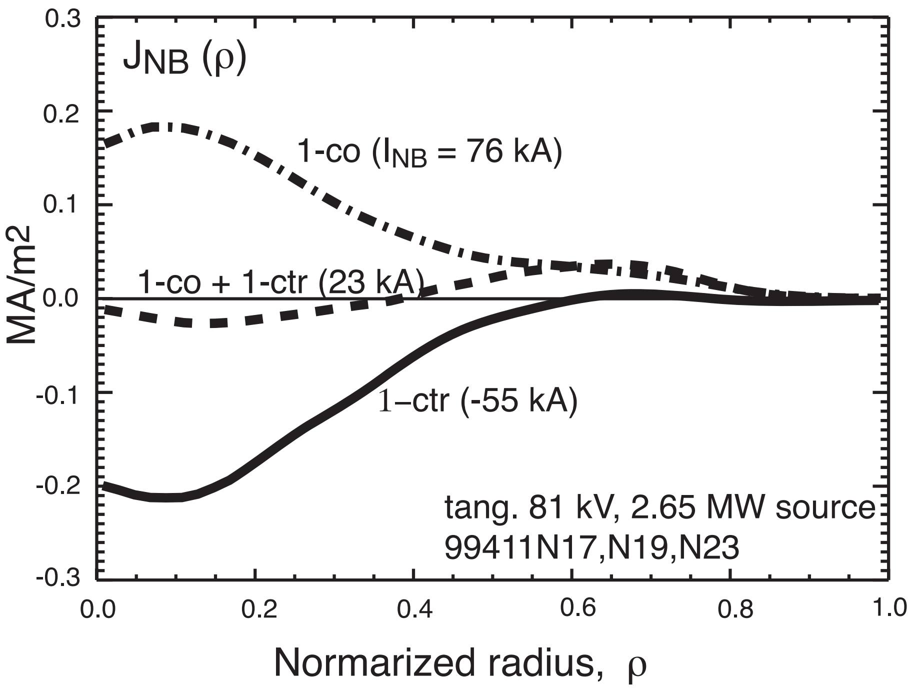
- **Excellent cooperation with MIT theorists and SciDAC group brings great theoretical and computational resources to bear on FW modeling**

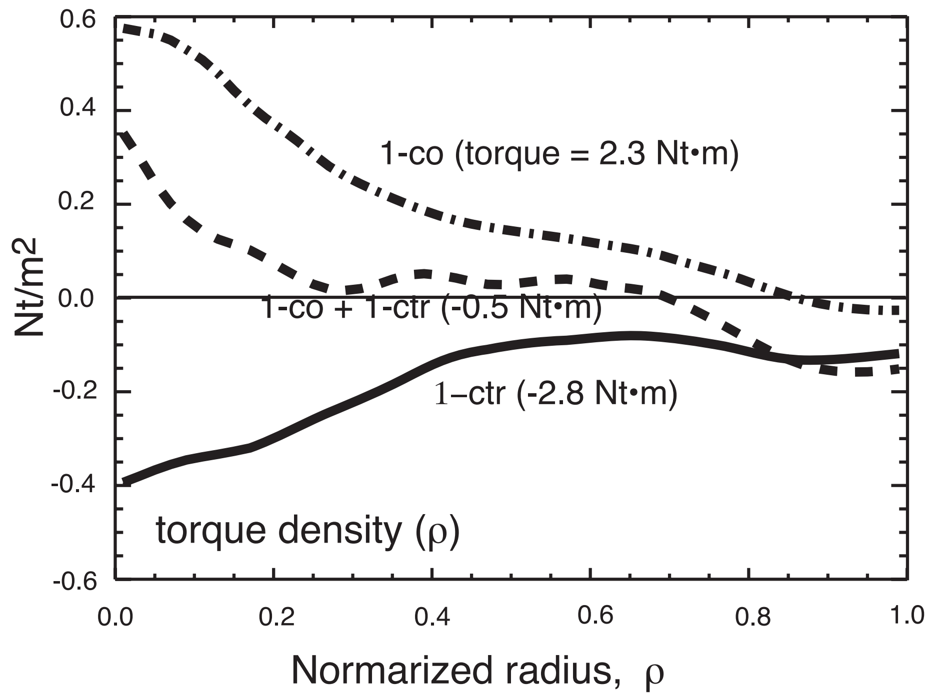
Reversed NB will Require Validation Prior to Routine Use

- **After operation is validated by the beam group, we need to compare power deposition, current drive profile, and applied torque for co- and counter -injection**
  - Provide a detailed comparison with models of NBCD and bootstrap current
  - Modulating co- and counter -NBCD out of phase provides a new level of accuracy
  - Use simplest case of no MHD, well confined orbits

- **One experiment day in early 2006**

Counter Beams Provide Ability to Control NBCD and Rotation



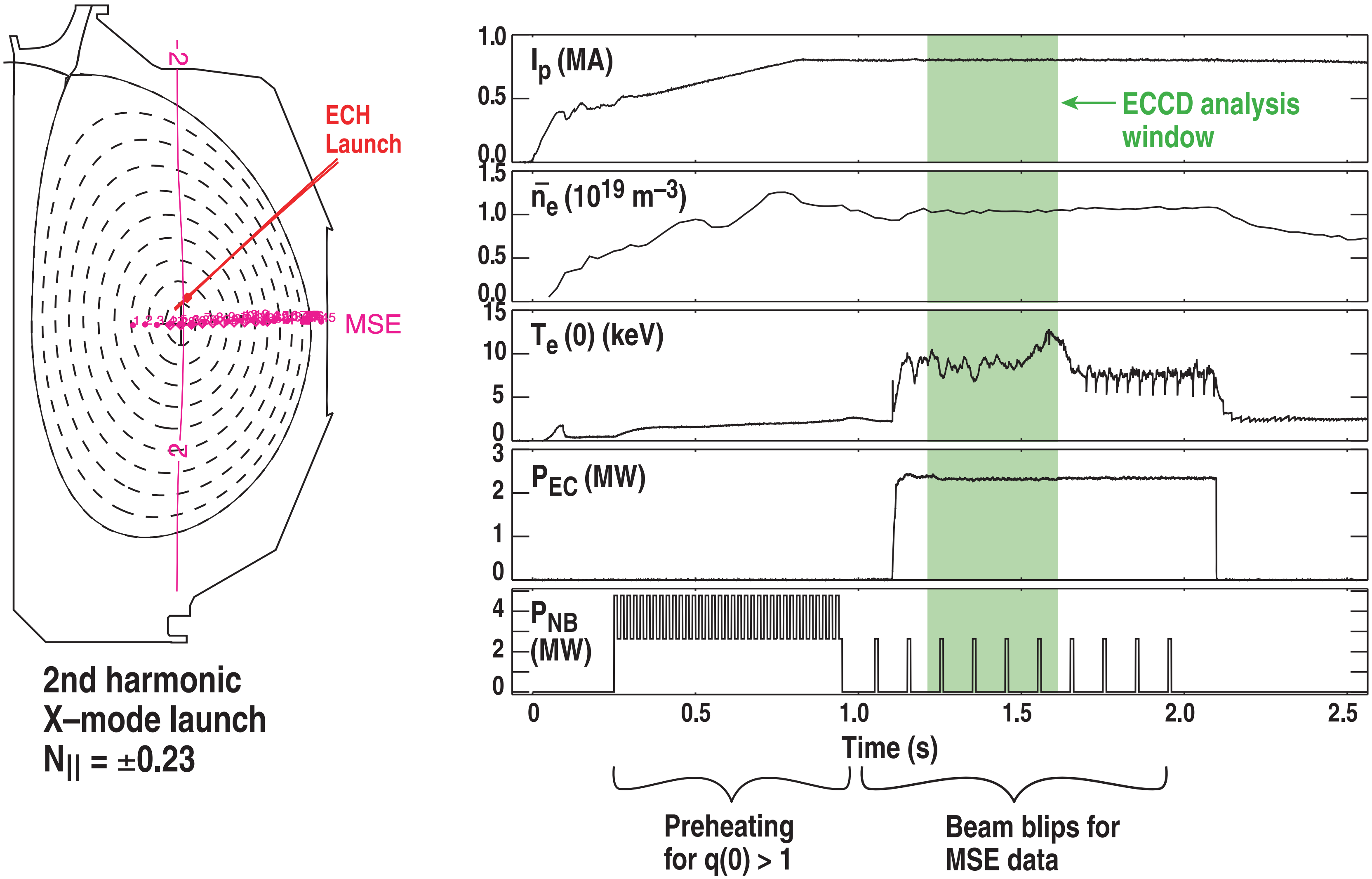


Modeling of ECCD is in Good Shape

- **Past work on DIII–D has validated the TORAY-GA/CQL3D model of ECCD for a range of conditions**
  - Need to extend validation from $\rho < 0.5$ to $\rho \sim 0.75$, which requires high power ECH

- **In 2005 experiments on ECCD at high T_e but low density showed agreement with CQL3D in a nonthermal plasma**
  - Need to extend validation to 10 keV in a thermal plasma

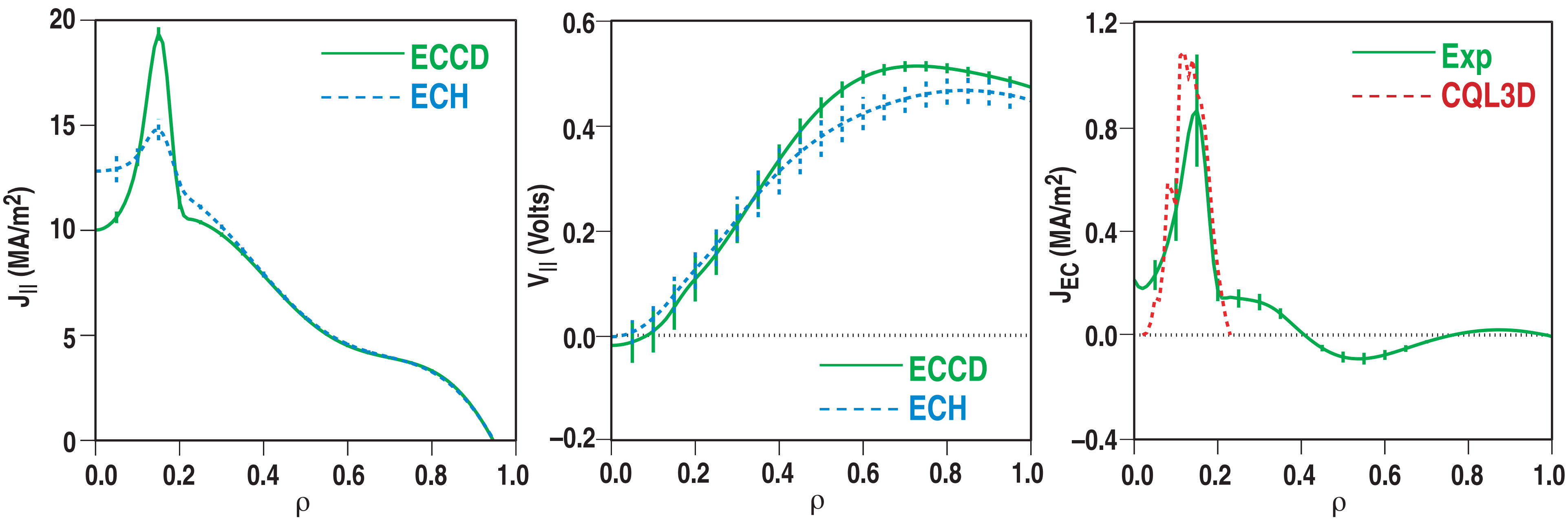
Nearly Central ECCD Measured in Low Density L–Mode Plasmas During Sawtooth-free Period



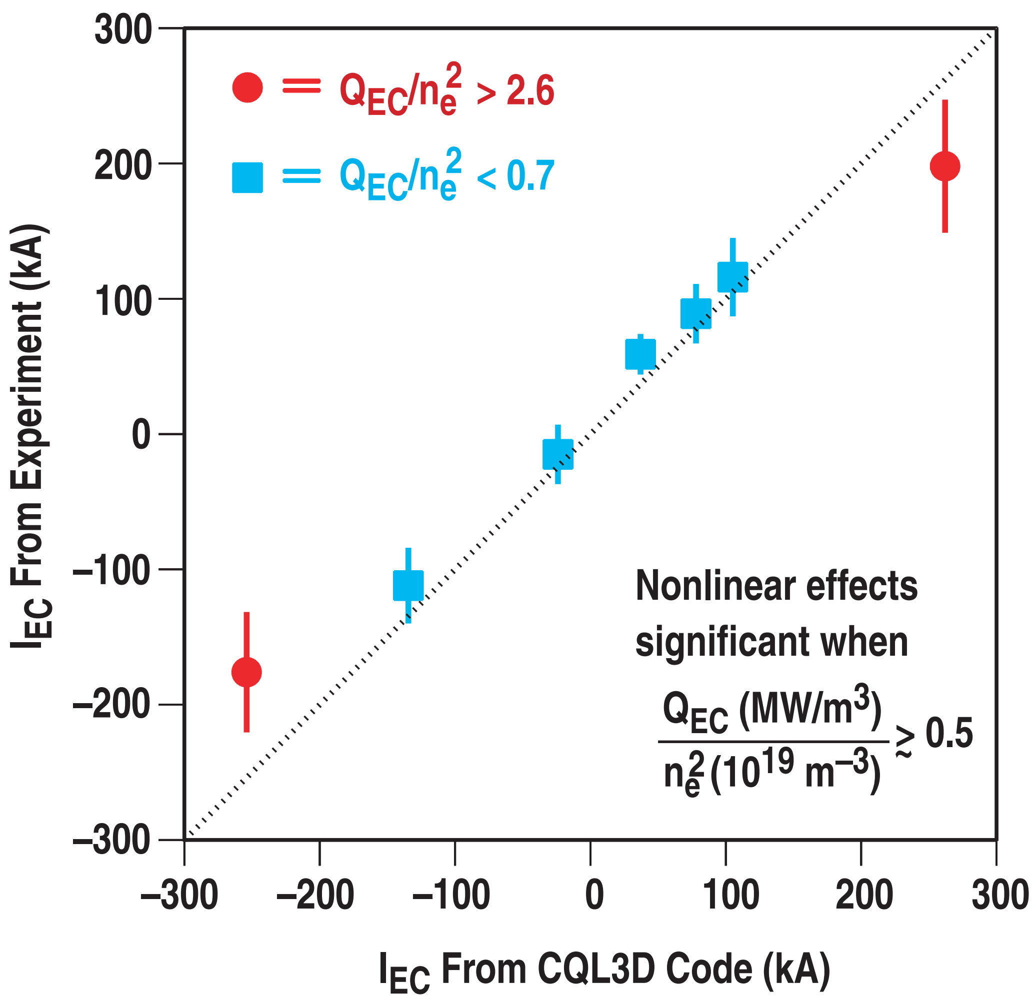
Narrow ECCD Profile is Measured By Loop Voltage Analysis of MSE EFITs for Single Gyrotron Case

$J_{NI} = J_{||} - \sigma_{neo} E_{||}$

$J_{EC} = J_{NI} \text{ (ECCD)} - J_{NI} \text{ (ECH)}$

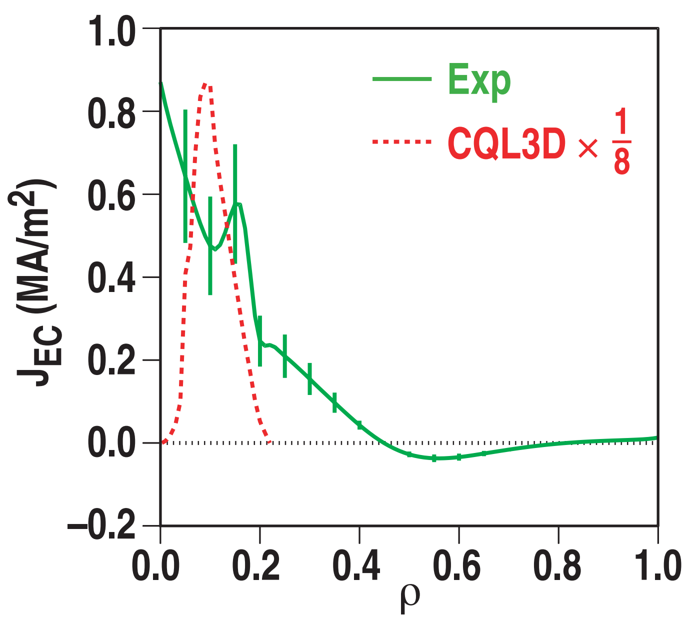


Experimental ECCD Agrees with CQL3D Fokker-Planck Code Except for Highest Relative Power Density Cases



T_e = 6 – 11 keV
$n_e = 1 - 3 \times 10^{19}\ m^{-3}$
P_{CD} = 0.6–2.3 MW

Radial transport may explain lower ECCD for high Q_{EC}/n_e^2 cases



Summary of ECCD in High T_e Discharges

- Experiments on DIII–D have measured up to 200 kA of ECCD at high electron temperture ($T_e \approx 10$ keV) in nonthermal plasmas
- Experimental ECCD is in agreement with CQL3D quasi-linear Fokker-Planck code except when $Q_{EC}/n_e^2 >> 1$
- Anomalously high radiation temperature (>20 keV) from non-thermal electron population is reproduced by Fokker-Planck code
- Future work on CQL3D will implement full transport modeling (real space and velocity space) that may bring theory and experiment closer together for $Q_{EC}/n_e^2 >> 1$

DIII–D ECH Resources for 2006–2007

- **Six CPI long pulse 1 MW gyrotrons**
  - Lion being repaired, Scarecrow working well
  - New gyrotrons Luke (May) and Leia (June) ready in early 2006
  - Depressed collector gyrotron Chewbacca by May
  - Tinman may be retrofitted with improved collector in cooperation with VLT
  - Improved sweeping of spent beam will be used to lengthen the fatigue life of collectors

- **Three PPPL antennas (P1999 no longer used)**
  - One will have fast steering capabilities for NTM experiments

- **Improved grid driver on ECH power supplies shows stability at high currents needed to run two gyrotrons**

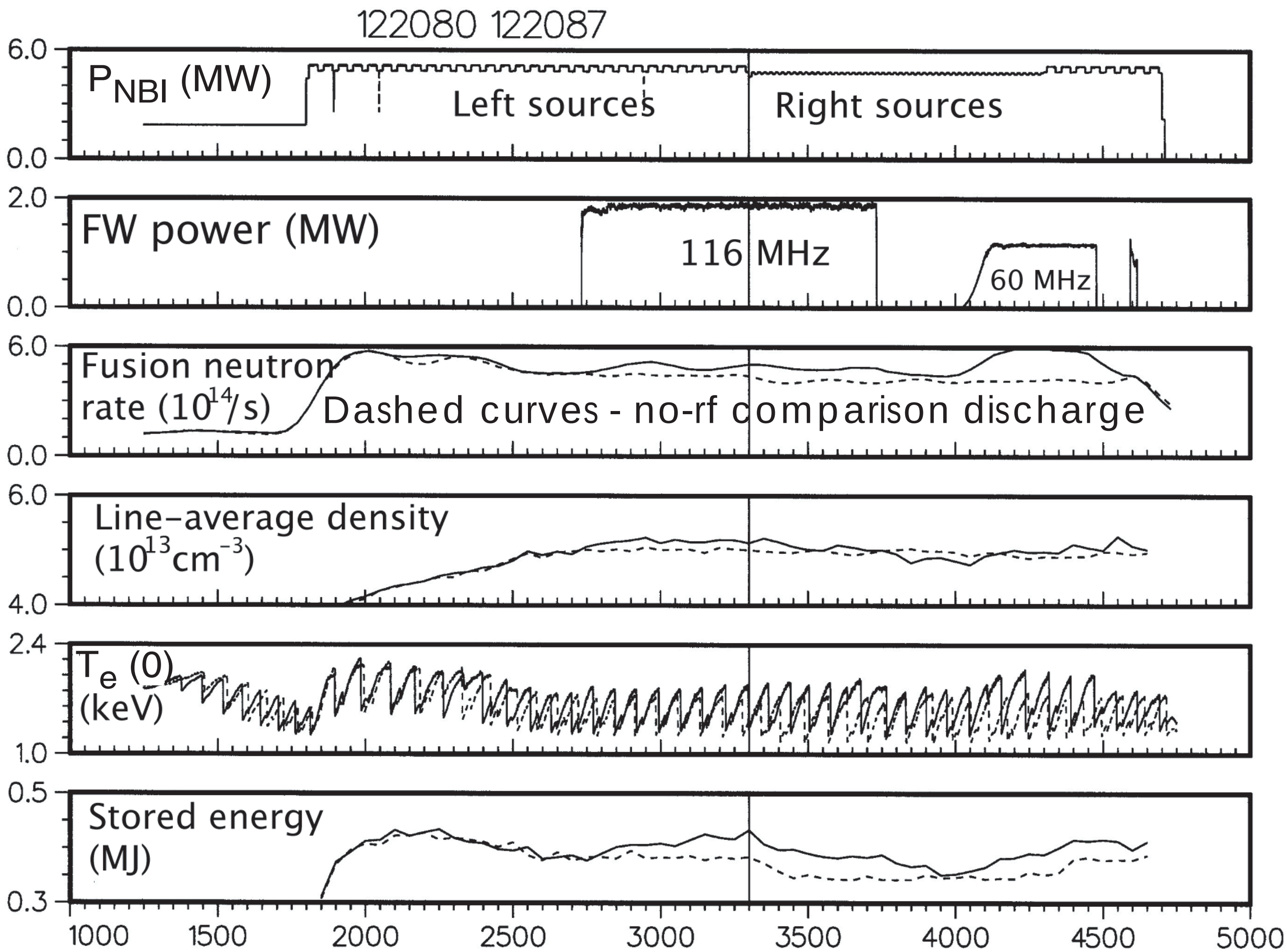
For FWCD, a Key Issue is Ion Cyclotron Absorption by Energetic Ions

- ITER will have alphas and injected beam ions, and FW power for heating and current drive
- Understanding absorption of FW power by energetic ions is essential for effective use on ITER
- Experiments were done on DIII–D in 2005 on wave damping at 4th–8th harmonic by neutral beam ions

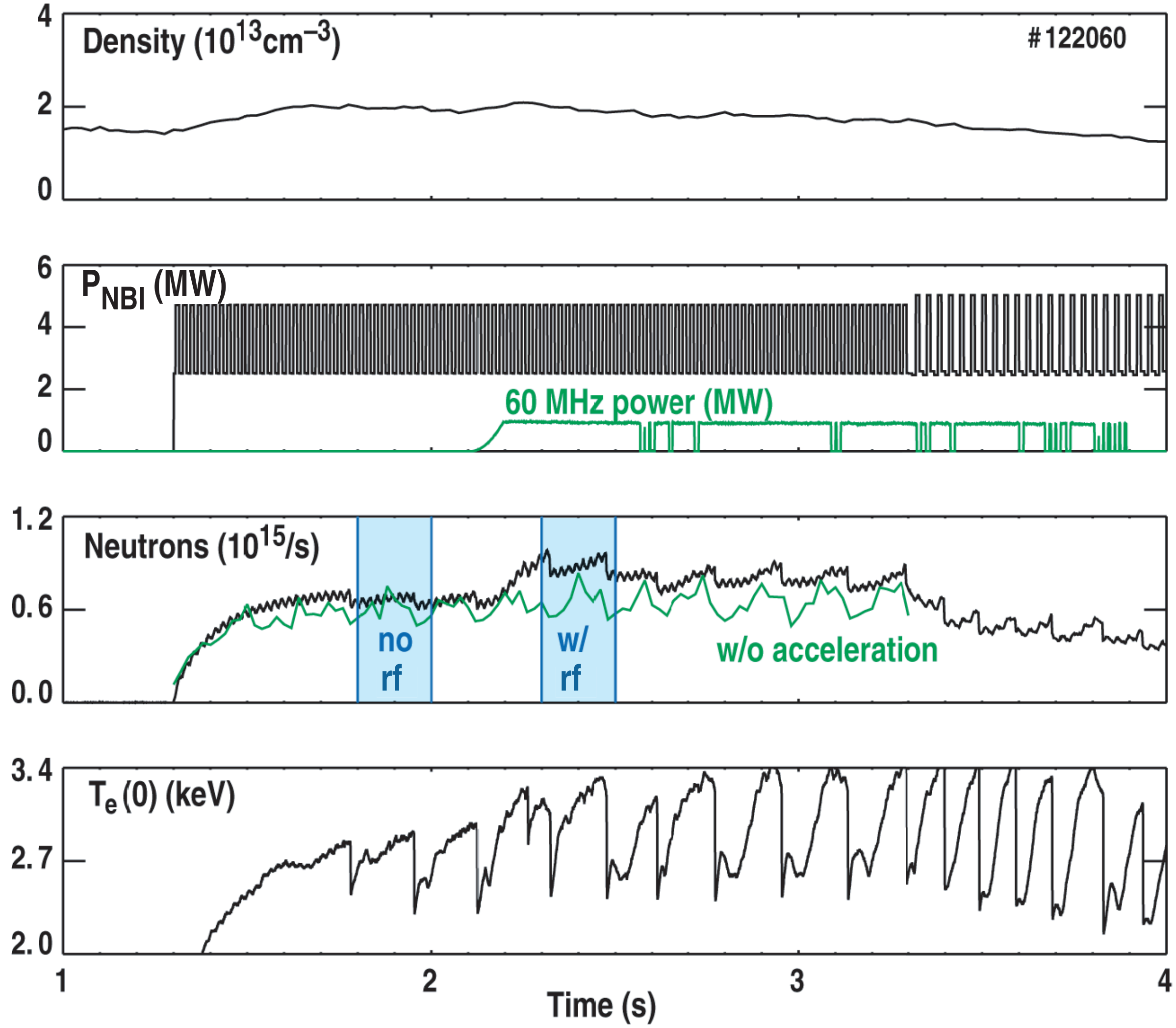
Ion Cyclotron Damping of Fast Waves on Beams

- In FY05, a new fast ion diagnostic was added to our toolkit for these studies: UCI D_α CER diagnostic prototype
- A sum of about two days was devoted to this topic in FY04–05
- Coupled FW power levels of up to 3 MW were achieved
- Strong absorption at 4th, 5th harmonics of 60 MHz demonstrated; fast ion acceleration observed with D_α CER
- Damping at 8th harmonic (~116 MHz) found to be weak compared with 4th harmonic at 1.9 T
- Theoretical picture is not clear at the moment; subject of much ongoing activity

$4\Omega_D$ Absorption Stronger than $8\Omega_D$ at Same B_T in High Density L-Mode

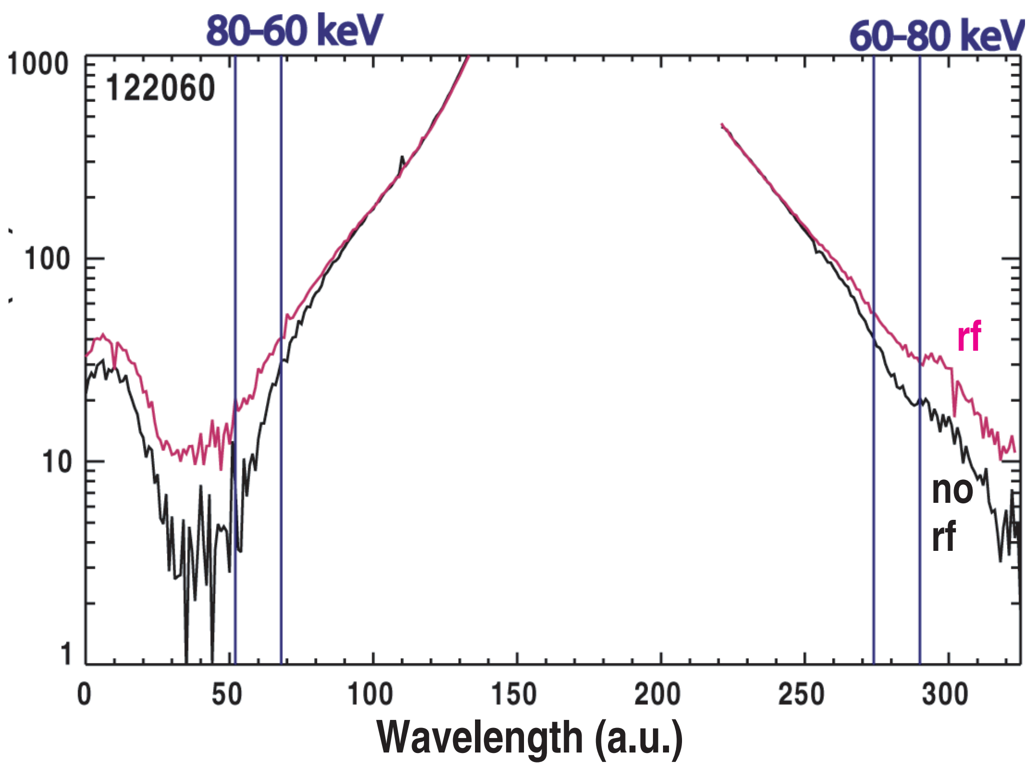


D_α Spectrum: Perpendicular Fast Ion Tail Observed During 4th Harmonic Heating



D_α measurement periods are shaded

D_α Spectrum: Perpendicular Fast Ion Tail Observed During 4th Harmonic Heating



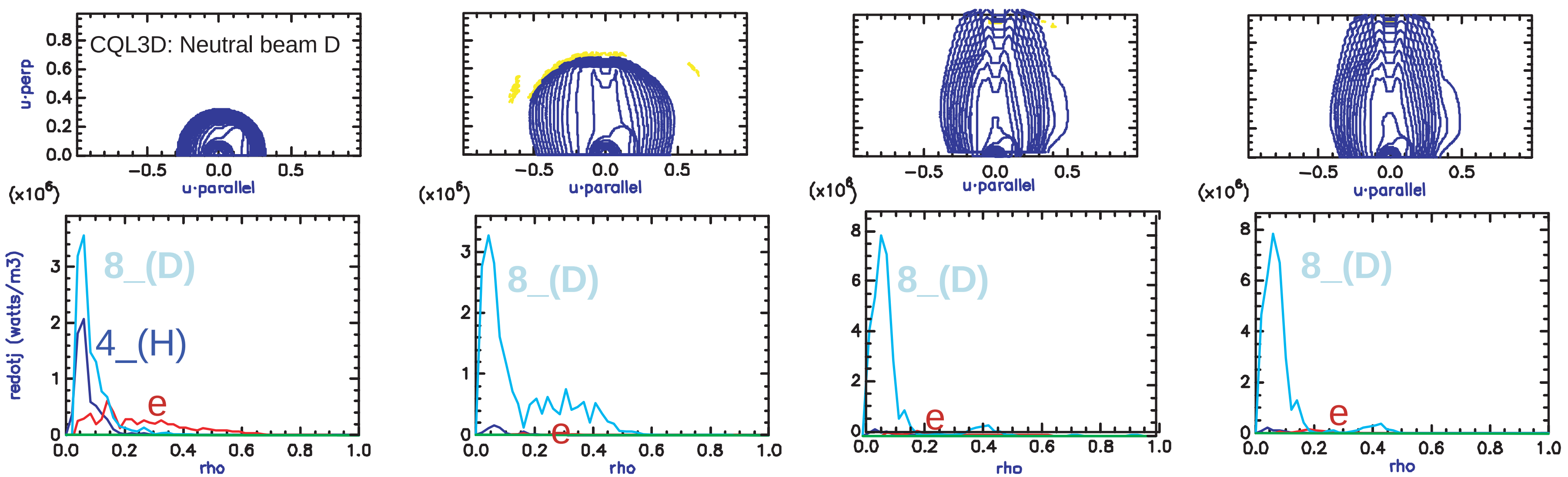
- Tail spectrum symmetric (expected for perpendicular ions)
- Spectrum altered at high energies (high harmonic heating)
- Signal between 60–80 keV increases 65% with rf
- Ions accelerated above injection energy
- Tail correlates with neutron enhancement

From 2005 APS invited talk by Fred Jaeger (ORNL)

At 116 MHz, about 95% of the power is absorbed by the deuterium beam

DIII-D shot 122080 (B. Pinsker) at *f* = 116 MHz (8th harmonic D; non-Maxwellian) and 2% minority H (4th harmonic H, Maxwellian)

0th iteration	1st iteration	7th iteration	8th iteration
$P_{RF} = 0$	$P_{RF} = 1.6$ MW	$P_{RF} = 1.6$ MW	$P_{RF} = 1.6$ MW



P(D) = .55 MW	P(D) = 1.54MW	P(D) = 1.47 MW	P(D) = 1.50 MW
= 34.5 %	= 96.2 %	= 92.3 %	= 94.6 %

This is in disagreement with the experiment which shows little power absorbed at the 8th harmonic (One possible explanation is that radial diffusion and finite orbit effects are becoming important at the higher frequency; see M. Choi's ORBIT-RF results, paper BO3.00013 at this meeting; also, B. Harvey's GENRAY/CQL3D results.)

DIII–D FW Resources for 2006

- **The ABB1/0 deg and ABB2/180 deg systems will be operated at a frequency ~90 MHz to reach a compromise between:**
  – High enough harmonic to avoid excessive damping on beams
  – Low enough to keep the current maxima well away from the feedthrough ceramics
  – High enough to have some advantage from antenna self-resonance (which occurs at ~115 MHz)
  – Low enough to be able to generate high power (2 MW below 80 MHz, 1 MW at 120 MHz)

- **Result will be <1.5 MW available at this frequency in 2006; maximum coupled power levels will depend on antenna performance in ELMing H–mode (not known at present)**

- **285/300 will be operating with refurbished antenna at 60 MHz: 2 MW available, but probably not able to couple more than 1 MW in ELMing H–mode**

Bootstrap Current Studies

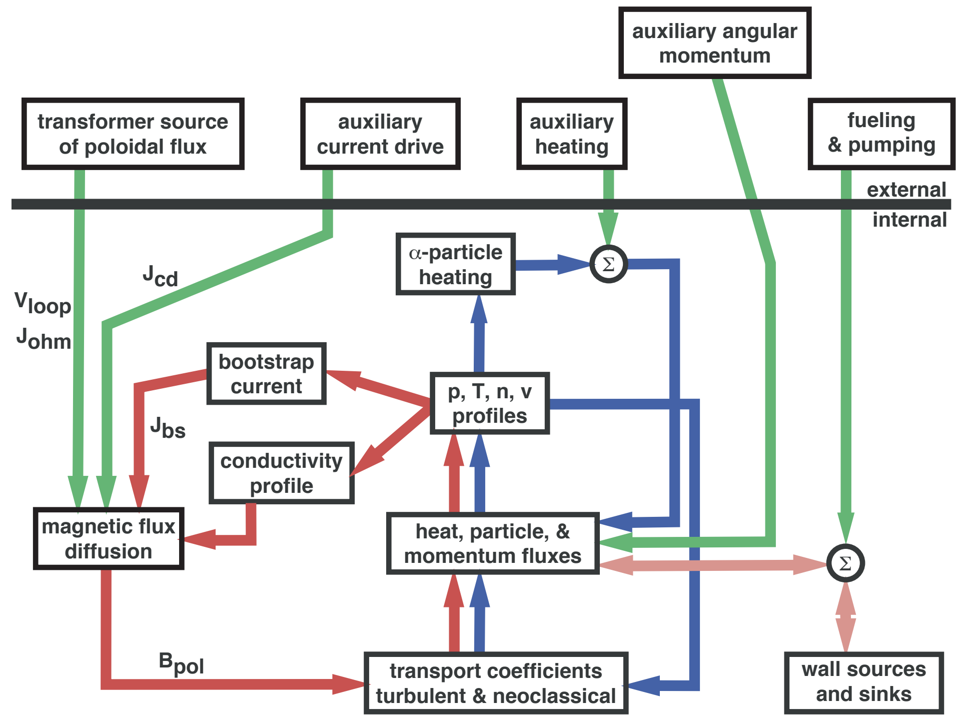
- Bootstrap current provides significant current in many ITER scenarios, but the models have not been validated in detail
- Core bootstrap current must be tested for its principal dependences
- Central bootstrap current where “potato orbits” dominate should be tested
- Pedestal bootstrap current has important effects on the edge stability

Pedestal Bootstrap Current Tests

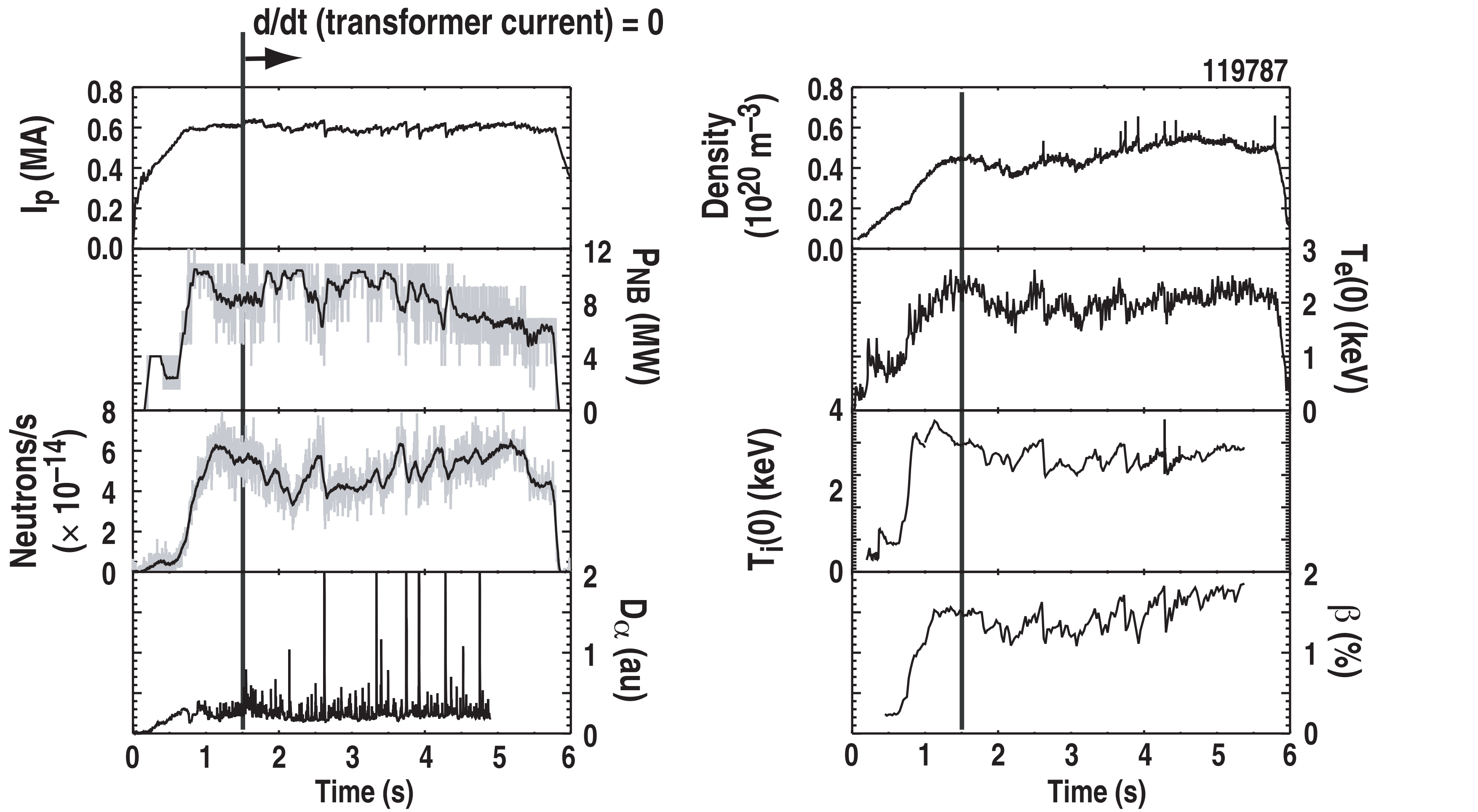
- **Pedestal performance (width and height) is critical to success of ITER**
- **The current profile near the H–mode pedestal strongly affects the plasma stability and performance. Measurements have shown existence of large edge currents in region of pedestal pressure gradient.**
  - Relatively good agreement with bootstrap current models under a limited set of conditions
  - General agreement is still an open question-need to validate and improve models
- **Goal is to test the bootstrap current under a variety of edge conditions with new measurements**
  - Improved LIBEAM performance
  - New edge MSE system
- **This experiment is the result of combining ideas from:**
  - H&DC and stability TSAs,
  - ELM thrust,
  - PedWid thrust
  - Ideas were grouped in this TSA to try and achieve a single day experiment

Studies of Stationary, High Bootstrap Fraction, Noninductive Plasmas

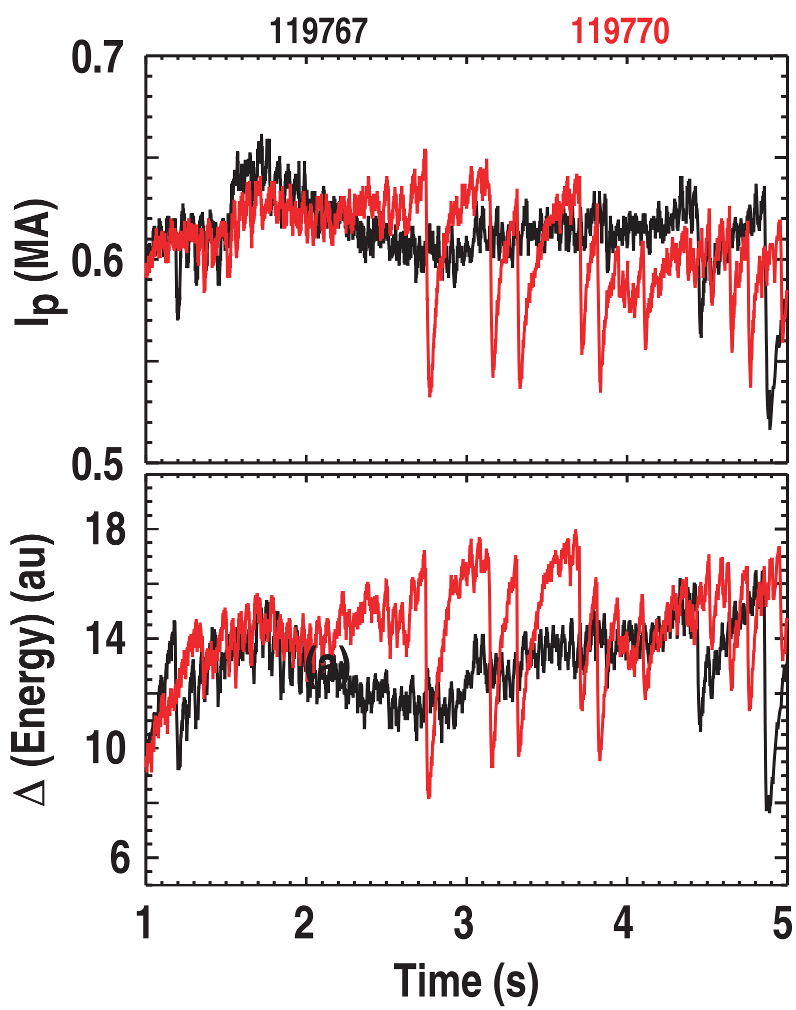
- Objective is to study the long-term evolution of discharges with high normalized performance (this doesn't necessarily require high absolute performance)
- Fully noninductive, high normalized performance, high bootstrap fraction, stationary current plasmas have been sustained without transformer assistance
- $I_p \approx 625$ kA, $\beta_p \approx \beta_N \approx 3.3$, $H_{89P} \approx 3$, $f_{bs} \approx 0.8$, noninductive for >4 s
- However, $q_{95} \approx 10$
- The objective is to study the self-consistent state of a plasma with maximum f_{bs} near the β limits



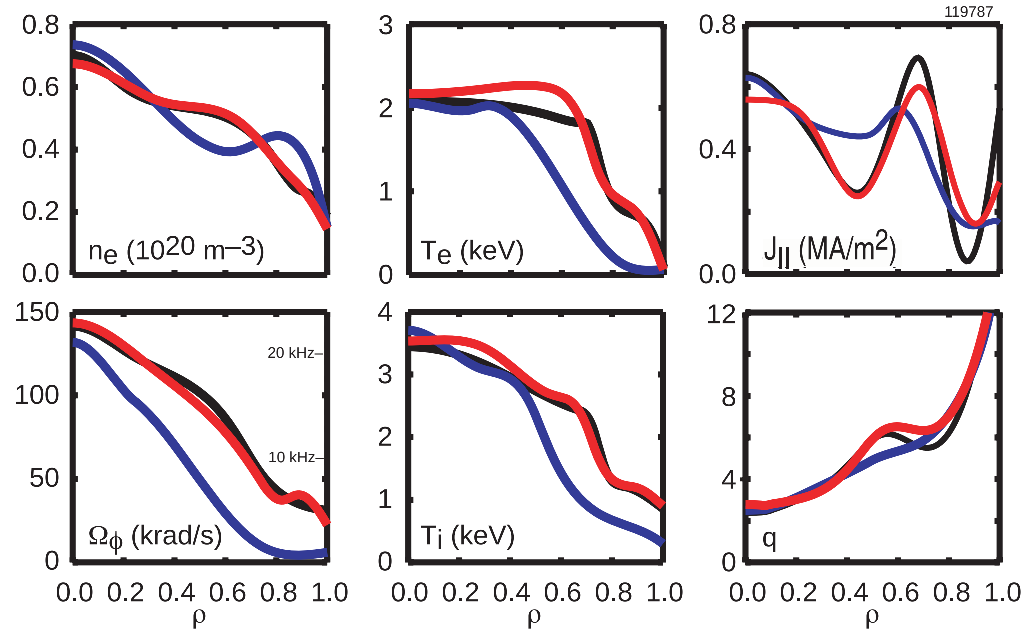
No Transformer (After Start-up), Improving β and H, for >4τ_R and ~1.5 Current Decay Times



β Limiting Process is Relaxation Oscillation of An ITB



- Increased power (by ~20%) leads to repeated formation and collapse of an ITB
- Collapse affects both stored energy and total current
- Plasma recovers previous state



H&CD Experiment Address Key Physics Issues

- **2006 experiments**
  - Validate neutral beam physics and current drive using reversed neutral beam
- **Experiments deferred to 2007 in 32-week plan**
  - Measure high harmonic FW absorption/theory
  - Measure perpendicular resistivity/theory
  - Advance fully noninductive discharges
  - Test theory of pedestal bootstrap current
  - Preionization and startup assist with 2nd harmonic ECH
  - “Alpha channeling” CD using NBI and TAEs
  - Far off-axis and high T_e ECCD
  - Test theory of core bootstrap current

Summary

- **The DIII–D H&CD program will use new heating systems and diagnostics to advance the validation of NBCD, ECCD, FWCD, and bootstrap current**
  - Good plasma science
  - Needed for effective use in the DIII–D program
  - Needed for ITER