Stationary, High Bootstrap Fraction Plasmas in DIII-D Without Inductive Current Control

P. A. Politzer,[1] A. W. Hyatt,[1] T. C. Luce,[1] F. W. Perkins,[4] R. Prater,[1] A. D. Turnbull,[1]
D. P. Brennan,[5] J. R. Ferron,[1] C. M. Greenfield,[1] R. J. Jayakumar,[2] R. J. LaHaye,[1]
E. A. Lazarus,[3] C. C. Petty,[1] and M. R. Wade[3]

[1]General Atomics, San Diego, California, USA
[2]Lawrence Livermore National Laboratory, Livermore, California, USA
[3]Oak Ridge National Laboratory, Oak Ridge Tennessee, USA
[4]Princeton Plasma Physics Laboratory, Princeton New Jersey, USA
[5]Massachusetts Institute of Technology, Cambridge, Massachusetts, USA

email: politzer@fusion.gat.com

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GENERAL ATOMICS

Summary & Observations:

✦ Fully noninductive, high performance (normalized), high bootstrap fraction, stationary current plasmas have been sustained in DIII-D without transformer assistance.

☞ $I_p \approx 625$ kA, $\beta_p \approx \beta_N \approx 3.3$, $H_{89P} \approx 3$, $f_{bs} \approx 0.8$, $q_{95} \approx 10$.

✦ The total current evolves as expected for a bootstrap-current-dominated plasma; current sustainment is favored by high density, high β_p, and low ℓ_i.

✦ For a range of initial values, the plasma current evolves toward a single value.

✦ As the current profile evolves toward lower ℓ_i confinement gradually improves (principally particles). This correlates with a change in ELM character (become less grassy) and reduced Mirnov activity. Lower ℓ_i may be leading to higher stability limits (with a wall).

✦ The current and stored energy are limited by a relaxation oscillation involving repetitive growth and collapse of an ITB at large minor radius. Higher power increases the frequency of these events. The collapse is due to an ideal MHD mode, with peeling-ballooning characteristics.

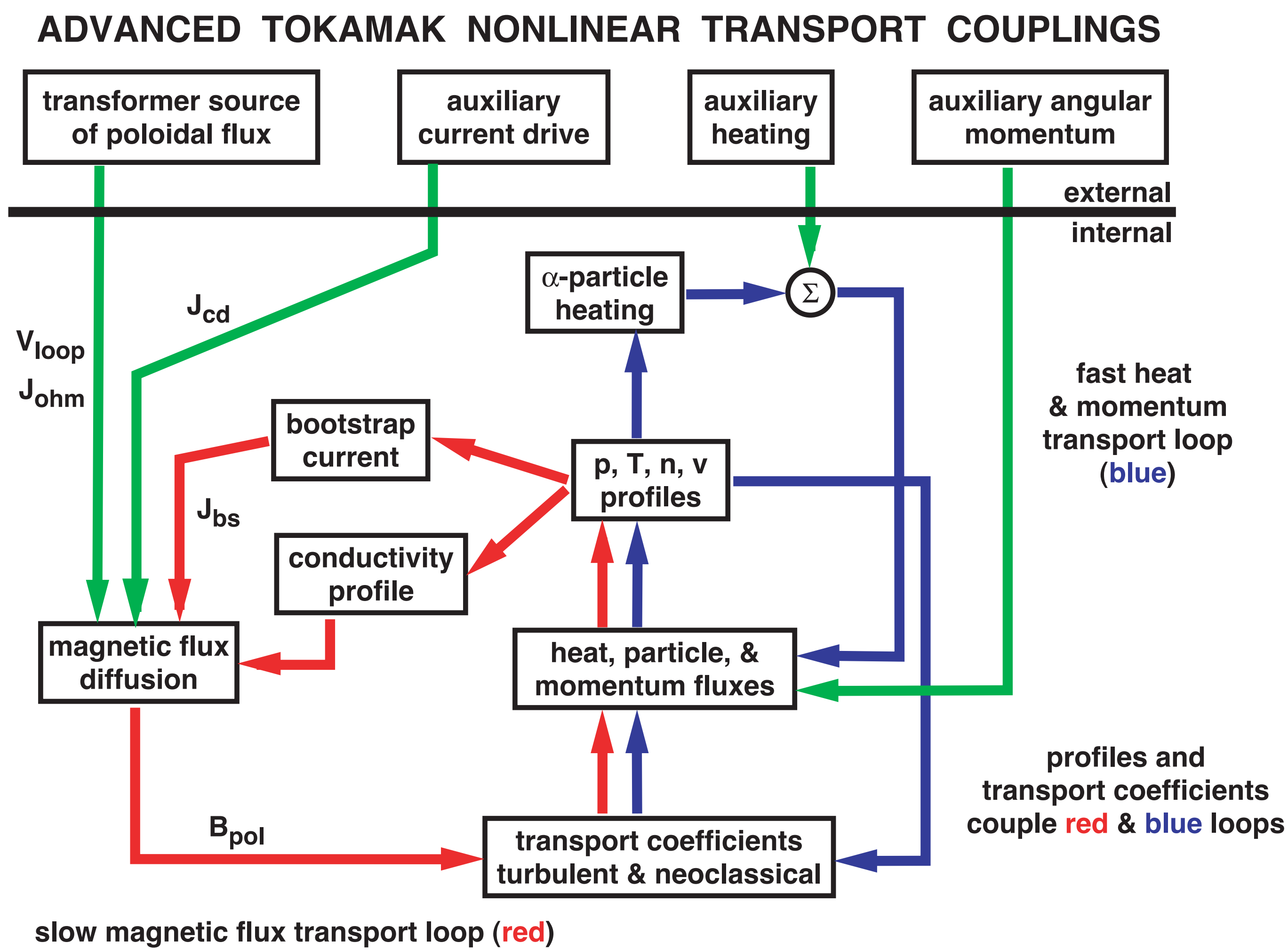
✦ The ITB collapse changes the equilibrium and can lead to undesirable contact with the wall. In a fusion plasma it will lead to fluctuations in fusion power.

✦ Without transformer control, the total current is very sensitive to minor changes in boundary conditions. Use of the transformer as a control tool may be necessary even for steady-state operation.

✦ The stationarity of the current on the magnetic time scale, the recovery of the plasma from ITB collapse events, and the tendency with time toward more stable behavior is promising for future steady-state operation.

Context:

Steady-state, advanced tokamak, burning plasmas require ~100% bootstrap current. However very little is known about the characteristics and behavior of fully noninductive, high bootstrap fraction plasmas.



✳ The properties of small tokamaks are entirely determined by external drives (green lines).

✳ In present tokamaks, the internal heat and momentum feedback loop (blue) competes with external sources, but the total current and current profile remain dominated by external drives.

✳ In a steady-state burning plasma all external controls will be weak and the plasma will assume entirely self-consistent profiles of J, n, T, and V.

Key Questions:

✧ What are the self-consistent n, T, J, and V profiles that the plasma wants?

✧ What are the beta limits associated with these profiles and what are the beta-limiting processes?

✧ What is the maximum current that can be sustained?

✧ Are these limits consistent with the expected fusion power production?

✧ Are these conditions dynamically stable? (I.e., if perturbed, does the plasma return to the same state?)

✧ What control methods are needed and what controls are possible?

Slow Evolution (on the Current Profile Evolution Time Scale)

Best Case (So Far):

✣ Fully noninductive plasma.

✣ Current is stationary (on average).

✣ limit cycle behavior (relaxation oscillations) at high heating power (on transport time scale).

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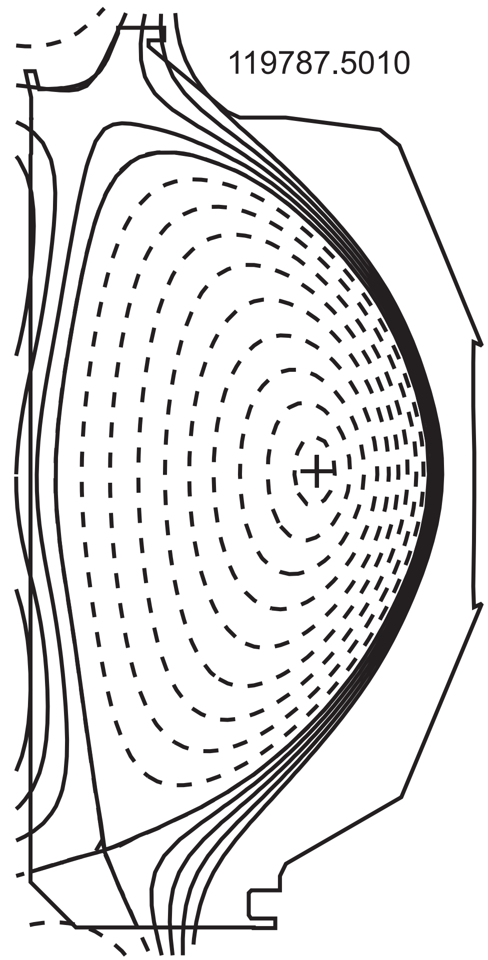
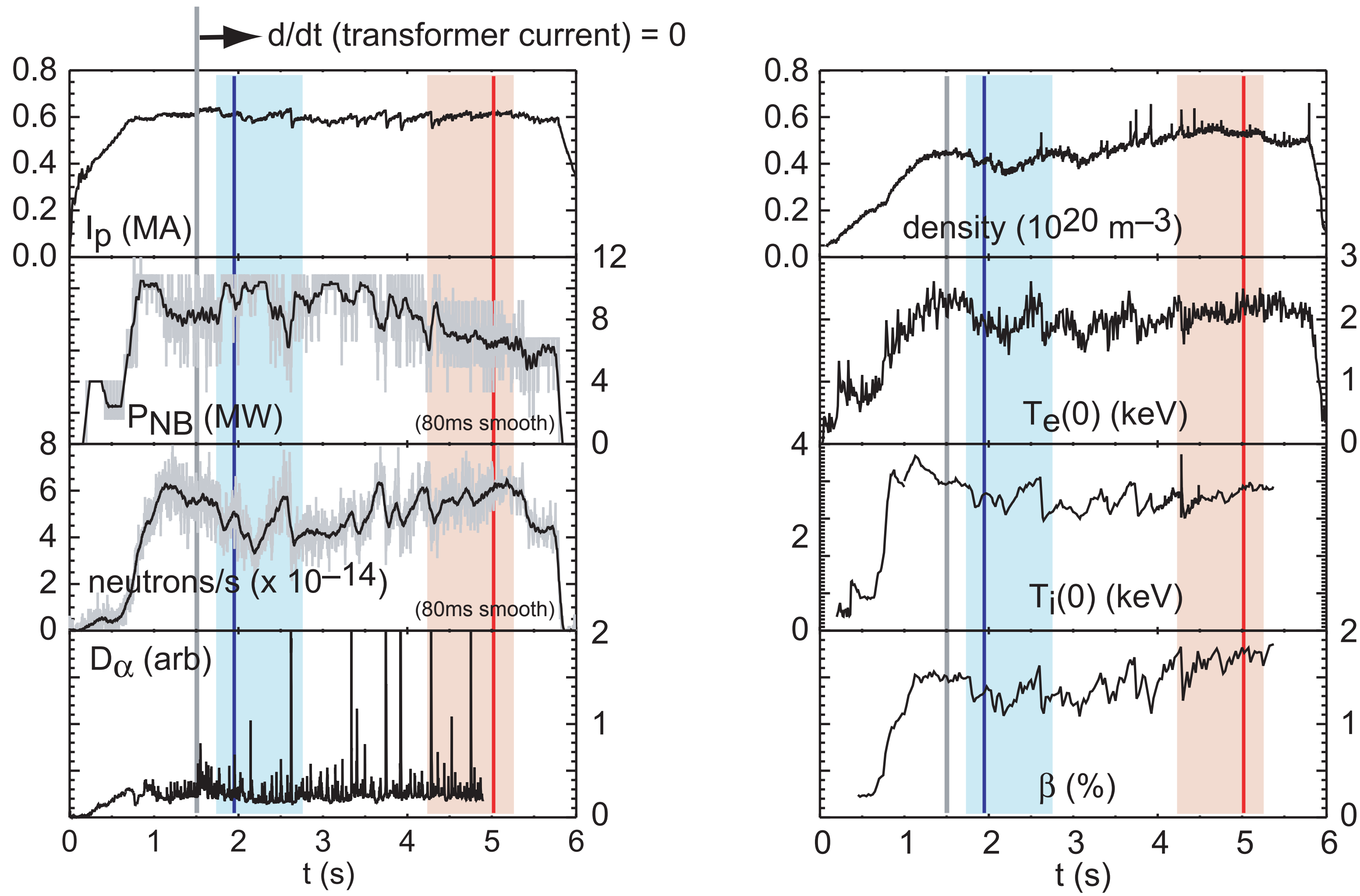
✣ Confinement gradually improves (on magnetic time scale).





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Long-term (Slow) Profile Evolution:

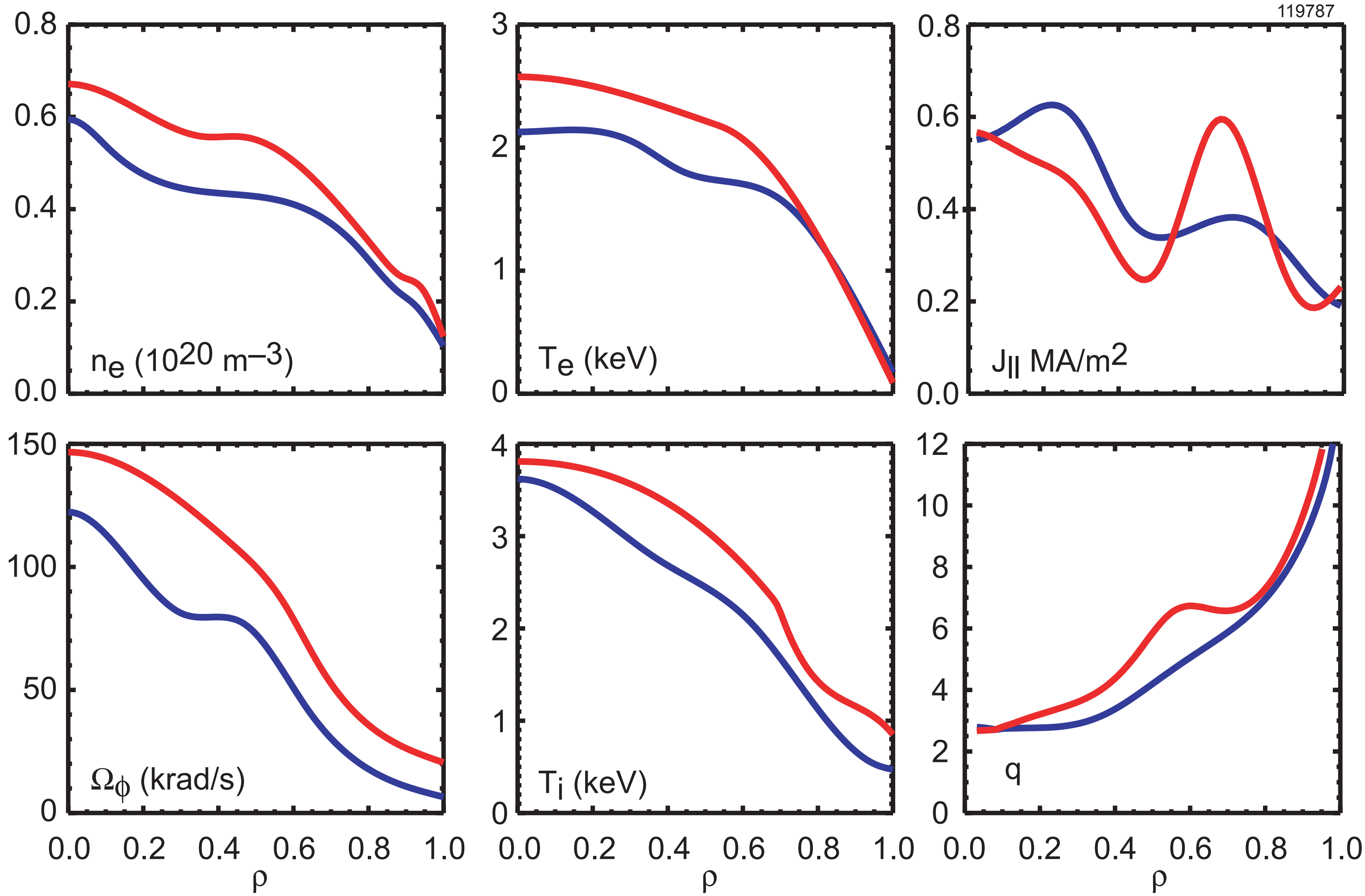
- Central ($\rho < 0.6$) density and electron temperature rise. Ion temperature and toroidal rotation increase across entire plasma.

- Pressure peaking is low, and doesn't change during pulse.

- Current profile broadens $\Leftrightarrow$ ℓ_i decreases, q_0 & q_{min} rise.

- Improvement is correlated with a change in the character of MHD fluctuations as seen on the Mirnov loops.

profiles at 1.97 s & 5.01 s



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Parameter Improvement Over 2.5 s:

parameter ±0.5 s avg	@2.25 s	@4.75 s	ratio
$\langle n_e \rangle$ (10^20)	0.338	0.437	1.29
$\langle T_e \rangle$ (keV)	1.41	1.49	1.06
$\langle T_i \rangle$ (keV)	1.93	2.08	1.08
H_{89P}	1.78	2.73	1.53
H_{98y2}	1.52	2.03	1.34
$p(0)/\langle p \rangle$	2.00	2.02	1.01
β_p	2.55	3.18	1.25
β_N	2.54	3.08	1.21
W (MJ)	0.549	0.677	1.23
q_{min}	2.61	2.94	1.13
ℓ_i	0.669	0.563	0.84
τ_E (ms)	59.6	97.9	1.64

- Energy and particle confinement improve slowly (on current profile relaxation time scale).
- Mainly better particle confinement.
- Current profile broadens.
- $\beta_N H_{89}$ ~ 8-10, but with q_{95} ~ 10, $\beta_N H/q^2$ is a factor of 4-5 below ITER baseline.
- Similar operation at q_{95} ~ 5 requires β_N ~ 6 (2x current, same f_{bs}, β_p).

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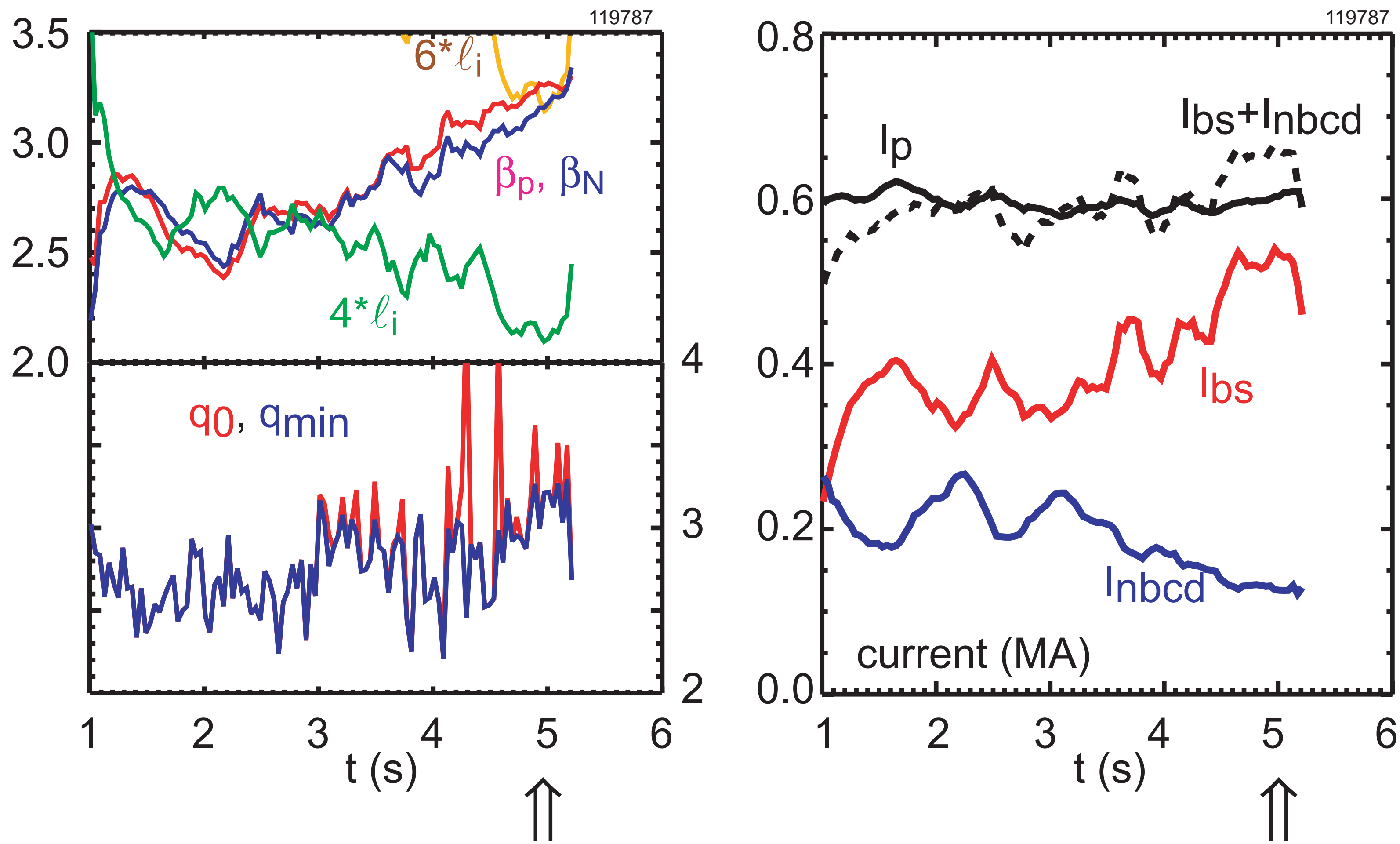
Improving Confinement & Broadening Current Profile Leads to Higher Bootstrap Current

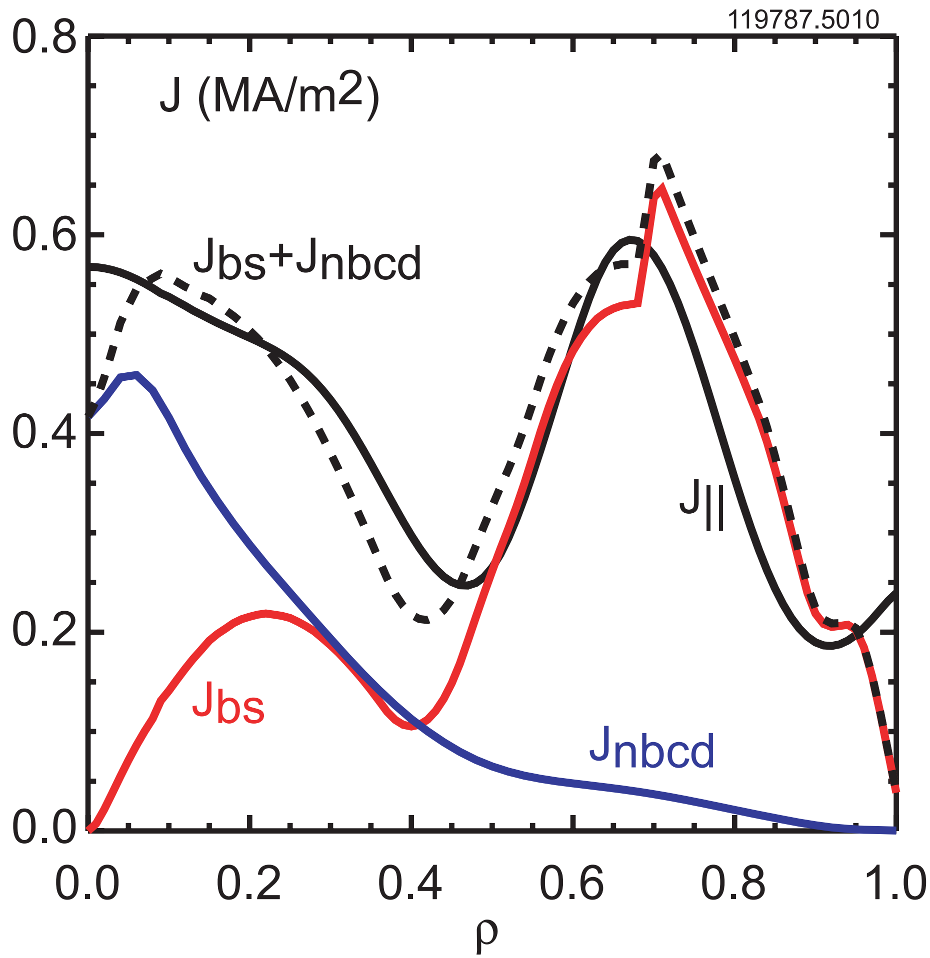


(βN reaches 6 ℓi)

(fbs > 80% for > 0.5 s)

* q profile monotonic or slightly reversed

Bootstrap & NBCD Calculated From Measured n_e, T_e, T_i, and Z_{eff} Profiles Agree With Total Current Profile From EFIT



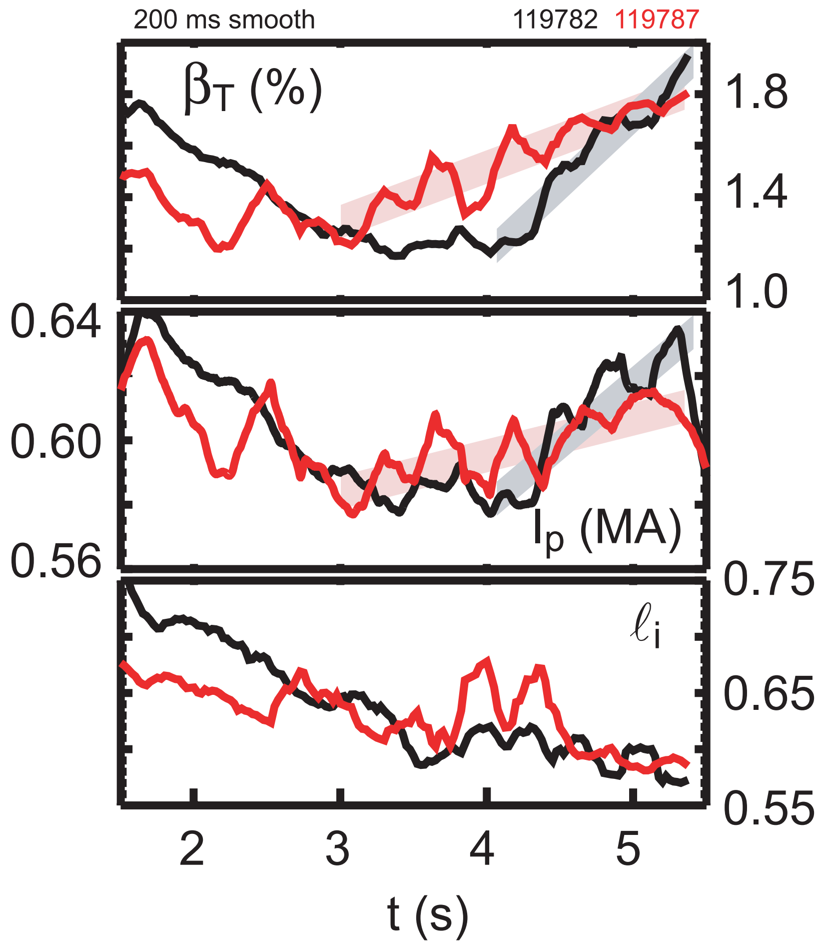
- $f_{bs} \approx 0.84$
- $f_{nbcd} \approx 0.20$
- accounts for total within uncertainty of experiment and model.
- Bootstrap alignment = 0.71

$$BSA = 1 - \frac{\int dV \frac{n_e}{T_e} |J_{||} - J_{boot}|}{\int dV \frac{n_e}{T_e} |J_{||}|}$$

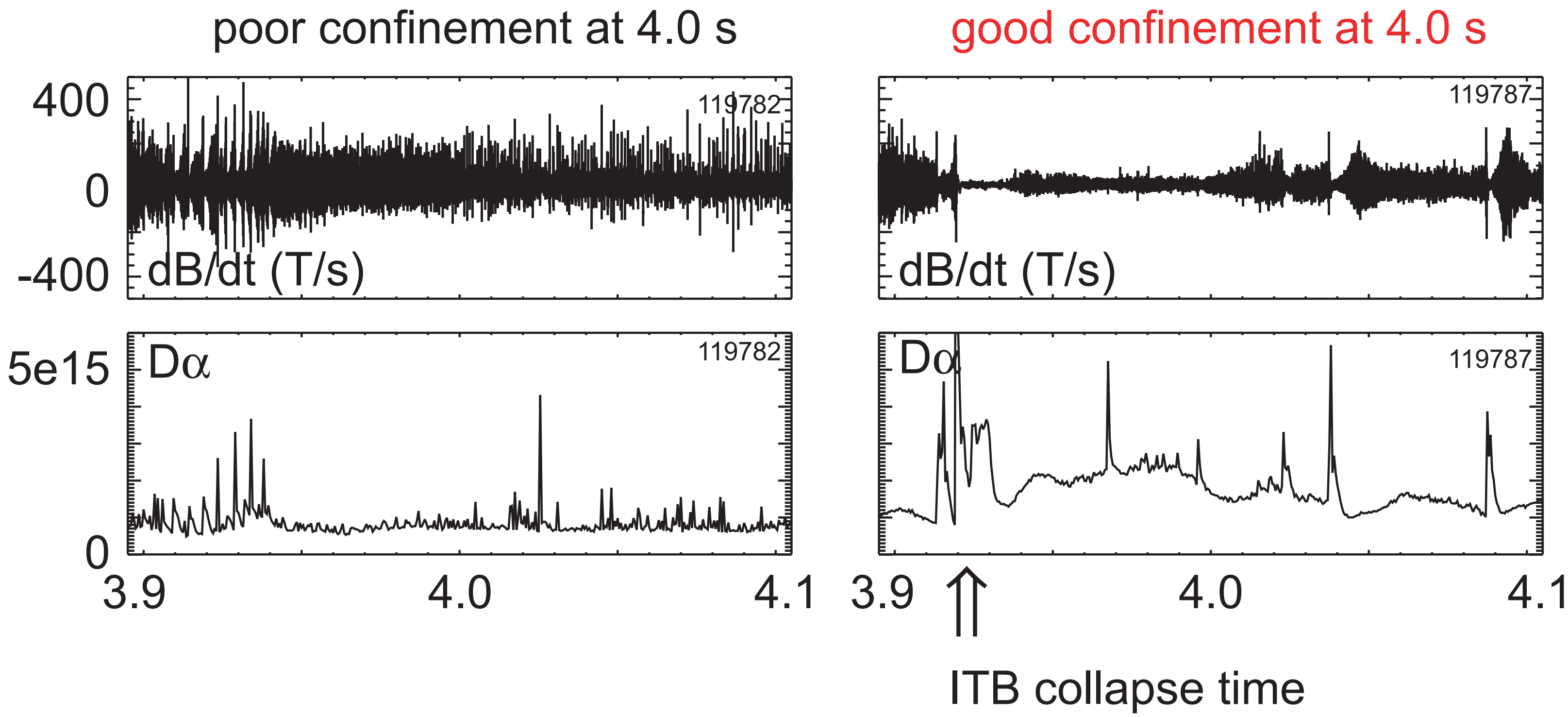
(measure of RF power needed to drive non-bootstrap current)

$J_{||} = \langle \mathbf{J} \cdot \mathbf{B} \rangle / B_{T0}$

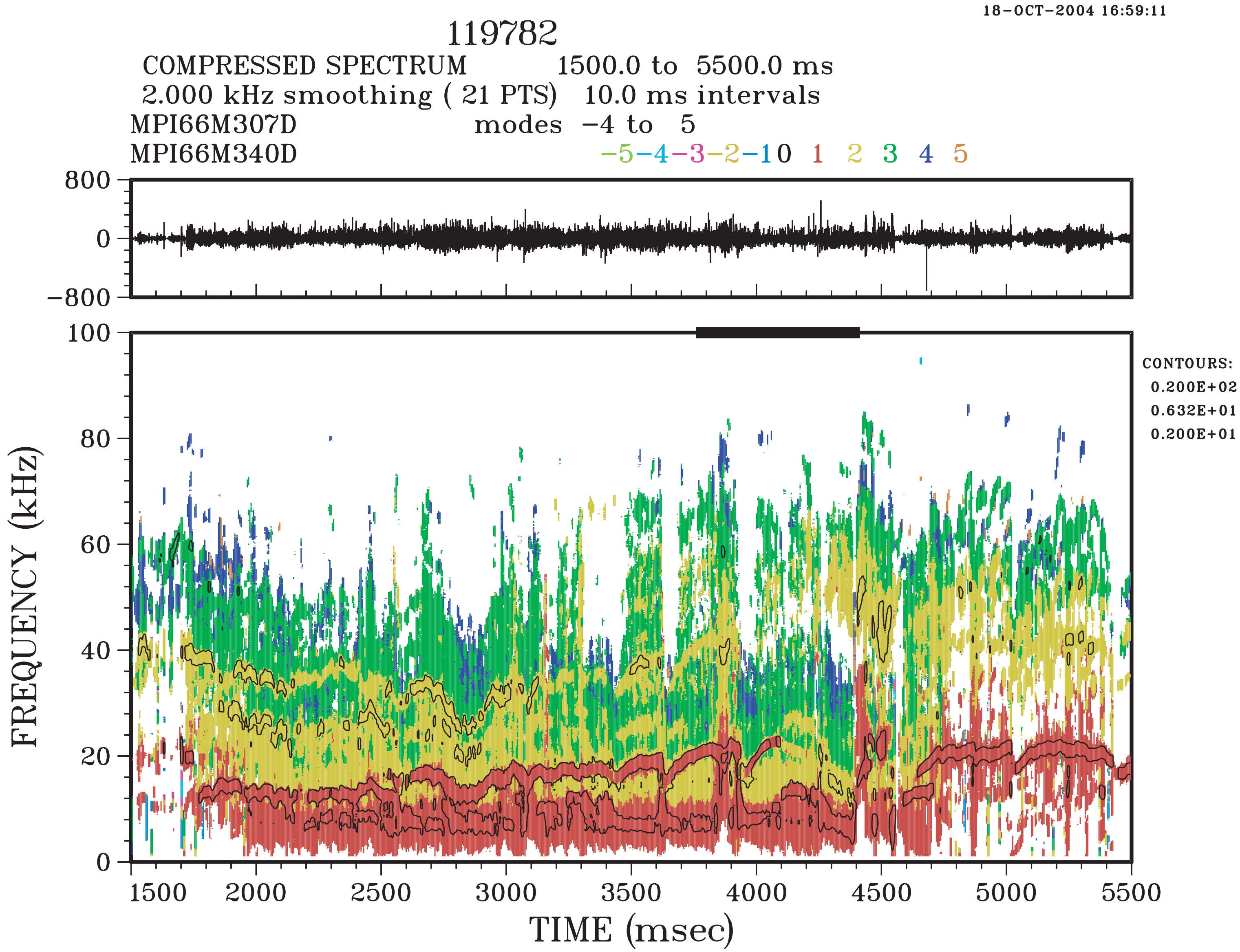
Good and Poor Confinement Phases of these Discharges Correlate With Different Mirnov and Dα Signals



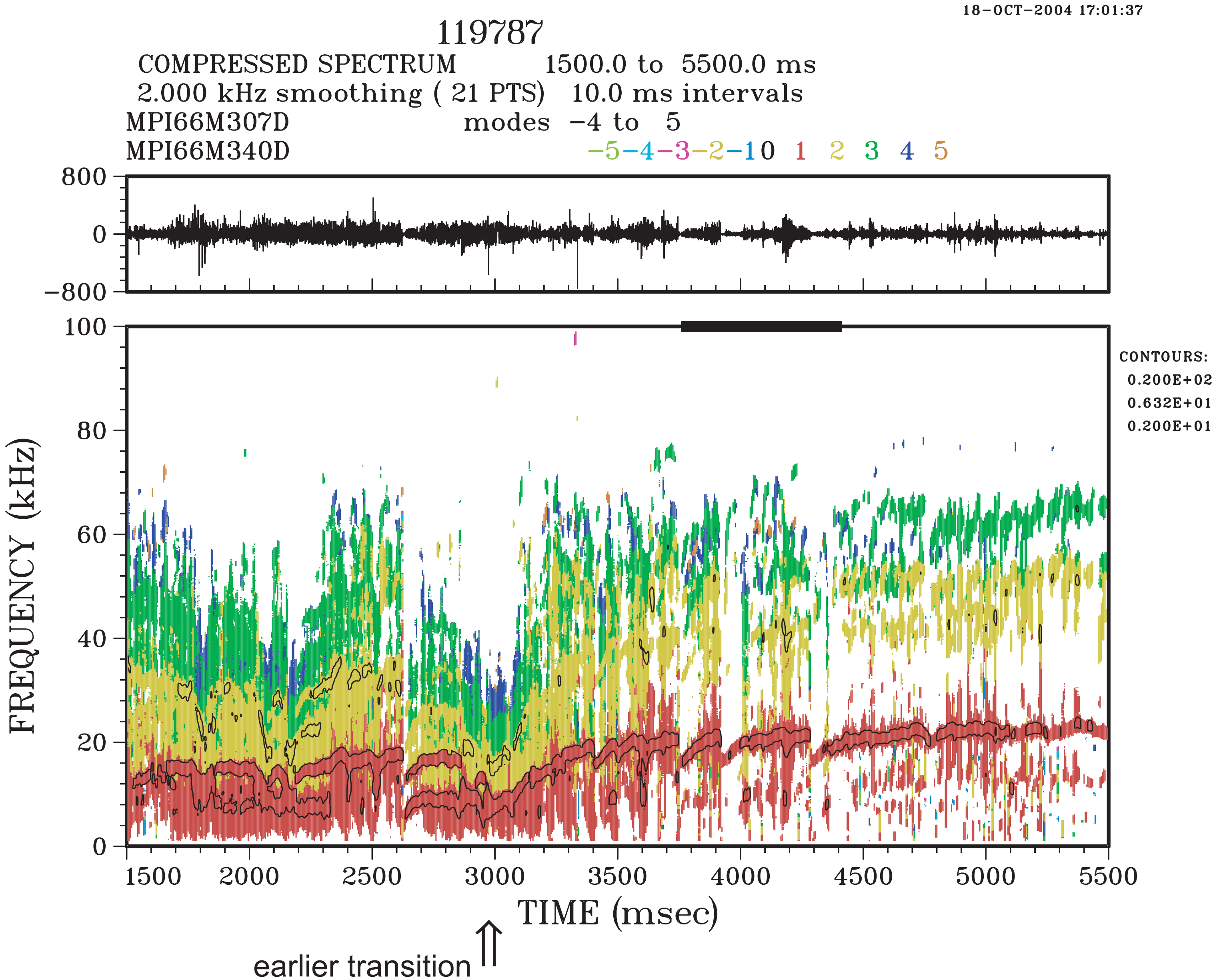
- Poor confinement corresponds to small, rapid ELMs and large rms dB/dt.
- Good confinement corresponds to fewer, larger ELMs and smaller, more coherent dB/dt.
- Detailed characterization of differences and determination of reason for transition to better confinement is work to be done.



poor confinement at 4.0 s
good confinement at 4.0 s
400
0
-400
dB/dt (T/s)
119782
119787
5e15
Dα
0
3.9
4.0
4.1
ITB collapse time

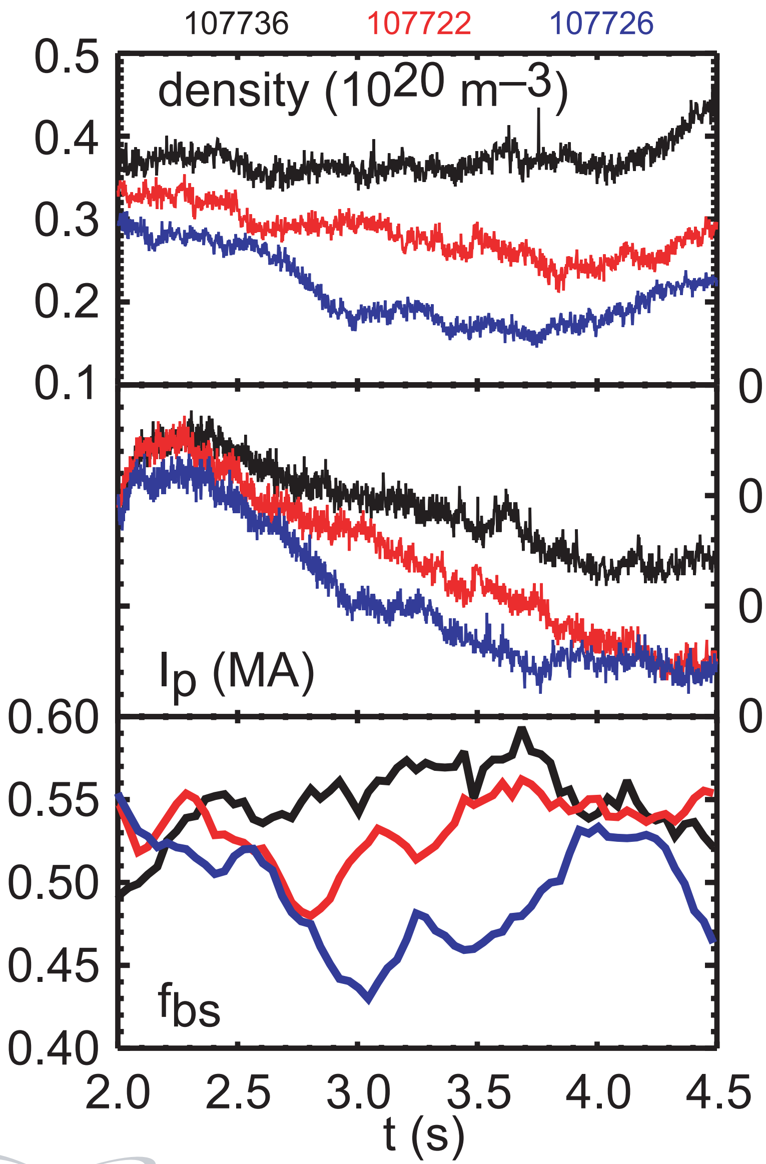


later transition ⇑


18-OCT-2004 17:01:37
119787
COMPRESSED SPECTRUM 1500.0 to 5500.0 ms
2.000 kHz smoothing (21 PTS) 10.0 ms intervals
MPI66M307D modes -4 to 5
MPI66M340D -5 -4 -3 -2 -1 0 1 2 3 4 5
800
0
-800
100
80
60
40
20
0
FREQUENCY (kHz)
CONTOURS:
0.200E+02
0.632E+01
0.200E+01
1500
2000
2500
3000
3500
4000
4500
5000
5500
TIME (msec)
earlier transition

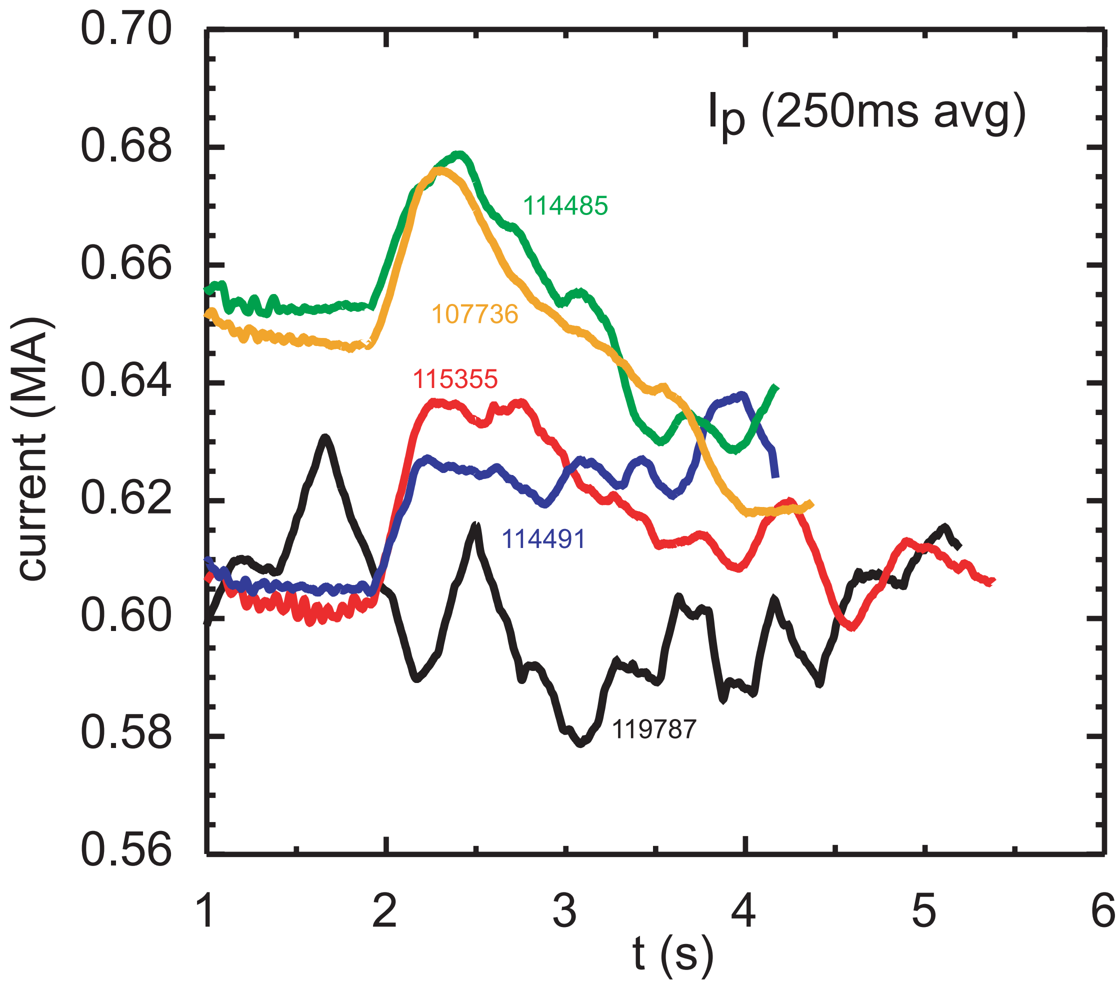
Parametric Variations

Higher Density Gives Higher Bootstrap Current



- The total noninductive current and the bootstrap fraction both depend strongly on the plasma density.
- Three discharges prepared identically except for differing initial (pre-L-H) density.
- With increasing density, the bootstrap fraction increases, and the rate of decay of the total current is reduced.
- Note also that variations in the total current are closely correlated with variations in the density, even on a short time scale.

Current Converges to a Single Value From a Range of Starting Points



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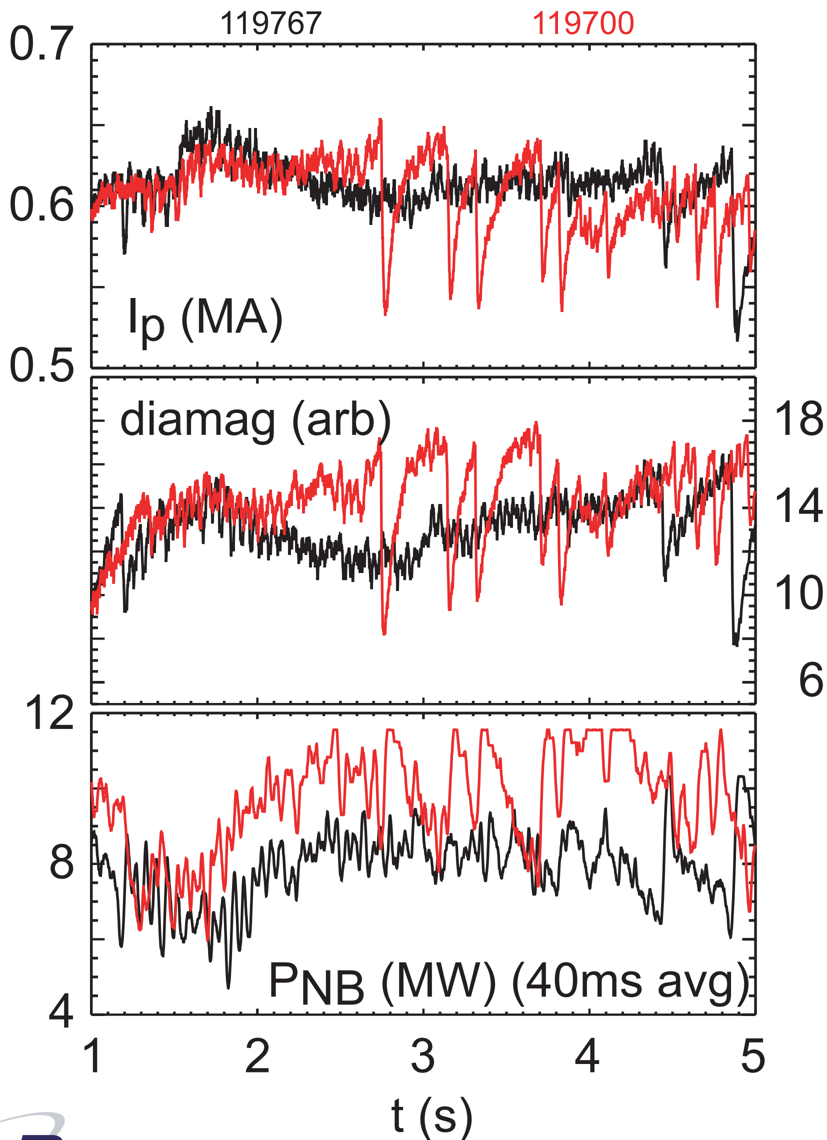
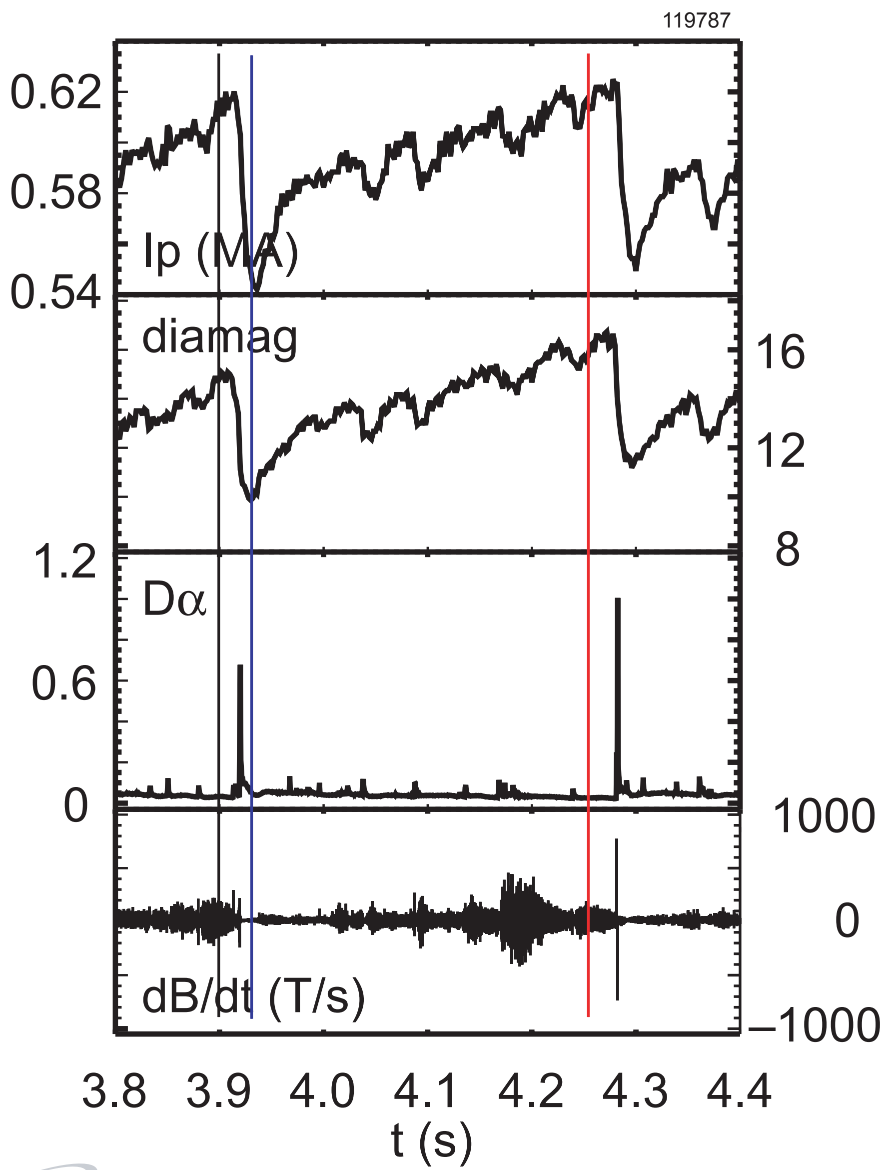
Relaxation Oscillation Limit Cycle of ITB, Energy and Current

Stored Energy and Current Are Limited by a Relaxation Oscillation



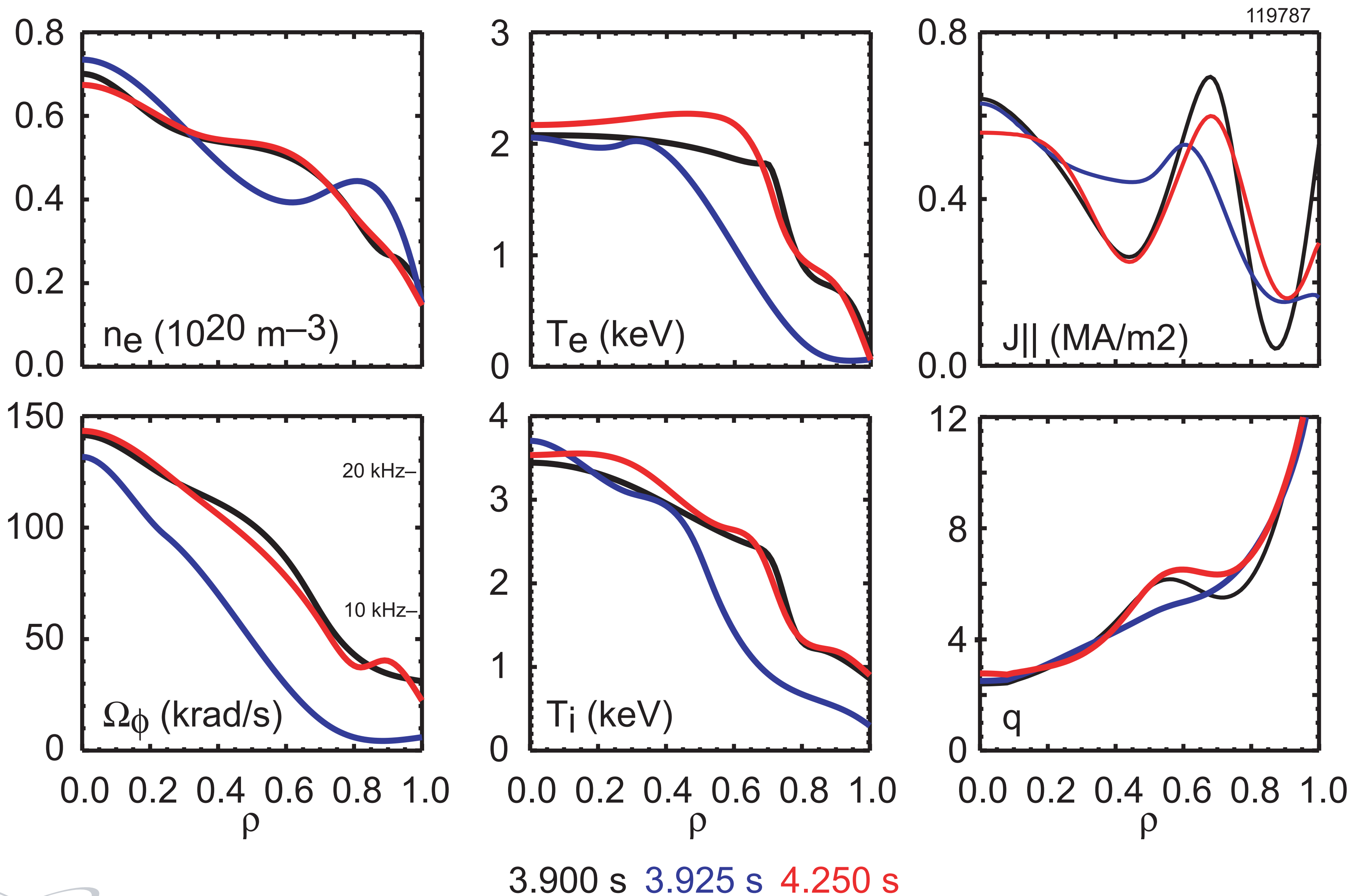
- With increased NB heating power, neither the stored energy nor the current increase significantly.
- Both W and I_p show intervals of rapid increase, terminated by a very fast drop. The time between events is 100's of ms.
- These events tend to become smaller as the discharge evolves.

Relaxation Oscillation on the Transport Time Scale

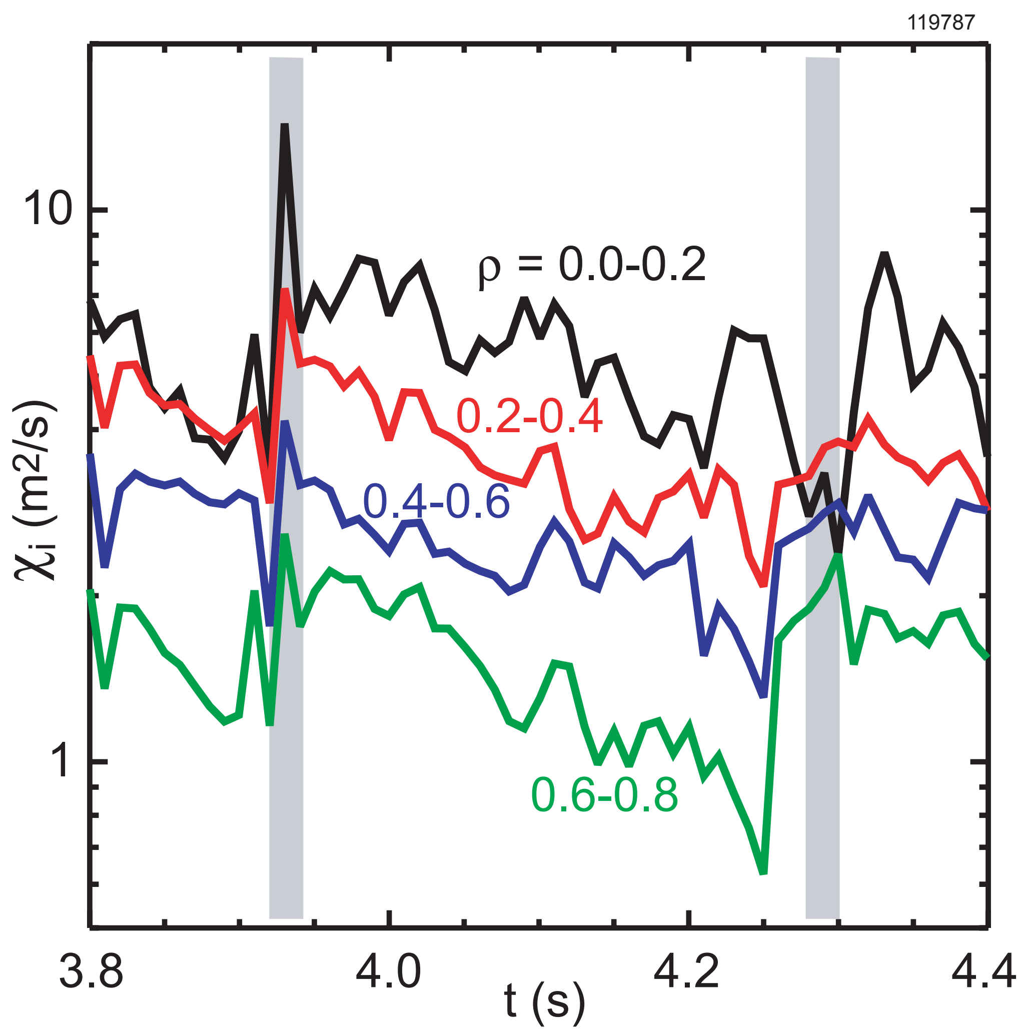


- Collapse is associated with a very large Dα pulse in the divertor region
- The Dα pulse is often, but not always preceeded by an ELM.
- The MHD has not yet been examined in detail.
- ITB occurs at large minor radius.
- After collapse, profiles recover to their previous values.

Profiles Show Internal Transport Barrier Collapses and Recovers

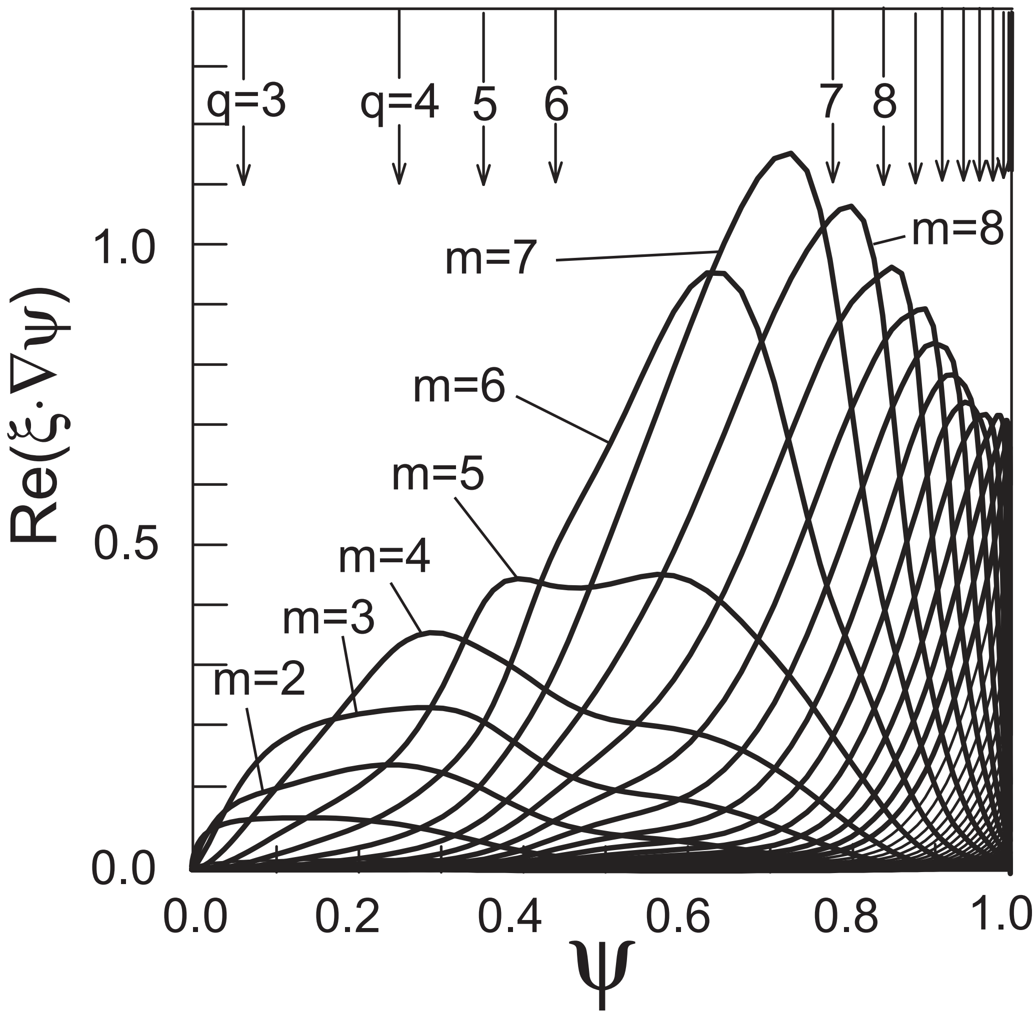


During Recovery, Ion Thermal Conductivity Improves Throughout Plasma Core



- Evaluate χ_i with TRANSP using measured profiles. Average over $\Delta\rho = 0.2$ zones.
- χ_i improves uniformly from center outward.

Initial Ideal MHD Analysis



- GATO ideal stability analysis of 119787.5010 indicates an unstable mode with peeling-ballooning character. (Sum of poloidal harmonics peaks at edge, even though largest single harmonic is at radius of max p'.)