Stabilization of Disruptive Locked Modes at DIII-D by means of ECCD and Magnetic Perturbations

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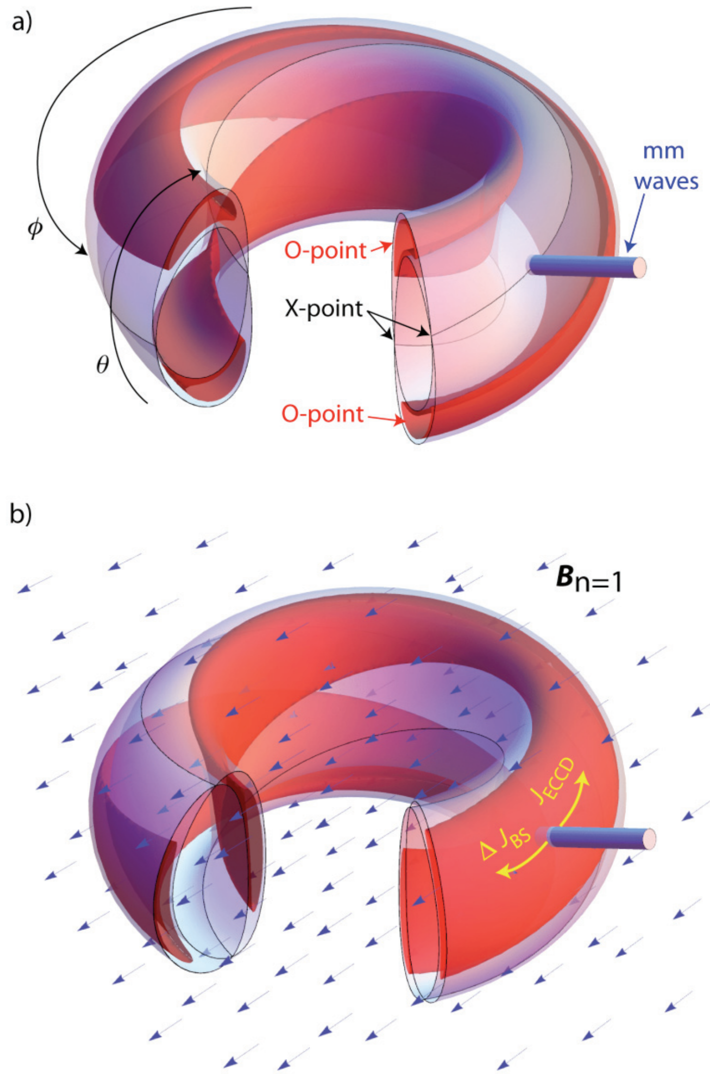


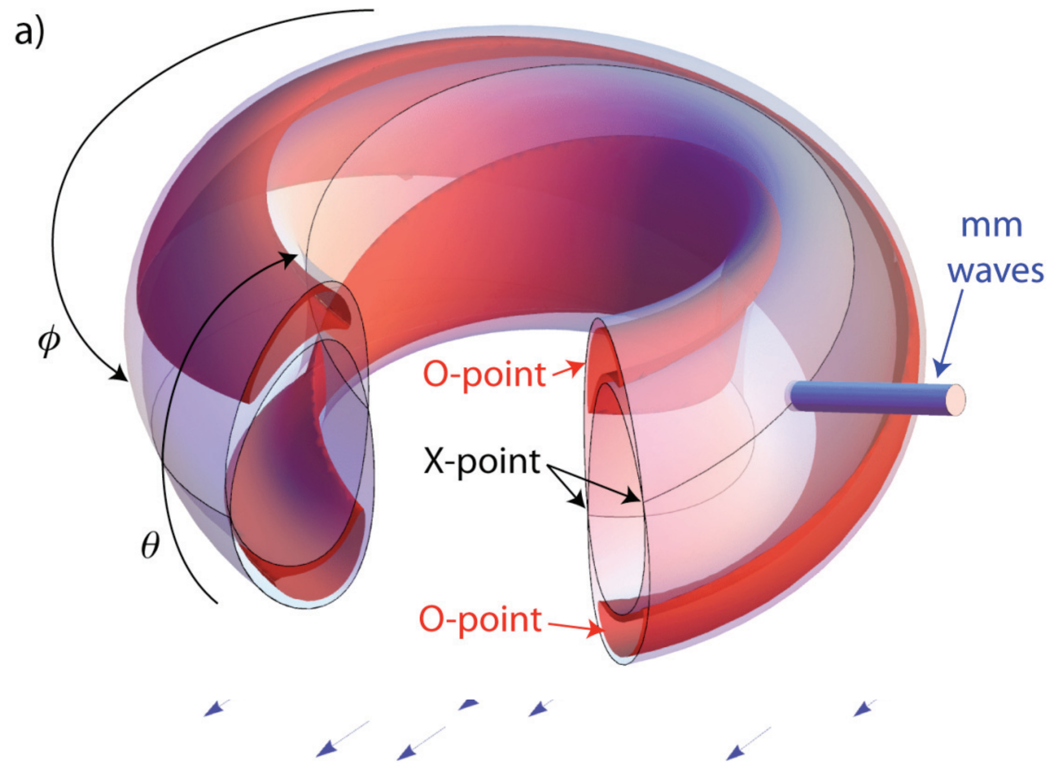
Outline

- **Motivation and previous work**
- **Toroidal phase of locking was controlled by magnetic perturbations**
- **Locked Modes were completely stabilized by ECCD**
- **Beneficial effects were observed in**
  - H-mode and ELMs
  - Confinement
  - β_N
- **Unlocking by NBI torque was facilitated by ECCD mitigation**
- **Quasi-stationary Modes were observed when the magnetic perturbation was too weak**

MOTIVATION
& PREVIOUS WORK

Unlike NTMs, LMs Cannot be Controlled by ECCD Alone

- **Islands can lock in a position not accessible by ECCD**
- **Locking likely in ITER due to low rotation and proximity to wall**
  - Locking at w=5-8cm
  - Saturation at w=35-40cm
- **Bootstrap deficit in the island is like a wire carrying a counter-current**
- **Magnetic forces can be exerted on this wire by I-coils and can be used to hold the island in the optimum position for ECCD**



Rotating Precursor is Slowed Down by Image Currents in the Wall and Locks to Residual EF

Torque exerted by resistively delayed image currents in the wall:

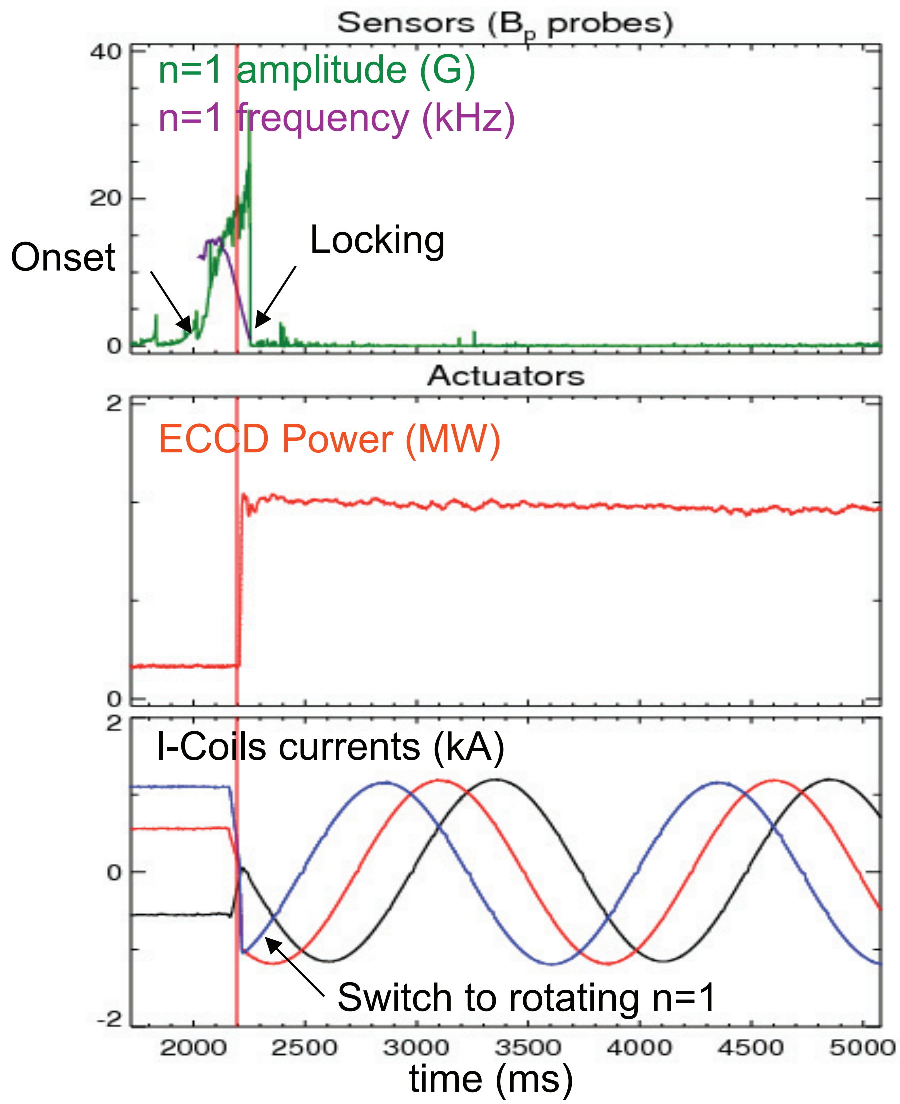
$$T_{\mathrm{wall}} = -\frac{[2\pi R B_R(b) r_{mn}]^2}{\mu_0 b}\left(\frac{r_{mn}}{b}\right)^{2m-1}\frac{\omega_{mn}\tau_w}{1+(\omega_{mn}\tau_w)^2}$$

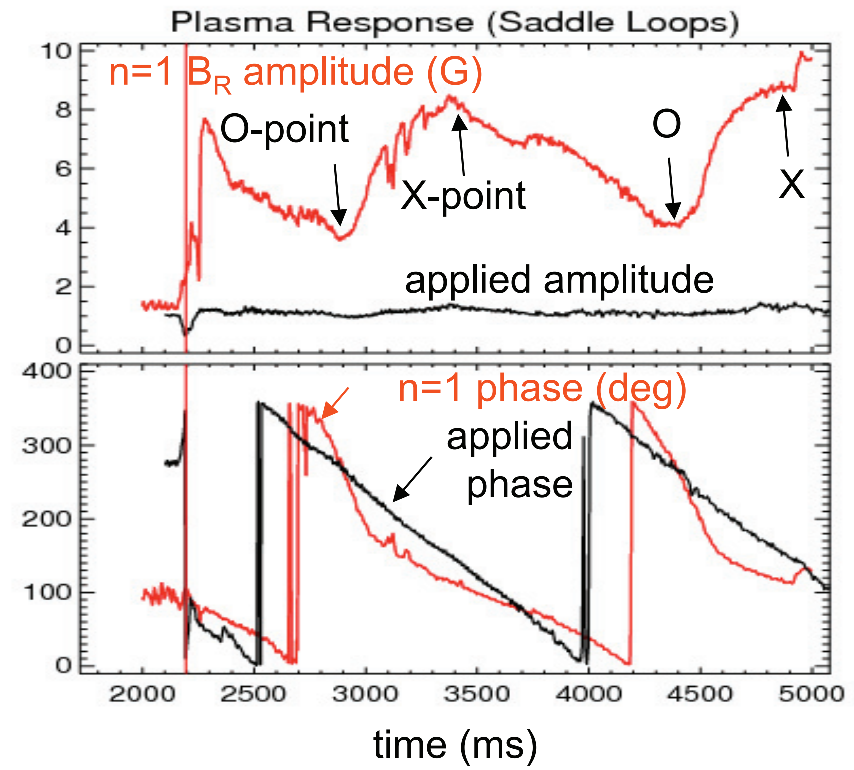
→0 for ω_{mn}→0

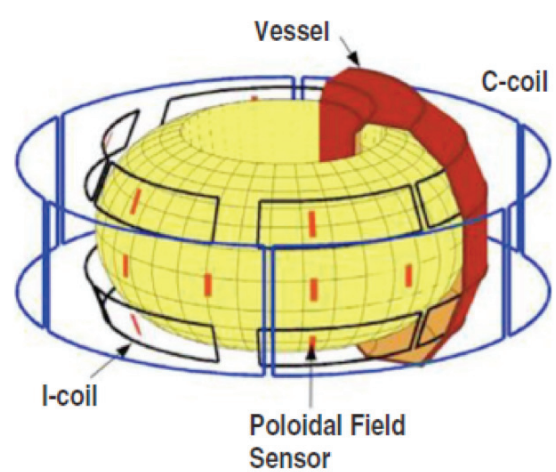
Torque exerted by EF trying to align magnetic dipole to it:

$$T_{\mathrm{EF}} = -\pi^2 R^2 m \frac{a}{r_{mn}} I_{\mathrm{EF}} B_R(a)\sin(n\omega_{mn}t - n\phi_{mn})$$

Locked Mode, Unlocked and Rotated by RMP, Illuminated by ECCD, was Observed to Change Amplitude

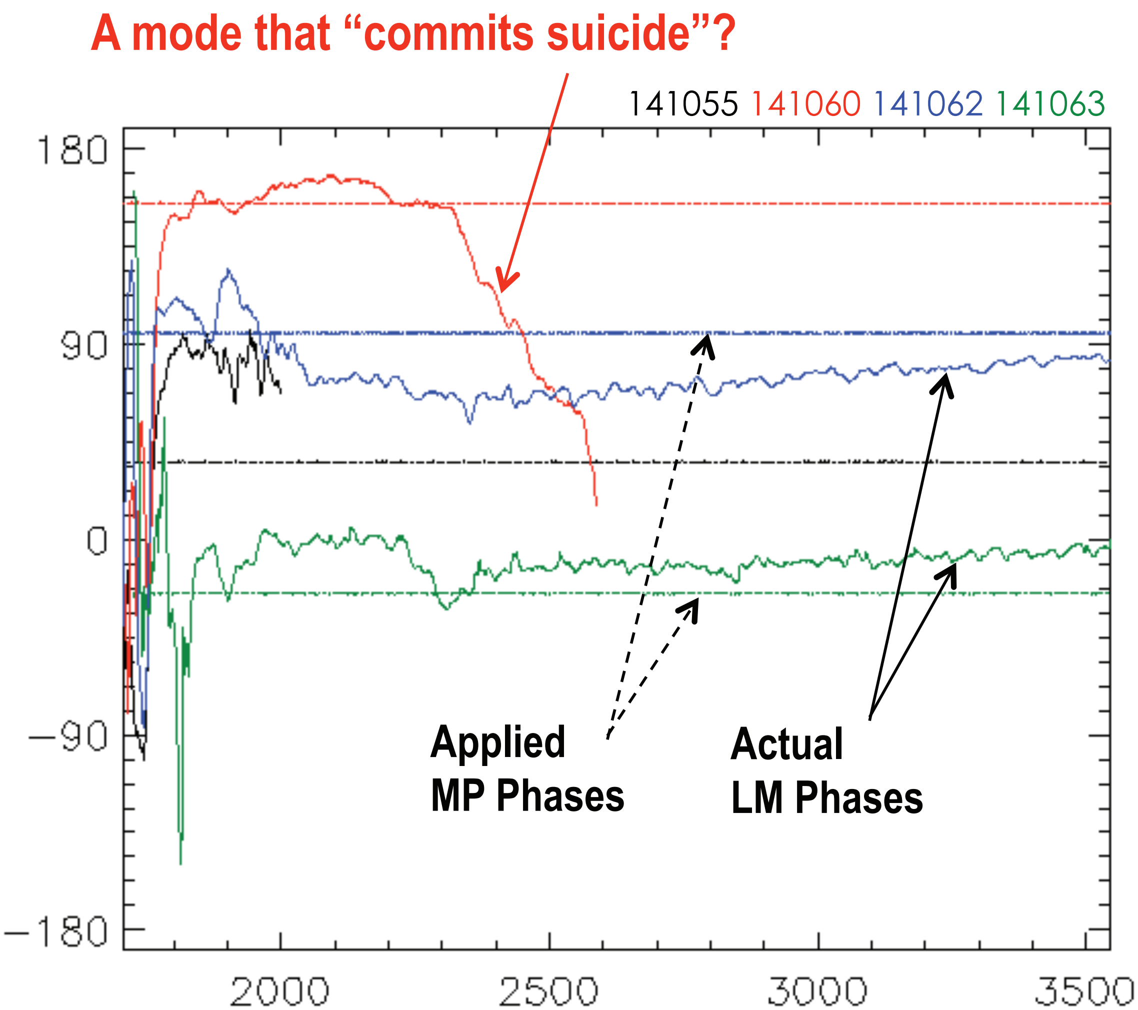






MAGNETIC CONTROL OF TOROIDAL PHASE OF LOCKING

Magnetic Perturbations of Sufficient Strength Give Control of LM Toroidal Position



- **Tendency to accumulation**
- **Mode locks to resultant of EF +MP**
- **360° control of toroidal angle requires |MP| > |EF|**
- **Here $I_{\text{I-coil}}$=1.6-2.5kA**

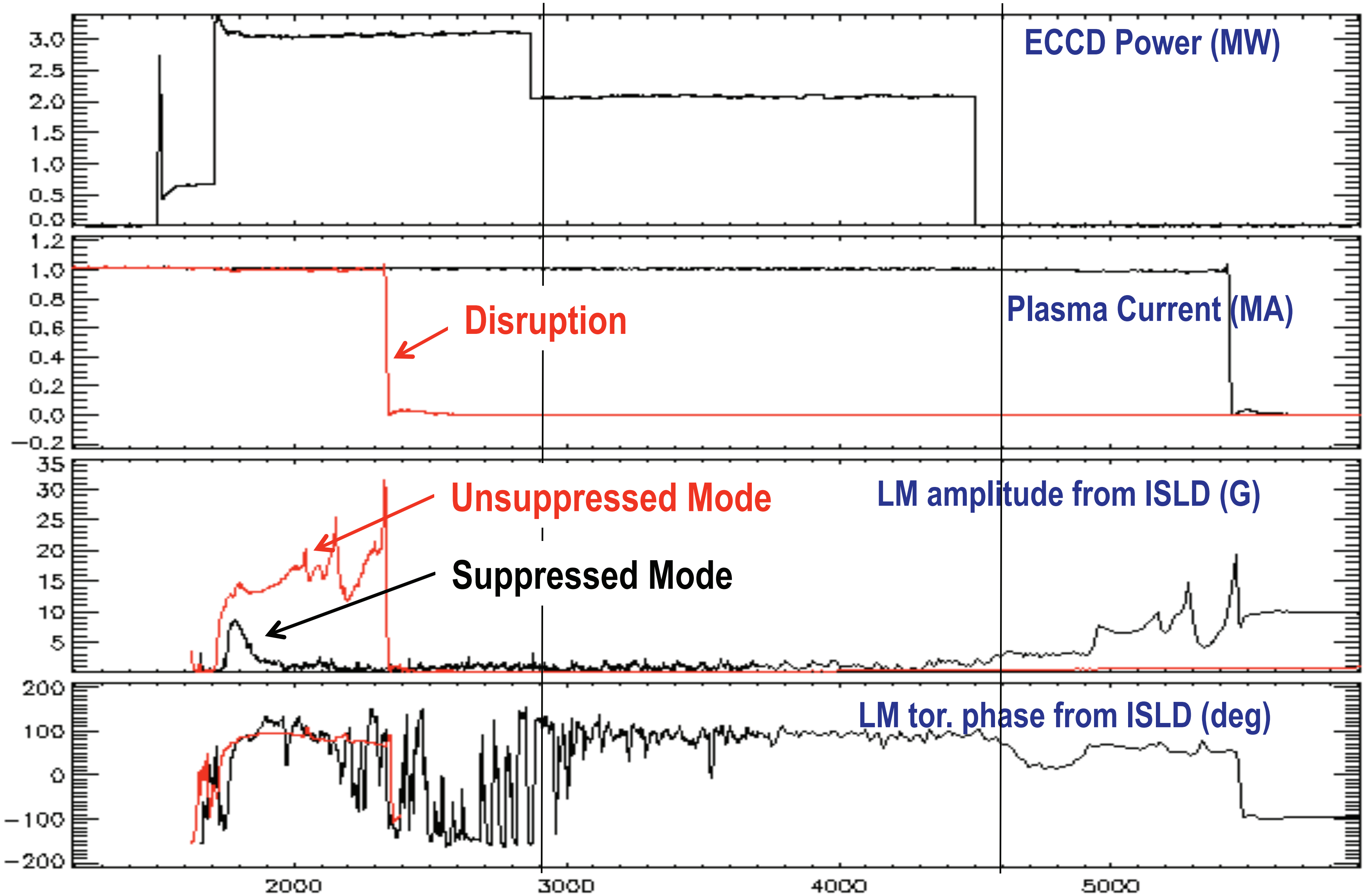
Discrepancy Between Applied I-coil Phase and Actual Mode Locking Phase Might Lead to Improved EFC at Finite β

- **2*N* equations in 2+*N* unknowns, including EF amplitude and phase**
  - Here *N*=no. steps in toroidal scan
- ***N*=2 locked phases are sufficient**
- **Toroidal number assumed *n*=1**

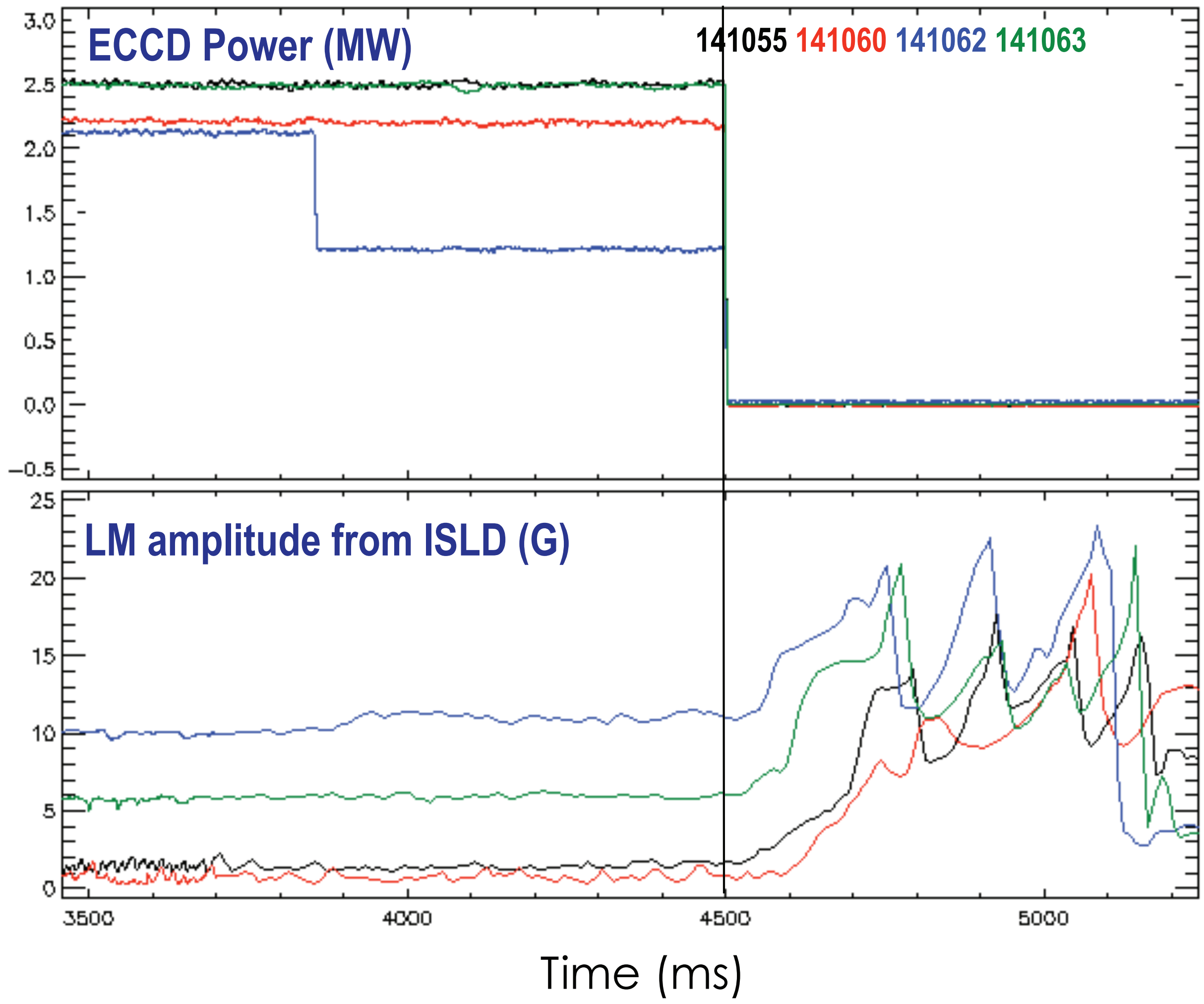
$$A_{\mathrm{EF}} \cos\phi_{\mathrm{EF}} + A_{\mathrm{RMP,1}} \cos\phi_{\mathrm{RMP,1}} = A_{\mathrm{tot,1}} \cos\phi_{\mathrm{tot,1}}$$
$$A_{\mathrm{EF}} \sin\phi_{\mathrm{EF}} + A_{\mathrm{RMP,1}} \sin\phi_{\mathrm{RMP,1}} = A_{\mathrm{tot,1}} \sin\phi_{\mathrm{tot,1}}$$
$$\ldots$$
$$A_{\mathrm{EF}} \cos\phi_{\mathrm{EF}} + A_{\mathrm{RMP,N}} \cos\phi_{\mathrm{RMP,N}} = A_{\mathrm{tot,N}} \cos\phi_{\mathrm{tot,N}}$$
$$A_{\mathrm{EF}} \sin\phi_{\mathrm{EF}} + A_{\mathrm{RMP,N}} \sin\phi_{\mathrm{RMP,N}} = A_{\mathrm{tot,N}} \sin\phi_{\mathrm{tot,N}}$$

ECCD STABILIZATION of LOCKED MODES

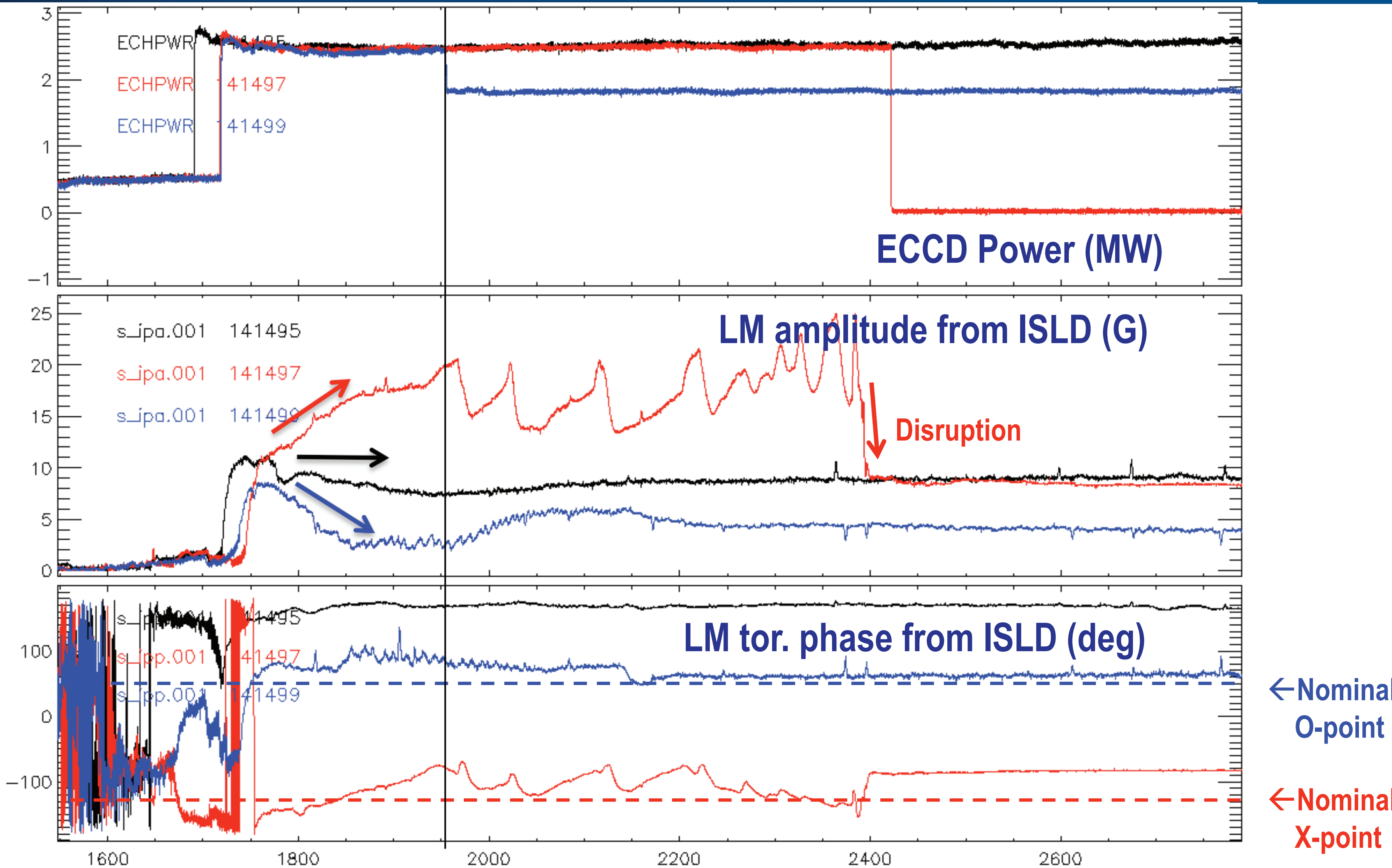
Locked Mode Completely Suppressed by ECCD — Without ECH/ECCD, It Caused a Disruption



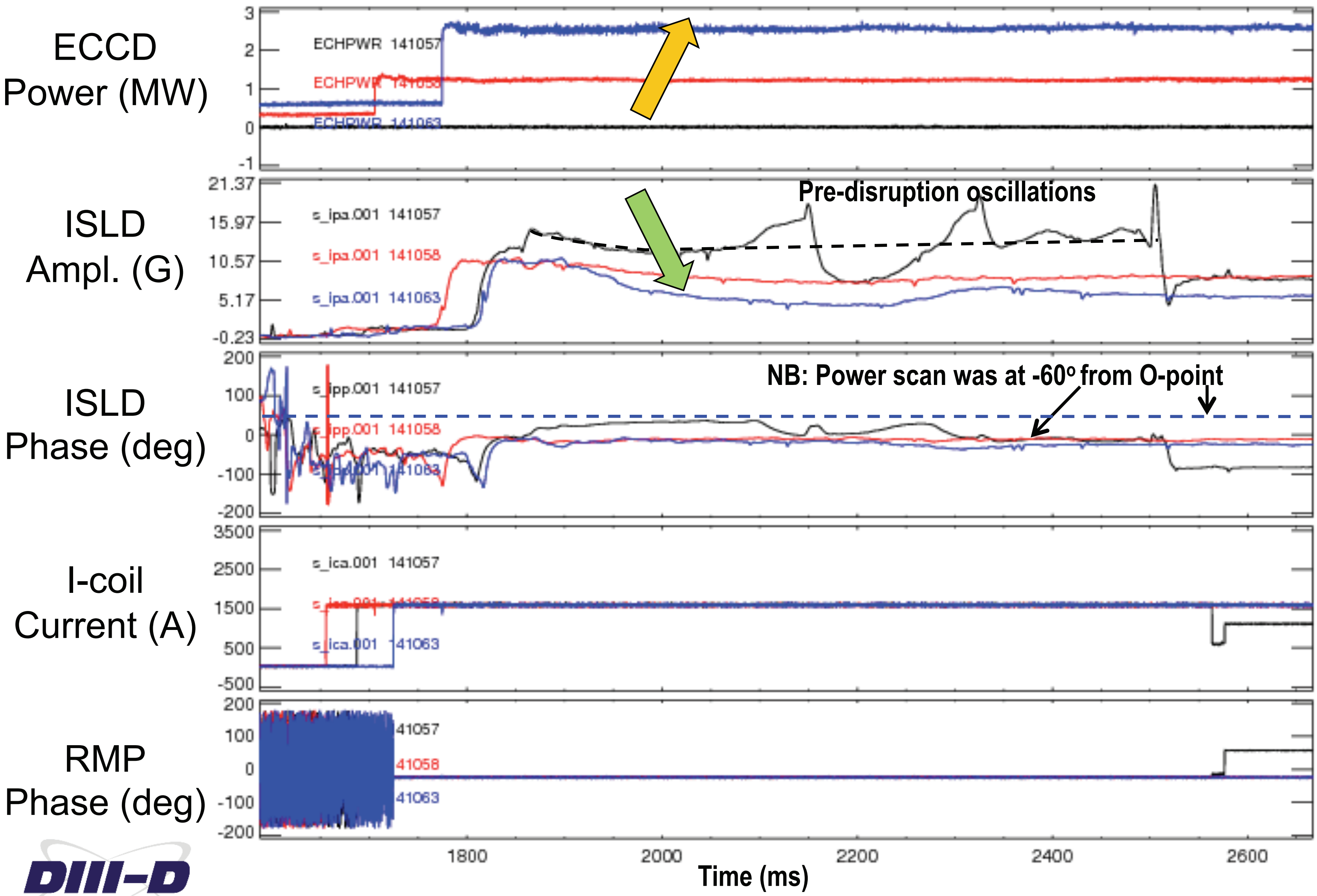
After ECCD Off, Locked 2/1 Mode Grows Again



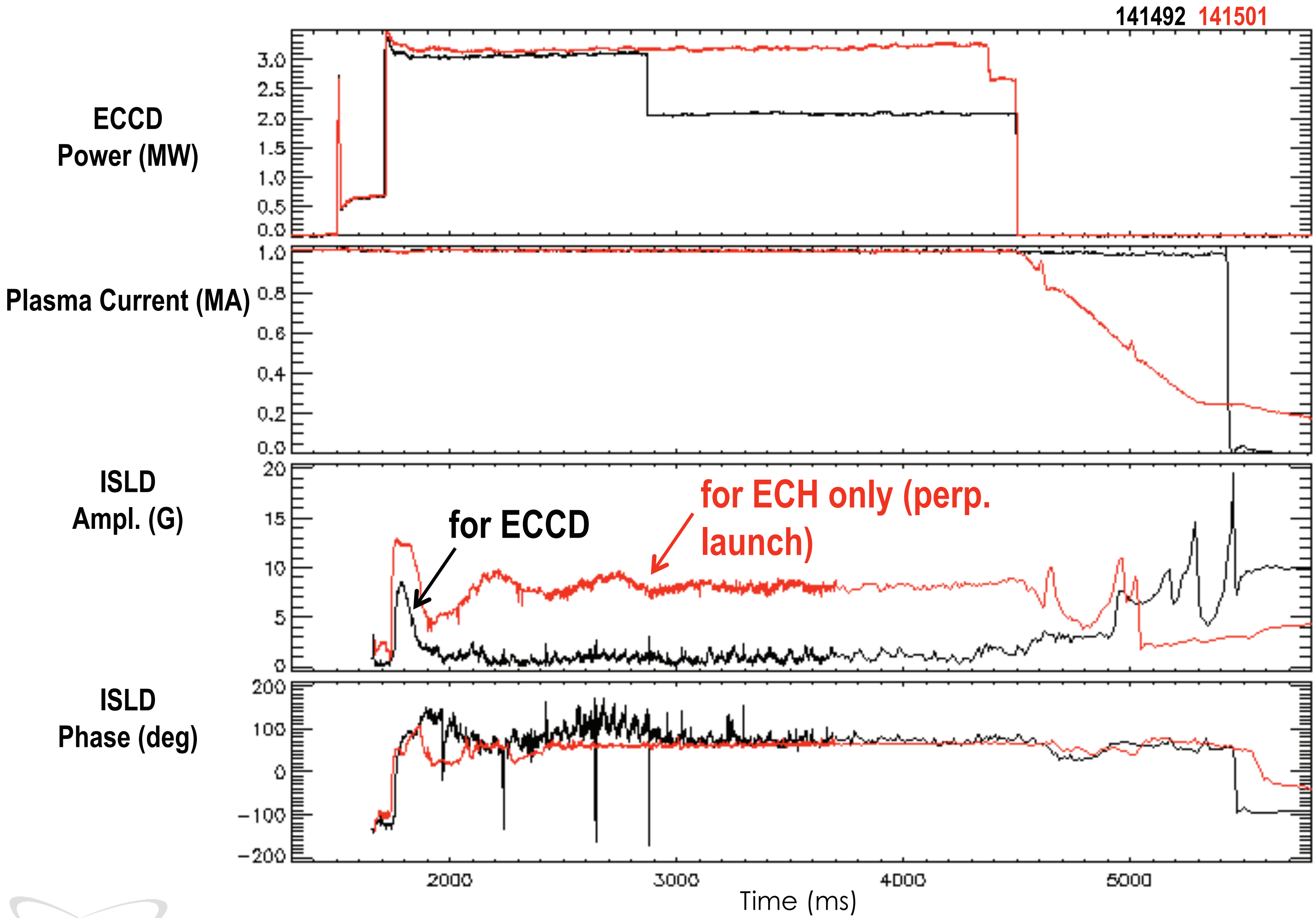
ECCD Deposition in O-point, X-point and in Between Stabilized, Destabilized and Held the LM, Respectively



Stabilization Improves with ECCD Power, as Expected



ECCD was more Effective than Pure ECH at Stabilizing the Locked Mode, as Expected*



* See for example De Lazzari and Westerhof., *Nucl. Fusion* 2009

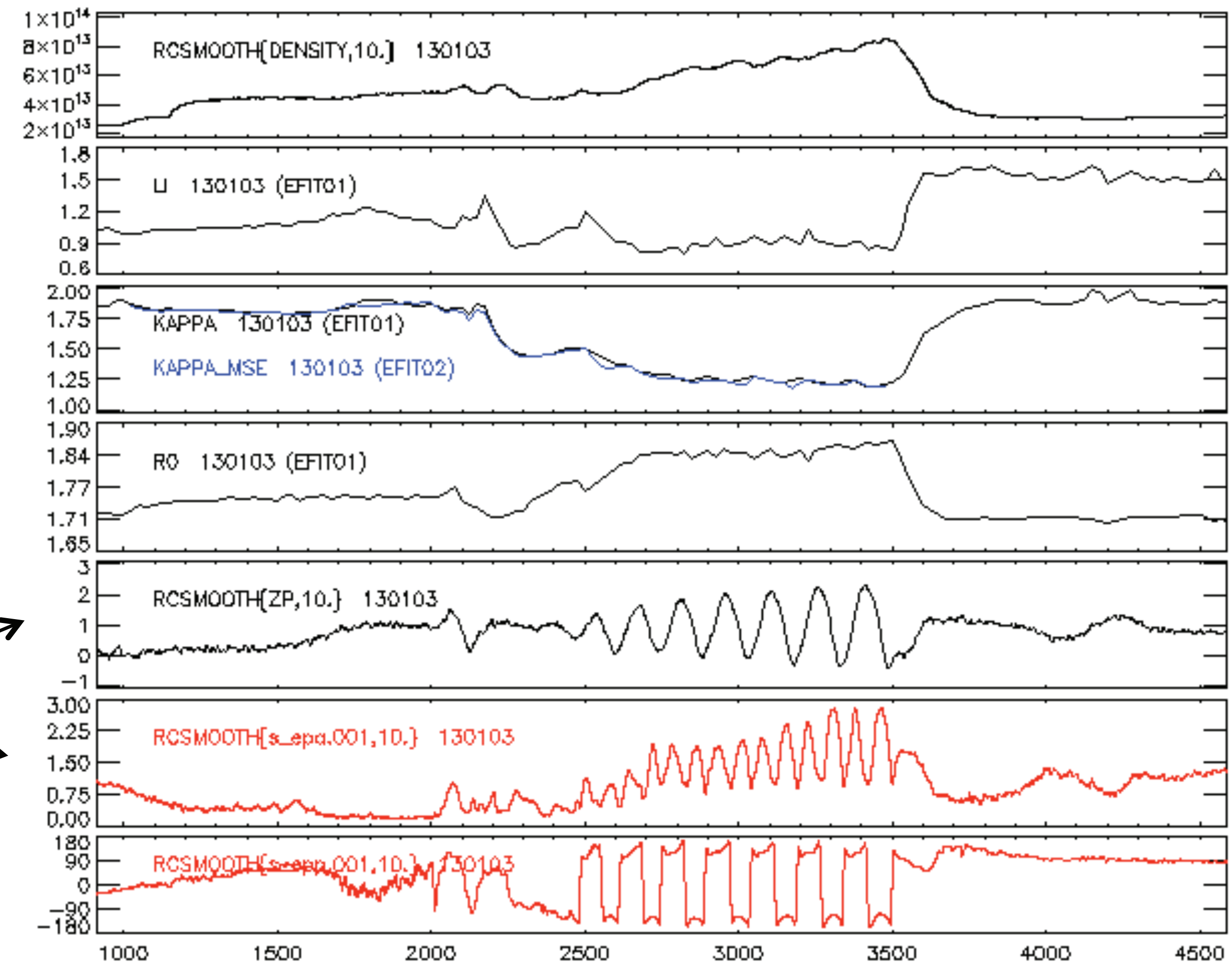
MAGNETIC MEASUREMENTS

Baseline Subtraction

- ESLs sensitive to B_R (including net component of B_p when plasma is vertically displaced/asymmetric)
- *n*=0 B_R cancels out in the difference (ESLDs), but not completely
- “Baseline”: pick-up from *n*=0 equilibrium
- Baseline is undesired (ESLDs are supposed to measure n=1, 3, etc.) but finite
- Baseline subtraction = choice of (time of) reference equilibrium
- Equilibrium can vary significantly during the shot (due to changes in density, L/H-mode, NBI and thus β, etc.) → some degree of arbitrariness
- Effect of E-coils should be subtracted

1cm of Vertical Displacement can cause "Signals" of 0.9G (ESLD) and Phase Errors of 40°

Period doubling, in agreement with expectation

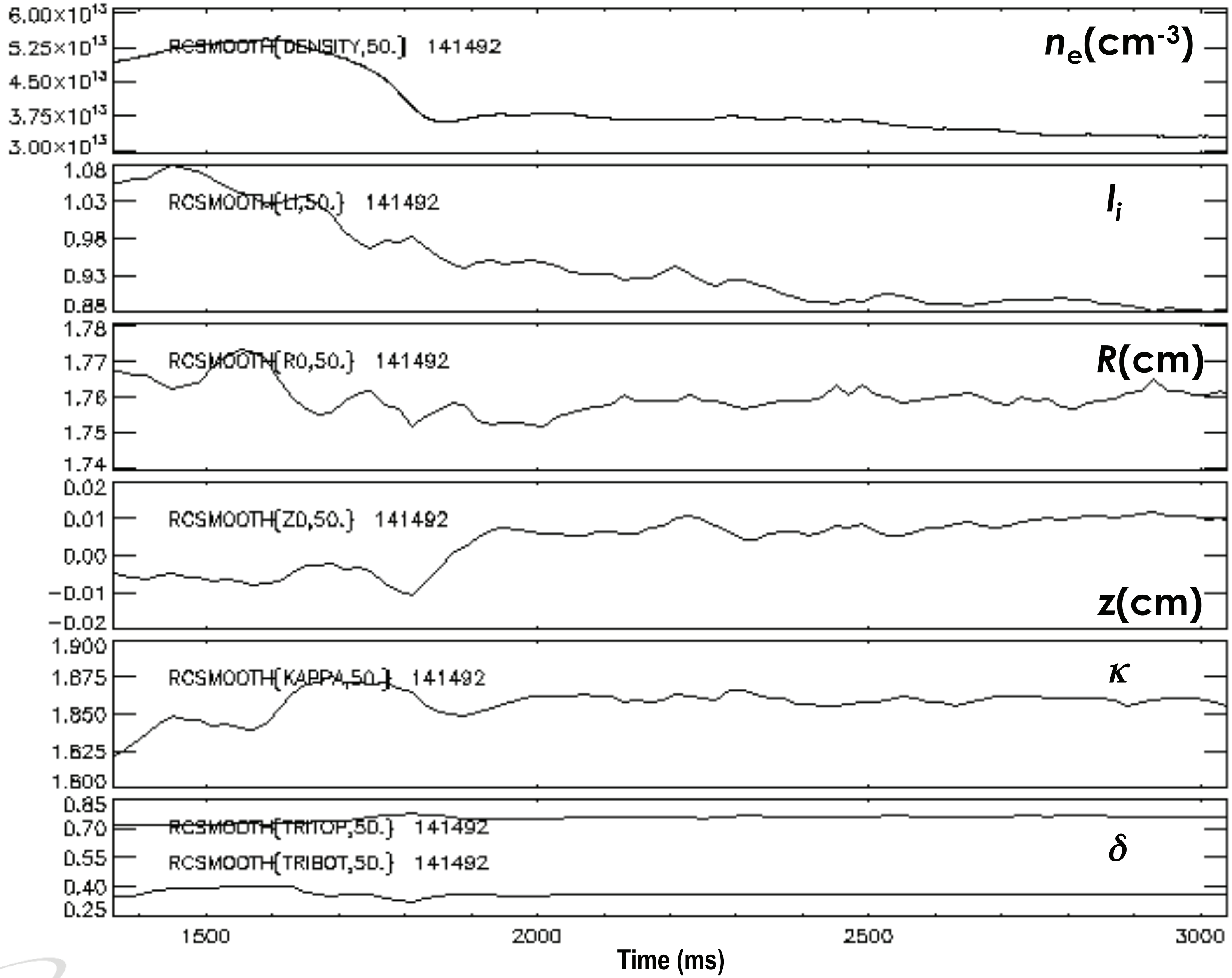


Changes of Equilibrium Cause Apparent Changes of Saddle Loop Measurements

Cause	Effect on ESLD measurement		Effect on ISLD measurement		Shot, time
	ΔA (G)	$\Delta\phi$ (deg)	ΔA (G)	$\Delta\phi$(deg)	
ΔR=6cm	0.7	40	1.6	0	141958, 2000-2800ms
$\Delta n_e=10^{19}m^{-3}$ *	0.7	0	1.8	0	128423, 1400-3200ms
Triangularity $\Delta\delta=0.25$	1.1	90			103828, 2000-3800ms
Δz=1cm	0.9	40			130103, 2500-3500ms

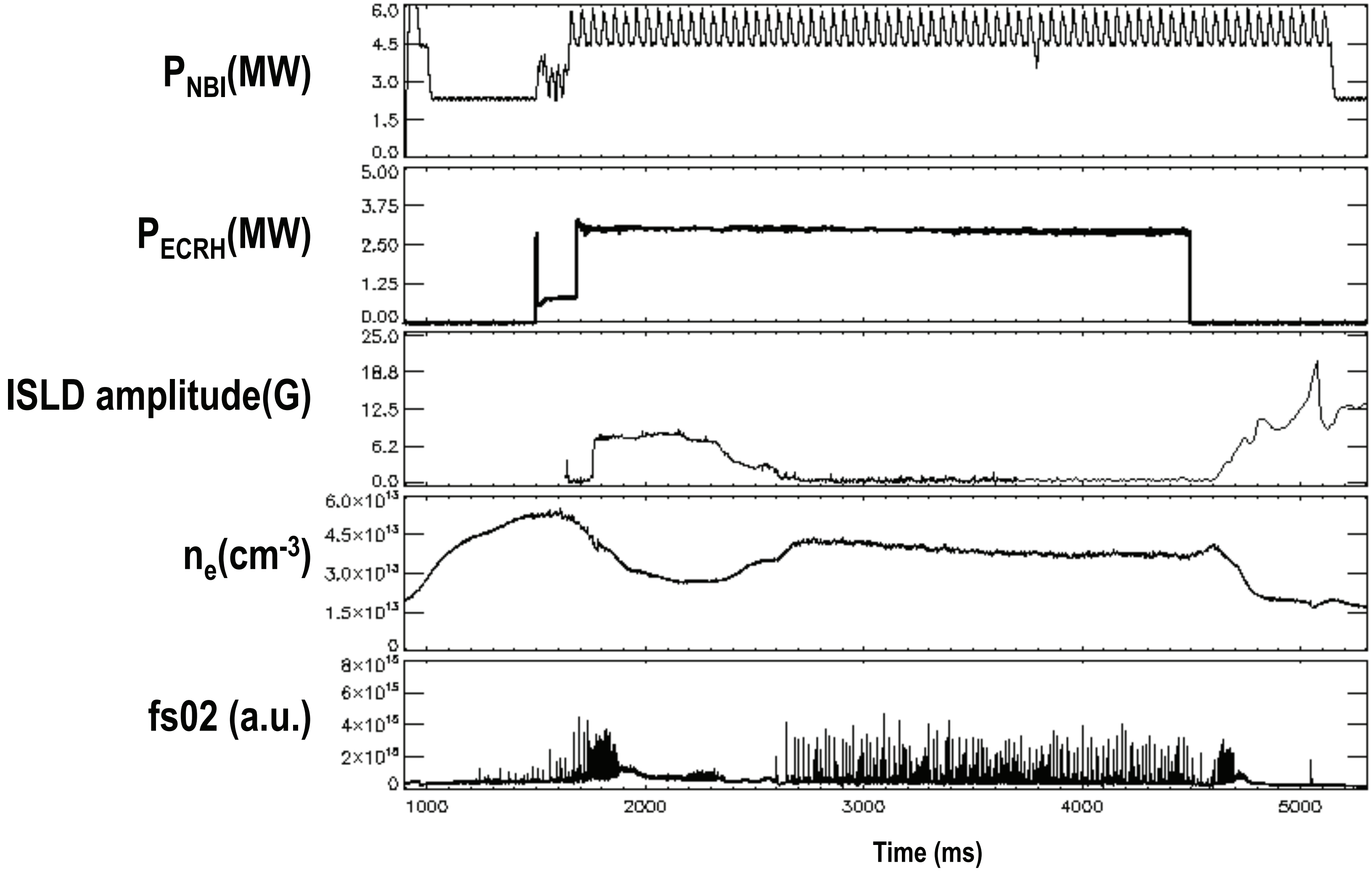
* Density affects measurements via plasma response, l_i and resistivity.

Equilibrium Changed in all LM Control Discharges, by far More than Enough to Explain 1G Baseline

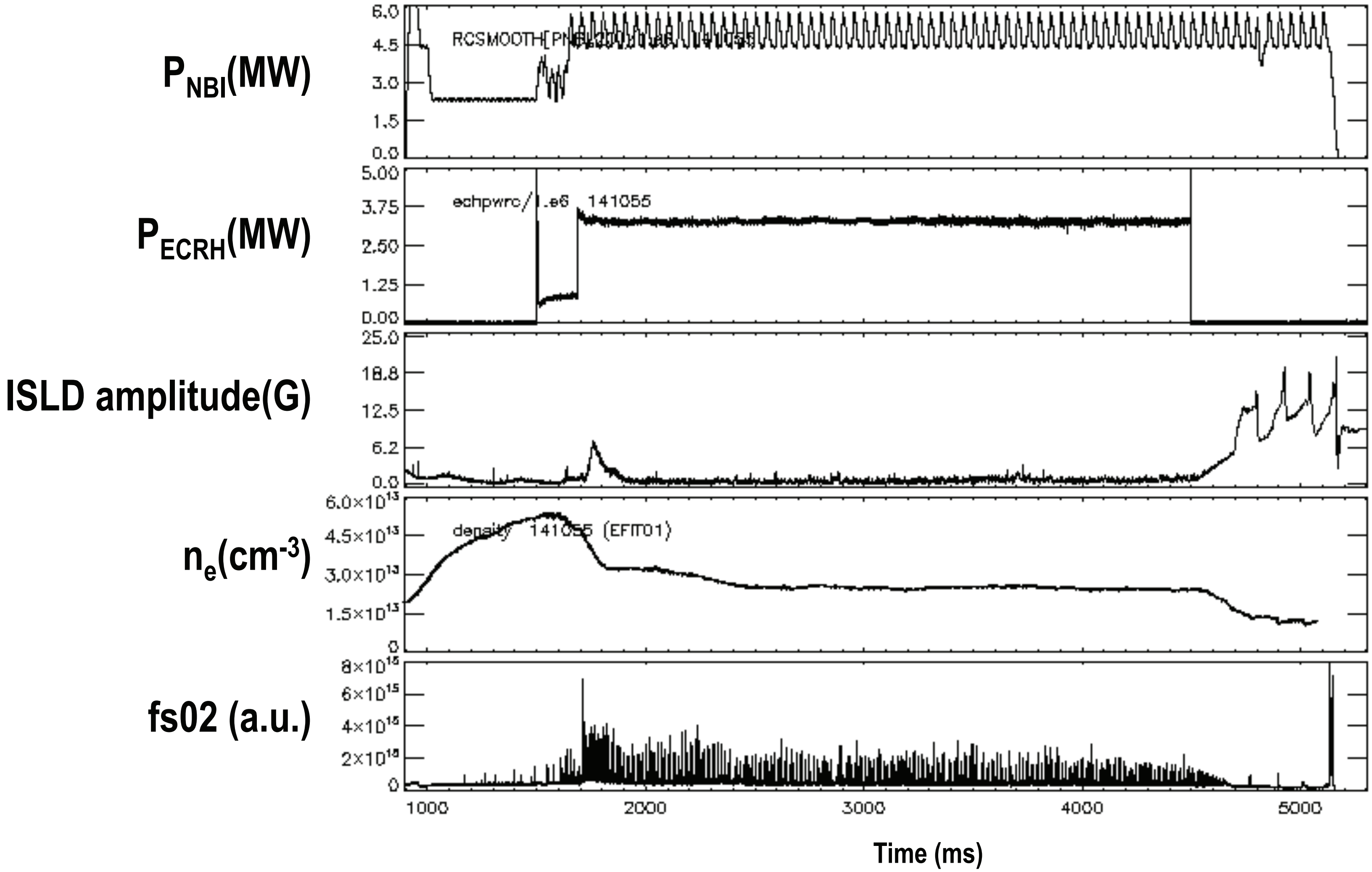


EFFECT on H-MODE and ELMs

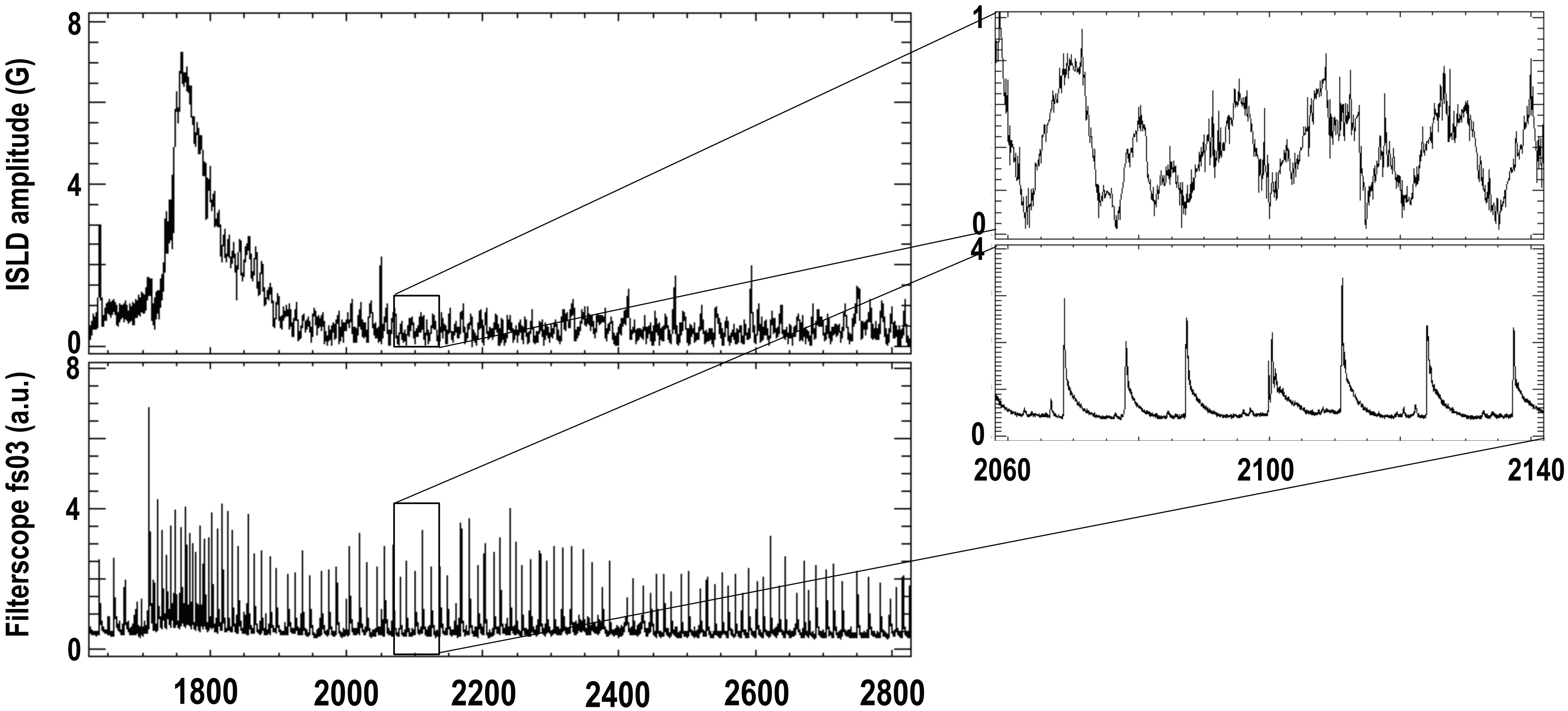
After LM Suppression, H-mode is Recovered



Often Shot doesn't even go out of H-mode

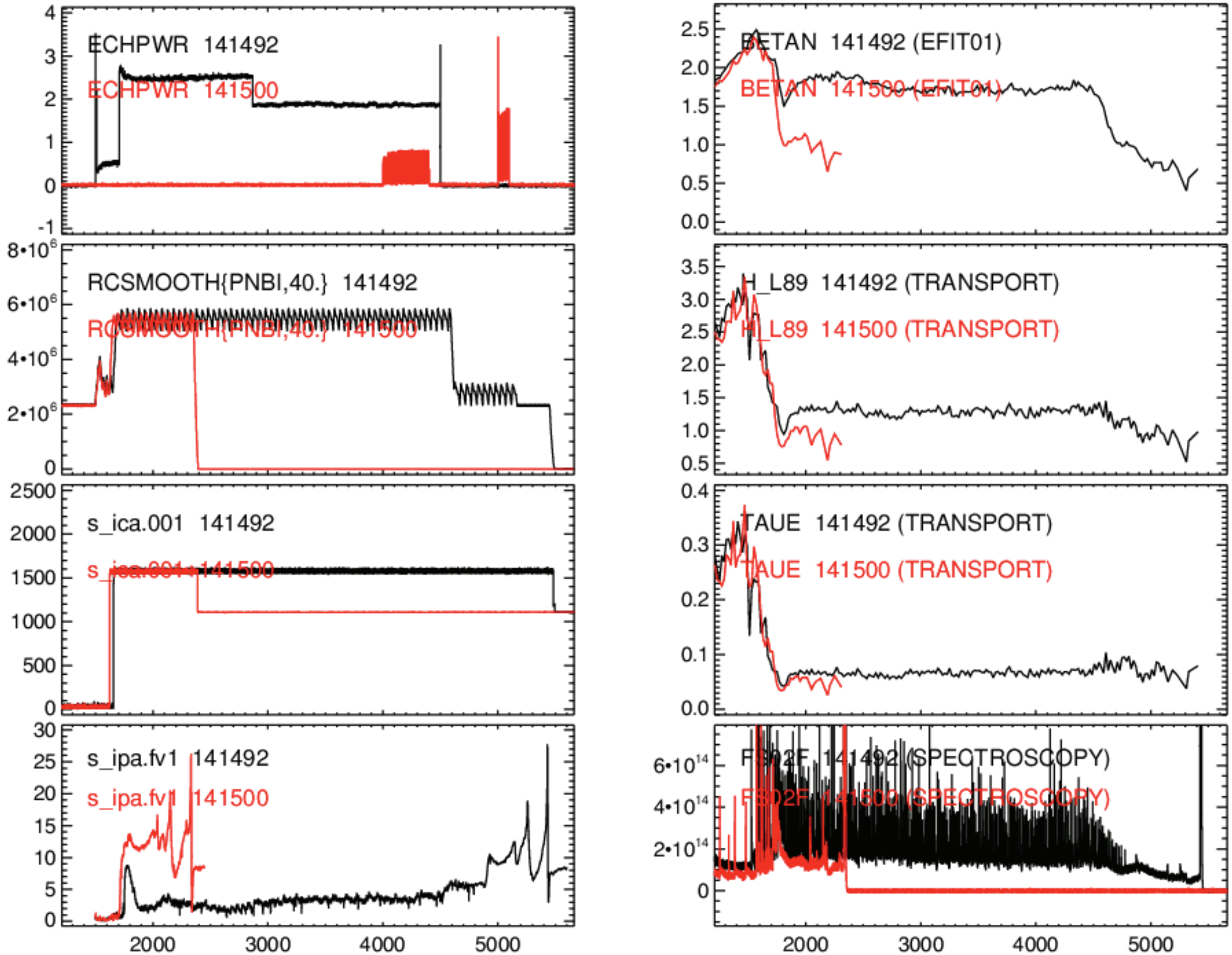


ELMs Modulate LM Signal (Saddle Loop, in General)

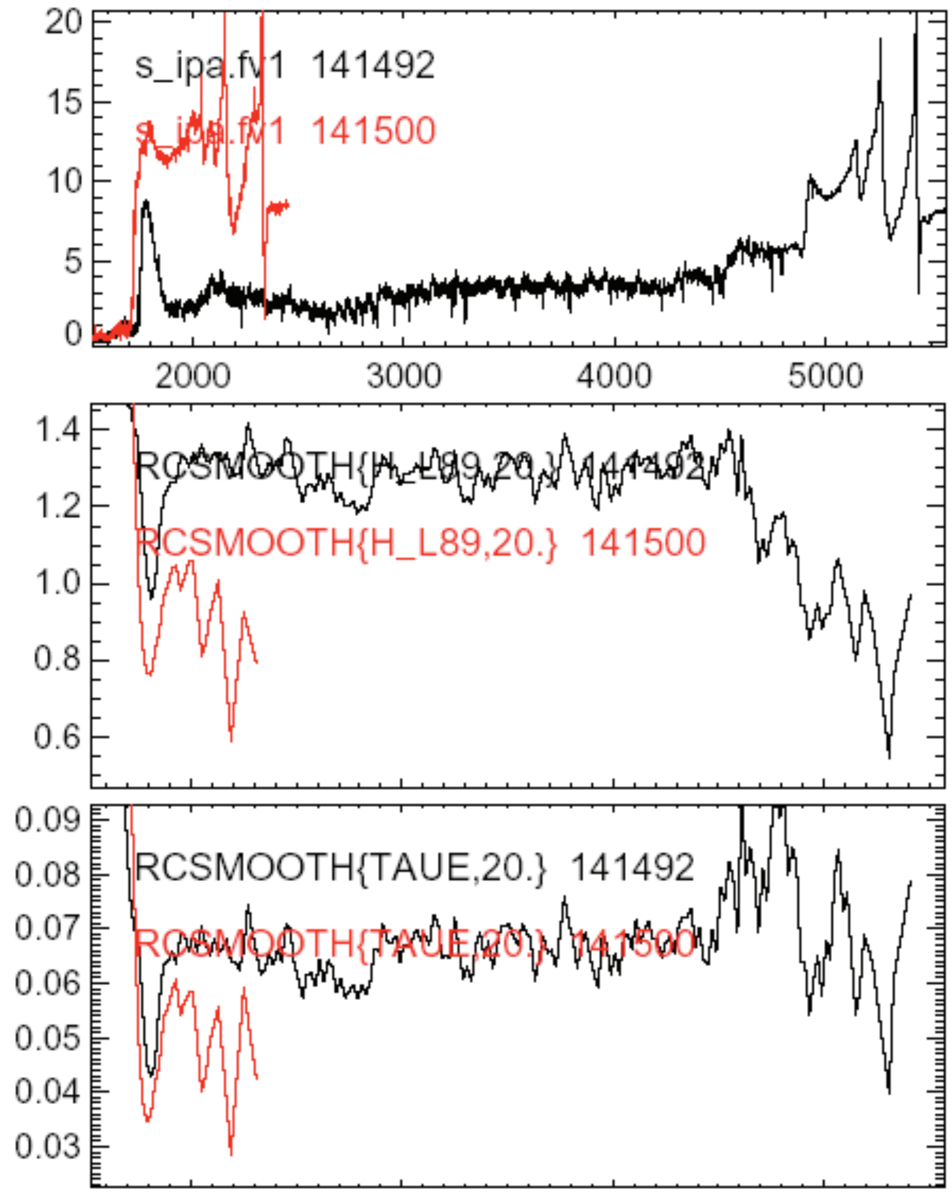


EFFECT on Confinement

Curing LM (that Degrades Confinement) with ECH & EF (that also Degrades Confinement) → Confinement doesn't Recover to Pre-locking Values

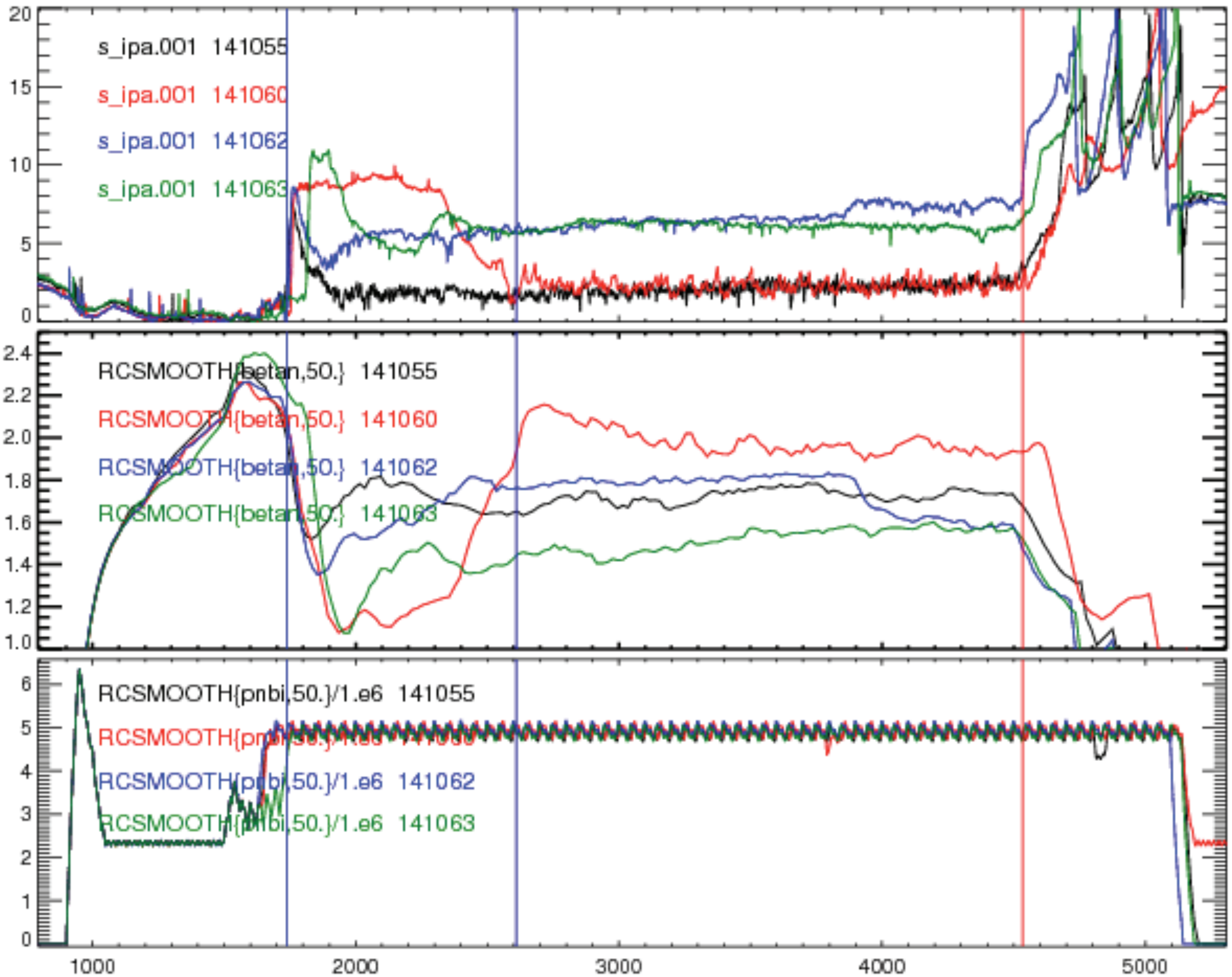


However, Confinement is Much Better with LM Controlled than Uncontrolled

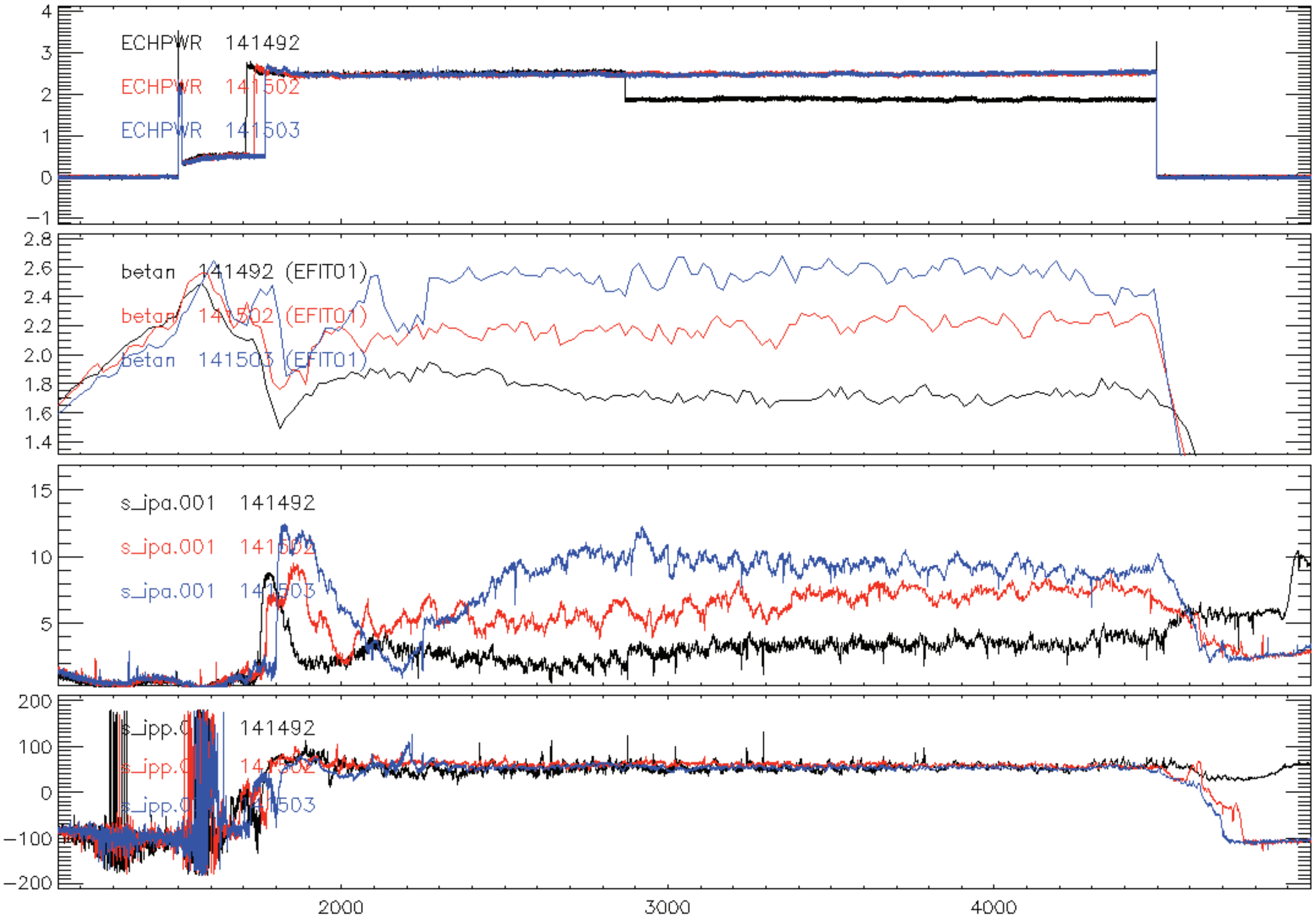


EFFECT on β_N

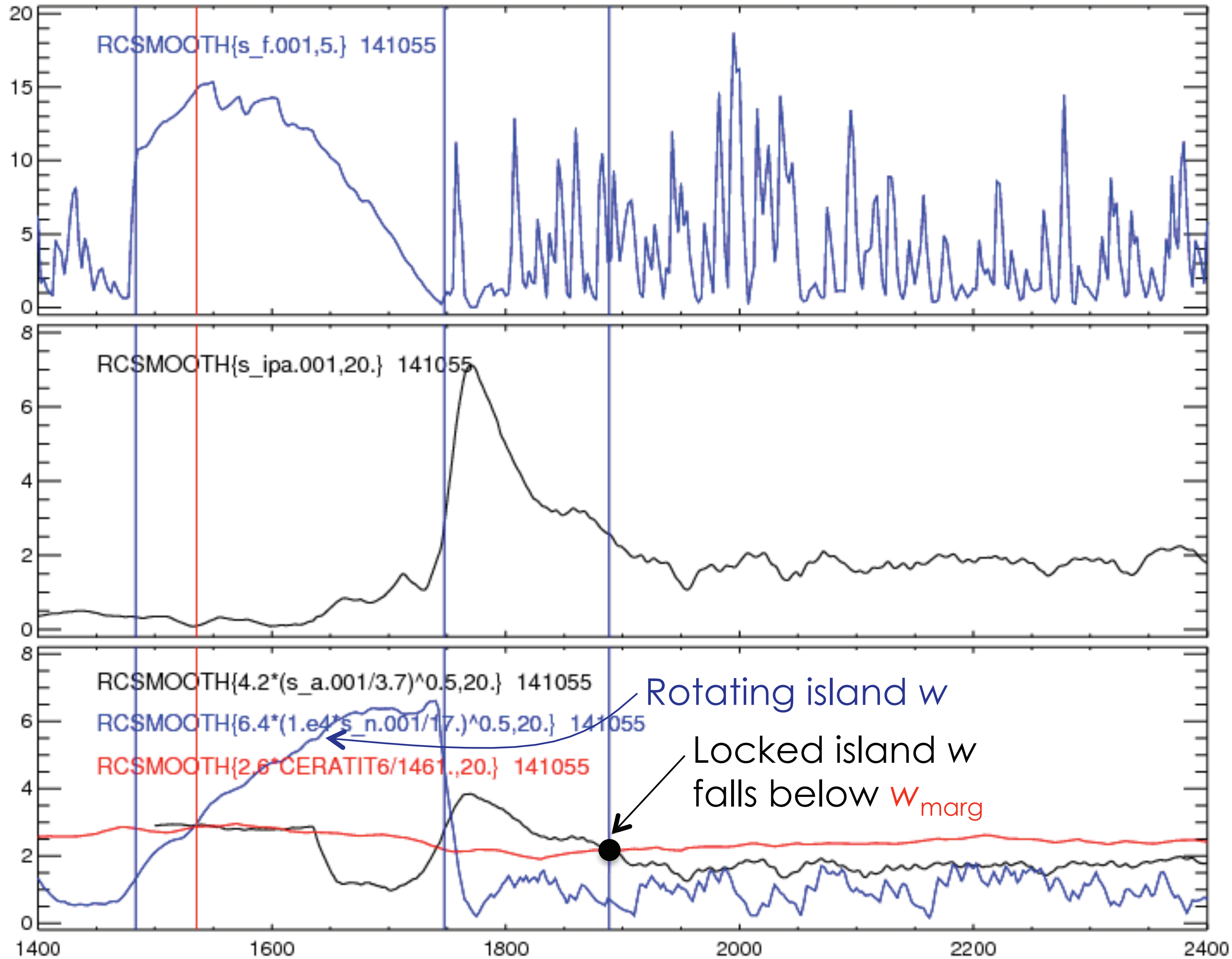
As Locked Mode is Stabilized, β_N Recovers. As Mode Reappears (when ECCD off), β_N Drops Again. Changes in β_N not Due to NBI



β_N was Increased from 1.7 to 2.5 and Yet No Disruption



Island Width Drops Below Marginal in Correspondence of Complete Stabilization

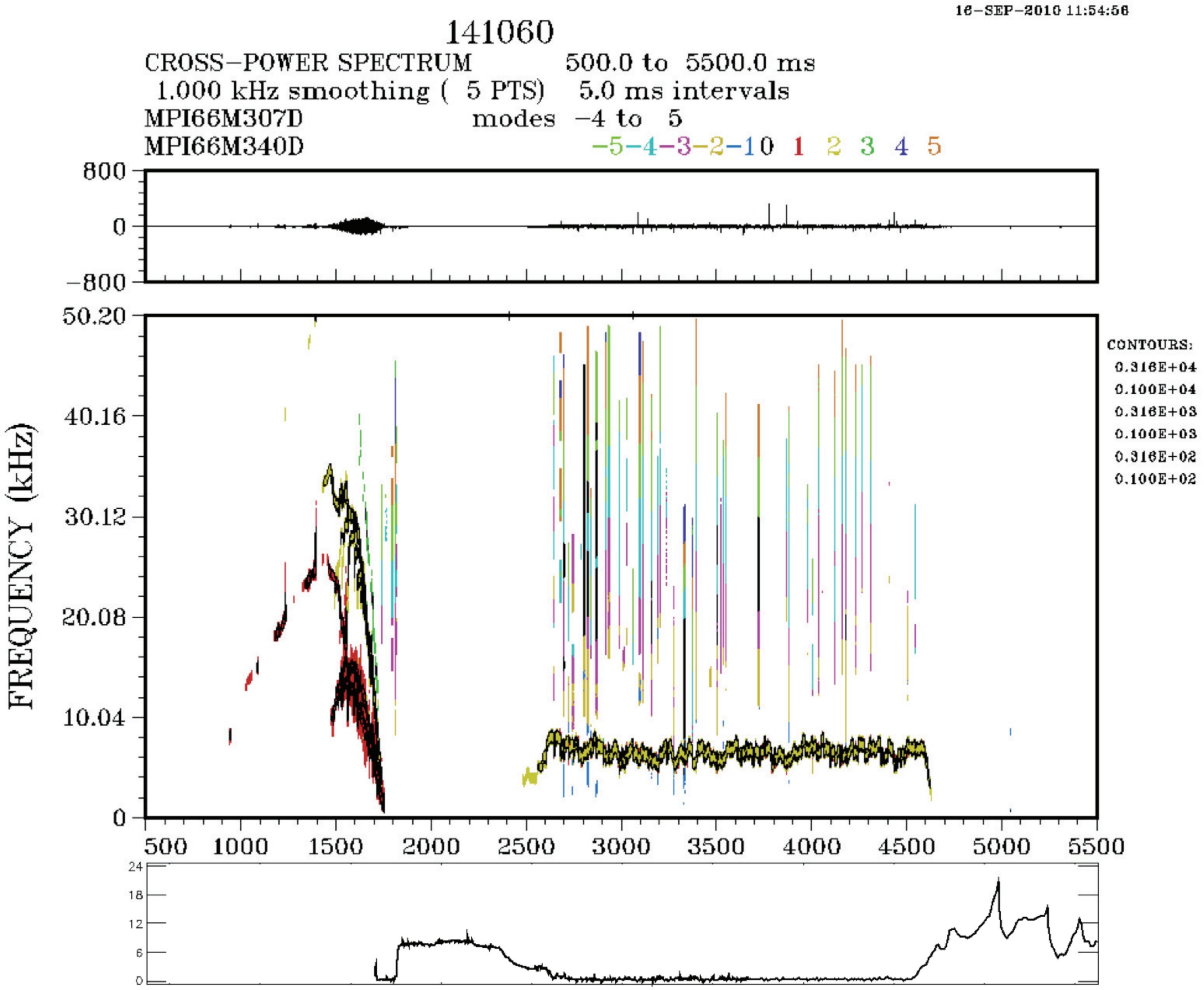


DIII-D NATIONAL FUSION FACILITY SAN DIEGO

AFTER STABILIZATION

No Rotating 2/1 after Stabilization of Locked 2/1
Rotating 3/2 Strikes Occasionally

…in 141055 and 060, but not in other fully stabilized shots (141046, 047, 491, 492)



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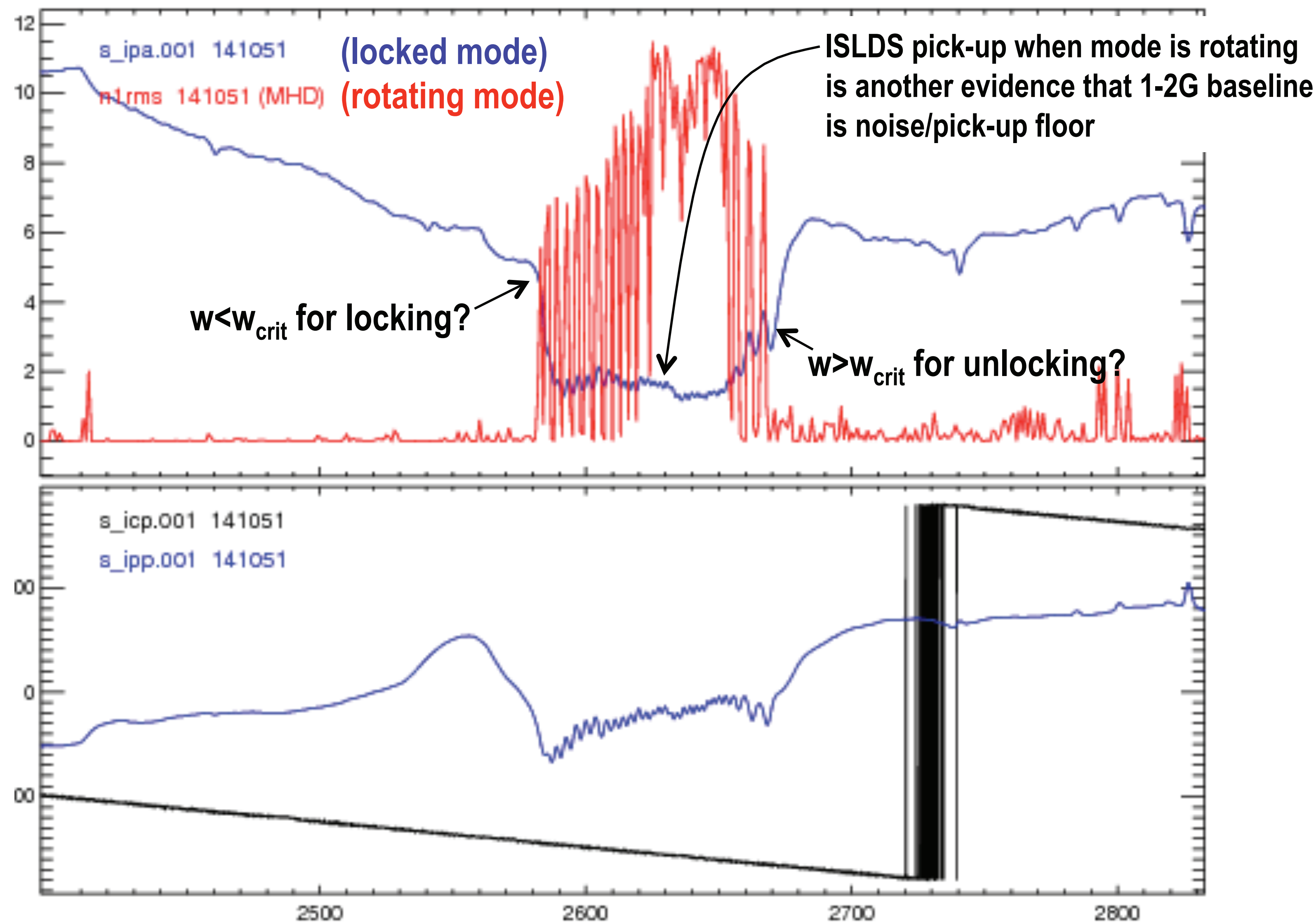
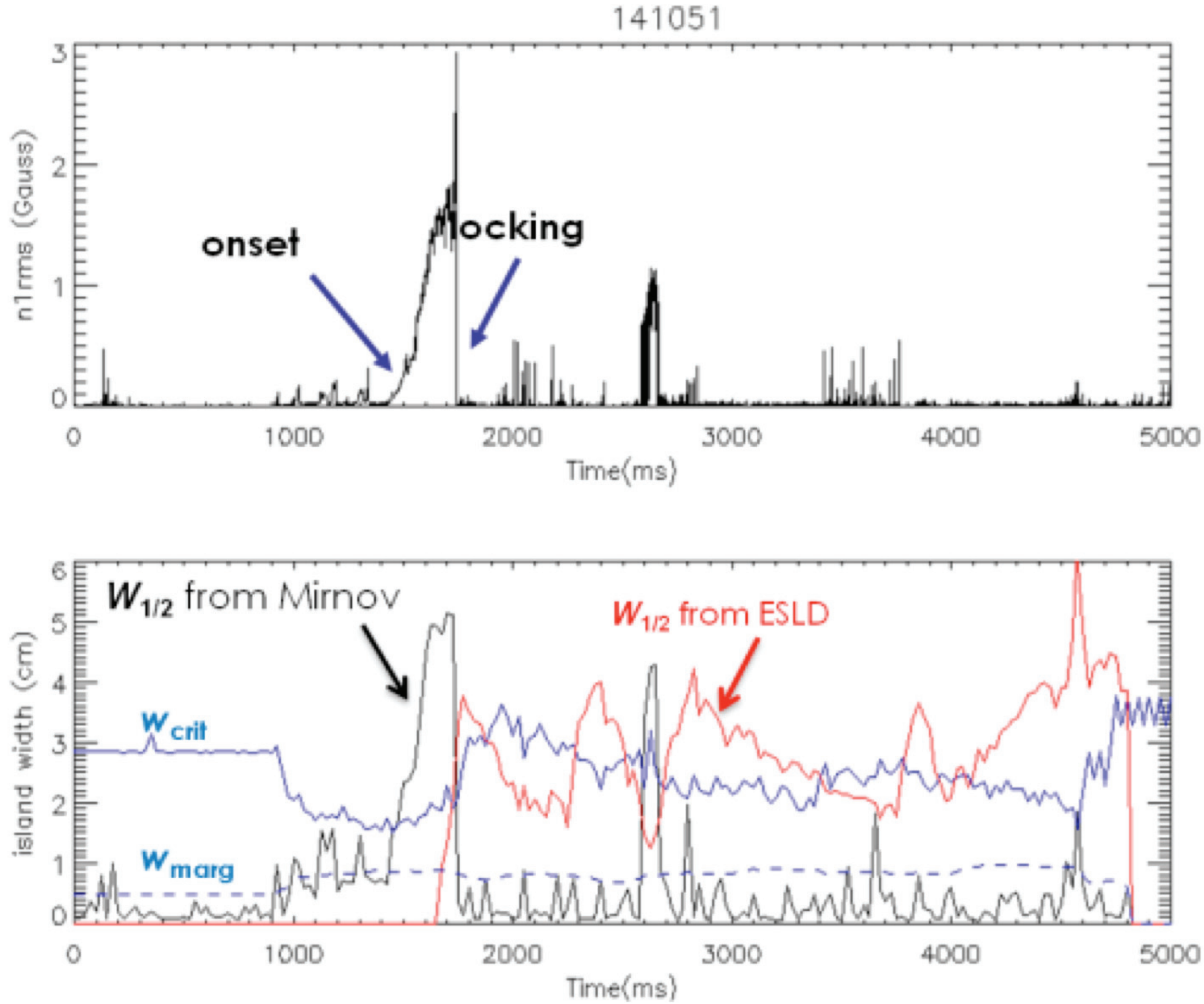
UNLOCKING

Unlocking



NBI torque and RMP are changing, explaining re-locking

Island Locks when a Critical width is Exceeded



And should unlock when width below critical, but changes of NBI torque need to be included in the analysis

Unlocking or Suppression? Depends on Competition Between NBI and ECCD Effects.

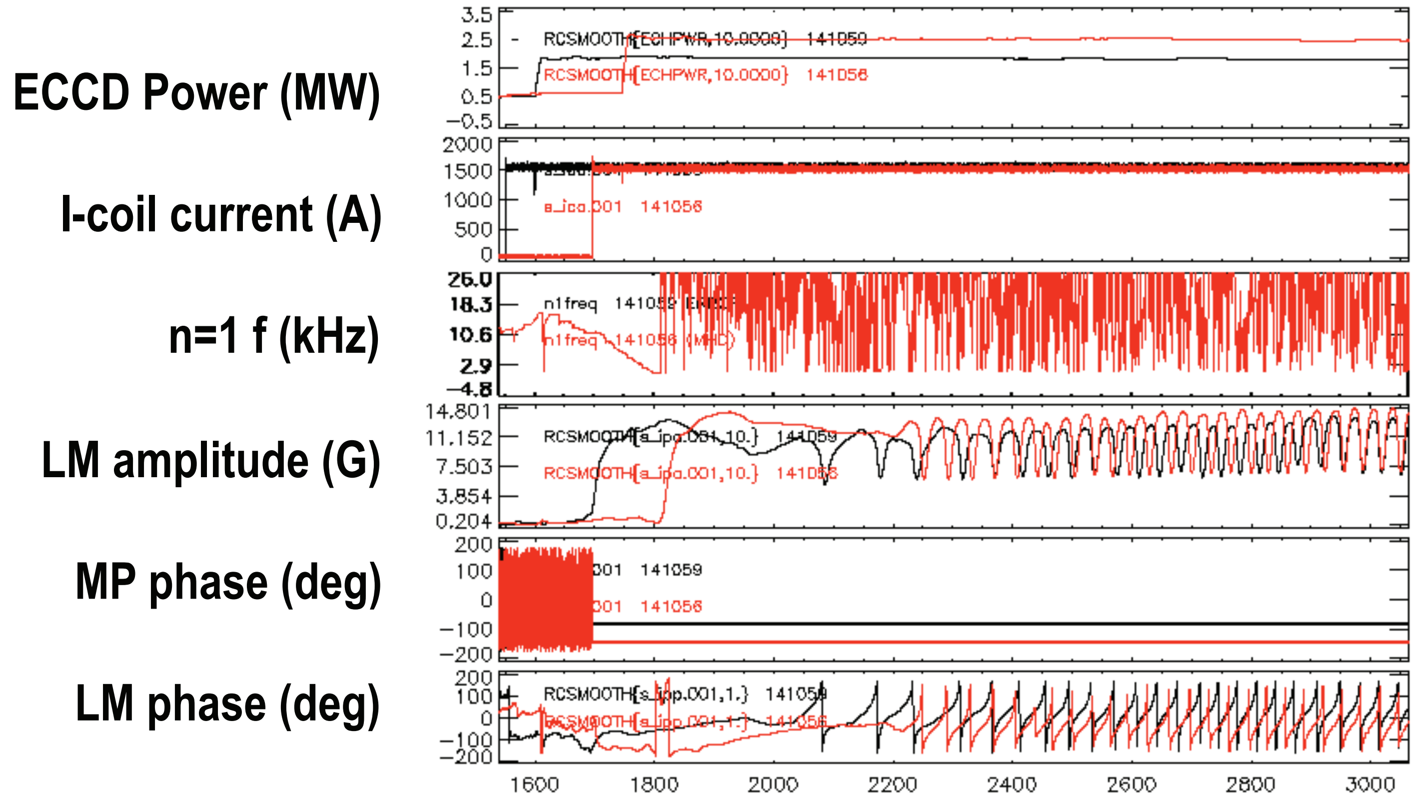
1) ECCD stabilizes mode

2) NBI imparts torque to plasma and, indirectly, to island

- Residual EF and RMP brake island and, indirectly, plasma
- EF+RMP torque depends on island width *w*, thus decreases as ECCD stabilizes the mode
- If/when NBI torque larger than EF+RMP torque, mode is unlocked, unless complete ECCD stabilization (1) has occurred before

Quasi-stationary Modes

Modes Locked to 120-180° (X-point and Vicinity) Slowly Drift and Decrease in Amplitude, then Unlock and Become "Quasi-stationary Modes" (QSMs)



- QSMs also obtained when RMP too weak (1.2kA) and EFC wrong (141052)
- Weak RMP, per se, didn't lead to QSM (141051)
- QSM strikes 0.3-1s after locking
- Slow QSM dynamics very interesting. Separate experiment will be proposed
- For now, avoid it and lock mode where requested

ECCD Affects QSM Frequency/Existence

ECCD Power (MW)

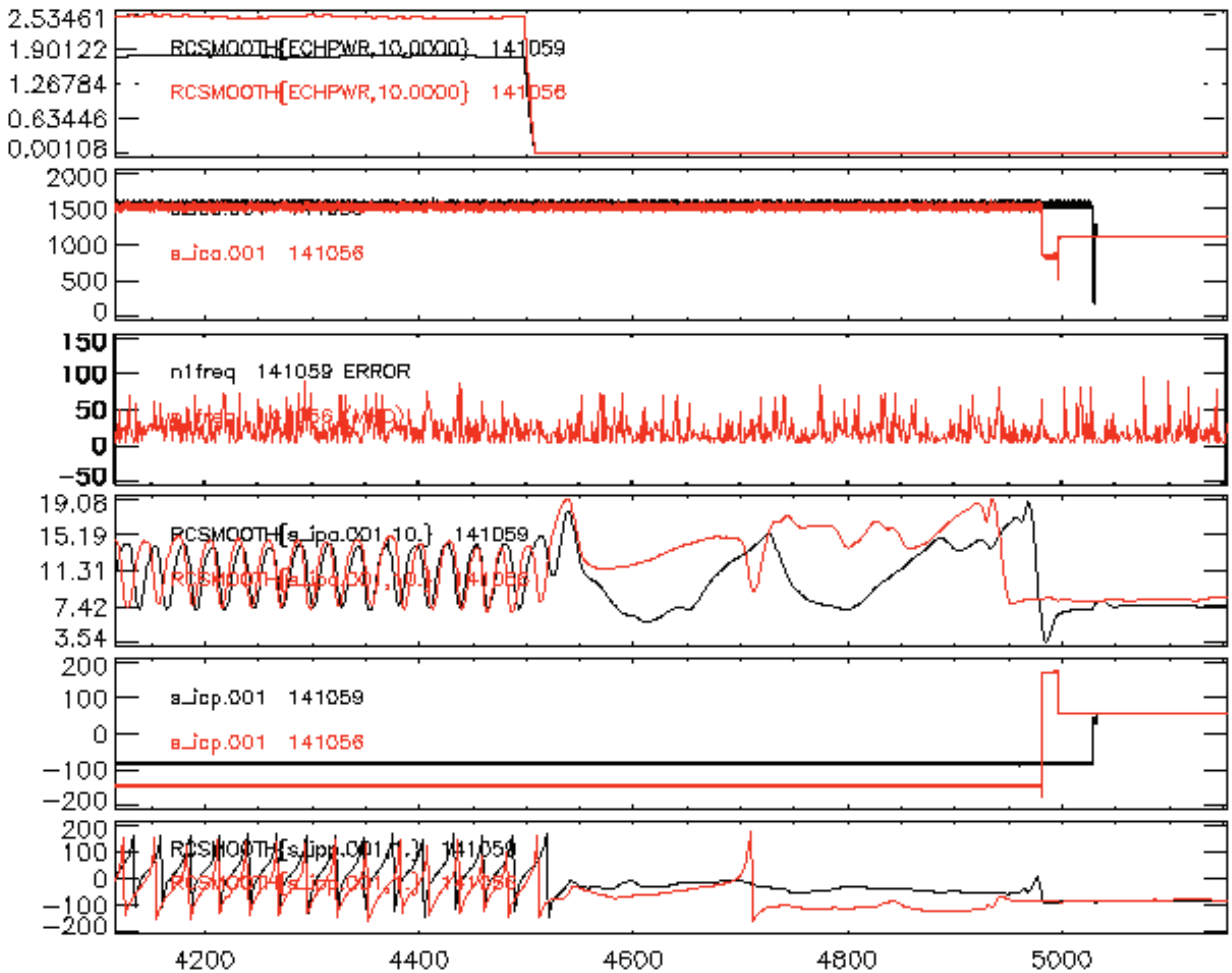
I-coil current (A)

n=1 f (kHz)

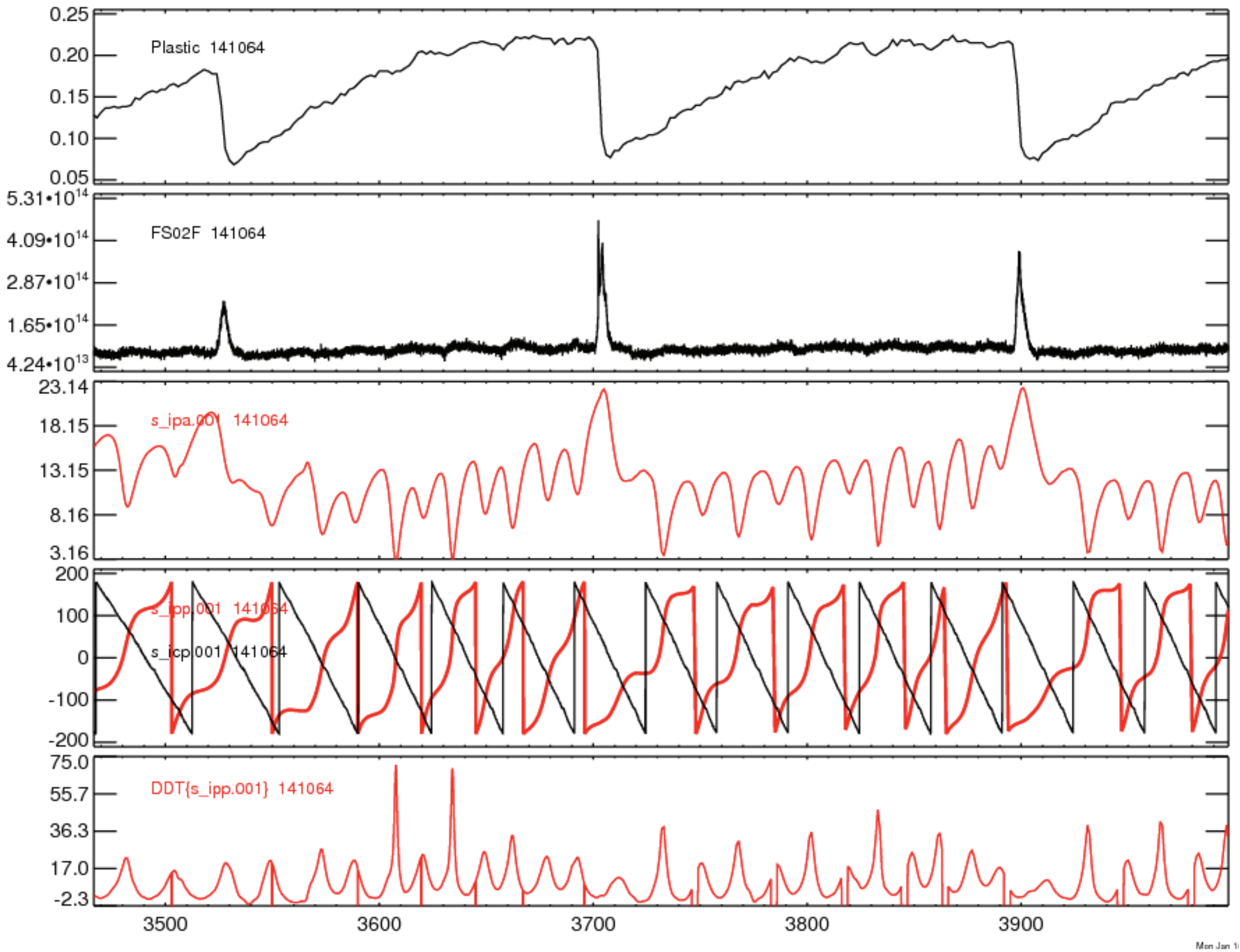
LM amplitude (G)

MP phase (deg)

LM phase (deg)



QSM Rotating Against Travelling Wave Repetitively Grew and Crashed, Accompanied ELM-like Flashes of Light, Particle and Energy Losses



Summary and Conclusions

- Locked modes that would have otherwise caused a disruption were stabilized by ECCD and RMPs
- RMPs were applied prior to complete locking, to force the rotating precursor to lock in a position accessible to ECCD
- β_N as high as 2.5 and yet no disruption. Without this technique, disruption at β_N =1.7
- Dependence on toroidal phase of locking as expected
- Dependence on ECCD power as expected
- ECCD more efficient than ECH at stabilizing the mode
- QSM problems solved by brute force (stronger RMP). Will be studied in separate experiment
- ECCD-facilitated unlocking also observed, in a shot with sufficient NBI torque