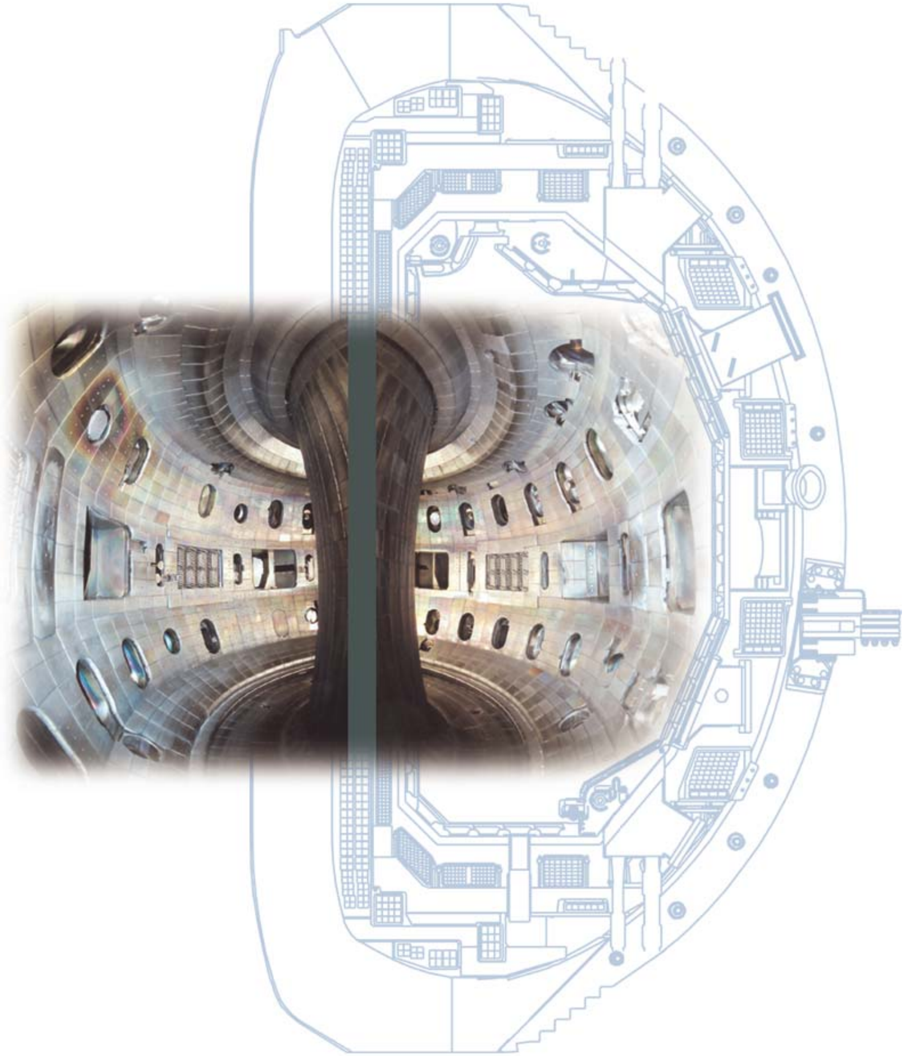
Magnetic Steering and ECCD Mitigation of Locked Neoclassical Tearing Modes at DIII-D



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Motivation

- ITER expected to have slow (few kHz) NTMs → high probability of locking.
- Locked 2/1 modes are a recurrent cause of disruptions.

- ECCD proved successful in suppressing *rotating* NTMs.
- Success of ECCD for *locked* modes not guaranteed, due to island locking in a position not accessible by gyrotrons.

- Resonant Magnetic Perturbations (RMPs) from I-coils used at DIII-D for RWM and ELM control.
- Although more challenging (modes lie deeper in the plasma and rotate faster), here RMPs are used to control NTM rotation and assist their ECCD Stabilization

A variety of sensors and criteria were used to predict or promptly recognize locking

Mirnov Coils

Criterion: **dB/dt >20T/s (200G/ms) for at least 200ms**

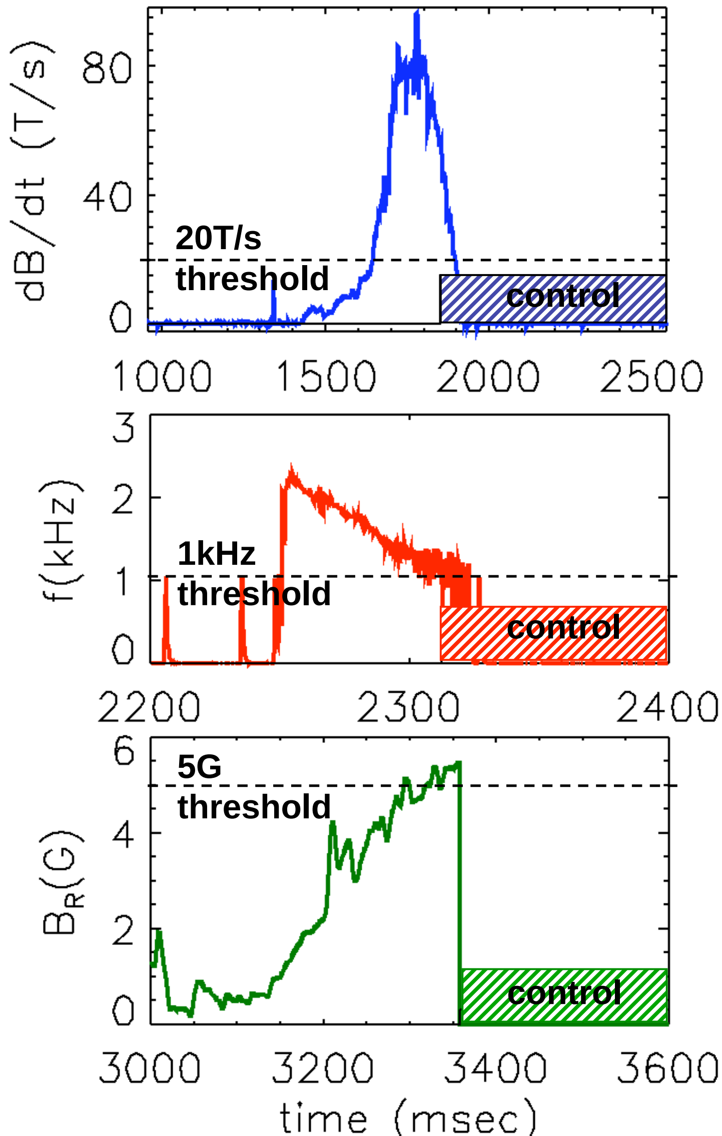
Mirnov Coils+Frequency Counter

(Mirnov spectrogram less noisy, but FFT and mode identification take time)

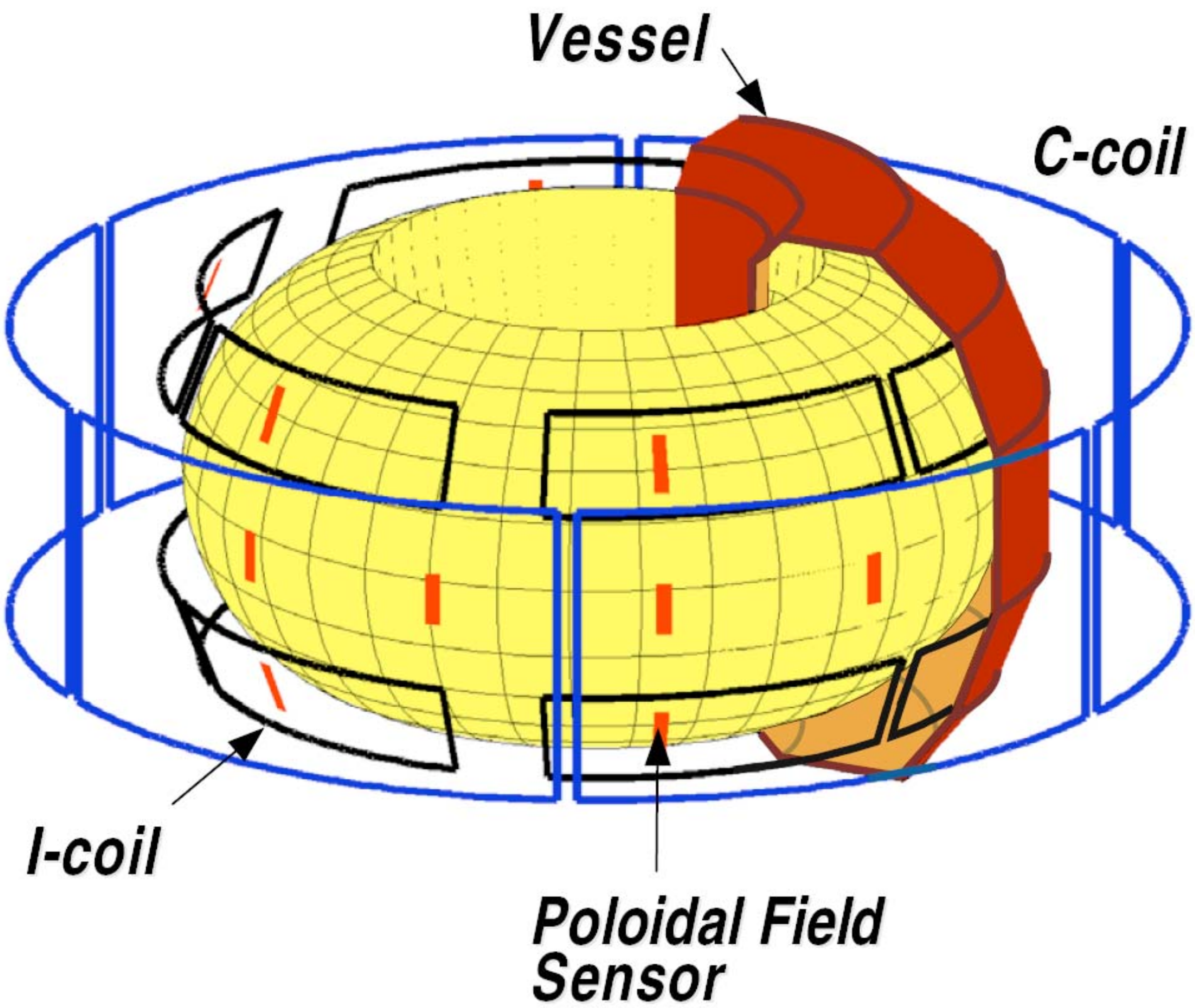
Criterion: **frequency drops below 1kHz for at least 1-10ms after having stayed above threshold for at least 50-200ms**

Saddle loops

Criterion: **>5G for at least 20ms as a signature of born-locked mode**



Toroidal phase and amplitude of NTM were controlled respectively by magnetic perturbations from internal (I) coils and by 2 gyrotrons



2x 110GHz, 600kW gyrotrons

Static/dynamic magnetic perturbations from the I-coils and cw/modulated ECCD can be combined in various ways

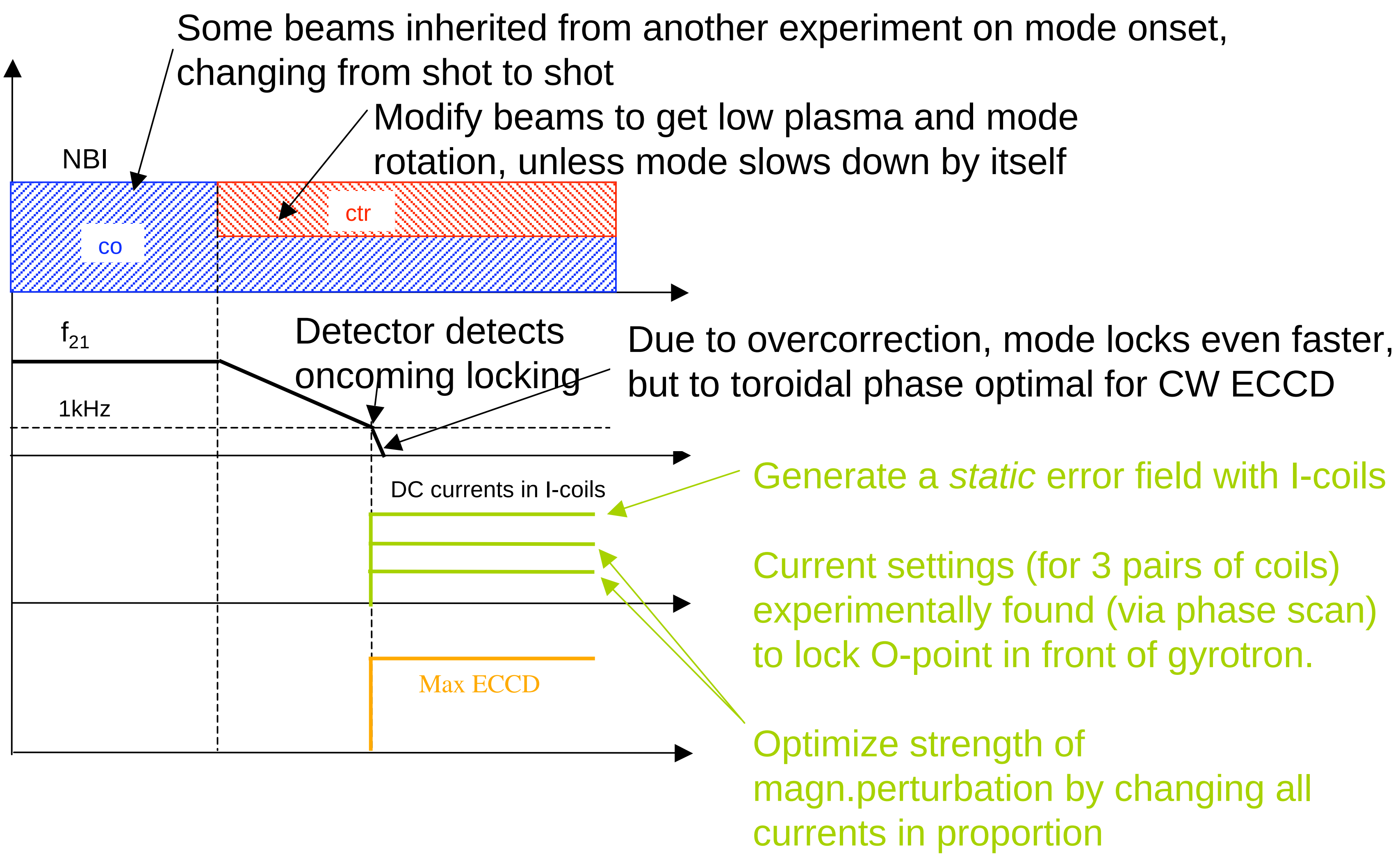
	Initial mode	Error Field Correction	Purpose of Error Field Correction	ECCD	Variables to adjust/scan
1a	Locked	Static	Pre-program toroidal phase at which mode will lock or change it as soon as it locks, to access island O-point with ECCD	CW	DC currents in I-coils
1b	About to lock				
2	Decelerating	Dynamic	Prevent further slowing down and locking by sustaining rotation at >1kHz	CW or Modulated	Amplitude and phase of AC currents in I-coils, MECCD phase
3	Rotating slowly	Dynamic	Like 2. Then make mode spin faster and shrink.	Not necessary	I-coil frequency waveform
4	Locked	Dynamic	Unlocking, then like 3.	Not necessary	

FIRST TYPE OF EXPERIMENTS:

Static EFC (to lock the mode with a preferential toroidal phase) + cw ECCD

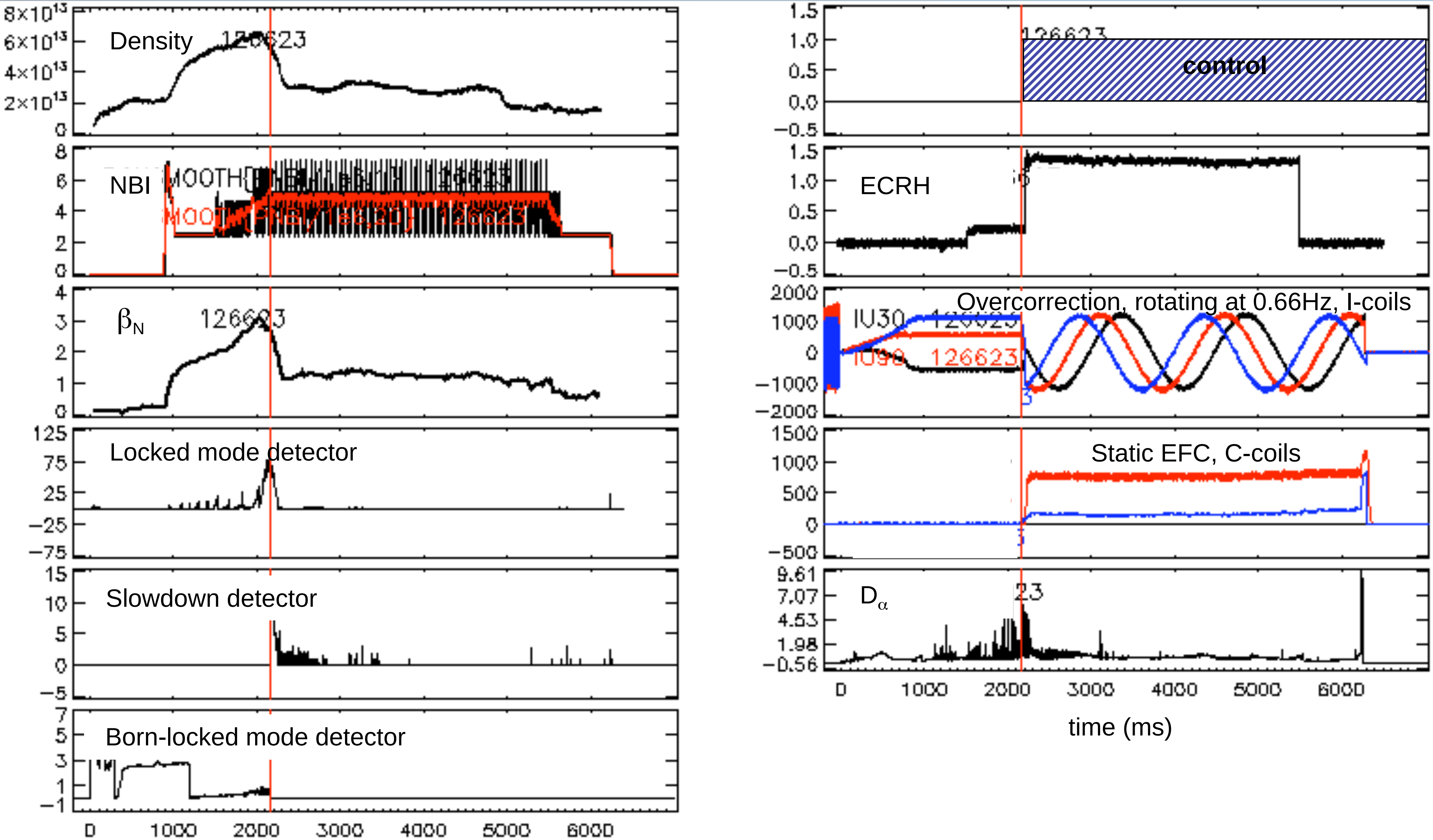
Slow travelling wave to find optimal tor. phase

Control locking (make mode accessible by gyrotrons). Then apply cw ECCD.



Other shots: inject in X-point and intermediate phase angles for comparison

Toroidal Alignment: at locking, 0.66Hz I-coil travelling wave and CW ECH were applied & change in mode amplitude observed.



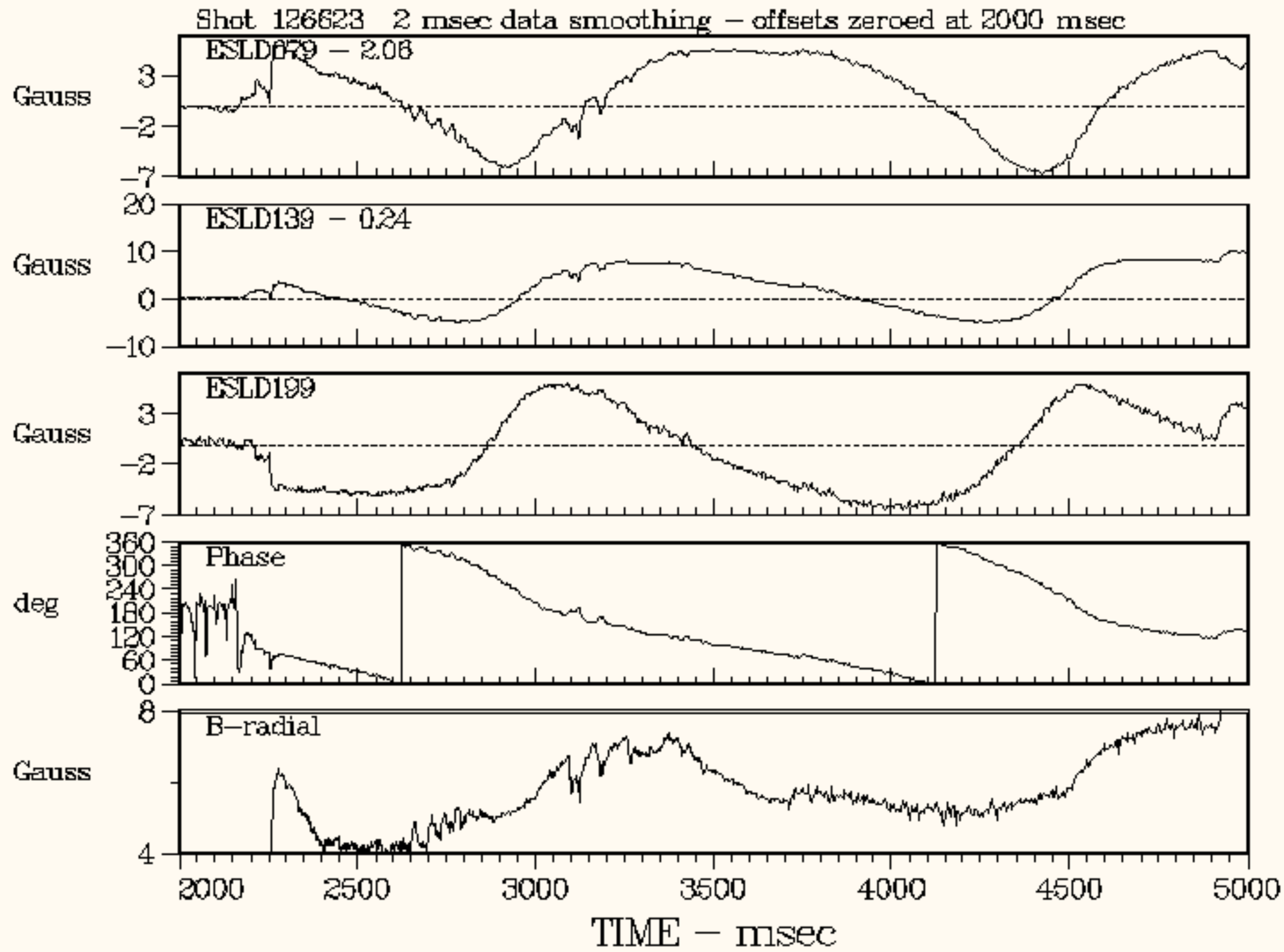
DIII-D NATIONAL FUSION FACILITY

The island, rotated by EFC and illuminated by ECCD, changes amplitude

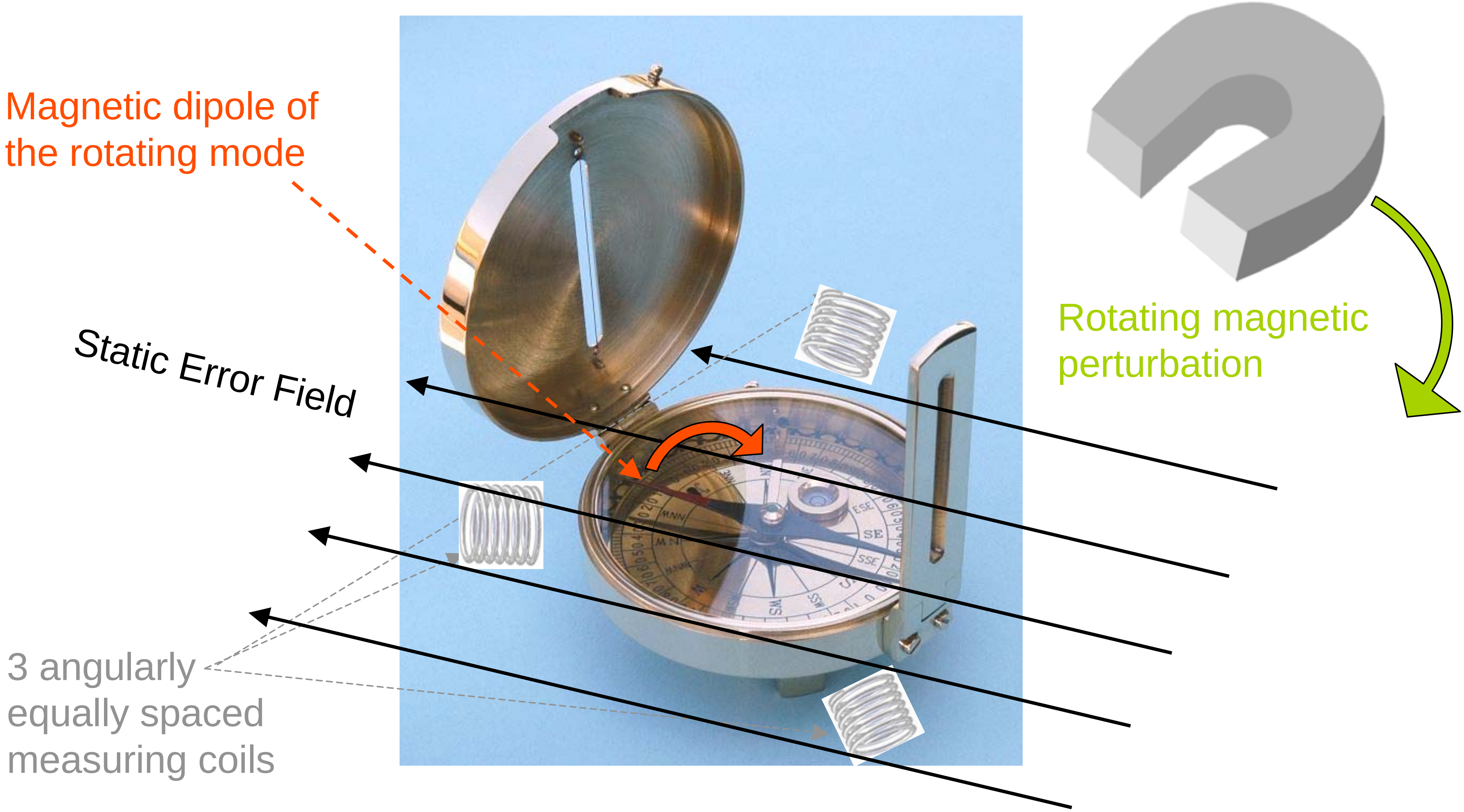
B_R as measured by Saddle Loops in 3 different toroidal locations

toroidal phase

“absolute” amplitude of island varies B_R=4-7.5G



Question: are we observing mode shrinking? Or are we just measuring, with diagnostic coils, the effect of perturbing coils?

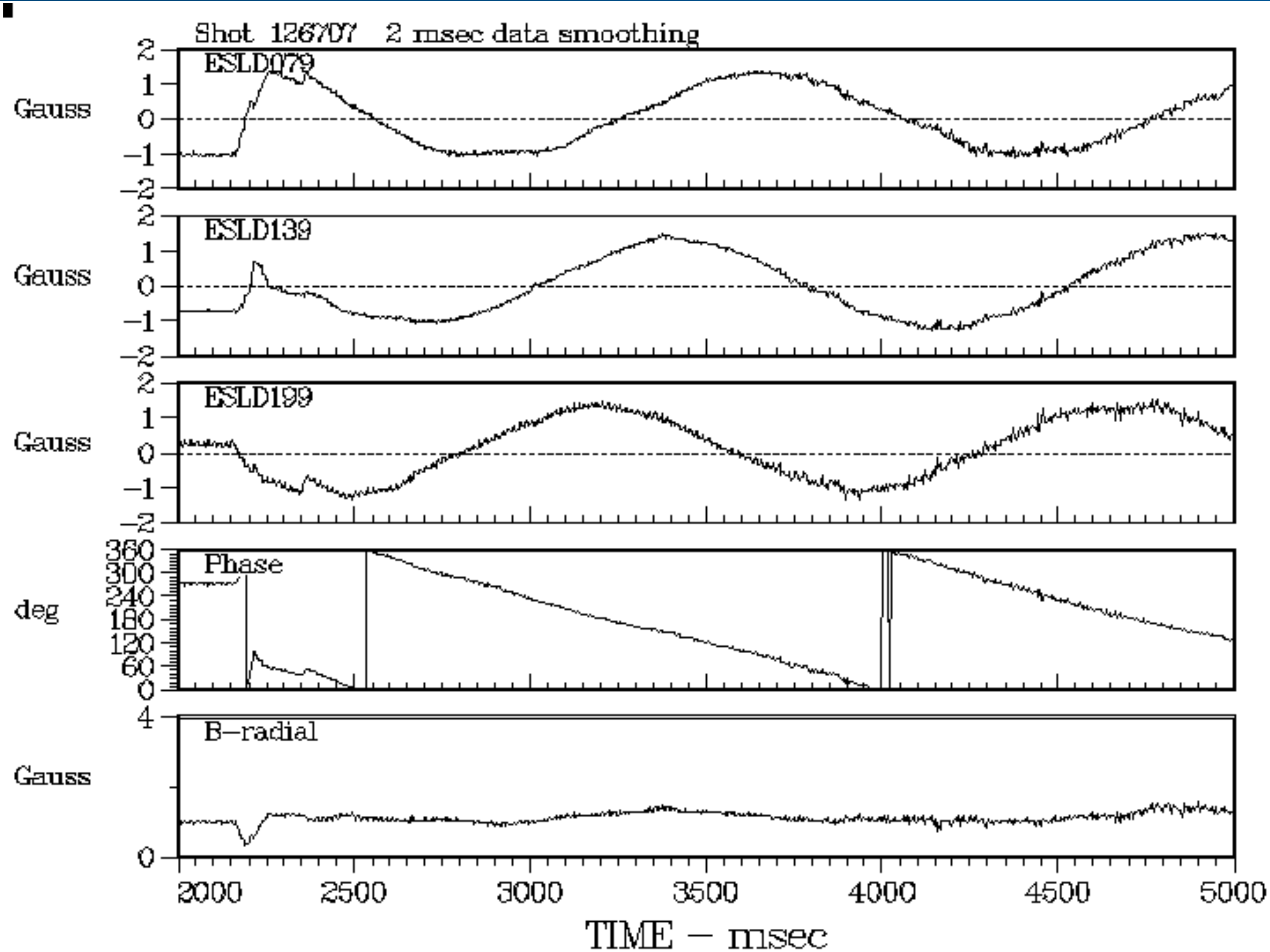


Answer: Vacuum shot allows to measure I-coils and C-coils rotating field at saddle loop locations. This is small and constant.

B_R as measured by Saddle Loops in 3 different toroidal locations

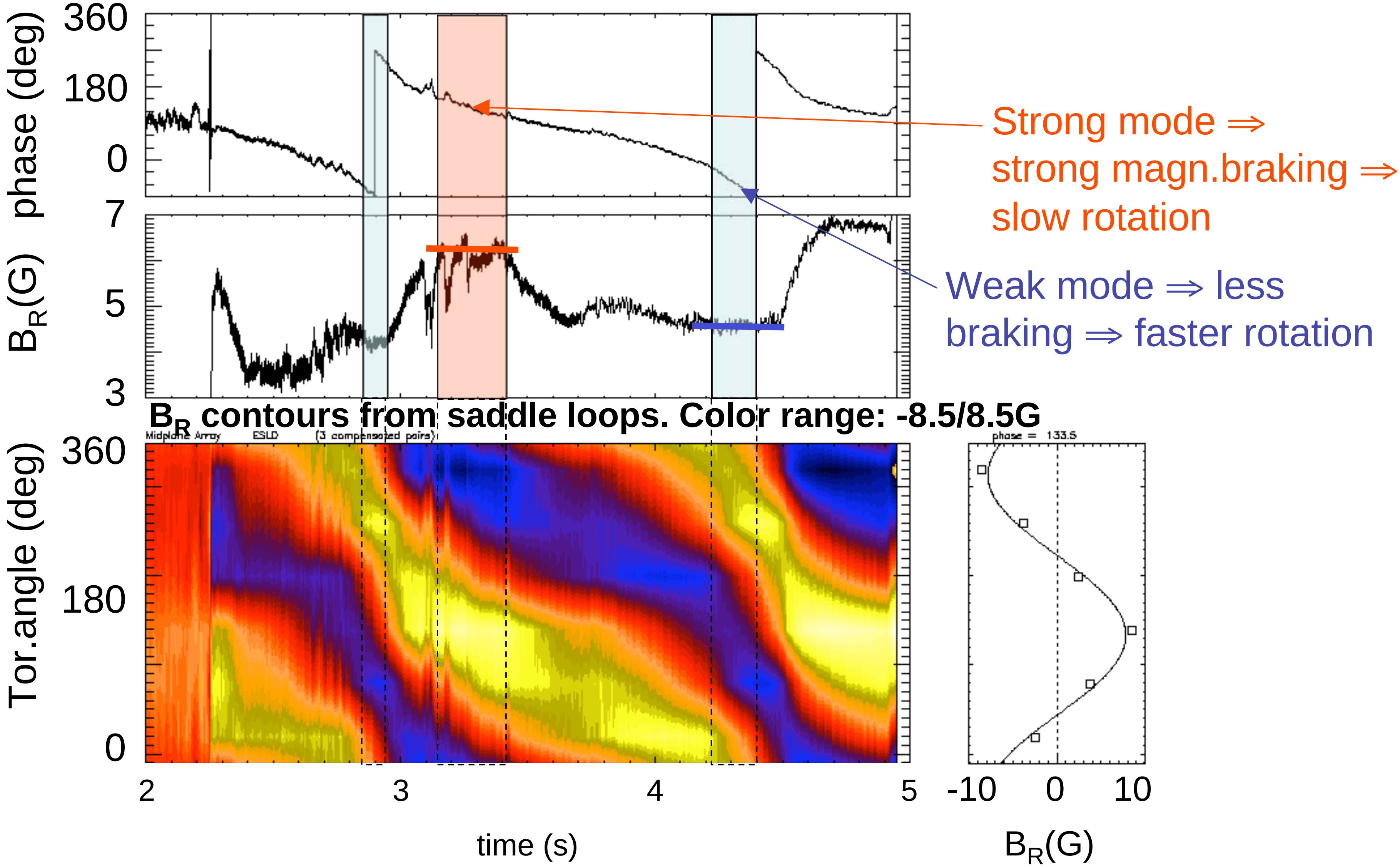
toroidal phase

“absolute” amplitude small and constant, B_R=1G

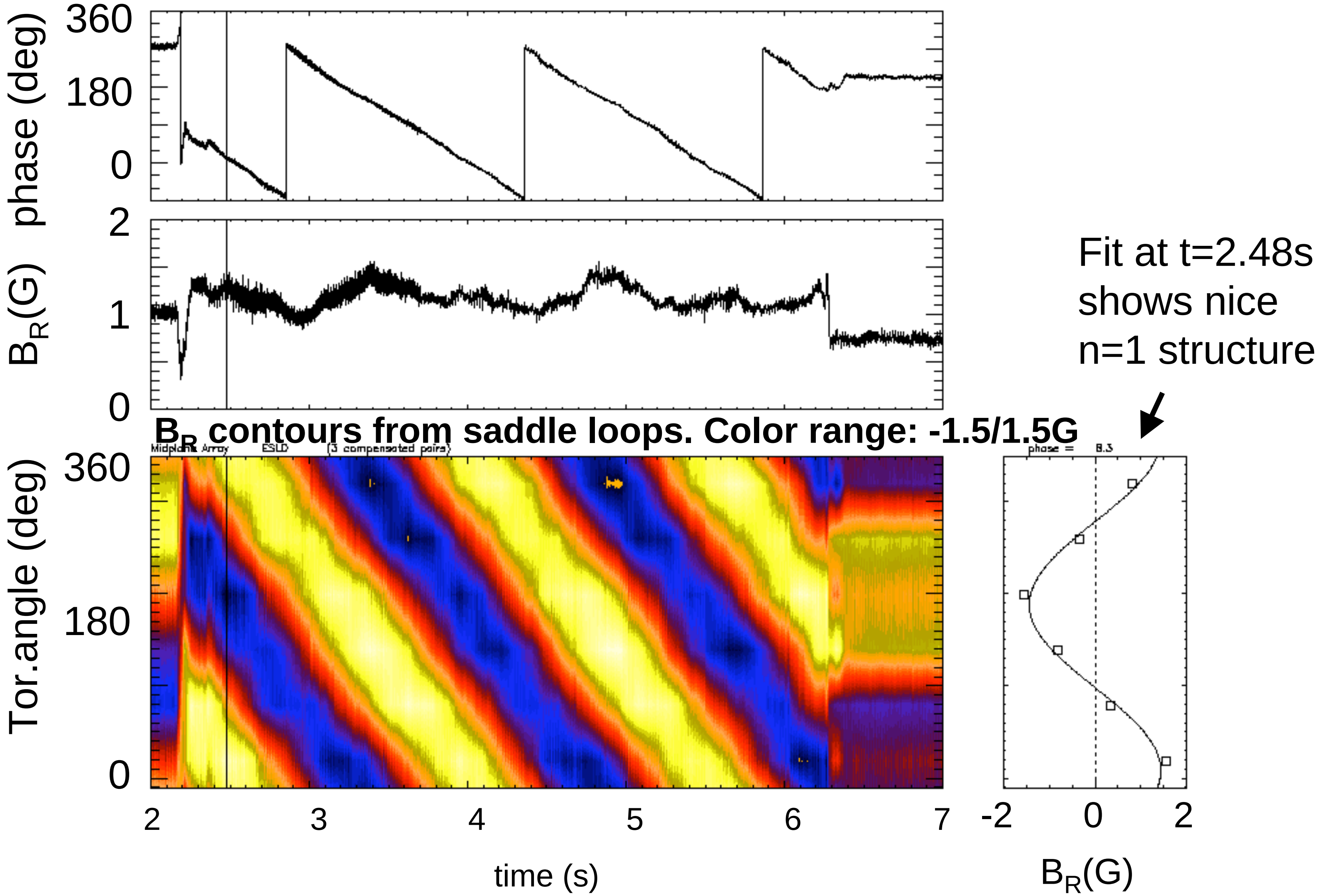


DIII-D NATIONAL FUSION FACILITY

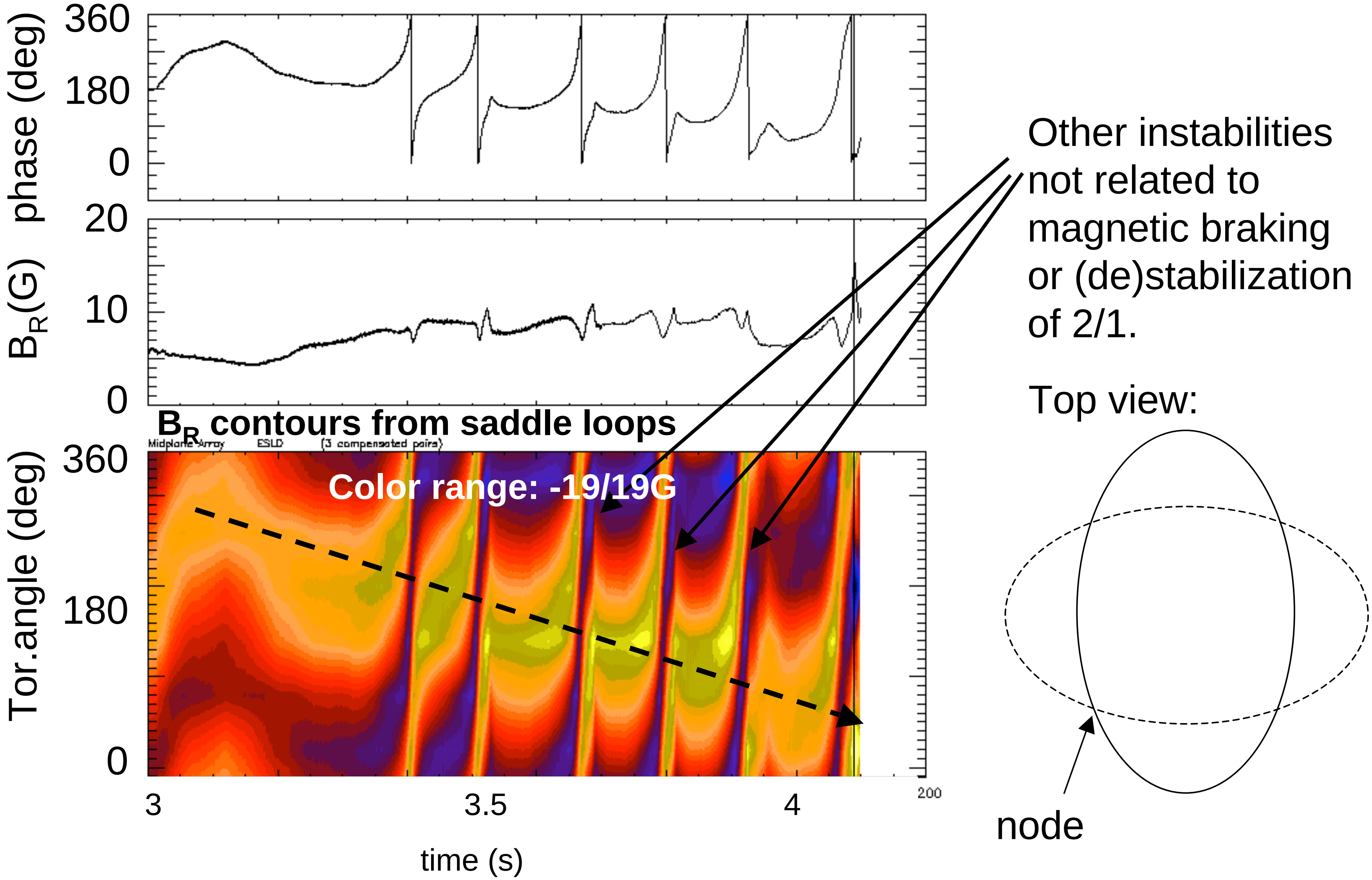
Even after subtraction of Vacuum Field, locked mode changes amplitude when toroidally steered in presence of ECH. Rotation appears non-uniform, in spite of EFC rotating uniformly.



Non-uniform mode rotation and strength in previous shot appears more evident after comparing with vacuum shot



ECH not deposited in the island (by lowering I_p and B_T by 3%). Same heating, β, n_e, shape, same mode-error field interaction but no ECCD mitigation. As expected, mode is stronger.



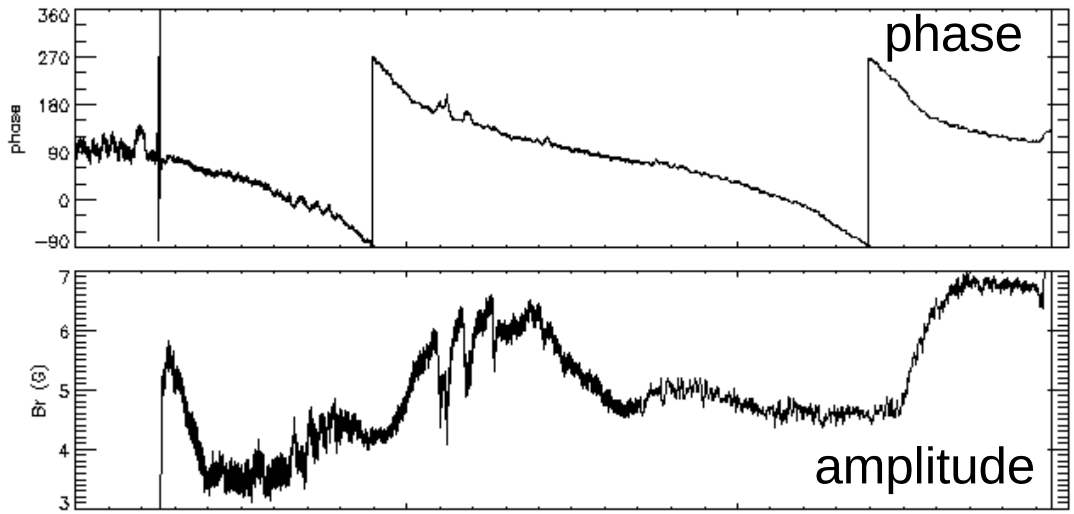
Clear Difference in Phase

Consistent with the fact that two different phases are relevant:

Between island and ECCD in ECH case (top)

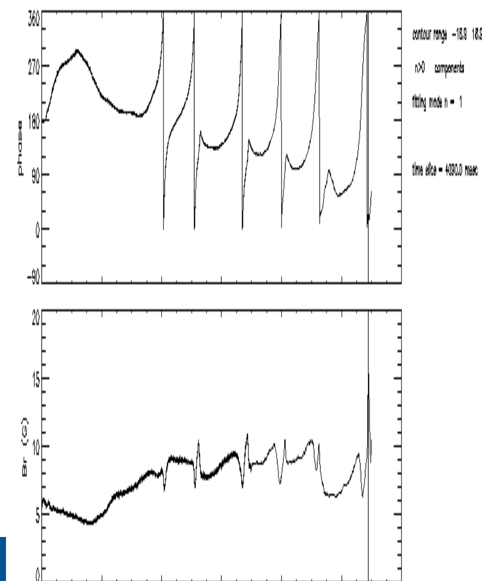
Between I-coil and Saddle-Loops in no-ECH case (bottom)

After vacuum field subtraction



With ECCD Stabilization

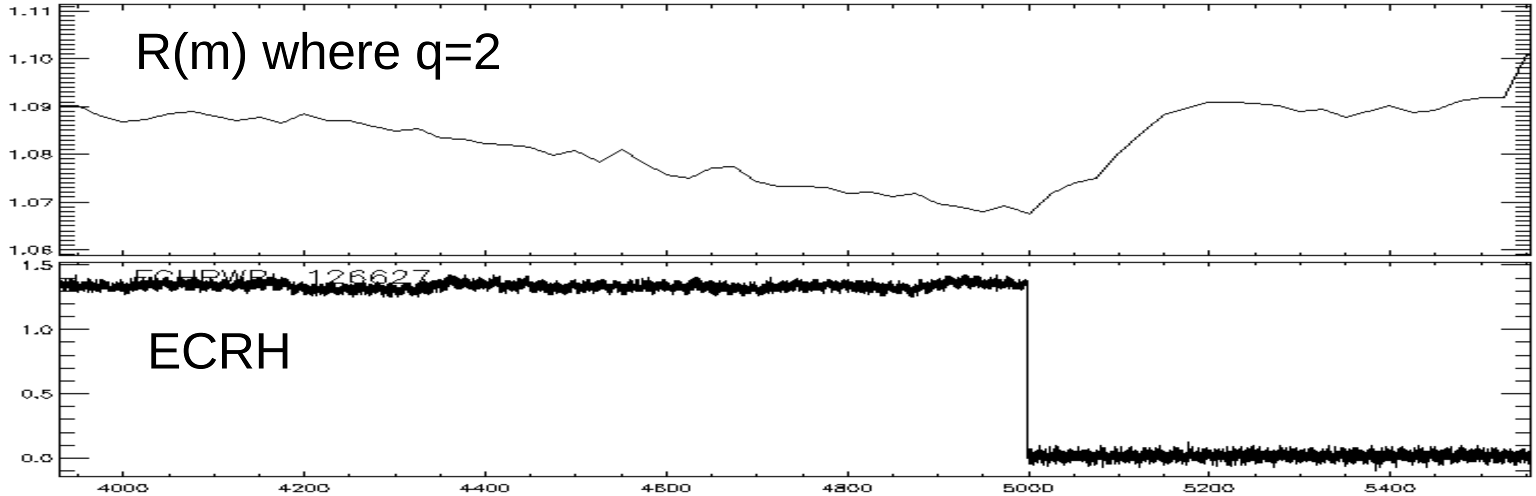
w/o ECCD Stabilization

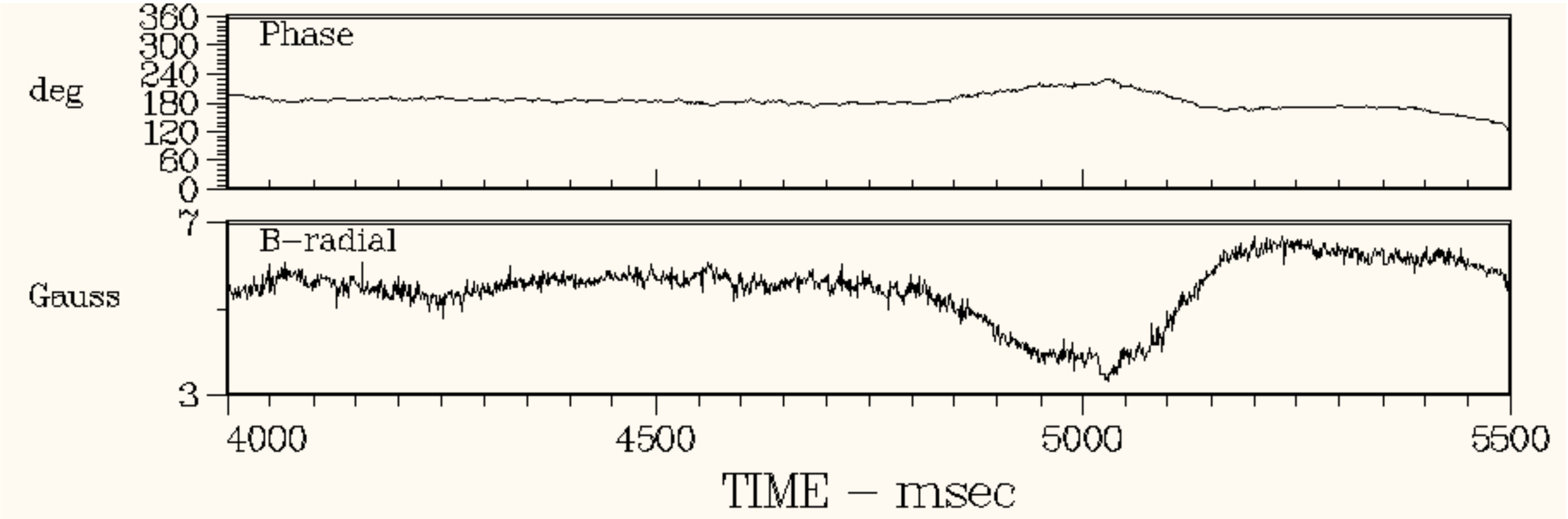


phase

amplitude

ECH aligned to island via radial jog of plasma.
Improved stabilization for ΔR=-2cm.



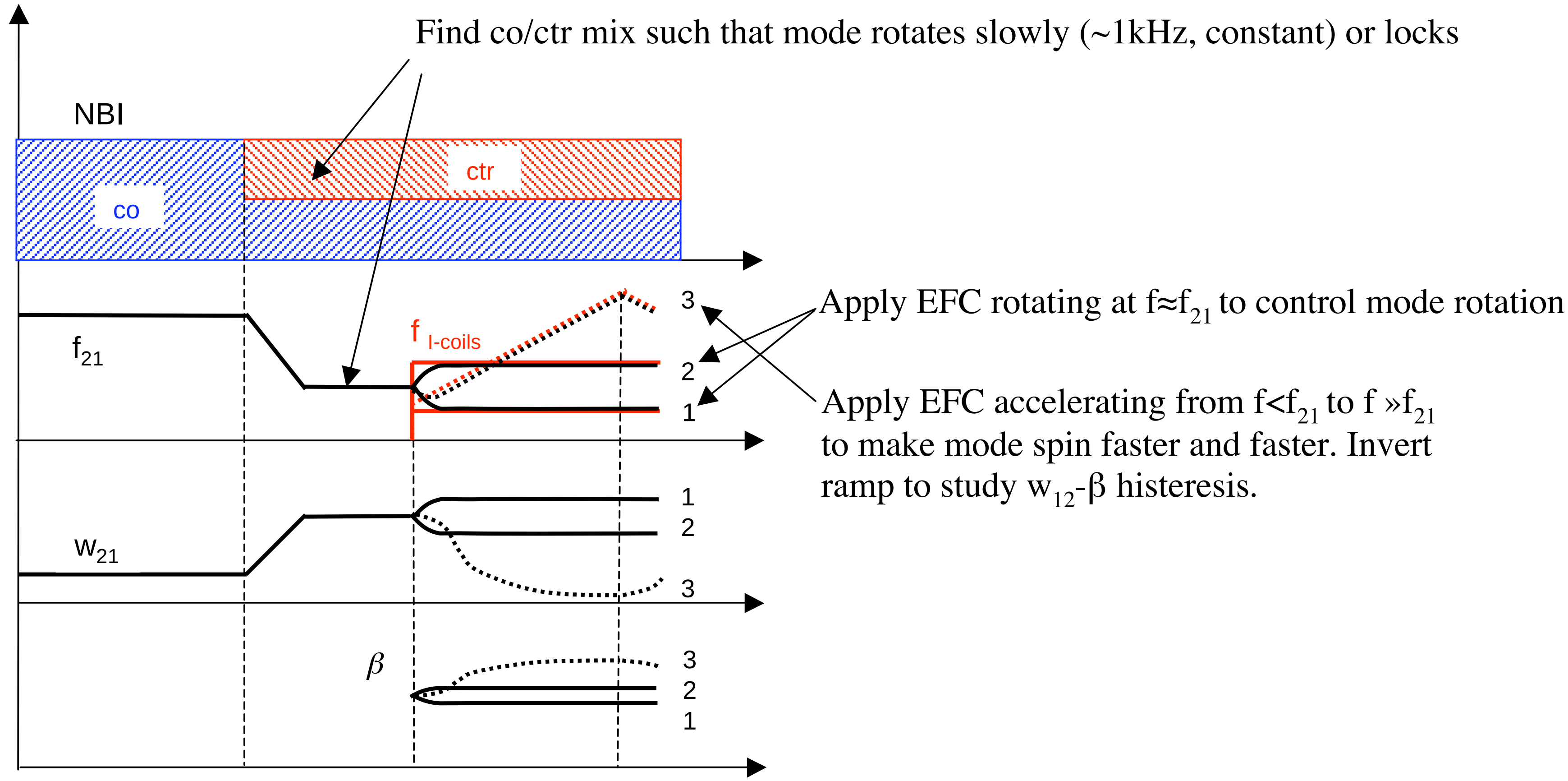


SECOND TYPE OF EXPERIMENTS

Dynamic EFC

fast travelling wave to sustain Mode Rotation

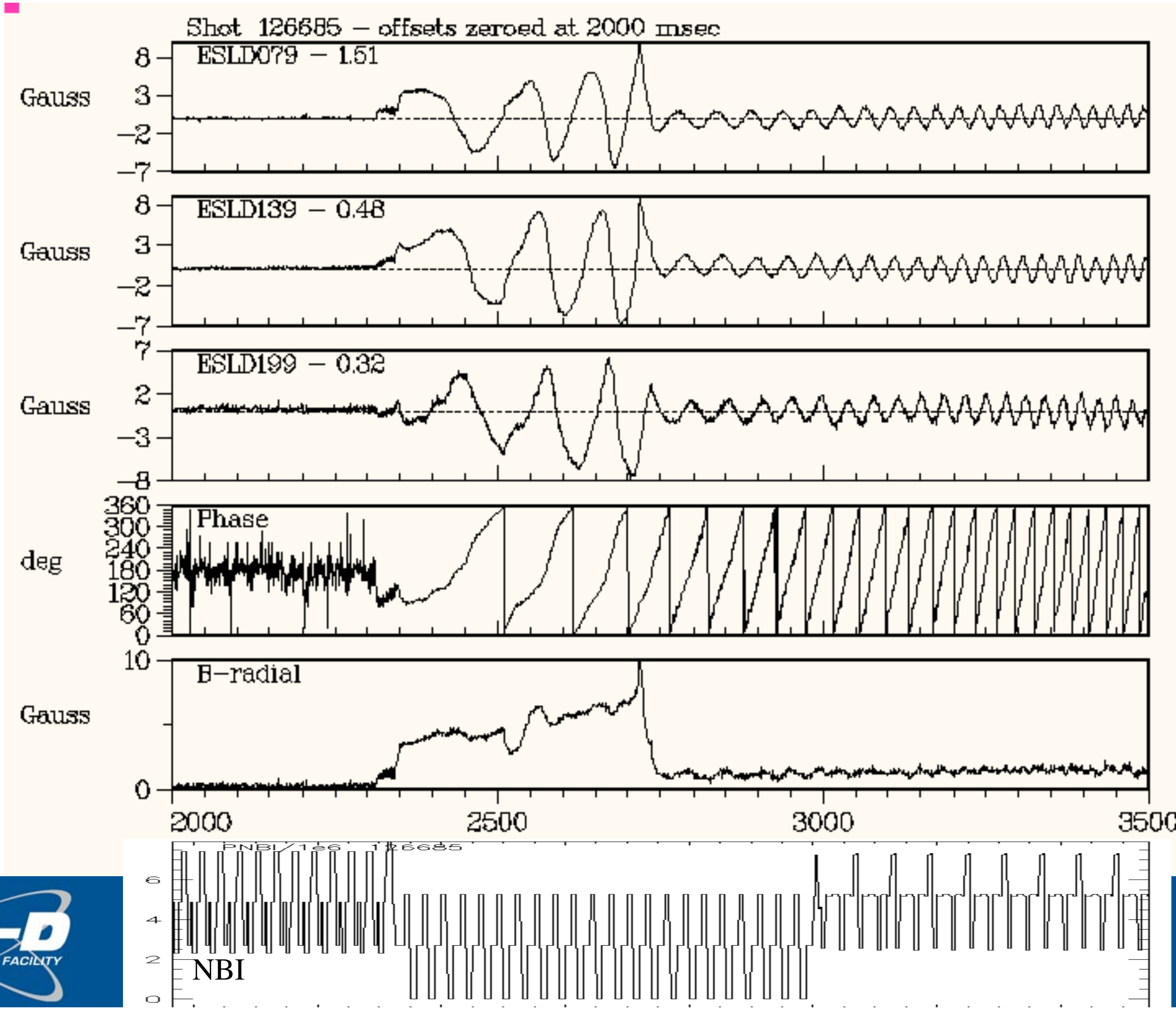
Impart magnetic torque with I-coils to unlock a locked mode or arrest its slowdown before locking, then spin mode up.



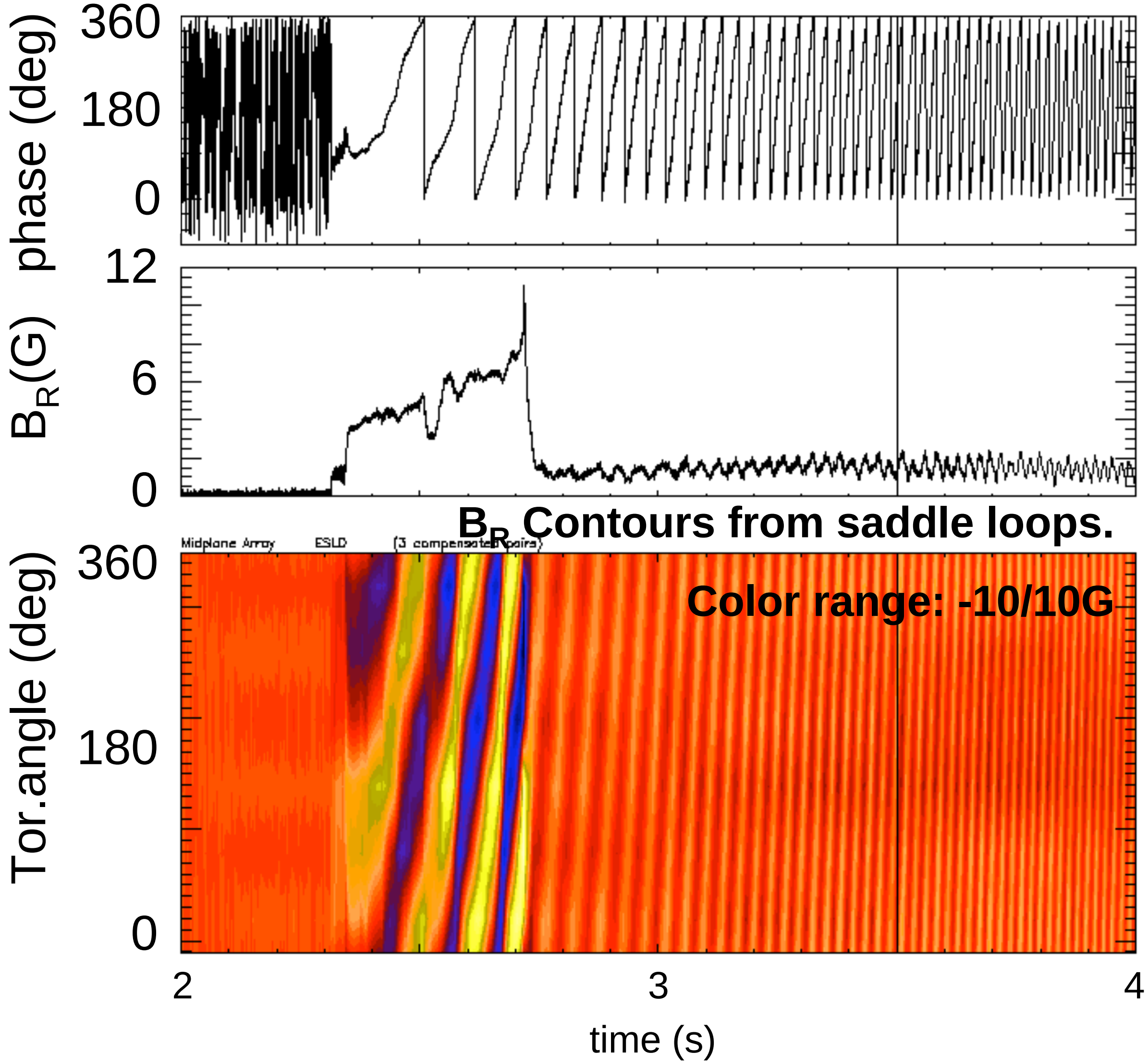
- Once the locked mode rotates again, the problem reduces to ECCD stabilization of rotating modes, which is proven and reliable.

- Actually ECCD not strictly necessary: if EFC makes the mode rotate very fast, it shrinks by itself.

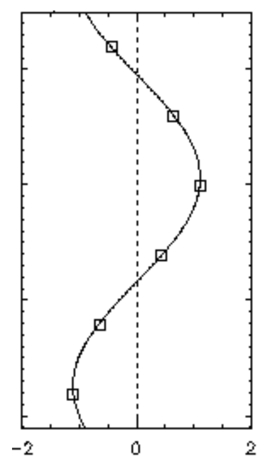
I-coil travelling wave entrained to mode if gently accelerated. Ramp 1-100Hz



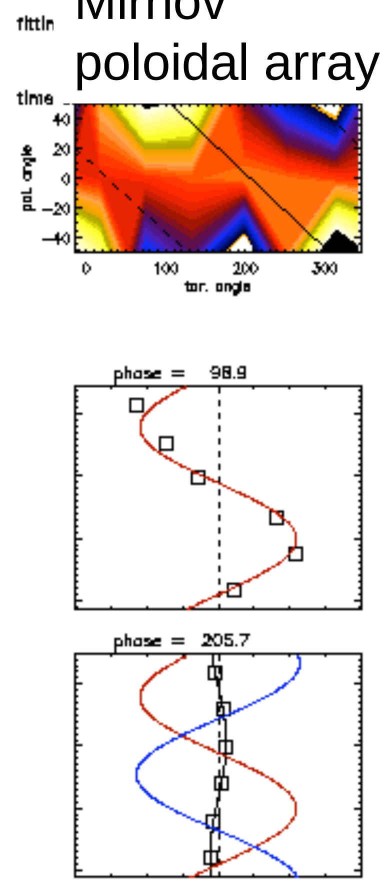
Travelling Wave of up to 60Hz coupled to 2/1 mode



n=1 from Mirnov toroidal array



m=2 from Mirnov poloidal array



I-coil Travelling Wave less effective at high frequencies

- **Current $I_{I\text{-}coil}$ delivered by power supplies falls off with f**

- **Besides, for the same $I_{I\text{-}coil}$, the magnetic perturbation exerted on the plasma decreases due to:**
  - Partial compensation from image currents in the wall (skin effect? Distance between I-coil & image comparable with wavelength?): -3dB @100Hz, -10dB @1kHz.
  - More Shielding associated with (faster) rotation
- **Furthermore, the same $B_{I\text{-}coil}$ couples less effectively with a faster, rotationally mitigated, weaker mode** (= compass of reduced μ immersed in the same B ⇒ B imparts reduced μxB torque)

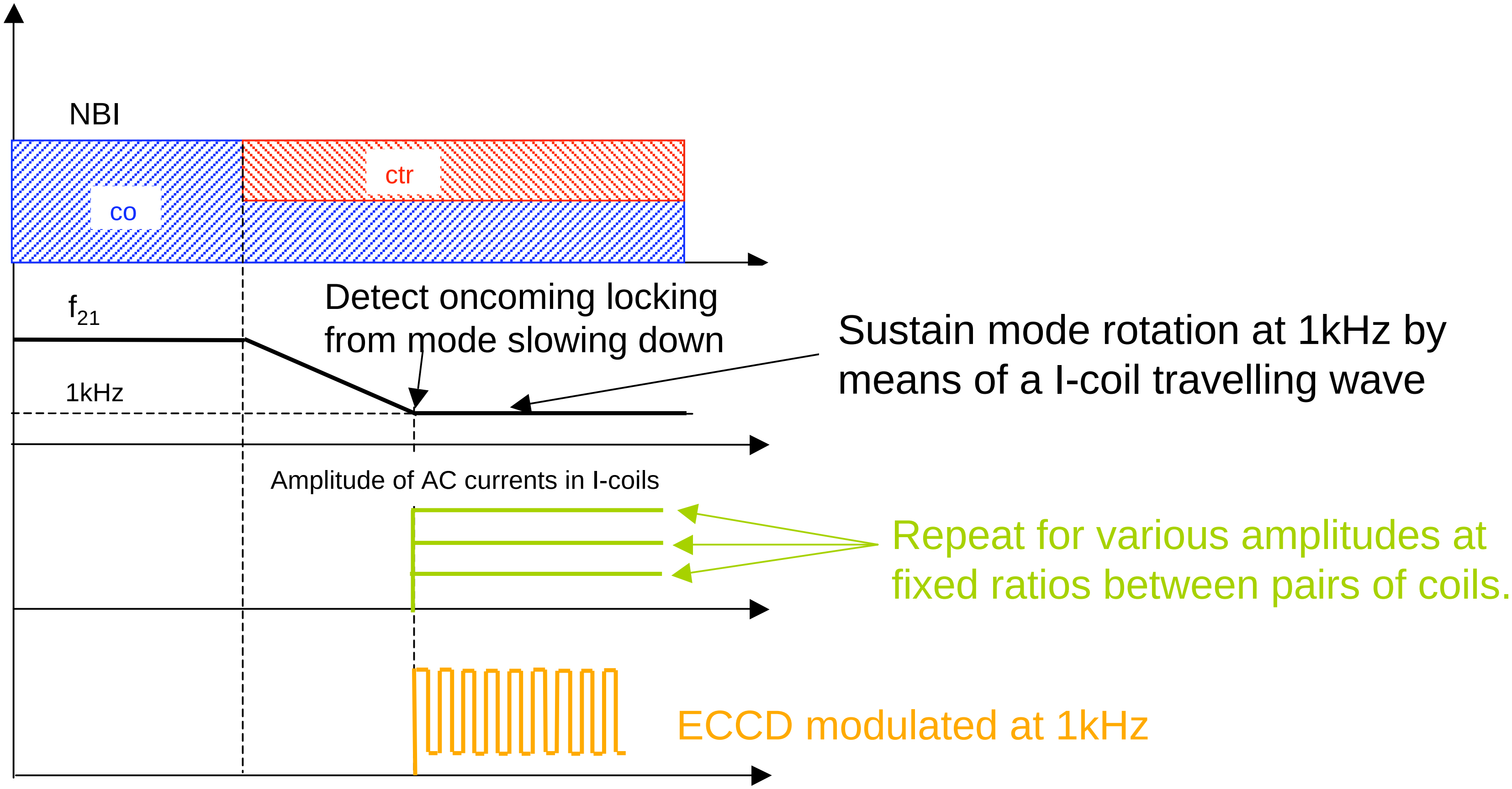
- **Phase delays in power supplies (SPAs)**
- **SPAs=<u>Switching</u> Power Amplifiers ⇒ discrete steps**

Summary and Conclusions

- Demonstrated "Preferential Locking" of NTM to a (static) toroidal phase such that it can be accessed and stabilized by ECCD
- Optimal Phase was found by slowly steering the mode (0.66Hz) while applying cw ECCD
- ECCD radially aligned to island by radial jog of plasma
- Mode Mitigation observed with 2 gyrotrons (full stabilization expected with 3-4)

- Sustained Mode Rotation up to 60Hz by means of I-coil travelling wave
- Travelling wave needs to be applied gently (0-60Hz ramp)
- More work needed to entrain faster waves and/or make ramp faster

Future Work: Prevent locking by sustaining mode rotation. Then apply ECCD (modulated or cw).



Shotplan:

- No ECCD (for ref.)
- MECCD at 1.001kHz (equivalent to phase scan, if I-coils at 1kHz)
- MECCD at 1kHz in O-point (and in another shot in X-point, for comparison)
- CW ECCD for reference

Backup Material

No-ECH Ref. Shot has potential for isolating interaction between mode & intrinsic error, but it also affects n_e, β, etc. and makes island more “sticky”