Advanced Techniques for Neoclassical Tearing Mode (NTM) Control in DIII-D

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With
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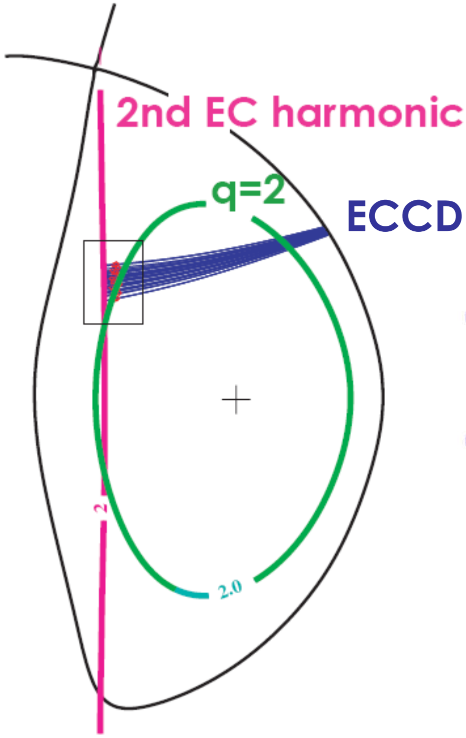

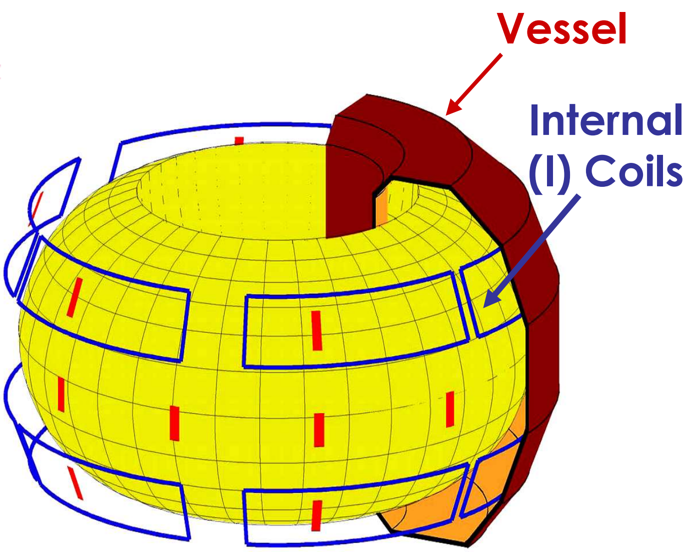

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DIII-D
NATIONAL FUSION FACILITY
SAN DIEGO

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NTMs are a principal limit to high performance in ITER Control needs to be effective

- **From the 2007 special issue of Nuclear Fusion, "Progress in the ITER Physics Basis":**

  "the NTM instability is predicted to lead to confinement deterioration… and possibly… disruption"

- **Stabilization by Electron Cyclotron Current Drive (ECCD) is a well-developed technique on several tokamaks**
  - Requires precise alignment
  - Efficiency benefits from modulation
  - Becomes impossible if mode locks in a position not accessible to ECCD

New Technique: Oblique Electron Cyclotron Emission (ECE)

New Technique: Rotating magnetic perturbations to move the island

Outline

- Motivation and principle of oblique ECE as a test of alignment and aid to modulation
- Experimental setup
- Results: alignment verified, complete 3/2 suppression

- Motivation for magnetic rotation in case of locking
- Slow, forced rotation of 2/1 NTM in presence of cw ECCD
- Fast, forced rotation of 2/1 NTM

- Summary and conclusions

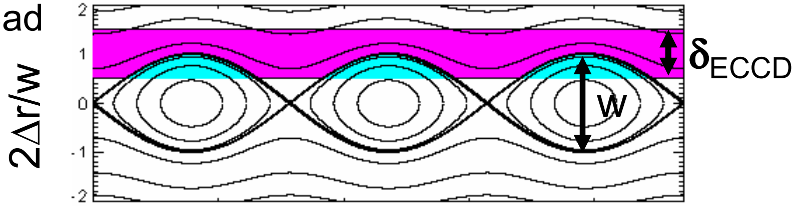
NTMs can be stabilized by Electron Cyclotron Current Drive at the location of the magnetic island

- **Modified Rutherford equation governs island growth**

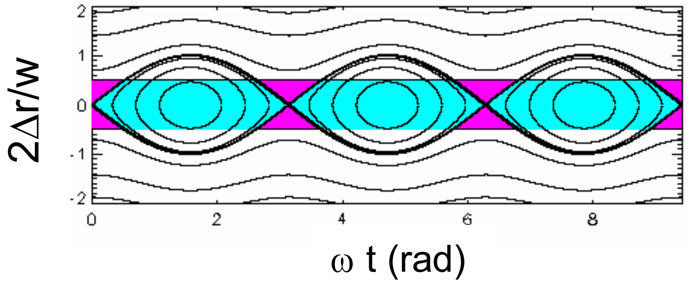
$$\frac{\tau_R}{r}\frac{dw}{dt} = \Delta'_0 r + \underbrace{\delta(\Delta' r)} + 3\,\frac{j_{boot}}{j_{total}}\frac{L_q}{w}\left[1 - \frac{(2\varepsilon^{1/2}\rho_{\theta i})^2}{3w^2} - K_1 \underbrace{\frac{j_{eccd}}{j_{boot}}}\right]$$

- **Well aligned co-ECCD at q=m/n improves classical stability (Δ' more negative)**

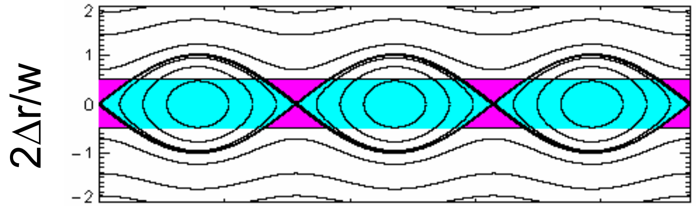
Bad



Good alignment:

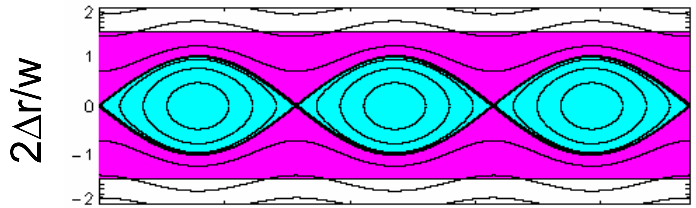


- **Replacing missing bootstrap current is stabilizing. Modulation helps:**



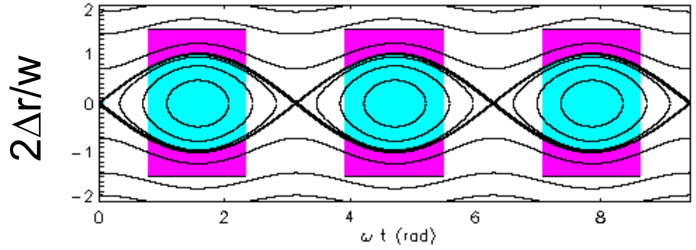
Narrow ECCD,

cw



Broad ECCD,

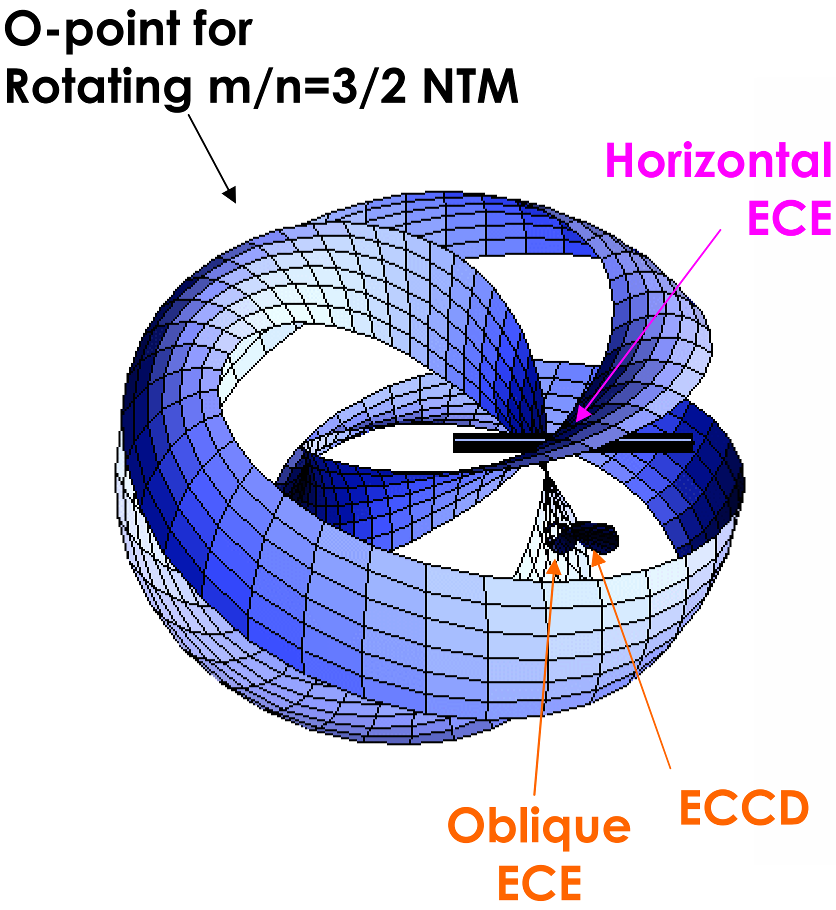
cw

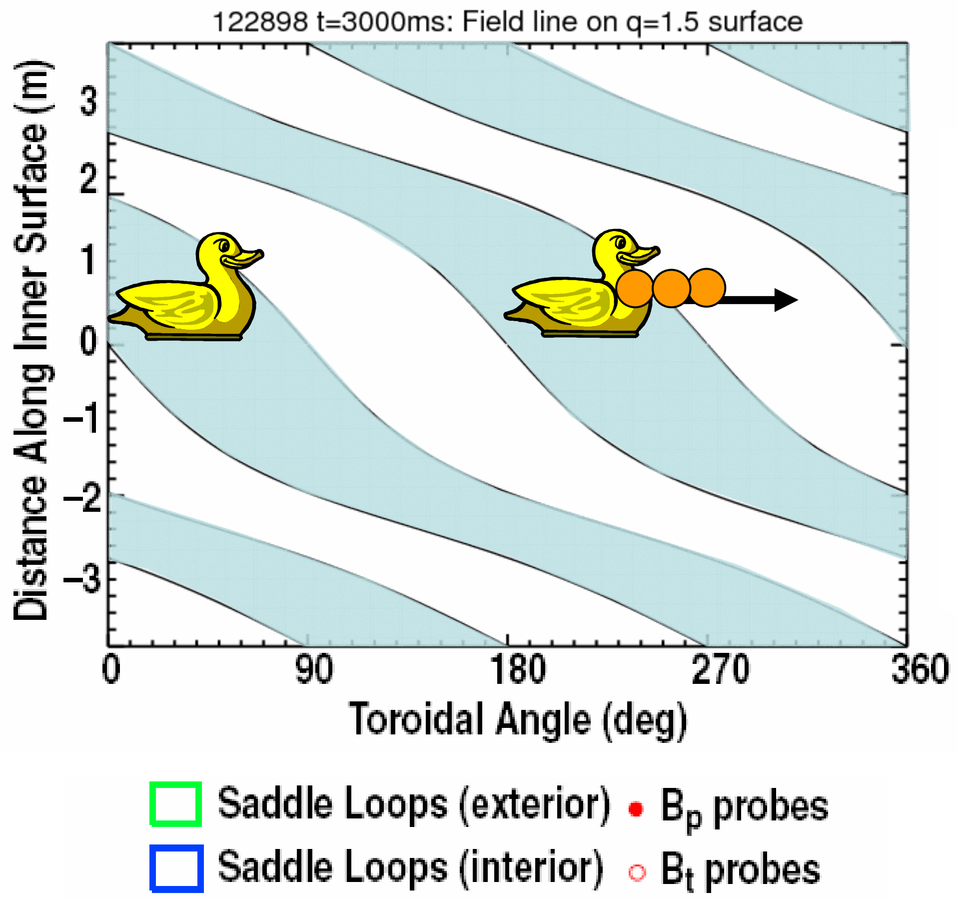


Broad ECCD,

modulated

Alignment and Modulation of ECCD to NTMs and Interpretation of ECE and magnetics are complicated 3D problems





Internal ECE tracking of NTMs has advantages compared with *external* magnetic probe data

- **Magnetic probes measure δB_θ at wall**

  Pro: best measurement of frequency

  Cons:

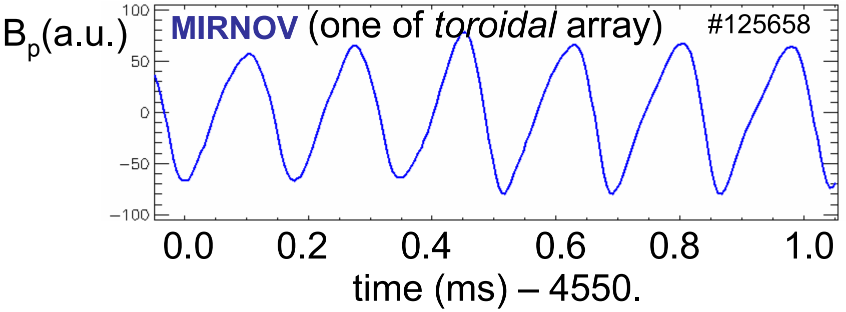
  - No data for radial alignment
  - Toroidal phase of island requires reconstruction of equilibrium and field lines

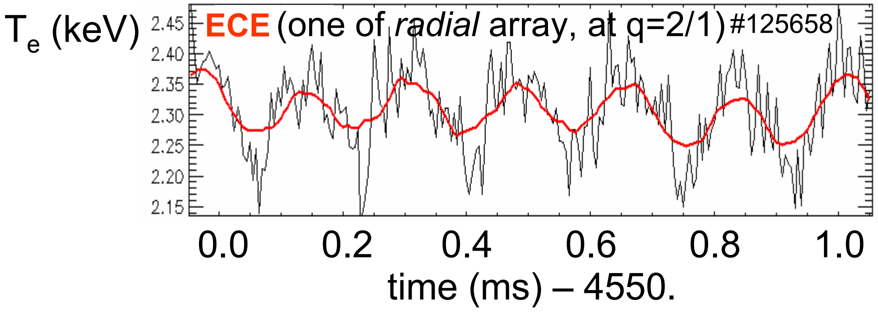
- **Horizontal ECE measures δT_e at q=m/n**

  Pro: Major radius of island can be determined

  Cons:

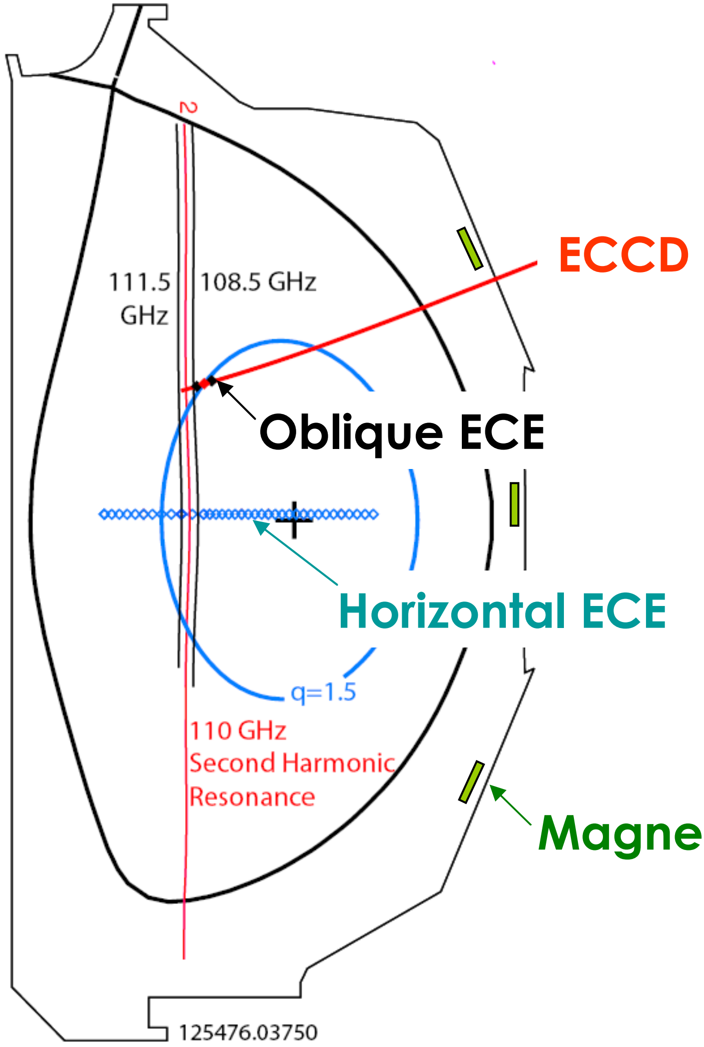
  - Also sensitive to other δT_e
  - Still requires toroidal phase mapping
  - Also requires radial mapping





Oblique ECE has advantages of horizontal ECE + no need for mapping

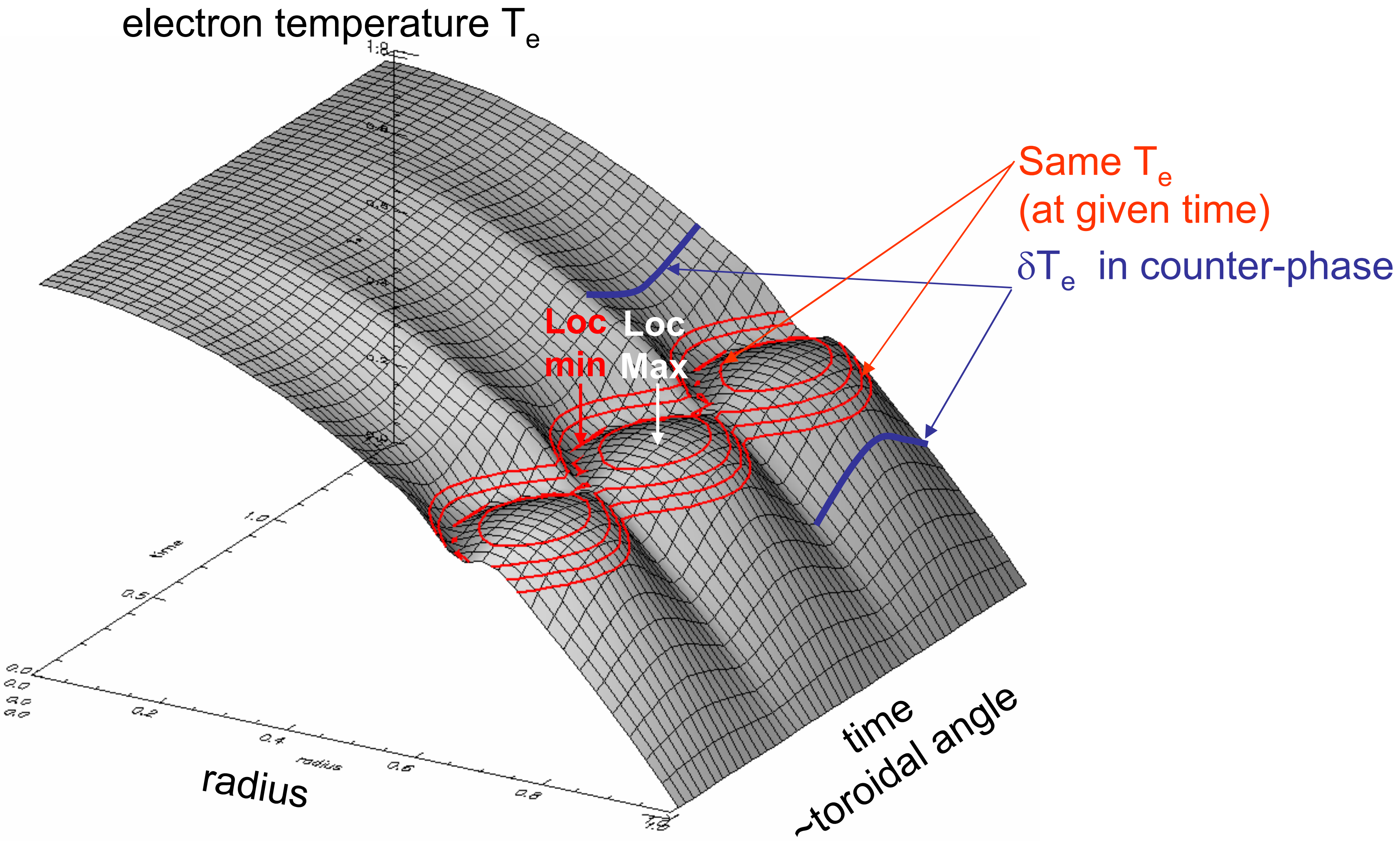
Oblique ECE, along same direction as ECCD, avoids need for equilibrium reconstruction and analysis



- **Island transit measured ‘in situ’**
  - same R, Z of CD
  - from same R, Z of ECRH launcher
  - same poloidal & toroidal view angles
- **Hence**
  - same relativistic downshift
  - same relativistic & Doppler broadening
  - island centre emits at $f=f_{gyr}=110$GHz

- **No need for flux surface shape or helical extrapolations in R,Z,ϕ.**

ECE signals on other sides of island are out-of-phase.

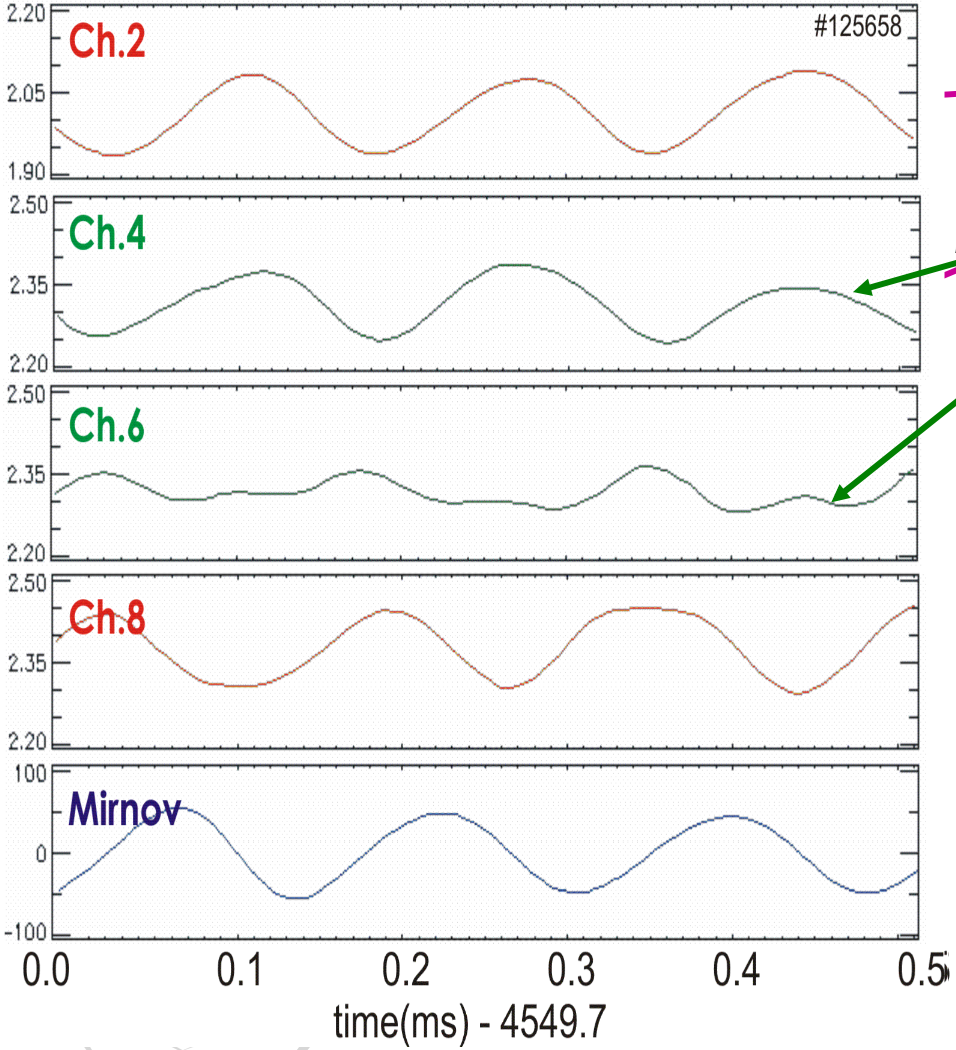


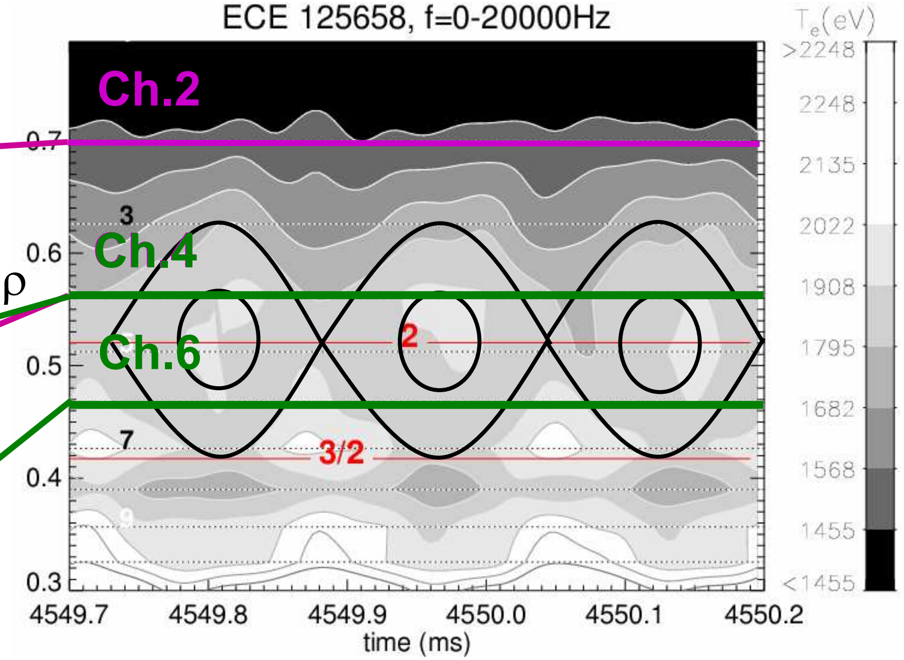
Same T_e
(at given time)

δT_e in counter-phase

Two ECE channels close to island track *toroidal* rotation and validate *radial* alignment of ECCD

Horizontal ECE with 50μs smoothing

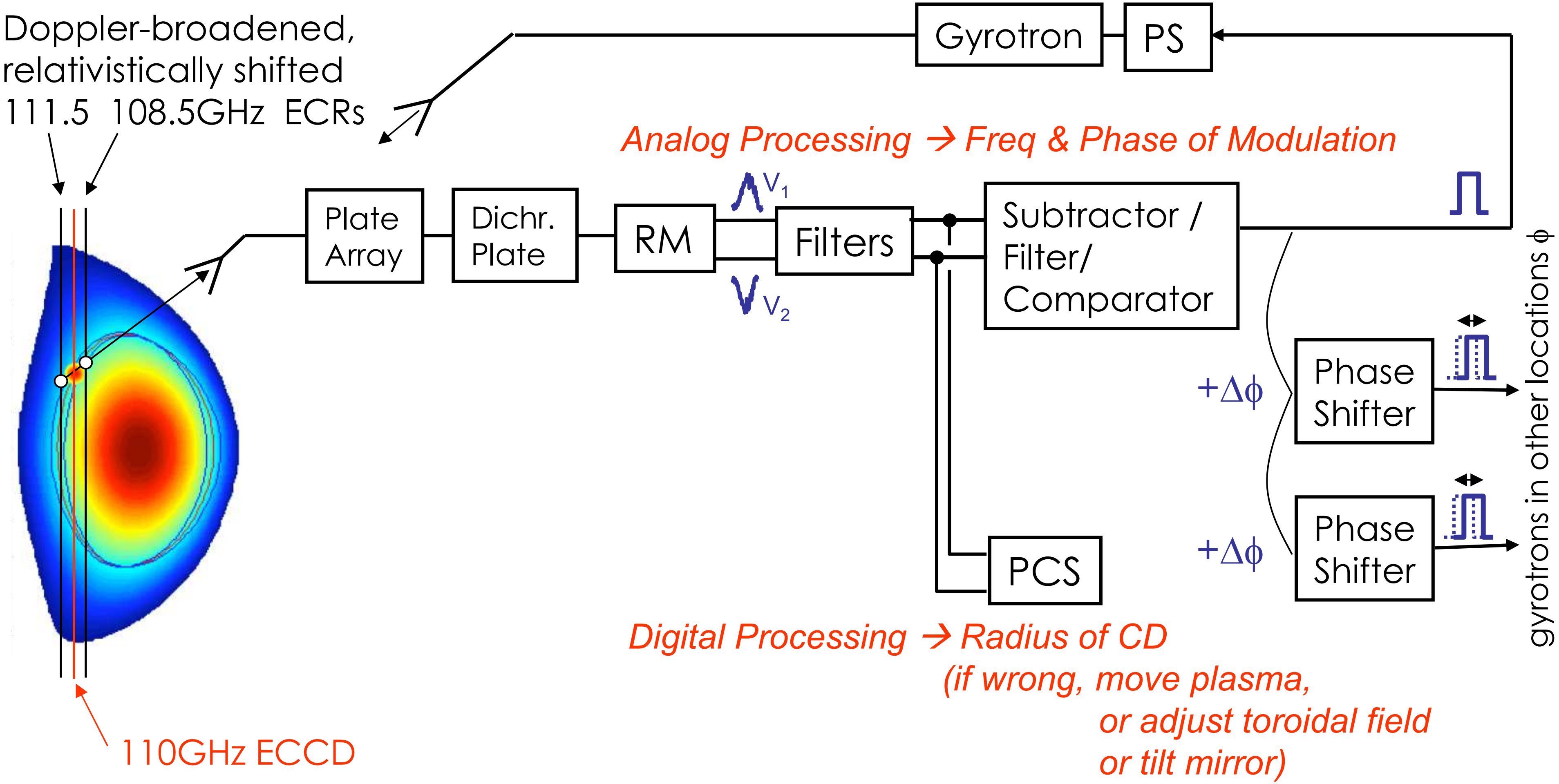




In-phase: on same side of island

Out-of-phase: on opposite sides

Oblique ECE as a waveform generator for modulated ECCD, radially aligned, in synch and in phase with island O-point



Doppler-broadened,
relativistically shifted
111.5 108.5GHz ECRs

Plate Array

Dichr. Plate

RM

V_1

V_2

Filters

Subtractor / Filter/ Comparator

Gyrotron

PS

Analog Processing → Freq & Phase of Modulation

$+\Delta\phi$

Phase Shifter

$+\Delta\phi$

Phase Shifter

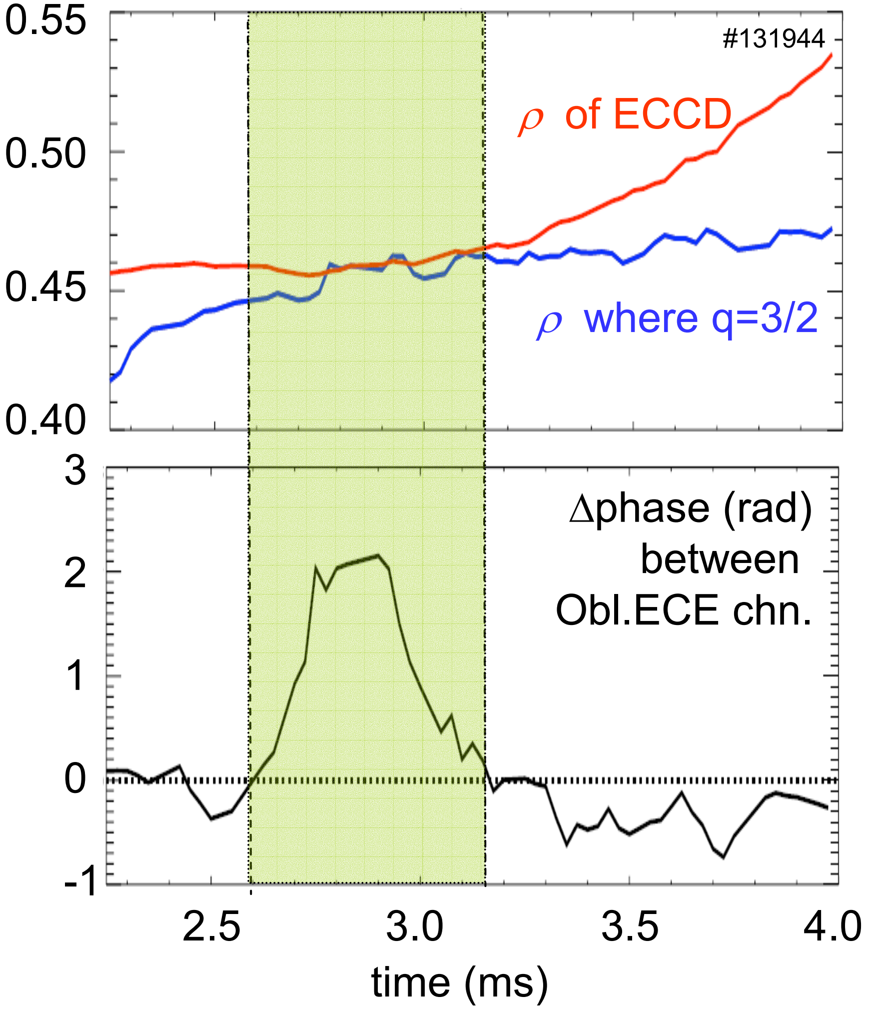
gyrotrons in other locations ϕ

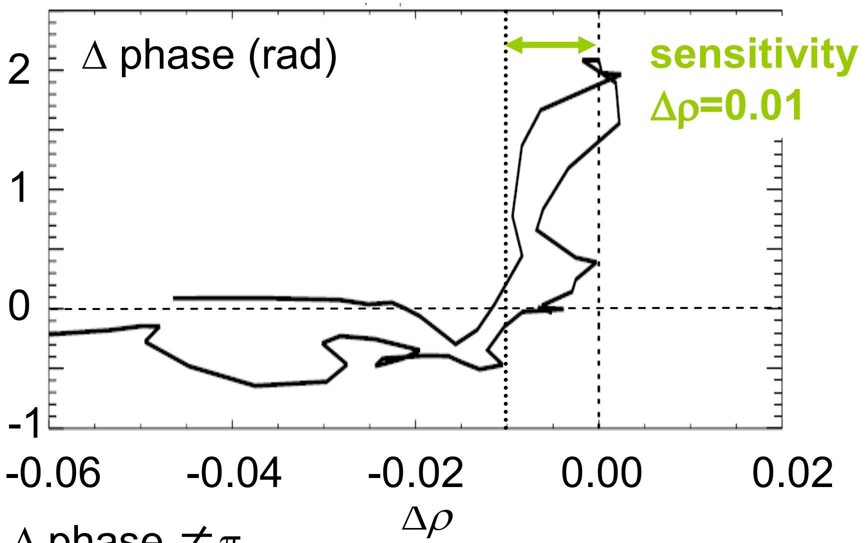
PCS

Digital Processing → Radius of CD
(if wrong, move plasma,
or adjust toroidal field
or tilt mirror)

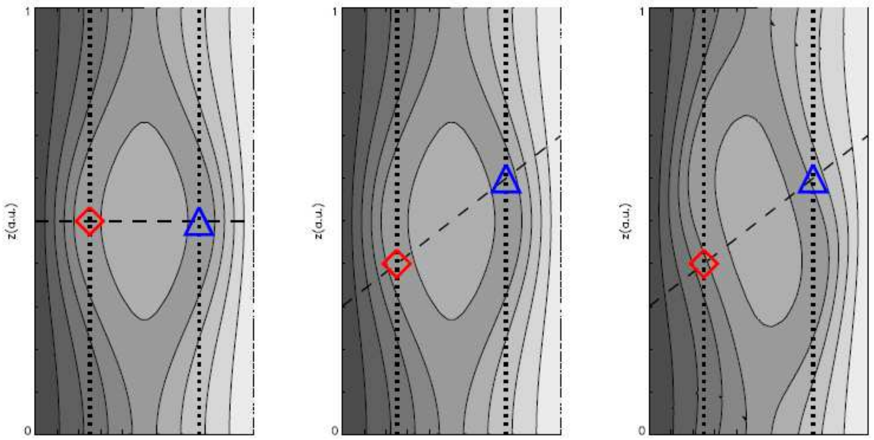
110GHz ECCD

Observed Phase Reversal, indication of good alignment

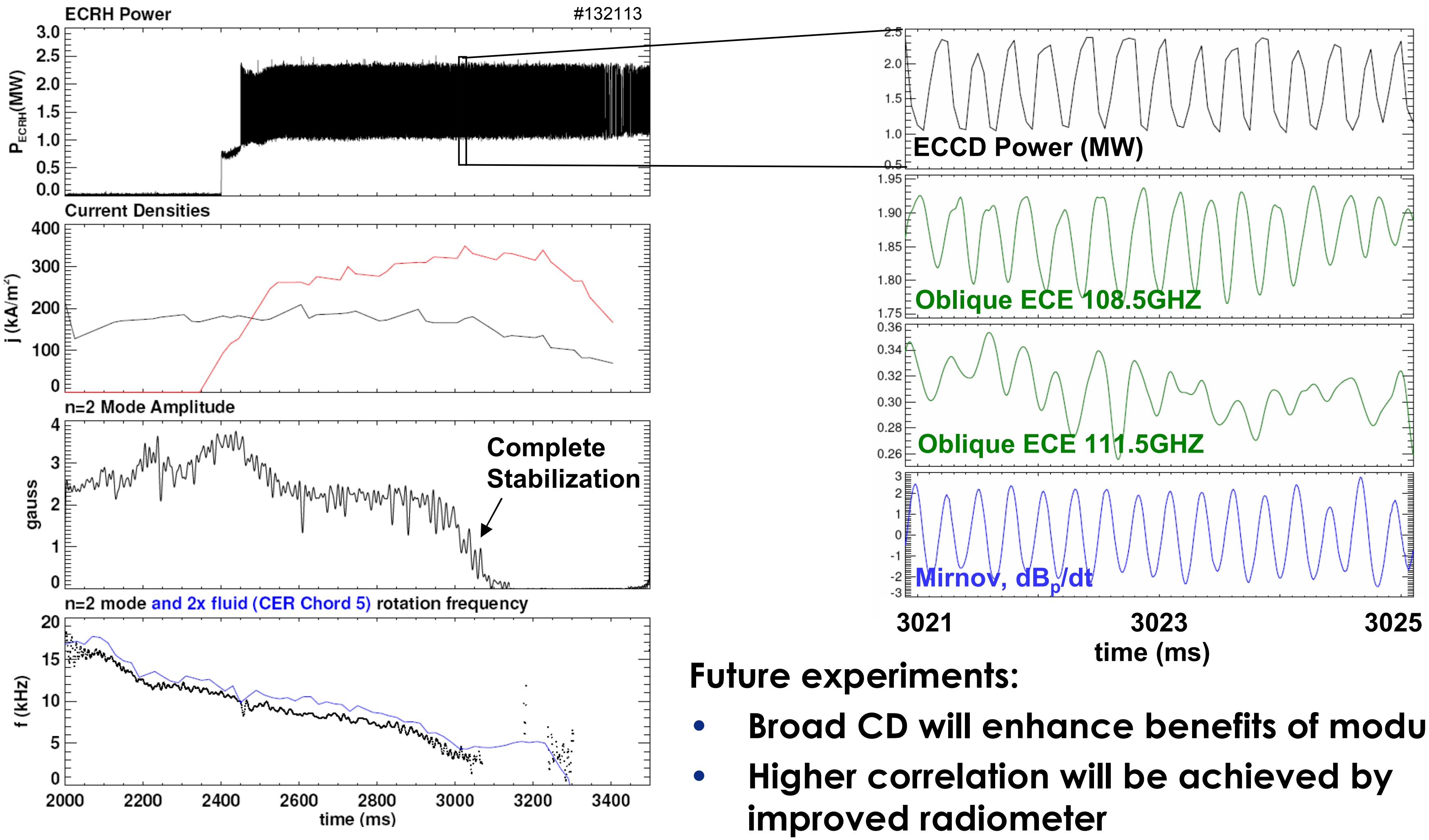




Δ phase ≠ π
because of oblique view and sheared island:



First complete suppression of 3/2 NTM by ECCD modulated by oblique ECE in phase with O-point

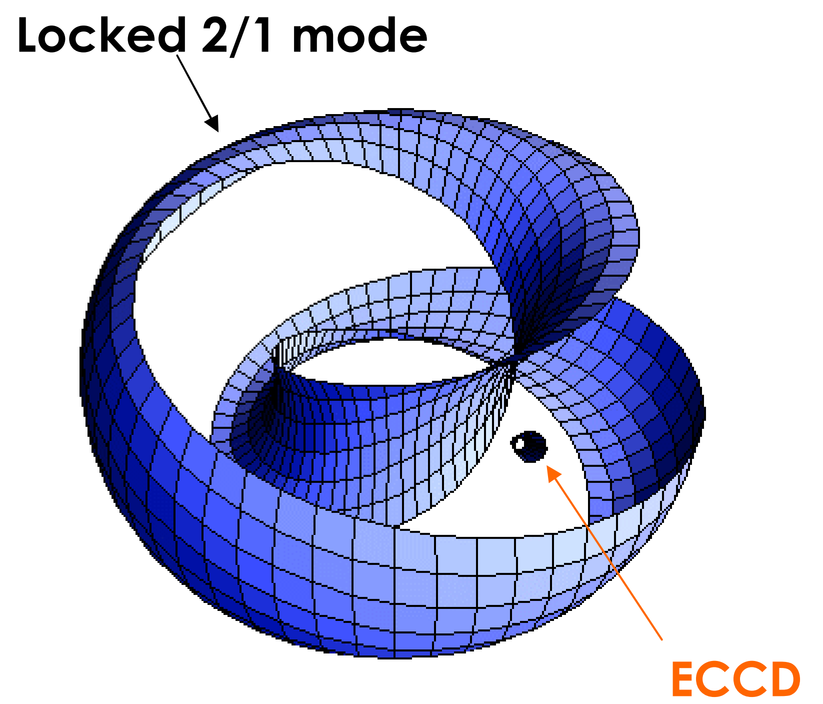


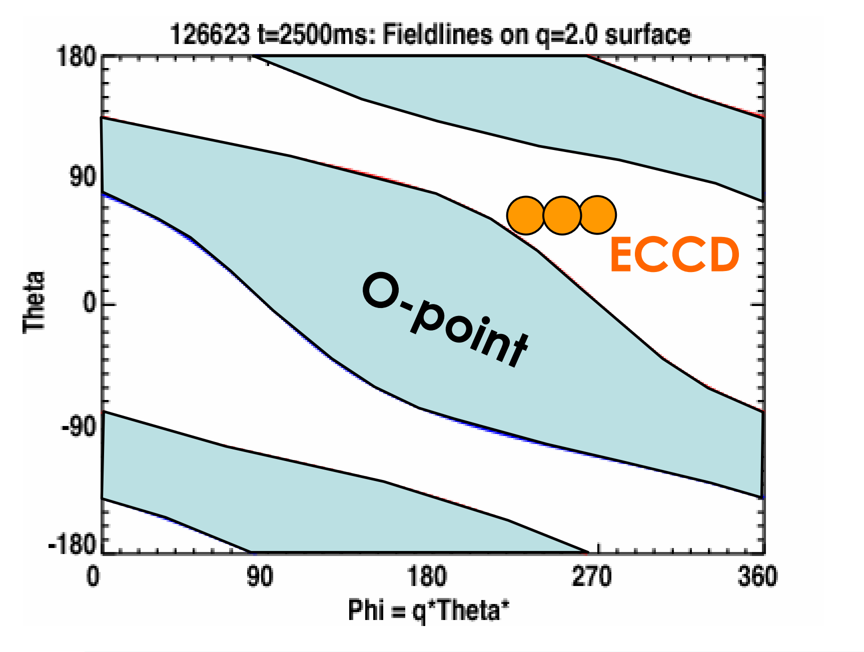
Future experiments:

- Broad CD will enhance benefits of modulation
- Higher correlation will be achieved by improved radiometer

What If the island grows, slows down and locks, or directly forms as a locked mode, not accessible to ECCD?

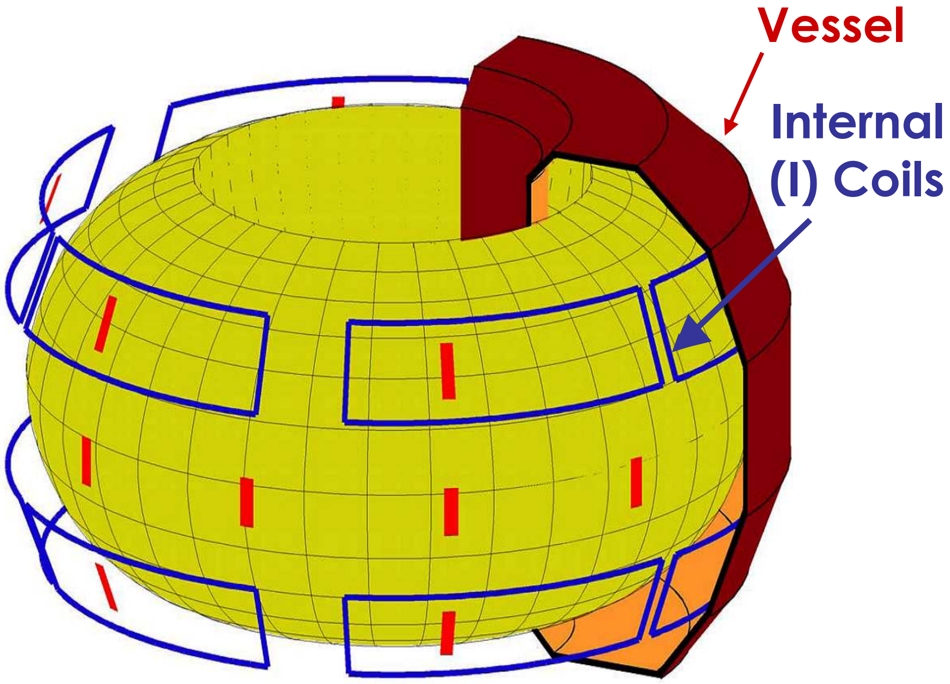
- Locking of 2/1 Tearing Mode likely in ITER, if insufficiently controlled (due to reduced NBI torque, consequent low rotation, and proximity to wall)
- Islands can lock in a position not accessible by ECCD:





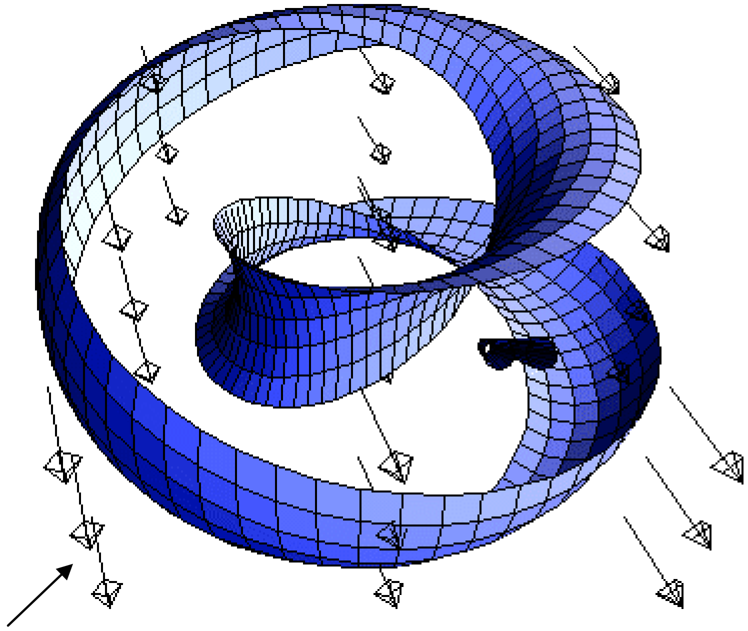
Current-carrying structures can be moved by externally applied magnetic perturbations

Bootstrap deficit in the island is like a wire carrying a counter-current. Forces can be applied to this wire by magnetic fields generated by external coils.



Vessel

Internal (I) Coils



Applied rotating n=1 field

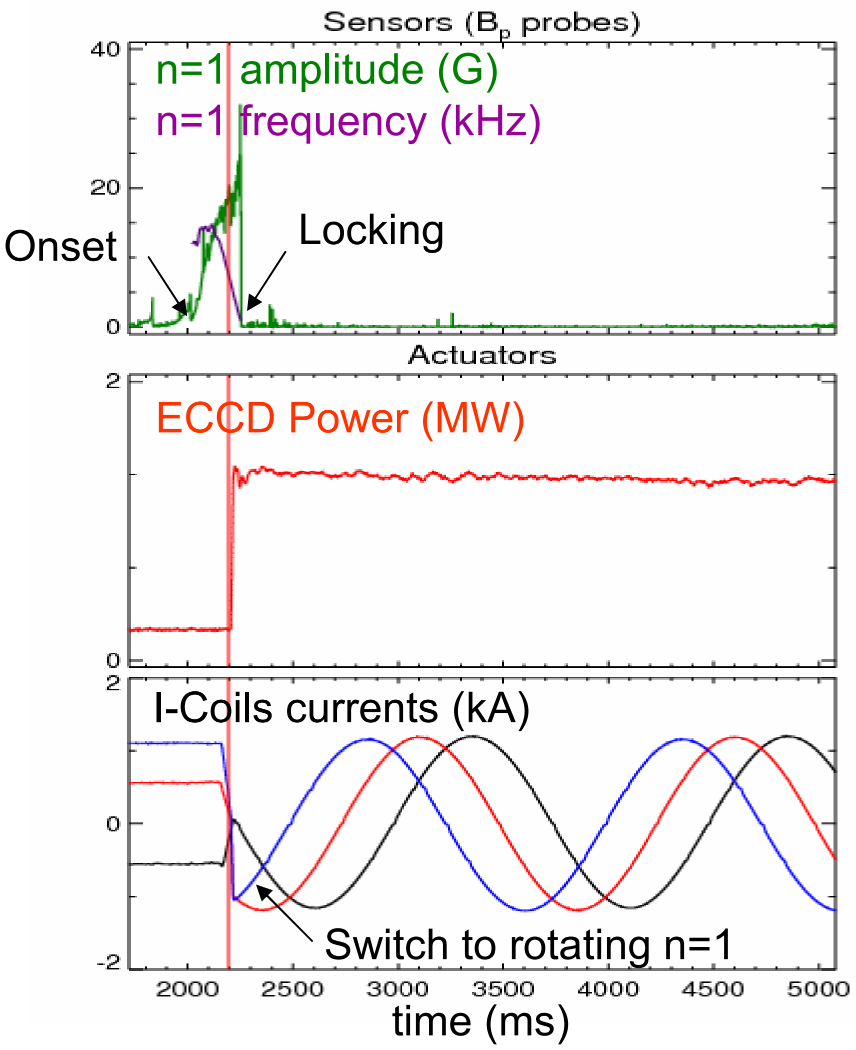
Magnetic perturbations can unlock and reposition or spin the mode and so assist its control by ECCD

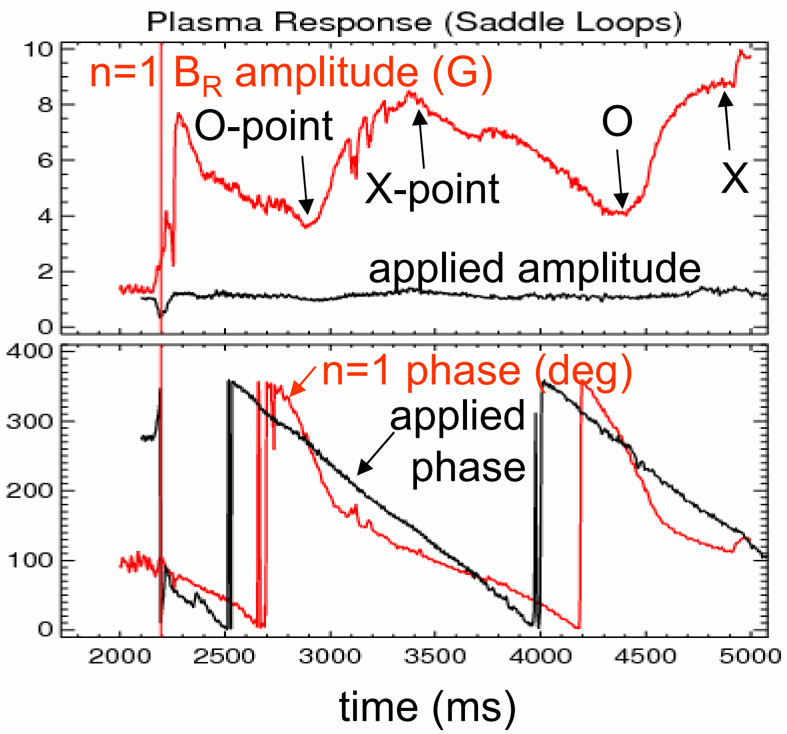
Approach 1 ("preferential locking"):
Island dragged to new position accessible by gyrotrons.
ECCD: CW

Approach 2 ("sustained rotation" or "entrainment"):
Island forced to rotate.
ECCD: CW or modulated*

* Simplified ECCD modulation:
freq. & phase determined by coil currents, not by "slippery" plasma

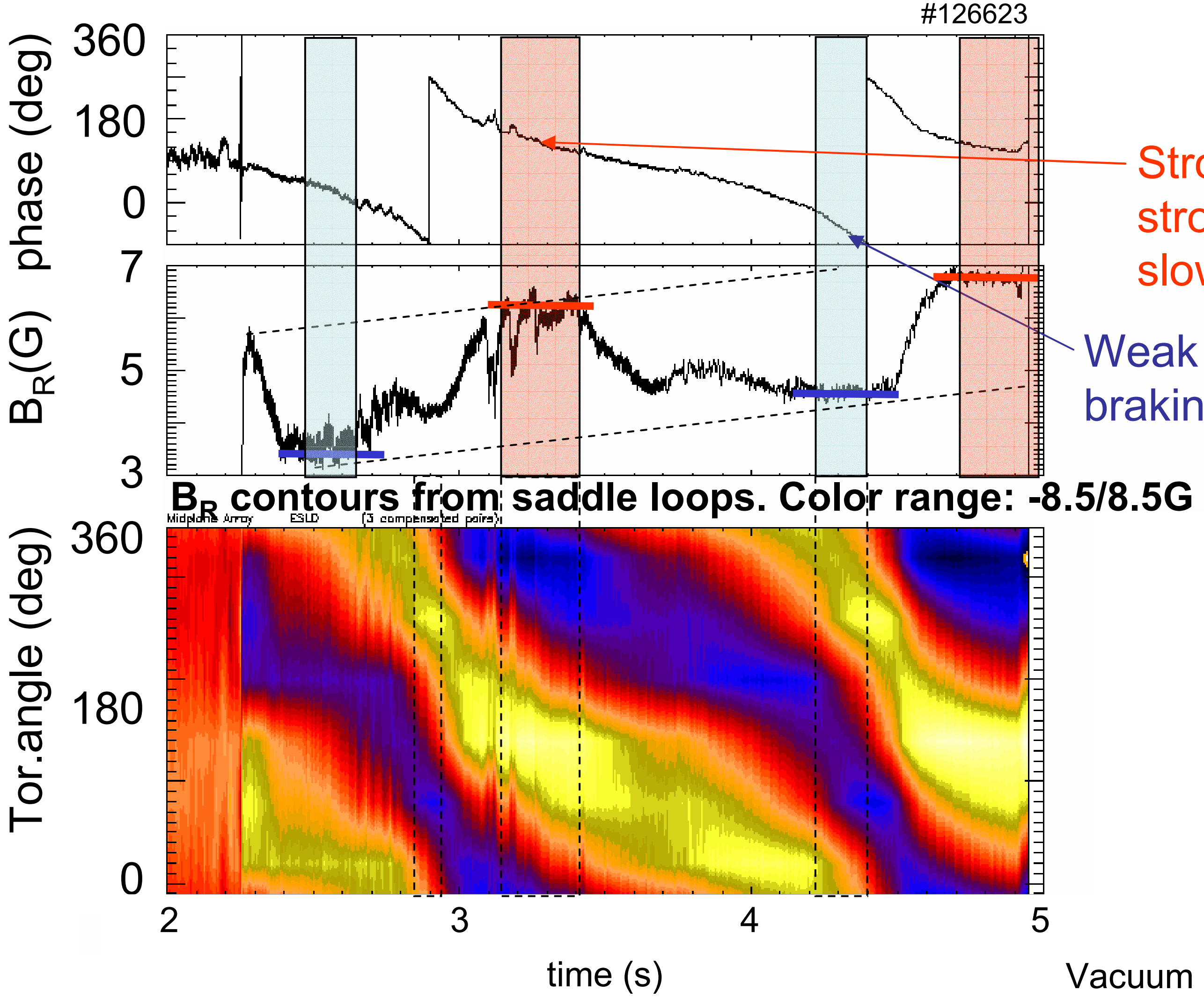
Tearing mode, rotated by magnetic perturbations and illuminated by ECCD, changes amplitude





tearing mode slips w.r.t. applied magnetic field (phase differs) when reduced in amplitude by ECCD

Subtraction of Vacuum Field confirms that initially locked mode changes amplitude when toroidally steered to location where ECCD is aligned with island O-point

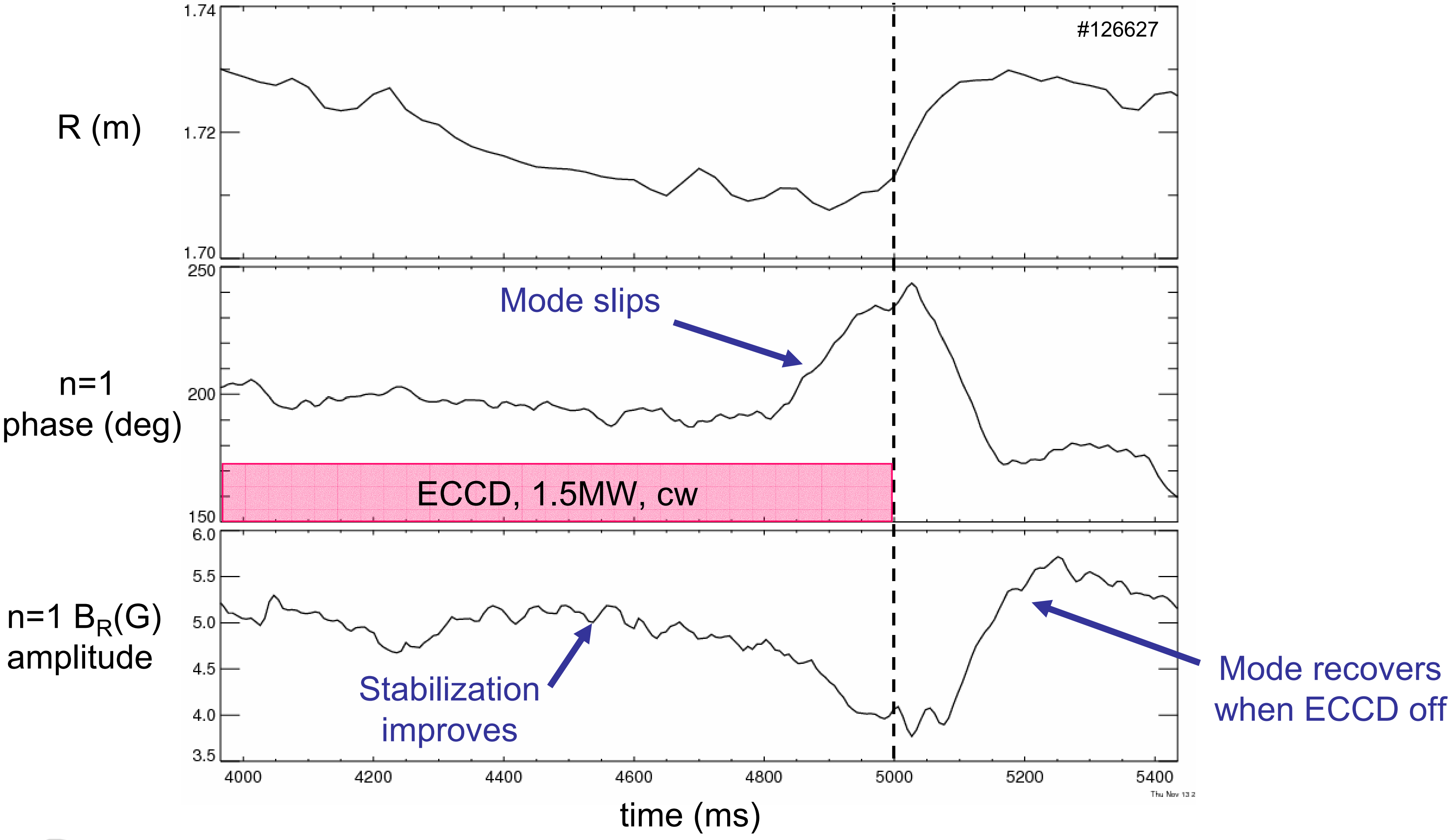


Strong mode ⇒ strong magn.braking ⇒ slow rotation

Weak mode ⇒ less braking ⇒ faster rotation

Vacuum shot #126707 subtracted

Mode starts slipping under the effect of ECCD
Mode recovers when ECCD off



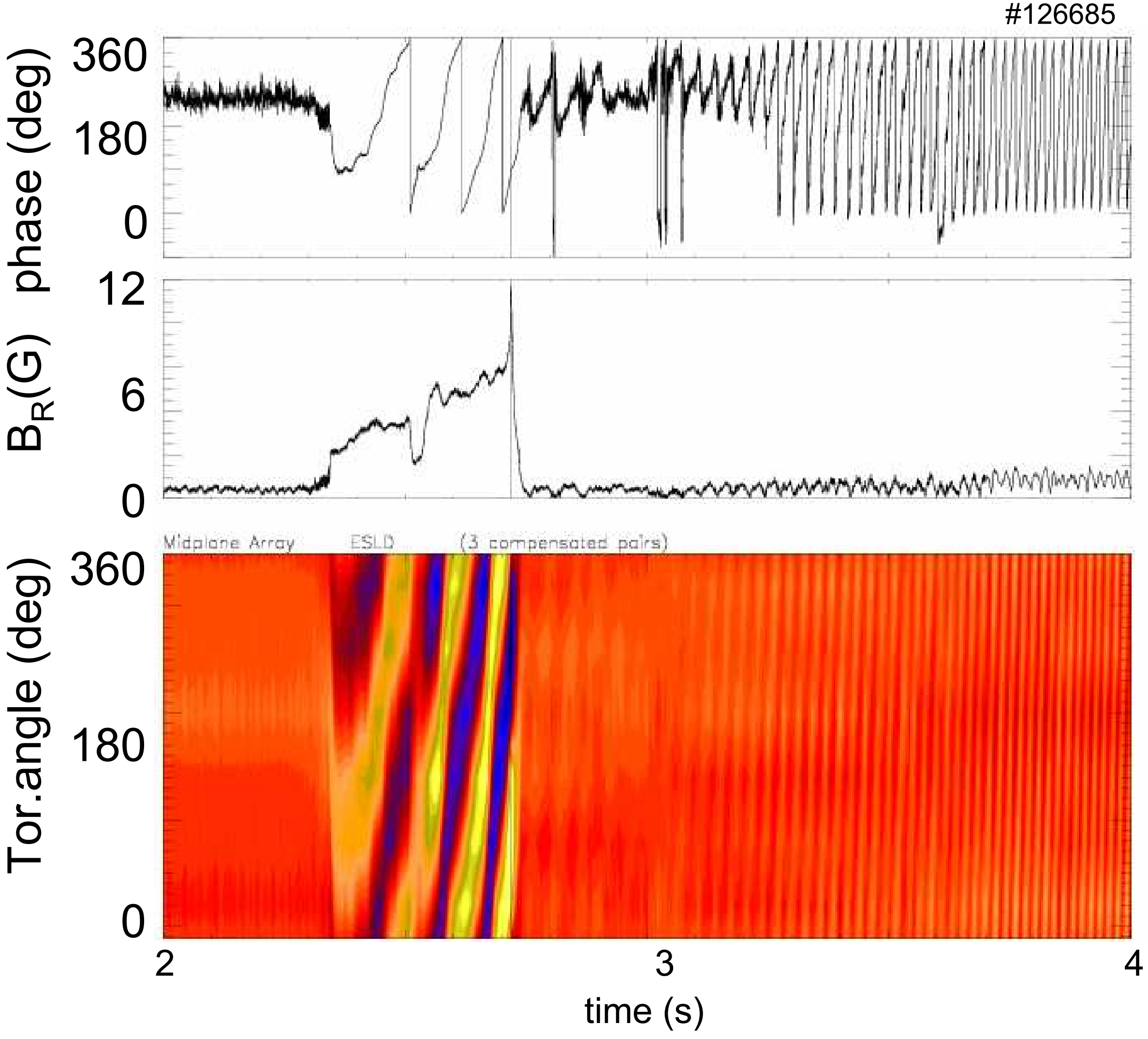
Mode slips

ECCD, 1.5MW, cw

Stabilization improves

Mode recovers when ECCD off

Magnetic perturbations also used to sustain more rapid mode rotation, in absence of ECCD

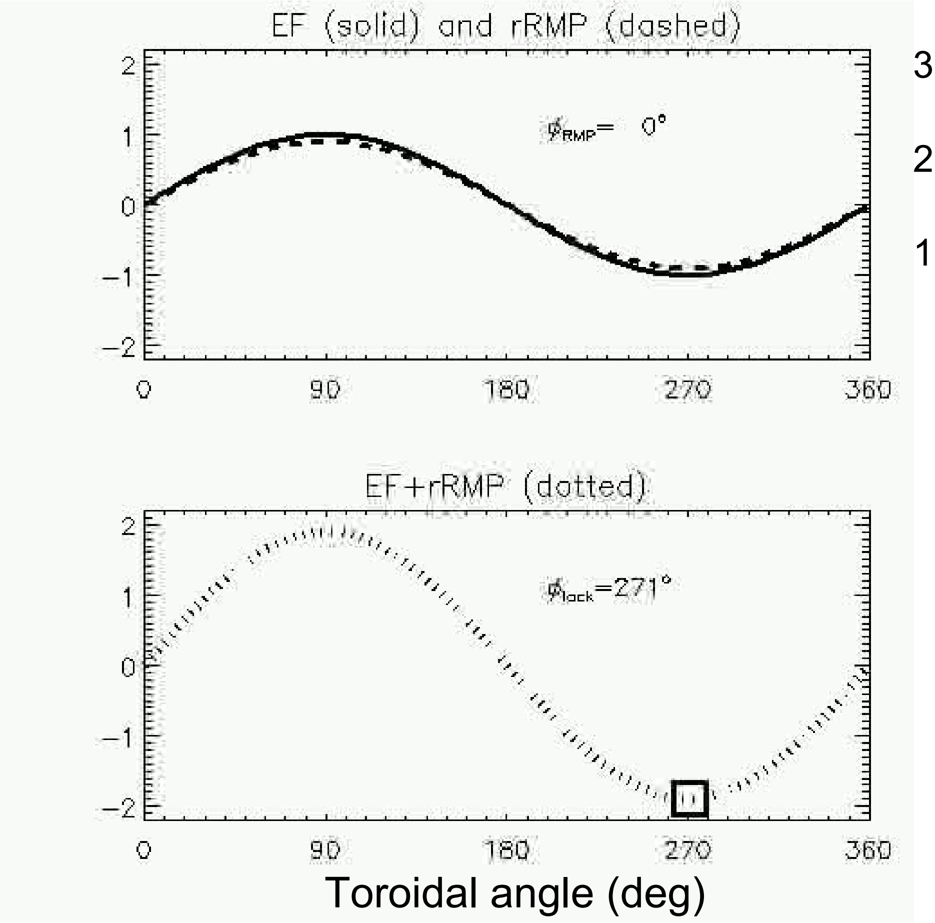


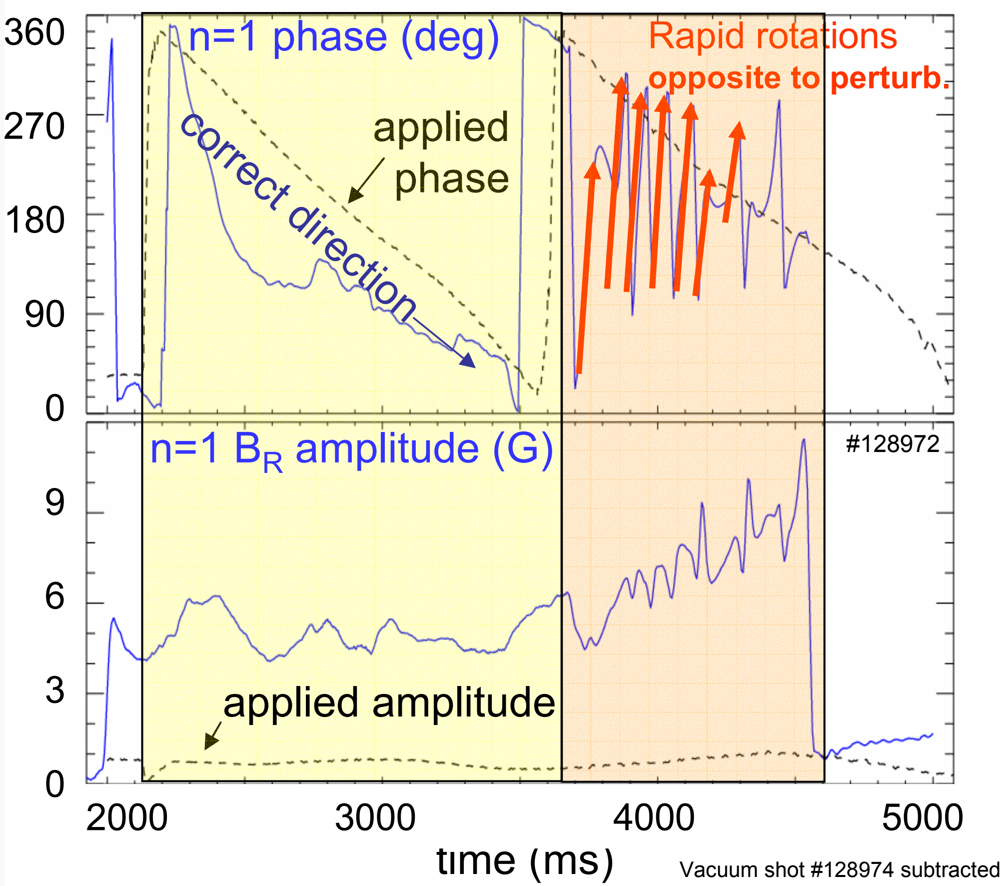
Several applications of driven mode rotation:

- Prevents locking
- Rotational mitigation
- Converts *locked* mode case to well-studied *rotating* NTM case
- Makes ECCD modulation easier than adapting ECCD to natural mode rotation

Vacuum shot #126769 subtracted

Balance between static error field and applied rotating field explains rich phenomenology when perturbation is too small





Model explains non-uniform rotation and sudden fast rotation opposite to perturbation. It doesn't explain yet multiple revolutions and occasional period doubling.

Summary, Conclusions and Future Work

3/2 NTM completely suppressed by ECCD modulated in phase with O-point, on the basis of oblique ECE

- Future Work: Stabilize 2/1 with this method

Oblique ECE channels out-of-phase indicate, off-line, good radial alignment between ECCD and NTM

- Future Work: Align in real-time

2/1 Locked Mode repositioned by magnetic perturbations and partly stabilized by ECCD

- Future work: complete stabilization (more power and sustained good alignment)

Mode forced to rotate at tens of Hz by rotating magnetic perturbations

- Future work: add ECCD, modulated at frequency and phase of applied rotation

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Ongoing and future work: Investigate physics of magnetically driven rotation.
Exploit new advanced techniques for control and physics.

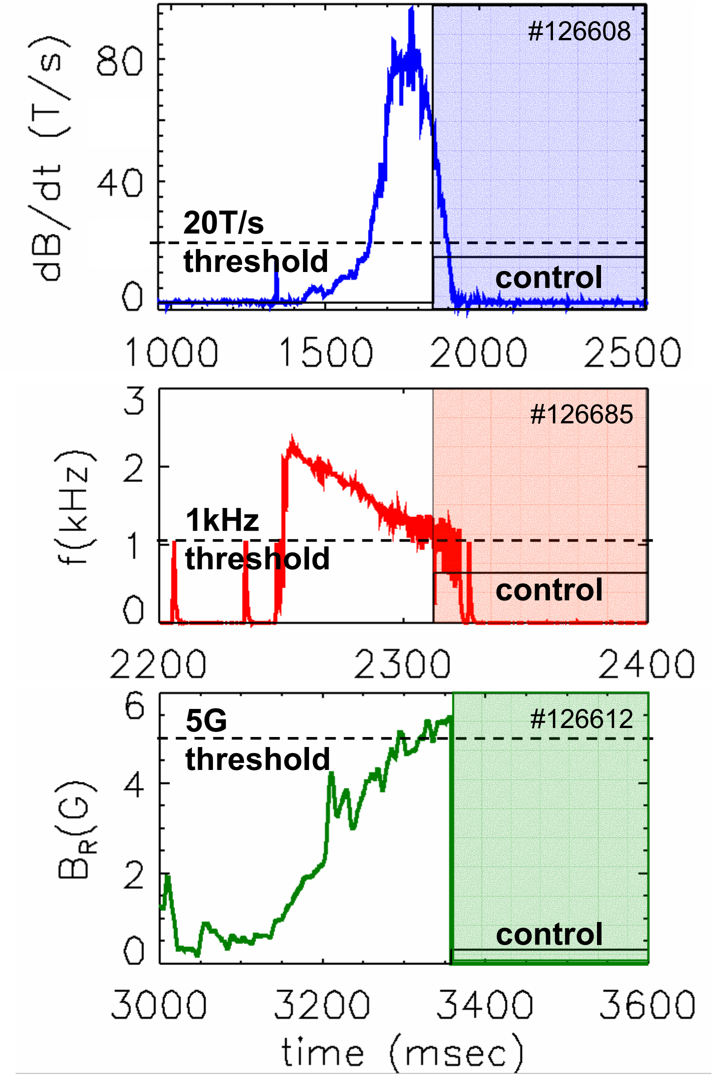
Backup Material

Magnetic measurements detect locked mode or imminent locking and trigger response

Mirnov Coils **(poloidal field sensors)**
measure mode amplitude at >100Hz

Mirnov Coils+Frequency Counter
measure angular frequency of mode, detect slowing down

Saddle loops **(radial field sensors)**
measure mode amplitude at <100Hz .
Suitable for "born locked" modes



I-coil Travelling Wave less effective at high frequencies

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

- **Besides, for the same $I_{\text{I-coil}}$, the magnetic perturbation exerted on the plasma decreases due to:**
  - Partial compensation from image currents in the wall
  - More Shielding associated with (faster) rotation

- **Furthermore, the same $B_{\text{I-coil}}$ couples less effectively with a faster, rotationally mitigated, weaker mode** (= compass of reduced μ immersed in the same B $\Rightarrow$ B imparts reduced μxB torque)

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

Mode Rotation and Locking are described by Torque Balance

$$I\frac{d^2\phi}{dt^2} = \underbrace{T_{wall} + T_{EF} + T_{RMP} + T_{TM}} + \underbrace{T_{visc} + T_{NBI}}$$

E.m. Torques on Island
modelled by Interaction between Helical Currents:

Viscous Torques
on resonant surface

(NB: Island not exactly “frozen”: rotates at $\leq \omega_{*s}$)

$$I_h = \pm 2|B_R(b)|b\left(\frac{b}{r_{mn}}\right)^m \frac{1}{m\mu_0}$$

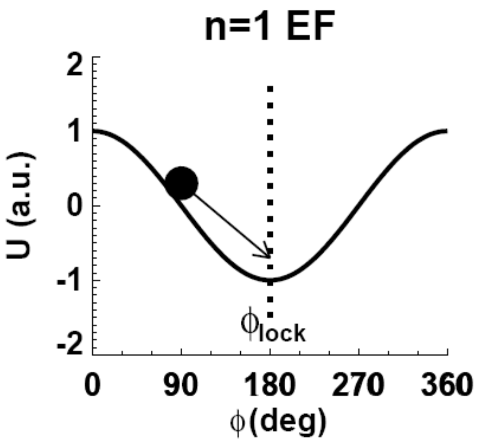
$$T_{wall} = -\frac{[2\pi R\, B_R(b) r_{mn}]^2}{\mu_0 b}\left[\frac{r_{mn}}{b}\right]^{2m-1}\frac{\Omega\tau}{1+(\Omega\tau)^2}$$

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

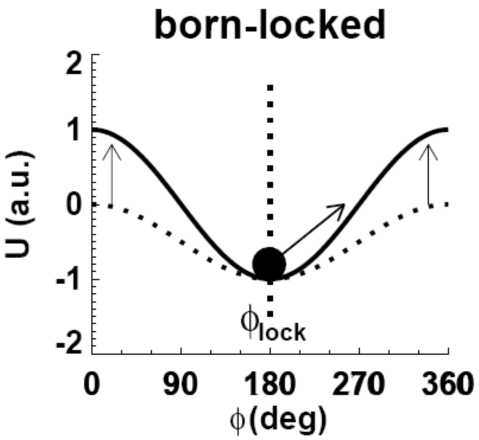
$$T_{RMP} = -\pi^2 R^2 m \frac{b}{r_{mn}} I_{RMP} B_R(b)\sin[n\phi(t) - n\phi_{RMP}(t)]$$

$$T_{TM} = -\pi^2 R^2 m \sum_{m',\,n'} \frac{r_{m'n'}}{r_{mn}} \sin[n\phi(t)] I_{m'n'} B_R[r_{m'n'}]$$

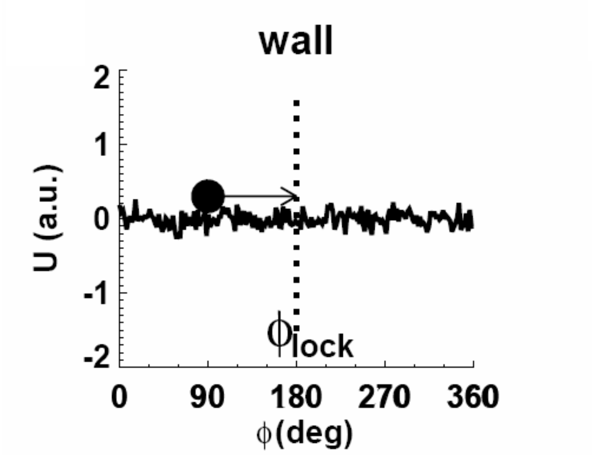
Gravitational Analogue: Island interaction with Error Field + Magnetic Perturbations modelled by *static* + *moving* Potential Well



Discrete Positions of Lock



is
Phase



Continuous Positions of Locking

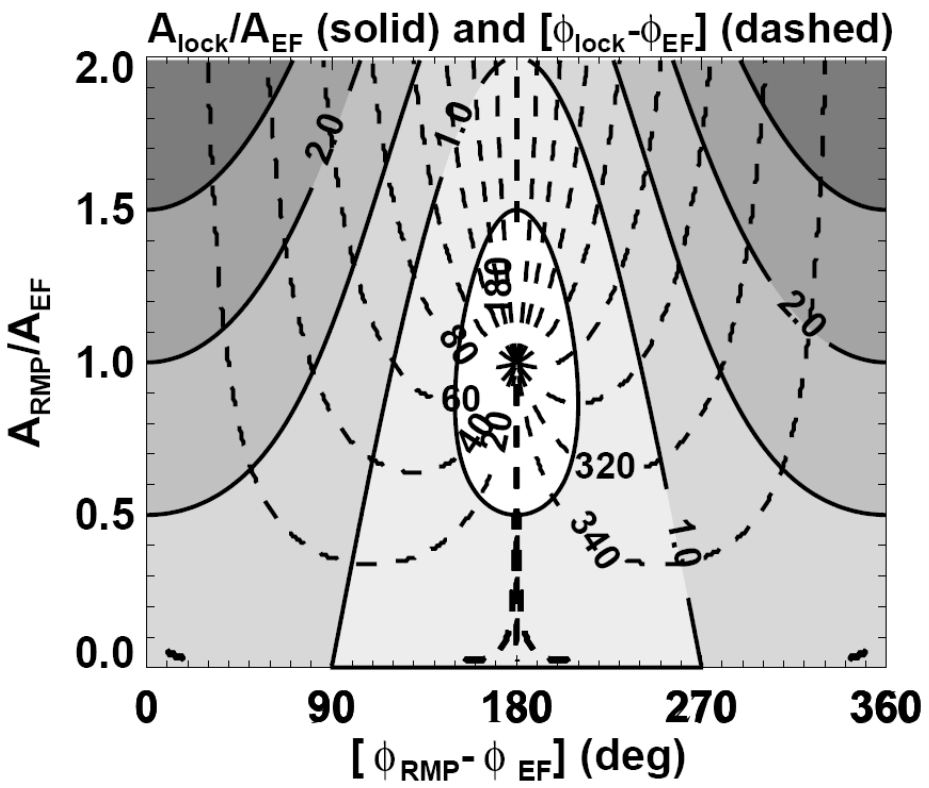
Plasma Rotation↘ ⇒

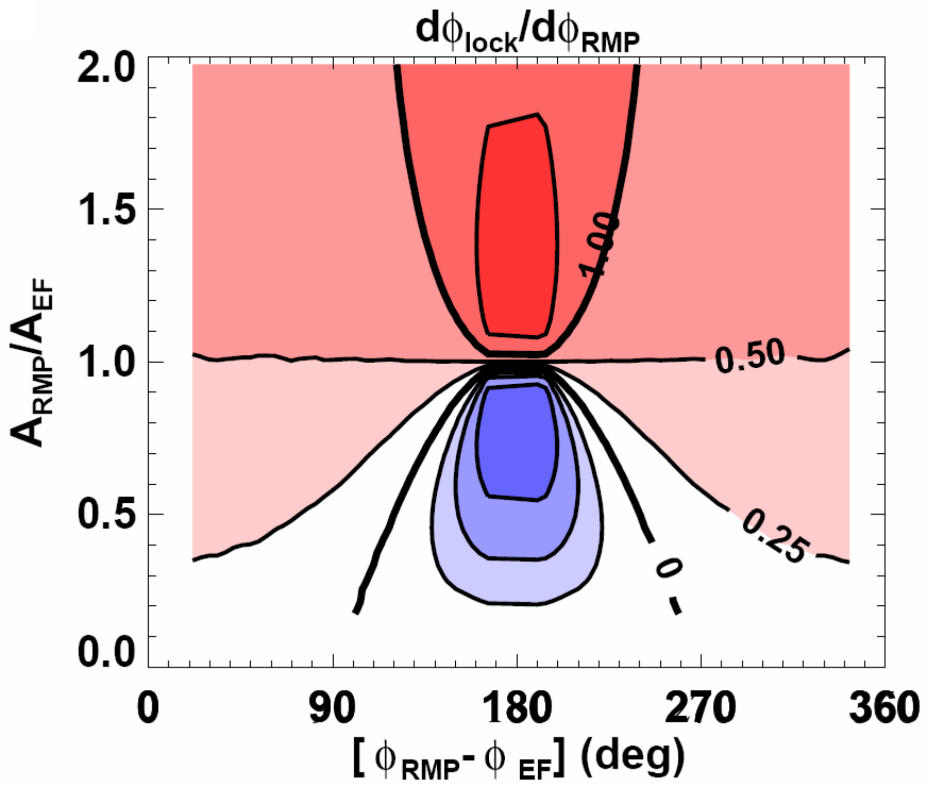
EF penetration↗ ⇒

New Locked Phase
= applied RMP Phase

1. Seed island
2. Pot.Well forms

Optimal RMP Amplitude and Phase depend on EF. Max Non-uniform Rotation for $A_{RMP} \approx A_{EF}$ and $\phi_{RMP} \approx \phi_{EF}$.





- **Applications:**
  - Sustained Rotation
  - New EFC Method? Spiralling RMP
  - Possible Explanation for Rotational Mitigation at ~10Hz