Oblique-ECE-assisted aligned, modulated ECCD stabilization of NTMs at DIII-D

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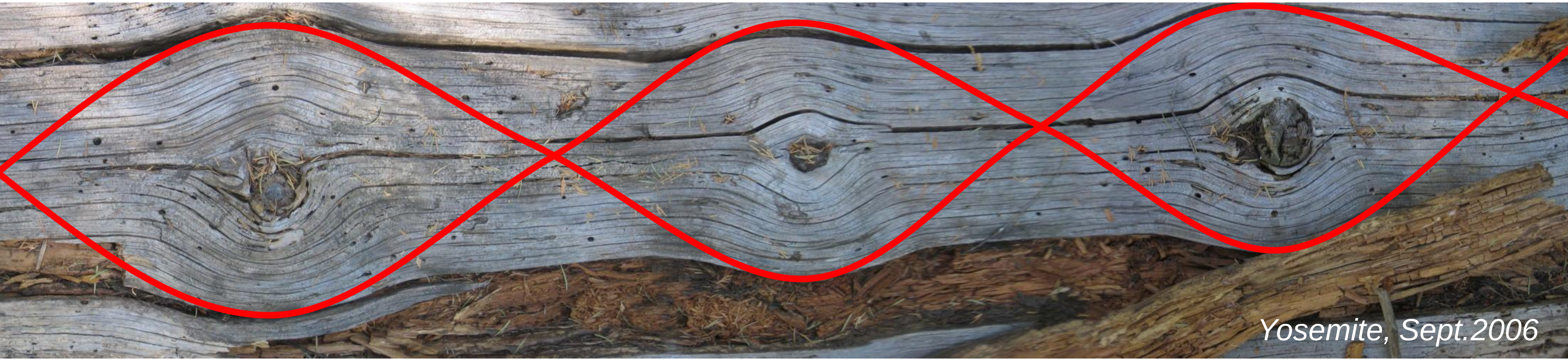

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NTMs are a principal limit to high performance in ITER Control needs to be effective

- **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

- **Both can be assisted by oblique Electron Cyclotron Emission (ECE)**

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**
- **Summary and conclusions**

Motivation & Principle

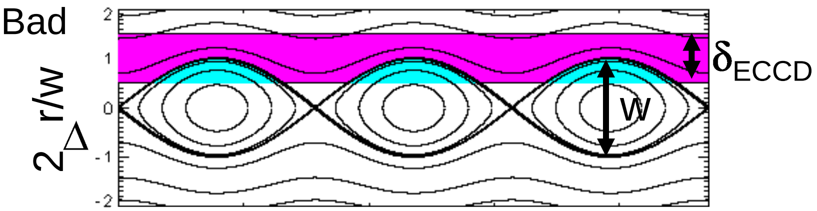
NTMs can be stabilized by Electron Cyclotron Current Drive at the location of the magnetic island

- **Modified Rutherford equation governs island growth**

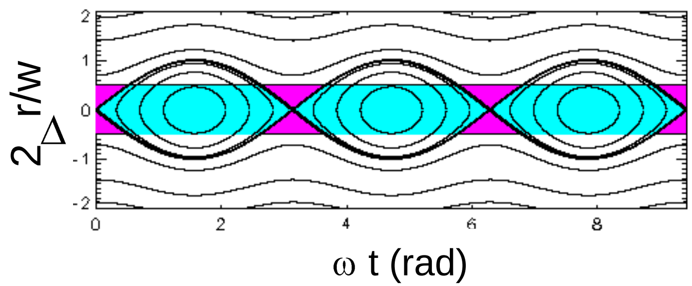
$$\frac{\tau_R}{r}\frac{dw}{dt} = \Delta'_0 r + \delta(\Delta' r) + 3\frac{j_{boot}}{j_{total}}\frac{L_q}{w}\left[1 - \frac{(2\varepsilon^{1/2}\rho_{\theta i})^2}{3w^2} - K_1\frac{j_{eccd}}{j_{boot}}\right]$$

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

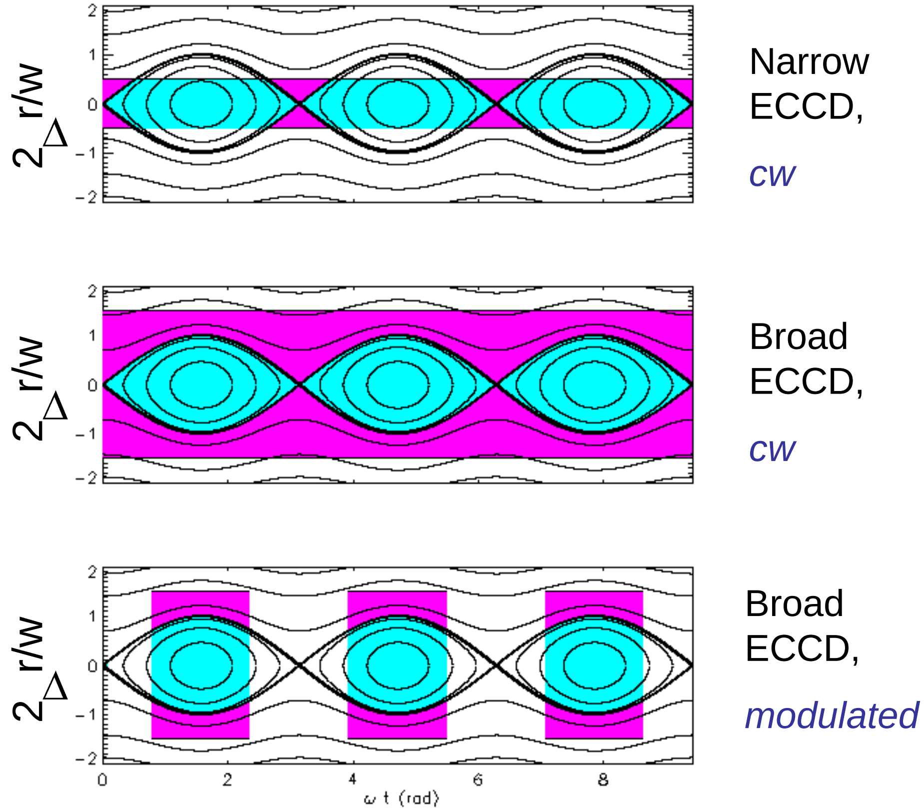
Bad



Good alignment:



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



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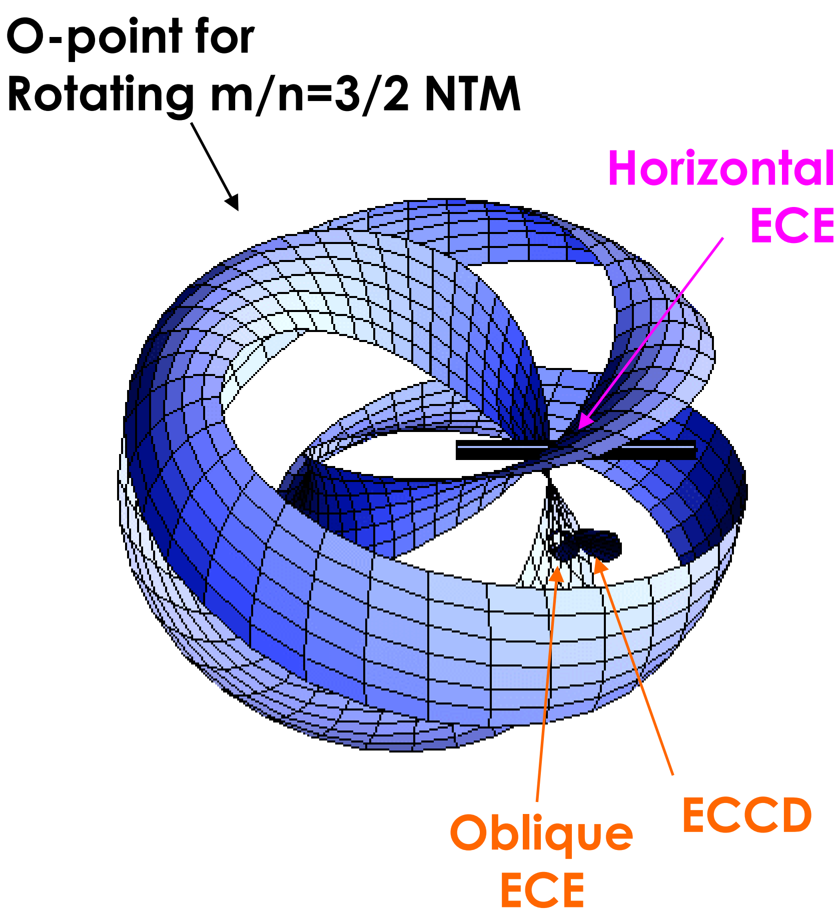
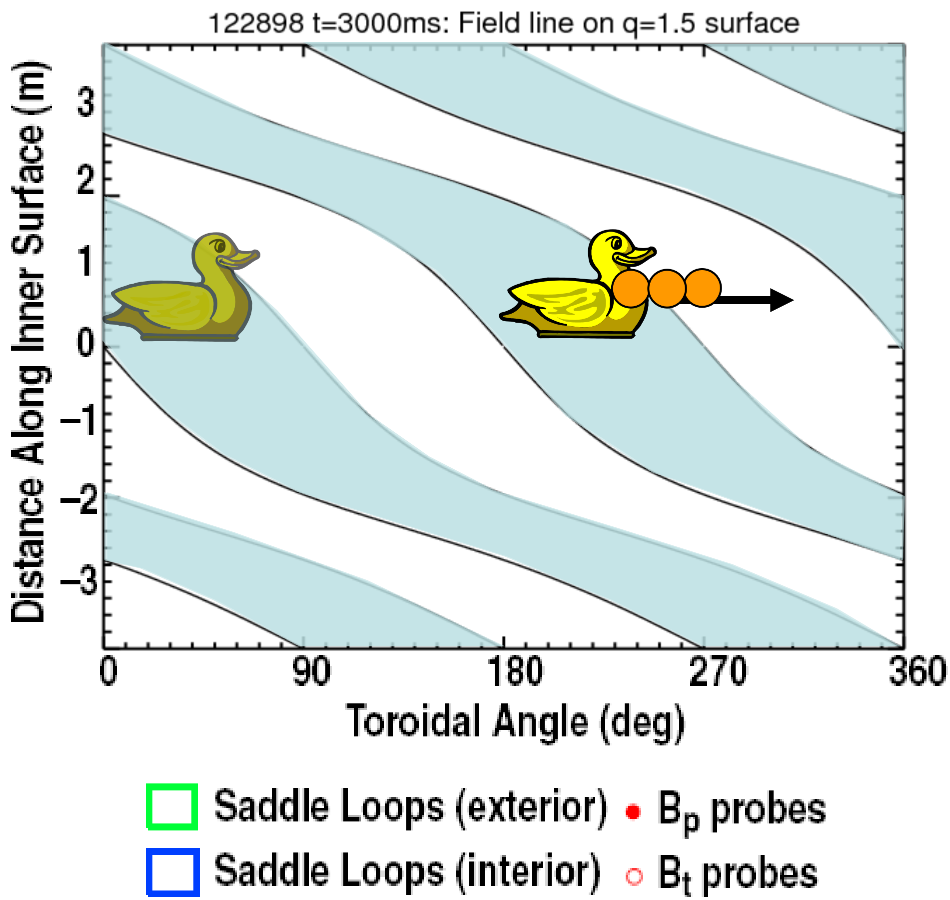
Alignment and Modulation of ECCD to NTMs and Interpretation of ECE and magnetics are complicated 3D problems



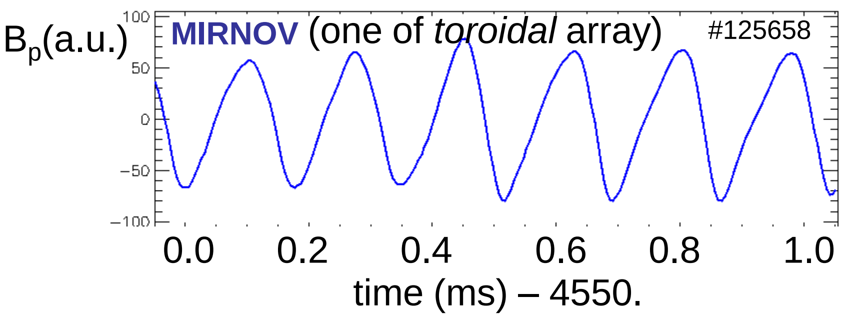


Internal ECE tracking of NTMs has advantages compared with *external* magnetic probe data

- **Magnetic probes measure δB_θ at wall**

  Pro: best measurement of frequency

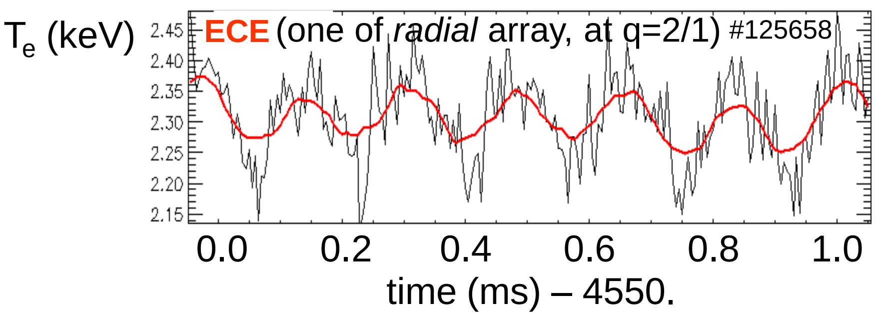
  Cons:
  - No data for radial alignment
  - Toroidal phase of island requires reconstruction of equilibrium and field lines



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

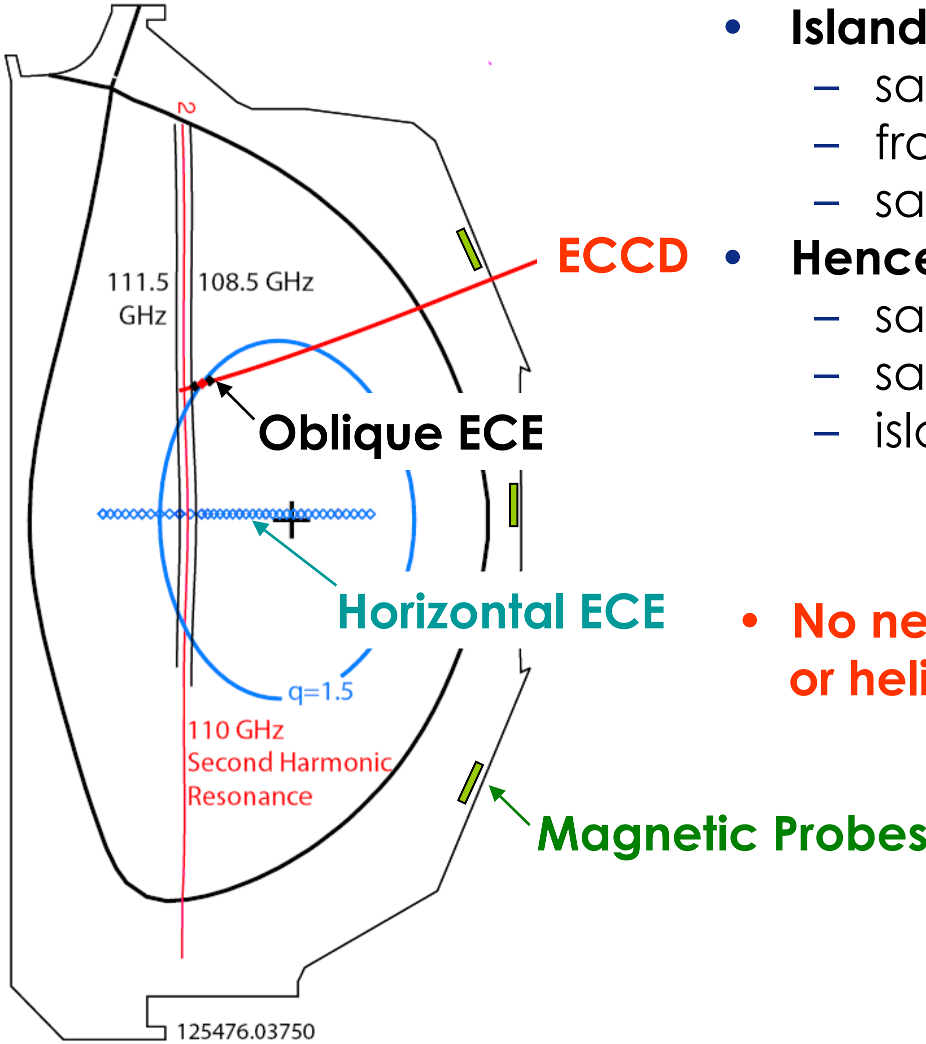
  Pro: Major radius of island can be determined

  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

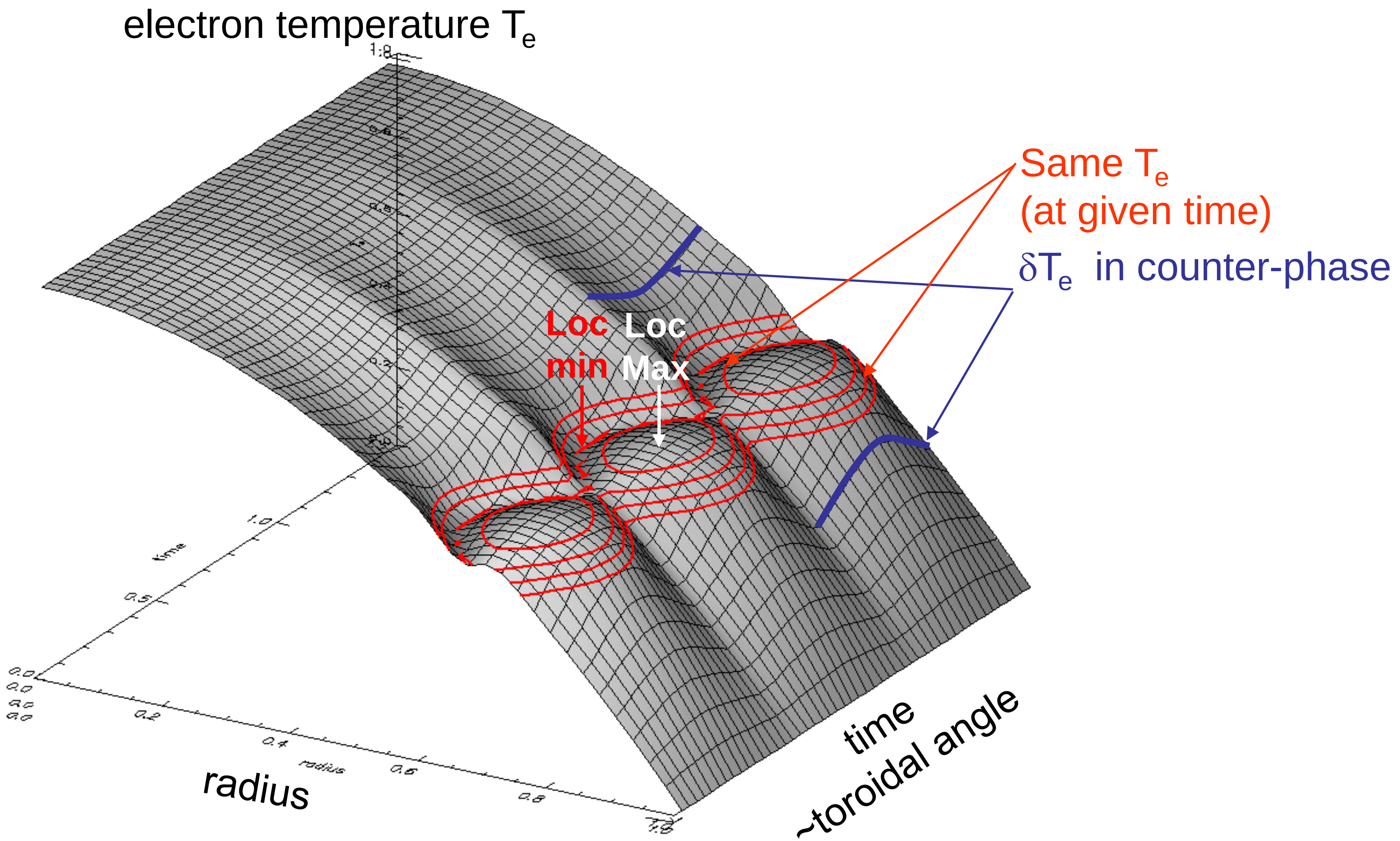
Oblique ECE, along same direction as ECCD, avoids need for equilibrium reconstruction and analysis



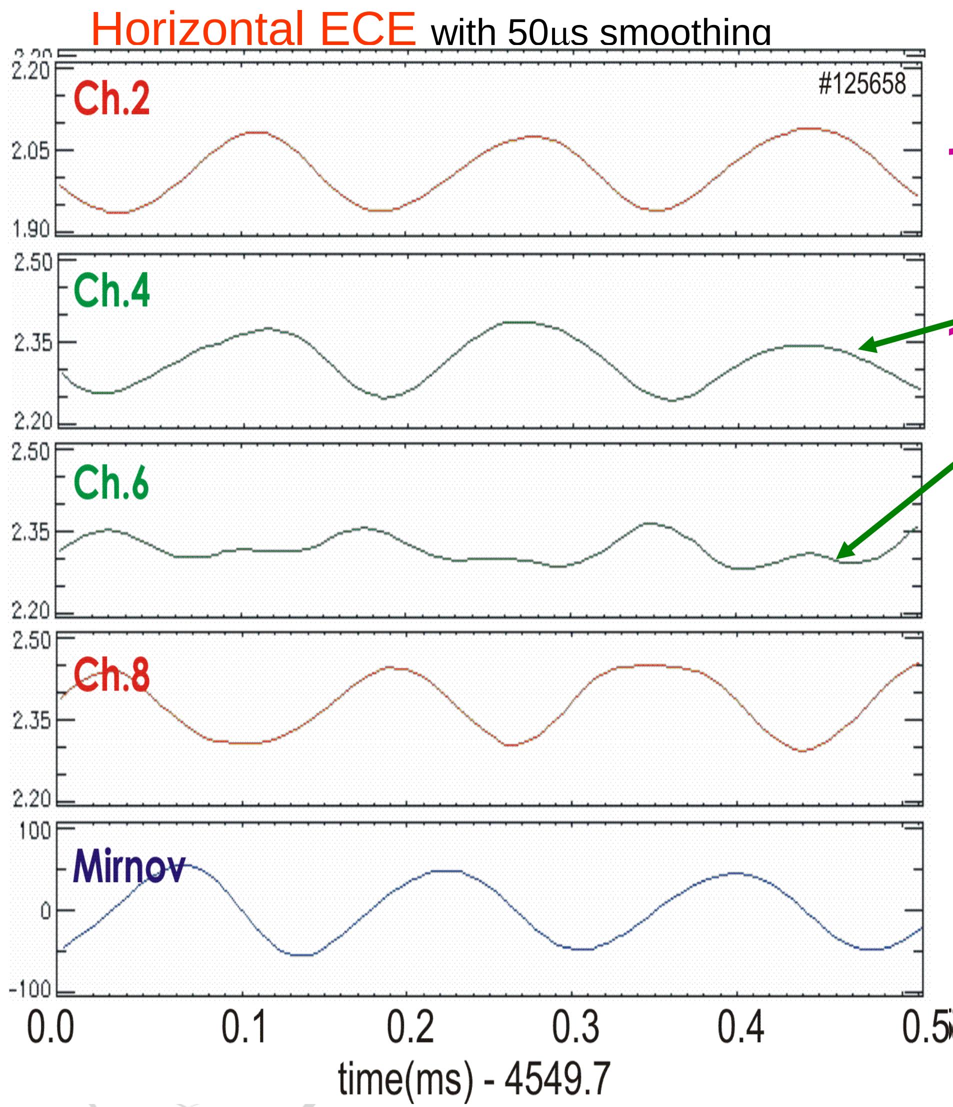
- **Island transit measured 'in situ'**
  - same R, Z of CD
  - from same R, Z of ECRH launcher
  - same poloidal & toroidal view angles
- **Hence**
  - same relativistic downshift
  - same relativistic & Doppler broadening
  - island centre emits at $f=f_{gyr}$=110GHz

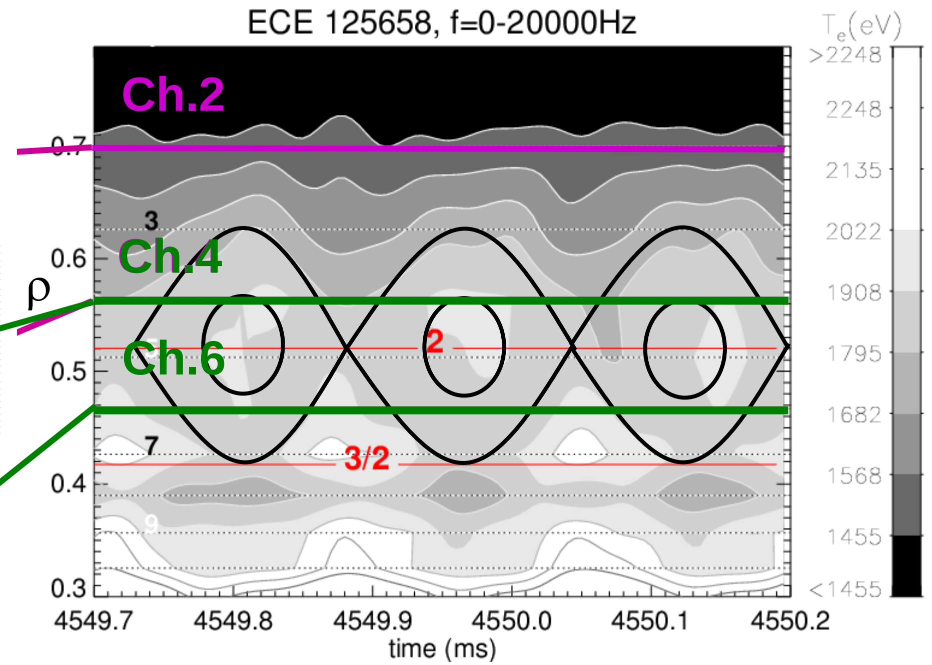
- **No need for flux surface shape or helical extrapolations in R,Z,ϕ.**

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



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



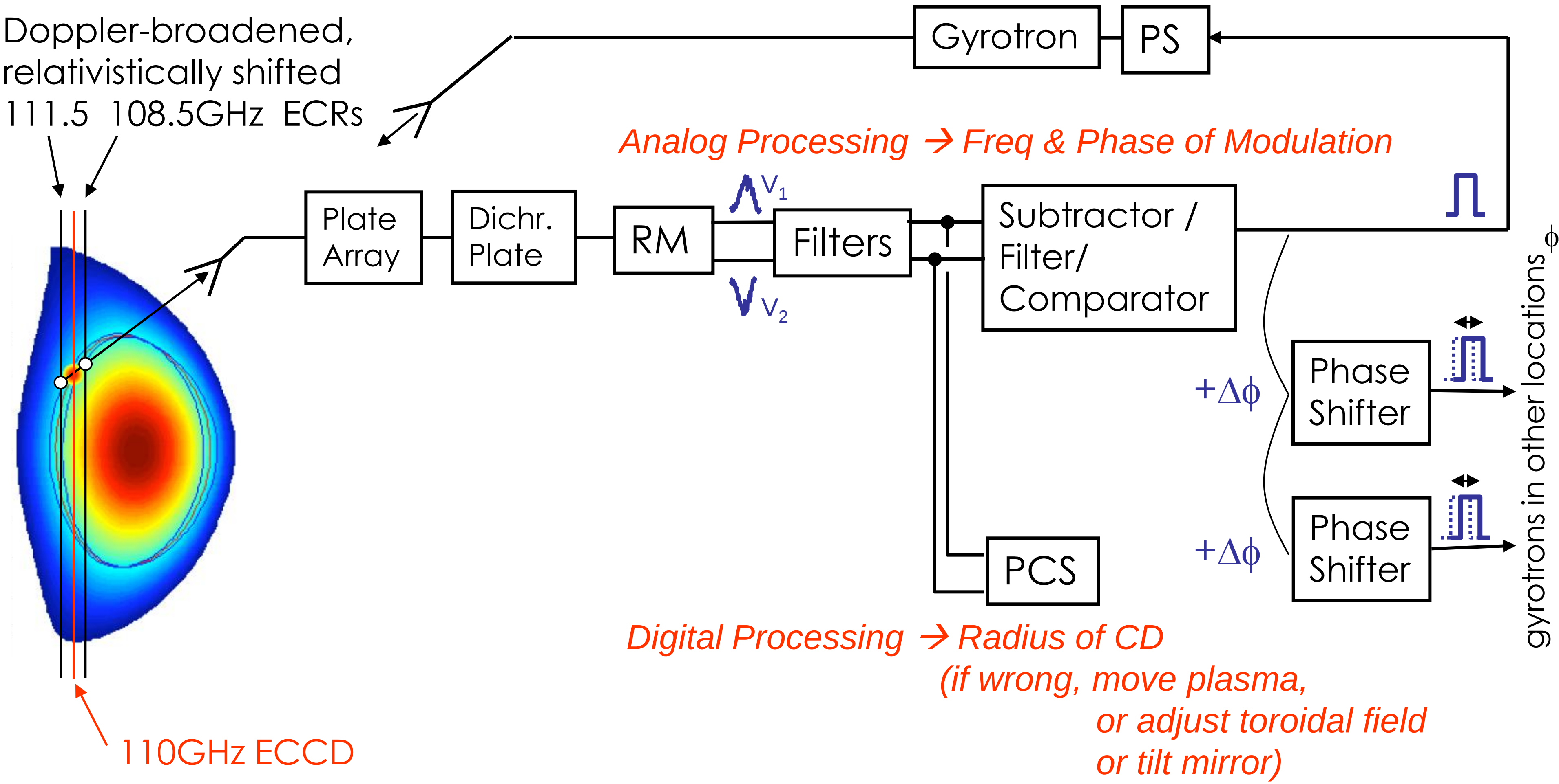


In-phase: on same side of island

Out-of-phase: on opposite sides

Experimental Setup

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



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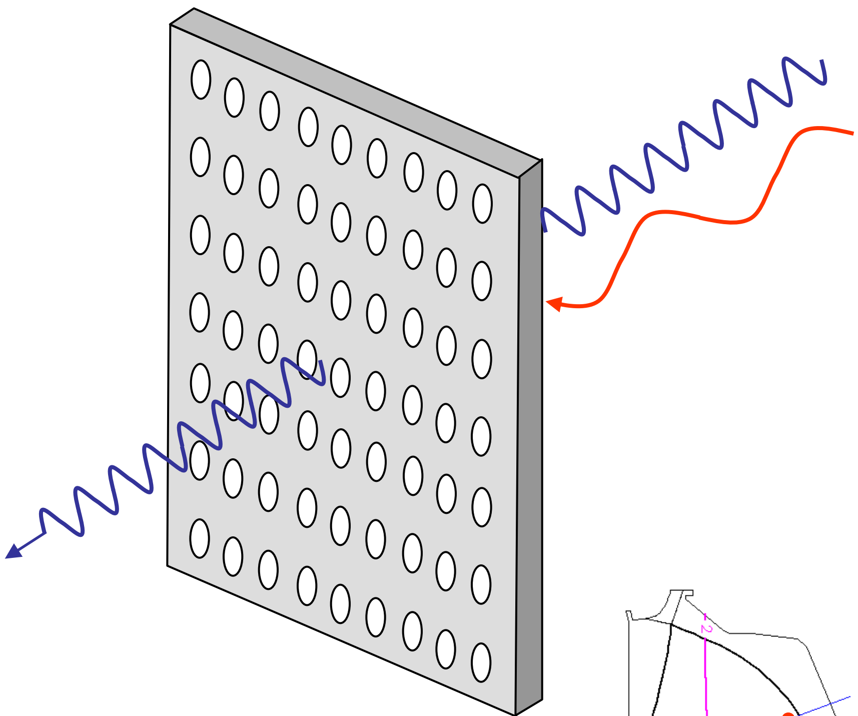
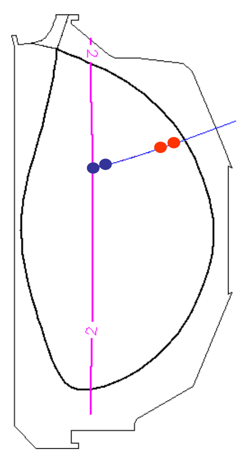
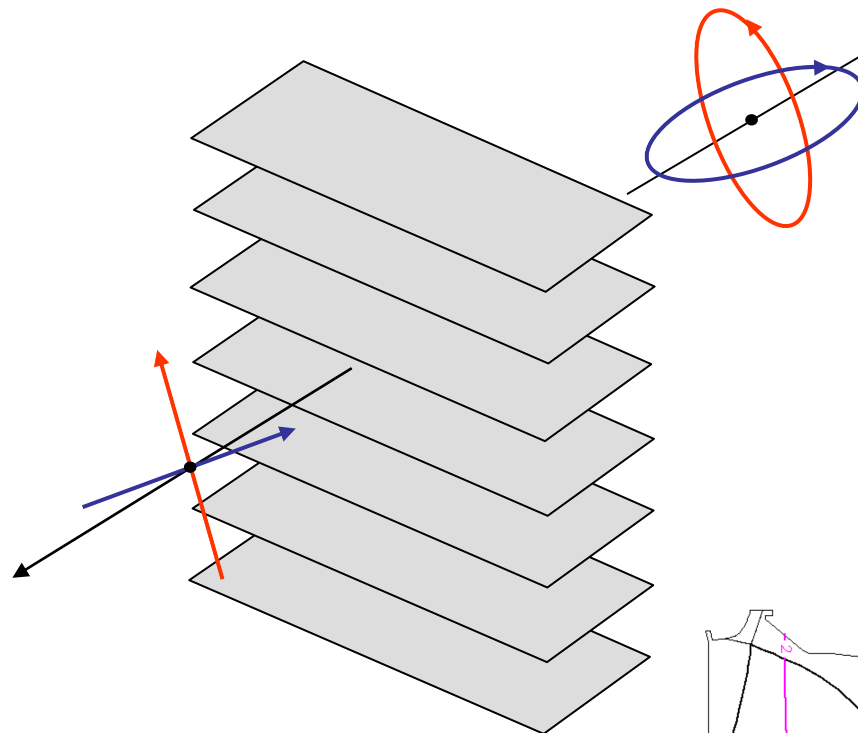
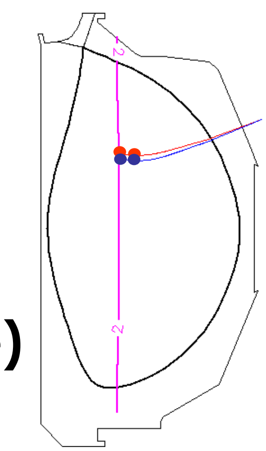
Dichroic plate and plate array





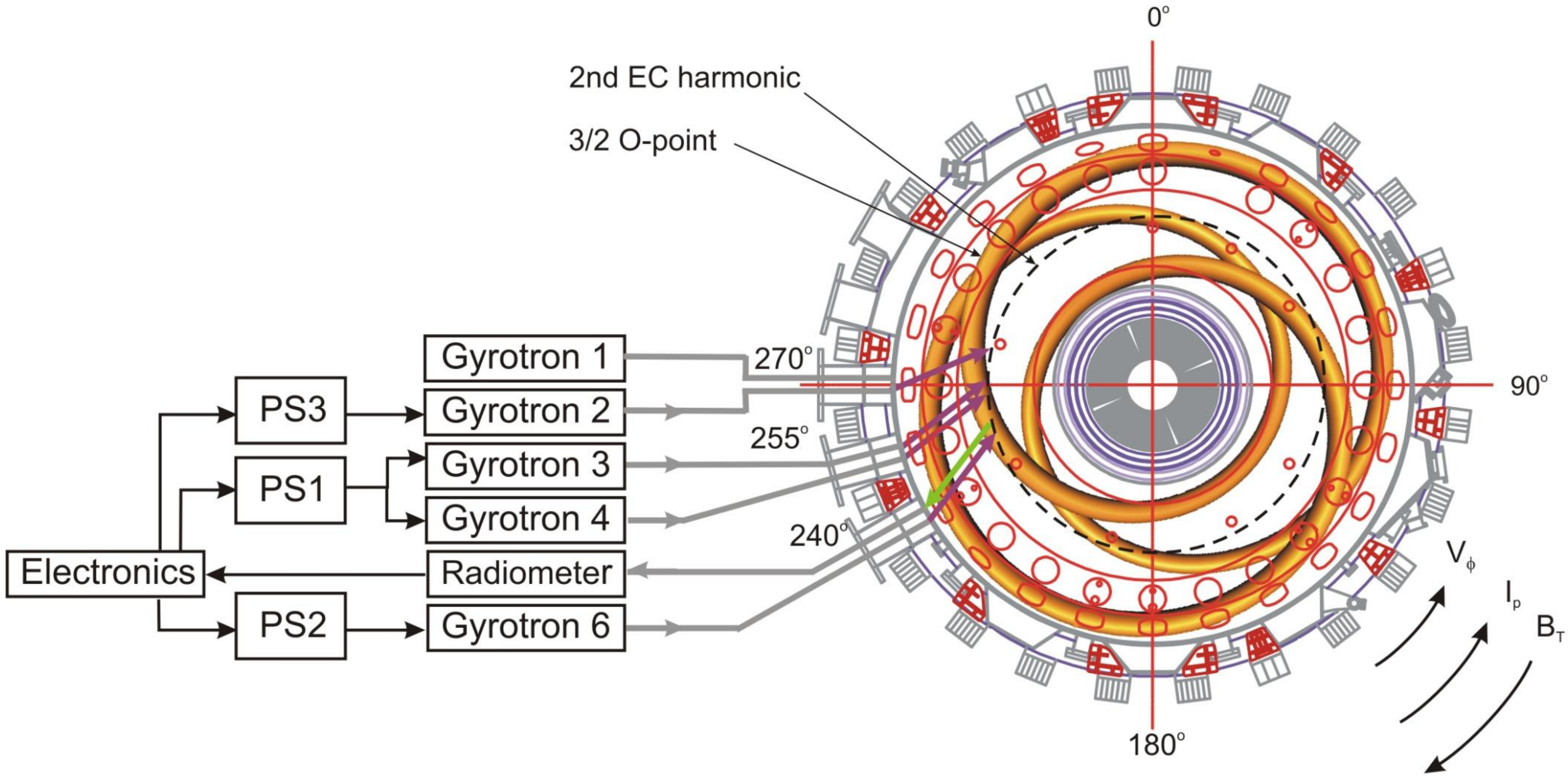




Frequency selectivity
(no mix-up with LFS)

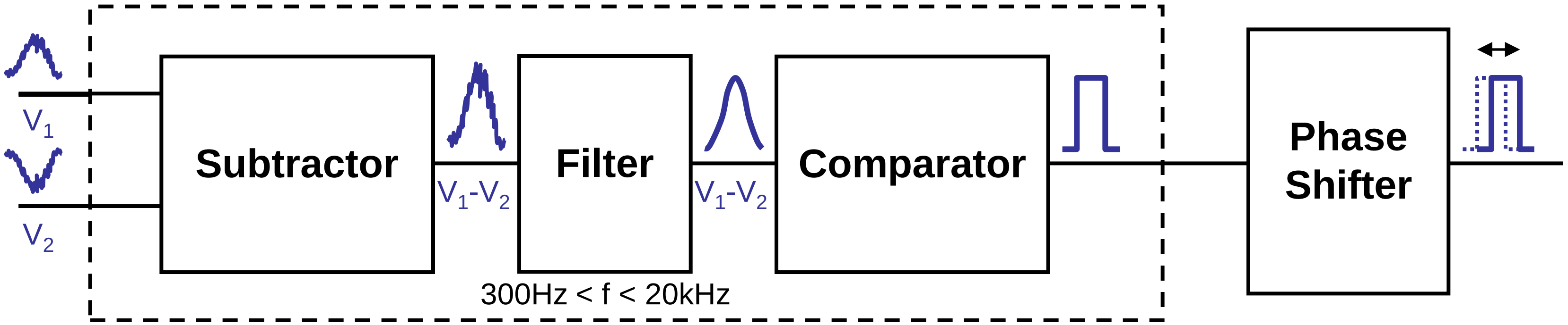
Modal Purity
(no mix-up with O-mode)

Oblique ECE from rotating island collected by transmission line 5
Modulated ECCD injected from lines 2, 3, 4 & 6 to stabilize island

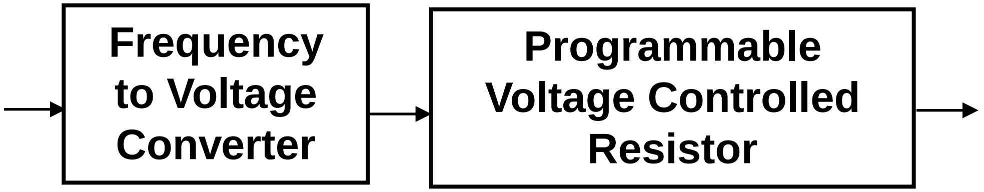


$\phi_{ECCD} \neq \phi_{gyr}$ but $\Delta\phi$ =15, 30, 330, 345° anyway

Analogue circuit modulates ECCD based on oblique ECE and corrects phase for different toroidal location



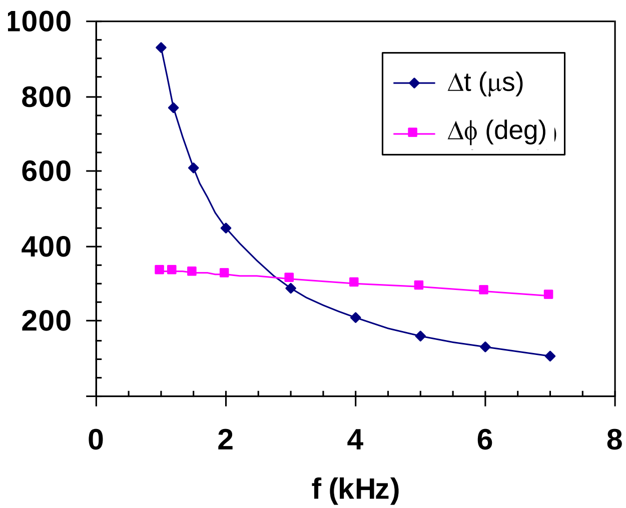
- Phase shifters usually provide fixed <u>time</u> delay
- Special design: flat frequency response in <u>phase</u>



$V \propto f$

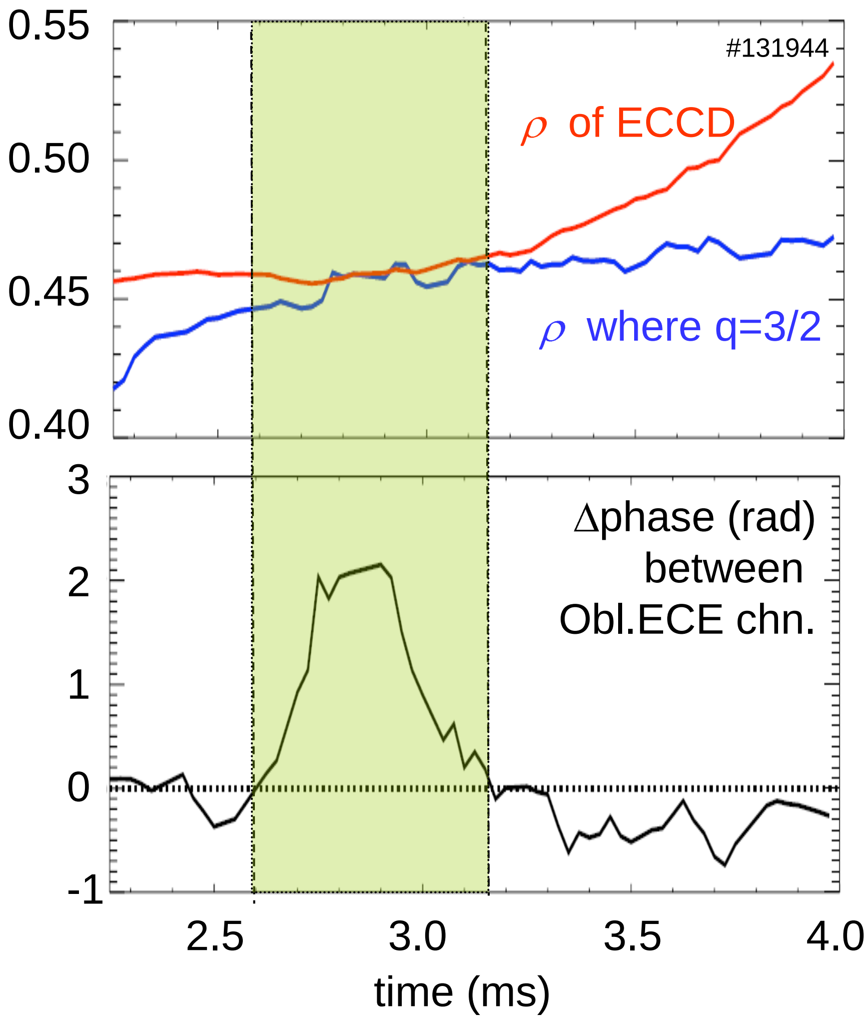
$R \propto 1/V \propto 1/f$

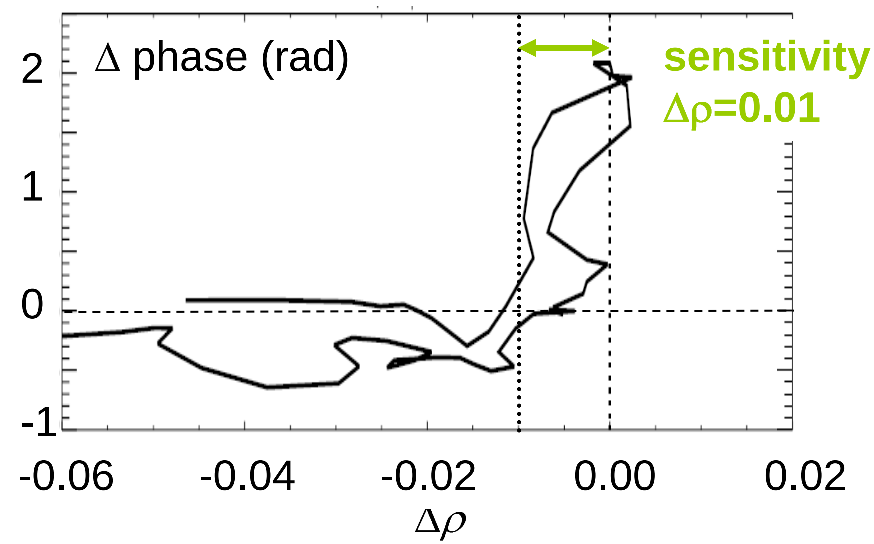
$\Delta t = RC \propto 1/f$
but $\Delta\phi$=const.



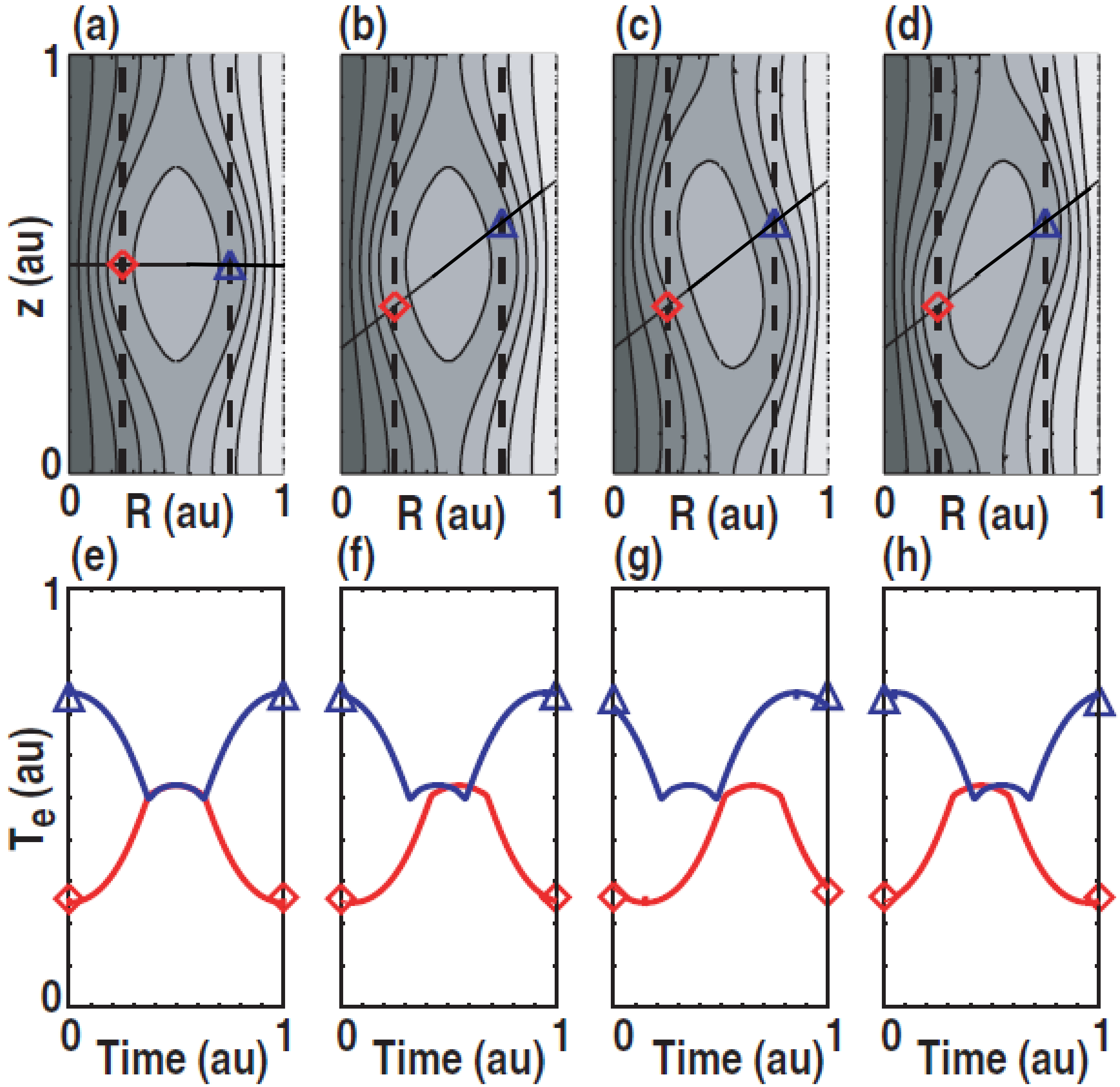
Experimental Results

Observed Phase Reversal, indication of good alignment

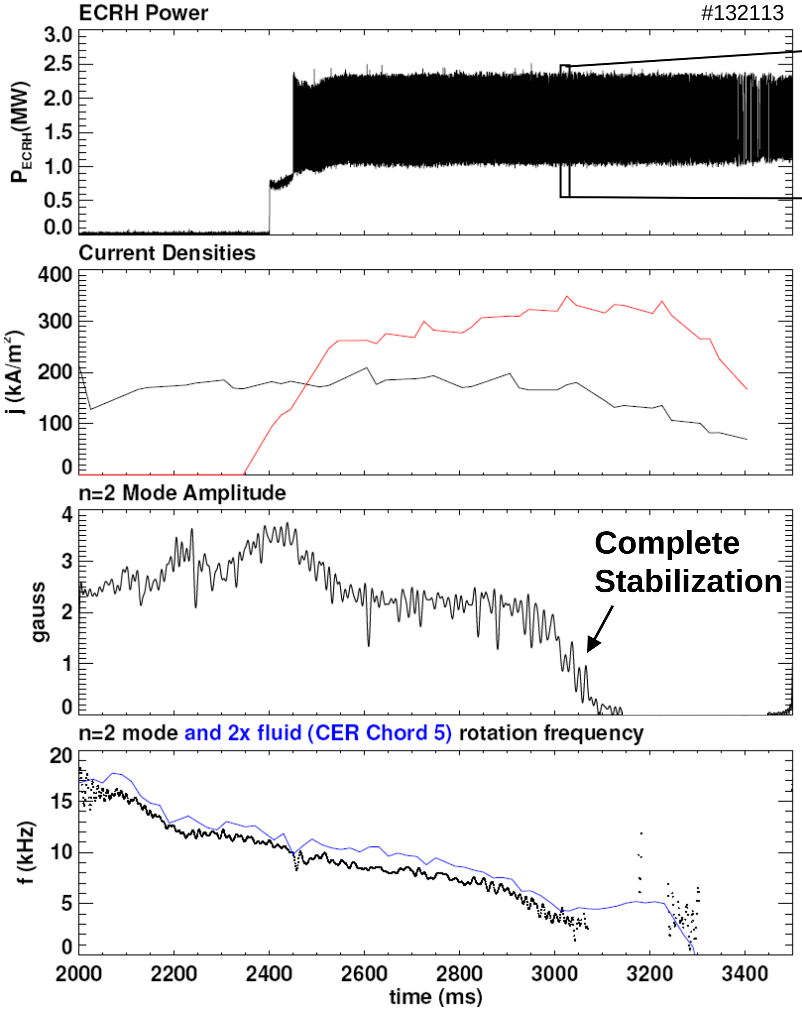


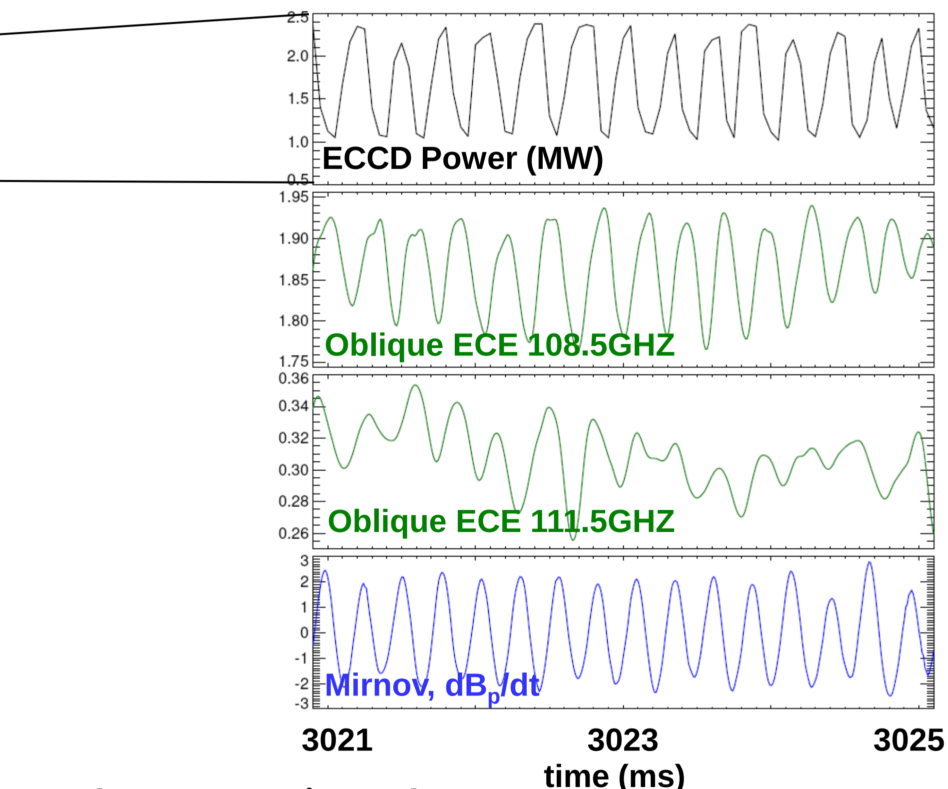


Phase jump ≠ π, because of oblique view and shear



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

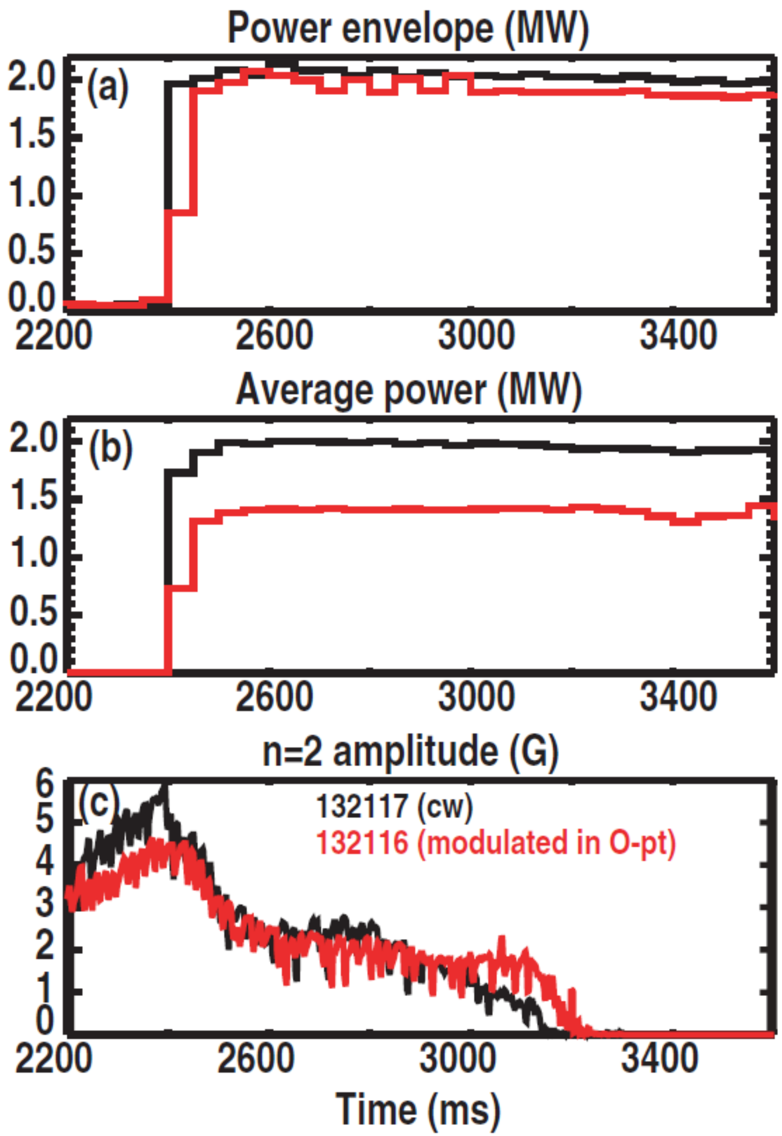




Future experiments:

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

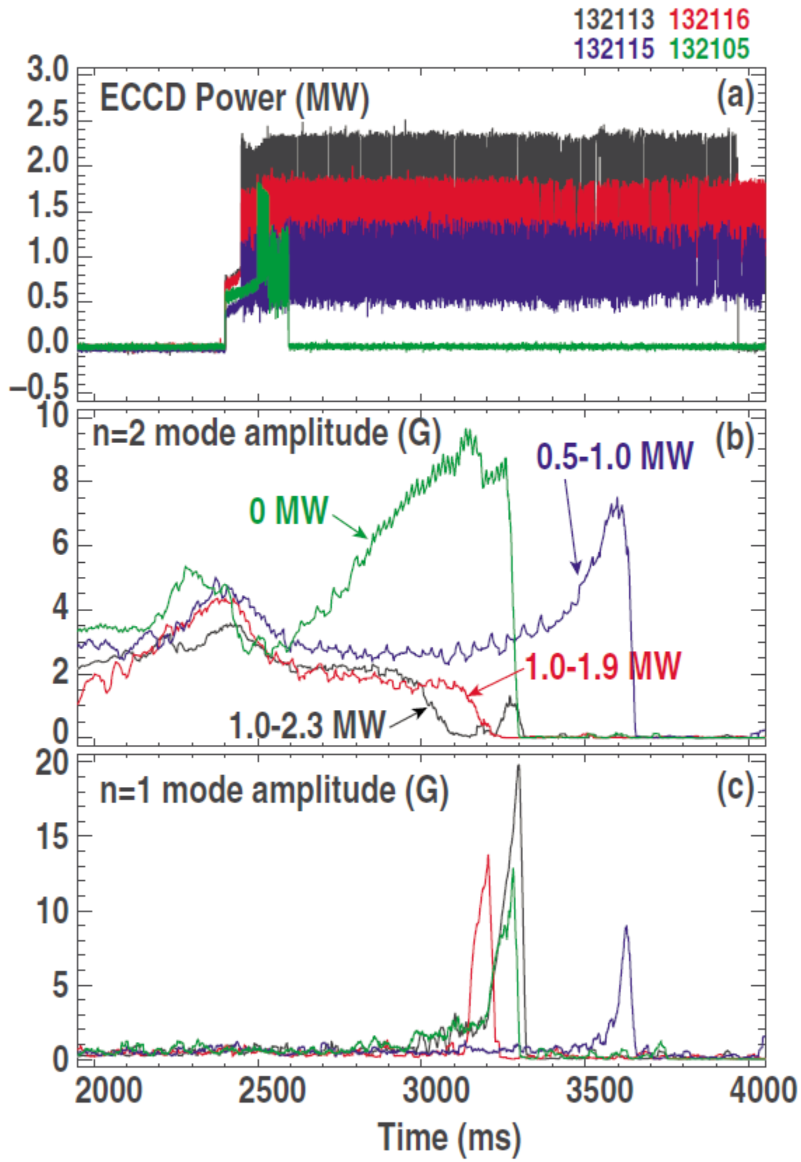
Modulated ECCD saves average power → electricity. If broad (ITER) it also saves peak power → hardware.



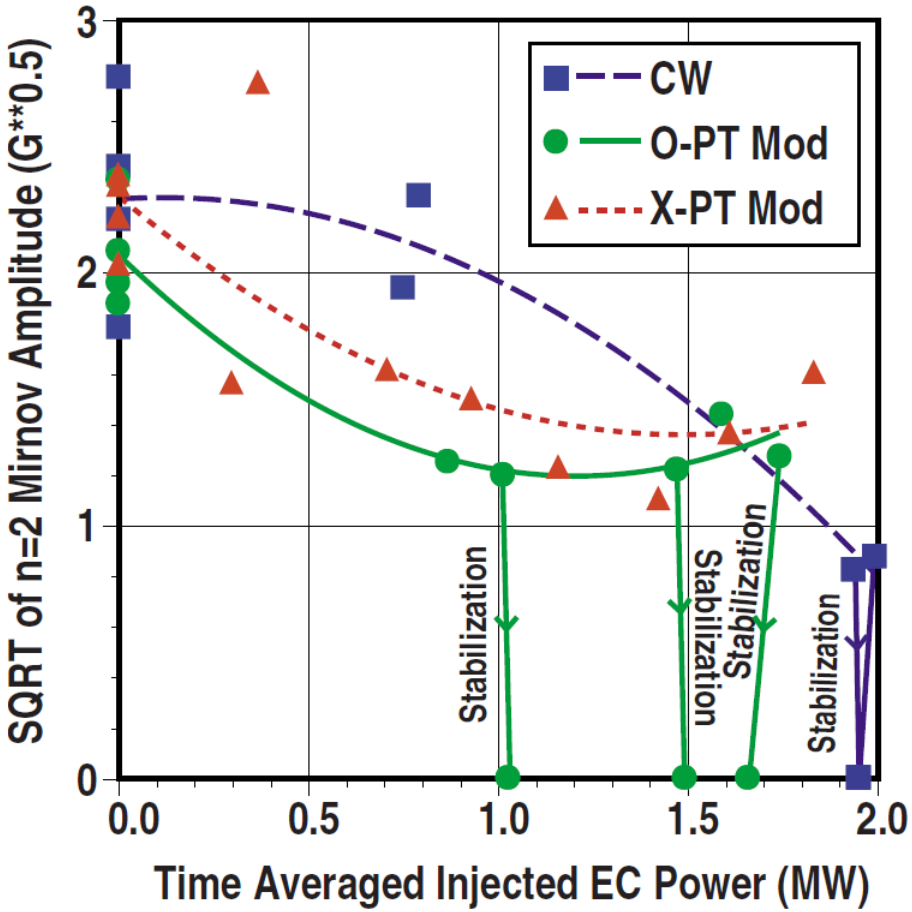
Same peak power

Similar stabilization with ~30% less power

More ECCD power stabilizes 3/2 NTM more rapidly



Modulation and O-point phasing make stabilization more efficient



- **Modulated ECCD more stabilizing than CW**
- **O-point phasing more efficient than X-point**
- **Sudden stabilization when $w<w_{marg}$**
- **No complete stabilization for X-point phasing**

Summary and Conclusions

- **Physical principle**
  - Oblique ECE tracks island along ECCD line of sight, toroidally shifted
  - Signals directly modulate ECCD
  - Radial alignment from anti-correlation of two channels

- **Demonstrated both techniques**

1. **Observed "Phase-reversal", indication of good alignment**
   - confirmed by equilibrium and ray tracing analysis
   - **Future work: align in real-time**
2. **3/2 NTM completely suppressed by ECCD modulated in phase with O-point on the basis of oblique ECE signals**
   - **Future work: stabilize 2/1**

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Advanced techniques for neoclassical tearing mode control in DIII-D[a)]

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Two techniques were developed at DIII-D [J. L. Luxon, Nucl. Fusion **42**, 64 (2002)] to tackle ITER-specific aspects of neoclassical tearing mode (NTM) control, namely, (1) the relatively small size of the rotating islands, smaller than the electron cyclotron current drive (ECCD) deposition region, and (2) the increased tendency of the islands, compared to present devices, to lock to the wall or to the residual error field, in a position not necessarily accessible to ECCD. Modulated ECCD is known to suppress small islands more efficiently, when "broad," than continuous ECCD. At DIII-D, a NTM of poloidal/toroidal mode numbers $m/n=3/2$ was completely stabilized by a new technique where oblique electron cyclotron emission acted at the same time as an indicator of good alignment between ECCD and the island, and as a waveform generator, for modulation in synch and in phase with the island O-point. In another experiment, after locking in an unfavorable position, a 2/1 island was steered by externally generated magnetic perturbations, brought in the view of the gyrotrons and partly stabilized by ECCD in the island O-point. Magnetic perturbations were also used to sustain and control the mode rotation, which has the potential for an easier ECCD modulation. [doi:10.1063/1.3232325]

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Observed Phase Reversal, indication of good alignment !