Feedback control of tearing modes through ECRH with launcher mirror steering and power modulation using a line-of-sight ECE diagnostic

Bart Hennen, Egbert Westerhof, Pieter Nuij, Marco de Baar, Waldo Bongers, Andreas Bürger, Hans Oosterbeek, David Thoen, Maarten Steinbuch
and the TEXTOR team

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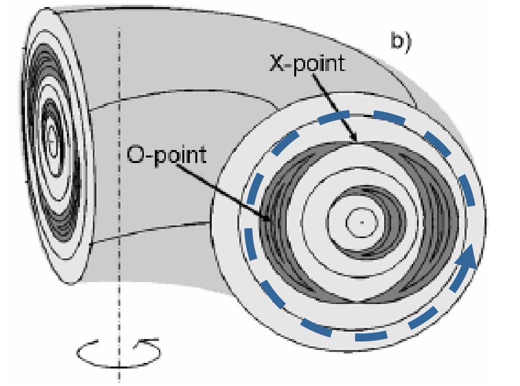
Feedback control of tearing modes

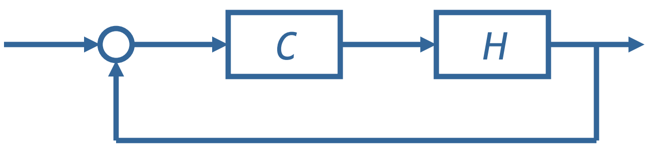


- Goal:

  Establish a real-time tearing mode control system

- Localized ECRH/ECCD applied for stabilization and suppression:

  - Fast & accurate mode detection
  - Align ECRH/ECCD power deposition w.r.t. mode centre ("tracking")
  - Modulate ECRH/ECCD power synchronously with mode rotation (1 Hz – 5 kHz)



- Why real-time feedback control ?

  guarantees fast and accurate alignment (100 ms, 1-2 cm), disturbance rejection, robustness and stability

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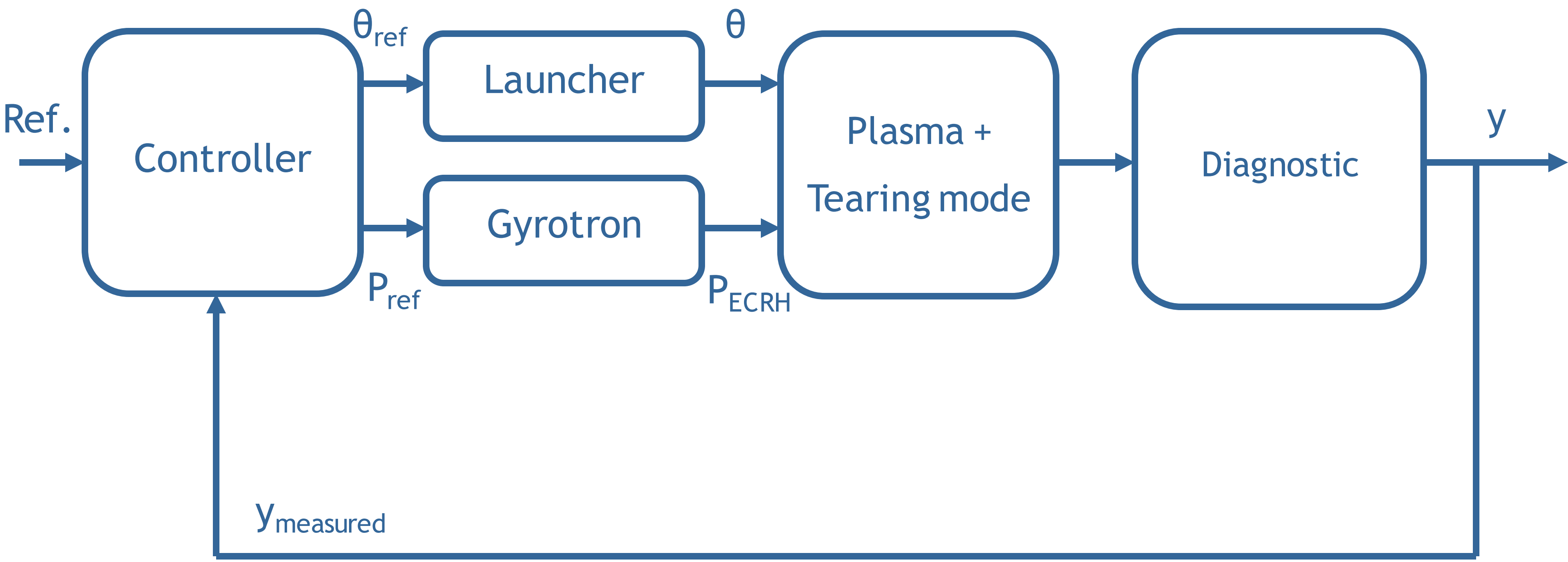
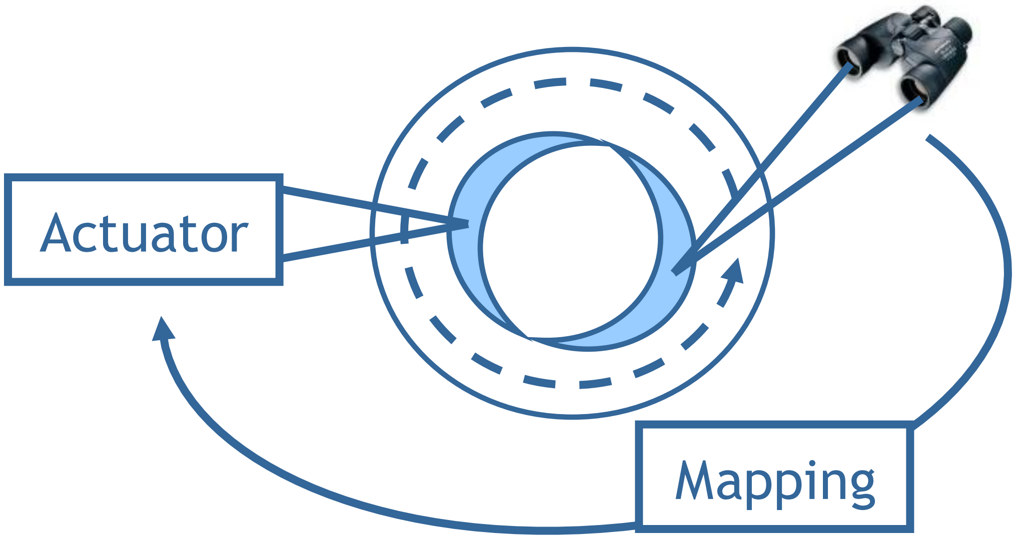


Feedback control of tearing modes

- In general, tearing mode control systems use:
  - Mapping between ECRH/ECCD actuator & diagnostics
  - Equilibrium reconstruction/estimation + beam tracing codes in feedback loop



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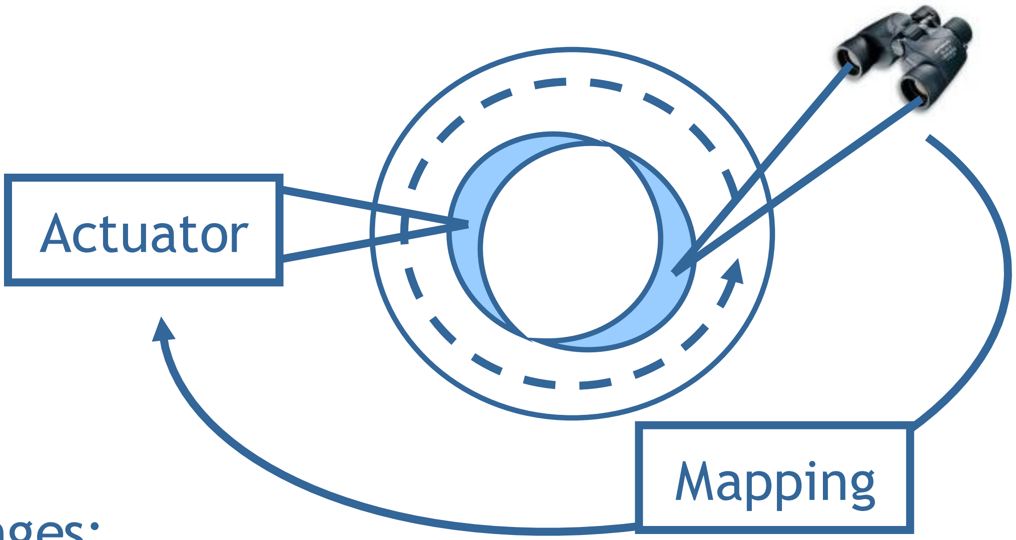

- Disadvantages:
  - Mapping introduces errors in control loop
  - Accurate calibration of actuator & sensor orientation required

(loss of orientation = loss of control)

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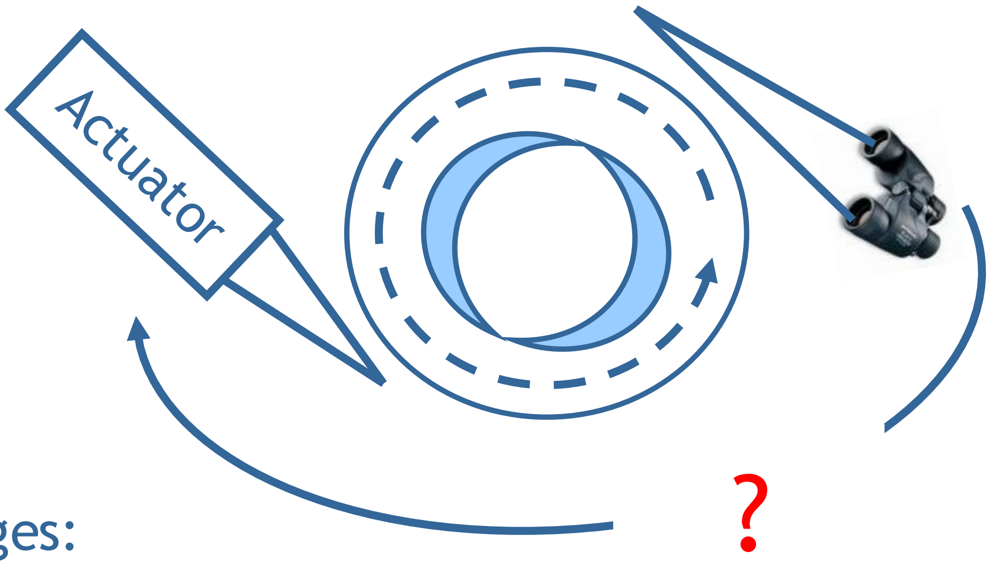

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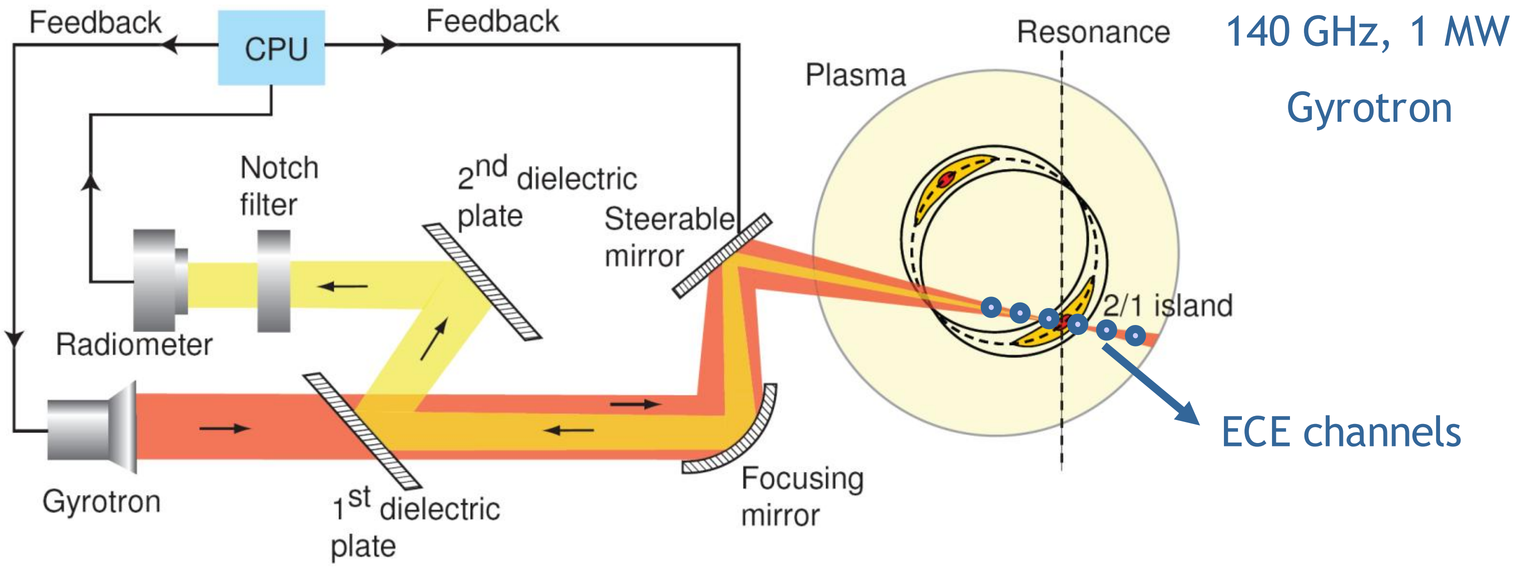
Feedback control of tearing modes

- Alternative: “line-of-sight principle”

→ *Use ECE diagnostic as feedback sensor in sight-line of ECRH/ECCD beam*



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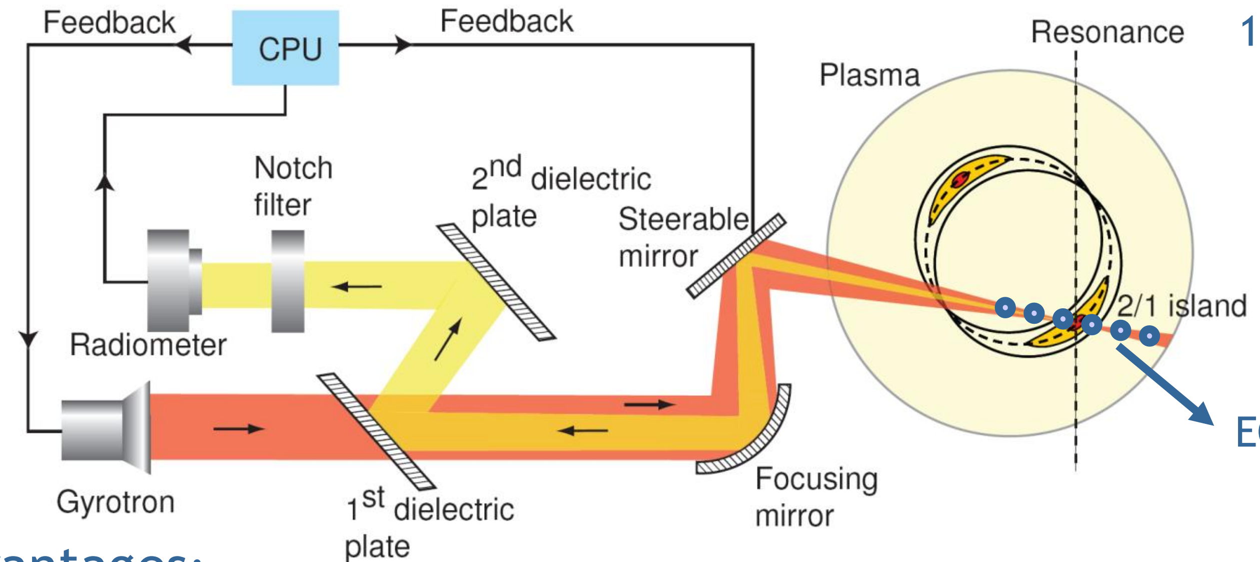

140 GHz, 1 MW Gyrotron

ECE channels

- Advantages:

- Actuator and sensor are always aligned (refractive properties identical)

- Guarantees tearing mode control even when launcher orientation is perturbed or calibration is lost

- Sensor is placed ‘far away’ from plasma (single access port needed)

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Feedback control of tearing modes

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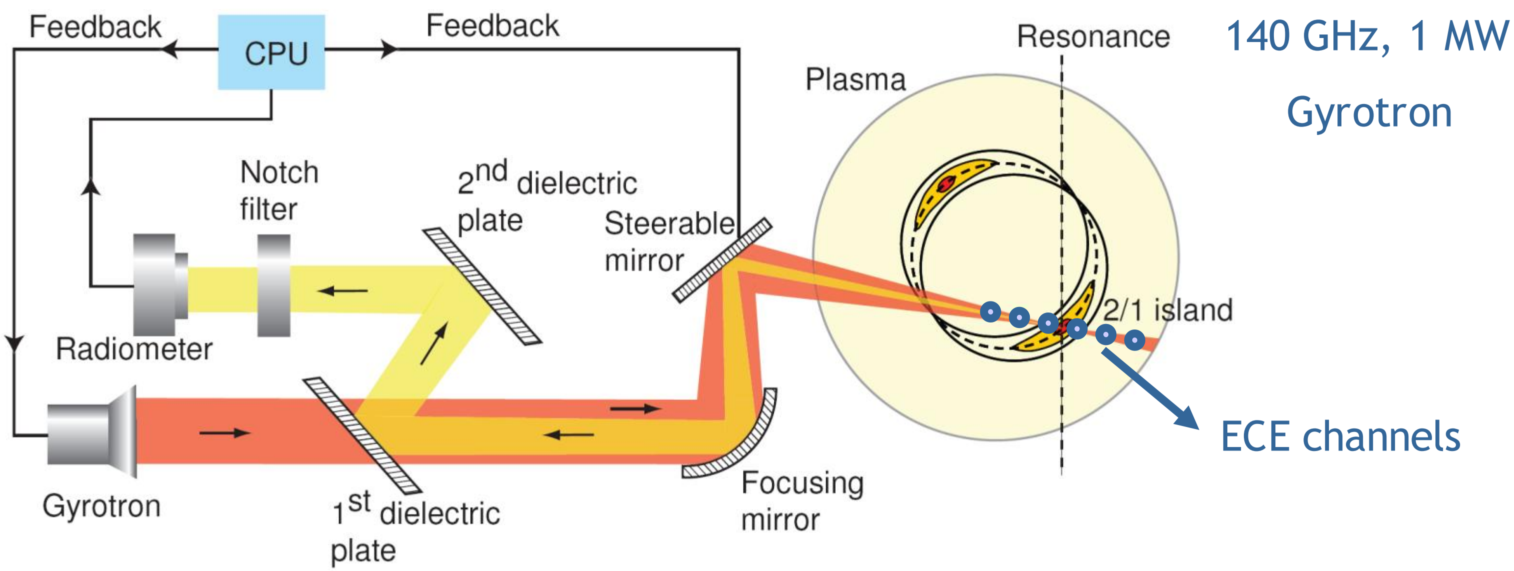


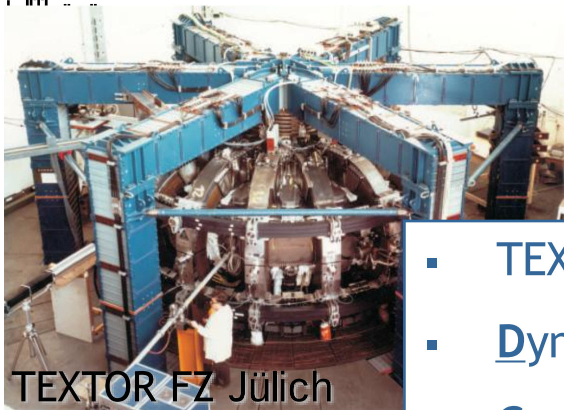
- Implementation in quasi-optical ECRH/ECCD transmission line on TEXTOR:

  - Radiometer: 6 channels, 132.5-147.5 GHz, 3 GHz spacing ~ 3 cm radial spacing

  - Frequency selective directional couplers separate **ECE** from **ECRH/ECCD**

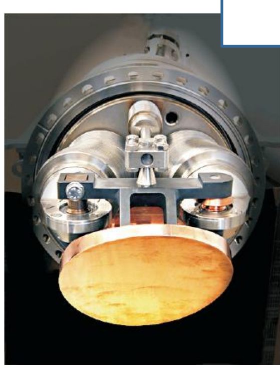
    (nW power versus MW power)

Experimental instrumentation

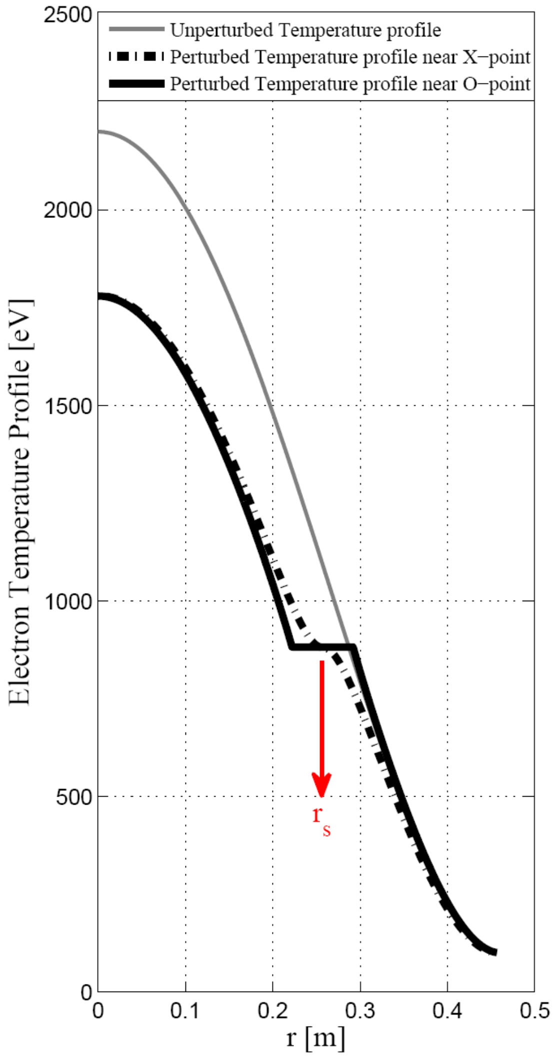


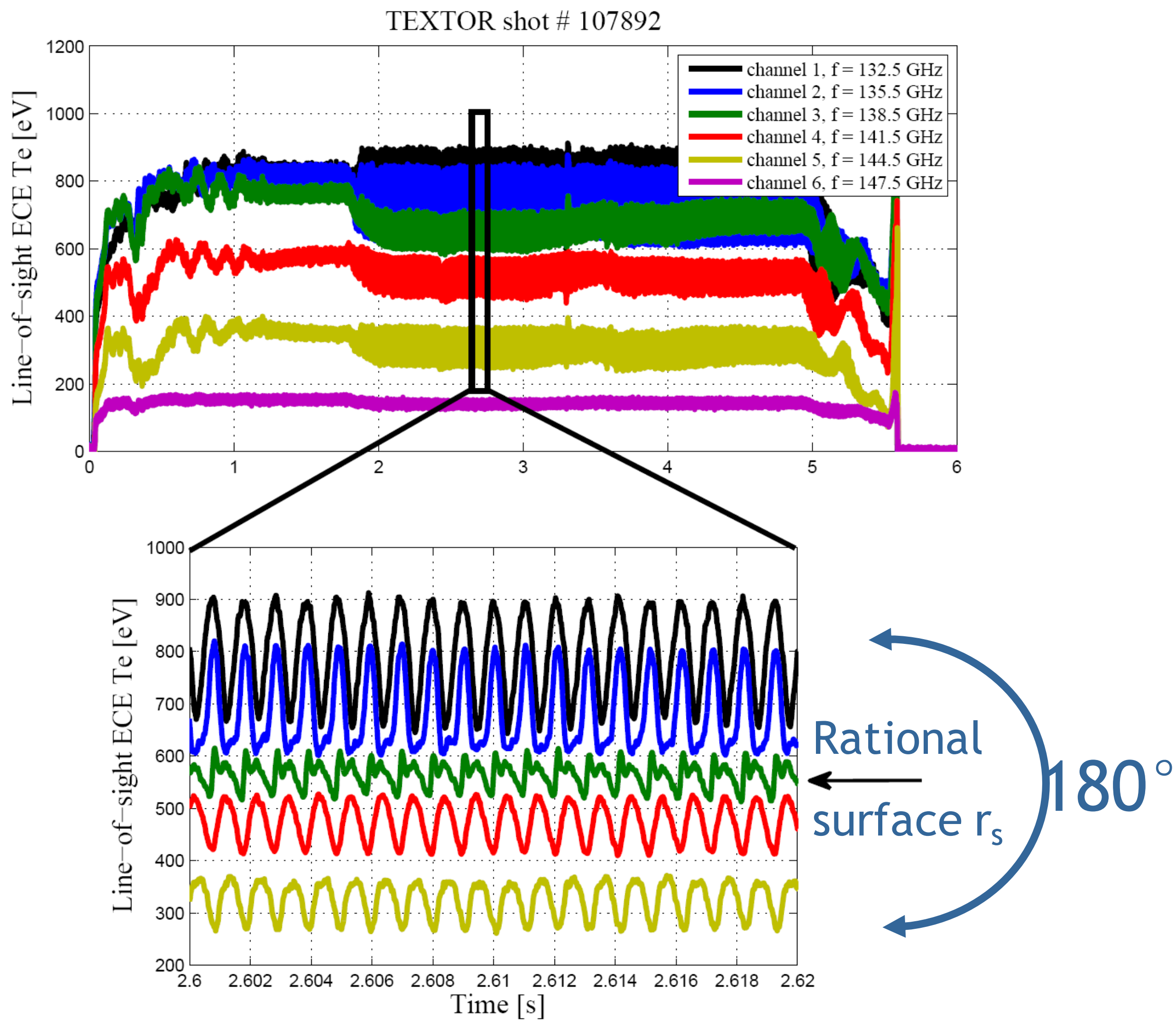
- TEXTOR (R = 1.75 m , a = 0.46 m)
- <u>D</u>ynamic <u>E</u>rgodic <u>D</u>ivertor (perturbation field)
- Gyrotron 140 GHz, 1 MW, 10 s
- Bi-directional, steerable launcher (tor. & pol.)
- Line-of-sight ECE diagnostic
- National Instruments DAQ & RT control system

  (Labview based, DAQ & <u>F</u>ield <u>P</u>rogrammable <u>G</u>ate <u>A</u>rray: sampling rate 100 kHz)



Real-time tearing mode identification





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Real-time tearing mode identification

- Real time tearing mode detection from correlation between ECE fluctuations (*algorithm implemented on FPGA*):

"Compute normalized correlation between ECE channels and apply weighted average over all possible channel combinations"

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Channel pair with 180° phase reversal

=

$f_{EC,\ tearing\ mode}$ GHz

"Mode location is resolved in real-time as frequency $f_{EC,\ tearing\ mode}$ GHz in ECE spectrum using weighted ECE correlations"

Real-time tearing mode identification

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"Compute normalized correlation between ECE channels and apply weighted average over all possible channel combinations"

Channel pair with 180° phase reversal

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$f_{EC,\ tearing\ mode}$ GHz

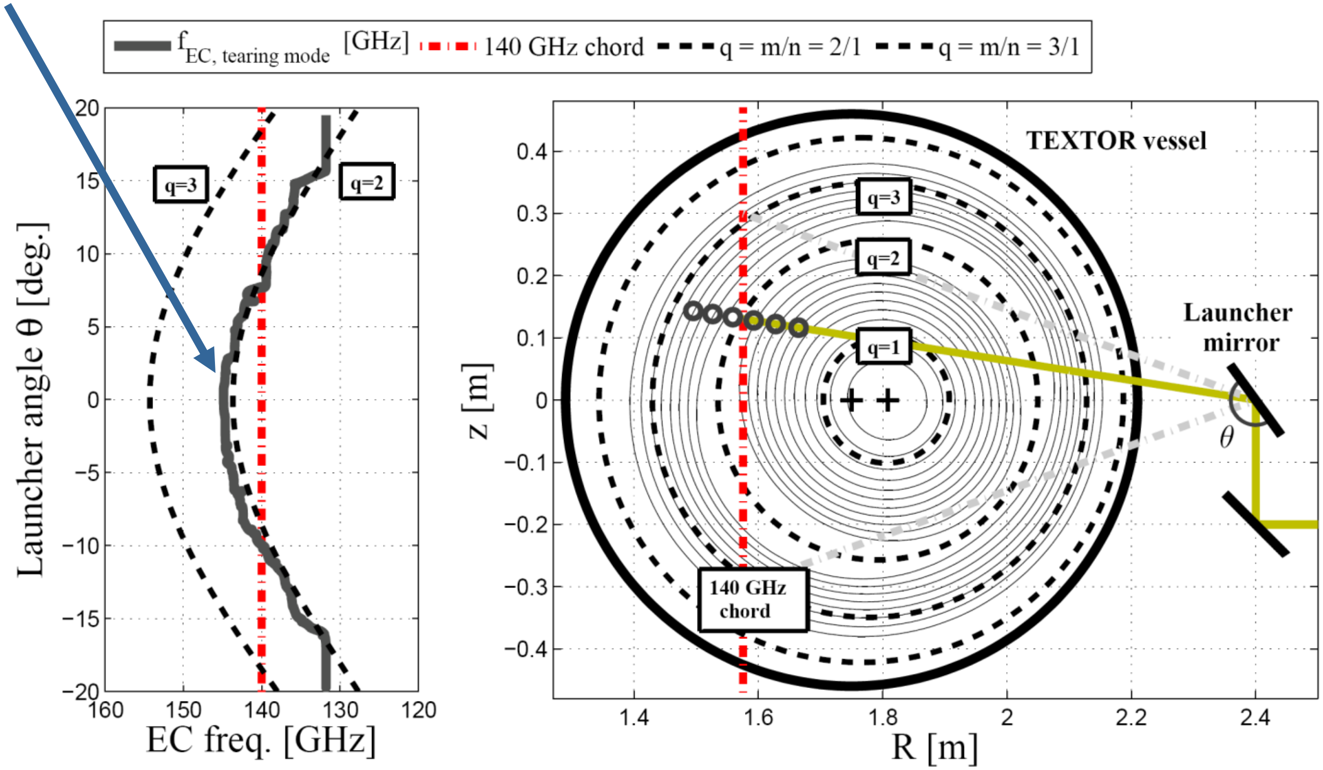
Clock-rate computation on FPGA:

16 μs

" Mode location is resolved in real-time as frequency $f_{EC,\ tearing\ mode}$ GHz in ECE spectrum using weighted ECE correlations"

Real-time tearing mode identification (Example)

☑ **2/1 magnetic island location determined from ECE during a launcher scan**

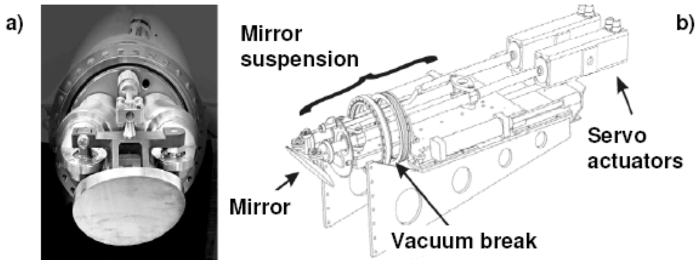


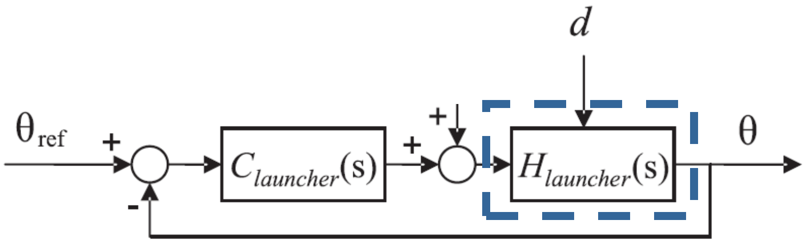
☑ **Alignment of ECRH deposition with magnetic island in feedback loop:**

Match actuator frequency of 140 GHz with $f_{EC,\ magnetic\ island}$ GHz through launcher steering (elevation angle θ)

Real-time control loop

- Launcher control loop
  - Analysis launcher dynamics using Frequency Response Function measurement $H_{launcher}(s)$





Real-time control loop

- Launcher control loop
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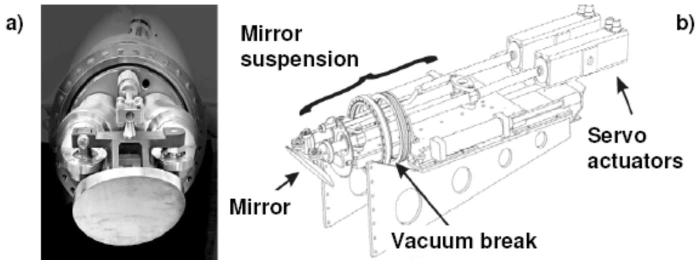
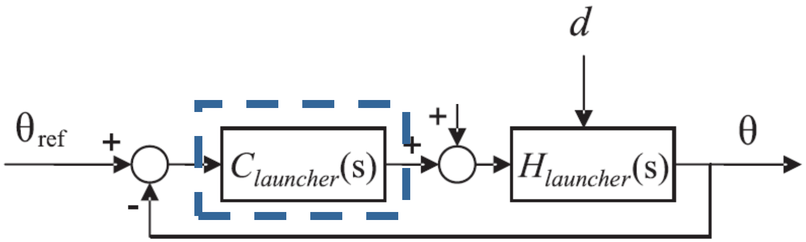
  - $C_{launcher}(s)$ = PID controller + lead/lag + low-pass filter





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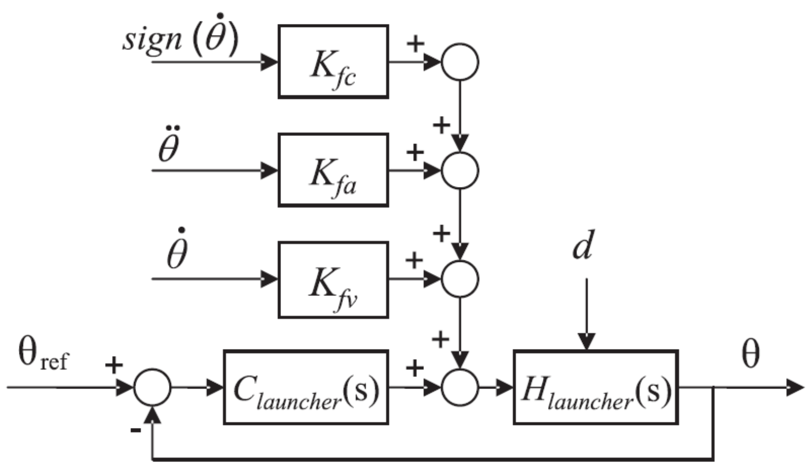

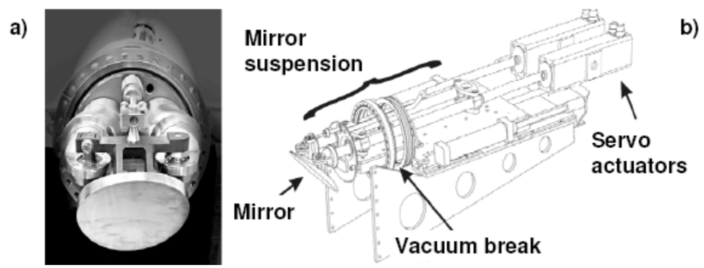

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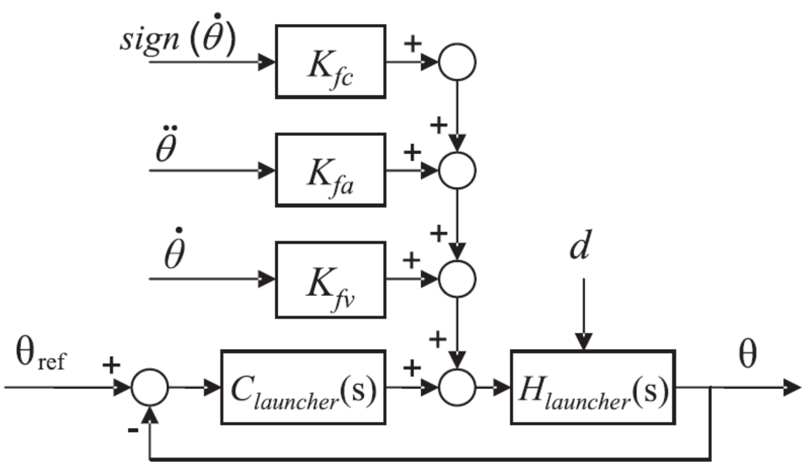

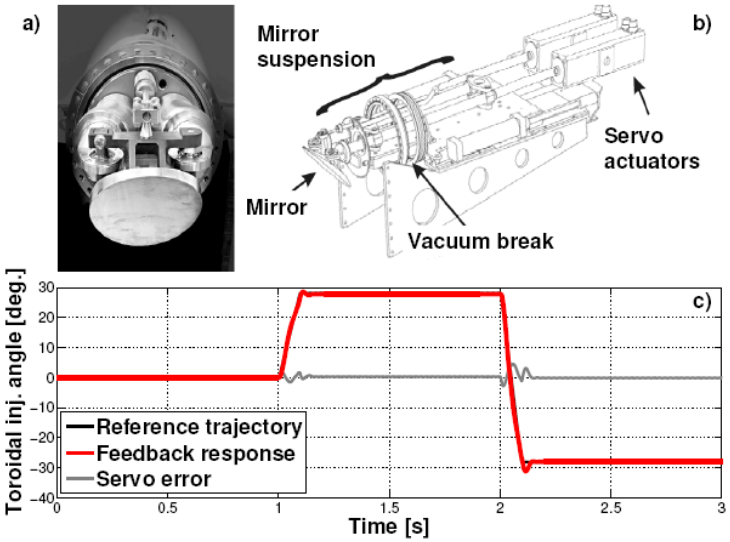

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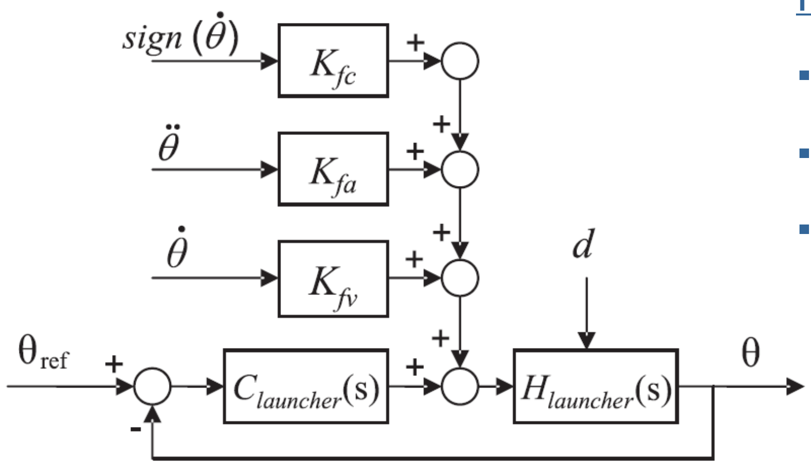
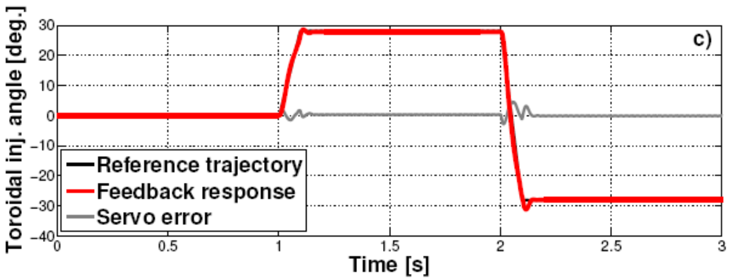


Performance:

- Response: $\theta = \pm\ 30°$ in 100 ms
- Max. steady-state positioning error: 0.6°
- Bandwidth: 12 Hz



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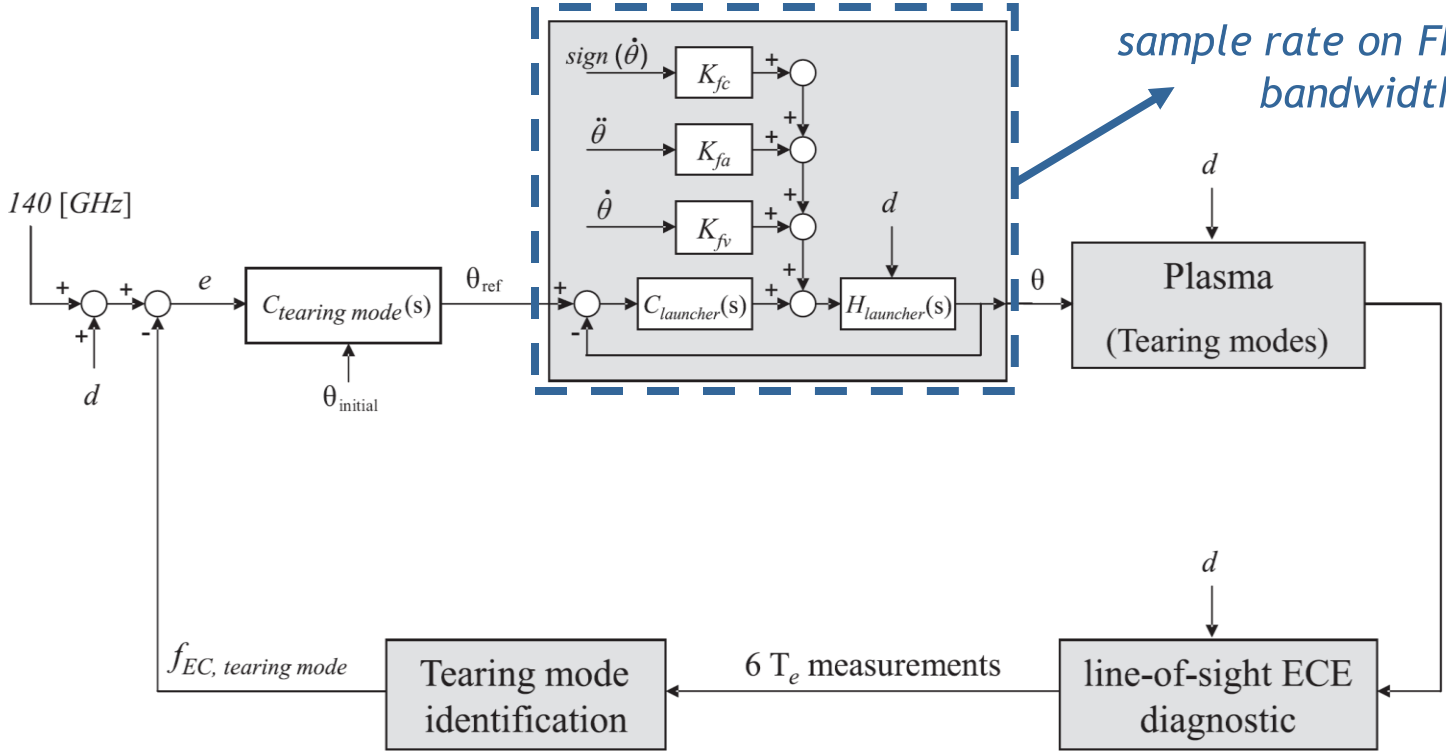
Real-time control loop

- Tearing mode "tracking" loop

Launcher control loop:

sample rate on FPGA: 5 kHz, bandwidth: 12 Hz



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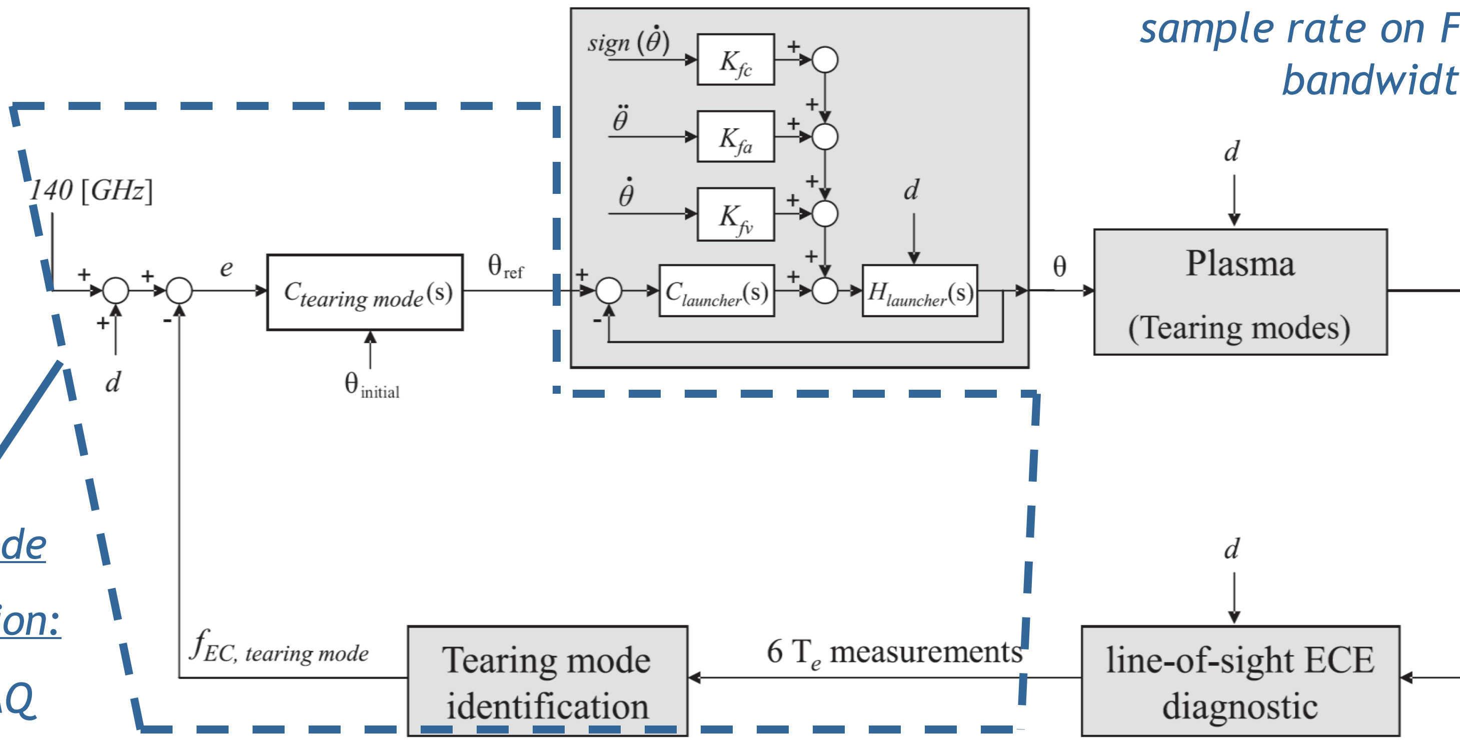


Tearing mode identification:

100 kHz DAQ

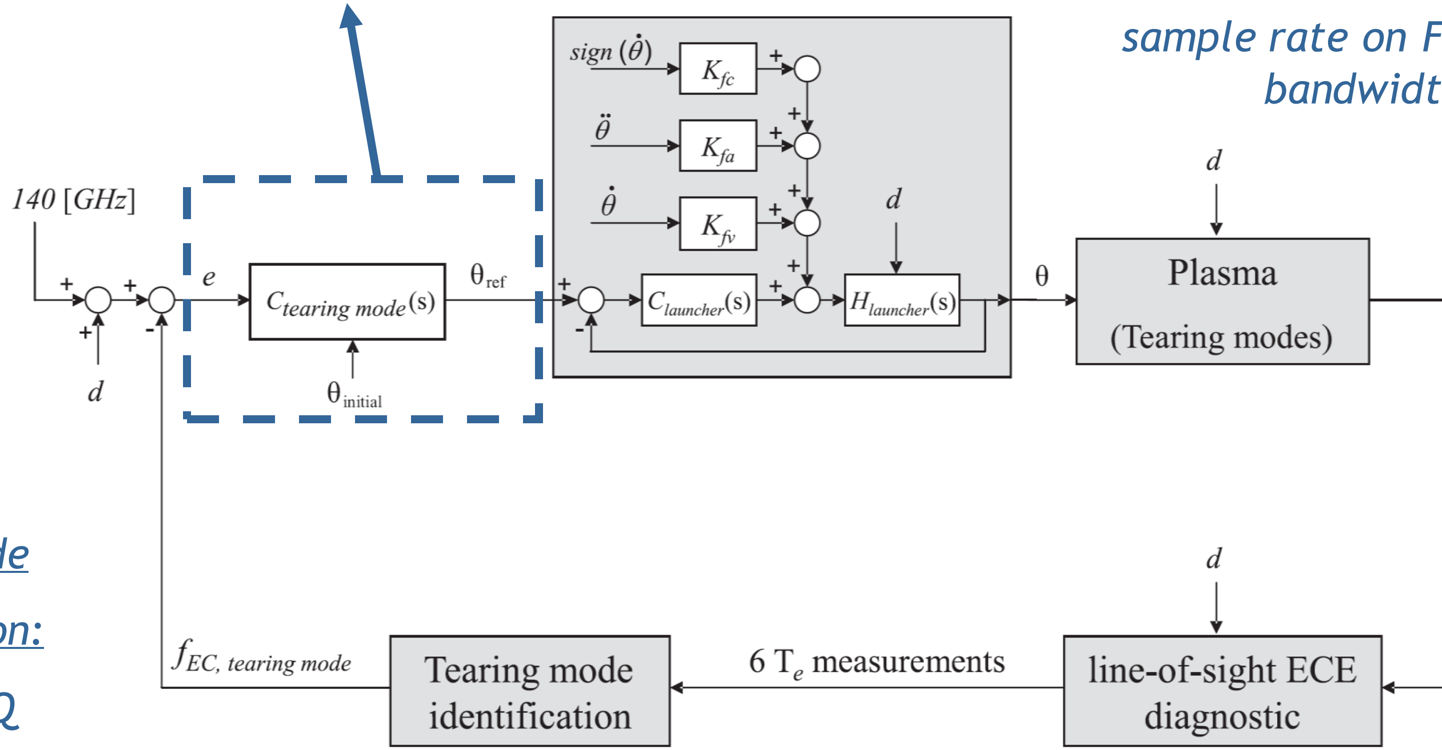
clock rate identification algorithm on FPGA: 16 μs

Real-time control loop

- Tearing mode "tracking" loop
  - Minimize error: $e = 140 - f_{EC,\ \text{tearing mode}}$ [GHz]
  - $C_{\text{tearing mode}}(s)$ = PI controller + low-pass filter

Launcher control loop:

sample rate on FPGA: 5 kHz, bandwidth: 12 Hz



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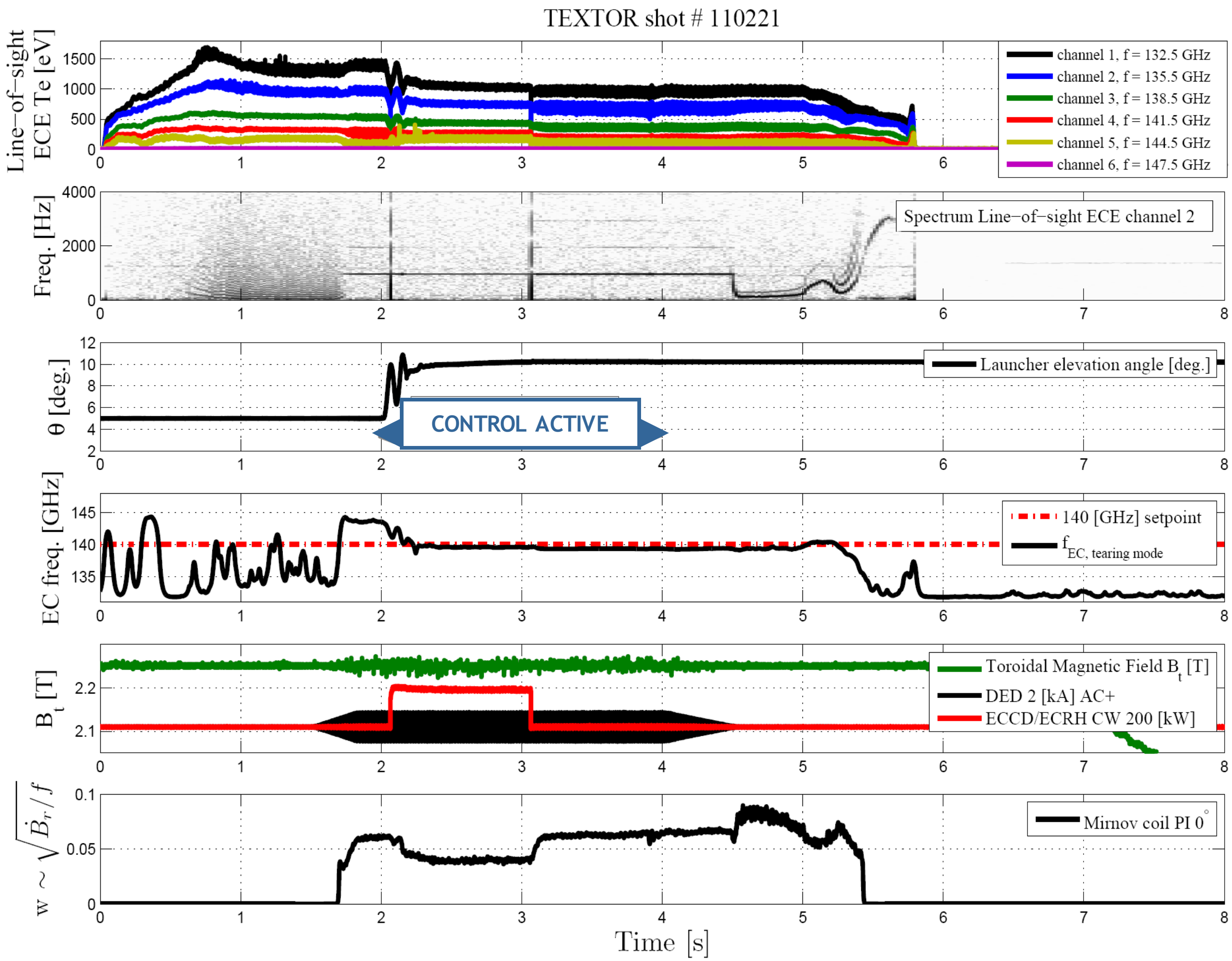
Experimental Results (1)

- 2/1 tearing mode **search-and-suppress**



- $\theta_{initial} = 5^{\circ}$
- $B_t = 2.25$ T
- $I_p = 300$ kA

- Continuous ECRH/ECCD 200 kW 1 sec.
- DED triggered
- m/n = 2/1 mode

- Controller active from t = 2-4 sec.
- Automatic trigger gyrotron

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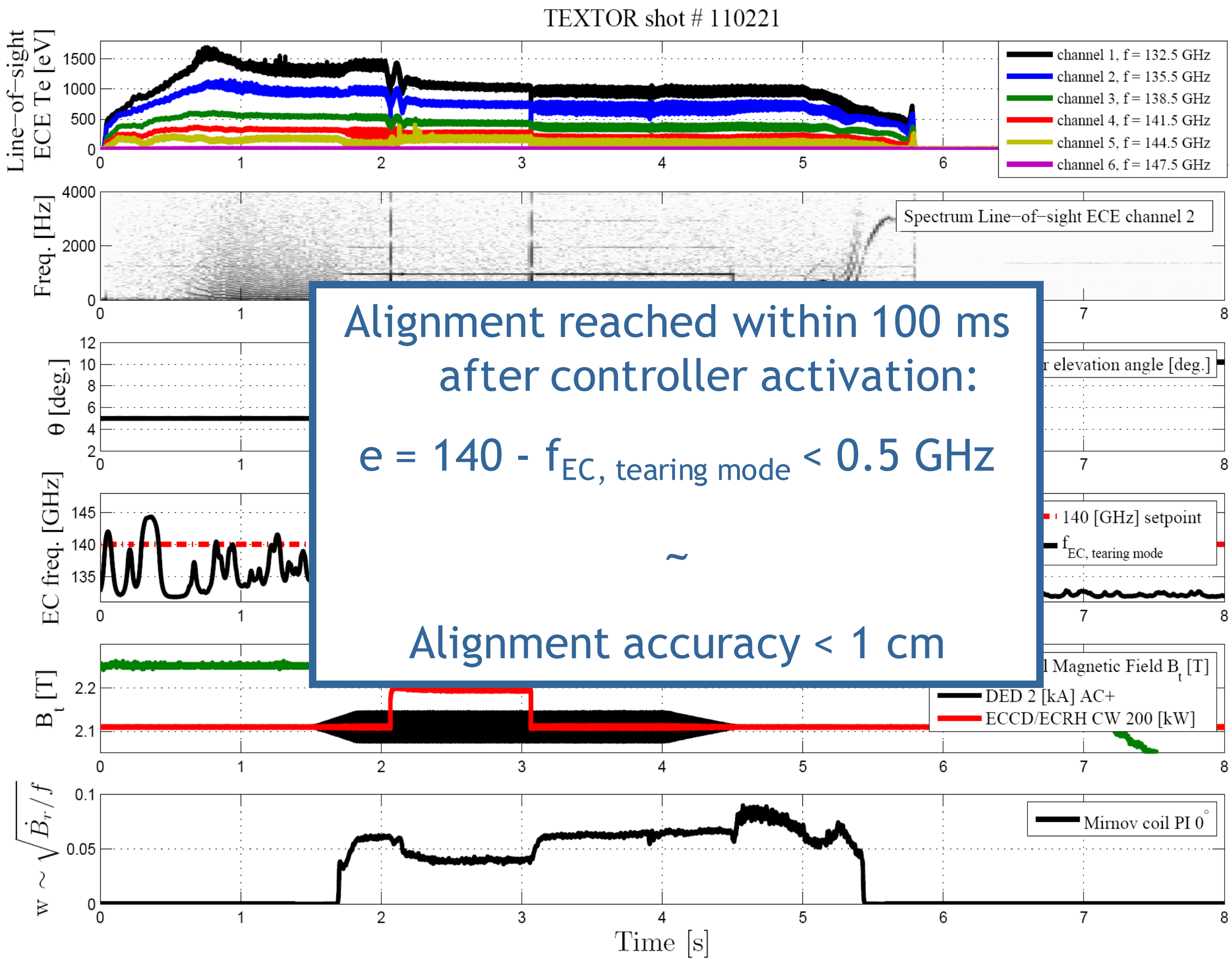

Alignment reached within 100 ms after controller activation:

$e = 140 - f_{EC,\ tearing\ mode} < 0.5$ GHz

~

Alignment accuracy < 1 cm

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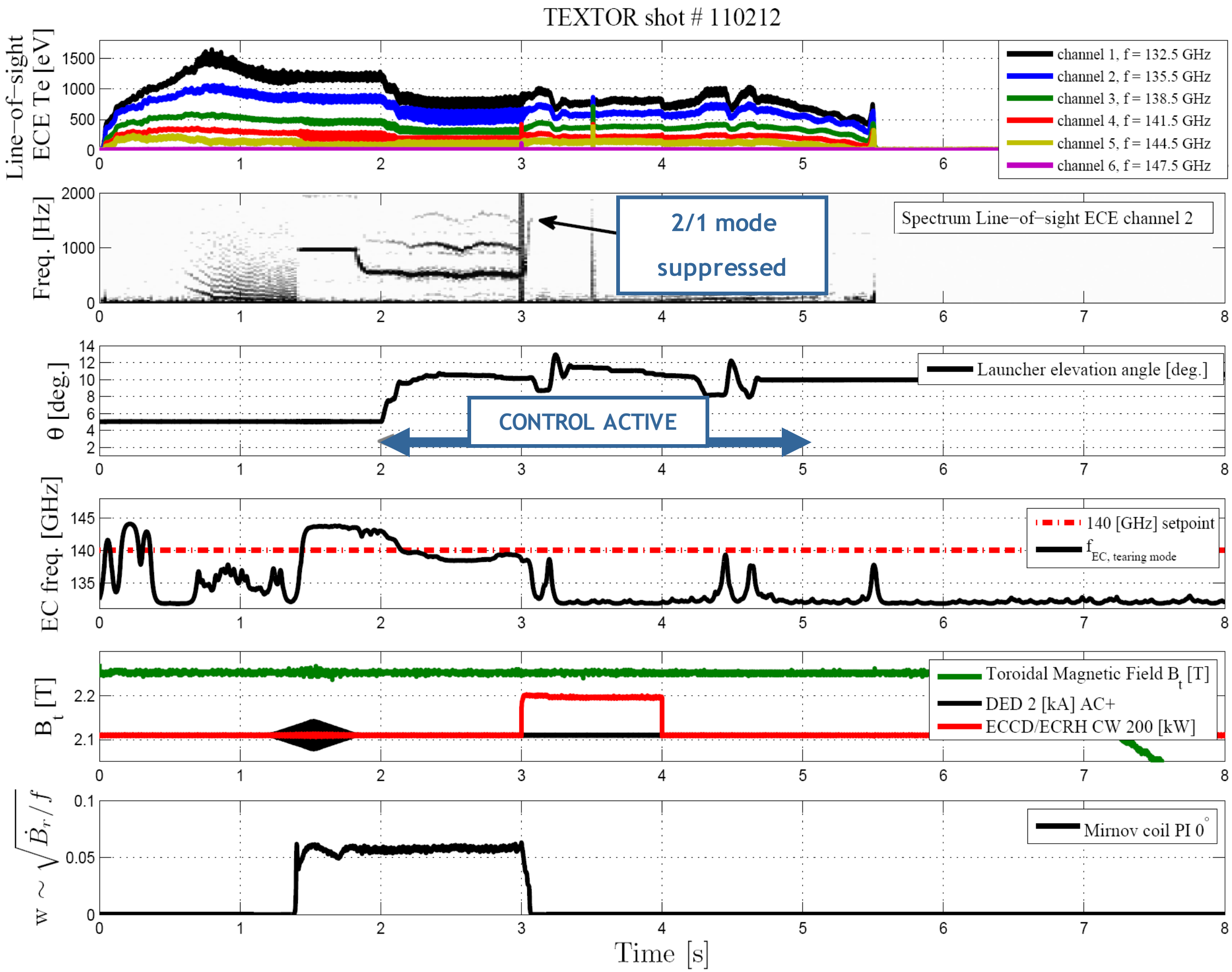
Experimental Results (2)

- 2/1 tearing mode **complete suppression**



- $\theta_{initial} = 5^\circ$
- $B_t = 2.25$ T
- $I_p = 300$ kA

- Continuous ECRH/ECCD 200 kW t = 3-4 sec.
- DED triggered
  m/n = 2/1 mode

- Controller active from t = 2-5 sec.
- Mode suppressed at t = 3.085 sec.

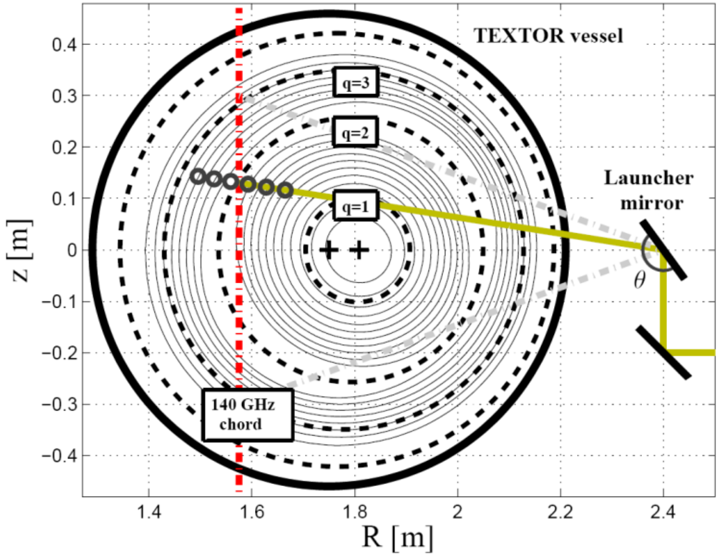
Experimental Results (3) - Intermezzo

Next: Tearing mode **tracking** experiment

Ramp in toroidal magnetic field B_t

→

Mimic change in tearing mode location



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Next: Tearing mode **tracking** experiment

Ramp in toroidal magnetic field B_t

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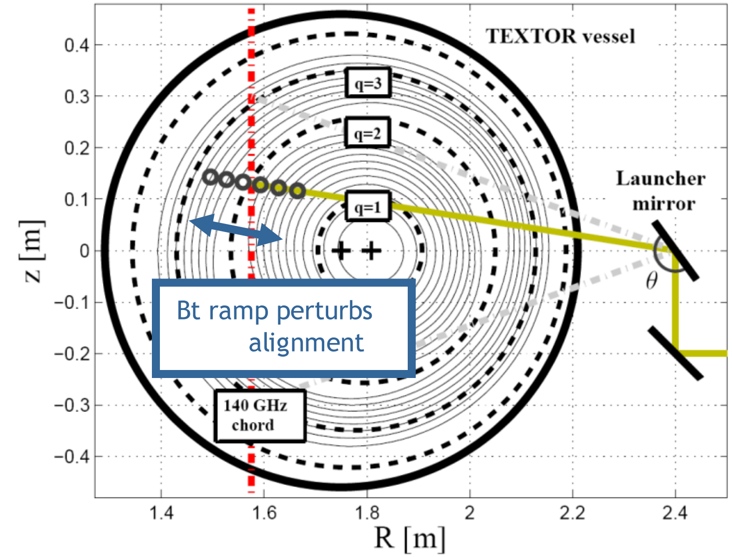
Mimic change in tearing mode location

(*ECRH/ECCD deposition location and r_s perturbed*)



- B_t = 2.25-2.35 T
- I_p = 300 kA

→

- 7 cm shift ECRH/ECCD deposition
- 0.5 cm shift r_s
- launcher should move ~ 6° up

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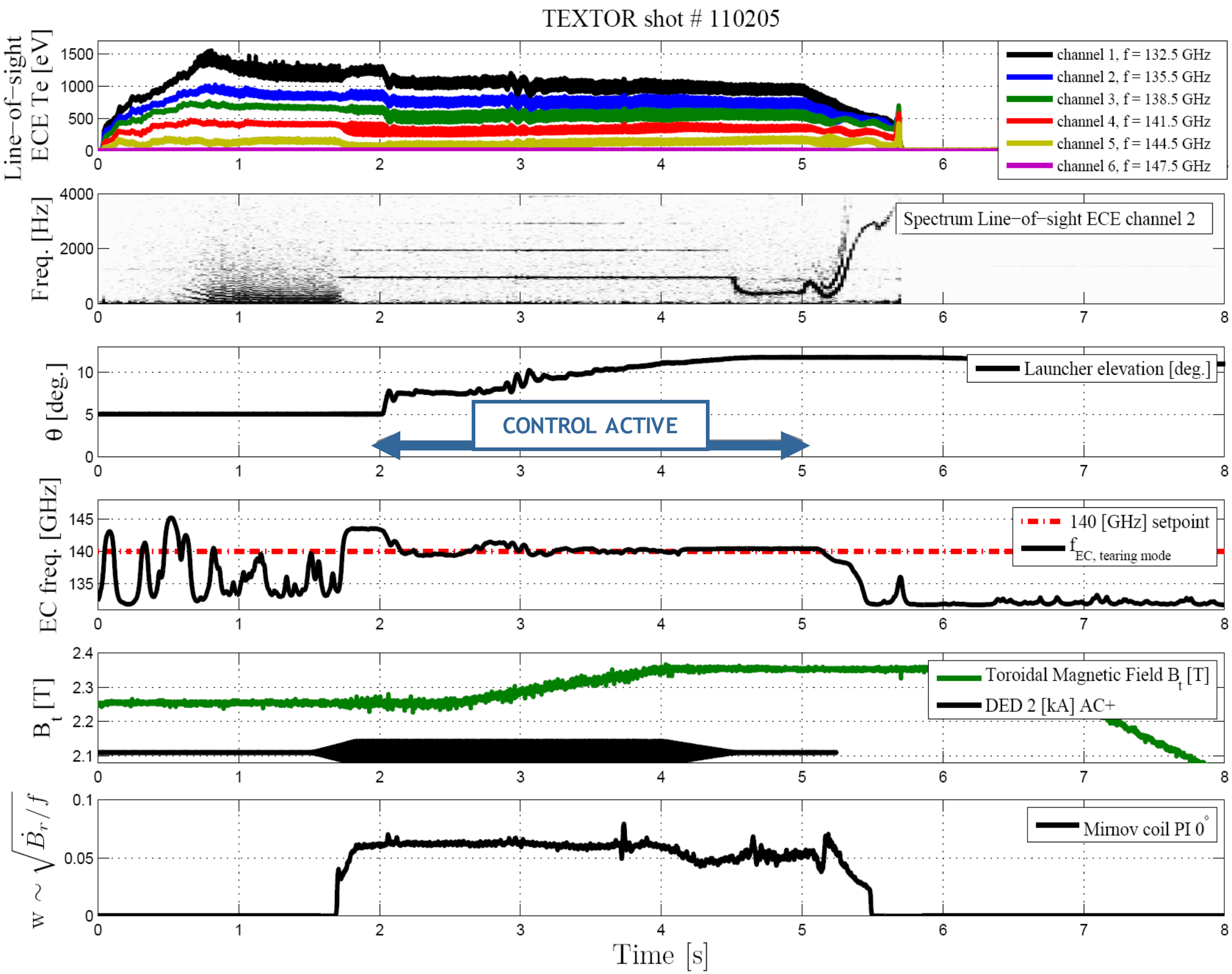
Experimental Results (3)

- 2/1 tearing mode tracking experiment



- $\theta_{initial} = 5^\circ$
- $B_t = 2.25\text{-}2.35$ T
- $I_p = 300$ kA

- No ECRH/ECCD
- DED triggered
  m/n = 2/1 mode

- Controller active from t = 2-5 sec.
- Alignment maintained during Bt ramp

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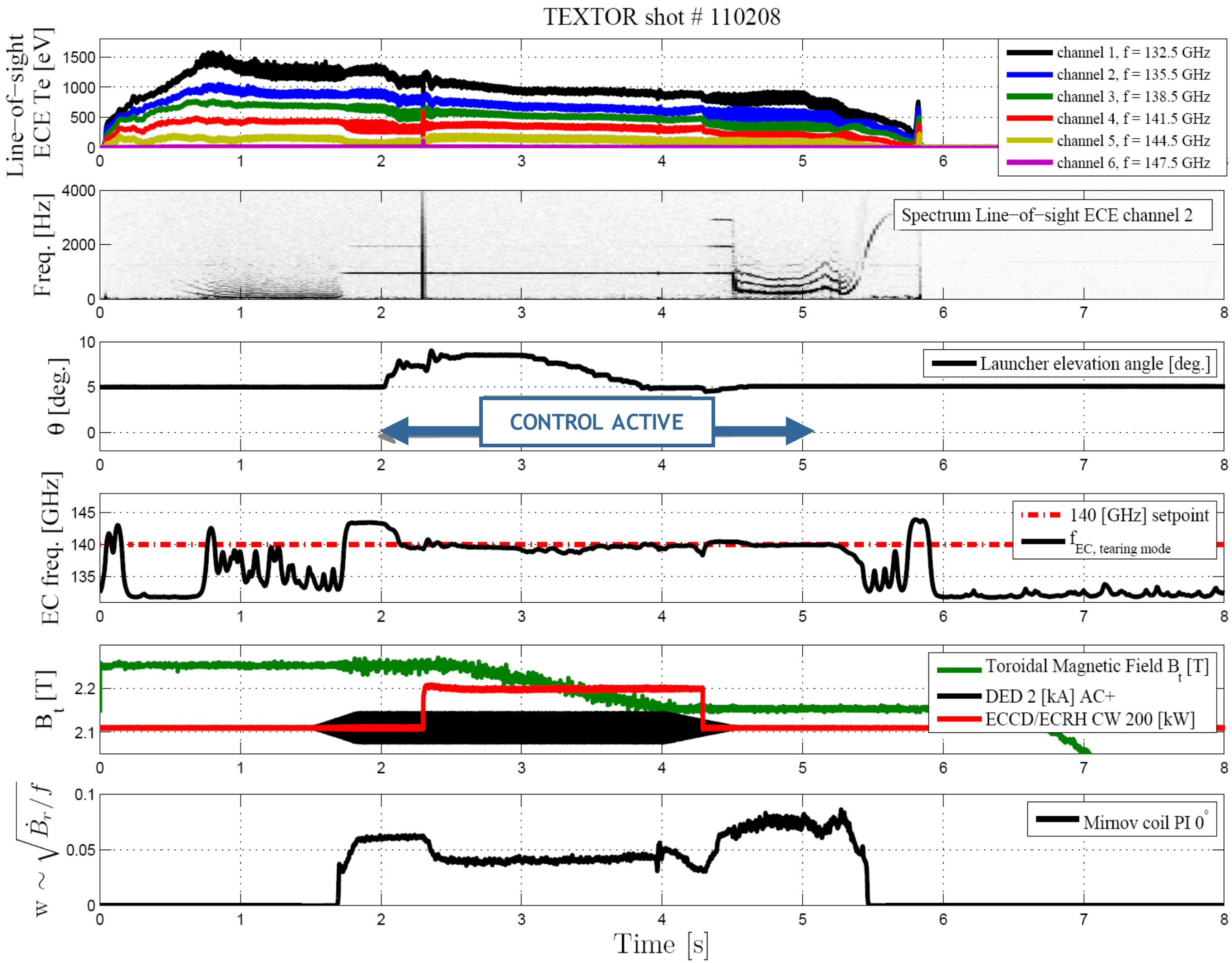
Experimental Results (4)

- 2/1 tearing mode tracking experiment



- $\theta_{initial} = 5^{\circ}$
- B_t = 2.25-2.15 T
- I_p = 300 kA

- Continuous ECRH/ECCD 200 kW t = 2.3-4.3 sec.
- DED triggered m/n = 2/1 mode

- Controller active from t = 2-5 sec.
- Alignment maintained during Bt ramp

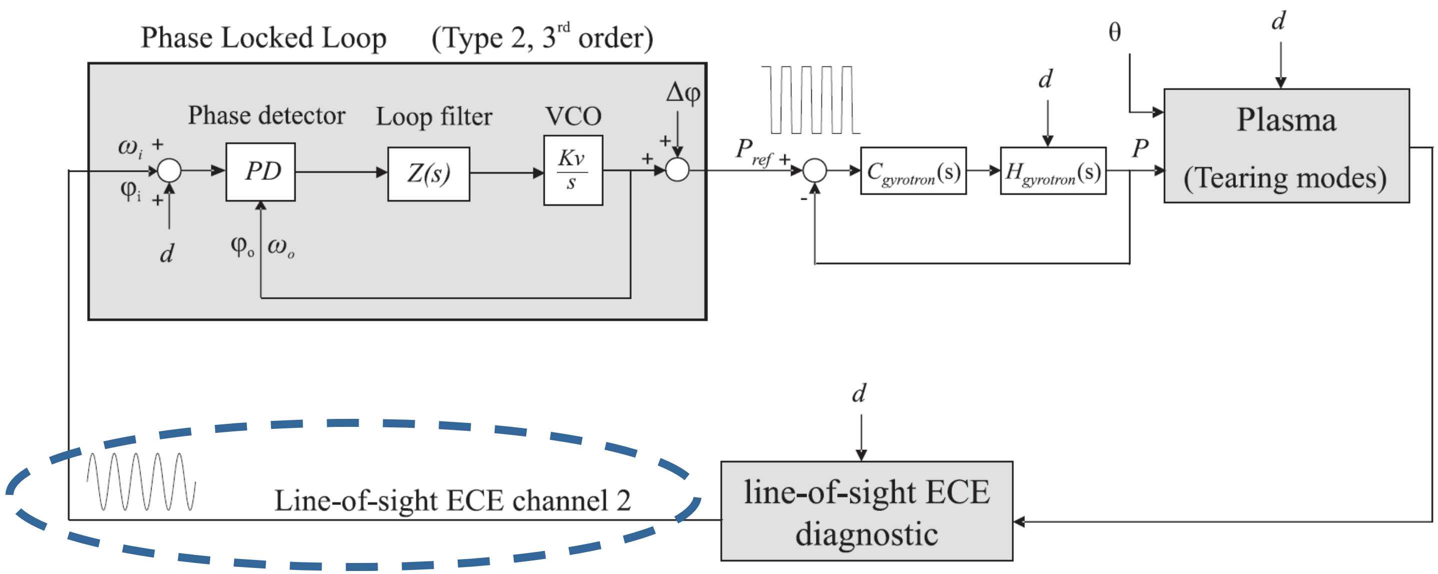
Real-time control loop

- Phase Locked Loop (synchronous ECRH/ECCD modulation on O-point)

Input PLL:

Line-of-sight ECE signal
(e.g. 2nd channel: 135.5 GHz)

- Monitor tearing mode's frequency and phase



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Real-time control loop

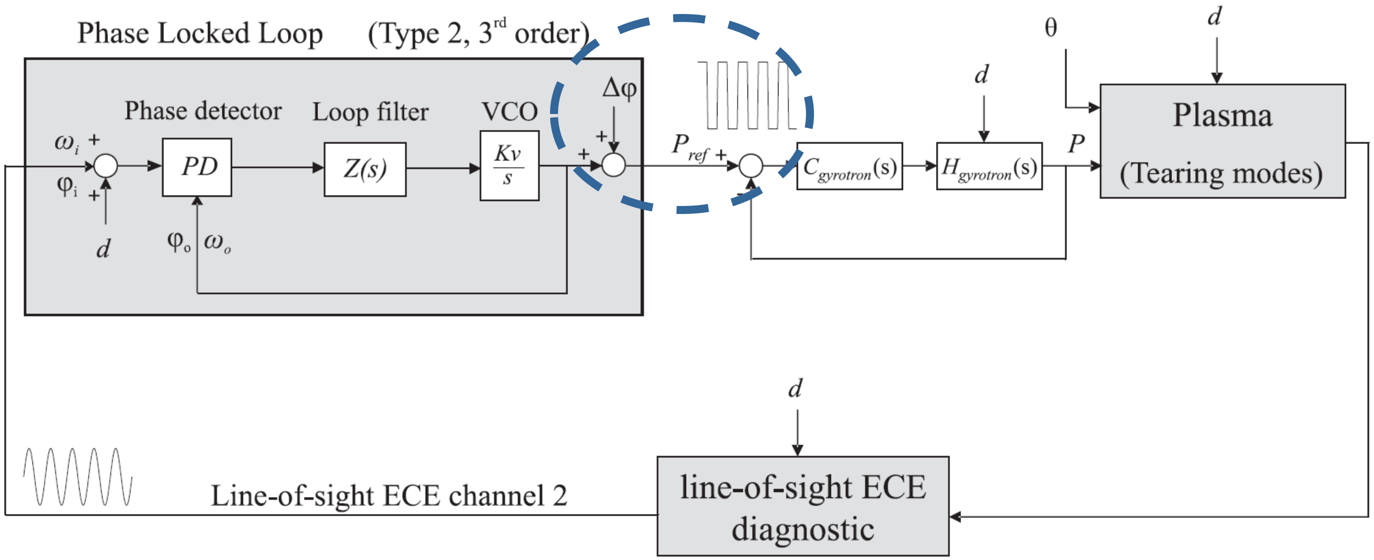
- <u>P</u>hase <u>L</u>ocked <u>L</u>oop (synchronous ECRH/ECCD modulation on O-point)

Input PLL:

Line-of-sight ECE signal
(e.g. 2nd channel: 135.5 GHz)

Output PLL:

Block-wave with controlled frequency & phase
(maintains 90° phase difference relative to
1st harmonic of noisy ECE input signal)



Real-time control loop

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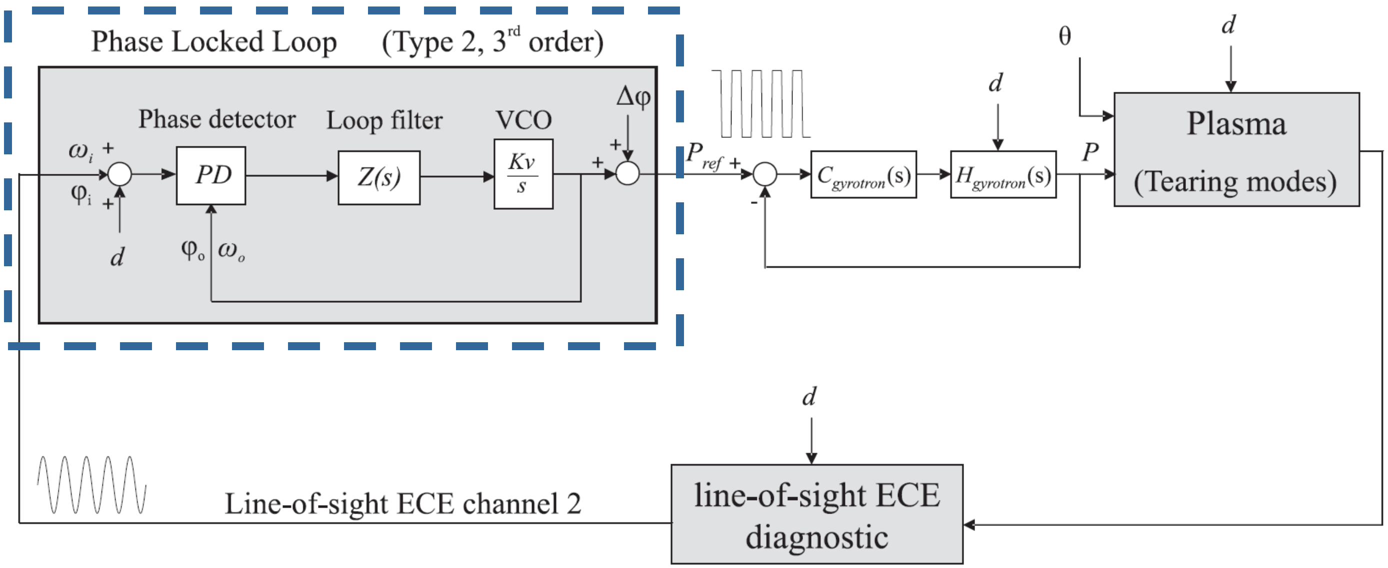
Input PLL:	Output PLL:
Line-of-sight ECE signal (e.g. 2nd channel: 135.5 GHz)	Block-wave with controlled frequency & phase (maintains 90° phase difference relative to 1st harmonic of noisy ECE input signal)

PLL: bandwidth: 150 Hz, operational domain: 300 Hz – 5 kHz



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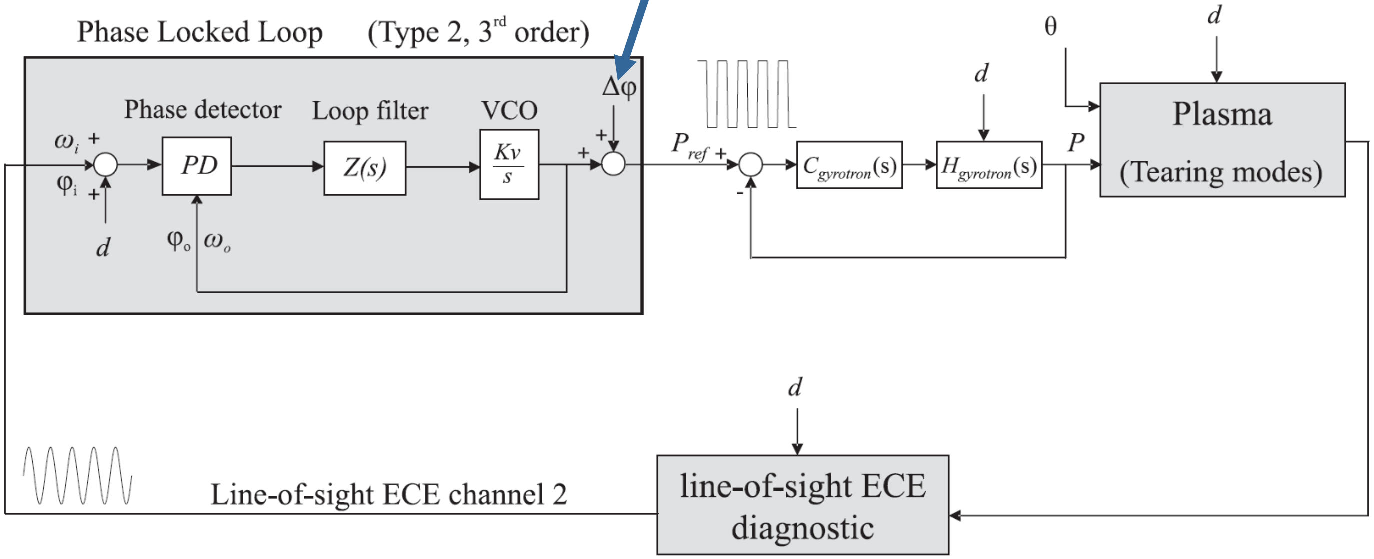
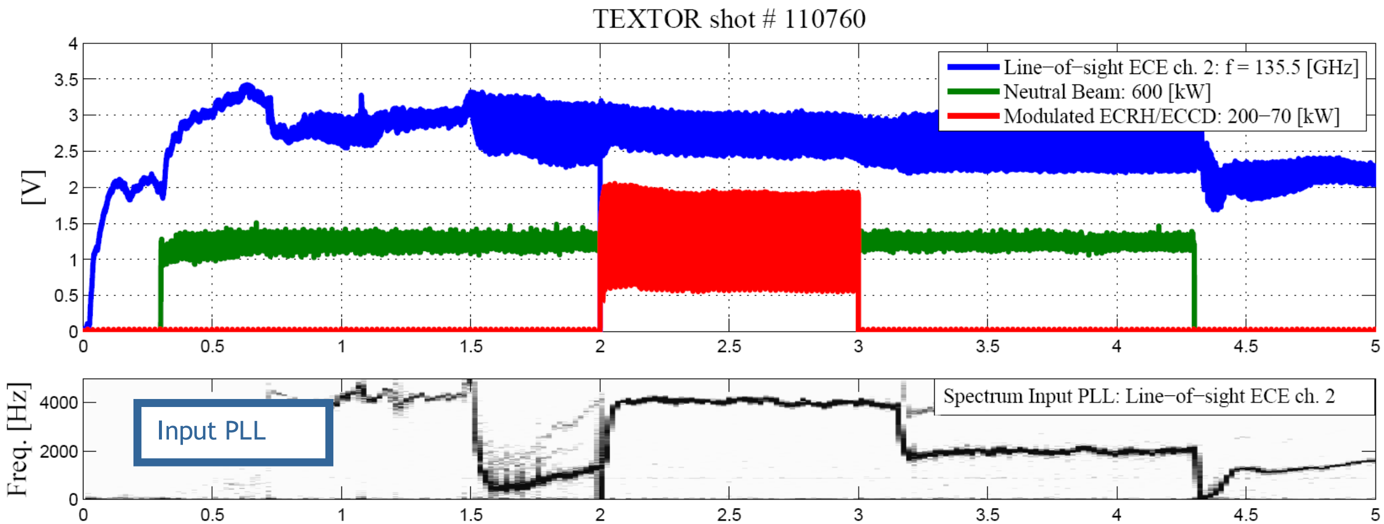
Note: focus on O-point by adding constant phase shift Δφ



Experimental Results (5)

- Synchronous ECRH/ECCD modulation on O-point



- $\theta_{fixed} = 10°$
- $B_t = 2.25$ T
- $I_p = 300$ kA

- Modulated ECRH/ECCD

  200 kW – 70 kW, t = 2-3 sec.
- Natural m/n = 2/1 mode
- Neutral Beam (co-direction) 600 kW

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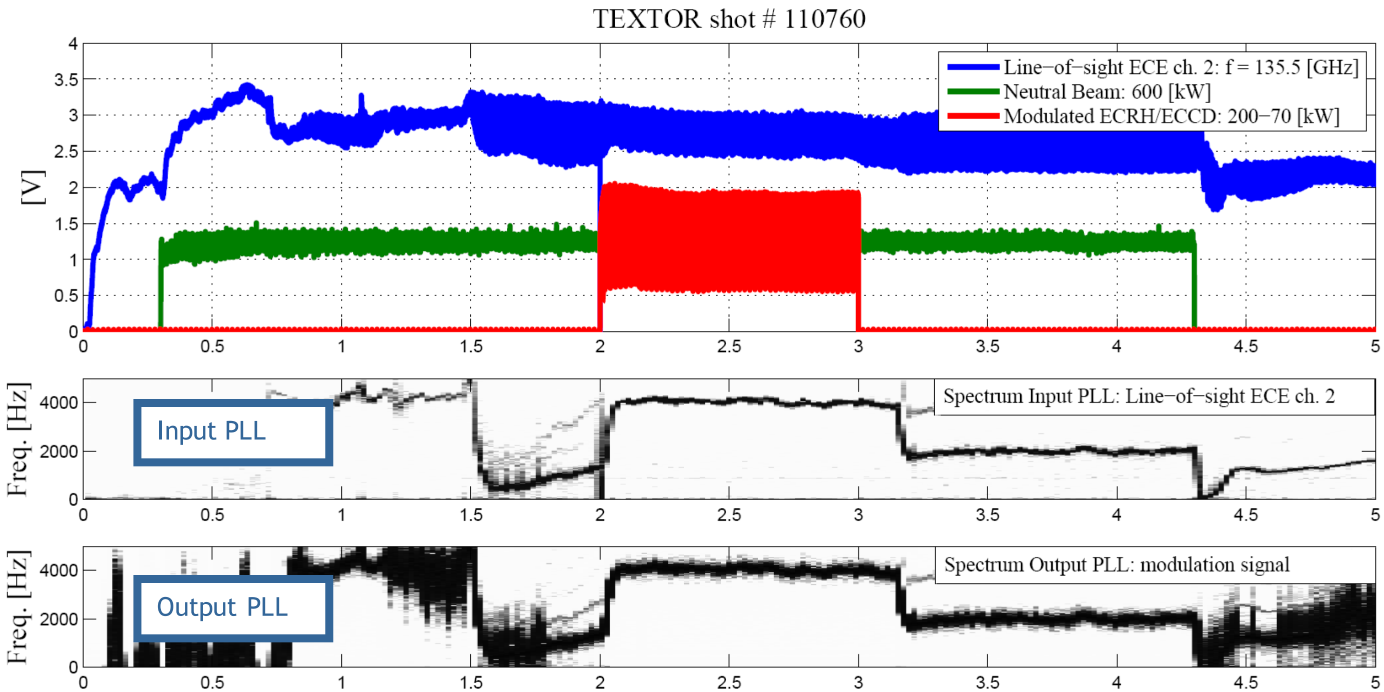
Experimental Results (5)

- Synchronous ECRH/ECCD modulation on O-point



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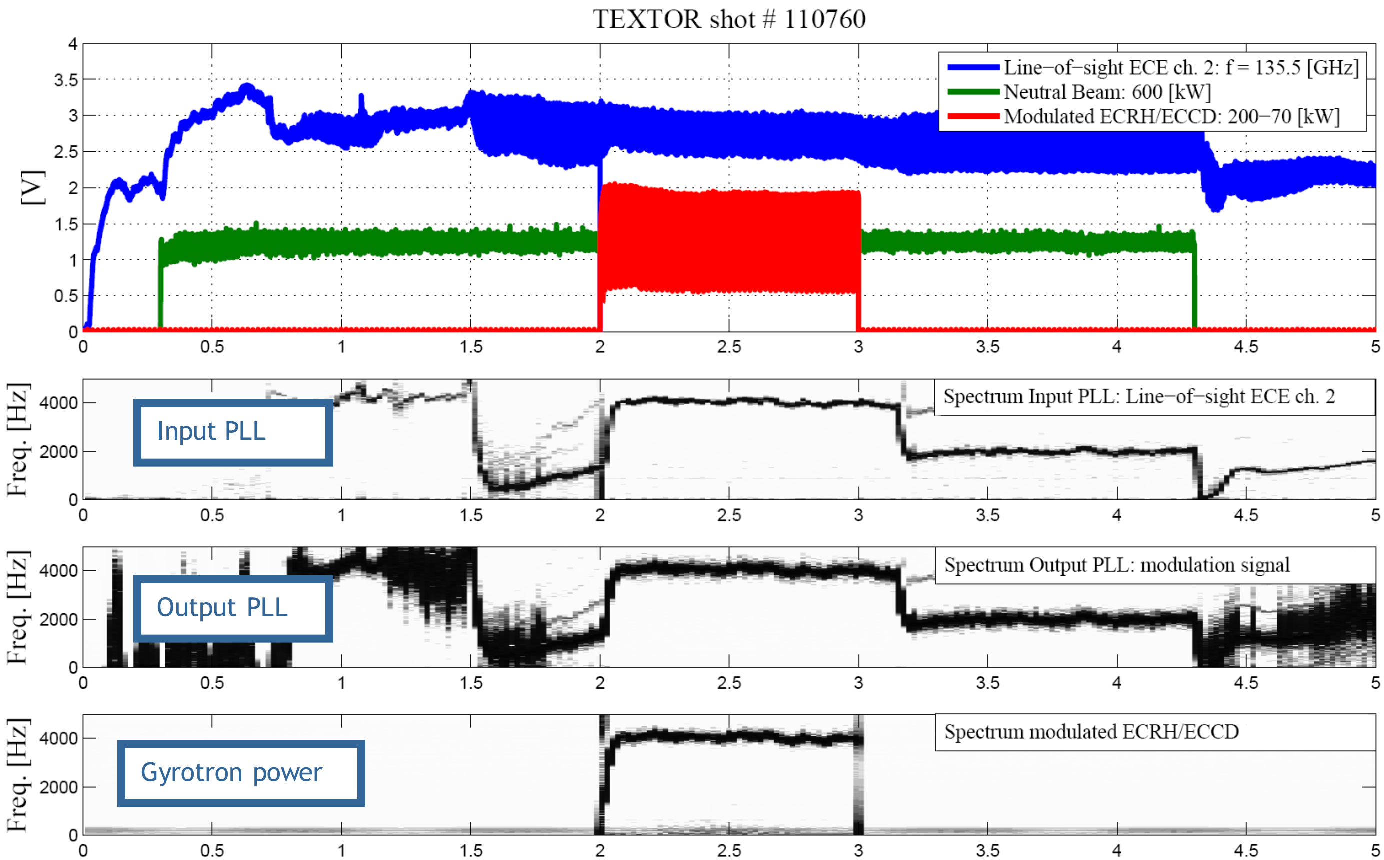
Experimental Results (5)

- Synchronous ECRH/ECCD modulation on O-point



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- Modulated ECRH/ECCD

  200 kW – 70 kW, t = 2-3 sec.
- Natural m/n = 2/1 mode
- Neutral Beam (co-direction) 600 kW

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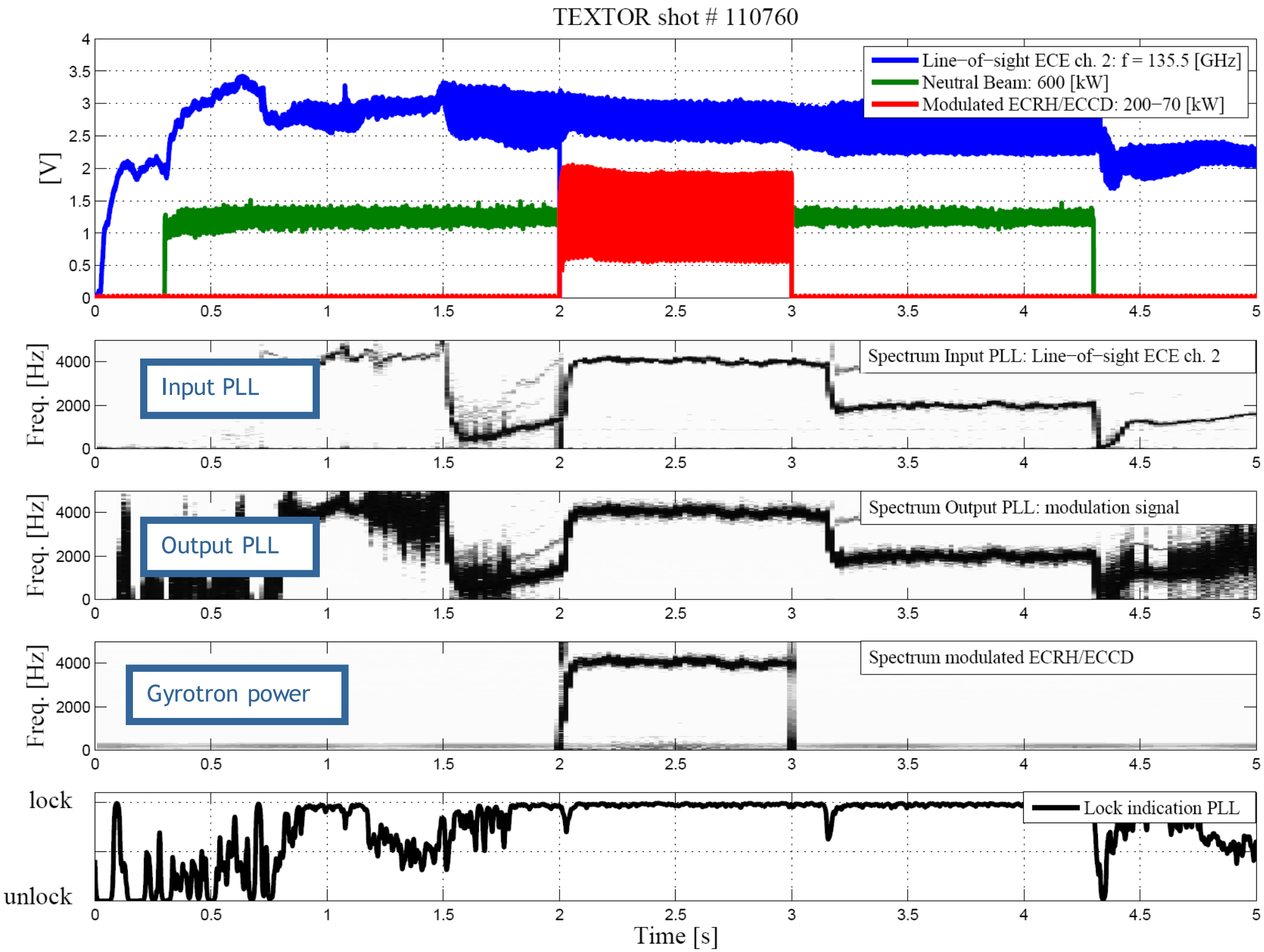
Experimental Results (5)

- Synchronous ECRH/ECCD modulation on O-point



- $\theta_{fixed} = 10°$
- $B_t = 2.25$ T
- $I_p = 300$ kA

- Modulated ECRH/ECCD

  200 kW – 70 kW, t = 2-3 sec.
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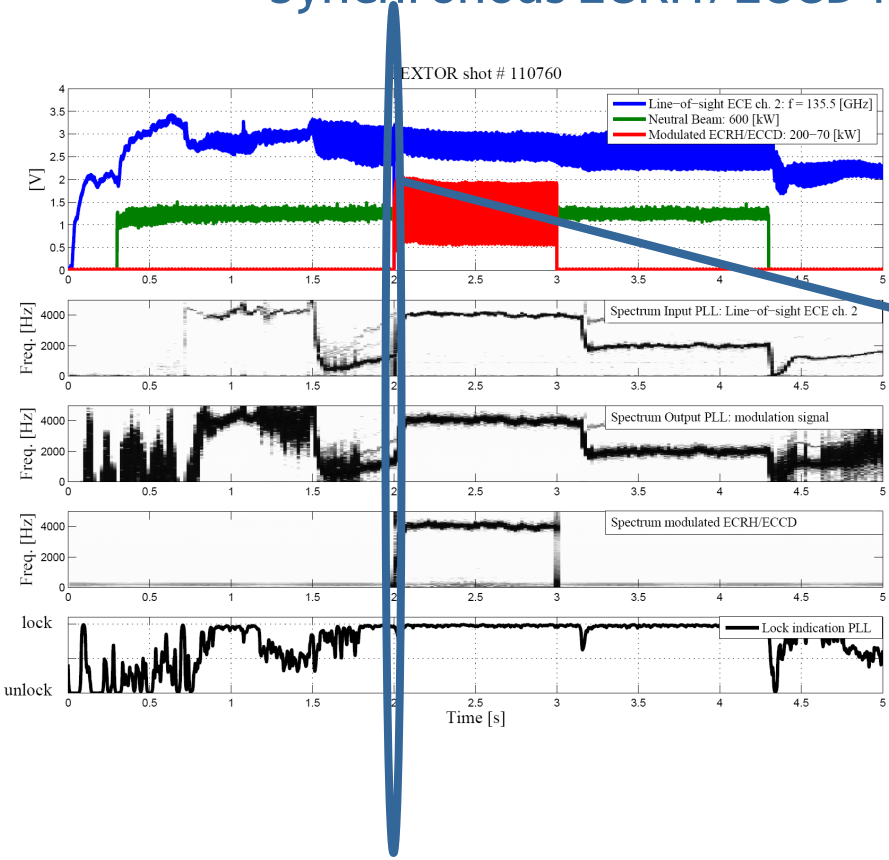

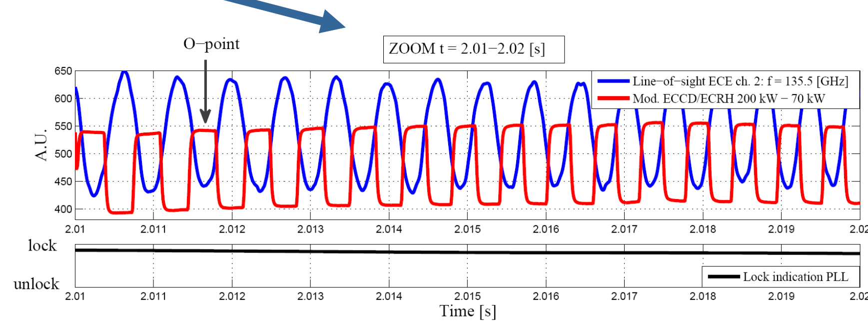

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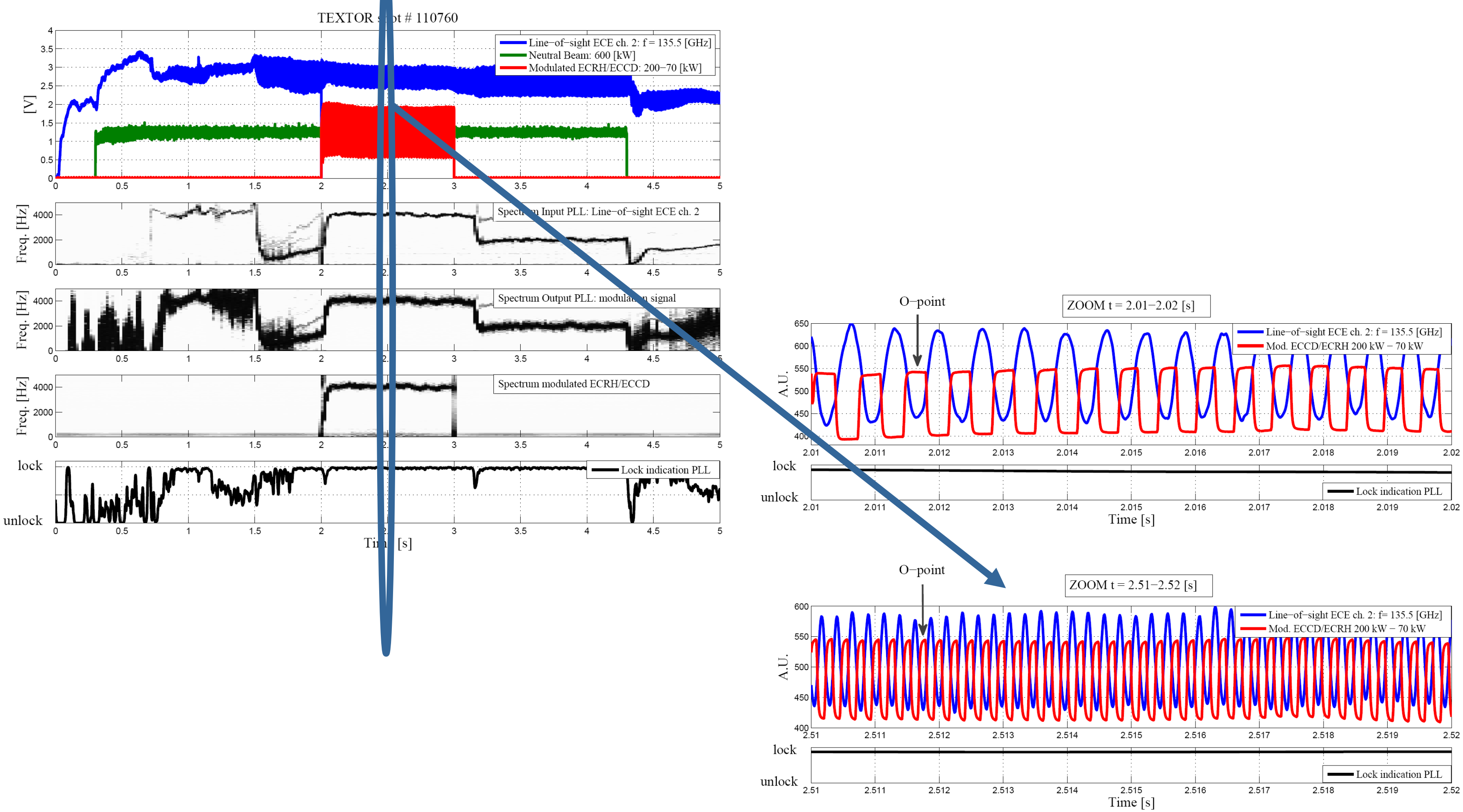

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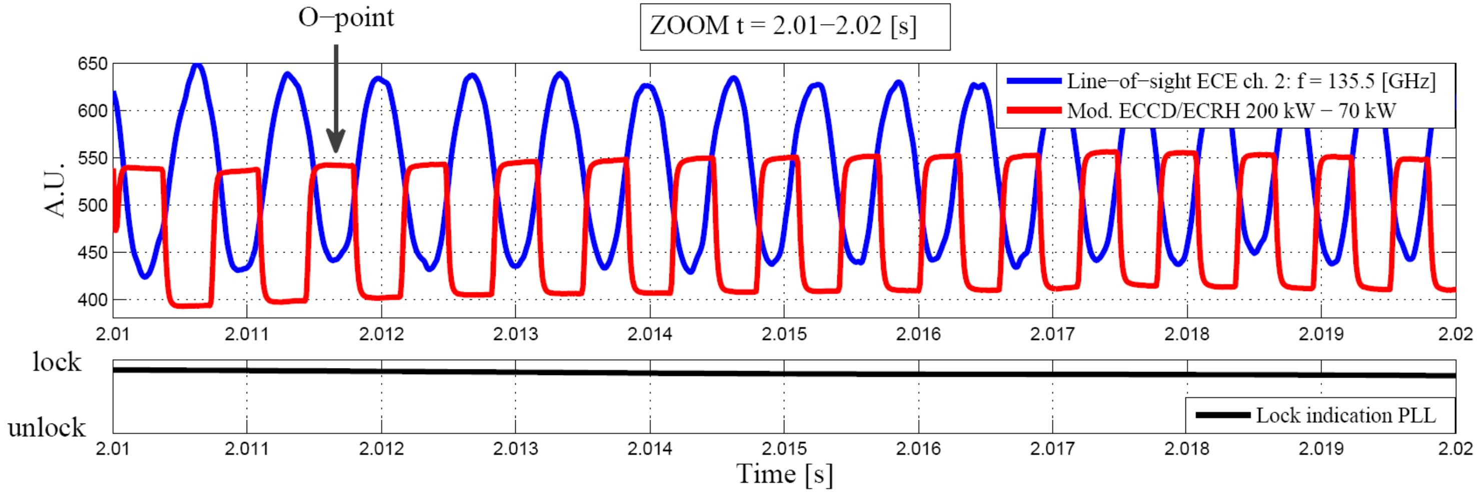
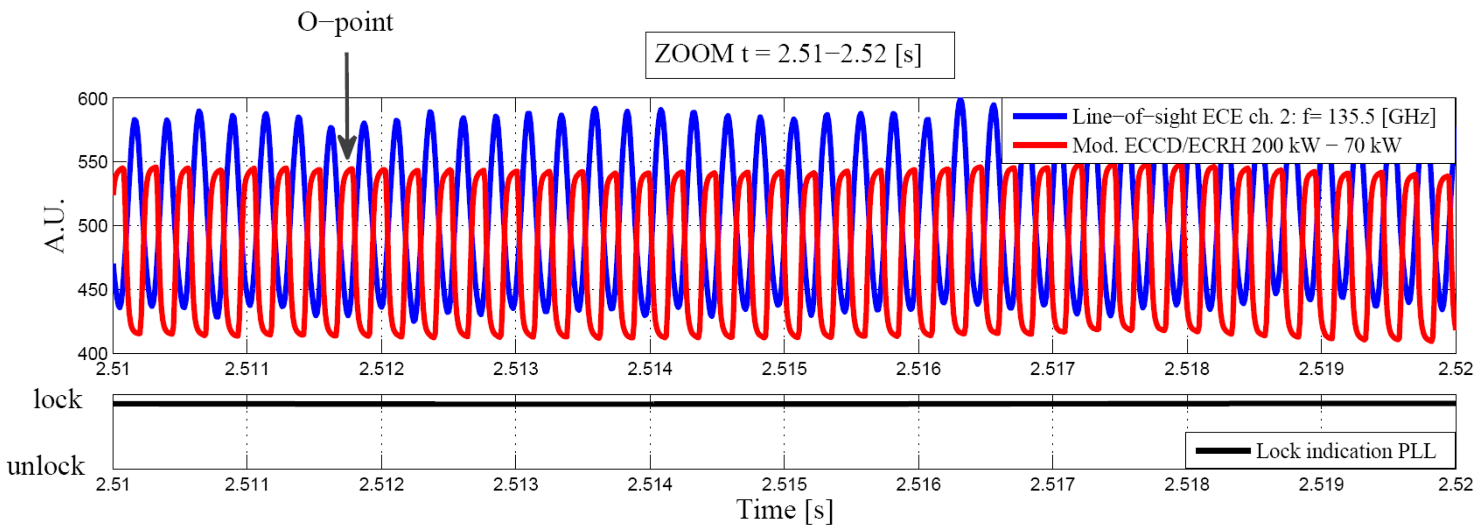


1 kHz rotation freq.



4 kHz rotation freq.

Conclusions

- Feedback stabilization of tearing modes realized in TEXTOR using a real-time tearing mode control system

in particular:

☑ Line-of-sight ECE applied as feedback sensor in control loop with steer-able launcher and gyrotron as actuators

☑ Algorithm for real-time detection of tearing modes implemented and demonstrated experimentally

☑ Launcher dynamics analyzed and optimized through controller design (FB + FF)

☑ ECRH/ECCD deposition aligned w.r.t. mode by matching actuator and sensor frequency in feedback loop (through launcher steering)

Conclusions

- Feedback stabilization of tearing modes realized in TEXTOR using a real-time tearing mode control system

in particular:

☑ Alignment achieved accurately and fast with a simple controller

☑ Tearing mode search-and-suppress demonstrated experimentally (both stabilization and full suppression achieved)

☑ Tracking capabilities control system demonstrated experimentally (subject to Bt ramp; mimic perturbation on tearing mode location)

☑ Synchronous ECRH/ECCD modulation on O-point of tearing mode using phase locked loop demonstrated experimentally

Outlook

- Future developments:

☑ Implement "Line-of-sight ECE" in waveguide environment (long pulse operation)

☑ Design of advanced controllers (model-based, including tearing mode dynamics)

☑ Increase number of radiometer channels (enhanced mode identification)

☑ Full control over tearing mode's width

- Open questions:

- How to deal with locked modes ?

- How to predict mode occurrence in advance ? (precursors ?)

- How to deal with multiple coupled modes ?

Questions ?

Thanks for your attention !

Further info → B.A. Hennen et al., Plasma Phys. Control. Fusion (to appear June 2010)

Real-time tearing mode identification

- Fast tearing mode detection from correlation between ECE fluctuations (*algorithm implemented on FPGA 100 kHz sampling rate*):

1. Subtract running average (over 256 data points ~ 2.56 ms)

$$\bar{x}_a(i) = x_a(i) - \frac{1}{N_{av}} \sum_{j=0}^{N_{av}-1} x_a(i-j),$$

$N_{av} = 256$ data points ($\sim$ 2.56 ms)
ECE signal $x_a(i)$ ($a = 1 \ldots 6$)

2. Normalize and correlate by multiplying all possible channel pairs
3. Compute running sum over 200 data points for each result

$$c_{a,b}(i) = \sum_{j=0}^{N_{corr}-1} \frac{\bar{x}_a(i-j)\bar{x}_b(i-j)}{|\bar{x}_a(i-j)\bar{x}_b(i-j)|}.$$

$N_{corr} = 200$
ECE channels $\bar{x}_a(i)$ and $\bar{x}_b(i)$

4. Find channel pairs for which correlator is negative and below threshold (= -100)

$$C_{a,b}(i) = \begin{cases} 1 & \text{if } c_{a,b}(i) \leq -100, \\ 0 & \text{if } c_{a,b}(i) > -100, \end{cases}$$

Real-time tearing mode identification

- Fast tearing mode detection from correlation between ECE fluctuations (*algorithm implemented on FPGA 100 kHz sampling rate*):

5. Define frequency estimate matrix

$$F = \begin{bmatrix} 132.5 & 134.0 & 135.5 & 137.0 & 138.5 & 140.0 \\ 134.0 & 135.5 & 137.0 & 138.5 & 140.0 & 141.5 \\ 135.5 & 137.0 & 138.5 & 140.0 & 141.5 & 143.0 \\ 137.0 & 138.5 & 140.0 & 141.5 & 143.0 & 144.5 \\ 138.5 & 140.0 & 141.5 & 143.0 & 144.5 & 146.0 \\ 140.0 & 141.5 & 143.0 & 144.5 & 146.0 & 147.5 \end{bmatrix} GHz,$$

6. Multiply by median EC frequency $F_{a,b} = \frac{1}{2}(f_{ECE,a}+f_{ECE,b})$ of corresponding channel pairs

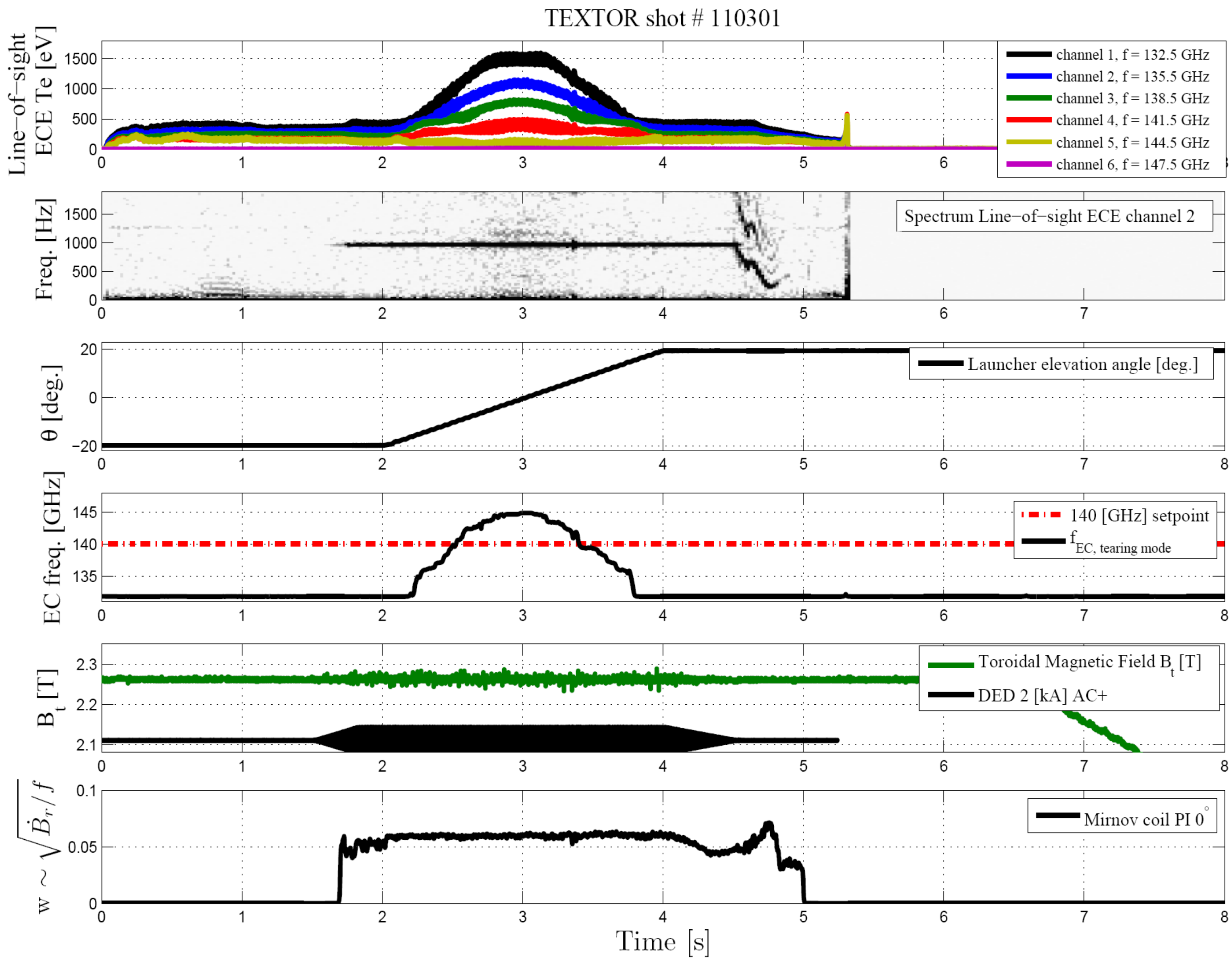
7. Weighted averaging over 15 possible channel pair combinations

$$f_{EC,\ tearing\ mode}(r_s, i) = \frac{\sum_{a=1}^{5}\sum_{b=a+1}^{6} C_{a,b}F_{a,b}W_{a,b}}{\sum_{a=1}^{5}\sum_{b=a+1}^{6} C_{a,b}W_{a,b}}. \qquad W_{a,b} = 2^{5-|a-b|}$$

→ Result: $f_{EC,\ tearing\ mode}$ GHz

(Estimate of mode location in the ECE spectrum for a given launcher orientation)

Real-time tearing mode identification (Example)



- $\theta = \pm 20^{\circ}$
- $B_t = 2.25$ T
- $I_p = 300$ kA

- DED triggered

  m/n = 2/1 mode