Real-time control of tearing modes using a line-of-sight Electron Cyclotron Emission diagnostic

a system engineering approach

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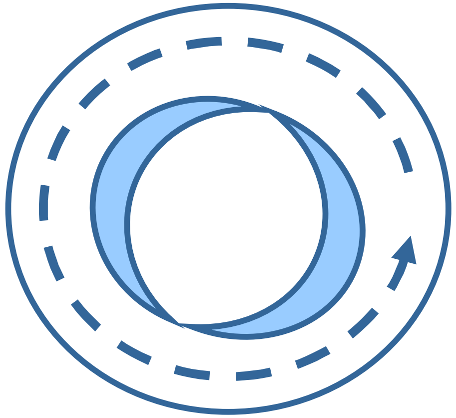
Real-time control of tearing modes

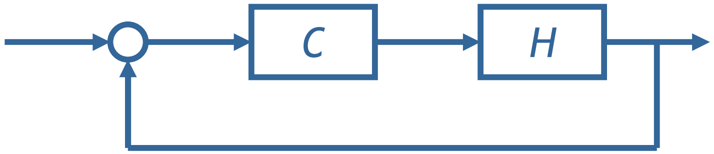


- Goal:

  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 (up to 5 kHz)

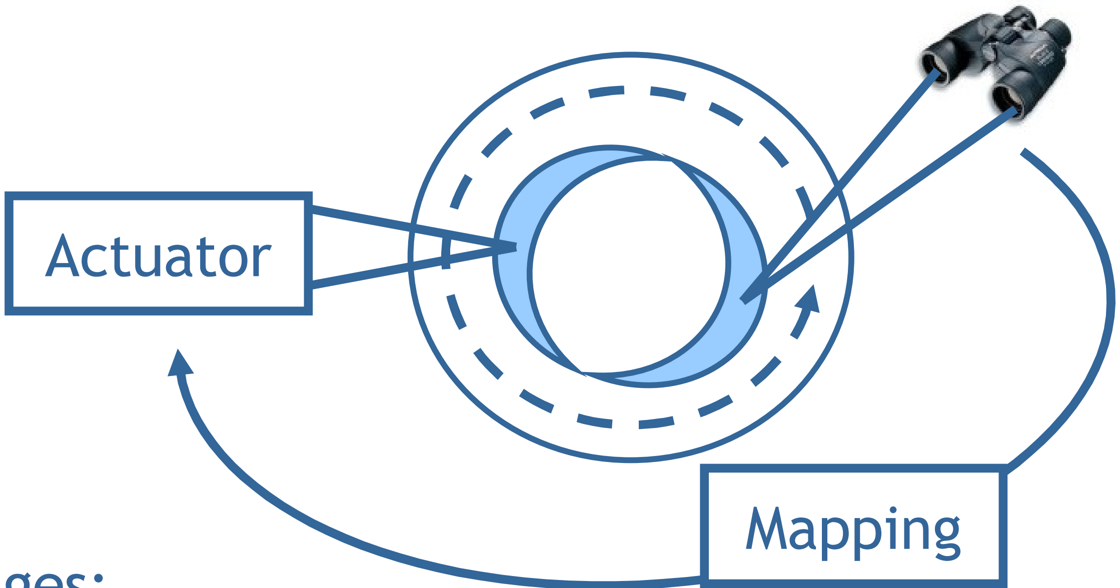


- Why real-time feedback control ?

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

Real-time 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



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

(loss of orientation = loss of control)

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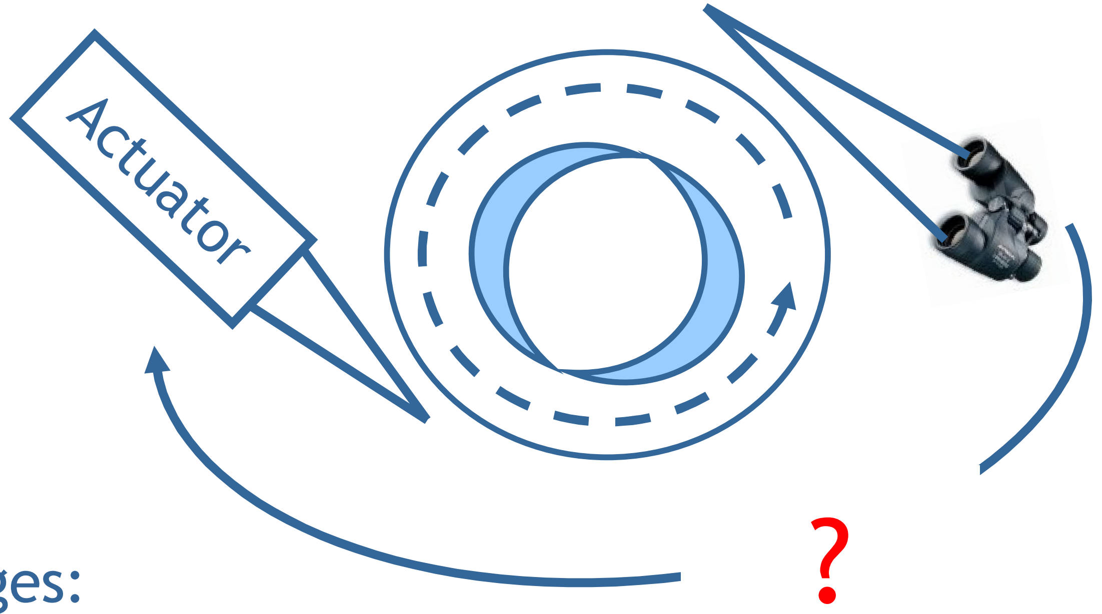

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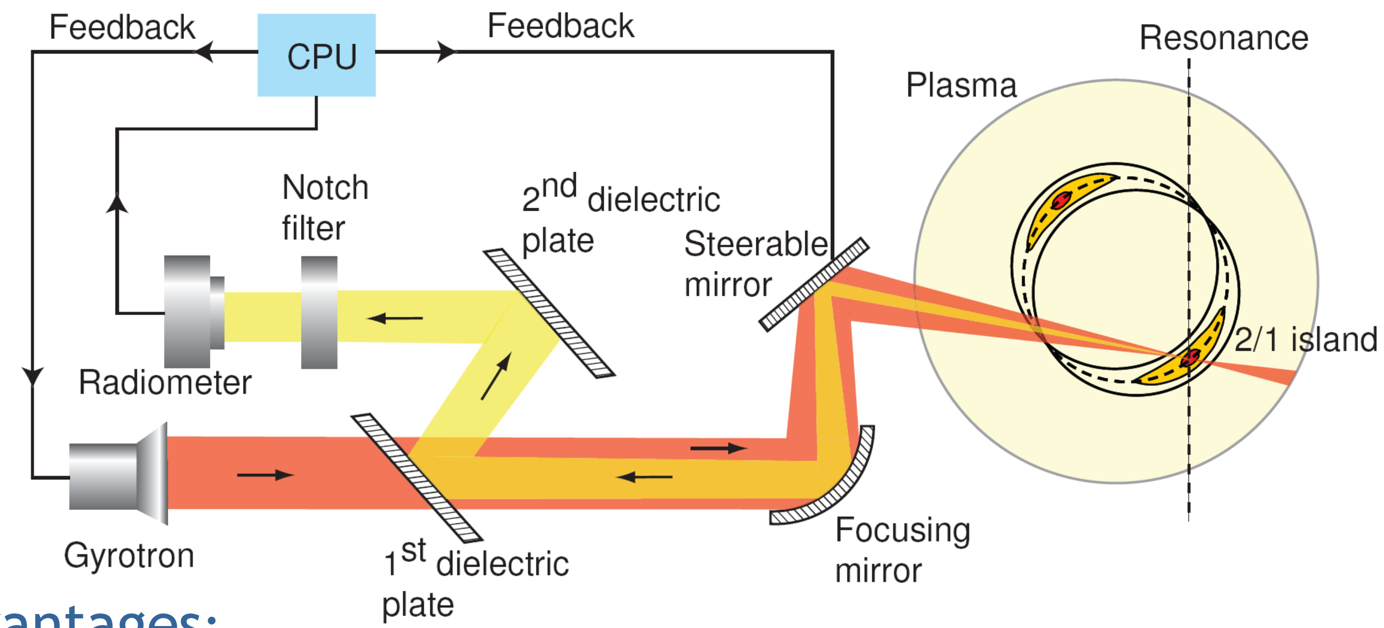
Real-time control of tearing modes

- Alternative: "line-of-sight principle"

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



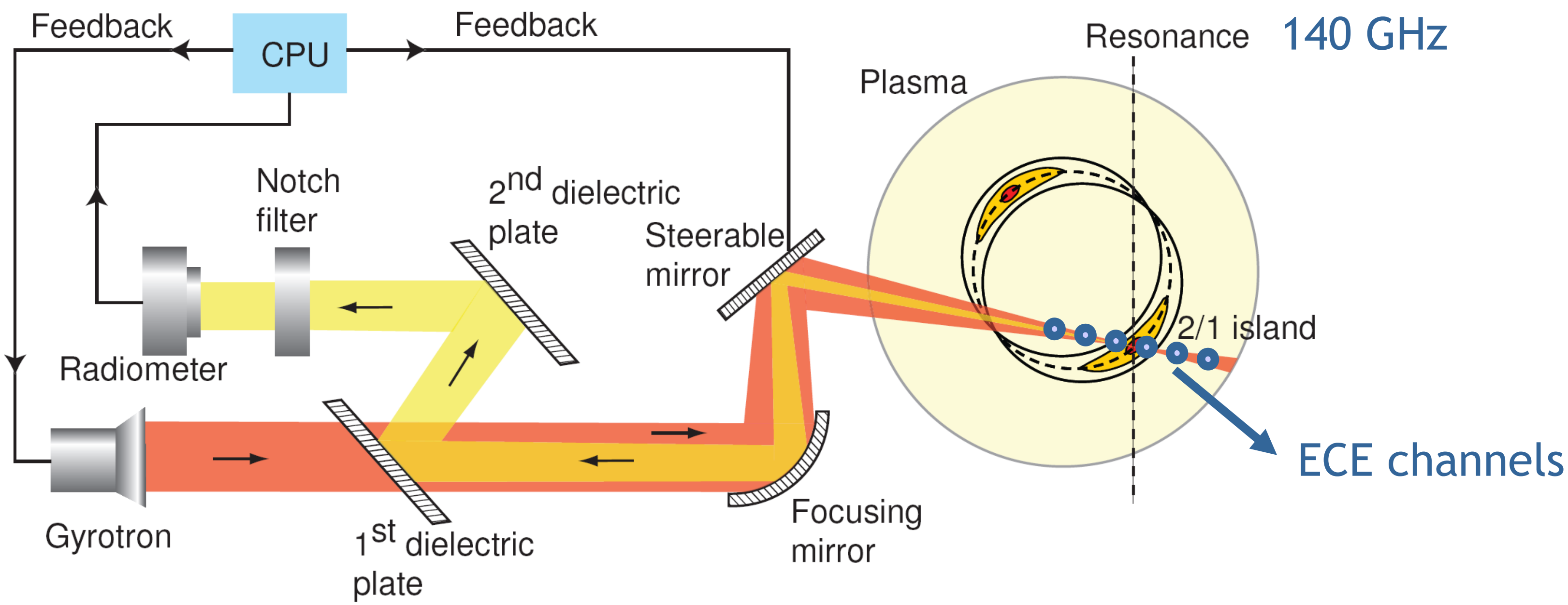
- Advantages:

  - Actuator and sensor are always aligned (refractive properties identical)
  - Guarantees tearing mode control even when launcher orientation is perturb or calibration is lost
  - Sensor is placed at distance from plasma (single access port needed)

Real-time control of tearing modes

- Alternative: "line-of-sight principle"

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



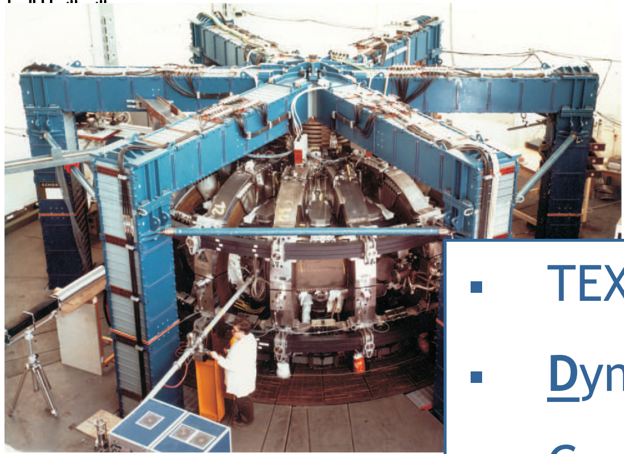
- Implementation in quasi-optical ECRH/ECCD transmission line on TEXTOR:

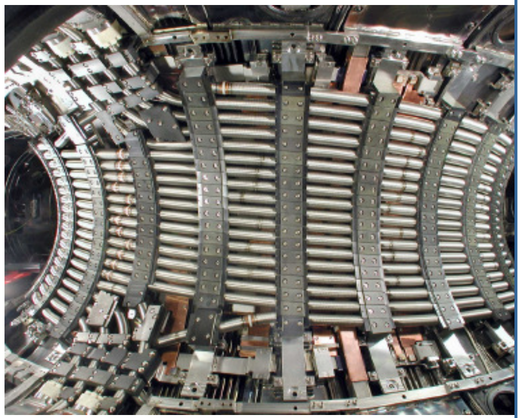
  - Radiometer: 6 channels, 132.5-147.5 GHz, 3 GHz spacing ~ 3 cm radial spacing

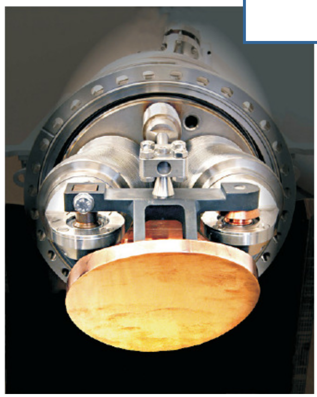
  - Frequency selective directional couplers separate **ECE** from **ECRH/ECCD**

    (nW power versus MW power)

Experimental instrumentation

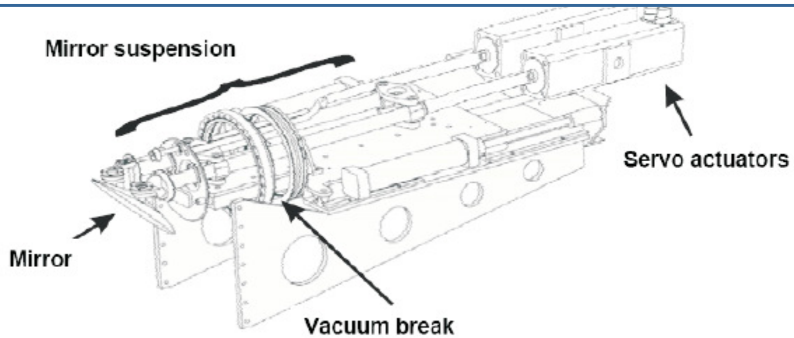




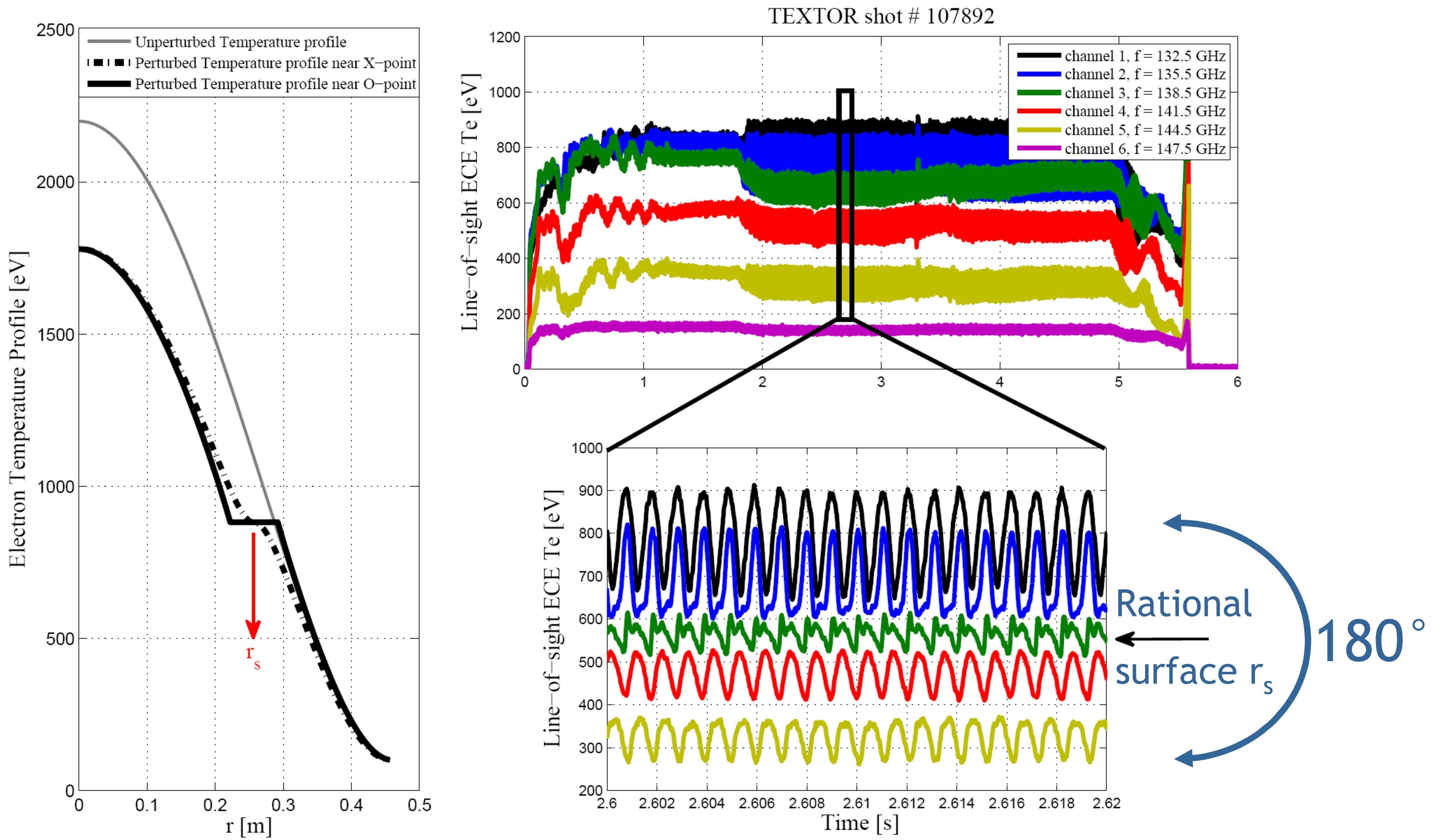


- TEXTOR (R = 1.75 m , a = 0.46 m)
- Dynamic Ergodic Divertor (perturbation field)
- Gyrotron 140 GHz, 1 MW, 10 s
- Bi-directional, steerable launcher (tor. & pol.)
- Line-of-sight ECE diagnostic
- National Instruments DAQ & RT control system

  (Labview based, DAQ & Field Programmable Gate Array: sampling rate 100 kHz)



Real-time tearing mode identification



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"

Channel pair with 180° phase reversal

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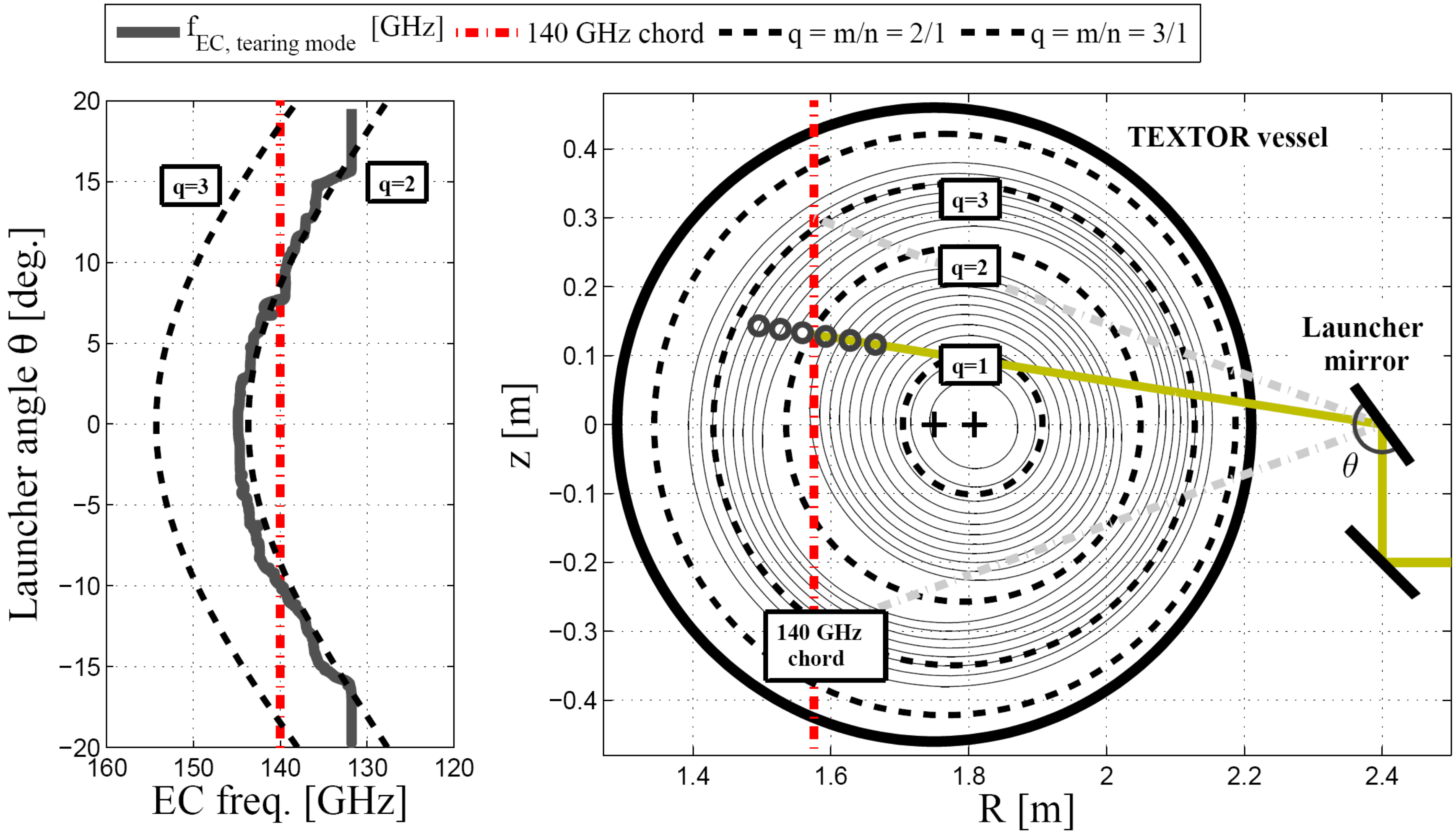
$f_{EC,\ tearing\ mode}$ GHz

Clock-rate computation on FPGA:

16 μs

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

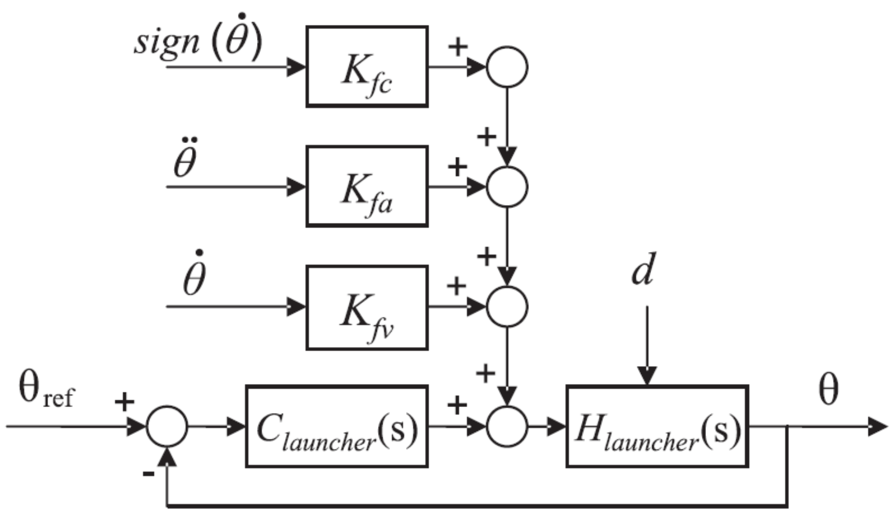
Real-time tearing mode identification (Example)

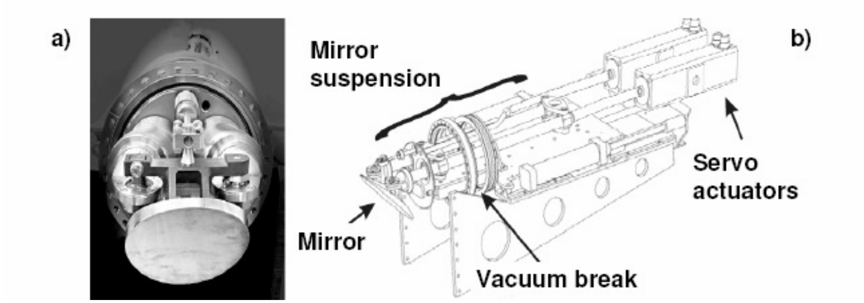


- Match actuator frequency 140 GHz with sensor frequency $f_{EC,\ tearing\ mode}$ GHz through launcher steering (elevation angle θ)

Real-time control loop

- Launcher control loop
  - Analysis launcher dynamics using Frequency Response Function measurement $H_{launcher}(s)$
  - Controller designed using "loop-shaping" in frequency domain
  - $C_{launcher}(s)$ = PID controller + lead/lag + low-pass filter
  - Feed-forward for friction compensation





Real-time control loop

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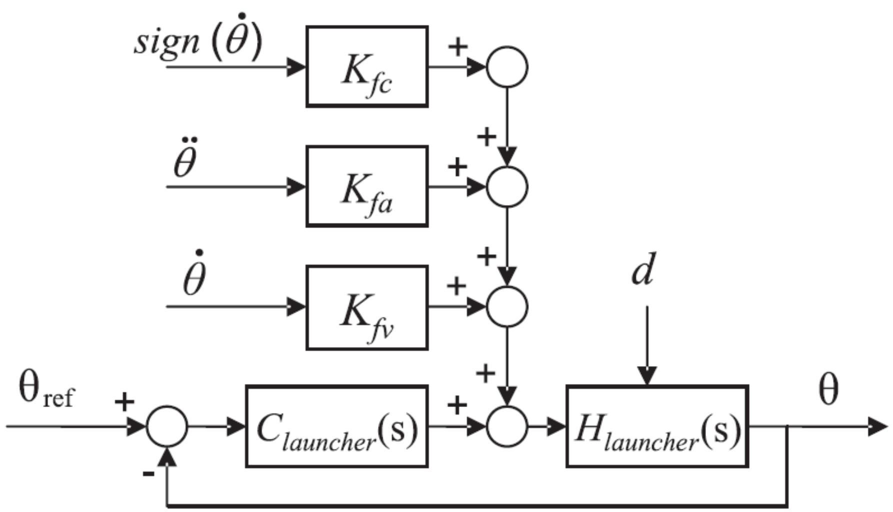
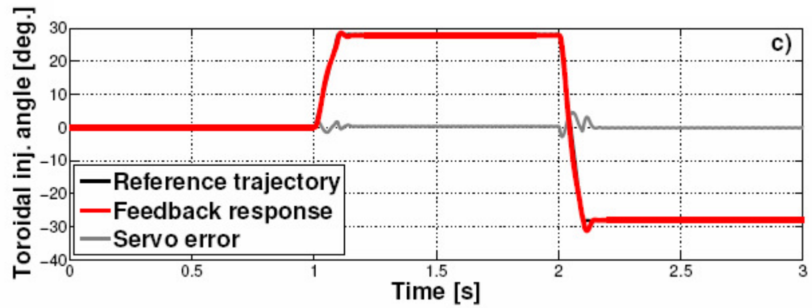


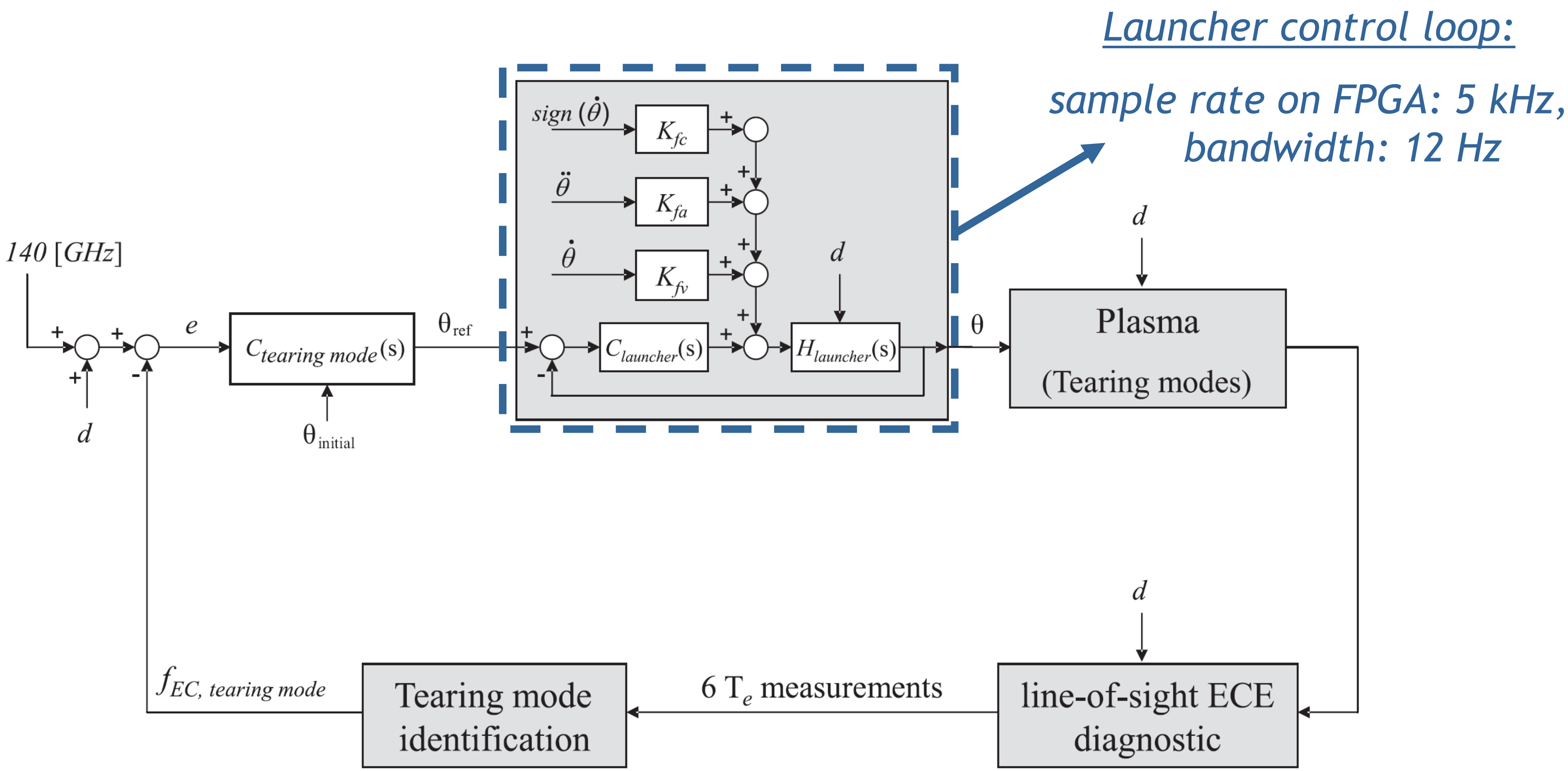
Performance:

- Response: θ = ± 30° in 100 ms
- Max. steady-state positioning error: 0.6°
- Bandwidth: 12 Hz



Real-time control loop

- Tearing mode "tracking" loop

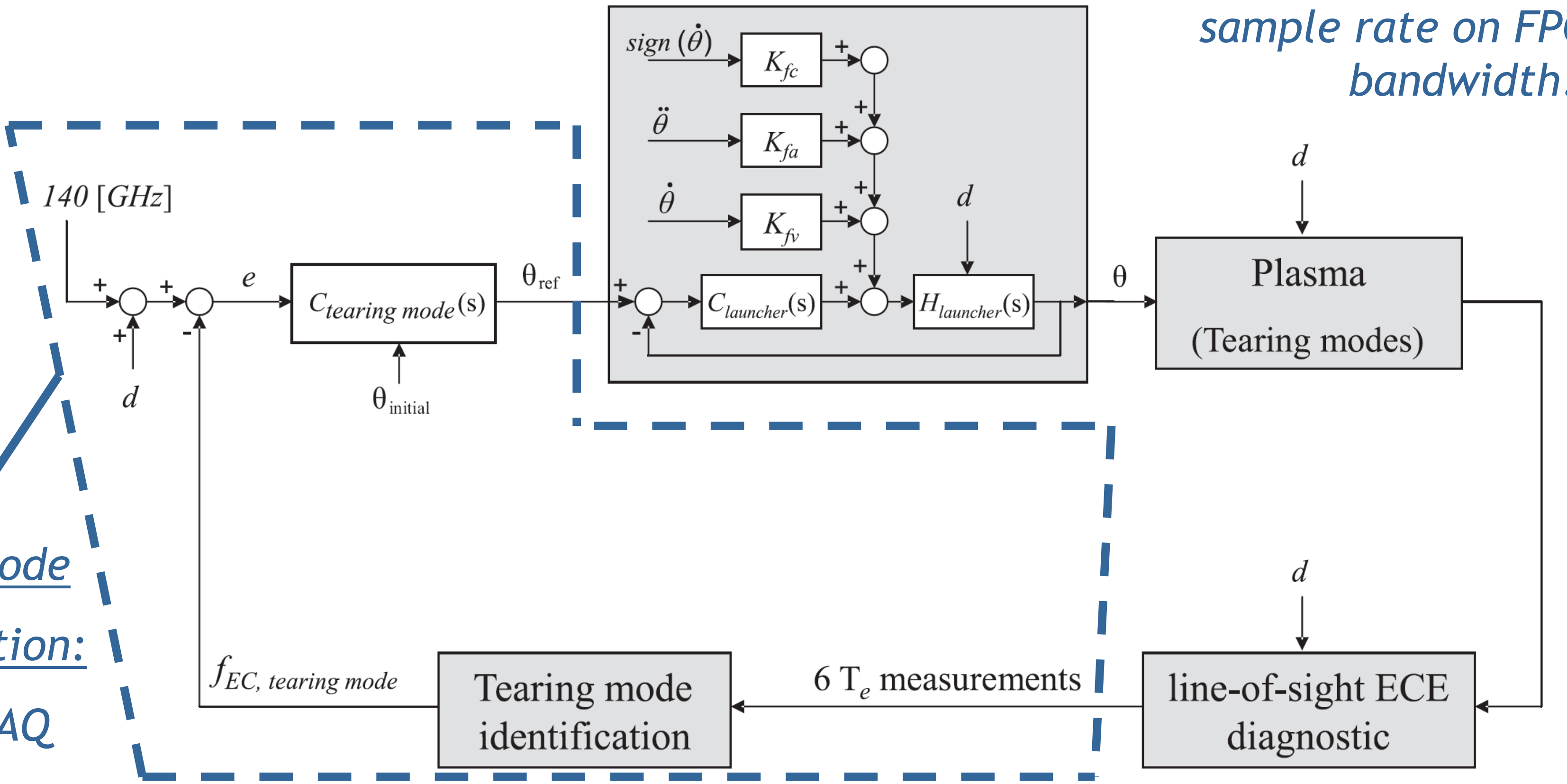


Real-time control loop

- Tearing mode “tracking” loop

Launcher control loop:

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



Tearing mode identification:

100 kHz DAQ

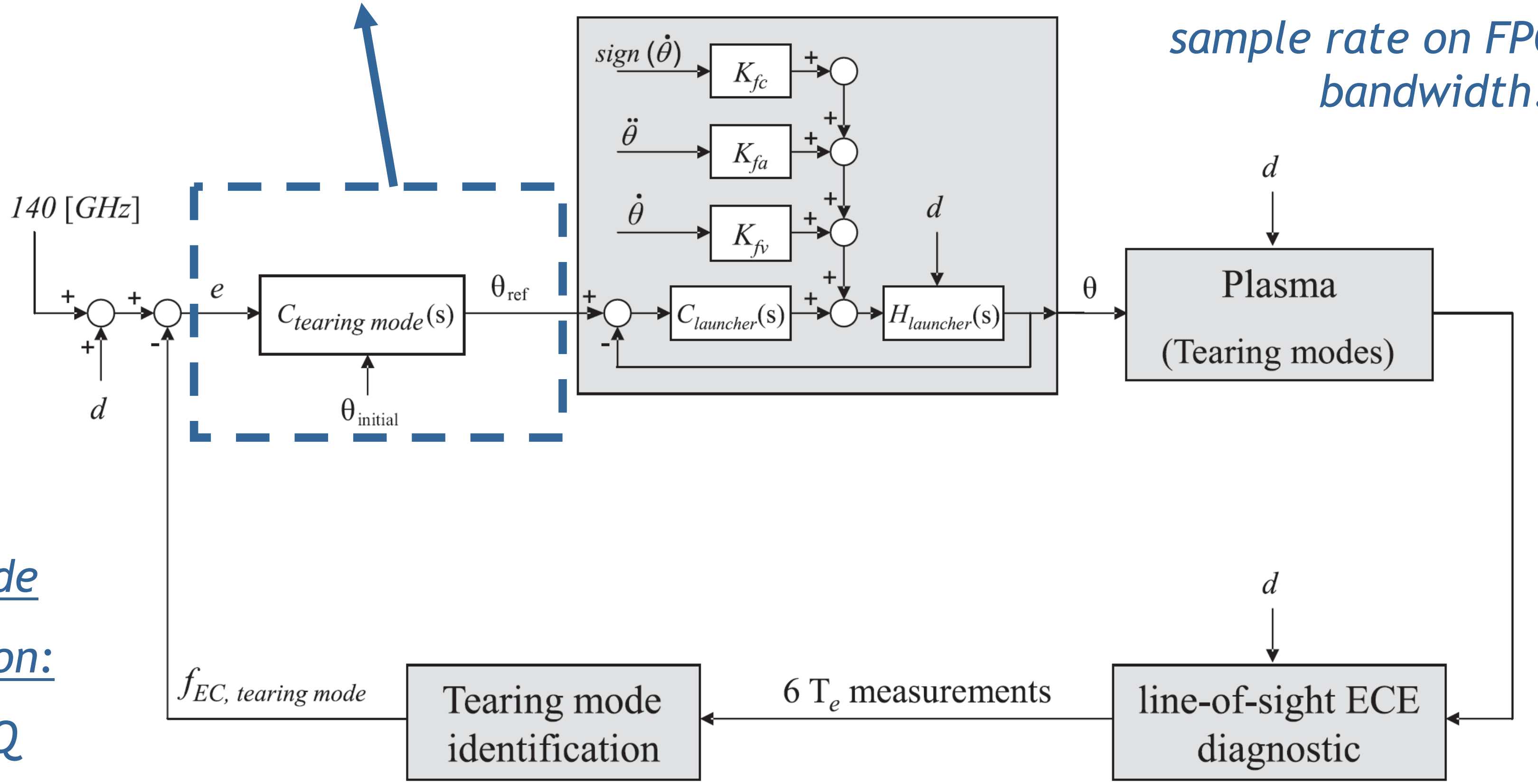
clock rate identification algorithm on FPGA: 16 μs

Real-time control loop

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

Launcher control loop:

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



Tearing mode identification:

100 kHz DAQ

clock rate identification algorithm on FPGA: 16 μs

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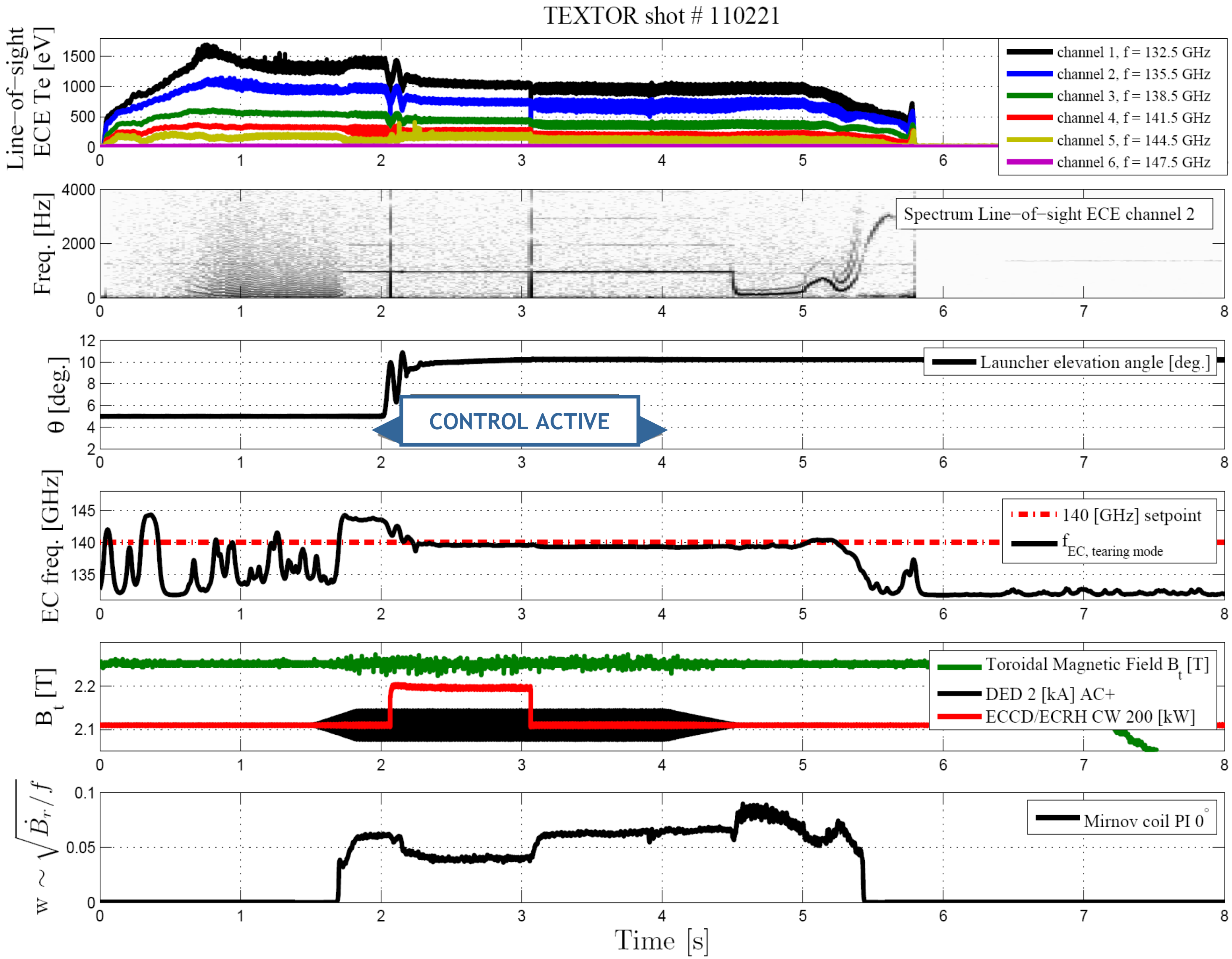
Experimental Results

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



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

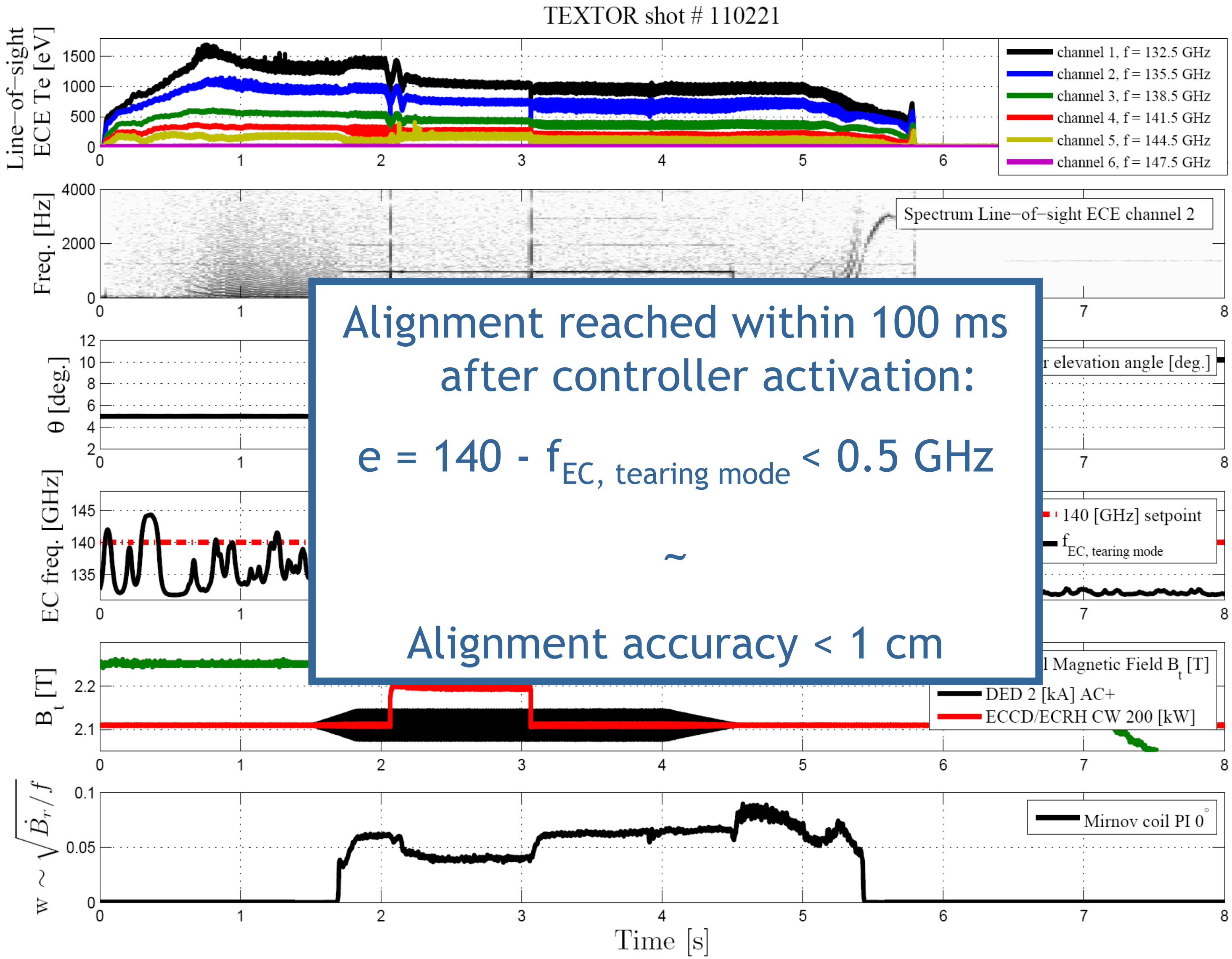
- Continuous ECRH/ECCD 200 kW, 1 sec.
- DED triggered

  m/n = 2/1 mode

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

Experimental Results

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



Alignment reached within 100 ms after controller activation:

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

~

Alignment accuracy < 1 cm

- $\theta_{initial} = 5°$
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- Continuous ECRH/ECCD 200 kW, 1 sec.
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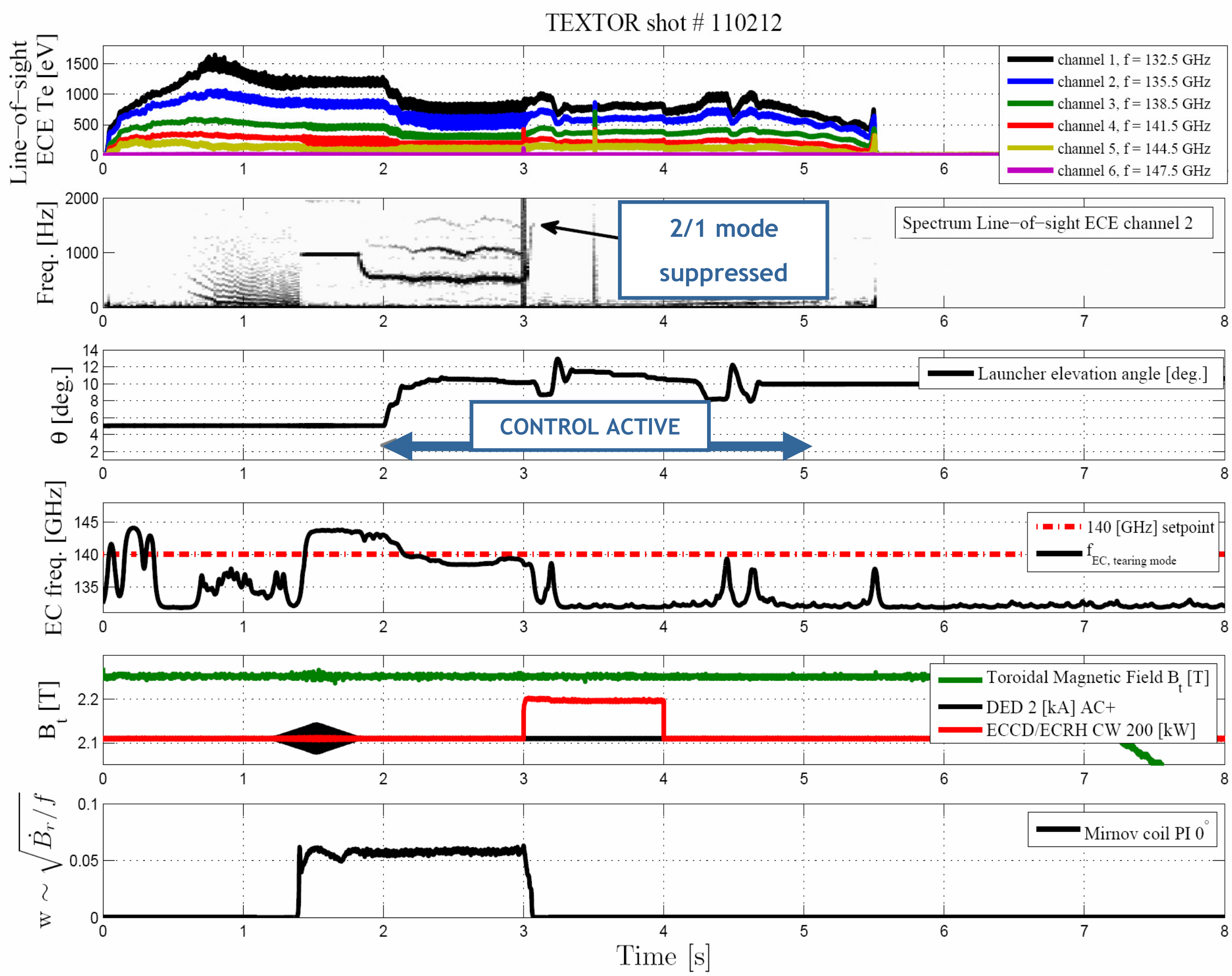
Experimental Results

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



- $\theta_{initial} = 5°$
- $B_t = 2.25$ 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

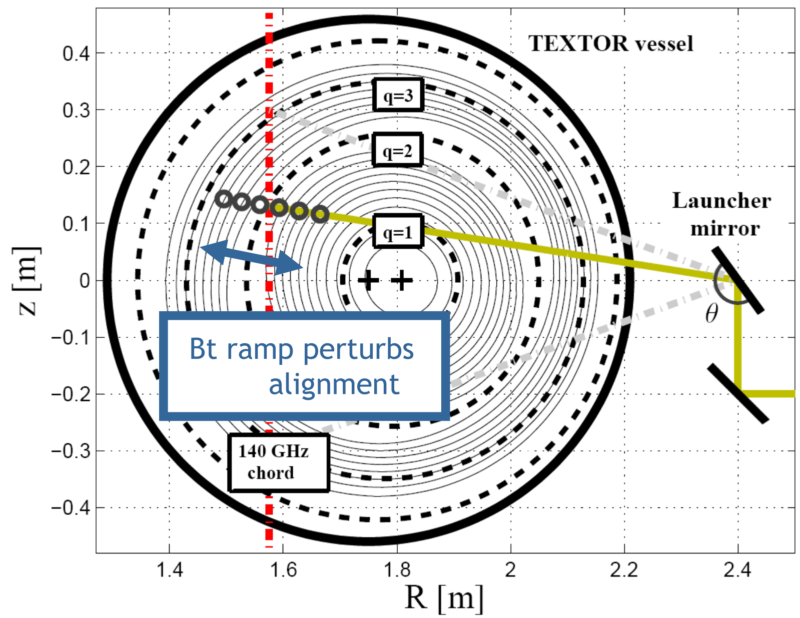
Next: Tearing mode **tracking** experiment

Ramp in toroidal magnetic field B_t

→

Mimic change in tearing mode location

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



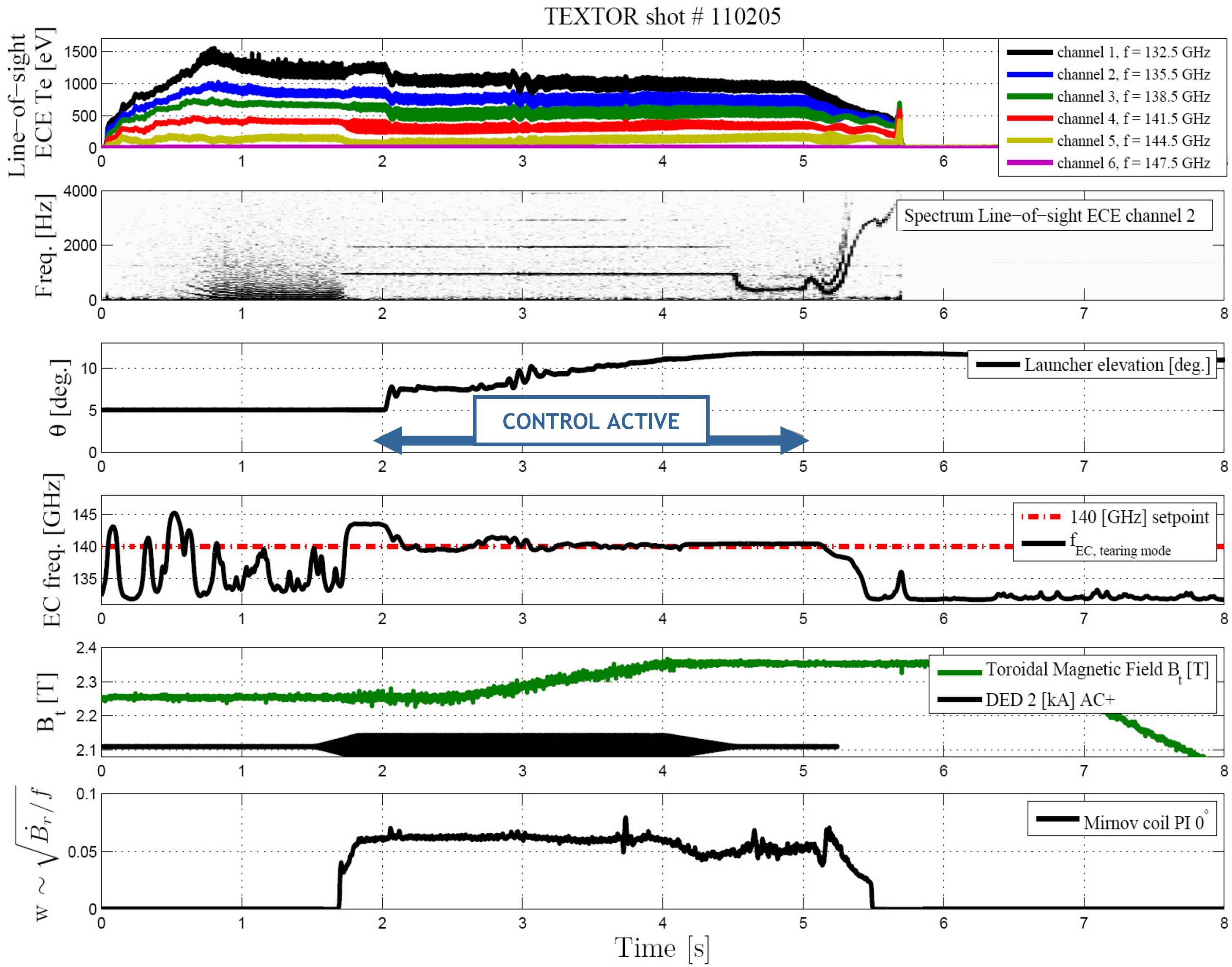
- B_t = 2.25-2.35 T
- I_p = 300 kA

→

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

Experimental Results

- 2/1 tearing mode tracking experiment



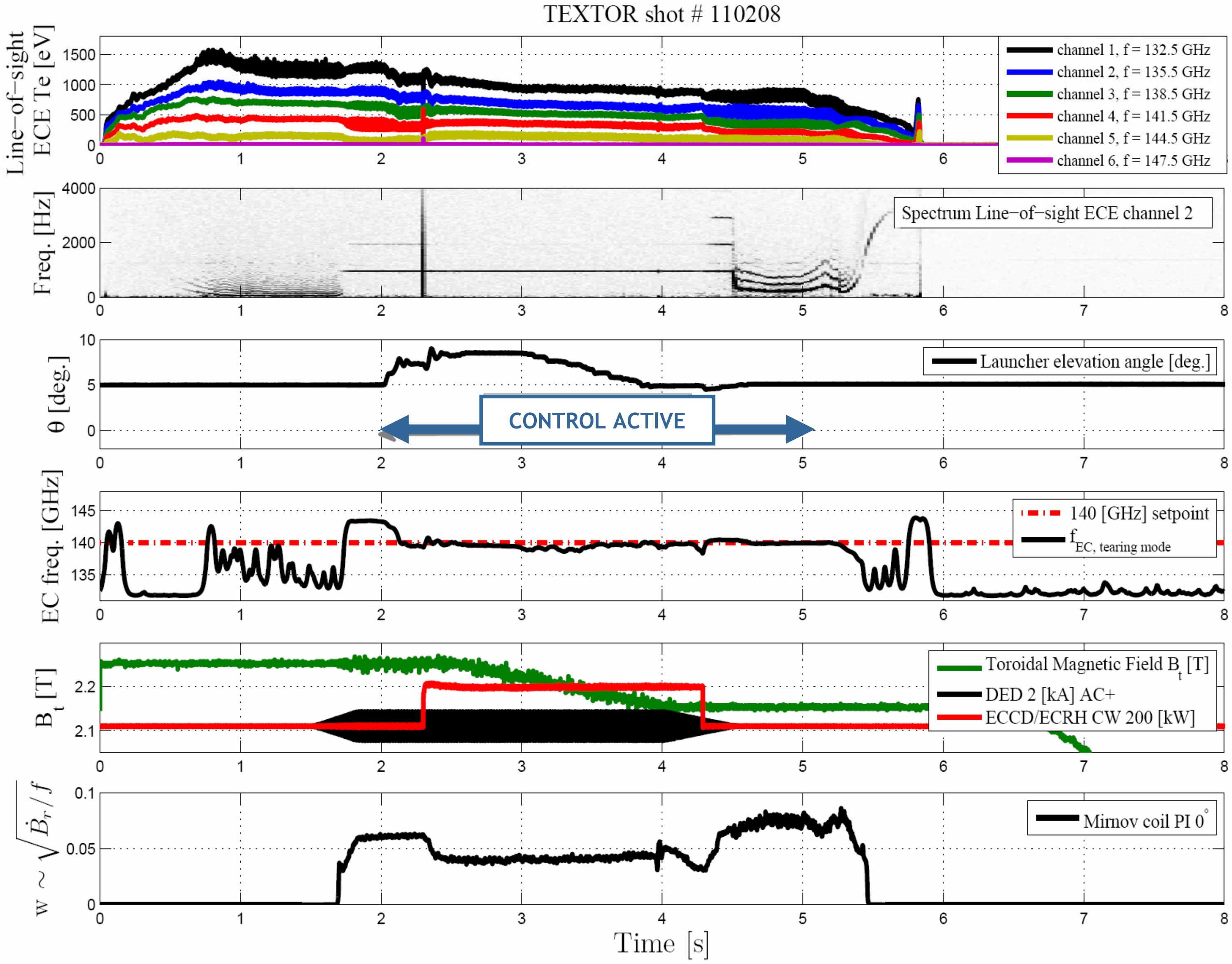
- $\theta_{initial}$ = 5°
- B_t = 2.25-2.35 T
- I_p = 300 kA

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

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

Experimental Results

- 2/1 tearing mode tracking experiment



- $\theta_{initial} = 5°$
- 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

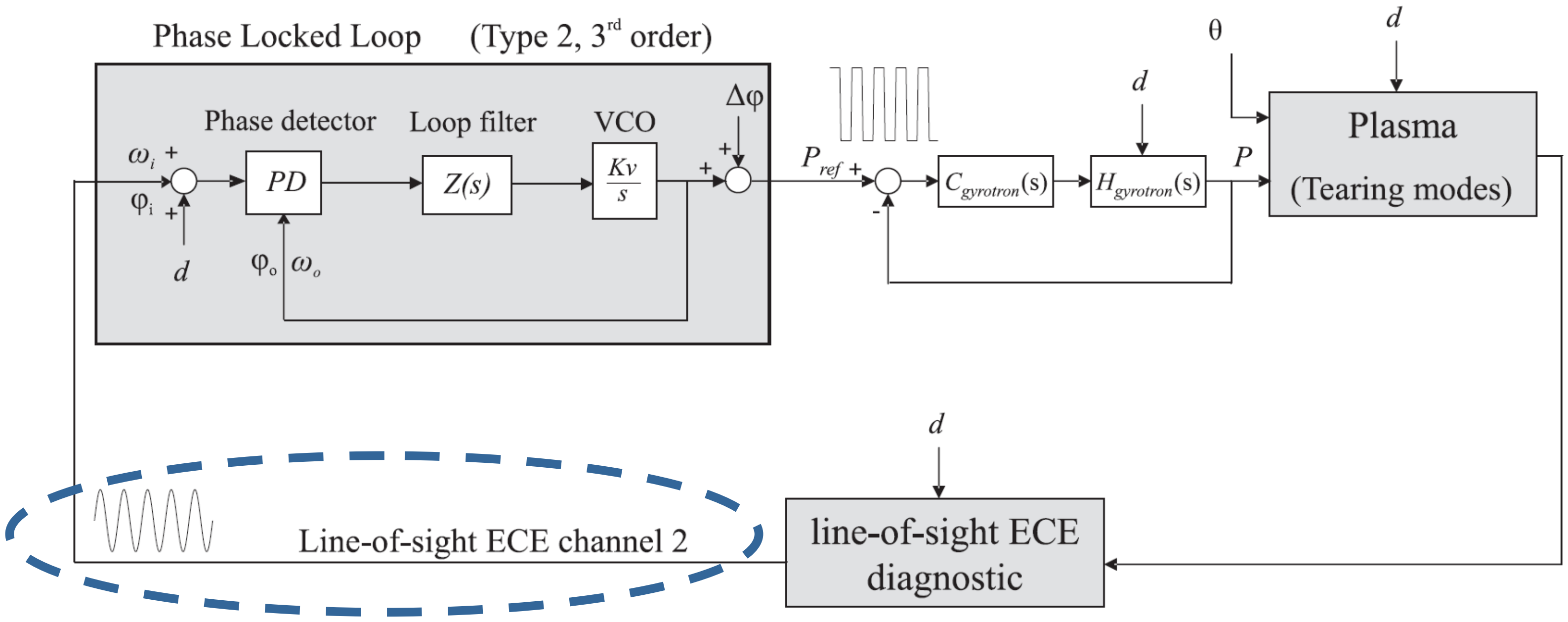
Real-time control loop

- 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

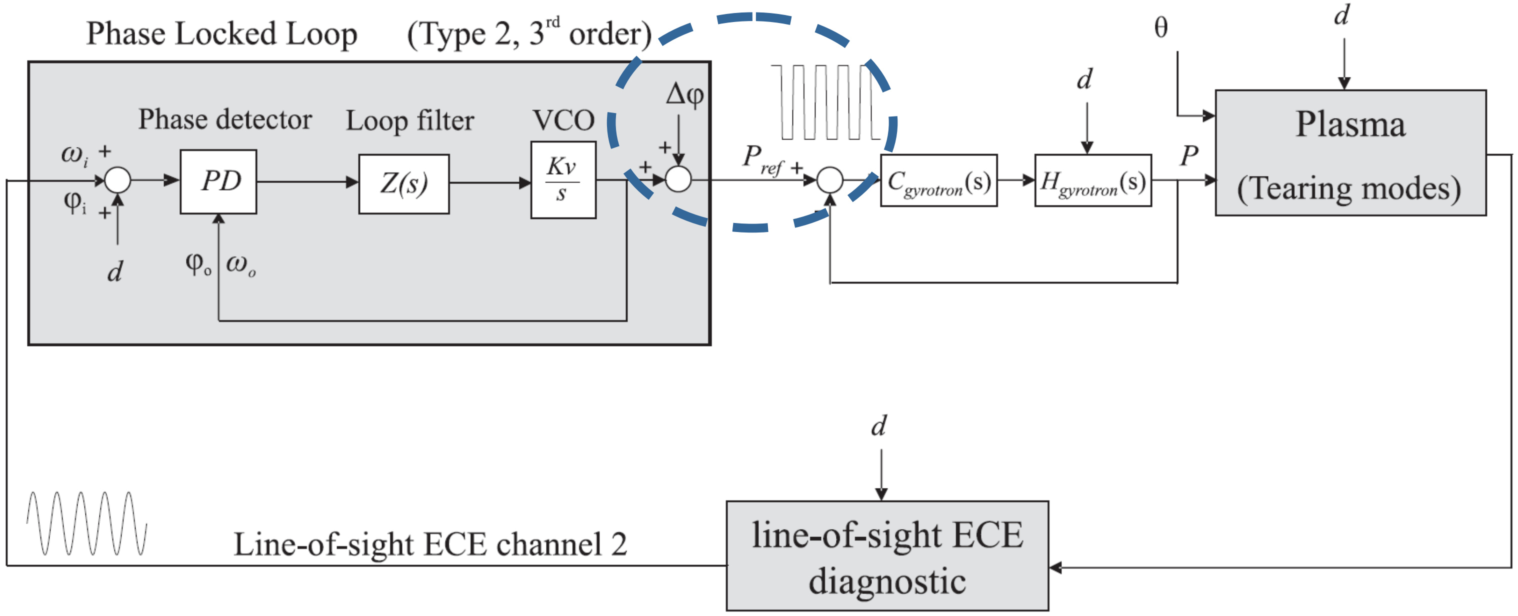
- Phase Locked Loop (synchronous ECRH/ECCD modulation on O-point)

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)



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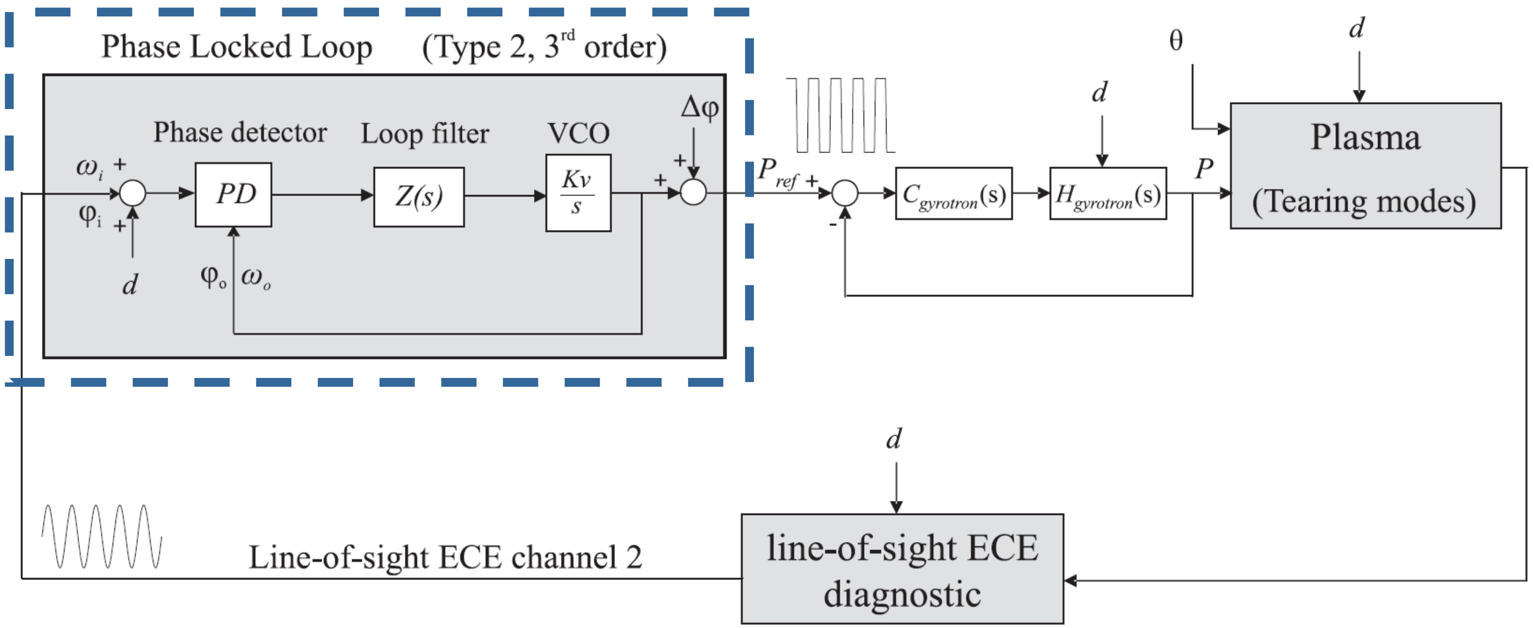
PLL: operational domain: 300 Hz – 5 kHz



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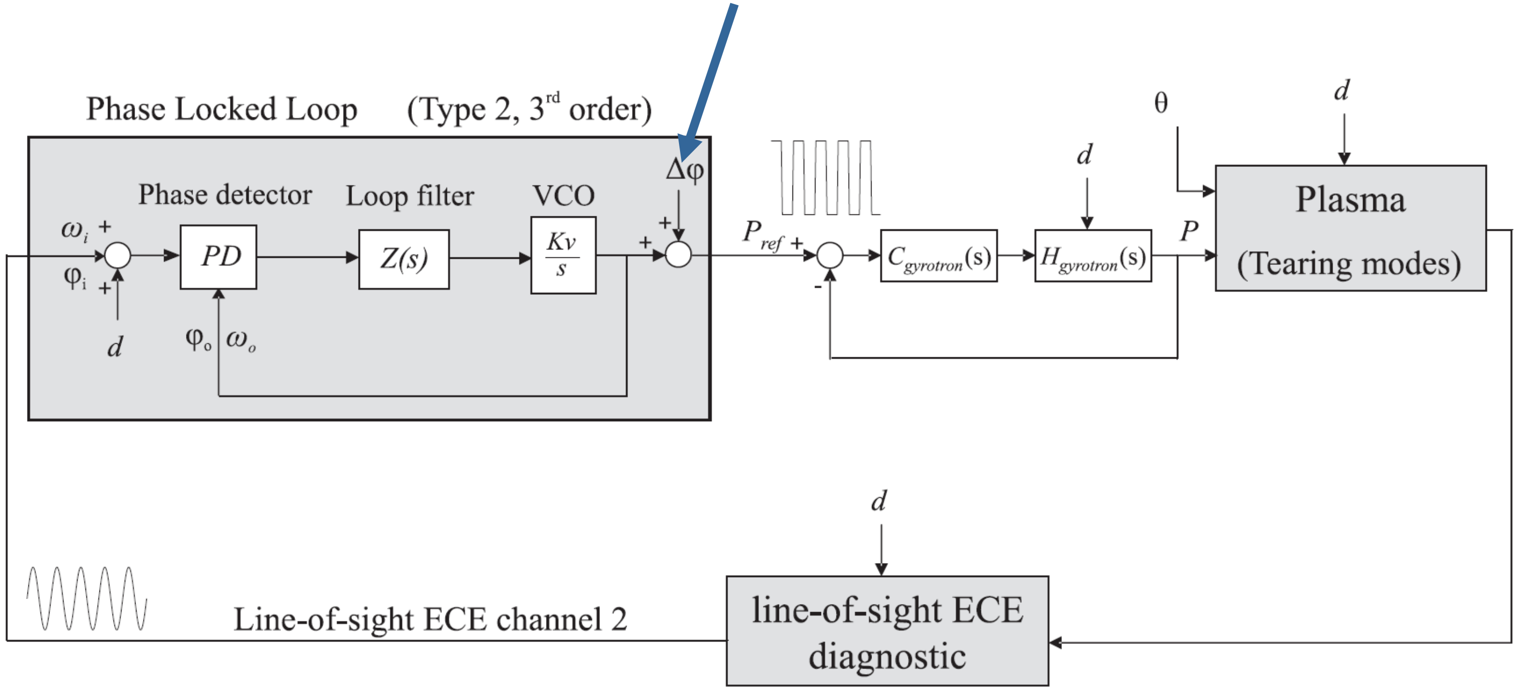
Note: focus on O-point by adding constant phase shift $\Delta\varphi$



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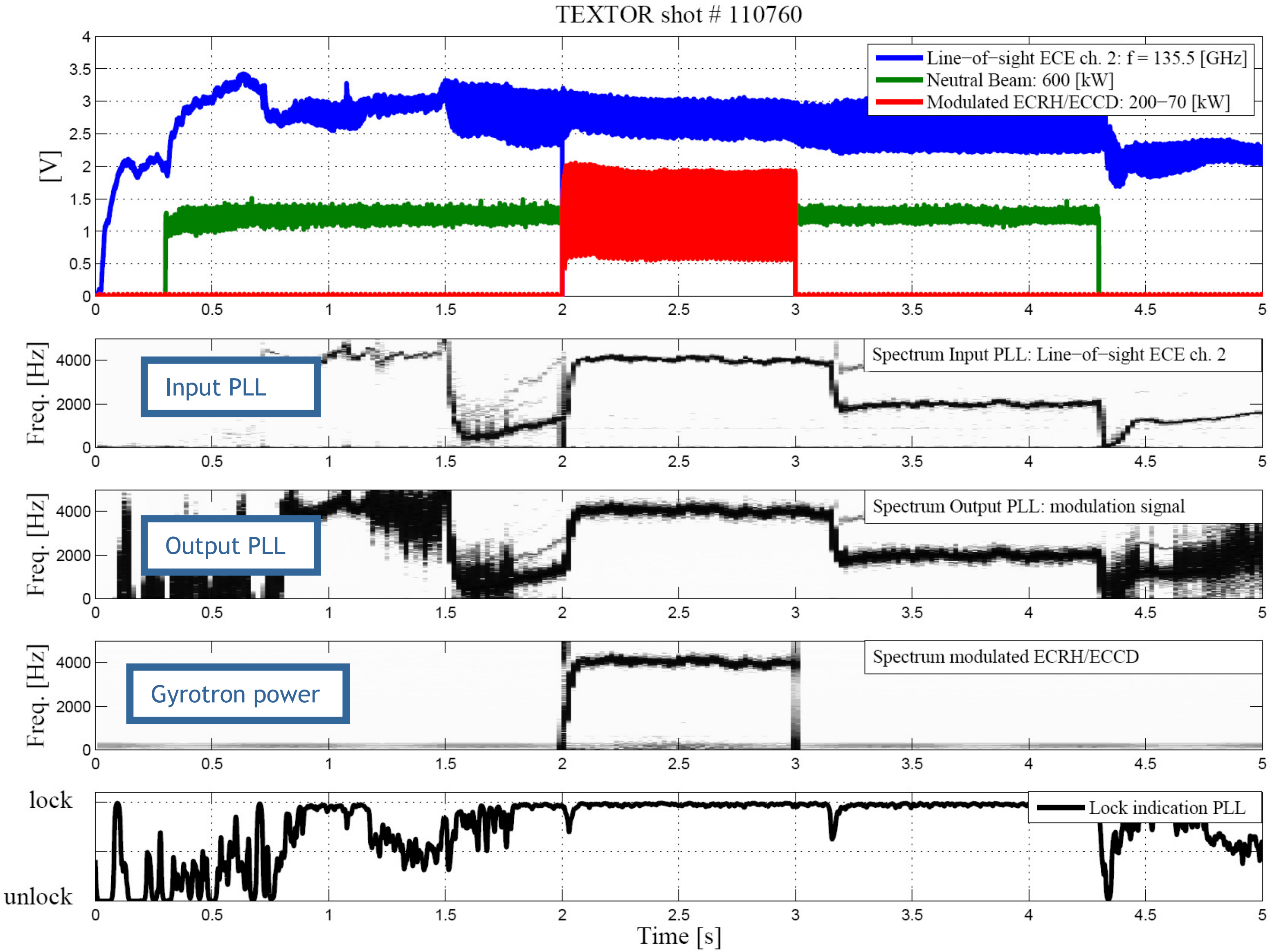
Experimental Results

- Synchronous ECRH/ECCD modulation on O-point



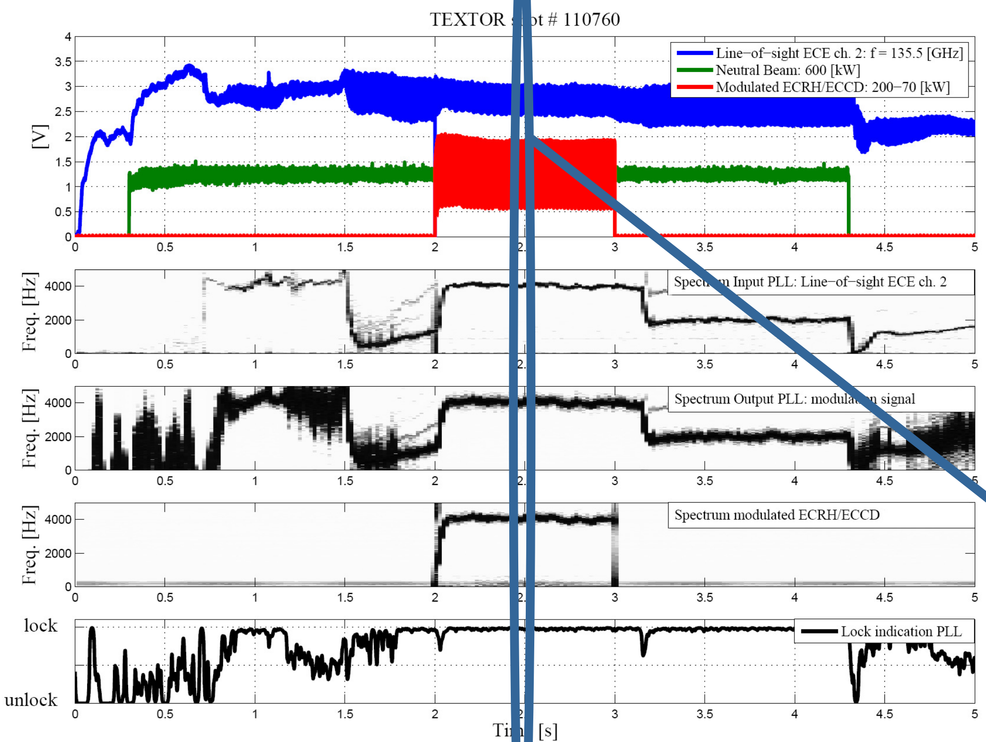
- $\theta_{fixed} = 10°$
- $B_t = 2.25$ T
- $I_p = 300$ kA

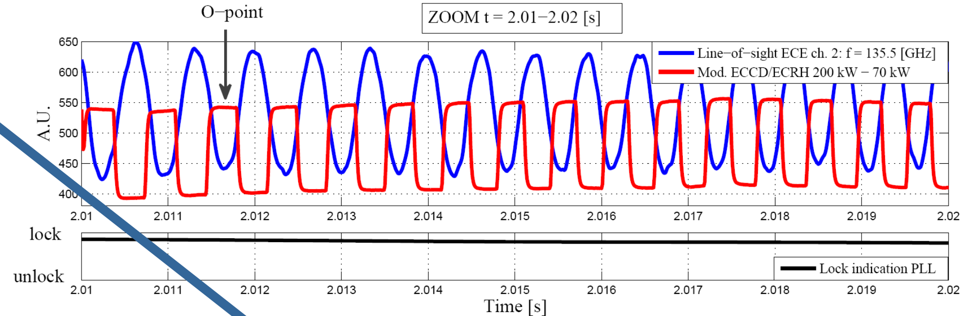
- Modulated ECRH/ECCD

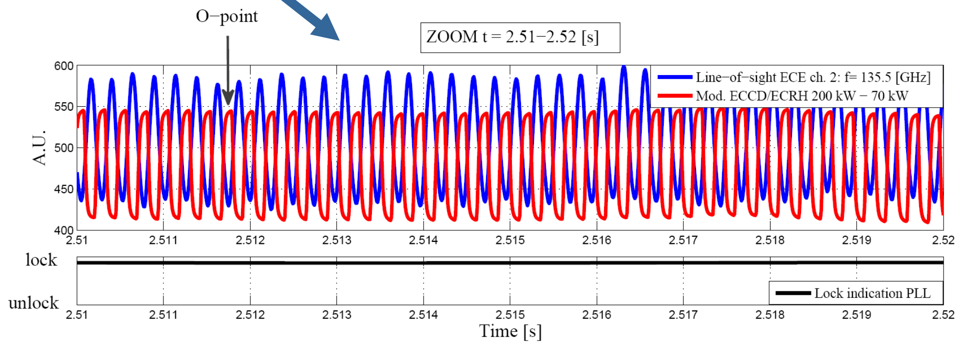
  200 kW – 70 kW, t = 2-3 sec.
- Natural m/n = 2/1 mode
- Neutral Beam (co-direction) 600 kW

Experimental Results

- Synchronous ECRH/ECCD modulation on O-point







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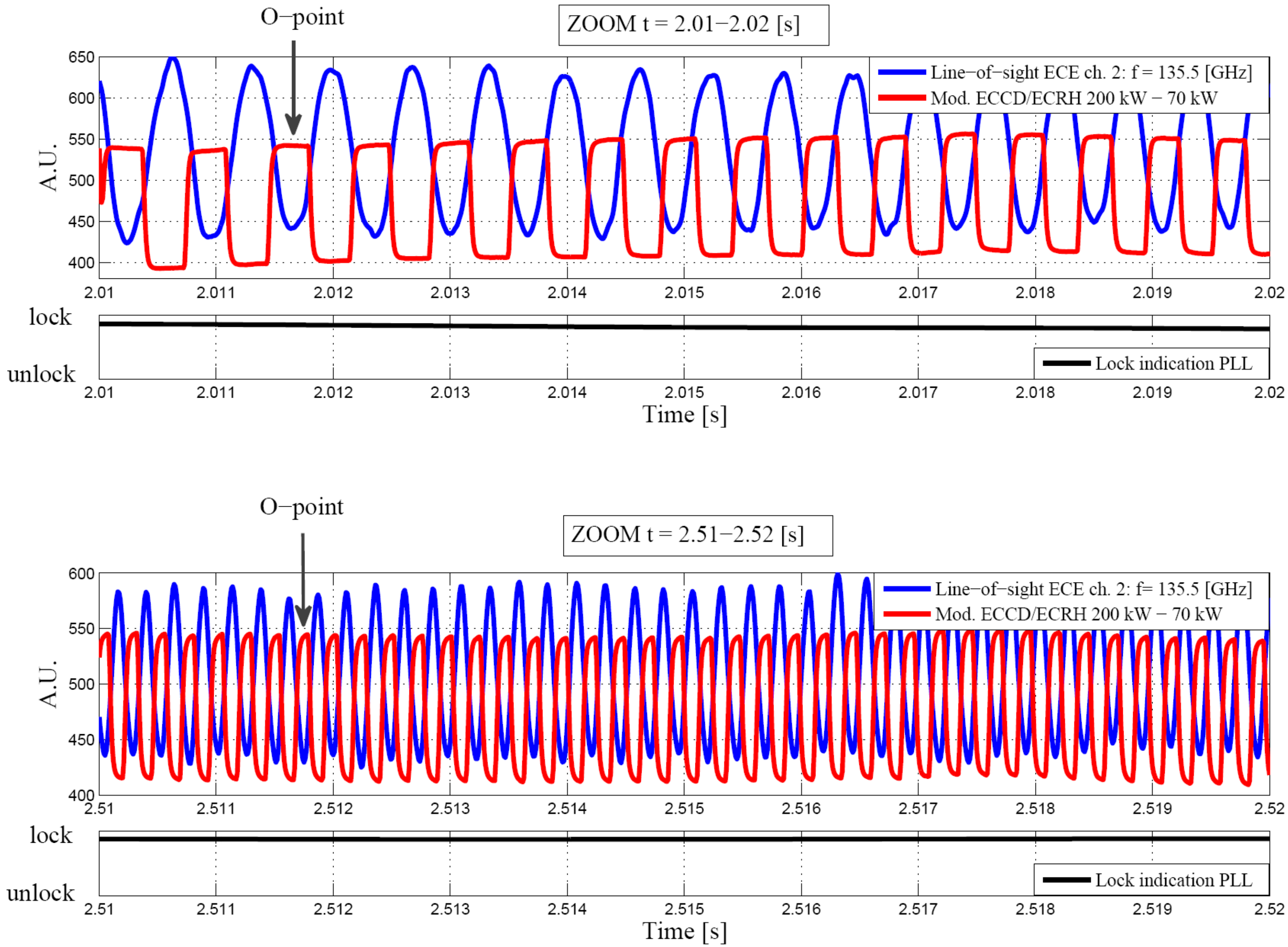

Conclusions

- Real-time tearing mode control system established on TEXTOR:
  - ☑ 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

- Real-time tearing mode control system established on TEXTOR:
  - ☑ 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 ?

Questions ?

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