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

*a system engineering approach*

Bart Hennen (b.a.hennen@tue.nl)
Egbert Westerhof, Pieter Nuij, Hans Oosterbeek, Marco de Baar, Waldo Bongers, Andreas Bürger, David Thoen, Maarten Steinbuch and the TEXTOR team
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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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

TEXTOR shot # 107892

Electron Temperature Profile [eV]

Line-of-sight ECE Te [eV]

Channel 1, f = 132.5 GHz
Channel 2, f = 135.5 GHz
Channel 3, f = 138.5 GHz
Channel 4, f = 141.5 GHz
Channel 5, f = 144.5 GHz
Channel 6, f = 147.5 GHz

Rational surface rs

180°
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”

  \[ f_{EC, \text{tearing mode}} \, \text{GHz} \]

  **Clock-rate computation on FPGA:**

  16 µs

Estimate of mode location in the ECE spectrum for a given launcher orientation
- Match actuator frequency 140 GHz with sensor frequency $f_{EC, \text{tearing mode}}$ through launcher steering (elevation angle $\theta$)
Real-time control loop

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

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  - Feed-forward for friction compensation

Performance:
- Response: $\theta = \pm 30^\circ$ in 100 ms
- Max. steady-state positioning error: 0.6°
- Bandwidth: 12 Hz
Real-time control loop

- Tearing mode “tracking” loop

**Launcher control loop:**

- Sample rate on FPGA: 5 kHz, bandwidth: 12 Hz
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]
  - $C_{tearing mode}(s) = \text{PI controller} + \text{low-pass filter}$

**Launcher control loop:**
- Sample rate on FPGA: 5 kHz,
  bandwidth: 12 Hz

**Tearing mode identification:**
- $100 \text{ kHz DAQ}$
- Clock rate identification algorithm on FPGA: 16 $\mu$s
Experimental Results

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

- $\theta_{\text{initial}} = 5^\circ$
- $B_t = 2.25$ 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
Experimental Results

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

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

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

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

Alignment reached within 100 ms after controller activation:

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

Alignment accuracy $< 1 \, \text{cm}$
Experimental Results

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

\[ \theta_{\text{initial}} = 5^\circ \]
\[ B_t = 2.25 \text{ T} \]
\[ I_p = 300 \text{ kA} \]

- Continuous ECRH/ECCD 200 kW, \( t = 3\text{-}4 \text{ sec.} \)
- DED triggered \( m/n = 2/1 \) mode

- Controller active from \( t = 2\text{-}5 \text{ sec.} \)
- Mode suppressed at \( t = 3.085 \text{ sec.} \)
Experimental Results

Next: Tearing mode tracking experiment

Ramp in toroidal magnetic field $B_t$

$\rightarrow$

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 $\sim 6^\circ$ up
Experimental Results

- 2/1 tearing mode tracking experiment

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

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

- Controller active from $t = 2-5 \, \text{sec.}$
- Alignment maintained during $B_t$ ramp
Experimental Results

- 2/1 tearing mode tracking experiment

- $\theta_{\text{initial}} = 5^\circ$
- $B_t = 2.25-2.15$ 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 $B_t$ 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**
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)
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)

**PLL**: operational domain: 300 Hz - 5 kHz
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)

Note: focus on O-point by adding constant phase shift $\Delta \phi$
Experimental Results

- Synchronous ECRH/ECCD modulation on O-point

- $\theta_{\text{fixed}} = 10^\circ$
- $B_t = 2.25$ 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

![Graph showing experimental results]

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Experimental Results

- Synchronous ECRH/ECCD modulation on O-point

![Graphs showing experimental results with time T = 2.01-2.02 [s] and T = 2.51-2.52 [s].]
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 ?