FOM-Institute for Plasma Physics Rijnhuizen

Association Euratom-FOM

Feedback control of ECRH for MHD mode stabilization on TEXTOR

Bart Hennen

Tuesday, 25 November, 2008

Technische Universiteit Eindhoven University of Technology

JÜLICH FORSCHUNGSZENTRUM

Trilateral Euregio Cluster TEC

With contributions from:
E. Westerhof, M. de Baar, J.W. Oosterbeek, G.W. Spakman,
D. De Lazzari, A. Bürger, E.M.M. Demarteau, P.W.J.M. Nuij,
M. Steinbuch, and the TEXTOR-Team

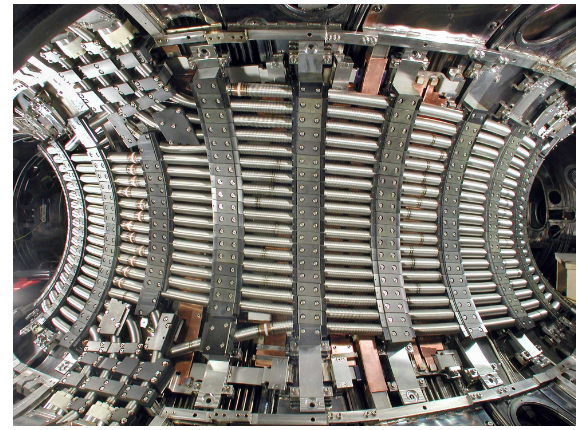
MHD stabilization

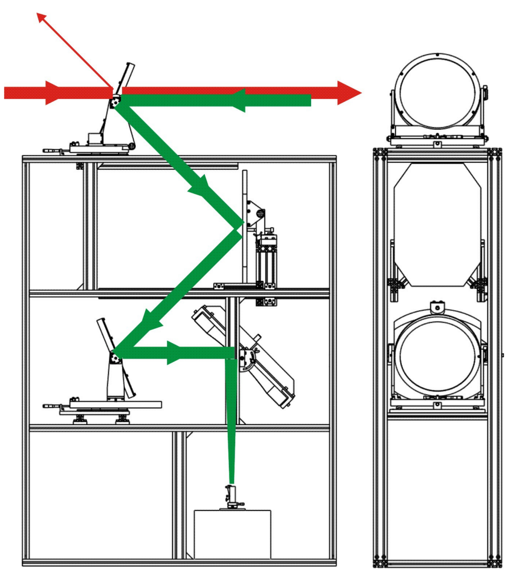
- Objective: Control of MHD modes
  - Magnetic islands (& sawteeth)
  - Preserve confinement & avoid disruptions
- Efficient & adequate ECRH / ECCD:
  - Fast & accurate mode detection
  - Alignment of ECRH power dep. w.r.t. mode (“tracking”)
  - Synchronize power modulation w.r.t. mode rotation
  - ‘Power-efficient’ ECRH application
- Feedback control:

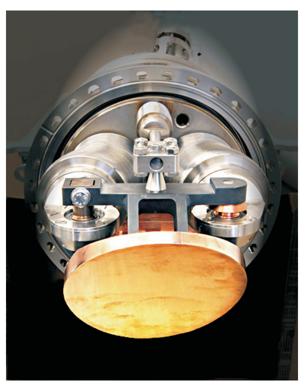
  guarantees fast response, accuracy, robustness and stability

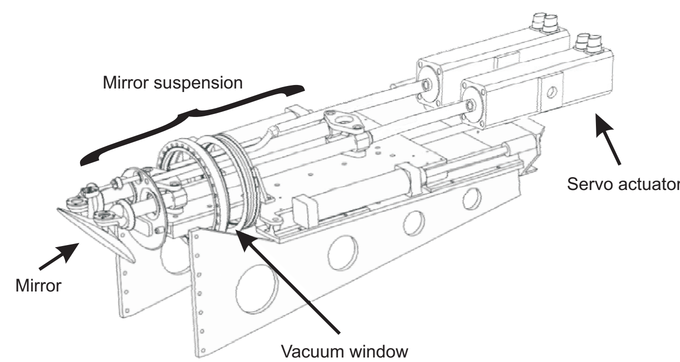
TEXTOR ECRH installation

- Major components:
  - DED generation of magnetic islands
  - Fast & flexible launcher
  - Gyrotron 140 GHz, 800 kW, 10 s
  - Line-of-sight ECE diagnostic
  - Real-time control & DAQ electronic hardware

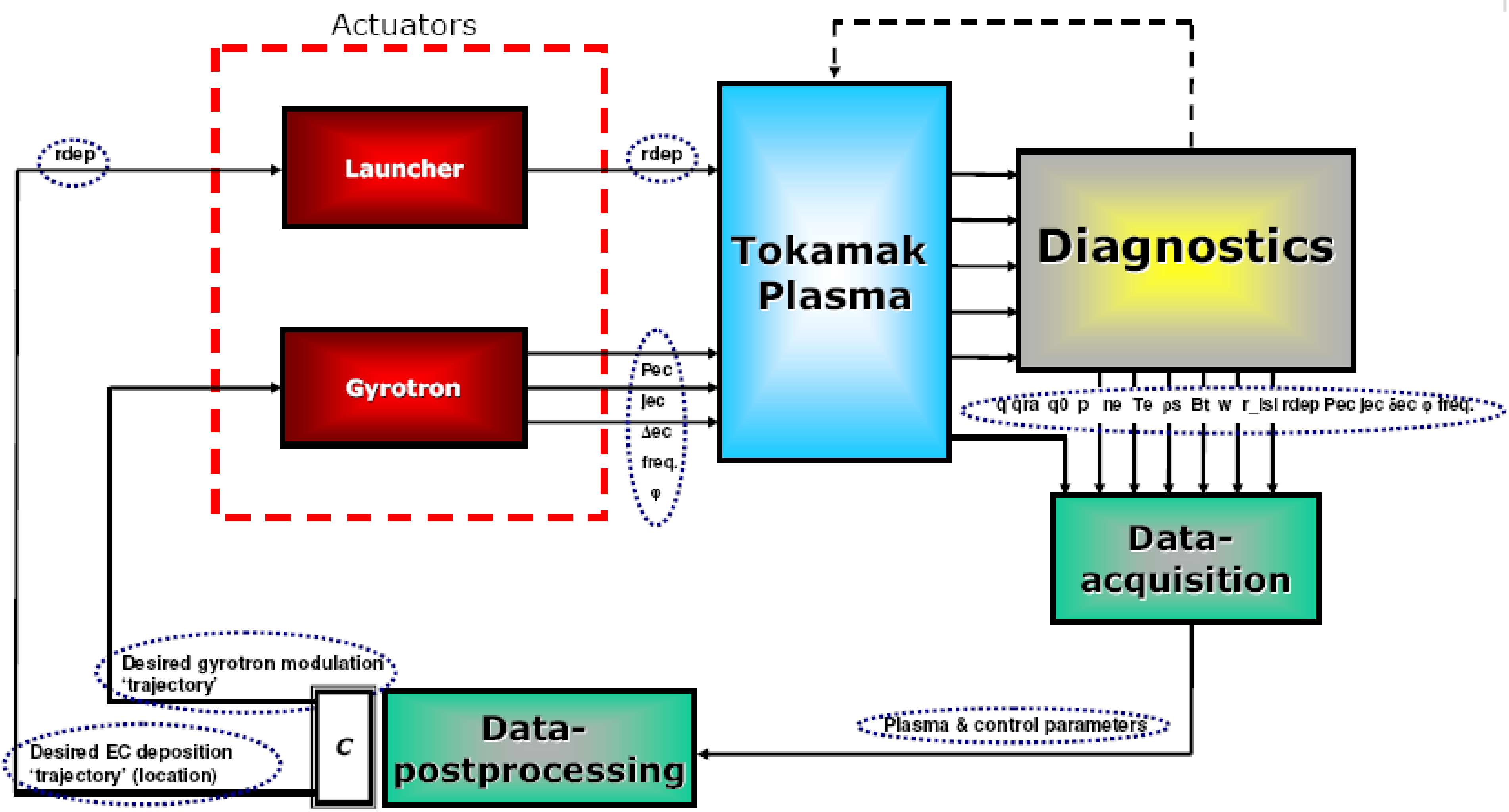








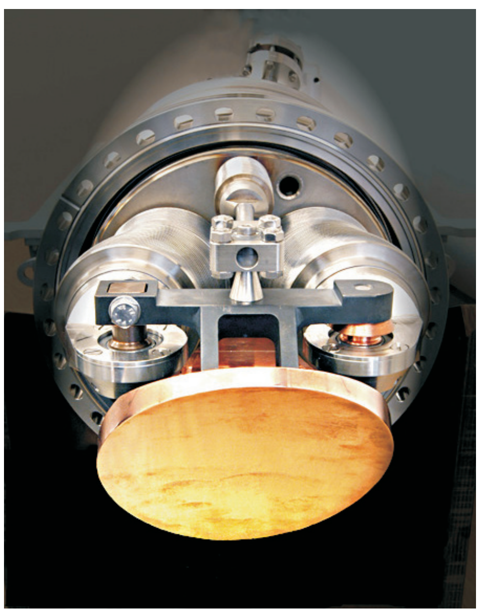
TEXTOR ECRH installation

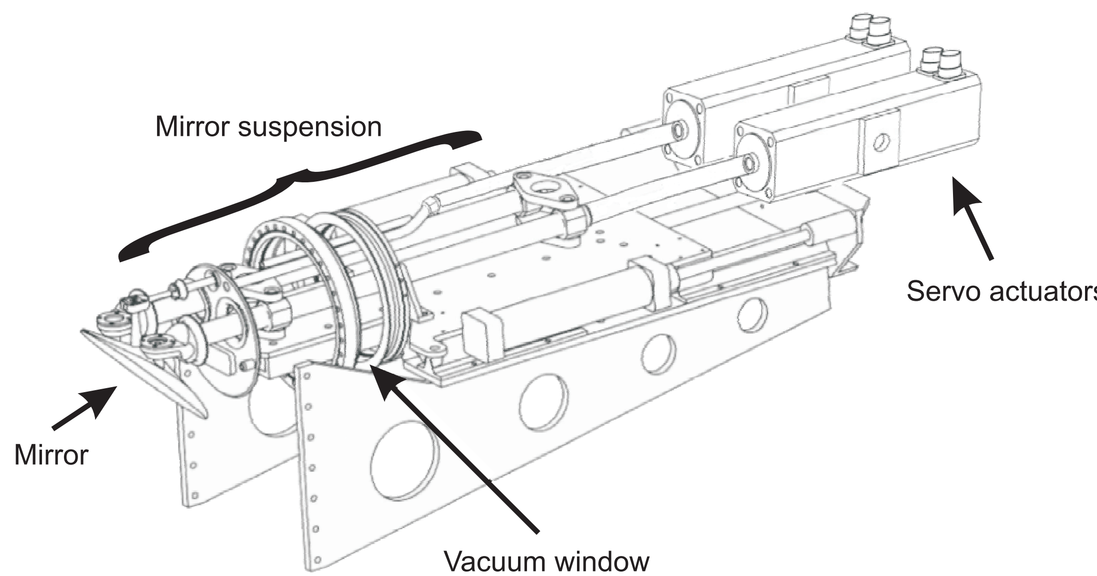


Intermezzo: Launcher

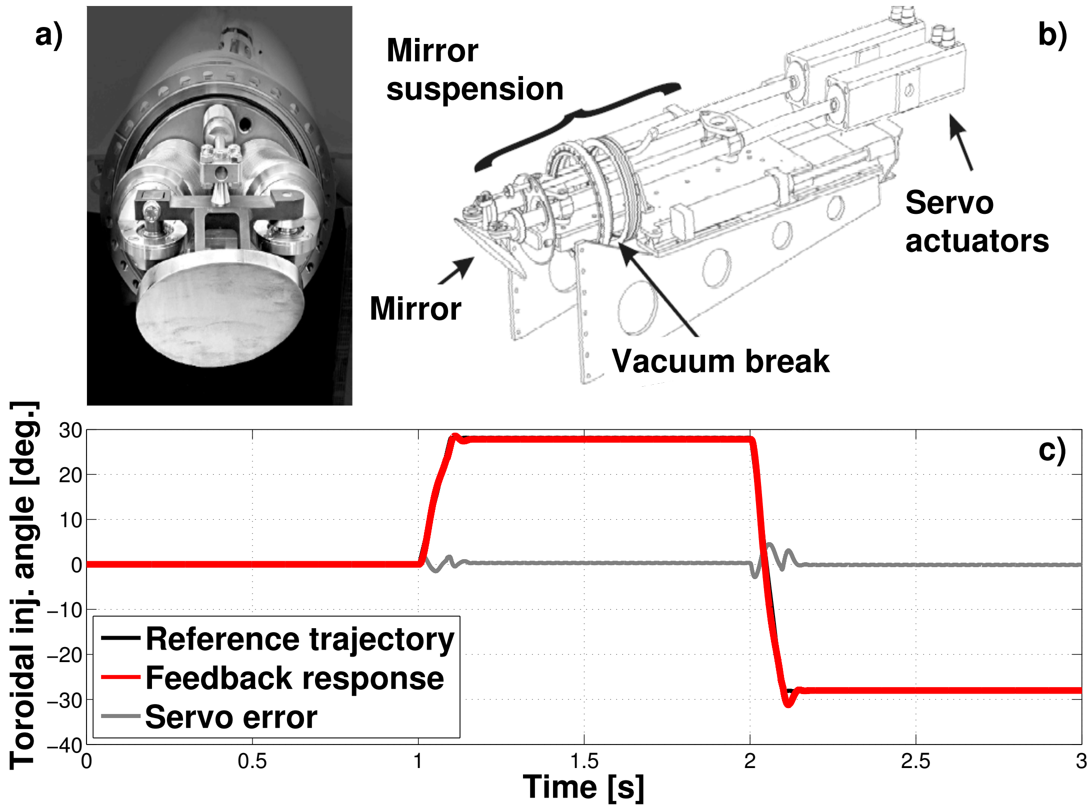
- Analysis of dynamics using Frequency Response Function measurements
- Design of feedback + feedforward control structure

  (PID + Lead/Lag + Low-pass filter)
- Analysis of stability robustness & performance in simulation
- Real-time control implementation & performance assessment on mock-up of the actual launcher





Intermezzo: Launcher

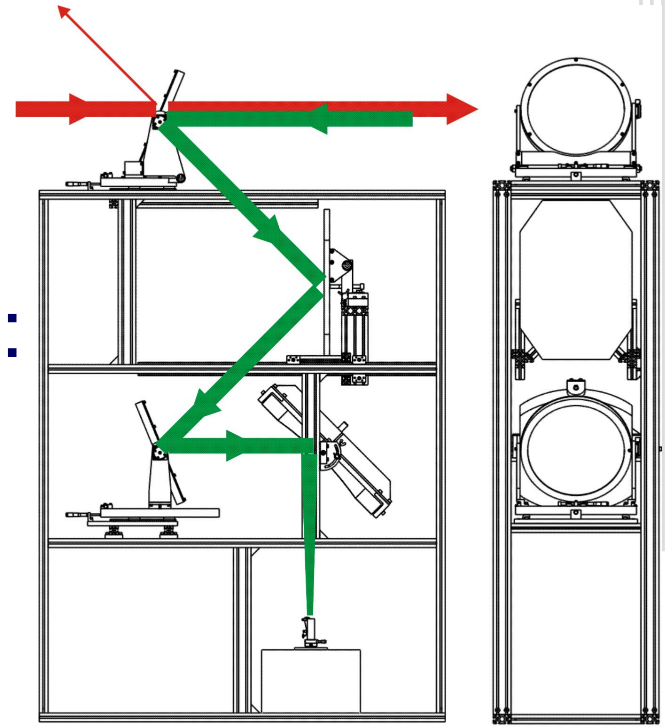


Feedback + feedforward control:

- Speed of response: ~ 56° rotation sweep in 100 [ms] ☺
- Positioning accuracy: 0.6° ☺
- Bandwidth ± 10 Hz

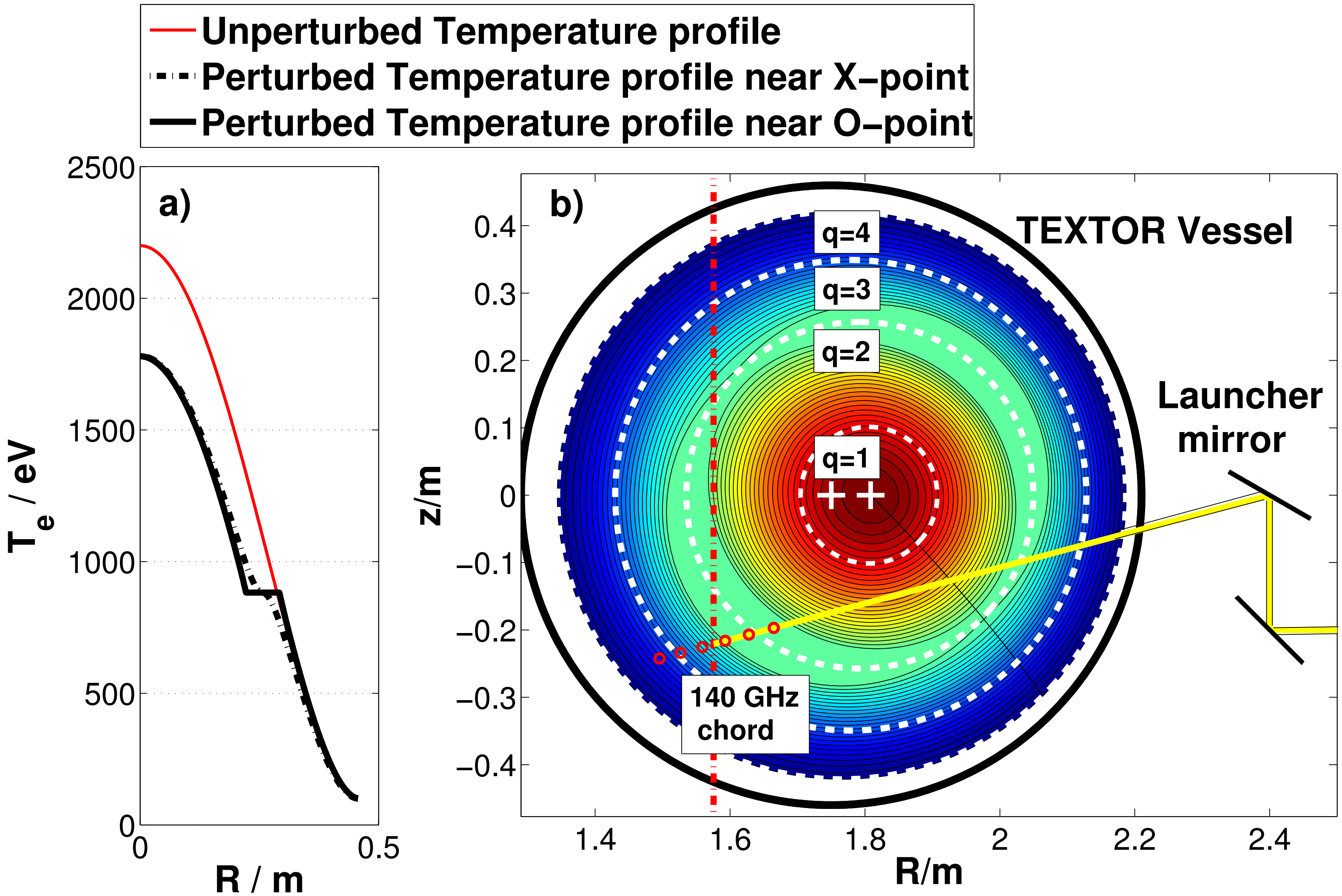
Intermezzo: Line-of-sight ECE diagnostic

- Line-of-sight ECE diagnostic:
  - Dedicated feedback control sensor
- Measure ECE spectrum in the transmission path of ECRH beam:
  - Frequency selective decoupling
  - Power separation



- Advantages:
  - Actuator & sensor operate in same metric frame (refractive properties identical)
  - No need for plasma eq. reconstruction / absolute coordinate mapping

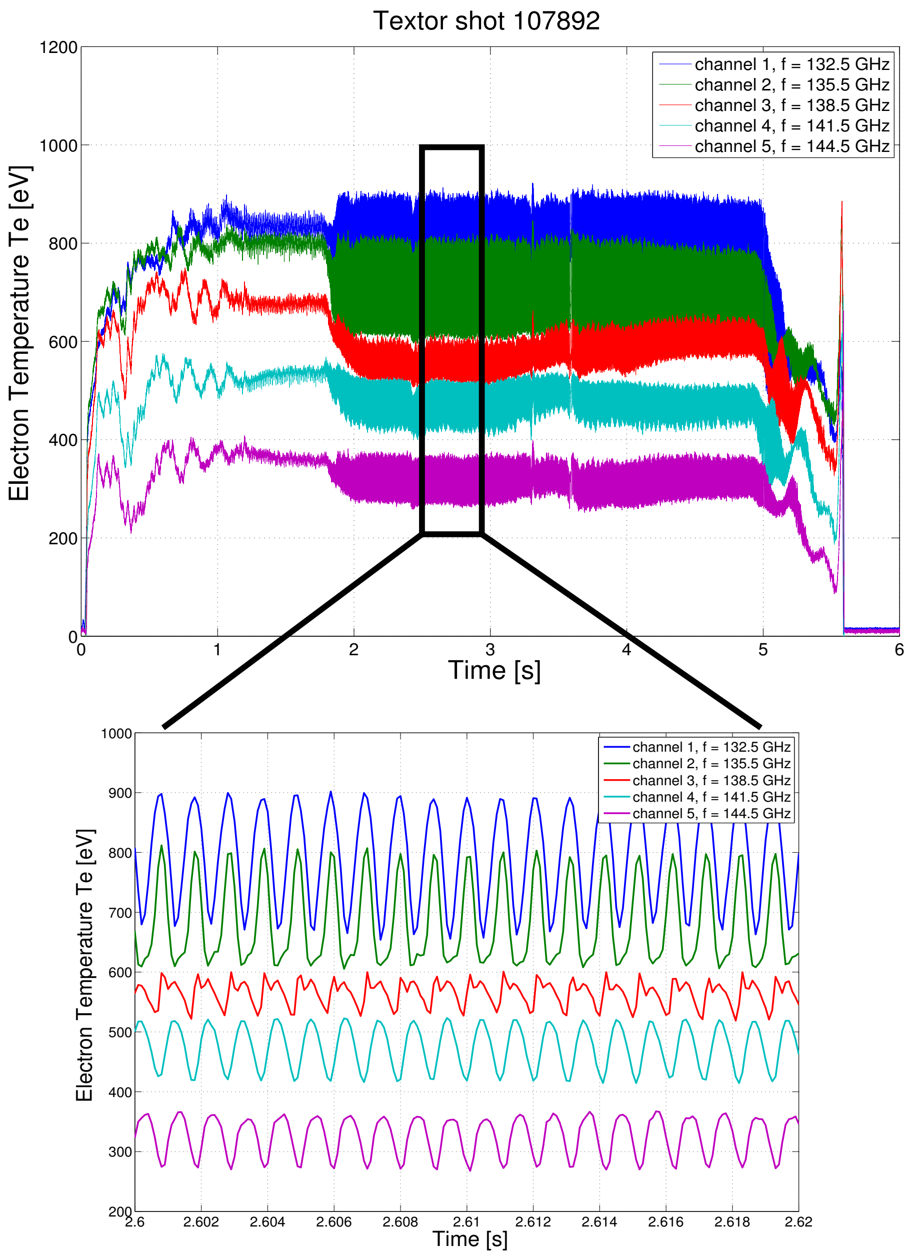
TEXTOR ECRH installation



Island recognition without ECRH

- Island recognition in ECE spectrum

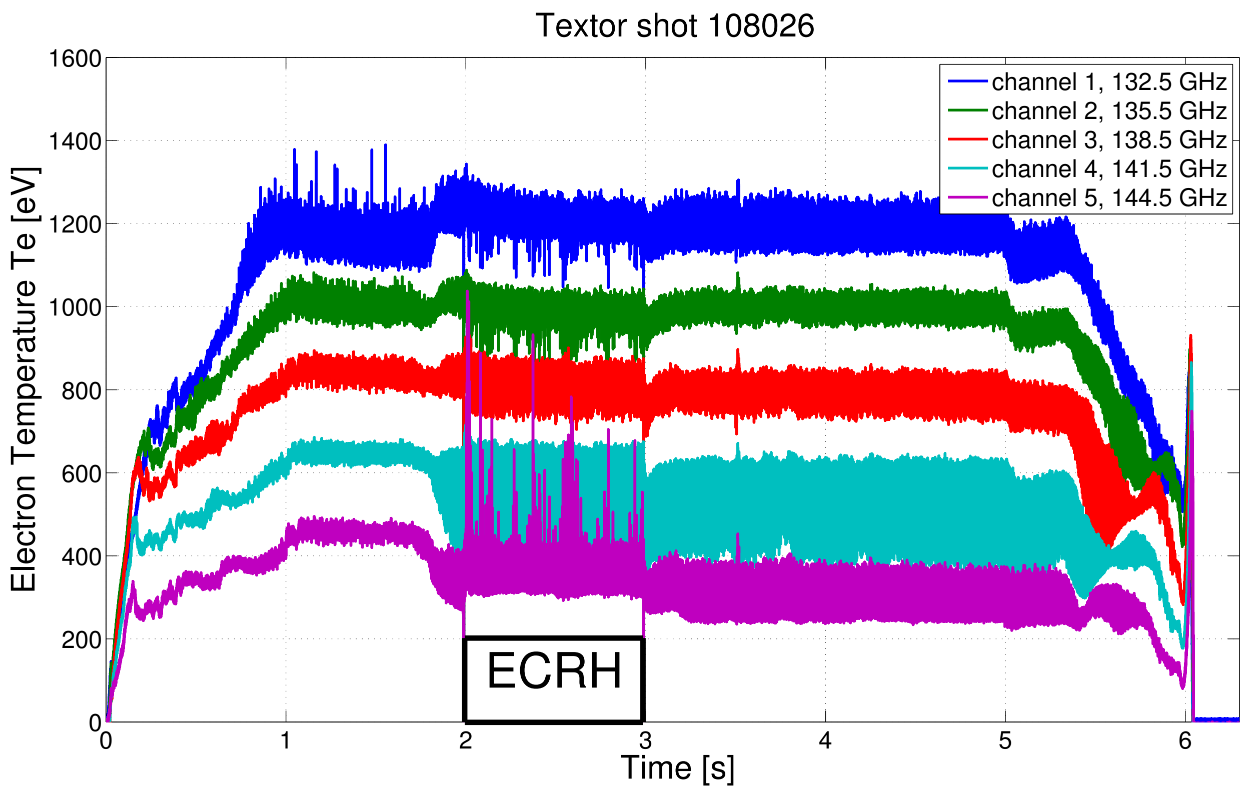
  - DED induced m/n = 2/1 island
  - launcher elevation @ 9°
  - island recognized between 135.5 GHz & 141.5 GHz



Island recognition with ECRH (200 kW CW)

- Island recognition in ECE spectrum

  - DED induced m/n = 2/1 island
  - launcher elevation @ 2°



Derivation of island control parameters

- Island control parameters:

  Radial location & rotation frequency / phase
- Generate reference trajectories for launcher and gyrotron in real-time
- Available hard- & software
  - NI PXI DAQ & RTC (FPGA based, Labview)
  - MATLAB / Simulink

Derivation of island control parameters

Fast mode detection from ECE fluctuations:

1. Subtract running averages $$\tilde{X}_{n,c} \equiv X_{n,c} - \frac{\sum_{i=n-N+1}^{n} X_{i,c}}{N}$$

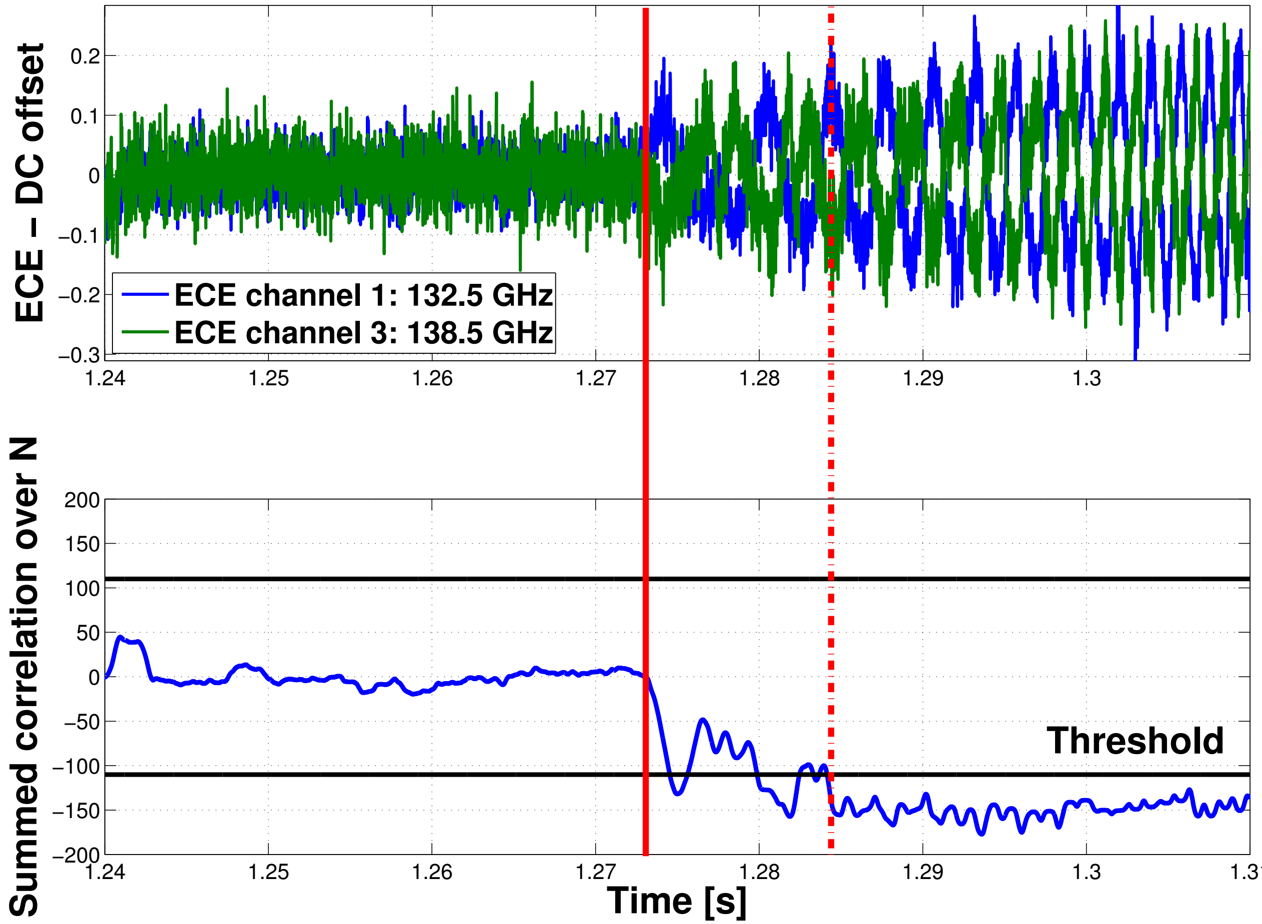
2. Normalize $$\tilde{X}_{n,c} \rightarrow \overline{X}_{n,c} \equiv \tilde{X}_{n,c} / | \tilde{X}_{n,c} |$$

3. Correlate $$C_{a,b}^{n} \equiv \sum_{i=n-N+1}^{n} \overline{X}_{i,a} \cdot \overline{X}_{i,b}$$

4. Localized between channels for which correlator is below threshold

Derivation of island control parameters

Fast mode detection from ECE fluctuations:



Real-time implementation: discrete FIR filter (running sum low-pass filter)

Derivation of island control parameters

Instantaneous frequency detection from ECE fluctuations:

1. Hilbert transform of real-valued function:
   Fourier Transform → 90° phase shift → Inverse FFT

$$X_r(t) \rightarrow \hat{X}(t)$$

2. Analytical signal:

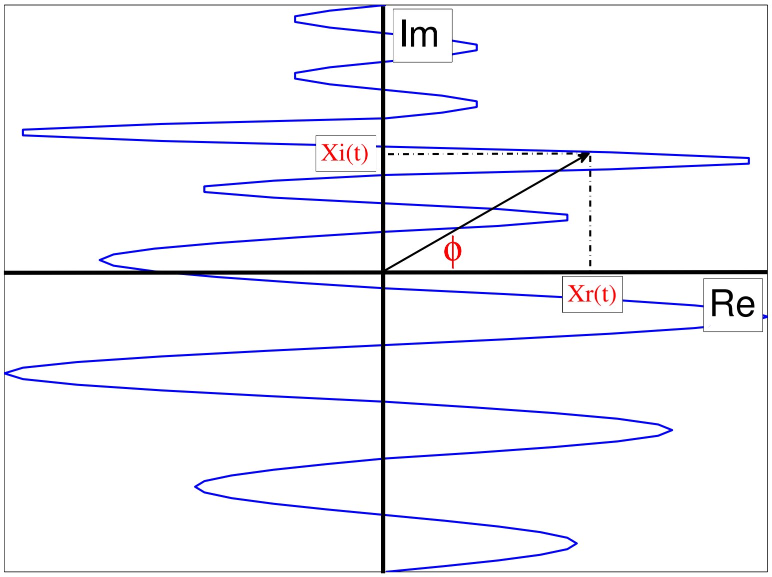
$$X(t) = X_r(t) + i \cdot \hat{X}(t)$$

3. Instantaneous phase:

$$\phi(t) = \tan^{-1}\left(\frac{\hat{X}(t)}{X_r(t)}\right)$$

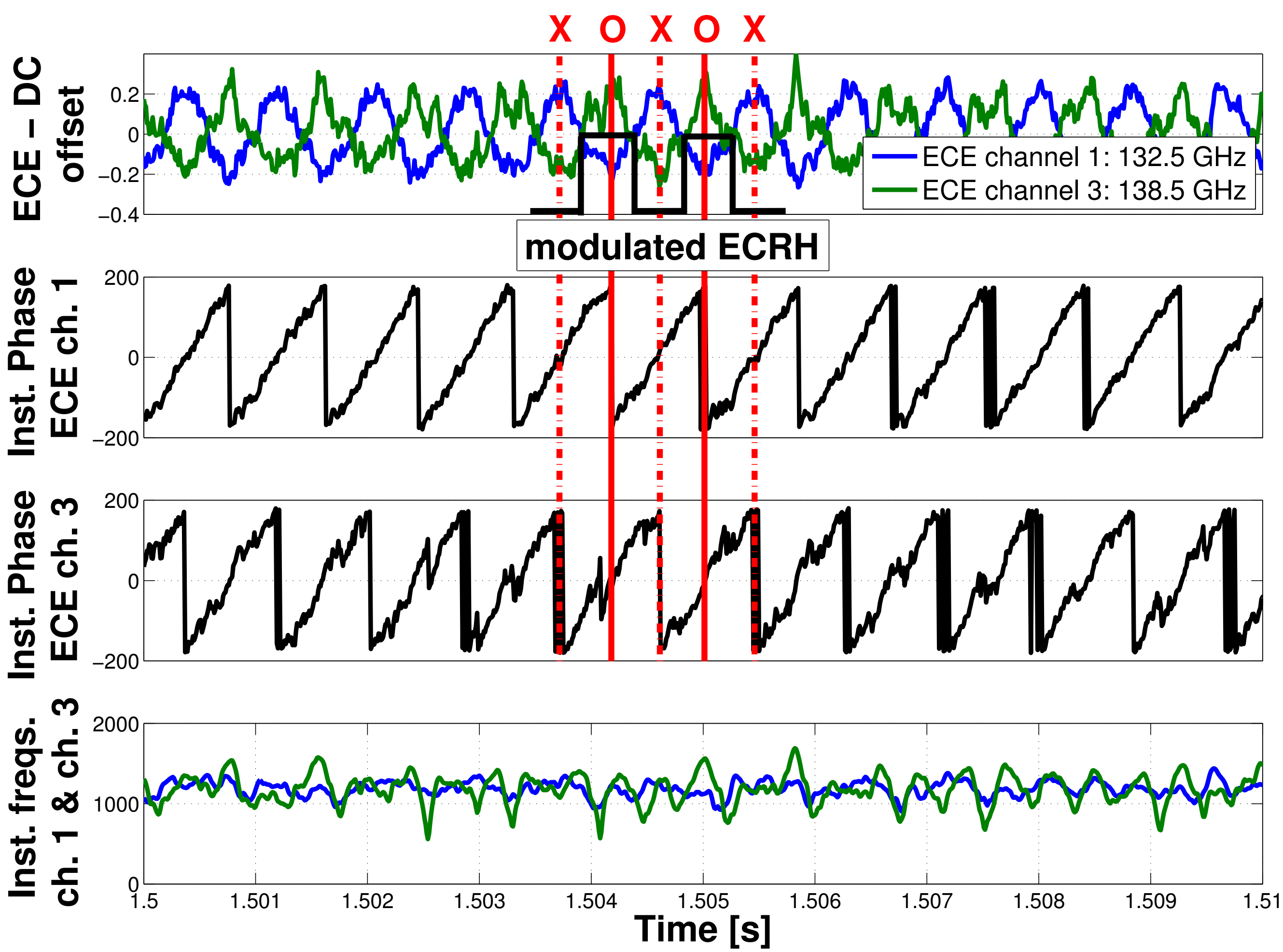
4. Instantaneous frequency:

$$f(t) = \frac{1}{2\pi}\frac{d\phi}{dt}$$



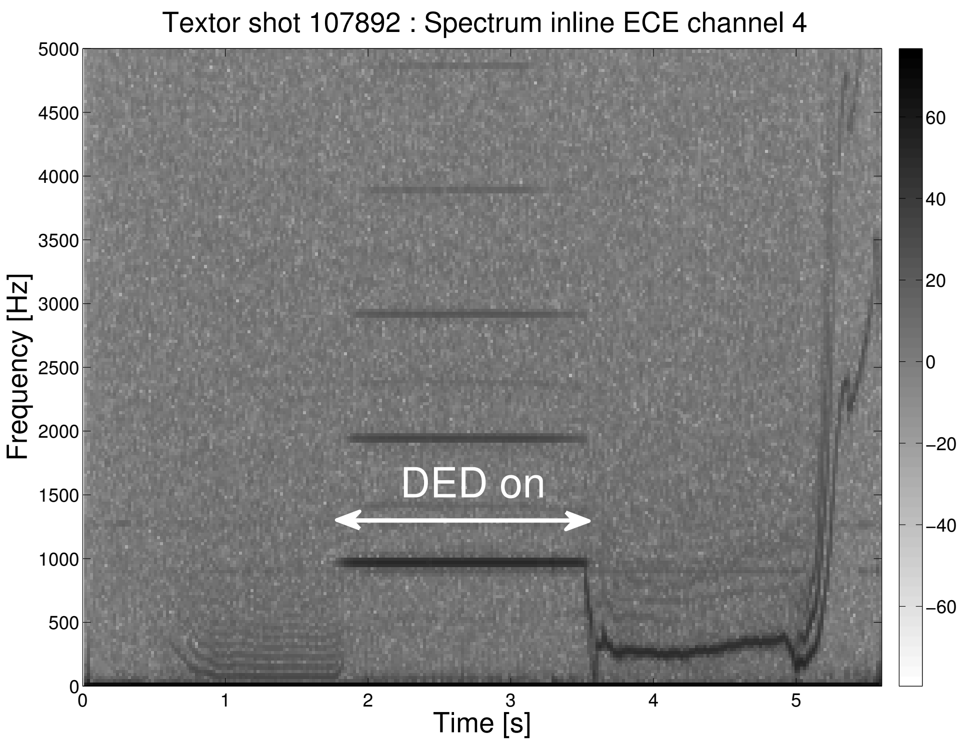
Derivation of island control parameters

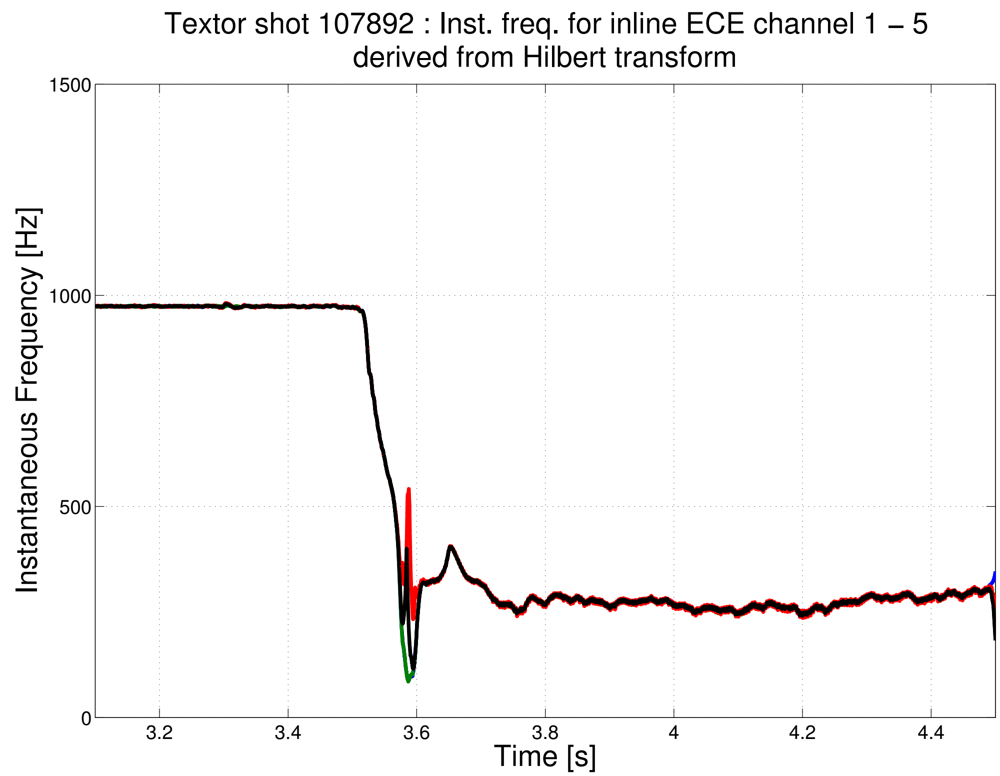
Instantaneous frequency detection from ECE fluctuations:



Derivation of island control parameters

Instantaneous frequency detection from ECE fluctuations:



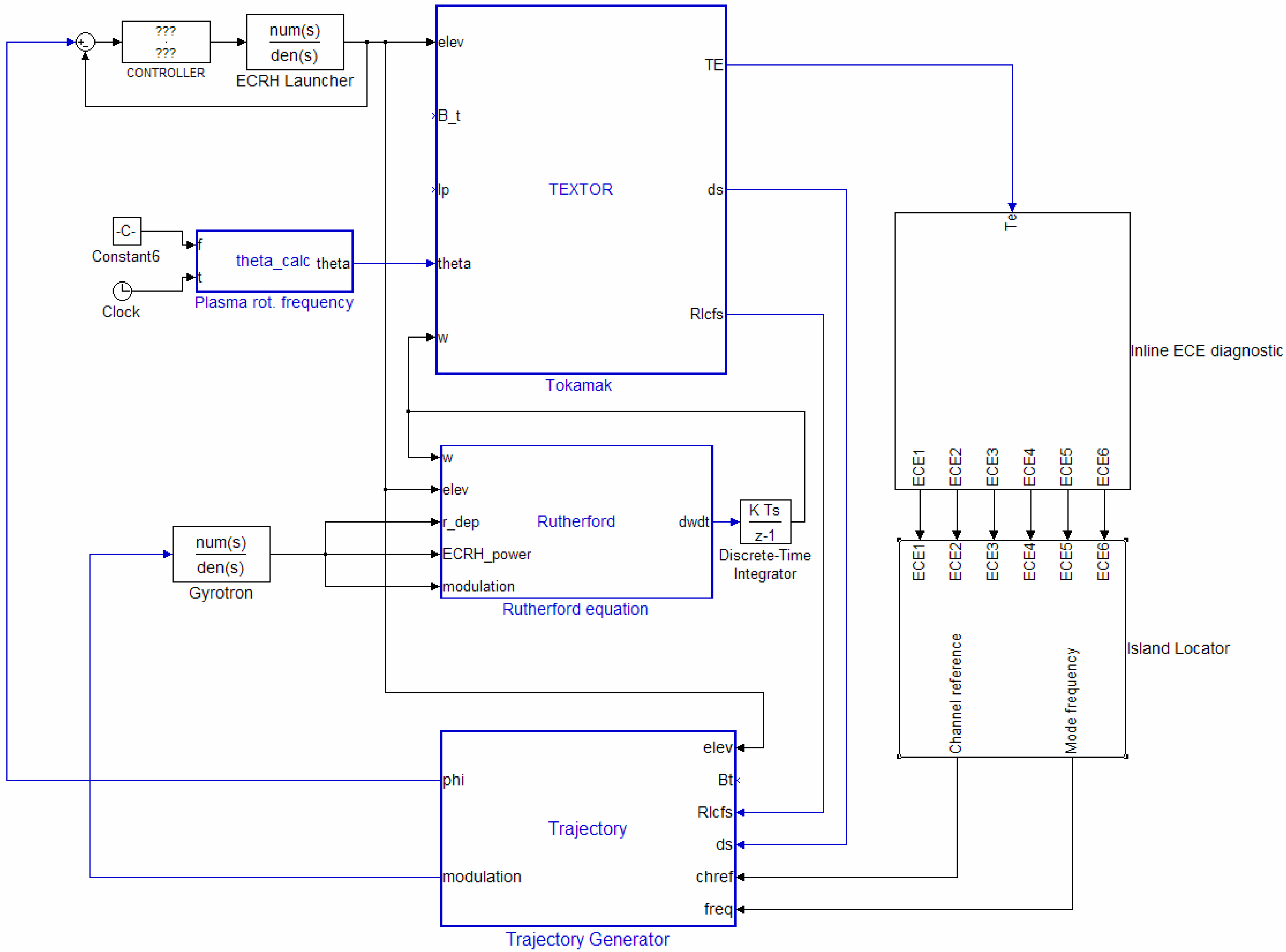


- Synchronization of ECRH power modulation w.r.t. island rotation frequency → Repetitive Control

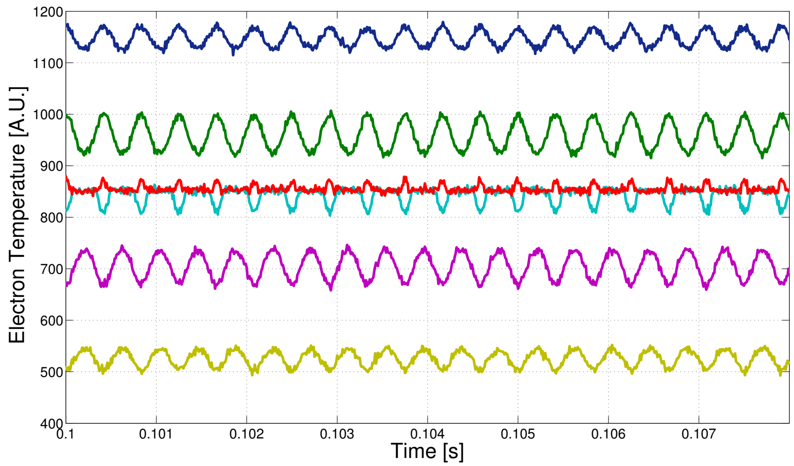
MATLAB / Simulink modeling

- Simplified plasma equilibrium (circular)
- Perturbed Electron Temperature profiles
- Synthetic line-of-sight ECE data
- Modified Rutherford equation:
  - Including efficiency terms for Heating & Current Drive
  - Including radial misalignment, deposition profiles, duty cycle modulation
- Trajectory generators (based on mode/freq. detection)
- Actuator models (launcher & gyrotron)
- Feedback loops

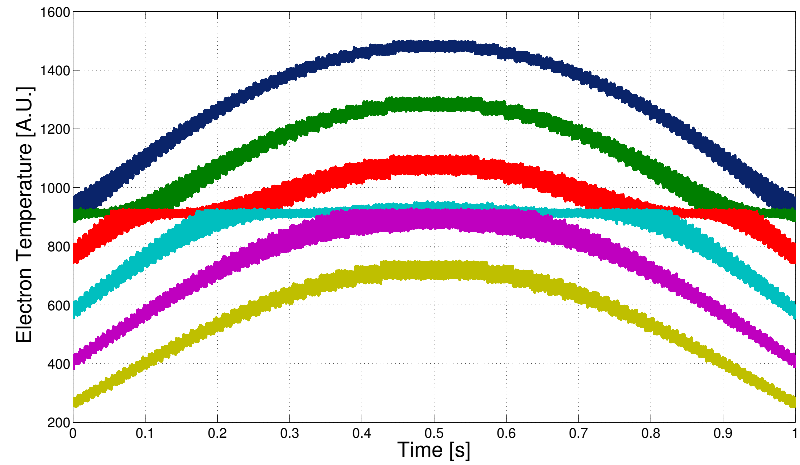
MATLAB / Simulink modeling



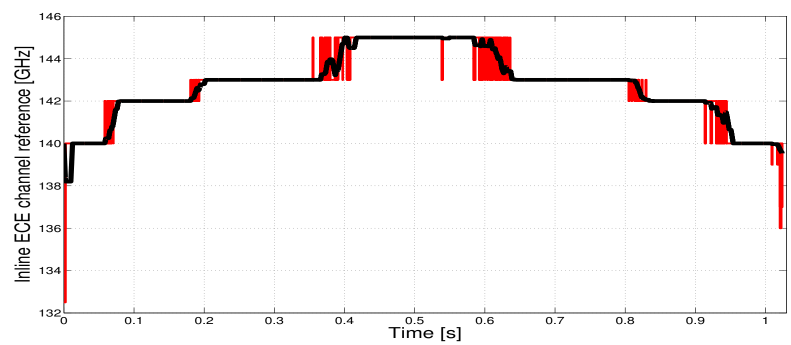
MATLAB / Simulink modeling



- Launcher elev.: ~ -9 °
- Island width: ~ 8 cm
- Bt = 2.25 T, Ip = 300 kA



- Launcher elev. scan:
  ~ -15 ° to 15 °
- Island width: ~ 8 cm
- Bt = 2.25 T, Ip = 300 kA
- Channel reference signal derived with mode detection algorithm



Summary & outlook

- TEXTOR well equiped for MHD feedback control experiments (DED, optimally controlled launcher, line-of-sight ECE)
- Capabilities of line-of-sight ECE diagnostic for integrated mode detection, phase tracking and ECRH launcher steering demonstrated
- Fast island detection algorithmes based on correlation techniques applied
- Instantaneous frequency & phase detection for synchronized gyrotron modulation applied
- Simulink model development for model-based controller design

Summary & outlook

What comes next:

- Integrated feedback control simulation
- Installation / implementation control hardware
- Experimental validation of the control algorithms

Thanks for your attention!

QUESTIONS?