Real-time control of tearing modes and current density profile in TCV

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Federico Felici

O. Sauter, T.P. Goodman, S. Coda, B.P. Duval, J-M. Moret, J.X. Rossel, J.I. Paley
and the TCV team

CRPP-EPFL, Association Euratom-Suisse, CH-1015 Lausanne Switzerland

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http://crpp.epfl.ch
federico.felici@epfl.ch

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Outline and summary

- Part I: Studies of effects of ECRH/ECCD on tearing mode creation and stabilization using real-time control
  - Tearing modes created on TCV by global *q* profile evolution via deltaprime effects.
  - Experiments using real-time control were performed to study the effect of localized ECCD on the island.
  - Results point towards dominant effect of heating with some specific effects due to current drive.

- Part II: Real-time simulation and control of current density profile
  - Implemented on TCV with closed loop experiments performed.

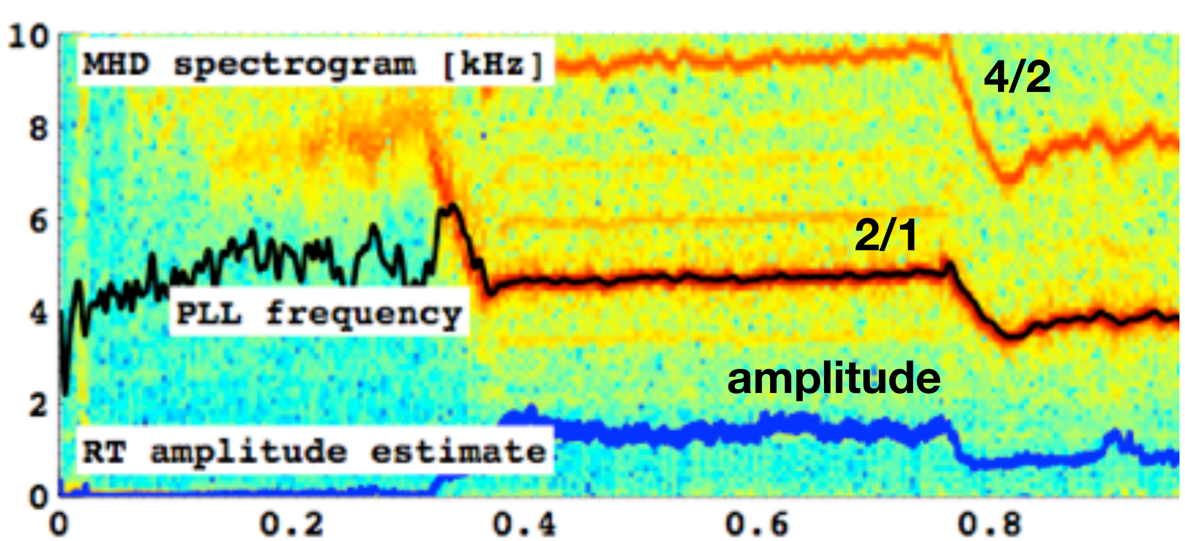
- Part I: Studies of effects of ECRH/ECCD on tearing mode creation and stabilization using real-time control
  - Objective of these experiments: separate direct ECH/ECCD effects on island through Δ'_{CD} and q profile effects through Δ'_0
  - Results of recent experiments, enabled by real-time control system, are presented here. Modeling will be focus of future work.

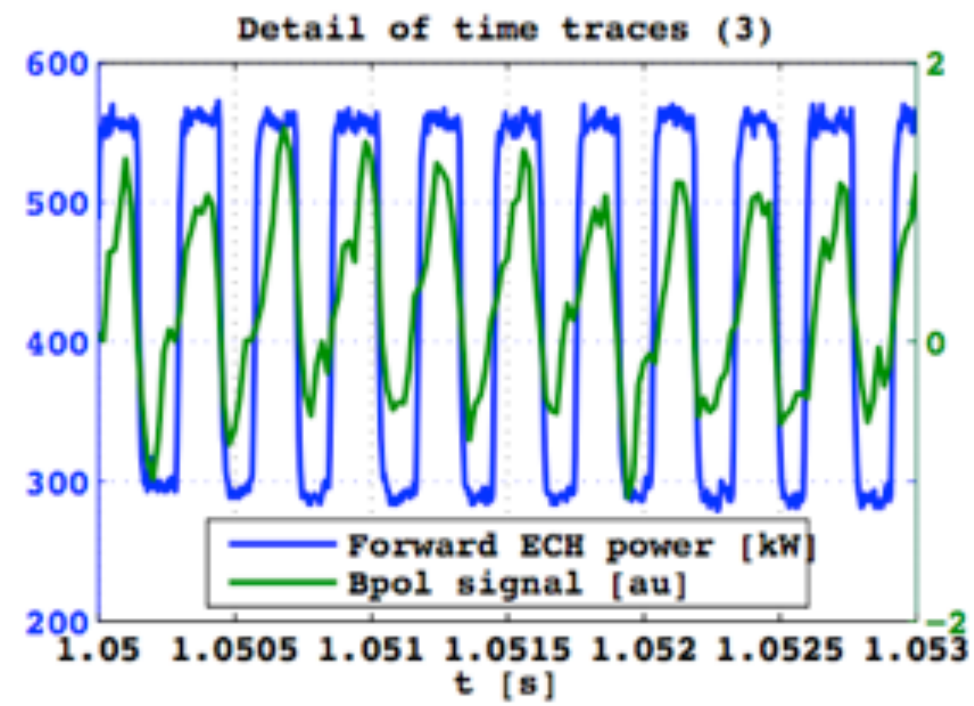
$$\frac{dw}{dt} \sim \boxed{\Delta'_0} + \Delta'_{BS} + \boxed{\Delta'_{CD} + \Delta'_H}$$

affected by ECCD

Recently expanded capabilities for NTM experiments on TCV thanks to new digital real-time control system

- 6 independently real-time steerable EC launchers (500kW each)
- Gyrotron power supply modulation possible, 40-100% duty cycle.
  - 0%-100% for <600ms
- New digital real-time control system is operational
  - Real-time NTM detection
  - Phased Lock Loop (PLL) for in-phase firing
  - Simultaneous control of
    - Mirror position
    - ECCD power
    - Modulation phase
    - Modulation depth
  - Flexible, rapid inter-shot reprogramming using Simulink

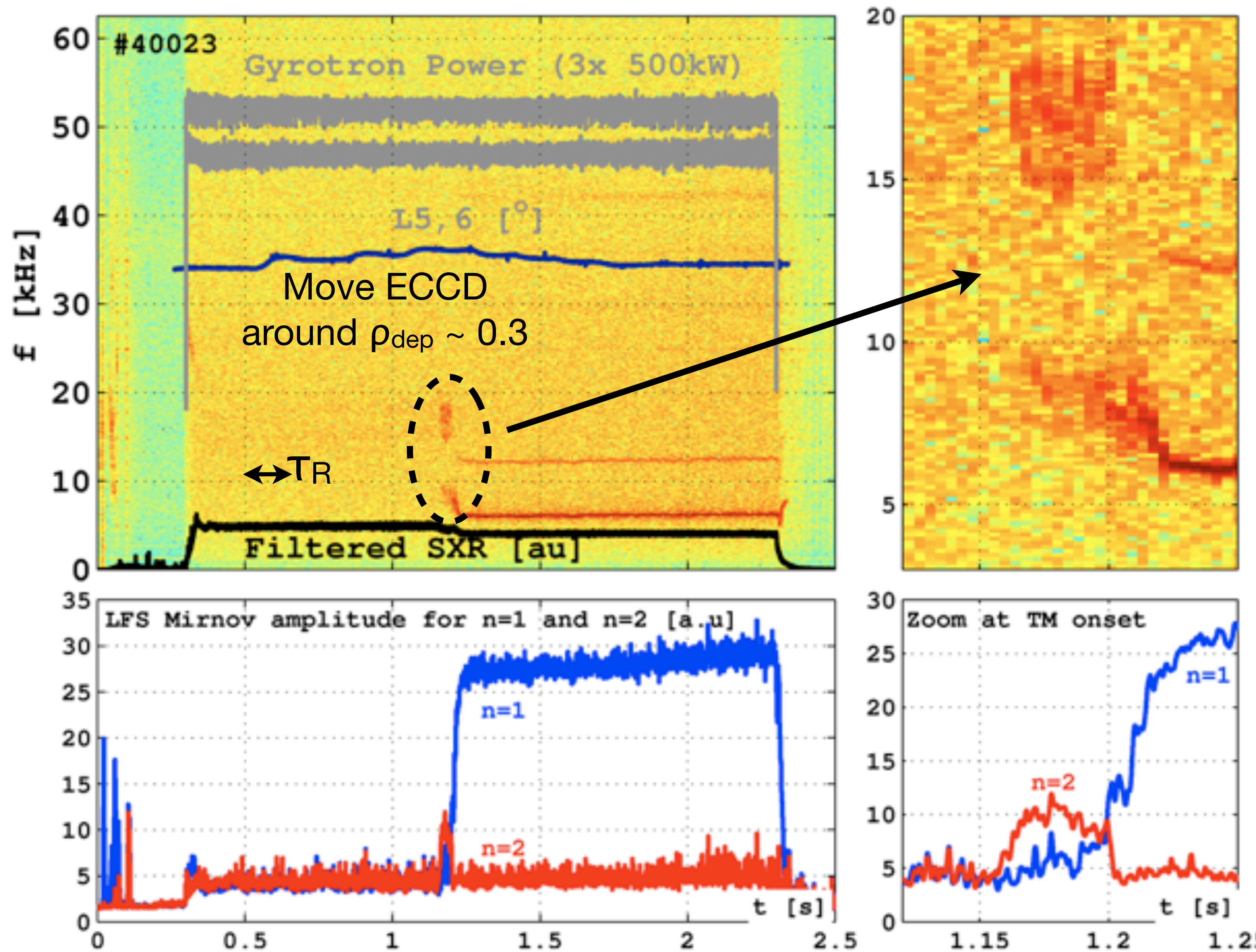




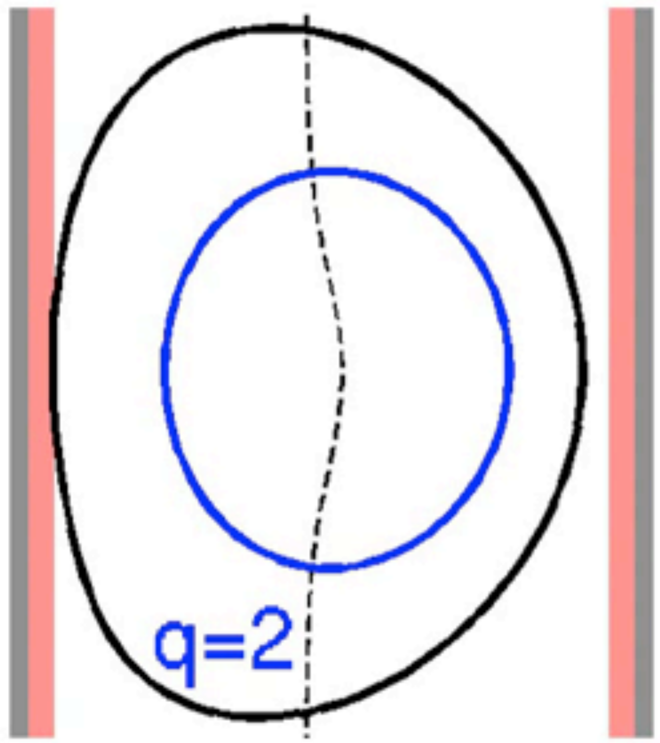
Δ'_0 destabilized modes created on TCV by global *q* profile changes using near on-axis ECCD

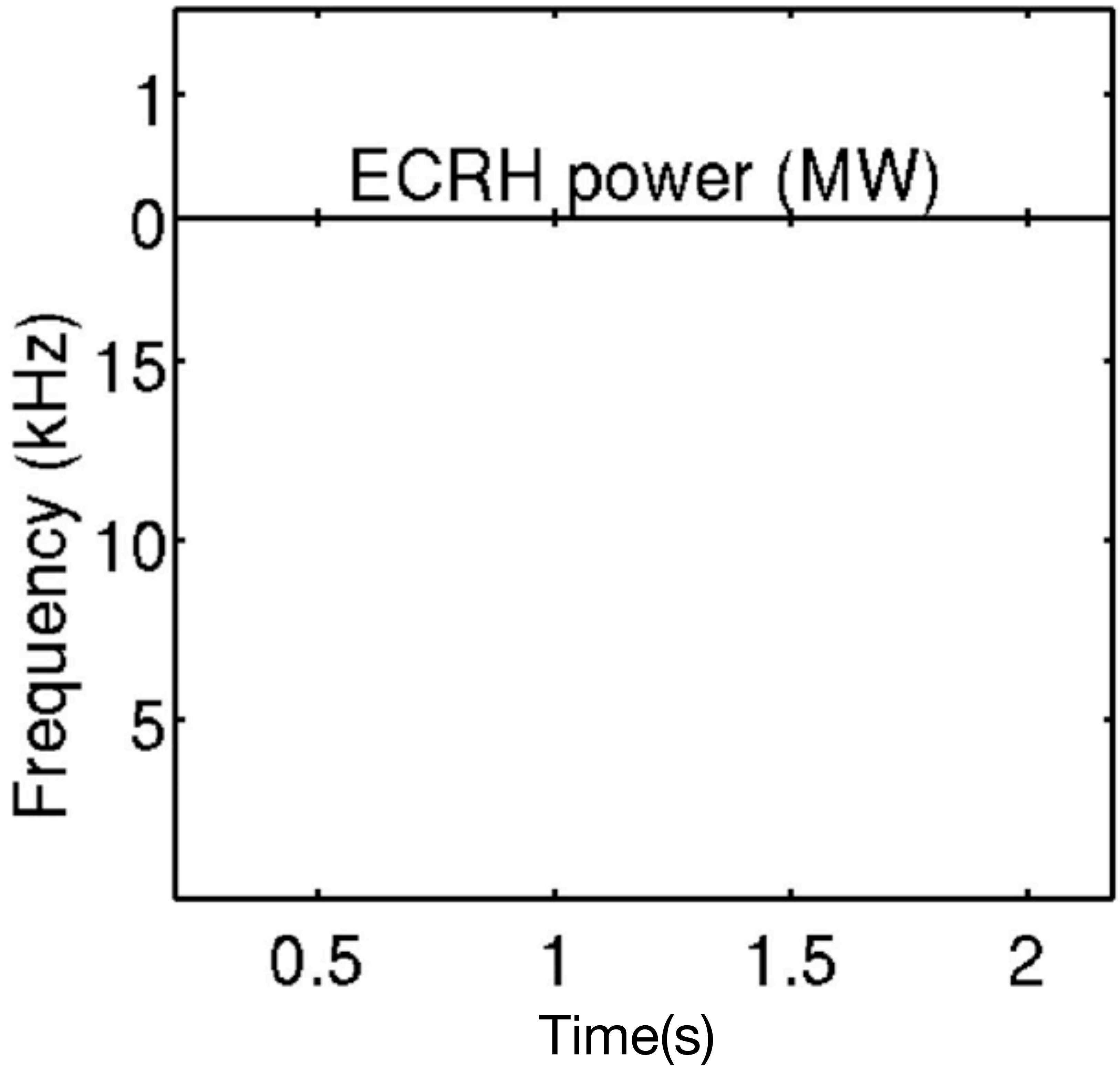
- No clear trigger from sawteeth in these cases
  - Sawtooth triggered NTMs have been seen on TCV with long, large, stabilized sawteeth (not these shots)
- 3/2 mode precursor observed
  - Suppressed by 2/1 growth
- Use these modes as target for stabilization experiments

Typical parameters for these discharges:
I_p=150kA B_T=1.45T q_{95}~ 6
T_{e0} = 3keV n_{e0}= 1.5x10^{19} m^{-3}
β_{pol}~0.7, β_{tor}~0.3%, β_N~0.8
L-mode plasmas

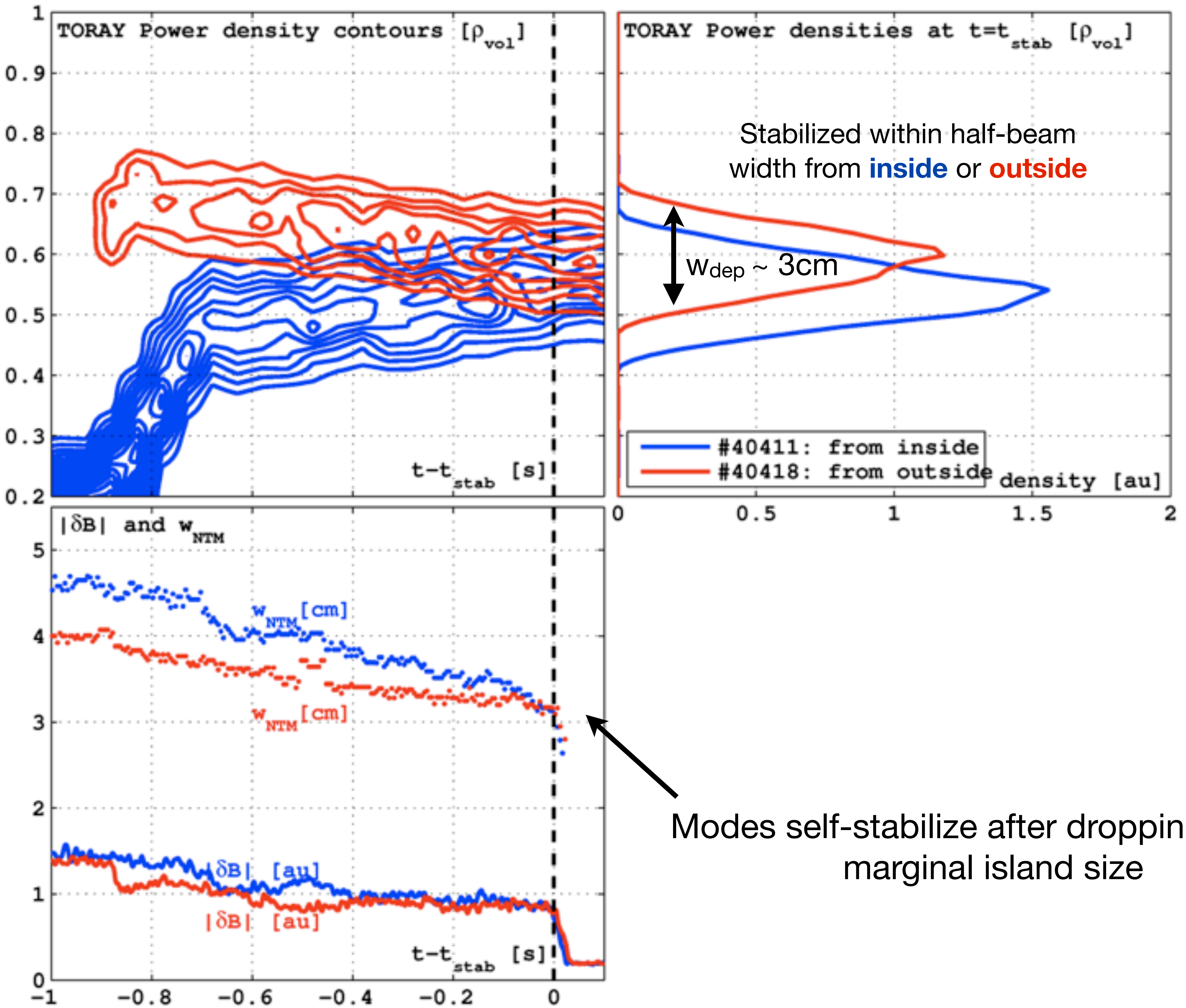


Stabilization by real-time control of ECCD deposition location and power





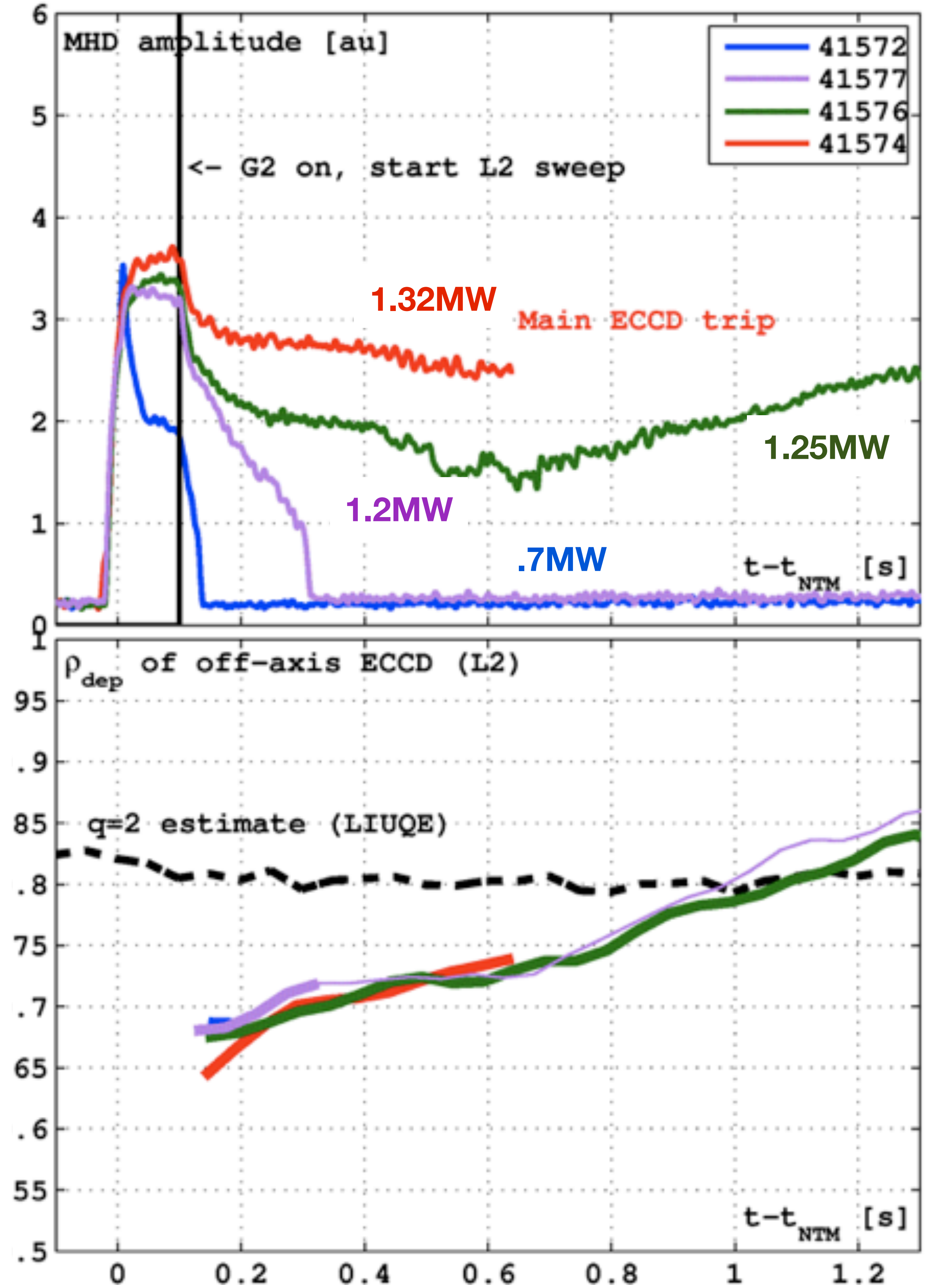
Mode stabilized both from inside and outside q=2 once mode shrunk to marginal island width



j_{ECCD} may we wider due to radial diffusion of fast electrons

Modes self-stabilize after dropping below marginal island size

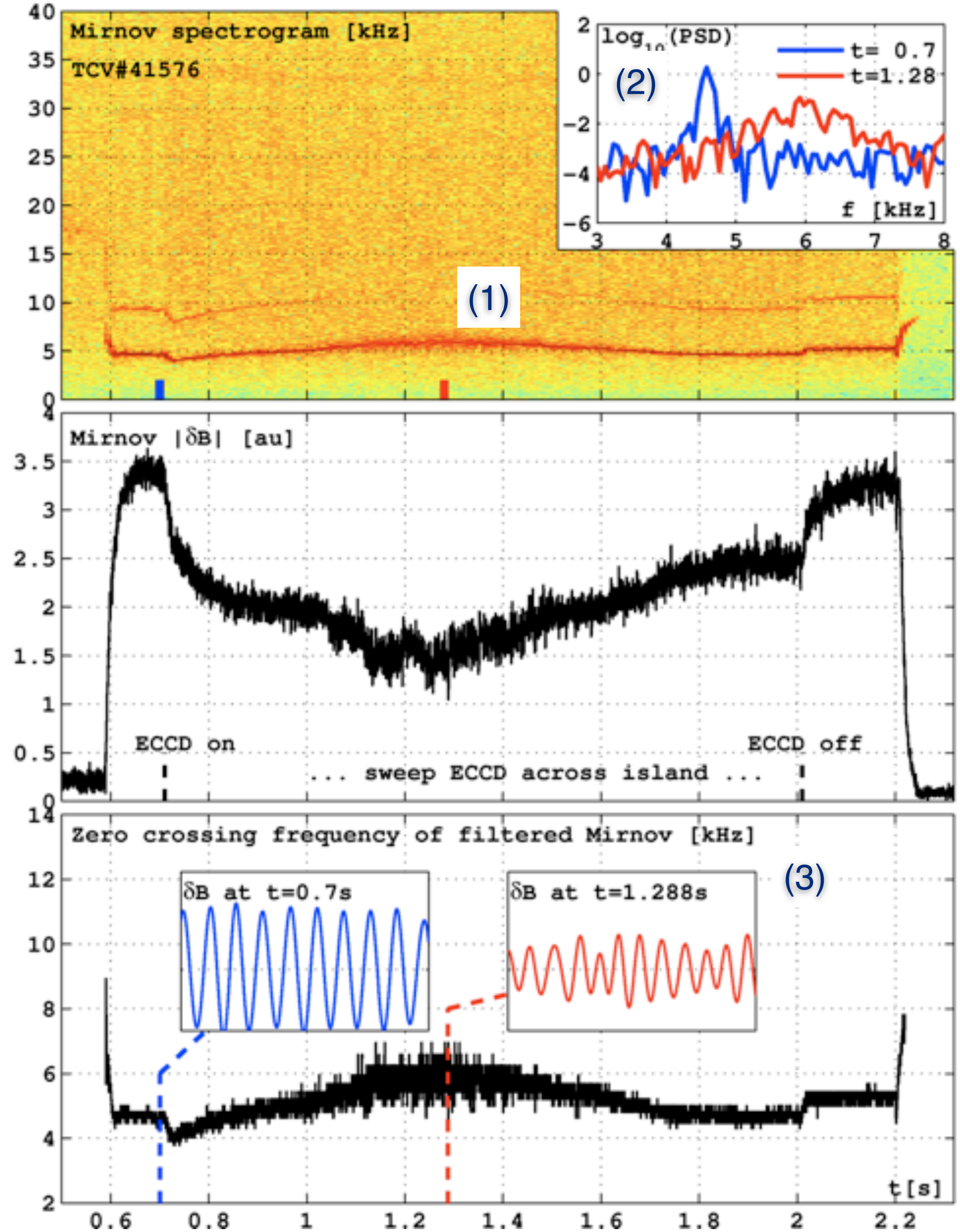
Create modes of varying strength by varying central EC power after TM is triggered



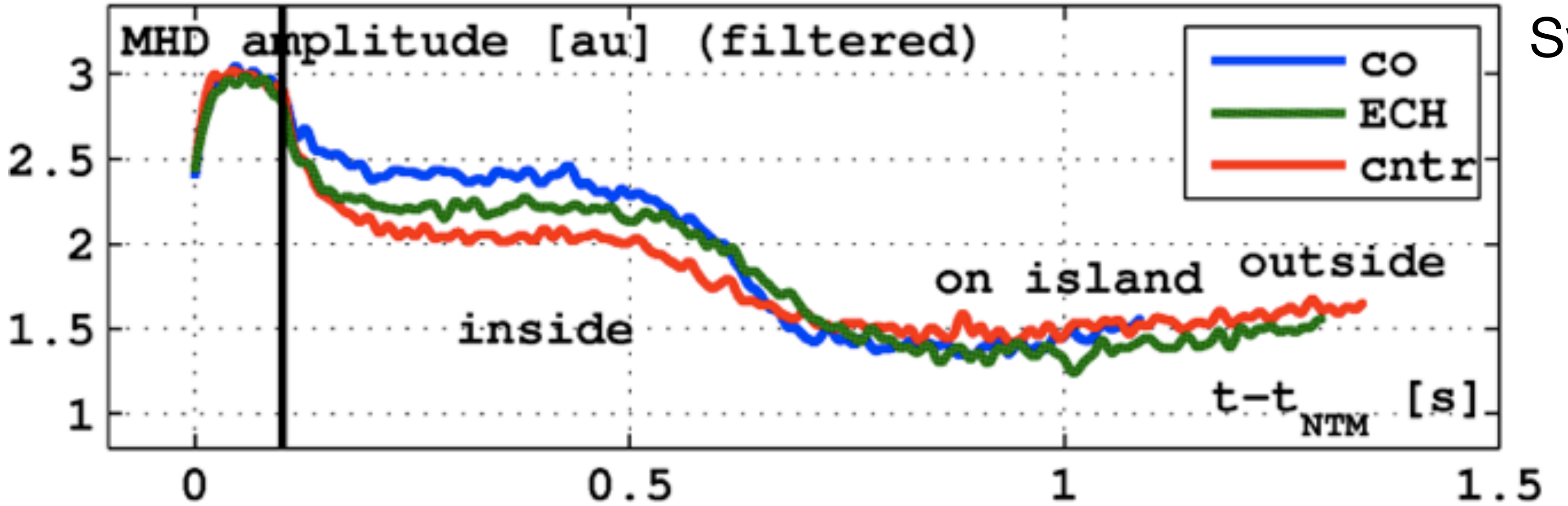
- Can create modes of varying strength by varying central ECCD
- Angle scan across mode -> different response to ECCD close q=2
  - Stabilized immediately upon off-axis EC power on (blue)
  - Stabilized only after longer time (violet)
  - Almost stabilized but not fully, even upon sweep across island (green)
- Marginal case used for subsequent studies

Mode near marginal island size shows increased variance in Mirnov probe oscillation frequency

- "Fuzzy" NTMs near marginal island limit
- Variance of oscill. freq is visible as:
  - (1) "Fuzziness" in spectrogram
  - (2) Broader power spectral density
  - (3) Less regular oscillations in Mirnov
- Also appears in last phases of mode before full stabilization
- Possible consequences for in-phase ECCD modulation
  - Windowing methods not adequate? (FFT)
  - Should use time-based methods? (PLL)
- Seen in other machines?
- Physics origin?

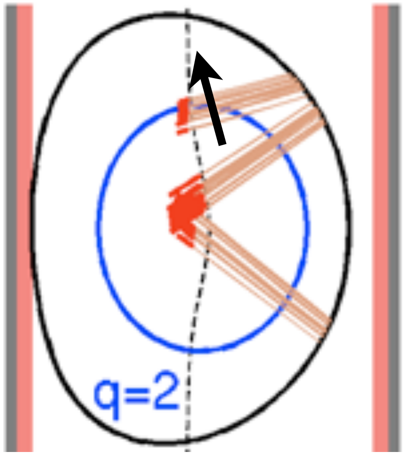


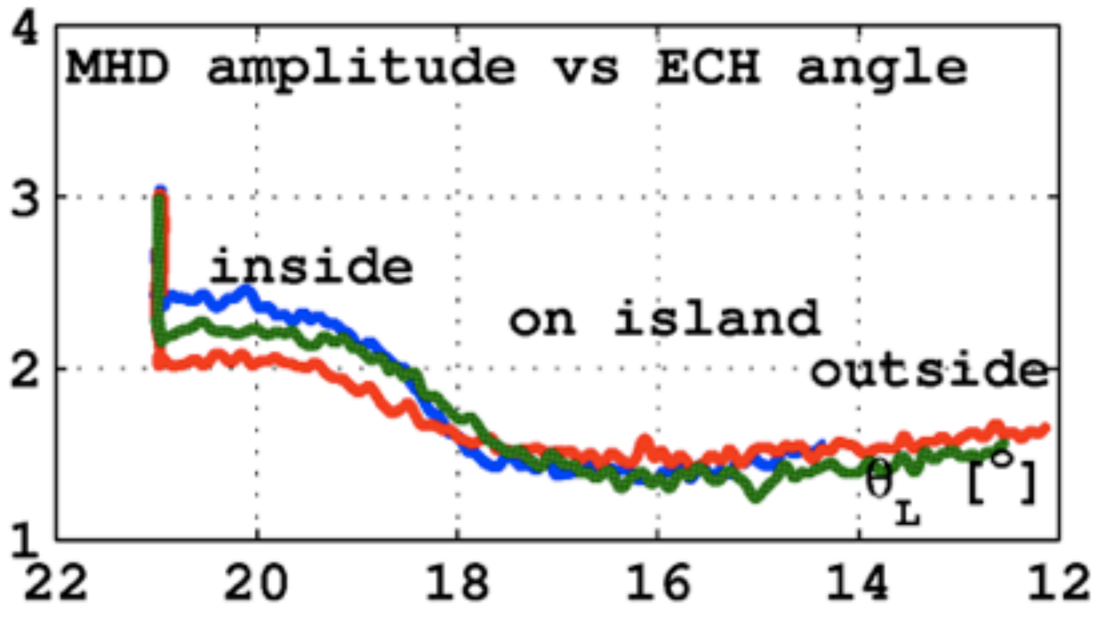
Misaligned ECCD deposited to the inside of the island is expected to be destabilizing [Westerhof1990]



Sweep EC beam across island

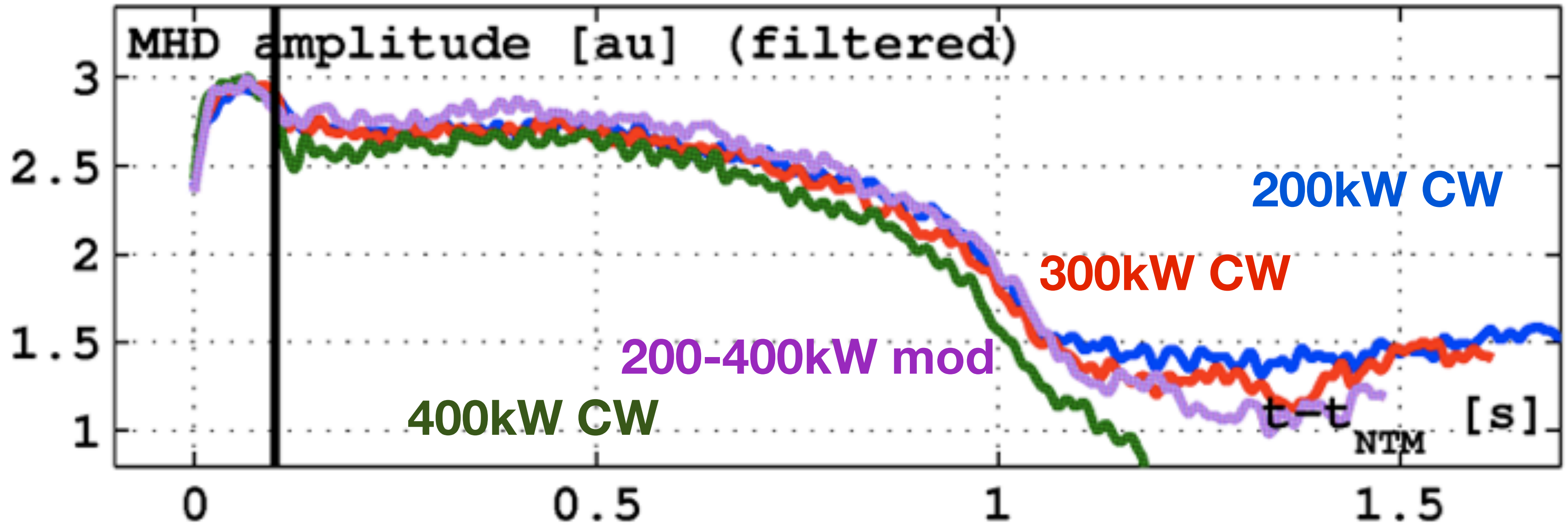
co-ECCD
ECH
cntr-ECCD



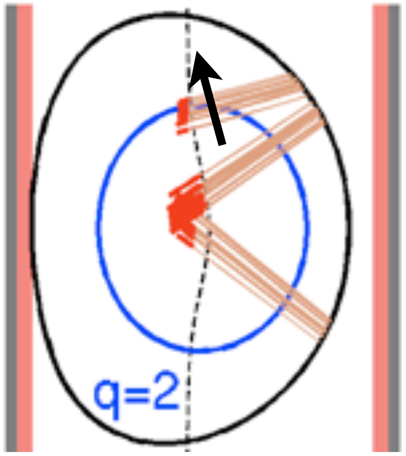


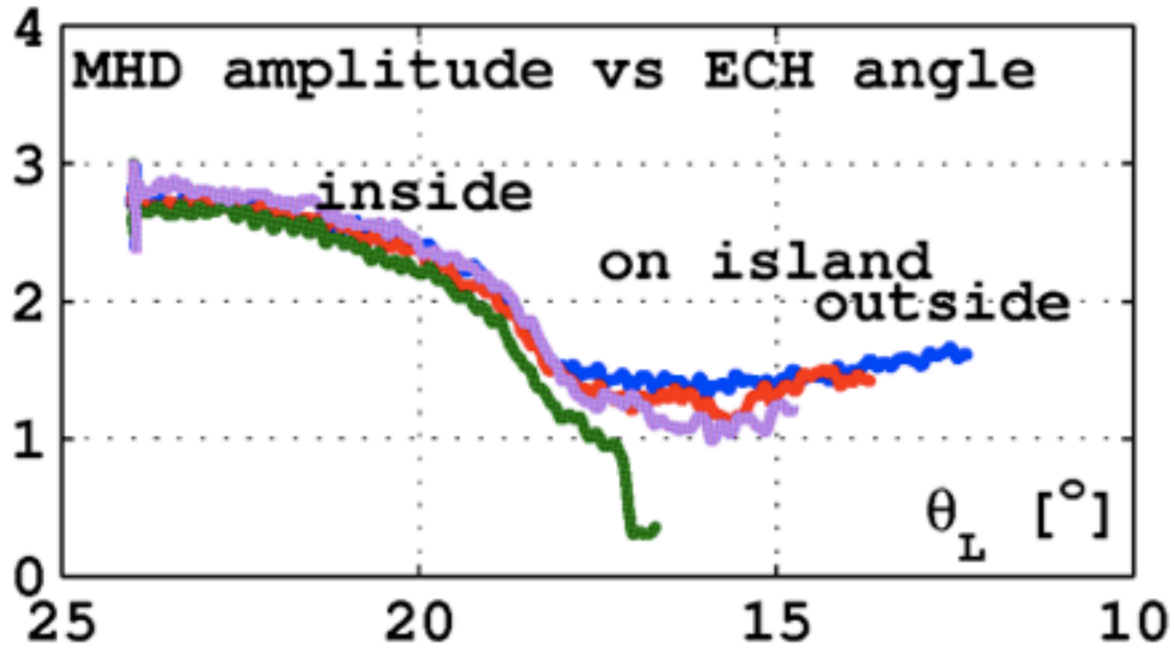
- We find a globally stabilizing effect of misaligned off-axis power
  - Smaller stabilizing effect with coECCD w.r.t. ECH and counterECCD
  - Separate effect of local current drive perturbation of *q* profile, and heating/CD effect inside island
- Little difference between coECCD/ ECH/ctrECCD when on-island
  - May be dominated by heating effects

Using all available CW power is more effective than partial power modulation in this case



Sweep co-ECCD across island





- Scan of CW powers and modulation
  - chose phase giving best stabilization.
- Full available CW power stabilizes mode.
- Modulated power is slightly more effective than mean power (but only when on-island)
  - Small effects, should become clearer by increasing current drive contribution

Conclusions and outlook for tearing mode studies

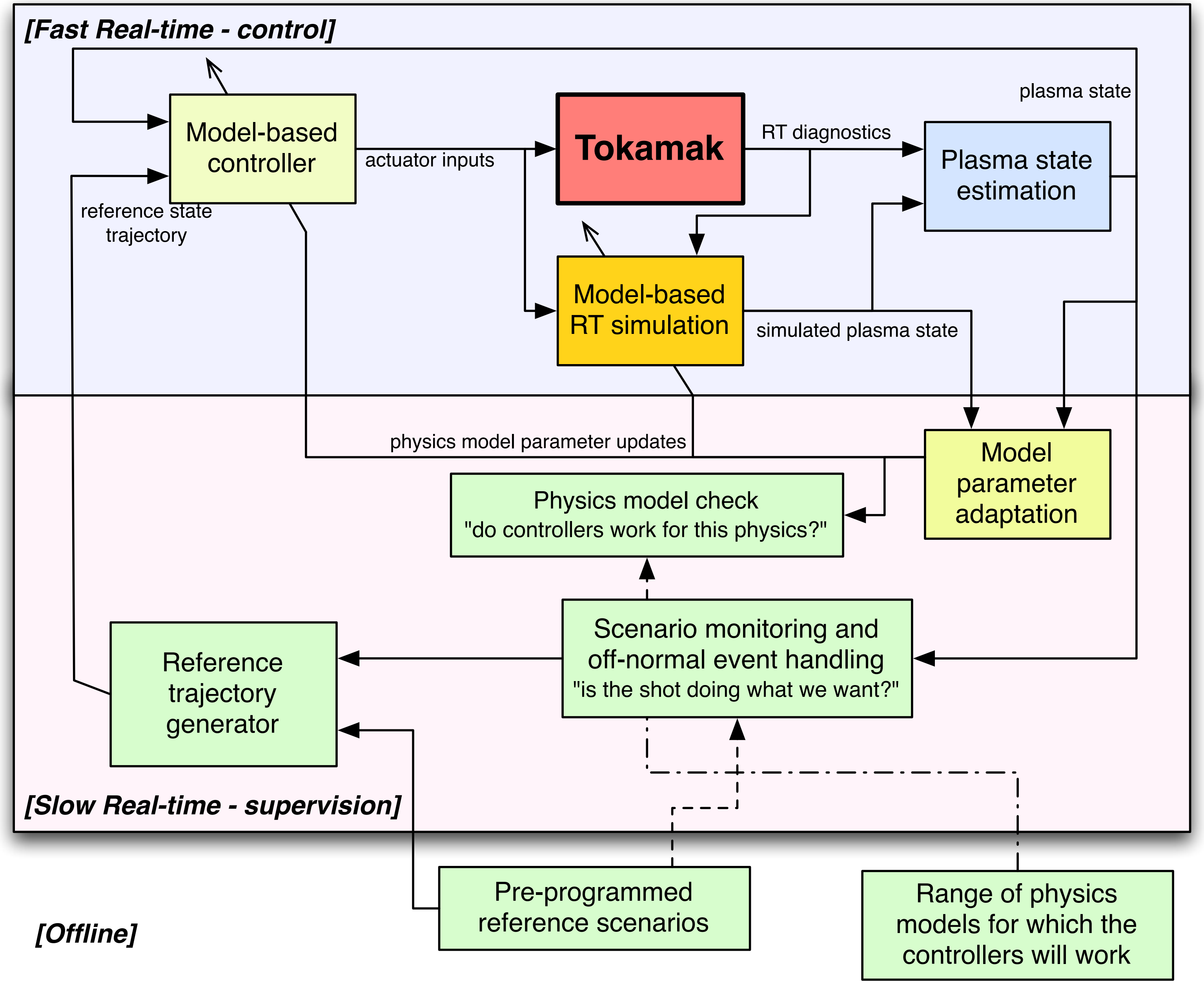
- Experimental results of detailed NTM studies
  - NTMs classically destabilized by *q* profile evolution
  - Metastable limit can be approached and studied, found “Fuzzy” NTMs, small island effects
  - Observed Westerhof effect of local current drive just inside of island
  - Modulation effects not very strong in this configuration.
- Modeling based on MRE is planned
- Further experiments including full power modulation

- Ideas are welcome for cross-machine benchmarking and comparisons.

- Part II: Real-time simulation and control of current density profile

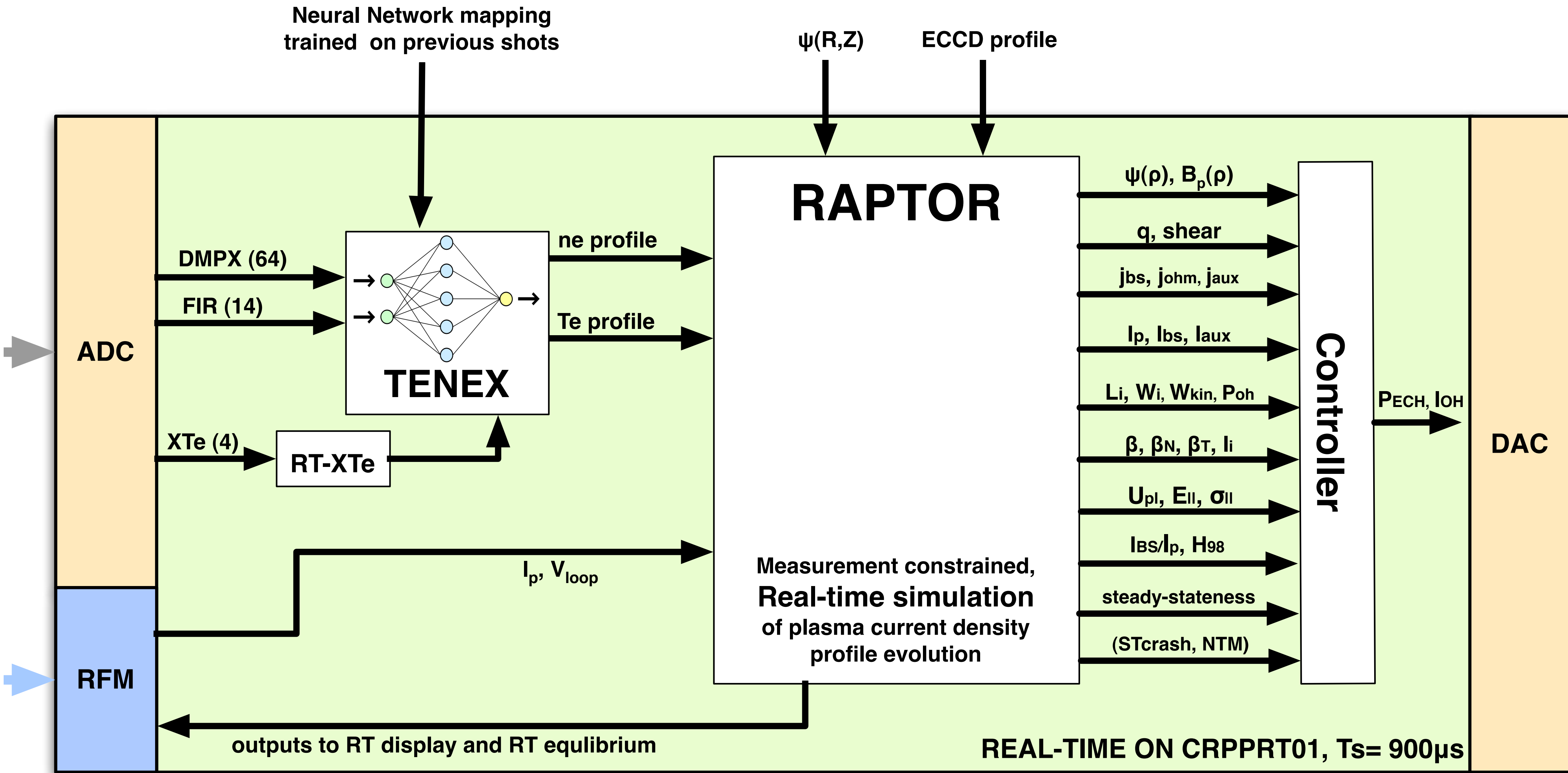
Real-time simulations: at the heart of future advanced Tokamak operation & control

- Today: run interpretative transport simulations post-shot
  - Combine diagnostic data to get kinetic profiles, simulate current profile, update equilibrium
- Tomorrow: routinely run interpretative simulations in real-time
  - ***Numerically evolve the plasma in a computer, while evolving in physically in the Tokamak***
- Possible uses
  - Plasma state estimation
  - Physics parameter estimates
  - Adaptive model-based control
  - Scenario monitoring & safety
  - Predictive control

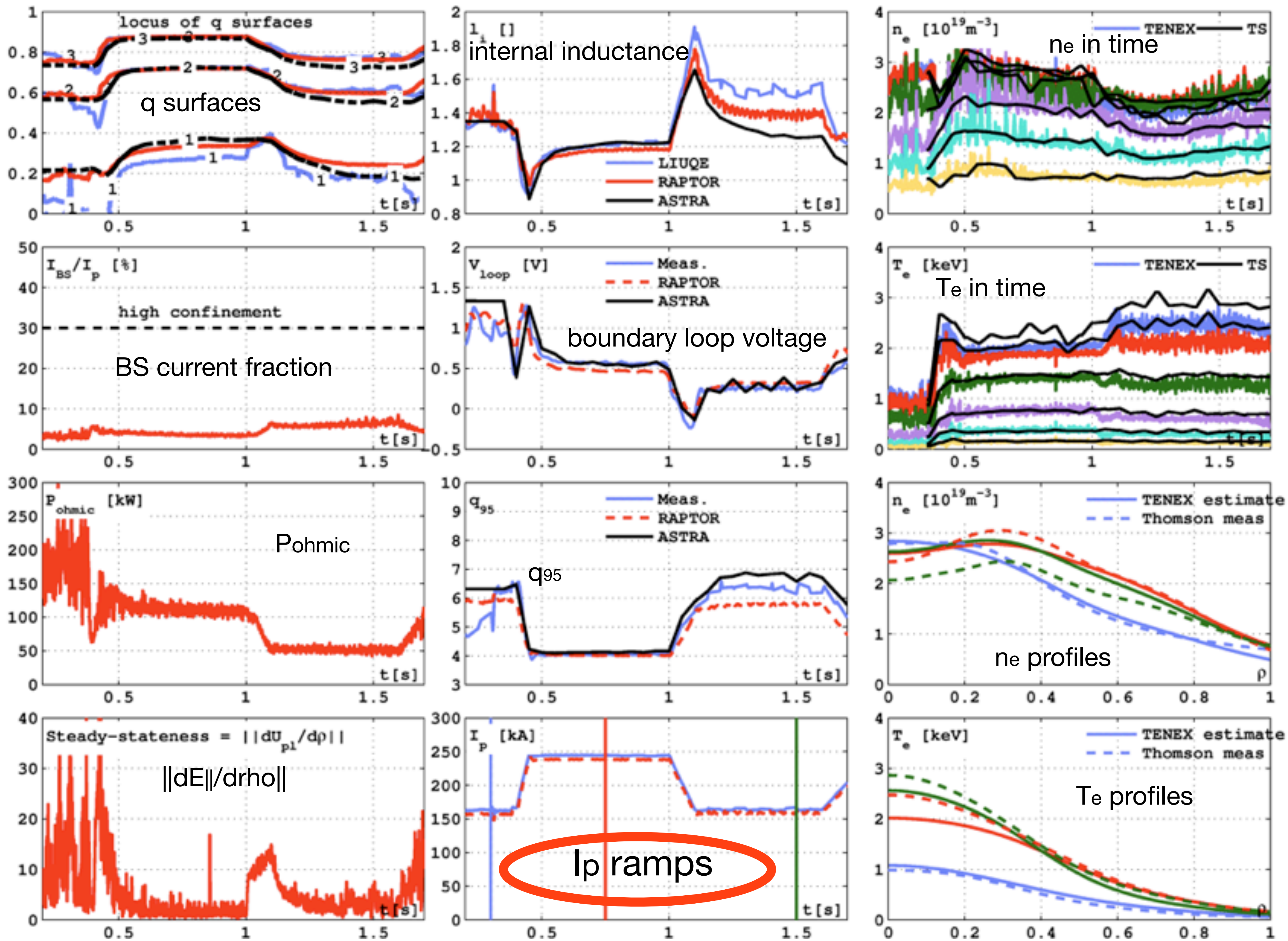


Implementation of fast real-time transport code "RAPTOR" in TCV digital control system

- RApid Plasma Transport Simulator - 1D $\psi(\rho)$ transport, finite elements
- $T_e(\rho)$, $n_e(\rho)$ profile estimates by combining Xray and interferometer data
  - One time step per 0.9ms (τ_R~150ms, shot time ~2s)
- Outputs are available which often difficult or impossible to measure

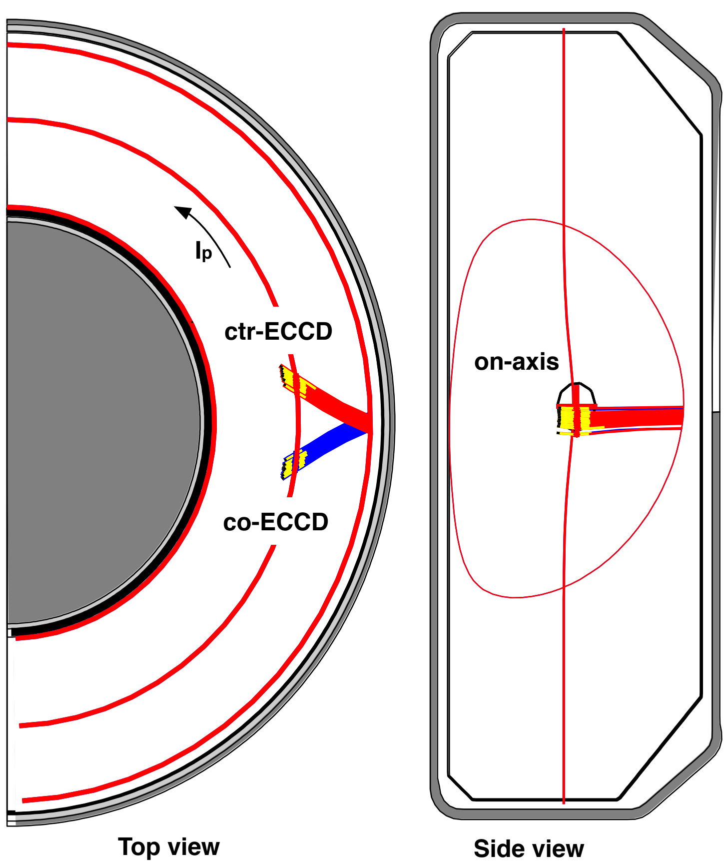


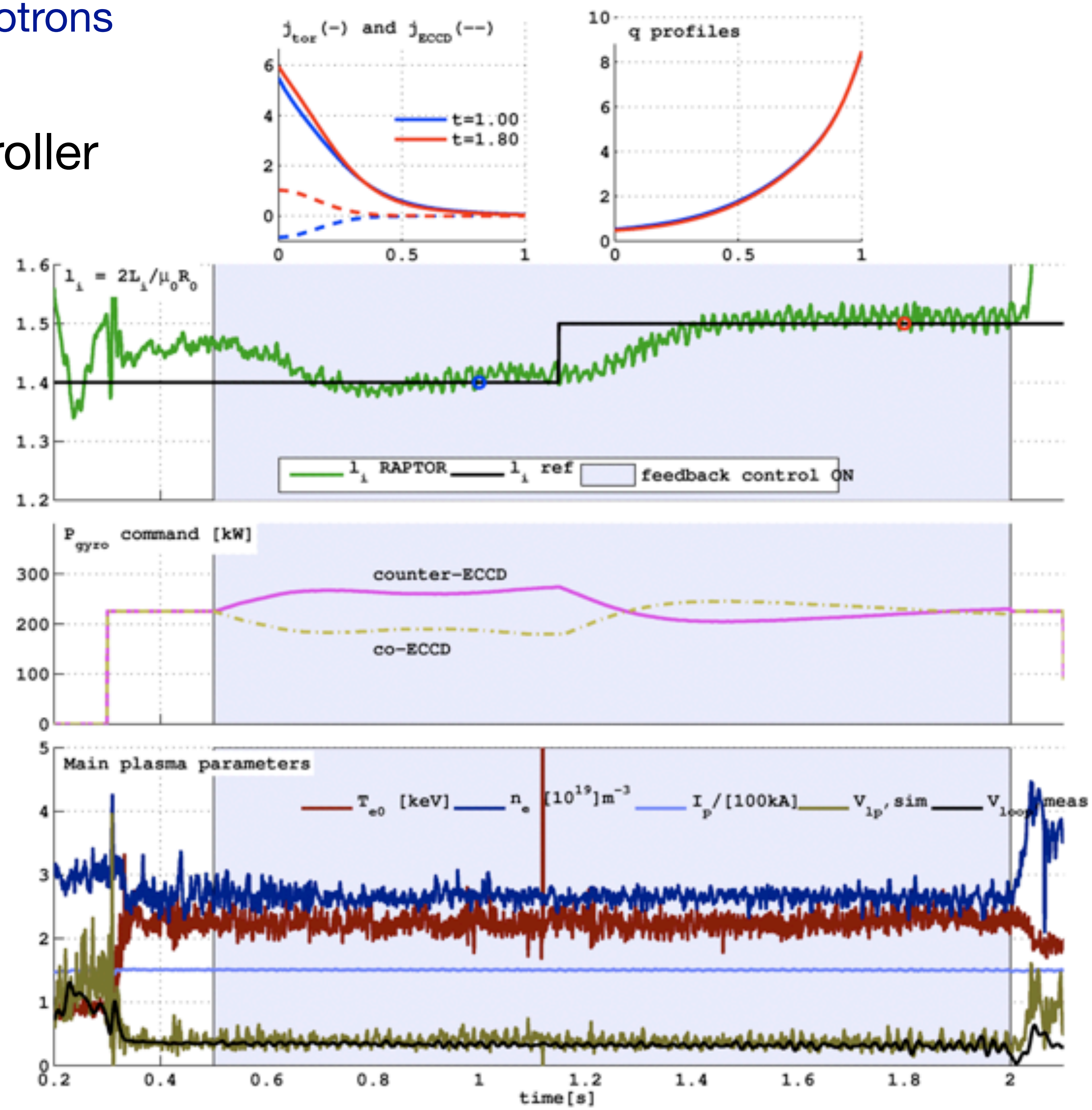
Experiments confirm that RT-RAPTOR gives good results compared to off-line transport modeling



First closed-loop experiments: feedback control of internal inductance using co/counter on-axis ECCD

- On-axis co-counter ECCD, peak or flatten j profile
  - Control ratio of powers in two gyrotrons
  - Effect on li
- Use proportional-integral controller
  - Tracks reference step change in li
- Comparison to off-line data
  - Vertical position drift cause reality and simulation to diverge





Thank you