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Citation for published version (APA):

Felici, F., Sauter, O., Goodman, T. P., Coda, S., Duval, B. P., Moret, J-M., Rossel, J. X., & Paley, J. I. (2010). Real-time control of tearing modes and current density profile in TCV. In *Proceedings of the 15th Workshop on MHD stability control : "US-Japan Workshop on 3D Magnetic Field Effects in MHD Control"*, November 15-17, 2010, Madison, USA

Document status and date:

Published: 01/01/2010

Document Version:

Accepted manuscript including changes made at the peer-review stage

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
- The final author version and the galley proof are versions of the publication after peer review.
- The final published version features the final layout of the paper including the volume, issue and page numbers.

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

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15th Workshop on MHD Stability Control & Joint US-Japan Workshop

University of Wisconsin, Madison, USA. Nov 15-17 2010

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 δq 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.

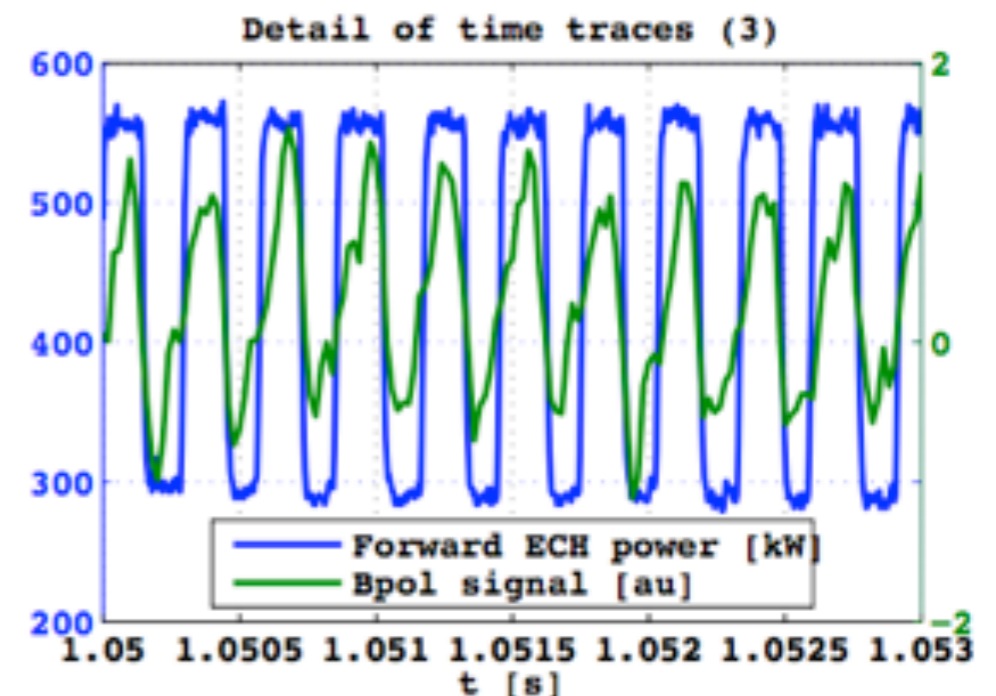
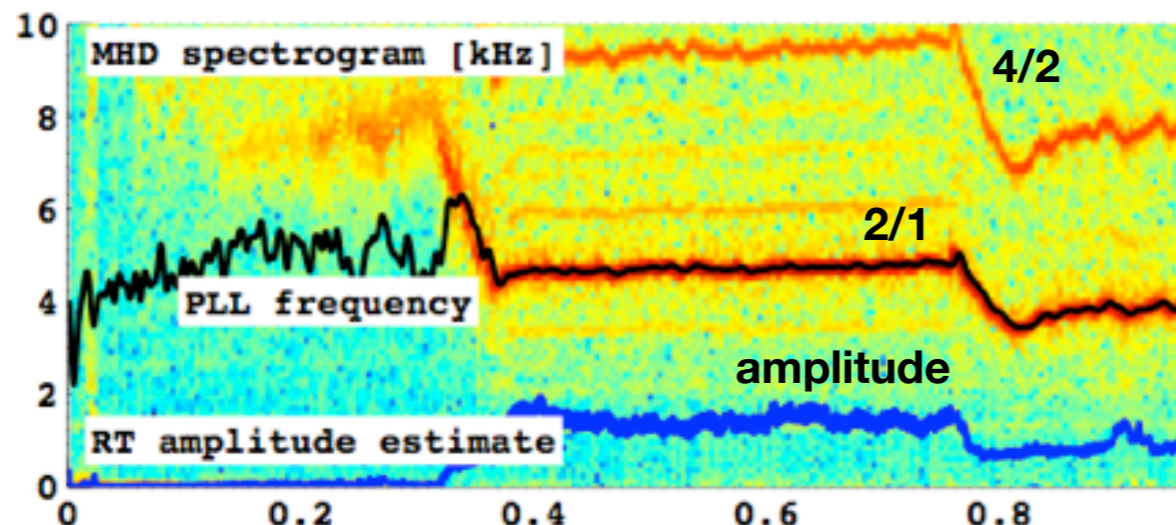
- Part I: Studies of effects of ECRH/ECCD on tearing mode creation and stabilization using real-time control
 - Objective of these experiments: separate direct ECH/ECCD effects on island through Δ'_{CD} and q profile effects through Δ'_0
 - Results of recent experiments, enabled by real-time control 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

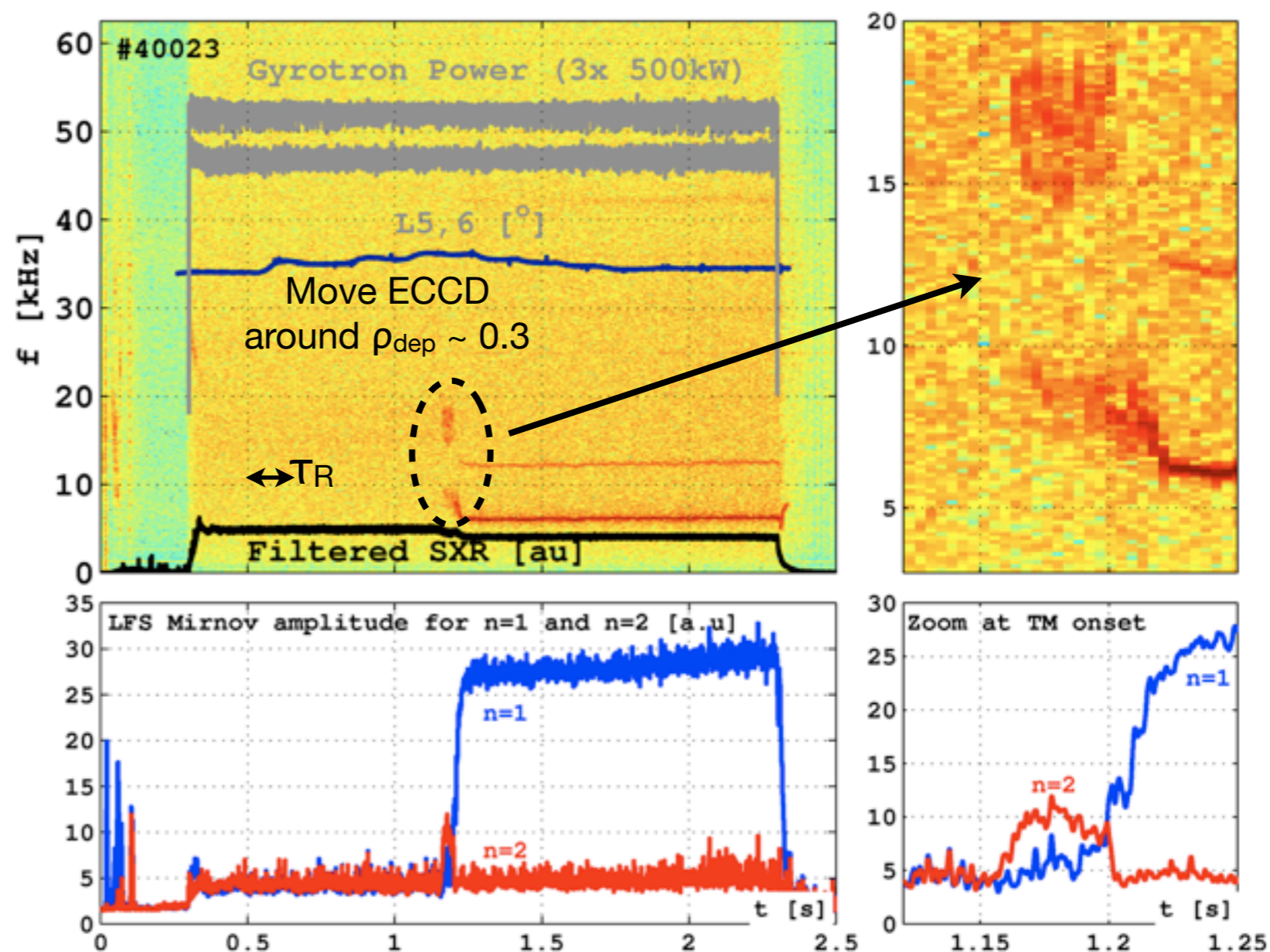


Δ'_0 destabilized modes created on TCV by global q profile changes using near on-axis ECCD

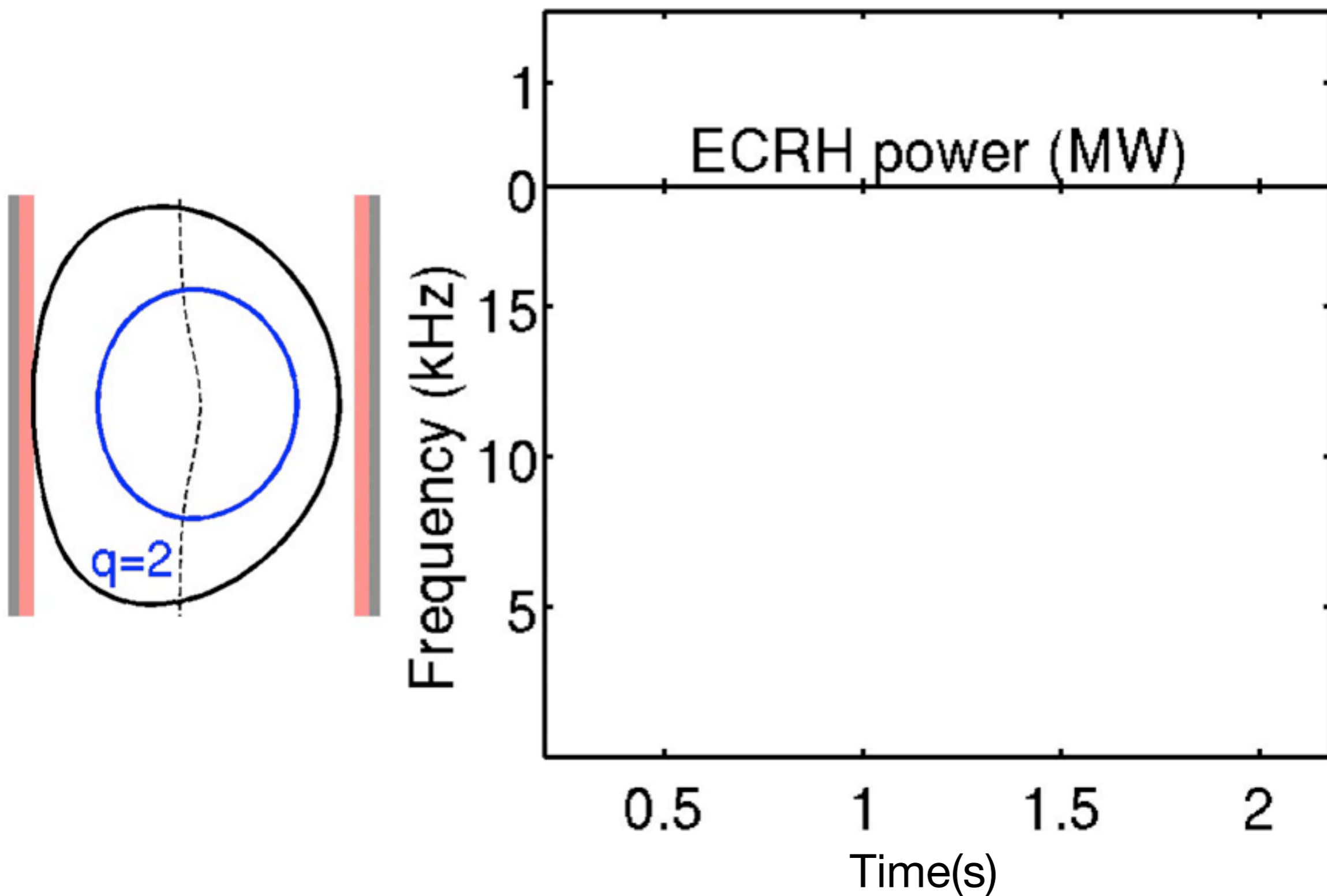
- No clear trigger from sawteeth in these cases
 - Sawtooth triggered NTMs have been seen on TCV with long, large, stabilized sawteeth (not these shots)
- 3/2 mode precursor observed
 - Suppressed by 2/1 growth
- Use these modes as target for stabilization experiments

Typical parameters for these discharges:

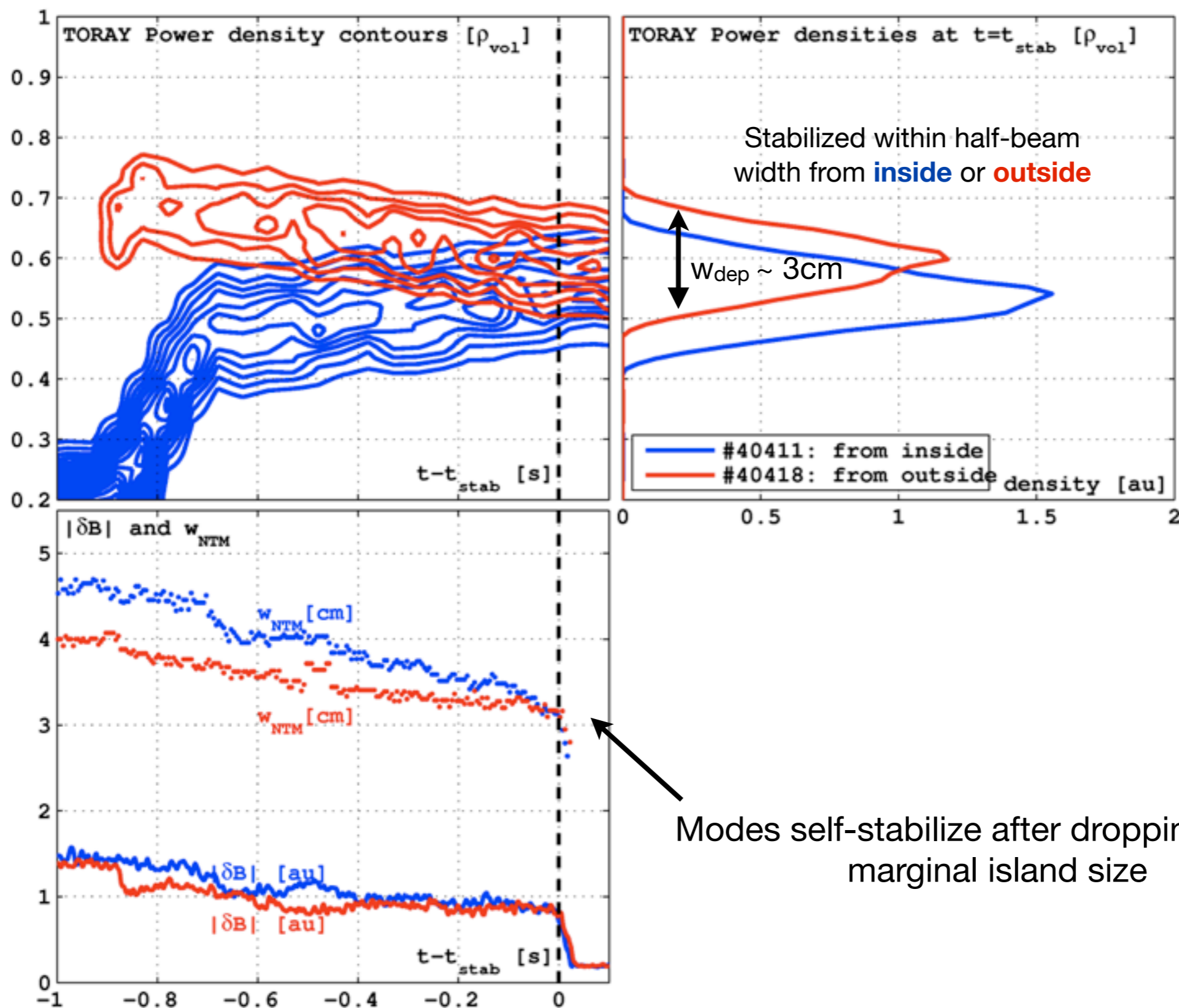
$I_p=150\text{kA}$ $B_T=1.45\text{T}$ $q_{95}\sim 6$
 $T_{e0} = 3\text{keV}$ $n_{e0}= 1.5\times 10^{19}\text{ m}^{-3}$
 $\beta_{\text{pol}}\sim 0.7$, $\beta_{\text{tor}}\sim 0.3\%$, $\beta_N\sim 0.8$
 L-mode plasmas



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

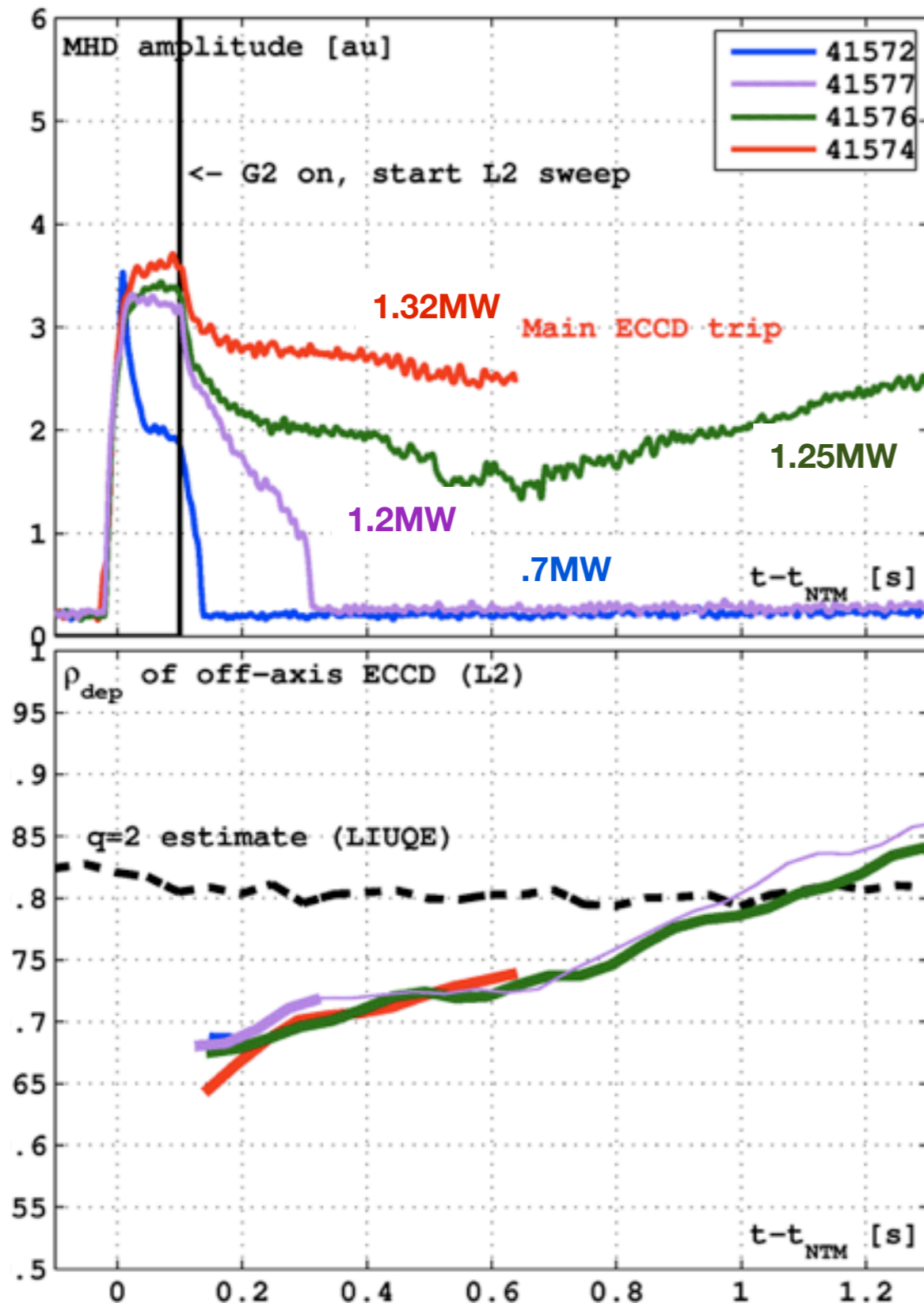


Mode stabilized both from inside and outside $q=2$ once mode shrunk to marginal island width



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

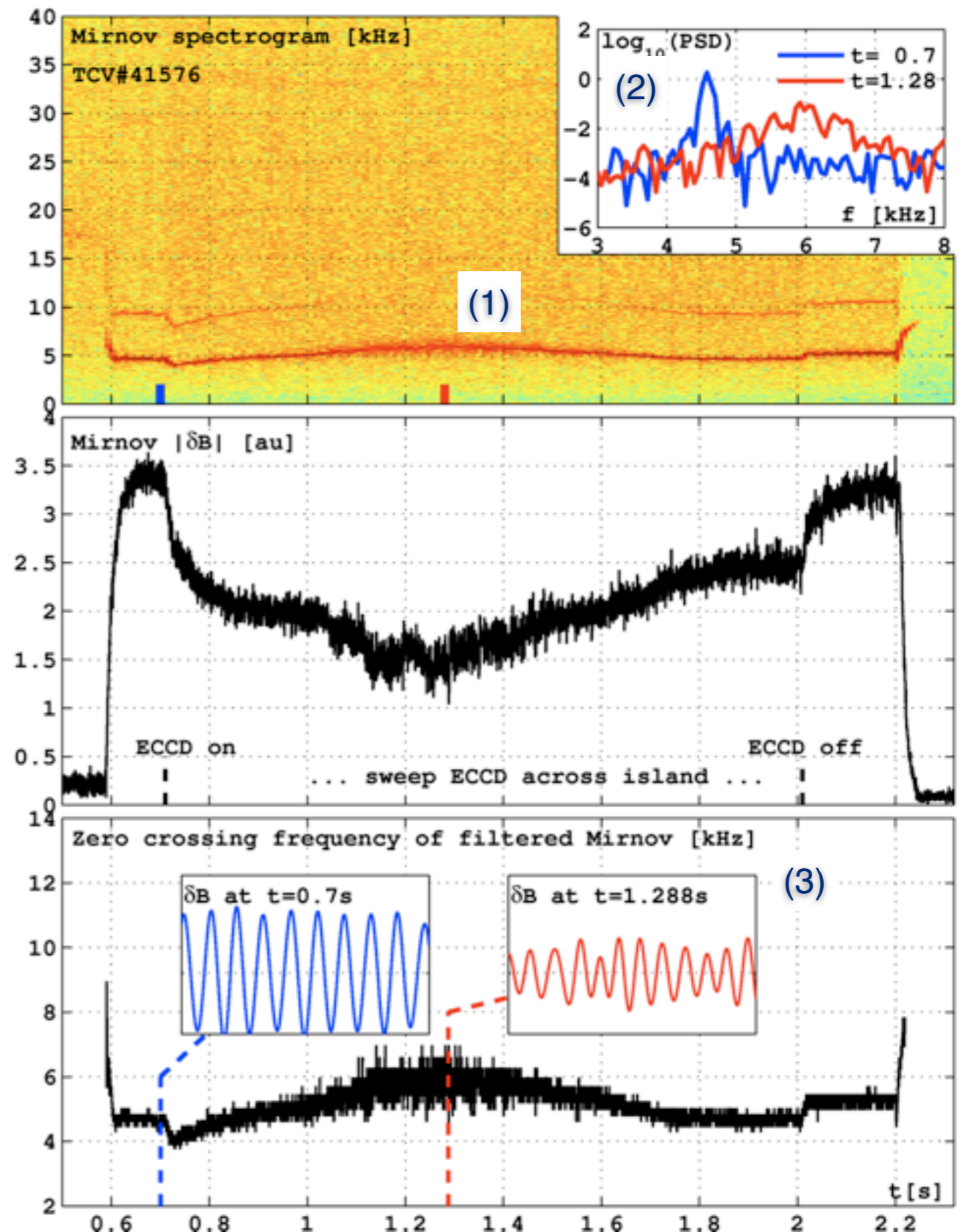
Create modes of varying strength by varying central EC power after TM is triggered



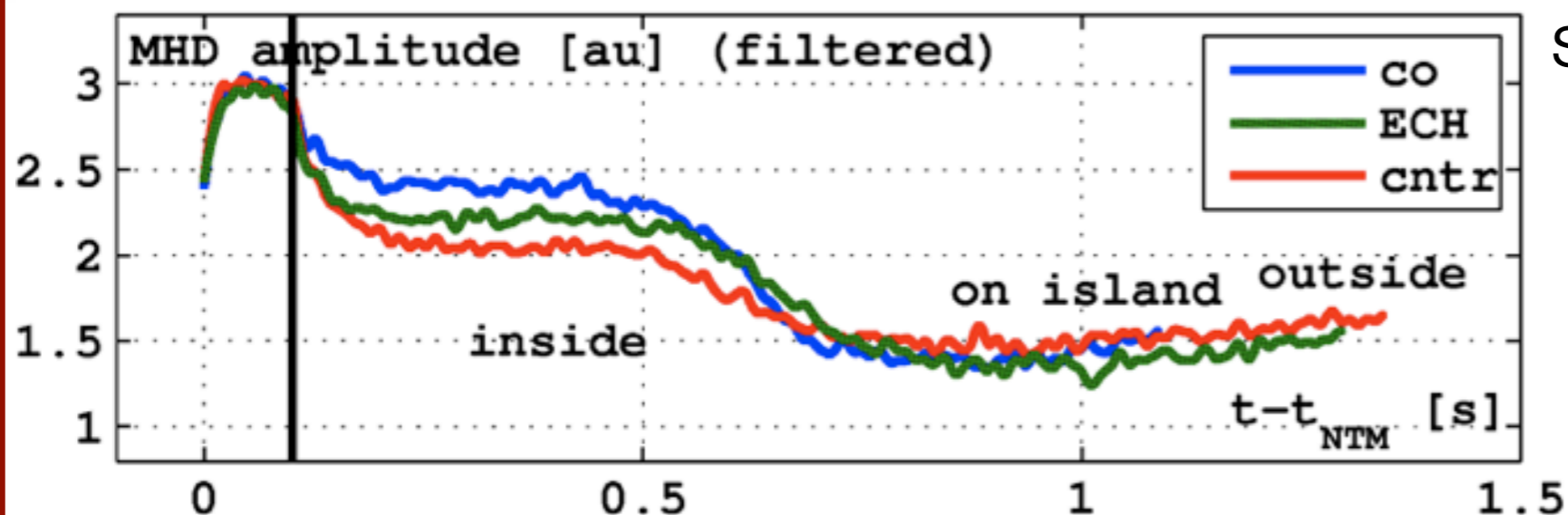
- Can create modes of varying strength by varying central ECCD
- Angle scan across mode -> different response to ECCD close $q=2$
 - Stabilized immediately upon off-axis EC power on (blue)
 - Stabilized only after longer time (violet)
 - Almost stabilized but not fully, even upon sweep across island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

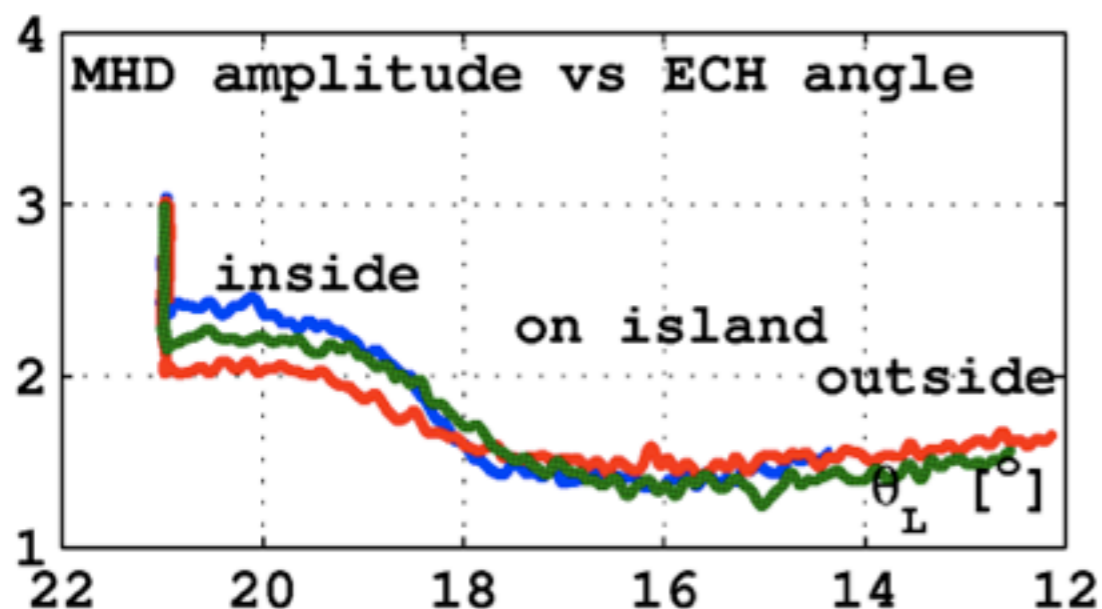
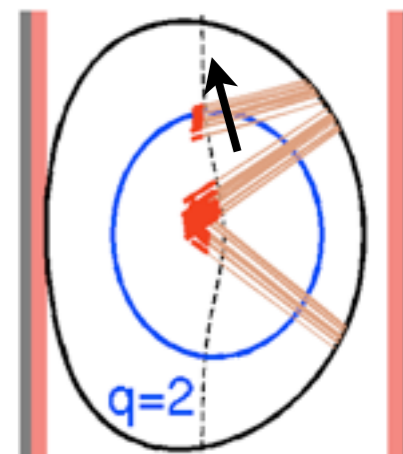


Misaligned ECCD deposited to the inside of the island is expected to be destabilizing [Westerhof1990]



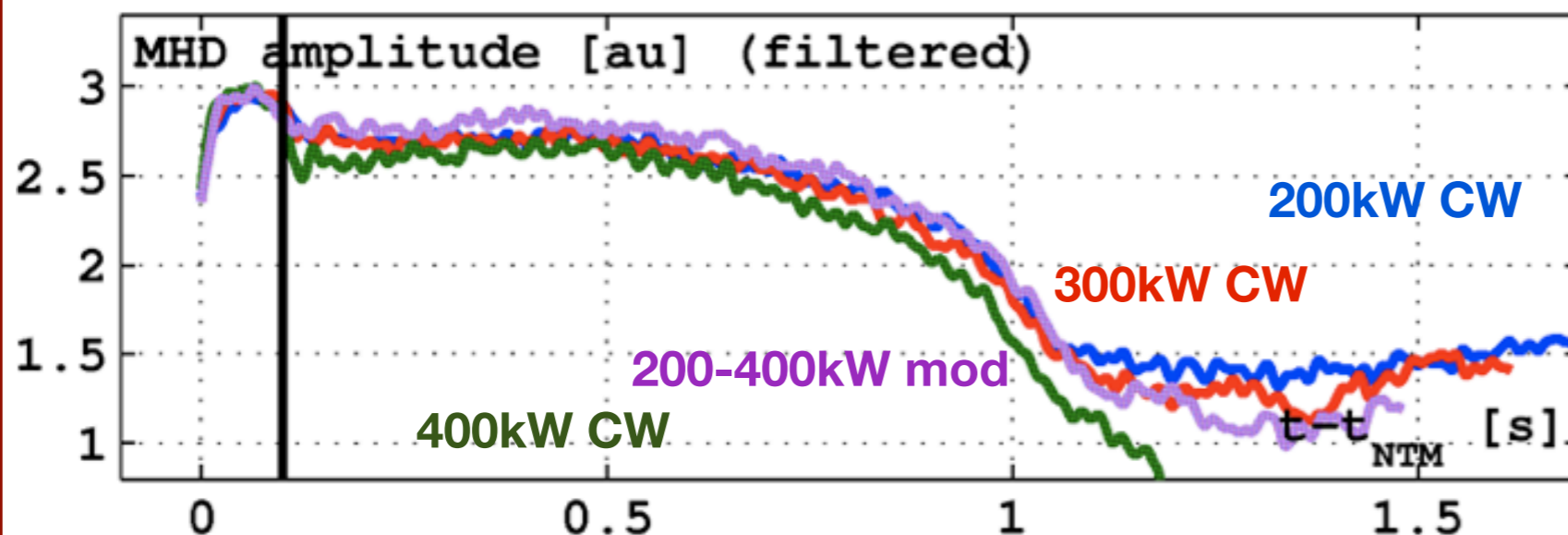
Sweep EC beam across island

co-ECCD
ECH
cntr-ECCD

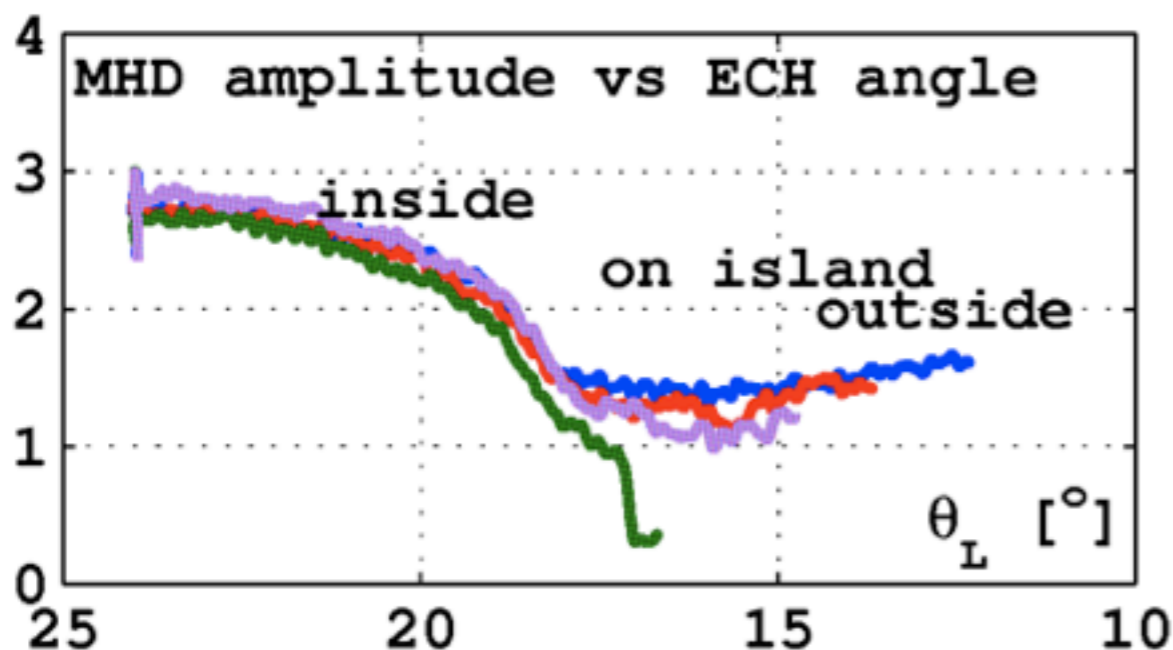
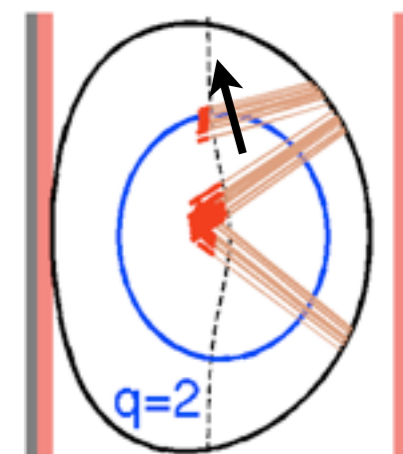


- We find a globally stabilizing effect of misaligned off-axis power
 - Smaller stabilizing effect with coECCD w.r.t. ECH and counterECCD
 - Separate effect of local current drive perturbation of q profile, and heating/CD effect inside island
- Little difference between coECCD/ECH/ctrECCD when on-island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

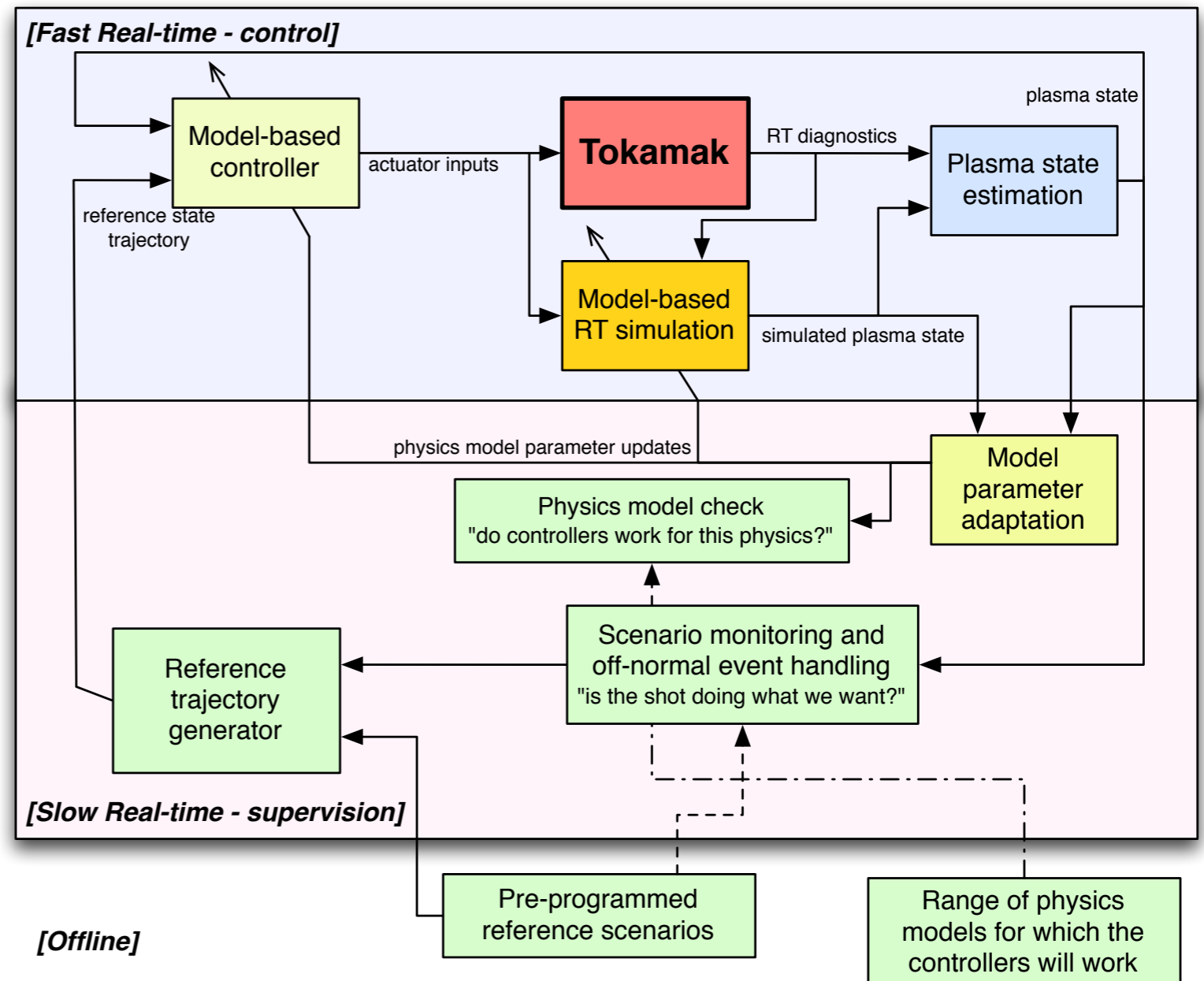
- Experimental results of detailed NTM studies
 - NTMs classically destabilized by q profile evolution
 - Metastable limit can be approached and studied, found “Fuzzy” NTMs, small island effects
 - Observed Westerhof effect of local current drive just inside of island
 - Modulation effects not very strong 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

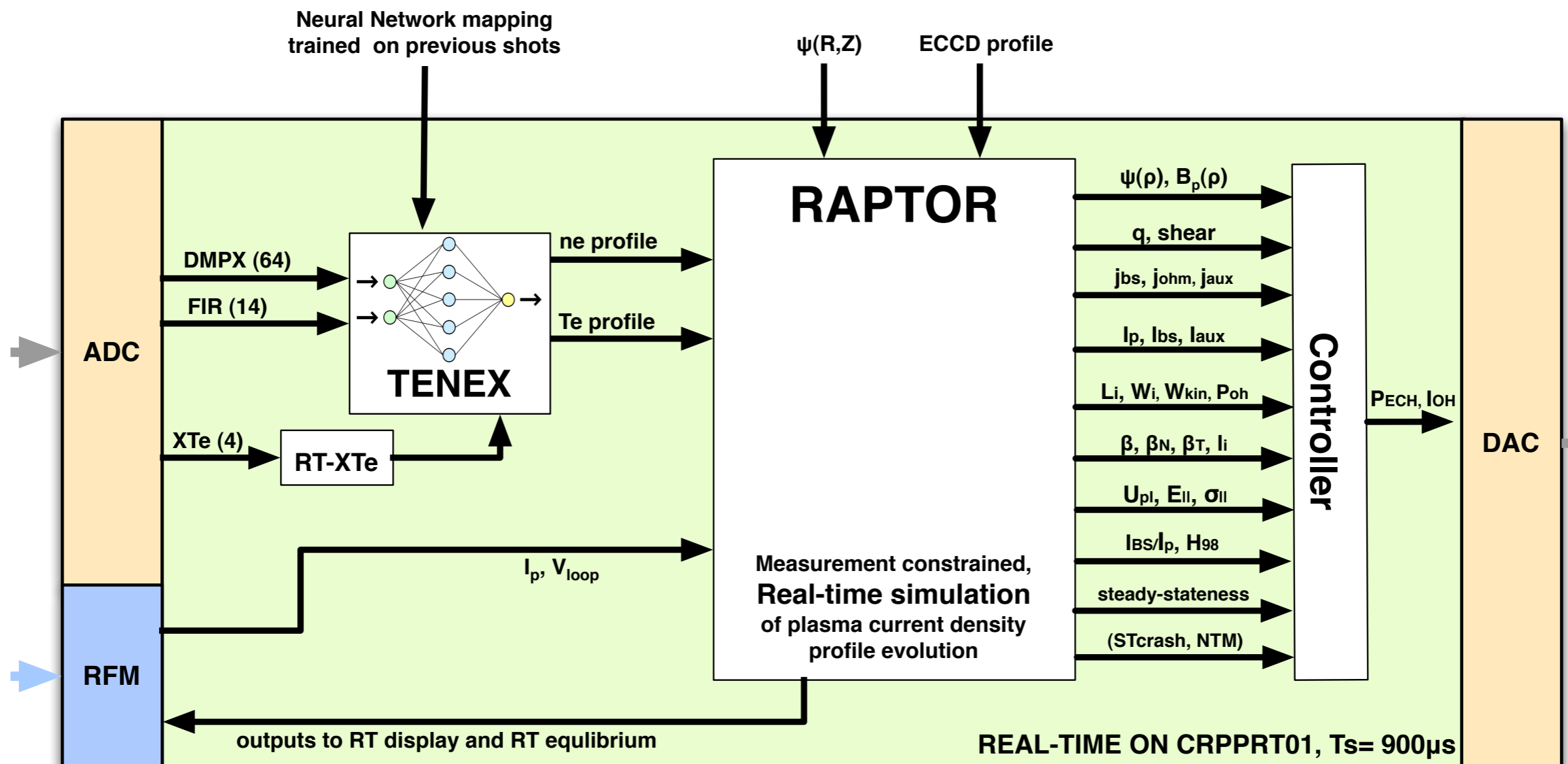
Real-time simulations: at the heart of future advanced Tokamak operation & control

- 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

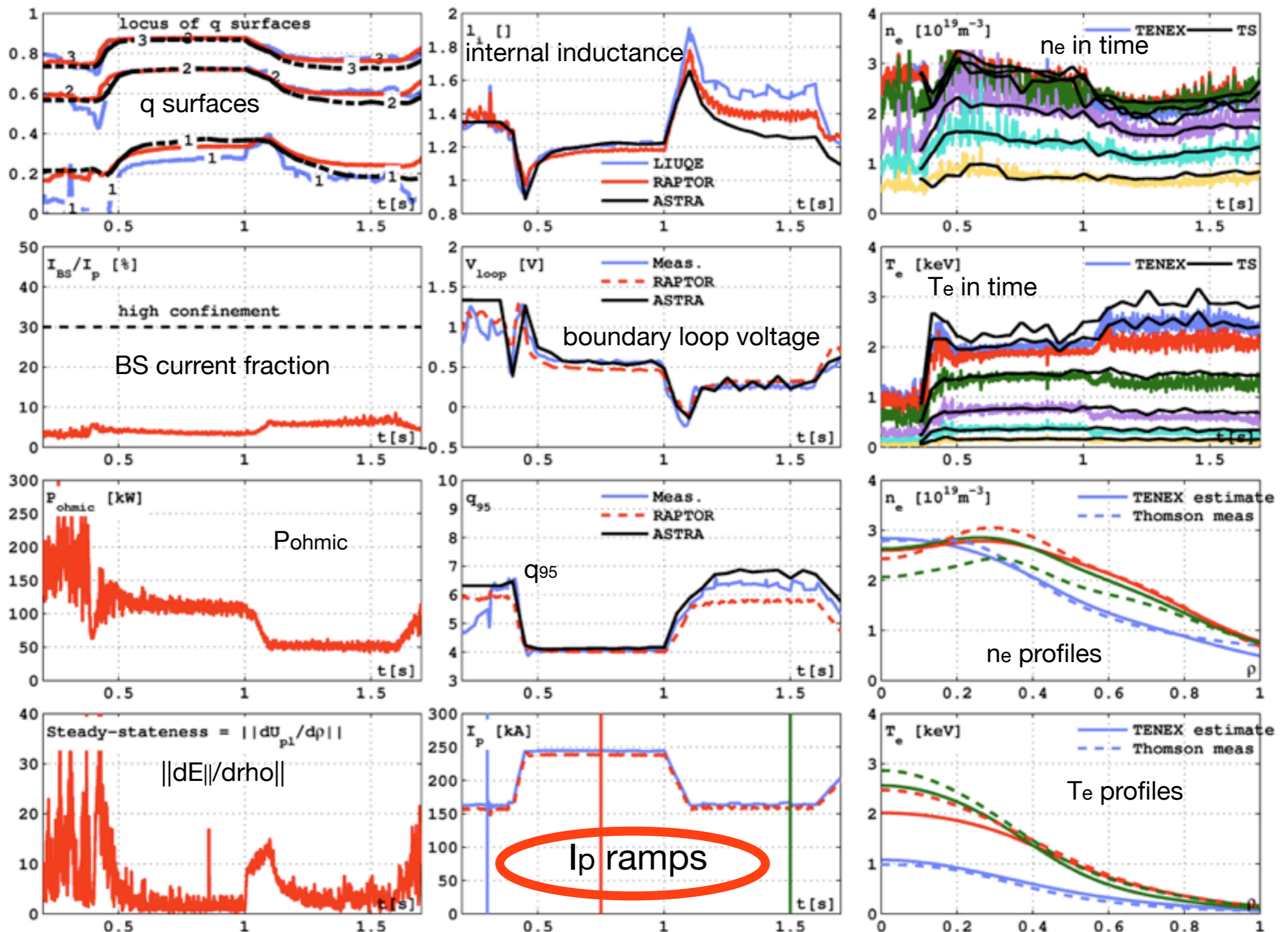


Implementation of fast real-time transport code "RAPTOR" in TCV digital control system

- 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 ($\tau_R \sim 150\text{ms}$, shot time $\sim 2\text{s}$)
- Outputs are available which often difficult or impossible to measure

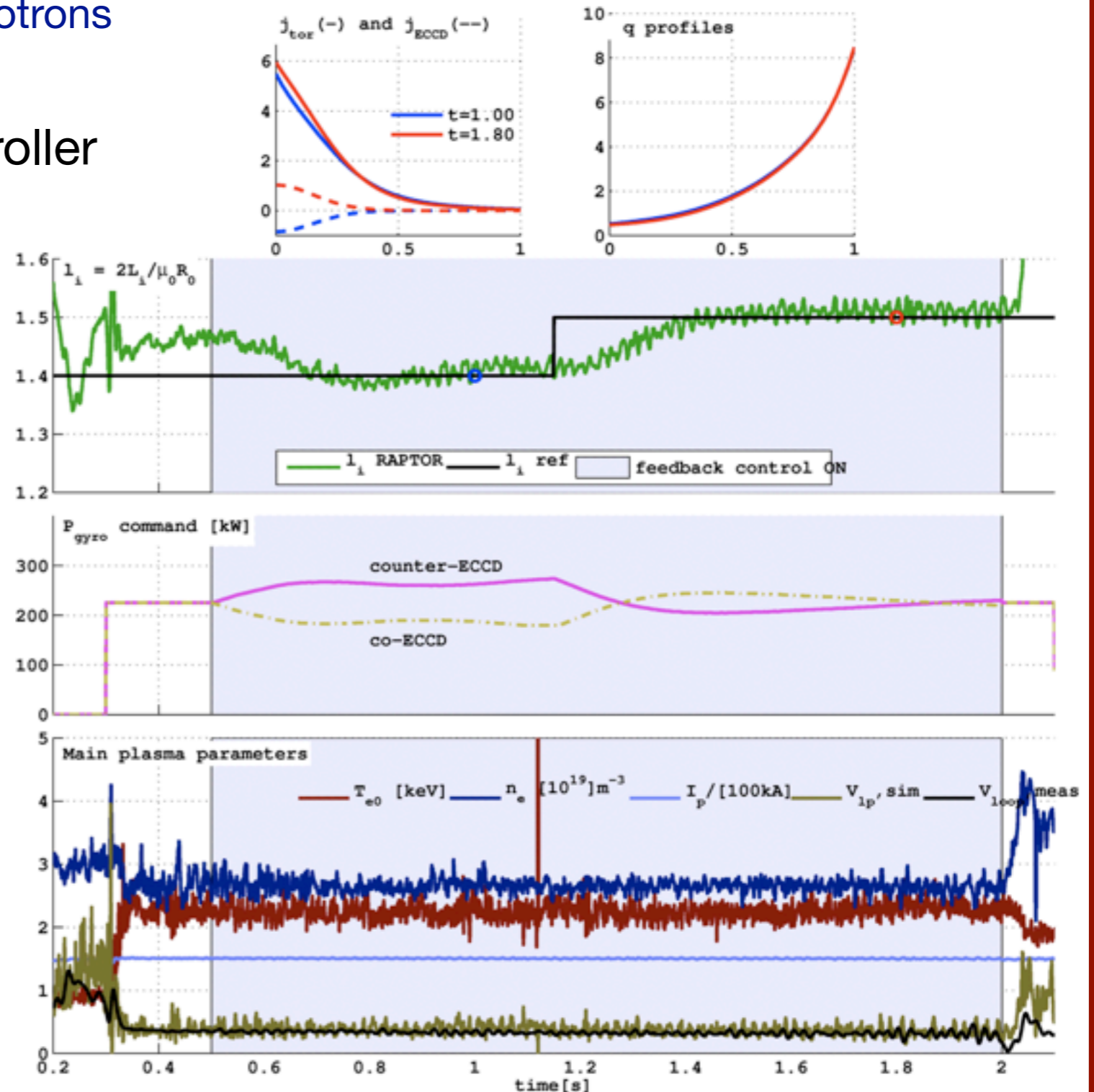
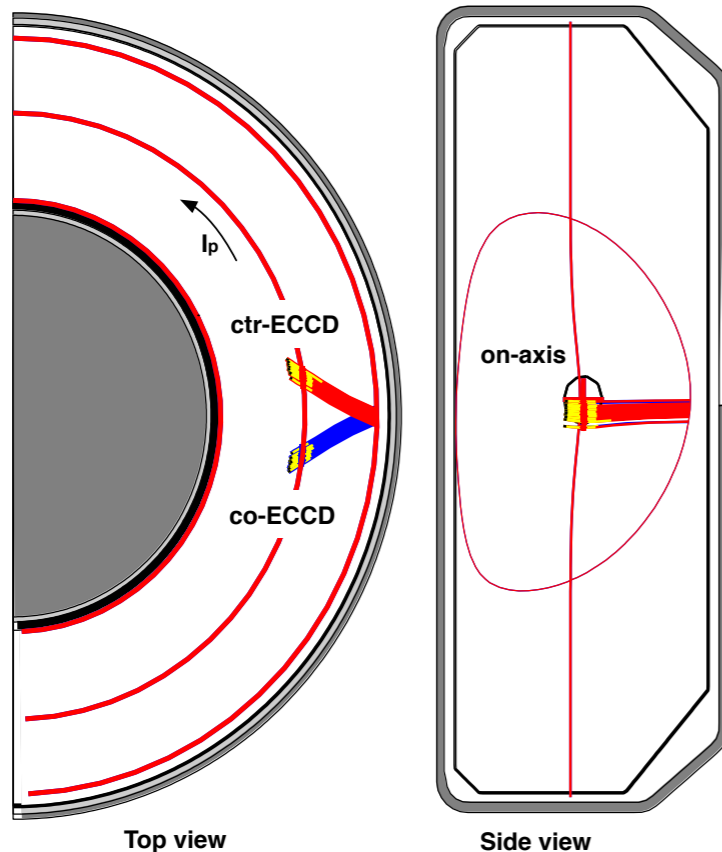


Experiments confirm that RT-RAPTOR gives good results compared to off-line transport modeling



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 l_i
- Use proportional-integral controller
 - Tracks reference step change in l_i
- Comparison to off-line data
 - Vertical position drift cause reality and simulation to diverge





Thank you