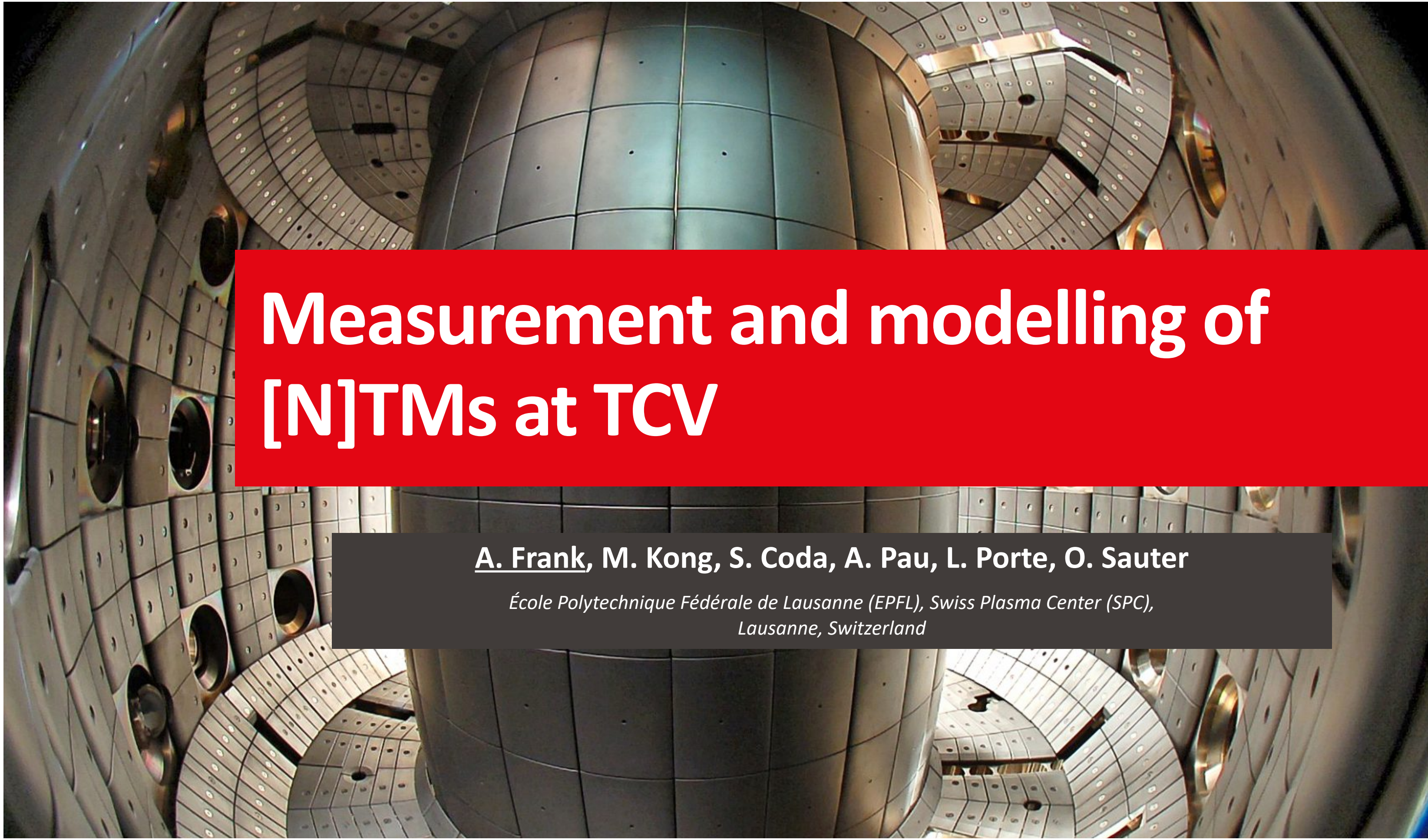

Measurement and modelling of [N]TMs at TCV

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2nd European Conference on magnetic reconnection in Plasmas, June 17-19 2025, Turin

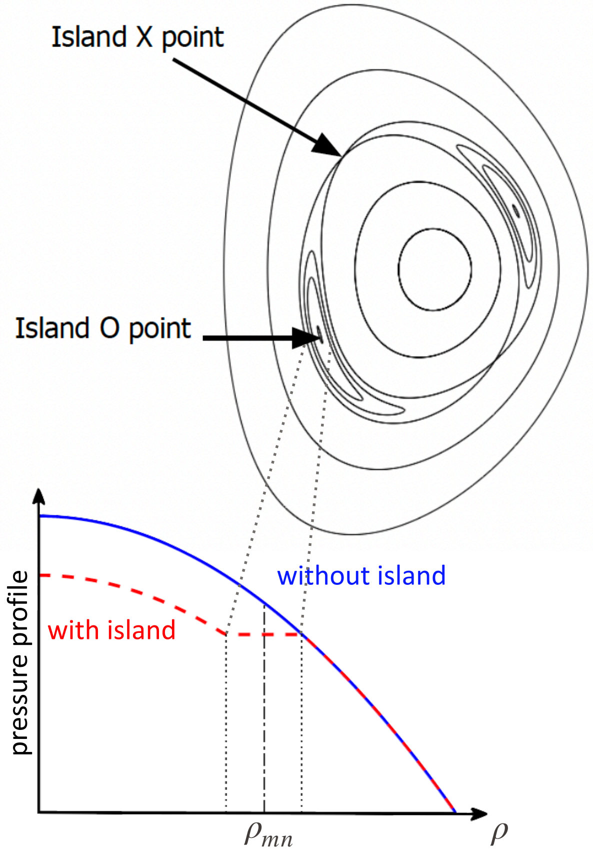
[Neoclassical] tearing modes ([N]TM)

- Resistive MHD instability that forms magnetic islands on surfaces of rational safety factor $q = m/n$
- Enhances radial transport flattens pressure profile, degrades confinement and limits operational ranges
- Confinement degradation can be estimated using the belt model [Chang and Callen (1990)]

$$\frac{\Delta\beta}{\beta} = \frac{\Delta\tau_E}{\tau_E} = 4\frac{\bar{\rho}^3}{a^3}\frac{w_{sat}}{a}$$

- For large islands the growth rate is dominated by effects of the perturbed bootstrap current (self-generated plasma current, neoclassical)

$$j_{bs} \propto \frac{\nabla p}{B_p}$$



Graphics adapted from
[Felici (PhD thesis, 2011), Kong (PhD thesis ,2018)]

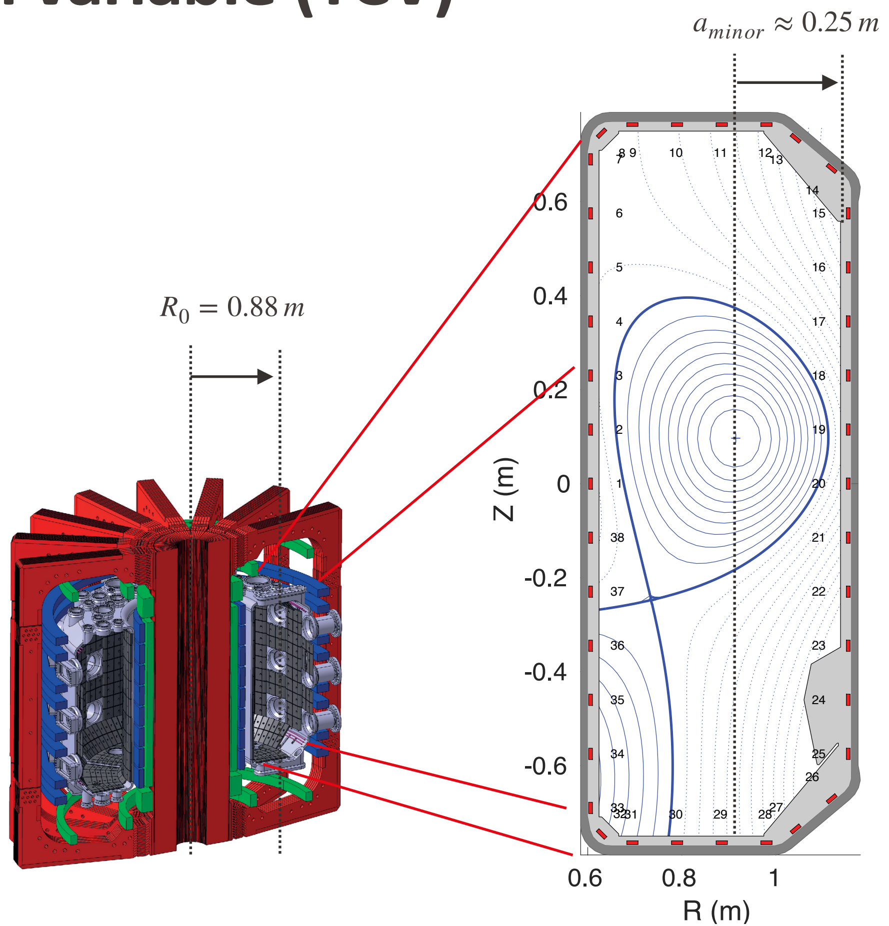
Outline

- Detection and measurement of NTMs at TCV
- NTM modelling with the Modified Rutherford equation
- NTM control at TCV
- Summary

Tokamak à configuration variable (TCV)

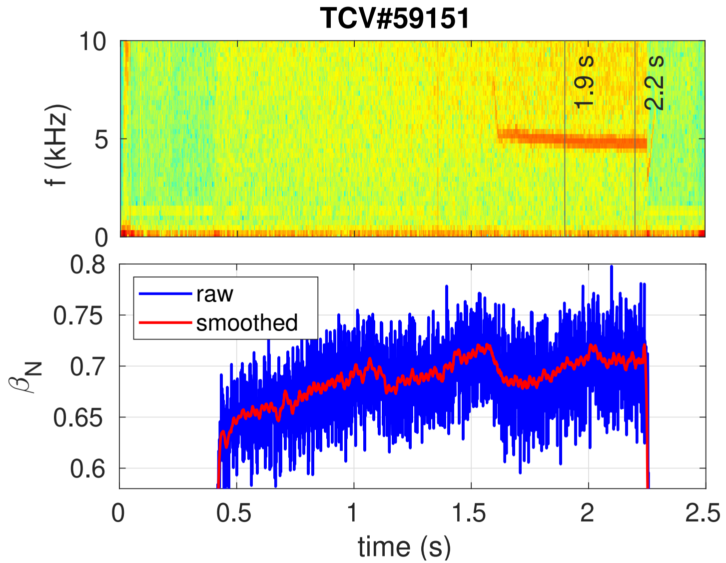
Antonia Frank

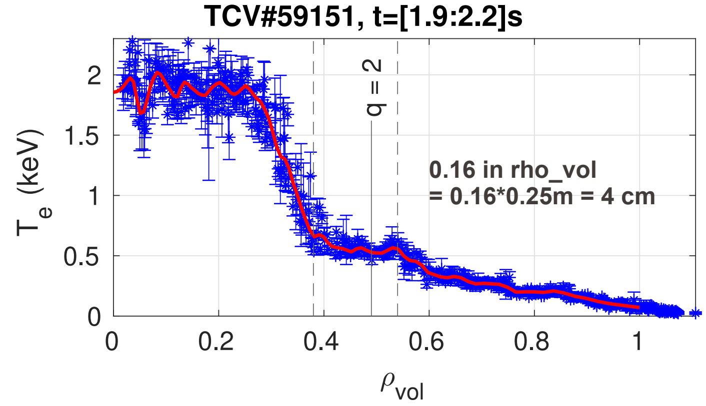
- Medium size tokamak
- High shaping capabilities due to
  - highly elongated, rectangular plasma vessel
  - 16 shaping coils
- Auxiliary heating systems:
  - Electron cyclotron (EC) wave system (X2,X3) with real-time steerable mirrors
  - Neutral beam injection (NBI)
- Main diagnostics relevant for NTM detection and analysis at TCV
  - Thomson scattering (TS) (T_e, n_e profiles)
  - CXRS ($T_i, n_i, v_\phi, Z_{eff}$)
  - Toroidal and poloidal magnetic probe arrays
  - …



Detection of NTMs at TCV

- Detection and rotation frequency from spectrogram ($f_{Mirnov} \approx 3 - 20$ kHz at TCV)
- Determine toroidal (n) and poloidal (m) mode numbers from magnetic probe arrays
  - Following the perturbations phase along the probe spatial locations
  - Using Single Value Decomposition (SVD) to get likelihoods
- Averaged $T_e(\rho)$ profiles show typically flattening at rational q
- Confinement degradation directly observable by drop in $\beta_N(t)$



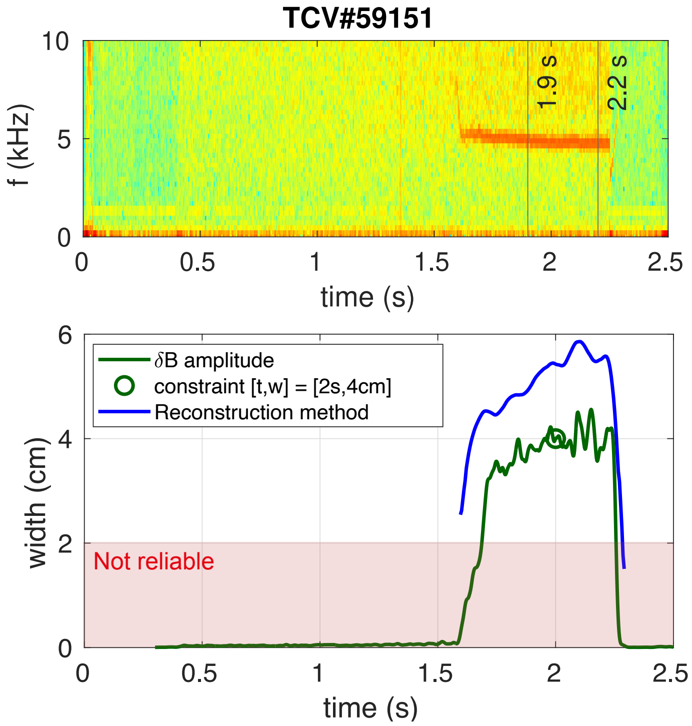


Measuring the magnetic island width

- Amplitude of perturbation δB or likelihood from SVD analysis scaled with conversion factor determined by
    - T_e profile flattening
    - NTM database (currently used in RT)

- Reconstruction by fitting modelled helical flux perturbations to the measurements in the magnetic probes **-> most reliable** [Schittenhelm and Zohm (1997), Reimerdes (2001)]

➡ Limits of detection by magnetic probes in TCV is **approx. 2 cm**



Outline

- Detection and measurement of NTMs at TCV
- NTM modelling with the Modified Rutherford equation
- NTM control at TCV
- Summar

The Modified Rutherford equation (MRE)

- Classical tearing mode (TM) evolution described by the Rutherford equation: [Rutherford (1973), White (1977)]

$$\frac{\tau_R}{\bar{\rho}_{mn}}\frac{dw}{dt} = \bar{\rho}_{mn}(\Delta'_0 - \alpha w)$$

linear at w = 0

nonlinear growth until saturation

w: island width

$\bar{\rho}_{mn} = a\,\rho_{tor,mn}$: island loc. in [m]

τ_R: resistive diffusion time

$$\Delta' = \left[\frac{\partial\delta\psi/\partial\rho}{\delta\psi(\rho_{mn})}\right]_{\rho_{mn}-\epsilon}^{\rho_{mn}+\epsilon}$$

- Modified Rutherford equation (MRE) considers also **neoclassical effects**
  - Main physics model to analyse/predict NTM dynamics in experiments and used for RT control applications
  - “Free” parameters a_i are in similar range for different machines and are fixed for full discharge simulation

$$\frac{\tau_R}{\bar{\rho}_{mn}}\frac{dw}{dt} = \bar{\rho}_{mn}(\Delta' \boxed{+ a_{bs}\Delta'_{bs}} + a_{ggj}\Delta'_{ggj} + a_h\Delta'_h + a_{cd}\Delta'_{cd} + a_{pol}\Delta'_{pol} + a_w\Delta'_w + \sum_i a_i\Delta'_i,)$$

classical

bootstrap current

plasma curvature

heating & current drive

polarisation current

wall stabilisation

any other contribution that modifies the eff. $j_{\parallel}$

The Modified Rutherford equation (MRE)

$$\frac{\tau_R}{\bar{\rho}_{mn}}\frac{dw}{dt} = \bar{\rho}_{mn}(\Delta' + a_{bs}\Delta'_{bs} + a_{ggj}\Delta'_{ggj})$$

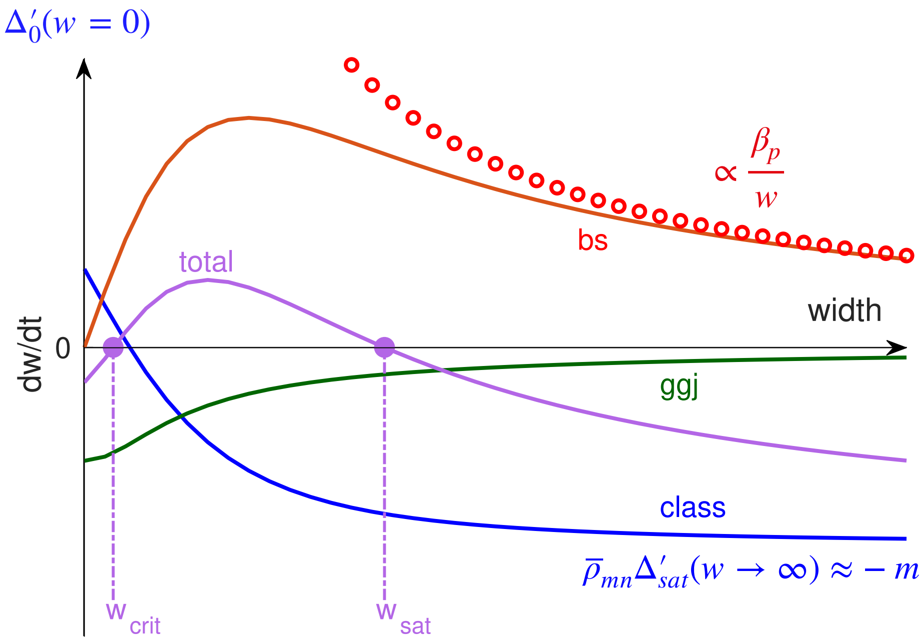
classical	bootstrap current	plasma curvature
> or < 0	**> 0**	**< 0**

- Classical stability index **> or < 0**

should be computed from the equilibrium
—> relies on very precise q-profile measures!

- For $w \to 0$: $\bar{\rho}_{mn}\Delta' = \bar{\rho}_{mn}\Delta'_0 - \alpha\frac{w}{\bar{\rho}_{mn}}$
- For $w \to \infty$: $\bar{\rho}_{mn}\Delta' = \bar{\rho}_{mn}\Delta'_{sat} \approx -m$
  [Sauter (1997)]

➡ "comprehensive" MRE (co-MRE) includes both



$$\boxed{w_{sat}(w \to \infty) = \frac{a_{bs}\Delta'_{bs}}{-\Delta'_{sat}}}$$

The Modified Rutherford equation (MRE)

$$\frac{\tau_R}{\bar{\rho}_{mn}}\frac{dw}{dt} = \bar{\rho}_{mn}(\Delta' + a_{bs}\Delta'_{bs} + a_{ggj}\Delta'_{ggj})$$

classical	bootstrap current	plasma curvature
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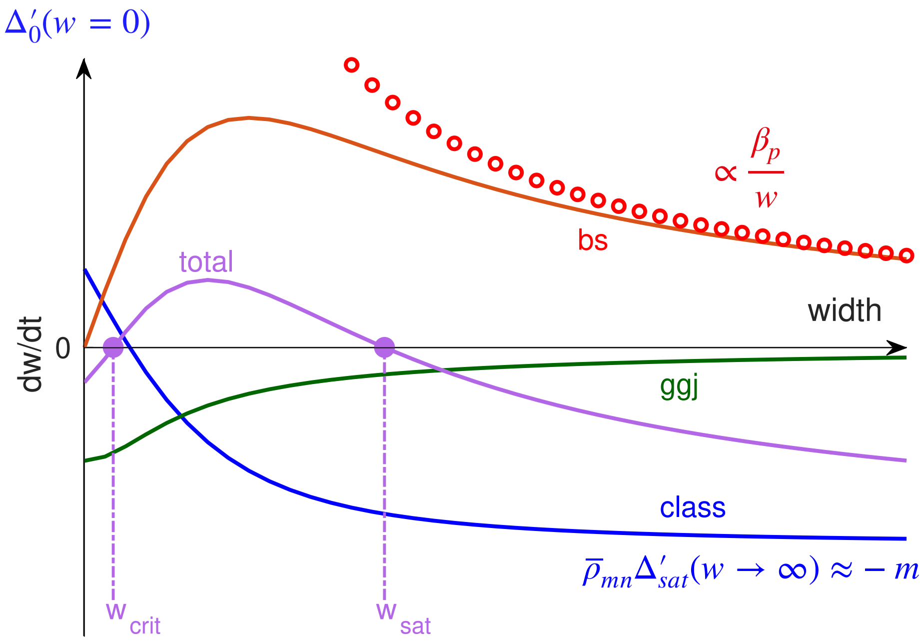

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$$\frac{\tau_R}{\bar{\rho}_{mn}}\frac{dw}{dt} = \bar{\rho}_{mn}(\Delta' + a_{bs}\Delta'_{bs} + a_{ggj}\Delta'_{ggj})$$

classical | bootstrap current | plasma curvature

> or < 0 | **> 0** | **< 0**

- Classical stability index **> or < 0**

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  - For $w \rightarrow 0$: $\bar{\rho}_{mn}\Delta' = \bar{\rho}_{mn}\Delta'_0 - \alpha \frac{w}{\bar{\rho}_{mn}}$
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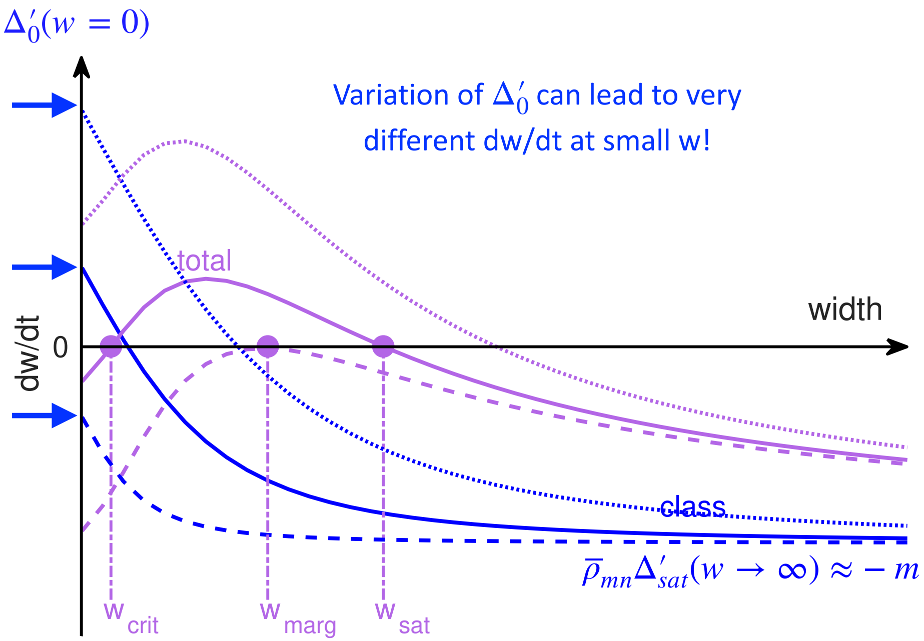


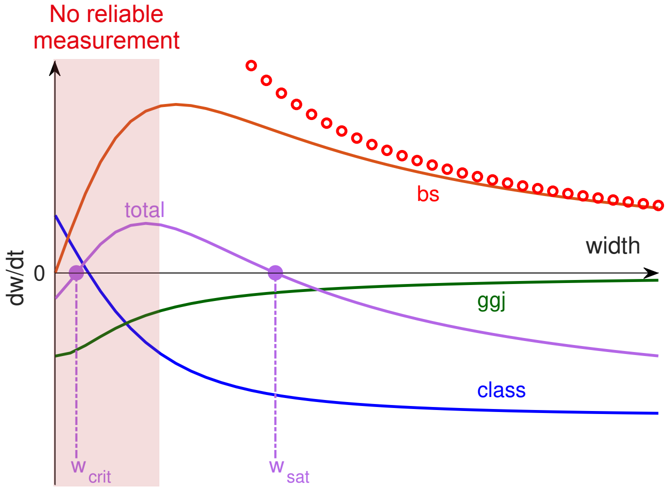
Variation of Δ'_0 can lead to very different dw/dt at small w!

NTM triggering mechanisms

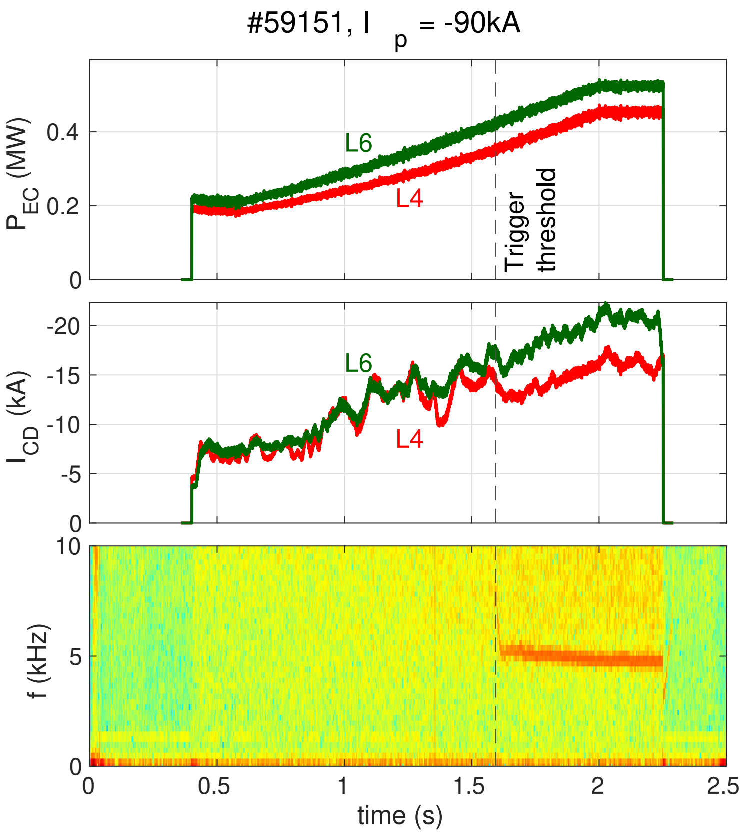
- Seed island $w_{seed} > w_{crit}$
  - MHD instability event (sawtooth crash, fishbone, ELM)
  - Turbulence [SI Ioth (2003)]

- *Triggerless* NTMs $\frac{dw}{dt} > 0$ at $w = 0$ ⟷ $\Delta_0' > \Delta_{ggj}'(w = 0)$
  - Perturbed flux is strongly dependent on q-profile measurement -> define Δ_0' dependent on the plasma state
    - On-axis co-ECCD -> global change of q-profile

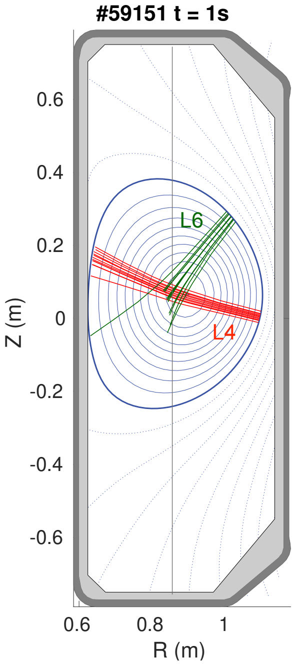
$$\bar{\rho}_{mn}\Delta_0' \propto \frac{I_{cd}}{I_p}$$



Example of triggerless [N]TM at TCV

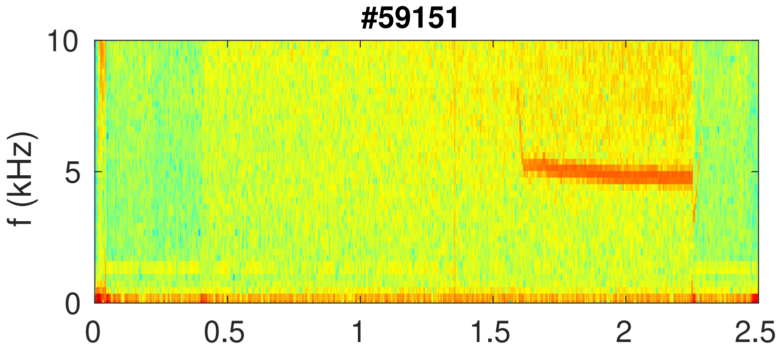


- 2 EC launchers drive current on-axis until triggering threshold is reached



Full discharge modelling with co-MRE

gitlab.epfl.ch/
spc/co-mre



$$\frac{\tau_R}{\bar{\rho}_{mn}}\frac{dw}{dt} = \bar{\rho}_{mn}(\Delta' + a_{bs}\Delta'_{bs} + a_{ggj}\Delta'_{ggj})$$

classical

$k = 6$

$\Delta'_{ohmic} = -1.3$

$\Delta'_{sat} = -0.5$

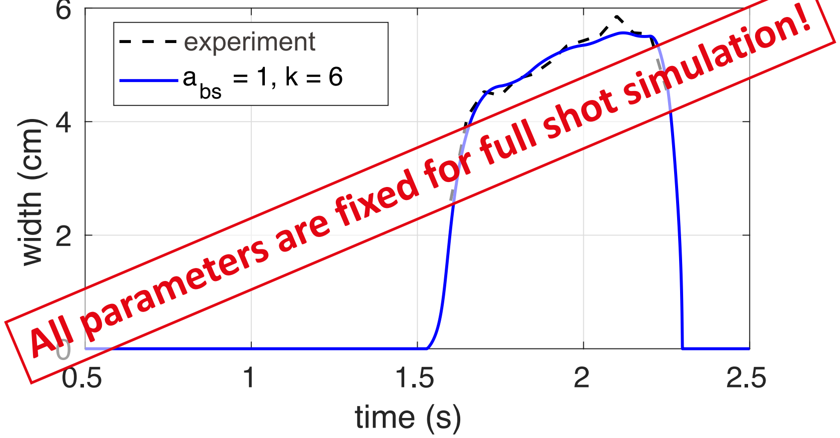
bootstrap current

$a_{bs} = 1$

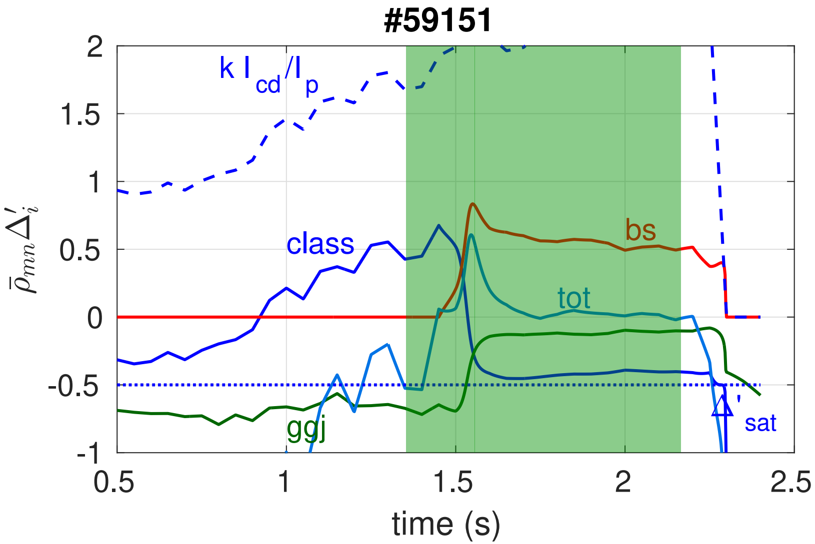
plasma curv.

$a_{ggj} = 1$

co-MRE simulation from 0.5s (w=0) to 2.5s



All parameters are fixed for full shot simulation!



Outline

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[N]TM control strategies

Avoidance

- Operation at e.g. $\beta_{max} < \beta_{marg}$
- Avoid seed island formation as secondary instability

Prevention/Preemption (island might form soon)

- Identify triggering events (global change of plasma parameters or precursor MHD instabilities) (might be easier than measuring a seed island)
- Activate actuator for preemptive actions

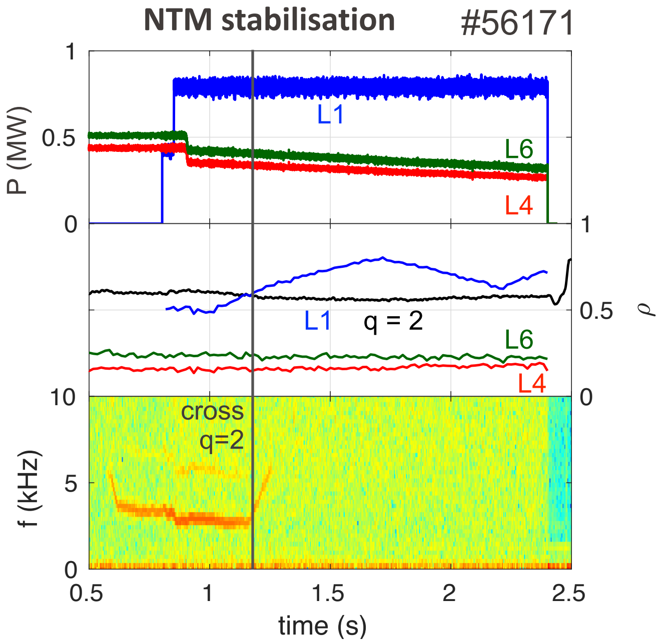
Stabilisation (island has already formed)

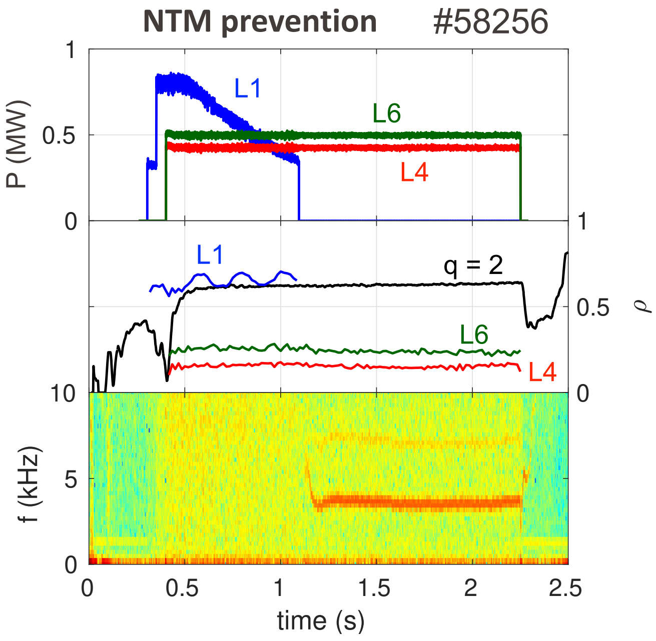
- Activate actuator to achieve full stabilisation
- Activate actuator to achieve partial stabilisation

➡ All strategies will affect the effective fusion power, the control system of the machine must be able to decide which strategy is best !

ECCD for [N]TM preemption and stabilisation

- **Electron cyclotron waves** applied at rational q surface to **replace missing bootstrap current**





ECCD for [N]TM preemption and stabilisation

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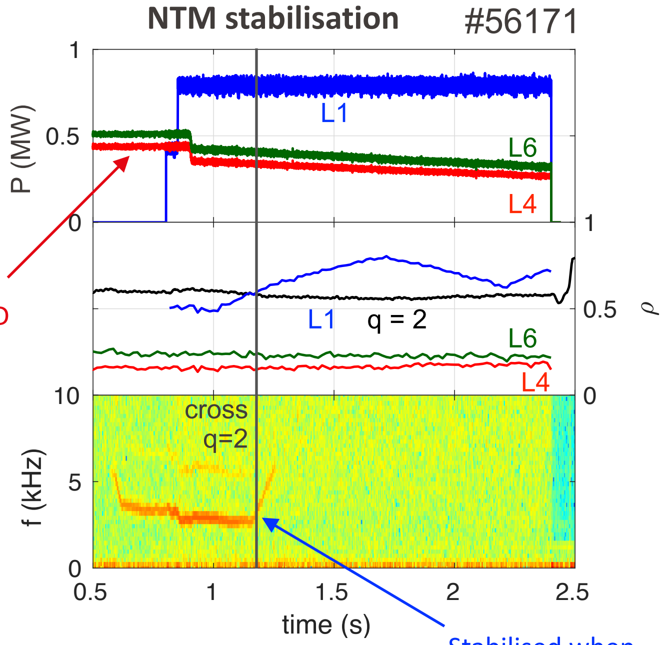
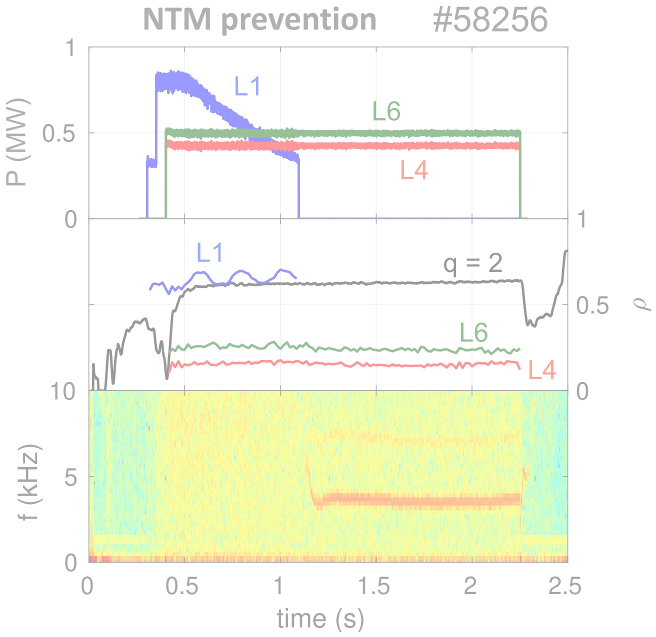


NTM stabilisation #56171

NTM triggered
by on-axis ECCD
$\Delta_0' \propto I_{cd}/I_p$

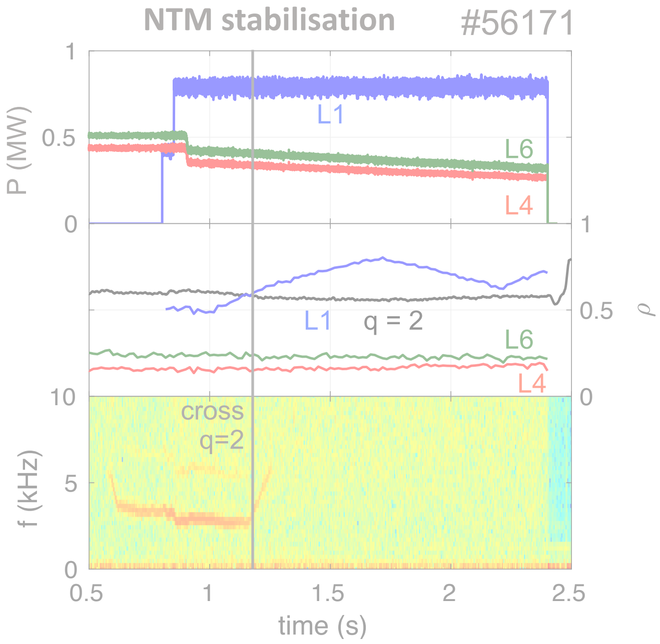
Stabilised when
q = 2 is crossed



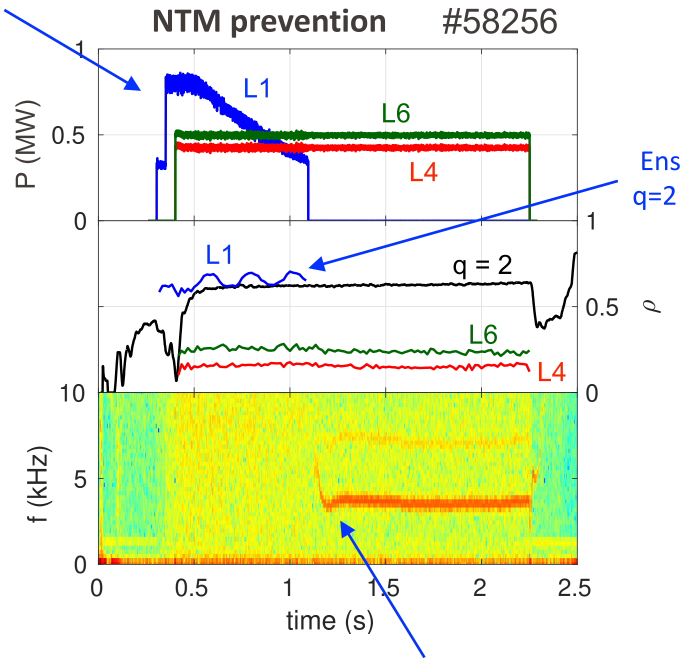
NTM prevention #58256

ECCD for [N]TM preemption and stabilisation

- **Electron cyclotron waves** applied at rational q surface to **replace missing bootstrap current**



Add preemptive EC before mode is triggered



Ensure crossing q=2 by sweeping

mode only triggered when EC power is turned off

Modelling of stabilisation/prevention with ECCD

$$\frac{\tau_R}{\bar{\rho}_{mn}}\frac{dw}{dt} = \bar{\rho}_{mn}(\Delta' + a_{bs}\Delta'_{bs} + a_{ggj}\Delta'_{ggj} + a_h\Delta'_h + a_{cd}\Delta'_{cd})$$

classical

bootstrap current

plasma curvature

heating & current drive

[O Sauter (PoP, 2004),
D De Lazzari (NF, 2009),
E Poli (NF, 2015)]

power modulation

misalignment

width dependence
$w^* = w_{NTM}/w_{dep}$

$$\propto -\frac{\eta P_{EC}}{w_{dep}^2} G(x_{norm}, w^*) M(w^*, D) N(w^*)$$

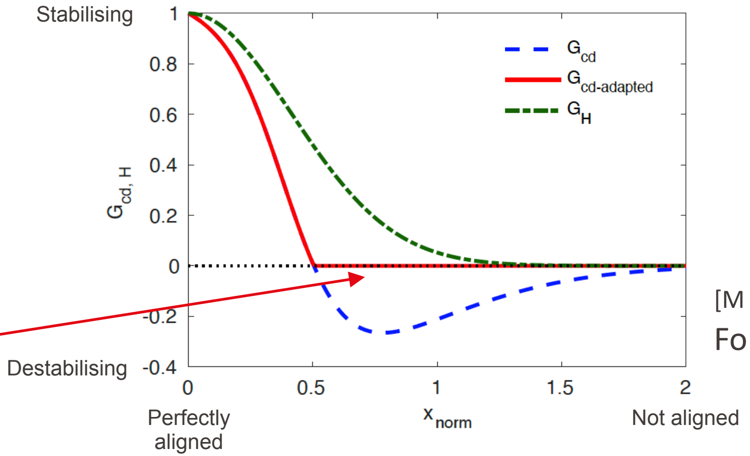
w_{dep} : EC beam deposition width

Strongly impacts NTM stabilisation efficiency!

Destabilising effect of misalignment not observed

- Theory predicts destabilising effect when not aligned with magnetic island [Pletzer (1999), De Lazzari (2009), Février (2016)]

Theoretical model used in co-MRE



Over large database good modelling results were obtained by **neglecting G_{cd}<0**!

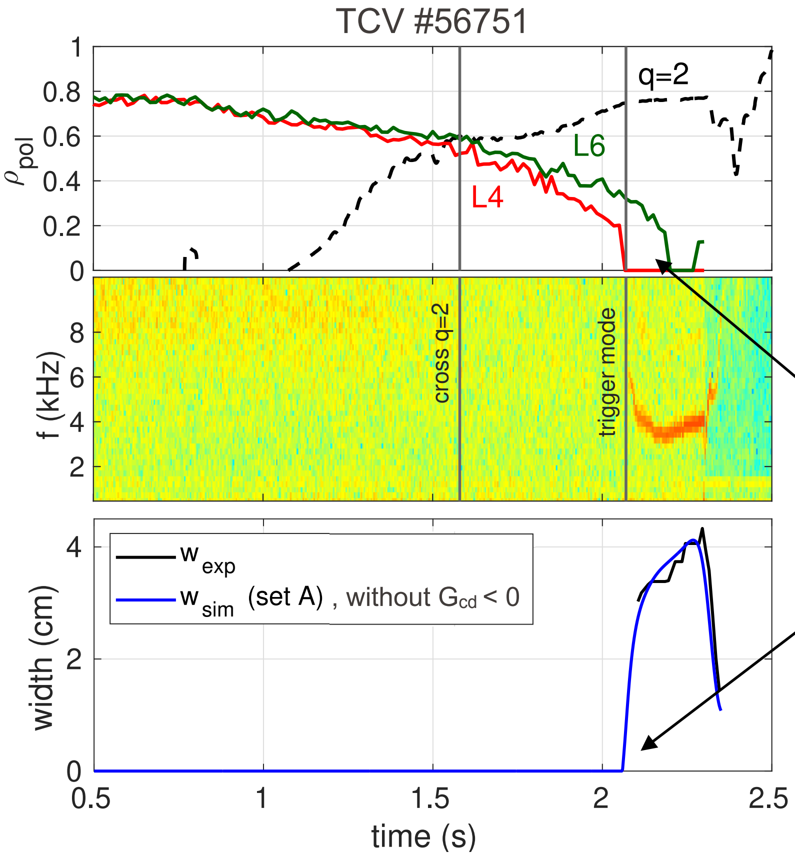
[M Kong (NF, 2019)]

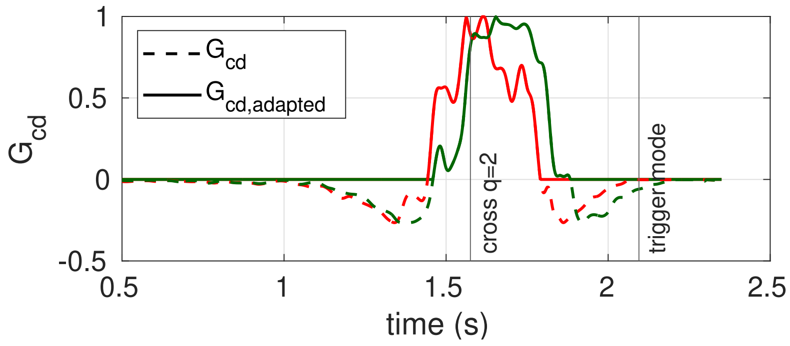
For $w^* = w/w_{dep} = 1$

➡ Experimentally, this destabilising effect is **not observed!**

- Sweeping around the rational q for preemption/stabilisation has been shown to be very efficient on several machines
- No [N]TM triggering is observed when crossing rational q

Destabilising effect of misalignment not observed

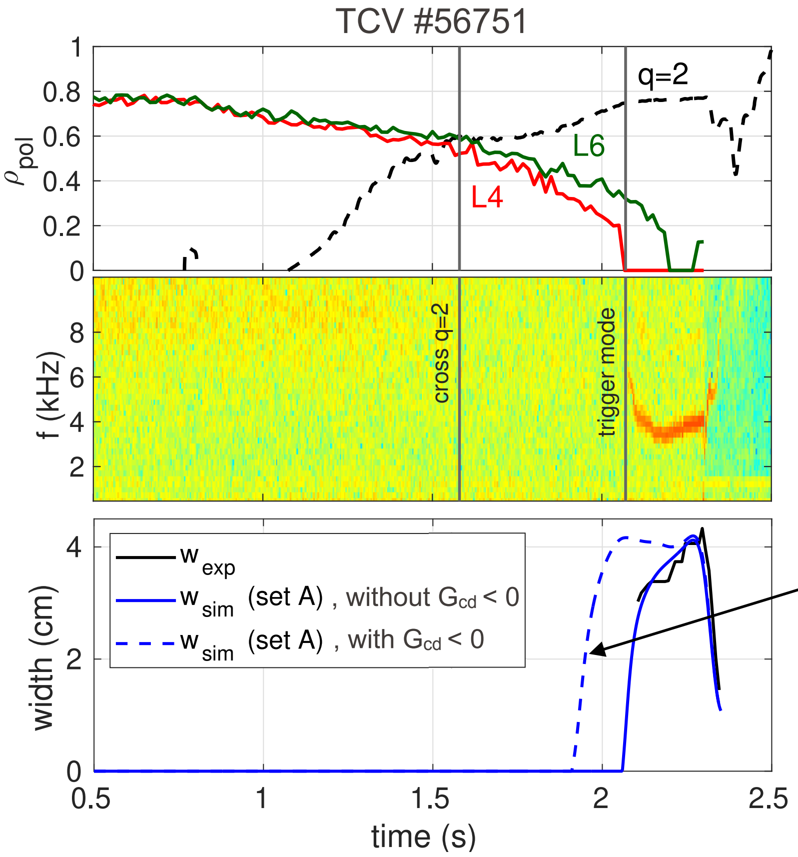


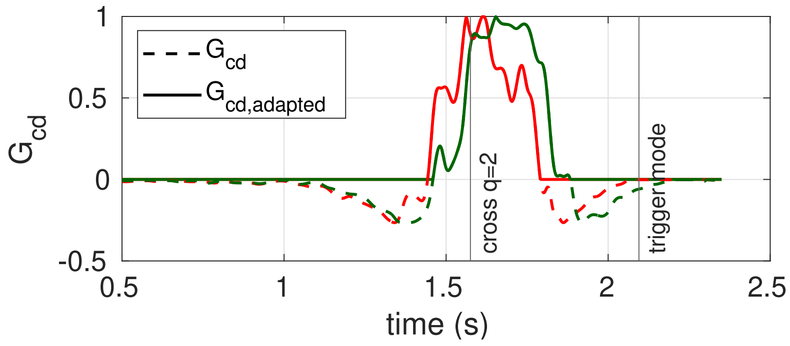


[N]TM is triggered due to unstable classical stability index

$$\bar{\rho}_{mn}\Delta_0' \propto \frac{I_{cd}}{I_p}$$

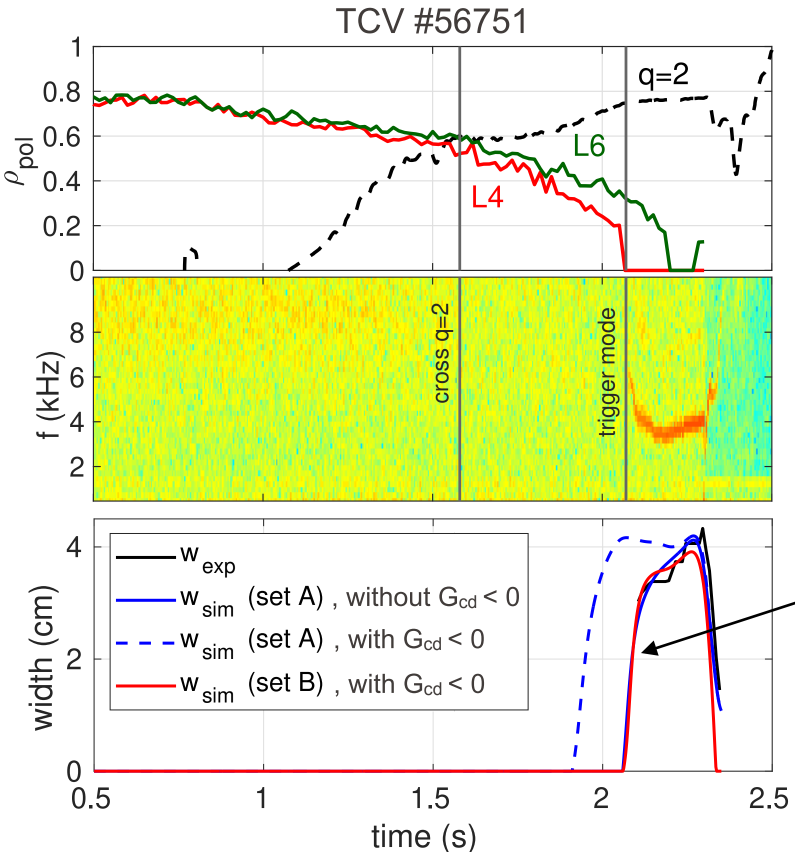
Destabilising effect of misalignment not observed

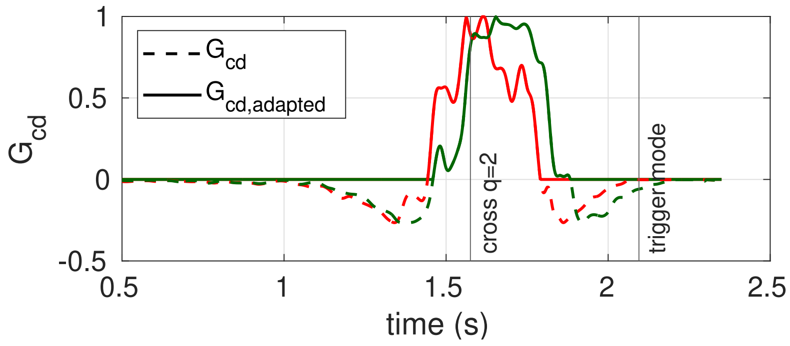




With the same parameters, but including negative G_{cd} we would trigger earlier!

Destabilising effect of misalignment not observed

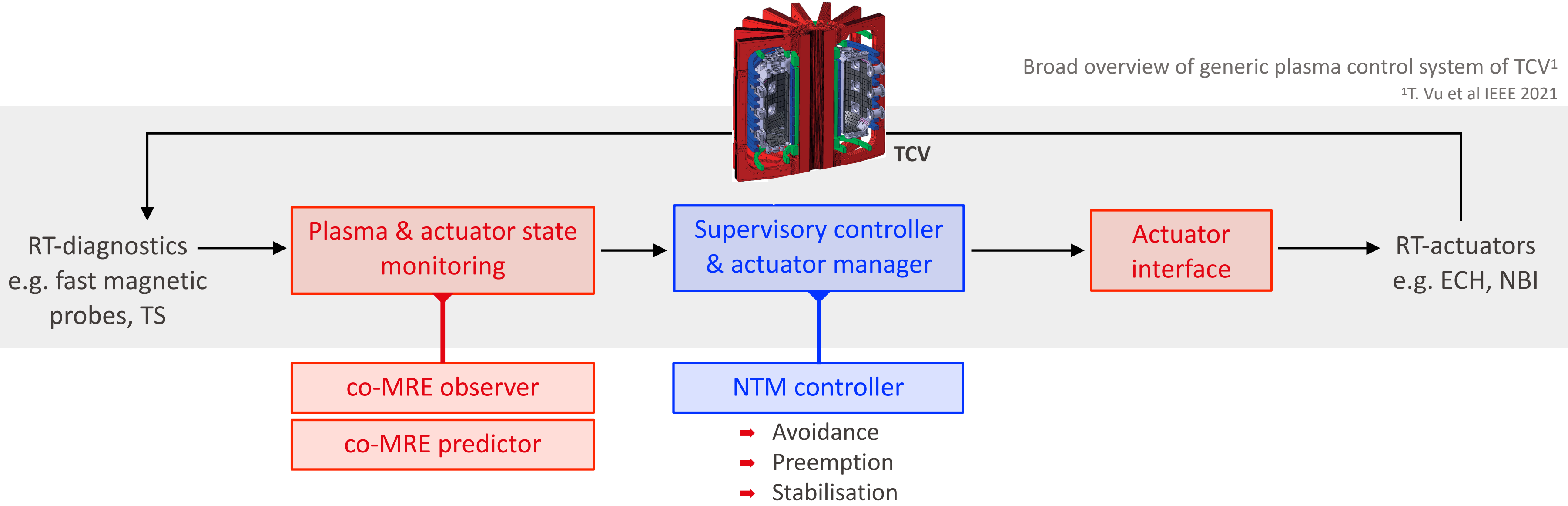




Classical Δ_0' must be more stable to match experimental data when including negative G_{cd}

co-MRE on the real-time control system of TCV

- co-MRE has proven ability to model NTM dynamics at several machines
- “Free” parameters can be kept fixed during a full discharge simulation -> once found we can predict!
- Solving the co-MRE is **very fast** so that it can be implemented in a real-time control system to provide information for an NTM controller!



Broad overview of generic plasma control system of TCV[1]

[1]T. Vu et al IEEE 2021

TCV

RT-diagnostics
e.g. fast magnetic probes, TS

Plasma & actuator state monitoring

Supervisory controller & actuator manager

Actuator interface

RT-actuators
e.g. ECH, NBI

co-MRE observer

co-MRE predictor

NTM controller

- ➡ Avoidance
- ➡ Preemption
- ➡ Stabilisation

MRE can be used as a real-time predictor

- MRE can provide the supervisory controller with more information to decide what is the best NTM control strategy

Example: RT prediction of EC power P_{EC} for mode stabilisation
[M. Kong PPCF (2022)]

- Use $\bar{\rho}_{mn}(\Delta'_{CD} + \Delta'_{H}) = f_{EC}(w, \rho_{dep}, w_{dep}) \cdot P_{EC}$
- Find EC power such that $\frac{dw}{dt}\Big|_{w=w_{req}} \leq 0$

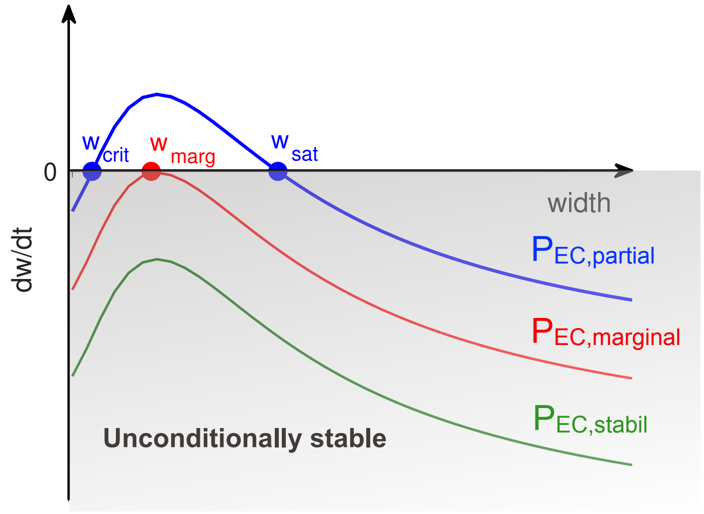
$$P_{req} = -\frac{\bar{\rho}_{mn}(\Delta' + \Delta'_{BS} + \Delta'_{ggj})}{f_{EC}(w, \rho_{dep}, w_{dep})}\Big|_{w=w_{req}}$$

Unconditionally/marginally stable

$$w_{req} \leq w_{marg}$$

$$w_{req} = w_{sat,req}$$

Partially stable



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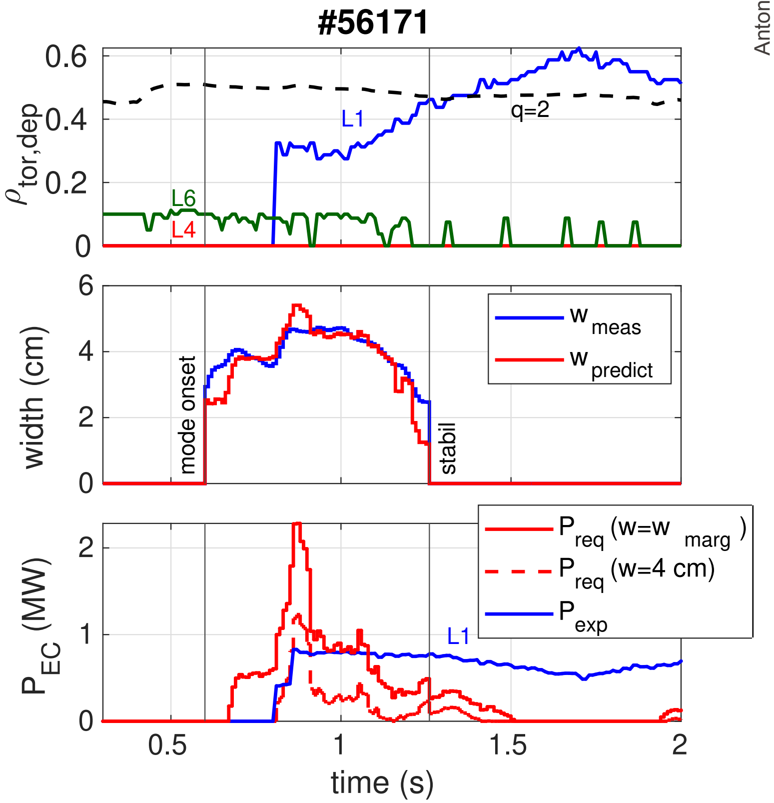

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Summary

- The co-MRE provides a reliable model to analyse and predict [N]TM dynamics of both classical and neoclassical TM in the same framework
- There remain open questions:
  Why don’t we destabilise TMs with local ECCD near q=m/n?, …
- Robust [N]TM control needs to be able to decide on best control strategy, hence needs to compile all possible information to optimise fusion gain and to avoid disruptions
- RT MRE can provide additional information to improve [N]TM control decision by finding [N]TM stabilisation power, checking ECCD alignment, …
- We can predict faster than real-time!