Separating the effects of heating and current drive on NTM evolution in TCV

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Introduction

- Neoclassical Tearing Modes (NTMs) have detrimental effect on plasma confinement, may even lead to disruptions → important to understand NTM evolution
- TCV has very flexible ECRH/ECCD system, suited for analysis of NTM birth, growth and suppression.
- Previous work [1]: successful simultaneous modelling of evolution of T_e, q and (2,1) NTM in TCV
- This poster: disentangle role of heating and CD in NTM evolution, using co- and counter-ECCD
- Use Rapid Plasma Transport simulatOR (RAPTOR) [2,3]; it self-consistently evolves T_e, q and w_{NTM}.

1. Experimental Observations

- In 2016 dedicated experiments performed in TCV to study NTM evolution & suppression.
- 2 gyrotrons with co-ECCD with nearly central deposition to trigger (2,1) NTM
- 3rd gyrotron with swept power deposition location, delivering co- or ctr-ECCD or pure ECRH

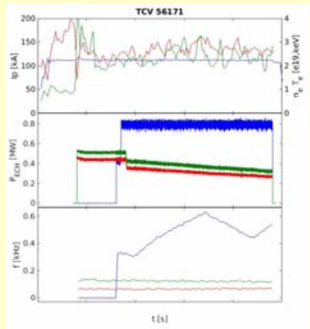


Fig.1: Time traces of Ip, central ne and Te (upper panel), P_{ECH} and ρ_{dep} of the 3 gyrotrons (middle and lower panels), for TCV shot #56171 (the other two sots have identical time traces)

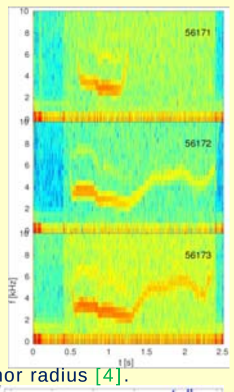


Fig.2: MHD spectograms for shots #56171 (co), #56172 (ctr), and #56173 (pure heating), showing full NTM suppression in the first shot and partial suppression in the other two shots

Estimation of NTM width

a) Relative drop of β_N due to NTM: $w_{sat} = \frac{\Delta\beta_N}{\beta_N}\frac{1}{4\rho_s{}^3}$
   ρ_s, w_{sat} : radius of resonant surface and saturated island width, both normalized to minor radius [4].
   From estimated $\Delta\beta_N$ ~ 8-10% we find typical w_{sat} ~ 5 cm around t = 1 s
b) Relative NTM width directly related to magnetic mode amplitude: $w_{\rm NTM} \sim \tilde{B}^{0.5}$
   Mode amplitude derived from Power Spectral Densities (PSDs) of magnetic pick-up coil signals; see Fig.3:
   - Good agreement with MHD spectra of Fig.2
   - Full suppression in #56171 after~1.2 s → amplitude below ~0.002 is noise
   - Clear reduction of NTM width for #56172 and #56173 when ρ_{dep} comes close to the NTM, but no full suppression

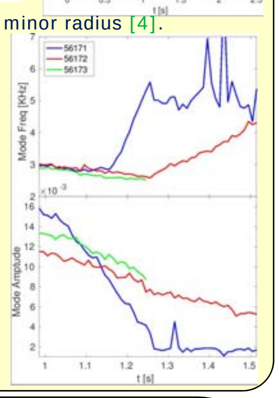


Fig.3: Time traces of mode frequency and amplitude for the shots #51671/2/3, as determined from Power Spectral Densities, showing full suppression in the first case and reduction of the NTM by ~30% in the other 2 cases.
Due to numerical problem the run for shot #51673 was not completed

2. Modified Rutherford Equation

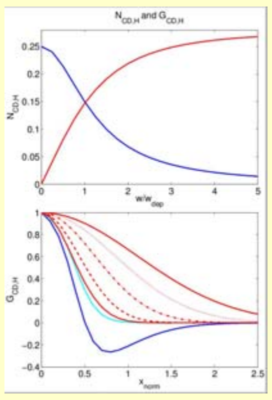
5 terms in evolution of NTM width [5,6]: $\frac{dw}{dt} = \frac{r_s{}^2}{\tau_R}(\Delta'_{class}(w) + \alpha_{BS}\Delta'_{BS}(w) + \alpha_{GGJ}\Delta'_{GGJ}(w) + \alpha_{CD}\Delta'_{CD}(w) + \alpha_H\Delta'_H(w))$
classical, bootstrap, Glasser-Green-Johnson, current drive, and heating term
In principle all $\alpha_{BS,GGJ,CD,H}$ = 1, however uncertainties in experimental data and possible approximations in derivations call for introduction of these terms ~1
Classical term: $r_s\Delta'_{class}(w) = r_s\Delta'_{class}(0) - (m + r_s\Delta'_{class}(0))f(w)$ with $f(0) = 0, df/dw(0) = \alpha_{CL}$ and $\lim_{w\to\infty}(f) = 1$

Sign of classical term at w=0:

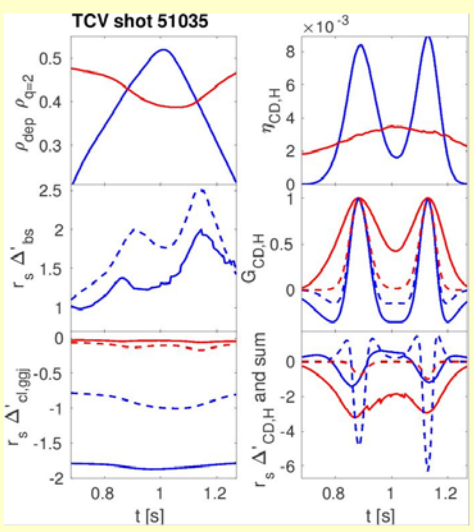
- Theoretically: Critically dependent on dq/dr - Calculations inconclusive:
  - using q from equilibrium reconstruction, at most time points $\Delta'_{class}(0) > 0$
  - using q from RAPTOR simulations, at most time points $\Delta'_{class}(0) < 0$
- Experimental evidence:
  - No visible NTM in ohmic and part of ECH phases → $\Delta'_{class}(0)$ cannot be >> 0
  - L-mode and low Ip, so no/tiny sawteeth → no seed islands → $\Delta'_{class}(0)$ cannot be << 0
- Concluding: $\Delta'_{class}(0)$ close to 0, probably small positive (which was also stated in [7])

Comparison of CD and H terms in NTM evolution:

Both terms have the same structure: $\Delta'_{CD,H} \simeq \eta_{CD,H}(w_{\rm dep}, \chi_e^{\rm ins})N_{CD,H}(w^*)G_{CD,H}(w^*, x_{\rm norm})M_{CD,H}(w^*, D)$
where $w_{\rm dep}$ is deposition width, $\chi_e^{\rm ins}$ is χ_e inside island $w^* \equiv w_{\rm NTM}/w_{\rm dep}$ is normalized island width,
and $x_{\rm norm} \equiv |\rho_{\rm dep} - \rho_{\rm mn}|/max(w_{\rm dep}, w_{\rm NTM})$ is misalignment of power deposition with respect to the island,
and η, N, G, M are the efficiency, normalization factor, geometry factor and modulation effect.
The latter is not considered here - only CW ECH/ECCD, i.e. duty cycle D = 1, hence M =1



←Fig.4: Normalization and geometry factor for CD (blue) and H terms (red), as function of w^* and $x_{\rm norm}$
In the lower plot various widths of the NTM are assumed, from 0 (narrowest curve) to 5 cm (widest curve).
Note that G_H is always positive whereas G_{CD} <0 (i.e. destabilizing) for misaligned power.
Cyan curve in lower panel: adapted G_{CD} such that destabilizing effect is cancelled.



→Fig.5: Various terms of the MRE for a discharge with a strong sweep of ρ_{dep} (upper panel), assuming fixed w_{NTM} = 1.5 (dashed) and 5 cm (full curves).
In lower left frame classical term in blue, GGJ term in red.
In all right-hand frames CD terms in blue, H terms in red.

- Under favourable conditions (large island, low χ_e inside island, which has been observed [8]), $\Delta'_H \simeq \Delta'_{CD}$
- Fig.5 shows: for large w_{NTM}, the destabilizing CD term for strongly misaligned ECCD, is compensated by the stabilizing H term
- Since Δ'_H critically depends on unknown χ_e inside island, we do some of the simulations without this term, but use adapted G_{CD} without destabilizing effect (cyan curve in Fig.4b).
- Fig. 5 also shows that, for well-aligned ECH/ECCD, the H and CD terms are stronger than any other term

Discussion and Conclusions

- Simultaneous evolution of T_e and q profile and (2,1) NTM width has been successfully simulated in TCV discharges with both co- and counter-ECCD and pure ECH.
- Two versions of the MRE were compared: (a) a simplified version without heating term and with adapted CD term; (b) the full version.
  - ✓ Both version work fine for the co-ECCD case
  - ✓ For the ctr-ECCD and pure-heating case, only the full version captures the NTM width in detail

Outlook

- Similar experiments in AUG have been done and will be simulated
- Understanding and prediction of NTM evolution is essential in setting up reliable control schemes
- NTM control is being integrated with multiple controllers in TCV [10]

3. Transport and MHD modelling

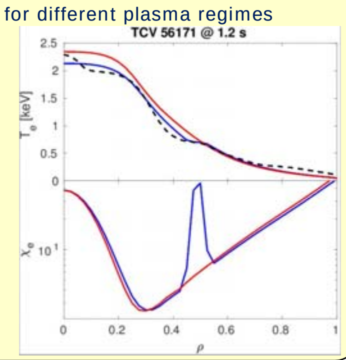
- RAPTOR self-consistently calculates simultaneous evolution of T_e and q profile and NTM width
- n_e from experiment; no T_i measurements, so for T_i educated guess (in typical TCV plasmas weak e-i coupling)
- Prescribed (CHEASE) equilibria are used (calculated for various time slices)
- RAPTOR has a module that solves NTM evolution based on MRE
- χ_e in RAPTOR prescribed semi-empirically, with several parameters tunable for different plasma regimes

Effect of NTM on plasma confinement in RAPTOR

Modelled by assuming increase of χ_e over area ~ NTM width [9]:

$$\chi_e(\rho) = \chi_{e0}(\rho)(1 + A_{\rm mn}exp(\frac{-4(\rho - \rho_{\rm mn})^2}{(C_{\rm mn}(w_{\rm NTM}/a))^2})$$

A_{mn} and C_{mn} assessed by using in RAPTOR prescribed NTM width, taken from experiment – simulated reduction of both T_e and β_N must match experiment.
Best results with narrow but strong χ_e enhancement – see Fig.6



→Fig.6: T_e and of χ_e profiles at 1.2 s for TCV shot 56171, for RAPTOR runs without NTM (red) and with NTM-enhanced χ_e with A_{mn}/C_{mn} = 8.0/0.5 (blue). Experimental T_e profile black dashed

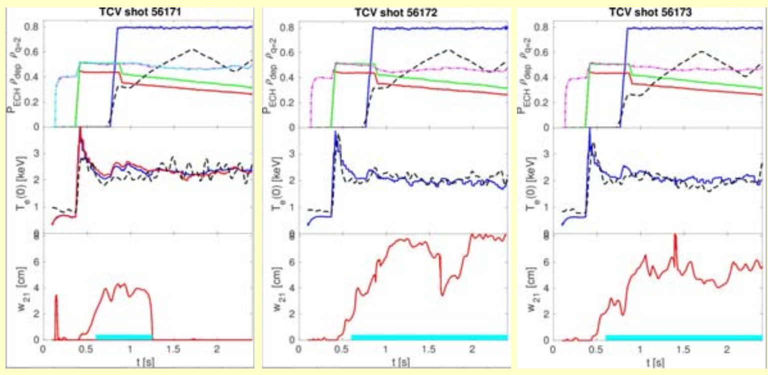
4. Results

Without H-term, and with adapted G_{CD} (see Fig.4)

Best reproduction of the observed NTMs in the 3 pulses considered were found with following values – see Fig.10:

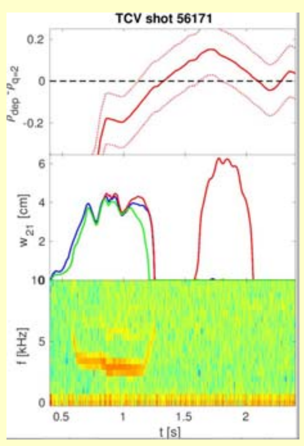
$$r_s\Delta'_{class}(0) = 0.3, \alpha_{CL} = 14, \alpha_{BS} = 2.1, \alpha_{GGJ} = 0.5, \alpha_{CD} = 1$$

Fig.7. RAPTOR simulations for #56171,-72,-73, no H-term, with adapted G_{CD}.
Upper: Powers of central (red, green) and off-axis gyrotron (blue), ρ_{dep} of the latter (dashed) and $\rho(q=2)$ (magenta).
Middle: $T_e(0)$ from experiment (dashed) and simulation (full blue); in 1st plot also for a run without NTM (red).
Lower: w_{NTM} from the simulations (red); cyan bar indicates when NTM was present in experiment.

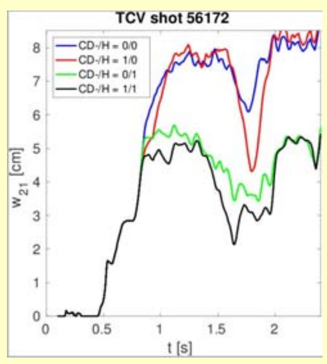


- Realistic size of simulated NTM, although on the high side for #56172,3
- Full suppression in #56171 correctly predicted, and at right time
- In #56172,3 no suppression, like in experiment; however, the observed reduction of the NTM width in #56172,3 when ECH is close to NTM *(see Figure 3)*, is *not* reproduced

Inclusion of H-term



←Fig.8. RAPTOR simulations for #56171 in middle panel:
Blue: no H-term, with adapted G_{CD}
Red: no H-term, with standard G_{CD}
Green: with H-term, with standard G_{CD}
Upper panel shows ρ_{dep} - $\rho(q=2)$ (full line), and this value +- w_{dep} (dashed lines)



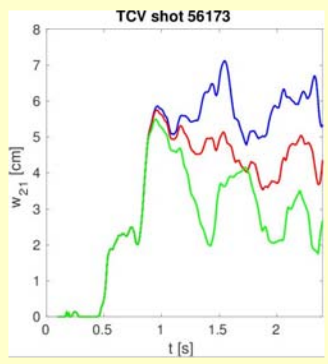


Fig.9. w_{NTM} for RAPTOR simulations for #56172 with all combinations of yes/no H-term yes/no adapted G_{CD}, showing that with the H-term w_{NTM} is reduced to more realistic values, and also is further reduced when the power deposition is close to the NTM, in agreement with experimental observation (see Fig.3)

Fig.10. w_{NTM} for RAPTOR simulations for the pure heating case #56173, with no H-term (blue) and with various strengths of the H-term (red, green).
The latter simulation (green) shows partial suppression of the NTM when ρ_{dep} is close to the NTM, in agreement with experimental observation (see Fig.3)

- For the co-ECCD case #56171, the simplified modelling without H-term and adapted G_{CD} yields results as good as the full modelling
- For the ctr-ECCD case #56172 and pure ECH-case #56173, the full modelling yields a more realistic width of the NTM, and also reproduces the partial suppression in the shot with heating only

References:

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