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Study of resistive MHD stability of COMPASS Upgrade scenarios

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INTRODUCTION

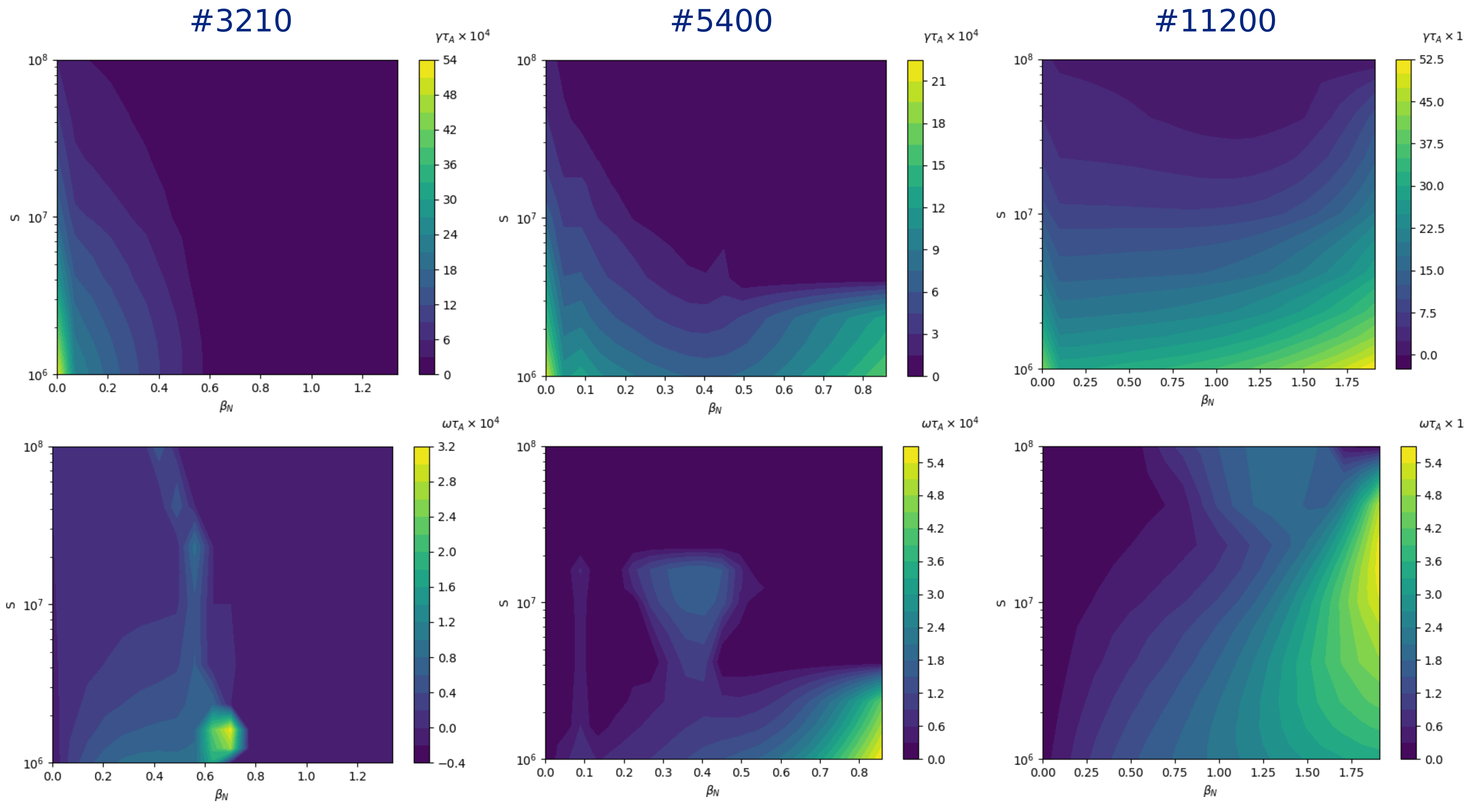
COMPASS-U will explore a broad range of parameters, such as magnetic field ($2.5 \leq B \leq 5$ T) and plasma current ($0.8 \leq I_p \leq 1.6$ MA) [1]. These scenarios, which represent the baseline for COMPASS-U operation, are labeled as early H-mode, ITER-like H-mode and high-performance H-mode. Other two scenarios that deviate from the baseline, either due to a larger plasma current or the shape of the plasma, have been explored; they are labeled as high-current and negative-triangularity.

Name	Scenario	$B[T]$	$I_P[MA]$	q_{95}	β_N
Early H-mode	3210	2.5	0.8	3.6	1.52
ITER-like H-mode	24300	4.3	1.3	3.8	1.19
High-performance H-mode	5400	5.0	1.6	3.4	1.15
High-current	4320	4.3	1.8	2.7	0.96
Negative-triangularity	11200	1.26	0.3	2.8	1.90

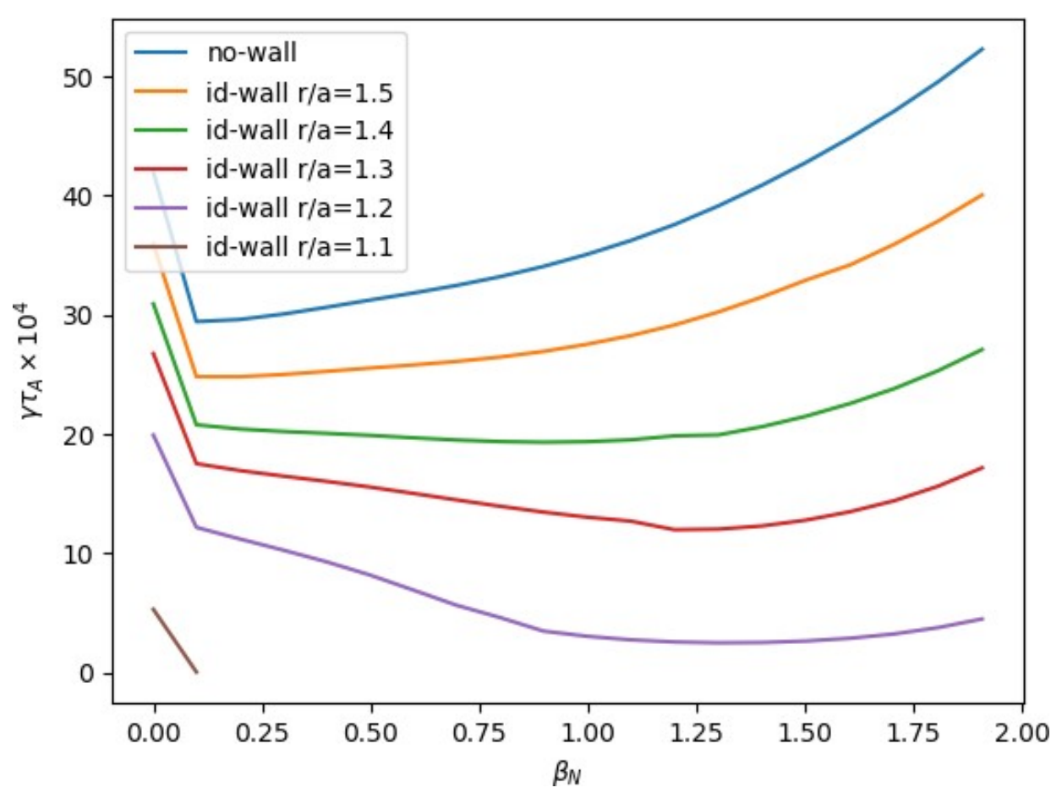
Study of linear stability of COMPASS-U scenarios was performed with the MARS-F code [2]. Systematic parametric scans were made to determine the operational limits of the different scenarios and to identify the most unstable MHD modes [3]. All the scenarios we explored are characterized by $q_0<1$, which makes them potentially unstable to internal kink mode. β_N for all scenarios falls below the no-wall limit β_{NW}, which means that the scenarios are ideally stable with respect to external kink modes. Although they are ideally stable, under some circumstances they can couple with TMs [4].

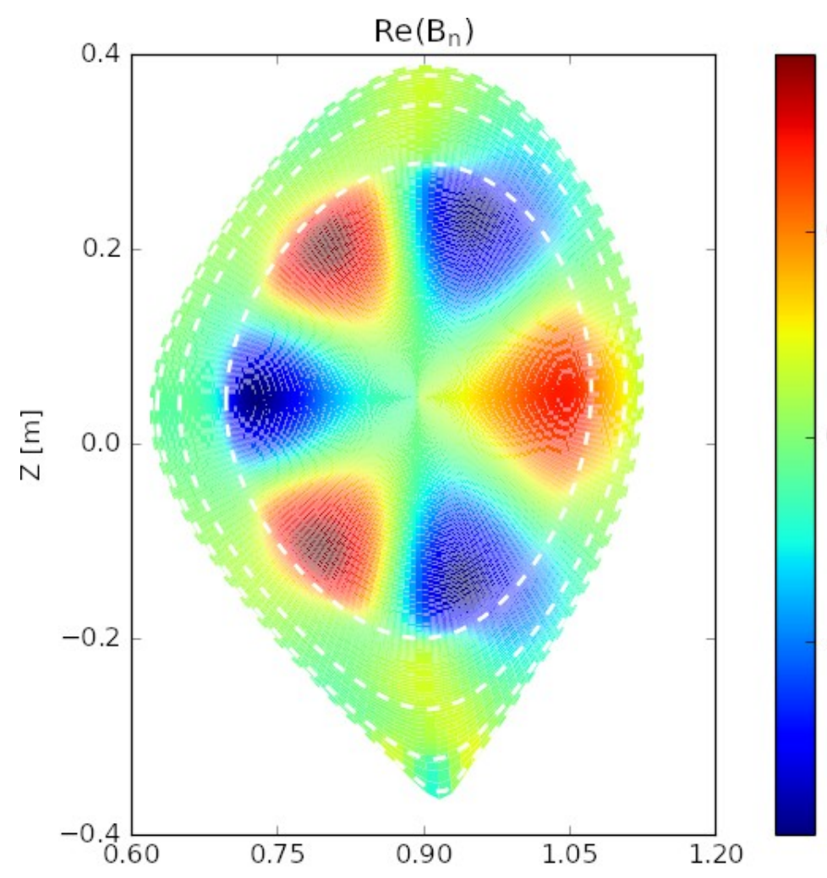
LINEAR TEARING MODE

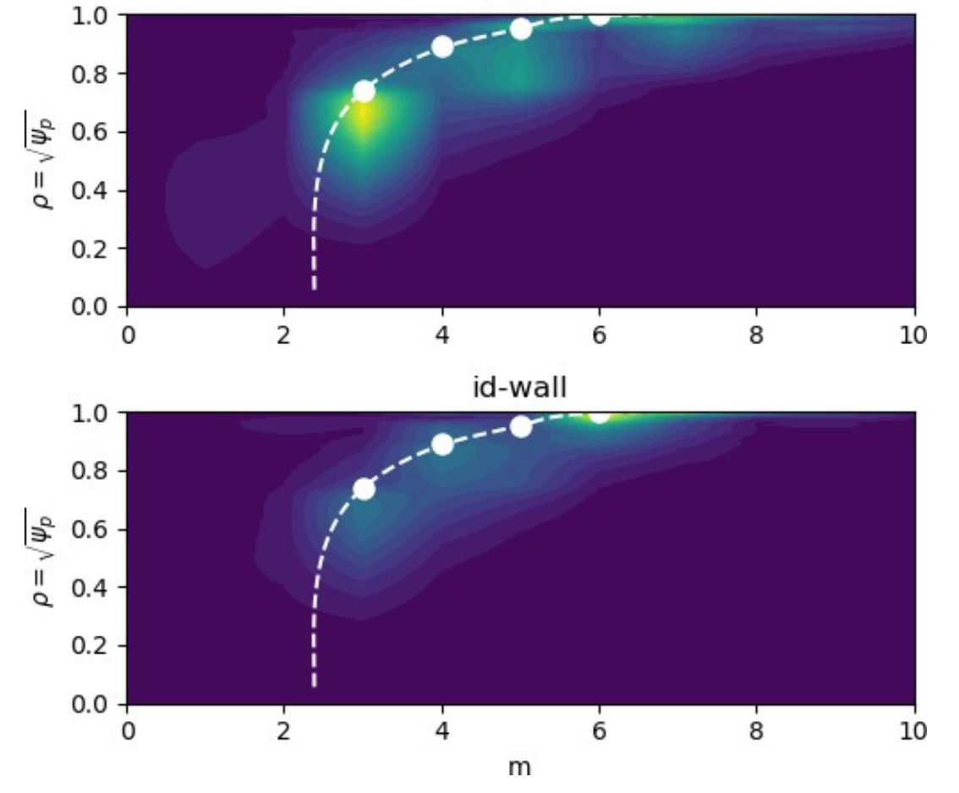
A scan over β was performed to evaluate the stabilizing GGJ effect [5]. In the baseline scenarios, the growth rate drops to zero as β_N reaches the nominal value, and the mode develops a finite rotation frequency. In scenario #5400, in the low S limit, the growth rate reaches a minimum for some intermediate β_N and then it grows again.



The high-current and negative-triangularity scenarios are characterized by lower q_{95} (the q=2 rational surface is closer to the plasma edge). When finite β is considered, the growth rate slightly drops but then it grows to even larger values for nominal β_N.







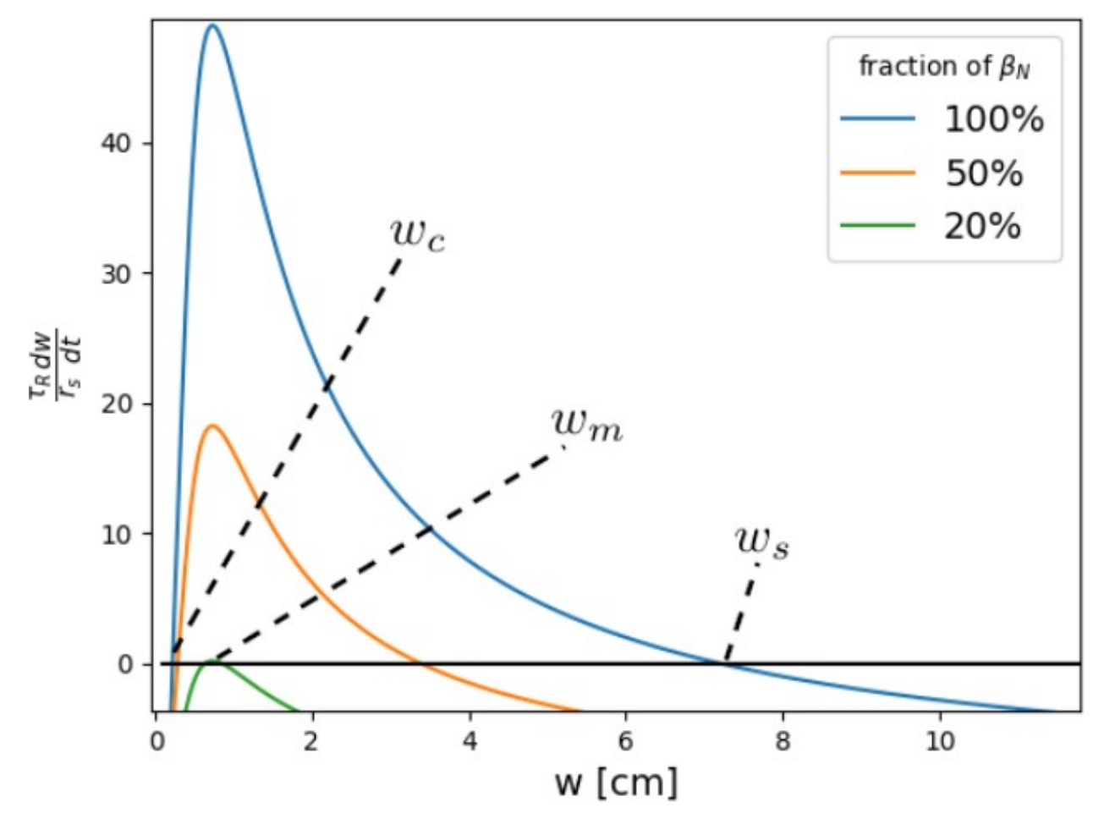
The presence of an unreconnected q=3 surface shields the (2,1) TM from the influence of the (3,1) external kink mode [4]. Introducing an ideal wall positioned at r/a = 1.1 produces complete stabilization for nominal β_N. Stability of the low-q95 scenarios with respect to (3,2) modes was also assessed and a similar behavior was observed, with destabilization at nominal β_N to be attributed to coupling to external modes.

NEOCLASSICAL TEARING MODES

Dynamics of Neoclassical Tearing modes (NTMs) is described by the generalized Rutherford equation (GRE) [6]:

$$\frac{\tau_R}{r_s^2}\frac{dW}{dt} = \Delta' + \Delta'_{BS} + \Delta'_{GGJ} + \Delta'_{pol} + \Delta'_{H} + \Delta'_{CD}$$

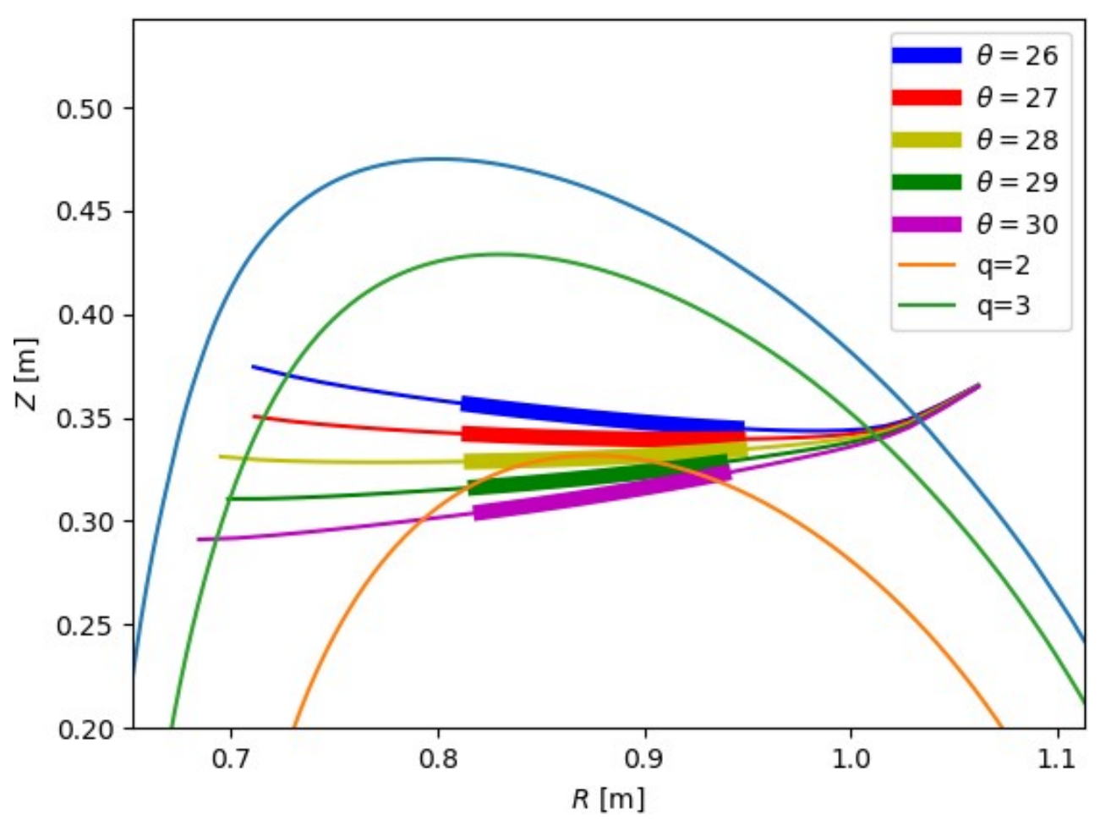
where τ_R is the resistive time of the plasma, r_s is the radius of the rational surface, w is the island width, Δ' is the linear stability index and the other terms on the rhs correspond to the contributions from bootstrap current, GGJ effect, ion polarization, EC heating and current drive. The saturation width w_s for the NTMs in the considered scenarios is comparable to the distance between the q=2 surface and the edge of the plasma, which make them susceptible to locking to error fields.

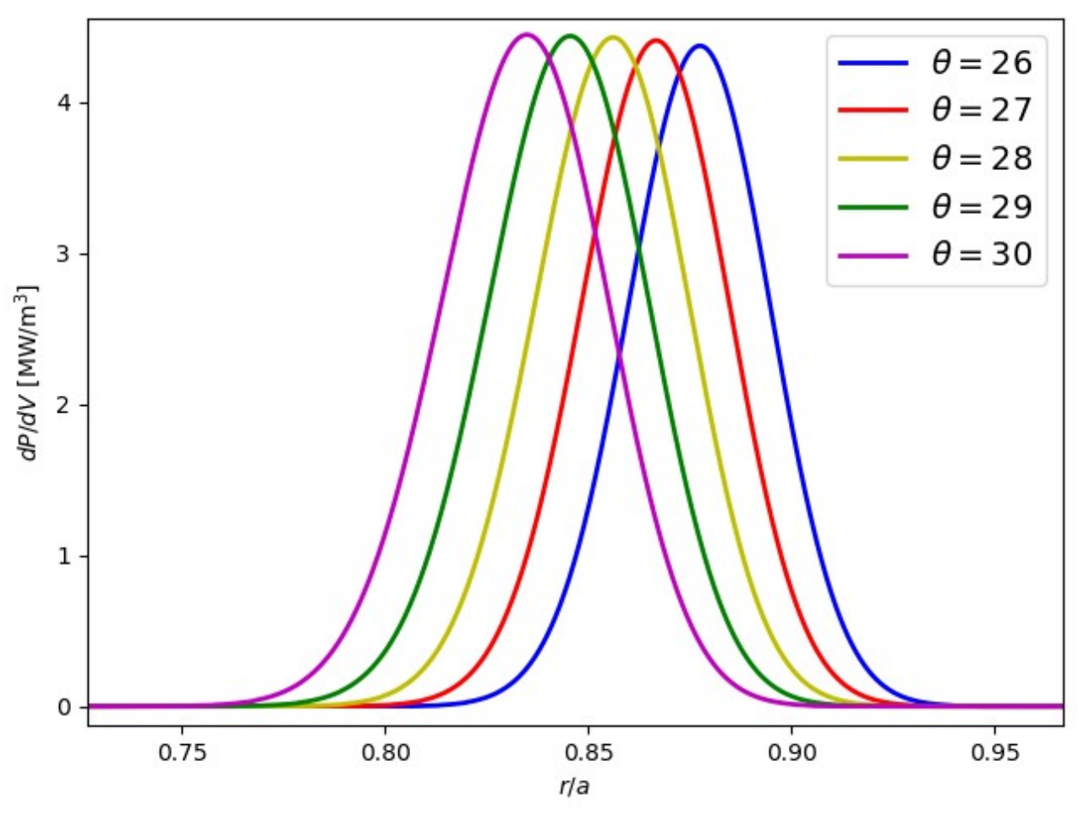


Scenario	w_c	w_m	w_s	Δ'
5400	0.26	0.78	7.19	-10.2
4320	0.35	0.82	8.45	-8.45
24300	0.24	0.75	6.37	-11.2

(w in cm)

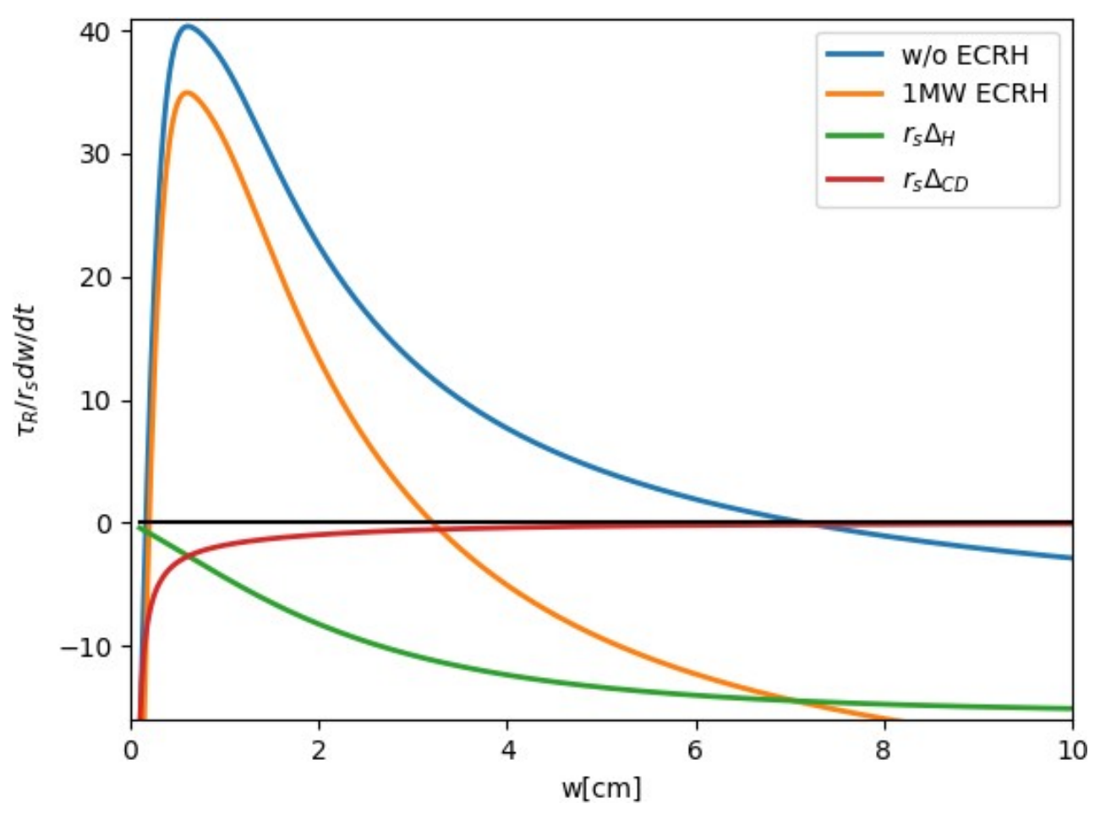
ECH and ECCD are the most widely adopted strategies to control and suppress NTMs. To realize the NTM suppression by EC waves, a poloidal and toroidal steering of the EC beam is necessary to aim precisely at the rational surface.





In the scenarios we considered, for 1 MW of EC power the current driven j_{CD} is smaller than the bootstrap current j_{BS} by at least one order of magnitude. For island width significantly larger than the deposition width of EC ($w/w_{dep} > 1$), ECH proves to be more efficient than ECCD in stabilizing NTMs [7]. The calculation of ECH and ECCD conversion efficiencies proves that ECH provides a sufficient stabilizing effect with only 2 MW of EC power.

The current condensation effect [8] can help reduce the requirements for the minimum injected power and the injection accuracy. Preliminary calculations suggest that current condensation effect will play a minor role in the initial phase of COMPASS-U operation.



CONCLUSIONS

- Baseline scenarios ($3<q_{95}<4$) are expected to be stable wrt TMs at nominal β because of the GGJ effect; high-current/negative-triangularity scenarios ($q_{95}<3$) are expected to be unstable because of coupling to external modes
- The destabilization of the (2,1) TM in the low q_{95} scenarios can be attributed to the presence of the (3,1) external kink mode; stabilization by an ideal wall close to the plasma surface supports this interpretation
- The analysis of nonlinear instability with respect to NTMs by means of the GRE shows that the saturation width of the (2,1) magnetic islands is comparable to the distance between the q=2 surface and the edge of the plasma
- In the examined scenarios, EC heating is significantly more efficient than CD: → we can rely on ECH only, which means that the launcher dedicated to targeting rational surfaces to suppress NTMs does not require toroidal steering of the EC beam

[1] M. Komm et al., Nuclear Fusion 64, 076028 (2024 [2] Y. Liu et al., Phys. Plasmas 7, 3681 (2000) [3] A. Casolari et al., Plasma Phys. Control. Fusion 68 025006 (2026) [4] R. Fitzpatrick et al., Nucl. Fusion 33, 1533 (1993) [5] A. Glasser et al., Phys. Fluids 18, 875–88 (1975) [6] O. Sauter et al., Plasma Phys. Control. Fusion 44, 1999 (2002) [7] D. De Lazzari D & E. Westerhof, Nucl. Fusion 49, 075002 (2009) [8] A. Reiman & N. Fisch, Phys. Rev. Lett. 121, 225001 (2018)

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