

# Analyses and modelling of MHD activities in runaway electron termination discharges on TCV

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## Introduction

Formation of a high-energy runaway electron (RE) beam could damage plasma facing components (PFCs) and surrounding structures in future large tokamaks like ITER [1]. A promising strategy to mitigate an RE beam is benign termination, where materials such as protium and deuterium are injected into a fully formed RE beam [2, 3]. Experiments on multiple tokamaks have demonstrated the effectiveness of this technique within a favorable neutral pressure range [3, 4]. A successful benign termination is typically attributed to the onset of a violent MHD instability that expels REs over a large wetted area on the PFCs and radiates strongly the magnetic energy [2–5]. More recently, the role of the linear growth rate ( $\gamma$ ) and saturated amplitude ( $\delta B_{p,sat}$ ) of the mode in the benignness of a termination was explored on JET [6], which calls for a multi-machine validation. In this work, we present analyses of MHD activities in the final termination of REs based on 120 TCV discharges and discuss initial simulations with the 3D non-linear hybrid fluid-kinetic code JOREK [7].

## TCV RE termination experiments and analyses method

The overview of a typical RE termination discharge on TCV is shown in Fig. 1. At time slice ①, impurities are injected to generate REs, leading to about 100% conversion from ohmic to RE

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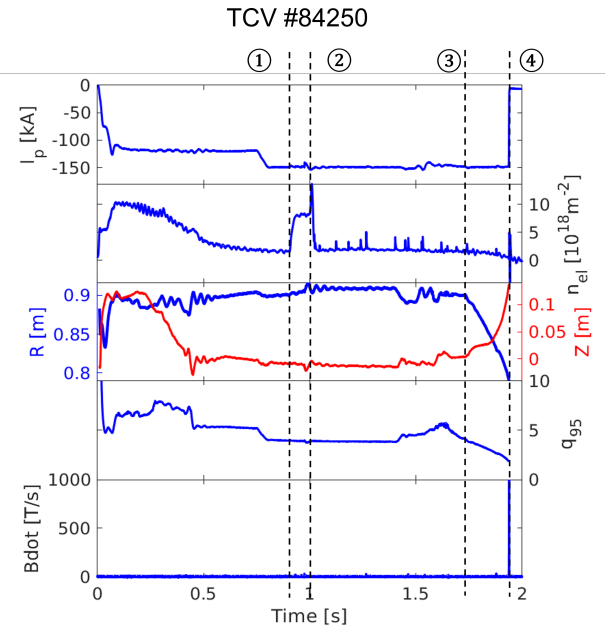


Figure 1: Overview of a typical RE termination discharge on TCV, showing  $I_p$ , central  $n_{el}$ ,  $R$  and  $Z$  of magnetic axis,  $q_{95}$  and signal from a magnetic probe.

current and an increase of central line-integrated electron density ( $n_{el}$ ); at ②, deuterium ( $D_2$ ) or protium ( $H_2$ ) neutrals are injected, which recombine the companion plasma and cause a drop of  $n_{el}$ ; at ③, plasma starts to compress against the inner wall (3rd panel), which leads to a drop of  $q_{95}$ ; at ④,  $q_{95}$  reaches around 2, triggering a large MHD activity (4th panel). To investigate the role of the MHD activity, in particular the  $n = 1$  component in the benignness of a termination, four magnetic probes located at the upper LFS of TCV and  $90^\circ$  apart toroidally are used, where  $n$  is the toroidal mode number. The analyses method used is detailed in Fig. 2.

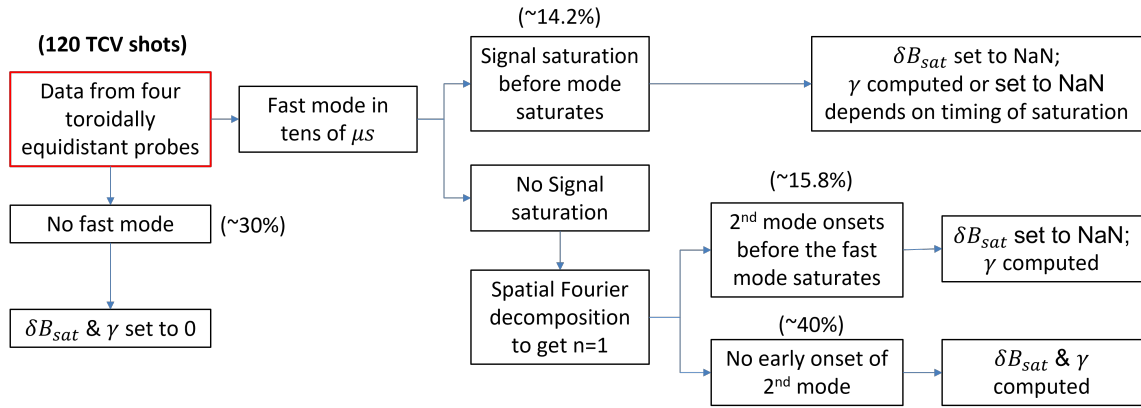


Figure 2: Analyses method used to obtain the growth rate and saturated amplitude of the  $n = 1$  mode.

### Examples of MHD signals and analyses

The existence of fast MHD modes is illustrated in Fig. 3, where (a) is an example without fast mode and (b) with modes on the time scale of tens of microseconds that eventually trigger the current quench (CQ). The onset of a second mode is shown Fig. 4, which typically occurs at the beginning of the CQ, possibly due to a change in the current density profiles. Here we focus on the first mode and if the second mode occurs before the  $dB/dt$  of the first mode drops below 20% of its maximum values,  $\delta B_{p,sat}$  is regarded unobtainable.

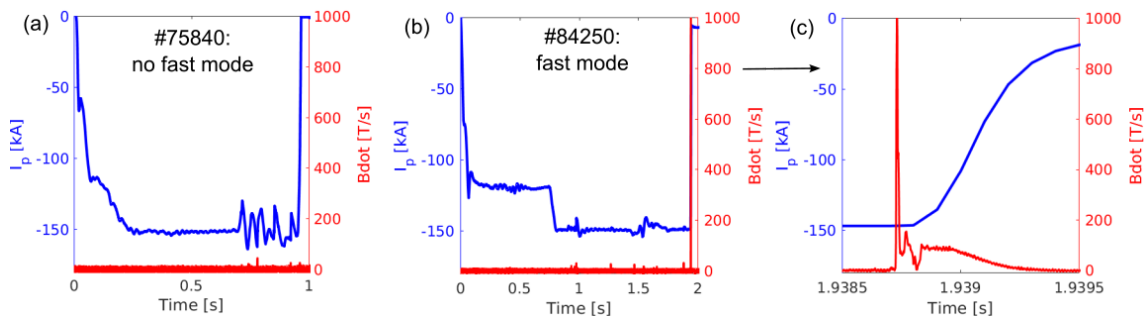


Figure 3: Example of the existence of a fast mode or not based on the signal of one selected probe (red traces). (a) No fast mode and (b) with fast mode. (c) Zoom of (b) around the mode.

## Experimental results: statistics based on TCV data

The dependence of  $\gamma$  and  $\delta B_{p,\text{sat}}$  of the  $n = 1$  mode on neutral pressure and radiated energy ( $W_{\text{rad}}$ ) is summarized in Fig. 5. Here only discharges with a runaway electron current ( $I_{\text{RE}}$ ) of 140 – 160 kA, on-axis toroidal magnetic field ( $B_T$ ) of 1.6 – 1.7 T and  $7e18$  neon atoms injected at ① (Fig. 1) are considered. It can be seen that both  $\gamma$  and  $\delta B_{p,\text{sat}}$  peak at the “benign” neutral pressure range marked by the two vertical black lines. In addition,  $W_{\text{rad}}$  increases, i.e. goes towards the benign regime with larger

$\gamma$  and  $\delta B_{p,\text{sat}}$ . Given similar  $I_{\text{RE}}$  thus similar magnetic energy in these discharges,  $W_{\text{rad}}$  is representative of the radiated energy fraction. These results suggest that benign termination of REs is correlated with strong MHD.  $\delta B_{p,\text{mode}}/B_T$  required for benign termination is consistent with previous findings on DIII-D, i.e. larger than 5% [2], though not shown here for conciseness, where  $\delta B_{p,\text{mode}}$  is  $\delta B_{p,\text{sat}}$  at the mode location.

## Initial JOREK simulations of RE termination on TCV

Preliminary simulations of RE termination were performed with JOREK, coupling reduced MHD equations (up to  $n = 5$ ), diffusive neutrals and a fluid model of REs, assuming convection at the speed of light ( $c$ ) in the parallel direction (wrt.  $B$ ) and including the avalanche generation of REs [9]. Ideal wall is imposed at the computational boundary that is well within the first wall (FW) of TCV.

The initial neutral density is set to be  $2e18$ ,  $3e19$  and  $4e20 \text{ m}^{-3}$  uni-

formly, corresponding to the low, benign and high neutral pressure range, respectively, based on SOLPS-ITER simulations [8].  $q_{95} = 2$  and  $I_{\text{RE}} = 149 \text{ kA}$  are set as in the experiments. One observation, not detailed here, is that  $\delta B_{p,\text{mode}}/B_T < 1\%$  in the JOREK simulations. This could be caused by the application of an ideal wall close to the mode location. Another observation,

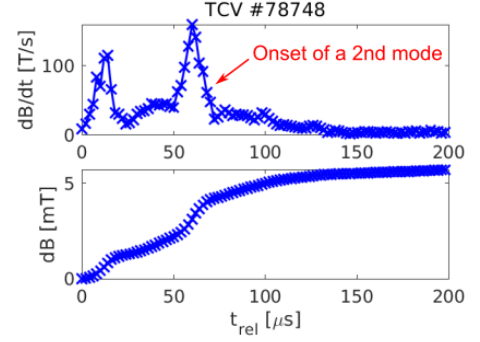


Figure 4: Example of second mode onset, where  $dB/dt$  in the top panel is the  $n = 1$  component and the bottom panel is its time-integration.

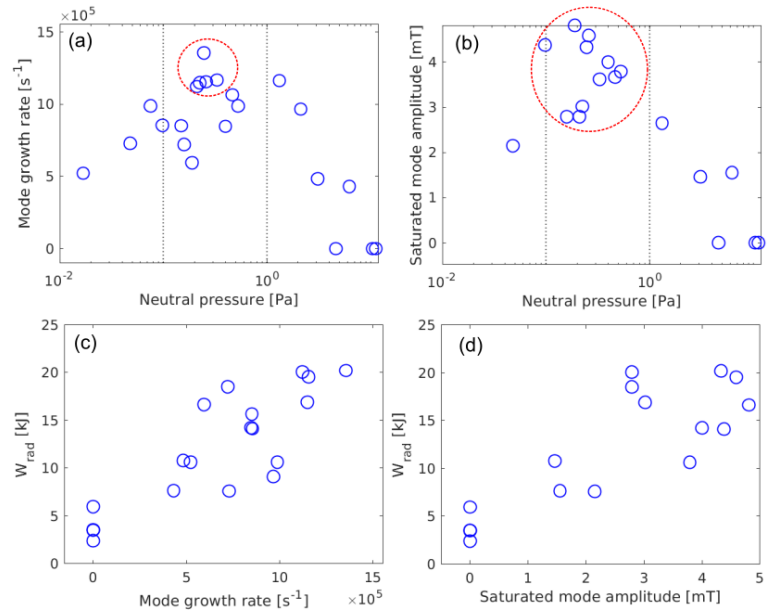


Figure 5: Dependence of  $\gamma$  and  $\delta B_{p,\text{sat}}$  on neutral pressure and radiated energy based on TCV baseline cases.

as illustrated in Fig. 6, is that there exists spurious loss of REs in the simulations:  $I_{RE}$  drops strongly at time window (a) despite that the flux surfaces are mostly closed;  $I_{RE}$  at (b) drops much faster than the RE loss time evaluated by  $L/c$  ( $\sim 1$  ms), where  $L$  is the connection length shown in the legends. The spurious loss could be attributed to the non-flux-surface-aligned grid used in the simulations, making it harder to resolve parallel convection at  $c$ . Further simulations will use flux-surface-aligned grid extended to the FW and a resistive wall at the vacuum vessel.

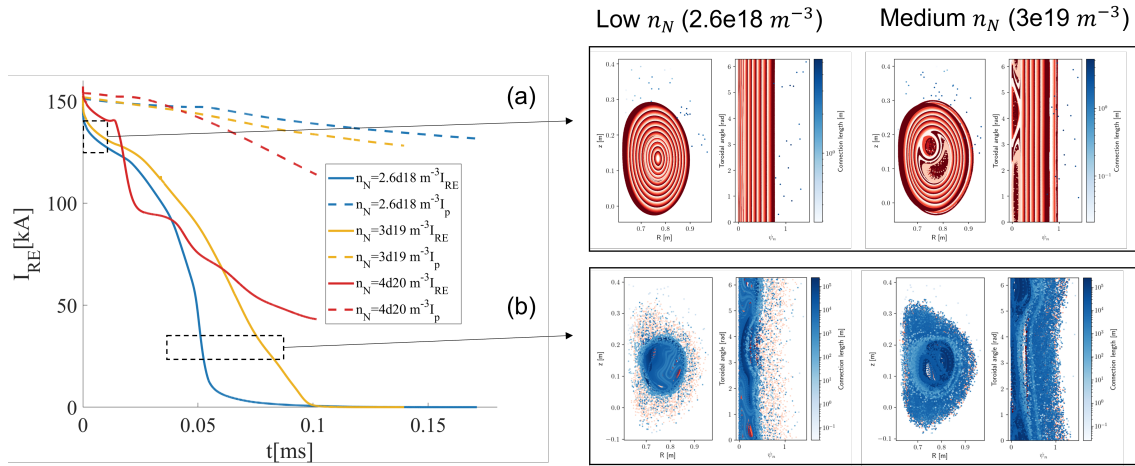


Figure 6: Illustration of spurious RE loss, where the Poincaré plots are generated by postprocessing magnetic topologies from JOREK via particle tracing (resulting connection length shown in the legends).

## Summary and outlook

The role of MHD activities in RE termination has been investigated based on TCV discharges. Statistics from TCV showed that the  $n = 1$  mode saturates on the time scale of tens of microseconds and found that larger linear growth rate and saturated mode amplitude contribute to the benignness of a RE termination. Interpretative simulations with JOREK are on-going. Initial results highlighted the importance of the grid and wall boundary on the modelled RE dynamics.

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## References

- [1] M. Lehnen et al. J. Nucl. Mater. 463 (2015) 39-48
- [2] C. Paz-Soldan et al. NF 61 (2021) 116058
- [3] U. Sheikh et al. PPCF 66 (2024) 035003
- [4] C. Reux et al. Phys. Rev. Lett. 126 (2021) 175001
- [5] V. Bandaru et al. Phys. Plasmas 31 (2024) 082503
- [6] C.F.B. Zimmermann et al. NF 66 (2026) 056004
- [7] M. Hoelzl et al NF 66 (2026) 116006
- [8] E. Tonello et al Joint REM and WPTE RT03 Analysis meeting (2026)
- [9] B.N. Breizman et al 59 (2019) NF 083001