

MHD instabilities in benign termination of high-current runaway electron beams in the JET tokamak

C. F. B. Zimmermann^{1*}, C. Paz-Soldan¹, C. Reux², O. Ficker³, S. N. Gerasimov⁴, C. J. Hansen¹,
S. Jachmich⁵, A. Lvovskiy⁶, N. Schoonheere², U. Sheikh⁷, I. G. Stewart¹, G. Szepesi⁴,
JET Contributors⁸ and the EUROfusion Tokamak Exploitation Team⁹

¹ Dept. of Applied Physics and Applied Mathematics, Columbia University, New York 10027, USA

² CEA-IRFM, 13108 Saint-Paul-les-Durance, France

³ Institute of Plasma Physics of the CAS, Za Slovankou 1782/3, 182 00 Praha 8, CZ

⁴ UKAEA, Culham Campus, Abingdon, Oxon, OX14 3DB, United Kingdom

⁵ ITER Organization, 13108 Saint-Paul-les-Durance, France

⁶ General Atomics, P.O. Box 85608 San Diego, California 92186, USA

⁷ Ecole Polytechnique Fédérale de Lausanne, SPC, CH-1015 Lausanne, Switzerland

⁸ see the author list of C.F. Maggi et al. 2024 Nuclear Fusion. 64 112012

⁹ see the author list of E. Joffrin et al. 2024 Nuclear Fusion. 64 112019

* E-mail: benedikt.zimmermann@columbia.edu

Introduction

Mitigation schemes for plasma disruptions will be essential for future high-current tokamaks such as ITER or commercial FPPs, as they can impose significant thermal and mechanical loads on tokamak components. A promising solution to mitigate the resulting runaway electron (RE) beams is the low- Z benign termination scheme in which an MHD instability deconfines the REs, increases the RE deposition wetted area, and terminates the RE beam *benignly*. Dedicated experiments were performed on the JET tokamak [1, 2], along with the successful demonstration of this technique on the DIII-D [3–5], TCV, and AUG tokamaks [6]. In most of these experiments, it was observed that there are limits of injected materials for which mitigation is successful and benign. Recent experiments on the JET tokamak reached higher pre-disruptive plasma and RE currents than on the other machines and have revealed challenges in achieving a benign termination at high pre-disruptive current values of $I_p > 3$ MA. Understanding these experiments is critical for reactor-relevant extrapolation.

Experimental Scenario

The focus of this analysis is on the nature and modeling of the terminating MHD event to understand what instability dynamic discriminates a benign and a non-benign termination on JET. This work addresses this issue through a systematic and empirical analysis of magnetic sensor data from a database of about 50 RE discharges from the campaigns between 2019–2023 that explored the benign termination scenario and its limits. Typical benign termination experiments have a short pre-disruptive flattop phase. A primary disruption is then triggered by means of high- Z gas puffing or shattered pellet injection (SPI). After the thermal quench, the hot-tail, avalanche, and Dreicer

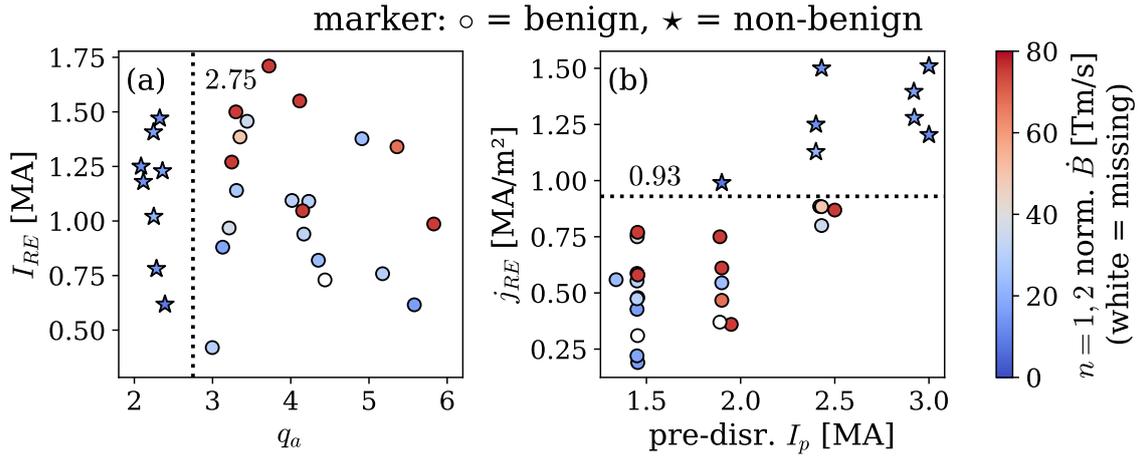


Figure 1: Panel (a): Runaway current I_{RE} versus the edge safety factor q_a immediately before the terminating MHD event. Panel (b): Runaway current density j_{RE} immediately before the terminating MHD event versus the pre-disruptive plasma current I_p . Benign termination cases are marked with a circle; non-benign cases with a star. Color coding reflects the measured peak amplitude during the terminating event.

mechanism generate a relativistic runaway current, such that after multiple 10 ms intervals, the entire current in the plasma is carried by REs. Into this RE beam, a secondary, low- Z injection is induced via SPI, massive gas injection, or using the disruption mitigation valves. Depending on kinetic processes, discussed, e.g., by Hollmann [7] or Hoppe [8], this injection either recombines the companion plasma (usually ending in a benign termination) or it stays ionized (usually ending in a non-benign termination). Consequently, by reducing the edge safety factor to rational values, a large-scale MHD event is triggered and terminates the RE beam without (benign) or with (non-benign) localized impact of the RE beam on the first wall or divertor structure. In order to determine the amplitudes of the terminating MHD modes, six fast Mirnov coils in a toroidal array are analyzed, which allows extracting the $n = 1, 2$ components of \dot{B} at reasonable condition numbers via matrix inversion. Knowledge about the plasma position and evolution is obtained via EFIT equilibria reconstruction with time steps of 0.2 ms, which have been run with special settings for convergence during the final termination event. The classification of (non)-benign terminations is based on IR camera observations documented in Reux *et al.* [2].

Analysis

The first analysis step concerns the plasma equilibrium. It is found that the termination onset of non-benign cases occurs at a lower cross-section, while termination of benign cases starts from a relatively larger cross-section and more central position. This indicates that the evolution of the RE beam until the termination is different between benign and non-benign cases. A closer analysis shows that, independent of the effectively produced RE current I_{RE} , the edge safety factor of non-benign cases immediately before the onset of the terminating phase is $q_a \approx 2$, con-

sistent with the onset of kink modes, see Fig. (1a). Benign cases, in contrast, terminate with an instability at the latest at $q_a \approx 3$. As the non-benign cases occur in particular for high pre-disruptive plasma currents I_p and together with the smaller cross-sections, this leads to a clear separation of benign and non-benign cases regarding their RE current density j_{RE} , see Fig. (1b). Most importantly, as indicated by the coloring of the markers in both panels, the non-benign cases end with MHD events with lower \dot{B} peak values of the analyzed $n = 1, 2$ modes, hinting at limitations in the instability drive or suppressed mode growth compared to most of the benign cases at similarly high I_p . This observation is in contrast to previous work on DIII-D by Paz-Soldan *et al.* [5], which showed that non-benign termination occurs at higher q_a , indicating that the involved MHD dynamics differ between DIII-D and JET. A more detailed analysis of the trajectory of I_{RE} versus q_a is shown in Fig. (2) for the non-benign cases, in which the coloring relates to a normalized \dot{B} measurement to facilitate comparison. Most of the non-benign discharges undergo MHD events when passing rational values, e.g., at $q_a = 3, 4$. While these events expel a significant fraction of the RE current, they are not capable of deconfining the RE beam before they reach $q_a \approx 2$. Interestingly, the current decay rate \dot{I}_{RE} of the non-benign cases tends to be negative and of greater magnitude than in the benign counterparts before $q_a \approx 3$. Additionally, the internal inductance appears to be higher. Both observations are shown in Fig. (3), suggesting a more peaked RE current distribution in the non-benign cases. This could make them less MHD unstable than their benign counterparts [9, 10], as also indicated by the weaker mode activity shown by the coloring. Furthermore, a more peaked and concentrated RE current density may hinder the effective recombination of

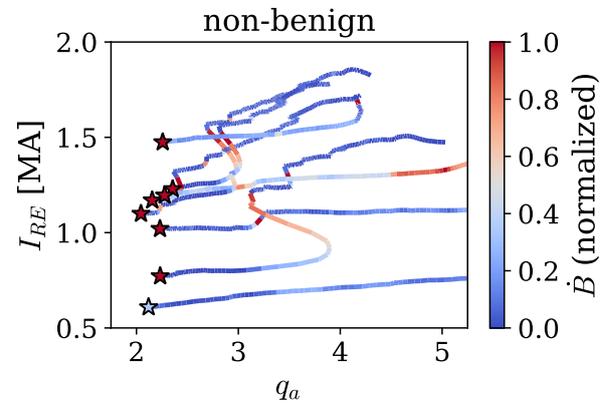


Figure 2: Trajectory of I_{RE} versus q_a during the last 200 ms before the onset of the final current decay, shown for the non-benign cases only. Coloring corresponds to \dot{B} , indicating non-terminating events at higher rational q_a .

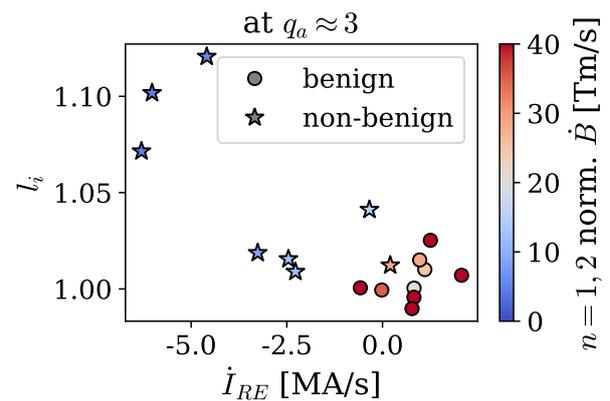


Figure 3: Current decay rate \dot{I}_{RE} versus internal inductance l_i of the benign and non-benign cases before the MHD events at $q_a \approx 3$, coloring corresponds to \dot{B} of the immediately following event. Higher l_i and more negative \dot{I}_{RE} suggest stronger current peaking. The expected higher MHD stability is supported by the measurements.

the companion plasma [8]. The variation in current profiles could potentially arise from the dependence of the RE current density distribution on the absolute pre-disruptive current, as discussed by Smith *et al.* [11], leading to more peaked RE current profiles for higher I_p in JET. The terminating MHD events show a correlation between the measured \dot{B} and the integrated δB , with \dot{B} serving as a more effective discriminator between benign and non-benign cases. Typical growth times are $\gamma^{-1} \approx 19 \mu\text{s}$ for non-benign cases, compared to $\gamma^{-1} \approx 11 \mu\text{s}$ for benign cases. Together with the absence of I_{RE} spikes during most of the terminating MHD events analyzed, these values suggest that resistive MHD effects are not dominant. Typical Alfvén times in these experiments are $\tau_A \approx 0.3 \mu\text{s}$ for a free electron density of $n_e \approx 1 \times 10^{20} \text{m}^{-3}$, as expected in the case of unsuccessful recombination of the companion plasma, and below $0.03 \mu\text{s}$ for a recombined plasma with $n_e < 1 \times 10^{18} \text{m}^{-3}$. Therefore, the observed differences in growth rates are not sufficient to support the hypothesis that Alfvén time alone determines the distinction between benign and non-benign terminations.

Summary and Outlook

This work serves as the starting point for a study on the nature of equilibrium evolution and associated MHD events in the benign termination of RE beams at high pre-disruptive I_p in JET. It was found that unsuccessful termination occurs at low $q_a \approx 2$ values, accompanied by relatively weak MHD events. The reduced mode growth could indicate that the instability does not grow fast enough to deconfine the RE beam efficiently. This may be due to more peaked RE current profiles at higher I_p . In contrast to previous experiments on DIII-D, TCV, and AUG, benign termination in JET typically occurs at higher $q_a \geq 3$. Future modeling and analysis efforts should therefore aim to develop a more detailed understanding of why benign and non-benign cases terminate or survive at $q_a \geq 3$, and why the MHD events at $q_a = 2$ are associated with lower \dot{B} .

[1] C. Reux et al. 2021 *Physical Review Letters*. 126. [2] C. Reux et al. 2022 *Plasma Physics and Controlled Fusion*. 64. [3] C. Paz-Soldan et al. 2019 *Plasma Physics and Controlled Fusion*. 61. [4] Y. Q. Liu et al. 2019 *Nuclear Fusion*. 59. [5] C. Paz-Soldan et al. 2021 *Nuclear Fusion*. 61. [6] U. Sheikh et al. 2024 *Plasma Physics and Controlled Fusion*. 66. [7] E. M. Hollmann et al. 2023 *Nuclear Fusion*. 63. [8] M. Hoppe et al. 2025 *Plasma Physics and Controlled Fusion*. 67. [9] J. A. Snipes et al. 1988 *Nuclear Fusion*. 28. [10] J. A. Wesson et al. 1989 *Nuclear Fusion*. 29. [11] H. Smith et al. 2006 *Physics of Plasmas*. 13.

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