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Runaway electron avalanche and macroscopic beam formation: Simulations of the DTT full power scenario

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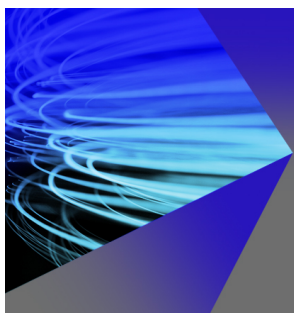
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ABSTRACT

The transition of the Divertor Tokamak Test (DTT) facility from its initial commissioning phase (Day-0 scenario, plasma current $I_p = 2$ MA) to the full power scenario, characterized by its highest nominal plasma current ($I_p = 5.5$ MA), introduces a critical shift in the dynamics of runaway electrons (REs) generation. While previous predictive studies of the low-current scenario indicated a robust safety margin against RE beam formation, this work reveals that the exponential scaling of the RE avalanche gain with plasma current severely narrows the safe operational window in the full power scenario. Using the non-linear magnetohydrodynamic code JOREK, we perform comprehensive 2D simulations of the current quench (CQ) phase of several disruption scenarios, systematically scanning initial RE seed currents and injected impurity levels. The results demonstrate that in the full power scenario, the avalanche multiplication factor is sufficiently high ($G_{av} \approx 1.3 \times 10^5$) to convert an initial 5.5 A seed current into macroscopic RE beams of ≈ 0.7 MA when large amounts of impurities are present. For even higher RE seeds, the RE current can peak at ≈ 3.2 MA, constituting up to $\approx 80\%$ of the total plasma current during the CQ. These findings suggest that, unlike the Day-0 phase, the disruption mitigation strategy for the full power scenario involves a careful balance between thermal load mitigation and RE avoidance, necessitating a well-chosen quantity of injected impurities. This work provides the baseline needed for future estimations of RE loads on the plasma-facing components of DTT, which will be essential for designing and positioning mitigation components like sacrificial limiters.

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I. INTRODUCTION

The successful operation of next-generation tokamaks requires robust strategies to prevent or mitigate plasma disruptions.^{1,2} Disruption mitigation typically relies on massive injection of impurities

(e.g., neon or argon) to radiate the plasma thermal energy and distribute the heat load more uniformly.^{1–4} This rapid cooling of the plasma (thermal quench, TQ) drastically increases the plasma resistivity, ending the discharge by leading to a fast decay of the plasma current

(current quench, CQ). However, the strong induced toroidal electric field can accelerate electrons to relativistic energies, generating a population of runaway electrons (REs).^{5,6} The primary RE population (RE seed) can be exponentially amplified via the avalanche mechanism, where relativistic electrons knock thermal electrons into the runaway region through close Coulomb collisions.⁷ The avalanche gain, defined as the amplification factor of the RE seed population in the limit of an extremely small initial seed, scales exponentially with the plasma current I_p [$G_{av} \approx e^{I_p/(I_A \ln \Lambda)}$, where I_A is the Alfvén current and $\ln \Lambda$ is the Coulomb logarithm], severely exacerbating the risk posed by REs in high-current regimes.^{7–12} If not suppressed, the resulting RE beam can carry a substantial fraction of the pre-disruption plasma current, eventually impinging on localized regions of the first wall and potentially causing the deep melting of metallic plasma-facing components (PFCs).^{2,13,14}

The Divertor Tokamak Test (DTT) facility,^{15,16} currently under construction, is designed to investigate power exhaust solutions in regimes relevant to ITER¹⁷ and EU-DEMO.¹⁸ With a nominal plasma current of $I_p = 5.5$ MA and auxiliary heating power up to 45 MW, DTT will achieve divertor heat flux densities comparable to those expected in future reactors.¹⁶ Although the ultimate goal is operation in the full power scenario, the operational plan of DTT includes an initial low-current commissioning phase [Day-0, characterized by $I_p = 2$ MA and a toroidal magnetic field of $B_\phi = 3$ T (Ref. 19)], where the potential for RE generation is substantially lower. Previous predictive studies²⁰ focused on this Day-0 scenario of DTT and indicated that, by controlling the amount of impurities injected via the disruption mitigation system (DMS), it is possible to avoid the conditions that generate a substantial RE beam, even with large RE seeds (≈ 20 kA). The primary mitigation strategy for the DTT DMS relies on shattered pellet injection (SPI),^{21,22} while massive gas injection (MGI)^{23–25} might be considered during the initial commissioning phases. For smaller RE seeds, the generation of RE beams remains minimal, even for high levels of impurities. However, the transition to the full power scenario ($I_p = 5.5$ MA, $B_\phi = 5.85$ T) introduces a drastic shift in disruption dynamics: since the avalanche gain G_{av} scales exponentially with the plasma current, the 5.5 MA scenario is susceptible to the conversion of even minute seed populations into macroscopic RE beams, rendering the system more sensitive to the amount of impurities injected by the DMS.

This work broadens the safety analysis of RE avalanches in DTT to the full power scenario, employing the non-linear magnetohydrodynamic (MHD) code JOREK^{26,27} and the resistive wall code STARWALL.^{28,29} While the DTT vacuum vessel is designed to withstand the electromagnetic forces of 750 worst-case disruptions,¹⁶ the tolerable limits for TQ heat loads and localized RE energy deposition are currently under evaluation. Quantifying the potential RE beam currents generated in this regime is a crucial prerequisite for the predictive assessment of RE-induced loads on PFCs. Building upon the work carried out for the Day-0 scenario,²⁰ we extend the 2D analysis to the reactor-relevant regime, investigating the CQ dynamics and the formation of macroscopic RE beams at 5.5 MA. We systematically vary impurity levels and seed currents to assess the dependence of the RE beam current on these factors, clarifying the specific combinations of parameters that lead to significant RE beam formation and thereby defining the risk boundaries for the full power scenario. This foundational assessment will ultimately guide the design and positioning of dedicated mitigation components, such as sacrificial limiters.

II. MODELS AND METHODS

The computational framework employed in this study combines the non-linear MHD code JOREK^{26,27} with the resistive wall code STARWALL,^{28,29} closely following what was done in our previous work.²⁰ We employ the reduced MHD formulation of JOREK,^{26,30} where the magnetic and electric fields are expressed through the poloidal magnetic flux ψ and the velocity stream function u . To study RE dynamics, the MHD equations are coupled with the RE fluid model described in Refs. 31 and 32. This model treats REs as a distinct fluid species, self-consistently capturing the feedback between the RE population and the bulk plasma. We prescribe a preexisting RE seed at the initialization to serve as a proxy for primary formation processes (e.g., hot-tail or Dreicer), which is then multiplied via the computation of the secondary volumetric source (RE avalanching). Previous applications of this framework include the study of RE formation and termination in JET,³³ ITER,^{34–36} and EU-DEMO.³⁷

Following the transport coefficients detailed in Ref. 20, the electrical resistivity η_e and parallel thermal diffusivity $\chi_\parallel$ follow the standard Spitzer ($\propto T_e^{-3/2}$) and Spitzer-Härm ($\propto T_e^{5/2}$) scalings, respectively, but are regularized by constant cutoff values for temperatures exceeding 500 and 350 eV to ensure numerical stability. Additionally, the parallel thermal diffusivity is subject to a low-temperature cutoff at 20 eV, which is introduced to prevent the underestimation of heat fluxes at the boundary.^{38,39} Regarding cross-field transport, we employ a constant particle diffusivity $D = 2$ m²/s and a perpendicular thermal diffusivity $\chi_\perp$ profile with a core value of 2 m²/s. The boundary condition for the electron temperature is fixed at 0.7 eV at the JOREK computational boundary, which is representative of the first wall surface. For the RE fluid, a dominant parallel diffusivity of $D_{\parallel,RE} = 1 \times 10^9$ m²/s is imposed to mimic the rapid transit of RE along magnetic field lines. As established in Ref. 32, this specific value is optimal for the fluid model, approximating well the parallel advection without introducing significant numerical artifacts in the perpendicular direction. Conversely, the perpendicular diffusivity is set at a low value of $D_{\perp,RE} = 1 \times 10^{-2}$ m²/s, which serves primarily to ensure numerical stability.³⁴ We restrict our analysis to toroidally symmetric 2D simulations, hence omitting non-axisymmetric perturbations. This yields an upper estimate of the RE beam current, as 2D simulations do not account for losses driven by stochastic field lines. Although 3D simulations are necessary to capture these loss mechanisms, their complexity and computational cost place them outside the scope of the present study.

To strictly focus on CQ dynamics and RE formation while maintaining computational efficiency, we adopt a single-fluid representation with equal ion and electron temperatures ($T = T_i + T_e = 2T_e$) and neglect neutral particles, diamagnetic drifts, and parallel background fluid velocity. While fluid variables rely on fixed boundary conditions, the poloidal flux ψ and the total toroidal current density j at the boundary are determined through implicit coupling with the resistive wall code STARWALL.²⁹ This allows the simulation to evolve the plasma dynamics alongside the currents induced in the passive and active structures of the DTT machine, making the simulation of the CQ phase more realistic by capturing the vertical motion of the plasma and the associated RE beam scrape-off against the PFCs.^{36,40,41} The computational boundary and the specific geometry of the DTT structures imported into STARWALL correspond to the layout detailed in Fig. 1 of our previous work.²⁰

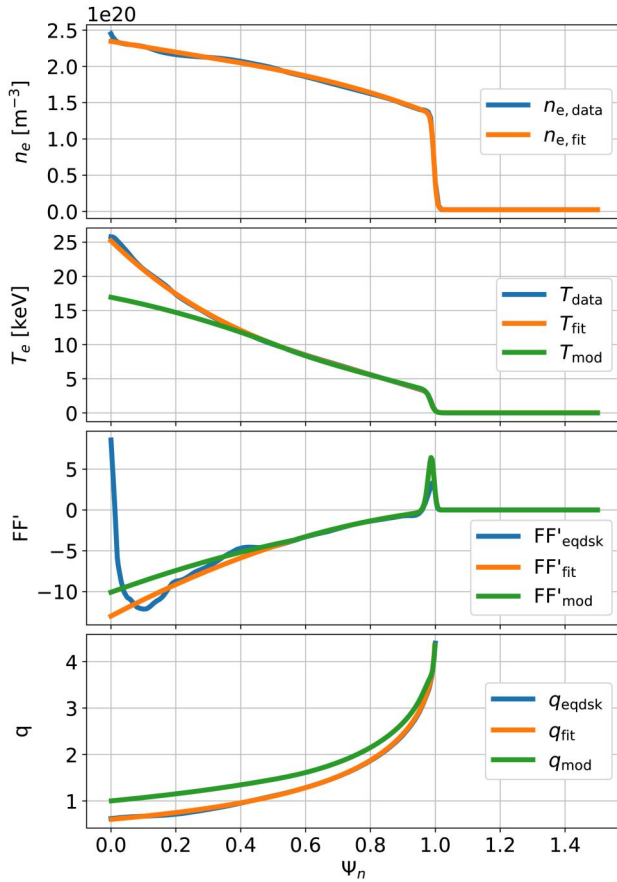


FIG. 1. Comparison of the equilibrium profiles for electron density n_e , electron temperature T_e , FF' , and safety factor q (from top to bottom) as a function of the normalized poloidal flux ψ_n . The plots display the CREATE-NL equilibrium data (blue) and their fitted approximations (orange). The fitted n_e profile was not modified, while for T_e , FF' , and q , the modified MHD-stable profiles employed in the simulations are shown in green.

To initialize the disruption and subsequent RE generation, we employ an artificial TQ (ATQ) mechanism.^{20,34,37–39} A comprehensive description and justification of this procedure can be found in our previous work.²⁰ This method bypasses the high computational cost of full 3D TQ physics (which JOREK can simulate self-consistently,^{42–45} and will be addressed in future work) by artificially establishing post-TQ conditions, providing a controlled environment in which to focus on RE generation, which is exclusively simulated during the self-consistent CQ phase that follows the ATQ. The ATQ is implemented in three sequential steps, visually demarcated by the thin brown vertical lines in Figs. 2–7. This separation into steps is strictly a numerical convenience, allowing us to address the thermal, magnetic, and impurity aspects independently. First, the perpendicular thermal diffusivity ($\chi_\perp$) is transiently increased to drive a rapid temperature collapse to ≈ 10 eV (region preceding the brown dotted line). Second, a high hyper-resistivity is applied to flatten the current density profile in the core, mimicking the effects of magnetic reconnection⁴⁶ (interval between the dotted and dashed-dotted brown

lines). Following established ATQ methodologies,³⁸ when the target flattened current profile is reached, the hyper-resistivity is returned to a negligible value for the rest of the simulation. Third, once the core current density is sufficiently flattened, the hyper-resistivity is lowered to negligible levels, and neon impurities are injected uniformly at a fixed rate (starting from the brown dashed-dotted lines). The injection rate is chosen to ensure that this phase is rapid compared to the CQ phase, while avoiding abrupt changes that could trigger numerical instabilities. Upon reaching the target density, the injection is stopped, and the resulting change in the slope of the plasma current traces in Figs. 2–7 signals the onset of the self-consistent CQ phase, where all modified parameters return to their physical values. Unlike in experiments where impurities trigger the collapse, here they are introduced to ensure a balance between radiative cooling and Ohmic heating, which is required for the self-consistent CQ.

In this work, we focus our investigation on the DTT single null full power configuration (scenario E1¹⁹) characterized by a nominal plasma current of $I_p = 5.5$ MA, a toroidal magnetic field of $B_\phi = 5.85$ T, and an auxiliary heating power of approximately 45 MW. Standard integrated modeling of this scenario typically predicts a safety factor $q < 1$ for a large portion of the core, possibly causing large sawtooth crashes.¹⁶ While work on sawtooth control optimization is ongoing, we focus here on an MHD-stable magnetic equilibrium ($q > 1$), obtained by modifying the FF' (where $F \equiv RB_\phi$ is the toroidal flux function and the prime denotes the derivative with

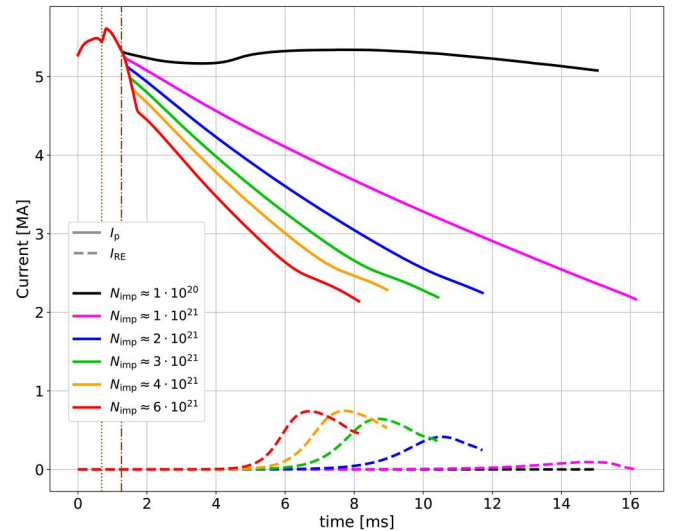


FIG. 2. Time evolution of the total plasma current I_p (solid lines) and RE current I_{RE} (dashed lines) for the lowest initial RE seed of our scan, $I_{seed} = 5.5$ A. The colors correspond to varying levels of injected neon impurities (N_{imp}), ranging from 1×10^{20} to 6×10^{21} particles. Thin brown vertical lines indicate the ATQ phases: the dotted line separates the thermal collapse from the current flattening phase, while the dashed-dotted line marks the onset of impurity injection. The transition to the self-consistent CQ is identified by the change in slope of the plasma current traces following the dashed-dotted line. Since impurities are injected at a fixed rate, higher N_{imp} values require longer injection times, delaying the CQ onset. Although this initial seed represents a microscopic fraction of the total current, macroscopic RE beams reaching ≈ 0.7 MA form at high impurity levels ($N_{imp} \approx 3 \times 10^{21}$), demonstrating the high avalanche gain of the full power scenario of DTT.

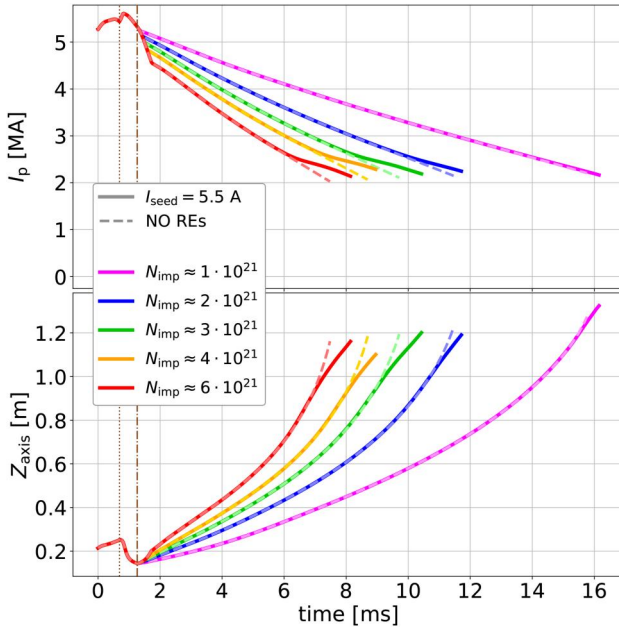


FIG. 3. Comparison of the total plasma current I_p (top) and the vertical position of the magnetic axis Z_{axis} (bottom) for the lowest-seed case of our scan ($I_{\text{seed}} = 5.5$ A, solid thick lines) and reference simulations without REs (dashed thin lines, obtained by numerically suppressing the avalanche source term). The colors correspond to varying levels of N_{imp} , and thin brown vertical lines demarcate the ATQ phases, consistent with Fig. 2. The bottom panel reveals that higher impurity levels lead to steeper vertical drifts. For this initial 5.5 A seed, the RE beam takes several milliseconds to become macroscopic and deviate from the RE-free dynamics, eventually slowing the vertical displacement.

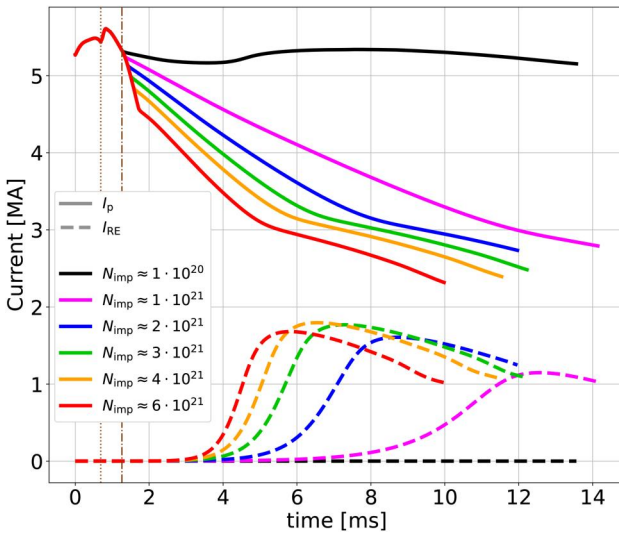


FIG. 4. Time evolution of the total plasma current I_p (solid lines) and RE current I_{RE} (dashed lines) for an intermediate initial RE seed of $I_{\text{seed}} = 550$ A. The colors correspond to varying levels of N_{imp} , and thin brown vertical lines demarcate the ATQ phases, consistent with Fig. 2. Significant RE beam formation occurs at lower impurity thresholds compared to the 5.5 A case. The highest RE current reaches approximately 1.8 MA (accounting for almost 60% of the total current).

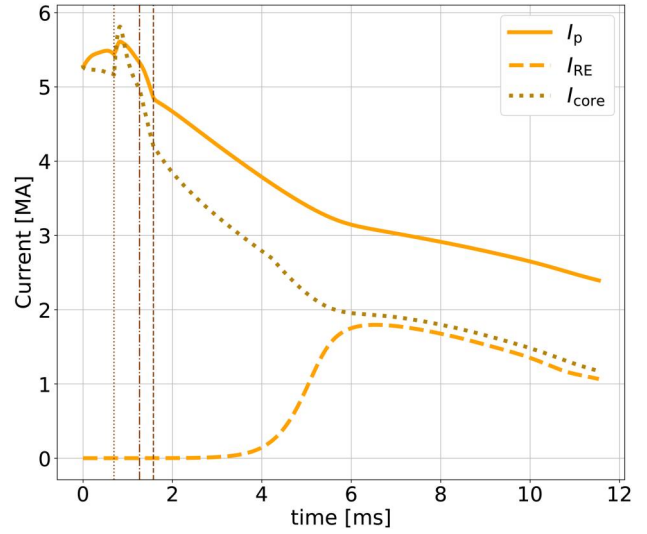


FIG. 5. Current decomposition for the intermediate seed scenario ($I_{\text{seed}} = 550$ A) with $N_{\text{imp}} \approx 4 \times 10^{21}$ particles. The solid (I_p) and dashed (I_{RE}) lines correspond to the orange traces in Fig. 4, while the gold dotted line shows the total current in the confined region (I_{core}). Thin brown vertical lines indicate the ATQ phases as in previous figures, with the addition of a dashed vertical line at $t \approx 1.6$ ms marking the end of the impurity injection and the start of the self-consistent CQ for this specific scenario. The proximity of the I_{core} and I_{RE} traces after $t \approx 6$ ms indicates that the confined current is dominated by the RE population, implying that the thermal current ($I_p - I_{\text{RE}}$) corresponds largely to halo currents.

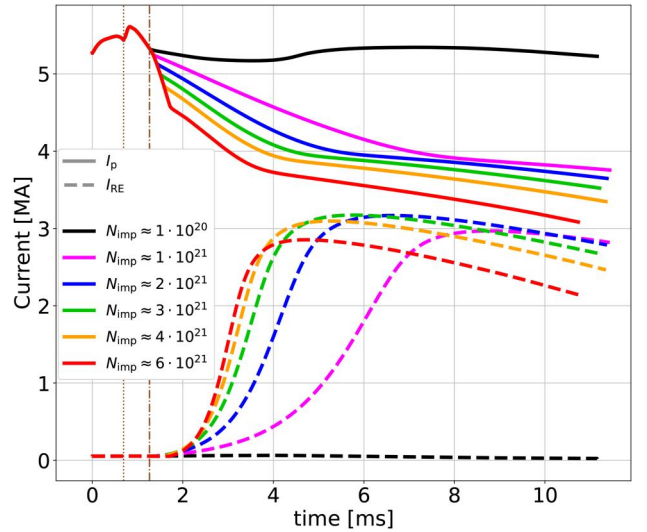


FIG. 6. Time evolution of the total plasma current I_p (solid lines) and RE current I_{RE} (dashed lines) for a large initial RE seed of $I_{\text{seed}} = 55$ kA. The colors correspond to varying levels of N_{imp} , and thin brown vertical lines demarcate the ATQ phases, consistent with Fig. 2. Within a few milliseconds, the RE current evolves into $\approx 80\%$ of the total current, even for impurity levels as low as $N_{\text{imp}} \approx 1 \times 10^{21}$. The maximum RE current reaches ≈ 3.2 MA, significantly slowing down the CQ.

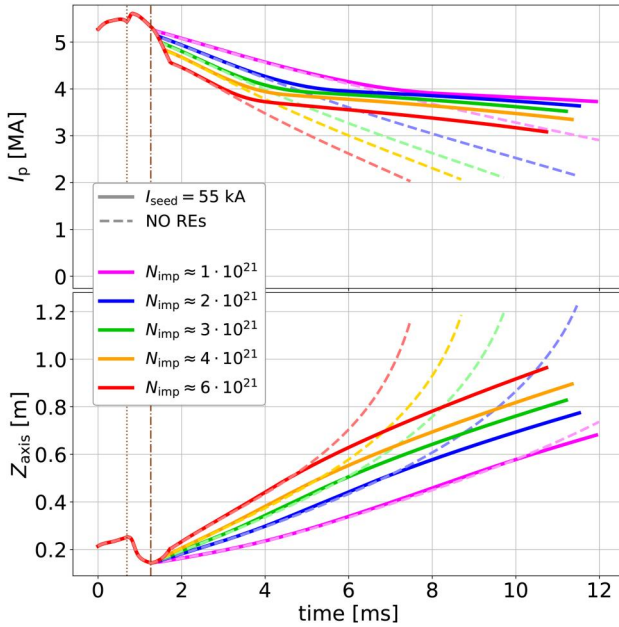


FIG. 7. Comparison of the total plasma current I_p (top) and the vertical position of the magnetic axis Z_{axis} (bottom) for the largest-seed case ($I_{\text{seed}} = 55$ kA, solid thick lines) and reference simulations without REs (dashed thin lines, obtained by numerically suppressing the avalanche source term). The colors correspond to varying levels of N_{imp} , and thin brown vertical lines demarcate the ATQ phases, consistent with Fig. 6. The high current carried by the REs in these scenarios causes a substantial reduction in the velocity of the vertical displacement and of the CQ compared to the RE-free scenarios.

respect to the poloidal magnetic flux ψ) and temperature profiles of a CREATE-NL⁴⁷ equilibrium for the full power scenario. Figure 1 displays the CREATE-NL equilibrium data (blue) and their fitted approximations (orange) for the electron density n_e , electron temperature T_e , FF' , and safety factor q (from top to bottom) as a function of the normalized poloidal flux ψ_n . The fitted n_e profile was not modified, while for T_e , FF' , and q , the modified MHD-stable profiles employed in the simulations are also shown (green). These profile modifications are justified by the specific nature of the ATQ procedure. The initial thermal collapse, which reduces the temperature by several orders of magnitude, renders the exact shape of the initial profile largely unimportant. Furthermore, the subsequent current-flattening phase inevitably reshapes the q profile in the core region, overriding the initial equilibrium adjustments. As a result, the changes made to ensure initial MHD stability do not significantly impact the CQ or RE avalanche dynamics. Accordingly, the equilibrium adopted for all simulations combines the modified profiles for T_e , FF' , and q (green lines) with the fitted electron density (orange line) shown in Fig. 1. Future work will ideally broaden this investigation by considering alternative, intrinsically MHD-stable DTT equilibria, provided such configurations become available, to assess the sensitivity of the RE avalanche to the initial magnetic configuration.

Since accurately estimating the amplitude of primary RE generation mechanisms is challenging,⁶ often yielding values that span several orders of magnitude, we treat the initial RE seed current as a scanning parameter. To provide a comprehensive RE safety assessment for the

DTT full power scenario, we select representative seed currents covering a wide parameter space, setting I_{seed} to 10^{-6} , 10^{-4} , and 10^{-2} of the initial plasma current $I_p = 5.5$ MA (yielding 5.5 A, 550 A, and 55 kA, respectively). Additionally, we explicitly include a seed value of 20 kA, identical to the maximum seed used in our previous Day-0 assessment,²⁰ to facilitate a direct comparison between the two operating points, allowing us to isolate the effects of the higher current regime. We emphasize that the upper bound of 55 kA constitutes a substantial initial population of REs. If the seed were an order of magnitude larger, it would pose a severe threat even with minimal subsequent avalanche multiplication. Such a scenario would shift the focus from CQ dynamics to primary RE generation physics, which lies outside the scope of this work.

Parallel to the seed scan, we vary the amount of neon impurities injected N_{imp} (defined as the total number of injected neon particles), which critically influences the CQ dynamics and RE avalanche gain. As highlighted in Ref. 48, bound electrons in partially ionized impurities can act as efficient targets for knock-on collisions, potentially enhancing the avalanche growth rate significantly. Furthermore, the impurity content dictates the radiative cooling rate, which critically determines the plasma resistivity and the subsequent induced electric field that accelerates electrons. In this study, the injected impurity inventory is varied from 1×10^{20} to 6×10^{21} particles (distributed uniformly within a computational volume of ≈ 52 m³). These values are consistent with the injection of a 12 mm mixed pellet with a 20% neon and 80% deuterium fraction (containing roughly 10^{23} neon particles), considering an assimilation of less than 10% before the TQ. In contrast to RE seeds, the quantity of material injected by the DMS is an experimentally controllable parameter. Although the final assimilated impurity content depends on complex disruption dynamics, adjusting the injected inventory remains a direct experimental method to influence the CQ evolution. By systematically exploring the parameter space defined by these seed currents and impurity levels, we aim to provide a broad parametric assessment of RE beam formation in DTT, characterizing the RE avalanche dynamics across widely different regimes. Future studies may extend this analysis to an even broader parameter space, consider different impurity species, or implement more realistic spatial distributions of impurities within the computational domain.

III. RESULTS AND DISCUSSION

This section presents the results of the JOREK simulations for the DTT full power scenario ($I_p = 5.5$ MA). The analysis focuses on the sensitivity of RE beam formation to the initial preexisting RE seed population (I_{seed}) and the amount of impurities injected by the DMS (N_{imp}). Following the ATQ procedure described in Sec. II, the plasma enters the CQ phase. Here, the electron temperature T_e evolves self-consistently inside JOREK, balancing Ohmic heating (driven exclusively by the thermal current) against impurity radiation. This balance determines the plasma resistivity and, consequently, the strength of the parallel electric field $E_{\parallel}$ that drives the RE avalanche.

We begin by considering the case with the lowest initial RE seed current (5.5 A, representing a fraction $I_{\text{seed}}/I_p = 10^{-6}$). This scenario mimics conditions where primary RE generation mechanisms are weak or have been effectively suppressed prior to the onset of the avalanche phase. The time evolution of the plasma current (I_p , solid lines) and the generated RE current (I_{RE} , dashed lines) is shown in Fig. 2. A striking feature of the full power scenario is its susceptibility to

macroscopic RE beam formation even from RE seeds as low as 5.5 A. For low impurity contents ($N_{\text{imp}} \approx 1 \times 10^{20}$, black curves), the radiative losses are insufficient to maintain a low electron temperature, resulting in an incomplete thermal collapse. Consequently, the plasma resistivity remains moderate, resulting in a current decay that is extremely slow. While the induced electric field remains below the critical threshold required to drive the RE avalanche (keeping the RE current negligible), this partially mitigated disruption regime carries risks of heat loads and halo currents that could damage the PFCs. However, as the impurity content is increased, the CQ dynamics change radically. For $N_{\text{imp}} \gtrsim 1 \times 10^{21}$ (the colored curves), the enhanced radiation clamps the post-TQ temperature to lower and lower values (typically $\approx 5\text{--}15$ eV). This drastic increase in plasma electrical resistivity leads to faster CQs. As the current decay rate increases, the induced toroidal electric field intensifies, leading to a more vigorous avalanche multiplication that causes the RE current to peak earlier in the simulation. Moreover, the resulting $E_{\parallel}$ in these cases is sufficient to trigger massive avalanche amplification of REs. Specifically, in the cases with the highest impurity contents ($3 \times 10^{21} \lesssim N_{\text{imp}} \lesssim 6 \times 10^{21}$), the 5.5 A seed is amplified by more than five orders of magnitude, resulting in a macroscopic RE beam of $I_{\text{RE}} \approx 0.7$ MA. Although substantial, this RE current remains limited to a fraction of the total plasma current, as the rapid vertical displacement of the plasma (bottom panel in Fig. 3) leads to the scrape-off of the RE population against the first wall,^{36,40,41} accelerating the reduction of the confined plasma volume and limiting further growth of the RE population. Comparing the solid lines ($I_{\text{seed}} = 5.5$ A) with the dashed lines (no REs) in Fig. 3, we observe that the curves diverge only in the final milliseconds of the simulations, indicating that the RE beam must grow to macroscopic levels before effectively slowing down the vertical displacement. A non-monotonic trend appears for $N_{\text{imp}} \approx 6 \times 10^{21}$ (red curve), where the RE current peak diminishes despite occurring earlier (Fig. 2). This confirms that at such impurity levels, the enhanced RE avalanche production is completely counterbalanced by the macroscopic losses driven by the accelerated vertical displacement and subsequent wall scrape-off (see Fig. 3). Without this scrape-off effect reducing the confined volume, the exponential avalanche would theoretically drive I_{RE} significantly higher. This result contrasts sharply with the Day-0 simulations,²⁰ where the lowest seeds invariably resulted in safe scenarios, with a maximum amplification (for the case with $N_{\text{imp}} \approx 3 \times 10^{21}$) of $G_{\text{av}} \approx 500$. At $I_p = 5.5$ MA, although, the avalanche gain G_{av} is so large ($\approx 1.3 \times 10^5$) that having an initial RE seed of this magnitude is not guaranteed to be a safe condition if the disruption dynamics creates a sufficiently strong electric field.

Figure 4 illustrates the current evolution for an intermediate RE seed of 550 A ($I_{\text{seed}}/I_p = 10^{-4}$), serving as a proxy for scenarios with moderate primary generation. The qualitative dependence on the impurity content remains consistent with the low-seed case: lower impurity levels ($N_{\text{imp}} \approx 1 \times 10^{20}$, black lines) result in negligible RE generation, as the electric field is insufficient to drive the RE avalanche (although, as previously noted, this represents a partially mitigated disruption). However, owing to an initial seed two orders of magnitude larger than in the previous case, the RE populations reach their peak values earlier, and the resulting beam currents are substantially higher. This difference is particularly evident at intermediate impurity levels ($1 \times 10^{21} \lesssim N_{\text{imp}} \lesssim 2 \times 10^{21}$, pink and blue curves).

In particular, with $N_{\text{imp}} \approx 4 \times 10^{21}$, the RE current reaches approximately 1.8 MA, accounting for almost 60% of the total current. To better characterize the current distribution for this impurity case, Fig. 5 compares I_p and I_{RE} from Fig. 4 (orange lines) with the confined current (I_{core}) extracted from the same simulation. As the avalanche proceeds, I_{RE} approaches I_{core} closely, indicating that the core current is predominantly carried by REs. This implies that the thermal current (visible as the difference between I_p and I_{RE}) corresponds largely to halo currents flowing on open field lines,⁴⁹ where the electron temperature is typically found to be ≈ 5 eV in the simulations. At this stage, the CQ dynamics are dominated by the RE beam, which significantly slows the current decay (an effect only marginally observable with $I_{\text{seed}} = 5.5$ A). This I_p decay is driven primarily by the vertical displacement of the plasma column rather than by resistive dissipation. As the plasma drifts vertically, the outer flux surfaces are successively scraped off by the first wall, leading to a gradual loss of the RE population (visualized in detail in Fig. 8). This interaction poses a severe threat to the PFCs, as the substantial energy stored in the RE beam is deposited onto localized wall regions. Although studying an MHD-induced broadening of the deposition area might show paths toward a benign RE termination scenario, it lies outside the scope of this work. Ultimately, the accelerated vertical displacement at higher impurity levels limits the beam growth: for N_{imp} exceeding 4×10^{21} (red lines), the maximum RE current begins to decrease, consistent with the non-monotonic behavior observed in the low-seed analysis.

Figure 6 presents the results for the largest initial seed ($I_{\text{seed}} = 55$ kA, $I_{\text{seed}}/I_p = 10^{-2}$), representing the upper bound of our investigation. This corresponds to a scenario where primary generation mechanisms have converted a significant fraction of the plasma current into REs immediately after the TQ. As noted in Sec. II, increasing the seed magnitude beyond this limit would pose a serious threat even with minimal multiplication, thus shifting the dominant physical mechanism from avalanche multiplication to primary generation. Although the qualitative behavior mirrors the trends observed for the intermediate seed, the drastic increase in I_{seed} both amplifies the maximum I_{RE} and accelerates its onset. In fact, there is almost no lag time between the start of the CQ and the formation of a macroscopic RE beam, which drastically slows the CQ. The impact of this high RE current on vertical stability is evident in Fig. 7: the RE beam significantly slows the vertical displacement compared to the RE-free reference cases (dashed lines), where the vertical position (Z_{axis}) rises much faster. Within a few milliseconds, the RE current rapidly constitutes $\approx 80\%$ of the total current, even for impurity levels as low as $N_{\text{imp}} \approx 1 \times 10^{21}$. The largest RE current for this 55 kA seed is now obtained with $N_{\text{imp}} \approx 3 \times 10^{21}$ (green curves), reaching $I_{\text{RE}} \approx 3.2$ MA (nearly 60% of the pre-disruption plasma current) at $t \approx 5.8$ ms. For higher levels of impurities (orange and red lines), the maximum RE current starts to decrease. This lower impurity threshold with respect to the previous cases confirms that the wall-scraping mechanism of the RE beam is accentuated in this scenario: the confined plasma current is almost entirely converted to RE current, and the slow current decay is primarily driven by the vertical drift of the plasma column. Figure 8 illustrates the process for the case with $N_{\text{imp}} \approx 3 \times 10^{21}$: as the vertical displacement proceeds, the confined plasma volume (delimited by the last closed flux surface, white contour) shrinks significantly. Consequently, although the RE density in

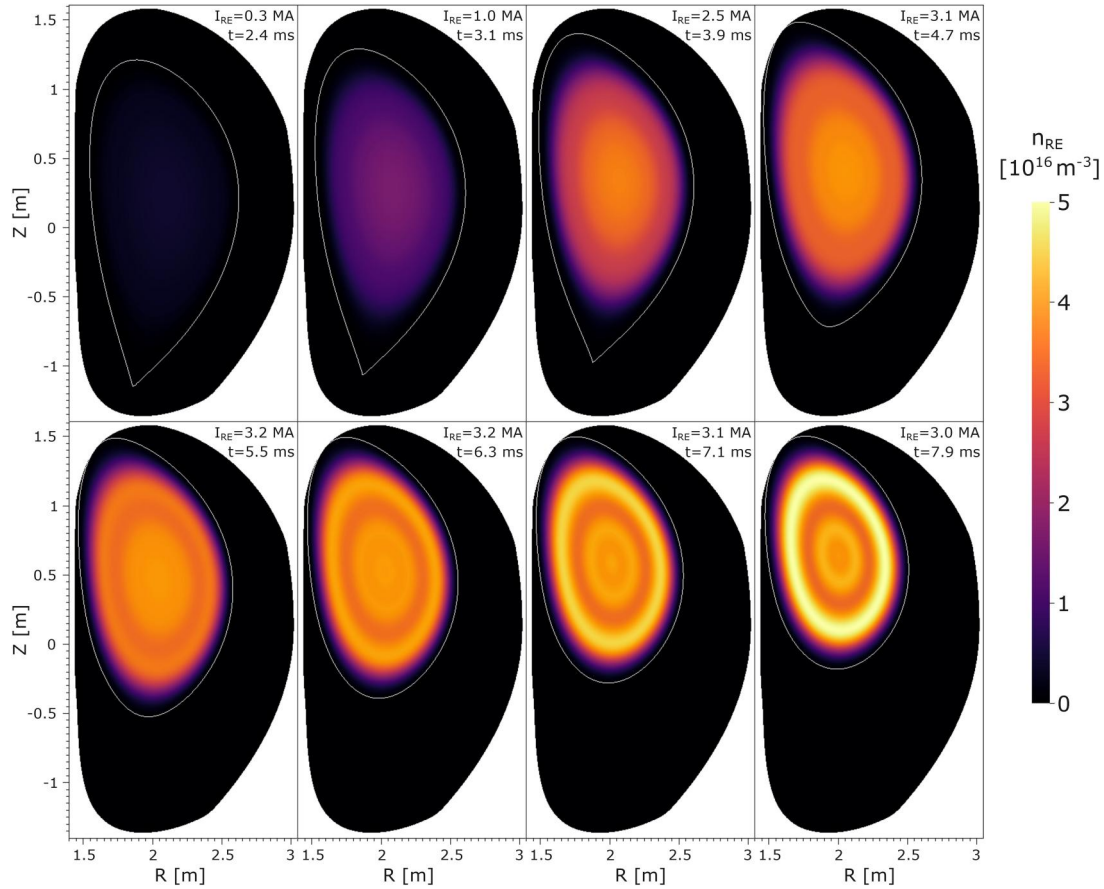


FIG. 8. Poloidal cross section evolution of the RE density n_{RE} (in 10^{16} m^{-3}) for the large-seed case ($I_{seed} = 55 \text{ kA}$) with $N_{imp} \approx 3 \times 10^{21}$ (corresponding to the green curves in Fig. 6 and the green solid lines in Fig. 7). The white contour is the last closed flux surface, separating the confined region from the open field lines. As the vertical displacement progresses, the plasma volume is scraped off by the first wall. Although the core RE density increases due to the avalanche, the total RE current (I_{RE} , top right of each panel) eventually decays due to the reduction of the confined volume. Note that the absolute maximum of I_{RE} for this scenario occurs at $t \approx 5.8 \text{ ms}$, falling between the discrete snapshots shown here.

the core continues to rise due to the avalanche, the total RE current (I_{RE}) peaks and eventually decreases as the flux surfaces are scraped off by the first wall. It is worth noting that even in this extreme I_{seed} case, the simulation with the lowest impurity content ($N_{imp} \approx 1 \times 10^{20}$, black lines) remains RE-free. This stresses the critical role of the impurities: without sufficient cooling to raise the background resistivity, even a massive 55 kA seed will eventually decay due to collisional drag and radial diffusion, rather than avalanching. However, as previously stated, the thermal loads and halo current forces in this partially mitigated disruption scenario could be above the machine limits.

To isolate the impact of the operational scenario on the generation of RE we performed a direct comparison between Day-0 ($I_p = 2 \text{ MA}$) and full power ($I_p = 5.5 \text{ MA}$), visualized in Fig. 9. The comparison relies on a 20 kA RE seed and on impurity levels equal to $N_{imp} \approx 1 \times 10^{21}$ and 3×10^{21} . These parameters were selected to compare the worst-case scenarios for both regimes, being the only cases found to yield a significant RE beam in the Day-0 scenario. The Day-0 simulation data used for this comparison were previously

reported in Ref. 20. The logarithmic scale in Fig. 9 reveals the profound difference in RE generation of the two scenarios. The dashed lines, representing the Day-0 case, show that I_{RE} increases only marginally from the 20 kA seed, even for high impurity levels, always remaining below 1 MA and, hence, posing minimal risks to the PFCs of DTT.²⁰ In stark contrast, the full power simulations (solid lines) exhibit explosive growth, with curve slopes that are much steeper than the Day-0 counterparts and reaching higher peak RE currents (nearly 3 MA). This confirms the risks highlighted by the avalanche gain analysis of the 5.5 A seed: in the presence of a relatively high RE seed, the very large amplification potential of the full power scenario ($G_{av} \approx 1.3 \times 10^5$) manifests itself as a rapid and robust conversion of the core plasma current into RE current.

The results of this parametric scan delineate a significantly narrower “RE safe” operational window for the DTT full power scenario compared to Day-0. Although the safety against RE beams of the 2 MA scenario was largely insensitive to the specific mix of initial RE seeds and impurities (since almost all reasonable paths led to negligible RE currents), at 5.5 MA, the system is highly sensitive to the

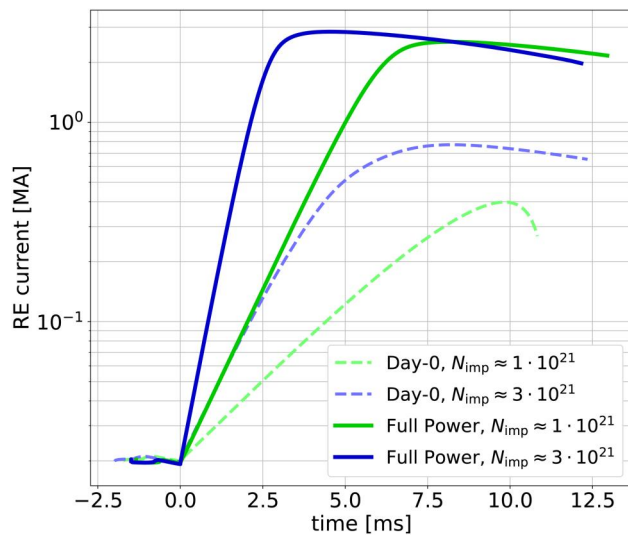


FIG. 9. Direct comparison of the RE current evolution in the Day-0 scenario ($I_p \approx 2$ MA, dashed lines) and the full power scenario ($I_p \approx 5.5$ MA, solid lines) for a fixed initial seed of 20 kA, with $t = 0$ ms aligned to the start of the CQ. Green and blue lines correspond to $N_{\text{imp}} \approx 1 \times 10^{21}$ and 3×10^{21} , respectively. Data points for the Day-0 scenario are re-plotted from Emanuelli *et al.*, Fusion Eng. Des. **223**, 115588 (2026).²⁰ Copyright 2026 Authors, licensed under a Creative Commons Attribution (CC BY) license. The logarithmic scale highlights that the full power scenario is characterized by much steeper slopes and higher peak currents, reflecting the exponential disparity in avalanche amplification.

combination of these parameters. We can identify three distinct regimes from the parametric scan (Figs. 2, 4, and 6).

1. Incomplete thermal collapse ($N_{\text{imp}} \lesssim 1 \times 10^{20}$). In this regime, the quantity of impurities injected is too low to extensively cool the plasma. The plasma resistivity remains relatively low, preventing the formation of the large electric fields required for avalanching. While effective at suppressing REs, the capacity of this regime to radiate sufficiently and mitigate heat loads or halo current forces requires further analysis, notwithstanding the mechanical robustness of the DTT vacuum vessel, whose design satisfies stress requirements for a fatigue life of 750 worst-case disruptions.¹⁶
2. Avalanche transition ($1 \times 10^{20} < N_{\text{imp}} \lesssim 1 \times 10^{21}$). This regime marks the onset of the avalanche mechanism, characterized by positive but moderate amplification. A low RE seed (5.5 A) can initiate an avalanche (Fig. 2, pink line), but the gain is insufficient to produce a macroscopic RE beam before the plasma column is scraped off against PFCs. Conversely, larger seeds can compensate for the moderate gain, resulting in significant RE currents (pink lines in Figs. 4 and 6). In this regime, the safety against RE beams depends on the magnitude of the primary seed, whose accurate prediction remains a significant challenge.
3. Macroscopic beam formation ($N_{\text{imp}} \gtrsim 2 \times 10^{21}$). In this high-impurity regime, the safety margin effectively vanishes. The avalanche gain is substantial enough to elevate even microscopic seeds to macroscopic RE currents. This result suggests that massive impurity injection for thermal mitigation carries a severe

penalty in terms of RE risk for the full power scenario, irrespective of the initial RE seed current.

It must be noted that the simulations presented in this work, being 2D (toroidally symmetric), neglect 3D MHD instabilities that may destroy the magnetic flux surfaces and create stochastic field lines. While 3D transport introduces significant RE loss mechanisms through radial transport, the resulting dynamics are complex and do not strictly guarantee a reduction in the final RE current.⁵⁰ Nevertheless, the fact that 2D simulations predict beams of up to ≈ 3.2 MA indicates that the source term is extremely strong, and relying solely on stochastic losses to suppress such a vigorous avalanche may therefore be insufficient.

IV. CONCLUSIONS

This work has extended the safety analysis of RE avalanches in DTT to the full power scenario ($I_p = 5.5$ MA). Building upon previous assessments of the Day-0 commissioning phase ($I_p = 2$ MA), we employed the non-linear MHD code JOREK and the resistive wall code STARWALL to simulate the current quench dynamics under conditions relevant to reactor-scale operations. By performing an extensive parametric scan of initial RE seed currents (ranging from 5.5 A to 55 kA) and injected neon impurity levels, we have quantified the risk of RE beam formation in this high-current scenario of DTT. The comparative analysis reveals a fundamental divergence from the Day-0 results. While the 2 MA scenario was characterized by a broad safety margin in which RE generation was typically negligible, the 5.5 MA scenario exhibits a high sensitivity to the input parameters. Specifically, the exponential increase in the avalanche gain allows even the lowest tested seed populations ($I_{\text{seed}}/I_p = 10^{-6}$) to be amplified into macroscopic beams if the impurity density is sufficiently high to drive a fast current quench ($N_{\text{imp}} \gtrsim 2 \times 10^{21}$).

Our analysis identifies three distinct physical regimes for the full power scenario. For low impurity levels ($N_{\text{imp}} \lesssim 1 \times 10^{20}$), the induced electric field is too small to sustain a RE avalanche; however, the reduced radiative cooling may result in thermal loads and electromagnetic forces that the PFCs and supporting structures cannot withstand. For higher values of N_{imp} up to $\approx 1 \times 10^{21}$, the avalanche multiplication becomes increasingly dominant. In this transition zone, the safety of the device against REs is highly dependent on the magnitude of the initial RE seed, which originates from primary RE generation mechanisms (e.g., Dreicer or hot-tail). Forecasting safety in this regime is challenging due to the inherent difficulty in predicting the primary seed amplitude. Finally, for $N_{\text{imp}} \gtrsim 2 \times 10^{21}$, the safety margin is drastically reduced: even the lowest initial seeds we tested are amplified into macroscopic RE beams, while larger seeds facilitate the conversion of almost all the confined plasma current into RE current. In such cases, the CQ is effectively stalled by the highly conductive RE population. Consequently, the discharge termination is governed by the vertical displacement of the plasma column and its subsequent interaction with the first wall, where the substantial energy carried by the RE beam is deposited onto localized surfaces, representing a severe threat to the integrity of the PFCs.

Given the severe risks identified in the high-current scenario of DTT, future studies will focus on identifying an optimal disruption mitigation strategy. While this study considered pure neon injection to isolate the impurity dependence, a practical solution will likely involve mixtures of neon and deuterium. Future simulations should

investigate these mixtures to determine the composition that best balances the suppression of RE production with the mitigation of other critical disruption loads, such as thermal fluxes and halo currents. Parallel to this, similar work to Refs. 44 and 51 is underway to simulate a realistic TQ triggered by shattered pellet injection using 3D modeling, which will allow us to bypass the ATQ setup by providing more accurate initial conditions for the start of the CQ. We will also extend our analysis to 3D simulations of macroscopic RE beam termination events, as done in Refs. 34, 35, and 37. This transition will simultaneously reveal how realistic MHD perturbations affect net avalanche growth compared to simplified 2D predictions and enable precise assessments of localized PFC damage, directly informing mitigation strategies like the placement of sacrificial limiters. These contributions will lay the foundation for safe DTT operations, safeguarding its strategic function within the European fusion program.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Enrico Emanuelli: Conceptualization (equal); Data curation (lead); Formal analysis (lead); Investigation (lead); Methodology (equal); Software (lead); Validation (lead); Visualization (lead); Writing – original draft (lead); Writing – review & editing (lead). **Francesco Vannini:** Conceptualization (equal); Methodology (equal); Software (lead); Supervision (lead); Writing – review & editing (supporting). **Matthias Hoelzl:** Conceptualization (lead); Methodology (lead); Project administration (equal); Resources (lead); Software (lead); Supervision (lead); Writing – review & editing (lead). **Eric Nardon:** Conceptualization (supporting); Methodology (supporting); Software (equal); Supervision (supporting); Writing – review & editing (lead). **Vinodh Bandaru:** Conceptualization (supporting); Methodology (supporting); Software (lead); Supervision (supporting); Writing – review & editing (supporting). **Nina Schwarz:** Conceptualization (supporting); Methodology (supporting); Software (lead); Writing – review & editing (supporting). **Daniele Bonfiglio:** Conceptualization (supporting); Methodology (supporting); Project administration (lead); Supervision (lead); Writing – review & editing (lead). **Giuseppe Ramogida:** Conceptualization (equal); Project administration (lead); Supervision (lead); Writing – review & editing (supporting). **Fabio Subba:** Conceptualization (equal); Project administration (lead); Supervision (lead); Writing – review & editing (supporting). **The JOREK Team:** Software (supporting).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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