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Impact of ECRH on Runaway Electron Generation during Plasma Disruptions in the HL-3 Tokamak

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ABSTRACT

This work investigates the impact of Electron Cyclotron Resonance Heating (ECRH) on runaway electron (RE) generation during MGI-triggered disruptions on the HL-3 tokamak. During these disruptions, a large RE current is formed, primarily through the hot tail generation and the avalanche process of REs. A comparative study found that applying 1 MW of ECRH during the disruption enhanced and sustained the RE beam, creating a higher-current and longer-lasting plateau compared to the non-ECRH case. Diagnostic analysis indicates this is because ECRH allowed the RE seed to be better confined. Furthermore, HXR spectra reveal ECRH actively heated the bulk RE population, raising its temperature from 0.13 MeV to 0.36 MeV. These findings demonstrate that active ECRH during a disruption can be harmful for tokamak operation, suggesting auxiliary heating systems must be integrated into disruption mitigation systems for immediate plasma termination.

Introduction

Major disruptions in tokamak plasmas are a critical challenge for fusion research, as they degrade confinement and can severely damage plasma-facing components (PFCs)¹⁻³. This damage is often driven by the generation of runaway electrons (REs), where an initial seed population is created via the Dreicer or hot-tail mechanisms^{4,5}. This seed population is then massively amplified by the avalanche process⁶ into high-energy, high-current beams with energies reaching several tens of MeV during the disruption⁷⁻¹⁰. The impact of these RE beams causes substantial damage, such as melting or brittle destruction, to the first wall or plasma-facing components¹¹. Therefore, their mitigation is a crucial focus of fusion operations. Extensive research over the past decades has focused on minimizing RE risks, primarily through methods like massive impurity gas injection (MGI)¹²⁻¹⁵ and shattered pellet injection (SPI)¹⁶⁻¹⁸.

The HL-3 tokamak is the newly commissioned upgrade of the HL-2M device, designed to support advanced fusion research and next-generation reactor scenarios¹⁹. Its design parameters feature a plasma current (I_p) of 2.5–3 MA, a toroidal magnetic field (B) of 2.2–3 T, a major radius (R) of 1.78 m, and a minor radius (a) of 0.65 m, with an elongation (κ) ≤ 1.8 and a triangularity (δ) ≤ 0.5 . The machine also employs multiple auxiliary heating systems, including Electron Cyclotron Resonance Heating (ECRH) units of 4 MW, Neutral Beam Injection (NBI) of 5 MW, and Lower Hybrid Current Drive (LHCD) systems of 2 MW²⁰. The HL-3 is equipped with a suite of diagnostics for characterizing electron temperature, plasma density, and plasma behavior under diverse operating regimes^{21,22}. Following several successful experimental campaigns, HL-3 has supported high-performance, high-current plasma operations under both limiter and divertor configurations, laying the groundwork for studies of energetic phenomena such as disruptions and runaway electron (RE) generation.

Recent studies on the Tokamak à Configuration Variable (TCV) have demonstrated that ECRH can effectively suppress RE generation²³. The application of central ECRH was shown to strongly reduce an existing RE seed population by up to three orders of magnitude within only a few hundred milliseconds. This RE expulsion rate increases with applied ECRH power, while off-axis ECRH has a comparatively limited effect. Furthermore, applying central ECRH before a disruption can prevent the formation of a post-disruption RE beam in scenarios where one would otherwise be expected. This reduction is sufficient to suppress the formation of an RE beam following a disruption triggered by massive gas injection. This RE expulsion driven by ECRH results from a transition into a low-RE current state where the avalanche generation of REs is overcome by RE losses²³.

Kinetic instabilities might develop during ECRH application when runaway electrons are present, similar to observations of post-disruption RE beams in FTU²⁴. Alternatively, the enhanced RE loss rate could be linked to an increase in microturbulence correlated with ECRH power²⁵.

Given the enhanced capabilities of HL-3, the device offers a unique opportunity to systematically explore the impact of ECRH on RE generation and mitigation during disruption scenarios. In contrast to previous approaches, the present work investigates the effect of applying MGI during the ECRH phase. By directly comparing RE dynamics between discharges with and without ECRH application, this study assesses the influence of ECRH on RE dynamics and evaluates its effectiveness as an operational strategy for controlling RE production. This approach tests the robustness of MGI under more reactor-relevant conditions, where mitigation and heating systems may operate simultaneously, providing new insights for improving disruption mitigation and operational safety in high-performance fusion devices²⁶.

The organization of this paper is as follows. Section describes the experimental setup. In Section , the experimental observations of runaway electron behavior in discharges with and without ECRH are presented, along with a discussion of the enhanced runaway electron generation resulting from ECRH application. Finally, the conclusions are summarized in Section .

Experimental Setup

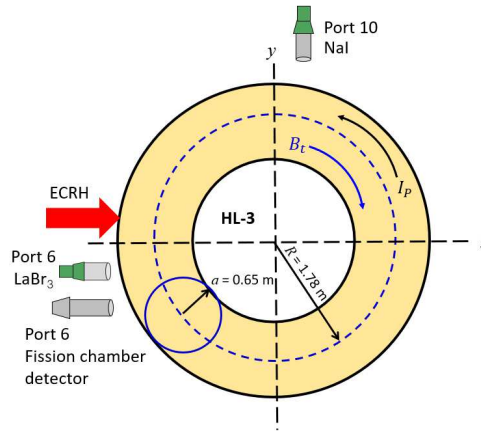


Figure 1. A schematic top-down (toroidal) view of the HL-3 tokamak, showing the layout of the key heating and diagnostic systems used in this study. The device parameters (major radius $R = 1.78$ m, minor radius $a = 0.65$ m) and the directions of the plasma current (I_p) and toroidal magnetic field (B_t) are indicated. The ECRH are injected from the low-field side midplane at port 6. The diagnostics dedicated to runaway electron (RE) measurements include a 3-inch LaBr_3 scintillator and a fission chamber detector (port 6), and a NaI scintillator detector (port 10).

The experiments in this study were carried out on the HL-3 tokamak for comparing two deuterium plasma discharge scenarios in a limiter configuration. Both discharges were created with a plasma current at the flat-top phase of 0.5 MA, a toroidal magnetic field (B_t) of 1.5 T, and an average electron density (n_e) of $6 \times 10^{19} - 8 \times 10^{19} \text{ m}^{-3}$. One discharge was a reference shot with no additional heating. In the second discharge, 1 MW of ECRH power was applied from $t = 400.0$ ms to 617.0 ms. For both discharges, an MGI of argon (Ar) was launched at $t = 606.0$ ms to trigger the disruption.

The experimental arrangement on the HL-3 tokamak is schematically illustrated in Fig. 1. For these experiments, the plasma current (I_p) and toroidal magnetic field (B_t) were operated in the counter-clockwise direction. The ECRH launcher is located at the low-field side midplane (port 6). Several diagnostics were employed. To monitor the bulk plasma, Electron Cyclotron Emission (ECE) diagnostics and Soft X-ray (SXR) arrays were used. For high-energy particle measurements, multiple diagnostics were employed to measure hard X-ray (HXR) and neutron emissions. At port 6, a 3-inch lanthanum bromide (LaBr_3) scintillator and a fission chamber were positioned. An additional sodium iodide (NaI) scintillator was located at vertical port 10. The HXR detectors (NaI and LaBr_3) measured bremsstrahlung emission from REs colliding with the bulk plasma or plasma-facing components, and both detector types cover an energy range of 0.5–10 MeV with a 1 ms temporal resolution. The fission chamber, also with a 1 ms temporal resolution, recorded neutron generation.

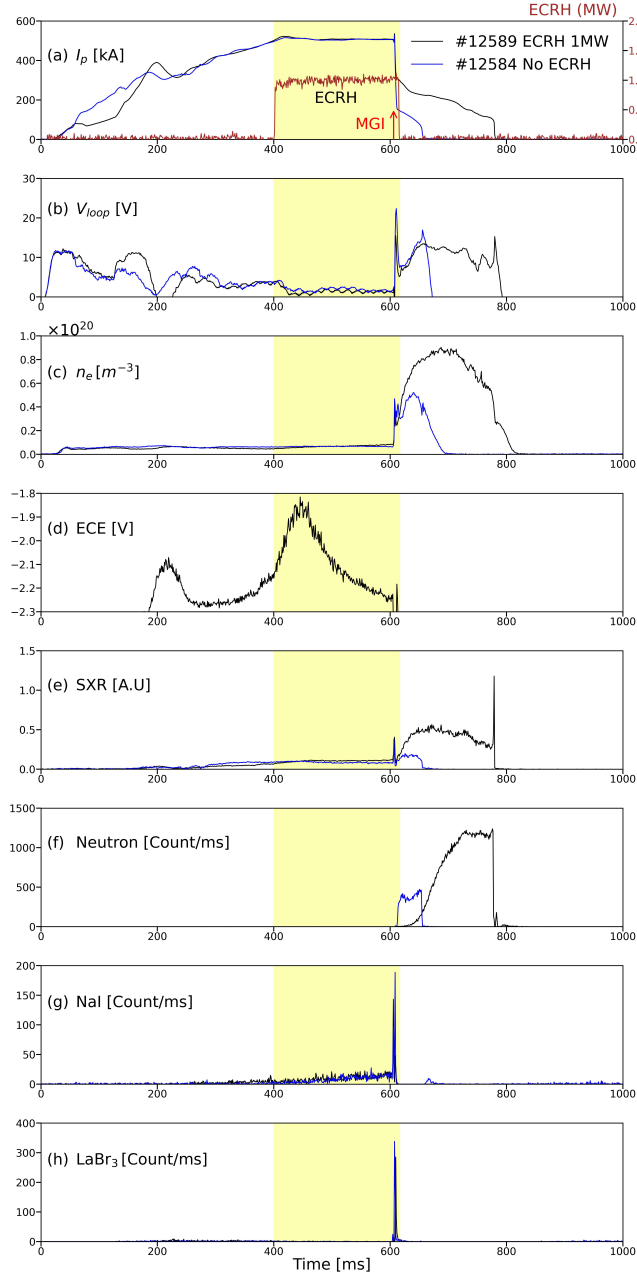


Figure 2. Time evolution of HL-3 discharges #12584 (no ECRH) and #12589 (with 1-MW ECRH), for which MGI was triggered at $t = 606.0$ ms. From top to bottom: (a) plasma current and ECRH power, (b) loop voltage, (c) electron density, (d) Electron Cyclotron Emission, (e) soft X-ray radiation intensity, (f) neutron yield, (g) HXR intensity (NaI), (h) HXR intensity ($LaBr_3$).

Results and Discussion

Figure 2 shows the temporal evolution of two comparative discharges: shot #12584 (no ECRH, blue line) and shot #12589 (with 1-MW ECRH, black line). Both discharges were initiated with similar parameters in a limiter configuration, reaching a flat-top plasma current of approximately 500 kA (Fig. 2a). In shot #12589, 1 MW of ECRH power was applied to the Ohmic plasma from $t = 400.0$ ms to $t = 617.0$ ms. This pre-disruption heating is confirmed by the significant increase in the ECE signal during this period, as shown in panel (d); however, the ECE signal was not available in shot #12584. In both scenarios, a disruption was triggered at $t = 606.0$ ms by a massive gas injection (MGI) of argon (as indicated with the red arrow).

During the current flat-top phase ($t = 100$ – 400 ms), both the ECRH discharge (#12589, black line) and the reference discharge (#12584, blue line) show a similar Ohmic loop voltage of approximately 1.84 V. When ECRH is applied to shot #12589 (from $t = 400$ ms to 617 ms), its loop voltage drops to lower voltage (1.32 V). This is a direct consequence of the ECRH increasing the electron temperature (T_e), which lowers the plasma resistivity ($\eta \propto T_e^{-3/2}$) and the voltage required to sustain the current. At the MGI-triggered disruption ($t = 606$ ms), both discharges exhibit a large positive spike in V_{loop} , characteristic of the thermal quench. Following this spike, the loop voltage in the ECRH shot (#12589) settle to a low positive value, which is consistent with the formation of the RE current plateau seen in panel (a). The loop voltage in shot #12584 quickly drops to zero, demonstrating shorter RE plateau.

Following the argon injection at $t = 606.0$ ms, both the electron density (Fig. 2c) and soft X-ray (SXR) radiation (Fig. 2e) increase significantly. This initial SXR spike is caused by the massive influx of argon impurities, which are heated and ionized, leading to intense line radiation and bremsstrahlung from the bulk plasma. This rapid radiative energy loss triggers the thermal quench of the major disruption, which occurs between $t = 607$ ms and 610 ms. During this interval, a substantial population of runaway electrons (REs) is generated. As these REs are lost and interact with the vacuum chamber walls, they generate hard X-ray (HXR) bremsstrahlung, resulting in a sudden increase in HXR emissions as seen by both the NaI (Fig. 2g) and LaBr₃ (Fig. 2h) detectors. A corresponding rise in the neutron flux is also observed (Fig. 2f). This neutron signal is an effective RE diagnostic; since fusion neutrons are negligible in HL-3 plasmas without NBI, the fission chamber (FC) primarily monitors high-energy photons produced by (γ, n) photonuclear reactions, which are induced by REs striking plasma-facing materials.

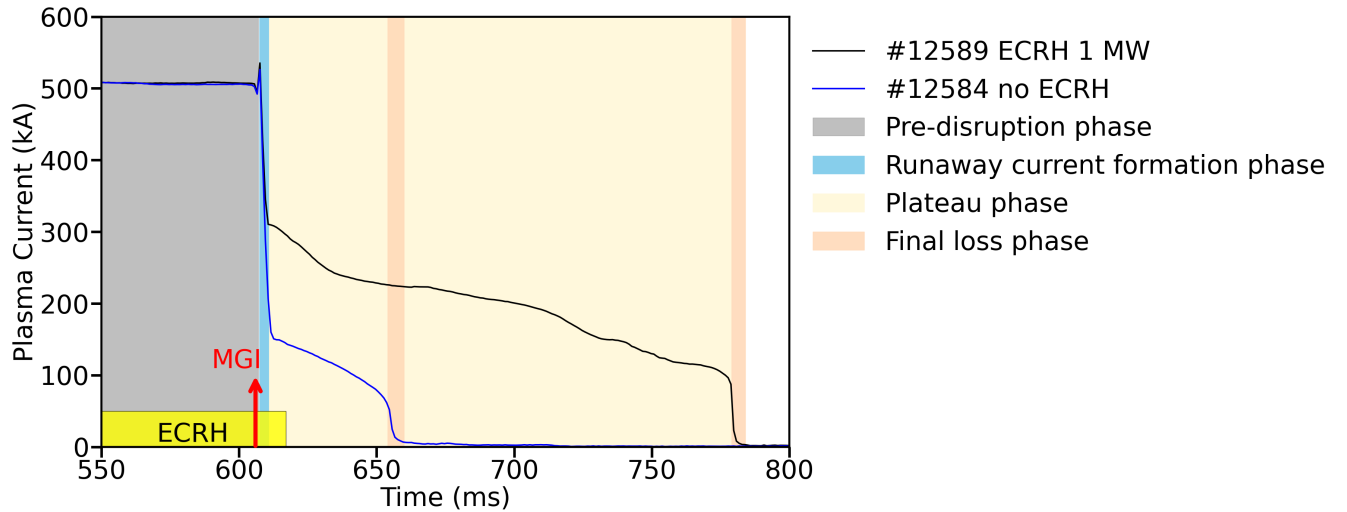


Figure 3. Evolution of the plasma current (I_p) in two disruptive discharges of HL-3: discharge #12584 (blue), operated without ECRH, and discharge #12589 (black), in which 1 MW of ECRH was applied. The disruption begins at $t \approx 607$ ms. The shaded bands denote the main stages: the pre-disruption flattop (gray), the RE seed and current formation stage (sky blue), the runaway electron plateau (corn-silk), and the final termination phase (peach).

Fig. 3 shows the time evolution of the plasma current (I_p) for two comparative HL-3 disruptions: discharge #12584 (without ECRH, blue) and #12589 (with 1 MW ECRH, black). The evolution of the disruption can be typically divided into four main phases²⁷:

1. Pre-disruption phase ($t < 606$ ms): Both discharges remain on a stable flat-top, maintaining a plasma current of approximately 510 kA.
2. Runaway current formation phase (sky blue, $t \approx 606$ – 625 ms): The disruption at $t \approx 610$ ms triggers a rapid thermal quench (TQ) and the onset of the current quench (CQ). During this brief phase, the plasma current decreases rapidly as

the plasma cools and becomes highly resistive, which generates the seed population of runaway electrons^{5,28,29}.

3. Plateau phase (corn-silk region, $t \approx 625 - 780$ ms): The remaining plasma current is largely carried by a beam of runaway electrons (REs). A clear difference is observed between the two discharges. In the absence of ECRH (discharge #12584), the RE plateau forms at a relatively low current of approximately 150 kA. This RE beam is poorly confined and decays completely within 50 ms, with the plasma current dissipating by $t \approx 670$ ms. In contrast, when 1 MW of ECRH is applied (discharge #12589), a much more robust RE plateau develops, stabilizing at a higher current of $I_p \approx 320$ kA. This plateau is sustained for more than 150 ms before the onset of the final loss.
4. Final loss phase (peach region, $t > 780$ ms): This phase corresponds to the final vertical displacement or instability, which causes the RE beam to strike the plasma-facing components, thereby terminating the discharge.

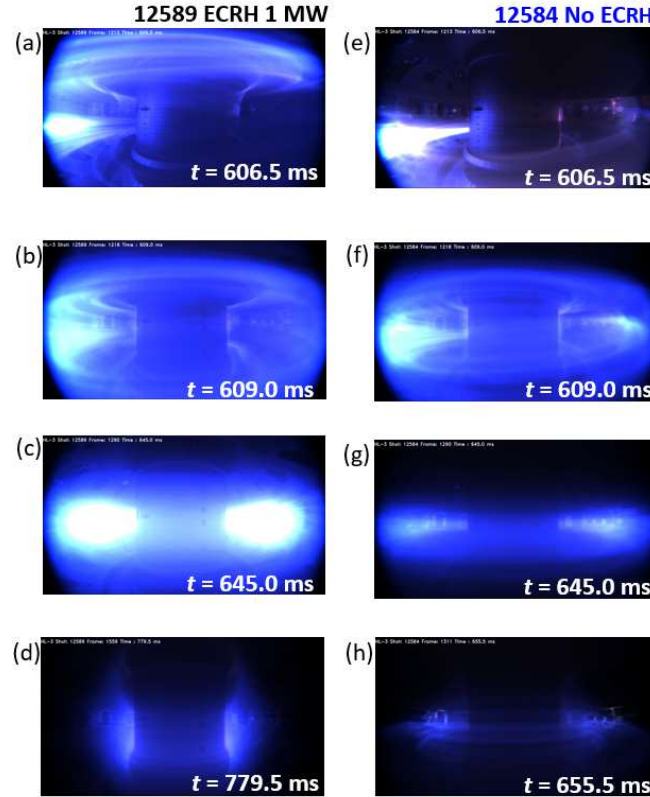


Figure 4. CCD camera images of plasma disruptions in HL-3, showing the evolution of runaway electron (RE) beams. The left column (a-d) is shot #12589 (1 MW ECRH), and the right column (e-h) is shot #12584 (no ECRH). The rows show specific time points: (a, e) pre-disruption phase, (b, f) runaway current formation phase, (c, g) RE plateau phase, and (d, h) late-stage beam.

Snapshots from a visible wide-angle camera shown in Fig. 4 visually confirm the evolution of the disruption process. The figures in the left column (a-d) are from shot #12589 (1 MW ECRH), and the figures in the right column (e-h) correspond to shot #12584 (no ECRH). The first row (panels (a) and (e)) shows a snapshot at $t = 606.5$ ms, capturing the initial thermal quench; the bright spots on the lower left of both figures are caused by the argon gas injection. During the subsequent runaway current formation phase (panels (b) and (f)), multiple filament structures showing the transport of argon are visible throughout the chamber.

A clear distinction between the shots becomes visible in the RE plateau phase. In the ECRH discharge (#12589), a bright, focused RE beam is formed by $t = 645.0$ ms (Fig. 4c). This is supported by the plasma equilibrium reconstruction at the same time point (see Fig. 5), which shows a stable, well-confined plasma column. This beam is visibly more intense and larger than the beam in the reference discharge (Fig. 4g), corresponding to its higher runaway current. This intense light emission persists late into the discharge, with a visible beam still present at $t = 779.5$ ms (Fig. 4d), matching the long-lived RE plateau shown in Fig. 3. In contrast, the reference discharge (#12584, right column) shows a much fainter beam (Fig. 4g) that decays rapidly, and

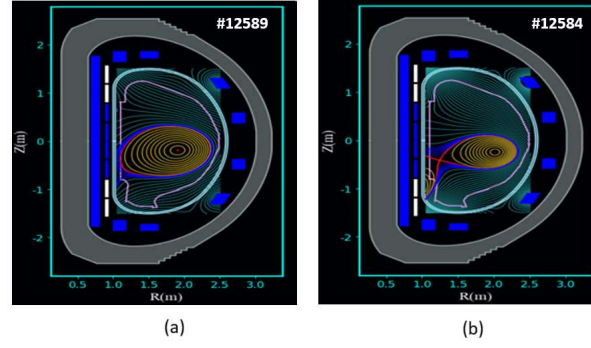


Figure 5. Plasma equilibrium reconstruction at $t = 645$ ms, during the runaway electron (RE) plateau phase, for (a) shot #12589 (1 MW ECRH) and (b) shot #12584 (No ECRH).

its corresponding equilibrium at $t = 645.0$ ms (Fig. 5b) shows a decaying, poorly-confined plasma. By $t = 655.5$ ms (Fig. 4h), the visible light has almost entirely vanished, in excellent agreement with the rapid dissipation of its plasma current. In the final loss phase, the RE beam gradually drifts towards the high field side of the plasma due the imbalance of the magnetic pressure and plasma pressure, and suddenly impacts the first wall (see Fig. 4d and 4h).

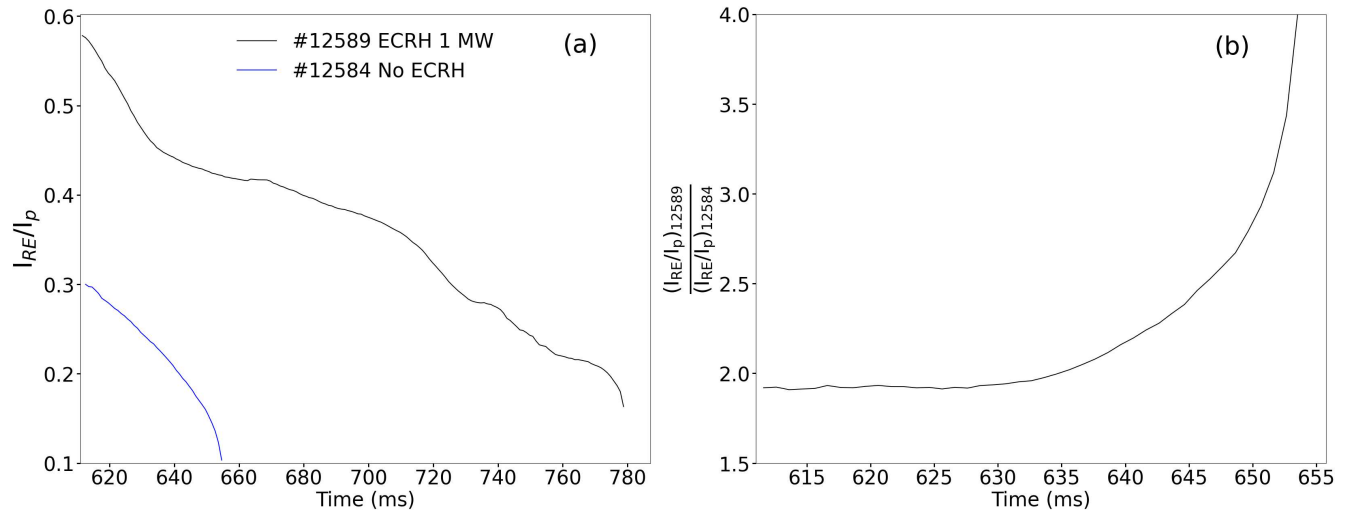


Figure 6. Comparison of runaway electron (RE) current evolution during disruptions with (shot # 12589, 1 MW ECRH) and without (shot # 12584, no ECRH) ECRH. (a) Time evolution of the RE current fraction (I_{RE}/I_p). The ECRH pulse sustains the RE beam for a significantly longer duration. (b) Ratio of the RE current fractions from both discharges.

The primary effect of electron cyclotron resonance heating (ECRH) on the runaway electron (RE) beam during plasma disruptions is illustrated in Fig. 6. The figure shows the time evolution of the RE current fraction (I_{RE}/I_p) for the two discharges: shot #12584 without ECRH and shot #12589 with 1 MW of applied ECRH. Here, the runaway current (I_{RE}) is the post-disruption plasma current, and the denominator (I_p) is the pre-disruption plasma current value taken at $t = 605.0$ ms.

Figure 6(a) clearly demonstrates the sustaining effect of ECRH on the RE beam. In the reference discharge without ECRH (shot #12584), the RE beam is generated but decays rapidly, with the RE current fraction decreasing from 0.3 to 0.1 within approximately 50 ms (blue line). In contrast, the application of 1 MW ECRH in shot #12589 produces a more robust RE beam, starting at a higher fraction of ~ 0.58 , and remaining sustained for over 160 ms (black line). The RE beam finally disappears at $t = 780.0$ ms when it strikes the inner first wall (see also Fig. 4d).

Figure 6(b) quantifies this enhancement by showing the ratio of the RE current fractions (shot #12589 / shot #12584). At the initial stage of the disruption phase, the ECRH discharge already has an RE current fraction approximately 1.9 times larger than the reference discharge without ECRH. This ratio remains nearly steady until $t \approx 635$ ms, at which point it increases exponentially. This rise reflects the rapid divergence as the RE beam in the non-ECRH discharge decays, and by $t = 655$ ms,

the RE current fraction in the ECRH discharge reaches four times that of the non-ECRH case.

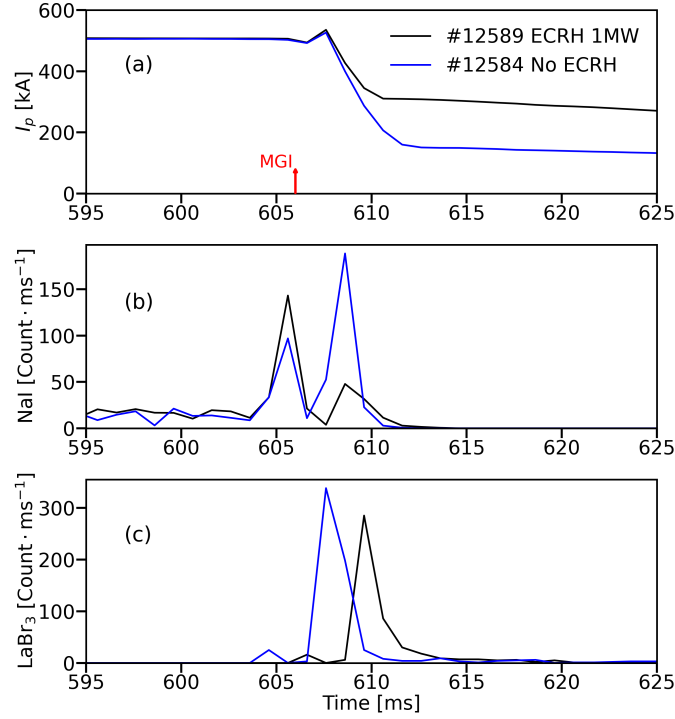


Figure 7. A zoomed-in view of the RE formation phase for discharge #12589 (ECRH, black) and #12584 (no ECRH, blue), following MGI at $t = 606.0$ ms. Panels show: (a) plasma current (I_p), (b) NaI HXR intensity, and (c) LaBr₃ HXR intensity.

Figure 7 provides a detailed, zoomed-in view of the disruption phase, comparing the initial runaway electron (RE) generation in the ECRH discharge (#12589, black line) and the reference discharge (#12584, blue line). The panels show: (a) plasma current (I_p), (b) NaI HXR intensity, and (c) LaBr₃ HXR intensity. The key observation is seen in the HXR signals in panels (b) and (c). The reference discharge without ECRH (blue line) exhibits a substantially larger and earlier HXR burst during the thermal quench, peaking around $t \approx 608 - 609$ ms on both NaI and LaBr₃ detectors. In contrast, the ECRH discharge (black line) shows a smaller initial HXR burst.

This difference in initial HXR emission correlates directly with the subsequent plasma current evolution shown in panel (a). The large, early HXR burst in the reference shot suggests a massive, immediate loss of the initial RE seed population to the wall, leading to a rapid and more complete quench of the plasma current (blue line). Conversely, the smaller initial HXR burst in the ECRH shot indicates that fewer REs were immediately lost. This suggests that the RE seed population to be better confined, survive the thermal quench, and subsequently build up to form the higher, sustained RE plateau (black line).

To analyze the energy distribution of the runaway electrons, the hard X-ray (HXR) spectra for both discharges were analyzed over the time window $t = 600 - 620$ ms, as shown in Fig. 8. The RE temperature (T_{RE}) is estimated by assuming the electrons follow a Maxwell-Boltzmann distribution^{30–32}. Under this assumption, the HXR intensity $I(h\nu)$ is proportional to $\frac{n_{RE}}{\sqrt{T_{RE}}} e^{-h\nu/T_{RE}}$ implying the slope of the spectrum on a semi-log plot is inversely proportional to the temperature ($T_{RE} \propto -1/\text{slope}$). The spectra for both discharges peak at approximately 2 MeV and extend to a maximum energy of around 9 MeV.

As seen in Fig. 8, the spectra cannot be fit by a single temperature. Instead, they clearly demonstrate two distinct slopes, indicating a two-temperature distribution: a bulk RE population (Slope 1) and a high-energy tail population (Slope 2). For the ECRH discharge (#12589, panel a), the fits show a bulk temperature of $T_{RE,1} = 0.36$ MeV and a tail temperature of $T_{RE,2} = 2.74$ MeV. For the reference discharge (#12584, panel b), the fits give a bulk temperature of $T_{RE,1} = 0.13$ MeV and a tail temperature of $T_{RE,2} = 3.18$ MeV.

The results show that the bulk RE temperature ($T_{RE,1}$) is nearly three times higher in the ECRH discharge (0.36 MeV) than in the reference shot (0.13 MeV). This fit to the first slope is highly reliable, with R^2 values of 0.78 and 0.84, respectively. In contrast, the line fitting for the high-energy tail ($T_{RE,2}$) has a much higher uncertainty, with low R^2 values ($R^2 = 0.54$ and 0.21 for shots #12589 and #12584, respectively). This is due to the poor signal-to-noise ratio at higher energies where the HXR counts are significantly lower. This makes the tail temperature estimation less reliable.

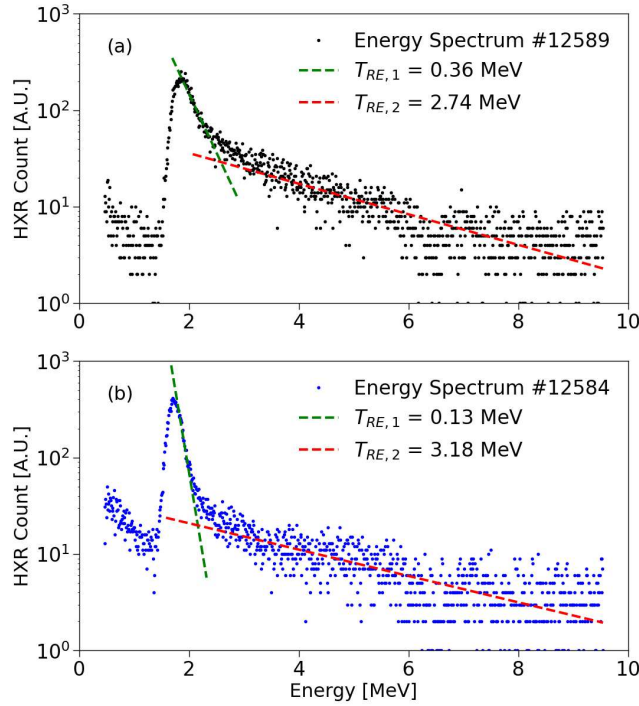


Figure 8. HXR energy spectra measured from the LaBr₃ detector during $t = 600 - 620$ ms for (a) shot #12589 (1 MW ECRH) and (b) shot #12584 (No ECRH). The dashed lines represent two-temperature fits to the RE energy distribution.

Summary

A comparative analysis was performed on the HL-3 tokamak to assess the effect of ECRH on runaway electron (RE) generation during argon-induced plasma disruptions. The study contrasted discharge #12589, where 1 MW of ECRH power was applied from $t = 400 - 617$ ms, with a reference discharge (#12584) without ECRH. While both shots produced an initial RE seed population at the thermal quench, their subsequent evolution diverged significantly. The discharge with ECRH (#12589) developed a robust, high-current RE plateau (peaking at ~ 320 kA) that persisted for over 150 ms. In contrast, the reference shot (#12584) showed a much weaker, poorly-confined RE beam that decayed completely in under 50 ms. This difference in current sustainment is supported by HXR diagnostics and neutron flux monitors. The reference shot exhibited a much stronger initial HXR burst during the thermal quench, suggesting a large, immediate loss of the RE seed population. Furthermore, analysis of the HXR energy spectra revealed that the bulk RE population in the ECRH discharge had a significantly higher temperature ($T_{RE,1} \approx 0.36$ MeV) compared to the reference shot ($T_{RE,1} \approx 0.13$ MeV), confirming that ECRH was actively heating the runaway population.

The observed enhancement of the RE beam with ECRH is the interplay between the pre-disruption electron temperature and the specific dynamics of the plasma density and toroidal electric field. The application of ECRH increases the pre-disruption electron temperature, which exponentially enhances the generation of the primary hot-tail seed population, scaling as $n_{\text{hot}} \propto \exp(-1/T_{e,0})$ ¹⁰. Following MGI, the rapid rise in impurity density ensures a radiative cooling timescale that is sufficiently short relative to the collisional slowing-down time, effectively decoupling superthermal electrons from the cooling bulk²⁹. Consequently, this enhanced seed population facilitates a prompt conversion of the pre-disruption current into a runaway current²⁹. This conversion stabilizes the toroidal electric field, mitigating the massive inductive spikes associated with a rapid current quench and preventing the immediate loss of the seed population, thereby maintaining the necessary conditions for the avalanche multiplication that sustains the high-current plateau¹⁰.

The observation that ECRH enhances RE generation in HL-3 presents a distinct behavior compared to TCV²³, where the suppression of runaway populations was reported. A critical difference lies in the ECRH power density and its effect on transport. The TCV experiments applied up to 1.4 MW of power in a relatively small plasma volume ($R = 0.89$ m, $a = 0.25$ m), resulting in a high power density that may induce stiff temperature profiles and enhanced turbulent transport, thereby increasing the RE loss rate beyond the avalanche gain²³. In contrast, this study on HL-3 applied 1-MW ECRH to a significantly larger plasma volume ($R = 1.78$ m, $a = 0.65$ m) with a higher plasma current (500 kA vs. 120 kA in TCV). The resulting lower power density in HL-3 appears insufficient to trigger the dominant turbulent expulsion observed in TCV, but sufficient to increase the

pre-quench bulk electron temperature, thus exponentially enhancing the hot-tail seed¹⁰. Furthermore, the ECRH pulse in HL-3 overlapped with the argon MGI thermal quench ($t = 606 - 617$ ms), actively energizing the cooling bulk plasma during the critical seed formation, whereas TCV strategies emphasized pre-disruption seed expulsion to prevent beam formation.

This work demonstrates that active ECRH during a disruption potentially enhances the runaway electron seed, counteracting mitigation efforts by maintaining a high-temperature bulk population. Therefore, for ITER and future reactors, we recommend implementing a mandatory interlock to trigger ECRH shutdown based on defined disruption precursor thresholds, rather than waiting for the thermal quench. This ensures the plasma cools before mitigation material arrives. Since Shattered Pellet Injection (SPI) relies on a rapid thermal quench for RE avoidance^{16–18,20}, any active auxiliary heating could compromise mitigation efficiency. Future kinetic modeling³³ is needed to optimize these thresholds and determine precise shutdown latency tolerances relative to pellet arrival times. Understanding this dynamics is essential for developing robust RE mitigation strategies and ensuring the operational safety of high-performance fusion devices.

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Data Availability

The datasets used and analysed during the current study available from the corresponding author on reasonable request.