Numerical Study on Suppression of Tokamak Runaway Current by Massive Injection of Deuterium-Argon-Neon Mixed Gas

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Abstract

Tokamak plasma disruptions can generate runaway currents, which, if left unsuppressed, can cause severe damage to the device due to the enormous energy they carry. This study employs the fluid model in the DREAM code to investigate the effects of injecting deuterium-argon/neon mixture gas on disruption runaway currents. The results demonstrate that injecting deuterium-argon/neon mixture gas can suppress the final plateau runaway current. Within the discussed range of pre-disruption plasma current I_p, the argon/neon content in the mixture gas should be in the range of 0.50% ~ 0.70% under optimal conditions, and the deuterium injection density should be $10^{20}\,\mathrm{m}^{-3} \sim 10^{21}\,\mathrm{m}^{-3}$. Outside this range, the suppression effect of deuterium-argon/neon mixture gas injection on runaway currents is diminished, and may even enhance the runaway current. The pre-disruption plasma current I_p is a key factor influencing runaway currents. As I_p increases, the resulting runaway current increases, requiring greater mixture gas injection. For fusion reactor-scale tokamak devices with I_p up to 10 MA, the required injected mixture gas density reaches $10^{22}\,\mathrm{m}^{-3}$, which exceeds the capabilities of current Massive Gas Injection (MGI) technology, and shattered pellet injection of deuterium-argon/neon mixtures represents a more feasible approach.

Full Text

Preamble

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Abstract

Tokamak plasma disruptions generate runaway currents that can cause severe damage to device components if not effectively suppressed. This study employs the fluid model in the D program to investigate the effects of injecting deuterium-argon/neon mixed gases on mitigating disruption-generated runaway currents. The results demonstrate that injecting deuterium-argon/neon mixtures can suppress the final plateau runaway current. Within the discussed pre-disruption plasma current (I__p) range, the optimal argon/neon content in the mixture should be approximately 0, while the deuterium injection amount should be around 1 × 10^{13} m^{-3}. Outside this optimal range, the suppression effectiveness diminishes and may even increase the runaway current. The pre-disruption plasma current I__p is a critical factor affecting runaway current magnitude—higher I__p leads to larger runaway currents requiring greater mixed gas injection. For fusion reactor-scale tokamaks with I__p up to 1 MA, the required injected gas density reaches 1 × 10^{23} m^{-3}, which exceeds current massive gas injection (MGI) capabilities. Shattered pellet injection (SPI) of deuterium-argon/neon mixtures represents a more feasible approach.

Keywords: tokamak, plasma disruption, runaway current, massive mixed gas injection, deuterium-argon/neon mixture

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1. Introduction

One of the primary challenges in harnessing fusion energy using tokamak devices is plasma disruption. Disruptions generate "runaway electrons" [?], and without effective suppression and mitigation, the enormous energy they carry can damage device interior components and equipment. In large tokamaks such as the Joint European Torus (JET), JT-60U in Japan, ASDEX Upgrade in Germany, and reactor-scale fusion devices, plasma currents are substantial. The International Thermonuclear Experimental Reactor (ITER) will have plasma currents reaching 10 MA, with disruption-generated runaway currents of several MA [?]. The high energy released by runaway electrons can destroy the first wall, cause severe damage, and even reduce device lifetime. Although current small tokamaks operate at lower plasma currents (~1 MA) where disruption-induced energy and thermal loads on device walls are negligible [?], investigating runaway electron physics and developing effective suppression methods remains crucial, particularly under high plasma current conditions above 1 MA. Developing efficient disruption runaway current suppression methods based on current device parameters will be essential for future higher-current tokamak fusion reactors.

During tokamak plasma disruption, thermal energy dissipates rapidly, causing a thermal quench (TQ) phenomenon. As the plasma cools, resistivity increases sharply, leading to rapid plasma current decay and current quench (CQ). During CQ, runaway electrons are generated through primary mechanisms and multiplied through secondary mechanisms. Primary mechanisms include the Dreicer mechanism [**?**], beta rays from tritium decay, Compton scattering of high-energy gamma rays from activated walls [**?**], and thermal tail mechanisms [**?**]. These primary mechanisms produce a small seed population of runaway electrons that subsequently multiplies through secondary avalanche mechanisms to form the runaway current [**?**].

In tokamak plasmas, the frictional drag force on electrons decreases with increasing velocity, while the electric field force is independent of electron velocity. Consequently, when electron velocity reaches a certain threshold, the drag force becomes smaller than the electric field force, causing sustained acceleration and runaway electron generation. During disruption, the rapidly decaying current induces an electric field E that typically far exceeds the critical electric field E_c = (n_e e^3 lnΛ)/(4π _0^2 m_e c^2), where e is electron charge, lnΛ is the Coulomb logarithm (a slowly varying function of plasma temperature and density, typically ~10 for magnetic confinement plasmas), n_e is electron density, _0 is vacuum permittivity, m_e is electron rest mass, and c is vacuum light speed. Thermal electrons gain energy through collisions with runaway electrons, enabling more electrons to become runaway. This exponential growth in runaway electron population constitutes the avalanche multiplication process.

Three primary methods currently exist to mitigate disruption hazards: massive gas injection (MGI), killer pellet injection (KPI), and shattered pellet injection (SPI). These methods inject gas or small particles into the plasma to dissipate runaway electron energy and enhance plasma stability and disturbance resistance. SPI has been implemented in few devices but presents design and optimization challenges, as large solid pellets may damage the first wall and require careful design to ensure most impurities ablate in the plasma core. MGI is the currently predominant method, with MGI facilities installed on EAST, HL-2A, and JT-60U for suppressing disruption-generated runaway currents. However, MGI alone often inadequately mitigates post-disruption runaway currents. Adding small amounts of high atomic number (high-Z) impurity gases more effectively suppresses runaway currents. Numerical simulations show that under ITER parameters, plasma disruption generates ~10 MA runaway current, which reduces to ~3 MA after MGI of deuterium-neon mixture [**?**]. Therefore, MGI of impurity-containing mixed gases is more suitable for suppressing disruption runaway currents.

Argon and neon are commonly used impurity gases for tokamak injection due to their high atomic numbers, enabling efficient plasma energy reduction through radiation. However, excessive argon or neon causes rapid plasma temperature drops, more easily triggering thermal quench and generating more runaway electrons. Deuterium, as a future fusion reactor fuel, offers good fuel compatibility when injected in large quantities and can reduce runaway electron energy by increasing plasma density. Therefore, MGI of deuterium-argon/neon mixtures represents a feasible approach for suppressing tokamak disruption runaway currents. The composition of deuterium-argon/neon mixtures is a key factor affecting suppression effectiveness. This study investigates the effects of massive deuterium-argon/neon mixed gas injection on suppressing disruption runaway currents under high plasma current discharge conditions in the HL-2M tokamak, comparing the effectiveness of deuterium-argon versus deuterium-neon MGI.

This work uses the tokamak disruption runaway electron simulation program D [?] to conduct numerical studies. This program can self-consistently simulate the temporal evolution of plasma parameters during tokamak disruption. Following the background and motivation in Section 1, Section 2 presents the numerical simulation methodology and runaway electron physics models. Section 3 presents the suppression effects of injecting different deuterium-argon/neon mixtures and provides comparative analysis. Finally, conclusions are summarized and future prospects discussed.

2. Physical Models

After plasma disruption, thermal energy releases within milliseconds during thermal quench (TQ), during which electron temperature T_e decays exponentially from initial T_0 to final temperature T_f with characteristic decay time constant τ_{TQ}. This exponential temperature decay [?] is described by equation (1):

[Equation for thermal quench]

Subsequent plasma cooling increases resistivity and causes current decay, initiating current quench (CQ). Faster current decay produces stronger induced electric fields, accelerating electrons into runaway currents.

Two important electric fields govern electron runaway in plasmas: the critical electric field E_c and the Dreicer field E_D. The critical field represents the electric field required for light-speed electrons to run away. When thermal electrons at temperature T experience electric fields exceeding E_D, the electric force exceeds frictional drag, causing sustained acceleration and runaway [?].

Multiple mechanisms generate runaway electrons after disruption, with primary mechanisms, thermal tail mechanisms, and secondary avalanche mechanisms being most significant. The thermal tail mechanism is neglected here [?] because in this study, the plasma has sufficient time to lose energy after disruption, with long cooling times reducing overall temperature and causing high-energy tail particles to lose energy, thus diminishing their contribution to runaway current. With sufficiently long cooling times, the Dreicer mechanism dominates while the thermal tail mechanism becomes negligible. Therefore, excluding the thermal tail mechanism, the total runaway electron density n_{RE} evolution equation [?] is:

[Equation for runaway electron density evolution]

In the primary mechanism, the Dreicer mechanism produces runaway seeds [?]:

[Equation for Dreicer seeds]

where *τ{rel} is the relativistic electron collision time and E* is the parallel electric field. Runaway seeds multiply through secondary avalanche mechanisms [?]:

[Equation for avalanche multiplication]

where n_{ij} and Z_{ij} are the density and charge number of charge state i of ion species j. Here, = (1 + 1.46√ + 1.72)^{-1} and = r/R. Assuming Z_{eff} = 1, 1, and E_ E_c, equation (4) simplifies to:

[Simplified avalanche equation]

Z_{eff} = 1 represents an ideal case; typically Z_{eff} > 1 because impurities (atomic number > 1) increase Z_{eff} beyond 1, except in pure hydrogen isotope plasmas. Experimentally, even hydrogen isotope plasmas have Z_{eff} > 1 due to impurities from plasma-wall interactions. In this study, deuterium-argon/neon injection makes Z_{eff} > 1, so equation (4) is used for all calculations.

Due to different collision times for electrons, deuterium ions, and impurity ions, separate energy balance equations are provided for these three particle types:

[Energy balance equations]

where n_e is electron density, _ is thermal diffusion coefficient, P_{OH} is ohmic heating power density, P_{brems} is bremsstrahlung radiation loss power density [?], and P_{ion} is ionization energy loss power density. The term represents collisional energy exchange between different particle species in the energy balance equation, with τ_{eq} being the thermal exchange time, where subscripts i, j refer to electrons, deuterium, and impurity ions.

P_{line} is line radiation power density, which is the sum over all charge state densities, with radiative rates obtained from the ADAS database [?]. Ionization rates are calculated through equations for the temporal evolution of each charge state density for each ion species [?]:

[Charge state evolution equation]

where I_k is the electron collisional ionization rate for charge state k, and R_k is the radiative recombination rate.

As plasma cools and conductivity decreases (σ T_e^{3/2}), an electric field E_ is induced to maintain plasma current. Current density distribution and electric field evolution over time are governed by equation (1):

[Current evolution equation]

where is elongation, plasma current density j = j_{Ohm} + j_{RE} is the sum of ohmic and runaway current densities, j_{RE} is runaway current density, σ_{Sp} is Spitzer conductivity, and _0 and c are permeability and vacuum light speed, respectively.

Based on these physical models, this study uses numerical simulation methods, setting total simulation time and maximum iteration count in the program, with evolution terminating when either condition is met. The study investigates MGI of deuterium and high-Z impurities (argon or neon) [**?**] for suppressing disruption runaway currents. The total simulation time is set to 5 seconds, at which point results show simulation parameters no longer evolve with time. When injected gas density reaches 1 × 10^{23} m^{-3}, collisional dissipation effects significantly dissipate runaway electron kinetic energy. Under these conditions, plateau runaway current does not form; instead, peak runaway current forms. Current MGI technology cannot achieve injected gas densities of 1 × 10^{23} m^{-3}, and the injected mixed gas is assumed uniform.

3. Simulation Setup

Simulations employ HL-2M tokamak [**?**] parameters: minor radius a = 0.65 m, major radius R = 1.78 m, toroidal magnetic field B = 2.2 T, and pre-disruption plasma current I_p = 0.5 MA. Initial radial distributions of electron temperature and density are shown in [Figure 1: see original paper], with central electron temperature and density of T_{e0} = 2 keV and n_{e0} = 3 × 10^{19} m^{-3}, respectively. Post-disruption plasma temperature drops rapidly, with TQ electron temperature evolution following equation (1) and reference [**?**].

[Figure 1: see original paper] shows the radial distribution of initial electron temperature (solid line) and density (dashed line).

After disruption, runaway current generates and forms a runaway plateau. [Figure 2: see original paper] shows that without impurity injection at I_p = 0.5 MA, approximately 0.3 MA plateau runaway current forms, with runaway current I_{RE} equaling plasma current I_p at ~8 ms—meaning runaway current completely replaces plasma current. From 8 ms to 10 ms, both I_{RE} and I_p remain constant, defining the plateau runaway current I_{RE}^{plateau}. Disruption hazard level depends partly on the ratio I_{RE}^{plateau}/I_p. In [Figure 2: see original paper], I_{RE}^{plateau}/I_p = 0.6. This ratio is unacceptable for large tokamaks; for ITER with I_p up to tens of MA, it would severely endanger device interior components and equipment. Therefore, this study investigates the effects of injecting deuterium-argon and deuterium-neon mixtures during disruption on plateau runaway current, providing optimal mixture compositions and resulting plateau runaway current magnitudes.

[Figure 2: see original paper] Temporal evolution of plasma current and runaway current without mixed gas injection.

3.1 Effects of Deuterium-Argon Mixed Gas Injection

To understand mixed gas injection effectiveness, this section examines deuterium-argon or deuterium-neon injection for runaway current suppression. Post-disruption deuterium-argon injection with densities n_D = 1 × 10^{22} m^{-3} and n_{Ar} = 1 × 10^{21} m^{-3} is shown in Figure 3: see original paper, displaying evolution of plasma current I_p, ohmic current I_{Ohm}, and runaway current I_{RE}. The plateau runaway current is significantly reduced, with I_{RE}^{plateau}/I_p decreasing from 0.6 to 0.1, demonstrating suppression capability. However, this composition still yields relatively high I_{RE}^{plateau}/I_p, requiring further optimization. Figure 3: see original paper shows post-disruption electric fields, revealing induced fields far exceeding E_D. Central electron density n_e = 3 × 10^{19} m^{-3}.

[Figure 3: see original paper] Results for deuterium-argon mixed gas injection. (a) Evolution of plasma current (solid line), ohmic current (dotted line), and runaway current (dashed line). (b) Evolution of ohmic electric field at different normalized radial positions.

[Figure 4: see original paper] presents plateau runaway current variation with injected deuterium-argon content. Figure 4: see original paper shows that with fixed n_D = 1 × 10^{22} m^{-3}, minimal plateau runaway current occurs at n_{Ar} = 1 × 10^{21} m^{-3}, with I_{RE}^{plateau}/I_p = 0.1. However, as argon content increases beyond this point, suppression weakens and plateau runaway current gradually increases. Figure 4: see original paper shows that with fixed n_{Ar} = 1 × 10^{21} m^{-3}, minimal plateau runaway current occurs at n_D = 1 × 10^{22} m^{-3}, with I_{RE}^{plateau}/I_p = 0.1, increasing as deuterium content grows further. Therefore, optimal deuterium-argon composition is n_D = 1 × 10^{22} m^{-3} and n_{Ar} = 1 × 10^{21} m^{-3}. Under these optimized conditions, I_{RE}^{plateau}/I_p = 0.1, significantly lower than the 0.6 without mitigation, with injected mixture density of 1.1 × 10^{22} m^{-3}. Excessive deuterium reduces argon content, limiting argon’ s effectiveness for radiative energy loss from runaway electrons, while excessive argon further decreases plasma temperature, inducing stronger electric fields and generating higher runaway currents.

[Figure 4: see original paper] Plateau runaway current variation with injected deuterium-argon content. (a) Fixed n_D, increasing argon content. (b) Fixed n_{Ar}, increasing deuterium content.

3.2 Effects of Deuterium-Neon Mixed Gas Injection

Although deuterium-neon mixed gas injection affects runaway electrons similarly to deuterium-argon, neon’ s lower atomic number results in weaker radiative power loss. [Figure 5: see original paper] shows plateau runaway current variation with injected deuterium-neon content, yielding similar results to [Figure 4: see original paper]. Under optimal conditions (n_D = 1 × 10^{22} m^{-3}, n_{Ne} = 2 × 10^{21} m^{-3}), plateau runaway current reaches minimum I_{RE}^{plateau}/I_p 0.1, with neon content n_{Ne} = 2 × 10^{21} m^{-3} in the injected mixture. Compared to optimal deuterium-argon injection, the deuterium amount remains unchanged but more neon is required, or neon content must be slightly higher.

[Figure 5: see original paper] Plateau runaway current variation with injected deuterium-neon content. (a) Fixed n_D, increasing neon content. (b) Fixed n_{Ne}, increasing deuterium content.

Analysis shows both deuterium-argon and deuterium-neon injection suppress plateau runaway current, but optimal mixture compositions exist beyond which suppression effectiveness diminishes. Since these results were obtained under medium-scale tokamak conditions, and for reactor-scale fusion tokamaks with higher plasma currents and pre-disruption temperatures, device size effects can be neglected to further investigate I_p and electron temperature effects.

4. Scaling Studies: Effects of I_p and T_{e0}

Neglecting device size effects, this section examines the influence of I_p and electron temperature T_{e0} on post-disruption plateau runaway current, calculating optimal deuterium-argon/neon compositions for different I_p and T_{e0} values. For comparison, presents plateau runaway currents without mixed gas injection when increasing I_p or T_{e0}. Higher I_p yields higher final plateau runaway current I_{RE}^{plateau}, with I_{RE}^{plateau}/I_p increasing with I_p. Increasing T_{e0} slightly reduces I_{RE}^{plateau}/I_p due to extended plasma cooling timescales. Comparing I_p and T_{e0} effects, I_p is the dominant factor affecting disruption runaway current. For fusion reactor tokamaks like ITER with I_p = 15 MA, effective runaway current suppression measures are essential.

Plateau runaway current without mixed gas injection for different I_p and T_{e0}.

Plateau runaway currents I_{RE}^{plateau} and corresponding I_{RE}^{plateau}/I_p ratios after optimal deuterium-argon/neon injection are listed in and . shows that after optimal deuterium-argon injection, plateau runaway current is greatly suppressed. At I_p = 0.5 MA, approximately 0.05 MA plateau runaway current forms, substantially reduced from 0.3 MA without mitigation, with I_{RE}^{plateau}/I_p also significantly decreased. However, when I_p doubles, I_{RE}^{plateau}/I_p more than doubles even with optimal injection. T_{e0} has minimal impact on post-injection plateau runaway current, further confirming I_p' s critical influence on disruption runaway current and its suppression.

Assuming the observed trends of I_{RE}^{plateau}/I_p and deuterium-argon content versus I_p, effective suppression in reactor-scale devices requires deuterium injection of 1 × 10^{23} m^{-3} and argon content of 1 × 10^{22} m^{-3}. Current MGI technology cannot achieve injection densities of 1 × 10^{23} m^{-3}. Therefore, future high-plasma-current fusion reactors require superior injection methods like shattered pellet injection (SPI) for runaway current suppression.

Varying impurity composition, presents results for deuterium-neon injection, showing similar suppression effectiveness to deuterium-argon but requiring more neon at the same deuterium injection level to maintain comparable I_{RE}^{plateau}, due to neon' s lower atomic number and weaker radiative loss capability.

5. Discussion

Analysis reveals that on medium-scale tokamaks with I_p typically below 1 MA, deuterium-argon/neon injection effectively suppresses post-disruption runaway currents without exceeding MGI density limits. Under optimized injection conditions from and , argon or neon content in the mixture should be 0-1 × 10^{21} m^{-3} and deuterium injection should be 1 × 10^{22} m^{-3} for most effective suppression. Under optimal conditions, suppressed runaway current is only 1-10% of I_p, forming ~0.05 MA runaway current. Thus, MGI, particularly deuterium-argon/neon mixtures, effectively suppresses disruption runaway currents on current medium-scale tokamaks. However, extrapolating to fusion reactor tokamaks with I_p up to 15 MA requires injected mixture densities of 1 × 10^{23} m^{-3}, beyond current MGI capabilities.

Since MGI cannot achieve densities of 1 × 10^{23} m^{-3}, collisional dissipation effects are minimal (E_ E_c in equation (4)), leading to plateau runaway current formation. However, if 1 × 10^{23} m^{-3} densities could be injected via SPI, critical electric field E_c would become comparable to post-disruption ohmic electric field E_ (E_ E_c), making collisional dissipation significant. As shown in [Figure 6: see original paper], runaway electrons would not form plateau current; instead, runaway current would peak then rapidly decay to zero, reaching ~0.1 MA peak current at ~1 ms and dissipating runaway electron energy by ~3 ms. Considering SPI injection of 1 × 10^{23} m^{-3} deuterium-argon/neon mixtures would produce even lower peak runaway current and faster energy dissipation.

Given the severe consequences of tokamak disruptions, effective prediction, avoidance, and suppression technologies must be developed based on current devices. Prediction and avoidance are highest priority, though beyond this study' s scope. However, even with prediction/avoidance capabilities, developing effective disruption suppression remains necessary, as these technologies cannot achieve 100% success—suppression represents the final defense line. [Figure 6: see original paper] shows collisional dissipation effects on runaway current at n_e = 1 × 10^{23} m^{-3}.

6. Conclusions

Using the fluid model in the tokamak disruption runaway electron simulation program D, this study investigated massive deuterium-argon or deuterium-neon mixed gas injection for suppressing disruption runaway currents. By comparing plateau runaway current to I_p ratios (I_{RE}^{plateau}/I_p) with and without injection, optimal mixture compositions and ratios were determined, and I_p effects were explored under optimal conditions. Key findings include:

1. Without mixed gas injection, post-disruption plateau runaway current is high (large I_{RE}^{plateau}/I_p), unacceptable for high-current large tokamaks. I_p is the key factor determining plateau runaway current magnitude.
2. Deuterium-argon/neon injection suppresses plateau runaway current I_{RE}^{plateau}. Optimal mixture compositions exist; beyond these, increased deuterium reduces argon/neon content, limiting radiative energy loss, while excessive argon/neon further decreases temperature, inducing larger ohmic fields and higher runaway currents.
3. Under optimal injection, plateau runaway current I_{RE}^{plateau} scales linearly with I_p, requiring increased total injection with I_p. At I_p = 1 MA, required injection reaches 1 × 10^{22} m^{-3}. For the studied I_p range, optimized argon/neon content should be 0-1 × 10^{21} m^{-3} and deuterium injection 1 × 10^{22} m^{-3}. Extrapolating to I_p = 15 MA reactor-scale tokamaks requires 1 × 10^{23} m^{-3} injection, beyond current MGI capability.
4. At densities of 1 × 10^{23} m^{-3}, collisional dissipation prevents plateau formation, creating peak runaway current that rapidly decays. SPI technology could potentially achieve such densities, making it promising for suppressing runaway currents in high-current fusion reactors.

Author Contributions

Han Zhenzhe: Investigation, numerical simulation, data processing, original draft writing. **Zheng Pingwei:** Conceptualization, critical review of intellectual content, supervision and manuscript revision.

References

[References listed with LinkOut markers]

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