Physics Processes in Disruption Mitigation Using Massive Noble Gas Injection*

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Thermal and electromagnetic damage from unmitigated disruptions pose a significant threat to tokamaks during operating point excursions which result in uncontrollable MHD instability. Divertor surfaces can be melted or ablated by thermal loads during the disruption thermal quench. Plasma facing components can be damaged by electromagnetic loads from induced eddy currents and attached halo currents, as well as by runaway electrons generated during the current quench. Although tokamak reactors will operate with sufficient control margin to limit the occurrence of disruptions, designs must provide protection for such off-normal events.

A method for mitigating these disruption effects using massive injection of noble gases (neon or argon) has been demonstrated on the DIII-D tokamak. The high injected gas density ($> 10^{24}$ m^{-3}) and pressure (> 20 kPa) enables the jet to penetrate the target plasma at the gas sound speed (300–500 m/s) and increases the atom/ion content of the plasma by a factor of 50 in several milliseconds. UV line radiation from the impurity species distributes the plasma energy uniformly on the first wall, reducing the thermal load to the divertor by a factor of 10. Runaway electrons are almost completely eliminated by the large density of free and bound electrons supplied by the gas injection. The highly resistive post-jet plasma produces rapid diffusion of current to the edge of the vessel and a rapid current quench, resulting in the plasma remaining centered on the midplane. The small vertical plasma displacement and high ratio of current decay rate to vertical growth rate results in a significant (>75%) reduction in peak halo current amplitude and attendant forces.

We present analysis and simulations of plasma equilibrium and kinetic evolution during the mitigated disruption process. Analysis of the MHD evolution of the plasma equilibrium and associated axisymmetric stability during the disruption demonstrates the role of differences in current profile evolution in reducing halo current loads. Simulations of radiation and ohmic power balance using detailed impurity line data illustrate the role of neutral and partially ionized charge states of the injected gases in producing the significant mitigation of disruption thermal effects. The resulting understanding of relevant physics processes allows extrapolation of the mitigation technique to a burning plasma device. Analysis of a mitigated disruption scenario in ITER shows that if sufficient penetration is achieved, a high-pressure gas jet can be as effective in a burning plasma regime as already demonstrated in DIII-D. The degree of penetration of high-pressure neutral gas jets expected in such plasmas is still an open question. Theoretical analysis of gas jet penetration in reactor-grade plasmas will be discussed in this context.

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