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Fast Plasma Shutdowns Obtained With Massive Hydrogenic, Noble and Mixed-Gas Injection in DIII-D

EX-S

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Massive gas injection (MGI) experiments conducted in DIII-D with hydrogenic, noble and mixed (H_2 + Ar and D_2 + Ne) gases injected into "ITER-similar" 1.3-MA ELMy H-mode plasmas are described. Gas species, injected quantity, delivery rate and intrinsic and added impurities (i.e., gas mixtures) are found to affect the disruption mitigation attributes of the resulting fast plasma shutdowns. With sufficient injected gas quantity, effective mitigation is obtained for all species. Optimal results for simultaneous disruption and runaway avalanche mitigation are obtained with pure helium injection, 3x10^{22} He delivery in ~2 ms. This short-pulse injection scenario yields a favorable combination of moderately-fast current quench, record free-electron densities, up to 2x10^{21} m^{-3} (Fig. 1), gas assimilation fractions, $N_{\mathrm{ion}}/N_{\mathrm{gas}}$, that approach 0.4 (Fig. 2) and avalanche suppression ratios, n_e/n_{RB} [1], that approach 0.1. Favorable scaling of assimilation fraction with increasing gas quantity is seen for all low-Z gases and D_2 + 2% Ne mixture. Experiments and new 2-D diagnostics (Fig. 3) provide a rich source of validation data for emerging MHD/radiation simulation models and insight about design of systems for disruption and avalanche mitigation in ITER. Gas pulse durations less than the time for onset of radiative thermal collapse are indicated. The injected gas quantity must also include allowance for finite assimilation at the time of current quench onset.

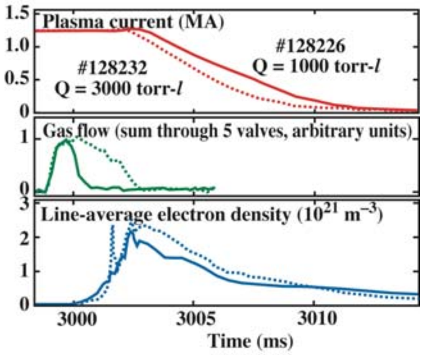

Fig. 1. High-density fast shutdowns with massive helium injection.

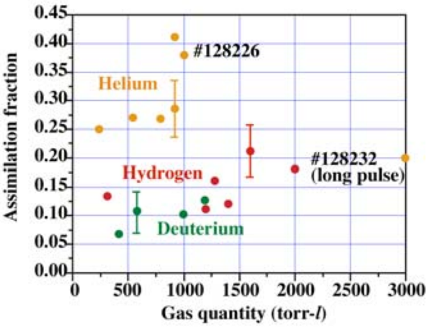

Fig. 2. Gas assimilation vs injected quantity for H_2, D_2 and He.

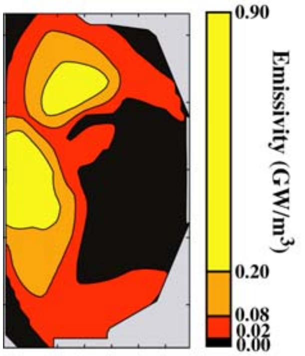

Fig. 3. Radiation during thermal collapse (neon).

<u>Experimental setup, diagnostics and phenomenology</u>. A six-valve "MEDUSA" injector [2] that provides independent control of the gas pulse duration, t_{inj}, injected gas quantity, Q, and gas delivery waveform, i.e., $Q(t)$ is used. Open/close times for each valve are 0.2 ms and t_{inj} for low-Z gases is typically ≤2 ms. A 4-chord CO_2 interferometer with upgraded electronics allows accurate dynamic measurement of the very-high free electron densities obtained. The same MGI phenomenology, fast shutdown sequence and lack of direct neutral penetration beyond the separatrix seen in previously-reported MGI studies in DIII-D [3-5] are observed. Short-pulse gas delivery under conditions where $Q(t)$ is less restricted by the injection tube rise time (~10 ms for experiments reported in [5]) results in faster onset of thermal collapse and global plasma current (I_p) decay. Total shutdown times, from valve opening to end of plasma current, are now as short as 8 ms. About 2 ms of this total is attributable to the gas sound-speed "flight time" from the valves to the plasma surface.

Thermal energy radiation. With sufficient Q, fast (within 1.5-2 ms) "thermal-collapse" radiative dissipation [5] of the plasma thermal energy (W_{th} = ~0.7 MJ) is obtained for all species. Most of the dissipation occurs during a ~1-ms period that coincides with the I_p "spike". Bolometric tomography (Fig. 3) indicates that the principal radiation comes from a shallow region near the plasma edge, and that the main-plasma radiation is more-or-less uniform toroidally. The radiated power waveform and coincidence of the radiation with the I_p spike show that the dynamics of the thermal collapse phase is mediated by a rapid outflow of central plasma energy initiated by rapid growth of internal MHD activity [5]. Efficient radiation of W_{th} by low-Z gases is observed. This observation is consistent with the simulations that include the presence of intrinsic (present in the target plasma) levels of carbon and/or boron. Carbon and other impurities sputtered from the divertor or first wall may also play a significant role. Simulations with emerging self-consistent 2-D + t models [6,7] that incorporate explicit or implicit calculations of MHD instability and 'mixing' effect are beginning to provide insight at the detail level about the complex physics basis of the gas assimilation and thermal collapse phases of MGI.

Current decay. High-Q MGI consistently produces a fast I_p decay. With sufficient Q, area-normalized current decay times [8], t_{CQ}/S, reach minimum values that are ~5 ms/m^2 for He and 2.5-3.5 ms/m^2 for all other gases. The fastest MGI decays are 1.5-3 times slower than the fastest decays obtained in natural DIII-D disruptions. Fast decays in DIII-D with $t_{CQ}/S \geq$ ~5 ms/m^2 are well-correlated with reduction of halo currents; hence we infer that all high-Q low-Z and high-Z MEDUSA examples provide effective mitigation of halo currents.

Electron densities at current decay onset and runaway avalanche mitigation. Very high total electron densities, $\geq 10^{22}$ m^{-3}, at or shortly after onset of the current decay are required to guarantee mitigation of the Fleischmann-Sokolov ("knock-on") avalanche. The simple model invoked by Rosenbluth shows that the total "no-avalanche" electron density, $n_{RB}(10^{20}\ \text{m}^{-3})$ = 8 E(V/m), where E is the in-plasma electric field, is ~4x10^{22} m^{-3} for DIII-D and ITER MGI. The maximum n_e obtained in DIII-D ranges from ~6x10^{20} m^{-3} for Ne and Ar to ~2x10^{21} m^{-3} for He and H_2 + 2% Ar. When the likely impurity ionization states and the corresponding I_p decay rates are taken into account, n_e(total)/n_{RB} ratios are 8%-10% for He and 2%-8% for other species. Hydrogen/deuterium, helium and D_2 +2% Ne show favorable (~Q^1) scaling with increasing Q. Other species, including Ne, Ar and D_2 + 5% Ne, exhibit onset or attainment of saturation (~Q^0 scaling) in their respective high-Q regimes. Low levels (≤ ~10 kA) of well-confined runaways are sometimes observed for high-Q Ne and Ar. All other MEDUSA fast shutdown examples are apparently runaway free.

Gas assimilation and limits on injection duration. Limitation in achievable n_e/n_{RB} in MEDUSA experiments stems from the ~10^6 torr-l/s limit on short-pulse delivery, and finite gas assimilation at current quench onset. Finite assimilation limits the resulting free and total electron densities. Helium shows the least limitation: assimilation approaches 40% and increases with increasing Q, whereas H_2, D_2, Ne, Ar and mixed gas assimilations are all appreciably lower (5%-25%). Neon and Ar show little or no indication of favorable scaling with increasing Q. Long-pulse experiments with He show that gas delivered after onset of the current decay is poorly assimilated. Hence He injection with pulses ≥ ~2-ms yields little further increase in n_e/n_{RB}, and longer-pulse (higher-Q) injection of higher-Z gases yields no improvement in n_e(total)/n_{RB}. Of the various species and mixtures tested, hydrogen or deuterium, helium and D_2 + 2% Ne so far exhibit the most promise for achieving n_e that will ultimately be high enough to effect avalanche mitigation at current quench onset.

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[1] M.N. Rosenbluth, *et al.*, Nucl. Fusion **37** (1997) 955.
[2] T.C. Jernigan, *et al.*, Bull. Am. Phys. Soc. **52** (2007) 171.
[3] P.L. Taylor, *et al.,* Phys. Plasmas **6** (1999) 1872; also D.G. Whyte, *et al.,* Phys. Plasmas **7** (2000) 4052.
[4] D.G. Whyte, *et al.,* J. Nucl. Mater. **313-316** (2003) 1239.
[5] E.M. Hollmann, *et al.,* Nucl. Fusion **45** (2005) 1046.
[6] V.A. Izzo, Nucl. Fusion **46** (2006) 541.
[7] V.A. Izzo, et al., "MHD Simulations of Massive Gas Injection Into Alcator C-Mod and DIII-D Plasmas," accepted for publication in Phys. Plasmas (2008).
[8] J.C. Wesley, *et al.*, "Disruption Characterization and Database Activities for ITER," Proc. of 21st IAEA Fusion Energy Conf., Chengdu, China, 2006, Paper IT/P1-21.