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Measurements of Injected Impurity Assimilation During Fast Shutdown Initiated by Multiple Gas Valves in DIII-D

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Massive gas injection (MGI) is a promising technique for reducing tokamak wall damage during disruptions, with reductions observed in both conducted wall heat loads and in halo currents, when compared with unmitigated disruptions [1]. It is unknown at present if MGI can prevent the formation and amplification of runaway electrons (RE) in future high-current tokamaks, so RE formation during MGI remains an outstanding concern.

To avoid RE during MGI shutdowns, efficient delivery of injected impurities into the plasma core is desirable. This is because complete collisional suppression of RE amplification is predicted to occur at very large total (free+bound) electron densities ($n_{crit} \approx 10^{16}$ cm^{-3} in DIII-D). To achieve a rapid gas delivery rate, a flange holding six fast-acting gas valves was installed. With all six valves fired simultaneously, up to 1000 torr-l of argon could be delivered to the plasma edge in a pulse about 3 ms long.

Previous (2005 and 2006) MGI experiments have suggested that rapid gas delivery rate is crucial for achieving large core impurity densities; this was confirmed in the present experiments. Schematics of MGI valves used in the last three years are shown in Fig. 1. In 2005, a single low-flow valve was used; this delivered about 1000 torr-l of argon to the plasma edge in a pulse about 15 ms long. In 2006, a single large-flow valve was used; this delivered about 10,000 torr-l of argon in a pulse about 10 ms long. However, the initial (several ms) delivery of impurities was not much faster than the 2005 valve. To improve initial impurity delivery in 2007, six

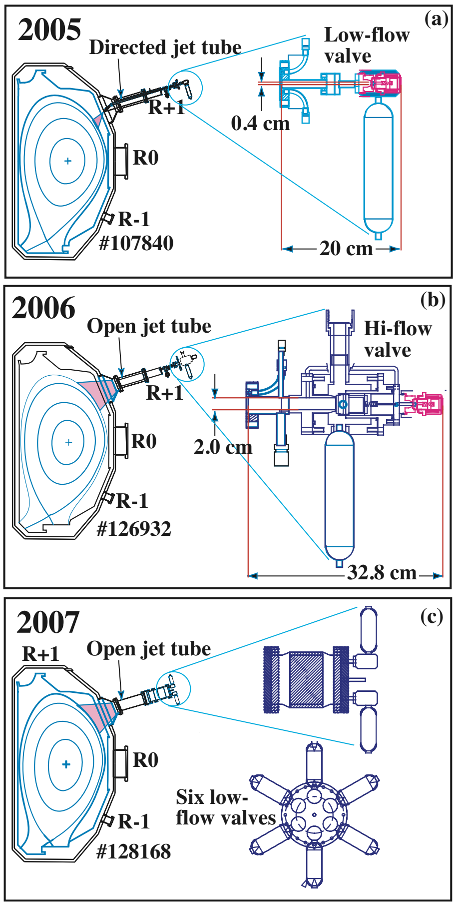

Fig. 1. Schematics of different MGI geometries showing (a) 2005 geometry with single low-flow valve and directed jet tube, (b) 2006 geometry with hi-flow valve and open jet tube, and (c) 2007 geometry with six low-flow valves and open jet tube.

low flow valves were used. With all six valves fired simultaneously, the 2007 configuration delivered about 1000 torr-l in an argon pulse 3 ms long.

Shutdown time traces comparing the three different valves with argon injection are shown in Fig. 2. The neutral delivery rate *dN/dt* is shown in Fig. 2(a), while central electron temperature T_e is shown in Fig. 2(b), line-averaged electron density n_e in Fig. 2(c), and plasma current I_p in Fig. 2(d). For high-Z MGI, such as shown in Fig. 2, the peak n_e is measured somewhat after the end of the thermal quench (TQ), while in lower-Z MGI (He, H_2, or D_2) the n_e peak is observed to occur near the end of the TQ. This suggests that the peak impurity assimilation occurs during the TQ phase and that the observed delay in the n_e peak is due to the slower toroidal mixing rate of the heavier high-Z impurities (the interferometer diagnostic is located on the other side of the tokamak from the gas injection port). The neutral delivery is obtained from experimentally validated fluid modeling for 2005 and 2007 valves; for 2006 data, flow is estimated from fast neutral pressure measurements (because of the complex valve opening behavior).

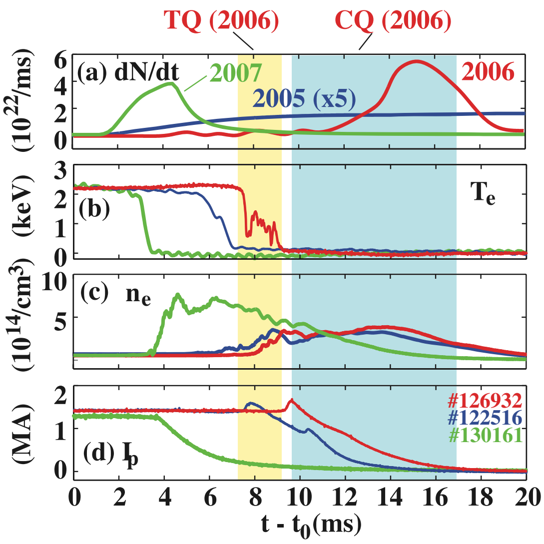

Fig. 2. Time traces of Ar MGI shutdowns from different valves (2005, 2006, 2007) showing (a) neutral delivery rate *dN/dt*, (b) central electron temperature T_e, (c) line-averaged electron density n_e, and (e) plasma current I_p. Shaded bands show thermal quench and current quench for 2006 valve (red curves). Times are shown relative to t_0, the valve open time.

The importance of the TQ for mixing impurities is illustrated more clearly in Fig. 3(a), where the total number of assimilated particles N_{assim} is plotted as a function of N_1, the amount of impurities delivered to the plasma edge within 1 ms after the first neutral arrivals. It can be seen that the number of early arrivals serves as a good indicator of N_{assim}. On the other hand, neutrals arriving much after the first several ms do not assimilate as well: this is shown in Fig. 3(b), where the total number of neutrals delivered N_{tot} is not found to provide a good indication of assimilation. N_{assim} is estimated from the rise in total electron number ΔN_e and the mean charge state $\langle Z \rangle$: $N_{assim} \approx \Delta N_e / \langle Z \rangle$. During the cold CQ, $\langle Z \rangle$ can be obtained by assuming that the plasma ions are in ionization/recombination equilibrium; this was shown to be valid with spectroscopy measurements in He plasmas [2]. To attempt to account for the finite toroidal mixing rate of impurities, N_{assim} is averaged over data from the beginning and middle of the CQ.

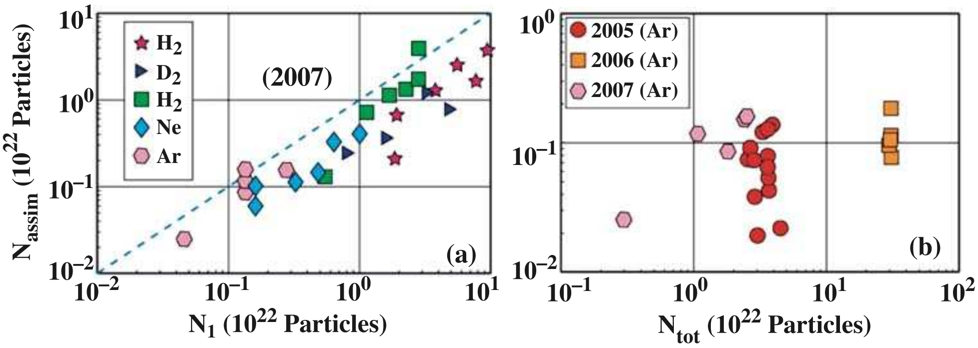

Fig. 3. Total assimilated impurity particles N_{assim} as a function of (a) N_1 the amount of particles injected within first 1 ms after first gas arrivals (2007 valve data, all species); and (b) N_{tot} the total number of neutrals injected (2005, 2006, and 2007 valve data, Ar injection).

To characterize mixing efficiency, we use $\bar{Y}_{mix} \equiv N_{assim}/N_{TQ}$, where N_{TQ} is the number of impurities delivered the end of the TQ (this definition is motivated by the assumption that mixing is negligible during the CQ). Figure 4 shows some various parameter scans to determine trends in $\bar{Y}_{mix}$. In Fig. 4(a), $\bar{Y}_{mix}$ is shown to increase slowly with increasing target plasma thermal energy W_{th}. In Fig. 4(b), $\bar{Y}_{mix}$ shows some evidence of increasing with initial neutral injection rate N_1, although the data is mostly flat. In Fig. 4(c), a decrease in $\bar{Y}_{mix}$ is observed with increasing edge safety factor q_{95}. In Fig. 4(d), an increase in $\bar{Y}_{mix}$ is observed with increasing level of TQ magnetic fluctuations $|dB_\theta/dt|$. Overall, the data are consistent with impurity assimilation occurring dominantly during the TQ with an efficiency around 0.1–0.4 and depending strongly on the level of magneto-hydrodynamic (MHD) mixing.

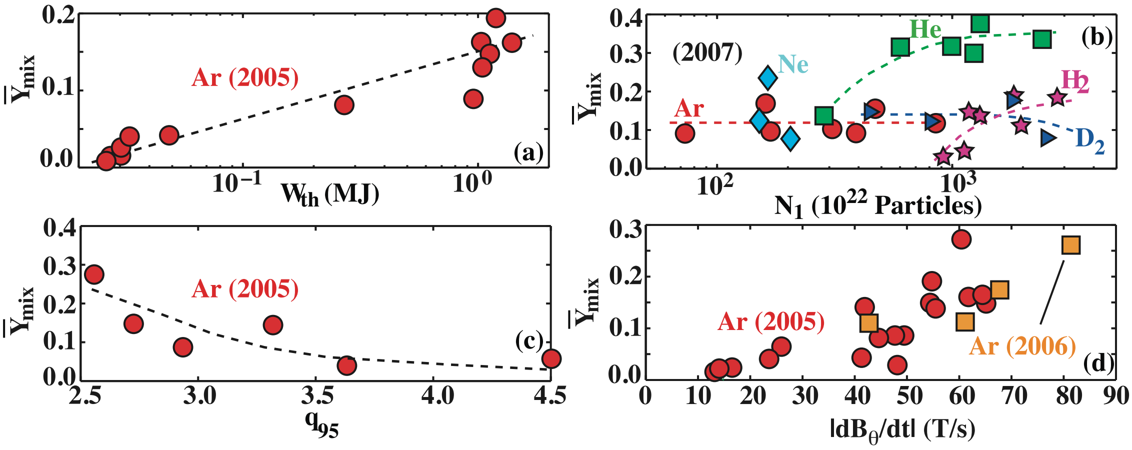

Fig. 4. Mixing efficiency $\bar{Y}_{mix}$ as a function of (a) initial plasma thermal energy W_{th}; (b) initial gas injection rate N_1; (c) plasma edge safety factor q_{95}; and (d) amplitude of magnetic fluctuations during TQ $|dB_\theta/dt|$.

To begin efforts to extrapolate DIII-D MGI results to larger tokamaks, 0D modeling is used [3]. Presently, the 0D model uses theoretical time-resolved gas delivery rates and atomic physics but requires the experimentally measured TQ mixing efficiency $\bar{Y}_{mix}$. Impurity mixing is assumed to be 0 during the CQ. In DIII-D, the 0D modeling is found to reproduce the observed TQ and CQ durations reasonably well (typically within ±25% or so), although shutdown onset times are underestimated (by around $2\times$), possibly because 1D (profile) effects are ignored in the model. To perform preliminary 0D modeling of ITER, we assume a TQ mixing efficiency $\bar{Y}_{mix}=0.5$ for He and $\bar{Y}_{mix}=0.25$ for Ar. To calculate neutral delivery rates, we assume that neutrals will be delivered with a L = 5 m drift tube and D = 2 cm valve. A 50 atm backing pressure, infinitely fast valve opening and infinite open duration, and infinite gas reservoir volume are assumed.

Figure 5 shows key shutdown parameters predicted by the 0D model for ITER: Fig. 5(a) shows $t_{CQ}-t_0$, the CQ onset time relative to the valve open time; Fig. 5(b) shows the TQ duration Δt_{TQ}; Fig. 5(c) shows the CQ duration Δt_{CQ}; Fig. 5(d) shows the runaway electron (RE) suppression factor γ_{crit}. All are plotted for He and Ar MGI as a function of the number of MGI valves N_{jet}. The RE suppression is defined as the critical electric field [4] divided by the actual electric field in the middle of the CQ: $\gamma_{crit}\equiv E_{crit}/E_{\phi}$. Blue bands indicate approximate range desired to avoid wall damage in ITER. Overall, the results suggest that MGI will work well in ITER with regards to disruption heat load and vessel force mitigation, but will not collisionally suppress REs with a realistic number of gas valves. These results therefore suggest that MGI shutdown in future large tokamaks be complemented by other techniques (e.g. applied magnetic perturbations) designed to prevent RE formation. Future experiments and modeling (1D and 3D) will be focused on validating these findings.

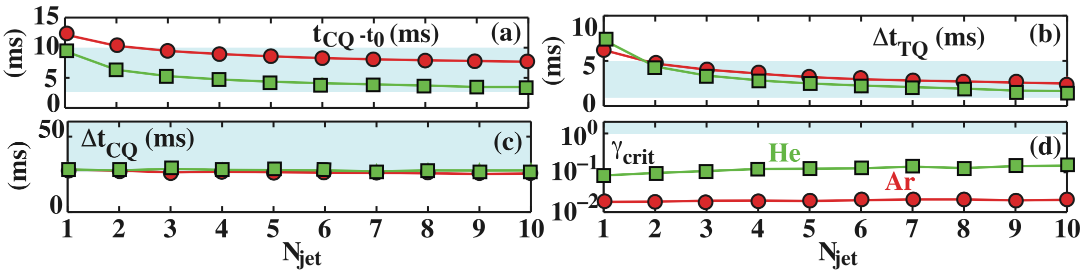

Fig. 5. 0D simulations of Ar (red circles) and He (green squares) MGI shutdowns of ITER showing (a) CQ onset time relative to valve open time $t_{CQ}-t_0$, (b) TQ duration Δt_{TQ}, (c) CQ duration Δt_{CQ}, and (d) runaway electron suppression factor γ_{crit}, as a function of the number of MGI valves. Shaded regions indicate approximate range of values desired to avoid wall damage in ITER.

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