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## DISCLAIMER

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# DIII-D Studies of Massive Gas Injection Fast Shutdowns for Disruption Mitigation

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Injection of massive quantities of gas is a promising technique for fast shutdown of ITER for the purpose of avoiding divertor and first wall damage from disruptions. Previous experiments using massive gas injection (MGI) to terminate discharges in the DIII-D tokamak have demonstrated rapid shutdown with reduced wall heating and halo currents (relative to natural disruptions) and with very small runaway electron (RE) generation [1].

Figure 1 shows time traces which give an overview of shutdown time scales. Typically, of order 5×$10^{22}$ Ar neutrals are fired over a pulse of 25 ms duration into stationary (non-disrupting) discharges. The observed results are consistent with the following scenario: within several ms of the jet trigger, sufficient Ar neutrals are delivered to the plasma to cause the edge temperature to collapse, initiating the inward propagation of a cold front. The exit flow of the jet [Fig. 1(a)] has a ≈9 ms rise time; so the quantity of neutrals which initiates the edge collapse is small (<$10^{20}$). When the cold front reaches $q$≈2 surface, global magneto-hydrodynamic (MHD) modes are destabilized [2], mixing hot core plasma with edge impurities. Here, $q$ is the safety factor. Most (>90%) of the plasma thermal energy is lost via impurity radiation during this thermal quench (TQ) phase. Conducted

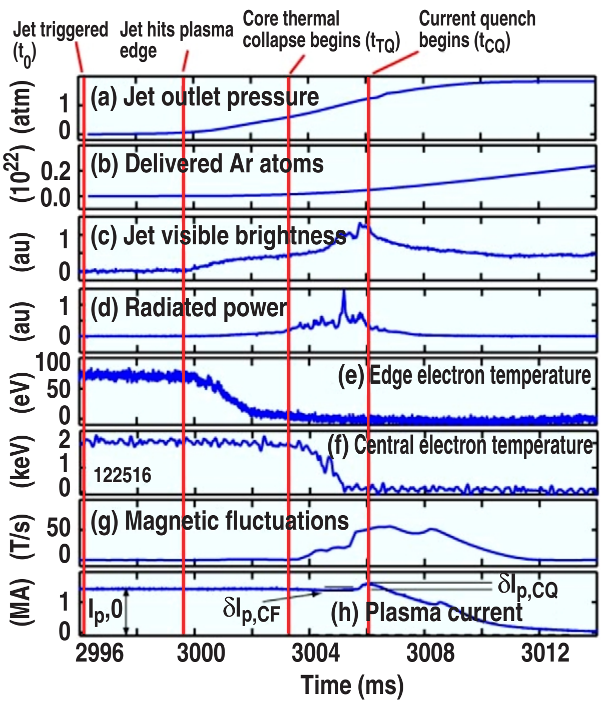


Fig. 1. Time traces during a typical Ar MGI experiment of (a) directed jet outlet pressure, (b) delivered number of Ar atoms, (c) jet visible emission, (d) radiated power, (e) edge electron temperature, (f) central electron temperature, (g) amplitude of poloidal magnetic field fluctuations, and (h) plasma current.

heat loads to the wall are low because of the cold edge temperature. After the TQ, the plasma is very cold (of order several eV), so conducted wall (halo) currents are low, even if the current channel contacts the wall. The plasma current profile broadens and begins decaying resistively. The decaying current generates a toroidal electric field which can accelerate REs; however, RE beam formation appears to be limited in MGI shutdowns.

Presently, it is thought that the conducted heat flux and halo current mitigation qualities of the MGI shutdown technique will scale well to a reactor-sized tokamak. However, because of the larger RE gain from avalanching and the presence of a RE seed population due to Compton-scattered fast electrons, it is possible that a RE beam can be formed well into the CQ, after the flux surfaces initially destroyed by the TQ MHD have had time to heal. Crucial MGI issues to be studied in present devices are therefore the formation, amplification, and transport of RE and the transport of impurities into the core plasma (important because the presence of impurities can, via collisional drag, help suppress RE amplification). In the study of impurity transport, both neutral delivery (directly driven into the core by the jet pressure) and ion delivery (mixed into the core by MHD) are of interest, as both contribute to RE drag.

Here, three new results relevant to RE suppression from MGI are presented: 1) evidence is presented that neutral jet propagation is stopped by toroidal magnetic field pressure, 2) MGI appears to cause the CQ to begin before sufficient impurities have been injected for complete collisional suppression of RE, and 3) flux surface destruction over the region $q \leq 2$ occurs during the TQ. The first result suggests that neutrals cannot be delivered to the core of large tokamak discharges by MGI, even during the CQ. The second result indicates that (at least for argon MGI in DIII-D), insufficient impurities (either neutral or ion) are delivered for collisional suppression of RE at the start of the CQ. The last result suggests that the destruction of good field lines resulting from MGI is quite extensive and should be sufficient to prevent RE formation, at least at the start of the CQ.

Over a wide range of initial target conditions (magnetic field $B$ varied from 0.5 T to 2.1 T and plasma thermal energy varied from 0.02 to 1 MJ), visible camera images of neutral Ar emission indicate that the propagation of jet neutrals is stopped at the plasma edge (≈0-5 cm past the separatrix) during the TQ. Jet stopping at the plasma edge could be due to a variety of mechanisms. In Fig. 2, squares show the jet ram pressure (estimated from bench test measurements) at the plasma edge $P_{\mathrm{jet}}$ at the TQ time $t$=$t_{\mathrm{TQ}}$. Triangles show the plasma kinetic pressure $P_{\mathrm{kin}} \approx 2n_eT_e$ at the plasma edge at $t$-$t_{\mathrm{TQ}}$ estimated from Thomson scattering. Circles show the ablation plume pressure $P_{\mathrm{abl}}$ arising from the plasma heating of the jet [3,4]. Finally, diamonds show the local toroidal magnetic field pressure $P_{\mathrm{mag}} = B^2/8\pi$. At the lower values of $W_0$,, $P_{\mathrm{jet}}$ appears to be significantly (20-50x) larger than $P_{\mathrm{abl}}$ or $P_{\mathrm{kin}}$. Here, it is possible that the very high toroidal field pressure $P_{mag}$ is pushing on the jet neutrals via surface currents pushing on the shell of impurity ions surrounding the jet [5].

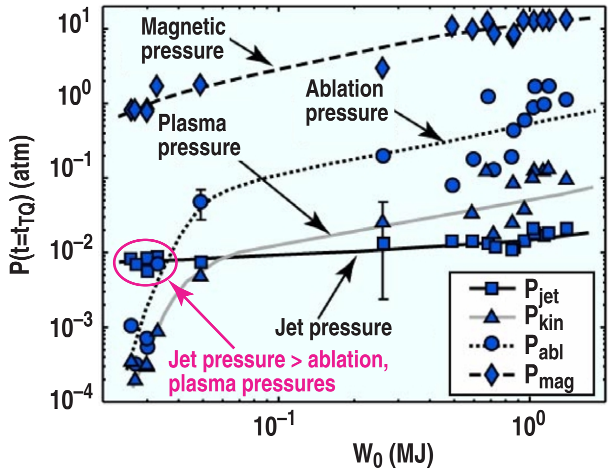


Fig. 2. Jet pressure at the plasma edge at the start of the TQ, compared with the local plasma kinetic pressure, the local ablation pressure, and magnetic pressure; as a function of initial plasma thermal energy $W_0$.

The result that insufficient impurities are delivered by MGI to cause collisional RE suppression by the start of the CQ is shown in Fig. 3. Higher energy plasmas tolerate more impurity input before collapsing, which in turn results in a longer time before CQ onset, as shown in Fig. 3(a). However, higher energy plasmas also tend to require more impurity delivery for collisional RE suppression - this is shown in Fig. 3(b), where the (0D, ideal-mixing) minimum total electron number $N_{crit}$ for collisional suppression of RE amplification [5] in each experiment is plotted. Also shown is $N_{jet}$, the total number of bound electrons injected by the jet into the vacuum chamber at the start of the CQ. Finally, $\Delta N_e$ the total observed electron number increase by time $t=t_{CQ}$ is plotted; this is estimated from simple inversions of $CO_2$ interferometer data. Overall, it can be seen that the quantity of injected impurities is 5-20x lower than that required for collisional RE suppression. The data suggest that multiple (or higher throughput) gas jets could achieve $N_{jet} > N_{crit}$ in DIII-D. This will be tested in 2006 DIII-D experiments, which will use a gas jet valve with up to 25x more throughput than the present valve.

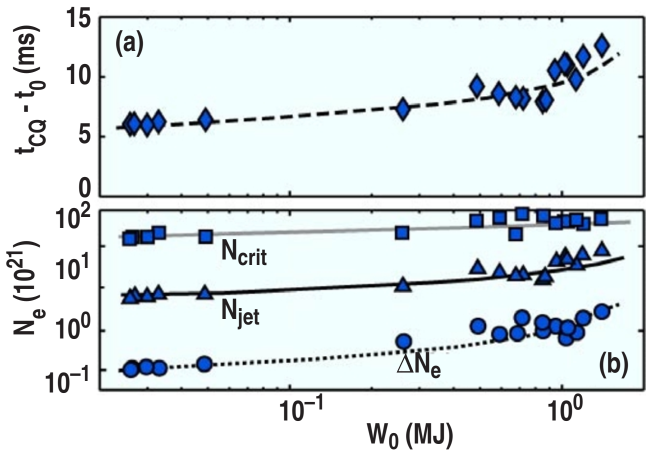


Fig. 3. (a) Time between jet trigger and start of CQ and (b) $N_{crit}$, minimum theoretical number of electrons for CQ collisional RE suppression, $N_{jet}$, actual number of delivered bound electrons at start of CQ, and $\Delta N_e$, observed free electron rise at start of CQ; all as a function of initial plasma thermal energy $W_0$.

In Fig. 3(b), it can be seen that $N_{jet}$ is about $20-50\times$ larger than $\Delta N_e$. For argon, with $Z$ = 18, this indicates a mean charge state slightly below 1 in the DIII-D experiments, i.e. the jet neutrals are mostly single ionized or neutral. Overall, this is a positive result in the sense that $Z_{eff} \approx 1$ is the best scenario for having as many electrons carried by ions as possible. It is expected that impurity ions will be mixed into the core plasma during the TQ and CQ by large-scale MHD activity; evidence for this was seen in fast bolometer data in previous DIII-D experiments [6].

The central role of low-order rational surfaces in setting MGI shutdown time scales and the destruction of flux surfaces out to $q \leq 2$ by the end of the TQ was demonstrated in experiments where the $q$-profile of the target plasma was varied while keeping the injected power constant. As the initial depth of the target plasma $q$=2 surface, $\Delta r_{q=2}$ (measured from the separatrix along the jet ray) is increased, the amount of current channel contraction and corresponding cold front propagation time required before onset of the TQ are seen to rise strongly, as shown in Figs. 4(a) and 4(b). This is consistent with the current channel needing to contract to $q$=2 before the large TQ MHD initiates and consistent with MGI MHD modeling [7].

Figure 4(c) shows the relative magnitude of the current channel expansion at the start of the CQ. The extent of this current channel expansion is expected to correspond roughly to the eextent to which flux surfaces have been destroyed by large MHD reconnection events. It can be seen that the current expansion observed is well-matched by a simple model that assumes flattening of the current profile all the way out to $q$=2.

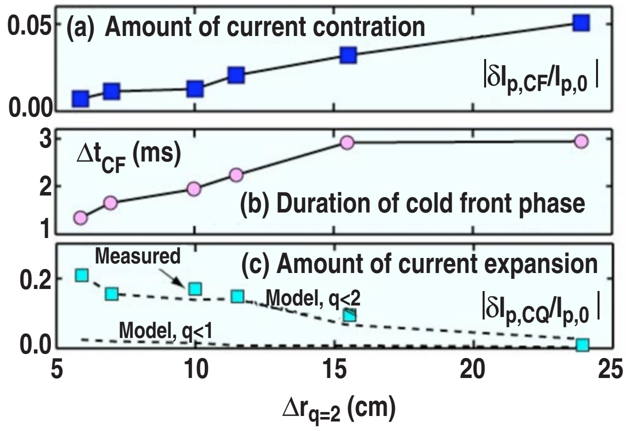


Fig. 4. (a) Fractional plasma current channel contraction before TQ onset, (b) duration of current channel contraction (cold front) phase, and (c) fractional plasma current expansion at start of CQ; all as a function of the initial depth of the $q$=2 surface from the plasma edge. The fractional current contraction and expansion represent increases and decreases, respectively, in internal inductance $l_i$, assuming $l_i I_p^2$ is conserved on these short timescales.

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