GA–A25832

STUDIES OF IMPURITY ASSIMILATION DURING MASSIVE ARGON GAS INJECTION IN DIII-D

by

E.M. HOLLMANN, T.C. JERNIGAN, M. BAKHTIARI, J.A. BOEDO, T.E. EVANS, M. GROTH, D.A. HUMPHREYS, R.A. MOYER, P.B. PARKS, D.L. RUDAKOV, H. SCOTT, E.J. STRAIT, J.C. WESLEY, W.P. WEST, D.G. WHYTE, and J.H. YU

JULY 2007

GENERAL ATOMICS

DISCLAIMER

GA–A25832

STUDIES OF IMPURITY ASSIMILATION DURING MASSIVE ARGON GAS INJECTION IN DIII-D

by
E.M. HOLLMANN,* T.C. JERNIGAN,† P.B. PARKS, L.R. BAYLOR,† J.A. BOEDO,* S.K. COMBS,† T.E. EVANS, M. GROTH,‡ D.A. HUMPHREYS, R.A. MOYER,* D.L. RUDAKOV,* H. SCOTT,‡ E.J. STRAIT, J.C. WESLEY, W.P. WEST, D.G. WHYTE,# and J.H. YU*

This is a preprint of a paper presented at the 34th EPS Conf. on Plasma Physics, in Warsaw, Poland, July 2-7, 2007 and to be published in the *Proceedings.*

*University of California-San Diego, La Jolla, California.
†Oak Ridge National Laboratory, Oak Ridge, Tennessee.
‡Lawrence Livermore National Laboratory, Livermore, California.
#Massachusetts Institute of Technology, Cambridge, Massachusetts.

Work supported by
the U.S. Department of Energy
under DE-FG02-04ER54758, DE-AC05-00OR22725, DE-FC02-04ER54698, W-7405-ENG-48 and DE-FG02-04ER54762

GENERAL ATOMICS PROJECT 30200
JULY 2007

Studies of Impurity Assimilation During Massive Argon Gas Injection in DIII-D

E.M. Hollmann,[1] T.C. Jernigan,[2] P.B. Parks,[3] L.R. Baylor,[2] J.A. Boedo,[1] S.K. Combs,[2] T.E. Evans,[3] M. Groth,[4] D.A. Humphreys,[3] R.A. Moyer,[1] D.L. Rudakov,[1] H.A. Scott,[4] E.J. Strait,[3] J.C. Wesley,[3] W.P. West,[3] D.G. Whyte,[5] and J.H. Yu[1]

[1] University of California-San Diego, La Jolla, California 92093, USA
[2] Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA
[3] General Atomics, San Diego, California 92186-5608, USA
[4] Lawrence Livermore National Laboratory, Livermore, California 94550, USA
[5] Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

Fast shutdown of discharges using massive gas injection (MGI) is a promising technique for reducing tokamak wall damage during disruptions [1]. An outstanding concern, however, is the generation of runaway electrons (RE) during the shutdown. Although RE formation observed during MGI in present-day experiments is quite small (typically <1% of the main plasma current I_p in DIII-D), it is thought that even this small RE current could be amplified to significant levels in reactor-scale tokamaks such as ITER [2].

It is expected that complete collisional suppression of any potential RE amplification during the CQ can be achieved for suppression parameters $\gamma_{crit} \equiv E_{crit}/E_\varphi > 1$, where $E_{crit} = [2\pi e^3 \ln\Lambda(2n_e + n_B)]/mc^2$ is the critical electric field [2] and $E_\varphi \approx [(\mu_0 l_i)/4\pi][-(\partial I_p/\partial t) + \alpha_L(I_w/\tau_w)]$ is the toroidal electric field resulting from the decay of the plasma current I_p. n_e is the free electron density, n_B is the bound electron density, $\alpha_L \approx 2[\ln(8R/r_w)-2]/l_i$ is the ratio of external (outside conducting wall) to internal (inside conducting wall) self-inductance, I_w is the wall current, and τ_w is the wall time. The densities required to achieve $\gamma_{crit} > 1$ are typically quite large, e.g. $n_{tot} \equiv n_e + n_B/2 \approx 10^{16}$ cm^{-3} for DIII-D. To have a possibility of achieving the required density in the DIII-D plasma (with volume $V_p \approx 20$ m^3), an MGI system using argon must be able to deliver of order 10^{22} argon atoms to the plasma within the shutdown timescale (jet trigger to CQ onset) of about 10 ms.

In 2005-2007, three different MGI delivery systems were tested on the DIII-D tokamak; these are shown in Fig. 1. In 2005, a single-stage low-flow D = 0.495 cm valve was used together with narrow D = 1.5 cm directed guide tube to aim the neutral jet at the plasma core. This valve delivered a total of about 3×10^{22} argon atoms to the plasma in a 20 ms pulse (at the plasma). In 2006, a new two-stage, large-orifice (D = 2 cm) gas valve was used to inject argon through a high-flow D = 15 cm guide tube. The 2006 setup delivered of the order 3×10^{23} argon atoms to the plasma in a roughly 10 ms pulse. Most recently, in 2007, tests are in progress using 1 to 6 single-stage valves simultaneously injecting gas through a high-flow guide tube. The 2007 setup has been tested with argon in a single actual plasma discharge to date, delivering of the order 2.6×10^{22} argon atoms to the plasma in a roughly 4 ms pulse (using 5 valves).

Neutral delivery rates at the plasma are shown in Fig. 2(a). The neutral flow rate for the 2005 geometry is obtained from 2D fluid modeling; this modeling has been validated through comparison of fast output pressure measurements in bench tests of the actual delivery system geometry and the simulations [3]. In the case of the 2006 geometry, the fluid modeling was not performed because of the complicated, poorly-known valve opening behavior of the valve. Instead, the flow was approximated as being proportional to the output pressure measured in bench tests, normalized by the known total amount of gas delivered. Finally, in the 2007 geometry, neither bench tests nor fluid modeling have been performed yet, so analytic expressions were used to estimate the flow rate. It can be seen that the two-stage valve has chatter [see time range $t - t_0 =$ 4-10 ms in red curve, Fig. 2(a)], leading to pulses in the flow which contain sufficient argon to initiate the plasma shutdown, as shown by the core electron temperature, Fig. 2(c), and plasma current, Fig. 2(f). The bulk of the argon in the 2006 experiment arrives in the second half of the CQ [CQ time period marked by red shaded area in Fig. 2(f)]. Surprisingly, the large two-stage neutral pulse has little effect on the n_e trace, [Fig. 2(d)] or in the I_p trace [Fig. 2(f)]. In Fig. 2(f), it can be seen that the 2007 valve geometry initiates the plasma CQ several ms before the other valves geometries; this rapid shutdown onset is desirable from the standpoint of timely response during or prior to a disruption.

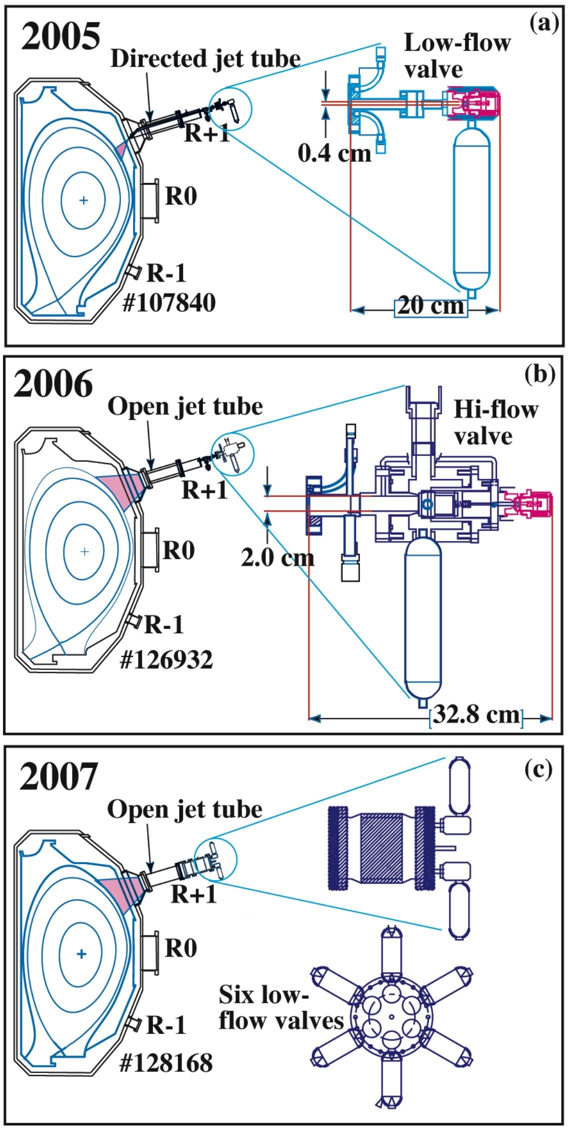

Fig. 1. Schematics of three DIII-D MGI geometries: (a) 2005 geometry using single-stage valve and directed jet tube; (b) 2006 geometry using two-stage valve and open jet tube; and (c) 2007 geometry using six single-stage valves with open jet tube.

To estimate the bound electron density n_B achieved in these experiments, the distribution of charge states in the plasma current channel needs to be known. This is estimated here with 0-D collisional-radiative modeling of the radiative shutdown [4]. The 0-D modeling uses the known neutral delivery rate to the vacuum chamber but varies the mixing of these neutrals into the core to match observed timescales. In the version of the 0-D model used here, three free parameters, the TQ mixing timescale τ_{TQ}, current quench mixing timescale τ_{CQ}, and TQ carbon delivery rate due to wall sputtering $\dot{N}_{C,TQ}$, are varied to best match the observed time TQ and CQ durations and current quench radiated power fraction due to carbon, $P_{rad,C}/P_{rad,Ar}$.

Typically, 1–5×10^{19} carbon atoms need to be added in the model to match the observed radiated carbon fraction (compared with ≈5×10^{20} D^+ and ≈1×10^{19} C^{6+} ions in the plasma initially). The current quench radiated power fraction due to carbon is estimated from the single-chord core-viewing VUV survey spectrometer, as shown in Fig. 2(e).

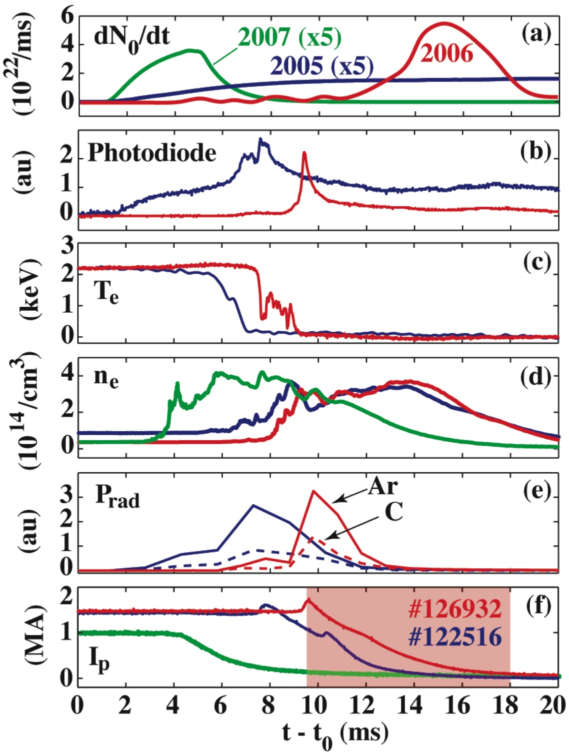

Fig. 2. Time traces (relative to valve opening time t_0) of (a) argon delivery rate (10^{22} particles/ms), (b) jet photodiode (visible light), (c) central electron temperature (keV), (d) line-averaged electron density (10^{14}/cm^3), (e) radiated power, and (f) plasma current (MA).

Figure 3(a) shows the amount of argon injected into the vacuum vessel N_{inj} (from the fluid calculations and/or bench tests) and the amount actually mixed into the plasma core N_{plasma} by the middle of the CQ (obtained from the 0-D modeling). It can be seen that the mixing efficiency $Y_{mix} \equiv (N_{plasma}/N_{inj})$ of argon from the edge into the core is relatively low, between 1%-5%. Also, it is apparent that the amount of argon injected by the middle of the CQ (N_{inj}) for the 2006 valve is similar to the 2005 valve, although the total amount injected (integrated over the entire pulse) is 10× larger.

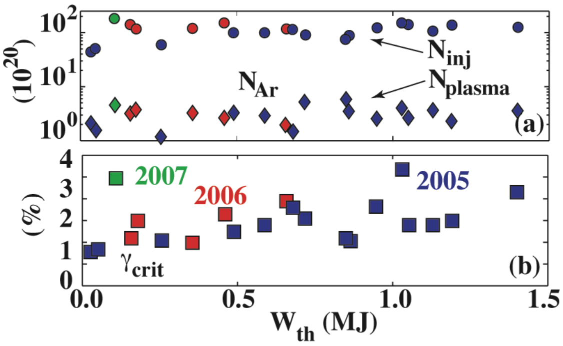

Fig. 3. (a) Number of argon atoms N_{inj} injected into vacuum chamber (circles) and N_{plasma} assimilated into plasma (diamonds) by middle of CQ; (b) runaway suppression ratio γ_{crit} for 2005 geometry (blue), 2006 geometry (red), and 2007 geometry (green) as a function of initial plasma thermal energy W_{th}.

Figure 3(b) shows the suppression ratio γ_{crit}; to obtain this, both free n_e and bound n_B electron densities in the current channel need to be known, as well as plasma and wall currents I_p and I_w. Here, we use n_e measured from line-average interferometer measurements. The line-average values are expected to be reasonably accurate by the middle of the CQ because the plasma is thought to be somewhat homogenous at this point; this is supported by observed ratios between different interferometer view chords. The plasma current is measured by magnetic loops inside the vessel. The bound electron density n_B and the wall current I_w are obtained from the 0-D modeling. It can be seen that the suppression ratios γ_{crit} are relatively low, about 1%-3%. A slight upward trend of γ_{crit} with increasing initial plasma thermal energy W_{th} is observed in the 2005 data – this is possibly due to higher-energy plasmas having more violent TQ MHD mixing and thus giving higher Y_{mix}. No significant improvement in γ_{crit} is noticed in the 2006 two-stage valve geometry over the previous 2005 configuration, although 10× more neutrals are being injected. This clearly demonstrates that the initial neutral rise, not the total amount of particles injected into the vacuum vessel, is crucial for achieving high γ_{crit}. Consistent with this, despite injecting less particles, the 2007 configuration, at least based on the single Ar MGI shot obtained to-date, appears to give a higher γ_{crit} than the previous configurations.

Several factors contribute to the overall low-achieved values of γ_{crit}. First, the finite delivery rate of argon neutrals causes the bulk of the argon neutrals to arrive after the CQ is over, at least for longer-pulse, higher total delivery, experiments (2005 and 2006). Second, argon neutrals are stopped at the plasma edge and spread sideways into the vacuum region instead of being absorbed into the plasma edge. This has been observed over a wide range of target plasmas [5] and is consistent with calculations of jet stopping [6]. Because of the resulting rapid neutral pressure buildup in front of the jet nozzle, less than half of the argon which is injected into the vacuum region during the CQ actually hits the plasma edge; this is estimated from absolutely-calibrated Ar-I imaging. The missing argon neutrals presumably go into side ports and beam ducts – this is seen in fast pressure gauge signals and has also caused difficulties with neutral beam sources after some MGI shots. Finally, even argon that is ionized at the plasma edge does not mix into the central current channel with perfect efficiency. Instead, a significant fraction is swept into the divertor region, indicated by divertor density measurements.

In summary, argon MGI using three different valve/delivery tube geometries has been tested in DIII-D in the last three years. The results indicate that only the argon neutrals delivered to the plasma in the first several ms of the shutdown affect the resulting CQ impurity assimilation, so a very clean, sharp neutral rise is essential for achieving high assimilation. Preliminary results in 2007 using up to six single stage valves firing simultaneously have given promising results and experiments using this geometry are ongoing.

This work was supported by the U.S. Department of Energy under DE-FG02-07ER54917, DE-AC05-00OR22725, DE-FG02-04ER54758, DE-FC02-04ER54698, W-7405-ENG-48, DE-FG03-95ER54309, and DE-FG02-04ER54762.

References

[1] D.G. Whyte, *et al.,* J. Nucl. Mater. **313**, 1239 (2003).

[2] M.N. Rosenbluth and S.V. Putvinski, Nucl. Fusion **37**, 1355 (1997).

[3] P.B. Parks and W. Wu, “Dynamics of Massive Gas Injection for Fast Plasma Shutdown in Tokamaks,” to be submitted to Nucl. Fusion.

[4] E.M. Hollmann, *et al.,* “0-D Modeling of Fast Radiative Shutdown of Tokamak Discharges Following Massive Gas Injection,” to appear in Contr. Plasma Physics (2007).

[5] E.M. Hollmann, *et al.,* “DIII-D Studies of Massive Gas Injection Fast Shutdowns for Disruption Mitigation,” Proc. of 33rd EPS Conf. on Plasma Phys., Rome (2006).

[6] P.B. Parks, “On the Deceleration and Stopping of Massive Gas Jets Injected into Tokamak Plasma Discharges,” to be submitted to Phys. Rev. Lett.