Experiments on rapid shutdown using shell pellets in DIII-D*

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Rapid discharge shut down by massive impurity injection is slated for use in future large tokamaks to reduce the risk of wall damage during disruptions [1]. Presently, the method of impurity delivery is envisioned as being massive gas injection (MGI). There is considerable interest in developing rapid shut down methods which are capable of delivering enough impurities into the plasma core by the end of the thermal quench (TQ) to be able to collisionally suppress runaway electron (RE) formation [2]. Presently, MGI experiments [3] have achieved perhaps 20% of the required density $n_{crit} \approx 5 \times 10^{16}$ cm^{-3}. Experiments are therefore underway to investigate alternates to MGI [4]. Methods presently being studied at DIII-D include shattered pellet injection [5] and shell pellet injection [6].

The concept behind shell pellet injection is to fire at the plasma a pellet consisting of a thin shell enclosing a dispersive payload. On reaching the plasma core, the shell breaks open, releasing the dispersive payload throughout the core region. In order to optimize dispersion of payload in the core, effects of shell thickness, payload material, and initial pellet velocity will all need to be understood. Two different types of dispersive payloads have been proposed: dust grains or high-pressure gas.

Preliminary shell pellet experiments [7] have been performed in the DIII-D tokamak [8] by firing shell pellets into initially stable H-mode discharges. Three types of pellets were tested: small (OD ~ 2 mm, t = 0.4 mm) polystyrene (C_6H_6) shells filled with either pressurized (10 atm) argon gas or with boron powder; and large (OD ~ 10 mm, t ~ 0.4 mm) polystyrene shells filled with boron powder. A schematic of the experiments is shown in Fig. 1.

Sample time traces from a small Ar gas-filled shell pellet experiment are shown in Fig. 2. In these experiments, the plasma did not disrupt and three pellets are injected per discharge. Figure 2(b) shows a drop of about 0.15 MJ in plasma thermal energy per injected pellet. This gives an estimated ionization cost of $E_{i,C} \approx 5$ keV per carbon atom (ignoring the trace Ar gas and weakly radiating H), consistent with CRETIN simulations. Very little effect on the plasma current is observed, Fig. 2(c); this is consistent with current diffusion simulations of the evolution of the current profile.

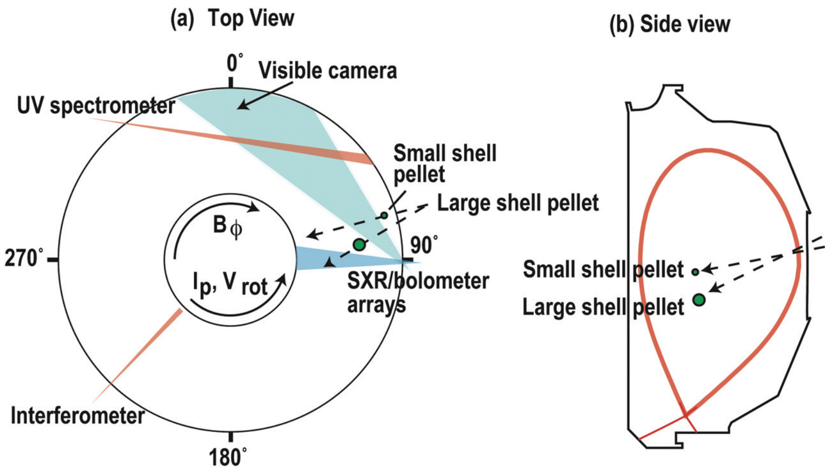

Fig. 1. Schematic of DIII-D from (a) top and (b) side showing shell pellet vacuum trajectories and essential diagnostics.

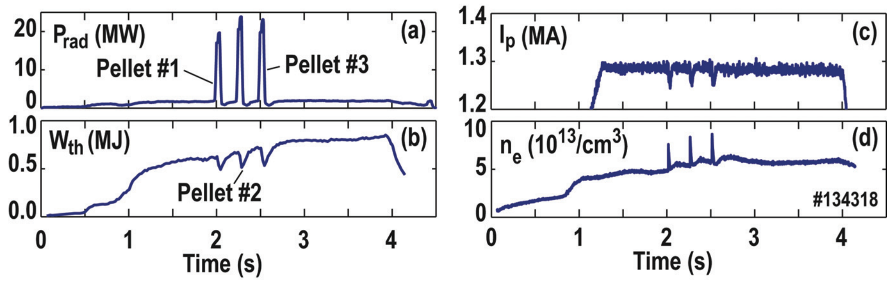

Fig. 2. Time traces of small shell pellet injection experiment showing (a) radiated power, (b) plasma thermal energy, (c) plasma current, and (d) line-average electron density.

Pellet trajectories are estimated from fast visible camera data, such as shown in Fig. 3(a). The small shell pellets were observed to burn up at normalized radius $r/a \sim 0.5$, as shown in Fig. 3(b). The large shell pellets initiated disruption/rapid shutdown upon crossing the $q = 2$ surface, as shown in Fig. 2(c), presumably due to the large amount of material ablated from the large pellet shell. The destabilization of the TQ MHD due to impurities reaching the $q = 2$ surface is consistent with previous MGI experiments.

For the small pellets, a slowing from 350 m/s down to 100 m/s as the pellets approached the magnetic axis was observed, which is not well-understood at present, but could possibly result from temperature gradients in the plasma. For the large shell pellets, an initial velocity of 200 m/s was used. Unlike for small pellets, no clear indication of pellet slowing in the plasma was observed.

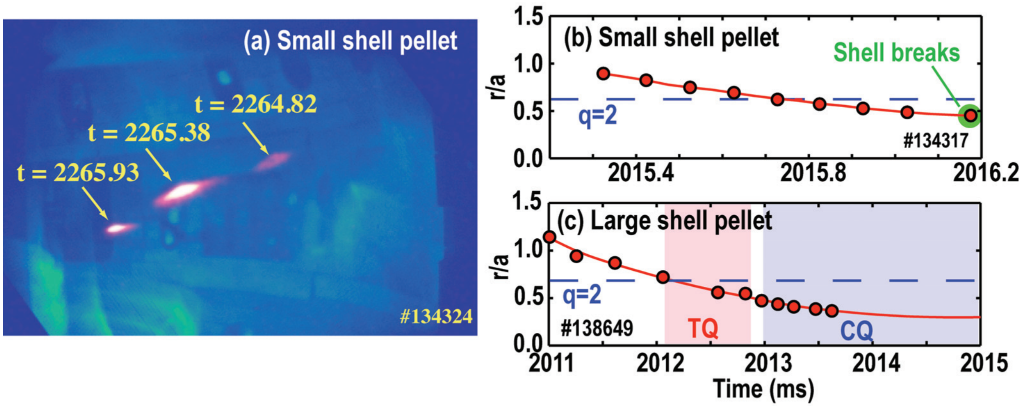

Fig. 3. (a) Fast camera images of small shell pellet at three time steps; (b) small shell pellet trajectory estimated from camera images; and (c) large shell pellet trajectory estimated from fast camera images.

The basis of the shell pellet concept is the shell burn-through and release of dispersive payload in the plasma core – this was demonstrated successfully with small shell pellets. Figure 4(a) shows filtered fast camera brightness (integrated spatially over the whole pellet spot) of line-filtered BII and CII emission. Because the pellet plume is very dense, significant bremsstrahlung (broadband) emission is emitted into the filter bandpass; nevertheless, a spike in BII emission and drop in CII emission is seen at the end of the pellet trajectory, consistent with shell burn through and boron powder release. Although the data of Fig. 4(a) is from two different shots, the distinct trends shown in BII and CII emission are consistent across multiple pellet injections. The characteristic spot size of the BII emission, shown in Fig. 4(b), does not significantly increase during the payload release, indicating that the low charge states of boron are burned through very quickly. Figure 4(c) shows charge-exchange recombination profiles of B_{VI} density vs normalized radius, where t_0 is taken as the pellet injection time. It can be seen that 15 ms after the pellet injection, fully-stripped boron ions are already mixed fairly well through the core and then relax to a centrally-peaked profile within 85 ms.

Experiments with large, boron-filled pellets did not achieve shell burn-through, although the shell thickness and material was the same as for small shell pellets. Normally, a target plasma thermal energy $W_{th} = 0.6$ MJ was used in these experiments. For the large shell pellets, the target plasma thermal energy was turned up to $W_{th} = 1.5$ MJ for one shot without seeing shell burn-through and payload release. Estimates of the ablated material quantity from the density rise in the plasma suggest that perhaps only 1/4 of the shell burnt through. These experiments thus clearly demonstrate that large, stronglyperturbing shells burn through much slower than smaller shells. This greatly reduced shell ablation rate in the large shell pellet is possibly due in part to rapid heat transport pre-cooling the temperature profile ahead of the pellet, although this has not been confirmed experimentally.

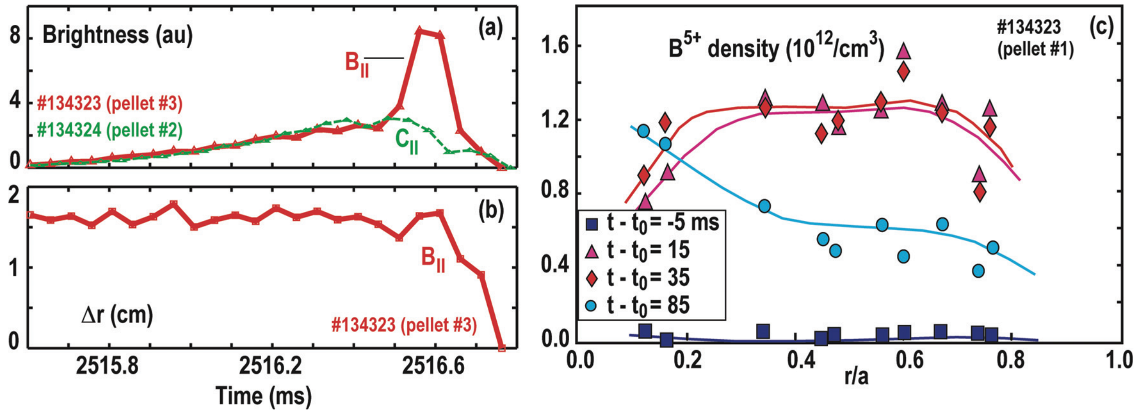

Fig. 4. Data for small boron-filled shell pellet injection: (a) fast camera B^+ and C^+ brightness vs time; (b) fast camera B^+ spot size vs time; and (c) charge-exchange recombination B^{5+} profiles vs time.

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