First demonstration of novel technique for disruption mitigation by core impurity deposition using shell pellets on DIII-D

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N.W. Eidietis[1], E.M. Hollmann[2], P.B. Parks[1], R.A. Moyer[2], J.L. Herfindal[3], V.A. Izzo[2], A. Lvovskiy[4], D. Shiraki[3]

[1] General Atomics, PO Box 85608, San Diego, California 92186-5608, USA
[2] University of California - San Diego, 9500 Gilman Dr, La Jolla, CA 92093-0417, USA
[3] Oak Ridge National Laboratory, PO Box 2008, Oak Ridge, TN 37831, USA
[4] Oak Ridge Associated Universities, Oak Ridge, TN 37831, USA

email: eidietis@fusion.gat.com

Disruption mitigation by core impurity deposition using novel shell pellet technology has been demonstrated for the first time, providing empirical tests of modeling [1] predicting improved mitigation compared to conventional edge-cooling technologies (e.g. shattered pellet injection (SPI)). Unlike those methods, which provide relatively low impurity assimilation into the plasma, shell pellets deposit 100% of their impurity payload to the core, providing a path to effectively radiate the plasma thermal energy while maintaining acceptable current quench times and suppressing runaway electron (RE) beam formation. On DIII-D, thin diamond shells filled with boron dust injected from the low-field side of the torus safely transport their payload deep into the plasma core before ablating and releasing the dust (Figure 1). Thomson scattering (TS) provides evidence for an inverted temperature profile after the pellet enters the plasma, indicative of the predicted “inside-out” quench mechanism (Figure 2). These initial experiments provide early proof-of-principle that this new mitigation technology may address major shortcomings in the edge-cooling shattered pellet injection presently planned for ITER and provide an effective solution for future fusion reactors.

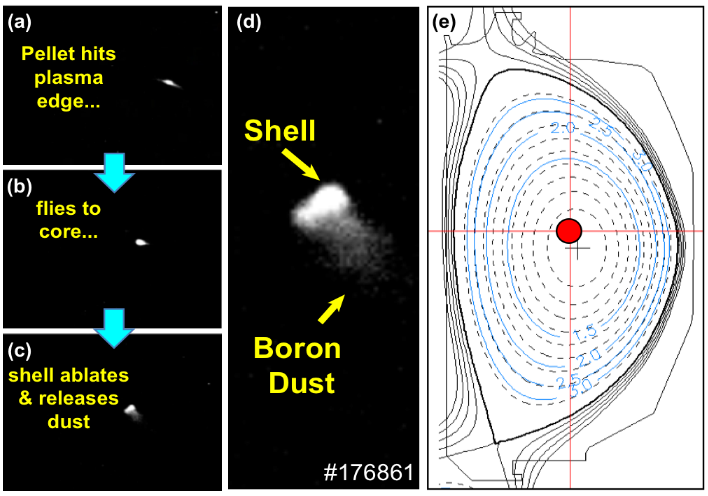

Figure 1: Visible imaging of (a) shell pellet hitting low-field-side boundary of plasma, (b) continuing through plasma toward core, (c) ablating and releasing boron dust in core. (d) Expanded view of (c), highlighting shell and dust. (e) EFIT reconstruction from just before pellet injection with red dot indicating pellet location at time of dust release (c). Shell: 40um thick, 3.6mm OD, 30mg B at v_{inj}=230 m/s.

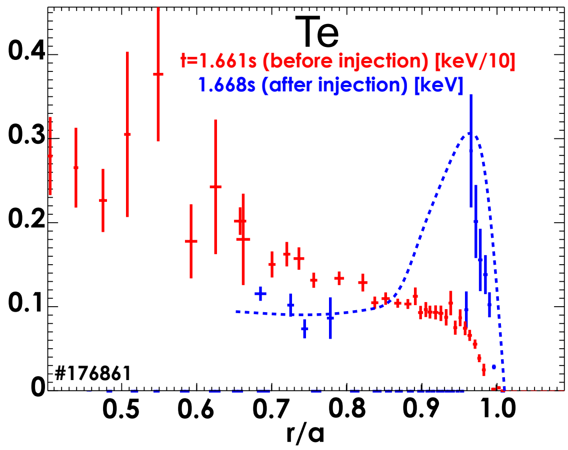

Figure 2: Te profiles before (red) and after (blue) pellet enters the plasma, showing inverted temperature profile resulting from pellet (dashed line is guide, not fit). Sparse Te profile points after injection reflect limited number of low Te polychromators available in the TS.

Conventional disruption mitigation techniques (SPI or massive gas injection) deposit radiating impurities near the plasma edge and rely upon global MHD induced when the resulting cooling front passes the q=2 surface to mix the radiating impurities into the core and radiate the plasma thermal energy (W_{th}). This mixing typically results in fairly low impurity assimilation (<20%), requiring high-Z (neon or higher Z) impurities to adequately radiate W_{th}, and limiting the total density available for runaway electron (RE) suppression. In contrast, NIMROD non-linear 3D MHD modeling [1] predicts core impurity deposition, wherein the injected radiating impurities enter the plasma core without significantly cooling the edge, to improve all stages of the disruption mitigation process over conventional methods. Core radiation inverts the thermal quench process, cooling from the inside-out and minimizing heat transport to the scrape-off layer to protect the divertor. 100% impurity assimilation enables the use of low-Z impurities to achieve high thermal radiation fraction while still providing acceptably slow current decay to avoid mechanical damage from eddy currents. In addition, the global stochasticity throughout the entire plasma cross-section (Figure 3) & high density suppress RE formation.

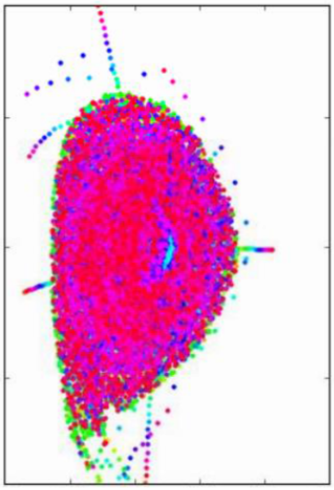

Figure 3: NIMROD DIII-D simulation. Poincare plot of field lines 0.1ms after Ar impurity deposited near but off-center from core.

In the DIII-D experiments, the radial depth of shell pellet penetration before the shell ablates and disperses its dust payload increases with injection velocity (Figure 4). Comparison of the observed depth of penetration to existing pellet ablation models exhibits good agreement within experimental variability (Figure 5). 0D mitigation metrics generally improve with increased deposition depth, indicating the benefit of deep deposition. A large fraction (>60%) of the total electron content of the shell pellet is accounted for in the maximum density perturbation following injection. This suggests atomic assimilation fractions nearing unity, assuming singly ionized or low ionization state impurities at low current quench T_e. However, only one shell size was tested (30 mg boron), so it is not yet demonstrated if assimilation remains constant with arbitrarily large payload masses.

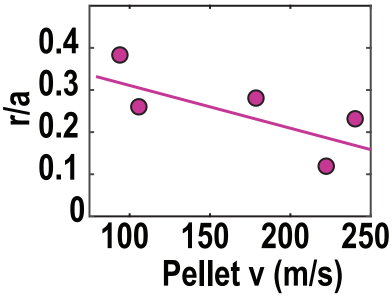

Figure 5: Pellet location at time of first observed dust dispersal vs. velocity.

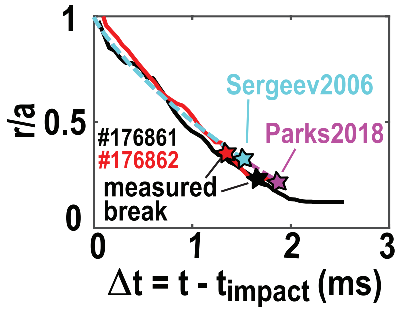

Figure 4: Comparison of measured pellet deposition depth to models. Lines indicate pellet trajectory. Stars indicate model predictions of radius of complete shell ablation & first dust dispersal in experiment.

Thus, core impurity deposition using shell pellet technology has been demonstrated as a viable disruption mitigation technique for the first time, validating predictions of its potential to transform the disruption process in a way that alleviates the primary shortcomings of conventional edge-cooling technologies. This new development offers exciting potential for an alternate and more effective disruption mitigation technology for ITER and future burning plasma devices.

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[1] V. A. Izzo and P. B. Parks, *Phys. Plasmas* **24**, 060705 (2017).