Recent Progress in Shattered Pellet Injection Technology in Support of the ITER Disruption Mitigation System

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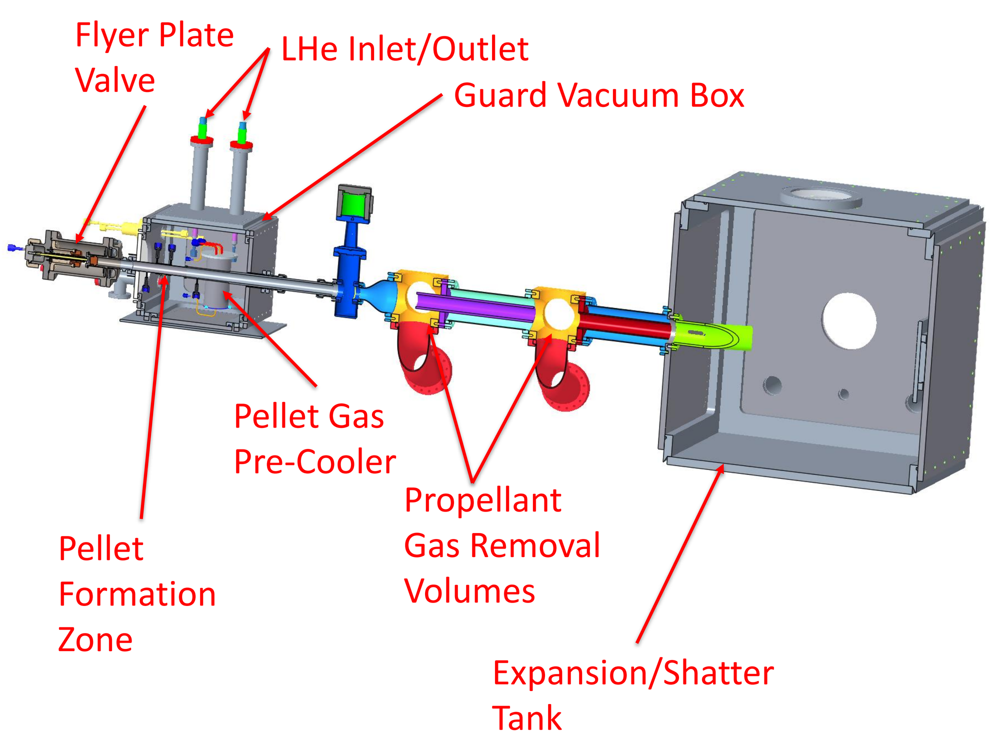
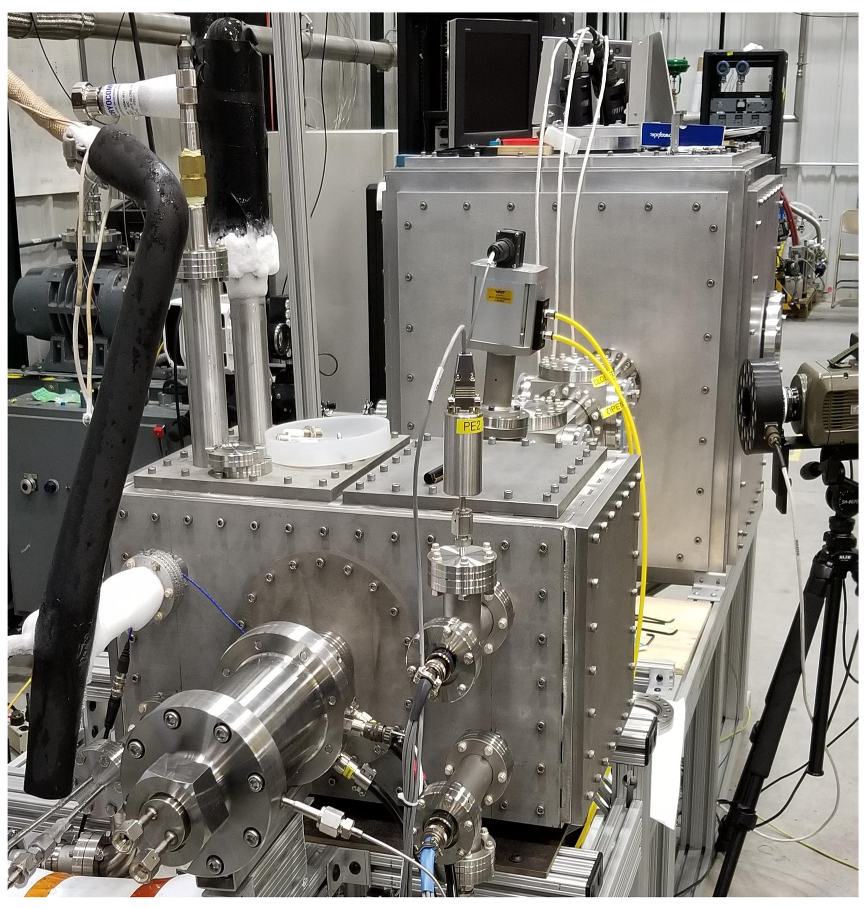
Background and Introduction

Shattered pellet injection (SPI) has been selected as the baseline disruption mitigation (DM) system for ITER. SPI utilizes cryogenic cooling to desublimate low pressure (<100 mbar) gases onto a cold zone within a pipe gun barrel, forming a cylindrical pellet. Pellets are dislodged from the barrel and accelerated using either a gas driven mechanical punch or high-pressure light-gas delivered by a fast-opening valve. SPI technology is currently deployed and operational on DIII-D, JET, and KSTAR. These SPI systems are in experiments for physics scaling of ITER thermal mitigation and runaway electron dissipation/avoidance. The pellet sizes used for these machines are in the range of 4 to 12.5 mm in diameter with length to diameter ratios (L/D) of ~1.5. The current plan for ITER SPI is to utilize pellets that are 28.5 mm in diameter with an L/D of ~2. The large pellet sizes, high steady-state magnetic fields, and limitations of operating in a radiation environment render much of the technology unusable. In addition to technology improvements, a deeper understanding of pellet material properties, formation, and release is being developed for implementation in future SPI designs, specifically ITER.

ITER SPI Test Facility

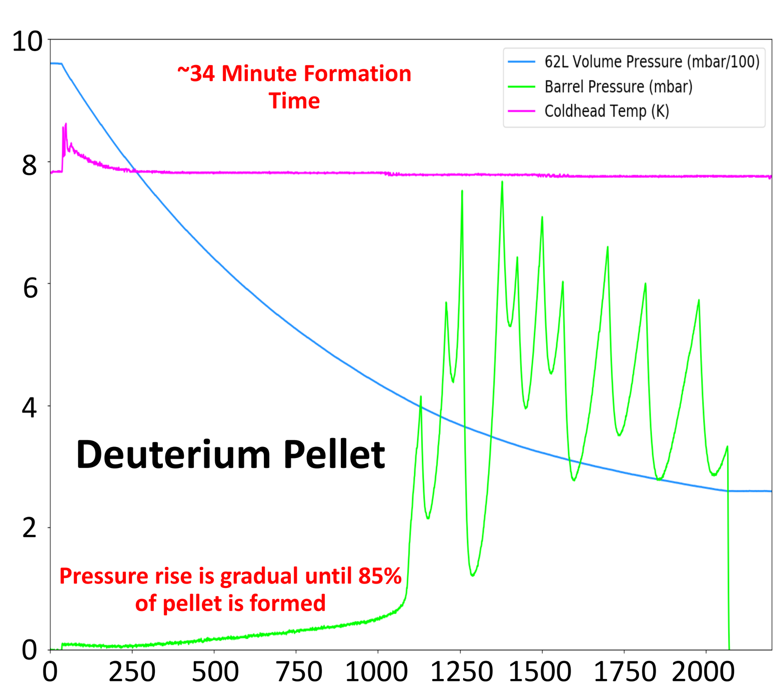
A liquid helium cooled shattered pellet injection system has been designed and built to test the technology for the ITER SPI system, to determine pellet formation techniques, and to assess the survivability and downstream fragmentation of ITER size pellets. The system design contains a barrel with similar sizes/flow paths as the current ITER design. A LN_2 pre-cooler is used to cool the incoming pellet gas prior to reaching the barrel cold zone to decrease pellet forming times. The downstream shatter tank is used to for fast camera imaging to quantify pellet flight dispersion or fragment plume characteristics.

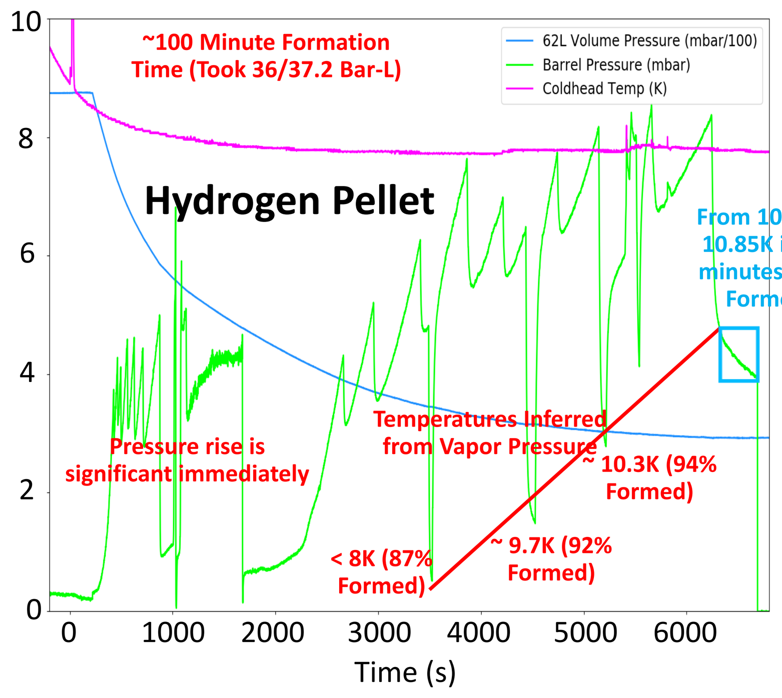




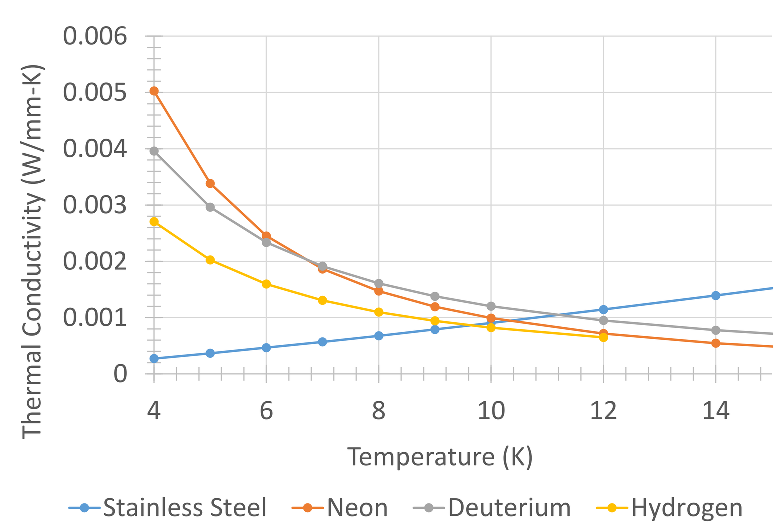
Pellet Formation Studies

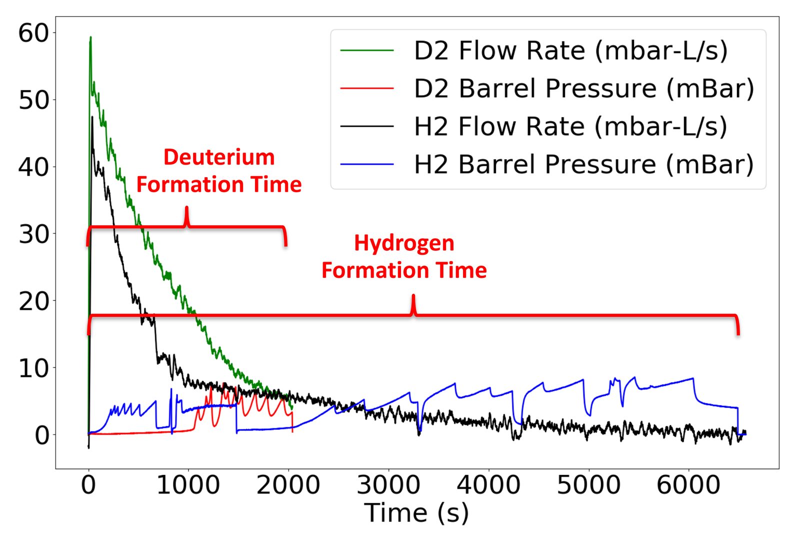
Formation of large pellets is not frequently done during a tokamak shot cycle as most SPIs installed on machines use an average pellet size of 8 mm in diameter. The 28.5 mm diameter pellets on ITER pose a timing issue for shot cycle timing on ITER. The current constraint is 30 minutes for pellet formation.

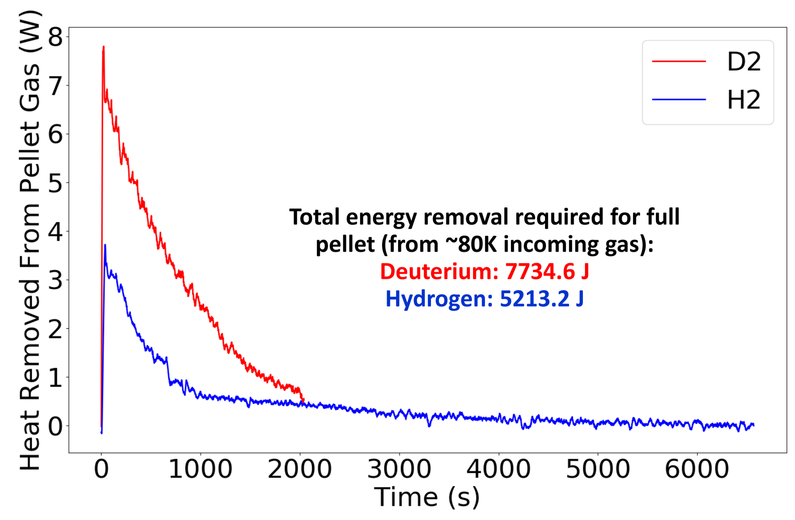




Due to poor thermal conduction, formation of pure hydrogen pellets requires an extensive amount of time. Tests were conducted to determine pellet surface temperature by closing the gas feed and measuring the vapor pressure, correlating it with pellet surface temperature.

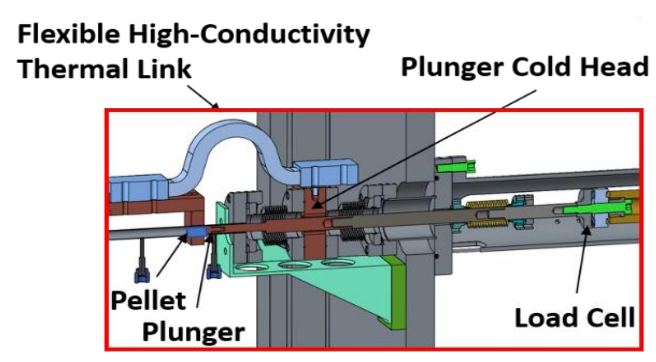




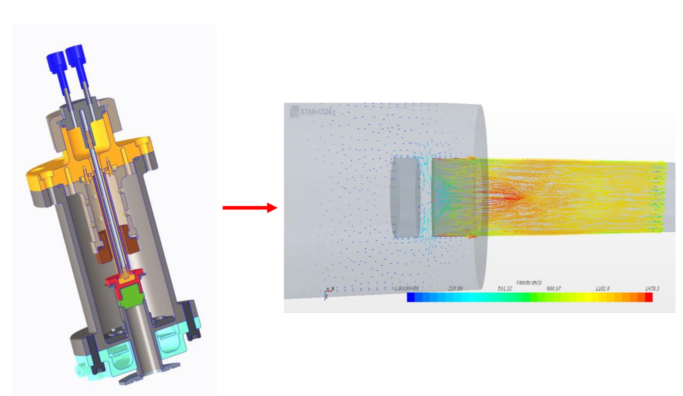


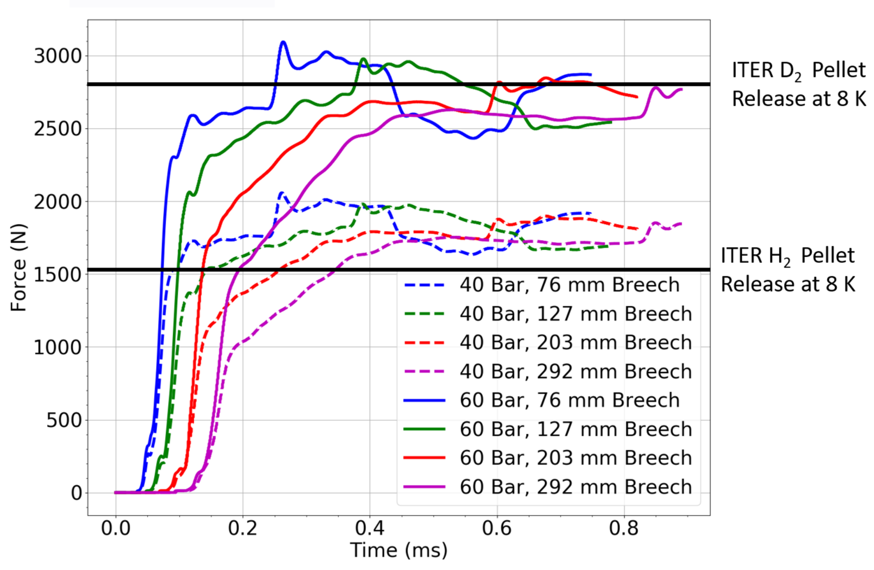
Pellet Release Forces

Pellet material, temperature, and L/D are all factors in the amount of force need to release pellets from the cold zone of an SPI barrel. Forces required to dislodge pellets over a range of SPI relevant temperatures were measured in [1] using the apparatus shown below.

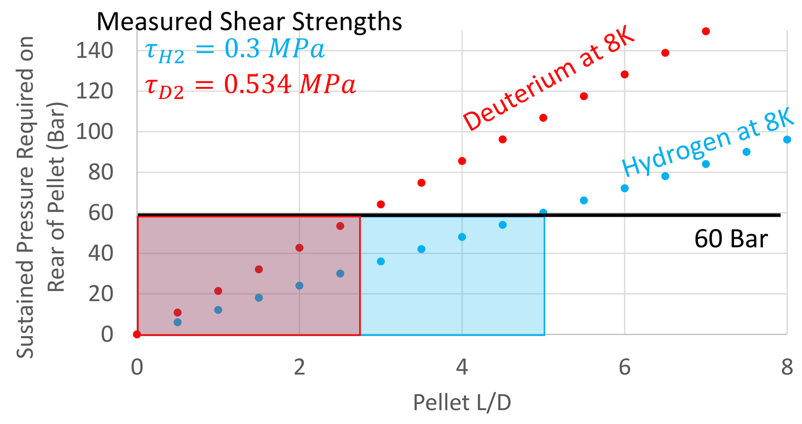


CFD modeling was conducted to determine the amount of force applied to the pellet by the ITER prototype valve with varying breech lengths for 40 and 60 bar propellant pressure [2].





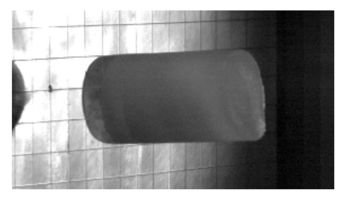
These forces can be scaled based on the L/D ratio of the pellet. A delicate balance is required to dislodge the pellet without fracturing it as it is dislodged from the cold zone. Currently, the ITER Test Facility operates a propellant valve at 60 bar, which is not adequate to release deuterium pellets at 8K as the force is not sustained for an adequate amount of time for release. This operating point also catastrophically fragments pure hydrogen pellets as they release from the cold zone.



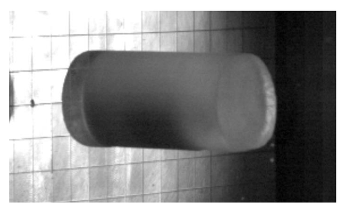
Pellet Dispersion Characterization

As pellets exit a barrel into free-flight the propellant gas used to accelerate the pellet will induce a non-uniform force on the rear of the pellet. This results in the pellet veering from a perfectly straight flight path. This dispersion has been characterized for multiple 28.5 mm diameter deuterium pellets. Dispersion is thought to scale inversely with mass; thus, hydrogen pellets will experience more drastic dispersion due to its lower mass, compared to deuterium.

Shot 71 – 2 L/D – Fired at 14.45 K
- Dispersion – 0.34 degrees
- Speed – 255 m/s
- Prop Gas Used: 1.53 Bar-L



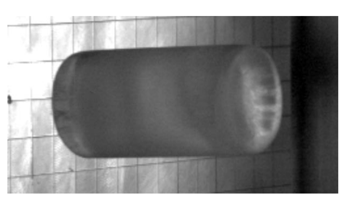
Shot 72 – 2 L/D – Fired at 14.38 K
- Dispersion – 0.52 degrees
- Speed – 266 m/s
- Prop Gas Used: 2.787 Bar-L

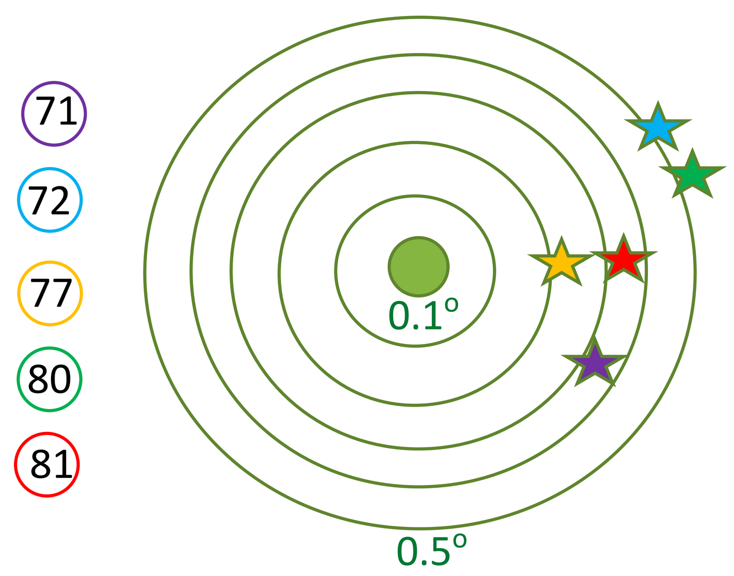


Shot 77 – 2 L/D – Fired at ~15 K
- Dispersion – 0.23 degrees
- Speed – 190 m/s
- Prop Gas Used: 0.86 Bar-L

Shot 80 – 2 L/D – Fired at ~15 K
- Dispersion – 0.52 degrees
- Speed –250 m/s
- Prop Gas Used: 2.757 Bar-L

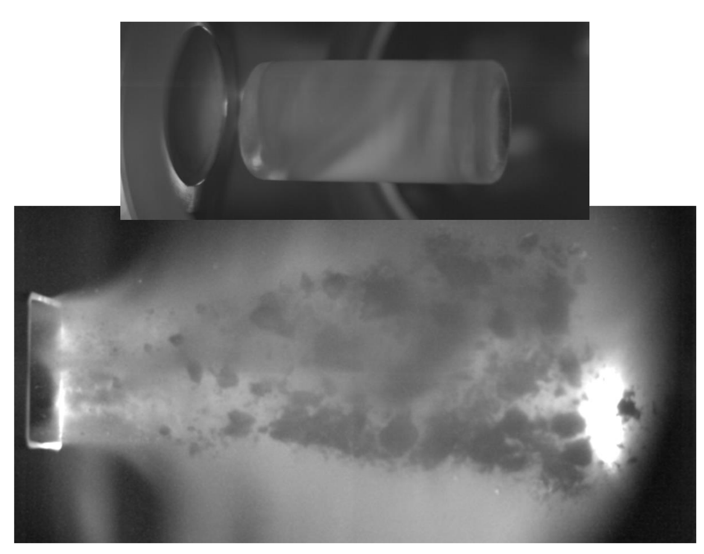
Shot 81 – 1.85 L/D – Fired at ~15 K
- Dispersion – 0.34 degrees
- Speed – 285 m/s
- Prop Gas Used: 2.71 Bar-L

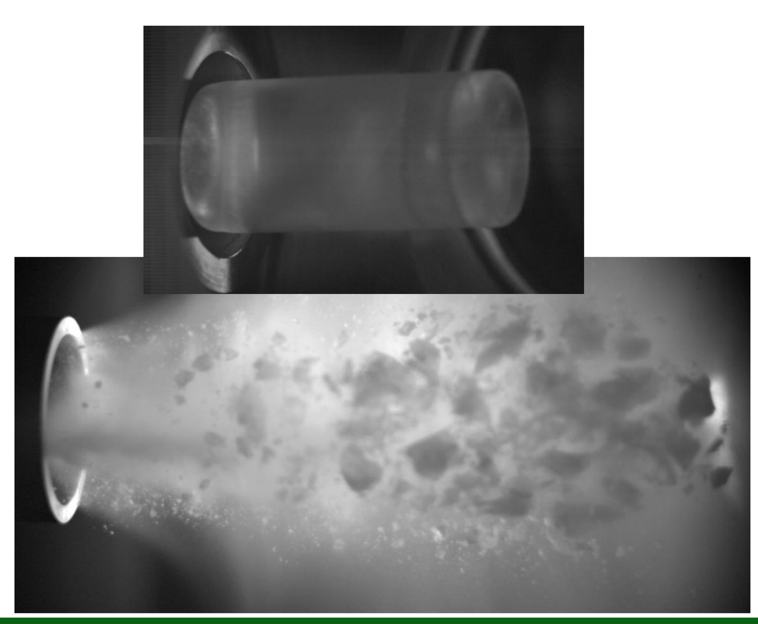




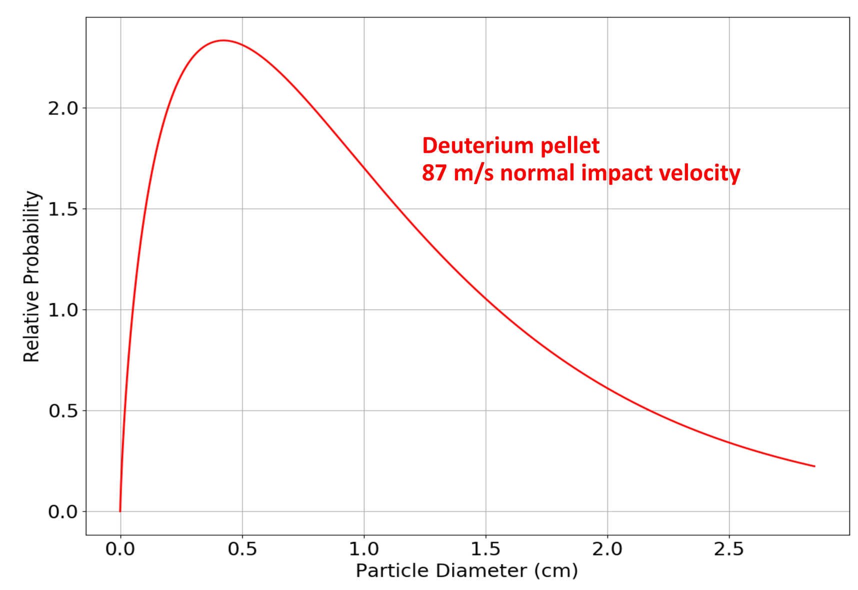
Pellet Fragmentation

High speed videos were captured of the fragment plumes generated by deuterium pellets impacting two shatter tube geometries; one with a square cross section and another with a circular cross section.



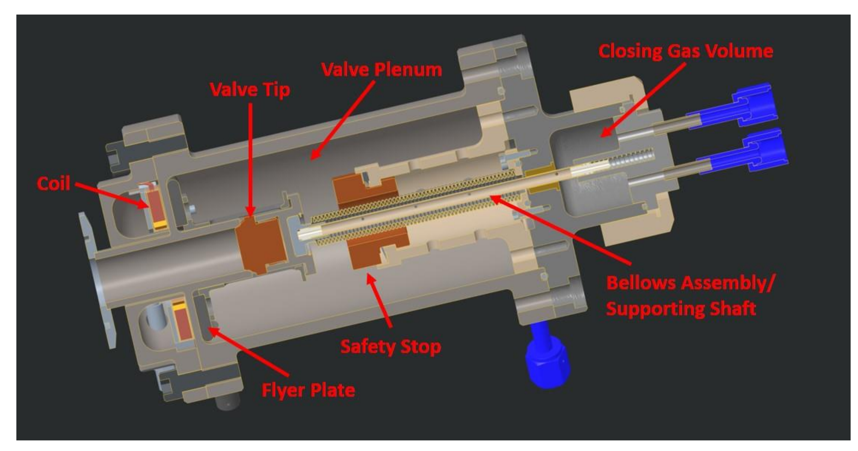


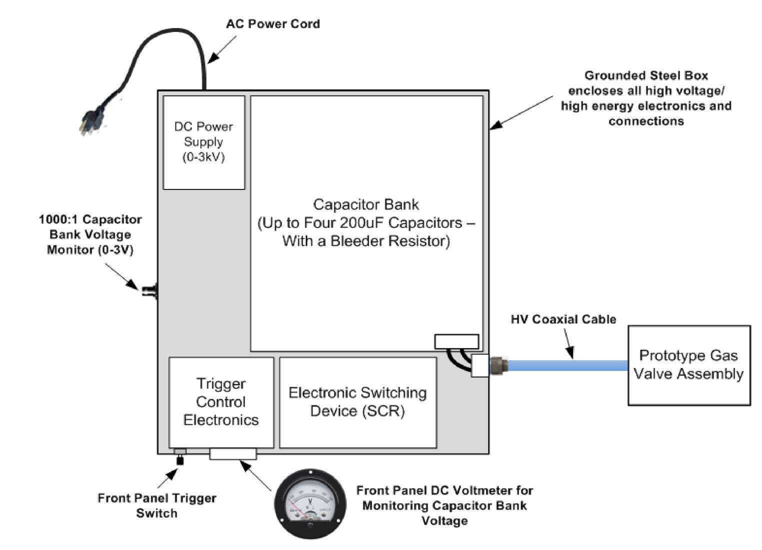
A model for fragmentation is presented in [3], but there is not suitable experimental data to compare to hydrogen pellets. Analysis can only be conducted using deuterium pellets. Fast videos are currently being analyzed to compare to the model shown below.

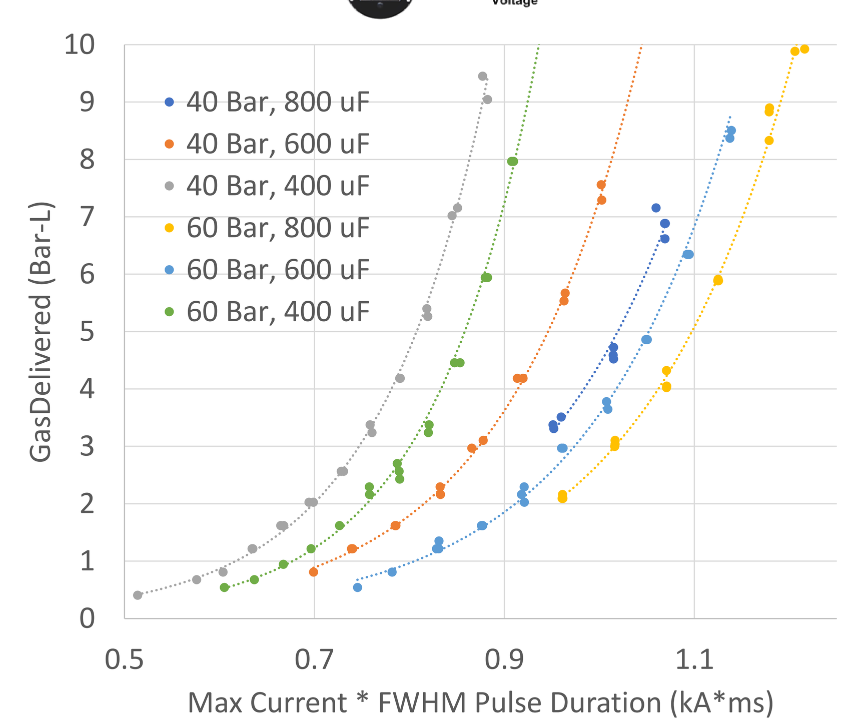


Flyer Plate Valve Operation

A propellant valve capable of operating in an ITER environment has been designed and tested. The valve operates by energizing a coil which induces eddy currents in an aluminum plate, which generates a repulsive force to open the valve [4]. The images and plots below show a CAD model of the valve, general schematics of the power supply, and the operational space of the valve.







Future R&D Plans

- Optimize hydrogen and hydrogen-neon mixture pellet formation, release, and fragmentation
- Measure threshold speeds of small hydrogen and hydrogen-neon mixture pellets
- Measure dispersion of large hydrogen pellets
- Characterize large pellet fragmentation
- Test flyer plate valve in ITER like B-field to qualify lifecycle survivability

References

[1] T. E. Gebhart et al., "Shear Strength and Release of Large Cryogenic Pellets from the Barrel of a Shattered Pellet Injector for Disruption Mitigation", Accepted for Publication, Fusion Science and Technology.

[2] A. G. Ghiozzi et al., "Pressure Response Optimization of an Eddy Current Driven Flyer Plate Valve for the ITER Shattered Pellet Injection System", Accepted for Publication, Fusion Science and Technology.

[3] T. E. Gebhart et al., "Experimental Pellet Shatter Thresholds and Analysis of Shatter Tube Ejecta for Disruption Mitigation Cryogenic Pellets", IEEE TPS, Vol. 48, Issue 6, June 2020.

[4] M. S. Lyttle et al. "Fast acting eddy current driven valve for massive gas injection on ITER", 2015 IEEE 26th Symposium on Fusion Engineering (SOFE), Austin, TX, 2015.

Acknowledgements

This manuscript has been authored by UT-Battelle, LLC under Contract No. DE-AC05-00OR22725 with the U.S. Department of Energy. The United States Government retains and the publisher, by accepting the article for publication, acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes. The Department of Energy will provide public access to these results of federally sponsored research in accordance with the DOE Public Access Plan (http://energy.gov/).