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

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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 used 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 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 current 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.

The present solenoid driven propellant valve used on the SPIs, cannot operate in the high steady-state magnetic field due to the magnetic circuits utilized to open the valve. A new valve is being designed and tested for operation in the ITER magnetic field and tritium environment. This valve operates by inducing eddy currents in an aluminum "flyer plate"[1]. The force from the eddy currents lifts the plate, which unseats the valve to allow high pressure light-gas to flow into the breech of the pipe gun to dislodge the pellet. The valve and corresponding power supply have undergone various design upgrades and multiple testing campaigns. Lifecycle testing with and without an external magnetic field will be conducted to ensure safe and reliable operation through the life of the valve. An image of the valve test stand can be seen in Fig. 1. Measurements have been made of the amount of gas delivered by the valve. Star CCM+ CFD simulations of the valve gas flow were conducted and validated against experimental data. The CFD model was then updated with an ITER relevant SPI barrel geometry. The breech volume was optimized for the maximum force on the pellet. The limitation on having the smallest possible breech volume is the thermal conduction to the cold-zone from close proximity to the room temperature surface.

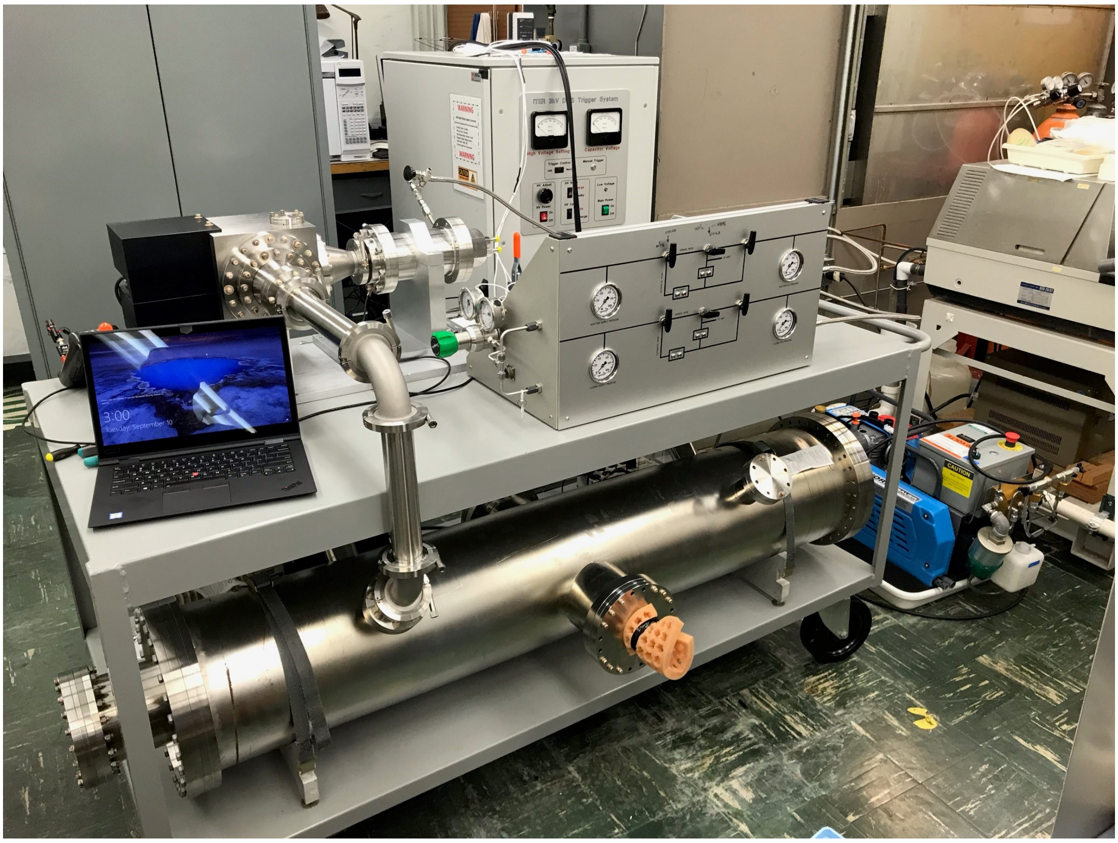

Figure 1: An image of the test set-up for the ITER relevant flyer plate valve without the external magnet.

The desire to use pure neon and argon in the SPI for runaway electron dissipation has introduced new challenges for the SPI technology. Pure neon and argon pellets are much more difficult to dislodge from the cold zone of the barrel due to high material strength compared to deuterium. The force needed to dislodge a pellet increases with size making release of the 28 mm ITER pellets a challenge. To better understand how to most effectively dislodge and accelerate pellets, the process of how they are formed, and the important influencing factors, such as temperature and pressure, must be understood and documented.
An experiment has been designed to measure the shear strength of pellets as a function of temperature. The experiment uses a load cell to measure the force applied by a motor driven shaft, which slowly compresses the rear of the pellet until it dislodges. The peak force is used to calculate the shear strength of the material in a pipe gun barrel. Four different barrel sizes were used to measure the shear strength of pellets made from pure deuterium, pure neon, deuterium-neon mixtures, and pure argon. These planned measurements, combined with ANSYS simulations of stresses produced by high-pressure gas flow and a mechanical punch striking the pellet, will allow for a more complete understanding of the pellet release process. This experiment will also be used to determine whether formation pressures and temperatures impact pellet breakaway strengths.

Understanding the pellet formation process and how pellet strength and release are related is an important aspect of SPI design. The propellant valve and mechanical punch must be designed to achieve the release parameters for the ITER SPI system to be reliable and successful. Pellets must also be able to survive the sometimes-treacherous flight path between the barrel and the plasma. Experiments were conducted to determine the pellet fracture threshold for pure deuterium, pure neon, various deuterium-neon mixtures, and pure argon pellets by measuring the perpendicular impact velocity [2]. It was found that pure deuterium, neon, and argon pellets have normal velocity thresholds for fracturing of 20, 8, and 6 m/s and there was no size dependence on these values. Deuterium-neon mixture pellets have a fracture threshold velocity that is dependent on the mass percentage of neon in the mixture. After pellets traverse their flight paths they are shattered before entering the plasma by impacting a bent tube or angled plate. A theoretical model of resulting fragment size in the plume, based on brittle fracture mechanics, has been developed [3]. This model is intended to provide a statistical description of the shattered material for computational simulations of disruption mitigation events using SPI. This model has successfully reproduced the fragment size distributions from the shatter tube geometries used on JET, DIII-D, and KSTAR. Figure 2 shows the estimated fragment size distribution for ITER sized pure deuterium, neon, and argon pellets. Estimated pellet speeds are 500, 350, and 150 m/s for deuterium, neon, and argon and the angle of the shatter surface is assumed to be 20-degrees. The deuterium and neon pellets are assumed to be accelerated using high pressure gas and the argon pellet is assumed to be accelerated using a mechanical punch. For a pure neon pellet to be fired using high pressure gas a thin shell of deuterium can be used to ease breakaway.

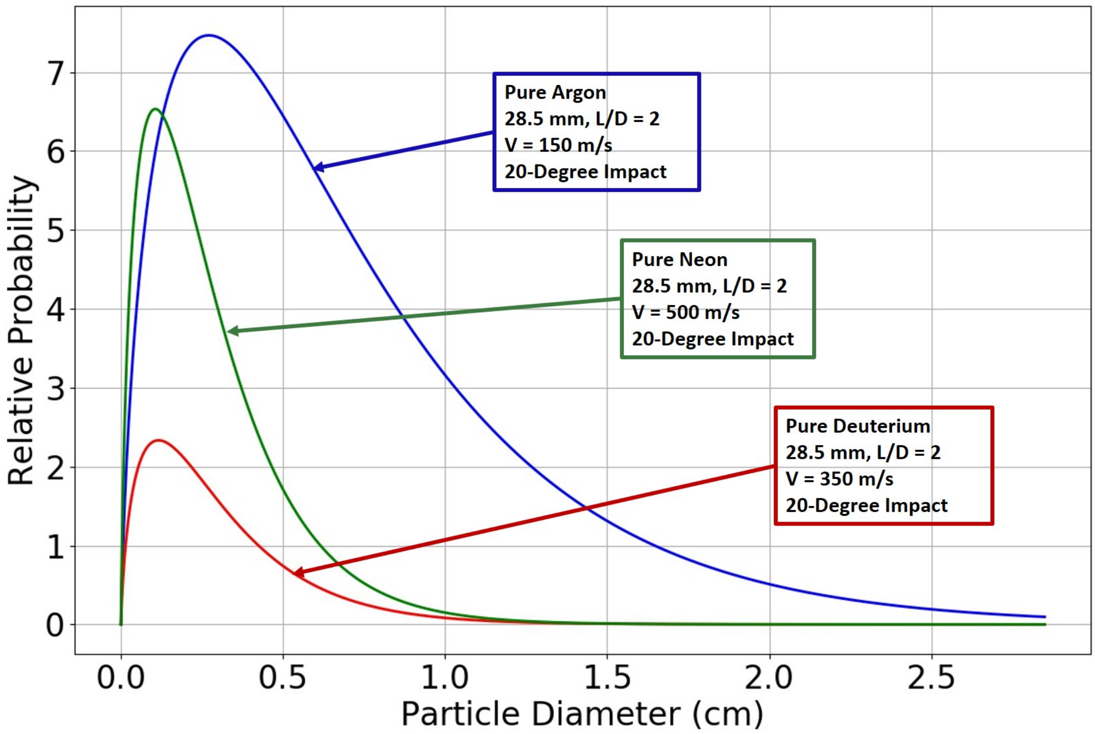

Figure 2: A plot showing the relative fragment size distributions for 28.5 mm diameter, 2 L/D, pure deuterium, neon, and argon pellets from the model in Ref. 3.

All these advances in technology and physical understanding of the SPI formation and shattering process will be incorporated in the ITER DMS design. An ITER prototype SPI test stand is under construction at Oak Ridge National Laboratory that incorporates our enhanced physical understanding of the SPI process. A new flyer plate valve will be used to dislodge and accelerate pellets that will be formed in conditions for rapid pellet formation, successful breakaway, guide tube survivability, and optimal shattering.

[1] S. A. Bozhenkov et al., Rev. of Sci. Inst. 78, 033503 (2007)

[2] L. R. Baylor et al., Nuc. Fus. 59 (2019)

[3] T. E. Gebhart et al., IEEE Trans. Plas. Sci. (2020)

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