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

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Abstract

Shattered pellet injection (SPI) has been selected as the baseline technology for the 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 developed at Oak Ridge National Laboratory (ORNL) is currently deployed and operational on DIII-D, JET, and KSTAR. These SPI systems are used in experiments for physics scaling to 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 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.

1. BACKGROUND AND INTRODUCTION

Effective disruption mitigation (DM) is an essential need for ITER to ensure that the machine is protected from the effects of high-current disruptions. Shattered pellet injection (SPI) has been chosen as the baseline DM method due to its ability to inject material deeper into the plasma for higher density assimilation when compared to massive gas injection (MGI) [1, 2]. There will be 24 shattered pellet injectors located on the equatorial plane of the ITER machine to rapidly inject material to thermally radiate the plasma energy, reduce the electromagentic loads on the machine and components, to suppress the formation of runaway electrons, and to dissipate a runaway electron beam, if one is formed. Experiments have been carried out on DIII-D, JET, and KSTAR to provide information for physics scaling to the much larger ITER machine. The injectors installed on these machines were able to utilize preexisting technology, understanding of pellet formation, and pellet survivability information due the the moderate pellet sizes and the relatively tame environment when compared to ITER. ITER has planned for 28.5 mm diameter pellets with a length-to-diameter ratio (L/D) of 2 [3]. This pellet size introduces many challenges; pellet formation, pellet release, in-flight pellet survivability, and scaling fragmentation models to large pellets. An ITER-like SPI was designed and built at Oak Ridge National Laboratory (ORNL) to conduct experiments intended to inform the design and reliability of the ITER SPI system. This test bed is a liquid helium cooled single-barrel pellet injector capable of forming and launching large ITER-sized pellets and has been used in initial characterization studies. The design and operation of this system, along with the results from initial investigations and implications to the ITER SPI design are presented in later sections of this paper.

The propellant valves used to dislodge and accelerate pellets used on DIII-D, JET, and KSTAR will not work properly in an environment with a high ambient magnetic field due to its use of a solenoid-plunger configuration. An eddy current driven valve [4] has been designed and optimized for launching large DM pellets. The design and testing of this prototype valve are discussed in this paper.

2. ITER SHATTERED PELLET INJECTION TEST STAND

The ITER SPI test stand at ORNL is meant to replicate the geometry of the current iteration of the ITER SPI design to most accurately study the most important operational parameters of pellet formation, acceleration, flight path survival, and fragmentation. It has a liquid helium cooled coldhead and utilizes a liquid nitrogen precooler to cool the incoming pellet material gas to ~80 K to decrease pellet formation time. Figure 1 shows a labeled cross-sectional view of the CAD image of the system. The system incorporates a human machine interface (HMI) to interface to a programmable logic controller (PLC) that operates valves throughout the system. A gas manifold is used to control the pellet formation process. Gas is fed from high pressure cylinders into a 62 L volume to provide an accurate measure of the amount of gas fed into the barrel. This method of inventorying the amount of material sent to the barrel ensures that the pellet formation process is repeatable and reliable. The 62 L volume...
also serves as a mixing reservoir for deuterium-neon or hydrogen-neon mixture pellets. This testbed was designed to easily incorporate modifications and expansions with the goal of eventually testing a full ITER-like injection line. Initial experiments to measure the dispersion of pellets directly out of the barrel were conducted without the propellant gas removal volumes. After the dispersion tests were completed, the propellant gas removal volumes were incorporated to allow for the study of fragment plumes without significant propellant gas. The main diagnostic used to determine pellet conditions downstream is high speed imaging. Two fast cameras are available to image the pellet in the propellant gas removal cubes or in the large expansion tank downstream. The expansion tank is designed to incorporate a flat target with a grid etched into the surface for dispersion measurements, or any conceivable shatter tube design. Figure 2 shows an image of the system with the pellet gas removal volumes in place. The results of the tests and analysis enabled by this testbed are presented in the following sections of this paper.

![Fig. 1. A labeled CAD cross-section of the ITER SPI testbed.](image1.png)

![Fig. 2. An image of the ITER SPI experimental device.](image2.png)

3. PELLET FORMATION STUDIES

Pellet formation is a critical aspect of the SPI process and largely depends on the physical properties of the pellet material and the cold zone temperature. Operation on ITER only allows for hydrogen pellets due to the classification of deuterium as a nuclear material. Since deuterium is commonly used as the primary fuel for most currently operating tokamaks, hydrogen has not been widely explored as a necessary option for SPI pellets. The ITER SPI test bed was used to conduct studies to compare the formation of hydrogen and deuterium pellets. The coldhead temperature was held constant at ~8 K and the pressure in the barrel was kept low (<10 mbar), to minimize conduction heat transfer from the gas to the barrel and pellet during formation. Figures 3 show the formation of ITER-sized deuterium and hydrogen pellets. The blue curve on both plots indicates the pressure in the 62 L reservoir, which is integrated to calculate flow to the barrel. The magenta line indicates the coldhead temperature and the green line indicates the pressure in the barrel. Deuterium sublimates at a rate much faster than hydrogen, so the pressure does not rise in the barrel at this flow rate until ~85% of the pellet is formed. While forming a hydrogen pellet, the pressure rise in the barrel is significant almost immediately. A rapid rise in pressure is a risk due to the ability of the gas to conduct heat and cause rapid sublimation of the partially formed pellet. This will result in a positive feedback cycle that can result in a rapid and significant pressure increase in the barrel. Full hydrogen and deuterium pellets require 38.2 and 44.4 bar-L of gas, which, if rapidly sublimated, would result
in a pressure hazard if the barrel volume is not properly pressure relieved. The ITER SPI testbed has a one bar relief valve to ensure pressure safety.

The time required to form a ~97% complete hydrogen pellet is ~100 minute which is much longer than the desired 30 minute target for ITER. A full 2 L/D deuterium pellet takes ~34 minutes to fully form. Figure 4 shows a plot comparing the calculated flow rates (mbar-L/s) and barrel pressures (mbar) for hydrogen and deuterium pellet formation. Due to the fast pressure rise in the barrel when forming a hydrogen pellet, the flow had to be decreased much earlier in the formation process than when using deuterium. The flow rates and the derivative of pressure multiplied by the barrel volume can be used to calculate the desublimation rate of material, which can be used to calculate the rate at which heat is removed from the pellet material as the pellet is formed. The amount of heat removed assumes gas the incoming gas is at 80 K and is brought down to the triple point temperature (13.8 K for hydrogen, 18.7 K for deuterium). Figure 5 shows a plot comparing the heat removal rates while forming hydrogen and deuterium pellets.

To fully form hydrogen and deuterium pellets 7734.6 and 5213.2 J of heat need to be removed from the pellet material. Heat removal is greatly impacted by the thermal conductivity of the material, which is temperature dependent. Figure 6 shows a plot comparing the thermal conductivity of hydrogen and deuterium from 4 K to the triple point of the material. To better understand how heat is removed from the material, tests were conducted to determine the temperature of the pellet surface while forming the hydrogen pellet. Feed gas flow was stopped during multiple points of the formation process and the pressure that the barrel dropped to was taken to be the vapor pressure of the material of the pellet surface. From this, a temperature can be inferred from known vapor pressure curves for solid hydrogen. The vapor pressure derived temperatures at different times is shown on Figure 3. The condensation coefficient [5], which is the probability of an impinging gas molecule condensing on the pellet surface is highly temperature dependent and approaches zero just below the triple point temperature. At a surface temperature of ~11 K, the condensation coefficient is very low, resulting in a very inefficient pellet formation process. One way to possibly remedy the formation time issue is to decrease temperature of the coldhead during the pellet formation process. Doing this, however, has negative effects on pellet release, which is to be explained in the following section.

Fig. 3. (left) A plot showing pellet formation parameters during the formation of a large deuterium pellet. (right) A plot showing pellet formation parameters during the formation of a large hydrogen pellet. The plot includes a test conducted to infer pellet surface temperature from vapor pressure throughout the formation process.

Fig. 4. A plot comparing the pellet material gas flow rates and barrel pressures from the formation hydrogen and deuterium pellets.
Fig. 5. A plot comparing the heat removal rate from hydrogen and deuterium pellet material during the formation process. The total energy to remove for a solid pellet is displayed.

Fig. 6. A plot comparing the heat removal rate from hydrogen and deuterium pellet material during the formation process.

4. SCALING PELLET RELEASE FORCES

Reliable release of intact pellets is a key issue for the design of a SPI system. The pellet material and coldzone temperature are the main factors in pellet material shear strength as reported in [6]. Using the measured shear strengths of hydrogen and deuterium at 8 K, the force needed to dislodge a pellet can be calculated. ITER-sized hydrogen and deuterium pellets require 1530 and 2800 N for release. Computational fluid dynamics (CFD) modeling of the ITER prototype propellant valve, known as the flyer plate valve (FPV), was conducted to calculate the force applied to the pellet face from the impinging high-pressure gas [7]. Experiments have shown that deuterium pellets at 8 K do not release when using the FPV with 60 bar propellant gas pressure, even though the CFD results indicate that required forces are marginally met. This result shows that the force must be applied for an adequate amount of time for the pellet to release. Firing deuterium ITER-sized pellets with this valve and pressure requires warmer temperatures. The FPV operating at 60 bar provides a large amount of force compared to what is required to dislodge a large hydrogen pellet. The impulse applied by the gas is so great that it results in catastrophic failure of the hydrogen pellet structure. The temperature gradient through the pellet material, as described in the previous section, may play a role in the fragile nature of large hydrogen pellets. These results point to a delicate balance of applying the correct amount of force for an adequate duration, but not allowing the applied force to present too large of an impulse. Future planned work will address these issues.

5. PELLET DISPERSION CHARACTERIZATION

As pellets exit a barrel into free-flight, the propellant gas used to accelerate the pellet can induce a non-uniform force on the rear of the pellet. This results in the pellet veering from a perfectly straight flight path and because of this, a dispersion angle must be accounted for in all non-guided free-flight that includes jumps across gate valves, diagnostic chambers, or pumping gaps. Since hydrogen pellet formation and release have thus far proven to be problematic, deuterium pellets were used to measure the dispersion of the ITER-like SPI geometry. Experiments were conducted by firing the pellet directly into the expansion chamber from the barrel, without the propellant gas volumes installed. Pellets were fired onto a target that contained a laser-etched grid. The barrel was laser aligned to the center of the target to ensure measurements were as accurate and precise as possible. Figure 7 shows images and information from five deuterium pellets and the measured dispersion. Factors such as amount of
propellant gas used and coldhead temperature are shown as well. Figure 8 shows a bullseye plot showing the strike locations of the pellets with respect to the centerline of the barrel. The shot numbers listed in Fig. 7 correspond with the shots shown in Fig. 8.

Completely formed deuterium pellets have a mass of 7.3 g, while a fully formed hydrogen pellet has a mass of 3.1 g. This mass differential is envisioned to result in an increased (~2X) dispersion due to the magnitude of the non-uniform force remaining the same without modifying the operation of the FPV. Future studies will be conducted to measure the dispersion of pure hydrogen pellets in a geometry similar to the most recent ITER SPI design iteration.

6. PELLET FRAGMENTATION

Pellets are launched into an angled tube, called a shatter tube, just before entering the plasma to fracture the pellet into many small fragments. Gas is also generated during the pellet impact primarily due to localized frictional heating causing sublimation of pellet material. Many experiments and analysis have been conducted on fragment plumes generated by pellets of many speeds, compositions, and shatter tube geometries [8 - 10]. The ideal fragment size distribution is not yet known and therefore the ideal shatter tube geometry for ITER has not been decided upon. Tests were conducted with the ITER SPI test stand to compare pellet fragmentation from two different shatter tube designs, a 60 mm square cross section and a 60 mm diameter circular cross section. Both tubes have an impact angle of 20-degrees and were tested using pure deuterium pellets. Figure 9 shows images of the resulting spray from each tube design. The circular cross section tube results in a more colulated spray compared to the square cross section shatter tube. When the pellet strikes the flat surface of the square shatter tube, the fragmented material fans out to the top and bottom surfaces forming a fan like plume. The material is colulated in the circular shatter tube due to the momentum of the material forcing the plume to the outside apex of the circular cross section.
Analysis of fragment sizes produced in laboratory experiments have been used to derive a model that provides a function for the relative probability that any particular fragment size will be produced [8]. This model requires the minimum perpendicular velocity required to fragment a pellet of a specific material (known as the threshold velocity), the actual normal impact velocity of the pellet, the pellet dimensions, and a material specific constant used to scale the probability function. Figure 10 shows the relative probability function for a 28.5 mm deuterium pellet with a 2 L/D striking a 20-degree shatter tube with an initial speed of 250 m/s. This results in a normal impact velocity of 87 m/s and the fragments are assumed to be spherical for volume calculation purposes. Hydrogen was not included in the initial studies to determine the threshold velocity and material specific constant, but will be studied in the future.

7. FLYER PLATE VALVE OPERATION

An eddy current driven valve for use on the ITER SPI has been designed and tested over a range of operational parameters. The valve operates using a high voltage power supply which utilizes a capacitor bank consisting of 2-4 3 kV, 200 µF capacitors with an RLC network to tailor the resulting current pulse. The capacitor bank capacitance values range from 400 – 800 µF. The valve coil is energized by the discharge of the capacitor bank which results in a 0.75 – 2 ms pulse with an amplitude that varies based on the RLC configuration. As current flows through the coil, eddy currents are generated in the aluminum “flyer plate” and a repulsive force is generated, lifting the flyer plate and moving the valve tip off of the sealing seat. Although the valve geometry is very different, the operating principal of this valve is similar to that of a valve developed at Juelich [11]. The FPV has a 1.35 L plenum volume, which is the volume that the propellant gas is stored until the valve is actuated. This allows gas to flow downstream to dislodge the pellet. Figure 11 shows a cross-sectional CAD image of the valve with all major components labeled.
The operational space of the valve was scanned at plenum pressures of 40 and 60 bar for two, three, and four capacitors. The operational scan reveals how the initial voltage on the capacitors is related to the amount of gas provided by the valve. For a more direct comparison, the amount of gas delivered is plotted versus the product of max current amplitude multiplied by the FWHM of the current pulse. This is to ensure that the output energy of the power supply is most accurately correlated with the amount of gas delivered. Figure 12 shows a plot of the scanned operational area.

![Plot showing gas delivery](image)

**Fig. 12.** A plot showing the amount of gas delivered by the valve compared to the product of max current amplitude and FWHM pulse duration for combinations of two plenum pressures and three capacitance values.

The amount of gas delivered by the valve has impacts on pellet survivability and design of downstream propellant gas removal volumes. Preliminary testing with ~15 K deuterium pellets show that if more than 5 bar-L of gas is delivered to the rear of the pellet with a 60 bar valve plenum pressure, it will result in a fractured pellet, decreasing reliability of the SPI system. Delivering under 2 bar-L of gas will result in the pellet not releasing from the coldzone. All tests with hydrogen pellets and a 60 bar valve pressure resulted in fractured pellets. Simulations show that 40 bar is adequate for dislodging hydrogen pellets, but this has yet to be proven experimentally.

Lifecycle testing of the valve in a magnetic field 1.3 times the maximum field that a valve will be subject to on ITER is necessary for qualifying of the components that are subject to torque from the ambient magnetic field. A helmholtz coil configuration test stand is currently under construction to conduct these tests. The valve must survive 3000+ in-field cycles. A new iteration of valve and power supply are currently in the design phase as well. The scan of capacitance is meant to inform the design of a new compact power supply. Reducing the number of sizable capacitors is essential for this effort and the operational scans show that desired gas delivery is possible at all capacitance values.

8. DISCUSSION AND FUTURE RESEARCH

The preliminary tests outlined in this paper are an important beginning to better understand the design needs for the ITER SPI system. Scaling to large pellets in a high-field, nuclear environment has proven to be a challenge. The ITER SPI test bed built at ORNL is a useful tool for determining optimal parameters for pellet formation, release, and fragmentation, enabling experiments to uncover information for system design constraints (such as dispersion and pellet survivability limits), and testing hardware such as the FPV, shatter tubes, and propellant gas removal designs.

Pellet formation studies have shown that hydrogen pellets take much longer to form than deuterium because the thermal conductivity is ~60% that of deuterium and the triple point temperature is 5 K lower. This means that the temperature gradient through the pellet during formation is steeper and the surface approaches the triple point temperature faster than deuterium. This results in a decreased condensation coefficient, resulting in elongated pellet formation times.

Dislodging deuterium pellets from the barrel with the FPV at 60 bar is not possible due to the large force required. Deuterium pellets need to be warmed to higher temperatures than the 8 K formation temperature prior to firing. Hydrogen has ~60% of the strength of deuterium, so the force required to dislodge them should be achievable, based on simulations. Due to its lower strength, however, the FPV operating at 60 bar causes a catastrophic failure of the pellet structure, resulting in an elongated spray of small fragments exiting the barrel instead of a full pellet.

The dispersion measured using deuterium pellets was ~0.54-degrees or less. Due to the lower density of hydrogen, a full hydrogen pellet will be less than half as massive as a deuterium pellet, meaning that the non-
uniform force imparted by propellent gas exiting the barrel around the pellet will likely have a greater effect on a hydrogen pellet.

Two shatter tubes were designed and tested using deuterium pellets, one with a circular cross section and one with a square cross section. The two tubes were tested and found to produce plumes with drastically different geometries. The square tube results in the fragments exiting in a fan-like sheet, where the majority of the mass is located at the top and bottom edges of the plume. The circular tube results in a more columnated fragment spray.

The FPV was used to fire many pellets with great success. Scans of its operational space were conducted to inform the design of future iterations and to better understand parameters needed for the design of downstream propellant gas removal volumes. Scans were conducted by varying the capacitance in the power supply system to allow for the design of a more compact system for use in ITER.

There are currently still significant unknowns for the ITER SPI system design. Many of these unknowns come from the required use of hydrogen as the base pellet material instead of deuterium. Future work will focus on characterizing pellet formation, release, and fragmentation of hydrogen pellets of all sizes. The FPV will undergo lifecycle testing in a magnetic field generated by a helmholtz coil configuration to simulate the ITER environment.

The overall goal of the findings presented here, and the future planned experiments, is to provide information to drive the design of a reliable SPI based DMS system for ITER.

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