SHATTERED PELLET INJECTION TECHNOLOGY
DESIGN AND CHARACTERIZATION FOR
DISRUPTION MITIGATION EXPERIMENTS*

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Abstract

The technology to form and shoot high-Z cryogenic solid pellets mixed with deuterium using a gas gun that are shattered upon injection into a plasma has been developed at ORNL for mitigating disruptions. This technology has been selected as the basis for the baseline disruption mitigation system on ITER. The development of shattered pellet injection systems has progressed to be able to accelerate large pellets of pure argon and neon with or without including deuterium. Impact studies have been carried out at shallow angles to determine funnel performance in guiding pellets from multiple barrels into a common injection line and across pumping breaks. The characterization of the shattered spray has also progressed with fragment size measurements as a function of pellet speed showing a strong inverse relationship. Results of these studies are reported with implications for applications on existing and future tokamak devices.

1. INTRODUCTION

The technology of forming and firing high-Z cryogenic pellets mixed with deuterium that are shattered upon injection into a plasma has been developed at ORNL for mitigating disruptions [1]. The successful mitigation research using this technique on DIII-D [2] has led to it being selected as the basis for the baseline disruption mitigation system on ITER. In the devices utilizing this technique, known as shattered pellet injectors (SPIs), large pellets of neon and argon that can be mixed with deuterium are cryogenically solidified from gas that desublimates on a cold section of a gun barrel. The pellets that form are shattered upon impact when fired into a bent tube just before entering into a disrupting plasma in order to radiate the plasma energy and mitigate possible damage to in-vessel components and to densify the plasma to suppress the formation of or dissipate already formed runaway electrons [2,3,4]. The shatter tubes for the SPIs are characterized in the laboratory before deployment and optimized for the specific device. The pellet mass and speed are measured before shattering, and this data combined with fast camera views of the SPI spray entering the plasma and plasma diagnostic data enable detailed studies of the disruption mitigation effectiveness [5,6,7].

In support of disruption mitigation research for ITER, SPI systems have been designed and fabricated for use in thermal mitigation and runaway electron dissipation experiments on DIII-D [8] and JET. Pictures of these devices inside of their guard vacuum chambers and without the normal thermal insulation material are shown in Fig.1. These systems have common features of 3 different size barrels that form pellets in-situ where the barrels are connected to a cooled copper block. When the pellets are fired by a high-pressure gas pulse they are collimated with a shallow funnel into a single injection line that enters the tokamak vacuum chamber. The large impurity pellets are formed by desublimation from a low-pressure gas that is fed into the barrels that are in contact with copper that is cooled with cold helium and are maintained cold intact ready to fire until needed. The pellets can remain in this state nearly indefinitely as long as they remain cold and do not sublimate away the pellet material. Pressurized gas is used to dislodge and accelerate the pellets in the barrel that directs them down an injection line that has gaps to remove as much of the propellant gas as is possible in the available space to avoid influencing the plasma shutdown before the shattered pellet material arrives. The bent shatter tubes are bent stainless steel tubes that are mounted inside the vacuum vessel of the tokamak. The pellets in the three barrels can be fired independently or simultaneously as is the example shown in Fig. 2.

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2. DESIGN ISSUES UNDER INVESTIGATION

Several design issues have been encountered in implementing shattered pellet injectors on present machines and in designing the disruption mitigation system for use on ITER. Among these issues are the propellant gas removal from the injection line, sufficient pumping to remove vapor released from the pellets before firing, dislodging argon pellets from the barrel cold zone, formation and acceleration of large pellets, shattered material spray optimization, shallow impacts from funnels and curved guide tubes, and simultaneity of injection of multiple pellets. Experimental investigations of these issues have been undertaken to improve the designs to make them compatible with the intended use and are reported in the remainder of this paper.

It was quickly discovered on the original SPI implementation on DIII-D [2] that the vapor from neon pellets formed in the SPI could impact the plasma breakdown. The pellets were formed well in advance of the plasma shot and the injection line valve was open at the beginning of the plasma breakdown. The pellet temperatures (~10 K) were such that the vapor pressure of the neon was in the $10^{-4}$ mbar range, which was high enough that some of the gas was able to enter the torus and inhibit the breakdown. Possible solutions were to operate at colder temperatures or add more pumping in the injection line. Colder operation turned out to be problematic as it became impossible to dislodge the pellets with the available gas pressure in the propellant valve. Therefore, additional pumping capability was added at the end of the gun barrel and in the microwave cavity diagnostic. It has also been found that vapor pressures above ~1 mbar can result a thermal runaway of the pellet from conduction to the barrel that builds up pressure behind the pellet in the breech and can lead to the pellet being self-fired. Curves of the vapor pressure for candidate SPI cryogenic materials are shown in Fig. 3 where it becomes clear the maximum temperatures that can be operated to prevent self-firing. The vapor from sublimating the pellet also forms at the pellet-barrel interface and loosens the bonds to the wall making the pellet easier to dislodge. When this self-firing happens the pellet only reaches speeds of < 50 m/s, but it would likely result in pellets entering the plasma or empty torus chamber when not desired.

The additional pumping capability also aided another issue, which is the removal of propellant gas before it can enter the torus in front of the pellet. Since the gas use to propel the pellet has a sound speed that is higher than that of the pellet, it can reach the plasma surface before shattered pellet material. If the gas is entirely made up of deuterium or helium it has little impact on the plasma before the pellet material reaches it. However, when pellets of neon or presumably argon are used, some small level of the pellet material can get entrained in the gas and have an impact on the plasma before the shattered pellet material can reach it. This can be some several milliseconds in advance if the pellet, which is enough time to begin the thermal collapse of the plasma and
reduce the effectiveness of the pellet material at radiating the plasma [7]. This was found to be the case on the SPI2 system on DIII-D and has required a redesign of the pumping breaks in the injection line. The use of computational fluid dynamics codes is required to optimize and verify the designs of the injection lines. The JET SPI system was designed with significantly more pumping capability than the SPI2 and therefore is not anticipated to have either a vapor pressure issue with the plasma or early gas arrival in mitigation experiments.

It is desirable to inject as much material simultaneously for effective disruption thermal mitigation in a large plasma device such as ITER. Tests have been performed in the laboratory to ascertain the maximum practical pellet sizes with respect to formation time and the ability to break them free and shatter. The largest pellets that have been successfully formed in laboratory experiments are 34 mm in diameter, which took on the order of an hour to complete the formation process. The solid material in the pellets has relatively poor thermal conductivity and thus large pellets cannot quickly remove the heat of fusion during the desublimation process that forms the pellets from the outside to inside. This time to remove the heat dictates how long it takes to form the pellet. Trying to form the pellet faster by introducing the pellet gas at higher pressure results on a thermal runaway condition and quick sublimation of the formed material. From these tests it was determined that the largest practical size was on the order of 28 mm diameter, which takes nearly 30 minutes to fully form a pellet with sufficient cooling. Dislodging and acceleration of such large pellets remains an area of research.

3. PURE ARGON AND NEON PELLET ACCELERATION

The high shear stress of solid argon in particular presents a challenge for dislodging and accelerating argon pellets that are formed in-situ in a cold barrel at allowable gas pressures. In order to keep the vapor pressure low, the pellet temperature must be kept cold (< 55 K) as shown in Fig. 3, which increases the shear stress and bonding to the barrel from than at higher temperatures closer to the triple point (84 K). Therefore, mechanical punches have been developed that can apply higher impact energies than high-pressure gas alone to dislodge these pellets from the cold barrel. Punches using high pressure gas and solenoid drivers have been developed for this application. The gas operated punch utilizes a piston inside the housing connected to a propellant valve to capture the gas impulse from the valve and uses it to accelerate the punch tip into the pellet. An example of such a punch design is shown in Fig. 4. The punch piston head is spring loaded for return after the pulse. The
housing allows gas flow around the piston after it reaches its maximum travel past the pellet location, where it then flows down the punch stem to flutes in the tip where it then accelerates the released pellet. The development of low mass punches that can dislodge the larger size pellets without buckling the shaft or cracking the piston head is quite challenging.

Tests of gas punches like that shown in Fig. 4 have demonstrated that argon pellets of up to 12.5 mm diameter can be dislodged successfully and accelerated to speeds up to 160 m/s. The punch itself reaches a measured speed of ~25 m/s when it hits the pellet, thus the primary acceleration of the pellet is from the 50-bar propellant gas that flows around the punch after it dislodges the pellet. The impact energy of the punch on the pellet is ~10 J, which is largely absorbed by a spring at the end of the punch travel. The punch has to be designed to survive a number of impacts with the spring with no pellet present. The speeds of the pure high-Z pellets are in general quite a bit slower than those used for thermal mitigation that has a large fraction of deuterium in the pellet because of the higher mass. This has a significant impact on the shattering fragment size achieved as discussed in the following section.

FIG. 4 A CAD model image of a pneumatic mechanical punch for dislodging and accelerating argon and pure neon pellets in an SPI. A picture of a 12.5 mm punch tip is shown at the bottom.

4. PELLET AND SHATTERING CHARACTERIZATION

An important aspect of how the SPI shatter spray impacts the plasma and mitigates disruptions is the speed and size of the fragments that are generated and how well collimated they are, both spatially and temporally. As a diagnostic to verify integrity before the pellet reaches the shatter tube, a resonant microwave cavity is used [10]. The pellet pass through the cavity that is typically installed down steam of the SPI barrel after one or more pumping breaks to remove propellant gas in order to measure the pellet mass, integrity, and speed. The dielectric constant of the pellet material detunes the cavity as it passes through producing a signal that gives the mass and speed. The pellet speed measurement accuracy is ~10% and the mass accuracy is ~5%. Fragments that may result from the acceleration are easily discerned in the cavity data. An example of the microwave cavity data from a large neon pellet is shown in Fig. 4 of Ref. 10.

The shattering characterization is measured in the laboratory by fast video camera imaging of the spray and alternatively by foil impacts. The latter measurement technique is compromised when multiple large fragments puncture the same location on the foil. The video imaging is complicated when large numbers of small fragments are generated that can block the view across the shattered plume. In this case, the foil technique is more reliable. Examples of these two types of sprays are shown in video images in Fig. 5.
The speeds achieved with such large high-Z pellets dislodged by a punch have been found to result in large fragment sizes in excess of 1 mm as can be seen in the right side of Fig. 5. This size distribution is much larger than for higher speed low-Z pellets at the same ~20-degree impact angle shatter tube [2] and is clear by comparing the two images of Fig. 5. The larger fragment size is desirable for deeper penetration in high performance plasmas. Higher speed pellets on the order of 500 m/s that are achieved with high pressure gas and have a high deuterium content result in much finer particles and higher gas content in the resulting shattered material spray and would not penetrate as deep in a large high temperature plasma. The addition of a gas operated punch like shown in Fig. 3 for pellets of pure argon and neon is being implemented for upcoming experiments on runaway electron suppression and dissipation for both the DIII-D and JET SPIs.

![Image of spray from an 8 mm shattered D₂ pellet at 500 m/s and argon pellet fired with a punch at 180 m/s after exiting a mockup of a shatter tube for the JET SPI. Fragments greater than 1 mm in size are observed from the argon pellet, but are mostly sub mm with significant vapor produced from the D₂.](image)

Studies have begun on the size distribution in order to optimize the shatter tube geometry and pellet speed for maximum shard size and penetration in the plasma [12]. An example of the size distribution from the video images from an argon pellet as in Fig. 5 is shown in Fig. 6. The fragment size distribution has been found to be quite repeatable at this velocity range. These same studies of the fragment size distribution also enable a temporal evolution of the fragments to be determined. Measurements of shattered argon pellets as in Fig. 5 have shown that the duration of fragments exiting the shatter tube is < 2.0 ms with the fast majority within 1 ms. Similar spray durations have been observed for neon shattered pellets in the same shatter tube. Modeling of the size distribution using a statistical fragmentation model originally developed for exploding munitions [13] has yielded good agreement with the size distribution function shape.

5. SHALLOW IMPACT STUDIES

The use of funnels in the injection line of an SPI system will be required whenever multiple barrels are combined into a common guide tube and when crossing a gap for pumping or when jumping across valve openings. An example of an SPI injection line being designed for use on DIII-D and KSTAR is shown in Fig. 7. In this example the pellets first cross a gap for pumping in a cube and then enter a funnel before entering a microwave cavity that allows gas to expand and be pumped in a cross just after the cavity. The funnels are usually needed to collimate the trajectory of the pellet after dispersion that naturally occurs when exiting a guide tube in the injection line. It is desirable to minimize the funnel length in order to shorten the overall injection line as much as possible to fit in the allowable space. Thus, a study has begun to investigate the maximum impact angle that a pellet can withstand in a funnel. From earlier experiments with D₂ pellets [1] it was found that velocities of the pellet normal to the inclined surface in excess of 20 m/s resulted in fracturing of the pellets. These studies actually gave the insight into developing the SPI concept. This result lead to the designs of funnels with 2-degree taper angles for D₂ fueling pellet applications and these have proven to function as intended and allow the delivery of intact pellets to the plasma.
The dispersion from 7 mm neon pellets exiting a guide tube similar to that shown in Fig. 7 has been measured with the use of a fast video camera to be less than a 2° half angle, with more than 90% of the pellets within 1.5°. Therefore, the gaps and collecting funnel design need to consider this dispersion in order to ensure the pellets are all entrained in the injection line without fracturing in transit.

**FIG. 6** Histogram (top) of fragment sizes observed from an argon pellet as in Fig. 5 and a time history of the fragment mass exiting the shatter tube.

**FIG. 7** CAD model image of the collector funnel, microwave cavity, and pumping system being designed for SPI systems similar to those shown in Fig. 2. Pellets travel from the barrels on the right to the left.
It is expected that neon and argon and D₂-neon mixture pellets will have different shallow impact fracturing properties than D₂ and therefore tests have begun in the laboratory to determine the allowable impact angles. An example result from these studies is shown in Fig. 8 where neon pellets with a D₂ shell were launched into a cylinder tilted at different angles to simulate a funnel impact. It has been found that neon pellets starts to fracture at normal velocities of 15 m/s (2° impact at 400 m/s). At this impact velocity the pellet fractures into a few large pieces that are roughly intact as shown on the right of Fig. 7, which would likely not impact the resulting SPI spray when entering the plasma chamber after transport through the shatter tube. At higher normal velocities of 35 m/s the pellets are broken more severely and spread apart spatially, which is more likely to result in a spray that is less collimated spatially and temporally. Thus far from these studies it is apparent that funnels with impact angles less than 2° are necessary for optimal performance of the SPI. Further detailed studies of actual size pellets and speeds with the actual injection line design are needed to ensure intact transport through the injection line.

Curved guide tubes are another place where shallow pellet impacts can occur. Small 2 mm D₂ fueling pellets have been found to survive transport in curved tubes with as small as 60 cm bend radius if kept below 200 m/s pellet speeds [14]. It is not known how larger impurity pellets survive in gradual bends as a function of pellet speed and is an area of future research to support future SPI applications where a direct line of sight to the plasma is not available.

6. SUMMARY

The SPI technology developed for disruption mitigation in high performance tokamak plasmas has progressed to the point of being selected as the baseline disruption mitigation system on ITER. The development of shattered pellet injection systems has been extended to include the ability to accelerate large pellets of pure argon and neon without including a deuterium shell in the case of neon. Pneumatically driven mechanical punches have been developed to dislodge and accelerate pure neon and argon pellets up to 12.5 mm in size and speeds of up to 200 m/s. Further development continues for larger pellets envisioned for use on larger tokamaks.

Experimental results on DIII-D have shown the importance of adequate vacuum pumping to remove the propellant gas that accelerates the pellet to prevent premature thermal collapse of the plasma before the shattered pellet material reaches the plasma. This has led to improved designs of the injection lines by adding more pumping capability and will lead to careful testing of the gas removal in future SPI system designs including the use of computational fluid dynamics codes to optimize the design. Another aspect of the injection line that has been studied is the possible fracturing of pellets from impacts with funnels that are used to collimate pellets into a guide tube when jumping across pumping breaks. Results thus far indicate that funnels with angles of less than 2° are necessary for optimal performance. It is also clear that testing a complete mock-up of an SPI injection line system is important to ascertain the overall delivery reliability to be expected.
The characterization of the shattered pellet spray has also progressed with fragment size measurements as a function of pellet speed showing a strong inverse relationship and substantial variation depending on the species of the pellet. Argon leads to much larger fragment sizes than deuterium with neon being somewhat in between. Comparison with a statistical fracturing model has been started and shows fragment size distributions similar to predictions. The temporal evolution measured of sprays of argon and neon from shattering in a bent tube indicate that the bulk of the fragments exit within a 1 ms window.

Future large plasma devices such as ITER will likely require multiple pellets to be injected simultaneously to symmetrically distribute the radiated power during the thermal quench mitigation. The achievable simultaneity from injection of multiple pellets remains as an issue to determine the level of timing jitter that can be accommodated and how best to assure identical pellet delivery. It is clear that the thermal collapse of plasmas occurs on such a fast time scale [7] that more than a few ms difference in pellet delivery times can be detrimental to the mitigation achieved. Characterization of the time and velocity jitter therefore needs to be studied in prototypic SPI injection systems.

The need for even larger high-Z impurity pellets for runaway electron mitigation is also anticipated. Therefore, future work is planned to further develop the capability to dislodge large ~28 mm high-Z pellets with punches and to better characterize the fragment distribution as a function of pellet properties and shatter tube design. Optimization of the shatter tube for the desired fragment distribution is also a future planned activity.

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REFERENCES