Shattered Pellet Disruption Mitigation Technology Development for ITER*

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Abstract. The mitigation of first wall thermal and mechanical loads and damage from runaway electrons during disruptions are critical for successful long term operation of ITER. Disruption mitigation tools based on shattered pellet injection are being developed at Oak Ridge National Laboratory that can be employed on ITER to provide the necessary mitigation of thermal and mechanical loads from disruptions as well as provide collisional damping to inhibit the formation of runaway electrons. Here we present progress on the development of the technology to provide reliable disruption mitigation with large shattered cryogenic pellets. An example of how this concept can be employed on ITER is discussed.

1. Introduction

Disruptions on ITER will present challenges to handle the intense heat flux, the large forces from halo currents, and the potential first wall penetration damage from multi-MeV runaway electrons [1,2]. Injecting large quantities of material into the plasma during the disruption can reduce the plasma energy and increase its resistivity and electron density to mitigate these effects [3-6]. Developing the technology to inject sufficient material deep into the ITER plasma for a rapid shutdown and runaway electron collisional suppression, which is estimated to require up to $3x10^{25}$ atoms of deuterium or other material to be injected in < 10ms [7,8], is an important capability needed for maintaining successful long term operation of ITER. A shattered pellet injection technology is being developed at Oak Ridge National Laboratory [9,10] that can be employed on ITER as part of a system to provide the necessary mitigation of disruptions. Large solid pellets injected intact would likely not fully ablate and present a hazard to the first wall materials, thus the pellet is purposely shattered before injection into the plasma. The shattered cryogenic pellet concept has recently been shown on DIII-D [4,11,12] to lead to deeper penetration, improved assimilation, and much higher plasma density with a single pellet containing $3x10^{23}$ atoms than with massive gas injection of the same quantity. This promising rapid shutdown result has motivated the development of a shattered pellet system for simultaneous injection of multiple large solid cryogenic pellets (> 10^{24} atoms each) that can provide ITER with reliable deep penetration of the material needed for disruption mitigation in less than 15 ms after actuation. Multiple pellets will also provide redundancy in the event that a single pellet fails to be injected.

2. ITER Disruption Mitigation System Development

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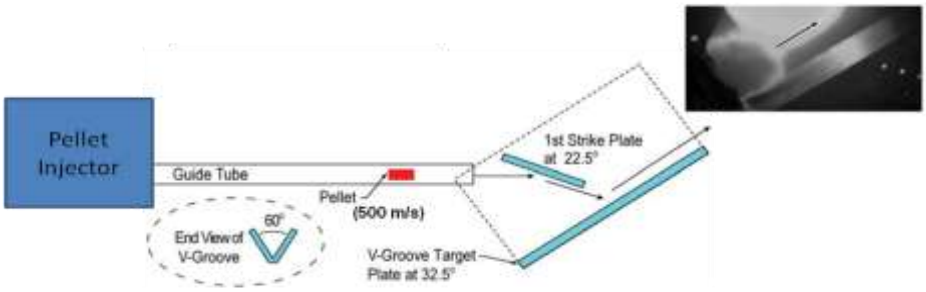


Fig. 1 Pipe gun pellet injector and shatter plate configuration for producing a mixture of solid fragments, gas and liquid for disruption mitigation. The inset picture shows the resulting mixture.

The shattered pellet injection technique shown schematically in Fig. 1 utilizes a pipe-gun type injector that forms a large cryogenic pellet in-situ in the barrel [13]. Cold helium is used to cool a section of the barrel where the pellet is formed. The pellet is accelerated by a high pressure gas burst and hits metal plates at the end of the barrel that are optimized to produce a spray of solid fragments mixed with gas and liquid at speeds approaching the sound speed of the material. The divergence of the plume and size distribution of shattered material has been measured and optimized [9]. Fig. 2 shows the resulting size distribution of solid fragments resulting from a 16mmx20mm cylindrical deuterium pellet impact on the shatter plates followed by impact of the fragments into a metal foil. The resulting angular dispersion of the material coming out of the shatter plate was kept below 30 degrees and the measured fragment impacts could account for ~1/3 of the pellet mass. The difference in the initial kinetic energy of the large pellet and final kinetic energy of the fragments may account for the fraction of pellet material that is converted to gas and liquid. Studies of the impact dynamics for further optimization for ITER have begun utilizing a fast framing camera to visualize the impacts, an example of which is shown in Fig. 3. The video images confirm the foil impact studies that indicated significant breakup of the solid pellet.

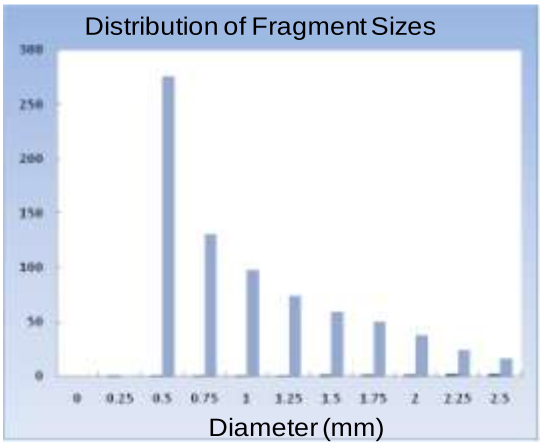


Fig. 2 Distribution of fragment sizes from a shattered D2 pellet hitting the shatter plate configuration shown in Fig. 1 at a speed of 500 m/s.

The transient dynamic finite element code LS-DYNA [14] is being employed to study the impact dynamics of the solid pellet on the shatter plates. A new material model has to be implemented in the code to take into account the phase changes in the material upon impact. These studies are being used to further optimize the shatter plate design for dispersion and size distribution. Smaller size fragments are desirable to improve the ablation rate and assimilation efficiency.

3. Shattered Pellet Technology

A technique to inject solid neon with this technology has been developed that is compatible with ITER requirements for compatibility with the vacuum system [15]. In order to avoid high vapor pressure that would flow into and poison the plasma while the pellet is waiting to be fired, it is necessary to keep the neon pellet temperature below 12K. In order to break away neon pellets from the barrel at that temperature, a technique of forming a deuterium outer shell of the pellet was successful in enabling the pellet to be sheared away from the barrel when fired. The outer shell is formed by introducing deuterium gas into the barrel during the initial freezing process and thereby producing a thin cylindrical shell of solid deuterium. Neon is then allowed to flow into the barrel and complete the freezing process by filling in the deuterium shell with solid neon. The resulting shattered neon pellets behave similarly to the solid deuterium pellets in the dispersion and distribution of particle sizes.

The time to form a large solid pellet is on the order of 5 minutes with sufficient cooling available. The pellet can remain in the barrel ready to fire indefinitely if kept cold enough to maintain a low vapor pressure. Deuterium has a low enough shear stress when cold (< 10 K) to enable firing at extremely low vapor pressures, thus it can be used by itself or to form an easy to break away outer shell for any cryogenic pellet mixture.

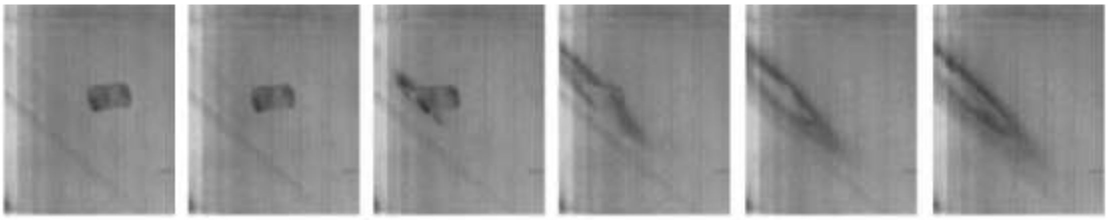


Fig. 3 Fast video camera images of a solid neon pellet with a deuterium outer shell impacting an inclined metal plate. The pellet is 16.5mm diameter and moving at 340 m/s from right to left. The time between frames is 0.045 ms.

4. ITER SPI Conceptual Design

A conceptual design of a shattered pellet injector system for ITER with multiple barrels is under investigation to be employed to mitigate disruptions and potentially suppress the formation of runaway electrons. Such an injector with multiple barrels is small enough to easily fit inside an ITER upper port plug for close coupling to the plasma, which is desirable for injection during the thermal quench phase and for faster mitigation.

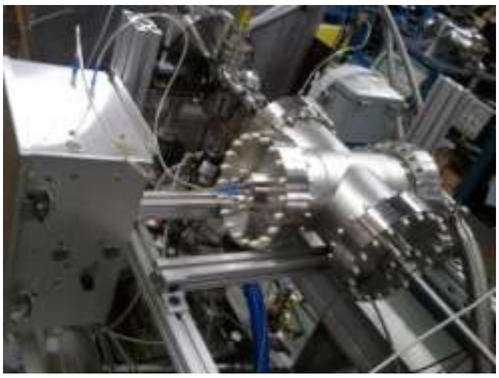
The device under development for ITER is a 6 barrel pipe-gun type injector with a 16 – 25 mm pellet diameter barrels and is shown in the CAD rendering in Fig. 4. More barrels could be included in such an injector if needed. Super critical helium at 4.5K with a flow rate less than 5 g/s is used to cool a copper block to less than 10K within the injector guard vacuum box. The cold block is in thermal contact with the barrels where the condensable gases are allowed to freeze and form a pellet. Gas is introduced through connections on the back of the injector and isolation valves at the end of the barrels are closed when making a pellet. The pellet is accelerated with a high pressure gas burst from propellant solenoid valves mounted on the back of the injector guard vacuum box. The pellets can reach speeds in excess of 500 m/s before combining and hitting a shatter plate. A microwave cavity diagnostic is mounted in series with each barrel after the isolation valves to provide a measure of the pellet mass and speed. An example of the data obtained from a single pellet fired through a microwave cavity is shown in Fig. 5. The pellet mass is proportional to the signal level and its speed is determined by the temporal width of the signal at half the maximum magnitude and the

Fig. 4. CAD model of the large diameter 6 barrel pipe-gun device for mitigating disruptions in ITER with large cryogenic pellets that are shattered before entering the plasma. Propellant valves are mounted on the back surface of the injector guard vacuum box. The 6 barrels are tapered to meet at the shatter plate.

mechanical size of the cavity. This type of diagnostic is also very useful in showing clearly when a pellet is broken after acceleration in the barrel. A microwave oscillator at 2.35 GHz is used to introduce < 10 mW of microwave power into the cavity and its Q is adjusted to a low value of < 350 in order to provide the sensitivity needed for the pellet size [9].

The toroidal divergence of the plume of shattered material is presently set at 30 degrees, but can be easily changed if future experimental data on the shattered pellet technique suggests a more optimal dispersion angle. The timescale for mitigation from shattered pellets is a function of the pellet distance from the plasma and the pellet speed. Firing times are on the order of 1-2 ms and the speed of the pellet is limited by the sound speed of the propellant gas and pellet mass. It is thus highly desirable to position the injector as close to the plasma as is feasible with the engineering constraints in order to achieve injection within 10 ms of a detected disruption [7].

Multiple injectors of this type could be employed on ITER to spread out the radiation from injected material and better mitigate the formation and presence of runaway electrons. The



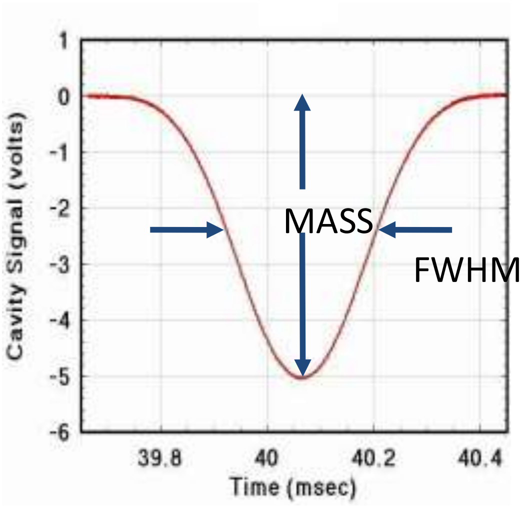


Fig. 5. Microwave cavity and resulting signal for a large diameter pellet showing the pellet mass is proportional to the magnitude and speed is determined from the full width at half maximum.

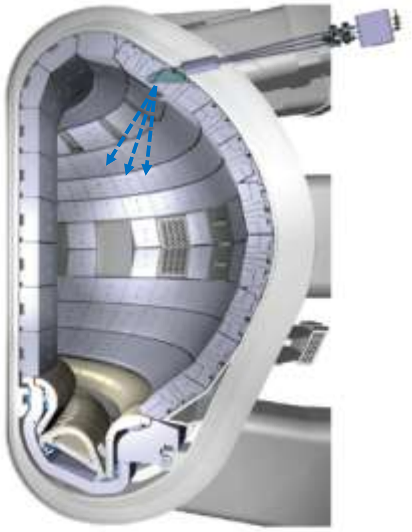


Fig. 5 A possible ITER shattered pellet disruption mitigation configuration with the injector located in an upper port plug.

number of injection points needed to minimize peak thermal loading on the first wall is still under systematic study [7]. This type of shattered pellet injector can also be designed to fit in a midplane port with the resulting material spray angled either vertically or toroidally. The service connections to the injector in the port are super critical helium with a flow rate of less than 5 g/s and pellet formation gas lines and instrumentation connections for temperature sensors and microwave cavities.

5. Discussion

The disruption mitigation system for ITER is projected to require the injection of $>10^{25}$ atoms of D_2 or an order of magnitude less atoms if higher Z impurities are used [8]. This needs to be introduced into the vessel in less than 20 ms, which means a flow rate of nearly 10^7 Pa m^3/s for D_2. To meet these particle delivery needs, ITER will need to employ either several large size > 20 mm orifice valves in parallel or some combination of gas jet and solid material pellet systems. The gas jet is limited by the sound speed of the gas, which for D_2 is ~ 1000 m/s and 450 m/s for neon. This implies that the valves for gas jets would need to be relatively close to the vacuum vessel, likely in the front of a port plug. Shattered pellet based injection systems will have similar injection speeds and would need to also be located in a port plug to achieve the fast injection timing needed. The radiation and magnetic field environment will dictate the materials used by the shattered pellet injection system and level of shielding and remote handling needed to maintain the system. The propellant valves are likely the only component that will require any significant magnetic or radiation shielding. It should be noted that this injection system can also produce gas jets of any gas by simply firing the propellant valve with a long opening time without a pellet formed in the barrel. The resulting gas jet will be limited by the sound speed of the gas and the conductance and deflection of the shatter plate.

How well a shattered pellet system works to collisionally damp the formation of runaway electrons remains to be tested. It is also not clear whether this technique can be useful in deconfining existing runaway electrons. Further research into these topics is needed as well as more data on the required toroidal symmetry of the injected material in order to determine how many injection locations will be needed. It may well be the case that this type of system will need to be employed in parallel with other techniques to prevent significant runaway electrons beams from forming during ITER disruptions [7].

6. Summary and Conclusions

In conclusion, progress is being made in the development of shattered cryogenic pellet technology to provide the necessary material throughput and plasma penetration for ITER disruption mitigation requirements. Tests of the concept on DIII-D have yielded valuable information on the penetration and assimilation of the material into the plasma, which is significantly better than with massive gas injection. A technique to make neon pellets with a deuterium outer shell has been developed that can produce pellets that are more easily accelerated and are more compatible with the ITER vacuum system than pure deuterium pellets.

The conceptual design of a shattered pellet injector located in an upper port looks very feasible. Several barrels can be combined into one injector minimizing the interface requirements and providing built in redundancy. A number of physics related questions remain in order to determine how many injection locations, size of pellets and material makeup of the pellets. Whether this method of material injection will be fast enough and provide high enough assimilation to prevent runaway electron formation during the current quench is the largest remaining physics question. Future tests of this concept will be very useful to provide answers to these questions in time for implementation of a disruption mitigation system on ITER.

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References:

[1] ITER Physics Basis, Nucl. Fusion **39** (1999) 2137
[2] Progress in ITER physics basis, Nucl. Fusion **47** (2007) S1.
[3] HOLLMAN, E.M., *et al*., Phys. Plasmas **17** (2010) 056117.
[4] WESLEY, J.C., *et.al.* Disruption, "Halo Current and Rapid Shutdown Database Activities for ITER", This conference ITR P1-26, 2010
[5] RICCARDO, V., *et al.*, Plasma Phys. Controlled Fusion **44**, (2002) 919.
[6] BAKHTIARI, M., et al., Nucl. Fusion **42**, (2002) 1197.
[7] PUTVINSKI, S., *et al.*, Disruption Mitigation in ITER, this conference ITR P1-6, 2010.
[8] WHYTE, D.G., *et al.*, IAEA FEC 2008, IT/P1-23.
[9] COMBS, S.K., *et al.,* Trans. Plasma Sci. **38** (2010) 400.
[10] BAYLOR, L. R., *et al*., Nucl. Fusion **49** (2009) 85013.
[11] COMMAUX, N. *et al.,* accepted for publication in Nucl. Fusion **50** (2010).
[12] COMMAUX, N., *et al*., Novel Rapid Shutdown Strategies for Runaway Electron Suppression in DIII-D , this conference EXS/P2-02, 2010.
[13] COMBS, S.K., *et al*., Rev. Sci. Instrum. **57** (1986) 2636.
[14] LS-DYNA, Livermore Software Technology Corp., http://www.lstc.com/lsdyna.htm
[15] MARUYAMA, S., *et al*., ITER Fuelling System Design and Challenges, this conference ITR P1-28, 2010.