Pellet Injection Technology and its Application to Mitigate Transient Events on ITER [*]

FIP/P4-4

L.R. Baylor[1], S.K. Combs[1], M.S. Lyttle[1], S.J. Meitner[1], D.A. Rasmussen[1], and S. Maruyama[2]

[1]*Oak Ridge National Laboratory, Oak Ridge, TN, USA*
[2]*ITER Organization, Route de Vinon sur Verdon, CS 90 046, 13067 Saint Paul Lez Durance Cedex, France*

E-mail contact of main author: BaylorLR@ornl.gov

Abstract. The technology to form and accelerate cryogenically solidified pellets of hydrogen isotopes has long been under development for fueling fusion plasmas. Injectors are being designed to provide this capability for fueling ITER with DT pellets injected from the inner wall. In addition to this fueling application, the pellet technology is being further developed for ITER to mitigate transient heat fluxes and energetic particle impacts from disruptions and edge localized modes (ELMs). Large shattered impurity pellets have been found to effectively mitigate disruptions and small pellets of deuterium have been used to trigger on demand rapid small ELMs to limit the transient heat flux damage from otherwise large naturally occurring ELMs. Both of these technologies are being implemented for ITER.

1. Introduction

Disruptions present a challenge for ITER to withstand the intense transient heat flux from the thermal collapse, the large forces from halo and eddy currents, and the potential first wall damage from multi-MeV runaway electron impacts [1]. Injecting large quantities of impurity material into the plasma during the disruption will reduce the plasma thermal energy by radiation and increase its resistivity and electron density to mitigate these effects. Technology has been developed to inject sufficient material deep into the plasma for a rapid plasma shutdown and runaway electron collisional suppression, which is estimated to require up to 90 kPa-m^3 of deuterium or neon to be injected within 20 ms for thermal mitigation and 10 ms for runaway electron suppression [1]. Both massive gas injection (MGI) and shattered pellet injection (SPI) technology are being developed at Oak Ridge National Laboratory for use on ITER as part of a system to provide the necessary mitigation of disruptions [2]. The shattered cryogenic pellet concept has been shown on DIII-D [3] to lead to deeper penetration and higher assimilation than from the same quantity of impurities injected as gas. MGI has been employed on JET to reliably mitigate thermal excursions from its disruptions with its ITER–like wall [4]. These promising results have motivated the development of shattered pellet injectors for ITER for simultaneous injection of multiple large solid cryogenic pellets (> 10^{24} atoms each) that can also be used for injection of gas. The preliminary design of the disruption mitigation system that has the capability of both of these technologies is now underway.

ELMs present another repetitive transient event that can lead to premature erosion and failure of divertor components from the high divertor transient heat fluxes. One of the methods being developed to mitigate this effect from large uncontrolled ELMs is the use of small deuterium pellets to preemptively trigger rapid ELMs before large deleterious ones can occur. The ITER pellet fueling system is being designed to provide this capability with the injection lines and injectors being capable of injecting both fueling pellets and ELM pacing pellets [5]. ELM

---

[*] This work was supported by the Oak Ridge National Laboratory managed by UT-Battelle, LLC for the U.S. Department of Energy under Contract No. DE-AC05-00OR22725.

pacing requires smaller pellets of D_2 that are to be injected from the outside wall or low field side (LFS). Modifications to the pellet cutting and acceleration technology are being made to accommodate the smaller and slower pellets for this application.

2. Shattered Pellet Injection

The SPI technique utilizes a pipe-gun type injector that forms a large cryogenic pellet in-situ in the barrel [6]. The pellets are accelerated by a high pressure gas pulse and just before reaching the plasma strike metal surfaces that are optimized to produce a spray of solid fragments mixed with gas and liquid at speeds in excess of 250 m/s. A 3 barrel SPI prototype for ITER shown in Fig. 1 has been fabricated and tested at ORNL. Neon would be the likely primary candidate material for injection by this method, with deuterium and argon as other candidates. In order to fire neon pellets at a temperature low enough to prevent the vapor from affecting the plasma, a technique of first forming a thin deuterium outer shell of the pellet before filling it in with neon was successful in enabling the pellet to be sheared away from the barrel when fired [7]. It has also recently been shown that it is possible to make and accelerate pellets intact with a mixture of neon and deuterium that can be optimized for pellet speed and mitigation properties [8,9]. The triple point temperatures of D_2 (18 K) and neon (23 K) are close enough that a mixture pellet can be formed in a barrel cooled to 7 K.


Fig. 1 A 3-barrel shattered pellet injector prototype installation in a guard vacuum chamber [5].

The prototype 3-barrel injector has been tested with deuterium-neon mixture pellets of up to 25 mm size for thermal mitigation and for runaway electron suppression and dissipation [5]. A bent guide tube, fabricated into an ITER port plug shield block, will be employed to shatter the pellets. The resulting angular dispersion of the material exiting the bent shatter tube is typically less than 20 degrees. The upper port plugs require a 65 degree bend for the resulting spray to be aimed toward the plasma center [5]. The results of testing a 65 degree miter bend tube that could be drilled into the shield block is shown in Fig. 2. This resulted in significant back reflected spray and nearly the entire gasification of the pellet with very few solid fragments. Something other than a miter bend with less of an angle is under investigation now for use on ITER. Whether the spray needs to be aimed toward the plasma axis for suitable thermal mitigation is a physics question that needs to be answered.


Fig. 2 Shattered pellet spray from a 25mm neon deuterium mixture pellet in a 65degee miter bend shatter tube. The spray results in mostly gas with significant backward reflected spray

Argon has also been successfully incorporated into the pellets at the front or back of the pellet up to 25% by volume by adding argon gas after the solid D_2/neon pellet has been formed. The argon triple point at 87K is too high for argon to be incorporated into the bulk D_2/neon pellet material that has a triple point closer to 20K. A mechanical punch has also been developed to break pure argon pellets free from the barrel before acceleration by high pressure gas [2]. The deployment of a punch with the SPI systems on ITER is a possibility if pure argon pellets are deemed necessary.

The three barrel design was chosen as it meets the ITER size constraints while allowing for additional redundant barrels to increase availability. Utilizing a single cold head for multiple barrels also helps to reduce the overall system complexity. Each barrel has a high pressure gas valve with a 25mm orifice for accelerating the pellets, which combine into a common injection 40mm guide tube before reaching the plasma. It takes 10-20 minutes to form the 3 large pellets in parallel using super critical helium cooling of the cold head. The pellets can remain in the barrel ready to fire as long as cooling is provided to maintain a low vapor pressure. If a pellet is not formed in the barrel, the gas valve, which will be of similar design to the MGI valves used on JET [10], can be used to inject gas just as an MGI system would. The injection line will contain a movable muzzle break in the port plug that when opened allows the propellant gas to enter the port plug rather than the plasma. When the muzzle break is closed all of the gas is directed into the plasma. Therefore the SPI system can in fact be a hybrid system offering more flexibility than a traditional MGI valve.

The pellet speeds from the testing done to date and modeling with a gas gun code shows that speeds from 250 to 500 m/s are expected for the ITER size pellets depending on the mass of the species used [11]. In order to minimize the injection response time, it is desirable to mount the DMS injectors as close as possible to the plasma. Space has been allocated for the DMS just outside of an equatorial port plug for runaway electron and thermal mitigation and three upper port plugs for thermal mitigation. The engineering challenge of fitting these systems in the allocated space on the equatorial port is motivating a more compact 4-barrel arrangement of the SPI systems for runaway electron mitigation shown in Fig. 3. The sizes of the pellets for thermal mitigation range from 13 to 19 mm diameter with a length to diameter ratio (L/D) of 1.5. The runaway electron injectors have a 28mm barrel with an L/D of 2.

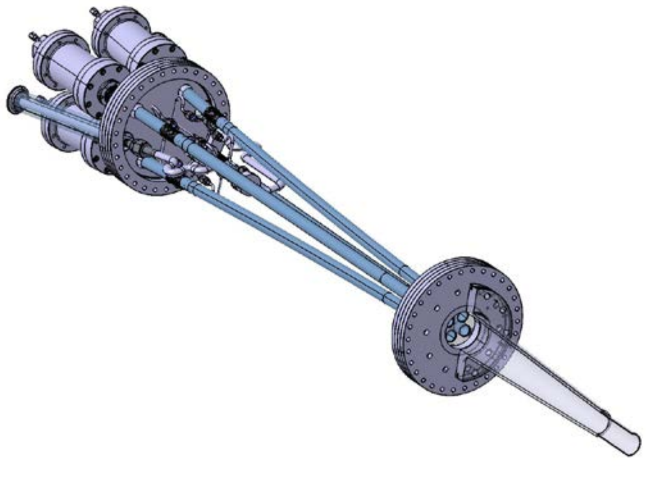

Fig. 3 4- barrel SPI design concept being developed for ITER to minimize the space required.

There remains some risk in deploying the SPI systems on ITER as they have thus far only been used for disruption mitigation experiments on DIII-D [3] and not employed as a true preemptive disruption mitigation system. To reduce this risk and gain valuable experience, a 3-barrel SPI system as shown in Fig. 1 being designed and fabricated for use on JET where mitigation of disruptions with MGI has been routinely employed since the installation of the ITER-like wall [4]. A key research element in this effort is the dissipation of runaway electrons to understand why MGI on JET has not been successful at this [12]. A new 3 barrel SPI system is now installed on DIII-D for experiments on synchronization of injection from multiple injection locations [13] and to investigate an off-axis injection angle by use of a rotatable shatter tube mounted on a machine upper port. Neither the JET or DIII-D system are designed for use as an MGI system as they already have dedicated MGI gas valves installed.

3. Pellet ELM triggering

.

The hydrogenic pellet material for fueling and ELM triggering on ITER is to be formed by a twin-screw continuous extruder [5]. The extruder produces a solid ribbon of DT and feeds it at ~14K to a dual cutting and loading mechanism that can produce either 5 mm fueling size pellets or high repetition rate 3 mm ELM triggering pellets utilizing a dual nozzle that can direct the extrusion for either pellet size. The dual nozzle gas gun system shown in Fig. 4 was designed with an adjustable extrusion size control providing up to 50% variation in the pellet length (width of the extrusion). Each branch of the nozzle feeds a dedicated stream to a gas gun barrel diameter sized for either fueling (~5mm) or ELM triggering (~3mm) [5]. The nozzle size adjusting mechanism can also be fully engaged to cut off extrusion flow to that gun so that the extrusion can be dedicated to the other gun. The system does not have the ability to feed both guns simultaneously.

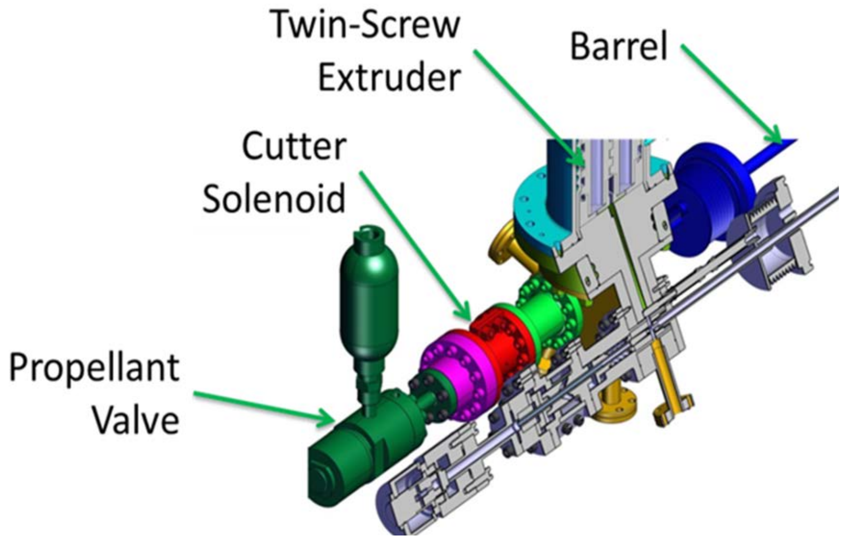

Fig. 4 ITER dual nozzle gas gun system for producing fueling or ELM triggering pellets. [5]

Acceleration of the pellets is accomplished with high-pressure deuterium gas at 40-60bar that is released by a fast acting solenoid driven propellant valve that is actuated for 1-2ms after the pellet is cut and loaded into the barrel. Fig. 5 shows how the pellets are cut from the extrusion and loaded into the barrel with a shaped cutter tip. The cutter tip has been designed to limit the propellant gas flow thus limiting the pellet speed to be able to withstand transport through curved guide tubes to the inner wall injection locations. This type of cutter tip has been employed on the DIII-D pellet injector that has been successfully used to demonstrate pellet ELM pacing in ITER like plasma scenarios [14,15]. This cutter with the limited gas flow was able to achieve reliable operation up to 30 Hz and was less variability in pellet size and speed than previous mechanical punches employed for slow pellets. A view port for each gun and a common lighting port are provided to be able to image the cutting of pellets and the solid fuel ribbon to aid in trouble shooting of the injector. The propellant gas for the injectors will be captured in the pellet injection system and recirculated [5] in order to minimize the gas load on the tritium processing plant.

The ability to adjust the size of the pellets will be crucial for the ELM triggering application where it has been shown that the triggering of ELMs is sensitive to the pellet size for a given injection geometry and plasma edge condition [15]. The pellet length can be adjusted dynamically on the order of a few seconds. Increasing the extrusion width and hence the pellet length takes longer than reducing it as the nozzle channel has to be filled with material before cutting can proceed. A prototype dual nozzle gun system has been fabricated and is undergoing testing with deuterium extrusions from an existing batch extruder.

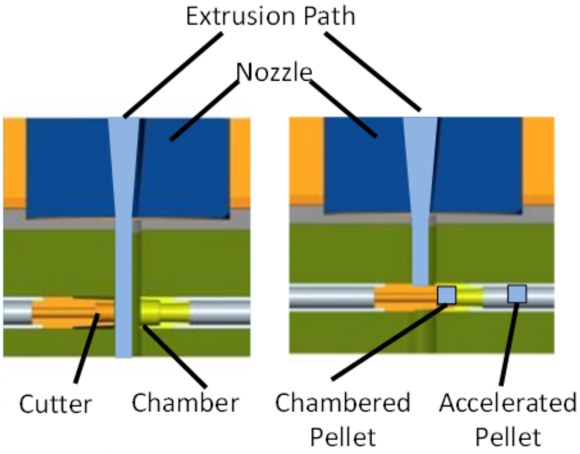

Fig. 5 Pellet cutting and loading mechanism for limiting the acceleration from high pressure gas. [5]

4. Summary

The disruption mitigation system under design for ITER will use the SPI technology with a hybrid MGI capability to inject impurity material from three upper port plugs and one equatorial port plug. The upper port plugs are to be used for thermal mitigation along with one injector on the equatorial port plug and in total can inject up to 10 kPa-m^3. The remaining 12 injectors on the equatorial port plug are to be used for runaway electron suppression or dissipation and can inject in total up to 100 kPa-m^3 of impurities. The impurity material is specified to be injected into the plasma in less than 20ms from when it is requested, which implies that pellet speeds in excess of 300 m/s are desired to achieve this time response from the port cell locations of the SPI pellet formation region [13]. Large propellant valves similar in design the JET MGI valves are being designed to meet these particle delivery needs. The SPI systems can also be used as MGI systems if the pellets are not formed in the barrels and a muzzle break in the port plug closed, providing additional flexibility.

The pacing of ELMs with on-demand triggering by high frequency small deuterium pellets to produce much smaller ELMs continues to be investigated as an ELM mitigation technique on tokamaks. These experiments on the injection of small pellets have yielded valuable information on this option for ITER and will continue to help in the determination of the optimal injection location, pellet size, speed, and frequency required. The flexible pellet injection technology and multiple injection locations being implemented for ITER, including the steady-state adjustable pellet size capability and multiple injectors will give the flexibility needed to be employed as an ELM mitigation system.

Acknowledgments

This work was supported by the Oak Ridge National Laboratory managed by UT-Battelle, LLC for the US Department of Energy under DE-AC05-00OR22725. The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

References

[1] M. Lehnen, et al., J. Nucl. Mat. **463** (2015) 39.
[2] L.R. Baylor, et al., Fus. Sci. Tech. 68 (2015) 211.
[3] N. Commaux, et al., Nucl. Fusion **50** (2010) 112001.
[4] M. Lehnen, et a;., Nucl. Fusion **53**, (2013) 093007.
[5] L.R. Baylor, et al., IEEE Trans. Plasma Sci. **44** (2016) 1489.
[6] S.K. Combs, et al., IEEE Trans. Plasma Sci. **38** (2010) 400.
[7] S.K. Combs, et al., IEEE Trans. Plasma Sci. **44** (2016) 1506.
[8] D. Shiraki, et al., Phys. Plasmas.23 (2016) 062516.
[9] D. Shiraki, et al., these proceedings, paper EX/9-2.
[10] U. Kreuzi, et al., Fusion Eng. and Design , 96-97 (2015) 286.
[11] S.K. Combs, et al., presented at TOFE 2016, to be published.
[12] C. Reux, et al., Nucl. Fusion **55** (2015) 129501.
[13] S.J. Meitner, et al., presented at TOFE 2016, to be published.
[14] L.R. Baylor, et al., Phys. Rev. Lett. **110** (2013) 245001.
[15] L.R. Baylor, et al., J. Nucl. Mat. **463** (2015) 104.