DESIGN AND COMMISSIONING OF A THREE-BARREL SHATTERED PELLET INJECTOR FOR DIII-D DISRUPTION MITIGATION STUDIES

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Disruptions are sudden unplanned terminations of tokamak plasmas that can lead to high thermal loads and runaway electrons (REs). Unmitigated disruptions in ITER are predicted to dissipate up to 350 MJ of thermal energy and generate several MA of multi-MeV runaway electrons. This intense heat and energetic particle beams can cause localized melting of the plasma facing components. Reliable and fast acting disruption mitigation (DM) techniques are therefore a critical requirement for ITER to safeguard the machine from damage.

The proven method for DM centers on injecting a large quantity of impurity particles into the plasma to quickly increase density and radiate the thermal energy to mitigate thermal effects. Additionally, if the particle injection can achieve sufficient density, it can create collisional drag which suppresses the formation of REs. Shattered pellet injection (SPI) has proven to be the most effective method of particle injection thus far attempted and is planned for the DM system on ITER. Recently, a new three-barrel second SPI (SPI-II) system has been developed for use on DIII-D to study injection effects from multiple toroidal locations and pellet timing. The three pellets can be formed and fired individually or simultaneously. The SPI-II has provisions for making and firing pure species pellets with deuterium, neon, or argon and also deuterium layered pellets with a core of neon and mixtures of neon and deuterium.

Keywords: Disruption Mitigation, Shattered Pellet Injection

I. INTRODUCTION

The two main stages of a tokomak plasma disruption are a thermal quench followed by a current quench. During the thermal quench, the thermal energy contained within the plasma is expelled onto the plasma-facing components. An unmitigated disruption of an ITER size plasma of ~350 MJ could deposit its thermal energy within 1-3 ms and yield heat loads in the divertor greater than 2000 $MJ/m^2s^{0.5}$. This would far exceed a 50 $MJ/ m^2s^{0.5}$ tungsten melt limit.[1] The thermal quench is followed by a current quench, which is a rapid current decay due to increased plasma resistivity from impurity assimilation. During the current quench, high electromagnetic forces are caused by the plasma current that returns poloidally through the vacuum vessel. ITER could potentially only withstand such an event 1-2 times in its lifetime due to forces produced by eddy and halo currents.[2] Also during the current quench, avalanche generated runaway electrons can be deposited locally which can penetrate plasma facing components. It is imperative to limit the number of disruptions and provide a mitigation method to minimize the damaging effects of any disruptions that do occur.

Mitigation methods of injecting high-Z impurities have been studied on multiple tokomaks.[3–5] The high-Z impurities mitigate thermal energy through increased radiation area, electromagnetic forces by shortening the current decay, and runaway electrons by collisional damping. Shell pellet injection, massive gas injection (MGI), and shattered pellet injection (SPI) are three methods of injecting high-Z impurities currently implemented on DIII-D. The SPI method has demonstrated deeper plasma penetration and higher assimilation over the MGI method for the same mass quantity injected.[6] Effects from injecting at multiple toroidal locations and variations in pellet timing remain to be studied.

The SPI method, developed at the Oak Ridge National Laboratory, utilizes a pipe-gun type injector that forms a cryogenic pellet in-situ from desublimated gas introduced into the barrel. The pneumatically accelerated pellets travel through a guide tube and encounter a shattering device that is optimized to break the pellets and produce a spray of solid fragments mixed with gas and liquid just before entering the plasma.[7] The SPI has provisions for making and firing pellets of pure deuterium, neon, or argon, deuterium layered pellets with a high-Z core, and a homogenous deuterium and neon mixture.

II. SPI-II DESIGN

The SPI-II follows the pipe-gun design concept of the first DIII-D SPI, but replicates the barrel three times around the guide tube axis at a two-degree angle. The barrels are designed to be easily replaced with different diameters up to a maximum of 9 mm. The current SPI-II has one 8.5 mm barrel (barrel 1) and two 7 mm barrels (barrels 2 and 3).

The SPI-II uses liquid helium (LHe) for cooling that is transferred from a pressurized dewar to the injector via a 3 m long vacuum jacketed transfer line. The transfer line is inserted into a tube-in-tube design bayonet that extends the injector guard vacuum ~350 mm outside the guard vacuum box and surrounds the transfer line to provide thermal insulation. Inside the guard vacuum, the LHe passes through the cryostat, a LHe control valve, a solenoid operated cryogenic rated shutoff valve, and finally through the exhaust bayonet where it returns to the cryogenic plant.

The cryostat is made from two plates of Oxygen Free High Conductivity (OFHC) copper. The base plate has a milled channel in a serpentine path around the barrel connections. An OFHC copper cover plate is welded around the circumference creating the sealed helium cooling channel. The control valve is a modified manual metering valve with an extended drive shaft, for thermal isolation, that is controlled by a DC stepper motor. The cryogenic solenoid shutoff valve stagnates the coolant flow between plasma shots and allows parasitic heat loads, along with a 25 W Nichrome wire resistive heater, to warm the cryostat so that any remaining cryogens frozen to the barrel walls will sublimate and be pumped away.

The barrels are brazed to cold heads which are bolted to the cryostat. The cold heads are 25.4 mm disks of OFHC copper with 9.5 mm inner diameters to match the barrel outer diameters. Indium foil is sandwiched between the cold head cryostat contact area to promote strong thermal contact. The cold head lengths determine the typical length of the pellets and are the same length as the pellet diameters. The barrels develop a temperature gradient outside of the cold head region which lengthens the freezing zone and therefore the maximum pellet length is about 1.3 times the diameter. The cold head and barrel design is shown in Figure 1.

A manifold adjacent to the injector contains a separate high-Z gas circuit for each barrel and one common deuterium gas circuit to all barrels as shown in Figure 2. The circuits contain reservoirs of a known 505 cm^3 volume, each bounded by two pneumatic shut-off valves. The reservoirs are filled by opening the upstream valves to a predetermined pressure which are measured by 3750 millibar (5000 torr) MKS Baratron capacitance manometers. After the reservoirs have been filled, the upstream reservoir valves and gate valves at the end of the barrels are closed and the downstream valves can be opened to allow the gas to flow into the barrels. A motorized metering valve with pressure feedback control maintains the barrel pressure while forming the pellet at ~50 mbar. The barrel cold zones cryopump the gas to form pellets and the downstream valves are then closed. The changes in reservoir pressures, which determine the size of the pellets, are recorded.

The common gas circuit and separate gas circuits are used together to form layered pellets. Only the separate gas circuits are required for pure gas species pellets and mixture pellets. For mixture pellets, the deuterium and neon gas are mixed within the separate gas circuit reservoir and solidified simultaneously as if it were a pure gas species pellet. A layered pellet is made by first allowing a small layer of deuterium with a thickness between 0.1 and 1 mm to be frozen to the barrel wall. This layer solidifies rapidly, typically within 1-2 minutes, so the common gas system can be used to sequentially create layers in each barrel. After the layers have been created, the common circuit is closed, and the separate gas circuits are opened to fill the high-Z cores in parallel. The formation rate of the core declines as the pellet thickness grows from the wall inward, due to the fact that the heat removal required has to conduct through the pellet material thickness itself. The typical time to complete the pellet formation is ~10 minutes each.

In order to fire the pellets, the barrel gate valves must first be opened to prevent a pellet from striking the valve seals and possibly damaging them. 1.7 bar pressure relief valves are incorporated on the barrel side of the gate valves to prevent over pressurization of the barrels if the pellets are fired with the valves shut. The pellets are accelerated by helium propellant gas from propellant valves, charged to ~60 bar. The propellant valves open in ~0.5 ms and release pressure behind the pellets until they break free. Pure high-Z pellets cannot be fired unless the barrel is warmed to near the triple point of the gas species, but this results in a high vapor pressure which travels into the tokomak while the pellet is ready to fire. Firing a pure high-Z pellet at a cold temperatures requires a mechanical pellet punch, driven by the propellant gas, to knock the pellet free.

The propellant gas has a higher sound speed than the pellets, so a significant quantity will bypass the pellets and arrive at the plasma first, which is undesirable because the initial propellant gas can trigger an magnetohydrodynamic instability leading to a non-axial symmetric thermal load. Three actively pumped expansion stages are located along the pellet flight path to remove about 90% of the propellant gas. The pumping stages also remove any pellet vapor pressure from reaching the plasma before they are fired. The pellets are accelerated down the 310 mm length barrels until they pass the gate valves and enter the collector stage. The collector stage is a system of three tubes that are 529 mm long with an inside diameter of 10.1 mm, aligned with the barrels, that bring the pellets together inside the first pumping stage cube where they traverse a 33.5 mm gap, before entering a single tube of the first guide tube stage.

Pellets have a typical free flight dispersion of up to two degrees, therefore the first guide tube stage has an opening of 26.1 mm that funnels to 19.0 mm diameter with a two-degree taper before extending 189.5 mm to the microwave cavity mass and speed measurement device. The pellets traverse the microwave cavity gap of 72.6 mm before entering the 28.4 mm diameter second guide tube stage. The microwave cavity gap provides a secondary propellant gas pumping location. The second guide tube stage is a 4 m long tube with a slight bend that routes the pellets from the horizontal injector down towards the R+1 DIII-D port where they are shattered. The guide tube is coupled to a bellows that accommodates torus thermal expansion and a ceramic union to electrically isolate the injector. A Torus Isolation Valve (TIV) joins the guide tube assembly to the port flange. The TIV has a port that serves as the final propellant gas pumping stage.

III. SHATTER TUBE PORT DESIGN

The port flange where the pellets are shattered is a multi-functional assembly incorporating components for low field side pellet injection, a viewport for a swing probe diagnostic, and the shatter tube on a 10 inch (DN200) metal knife-edge (CF) flange as shown in Figure 3. The low field side pellet injection is for edge localized mode (ELM) triggering, which requires a guide tube to direct deuterium pellets of 1.3 mm diameter to the plasma edge. A 13 mm inner diameter tube is curved with a 610 mm radius and clocked to align with the magnetic field lines. The swing probe viewport is located 60 degrees from the ELM pellet guide tube. The swing probe diagnostic takes measurements along a 180° vertical arc of 20 cm radius by swinging vertically through the plasma scrape off layer at the DIII-D centerpost.[8] It is important for the viewport to permit a view of the entire swing probe travel to ensure the probe has fully retracted behind the wall tiles between shots. A quartz viewport with a 68 mm viewing diameter is bolted to a recessed 4.5 inch CF (DN63) profile machined into the flange. A 12.6-degree view angle is required to see the complete motion of the probe 1.7 m away from the viewport.

The shatter tube is similar in design to the first DIII-D SPI, which has provisions for clocking the angle of the tube in 30 degree increments with respect to the face of the port. The shatter tube is a 34.8 mm diameter tube that is bent 25 degrees with a 152 mm radius. The tip of the shatter tube extends only 231 mm from the port flange surface so it remains behind the graphite shield tiles. The shatter tube resides within a system of two, three spoked stars that are welded within a 4.5 inch CF (DN63) half nipple on the port flange but not to the shatter tube, which allows the tube to rotate. The indexing star has a pattern of slots every 30 degrees which engage with two teeth on the indexing ring that is welded to the shatter tube. A locking nut captures the indexing ring and locks it to the indexing star. The shatter tube is limited to 240 degrees of rotation because of interference with the ELM pellet guide tube.

IV. PRELIMINARY LABORATORY TESTING

The SPI-II was tested at ORNL to determine that the SPI-II could reliably create pure gas species pellets, layered pellets, and mixture pellets. Reliability is verified by recording images of intact pellets with a Vision Research high-speed camera at the exit of the collector stage. Pellet velocity is determined by time of flight between the collector stage and a strike plate with a piezo shock accelerometer.

Before beginning pellet production, it is vital that a pipe gun is leak tight to prevent any air from cryopumping into the barrels. A leak of this type would dramatically increase the shear strength of the pellets, rendering them unable to fire. The small isolated volumes of the barrel and the reservoirs make in-situ, pressure rate-of-rise leak checking straightforward before cooling the injector. A second possible leak location is through the propellant valve seat. DIII-D will use helium propellant gas that can easily leak through imperfect valve seats and enter the barrels, which will prevent the pellets from forming. The propellant valve seat is a polyimide disk that sits on a stainless steel tube with a fully radius end. It is critical that the surface of the two mating materials be polished to less than a 0.2 micron finish. Pressurizing the valves and performing rate-of-rise tests in the barrels verified the integrity of the valve seats. Finally, an initial cooldown was performed to verify the temperature stability and a minimum base temperature of 5 K.

An important test was to verify that three pellets could be fired simultaneously without colliding and causing premature breakage that would prevent delivery of the majority of the pellets' mass into the tokomak. A maximum probability estimation of ~0.7% was experimentally derived that two pellets could collide with enough normal velocity to break the pellet. A set of three pure deuterium pellets were made at a barrel temperature of 8 K and then fired simultaneously and photographed as shown in Figure 4. The pellet velocities were ~880 m/s and the time from the first pellet to the third, or overall time spread, was ~200 µs with no collisions.

Next, layered pellet formation was verified using barrel 2. First, a 0.3 mm thick layer of deuterium was formed on the barrel wall at 5.5 K and then neon gas was slowly introduced at ~27 mbar barrel pressure. It is important to feed the core gas slowly so it does not displace the layer and cause a high shear strength pellet. Two pellets of similar quality were fired and photographed as shown in Figure 5. The pellet velocities were ~575 m/s.

Mixture pellet formation was verified next. A 50% D_2 and 50% Ne by volume pellet was made by releasing premixed gas into the 5.5 K barrel 2. It is important that the barrel be as cold as possible when forming mixture pellets so the high-Z gas does not preferentially form on the barrel wall and create a high shear strength wall bond. The pellet velocity was ~535 m/s. A second pellet was formed with similar results. Both pellets are also shown in Figure 5. All pellet sizes are summarized in Table I.

V. SUMMARY

A second three-barrel shattered pellet injector has been designed, fabricated, and tested at the Oak Ridge National Laboratory for disruption mitigation experiments at DIII-D. The injector uses the pipe-gun pellet formation technique. One 8.5 mm and two 7 mm barrels are currently installed and can be quickly replaced for different sizes. The pellets are shattered in a port flange assembly that includes accommodations for an ELM pellet guide tube and swing probe viewport. Tests have verified the injector can reliably form and accelerate pure gas species pellets, layered pellets, and mixture pellets.

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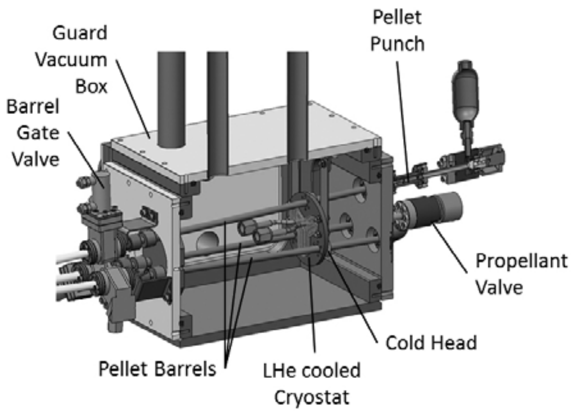

Fig. 1. The SPI-II injector with LHe cooled cold head and barrel design. The 8.5 mm barrel is at the top and 7 mm barrels are at the bottom. The pellet punch is required to fire pure high-Z pellets.

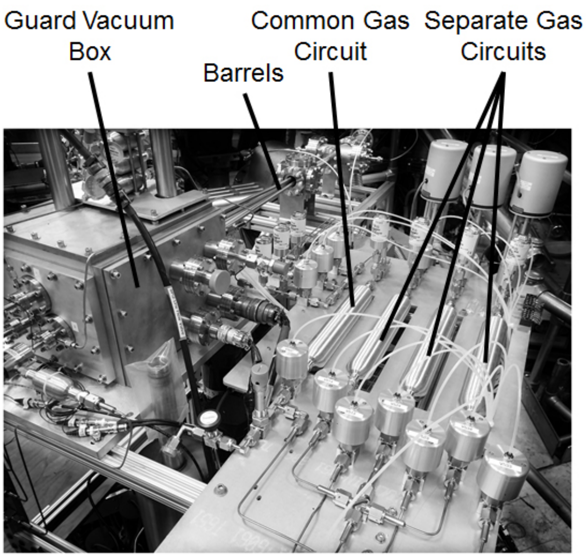

Fig. 2. Pellet gas manifold with separate high-Z gas circuits for each barrel and one common gas circuit to all barrels. The circuits contain reservoirs of a known volume to determine pellet sizes.

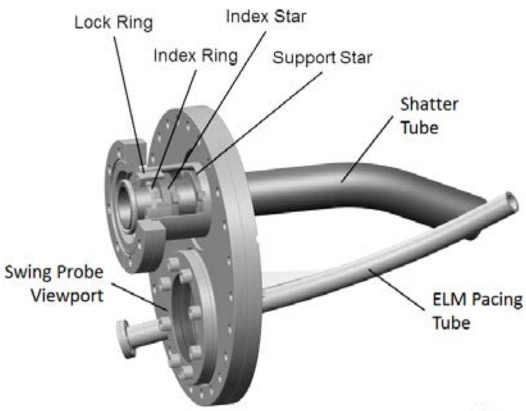

Fig. 3. 10 inch CF R+1 port flange with components for low field side ELM pellet injection, a swing probe optical viewport, and the rotatable SPI-II shatter tube.

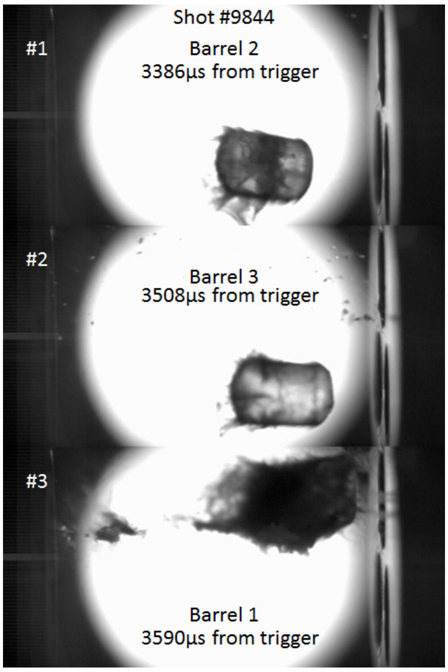

Fig. 4. Photographs of three pure deuterium pellets fired simultaneously. The pellets are travelling from right to left and show no collisions. The time is from the trigger of the propellant valves.

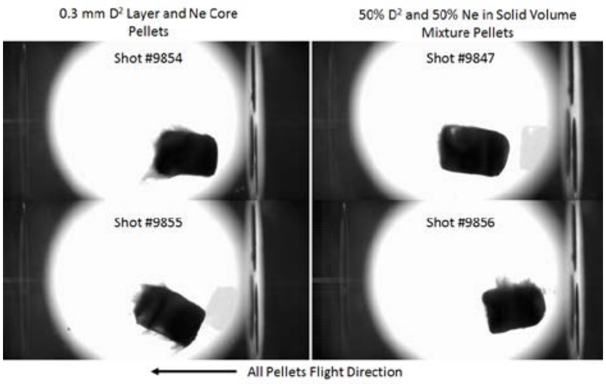

Fig. 5 Photographs of layered and mixture pellets travelling from right to left.

TABLE I. Example Pellet Sizes and Constituents.

Shot #9844 - Pure Deuterium

	Pellet Size (mbar-L)
Barrel #1 (8.5 mm)	771
Barrel # 2 (7mm)	443
Barrel # 3 (7mm)	443

Shot #9854 - 0.3 mm D2 Layer and Ne Core

	Gas Species	Pellet Size (mbar-L)
Barrel # 2 (7mm)	D2	58
	Ne	423

Shot #9855 - 0.3 mm D2 Layer and Ne Core

	Gas Species	Pellet Size (mbar-L)
Barrel # 2 (7mm)	D2	68
	Ne	495

Shot #9847 - Mix 50% D2 and 50% Ne in Solid Volume

	D2 Pressure (mbar)	Ne Pressure (mbar)	Pellet Size (mbar-L)
Barrel # 2 (7mm)	437	643	519

Shot #9856 - Mix 50% D2 and 50% Ne in Solid Volume

	D2 Pressure (mbar)	Ne Pressure (mbar)	Pellet Size (mbar-L)
Barrel # 2 (7mm)	433	623	481