Design and Testing of a Prototype Eddy Current Actuated Valve for the ITER Shattered Pellet Injection System*

T. E. Gebhart, M. N. Ericson, S. J. Meitner, L. R. Baylor, W. L. Gardner, T. S. Bigelow, and D. A. Rasmussen

Oak Ridge National Laboratory, Oak Ridge, TN, 37830
Email: gebhartge@ornl.gov

***Abstract*— Reliably mitigating disruptions is essential for ITER to meet its long-term operational research plan without damage to the in-vessel components. Currently, the shattered pellet injection (SPI) technique is the most effective radiator of thermal energy and has been chosen for the baseline disruption mitigation system (DMS) for ITER. The SPI process utilizes cryogenic temperatures to desublimate material into the barrel of a pipe gun forming a solid cylindrical pellet. Pellets for ITER will initially be hydrogen and hydrogen-neon mixtures. Once formed, pellets are dislodged and accelerated using high pressure gas (40 – 60 bar) delivered by a fast-opening valve. The solenoid valves currently used for SPI experiments will not operate in an ITER environment due to the large background magnetic field. An ITER prototype fast-opening valve, called a flyer plate valve (FPV), has been designed and undergone a wide range of testing. The FPV operates by pulsing current through a pancake coil that is closely coupled with a "flyer plate". The flyer plate is an aluminum plate in which eddy currents are generated creating a repulsive force from the pancake coil. The force generated in the flyer plate rapidly lifts the valve tip off the seat and delivers a pulse of gas to the rear of the pellet, breaking it free from the barrel and accelerating the pellet downstream to its intended target.**

The design of the valve has been iterated on over the lifetime of this project, as the DMS for ITER shifted from massive gas injection (MGI) to SPI. The most recent design has been tested and operational ranges have been mapped. The valve must survive 3000+ cycles in an ITER-like magnetic field. The principal functional requirement of this valve is to reliably dislodge and accelerate hydrogen (or H-Ne mixture) pellets into ITER. The valve was mated with an ITER SPI test stand and has been shown to be capable of launching pellets reliably. The valve and power supply design will be discussed in this paper, along with the various testing setups used to determine the feasibility of this valve for use on ITER.

***Index Terms*— shattered pellet injection, disruption mitigation, fast valve, ITER**

I. Introduction

THE ITER shattered pellet injection (SPI) system will be used to mitigate damage from the large thermal loads and electromagnetic forces generated during a disruption event. Shattered pellet injection utilizes cryogenics to desublimate material in the barrel of a pipe gun to form a solid pellet [1]. Pellets for ITER will typically consist of protium or deuterium with a small amount, ~10% by mole, of neon. Once formed, pellets are dislodged from the pipe gun barrel using a burst of high-pressure gas delivered by a fast-operating valve. The valves currently used for SPI experiments [2] on DIII-D [3, 4], JET [5], and KSTAR [6] are solenoid actuated and cannot operate at the SPI locations on ITER due to the background magnetic field. A new valve, called the "flyer plate valve" (FPV), was designed to work in the background magnetic field that will be present at ITER. The FPV utilizes a pulsed power supply [7] to drive current with an amplitude in the range of 800 A to 1.5 kA and a duration on the order of 0.8 to 2 ms. The pulsed current flows through a coil within the valve, which induces eddy currents in an adjacent aluminum "flyer plate". The eddy currents repel the field from the coil and provide enough force to open the seat of the valve allowing gas to flow downstream. ITER will have 27 separate SPI systems, each including a single barrel. Each barrel requires a dedicated valve and power supply.

Initially, massive gas injection (MGI) [8] was the baseline disruption mitigation (DM) scheme and the original FPV was designed with this application in mind [9]. The initial design was a large (~100 kg) valve that was intended to deliver a very large amount of gas (~40-50 bar-L) and operate in a 3.5 T background magnetic field due to its close proximity to the plasma. The valve was designed to deliver the entire plenum inventory during each shot. This resulted in the need for a second volume to seal the valve seat prior to filling the plenum reservoir so fill gas did not flow directly downstream when the plenum was being filled. This volume utilized a formed bellows to allow movement of the valve tip as well as allowing the sealing volume to apply the appropriate force to the sealing surface. Due to the high background magnetic field and generation of eddy currents, a large torque would be applied to the aluminum plate introducing a possible avenue for mechanical fatigue failure. To mitigate this, a second coil was added and current flowed in the opposite direction to offset the

*This manuscript has been authored by UT-Battelle, LLC, under contract DE-AC05-00OR22725 with the US Department of Energy (DOE).

torque generation.

The baseline DM scheme was shifted to SPI due to the more effective density assimilation performance [10] and the location of the valve was also changed to outside the port plugs. The remainder of this paper will discuss the design evolution, operation, and testing of the ITER prototype valves.

II. Bellows Valve Design and Operation

The change of application and location prompted a redesign of the valve, but many of the features of the MGI valve were retained. The background field at the new valve locations is in the range of ~0.25 to 0.35 T, reducing the torque generated on the aluminum plate and negating the need for a second coil. This drastically reduced the size of the valve from ~100 kg to ~15 kg. The gas delivery requirements for SPI on ITER are significantly less than those required for MGI. A high-pressure (40-60 bar) pulse of gas containing 2-4 bar-L of gas is sufficient to dislodge and accelerate pellets downstream to the plasma. Propellant gas needs to be removed before it makes it to the plasma due to possibly causing magnetohydrodynamic instabilities before the pellet reaches the plasma. Limiting the gas load in an SPI system is essential to reliable and effective operation. This iteration of valve design retained the formed bellows "closing gas" volume. Figure 1 shows a cross sectional view of the bellows valve design.

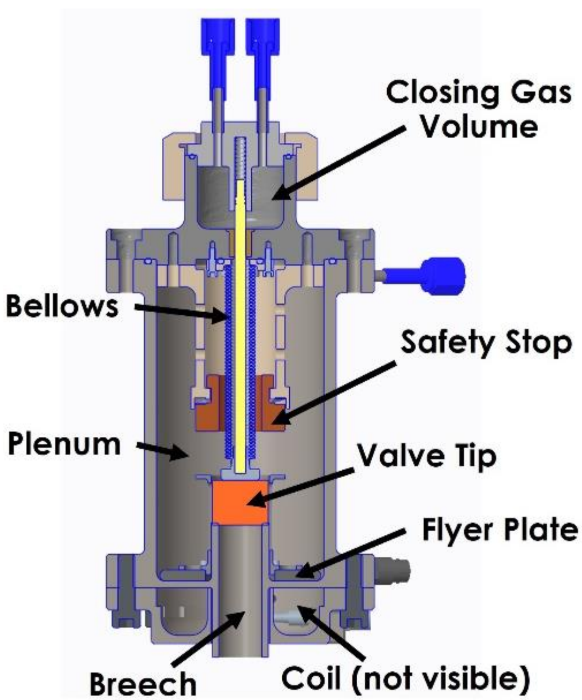

Fig. 1. A cross section view of the bellows FPV design showing labels for the relevant components.

The bellows valve was designed in accordance with the ASME Boiler and Pressure Vessel Codes and was authorized to be operated at pressures up to 70 bar. This valve was initially tested in a configuration that utilized an optical positioning sensor to track the position of the valve tip during the duration of the valve pulse. Figure 2 shows a plot of gas delivered versus peak opening distance. The amount of gas delivered was determined by measuring the pressure in the plenum before and after the pulse and multiplying the difference by the volume of the valve (1 L). This valve was then moved to an SPI-testbed to be tested in a pipe gun configuration, and to fire pellets for ITER SPI studies. This valve iteration was very successful in firing pellets for a multitude of studies [1]. Figure 3 shows an image of a pellet fired by the bellows FPV valve design. The valve plenum contained 60 bar of helium propellant gas and delivered ~3.2 bar-L of the gas to dislodge and accelerate this pure 28.5 mm diameter deuterium pellet. This pellet had a length-to-diameter ratio of 2.

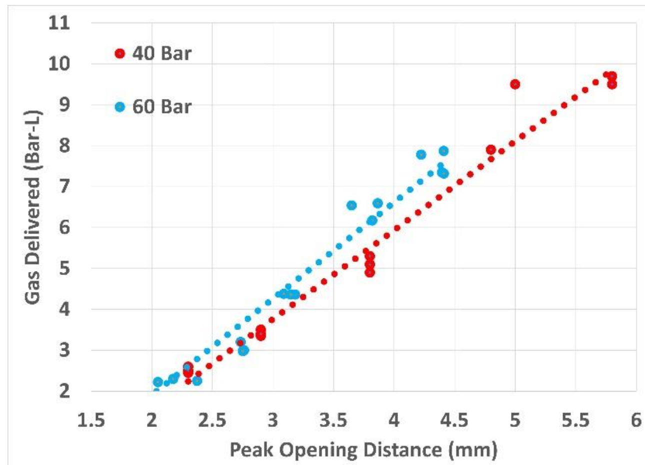

Fig. 2. A plot showing the amount of gas delivered versus the peak valve opening distance.

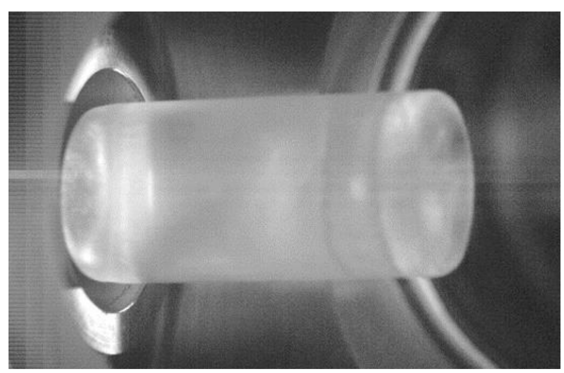

Fig. 3. An image of a 28.5mm diameter deuterium pellet fired by the bellows FPV.

Further valve operational testing was also conducted to determine the effects of decreasing the capacitance of the pulsed power supply. The power supply initially contained 4-200 µF, 3 kV capacitors: for a total of 800 µF. Four capacitors require a large volume in a power supply and ITER requires this power supply to fit in an 8U rack. Scans of valve gas delivery versus peak valve coil current were conducted for 400, 600, and 800 µF capacitor values. Two plenum pressures were scanned, 40 and 60 bar. These results are shown in Figure 4. The plots show the asymptotic nature of gas delivery versus the product of peak coil current and the FWHM pulse duration.

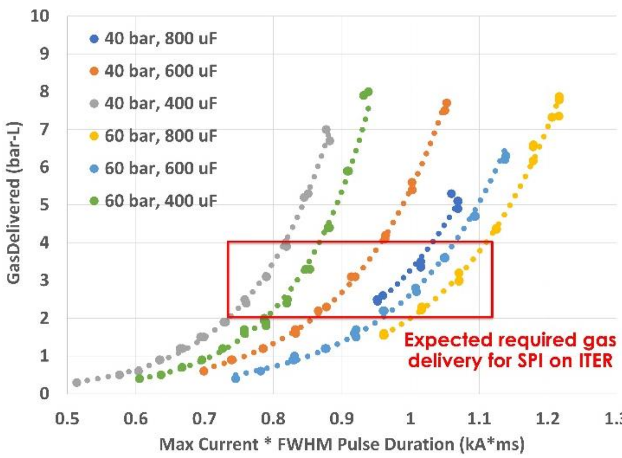

Fig. 4. A plot comparing the gas delivered by the bellows FPV versus the product of the peak current and the FWHM pulse duration, for varied capacitances and plenum pressures.

The bellows FPV was successful at meeting laboratory requirements for testing ITER-like pellets and providing a testbed for minimizing the size of the pulsed power supply. Deployment on ITER will require more rigorous testing and less inherent risk of component failure as the components will be very difficult to replace once ITER is operating with deuterium-tritium fuel. There are three main risks that needed to be addressed with the bellows valve: 1) threading of the valve tip, 2) the large valve plenum, and 3) the inclusion of a formed bellows. The threaded valve tip is designed such that all the force (rapid acceleration) required to open the valve is applied to these threads. Any slight unevenness in the threads will result in a significant stress concentration. This resulted in a failure during laboratory testing where the tip material failed in tension due to a stress concentration in the threads. At 60 bar, this valve is a category 4 pressure vessel by ITER standards, which requires very stringent documentation and poses various safety risks, especially with hydrogen propellant gas. As the valve operates, a large amplitude transverse wave is sent through the bellows due to the large forces and fast movement of the valve tip. Formed bellows are known to have a finite lifecycle in these conditions, and therefore it poses a large risk for leaks to develop. A new iteration of the valve was designed due to these design issues, and it is discussed in the following section.

III. Compact Valve Design and Operation

The issues discussed above for the MGI valve prototype were resolved through the design of a more compact and simplified valve. The valve tip was re-designed to only carry the pressure differential load, and not the load from the rapid momentum changes. This was achieved by elimination the threads in the tip design and allowing the flyer plate mechanism pre-travel before engaging the tip. The volume of the compact valve design was decreased to ~0.75 L and the bellows was removed. It was found through testing that the “closing gas” volume was not needed and that the valve would seat and seal effectively while pressurizing the plenum. The gas delivery requirements are such that after the valve pulses, residual plenum pressure is more than adequate to re-seat the valve. Figure 5 shows a labeled cross section of the compact valve design. The coil and flyer plate geometry did not change from the previous valve design to maintain semi-consistent gas delivery to valve current scaling. The operation of the compact valve was compared to the bellows valve and the results are displayed in Figure 6. To deliver the same ~3.5 bar-L of gas, the compact valve requires ~10% more energy. This comparison was conducted using 400 μF capacitance. This is due to the valve tip design and the underlying mechanics of the FPV. The largest force possibly generated by a FPV would occur at the highest current amplitude if the aluminum plate did not move prior to the current peak. In the bellows valve design, the tip and supporting structures were rigid and were held in place longer until the coil-plate system generated enough force to open the valve seat, holding the plate as close to the coil as possible. The compact valve design allows for a small amount of pre-travel of the supporting structures before the tip is engaged. This results in the plate being farther away from the coil, resulting in less force generated, thus requiring more energy to be applied to obtain the same gas delivery result. Overall, the compact design is a capable valve and will be used to fire pellets in upcoming experiments. It will also be used for lifecycle testing in a magnetic field to qualify it’s use on ITER.

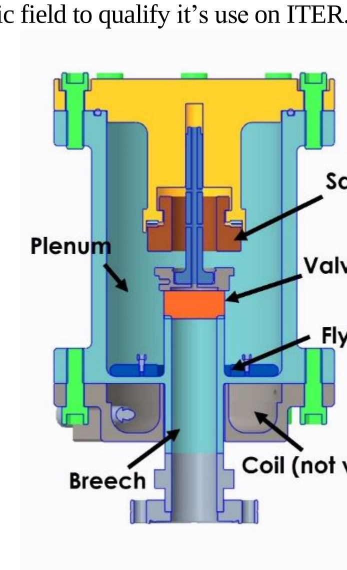

Fig. 5. A cross section view of the compact FPV design showing labels for the relevant components.

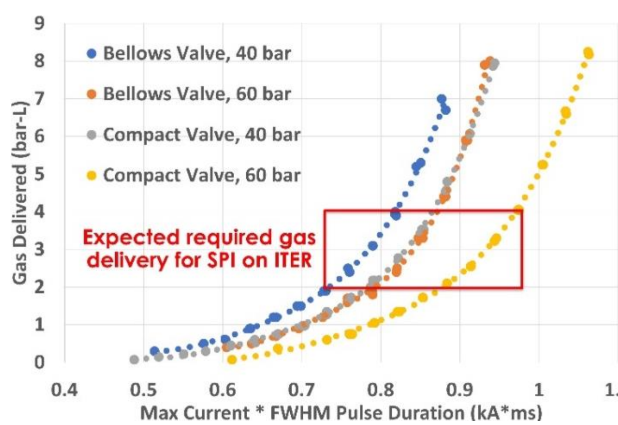

Fig. 6. A plot comparing the gas delivery versus the product of the peak current and the FWHM pulse duration for the bellows valve and new compact valve design at 40 and 60 bar propellant pressures. The capacitor bank contained 400 μF of capacitance for these comparison shots.

IV. LIFECYCLE TESTING IN MAGNETIC FIELD

The FPV is to be tested in a background magnetic field 1.4X the largest magnitude expected at ITER and must survive 3000+ cycles with no failures and minimal mechanical wear. There are 27 locations around ITER that will contain a FPV. Four drawers will contain six guns each around the equatorial plane of the machine, for a total of 24 guns. These drawers will see similar fields and thus the field in only one port, containing two drawers, was analyzed. The three SPIs contained in the upper ports were also accounted for and compared to the fields of the equatorial plane. Table 1 shows each valve and the field components with respect to the valve orientation. The components are adjusted for the tilt of the valve axis from horizontal, with respect to the machine. The labels in Table 1 refer to the left and right drawers of the port in question. Of the values in the table, the cases with the largest of each field component (highlighted in red and green) were simulated in Opera [11] to determine the effect on the valves during a pulse. Figure 7 shows the force exerted by the valve in the two background field cases highlighted in the table, compared to a case with no background field. It is apparent that the effect of the external field is minimal when compared to the overall jxB force generated by the coil and flyer plate. Figure 8 shows a plot comparing the torque generated on the flyer plate during a pulse for the same three cases shown in Figure 7. The case with the highest Bz value exerts the largest amount of torque on the valve. This is due to the torque only being generated by the field that runs parallel to the plate. Any field perpendicular to the plate applies an insignificant amount of uniform force in the direction of valve movement. Each of these simulations were conducted with a 1200-A peak valve coil current pulse.

Table 1. Magnetic field values for each FPV location around ITER.

Valve	Br (mT)	Bz (mT)	B Max (mT)
Left Bank 1	-84.254	-250.207	264.012
Left Bank 2	-87.915	-238.986	254.644
Left Bank 3	-89.857	-228.177	245.233
Left Bank 4	-90.489	-220.359	238.215
Left Bank 5	-90.231	-214.435	232.646
Left Bank 6	-88.445	-213.75	231.326
Right Bank 1	-101.138	-261.301	280.191
Right Bank 2	-104.871	-246.495	267.876
Right Bank 3	-106.493	-232.917	256.108
Right Bank 4	-106.751	-223.655	247.825
Right Bank 5	-105.985	-217.208	241.686
Right Bank 6	-103.514	-218.012	241.339
Upper Port Unit	285.236	-160.809	327.372

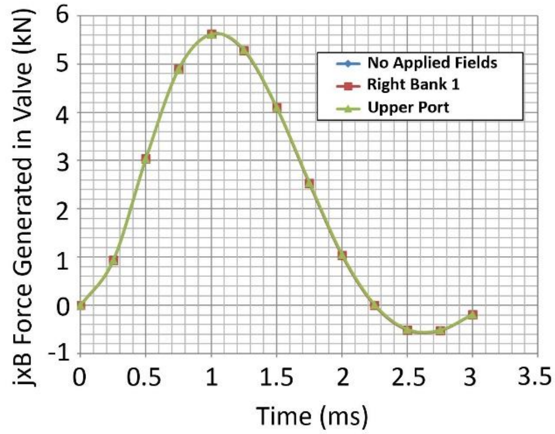

Fig. 7. A plot comparing the axial force generated in the FPV for three external field cases: no applied external fields, the Right Bank 1 case, and the Upper Port case. Cases were compared using a pulsed valve coil current of 1200 A.

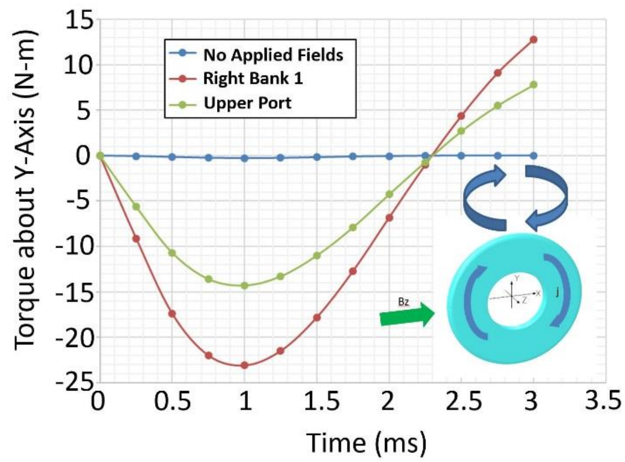

Fig. 8. A plot comparing the torque generated about the Y-axis of the flyer plate during a pulse for three cases of applied external magnetic fields: no applied external fields, the Right Bank 1 case, and the Upper Port case. Cases were compared using a pulsed valve current of 1200 A.

These simulations were conducted to determine the maximum torque applied to the FPV during a pulse in the background field seen on ITER. The case highlighted in red has been shown to be the worst-case scenario. Further simulations were conducted to compare a field generated by a Helmholtz coil configuration to the worst-case background ITER field felt by a single valve. The current in the Helmholtz configuration was set to match the Bz component of the ITER background field. Figure 9 shows the resulting torque for each case using a 1680 A valve current pulse. These results verify that using a Helmholtz coil configuration for in-field lifecycle testing is an acceptable approximation to the field on ITER, with respect to torque generated in the valve. A Helmholtz coil component testbed is currently being constructed and will be used for the above-mentioned lifecycle tests. Figure 10 shows an image of this coil testbed.

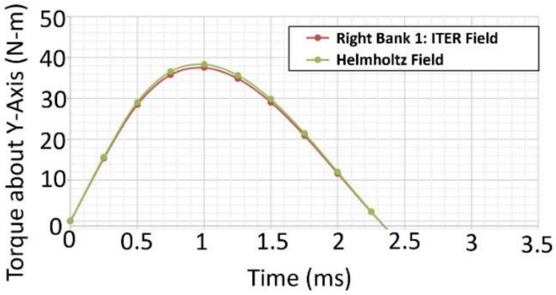

Fig. 9. A plot showing a comparison of the torque generated from the two field scenarios: a Helmholtz coil field, and the background field on ITER. Cases were compared using a pulsed valve current of 1680 A.

Fig. 10. An image of the Helmholtz coil component magnetic field testing facility currently under construction.

V. Discussion and Conclusion

The design specifications for the FPV have evolved along with the method of DM on ITER. The valve was initially designed for MGI; to deliver a large amount (~40-50 bar-L) and to operate in a 3.5 T background magnetic field. A single pulse of this valve would deliver the entirety of the valve plenum inventory, so a second volume was added to this valve to seal the valve while the plenum was being filled to reduce the amount of gas that flows downstream before the valve seals. The inclusion of this second volume introduced a formed bellows to the design. The background magnetic field induces a torque in the flyer plate within the valve. The FPV designed for MGI incorporated two coils that directed current in opposite directions, which was intended to cancel out the torque generation. The shift from MGI to SPI resulted in a change in the gas delivery specifications (2-4 bar-L) and a change in location with respect to the machine. The change in location resulted in a reduced background magnetic field. The FPV initially designed for MGI was redesigned for the new location. In this design, the second coil, for reducing torque, was removed and the valve was downsized significantly. The formed bellows and the closing gas volume were still included in the design. This valve was fabricated and extensively tested to determine operational parameters. This valve was also used to fire ITER-sized pellets. The obsolete closing gas volume (bellows), valve tip design, and plenum volume were all identified as design risks for the operation and longevity of the valve.

A redesign of the valve was conducted to mitigate these risks. Operational scans of the new valve have been conducted and it was found that the new valve design requires ~10% more coil energy to deliver a similar amount of gas as the bellows-based FPV. This is due to how force is generated in the coil-plate system and how this force is applied to the tip. Lifecycle testing of this valve will be conducted on this valve to ensure its survivability through 3000+ cycles in a magnetic field 1.4X the background field anticipated on ITER. The ITER magnetic field map was used to calculate the maximum background field at each planned location of the 27 valves. The torque generated within the flyer plate was calculated using the background ITER field and a planned Helmholtz configuration, intended to be used for lifecycle testing. There was little difference in torque between the two cases, showing that the Helmholtz coil configuration is a proper surrogate for the ITER background field. Future work will entail complete lifecycle testing and analysis of the valve operation in-field and producing a design package to be used for valve fabrication for use on ITER.

Acknowledgment

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