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Design and operation of a fast electromagnetic inductive massive gas injection valve for NSTX-U[a)]

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Results from the operation of an electromagnetic valve, that does not incorporate ferromagnetic materials, are presented. Image currents induced on a conducting disc placed near a pancake solenoid cause it to move away from the solenoid and open the vacuum seal. A new and important design feature is the use of Lip Seals for the sliding piston. The pressure rise in the test chamber is measured directly using a fast time response Baratron gauge. The valve injects over 200 Torr l of nitrogen in less than 3 ms, which remains unchanged at moderate magnetic fields. © *2014 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4885545]

I. INTRODUCTION

Massive Gas Injection (MGI) is the most developed disruption mitigation system to-date and will be implemented on ITER to protect internal ITER components during unplanned tokamak disruptions. However, much research is still required from existing facilities to better understand massive gas injection requirements for ITER, and gas penetration past the ITER SOL and pedestal regions. NSTX-U research will offer new insight by studying gas assimilation efficiencies from MGI injection from different poloidal locations using identical gas injection systems. In support of this activity, an inductive electromagnetic valve has been designed, built, and tested for installation on NSTX-U. The valve is similar in design to that planned for installation on ITER.[1] The valve has similarities in design to several valves we built for a Compact Toroid (CT) injector,[2] but draws on design features used in the TEXTOR valve,[3,4] and is motivated by the work of Lehnen.[1] The valve operates by repelling a conductive disk due to eddy currents induced on it by a rapidly changing magnetic field created by a pancake disk solenoid positioned beneath a conducting disk connected to a piston. An important design improvement in this valve is the use of Parker Lip Seals, instead of Teflon-coated O-rings that have been used in the TEXTOR valves.[1] In addition, while previous studies of gas throughputs from valves such as these were estimated based on valve opening times and orifice size, in these studies the vessel pressure increase following valve activation is measured directly using a fast baratron (MKS Model 617A) that has a rated time-response time of 1 ms. Results show that for the planned initial operating conditions on NSTX-U, the valve injects the required amount of gas (200 Torr l, at an operating pressure of just 7000 Torr) in less than 3 ms.

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II. DESIGN AND OPERATION OF THE VALVE

Figure 1 shows the main features of the valve. The primary plenum holds the gas to be injected into the vessel. The lower part of the piston makes an O-ring seal with the flange that would connect to the NSTX-U vessel. The piston shaft slides along the Lip Seals that are located in the cavity shown in the figure. The top part of the piston is attached to a large flat conducting disk and is located in the secondary chamber. The gas pressure in the secondary plenum tends to push the piston against the lower sealing O-ring, while the gas pressure in the primary plenum acts on the area between the O-ring and the outer edge of the piston and tends to open the O-ring seal by pushing the piston up. Thus for a given pressure in the primary plenum, the pressure in the secondary plenum can be adjusted so that there is just enough over pressure from the secondary plenum to make a good O-ring seal. The primary advantage is that the requirements on the power supply to operate this valve are nearly independent of the pressure in the primary plenum. The design has been used on JET for operation at pressures up to 34 atm.[1] NSTX-U test cell

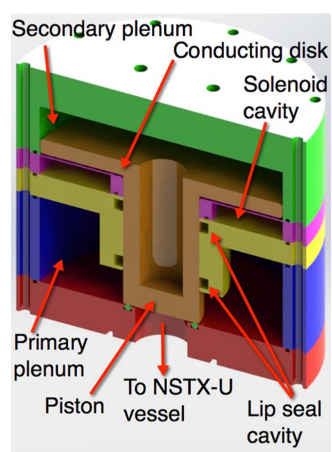

FIG. 1. Components of the version 4 MGI valve. It measures 12.7 cm in diameter and is 12.7 cm long.

pressure limits for gas systems is limited to about 5000 Torr, but it is planned to increase this limit during 2016. The pancake solenoid contains 21 turns of 1.4 mm diameter magnet wire. A 0.5 mF capacitor charged to <1 kV is used to drive the coil. The quarter cycle current pulse width is about 100 μs, with peak currents of about 2 kA at 770 V. The rapidly changing current in the pancake coil induces eddy currents on the lower part of the flat surface of the conducting disk, which causes the disk to move away from the solenoid. This causes the O-ring seal on the lower part of the valve to open and causes the primary chamber to partially empty, before the lower seal is re-established. In order to retain a high gas flow-rate only part of the primary chamber volume is allowed to empty. To inject more gas, the desired operating condition would require the primary plenum pressure to be further increased.

III. STAGES OF VALVE DEVELOPMENT

Four different valves were designed, built, and tested. The first version of the valve used a 1.08 cm orifice. The solenoid was sealed from the secondary chamber by a 1.3 mm thick SS304L disk held in place by O-ring seals and retainer rings. In the second version, the entire solenoid cavity was fabricated out of a single block of metal. The third version of the valve increased the size of the orifice to 2.3 cm. All these valves were fabricated out of aluminum 6061 for ease of fabrication of the test versions. In the fourth version of the valve, the solenoid cavity was fabricated out of SS304L and the piston O-ring seals were replaced by Parker Lip Seals.

Although the valves with the O-ring sliding seals worked well, O-rings have a tendency to flatten when subjected to continuous compression, yet have to make a good seal when the piston moves on a rapid sub ms time scale. So these were replaced by Parker U-Cup Lip Seals,[5] that are specifically designed for piston operation. The seal's material is Parker Nitroxyl compound. It has several features that are advantageous for this type of arrangement. It is rated for operation at up to 120 °C. It is the highest-grade seal material available, it is self-lubricated, wear resistant and has low friction. It is also rated for operation at pressures over 100 atmospheres, making it well suited for this valve design. While use of a lubricant may not be necessary for this seal, we used a mild coating of Dupont Krytox LVP high-performance O-ring lubricant rated for operation at 300 °C. The vapor pressure at 200 °C is 1×10^{-5} Torr and at 20 °C it is 1×10^{-13} Torr. On NSTX-U, the valve would operate at normal ambient temperatures, but the valve could be subjected to some bake-out without issues.

For the valves that are being fabricated for NSTX-U, the solenoid cavity will be fabricated out of Inconel 625. The higher resistivity of Inconel should allow it to operate more efficiently as the fast rising magnetic field from the solenoid can more easily penetrate the liner separating the piston from the solenoid. In addition, all valve components will be fabricated out of SS-304L. Each of the valves to be installed on NSTX-U would be calibrated on the test chamber prior to installation on NSTX-U.

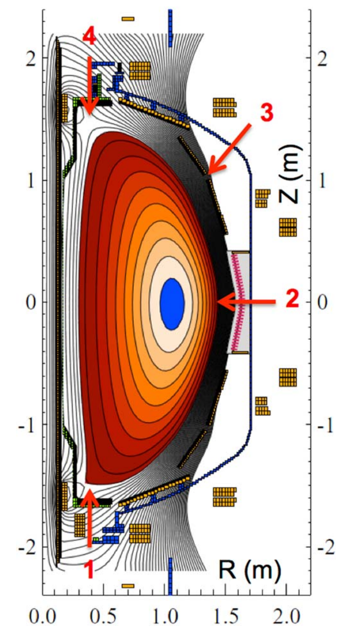

FIG. 2. MGI gas injection locations on NSTX-U.

IV. NSTX-U MGI LOCATIONS

Figure 2 shows the planned MGI locations on NSTX-U. In location 1 the valve would be oriented so that the dominant toroidal field is perpendicular to the flat surface of the piston. In this arrangement, J × B forces acting on the piston would be in the radial direction and would cancel out so that there is no net torque on the piston or the solenoid. For location 4, the valve would be oriented so that the dominant toroidal field is parallel to the piston surface. In this case, the forces acting on the piston would tend to tilt the piston to one side of the valve. The valves in location 2 and 3 can be configured to assume the piping configuration used for locations 1 or 4, to allow a comparison of the poloidal injection location with identical valve set-ups. Initial experiments for 2015 would use valves 1 and 2. Valve 4 would also be available, but its operating limits will be established after additional off-line tests in which the valves are operated in an external magnetic field with the fields approaching 1 T. Figure 3 shows the test assembly. The valve is located between two segments of the solenoid that were used on the HIT-II experiment[6] at the University of Washington. Calculations show that with 2 kA in the solenoid the magnetic field between the two solenoids is 1.8 T. For typical plasma discharges planned for use in MGI experiments on NSTX-U, the maximum magnetic field parallel to the piston surface, for location 1, is 0.12 T, and 0.75 T for location 4.

V. EXPERIMENTAL RESULTS FROM VALVE OPERATION

Initial experiments were conducted at low gas throughput of 3–4 Torr l nitrogen injections so that the time response of the pressure rise in the 1.3 m^3 test chamber could be measured with a fast micro ion gauge.[7] This was then compared to the time response seen by the Baratron operated in the

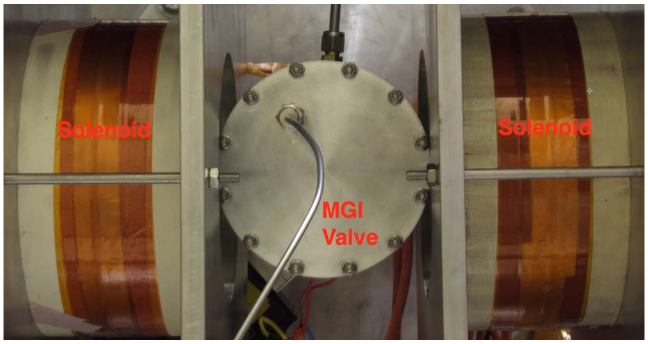

FIG. 3. Set-up used for operating the MGI valve in an externally imposed magnetic field.

standard "slow" mode and in the "fast" mode. Figure 4 shows the results of this comparison. For 5000 Torr in the primary chamber and 300 V operating voltage for the version 1 valve, the micro gauge shows the pressure in the vessel to rise in about 4 ms. The fast Baratron signal shows it to increase on a slightly longer time scale, and the slow Baratron takes over 50 ms to respond to the pressure increase in the vessel. These measurements show that the valve opens on a sufficiently fast time-scale.

Figure 5 shows the time response of the version 4 valve as measured by the fast Baratron signal as the operating voltage is increased from 710 V to 800 V. At 710 V, 125 Torr l of nitrogen is injected with an effective pressure rise time of less than 3 ms. This is consistent with the thermal velocity of nitrogen molecules. At 770 V, the amount of injected gas increases to 220 Torr l. For these experiments the valve was operated at a primary plenum pressure of 7000 Torr. In future tests it is planned to increase this pressure to at least 15 000 Torr.

Figure 6 shows results from valve operation in a magnetic field corresponding to the configuration shown in Figure 3.

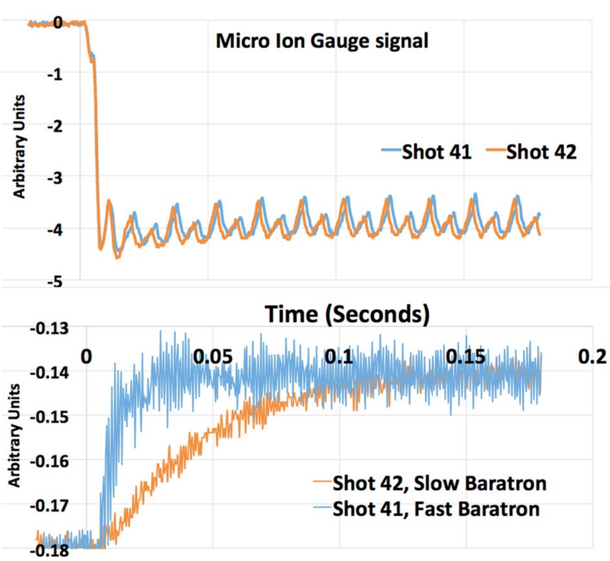

FIG. 4. Vessel gas pressure measurements using a Micro Ion Gauge (MIG) and Baratron to compare the Baratron response to the faster MIG response time.

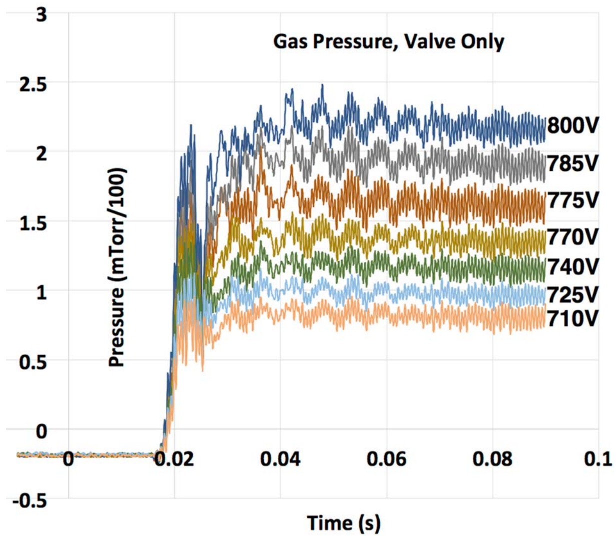

FIG. 5. The time response of the version 4 valve as measured by the fast Baratron signal as the operating voltage is increased from 710 V to 800 V.

The valve is energized 14 ms after the solenoid trigger time. Five discharges showing measurements from the fast Baratron signal are overlaid. In discharge 19 to 21 the solenoid current was 750 A, corresponding to a peak magnetic field of 0.67 T. Discharge 22 and 23 are comparison discharges with no current in the solenoid. All discharges have the same pressure rise time and signal response. The absolute amount of injected gas was 230 Torr l for the case with the solenoid and 220 Torr l for the cases without the solenoid. Additional tests are required to establish if the small increase in the injected gas amount is due to the influence of the externally imposed magnetic field. The frequency of the solenoid current waveform is about 20 Hz. The droop in the solenoid current signal is due to the droop associated with Pearson 301X current transducer limitations for measuring pulses with such a long time scale. The 6061 Aluminum used for this valve has a resistivity of 4×10^{-8} Ω m, resulting in a skin depth of 2.2 cm. The valve wall thickness is 1 cm. Thus the magnetic field inside the aluminum sidewall of the valve should be about 0.4 T.

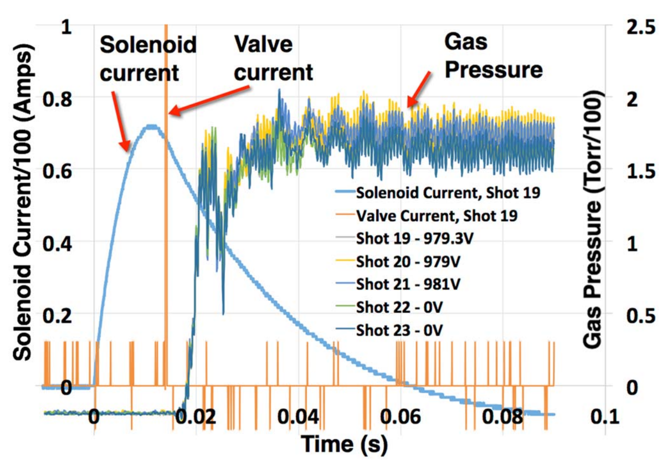

FIG. 6. Operation of the valve in the presence of an external magnetic field in the 0.3–0.4 T range.

Future tests will use valves with the SS304L walls. This in combination with further slowing down the current rise time in the solenoid, and at a higher solenoid current should allow tests of valve operating behavior to be characterized at magnetic fields in the range of 1 T.

VI. SUMMARY

In summary, an electromagnetic valve of the design to be used on ITER has been successfully built and tested. At an operating pressure of 7000 Torr, the pressure rise-time in a 1.3 m^3 chamber is 3 ms for gas throughput of 200 Torr l nitrogen. Operation at moderate magnetic fields in the 0.3–0.4 T range show the valve characteristics to not substantially change. Pressure rise has been measured directly using a fast Baratron attached to the test chamber. The valve uses novel Parker Lip Seals for the sliding seal mechanism.

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