NSTX-U Contributions to Disruption Mitigation Studies in Support of ITER

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Abstract: Predicting and controlling disruptions is an important and urgent issue for ITER. In support of this activity, NSTX-U will employ three Massive Gas Injection (MGI) valves that are similar to the double flyer plate design being developed for ITER [1]. NSTX-U experiments will offer new insight to the MGI database by studying gas assimilation efficiencies for MGI gas injection from different poloidal locations, with emphasis on injection into the private flux region. Results from the operation of the valve, including tests conducted in 1 T external magnetic fields, are described. The pressure rise in the test chamber is measured directly using a fast time response baratron gauge. At a plenum pressure of just 1.38 MPa (~200 psig), the valve injects 27 Pa.m^3 (~200 Torr.L) of nitrogen with a pressure rise time of 3 ms. A limitation with the use of gases for pellet propulsion, whether they be solid refractory, shell, or cryogenic shatterable, is that the propellant gas limits the velocity to about 300-400 m/s [1]. The Electromagnetic Particle Injector (EPI) described here overcomes this limit by relying on an electromagnetic propulsion system for pellet acceleration. The system has the potential to inject impurities deep into the plasma, inside the q = 2 surface, and in amounts greater than the amounts that can be assimilated by the plasma during edge impurity injection. We describe a system that could inject 15 g of boron, beryllium of boron nitride at over 1 km/s and a response time of 3 ms. Initial results from an off-line NSTX-U sized device will be available in the very near future.

1. Introduction

Massive Gas Injection (MGI) is the most developed disruption mitigation system to-date and will be implemented as a secondary disruption mitigation system on ITER to protect internal ITER components during unplanned tokamak disruptions. NSTX-U research will offer new insight by studying gas assimilation efficiencies for MGI injection from different poloidal locations using identical gas injection systems. At present three valves have been installed on NSTX-U corresponding to locations 1, 2 and 3 in Fig. 1. An unique aspect of NSTX-U MGI experiments is that poloidal injection comparisons will be made using near-identical systems because, identical valves, and nearly-identical piping configuration between the valve and the vacuum vessel will be used.

A limitation with the use of gases for pellet propulsion, whether they be solid refractory, shell, or cryogenic shatterable, is that the propellant gas limits the velocity to about 300-400 m/s [1]. In addition it is difficult to characterize the size and velocity of the shattered fragments injected into the tokamak. The Electromagnetic Particle Injector (EPI) described in Section 3 overcomes this limit by relying on an electromagnetic propulsion system for pellet acceleration. The primary advantage of the EPI concept over gas-propelled injectors is its potential to meet short warning time scale events. The system could also be located very close to the reactor vessel. The system has the potential to inject impurities deep into the plasma, inside the q = 2 surface, and in amounts greater than the amounts that can be assimilated by the plasma during edge impurity injection. In Section 3 we describe a system that could inject 15 g of boron, beryllium of boron nitride at over 1 km/s at a response time of a few ms. Initial results from an off-line NSTX-U sized device will be available in the very near future.

2. The ITER-type NSTX-U MGI valve

In support of NSTX-U MGI experiments, an electromagnetic MGI valve was designed, built, and tested. Fig. 2 is an internal view of the NSTX-U MGI valve. The valve operating principle is similar to that being considered for the for the ITER MGI valve. 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 [5]. 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.

The initial valve used a single solenoid, and a single repelling disk. Motivated by the work of Baylor, [1] for an ITER test valve, we incorporated a second solenoid and a second conducting disk for valve operation. The current in the second solenoid is opposite in direction to that in the first solenoid. The effect of these oppositely driven currents is to nearly cancel the J X B torque the valve would experience in a magnetic field.

The valve has been operated in two different configurations. In the first configuration, the coils are connected in series so that the same current passes through each solenoid. In the second configuration, both coils are connected in parallel to the power supply. This configuration reduces the total system inductance, reduces the coil current pulse width, but increases the peak power supply current by about a factor of two. Both these operating conditions inject similar amounts of gas with similar gas pressure rise times in the test chamber (27 Pa.m^3 of nitrogen with a 3 ms gas pressure rise time).

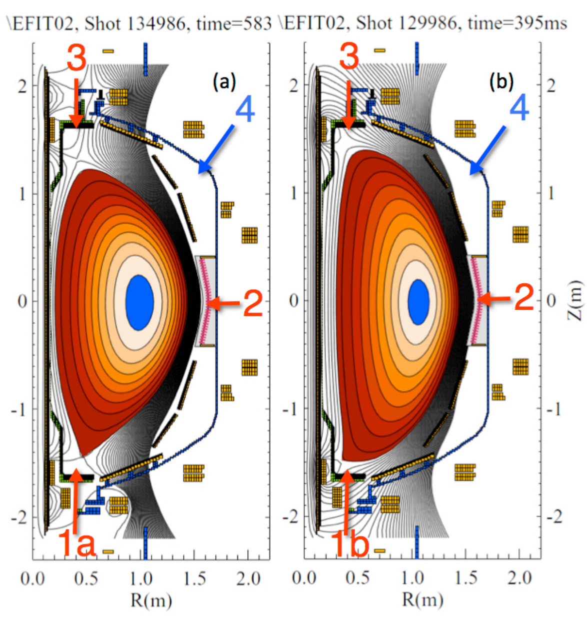

FIG. 1. MGI valve installation locations on NSTX-U. At present three valves are installed (shown by locations 1, 2 and 3). The fourth valve at location 4 is planned for a future installation. These locations are: (1a) private flux region injection, (1b) lower scrape-off-layer and lower diverter injection, (2) conventional mid-plane injection, and (3) upper diverter injection.

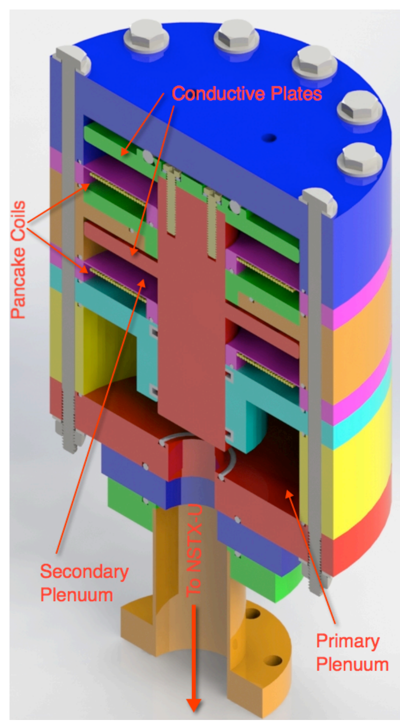

FIG. 2. Internal view of the NSTX-U double flyer plate MGI valve. Gas from the primary plenum is injected into the plasma discharge.

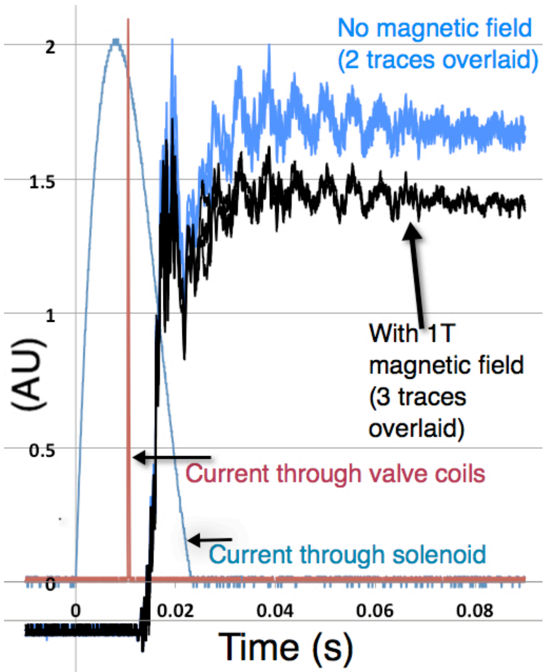

FIG. 3: Experimental traces from the operation of the valve with and without the presence of an external magnetic field. Shown are the current pulse duration through the solenoid and the current pulse through the gas valve pancake coils. The gas valve is discharged 10 ms after the solenoid discharge is initiated. Shown are two gas pressure traces for cases in which there was no external magnetic field. Shown also are three gas pressure traces during the presence of a 1 T external magnetic field in a configuration in which the field is parallel to the pancake solenoid surface.

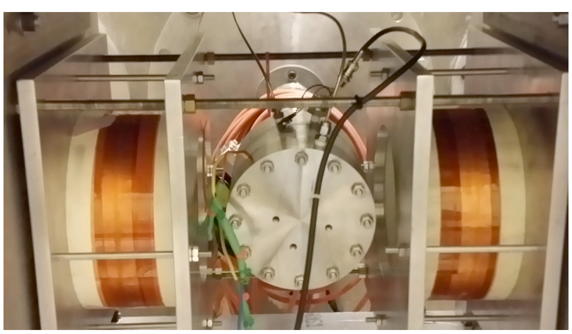

FIG. 4. Setup used for MGI valve testing in an external magnetic field. The valve is located between two solenoid coils.

An important observation was that, compared to the single flyer plate design, adding a second solenoid did not substantially increase the size of the capacitor bank power supply or the operating voltage for injecting similar amounts of gas, and with similar gas pressure rise times in the test chamber. The double solenoid valve was also operated with the two coils connected in a parallel and series configuration. The series connection required a lower operating voltage, but the measured gas time response was nearly the same for both cases. This is because the longer current pulse duration for the series configuration results in the magnetic forces acting on the piston for a longer period. The valve operation is not affected by fields < 0.8 T. As shown in Fig. 3 for a 2 MPa fill pressure, as the field increases to 1 T, there is a 10% reduction in the amount of injected gas.

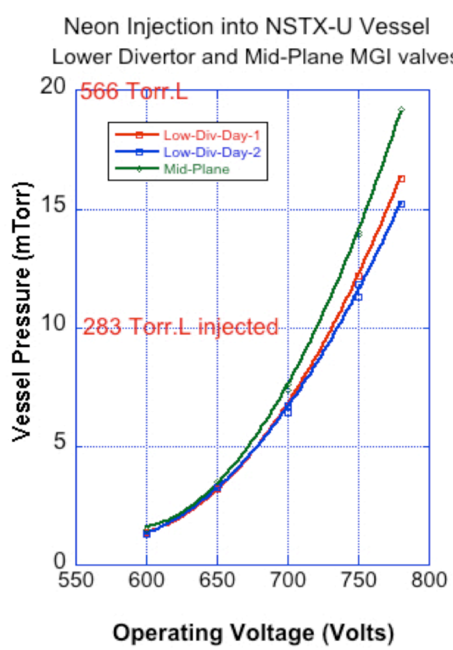

FIG. 5. Vessel pressure increase as a function of valve operating voltage for the lower divertor and mid-plane MGI valves on NSTX-U.

Fig. 4 shows the experimental setup used for tests during the presence of an external magnetic field. Fig. 5 shows the amount of injected neon as function of operating voltage for valves located at location 1 (lower divertor) and 2 (mid-plane) on NSTX-U. The valves on

NSTX-U inject over 400 Torr.L of neon at an operating voltage of less than 800 V, and a plenum fill pressure of 200 Psig.

3. The EPI Concept

Fig. 6a describes the injector operating principle. The projectile is placed between two conducting rails separated by about 1 to 2 cm. The length of the rails would be about 1 m long. The projectile is placed in front of a conducting spring, as shown in Figure 1b. A capacitor bank is connected to the back end of the rails. Discharging the capacitor bank causes the current to flow along the rails as shown in Figure 1a. The J x B forces resulting from the magnetic field created in the region between the rails, and the current through the spring armature accelerate the projectile. Because of its simplicity and ability to accelerate projectiles to very high velocities (of over 5 km/s) it is being actively developed for mass acceleration purposes. An issue that needs to be resolved for these high duty cycle applications is electrode erosion. However, in a disruption mitigation system, due to the low duty cycle, electrode erosion is not expected to be an important issue. Furthermore, because of the relatively simple configuration, if it is positioned at a location that provides easy access, the entire injector could be removed for refurbishment, and a refurbished injector installed in its place.

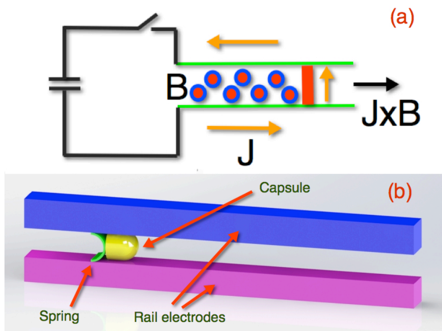

FIG. 6. (a) Cartoon showing rail gun operating principles. (b) Electrode configuration for initial NSTX-U level test.

Fig. 6a shows the direction of the magnetic field generated by currents flowing along the rails. One way to increase the efficiency of the injector is to increase the magnetic flux that penetrates the region between the rails. This is because; the current flowing in the spring armature and the magnetic field generates the accelerating J x B force. To increase this field, other more complex electrode geometries are also being considered. However, the tokamak environment offers another potential advantage to a linear rail gun system. The ambient magnetic fields that exist near the tokamak vessel could be used to augment the gun-generated magnetic field, and as shown in the next section, further increasing the efficiency of the injector. Typical magnetic fields generated by the rail current are about 2 T, while the ambient magnetic field near a reactor vessel could be much larger. If the injector could be positioned sufficiently close to the vessel, and the rail gun electrodes aligned with the external magnetic field, the efficiency could be further improved. For example, the magnetic field in the ITER port plug is reported to be as high as 3 T. This has the advantage that a smaller power supply, and a lower level of gun current would be adequate to attain the same acceleration force. Thus, while the large ambient magnetic fields are generally an issue for most systems, it helps the linear rail gun injector improve its performance, and makes the system faster acting, by reducing the projectile delivery time. This is the most important advantage of the rail gun pellet delivery concept over other methods being considered for disruption mitigation applications.

The velocities that can be achieved with the electromagnetic particle injector can be calculated by solving the rail gun equations for a linear geometry, and are described in Reference [6]. As described in Reference [6], the sabot used for acceleration is captured before pellet injection into the plasma. As shown in Fig. 7, the high levels of external

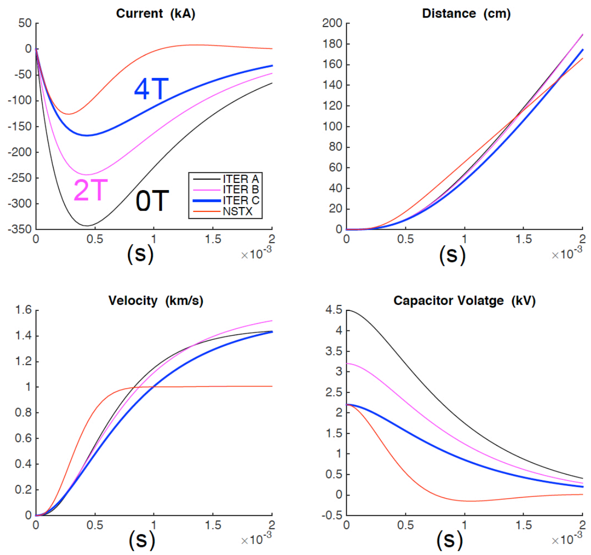

FIG. 7. Shown are traces from simulation results showing the injector current, pellet velocity, distance traveled by the pellet, and capacitor bank voltage, as a function of time. ITER cases B and C use 2 and 4 T external magnetic field augmentations, which results in the substantially reduced injector current, and reduced power supply requirements for otherwise similar acceleration parameters.

magnetic fields that are present near the reactor vessel actually help to improve the efficiency of the system. The system has the potential to respond very rapidly by injecting impurities, into the plasma, within 3 ms after a command to inject is issued to the system. Fig. 7 (ITER cases) show acceleration parameters for a 15 g projectile composed of micro-spheres of boron, boron nitride or beryllium. The dramatic reduction in the injector current for a modest 2 T external magnetic field augmentation is seen in the ITER B case, compared to ITER case A that has no external magnetic field assistance. All three ITER cases have a bank capacitance of 100 mF. The NSTX case is for a near term off-line, non-tokamak test, which is underway with results to be available in the very near future. Fig. 8 shows a hypothetical installation configuration on an ITER mid-plane port plug.

A cylindrical shell pellet capsule would be fabricated out of thin (< 0.5 mm thick) boron nitride, with a rounded front end. The cylindrical shape in combination with a rounded front end is chosen to allow the capsule to easily travel through the guide tube with a shallow bend to avoid direct streaming of neutrons back to the injector. The hollow shell pellet would be filled with boron nitride spheres, although for ITER applications, beryllium or pure boron spheres could also be considered. The simplest case would be pure radial injection, for which, the capsule would be fragmented prior to injection using a shatter plate, or by introducing sharper bends in the guide tube itself to fracture it inside the guide tube. The capsule must be filled with particles (spheres) of proper size, so that they penetrate deep into the plasma before being fully ablated. The second possibility is to inject the capsule intact. In this case, the capsule would be injected tangentially, or with a guide tube bend along the horizontal direction as shown in Fig. 8, so that in the absence of plasma the capsule could leave the vessel though a suitably located port at end of the pellet's trajectory. However, this is a much more difficult scenario for the following reasons. Experimentally, one needs to know the minimum shell thickness that allows the pellet to propagate through a guide tube intact. This would be a function of both the guide tube bend radius and the pellet

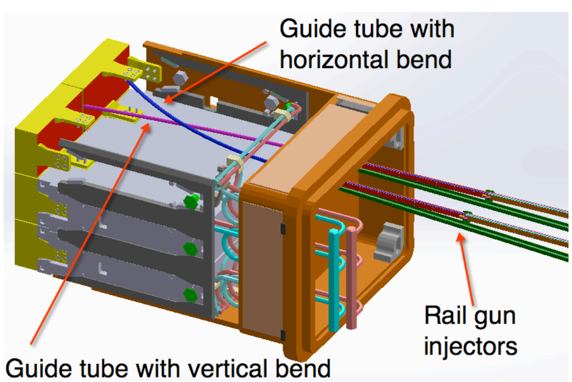

FIG. 8. Hypothetical installation configuration for two EPI injectors on the ITER mid-plane port plug.

velocity. Additionally, pellets with this wall thickness must be able to fragment inside the plasma discharge as a result of heating and pressurization of the pellet cavity due to energetic particle bombardment. For fragmented pellet injection, only the impurity particle size (size of the spheres) inside the capsule needs to be established; this should largely be a function of the velocity of the impurity particles and the plasma parameters.

4. Summary

An electromagnetic valve to support NSTX-U MGI experiments has been built and tested. Although neon or argon would be the impurity gas used in NSTX-U disruption mitigation experiments, the valve has been tested using nitrogen gas. The valve has been calibrated for injecting 27 Pa.m^3 of nitrogen, similar to the levels planned for NSTX-U experiments. The gas pressure rise time is about 3 ms, consistent with the gas sound speed for nitrogen gas. The valve for NSTX-U uses a double solenoid configuration. This has the benefit of nearly cancelling the J x B torque that acts on the valve when it is operated in an ambient magnetic field. The valve has been tested in ambient magnetic fields up to 1 T, and found to operate well at these field levels.

An electromagnetic particle injector based on a linear rail gun concept has the potential for rapid response, and ability to accelerate a payload capsule of about 15 g to 1-2 km/s in less than 2 ms, which is adequate to meet a fast response time needed for a disruption mitigation system. Increases to the size of the injector to transport a larger capsule are possible. However, a better approach is to have multiple injectors at different toroidal locations so that there is more flexibility in the amount of injected impurities, as a low power Ohmic plasma would require much less impurity injection than a full power ITER discharge. In addition, for a full power disruption, the ability to inject from different toroidal locations would improve impurity mixing and reduce the radiated power peaking factors.

A very important advantage of the EPI system is that its performance substantially improves if could be installed closer to the reactor vessel, which is possible because it does not use plastic seals, and augmentation by the external magnetic field reduces the injector current to attain the required injection velocity.

As a next step, a small prototype system has built for verification of velocity and time response parameters. Such a system could be tested on NSTX-U or on an existing tokamak to qualify its ability to rapidly quench a plasma discharge, and to develop the experimental database on macro particle penetration and ablation physics inside high-temperature plasma.

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