ELECTROMAGNETIC PARTICLE INJECTOR (EPI) AS A FAST TIME RESPONSE DISRUPTION MITIGATION CONCEPT

R. RAMAN
University of Washington, Seattle WA USA
SEATTLE, WA, USA
email: raman@aa.washington.edu

W-S. LAY
University of Washington, Seattle WA USA
SEATTLE, WA, USA

T.R. JARBOE
University of Washington, Seattle WA USA
SEATTLE, WA, USA

J. SACHDEV
Princeton Plasma Physics Laboratory
Princeton, NJ, USA

R. LUNSFORD
Princeton Plasma Physics Laboratory
Princeton, NJ, USA

R. NAZIKIAN
Princeton Plasma Physics Laboratory
Princeton, NJ, USA

J.E. MENARD
Princeton Plasma Physics Laboratory
Princeton, NJ, USA

M. ONO
Princeton Plasma Physics Laboratory
Princeton, NJ, USA

Abstract

The Electromagnetic Particle Injector (EPI) is a novel fast time response system for tokamak disruption mitigation. It is being proposed as a backup option for disruption mitigation in ITER. Disruption mitigation in tokamaks is achieved by injecting a radiative payload into the tokamak plasma. EPI has the potential for delivering the radiative payload composed of micro spheres of B, BN or Be, inside the q = 2 surface on a <10 ms time scale, much faster, and deeper, than what can be achieved using present methods. Experimental tests on a proto-type system have been able to verify the primary advantages of the EPI concept over other disruption mitigation concepts for a tokamak. These are the rapid response time and the capability to attain the projected speeds on this fast time scale. In support for a tokamak test of the concept, a much-improved compact system is being built. Compared to the initial test version, this system employs 2 T magnetic field augmenting coils to substantially reduce the current through the sabot, which is used to accelerate the payload, to attain the required velocity at much reduced rail current. Other important advantages of the EPI concept are its potential capability to deposit the radiative payload in the region where the runaway current initiates, thus providing a means to suppress the formation of this current. With EPI, one can precisely calculate the injection parameters needed for deep penetration into any plasma, including the ITER plasma giving confidence that simulation capabilities validated with present tokamak experiments can be used to reliably project to ITER.

1. INTRODUCTION

The Electromagnetic Particle Injector (EPI) is a novel fast time response system for tokamak disruption mitigation. It is being proposed as a backup option for disruption mitigation in ITER. Disruption mitigation in tokamaks is achieved by injecting a radiative payload into the tokamak plasma. The EPI has the potential for delivering the radiative payload to the plasma center on a <10 ms time scale, much faster, and deeper, than what can be achieved using present methods. Predicting and controlling disruptions is an important and urgent issue for ITER. While a primary focus is the early prediction and avoidance of conditions favorable to a disruption, it is understood that some disruptions may be inescapable. For these cases, a fast time response method is essential to protect the ITER facility. Experimental tests on a proto-type system have been able to verify the predicted rapid response capability of the EPI system by accelerating a 3.2 g sabot to 150 m/s in 1.5 ms.

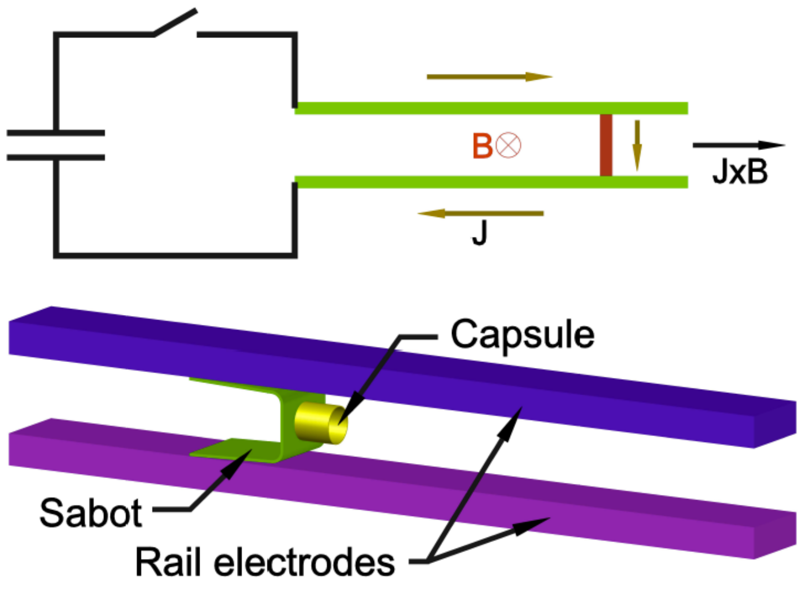

Fig. 1: Cartoon showing the EPI electrical circuit, EPI electrodes, the sabot, and the chamber that would contain the radiative payload. A JxB interaction between the current through the sabot and the magnetic field between the rails accelerates the sabot.

The primary advantage of the EPI concept over present systems is its ability to meet short warning time scales while accurately delivering a radiative payload to the plasma. This is done at velocities required to achieve core penetration in high power ITER discharges, thus providing thermal and runaway current mitigation. The EPI system described here overcomes the physics limitations of present gas-based disruption mitigation systems by relying on an electromagnetic propulsion system for pellet acceleration as described in Fig. 1. The EPI system accelerates a metallic capsule, termed a sabot, to high velocity within 2 ms. At the end of its acceleration, the sabot releases a payload of radiative granules of a known velocity and distribution. Alternately it could also release a shell pellet containing smaller pellets or noble gas. Studies previously indicated the capability of the system to both respond on a 1-2 ms time-scale and to achieve 1 km/s velocities [1]. The present understanding, based on the theoretical work of Konavalov, et al., [2] is that as little as 5 g of Be, if it is deposited deep inside the plasma, may be adequate for both thermal quench and runaway electron mitigation in ITER.

It is useful to note that at present MGI (Massive Gas Injection) and Shattered Pellet Injection (SPI) are the most tested methods for disruption mitigation in present tokamaks [3,4,5,6,7,8]. The MGI method [9,10] relies on a fast-acting gas valve that empties a high-pressure plenum, filled with high-z gas, into the plasma discharge. Due to limitations such as, for example, high radiation fields that exist near a reactor vessel, the valve needs to be located some distance away from the vessel [11]. On ITER, this is many meters away from the plasma. The Shattered Pellet [12,13] injection system accelerates a frozen high-z gas such as argon, neon, deuterium or some combination of these gases using a high-pressure gas pulse from an MGI valve to propel the pellet [14]. Before injection into the plasma discharge, the pellet is fragmented, and smaller fragments are injected into the vessel.

Because of the use of gases in the MGI system, or for SPI propulsion, or for shell pellet propulsion, the propellant gas limits the pellet velocity to about 300-400 m/s [15] Consequently, the projected response time for the MGI system on ITER is about 40 ms, and over 30 ms for the Shattered Pellet system [16].

In addition, as described by Leonov et. al., in simulations examining the impurity gas assimilation by the JET plasma, MGI gas assimilation is a complicated process that may be influenced by the plasma response to the gas injection itself [17]. The EPI overcomes these issue by relying on a simple electromagnetic propulsion system.

2.0 PRESENT STATUS

Promising experimental results have been achieved on a proto-type EPI system. In the experimental set-up shown in Fig. 2, a sabot is placed between the EPI electrodes and a 40 kJ capacitor bank is discharged using an ignitron switch. Magnetic probes, located below the rail electrodes, are used to track the motion of the sabot. A fast camera, positioned above the rails (out of frame in Fig. 2) also visually tracks the motion of the sabot. These images combined with the magnetic probe data measure the acceleration and the velocity of the injector payload.

Fig. 3 shows the calculated current and velocity profiles for the proto-type system. Overlaid on the calculated traces are the experimentally measured rail current and payload velocity. The data shows acceleration of a 3.2 g sabot to over 150 m/s within 1.5 ms, and is consistent with model calculations, giving confidence that scaled-up systems could achieve the projected needs of an ITER-scale injector.

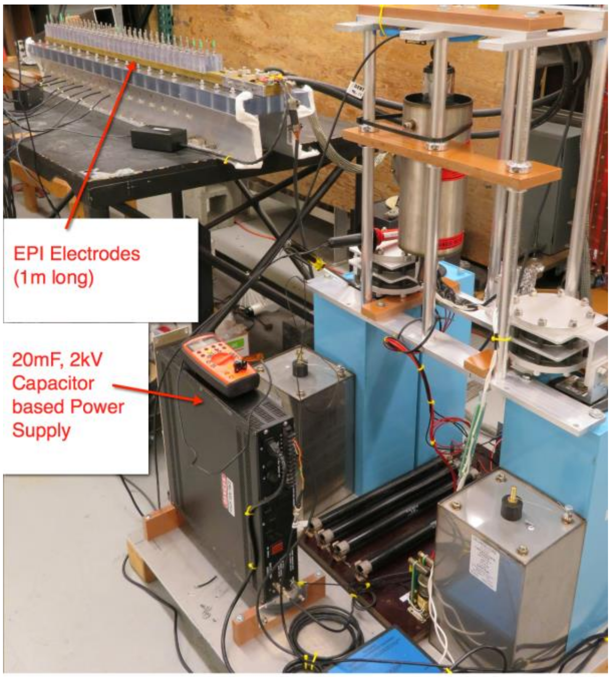

Fig. 2: Small-scale experimental setup of the EPI system showing the main EPI electrodes and the 40 kJ capacitor power supply.

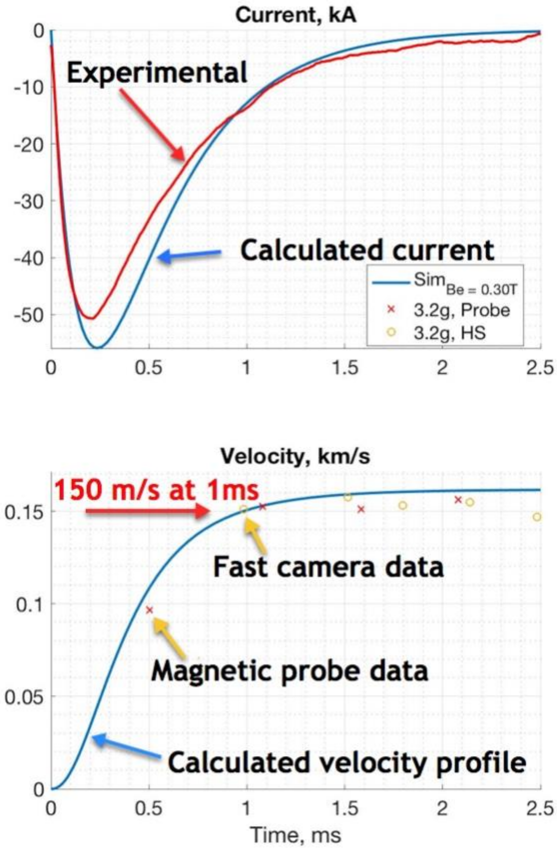

Fig. 3 Experimental data showing the current through a 3.2 g EPI sabot and the attainment of 150 m/s in 1.5 ms, consistent with the calculated values for this off-line system test to verify the EPI system response time.

Another important advantage of the fully electromagnetic EPI system is that it has no mechanical moving parts that can undergo fatigue damage due to repeated cyclin; and it can be positioned near the reactor vessel. In such cases, this has the added benefit of utilizing the existing tokamak fringing field to dramatically increase performance of the injector while simultaneously reducing the transit time of the radiative payload from the injector muzzle to the tokamak plasma. This substantially enhances overall system effectiveness by minimizing required lead time thus providing a larger safety margin.

Thus the EPI concept has the potential to meet the short warning time scales needed for ITER, while attaining the required velocities for deep penetration in reactor grade plasmas. In this proposed method, a radiative payload consisting of micro spheres of Be, BN or B, a shell pellet [18], or other acceptable low-Z materials would be injected into the plasma center for thermal and runaway electron mitigation. The radiative payload would be accelerated to the required velocities (~500 m/s for present tokamaks, and ~1 km/s or higher for ITER) for deposition at the required location within the plasma. This capability will provide the means for initiating a controlled plasma termination that originates at the plasma center, rather than from the outer periphery. This added capability, in addition to the fast time-response capability, should provide greater flexibility in controlling tokamak disruptions.

3.0 NEAR TERM PLANS

Motivated by the promising results from the proto-type EPI system, we are now assembling a more optimized version of the EPI system. This system, termed EPI-2, will have an external boost field capability of at least 2 T. The progress and plans related to the development and tests with the EPI-2 system are described below.

Prior to the development of an EPI system for a tokamak installation, some additional development is needed. The goals of the EPI-2 system development are:

(1) Operate the system with at-least 2 T external magnetic field augmentation
(2) Test the EPI system under vacuum to ensure there is good current contact between the sabot and the rails, and that the system is able to operate under vacuum
(3) Assess electrode lifetime
(4) Demonstrate sabot recovery to show that the sabot is retained within the EPI tank, while the payload exits the EPI system

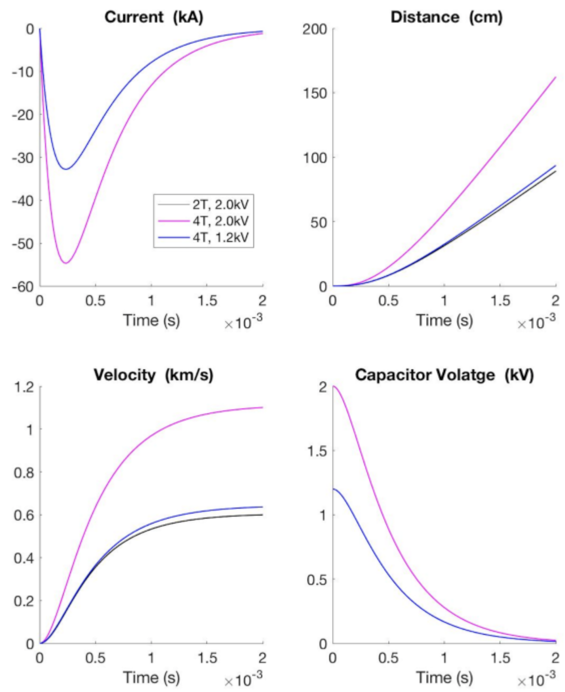

Fig. 4: Calculated velocity parameters for a present tokamak scale experiment.

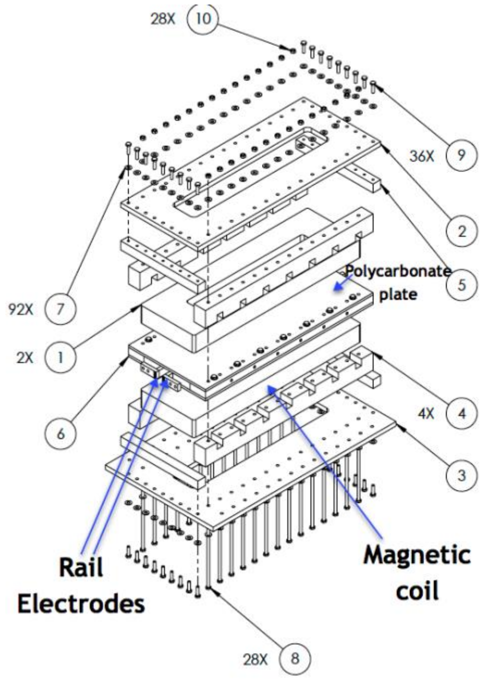

Fig. 5: Exploded view of core components of the EPI-2 main assembly showing the rail electrode region and the magnetic field boost coils.

The calculated parameters for a near-term tokamak experiment are shown in Fig. 4. Although a near-term EPI for a present tokamak installation should be able to verify the ~ 1km/s velocities needed for an ITER-scale injector, much of the optimization for the next-step experiments would be for operation in the 200 to 500 m/s velocity range. From Fig. 4, at an external field of 4 T, operating at a voltage of just 1.2 kV (for a 20 mF capacitor bank) should permit velocities exceeding 0.5 km/s.

The core components of the EPI-2 system (shown in Fig. 5) consists of two metal rails measuring 2 cm in height x 0.95 cm wide. They are 58 cm long and are separated from each other by 2 cm. On either side of the rails are present 58 cm long, 2 cm high plastic insulators, followed by a metal block. All these are sandwiched between two flame resistant transparent polycarbonate sheets that are 0.63 cm in height. This assembly is marked with the number 6 in Figure 5. In this magnetic field augmentation design, the magnetic field enhancing coils are positioned on the top and bottom of the polycarbonate sheets. This entire assembly is compressed using metal plates (No. 2 and 3 in Fig. 5), and additional metal bars (No. 4 in Fig. 5) that are positioned on either side of the boost coils. This assembly shown in Fig. 5 forms the core component of the EPI-2 hardware. It would have a pulse rate of one pulse every 10 to 20 minutes. It will be tested under a vacuum base pressure of better than 3.0e-7 Torr (4E-5 Pa).

The full configuration for a future tokamak installation is shown in Fig. 6. Fig. 6 shows the main vacuum tank that will house the injector, the sabot loading system, and the sabot retrieval system. The overall dimensions are

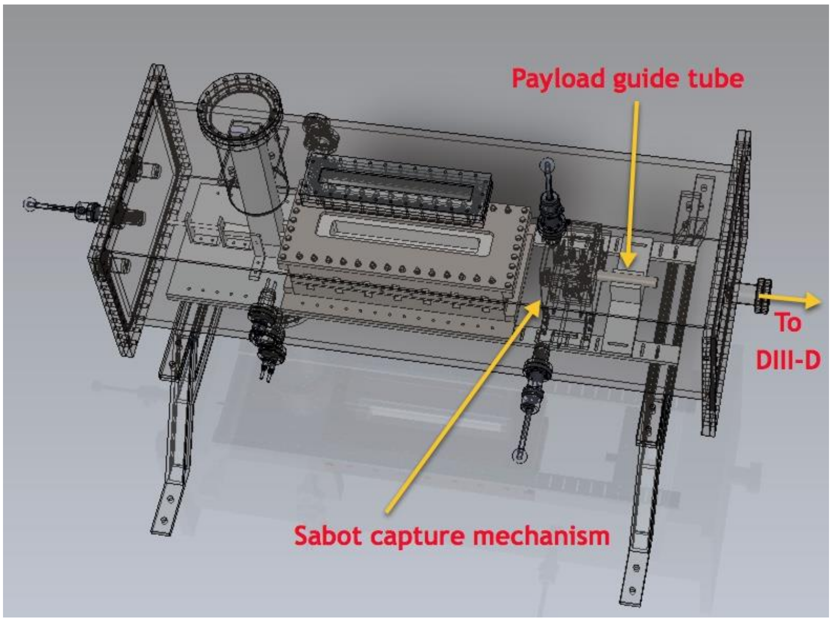

Fig. 6: Guide tube configuration for payload injection into a currently operating tokamak such as DIII-D or KSTAR. The core of the EPI system (from Fig. 4) is located near the center of the vacuum tank. In front of the core assembly is the sabot capture system. Behind the core system is an automatic sabot loading system.

about 0.6 m x 0.7 m x 1.5 m. A small turbo pump and an oil-free roughing pump would be used to keep the system under vacuum. The main components inside the vacuum tank are: (a) the core injector region (from Fig. 5) that has an electrode acceleration length of 55cm, (b) the sabot loading system that is located behind the core EPI components, and (c) the sabot retrieval system that is located in front of the core EPI hardware. The configuration can store 20 or more sabots and the contained payload. After each discharge, a new sabot could be remotely loaded from the tokamak Control Room. The sabot loading and removal arms would be composed of pneumatic actuators to perform the needed actions using a control signal from the EPI system controller.

It is anticipated that approximately two years are required to conduct the tests related to sabot recovery and vacuum field operations at an external field of at about 2 T. This would be followed by the test at up to 4 T, in a further enhanced EPI system designed specifically for a tokamak facility. This system would demonstrate payload transport through a guide tube and remote operation of the sabot loading and recovery processes. Supporting low-z pellet penetration in tokamak plasmas, and the resulting full 3d response of the tokamak discharge are being conducted by members of the PPPL and DIII-D theory team.

4. CONCLUSIONS

The EPI method to inject high velocity granules of the required size for ITER discharge termination holds great promise for addressing this critical ITER need. The EPI system accelerates a sabot. The sabot is a metallic capsule that can be accelerated to high velocity by an electromagnetic impeller. At the end of its acceleration, within 2-3 ms, the sabot will release granules of a known velocity and distribution, or a shell pellet containing smaller pellets or noble gas.

The primary advantage of the EPI concept over SPI and other gas propelled systems is its potential to meet short warning time scales, while accurately delivering the required particle size and materials at the velocities needed for achieving the required penetration depth in high power ITER discharges. The present understanding is that as little as 5 g of Be may be adequate for both thermal quench and runaway electron mitigation in ITER. This radiative payload must be deposited in the core of the plasma (and not at the edge as in present methods such as SPI).

In this proposed method, a radiative payload consisting of micro spheres of Be, BN or B, or other acceptable low-Z materials, or a shell pellet, would be injected to the plasma center for thermal and runaway electron mitigation. The radiative payload would be accelerated to the required velocities (~200-1000 m/s for present tokamaks, and ~1 km/s or higher for ITER) by the EPI system. Calculations indicate that the system is capable of attaining the required velocities for the required granule sizes in less than 1.5 ms after a command is issued to trigger the system. A proto-type system has been tested off-line to verify the projected system response time and attainable velocities. Both are consistent with the model calculations, giving confidence that larger systems can be built to attain the target ITER goals. An important advantage of the EPI system is that because it is fully electromagnetic, with no mechanical moving parts, it could be positioned very close to the reactor vessel. This has the added benefit that if the injector is aligned with the external fields, the performance dramatically increases, while simultaneously reducing the transit time of the payload from the injector to the tokamak plasma.

The EPI system controls both the size and velocity of the particles ensuring that the radiative payload can penetrate to the required location, and on a fast time scale to quench the runaway electrons. The ITER DMS requires the level of capabilities offered by the EPI system to ensure safety of the ITER facility.

5.0 ACKNOWLEDGMENS

We are grateful to Dr. M. Lehnen of the ITER Organization for providing information related to materials that are suitable for use in an ITER DM System. Many thanks to R. Feder (PPPL), G. Loesser (PPPL), J. Kiabacha (PPPL), L. Konkel (PPPL), V. Barabash (ITER) and M. Raphael (ITER) for providing drawings of the ITER port plug, for providing information on materials allowed in ITER, and for other help. We would like to thank Mr. J.A. Rogers of the University of Washington for support with experimental operations. This work is supported by US DOE contract numbers DE-SC0006757, DE-AC02-09CH11466 and DE-FG02-99ER54519 AM08

6.0 REFERENCES

[1] R. Raman, T.R. Jarboe, J.E. Menard, et al., “Fast time response electromagnetic disruption mitigation concept,” Fusion Science & Technol., **68** 797, 2015.

[2] S.V Konovalov, V.M. Leonov, R.R. Khayrutdinov, et al., proceedings of the IAEA-FEC 2012 conference, ITR/P1-38.

[3] D.G. Whyte et al., “Disruption mitigation with high pressure noble gas injection,” Journal of Nuclear Materials, **313-316**, 1240, (2003).

[4] E.M. Hollmann et al., “Measurements of injected impurity assimilation during massive gas injection experiments in DIII-D,” Nucl. Fusion, **48**, 115007, (2008).

[5] G. Pautasso et al., “Disruption studies in ASDEX Upgrade in view of ITER,” Plasma Phys. Control. Fusion, **51**, 124056, (2009).

[6] M. Lehnen et al., “Disruption mitigation by massive gas injection in JET,” Nucl. Fusion, **51**, 123010, (2001).

[7] C. Reux et al., “Experimental study of disruption mitigation using massive injection of noble gases on Tore Supra,” Nucl. Fusion, **50**, 095006, (2010).

[8] R.S. Granetz, et al., “Disruption mitigation studies on ALCATOR C-MOD and DIII-D,” Nuclear Fusion **47**, 1086 (2007)

[9] S. A. Bozhenkov, K.-H. Finken, M. Lehnen, and R. C. Wolf, “Main characteristics of the fast disruption mitigation valve,” Rev. Sci. Instrum., vol. **78**, no. 3, p. 033503, 2007.

[10] K. H. Finken, M. Lehnen, and S. A. Bozhenkov, “Gas flow analysis of a disruption mitigation valve (DMV),” Nucl. Fusion, vol. **48**, no. 11, p. 115001, 2008.

[11] S. Maruyama, et al., “ITER fueling and glo discharge cleaning system overview,” ITR/P5-24, Proc. 24th IAEA Fusion Energy Conf., San Diego, USA (2012).

[12] D. Shiraki, et al., “Thermal quench mitigation and current quench control by injection of mixed species shattered pellets in DIII-D,” Phys. of Plasmas **23**, 0625516 (2016)

[13] N. Commaux, L.R. Baylor, T.C. Jernigan et al., “Demonstration of rapid shutdown using large shattered deuterium pellet injection in DIII-D,” Nucl. Fusion **50,** 112001, (2010).

[14] L.R. Baylor, et al., Disruption Mitigation Technology Concepts and Implications for ITER, IEEE Transactions on Plasma Science **38**, 419 (2010)

[15] L.R. Baylor, C.C. Barboer, J.R. Carmichael et al., “Disruption mitigation system developments and design for ITER,” Fusion. Science and Technology **68**, 211 (2015).

[16] M. Lehnen, ITER Disruption Mitigation Workshop Report, ITER HQ, 8-10 March 2017

[17] V. Leonov et al., “Simulation of the pre-thermal quench stage of disruptions during massive gas injection and projections for ITER,” Proceedings of the IAEA-FEC 2014 Conference, TH/P3-35, St. Petersburg, Russia, October 13-18 October (2014).

[18] E.M. Hollmann et al., “Low-Z shell pellet experiments on DIII-D,” CP1161, Atomic Processes in Plasmas, edited by K. B. Fournier, 2009 American Institute of Physics 978-0-7354-0698-8/09