Pellet Fueling, ELM pacing, and Disruption Mitigation Technology Development for ITER*

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Abstract. Plasma fueling with pellet injection, pacing of edge localized modes (ELMs) by small frequent pellets, and disruption mitigation with gas jets or injected pellets are some of the most important technological capabilities needed for successful operation of ITER. Tools are being developed at Oak Ridge National Laboratory that can be employed on ITER to provide the necessary core pellet fueling and the mitigation of ELMs and disruptions. Here we present progress on the development of the technology to provide reliable high throughput inner wall pellet fueling, pellet ELM pacing with high frequency small pellets, and disruption mitigation with gas jets and pellets. Examples of how these tools can be employed on ITER are discussed.

1. Introduction

Pellet injection is the primary fueling technique planned for efficient core DT fueling of ITER burning plasmas, which is necessary for achieving high fusion gain. Injection of pellets from the inner wall has been shown on present day tokamaks to provide efficient fueling and is planned for use on ITER [1,2,3]. The technology to achieve the pellet throughput needed by ITER is under development and we report on progress achieved with a newly developed novel twin-screw continuous extrusion system.

ELMs have been observed to be triggered by fueling pellets on several tokamaks, irrespective of injection location. This led to the attempt to increase the natural ELM frequency by injected pellets at twice that frequency [4]. The results were smaller ELMs at twice the natural ELM frequency. Here we present progress on the development of the pellet technology to provide ELM pacing with a minimal pellet speed using only gravity as the accelerator. The developed device known as a pellet dropper has obtained 50 Hz 1-mm pellet formation for up to 5 seconds [5]. The dropper achieves 10 m/s pellet speeds for shallow pellet penetration to minimize fueling while providing the necessary localized plasma edge perturbation to trigger rapid ELMs.

Disruptions on ITER present challenges to handle the intense heat flux, the forces from halo currents, and the potential first wall damage from energetic runaway electrons. Injecting large quantities of material into the plasma can reduce the plasma energy and increase its resistivity to mitigate these effects. High flow rate single-valve and multi-valve gas jet systems have been developed for gas jet formation and used to mitigate heat fluxes and high forces from halo currents in disruptions on DIII-D [6,7]. Gas jets systems such as these or a large pellet based system are under consideration for use on ITER. Details of the gas jet designs and

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performance and the design for an extremely large disruption mitigation pellet injector are presented.

2. ITER Fueling System Development

The ITER pellet fueling system is designed to inject pellets through an inner wall pellet guide tube and a guide tube for outer wall injection [8]. The inner wall guide tube would provide high throughput pellet fueling while the outer wall guide tube would be used primarily to trigger ELMs to pace then at a high frequency of >15 Hz. The pellet fueling rate is to be up to 100 Pa-m^3/s, which will require the formation of solid DT at a volume rate of ~1.5 cm^3/s.

Single screw extruders have demonstrated the continuous production of solid hydrogenic material and have been mated to pellet injectors [9]. The ITER requirement for each injector is more than 5 times higher throughput than previously achieved with a continuous extruder and so a new twin-screw approach is under development that promises to have greater throughput and stability than a single screw. The screw extruder supplies the solid DT that is cut into pellets and positioned in a barrel for acceleration by a gas burst from low throughput fast acting propellant valve.

A novel high throughput twin-screw extruder has been designed that can supply the 0.3 g/s (~1.5 cm^3/s solid DT) needed by ITER for fuel pellet formation and for ELM pacing pellets.

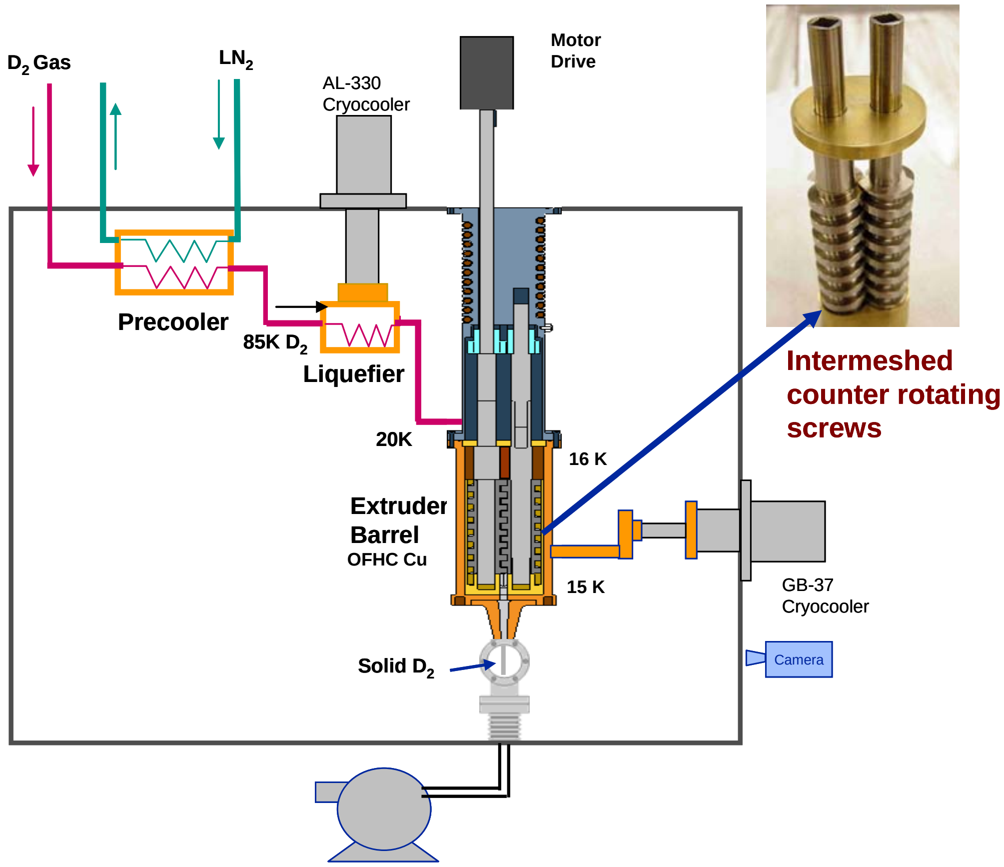

FIG. 1. Intermeshing counter-rotating screws used in a prototype twin-screw deuterium extruder. Cryocoolers provide the needed cooling for liquefaction and solidification.

A prototype extruder of this type has been built and is under test to determine throughput and steady-state performance [10]. A schematic of the prototype extruder and photo of the intermeshing screws that are inserted into the copper barrel in the extruder is shown in Fig. 1. The screws counter rotate and are intermeshed to force the solid material through a nozzle at the bottom of the barrel. This type of extruder offers the advantage of positive displacement of the solid material that is not strongly dependent on friction between the ice and screw threads.

Results from initial tests of the prototype extruder have demonstrated solid deuterium extrusions can be generated at a rate of 0.2 cm^3/s for as long as 30 minutes. Fig. 2 shows a video image of the solid deuterium produced from one of these tests. The main limitation to the duration being the amount of deuterium consumed. A recirculation system as planned for the ITER pellet injector is to be implemented to minimize the deuterium consumption in our testing. This will require the use of dry vacuum pumps and an oil free diagram compressor.

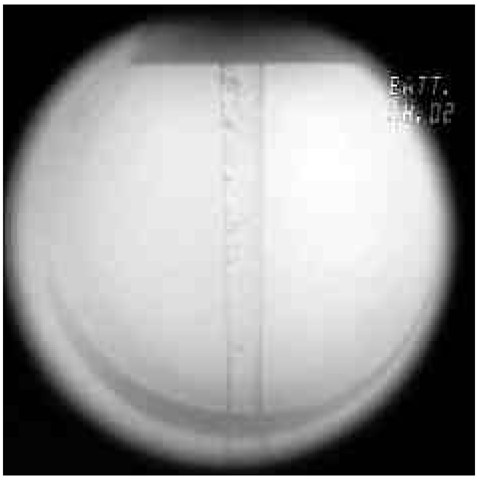

FIG. 2. Solid deuterium rectangular ribbon with a width of 3mm being extruded at a rate of 0.2 cm^3/s from the prototype twin-screw extruder at a temperature of 16K.

The next step of development for the pellet injection system is the design and testing of the system for pellet formation and acceleration. A movable barrel that cuts the pellet from the solid ribbon shown in Fig 2 will be used along with a fast acting propellant valve [11]. The valve will be designed for minimal gas flow to simplify the recirculating propellant gas system [8] that is employed in order to not burden the tritium plant with real time propellant gas processing. Since the pellet speeds are desired to be less than 500 m/s to survive the curved guide tubes, it is expected that a very low gas flow rate (< 10 mbar-L per pellet) will achieve that pellet speed.

3. ELM Pacing Technology

The injection of small pellets to purposely trigger rapid small ELMs, a technique known as pellet ELM pacing [4], has been proposed as a possible solution to the ELM thermal damage to the divertor in ITER [12] . The ELM pacing pellets will need to be small enough to not adversely affect the plasma confinement from over fueling, yet penetrate deep enough to reliably trigger a small ELM with each pellet. Research is underway at several laboratories to determine the optimal pellet size and injection location for ELM pacing and then scale these results to ITER.

A pellet dropper ELM triggering tool has been developed for testing the ELM pacing concept on the DIII-D tokamak [5]. It is designed to cut pellets from a 1 mm diameter horizontally batch extruded ribbon of solid deuterium and drop them into a funnel that guides the pellets to the top of the plasma using gravity as the accelerator. The dropper shown in the photo in Fig. 3 is simpler than a gas gun injector since it does not need a propellant valve and gas handling system. It results in slow pellets < 10 m/s to minimize penetration into the plasma. It has

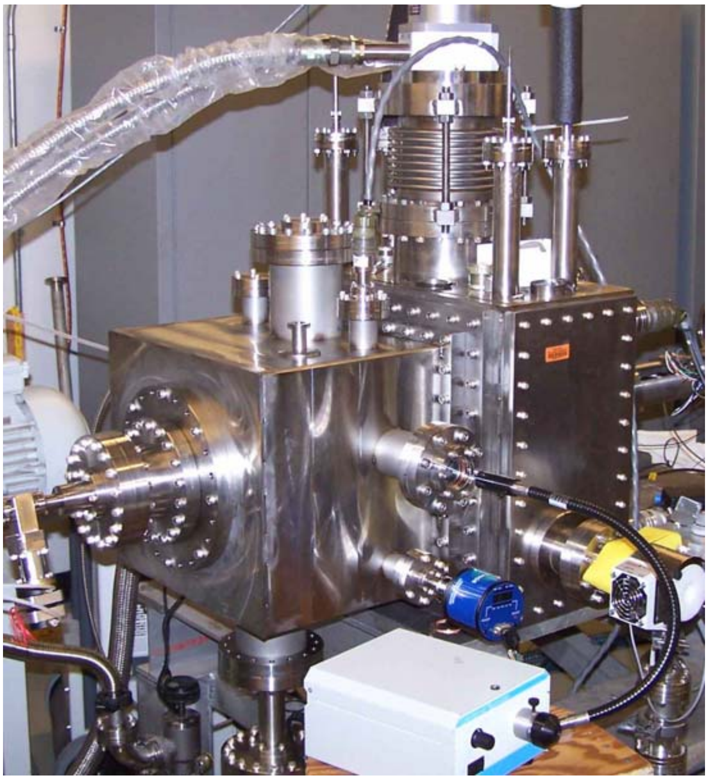

FIG. 3. Photo of pellet dropper device under test in ORNL pellet fueling laboratory.

obtained 50 Hz 1-mm pellet formation for up to 5 seconds [5]. An example showing the pellet mass measured by a microwave cavity for a string of pellets is shown in Fig. 4. The dropper achieves ~10 m/s pellet speeds for shallow pellet penetration to minimize fueling while providing a localized plasma edge perturbation to trigger rapid ELMs. Initial results with the pellet dropper indicate that fast ions deflect the pellets toroidally before penetrating deep enough to trigger ELMs [13]. Modifications to the injection geometry are planned to increase the pellet velocity normal to the plasma surface by a factor of 3. A pellet dropper type device is not suitable for ITER due to lack of vertical injection (dropping) ports. The ITER pellet injection system is being designed with higher speed pellet capability and to have the flexibility in pellet size and repetition rate to be employed as an ELM pacing tool in addition to its primary fueling mission.

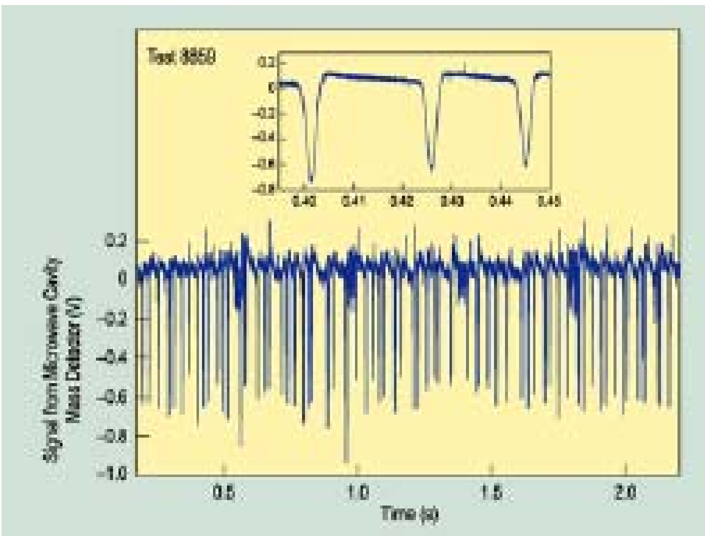

FIG. 4. Microwave cavity mass measurement of 1-mm deuterium pellets cut and dropped by the pellet dropper. Signal level is proportional to the pellet mass.

4. Disruption Mitigation Technology

Gas jet systems have been used to mitigate disruptions on a number of tokamaks and are being considered for use on ITER [6]. A high flow rate single-valve and a multi-valve "Medusa" gas jet system have been developed at ORNL for gas jet formation and used to mitigate high forces and halo currents in disruptions on DIII-D [7]. The high flow single-valve shown in the picture in Fig. 5 has an orifice diameter of 22 mm and can obtain flows in excess of $1x10^7$ mbar-L/s (10^6 Pa-m^3/s) [14]. The multi-valve jet has achieved flows in excess of $3x10^6$ mbar-L/s and has a fast rise time of less than 1 ms. A photo of the "Medusa" gas jet system is shown in Fig.6. The pressure of deuterium gas jets from all the valves fired simultaneously is overlaid in Fig. 7 showing that the rise time of all the valves is well matched and that it achieves a pressure greater than 3 MPa at the valve exit in less than 1 ms. The valves all use low-inductance solenoids driven by a capacitive discharge circuit. The valve seat material used in these valves is VESPEL polyimide with the body made of stainless steel.

FIG. 5. High flow rate gas valve used for disruption mitigation testing. The valve orifice size is 22mm and has a maximum flow rate of $1x10^7$ mbar-L/s.

A new digital holography diagnostic has been developed to measure gas jets and plasma density and has been used to measure the gas jet plume density [15]. An example of this measurement is shown in Fig. 8 for a gas jet leaving a 10 mm diameter tube that is used to direct the gas jet. The measured plume qualitatively agrees with gas dynamic code calculations of the plume shape.

FIG. 6. Photo of the Medusa multi-valve gas jet system installed on the DIII-D tokamak.

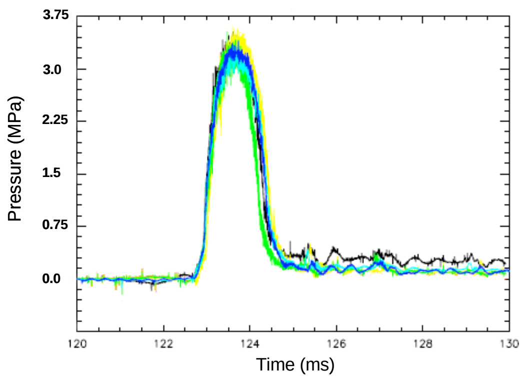

FIG. 7. Pressure of deuterium exiting the individual valves of the Medusa gas jet system when 5 valves are fired simultaneously.

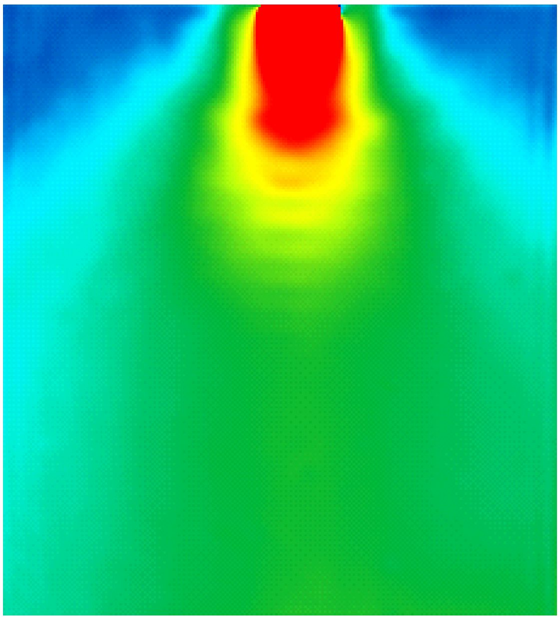

FIG. 8. Gas jet line integrated density image from a digital holography diagnostic developed by TDT LLC. The gas jet exits a 10mm diameter tube at the top.

Gas jet systems have not produced high assimilation rates of the gas into the disrupting plasma leading to uncertainly for such systems to be able to mitigate runaway electrons in ITER [16]. Development of a pellet injection system that can produce a well collimated stream of high speed particles of solid deuterium or other light elements is ongoing. Pellets as large as 10mm have been formed in a pipe-gun type system. Pellets have been purposely broken into small particles by accelerating them through a sharp bend or hitting a shatter plate.

A new large pellet device is being built at ORNL to test the capability of large shattered pellets to mitigate disruptions and prevent runaway electron damage. The device under development is a pipe-gun type injector [17] with a 16mm pellet diameter and length and is shown in the CAD rendering in Fig. 9. Liquid helium is used to create a cold zone in the barrel where deuterium with trace levels of other condensable gases is allowed to freeze and form a pellet. The pellet is accelerated with a high pressure gas burst and can reach speeds up to 500 m/s before hitting a shatter plate. The divergence of the plume of shattered material is being measured and optimized for the DIII-D tokamak where it will be put into use for disruption mitigation studies in 2009. Multiple systems of this type could be employed on ITER to mitigate the formation and presence of runaway electrons.

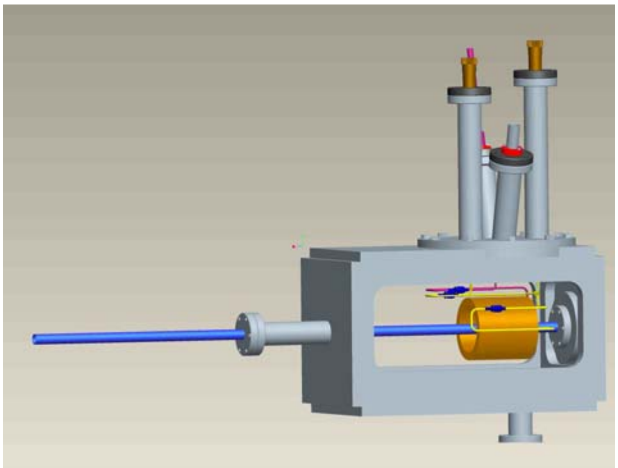

FIG. 9. CAD model of the large diameter pipe-gun device being developed for mitigating disruptions with large 16mm deuterium pellets that are shattered before entering the plasma.

5. Discussion

The pellet injection system specified for ITER will have the capability to fuel with tritium rich pellets from the inner wall at a sufficient rate to maintain high density in burning plasmas. Extruder technology to achieve the needed reliable high throughput pellets is still under development, but is anticipated to be available well within the needed ITER time scale. A gas gun accelerator based on existing repeating gas gun injectors is being designed. Low throughput propellant gas valves to minimize the required propellant gas and adjustable extrusion sizes for variation of the pellet size are areas to be developed.

The use of pellets as an ELM trigger continues to be investigated as an ELM mitigation technique on present day tokamak. Future experiments with low field side injection of small pellets will yield valuable information on this option for ITER and will help in the determination of the pellet size, speed, and frequency requirements. The pellet injection technology being developed for ITER, including the steady-state extrusion capability discussed in this paper, will have the flexibility to be employed as an ELM mitigation system if needed. Small pellets injected at 15 Hz from the low field side injection line may be sufficient to maintain an ELM frequency of 15 Hz, thus keeping the size of the ELMs much lower than they would become at a much lower natural ELM frequency.

The disruption mitigation system for ITER is projected to need to inject $>10^{25}$ atoms of D_2 or an order of magnitude less atoms if higher Z impurities are used [18,19]. This needs to be introduced into the vessel in less than 10 ms, which means a flow rate of nearly 10^7 Pa m^3/s for D_2. To meet these particle delivery needs, ITER will need to employ either several large jumbo size 22mm orifice valves in parallel or some combination of gas jet and solid material pellet systems. The gas jet is limited by the sound speed of the gas, which for D_2 is nearly 1000 m/s. This implies that the valves for gas jets need to be relatively close to the vacuum vessel, likely in a port plug. Solid material pellet based systems will have similar speeds and would need to also be located in a port plug. The radiation and magnetic field environment will dictate the materials used by the disruption mitigation system and level of shielding and remote handling needed to maintain the system.

6. Summary and Conclusions

In conclusion, progress is being made in the development of technology to provide the necessary throughput of solid DT for ITER fueling and pellet ELM pacing requirements. The twin-screw extruder prototype under test has demonstrated the capability to produce steady-state extrusions and looks promising for scaling up to the full ITER throughput requirement. A gas gun accelerator and recirculation system is planned to couple to the extruder to demonstrate the basic capabilities of the ITER pellet injection system.

Disruption mitigation techniques using gas jets and solid material injection are being developed and tested in support of ITER. The gas jets that have been tested have demonstrated the ability to largely mitigate the halo currents and high heat fluxes from disruptions. This type of technology can be utilized on ITER with some additional engineering to make the valves compatible with the ITER environment. Solid material injection with extremely large pellets that are shattered just before injection is less well developed but looks promising for mitigation of runaway electrons that may be a more serious problem for ITER than in present day tokamak experiments. The upcoming tests of this concept in the coming year will be very useful to determine which method or combination of methods will be most suitable for ITER.

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