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***Abstract*—An injector device to trigger frequent edge localized modes (ELMs) was developed at Princeton Plasma Physics Laboratory (PPPL) and subsequently installed and operated on DIII-D, to inject lithium spherical granules to launch into tokamak plasmas. One size granule per shot, selectable between shots, of four different spherical lithium granule sizes are available to launch horizontally into the plasma mid-plane at speeds up to 120 m/s. Pre-sorted granules are stored in a 4-chamber reservoir containing granules at various sizes, 900, 700, 500, and 300 micron. A manually controlled gating device opens the subject reservoir compartment channeling granules to a piezo crystal with a central aperture. The disk is then electrically vibrated at its resonant frequency causing granules to fall through the aperture into a vertical tube that terminates slightly above a rotating impeller strike zone. The variable speed rotating impeller, hits the granules through an aperture gated drift tube into the plasma. The 44 cm vertical drop imparts sufficient vertical speed to the granules to reach to the impeller center. A high-speed camera records granule/impeller interaction events to provide the injection count. Another on-axis high-speed camera records the plasma edge ablation events. Impeller speed is monitored via a photodiode using an external illumination system. Initial operations injected granules at frequencies up to 120 Hz (900 micron) and >600 Hz (300 micron). ELM triggering efficiency approached 100% for 700 and 900 micron in ELMing H-mode plasmas. The injector can be used to inject other materials e.g. boron, tungsten, carbon, etc. The system and planned upgrades are discussed.**

Keywords—Lithium; granular; injector; piezo; injection

I. Introduction

Naturally occurring, periodic, relaxations of the plasma edge called Edge Localized Modes (ELM), characteristic of the H-mode confinement of tokamak plasmas, are likely to cause unacceptable damage to wall components in next-step tokamak fusion devices [1]. Present day projections estimate that safe operation in ITER would require a 20-50X reduction to the peak heat flux deposited on the divertor tiles during a spontaneous ELM event [2]. This motivates the development of techniques to reliably suppress ELMs or mitigate their detrimental effects. Experimental demonstration of mitigation has been obtained by actively inducing ELMs at frequencies much larger than the natural ELM frequency [3], effectively reducing of the amount of energy per ELM lost by the plasma and conveyed onto the divertor tiles. While reliable and effective ELM pacing has been achieved by injection of deuterium pellets [4], concern is arising about the amount of deuterium required to maintain a robust, high frequency ELM pacing in ITER, where the total fuel throughput in the vessel is limited by the capacity of pumping and tritium processing systems [5]. In that respect, the use of non-fuel pellets, e.g. low Z non-recycling elements such as Li or Be, would alleviate the load to the gas post-processing systems, and at the same time decouple ELM pacing from plasma fueling. A simple prototype device capable of injecting Lithium granules at velocities up to 100 m/s was shown to trigger ELMs in the EAST tokamak [6]. Building on that experience, an upgraded version of the Lithium Granule Injector (LGI) was recently installed on DIII-D, to study pacing efficiency dependence on granule size and velocity, and characterize LGI induced ELMs.

This paper discusses in detail the engineering aspects of the LGI project on DIII-D (design, construction, implementation on the DIII-D device, commissioning, operation and decommissioning), including preliminary results on the ELM pacing performance.

II. Technical Description

The LGI installed at DIII-D (Fig. 1) consists of several sections, 1. A selectable four compartment storage reservoir mounted above a piezoelectric metering disk, (granules are loaded prior to operations through the reservoir top flange), 2. A rotating impeller, with 2 paddles, (up to 10,000 rpm), that hits dropped granules into the plasma edge through a vacuum valve shield drift tube, 3. A vacuum system with low base pressure ~1.33 mPa, and 4. Diagnostics for measuring granule injection rate, impeller speed, and plasma ablation. The following sections describe each of these sections. See Fig. 2 for the configuration.

A. Reservoir Design

The 304 stainless steel reservoir is brazed out of discrete parts that include a solid axial shaft chamber selector held by

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granules per hit, 5) injection time, and 6) injection frequency. The distribution of the inverse of inter-injection periods can be used to visualize the spectrum of injection frequency, as shown in Fig. 3c for an experiment with 250 Hz impeller rotation frequency.

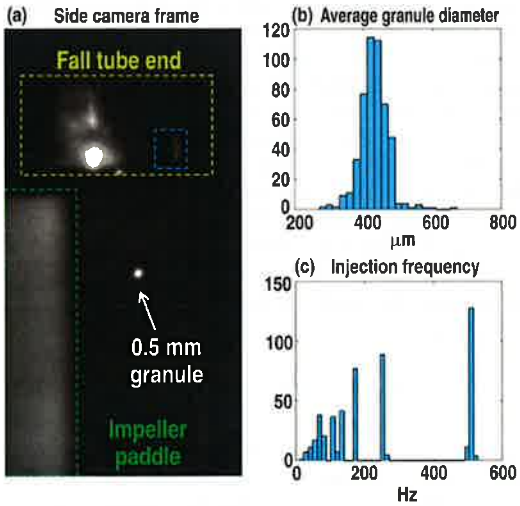

Fig. 3. (a) Fast camera image-capturing the fall of a 0.5 mm diameter granule before impeller hit (left). Image post-processing techniques are used to compute the distribution of the size of injected granules (b) and the spectrum of injection frequencies (c).

By monitoring the increase of LGI internal background light due to pellet/plasma ablation light coming back through the injection tube, a time history of the sequence of pellet ablation events could be obtained. This information can be used to discriminate actual injections into plasma from errant strikes or "foul balls", and determine an injection efficiency (number of granules ablated/number of granules dropped), which over these experiments was ~ 85% or better. In addition, by cross-correlating the time histories of granule hits and ablation events, an estimate of the granule time of flight is derived, and consequently the granule velocity. Although granule velocity up to 110 m/s was routinely attained, this was much lower than the nominal velocity expected for elastic impacts, indicating that the Li-impeller hit is deeply inelastic, as expected from the softness of Lithium. These techniques-correlating the ablation history with other ELM behavior monitors- quantifies the ability of the LGI to trigger ELMs.

A valuable real-time impeller rotation frequency was available in the control room, obtained from the periodic light signal from a photodiode. A fast color camera (Miro II, http://www.visionresearch.com) was used to observe the plasma edge from a window located on the back of the LGI body, providing a radial view of the ablation region through the LGI injection tube. Color acquisitions at frame rates up to 40 kHz, were able to capture the dynamics of the granule ablation/penetration, characterized by the expansion of a field aligned cloud of ablated material (Fig. 4). The images are dominated by the green light from line emission at 548 nm, from the singly ionized Li II.

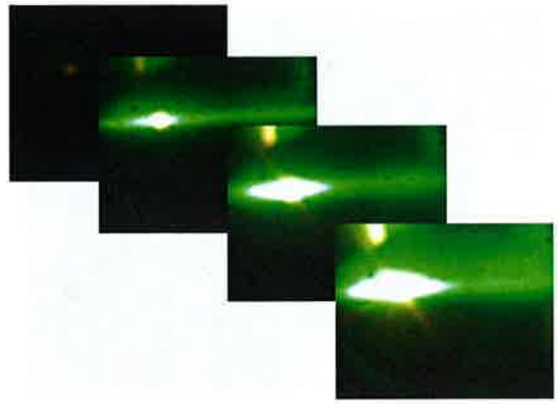

Fig. 4. Sequence of images captured by color camera, view down axis of injection tube, showing the ablation of a 0.5 mm granule. Frames are separated by 50 μs intervals.

III. Pre-operational Tests

The LGI was assembled and calibrated/tested in the lab initially using polyethylene beads for operational readiness. The beads worked well in the dropper but shattered when hit by the impeller, requiring an extended cleanup. Calibration with Lithium was subsequently performed with a target made from aluminum foil stuck to a vacuum window, using vacuum grease, located at the torus end of the flight tube. The granule drop is ~1.0 degree, nominally leaving the LGI injector tube 12.0 mm below mid-plane as shown in Fig. 5. An aperture masks the baffle tube entrance to provide only a line of sight path from the impeller strike zone to the vessel. (Fig. 6) Tests with 0.3 mm and 0.5 mm granules demonstrated injection rates ~ 600-800 granules per second at piezo excitation of ~0.5 V peak-peak, and the 0.7 mm – 0.9 mm were 100-150/s at 40 V peak-peak PZD excitation. The trajectory drop angle is approximately 1° from horizontal reaching plasma 1.6m away. View ports were covered (60 mesh SS screen) for protection from the lithium granules and the 110 GHz high power ECH that occasionally reflects back into ports from over dense plasma. The viewing window had a 6 mm thick quartz window in addition to the mesh for protection.

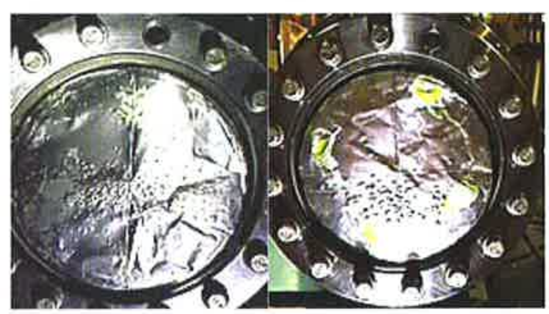

Fig. 5. Targets showing scatter of granules at the vessel flange entry point, 0.3 mm on left and 0.9 mm on right.

natural ELM frequency (20-30 Hz). Moreover, as a result of the fluctuations of the injection frequency, transient phases of ELM pacing at frequencies above 200 Hz were observed.

Detailed analysis of the acquired dataset is in progress and will be the subject of a future publication [9]. In general, LGI high frequency pacing appeared to be compatible with high plasma performance, both in terms of global confinement and pedestal characteristics.

IX. Findings after Operations

Upon LGI removal from the vessel it was disassembled and cleaned. Lithium granules, pieces, and dust, were found scattered throughout the LGI. The TIV's operation or seal was not compromised with some small granules discovered in the valve body bottom. There was however lithium dust and small pieces inside the shield tube, Conflat® seal zone, and TIV housing bottom shown in Fig. 9.

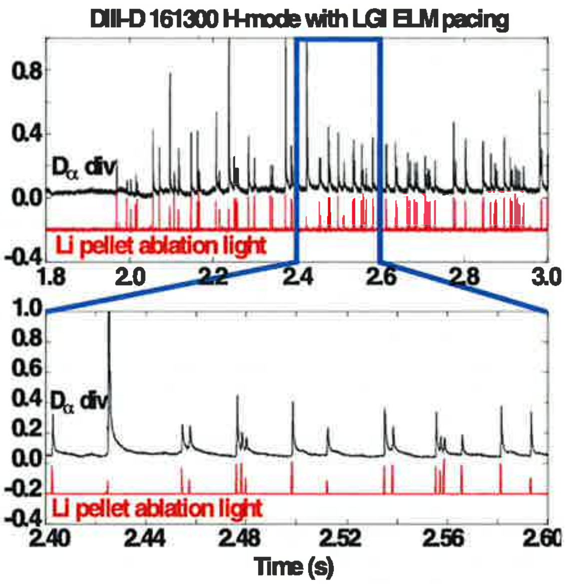

Fig. 8. (a) Spikes in the Dα emission from the divertor indicative of ELM activity (black) correlate with light bursts associated with granule ablation (red).

Accumulations of dust were found in all Conflat® flange bottoms in the gap between flanges against the copper Conflat® seal. No copper corrosion was found due to Lithium contact on any of the surfaces. Surprisingly few granules were found in the bottom of the bellows and vessel port nozzle downstream of the TIV. Granules were also found in ports toroidally adjacent to the LGI port and associated with an inadvertent launching of granules during a mechanical impulse with impeller testing between shots with the TIV open. The LGI was taken apart to install a larger PZD with a 3 mm center hole after the initial run using a PZD with a 2.5mm hole. This successfully increased the large granule injection rate from ~100 to 150/s. The reservoir was clogged at the end of the first run and disassembled and inspected for root causes. Granules were found stuck in the "gateway" and on the PZD which appeared due to a liquid that stained the PZD (Fig. 9). The PZD oil stain evaporated after 1 day air exposure, and appeared to be mineral oil residue from the manufacture of the 0.7 and 0.9 mm granules. This process included a final granule wash with hexane, and drying them in a vacuum system with a mass spectrum until the oil peaks were at noise level. The granules were recovered from the reservoir and reused for the next run without washing; the PZD and gate were found to remain clean after the second run (Fig. 10).

Fig. 9. Lithium granules (gray spheres) on the bottom of the injection baffle, and TIV copper seal and valve bottom.

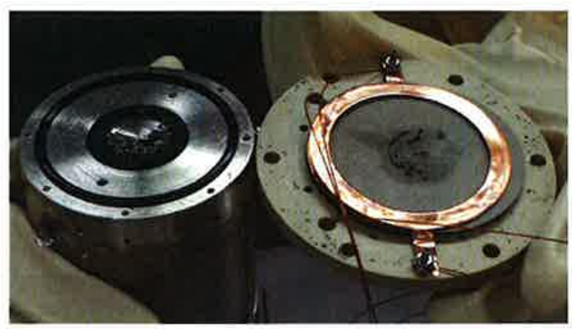

Fig. 10. Reservoir bottom on left and PZD on right, both with granules of various diameters stuck on the drop zone surfaces. The liquid stain on the PZD was suspected to be mineral oil from granules production.

An additional finding was the gate rod annular accumulation of Lithium thought due to small granules being extruded into this gap. The radial gap on the first unit was ~0.2 mm, which needed increasing amounts of torque to rotate after few rotations, leading to the prospect of seizure. The second reservoir radial gap is much tigher at .025 mm, and the rotational torque of the gate rod remained more constant enabling easier rotation wihout fear of seizure. Fig. 12 shows that the tighter gap had significantly less Lithium annular accumulation in the gate rod section.

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