A Quasi-Periodic Linear Feeder for the Impurity Granular Injection on DIII-D

Alex Nagy, A. Bortolon, W. Brown, Peter Fisher, R. Lunsford, R. Maingi, D. Mansfield, D. Mauzey, R. Nguyen, and Madeline Vorenkamp

Abstract*— Injection of solid nonfuel pellets has been actively used as a tool for pacing and mitigation of edge localized modes (ELMs). In DIII-D, effective ELM pacing has been demonstrated by the high-frequency injection of lithium and carbon submillimeter spheres, using the impurity granule injector (IGI). This device injects granules into the plasma at speeds up to 150 m/s, through impact with a rotating impeller. In the IGI, high-frequency granule delivery was accomplished through a vibrational granule dropper, in which high time-average rates are obtained at the cost of lack of period control. We present a new in-line granule feeder, capable of delivering granules of size 0.2–2 mm with no restriction of material properties, at quasi-periodic rates of up to 150 Hz, for 0.7-mm diameter lithium granules (600 Hz using 0.3-mm granules). The new dropper mechanism combines two piezo-in-line units; one which feeds the impeller and one which circulates granules that are filtered out of the feeder path. A remotely adjustable filter eliminates granules that are stacked, oversized, or side by side allowing the formation of a single moving granule injection line. The granules fall off the in-line feeder exit one at a time, achieving a quasi-periodic delivery rate proportional to the exit speed. At higher rates, the periodicity deteriorates. This behavior was studied using high-speed cameras and electrostatic measurements, and it was found that at drop rates <60 Hz, the granule delivery period has a variation of ±25% which appears to be caused by gaps which develop in the last centimeter of the injection line, as granules exit off the moving track. The linear feeder concept is robust against bridge instabilities and clogging issues, thanks to the simple diverter filter and constant recirculation of granules. Furthermore, the open-top design of the device facilitates refilling the device from separate reservoirs and has easy access for directly monitoring operation and adjustment. This paper describes the details of the in-line feeder design, along with several design iterations. The goal is a robust in-vacuum mechanism that can deliver granule flow ranging from a single particle to a line of particles at 150 per second, using different sizes and materials from the same apparatus.

***Index Terms*— Edge localized mode (ELM) trigger, impurity, injector, lithium.**

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I. Introduction

A RELIABLE device is needed to trigger edge localized modes (ELMs) in a controlled periodic manner for fusion reactor performance for handling first wall heat loads. ELMs have been found to damage fusion reactor walls due to their high heat flux loads [3]. Control of the size of the ELM heat loads by triggering frequent ELM events has been proven possible on DIII-D and EAST, using a lithium granular injector (LGI) [3], [4]. The LGI uses a gasless injection technique by hitting the granules into the plasma with an impeller rotating at up to 12 000 rpm to attain injection speeds up to ~100 m/s [5].This injector successfully propelled granules into the plasma edge triggering ELMs; however, the periodicity is not regular [6] and during experiments on DIII-D the LGI experienced operational difficulties caused by lithium galling between the reservoir mating parts of the mechanical selector. An upgrade to the LGI was performed to optimize the unit to inject other materials, automatically count dropped granules, and register granule ablation events [7]. The redesign of the LGI dropper section to address the periodicity regulation is the subject of this paper.

The original dropper used a piezoelectric disk loaded with granules in its central section, and bordered by an O-ring. It is driven at its (2150 Hz) resonant frequency causing nodes to appear at the outer edge and half the radius (O-ring location). An antinode is present at the center of the disk that oscillates vertically, moving granules to the center hole, where they drop through a guide tube into the rotating impeller which then propels them through a drift tube into the plasma edge triggering ELMs, shown in Fig. 1. The granules enter the guide tube randomly, including single, double, and triple granule groups distributed throughout the dropped granules. These granules travel together and are hit as a group by the impeller into the plasma causing irregularity in the triggering of ELMs.

The modification of the original dropper was considered to address the following specific problems:

1) jamming of the reservoir selector gate;
2) bridge instabilities (where the granules form a bridge over the hopper opening after the lower granules have exited) occurring in the reservoirs which stop granule flow;
3) avalanche free (experienced using carbon spheres that flow freely);
4) clearing of the piezoelectric disk for change of materials/size;

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TABLE I
DROPPER TYPES AND FEATURES FOR 0.5-mm GRANULES

Series	Type	Drop Rate (Hz)	Jam Free	Features	Design
1	Large V-groove	1-80	50%	Few jams, reservoir size small but adequate, set for single size granules, serial line output	
2	Small V-groove	1-120	50%	Larger reservoir, tuned for single size, issues with double stacked granules	
3	1/2 V-groove	1-120	90%	Reservoir jams intermittent, line gaps, no double stacking, no bridge instabilities	
4	Recycle feeder	1-150	100%	Filtered granule line, no double stacking, filter rejected are recycled, no bridge instabilities, off feeder reservoirs for material change out, full emptying capable	

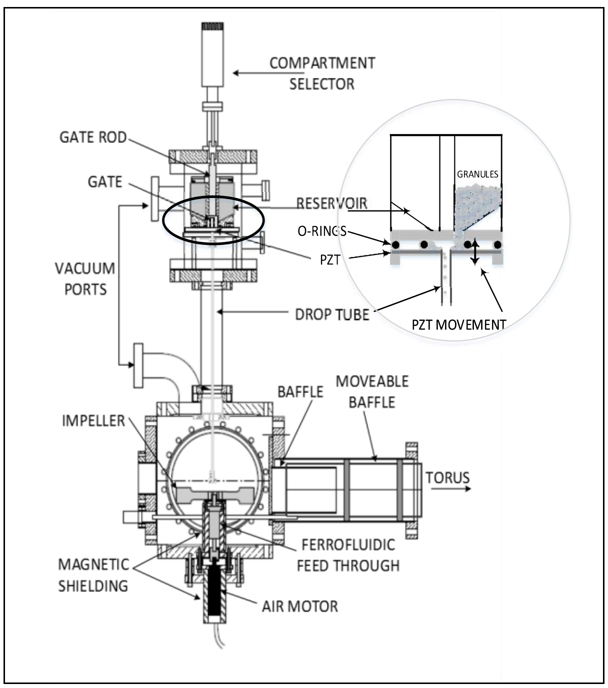

Fig. 1. Original impurity injector created by Mansfield and Roquemore at PPPL used a PZT disk to move granules to the entrance of the drop tube.

5) serial granule dropping;
6) regular periodicity coupled with a variable drop rate from 1 to 600 granules per second.

During ELM triggering experiments it also became important to strongly link regularly triggered ELMs with granule injection events to identify the onset of untriggered ELMs and assess trigger efficiency. The reservoir selector presented challenges that were too large to overcome with the original design and a new approach is undertaken using a vibratory in-line feeder repurposed from the small parts handling business world. This approach provided a solution to many of the problems; however, the ultimate goal of regular drop rate periodicity still eludes a perfect solution.

An overview of the development of this new approach is presented in Section II below.

II. GRANULE DROPPER DEVELOPMENT OVERVIEW

Granule management includes both bulk and individual granule treatment in order to merge and convert their bulk behavior into single granule events. The challenges are multifaceted in both the bulk behavior and the transition to individual behavior. The bulk handling is relatively simple; sieve the granules by size (± 0.1 mm), then using containers, gravity, and volumetric methods with appropriate moving mechanisms to guide the particles into a line and make them fall into a guide tube at regular rates from 1–600 Hz.

An initial investigation started with filling hypodermic tubes with small inside diameter sized at 1.5 times the granule diameter ranging from 0.2 to 1 mm and serially metering them out of the tube with a piezodriven pin. This approach did not work due to jamming in the tube. The more successful development designs are listed in Table I, each adding its own contribution to solving the problems listed above.

An in-line feeder was purchased from Sanki–Mirai that is used for small parts handling, and uses a magnetic field compatible piezoelectric driven rectangular rod to move, both upward and forward at an angle, to lift and move material in a preferential direction. The unit must run at its mechanical resonant frequency in order to amplify the piezoelectric vibrations into larger mechanical movements, typically 0.25-mm maximum.

The first design directly used the Mirai Technology with a V-shaped aluminum angle mounted to the in-line feeder with a shallow granule "reservoir" at the inlet end, as shown in Fig. 2. This was tested to see if the in-line feeder could

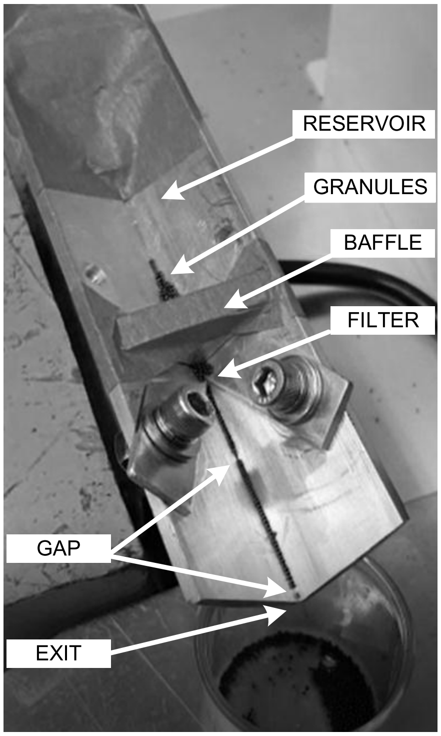

Fig. 2. Large V-groove in-line feeder bench tested successfully at low injection rates 0–60 per second using 0.7-mm carbon granules.

be utilized to deliver granules in a single file line. The reservoir outlet fills the V-angle when oscillated by the piezoelectric transducer (PZT) at the overall assembly resonant frequency, typically 150–250 Hz. Granules are vibrated down the V-groove and fall off the end of the aluminum angle.

This piezoelectric mounting method resolved bridge instabilities in the reservoir and filter zones by using continuous mechanical vibration fluidizing the bulk granules. Feed rates are calibrated by comparing the piezoelectric drive voltages ($\sim$150–640 Vp-p sine wave at the piezoelectric) to the drop rate, counted by a granule counter which had been developed as an upgrade to the original LGI dropper [6]. See Fig. 3 for details.

Granule double stacking is addressed using various sized holes in baffle filters to form granules into a single line edge to edge. This design was limited by slow drop rates and in-line gaps at higher frequencies that ruined regular periodicity, which represents our main goal.

The second design used a 25 mm wide by 150 mm long and 6-mm-thick aluminum "diving board" with a 2-mm-deep 45° V-groove down the middle and a single reservoir with an outlet that discharged granules to the groove starting point. The piezoelectric oscillation simultaneously shakes the hopper, (preventing bridge instabilities), and the V-groove to move granules down the groove to the end of the board and then dropping them into the guide tube. Although this worked better than the large V-groove design; the double stacked granules, reservoir bridge instabilities, line gaps, and low feed rates hampered the design. See Fig. 4 for details.

The third design uses a similar single-groove which evolved into a single sided V-groove with one side positioned at 90° and the other at a 45° to positively prevent double stacking, (see Fig. 5). This design added a new filter feature adding an off-ramp with a downward angle near the exit point. The feed linewidth is set to the granule diameter above the ramp so that double stacked or not-in-line granules are rejected falling down the ramp into a container. This design tested well up to $\sim$150 granules per second, with single line output, and minimal gap formation. The reservoir used baffles inside to throttle the outlet onto the feed groove but still had jamming problems. The full dropper assembly was envisioned having four independent feeders arranged in a circle spaced annularly 90° apart that drop into a central guide tube. This approach was abandoned as you will see in Section VI.

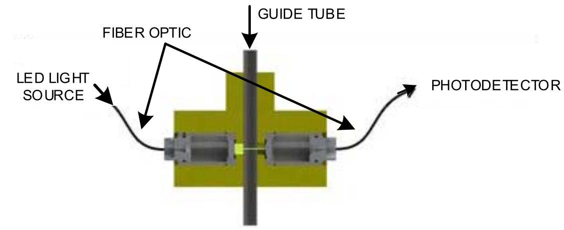

Fig. 3. Granule counter uses light attenuation to photodetector to indicate granule passage, with amplitude related to granule size.

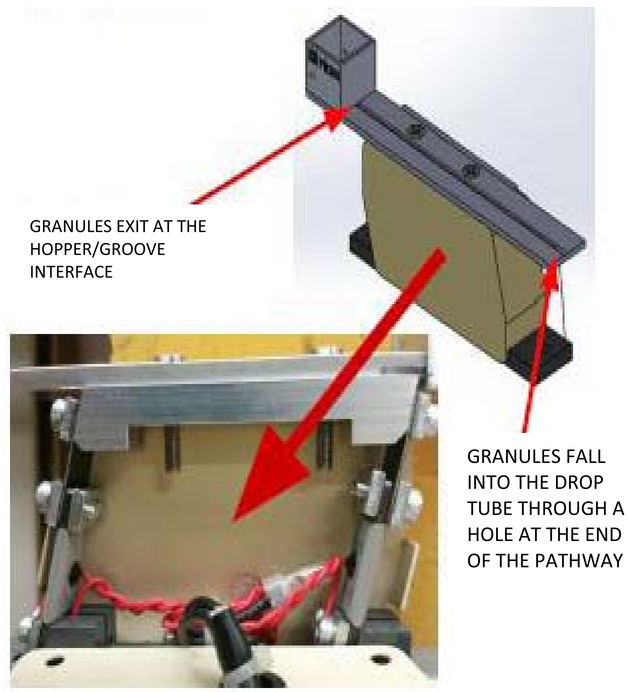

Fig. 4. Second design used the Mirai–Sanki piezoelectric in-line feeder, internal parts shown above, with a storage hopper and small V-groove.

The fourth and final version incorporated the narrow ramp filter design with a return feeder to recycle filtered granules rejected down the filter ramp, back to the inlet of the feeder. The return feeder is an in-line feeder mechanically running in the opposite direction from the feed drive. Both feeders are tuned 3 Hz apart and both driven in phase at the middle frequency to minimize beat frequencies. The resonant frequency range is typically 150–230 Hz. The feeders mechanically face in opposite directions and are by definition 180° out

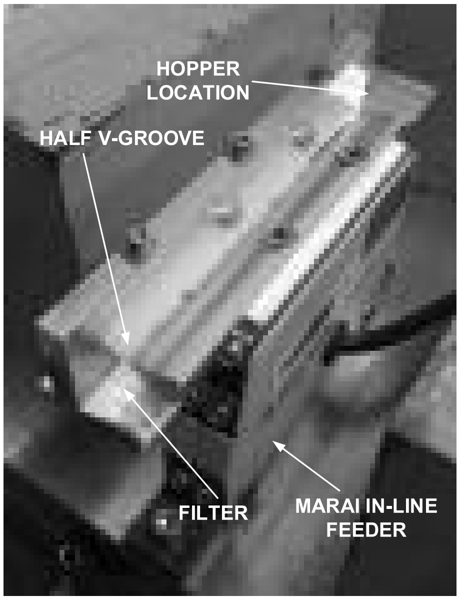

Fig. 5. This approach used a 1/2 V-groove to eliminate double stacking, and is the first to use a ramp filter. The vertical wall of the V-groove is movable to vary the groove width for various sized granule diameters 300–1000 μm.

of phase. The reservoir is eliminated since the return side feeder has enough volume for a full operational day. This design conserves granule use via recycling, and prevents bridge instabilities since both sides are vibrated and relatively flat. As with the earlier designs, avalanching is prevented and granule injections can be started and stopped within ~10 ms, with injection rates up to 150 Hz for granule sizes ranging from 0.7 to 1 mm. See Fig. 6 for details.

III. Bench Test Results

The final in-line dropper refined several features synthesized from previous designs. The gap between the out of phase moving feeder bodies is 0.05 mm preventing granules or their pieces from jamming between the two feeders. Additional sheet metal barriers were installed to guard the shear zones between the two feeders and direct granules in their respective directions.

It was discovered that the return side would successfully operate up to a maximum angle of 7° for granules to climb for recycling, and was reduced to 5.5° for margin. The filter ramp length is extended to minimize the return side climb angle. When using spherical granules, the return feeder climbing granules tended to fall back down the return feeder flat smooth surface when reaching the top. Forty-five degree 0.5-mm deep V-grooves, are cut into the granule contact surface, in the direction of granule travel, providing a two-point contact which doubles the effective friction. This forces granules to climb in lines, instead of randomly, increasing the climbing efficiency per cycle. At the return feeder bottom, a level and nongrooved surface zone was made to catch the filtered granules to increase the return feeder volume. It was also discovered that the feeder would not completely empty itself of granules, leaving a residual of ~40–80 granules in the bottom of the return side feeder. Upon reaching the top of the filter ram, this residual would get to the top and roll back

Fig. 6. Final version shown successfully bench testing using 0.7-mm lithium granules in an Argon-filled glove box.

down to the bottom of the feeder before starting the climb back up thus repeating an endless cycle without crossing over to the injection feeder. This is unacceptable as cross-contamination of materials and sizes requires a smaller residual for higher purity. Inserting larger odd shaped granules, like 0.3–0.5-mm boron carbide chunks, shaped-like small gravel, provided a stable climbing backstop to push the smaller spherical granules up the ramp. These gravel pieces travel with the experimental spherical granules and flowthrough the injection line, getting filtered out into the return feeder to get recycled. Using this method granule residuals are reduced to ~1–2 granules thus providing high purity when switching between materials.

IV. In-Line Feeder Periodicity

Injection rates were measured for all of the designs with limited success for regular periodicity at higher injection rates. Single granules could be dropped by pulsing the feeder with a burst of ~10–12 cycles at the resonant frequency which moves 1–2 granules off the end. Repeating one granule drops with this method was not 100% reliable.

The periodicity of 0.5-mm carbon granules was observed using the granule counter output scope traces shown in Fig. 7. The nonperiodicity tended to be cyclic as well, as shown in Fig. 8. When higher drive voltages are used to increase the injection rate, gaps in the exit end of the granule line appear as the falling sphere leaves the granule lineup. It appears that the momentum of the moving line spreads the trailing granules out in this section, having no mass to push against. As the drive is increased for higher rates the gaps tend to migrate further up the feed line. Tests with lithium and carbon had similar line gap behaviors and injection rates.

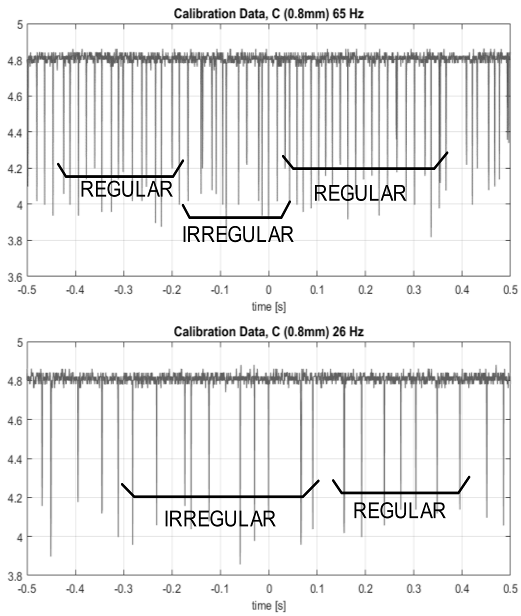

Fig. 7. Granule counter scope traces show zones of regular and irregular periodicity at both low and mid-frequencies.

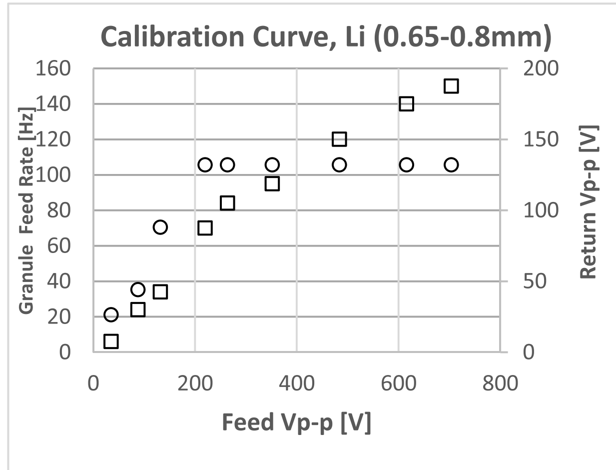

Fig. 8. Calibration curve for lithium injection and the return feeder drive voltage. The return side voltage ramps up faster to keep the feed side full, saturating at ~200 Hz.

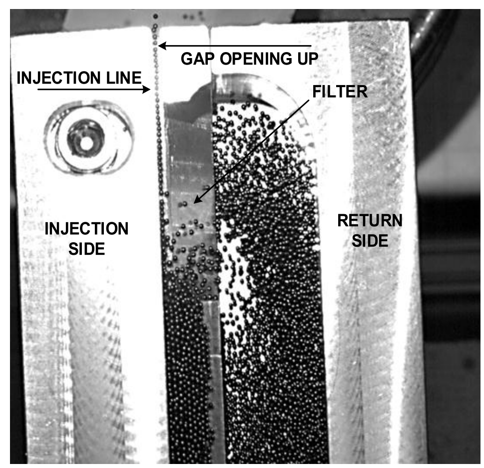

Fig. 9. When feed rates are >60 Hz, gaps form in the feed line causing regular periodicity drift in a cyclic basis, while granule lines without gaps produce a more regular periodicity.

V. In-Line Feeder Design Discussion

The secondary goals of this design, i.e., nonclogging, serial granule drops (no double granule drops), and multiple material capability without the need to break vacuum, were achieved by moving to the piezoelectric in-line feeder. Regular periodicity became quasi-periodic as many designs and test trials were made to try and lock in periodicity at all feed rates. Granule injection rates regular periodicity was sporadic as shown in Fig. 7, for both low-frequency and mid-frequency cases. We considered the possibility that the root cause of the line gaps might be static electric charge. The feeder electrostatic voltage was measured during operations to be ~46 V at the injection line which is well below the 72-V threshold considered to be the onset of electrostatic repulsion courtesy of Keyence Inc. [7].

The chart in Fig. 8 characterizes the calibration curve for the piezoelectric drive voltage versus feed rate, which is linear up to the piezovoltage 700 Vp-p at ~150-Hz injection rate. The return feeder is driven at a lower voltage to prevent over loading of the feed side with recycled granules.

By using a fast camera to record the linear oscillator, gaps forming in the injection line are observed to occur as the injected granules leave the diving board (see Fig. 9). The granules behind the open gap then move forward to fill the gap, resulting in more gaps compromising regular periodicity. A handicap with using spherical granules is that they roll both forward and backward without preference. The feeder surface was also modified for frictional purposes which helped move granules and also helped slow them down but was abandoned, and only a V-groove installed. Grooving in the return feeder, parallel to granule travel, worked the best to move the granules up the incline, in light of other texturing trials.

Observations using the fast camera found granules are hit by the end of the feeder as they fall down to the guide tube, and the front edge was undercut to prevent this collision. A stationary exit platform was also installed to solve the exit problem. However, when tested, the moving line of granules simply bumped the few nonmoving ones causing them to follow the incoming line's sporadic behavior.

VI. In-Line Feeder Vacuum Design

Initial plans call for four ~700-mm-long in-line feeders, set for specific granule diameters or materials, to be assembled annularly in a quadrant around a central drop tube, which requires a large circular vessel. By employing a remotely adjustable filter using micromotor drives for movement and a clamping drive we can vary the filter settings. This allows a filling of the feeder with various granule sizes from an adjacent in-vacuum reservoir, allowing the use of only one feeder mechanism thus reducing the chamber size. The vertical wall angle was reduced to 88° leaning toward the filter side to positively push double stacked granules down the filter ramp. This design was tested and worked 100% of the time. To change granule sizes, the wall is pivoted at the inlet end moved via a piezo-micromotor, with the position measured

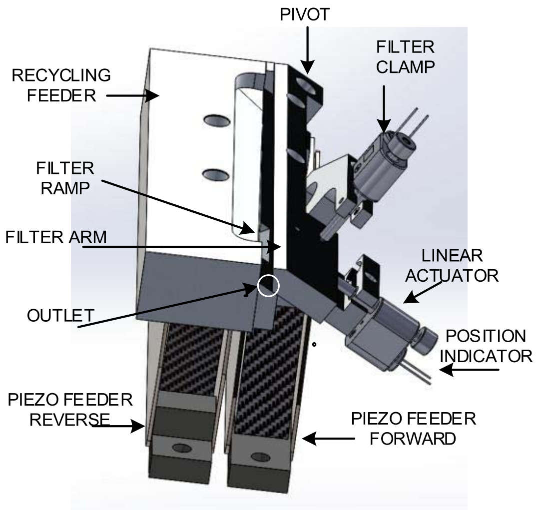

Fig. 10. Final in-line feeder designed for vacuum using piezovacuum compatible actuators and position indicators.

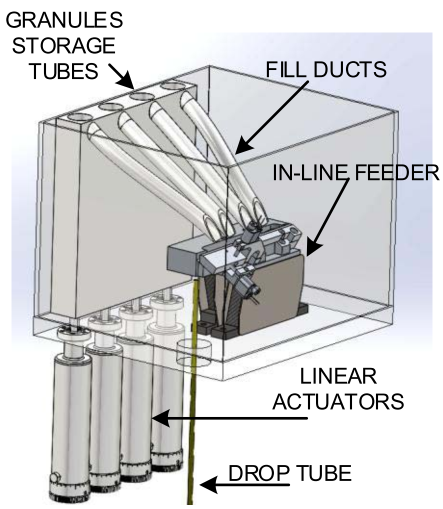

Fig. 11. In-line feeder vacuum assembly design with four material reloading capabilities without a vacuum cycle.

using a capacitive position indicator. This allows a single feeder to filter granules sizes from 0.2 to 2 mm. The movable arm is held in any position using another micromotor, as shown in Fig. 10.

Four adjacent 25-mm diameter granule reservoirs provide material and size flexibility. They are connected to the dropper via tubes to convey granules to the return side feeder, as shown in Fig. 11. The cassette configuration can be filled while in the vacuum chamber or on the bench, and loading is accomplished with or without the required argon backfill needed for lithium. The pistons have a recess on the bottom end that connects with right angle tabs at the ends of linear actuators so they can be loaded as a cassette.

The cylinders use Vespel pistons, driven by linear actuators to push the granules up to the connecting tubes, and can be pulled back down to prevent inadvertent cross-contamination. The replenishment of the return side feeder is a manual operation and visible through a vacuum view port.

VII. Conclusion

A quasi-periodic granule dropper, using in-line piezoelectric feeders, qualified for in-vacuum use, is developed and bench tested, with quasi-regular granule periodic drop rates. This device can be loaded with both rigid and ductile materials in spherical form from 0.2 to 2 mm. Several design approaches were developed with the best features synergized into a final version. While the major goal of tight regular periodicity still eludes the investigators, the secondary goals were achieved making this new design more flexible and robust than earlier designs. Resolved problems are as follows.

1) No bridge instabilities in the reservoirs.
2) Injection is avalanche free.
3) ~100% clearing of the feeders for the change of materials and sizes.
4) Serial granule dropping, coupled with a variable drop rate from 1 to 600 per second (using 0.3-mm granules).

Future development paths are being considered using individual granule exit clocking attached to the moving inline feeder.

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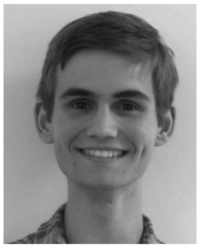

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