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A fast rise-rate, adjustable-mass-bit gas puff valve for energetic pulsed plasma experiments

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A fast rise-rate, variable mass-bit gas puff valve based on the diamagnetic repulsion principle was designed, built, and experimentally characterized. The ability to hold the pressure rise-rate nearly constant while varying the total overall mass bit was achieved via a movable mechanical restrictor that is accessible while the valve is assembled and pressurized. The rise-rates and mass-bits were measured via piezoelectric pressure transducers for plenum pressures between 10 and 40 psig and restrictor positions of 0.02-1.33 cm from the bottom of the linear restrictor travel. The mass-bits were found to vary linearly with the restrictor position at a given plenum pressure, while rise-rates varied linearly with plenum pressure but exhibited low variation over the range of possible restrictor positions. The ability to change the operating regime of a pulsed coaxial plasma deflagration accelerator by means of altering the valve parameters is demonstrated. © *2015 AIP Publishing LLC.* [http://dx.doi.org/10.1063/1.4922522]

I. INTRODUCTION

There is a consistent need for a source of high density process gas in a number of pulsed plasma devices. A pulsed coaxial plasma accelerator, in particular, requires the process gas to be introduced rapidly into an otherwise-evacuated electrode region in order to properly access the deflagration mode. The deflagration mode, first identified by Cheng,[1] is desirable in some applications, particularly those that require high directed kinetic energy and charged particle flux. These applications include space propulsion,[2,3] material-interaction studies[4] at extreme conditions, and magnetized target fusion.[5] A particular version of this class of plasma accelerator, the Stanford Plasma Gun (SPG), continues to be developed and studied at Stanford University.[6,7]

Typically, the necessary high pressure rise-rates for these devices are achieved by means of so-called "puff valves" that inject a transient, high density gas slug into the inter-electrode region to initiate the discharge.[8] Increased rise-rates are generally achieved by increasing the upstream pressure within the plenum of the puff valve. However, in a valve of fixed plenum size, increasing the upstream pressure likewise increases the overall mass of gas that is delivered to the inter-electrode region. In some applications, particularly those where total mass utilization is an important parameter, failing to mitigate this effect results in wasted process gas. The utilization of the gas by the driving circuit of the plasma source is dictated by the pulse energy and discharge current, which dictates the recruitment of charge carriers from the injected neutral gas during the ionization process. For a fixed driving current waveform, there is a particular mass flow profile that can be sustained without wasting undue amounts of injected gas. While the fast rise rate afforded by a particular high plenum pressure may be necessary to access the deflagration mode, a shorter characteristic decay time of the discharge current may require a lower overall mass flow. Matching these conditions is difficult, if not impossible, without a means for varying the mass bit independently from the rise rate, or "sharpness," of the pressure front of the puffed gas.

Some attempts have been made to adjust the plenum size and/or duty cycle time of the valve according to the needs of an individual experiment, but the existing methods for doing so come with attendant difficulties. One previously implemented solution is to modify the valve driver circuit to produce different valve opening times, but this process is highly nonlinear due to the coupling between the electromagnetic drive mechanism and the gas dynamic resistance to the valve opening, leading to intensive calibration requirements at each desired operating point.[8] Other designs incorporate an adjustable plenum size, but require disassembly of the valve in order to change the mechanism and thus fail to allow real time adjustment and calibration while the valve is in use.[9] Overcoming these limitations typically requires an excessively complex (and thus expensive), high part-count mechanism. In this work, we describe the design and operation of a fast rise-rate puff valve with a dynamically and continuously variable mass bit, wherein the effective actuation time of the valve can be mechanically adjusted while the valve is in use. This feature allows rapid tuning of the mass flow characteristics to match a given plasma driver circuit, and does so without a complex mechanism or high part-count. We also demonstrate an example application of the tunability of this gas puff valve design in conjunction with the Stanford Plasma Gun.

II. DESIGN AND CONSTRUCTION

As shown in Fig. 1, the valve consists primarily of a plenum, driver coil, aluminum hammer ring, and a poppet, all

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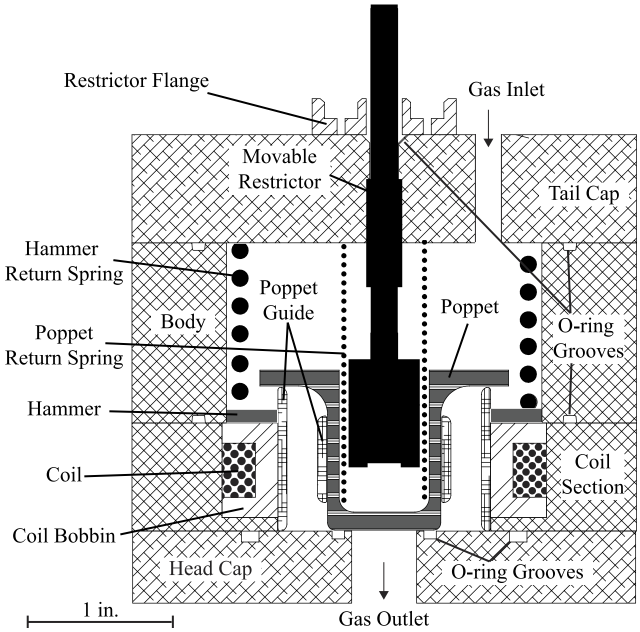

FIG. 1. A cross section view of the valve assembly in the closed position, with all principal elements labeled.

contained within a housing. When the coil is energized with a pulsed current, the hammer is diamagnetically accelerated upwards by the induced eddy currents within the aluminum hammer. When the moving hammer strikes the outer rim of the poppet, it impulsively drives the poppet off of an O-ring seal, opening the valve and releasing a puff of gas. The valve in the open position, with the hammer driving the poppet against the movable restrictor, is shown in Fig. 2. A return spring for both the hammer and the poppet, respectively, resets the valve to its initial state after actuation, enabling operation of the valve in any orientation. This overcomes a drawback present in other designs that employ the gravity-assisted pressure differential

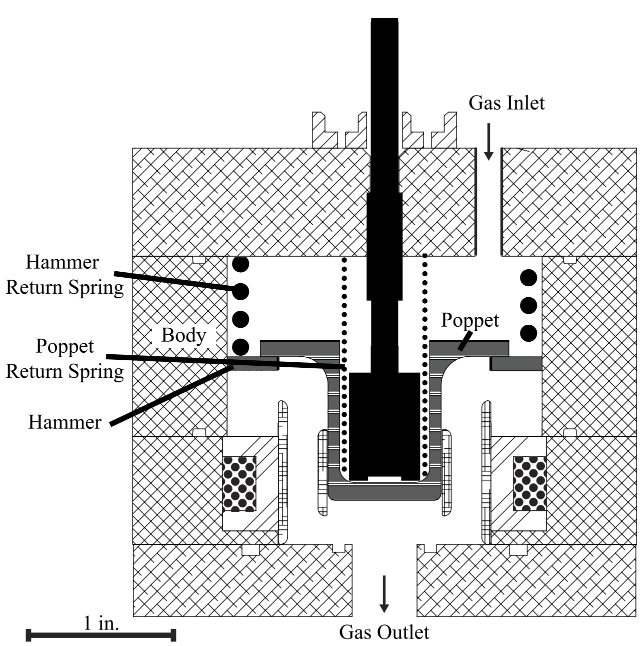

FIG. 2. A cross section view of the valve assembly in the open position, with only the elements that move during actuation labeled.

as the only means of resetting the valve,[10] which prohibits operating the valve in inverted or horizontal positions. The concentricity of the poppet travel is maintained by a 3D-printed guide that mechanically locates the poppet in the center of the driver coil and over the O-ring seal, while permitting gas flow through and around the guide. The travel distance or "throw" of the poppet during actuation is determined by the position of the restrictor, which is adjustable while the valve is pressurized. This adjustment is achieved by means of rotating the externally accessible, threaded stem of the restrictor either clockwise or counterclockwise, which linearly positions the restrictor either closer to or farther away from, respectively, the base of the interior cavity of the poppet. This mechanically limits the travel distance of the poppet when the valve is actuated. Pressure integrity of the plenum during restrictor positioning is maintained by a dynamically sealing O-ring located around the stem of the restrictor, that is itself captured by a recessed groove in the valve tail-cap and the removable restrictor flange. Additional O-ring grooves at the planar interface of each valve section prevent static leakage, as shown in Fig. 1.

The valve body is constructed of a clear thermoplastic, which allows visual confirmation of proper valve operation during use. The head and tail caps are made of aluminum, as is the restrictor, restrictor flange, and the hammer ring. The mass of the hammer ring was selected to match the mass of the poppet, itself made of machinable nylon, in order to maximize efficient momentum transfer between the hammer and poppet during impact. The driver coil was wound from 18 gauge copper magnet wire on a custom-fabricated Delrin bobbin and was designed to have an inductance of 100 μH, a value that was verified after winding the wire onto the bobbin using an inductance meter. The poppet guide was 3D-printed in an acrylic-like plastic resin on a 3D Systems ProJet 3500 HD.

The design of the valve is such that the rate of pressure rise of the gas front expelled from the valve is determined by the plenum pressure, while the overall mass bit is determined by a combination of the plenum pressure and the throw of the poppet, controlled by the restrictor position. The construction materials and the nature of the design were selected to enable low part count, straightforward fabrication, and maximum ease of use with a variety of operating conditions.

III. TEST APPARATUS AND PROCEDURE

In order to verify the reliable tunability of both the pressure rise rate and mass bit, an extensive characterization study of the valve properties was conducted. The experimental apparatus, as shown in Fig. 3, consisted of an array of piezoelectric pressure transducers (PZTs) as well as a Baratron pressure gauge positioned within a small vacuum chamber. The specific PZTs were PCB Piezotronics ICP pressure sensors, Model No. 113B26, and were driven by an eight channel power supply/signal conditioner also manufactured by PCB Piezotronics, Model No. 482A20. With this signal conditioner, the rise time is ≤1.0 μs with a sensitivity of 1.45 mV/kPa. The rise rate of the pressure in the vicinity of the valve output was measured directly by the PZTs, while the mass bit was

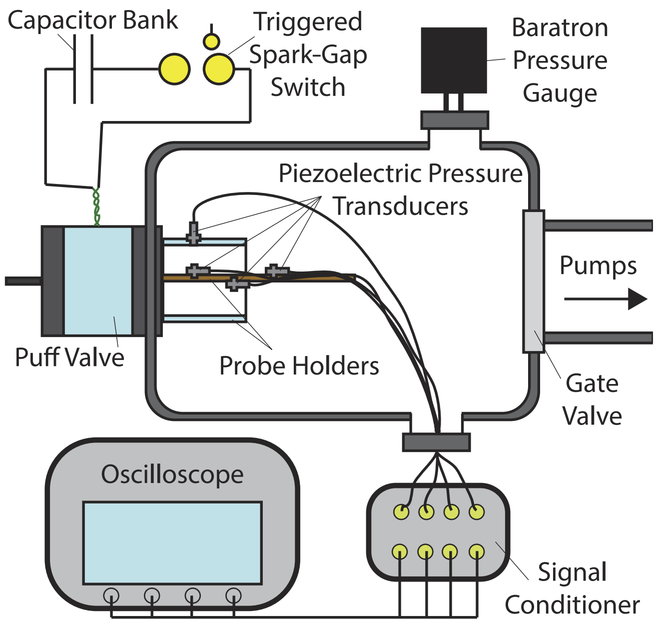

FIG. 3. Schematic of the valve and driver circuit installed on the test chamber, along with the data acquisition equipment.

calculated based on the equilibrium pressure in the chamber after a single actuation of the valve. The chamber volume was measured to be 17.07 L by filling the chamber with a known mass of gas using a calibrated mass-flow controller. With the chamber having a known volume, the mass bit for a given firing of the valve was estimated assuming the gas to be ideal and at an equilibrium ambient temperature of 293 K upon reaching its equilibrium pressure after valve actuation.

The plenum pressure was varied between 10 and 40 psig in increments of 5 psi and the restrictor position was varied over ten increments from 0.02 to 1.33 cm away from the base of the interior cavity of the poppet. Each combination of plenum pressure and restrictor position was tested three times to establish an estimate of the repeatability of the valve output from firing to firing. The valve was driven by a capacitor bank with a capacitance of 1350 μF, charged to 900 V for all trials. The chamber into which the valve was fired was evacuated before each firing to a background pressure on the order of 10^{-3} Torr; the specific pressure was recorded precisely for each individual test and used to calculate the ΔP. A gate valve was used to isolate the chamber during each firing in order to allow the pressure to rise to an equilibrium value. The process gas used for all trials was N_2.

IV. RESULTS

The results of the valve operating characteristics are summarized in Figs. 4 and 5, which show the mass bits and rise rates, respectively, of the gas puffs under various combinations of plenum pressure and restrictor position. Fig. 4 in particular shows that the mass bit can be varied substantially linearly by adjusting the restrictor position, with the mass bits for the shown plenum pressures converging as the overall poppet

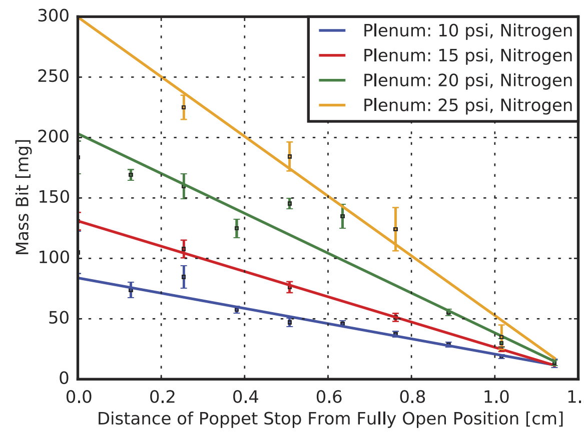

FIG. 4. Mass bit as a function of restrictor position, along with linear fits, for plenum pressures from 10 to 25 psig.

throw decreases. At lower pressures, the pressure effects that work against the opening mechanism are weaker, leading to less mechanical jitter and thus closer overall agreement with the linear trend.

The resulting mass bit is consistent with estimated mass contained inside the valve plenum at the tested pressures, implying that, at a maximum, only the gas contained within the plenum is released. At increasingly limiting restrictor positions, only a fraction of the plenum gas is measured to have been emitted by the valve. The measured mass bit is proportional to the overall time that the valve is in the open position, and the results are consistent with the movable restrictor mechanism successfully varying the opening time of the valve during actuation in a linear fashion.

Fig. 5 depicts the steady increase in pressure rise-rate obtainable with increasing plenum pressure. Each data point in Fig. 5 represents the measured rise-rate over the entire range of all ten restrictor positions at that plenum pressure. The presented error is based on the residual of the measured rise-rates against the average value of all ten operating points for the specified plenum pressure, wherein each operating point was tested three times, as specified above.

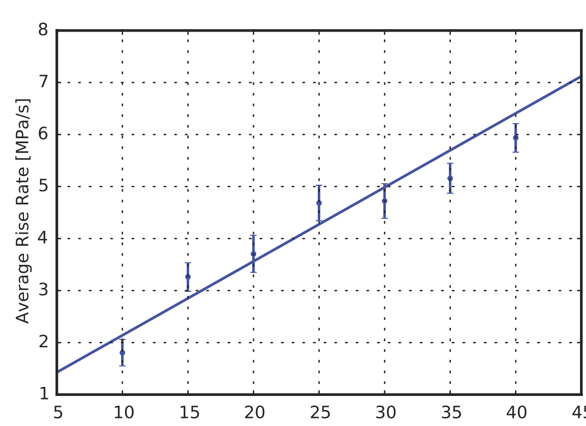

FIG. 5. Rise rate as a function of plenum pressure, each point representing an average over all 10 tested restrictor positions.

V. DISCUSSION

We have shown, through careful experimental analysis, that the valve behaves gas dynamically as designed: the mass bit and rise rate can be selected from a partially decoupled combination of the plenum pressure and restrictor position. In this section, we demonstrate the utility of this feature in an actual experimental device by applying this valve as a transient gas source for the Stanford Plasma Gun. In its current configuration, the SPG consists of a circularly arranged set of stainless-steel rod anodes, arrayed around a central copper cathode. There is a plastic sleeve around the rod anode array that serves to confine the gas as it is injected and accelerated, extending from the breach end up to the last 3 cm of the electrodes.

Fig. 6 illustrates two different SPG modes of operation that occur under specific mass flow conditions. The diffuse discharge zone, or "deflagration wave," that is established at the breach of the accelerator post-breakdown is typically quasi-stationary in the laboratory frame during the bulk of the acceleration process. Neutral gas that enters the discharge zone through the breech is ionized and is electromagnetically accelerated axially along the electrodes. If the flow of neutral gas is cutoff before the flow of driving current, the discharge zone will cease to be quasi-stationary in the laboratory frame and will itself be accelerated out of the coaxial electrode volume. This can be called the "underfed" condition. If the driving current diminishes at a faster rate than the neutral gas flow into the breech, the quasi-stationary nature of the discharge is maintained, the current flow remains diffuse along the electrodes, and the behavior under these criteria can be called the "overfed" condition. The ideal operating point for a given driver current could be considered the "matched" condition, in which the mass flow into the breech coincides with the driving current, and all of the injected neutral gas is properly processed by the deflagration wave. This effect dominates the overall gas-utilization of the device, and control over the transition between the "overfed" and "underfed" conditions is the primary application of this valve design.

In order to highlight this effect and demonstrate how it can be controlled with the novel puff valve described herein, the SPG was photographed during operation using a Cordin 220 fast-framing ICCD camera. A 56 μF capacitor bank charged to 3 kV was used as the driving circuit for the discharge. In order to fire the SPG, the electrode region is initially evacuated, and when the neutral gas is injected, the field in the gap approaches the breakdown field from the vacuum side of the Paschen curve. Thus, the injected gas serves as the trigger for discharge initiation, as the initial breakdown of the gas serves to switch the capacitor bank into the load.

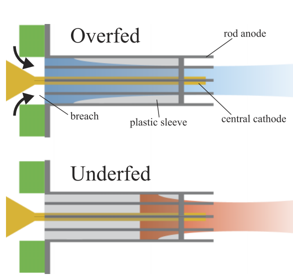

FIG. 6. Schematic of SPG operation in the "overfed" vs. "underfed" conditions.

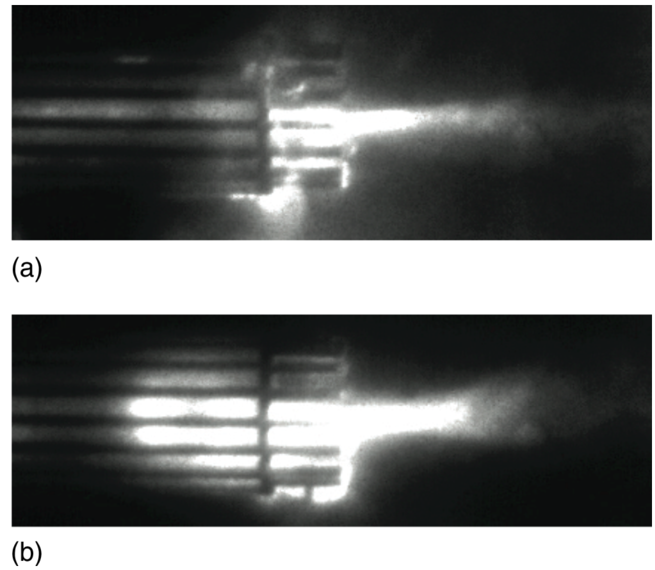

FIG. 7. (a) Accelerator operating with valve plenum pressure of 10 psig, restrictor 1.33 cm from bottom of poppet travel. (b) Accelerator operating with valve plenum pressure of 10 psig, restrictor 0.02 cm from bottom of poppet travel.

Fig. 7 shows two images of the accelerator during operation with different valve input conditions. The plastic sheath covers up to the last ~3 cm of the visible electrodes and uniformly dims the light emitted from the plasma in this region. Fig. 7(a) shows a fast-framing ICCD image of the accelerator firing with the valve operated at a plenum pressure of 10 psig, and the restrictor fully open (maximal throw) to 1.33 cm from the bottom of the restrictor travel. The image is a 150 ns exposure taken 5.5 μs after initial breakdown of the gas. We see that the plasma is being ejected from the muzzle of the accelerator, and the discharge zone is diffused and of substantially equal emissive brightness along the center axis. Fig. 7(b) shows the accelerator firing with the valve operated at a plenum pressure of 10 psig, and the restrictor positioned 0.02 cm from the base of the interior of the poppet (minimum throw). In this image, the localized brightly emissive region is the discharge zone being accelerated out of the accelerator. This occurs due to the curtailed mass flow at the breach end, which is the result of the highly restricted poppet travel.

As shown in the images in Fig. 7, the accelerator is being made to operate in two different regimes: an "overfed" condition and an "underfed" condition. Transitioning between these conditions is enabled simply by altering the valve mass bit at the plenum pressure of 10 psig by adjusting the restrictor position. For different SPG conditions, the proper combination of plenum pressure and restrictor position to achieve an "overfed" or "underfed" condition may change, highlighting the necessity of a dynamically adjustable valve in practical use. Furthermore, since a continuum of restrictor positions is available, the matched condition can be determined empirically for a given pulse driver current. This example demonstration was carried out at a comparatively low pulse energy, at the lowest tested plenum pressure; the method can be extended to much higher pulse energies by utilizing higher mass bits, obtainable at higher plenum pressures.

We have described the design, testing, and operation of a unique gas puff valve that enables the variation of the overall mass-bit and pressure rise-rate largely independently of one another and via simple *in situ* modification of the mechanical restrictor. This instrument is useful for gas dynamically tuning the operation of various pulsed plasma experiments and, in particular, for selecting the mass flow profile for use in pulsed deflagration accelerators. We have demonstrated this application on the Stanford Plasma Gun, by capturing via ICCD camera the transition from an "overfed" to "underfed" condition by reducing the valve mass flow through adjustment of the mechanical restrictor.

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