

## Improved piezoelectric actuators for use in high-speed pulsed valves

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We describe the assembly of piezoelectric actuators suitable for use in Proch–Trickl pulsed gas valves employed in pulsed molecular beam experiments. In their simplest form, these actuators have performance equal to and resistance to chemical attack far superior to the recently discontinued commercial actuator around which the valve was originally designed. New actuators have been designed employing several different dual piezo configurations. The dual piezo design reliably produces shorter pulses than the original actuator, resulting in reduced gas consumption and lower average source chamber pressures for a given backing pressure and pulse rate. By electrically isolating the actuator assembly, active adjustment of the closed position may be achieved by simple addition of a continuous voltage bias. © 2010 American Institute of Physics.

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### I. INTRODUCTION

Pulsed molecular beams are generated by supersonic expansion from a high-pressure gas reservoir to a low-pressure vacuum chamber through an orifice opened briefly by a high-speed pulsed valve.<sup>1</sup> These beams are routinely used in scattering and spectroscopy experiments where the low duty cycle of the gas load makes the most efficient use of available pumping speed. In many cases, the molecular pulse repetition rate can be matched to that of pulsed lasers being used in beam generation or product detection. The primary difference in equipment between a pulsed and a continuous beam source is the pulsed valve, for which many designs have been proposed and several are now widely accepted.<sup>1</sup> One design that is in current widespread use is the piezoelectrically actuated valve of Proch and Trickl.<sup>2</sup> This valve uses a commercially available piezoelectric disk bimorph actuator manufactured by Physik Instrumente (PI) for motion transduction. By using this “off-the-shelf” actuator, the user needs only to enlist the aid of a competent machinist to fabricate a set of relatively simple mechanical components to obtain a working valve.

The Proch–Trickl valve has many characteristics of the ideal pulsed valve: repetition rates up to 1 kHz, no upper limit to the pulse length, orifice sizes up to 1 mm, a simple power supply, easy setup and operation, and long-term stability and reliability. The most prominent shortfalls of this valve are its minimum pulse length—with careful adjustment, a minimum of  $\sim 250$   $\mu$ s to achieve full opening of a 1 mm nozzle ( $\sim 150$   $\mu$ s for a 0.2 mm nozzle)—and the susceptibility of the polymeric coating on the piezo actuator to chemical degradation.

Despite the convenience of this commercially available actuator, we recently undertook a project aimed at assembling our own actuators. We did this with the three following goals in mind: (1) to explore new actuator designs that might produce shorter pulses while still achieving full opening of a 1 mm orifice, (2) to find an insulating coating for the piezo

crystal more chemically inert than the polymer used by PI, and (3) to have actuators available with a shorter lead time and lower cost than the PI component. We recently learned that PI has ceased production of the actuator around which the Proch–Trickl valve was designed. This project has thus taken on a more urgent purpose: our materials and methods will help facilitate continued use of the valve design.

### II. ACTUATOR DESIGNS AND CONSTRUCTION

The PI P-286.23 disk translator originally used by Proch and Trickl is a piezoelectric bimorph actuator consisting of a 0.5 mm thick stainless steel annular shim [41 mm outer diameter (OD), 10 mm inner diameter (ID)] concentrically glued to a 0.5 mm thick annulus of lead zirconate titanate (PZT) piezoelectric ceramic (38 mm OD, 13 mm ID) silver coated on both sides. The shim is sandwiched on its outer edge by a pair of stainless steel rings, which provide a bolt circle for mounting the actuator to the valve (Fig. 1). A lead is electrically connected to the “front” surface of the piezo and another to the inner surface of one of the mounting rings. The two rings are in electrical contact with the steel shim and hence the “back” side of the piezo crystal. The valve is opened by applying a negative high voltage pulse to the “front” lead attached to the piezo while the back lead is held at ground [Fig. 2(a)]. Although high voltage amplifiers are available from PI, we employ homebuilt units that can generate adjustable pulse amplitudes falling from 0 V to between  $-200$  and  $-800$  V and adjustable pulse durations of  $50$ – $500$   $\mu$ s. The applied voltage induces a radial contraction of the piezo crystal and hence a radial shear between the crystal and shim, causing the assembly to cup. A plunger, attached to the actuator through the center hole via a threaded insert, carries an o-ring at its tip to seal the orifice between pulses (Fig. 1).

We constructed actuators with shims and piezo crystals of the same dimensions as those manufactured by PI to facilitate reuse of the PI piezo mounting rings and other valve

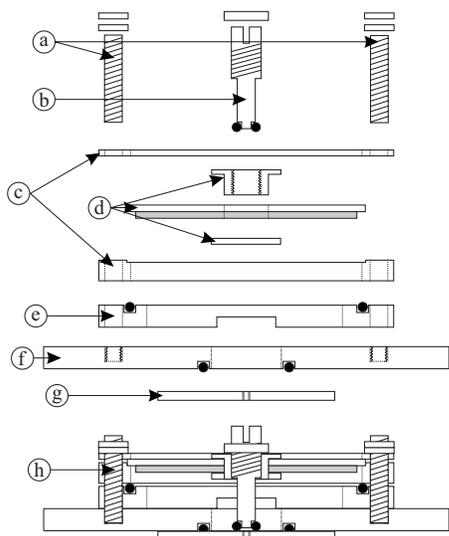


FIG. 1. Assembly drawing of the piezoelectric pulsed valve. (a) 4–40 stainless steel threaded rod and nuts (replaced with nylon for continuous biasing of piezo), (b) plunger with lock nut, (c) actuator mounting rings, (d) actuator with threaded inserts for attaching plunger (piezoelectric disc shaded), (e) spacer ring with o-ring “bounce damper” (replaced with 4–40 nylon nuts for continuous biasing of piezo), (f) front plate, (g) nozzle plate with orifice, and (h) assembled pulsed valve.

parts already on hand. The shims were fabricated from 304 stainless steel shim stock using standard machining techniques and the piezo crystals were obtained from PI (part PTYY-0153) with fired silver electrodes on both faces, the polarity being marked on the positive face. Note that PI currently has no plans to discontinue production of this item.

We first constructed a near replica of the PI P-286.23 to ensure that our actuators would have, at a minimum, the same performance to which we were accustomed. A shim and piezo were first cleaned with anhydrous methanol and allowed to dry. Then the positive face of the piezo was glued to the shim using a thin layer of solvent-free, silver-filled epoxy (Resinlab SEC1233) to ensure electrical contact. Care must be taken to avoid excess epoxy on the edge of the piezo disk, which could short out the piezo assembly. The epoxy was also used to attach a polytetrafluoroethylene (PTFE) insulated lead to the exposed negative face of the piezo. We found this to be more reliable than soldering the lead, which

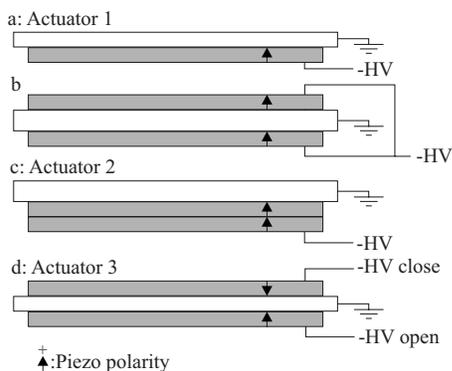


FIG. 2. Actuator designs tested in this work. Shaded region represents the piezoelectric disc. The nozzle orifice is towards the bottom of the page, and the valve opens when the center of the actuator bows up.

risks overheating the piezo. After allowing the epoxy to cure for 24 h, the assembly was again cleaned with anhydrous methanol and the exposed negative face of the piezo coated by hand using a small paintbrush with an automotive paint designed for rust prevention (Magnet Paints Chassis Saver–Black), commonly available at auto paint stores. We have found that this coating even withstands extended submersion in liquid acids and halogenated hydrocarbons with no evidence of degradation. The paint should be mixed by stirring rather than shaking to avoid formation of bubbles in the finish. After curing overnight, the actuator was installed in a valve and found to perform indistinguishably from the commercial PI part.

Having accomplished the goals of replicating the commercial actuator and enhancing its resistance to chemical attack, we explored alternate configurations hoping to achieve shorter minimum pulse durations. As described by Proch and Trickl,<sup>2</sup> reliable full opening of a valve with 1 mm nozzle diameter is readily achieved only when the duration of the gas pulse is  $\geq 250 \mu\text{s}$ . By careful adjustment of the “closed” position of the valve, we have found that one can achieve gas pulses as short as  $200 \mu\text{s}$  with little or no loss in peak intensity. However, achieving such performance at short opening times requires very careful iterative adjustment of the valve and is not very reproducible.

In a first modification attempt to more reliably produce shorter pulses, we employed a thicker, stiffer shim to increase the resonance frequency and hence the restoring force that closes the valve. A single piezo can be driven at a higher voltage to provide more opening force. Such an actuator was constructed with a 0.71 mm thick shim, but its performance was roughly equivalent to a normal actuator. This was because the capacitance of the piezo limits the voltage rise time such that the longer pulse duration required to achieve a higher opening voltage also extended the duration of opening beyond the natural resonance time of the actuator.

We reasoned that by increasing the opening force of the actuator and by using a thicker shim, one might achieve full opening of the valve with a shorter pulse duration. To increase the opening force of the actuator without requiring higher voltages, we constructed a dual-actuator design using a stainless steel shim 0.71 mm thick with one piezo crystal glued to each side. One crystal was oriented with its positive face exposed, and one with its negative face exposed [Fig. 2(b)]. An electrical lead was glued to each piezo allowing application of the same negative high voltage pulse to both piezos. In this arrangement, the front piezo is arranged as in the PI actuator, but the additional back piezo is expanded rather than contracted because the applied voltage is opposed to its internal polarity. This design was found to provide shorter opening times than the PI part, but two shortcomings convinced us to continue investigating other designs. First, the total applied voltage had to be limited to  $-500 \text{ V}$  to avoid depolarizing the back piezo, as the voltage applied to it is opposed to its internal polarity. Second, the voltage rise time was significantly longer than for the single piezo actuator, limiting the minimum electrical pulse duration to  $160 \mu\text{s}$  to achieve  $-500 \text{ V}$ . This is due to the doubling of the capaci-

tance by placing the two piezos electrically in parallel. To overcome these limitations, we pursued other designs.

In a second dual-piezo design, we used the thicker shim but placed two piezo crystals electrically in series by gluing the second piezo directly to the first one, forming a stack to which a single high voltage lead attached to the exposed negative face of the top piezo could charge both crystals, with each seeing half of the total voltage [Fig. 2(c)]. By placing two piezos in series, the equivalent circuit capacitance is halved and the overall voltage rise time becomes much shorter. This leads to a faster opening time and increased opening force. A small construction note: the two piezos are thick enough that the top surface of the stack will interfere with the ground lead solder joint on the PI mounting ring. This lead is redundant if the actuator is affixed to the grounded valve body with conductive screws, so we removed it.

We also constructed a third dual-piezo actuator based on a different design principle altogether. Rather than using a stiffer shim to passively close the valve faster, we used a labile (i.e., a 0.5 mm thick) shim in conjunction with a second piezo configured to drive the valve closed when energized by a separate delayed voltage pulse. To accomplish this, a piezo was glued to each side of a 0.5 mm thick shim with the negative faces of both crystals exposed [Fig. 2(d)]. A valve body was modified to include a second electrical feedthrough so each piezo could be supplied with a separately timed voltage pulse.

### III. MODIFICATION TO ALLOW CONTINUOUS BIASING OF PIEZO

It is sometimes desirable to heat the nozzle to reduce formation of van der Waals clusters. Upon heating, the optimal “closed” position of the valve, set by appropriate adjustment of the plunger’s o-ring on the orifice, changes with nozzle temperature—a pulsed valve that was properly adjusted at room temperature will generally not open fully when hot. We have found that the valve can be operated with the nozzle heated to 100–200 °C if it is assembled at room temperature so that it leaks slightly when closed. However, after the valve has been heated to the desired temperature, one would like to have the ability to fine adjust the “closed” position of the valve by applying an appropriate bias using an adjustable continuous dc voltage.

We sought a method to allow continuous biasing of the piezo that would allow us to avoid building new and more complex pulse generators. We have found that an effective and convenient approach is to electrically isolate the piezo mounting ring from the valve body, and then bias the (normally grounded) piezo shim with a dc power supply. Application of a negative dc bias voltage to the shim closes the valve more tightly. A positive voltage will decrease the force on the o-ring seal. This facilitates direct *in situ* fine adjustment of the valve closed position during operation.

The electrical isolation necessary for biasing the shim was achieved by replacing the stainless steel 4–40 threaded rods that normally hold the piezo mounting ring to the valve front plate with nylon ones and replacing the spacer ring (with o-ring “bounce damper”—see Fig. 1) with a nylon nut

on each nylon screw. Because the sealing action of the valve is achieved by an electrically insulating o-ring, the entire piezo/mounting ring/plunger assembly is thus electrically isolated from ground and may be biased. By biasing and pulsing the piezo from opposite sides, one avoids having to put the dc and pulsed signals on the same transmission line. In this way, the dc and pulsed signals are coupled through the piezo itself, which acts as a leaky capacitor. Our pulse generator is unaffected by the dc voltage because its output is coupled through switching transistors; commercial dc power supplies are unaffected by the pulsed high voltage (HV) due to the presence of a capacitor on their output. Because the output capacitor is so much larger than the capacitance of the piezo, to the pulser the dc supply resembles ground. Biasing the piezo shim also requires two electrical feedthroughs on the pulsed valve body.

An attempt was made to construct a bias-T in order to avoid needing a second feedthrough on the chamber and pulsed valve. However, we were unable to find a configuration that worked as well as that described above. It is important to note that application of a negative bias to the piezo mounting ring is equivalent to applying a positive voltage to the negative face of the piezo. The piezo disk may be depolarized if the magnitude of the applied bias voltage exceeds 500 V.

### IV. RESULTS

The newly built actuators were installed in a 1 mm orifice valve and tested in the Cornell Rotatable Source Crossed Molecular Beams Machine.<sup>3</sup> Comparative data is provided below for the single piezo actuator [actuator 1, Fig. 2(a)], the series dual-piezo actuator [actuator 2, Fig. 2(c)] and the actively closed actuator [actuator 3, Fig. 2(d)]. A number of different gases were used to test the actuators. These included He, 40% N<sub>2</sub> in He, 10% and 40% O<sub>2</sub> in He, and 10 Torr C<sub>6</sub>H<sub>5</sub>Cl in H<sub>2</sub> with various backing pressures. In all cases, backing pressures ranged from 5 to 60 psi (gauge).

The valve, energized by a square negative high voltage pulse of adjustable height and duration provided by a home-built pulser (or two pulsers, for actuator 3), was mounted in a source region pumped by two 6 in. diffusion pumps. Note that due to the capacitance of the piezo, the rise time of the high voltage, measured using an oscilloscope, is approximately 50 μs when a single piezo is attached to the pulse driver. The beam passed through a 1.8 cm high, 2 mm diameter conical skimmer (Precision Instruments or Beam Dynamics) into a second differentially pumped region, then through a defining aperture (3 mm<sup>2</sup>) into the main chamber evacuated by a 2000 l/s turbomolecular pump. For velocity analysis, the beam could be chopped by a high-speed mechanical chopper wheel (two 1 mm wide slots, 10.9 cm radius, 210 Hz rotational speed) transmitting a segment of the pulse approximately 8 μs long. The rotatable source assembly was set to point the beam directly at the 200 μm diameter input aperture of the detector, a triply differentially pumped quadrupole mass spectrometer (Extrel Merlin with 0.75 in. rods) using 100 eV electron impact ionization, –4 kV conversion dynode, and a continuous electron multiplier

operating in the pulse counting mode. The output signal of the multiplier was fed to a multichannel scaler (SRS SR430). A digital delay generator (BNC 555) provided 30 Hz triggers to the pulser(s) and scaler. The delay generator and scaler settings were controlled through a general purpose interface bus (GPIB) interface to a personal computer via a custom LABVIEW data acquisition program.

The intensity of the beam as a function of time was measured by setting the quadrupole mass filter to transmit the parent mass of interest and measuring the time of arrival distribution with the multichannel scaler *without* chopping the beam. The high voltage pulse settings (amplitude and duration) for each actuator were adjusted to obtain the largest signal at the peak of the distribution for each actuator. Experiments were carried out in order to directly compare the peak intensities for the three different actuator designs under a range of experimental conditions. In all experiments, the peak intensity was used as the optimization criterion for the adjustment of pulse conditions, rather than peak intensity while avoiding secondary pulses caused by bouncing of the seal upon closing.

For each piezo design, the optimum conditions for the voltage pulse amplitude and pulse length depend upon a number of factors. These include (1) the tightness of the o-ring seal against the orifice, (2) gas mixture, (3) nozzle skimmer distance, and (4) skimmer shape. The amplitude of subsequent pulses resulting from the plunger bouncing and reopening subsequent to the primary pulse depends upon how tightly the piezo disk mounting nuts are screwed down on the four threaded rod mounts. Overtightening of these nuts leads to overcompression of the “bounce” o-ring and considerably increased secondary pulsing.

For the single piezo actuator (actuator 1), the use of electrical pulses longer than 150  $\mu\text{s}$  and voltages greater than the minimum required to achieve optimum intensity did not further increase the peak beam intensity, but did increase the pulse length and average pressure in the source region as measured with a Bayard–Alpert ionization gauge. This is evidence that full opening of the 1 mm orifice was readily achievable using 150  $\mu\text{s}$  or longer electrical pulses. Employing a carefully adjusted pulsed valve, the use of electrical pulses as short as 75  $\mu\text{s}$  produced gas pulses with comparable peak intensities, demonstrating that full opening of the orifice could still be achieved. In Fig. 3, the gas pulse was monitored using three different electrical pulse lengths using the mass spectrometer with no chopper wheel installed. A 100  $\mu\text{s}$  input pulse resulted in gas pulse lengths of about 260  $\mu\text{s}$  (full width at half maximum), and a 75  $\mu\text{s}$  input pulse led to gas pulses with durations of about 240  $\mu\text{s}$ . With a 50  $\mu\text{s}$  electrical pulse duration (the minimum achievable using our pulse generator), the peak intensity was reduced by about 10% and the pulse duration further decreased to 200  $\mu\text{s}$ . Clearly, the use of decreased electrical pulse lengths below 100  $\mu\text{s}$  leads to decreased gas pulse durations. However, the gas pulse duration using the single piezo actuator is limited by the relatively slow closing of the valve owing to the limited restoring force offered by the thin stainless steel shim. Production of gas pulses with durations shorter than

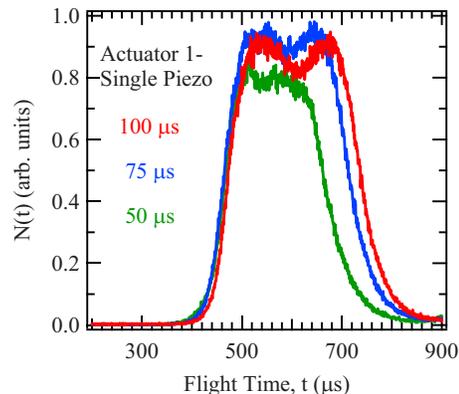


FIG. 3. (Color online) Beam intensity profiles from actuator 1 (single piezo) using 40%  $\text{N}_2$  in He at 10 psi (gauge) using three different electrical pulse durations.

200  $\mu\text{s}$  using actuator 1 will be accompanied by decreased peak intensities because full opening cannot be achieved.

The dual piezo actuator (actuator 2) opened the valve much earlier than the single actuator relative to the voltage pulse, by 30  $\mu\text{s}$  at 5 psi (gauge). The benefits of using the dual piezo design were immediately obvious in our tests. Most notably, due to the increased opening force, the valve is easier to adjust for optimum performance. As in the case of the single piezo valve, using electrical pulse lengths longer than 150  $\mu\text{s}$  led to longer gas pulses and the expected increase in gas load on the source chamber. Decreasing the input pulse length from 150 to 75  $\mu\text{s}$  led to a twofold decrease in source gas pressure with negligible decrease in peak intensity. The measured gas pulse length also decreased by a factor of 2, indicating that actuator 2 is easily capable of producing substantially shorter gas pulses than actuator 1 while still maintaining full opening of a 1 mm orifice.

The effect of decreasing the electrical pulse length using the double piezo design (actuator 2) is shown in Fig. 4. Using a 100  $\mu\text{s}$  electrical pulse produced pulses with durations of 190  $\mu\text{s}$  (70  $\mu\text{s}$  shorter than with the single piezo). When the electrical pulse duration was then decreased to 75  $\mu\text{s}$ , the resulting gas pulse duration was 170  $\mu\text{s}$ . Using a 50  $\mu\text{s}$  electrical pulse (the minimum achievable using our power supply), gas pulse durations of 130  $\mu\text{s}$  were readily ob-

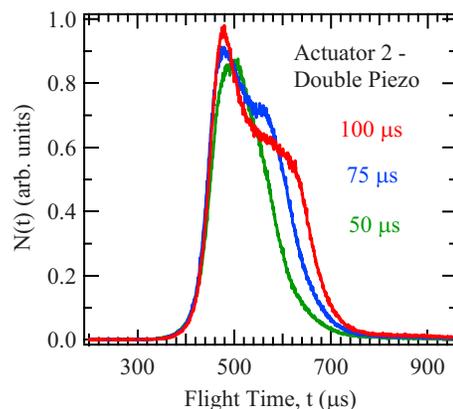


FIG. 4. (Color online) Beam intensity profiles from actuator 2 (dual piezo) using 40%  $\text{N}_2$  in He at 10 psi (gauge) using three different electrical pulse durations.

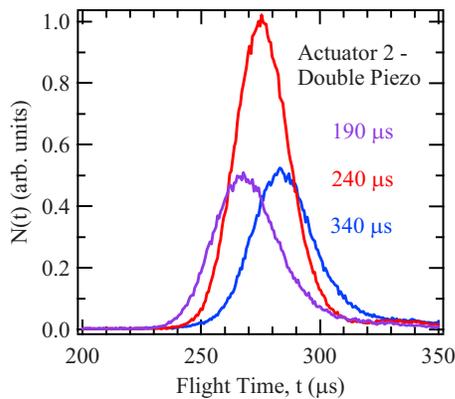


FIG. 5. (Color online) Beam time-of-flight distributions for 40%  $N_2$  in He at 10 psi (gauge) recorded using the slotted chopper wheel and electrical pulse duration of 150  $\mu s$  at three different pulsed valve trigger times prior to opening of the slotted chopper wheel.

tained. We conclude that the double piezo actuator (actuator 2) facilitates production of gas pulses with durations of approximately one-half of the minimum possible using actuator 1, while still maintaining full opening of a 1 mm orifice. This will be of particular value in experiments using expensive reagents (e.g., isotope labeled) or in cases where higher backing pressures can lead to increased peak beam intensities and pumping speed is a limiting factor.

For many applications, a pulse duration in the 10–20  $\mu s$  range is required for time-of-flight analysis in crossed molecular beam scattering experiments. Even under the best conditions, the Proch–Trickl valve (and all other designs with two notable exceptions<sup>4,5</sup>) produces pulses that are substantially longer than this, so beams must be mechanically chopped by a rotated slotted disk. In this case, the valve's firing can be timed such that the peak intensity is directed through the chopper and small secondary pulses cause no detriment to the experiment except to slightly increase the gas load in the source region.

In order to further characterize the dual-piezo design, the beam was sampled using the slotted chopper wheel. Figure 5 shows the beam time-of-flight spectra recorded using 150  $\mu s$  wide input electrical pulses triggered at varying times prior to the opening of the slotted wheel. The behavior illustrated here is typical of the gas pulses produced by this valve using any of the piezo actuators or pulse lengths. The peak velocity ( $v$ ) and speed ratio  $s$  ( $\approx v/\Delta v$ ) is somewhat dependent on which part of the pulse is sampled, being fastest at the beginning of the pulse and slowest in the late tail. As illustrated in Fig. 5, with the pulse valve triggered 240  $\mu s$  before the opening of the slotted wheel, corresponding to the peak intensity of the pulse, the peak velocity was 930 m/s with  $s=17$ . Triggering the pulse valve at later times (190  $\mu s$  prior to the wheel opening), effectively sampling an earlier part of the pulse, produced a peak velocity of 950 m/s and  $s=14$ . Earlier triggering of the valve (340  $\mu s$  prior to the wheel opening), thereby sampling a latter part of the pulse, led to a peak velocity of 900 m/s and  $s=16$ . This change in peak velocity for different portions of the beam leads to a broadening of the unchopped distributions. Because of this, it should be kept in mind that the widths of the

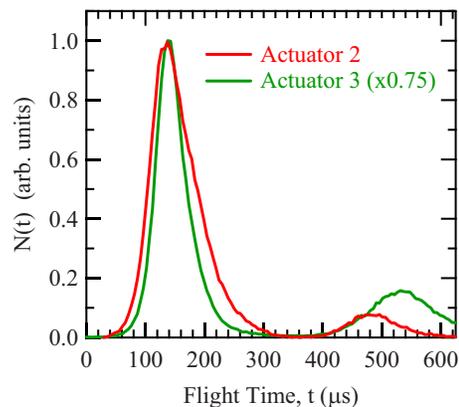


FIG. 6. (Color online) Comparison of beam intensity profiles from actuator 2 (dual piezo) and actuator 3 (actively closed) using neat He at 5 psi (gauge).

distributions in Figs. 3 and 4 are 15–20  $\mu s$  greater than they would appear if measured close to the valve. Although our measurement procedure involves passage through a skimmer and a relatively long flight distance ( $\sim 33$  cm from nozzle to detector) rather than probing the gas pulse directly in front of the nozzle as is typical when using a fast ion gauge,<sup>4</sup> it does examine as a unit the valve/skimmer system commonly used to produce a supersonic molecular beam. The data in Figs. 3 and 4 therefore represents gas pulses actually delivered to the interaction region of a typical scattering experiment.

A series of experiments were carried out with neat He at 5 psi (gauge) in order to optimize the performance of actuator 3 and compare its performance to that for actuator 2. Using this mixture, the optimum high voltage pulse settings for actuator 2 (to achieve full opening of the valve) was 60  $\mu s$  at  $-760$  V. We then installed actuator 3 into the same valve and optimized its performance using two driving pulses. The valve was opened using 60  $\mu s$  pulses at  $-550$  V; the valve was then closed using a 60  $\mu s$  pulse at  $-550$  V delayed by 60  $\mu s$ . The resulting profiles, with no chopper wheel, were translated such that the peak intensities coincide to allow easy comparisons between the widths and shapes of the profiles. As illustrated in Fig. 6, using the double piezo valve (actuator 2), pulse durations of 90  $\mu s$  were achievable using neat He. By actively closing the valve (actuator 3), pulse durations of 60  $\mu s$  were observed, corresponding to a further 30% reduction of pulse duration relative to actuator 2 while still achieving full opening of the 1 mm orifice. Similar reductions in pulse durations were observed using other gas mixtures with actuator 3.

At 5 psi (gauge), we investigated the effect of changing the duration of the gas pulse, while keeping all other parameters held constant. This was carried out by operating actuator 3 with and without the “close” pulse. When the close pulse on actuator 3 was disabled, causing it to behave essentially like actuator 1, not only did the profile become wider and the source pressure increase, both to levels similar to that of actuator 1, but the peak intensity also decreased by approximately 15%. This lower intensity under identical opening forces and backing pressures but different closing forces is especially clear evidence that, in the case of a skimmed beam from a valve with a relatively long opening duration,

the gas dynamic shutter effect<sup>6,7</sup> limits the peak beam intensity. Therefore, decreasing the pulse duration without increasing the backing pressure will not only reduce gas consumption under these conditions but will increase the peak beam intensity.

## V. DISCUSSION AND CONCLUSIONS

These profiles demonstrate that actuator 3 provides the shortest gas pulse duration (60  $\mu$ s) while still maintaining full opening of a 1 mm valve orifice. This comes at the cost of added complexity, requiring two independent high voltage pulses to actuate the valve. Actuator 2 provides universally shorter pulses than actuator 1 and would be the most appropriate actuator in the case of an experiment where gas pulses shorter than achievable using actuator 1 are desired and a second high voltage pulse is not available to allow the use of actuator 3. In general, we have found that the double piezo configuration with two piezos in series (actuator 2) is ideal for day to day use as it produces relatively short pulses and the increased force and amplitude of motion resulting from the use of two piezos makes the valve considerably easier to adjust for full opening operation than the single-piezo configuration.

An obvious question is whether the use of more than two piezo actuators might lead to further improvement in valve operating characteristics. For example, the use of a three piezo system, with two piezos in series to open the valve and a single piezo to actively close it might lead to even shorter pulse durations while maintaining full opening of the valve. To date, we have not tried such combinations but we do plan to test such configurations in the future.

## ACKNOWLEDGMENTS

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<sup>1</sup>W. R. Gentry, in *Atomic and Molecular Beam Methods*, edited by G. Scoles (Oxford University Press, New York, 1988), Vol. 1, pp. 54–82.

<sup>2</sup>D. Proch and T. Trickl, *Rev. Sci. Instrum.* **60**, 713 (1989).

<sup>3</sup>P. A. Willis, R. Z. Hinrichs, H. U. Stauffer, and H. F. Davis, *Rev. Sci. Instrum.* **70**, 2606 (1999).

<sup>4</sup>W. R. Gentry and C. F. Giese, *Rev. Sci. Instrum.* **49**, 595 (1978).

<sup>5</sup>U. Even, J. Jortner, D. Noy, N. Lavie, and C. Cossart-Mangos, *J. Chem. Phys.* **112**, 8068 (2000).

<sup>6</sup>D. Bassi, S. Iannotta, and S. Niccolini, *Rev. Sci. Instrum.* **52**, 8 (1981).

<sup>7</sup>G. N. Makarov, *Chem. Phys. Lett.* **358**, 307 (2002).