Real-time Adjustable, 11 µs FWHM, > 5 kHz, Piezo Electric Pulsed Atomic Beam Source

Anthony Catanese, Spencer Horton, Yusong Liu, and Thomas Weinacht
Department of Physics and Astronomy, Stony Brook University, NY 11790

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This paper provides a detailed description of how to construct a pulsed atomic beam source (including a fast ionization gauge for characterization) with a unique combination of characteristics. We include technical drawings for a real-time adjustable piezo electric actuated pulsed valve capable of generating a 11 µs duration pulse of gas at a repetition rate of > 5 KHz, with a shot-to-shot stability of 0.6%, and maximum densities of $10^{15}$ particles/cm$^3$. We also include details on how to construct a fast ionization gauge (FIG), with a 4 µs rise time, to measure the pulse. We report a 3D density map of a supersonic expansion of Helium gas with a speed ratio $S = 46$ and a calculated longitudinal temperature of 0.3 K. Finally, the results of a laser ionization test are provided in order to verify the performance of the pulsed valve in a typical experimental configuration.

I. INTRODUCTION

Pulsed valves have been used to deliver molecular beams to experiments since the early 1980’s. The advantages of using a pulsed source over a continuous source stem from the decreased duty cycle, which allows for operation at significantly higher backing pressures while maintaining low vacuum chamber pressures. Therefore, gas can be delivered at far greater densities than when using continuous flow nozzles. This results in increased expansion of the molecular beam, and cooling to temperatures below 1 K.[1]

Three competing technologies have been used to actuate fast pulsed valves: Lorentz force, solenoid valves, and piezo electric (PZT) crystals. Lorentz force valves rely on the repulsion between two wires carrying currents in opposite directions, and have provided short pulse durations ($\sim 10 - 20$ µs). However, they have been restricted to low repetition rates ($\sim 10$ Hz) due to heating limitations.[2] [3] Solenoid valves operate using a magnetic plunger inside a coil and include the Even Lavie valve, which can generate 20 µs pulses at up to 1 kHz and 180 bar backing pressure.[4] However, solenoid valves generate substantial RF noise and produce strong magnetic fields which must be shielded. Additionally, shot-to-shot fluctuations of order $<10$ % can develop as the gasket sealing the valve wears. PZT actuators are attractive because they are self contained and easy to mount; they require modest driving voltages and currents; their mechanical properties can be easily controlled by varying the dimensions of the ceramic element; and they can be driven rapidly at high repetition rates well above 1 kHz. However, there are drawbacks. For example, the low forces generated by piezo elements ($\sim 0.5$ N) makes opening against high backing pressures difficult. They’re also finicky and difficult to adjust since their performance depends sensitively on the distance between the piezo and the sealing surface—which must be re-adjusted when heating the nozzle, changing backing pressures, or changing carrier gases. As a result, a design which offers all of the advantages of piezo ceramics and can be adjusted in real time from outside the vacuum chamber is very attractive. This is what we have developed and describe in this paper.

At least three unique piezo electric valve designs have been tested and published: Proch and Trickl[5], Irimia et al.[6], and Abeysekera et al.[7]. The history of piezo electric pulsed valves and their demonstrated performance are summarized in table I. Only the Abeysekera et al. valve allows for adjustment of the piezo-to-seal distance via a micrometer feed through; however the maximum repetition rate of this design is limited to 100 Hz, and the valve is physically large. We argue that real-time adjustability is a critical feature, since the valve performance is very sensitive to the piezo-to-seal distance, which needs be controlled to optimize performance (molecule throughput, pulse duration, and beam contrast) under varying operating conditions.

This paper presents a design, complete with detailed technical drawings, for an externally adjustable pulsed atomic beam source, and the results of an experiment to map the propagation of a 11 µs duration pulse in 3D space and time. Our design allows for adjustment of the valve while in operation via a reach rod through the vacuum chamber wall. It can also be adjusted by a remote control motor. It can produce 11 µs pulses at repetition rates of 6.2 kHz. It has been tested over several months and run continuously for 2 weeks (over 7.5 billion cycles). It has been operated at backing pressures of 21 bar and heated to 90 °C while running for 2 weeks. The valve and nozzle can produce atomic beams with densities as high as $2 \times 10^{15}$ particles/cm$^3$ at longitudinal temperatures as low as 0.3 K, which was calculated from a measured average speed ratio of 46. Additionally, it has shot-to-shot fluctuations of only 0.56%. In addition to the technical advantages of our design, it is simple, and easy to construct and operate.
TABLE I. History of Piezo Electrically Actuated Pulsed Valves, and Demonstrated Performance

<table>
<thead>
<tr>
<th>Date</th>
<th>Min. Pulse Width (µs)</th>
<th>Max. Frequency (Hz)</th>
<th>Max. Pressure (bar)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1980</td>
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<td>20</td>
<td>1</td>
</tr>
<tr>
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<td>750</td>
<td>14</td>
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<td>1000</td>
<td>30</td>
</tr>
<tr>
<td>2009</td>
<td>7</td>
<td>5000</td>
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</tr>
<tr>
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<td>1000</td>
<td>30</td>
</tr>
<tr>
<td>2014</td>
<td>20</td>
<td>100</td>
<td>6</td>
</tr>
</tbody>
</table>

II. TECHNICAL DESCRIPTION

A. Pulsed Valve

The design uses a piezo electric transducer (PZT) bender actuator—a concept which was first conceived by a German group in 1989 [12]. Our contribution is to mount the PZT on a movable piston, which can be adjusted via a micrometer feed through from behind the valve body. The ability to finely control the distance between the piezo and the o-ring without having to disassemble the valve was a central requirement of our design. The valve is constructed from five major components: valve body, piston, micrometer, face plate and nozzle, and PZT (figure 1). A complete set of dimensioned technical drawings of the valve components are included in the supplemental documents.

The body of the valve (1) is approximately 50 mm in diameter by 40 mm in length and is manufactured from 303 Stainless Steel. The faceplate is secured to the body using flat head screws and is sealed with a Viton o-ring. Ports for the micrometer feed through, gas inlet, and electrical connections are 5/16-24 UNF thread with a Viton o-ring. The gas connection is 1/8” Swagelock and the electrical connections are LEMO connectors [13].

At the heart of the internals is a brass piston (2) which functions as the motion platform on which the piezo is mounted. Inside the piston is a spring which pushes against the valve body with approximately 62 N of pressure. The restoring force of the spring is counteracted by the micrometer feed through, which is threaded into the piston. [14] Turning the micrometer counterclockwise allows the spring to move the piston forward thereby decreasing the distance between the piezo and the o-ring. This closes the valve. Turning the micrometer clockwise opens the valve. Note that this is opposite from traditional valve operation. Although the micrometer was designed to be turned via a rotary feed though, it is conceivable that a servo motor could be attached to the valve to allow it to be adjusted in remote applications.

The 80 TPI thread of the micrometer feed through (3) allows the user to finely adjust the piezo to o-ring spacing while the valve is operating. Furthermore, a 7/16” hex nut machined into the end allows the micrometer to be turned from outside the vacuum chamber via a reach rod assembly with a standard 7/16” socket wrench. To ensure a leak proof operation the micrometer is constructed with a double o-ring seal, which seals reliably even with movement. No change in vacuum pressure, due to leakage through the double o-ring seal, has been noticed when rotating the micrometer during operation. The micrometer is also machined from 303 Stainless Steel.

The nozzle (4) is constructed from MACOR ceramic.
(chosen for its electrical insulating properties) and has a 250 $\mu$m orifice which opens to a 40° full angle cone. It is glued into the faceplate using high temperature epoxy, which can withstand continuous operation at 200 °C [15]. Resistance to high temperature is essential for allowing the nozzle to be heated during operation. A 40° full angle conical nozzle shape was chosen because of both physical considerations as well as ease of machinability. As compared to a sonic nozzle (180° opening angle), a 40° cone will generate a collimated beam with a higher beam density along the axis of the nozzle, and this will have the effect of slightly elevating the beam translation temperature.[16] It is also reasonable to believe that it would promote clustering because of the increased confinement of the particles. The conical aspect was chosen (as opposed to other shapes like a "trumpet" nozzle) because 40° "V" shaped cutting tools are readily available. Conceivably any form tool could be used to machine the nozzle profile.

Epoxied to the nozzle orifice is a micro Viton o-ring with a 254 $\mu$m inside diameter and cross section.[17] The o-ring was installed by threading it onto a wire and then threading the wire through the nozzle. In operation the o-ring seals against 5 mil Kapton tape (127 $\mu$m thick) on the PZT. The seal is good enough such that increasing the valve backing pressure from 1 bar to 6 bar produces no detectable change in a 10⁻⁶ torr vacuum maintained by a 100 l/s turbo pump. A small diameter o-ring is essential for allowing the valve to be operated at high backing pressures, since the maximum force available from a PZT bender actuator is typically quite low. Additionally, the small diameter o-ring minimizes effects of misalignment in tilt between the o-ring and Kapton gasket. The service life of the o-ring has not been determined past approximately 7 billion cycles, and some degradation of the o-ring is expected (especially in the presence of certain molecular samples). To replace the o-ring, the old o-ring must be popped off with an X-Acto knife, and then the old epoxy can be cleaned up by taking a skim cut on the lathe. Finally, a new o-ring can be glued on. It is recommended that this be done no more than two times before replacing the MACOR nozzle insert entirely.

The PZT is a parallel polled, biomorph, bender actuator constructed from 2 layers of PZT-5H material with a brass shim sandwiched between.[18] A 20 $\mu$s, 200 V (max), signal is applied to the center electrode to open the valve. The active region of the PZT is 10.16 mm square, and when clamped into the valve it has 5.38 mm of free length. This gives the PZT a series resonance frequency of 5650 Hz, which was measured by applying a sine wave and noting when the current and driving voltage were in phase. The maximum static displacement at 100 V was measured to be 20 $\mu$m using a machinists test indicator. All layers are electrically isolated from one another with Kapton tape, and a sheet of mica beneath the bridge clamp.

### B. Chemical, Heat, and Pressure Resistance

The performance and stability of the valve while flowing Helium and Argon has been thoroughly tested, however we are still in the early stages of testing with molecular samples. Recently, the valve has been tested with $CH_2I_2$ and $C_6H_6$ injected into the carrier gas and we have seen no ill effects. Concerning chemical compatibility, this design is generally not as robust against corrosive samples because the gas fills the entire valve body and piston, and is in contact with the PZT as well as the rest of the materials: stainless steel, brass, Teflon, ceramic, epoxy, Kapton, and Viton. Therefore, caution must be used when choosing molecular samples (especially with molecules containing Fluorine or acids). There are some design improvements which could increases the resistance of the valve to corrosives. For example, Brass was chosen for the piston material because of ease of machinability and could be replaced with stainless steel. Additionally, PZT elements can be bought which have a stainless steel center reinforcing strip instead of a brass strip. These are available from Piezo Systems in Woburn Massachusetts.

Conceivably the valve could perform with the nozzle heated to higher temperatures than 90 °C, since the epoxy and Viton o-ring can sustain continuous operation up to 200 °C. However, the limiting factor might be the curie temperatures of the PZT, which is made from Navy Type VI material and has a curie temperature of 220 °C. Exposure to temperatures in excess of the curie temperature will cause the material to lose its piezo electric properties. The PZT generates heat when it runs, so it is conceivable that the curie temperature could be exceeded even during modest heating of the valve body. The best strategy for heating the nozzle is to focus the heat on the faceplate and allow the PZT to run at slightly cooler temperatures due to the temperature gradient this method would produce in the valve body.

The maximum backing pressure of 21 bar was chosen because of limitations of our experimental apparatus. Testing the valve up to 21 bar never resulted in failure—breaking of the PZT or the inability to open.

### C. Electronics

The electronics, which drive the piezo, can be divided up into a power circuit and a control circuit. The power circuit consists of a totem pole amplifier which utilizes an op amp to provide the voltage gain, and two transistors to provide the current gain. The circuit diagram is included in the supplemental documents. The power for the circuit is provided by a 200 V (190 mA) supply and a -20 V (650 mA) supply, which are adequate because the duty cycle is only 2 %. The op-amp is wired as a comparator, which means the op-amp is essentially a binary switch. When the signal from the control circuit rises above approximately 1.5 volts the output of the op-amp goes from 0 V to the maximum supplied (typically 100-
The time it takes to do this is a function of the slew rate of the op-amp, and the op-amp we used takes about 5 \( \mu s \) to rise to this voltage. So, the resulting waveform looks like an isosceles trapezoid, which is 20 \( \mu s \) in duration at the base and has 5 \( \mu s \) ramps up and down at the leading and trailing edge.

The control circuit is an embedded controller which takes a trigger from the laser, and outputs a square wave to the power amplifier with a variable valve-laser delay, variable repetition rate, and variable pulse duration. It was designed to function with our laser which operates at 1 kHz, but the programming principle can be applied to a laser of any repetition rate. Basically, the microcontroller acts as a countdown timer. For example, if we want to pulse the valve 100 Hz, after every 10\(^{th}\) laser trigger the controller will wait some number of \( \mu s \) (between 0 and a laser period) before outputting the signal to the amplifier. By varying the valve-laser delay we can walk the laser shot through varying gas pulse densities in order to map the entire temporal width of the pulse. The microchip is programmed in C and controlled via a laptop running PuTTY SSH client and a USB to serial converter. The user can select the valve-laser delay, the repetition rate of the valve, and the driving pulse duration.

III. MAPPING A SUPersonic EXPANSION

A. Fast Ionization Gauge

In order to map the density of the pulse, a fast ionization gauge (FIG) was built, which was conceptually based on a 1977 design by Gentry and Giese.\(^2\) The FIG works according to the same physical principles as a Bayard-Alpert hot filament pressure gauge; however because of the FIG’s small diameter grid, the measurement is relatively localized in space as well as in time. A CAD model of the FIG, and dimensioned drawings, are available in the supplemental materials.

The major components of the FIG are a filament, grid, collector, and amplifier. The filament is helically wound from 127 \( \mu m \) tungsten wire, and applying 15 volts and approximately 1 amp to the filament causes it to become yellow hot and emit electrons. The grid is helically wound from 254 \( \mu m \) tungsten wire, and held at a 130 \( V \) potential which accelerates the electrons emitted by the filament. Down the center of the grid is a tungsten collector where ions are collected and then amplified via a transimpedance amplifier.

The FIG electronics are installed inside the vacuum chamber and plugged directly into the collector. During a pulse, the current output by the collector is on the order of tens of nA, which is dropped across a 750 k\( \Omega \) resistor and then amplified 25 times by an op amp. The resulting output is sent to an oscilloscope and ranges from tens of m\( V \) to volts.

The FIG was tested by comparing its output to the chamber pressure measured by a factory ion gauge. It was determined that, under DC operation, the FIG responds linearly throughout the \( 10^{-5} \) and \( 10^{-4} \) torr pressure ranges. Additionally, the AC response of the FIG was tested by constructing a pulsed electron source from an old vacuum tube. It was determined that the rise time of the FIG is on the order of 4 \( \mu s \), which is sufficiently fast for this application.

B. Valve Performance

The valve was mounted inside a vacuum chamber, pumped by a turbo pump with an effective pumping speed of 100 l/s, and the FIG was attached to a three dimensional motion feedthrough so that it could be moved around the inside of the chamber. In the coordinate system used the origin is located at the nozzle, the \( z \) dimension is the direction the gas pulse is propagating, the \( x \) dimension is transverse to the beam propagation in the horizontal plane, and the \( y \) dimension is transverse in the vertical plane. This experimental setup was used to measure the valve’s performance in three regimes of its operating envelope: (1) moderate frequency and backing pressure (1 kHz and 7 bar), (2) low frequency and high backing pressure (10 Hz at 21 bar), (3) and high frequency and low backing pressure (6.2 kHz at 3.5 bar). The most detailed analysis was performed on the data collected at 1 kHz and 7 bar. Therefore, the following analysis will focus on these results while drawing comparisons with the results obtained in each test.

The valve was backed with 7 bar of Helium and pulsed at 1 kHz, with a 20 \( \mu s \) duration driving signal. The chamber pressure increased from 1 \( \times \) \( 10^{-5} \) to 9.5 \( \times \) \( 10^{-5} \) torr. Measurements of the gas density as a function of time were recorded at 36 points in space by moving the FIG around the inside of the chamber. The 36 points were all in the x-z plane and divided into 4 groups, each of which had approximately equal radius from the nozzle. The \( z \) axis is along the direction of the beam propagation, and the \( x \) dimension is the horizontal transverse displacement. Since the nozzle is a cone, it is assumed that the beam is rotationally symmetric in the x-y plane. The ion signal from each of these locations was used to reconstruct the propagation of a single gas pulse.

Figure 2 shows normalized ion yield as a function of time since the valve trigger with the FIG located on the axis of the nozzle and 1.6 cm from the valve orifice. This pulse duration is 11.5 \( \mu s \) at FWHM and has a rise time of 8 \( \mu s \). The slightly longer fall time is probably due to the the pump taking a finite amount of time to clear the Helium gas from the chamber. The pulse-to-background ratio is 65, which can be interpreted as the increase in peak pulse density over the background density.

By plotting the maximum ion signal recorded at each FIG position at an instant time, still frames of the pulse propagating were constructed. Figure 3 starts 48 \( \mu s \) after the valve is triggered and each frame is separated by 2 \( \mu s \). The heat map is indicative of gas density with the
The angular distribution of the beam is 20° from the nozzle, and is consistent with density providing a high density on axis even for significant distances from the nozzle, and the valve running at 1 kHz and 7 bar backing pressure. The FWHM of the pulse immediately after exiting the nozzle is 11.5 µs.

FIG. 2. Plot of normalized ion yield versus time since the signal was sent to the piezo to open. The measurement was taken with the FIG at 0° and 1.6 cm away from the nozzle, and the valve running at 1 kHz and 7 bar backing pressure. The FWHM of the pulse immediately after exiting the nozzle is 11.5 µs.

The density of the beam is proportional to $r^{-1.2}$, which provides a high density on axis even for significant distances from the nozzle, and is consistent with density simulations from pulsed sources performed by U. Even [19]. The angular distribution of the beam is 20° (full angle). As a comparison, when the pressure behind the nozzle was increased to 21 bar the angular width of the beam decreased to 16°. This is expected, given that higher backing pressures produce colder beams in which the molecules have a tighter speed distribution.

It was estimated that each pulse contains approximately $2 \times 10^{14}$ atoms. This was calculated from the rise in chamber pressure when the valve was activated, considering the effective speed of the turbo pump. The peak density can be estimated using the Ideal Gas Law $N/V = p/K_BT$ by first calculating the density of the background and then multiplying this by the pulse-height-to-background ratio recorded by the FIG. Where $p$ is the chamber pressure with the valve turned off (1 × 10^{-5} torr), $T$ is room temperature, and the pulse-height-to-background ratio is 65. The peak density was estimated to be $2 \times 10^{14}$ atoms/cm³. When the backing pressure was increased to 21 bar, and the valve was adjusted to achieve the maximum FIG signal, the magnitude of the FIG signal increased by a factor of 10. Therefore, the maximum density can be approximated as $2 \times 10^{15}$ atoms/cm³.

The longitudinal dispersion of the pulse was used to infer the speed ratio and temperature of the beam. Considering only points along the axis of nozzle, lines were fit to the FIG-to-valve distance versus time of arrival for different gas densities (interpolated from the fraction of the pulse peak height), and from the slopes of these line, a gaussian distribution of speeds was constructed (Figure 4). For 7 bar of backing pressure, the most probable speed was 1960 ± 130 m/s. This value is within 1σ of the accepted value of 1856 m/s. [20] Our uncertainty in speed stems from to our distance measurement error. Repeated measurements of the same radius result in errors of about ±1 mm, which is consistent with speed errors on the order of ±100 m/s.

According to the formula given by Hillenkamp, Keinan and Even, the speed ratio $S = \sqrt{2} \mu/\sigma$, where $\mu$ is the most probable velocity and $\sigma$ is the standard deviation. This yielded a speed ratio $S = 21$. From this, the average longitudinal temperature of the beam was estimated to be 1.7 $K$ using the following formula and room temperature as $T_o$ [1]

$$T = T_o(1 + \frac{2}{5}S^2)^{-1}$$

At 21 bar backing pressure the speed ratio increase to $S = 46$. This corresponds to a longitudinal beam temperature of 0.3 $K$. This is consistent with atomic beam speed ratio and temperature as a function of backing pressure published by Hillenkamp, Keinan, and Even.[1]

As for a temperature prediction of sample molecules injected into the atomic beam, this is a complex question. However, since the mechanical properties of our valve are similar to the properties of the Amsterdam Piezo Valve (APV), it is reasonable to believe our valve would perform similarly. In one publication, the developers of the APV, reported on the results of a supersonic expansion of 0.1% $CD_3I$ in 6 bar of neon. They measured a speed ratio of 135 within the densest part of the beam (their experimental setup enabled them to probe slices of the beam) and concluded that the longitudinal temperature of $CD_3I$ was 294 mK. [6] We believe our valve would perform similarly given the same experimental conditions.

The shortest pulse duration was recorded when the valve was running at 6.2 kHz with 3.5 bar backing pressure, and the FIG was located on the axis of the nozzle, 1.6 cm away from the valve. Under these conditions the chamber pressure increased from $6 \times 10^{-6}$ to $5 \times 10^{-4}$ torr. This pulse measured 10.6 µs FWHM. The pulse-to-background ratio is only about 4, which is a result of the limited pumping speed of this chamber. This result is similar to that published by Frimia et al.[6], where they also measured low pulse-to-background ratios at 5 kHz. For comparison purposes, when the backing pressure was increased to 21 bar, the duration was observed to increase to 15 µs and the pulse-to-background ratio also increased to 148.

The shot-to-shot stability of the valve was characterized by constructing a histogram of the area beneath the ion signal curve for 1000 pulses. Data recorded from these pulses at 1 kHz and 7 bar backing pressure yielded a $\sigma/\mu = 0.56\%$, indicating that shot-to-shot fluctuations are less than 0.6%. The shot-to-shot waveform is unimodal (all the pulses look like the waveform depicted in
FIG. 3. Fast ionization gauge signal in volts as a function of \( z \) (gas pulse propagation direction) and \( x \) (transverse dimension) at snapshots in time. These snapshots begin 48 \( \mu s \) after the valve is triggered and are each separated by 2 \( \mu s \). The heat map denotes the density of Helium gas, which was plotted using the peak of the ion signal, at the specified time, measured by the fast ionization gauge placed at 36 locations in the \( x-z \) plane. The nozzle is located at the origin of each plot, and the \( x \) and \( z \) axis are in centimeters. The gas density falls off like \( r^{-1.2} \), and the angular spread of the beam is 20° (full angle).

IV. LASER IONIZATION TEST

An experiment was performed using a femtosecond laser to ionize a skimmed Argon beam. The ion yield was amplified via a micro channel plate, and the laser-valve timing delay was varied in order to map the temporal duration of the pulse. Additionally, the transverse extent of the pulse was measured by adjusting the focus of the laser.

The valve was backed with 7 bar of Argon and pulsed at 1 kHz. The valve adjustment was set using the micrometer so that the pressure in primary chamber, which was pumped by a 250 l/s turbo pump (100 l/s effective at the chamber), remained in the high \( 10^{-5} \) torr while the valve was operating. Approximately 2 cm from the pulsed valve nozzle was a molecular skimmer (Beam Dynamics) with an orifice of 200 \( \mu m \). Although it is well known that pulsed beams require skimmers with entrance diameters on the order of \( \text{mm} \) to prevent substantial beam attenuation, a 200 \( \mu m \) skimmer was freely available and deemed acceptable for this test. The secondary chamber was pumped via a turbo pump with an effective speed of 33 l/s, and the pressure remained in the high \( 10^{-7} \) torr during valve operation. The laser crossing point was located 14.5 cm from the valve nozzle.

Figure 5 shows the integrated ion yield vs. the time delay between the valve trigger and the laser shot. From a normal distribution fit to this data it was determined that FWHM=65 \( \mu s \). This duration is consistent with the measurements made using the FIG, which showed that
the FWHM of a pulse of Argon will increase by about 3.7 µs per cm traveled. It corresponds to a pulse duration of 17.2 µs directly in front of the nozzle.

Finally, measurements of the transverse profile of the atomic beam show that the beam is gaussian shaped with a FWHM=650 µm, and a 400 µm density ramp. This gives an angular dispersion of 0.25°, which is consistent with the expected value of 0.28° calculated using the nozzle-skimmer geometry.

V. CONCLUSION

We developed and tested a PZT actuated pulsed valve which can generate 11 µs pulses of gas at a maximum demonstrated frequency of 6.2 kHz, and peak densities of 10^{15} particles/cm^3. The valve has also demonstrated prolonged operation at 21 bar backing pressure and temperatures of 90 °C. A unique feature of this design is that the PZT bender actuator is mounted to a motion platform, which we control via a rotary feed through from outside the vacuum chamber. This allows for real-time adjustment of the distance between the piezo and the sealing o-ring. This is essential for overcoming some of the shortcomings of piezo valves, such as sensitivity to temperature, changes in backing pressure, and carrier gas type.

Additionally, a fast ionization gauge was developed, based on an earlier design by Gentry and Giese, in order to map the gas density within the pulse in 3D. We measured an 11 µs duration pulse of Helium, supersonically expanded from 7 bar into 10^{-5} torr vacuum from a 40° conical nozzle, and determined that the beam contains approximately 2 × 10^{14} particles per pulse, a divergence of 20°, and a density which falls off like r^{-1.2}. The calculated the speed ratio of this beam is 21, which corresponds to a longitudinal temperature of 1.7 K. Increasing the backing pressure to 21 bar resulted in a speed ratio of 46 and a corresponding beam temperature of 0.3 K.

FIG. 5. Integrated ion yield as a function of valve-laser delay. By fitting a normal distribution FWHM was determined to be 65 µs. This is consistent with the longitudinal dispersion of a pulse of Argon gas predicted by the FIG data.

VI. ACKNOWLEDGEMENTS

We thank Eugene Shafto and Richard Lefferts, whose support and expertise were invaluable. This research was supported by the National Science Foundation Grant No. 1505679.
[13] The LEMO connectors have part number EWV.00.250.NTLPV and the plans for the adapter to mate them with the body of the valve are included in the supplemental documents.
[14] The spring is distributed by LeeSpring and has a part number LC 093M 04 S.
[15] This epoxy was purchased from Thorlabs and has part number 353NDPK.
[17] The o-ring was manufactured by Precision Associates Inc. and has a part number 10-10 9746.
[18] The piezo element is cut down, according to the plans in the supplemental documents from a stock model distributed by Steminc which has a part number SMBA4510T05M.