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A short pulse (7 μs FWHM) and high repetition rate (dc-5kHz) cantilever piezovalve for pulsed atomic and molecular beams

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In this paper we report on the design and operation of a novel piezovalve for the production of short pulsed atomic or molecular beams. The high speed valve operates on the principle of a cantilever piezo. The only moving part, besides the cantilever piezo itself, is a very small O-ring that forms the vacuum seal. The valve can operate continuous (dc) and in pulsed mode with the same drive electronics. Pulsed operation has been tested at repetition frequencies up to 5 kHz. The static deflection of the cantilever, as mounted in the valve body, was measured as a function of driving field strength with a confocal microscope. The deflection and high speed dynamical response of the cantilever can be easily changed and optimized for a particular nozzle diameter or repetition rate by a simple adjustment of the free cantilever length. Pulsed molecular beams with a full width at half maximum pulse width as low as 7 μs have been measured at a position 10 cm downstream of the nozzle exit. This represents a gas pulse with a length of only 10 mm making it well matched to for instance experiments using laser beams. Such a short pulse with 6 bar backing pressure behind a 150 μm nozzle releases about 10^{16} particles/pulse and the beam brightness was estimated to be 4×10^{22} particles/(s str). The short pulses of the cantilever piezovalve result in a much reduced gas load in the vacuum system. We demonstrate operation of the pulsed valve with skimmer in a single vacuum chamber pumped by a 520 l/s turbomolecular pump maintaining a pressure of 5×10^{-6} Torr, which is an excellent vacuum to have the strong and cold skimmed molecular beam interact with laser beams only 10 cm downstream of the nozzle to do velocity map slice imaging with a microchannel-plate imaging detector in a single chamber. The piezovalve produces cold and narrow ($\Delta v/v=2\%-3\%$) velocity distributions of molecules seeded in helium or neon at modest backing pressures of only 6 bar. The low gas load of the cantilever valve makes it possible to design very compact single chamber molecular beam machines with high quality cold and intense supersonic beams. The high speed cantilever piezovalve may find broad applicability in experiments where short and strong gas pulses are needed with only modest pumping, the effective use of (expensive) samples, or the production of cold atomic and molecular beams. © *2009 American Institute of Physics.* [doi:10.1063/1.3263912]

I. INTRODUCTION

During the last decade a renewed interest emerged in the production of pulsed atomic and molecular beams with short pulse widths. On the one hand such a short gas pulse at high backing pressure is able to produce a supersonic beam with a narrow velocity distribution or a cold internal rotational state distribution.[1,2] Furthermore, many atomic and molecular beam experiments are performed using (ultrafast) lasers and the rapid technological advances in femto- and attosecond laser sources pushed the repetition rates of laser systems to well above 1 kHz. These high repetition rate laser systems have now created a demand for pulsed gas sources running at rates between 1 and 5 kHz.

During the last 30 years there have been various different designs of pulsed valves for the production of supersonic beams.[3–11] The repetition rate of these valves varied between 1 Hz and 1 kHz. The valve reported by Gentry and Giese[3] in 1978 produced gas pulses of a helium beam with a full width at half maximum (FWHM) down to about 10 μs measured 10 cm downstream from the nozzle by a fast ion gauge. This valve operated on the principle of two magnetically repelling bars through which a large current was pulsed and worked only at low repetition rate of 1–10 Hz.[3,4] Piezodisk pulsed valves were developed and improved by various groups.[5–7,10] They operate on the principle of flexing a cylindrical piezo disk when a voltage pulse (typically a few hundred to a thousand volts) is applied. Pulse widths of about 100–150 μs were measured at repetition rates up to 1 kHz. Widely used in the field of atomic and molecular beams are magnetically activated plunger valves like the commercially available General Valve Series 9.[8] These solenoid valves produce pulses with a typical width of a few hundreds of microsec-

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onds and can operate at repetition rates of tens of hertz. Around 2000, Even and co-workers[9,11] developed an optimized magnetically activated plunger valve that can operate at high backing pressures and has been shown to produce pulsed beams with a duration down to about 10 μs. A special high repetition rate version of this Even–Lavie valve was developed that can operate at 1 kHz. The valve of Even–Lavie is currently used in many experiments, e.g., to obtain seeded molecular beams with rotationally cold molecular species for the production of highly aligned molecules by strong laser field alignment.[12] About two decades ago Gerlich *et al.*[13] developed a cantilever piezovalve, however, this work was never published in the open literature and this may have hampered more widespread use of cantilever piezovalves in the atomic and molecular beams community. In 2000 we followed the German design notes of Gerlich in the construction of our first piezovalve that we operated at 1 kHz repetition rate in femtosecond ion imaging experiments.[14–17] Recent demands in our group[18,19] to run experiments at 5 kHz and the need to make translationally (and rotationally) cold pulsed molecular beams inspired us to reconsider the design of the cantilever piezovalve.

Very recently,[20] we reported our first results using femtosecond velocity map ion imaging[15,16] to characterize *in situ* the speed distribution at various temporal positions within a short gas pulse produced by a novel cantilever piezovalve. Furthermore, we demonstrated the operation of the cantilever valve at repetition rates between dc and 5 kHz. In this paper we provide a detailed account of the design of our novel cantilever piezovalve and the piezo's electromechanical performance. We further improved the mechanical design of the valve as compared to our recently reported version.[20] At present we are able to produce seeded molecular beams in helium with pulses as short as FWHM=7 μs measured 10 cm downstream of the nozzle exit. In our improved design reported here no bouncing of the valve is observed even at repetition rates as high as 5 kHz.

II. THE PIEZOCANTILEVER VALVE

A. Design and choice of piezo

Piezomaterials are widely used in microelectromechanical systems in a very diverse range of applications such as microvalves for microspacecraft applications,[21] aerodynamic flow control in flying vehicles,[22] scanning tunneling microscopes down to low temperatures,[23] and high speed medical imaging.[24] During the last decade innovative multilayer piezoelectric stack actuators were developed in the automobile industry for high-speed high-pressure direct injection engines.[25–28]

For the application of pulsed molecular beams the typical displacement needed is of the order of 30–70 μm for nozzle diameters of 100–300 μm. Cantilever piezos can deliver large displacements up to hundreds of micrometer to 1 mm.[29,30] However, both the blocking force and the displacement strongly depend on the dimensions of the cantilever piezo. For a cantilever the blocking force and the attainable dynamical response decrease substantially with increasing free length, whereas the displacement increases with the square of the free length. In our design considerations we aimed for an optimal compromise between sufficient displacement (30–70 μm), high-speed dynamical response (10 μs or less), variable repetition rate (dc-5kHz) and sufficient blocking force (about 1–2 N) by choosing state-of-the-art piezoceramic material and an optimized cantilever design.

Piezoelectric ceramics can be manufactured as unimorph, bimorph, or multilayer stacks.[31] For the operation of a cantilever piezo the deflection is determined by the value of the piezoelectric charge constant d_{31}.[32,33] We selected PZT507 as piezoelectric ceramic for our cantilever because it has one of the largest piezoelectric charge constants d_{31} and can be reliably manufactured in optimized bimorphs. The officially specified value for PZT507 material by the manufacturer[31] is $d_{31}=-280$ pm/V. However, d_{31} of the piezoceramic selected for the bimorphs used in our cantilever valve is typically about $d_{31}=-370$ pm/V.[34] This latter value is about 75% larger than the value of $d_{31}=-215$ pm/V for PZT503 (also known as PXE5) piezoceramic. PXE5 was used by us since 2000 in our first series bimorph cantilever valve that was running at 1 kHz and was recommended in the German notes by Gerlich and co-workers.[13–16]

Piezoelectric ceramics are poled before operation and the effect of a strong reverse oriented electric field on the (mal)function and domain reorientation of the ceramic has been well documented and studied.[30] To obtain maximum deflection of the cantilever we want to drive the piezoceramic at high field strength near 1000 V/mm. Therefore, we selected a parallel poled bimorph configuration and applied the electric field across the two piezolayers such that it is always along the poling direction. The present operation is different from the operation of the series bimorph cantilever that we used since 2000.[13–16] The series bimorph can only be operated at a more reduced electric field (typically 350 V/mm) due to the coercive operation on one of the layers of the series bimorph which is antiparallel poled with respect to the applied drive field. When we drive a parallel bimorph at high field strength we benefit, in principle, from the nonlinear response of piezoelectric materials.[32,33] Yao *et al.*[33] studied and modeled the nonlinear static response of piezoelectric materials and applied these models to calculate the deflection and blocking forces of various unimorph and bimorph cantilevers. Furthermore, van den Ende *et al.*[35] recently reported on the effects of nonlinear stiffness when bimorphs are strained when operated in the parallel configuration when only a single piezolayer is actuated. These nonlinear effects are due to mechanical domain reorientation and a model was developed which incorporates the nonlinear stiffness of the passive piezolayer.

B. Static deflection and resonance frequency

In the limit of a linear response and static operation the deflection of a cantilever, δ, can be expressed as[32,33]

$$\delta \propto d_{31}\frac{l^2}{t}. \tag{1}$$

Here l is the free length of the cantilever and t is the total thickness of the cantilever. The first natural resonance frequency, ν_1, of a clamped free cantilever can be written as[30,32]

$$\nu_1 \propto \frac{t}{l^2}. \tag{2}$$

The blocking force, F_{bl}, in the limit of linear response, is given by[32]

$$F_{\mathrm{bl}} \propto wt^2/l, \tag{3}$$

with w as the width of the cantilever.

From Eqs. (1) and (2) we can readily observe that the deflection decreases strongly with decreasing length and the resonance frequency increases with decreasing length. As we want to operate the cantilever at high dynamical speed and high repetition rate up to 5 kHz we need to increase the resonance frequency to be well above this value. This forces us to use cantilevers with rather short lengths of 4–6 mm. The advantage of the cantilever piezo versus a cylindrically shaped disk piezo[7] is that the free length of the cantilever can be readily adjusted by clamping the piezo at a different position. In this way we can adjust the dynamical response to the time scale needed in the experiment.

In Fig. 1, panel A, we show a photo of the inside of the valve with the piezocantilever clamped at a free length of about 5–6 mm. Also visible are the three set screws which are used to carefully adjust the distance of the O-ring seal to the nozzle. In panel B the closed valve body, with an outer diameter of 40 mm, is shown. In panel C we show a photo of the piezovalve mounted in a heatable holder on which also an electrically isolated skimmer is mounted. The whole assembly is attached to a standard ISO160 flange.

To obtain quantitative data of the deflection of the piezocantilever we measured with a confocal microscope the static deflection of the piezosurface in the middle of the piezo near the free edge of the cantilever, see Fig. 2. The microscope was operated in the automatic focusing mode to obtain smaller errors in the measured deflection as compared to operation in the manual focusing mode. We measured two traces, one trace where we started with a field across the piezo such that the valve was initially closed, a second trace was measured in the reverse direction starting with the piezo initially in the fully open position. The maximum field strength that we applied was 1000 V/mm and we measure a typical full deflection of about 40 μm at this field strength. We notice that the deflection is increasing almost linearly with field strength and shows a small concave curvature at the highest field strength. With the confocal microscope we determined the distance between the position where we measured the deflection and the outer edge of the isolation around the clamp to be about 4.475 mm.

Van den Ende *et al.*[35] measured the static deflection of a similar parallel bimorph, however, this cantilever was made of PZT5K material that had an even higher value of the piezoelectric charge constant, $d_{31}=-438$ pm/V. They measured the deflection with only one of the piezolayers activated, i.e., their reported deflection correlates to half of the full deflection that we report in Fig. 2. At 1000 V/mm they measured a deflection of about 900 μm for a cantilever length of 36 mm. If we scale [see Eq. (1)] a deflection of 900 μm to the value of 20 μm measured here we can esti-

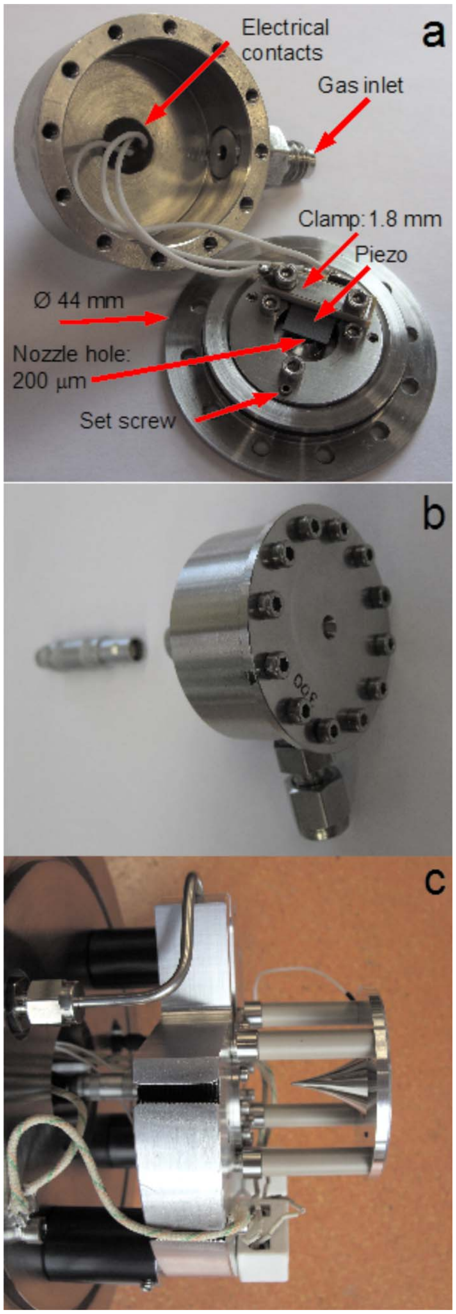

FIG. 1. (Color online) Panel (a): photo of the inside of the cantilever piezovalve, with the relevant dimensions indicated. The O-ring is glued to the back side of the piezo, which forms the vacuum seal to the nozzle hole. Typically, the nozzle has an opening diameter of 150–300 μm and a conical shape with a full angle of 40° [see also panel (b)]. The nozzle to seal distance can be carefully adjusted with three set screws as indicated. Proper operation and adjustments of the valve are made on a leak tester before the valve is mounted inside the vacuum machine. The piezo free cantilever length is about 5–6 mm. The length of the cantilever can be easily adjusted by moving the clamp. This allows for optimal matching of the dynamic response and maximum deflection of the valve with changing experimental demands. Panel (b): photo of the closed valve which has an outer body diameter of 44 mm. Panel (c): photo of the piezo valve body mounted in a heatable holder on a standard ISO160 vacuum flange. An electrically isolated skimmer is also attached to the holder. This complete unit operated in a vacuum chamber pumped by a single 520 l/s turbo pump that also contained velocity map ion lenses with a MCP particle detector. Cold supersonic molecular beams are produced that are crossed by ionizing lasers at short distances of only 10 cm without the need for expensive differential pumping.

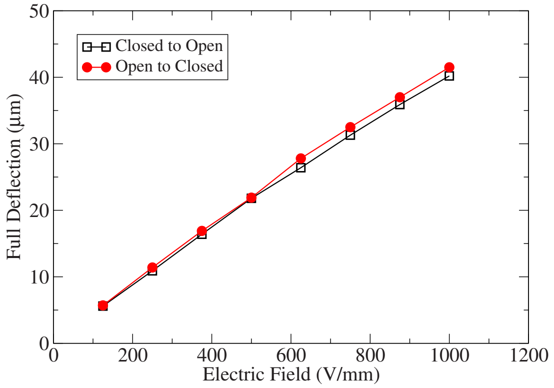

FIG. 2. (Color online) Measured full deflection of the cantilever as a function of the applied field strength across the piezo layer. The deflection was measured with a confocal microscope. Two cycles were measured, one where we started with applying a static voltage on the piezo such that initially at high field strength it is fully open, a second one starting where the voltage is applied such that the piezo is initially closed at high field strength. At any moment the field is applied only across one of the two piezolayers, the second layer has no effective field applied. The total difference in deflection (called full deflection) between the application of the voltage across each of the two layers individually is shown. This is the deflection that is generated when we pulse the piezo.

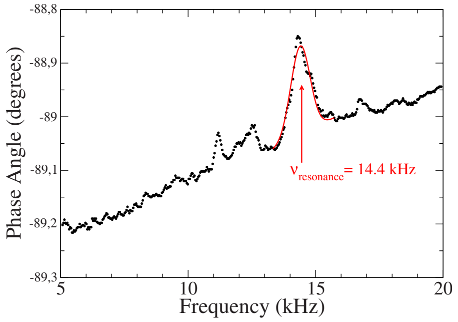

FIG. 3. (Color online) Measured phase angle of the impedance of the mounted cantilever as shown in Fig. 1(a). The piezo was driven with a low voltage ac signal. The first resonance is observed near 14 kHz.

mate the effective length of our cantilever as $l = \sqrt{(20/900)(438/370)36^2} = 5.8$ mm. This length is slightly longer than the distance we measured with the confocal microscope, however, taking into account the construction of our clamp (isolation and rounded lower support surface) it does not seem unreasonable that the effective length may be somewhat longer than the value obtained from the measured outer edge of the clamp by the confocal microscope.

We can use the equations derived by Wang *et al.*[32] and Yao *et al.*[33] to estimate our deflection. Because we use the parallel bimorph in an electrical configuration where only one of the piezolayers is activated at any moment we use Eq. 7 in Ref. 32 and Eq. 40 in Ref. 33 to estimate the deflection in case of linear or nonlinear response, respectively. If we assume a cantilever length of $l=6$ mm, a piezoelectric constant $d_{31}=-370$ pm/V and similar nonlinear piezoceramic material parameters as in Ref. 33 we find for a field of 1000 V/mm a full deflection swing of 33 μm for linear response and 93 μm for nonlinear response. In comparison with our measured full deflection of 40 μm we conclude that for our relatively short length of only 6 mm the effect of nonlinear response is about 20%.

At this field strength of 1000 V/mm we calculate the blocking force (using Eq. 8 in Ref. 32) to be about $F_{bl} = 1.6$ N. This force is sufficiently strong to open the valve even with a large pressure differential across the vacuum seal when operating the valve at large backing pressures (e.g., several tens of bar) and nozzles up to 500 μm in diameter. In some test experiments we operated the valve at nozzle backing pressures up to 20–30 bar.

In Fig. 3 we show the measured phase angle at varying frequency in an electrical impedance measurement of the piezocircuit when driving the cantilever system by an ac voltage of about 1 V peak to peak. The piezocantilever was mounted as shown in Fig. 1(a) and the impedance was measured with the electrical contact close to the cantilever. We observe the first resonance at a frequency of about 14.4 kHz and no resonances are observed below this frequency. To compare this with theoretical calculations we use Eq. 3 in Ref. 32 and for a free cantilever length of 6 mm we calculate $\nu_1 = 11.5$ kHz. This value is somewhat lower than measured, however, our electrical measurement may suffer from nonoptimal electrical contact or we overestimated our free cantilever length. If we reduce the cantilever length to 5.4 mm a value of 14 kHz is calculated. Furthermore, it is to be noted that resonance frequencies in cantilever piezos have been observed[30,32] to depend on the driving field strength across the piezo, and in general the resonance shifts to lower frequency at higher driving field strength.

In summary, the first resonance frequency of our short cantilever is measured and calculated to be well above the maximum used repetition frequency of 5 kHz in this paper. The measurement and calculation suggest that there is quite some range to operate the piezo at even higher repetition frequency, perhaps close to 10 kHz, however this has not been tested so far.

III. GAS PULSE DURATION AND VELOCITY DISTRIBUTION

We measured in two different molecular beam machines the gas pulse duration and the velocity distribution of seeded molecular beams produced by the cantilever piezovalve. In Fig. 4 we show the measured gas pulse duration of a seeded beam of 0.1% NO in helium or neon. The gas pulse was measured with the piezovalve mounted as shown in Fig. 1, panel C, in a singly pumped (520 l/s turbomolecular pump) vacuum chamber containing velocity map ion lenses and a microchannel-plate (MCP)/phosphor screen ion detector. The valve had a nozzle diameter of 150 μm and a skimmer mounted some 2 cm from the nozzle exit. The backing pressure behind the nozzle was 6 bar. The pulsed gas beam was crossed 10 cm downstream from the nozzle exit by a frequency doubled tunable nanosecond laser. The laser was tuned near 226 nm to rotationally state-selectively ionize $NO(^2\Pi_{1/2}, J=1/2)$ by (1+1) resonance-enhanced multiphoton ionization. NO^+ parent ions were accelerated by ion lenses to the detector and the total ion yield was measured by detecting the light of the phosphor screen with a photomultiplier (PMT). The pressure in this chamber was low 10^{-7} Torr when the molecular beam was off and increased to

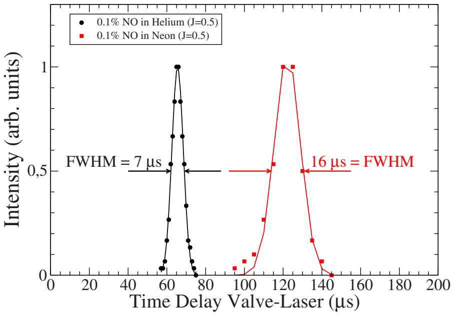

FIG. 4. (Color online) Total NO^+ ion yield, as measured by the PMT of the light of the phosphor screen behind a MCP detector, of two different skimmed beams of 0.1% NO in helium and neon. The intensity of NO ($J=1/2$) was measured as a function of time delay between the piezovalve and the tunable nanosecond laser. The piezovalve was running at 10 Hz repetition frequency and was mounted as shown in Fig. 1(c). The distance between nozzle and laser ionization region was 10 cm. Pulsed beams with FWHM duration as short as 7 μs can be made with the cantilever valve.

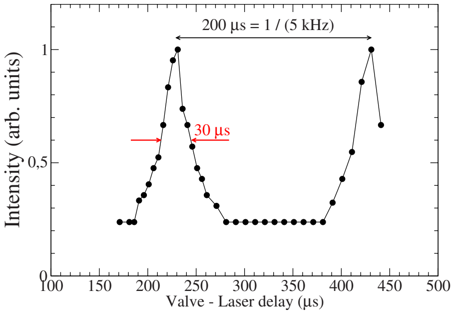

FIG. 5. (Color online) Total Xe^+ ion yield, as measured by the PMT of the light of the phosphor screen behind the MCP, of a doubly skimmed beam of 0.1% Xe in neon. The intensity of Xe ions was measured as a function of time delay between the piezovalve and the ionizing femtosecond laser. The piezovalve was running at 5 kHz repetition rate and was mounted in a differentially pump molecular beam machine consisting of three separately pumped vacuum chambers (Refs. 16 and 20). The distance between nozzle and laser ionization region was 15 cm. Strong and cold supersonic pulsed beams with individual gas pulses separated by only 200 μs can be made with the high speed cantilever valve.

about $5-6\times10^{-6}$ Torr (uncorrected pressure reading of ion vacuum gauge) when the valve was pulsing at 10 Hz, the repetition rate of the nanosecond laser system. The electrical drive pulse to the piezo was set to obtain a short gas pulse. The laser timing was scanned with respect to the trigger of the valve driver to measure the gas pulse shape and duration. As can be seen in Fig. 4 a seeded supersonic beam of NO in helium with a pulse duration of FWHM=7 μs is measured. For NO in neon a typical pulse of FWHM=16 μs is measured. We have not made a measurement yet of the internal rotational state population of the seeded NO beams. Other preliminary experiments using this piezovalve in combination with a hexapole quantum state selector suggest that rotationally cold seeded beams can be produced. The hexapole spectra observed indicate that the rotational temperature is much lower than the hexapole spectra typically observed by us using the commercial solenoid General Valve Series 9. A more detailed study of the rotational state population will be reported elsewhere.

From the increase in pressure to about $5-6\times10^{-6}$ Torr$\approx7\times10^{-9}$ bar at a repetition rate of 10 Hz we calculate a load in this chamber, pumped by the 520 l/s turbo pump, of about 3.6×10^{-7} bar l/pulse. This means each pulse releases about 10^{16} particles/pulse when operating at 6 bar backing pressure in the nozzle. As discussed in our previous paper,[20] our nozzle has a similar conical design as those reported by Even and co-workers,[9,11] so we estimate that the full angular distribution of the expansion is only about 12° FWHM. This means that the gas pulse with a FWHM of 7 μs has an estimated beam brightness of 4×10^{22} particles/(s str).

In Fig. 5 we show the measured gas pulse duration when we operate the cantilever valve at 5 kHz. This experiment was performed using femtosecond ion imaging in the molecular beam machine that we also used in our first report on the novel cantilever valve.[20] The molecular beam was a seeded beam of 0.1% Xe in neon, the nozzle diameter was 200 μm, and the backing pressure was 6 bar. The gas pulses are crossed by the femtosecond laser pulses some 15 cm downstream of the nozzle. With the adjustments made in the mechanical clamping of the cantilever and the O-ring sealing, we do not observe any mechanical bouncing anymore of the valve, compare Fig. 5 with Fig. 3 in Ref. 20 where small bounces were observed. At high repetition rate these small bounces appeared to come closer to the strong main pulse. This leads to an asymmetric pulse shape with a fast rising edge but a somewhat longer tail in the region where the mechanical bounce was observed. In our improved design the pulse shape at 5 kHz is much more symmetrical. This pulsed beam at 5 kHz is produced in a molecular beam machine consisting of three differentially pumped chambers.[16] Because of the limited pumping speed of the second buffer chamber we think that at this high repetition rate of 5 kHz there is some residual gas present in between the pulses leading to a background level in between the pulses, see Fig. 5. When operating the valve at low repetition rate of 20 Hz we have a much lower average gas load in the buffer chamber, and the background ion signal in between the pulses reduces to zero. It is clear that pulsed molecular beams at a repetition rate of 5 kHz can be readily produced by the fast cantilever piezovalve. Using the femtosecond ion imaging technique reported recently[20] we also measured the velocity distribution of the gas pulses. For a pulsed beam at 5 kHz of 0.1% Xe in neon typical values of the speed ratio[36] are $S=40-55$, depending somewhat on where in the pulse the velocity distribution is measured.

IV. CONCLUSIONS AND SUMMARY

In this paper we report on the design and operation of a novel homebuilt cantilever piezovalve for the production of short and cold pulsed molecular beams. The piezovalve can operate from continuous to pulsed with the same drive electronics and was tested at repetition rates up to 5 kHz. A parallel poled bimorph of PZT507 piezomaterial with a high piezoelectric charge constant was selected for the cantilever. This makes it possible to operate the cantilever at high field strength with a relatively short length of 5–6 mm for high speed dynamical applications. Still a sufficiently large deflection of 40 μm is obtained to produce strong and cold supersonic beams with nozzle diameters of 150–300 μm.

The free length of the cantilever can be readily adjusted to match the particular demands of an experiment regarding dynamical speed, repetition rate, and pulse length. Short pulses with a FWHM=7 μs are measured at a distance of 10 cm downstream of the nozzle and the seeded molecular beam has an estimated beam brightness of 4×10^{22} particles/(s str). The short gas pulses make it possible to operate the pulsed valve in setups with very modest pumping. Operation was demonstrated in a single vacuum chamber, pumped by a 520 l/s pump maintaining a pressure of $\approx 7 \times 10^{-6}$ mbar, which contained both the pulsed valve and a particle MCP detector. The low gas load of the cantilever valve makes it possible to design very compact molecular beam machines with high quality cold and intense supersonic beams.

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