Optimization and characterization of supersonic gas jet target for laser-plasma interaction studies

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Introduction

Gaseous targets are applied in a large number of laser plasma interaction experiments such as high harmonic generation, particle acceleration, incoherent x-ray generation and optical field ionizing x-ray laser schemes. While the density can easily be adjusted by varying the backing pressures of the gas, specific nozzles such as have been suggested by Semushin and Malka offer the possibility to shape the spatial profile of the gas flow[1)]. Hereby steep density gradients of a few hundred microns followed by a plateau of several millimeters can be achieved using supersonic expansions. This long interaction region is important for the success of a multitude of plasma-based acceleration experiments such as the Laser Wakefield Accelerator (LWFA) scheme.

In this report we focused on both the optimization of the time response of such a nozzle-valve combination and its mass flow rate. This was motivated by the fact that though the flow can be treated as stationary during the interaction period, a slow build-up of the density can result in a degradation of the surrounding vacuum region prior to the interaction. This can result in re-absorption of VUV-radiation emitted by the plasma or affect laser-induced proton or electron beam. This is in particular important in the context of the proton-imaging technique.

Optimization of mass flow rate

As in many laser plasma interaction experiments steep density profiles are required, nozzles with high expansion rates and thus high Mach numbers are used. On the other hand, beside specific profiles also high densities are often needed to create overcritical plasmas. Here the backing pressure has to be increased to compensate the rarefaction of the gas.

Any gas flow system is characterized by the fact that a Mach number of M = 1 is obtained at the location of minimal cross section A* (in m^2) of the duct. For an optimum performance of nozzle-valve combinations for production of supersonic-flows, the minimal cross section should be located at the nozzle throat, since the mass flow rate is fundamentally limited by A*. If a one-dimensional isentropic flow (i.e. adiabatic and frictionless) of a perfect gas is assumed, it is given by

$$\dot{m} = \sqrt{\frac{k}{R}}\,\frac{p_0}{\sqrt{T_0}}\left(\frac{2}{k+1}\right)^{(k+1)/2(k-1)} A^* \quad \left[Kg/s\right]$$

with k as adiabatic coefficient of the gas, R its specific gas constant, p_0 the stagnation pressure of the gas at rest (in Pa) and T_0 the stagnation temperature (in K), respectively[2)].

Thus, if a smaller cross section will be present anywhere else in the duct, the mass flow and with it the maximum achievable density at a given backing pressure p_0 will be limited. Hence an important design criterion for a laser gas target is to ensure an optimum mass flow rate for a given valve-nozzle system.

The valve used was a commercial solenoid pulse valve of Parker Hannifin series 9. This valve meets the requirements of both a fast response time of a few hundreds of microseconds and a high mass flow, besides a high-level vacuum sealing. In addition, it is used in a number of laboratories[3)]. Figure 1 (left) shows a cross section of the series 9 valve.

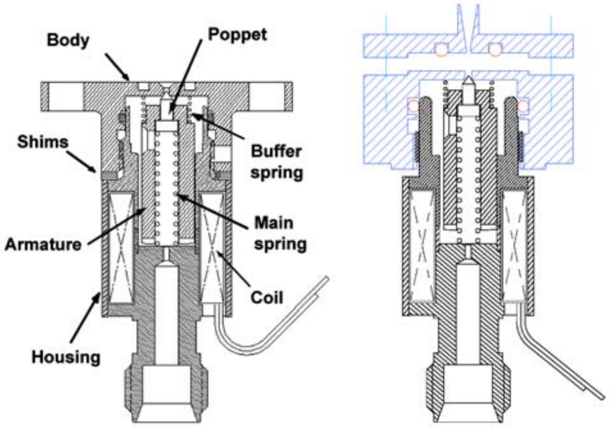

Figure 1. Left: schematic of series 9 valve. Right: modified body head with supersonic Mach 5.5 nozzle (shims are not drawn). The vertical lines indicate the position of fixing screws.

In a first step we measured the flow performance of the valve in order to clarify that it is not choked internally. Therefore the flow through the open valve was measured in steady state with and without poppet. This was done by measuring the pressure increase in a target chamber. As the orifice had a diameter of 0.78 mm, a flow of about 93 mbar l/s is expected using Argon (k = 1.667, R_S = 208 J/(Kg K), R_S = 39.94 mg/mol, p_0 = 1 bar). However, the measured value was 17 mbar l/s that shows that the valve was significantly underperforming. We measured the stroke of the armature and found that it is in the order of 200 μm what seems to be the reason for an effective A* smaller than that of the orifice used.

An improvement of the outflow could be obtained by modifying the vacuum sealing poppet as shown in Figure 2. As the poppet tip was cut under a microscope a significant higher flow of ~ 67 mbar l/s was measured that corresponds to an effective orifice diameter of about 0.66 mm. As also shown in Figure 2 the vacuum sealing, i.e. the leak rate, was not affected.

Optimization of time characteristics

In order to minimize the time response of the laser gas target, i.e. minimize the delay between firing the valve and the build-up of a dense gas jet above the nozzle exit, we used a modified flange head where the nozzles could directly be attached to the valve. Hereby the nozzles are fixed with screws and thus can easily be exchanged without readjustment when the Mach number of the expansion is changed.

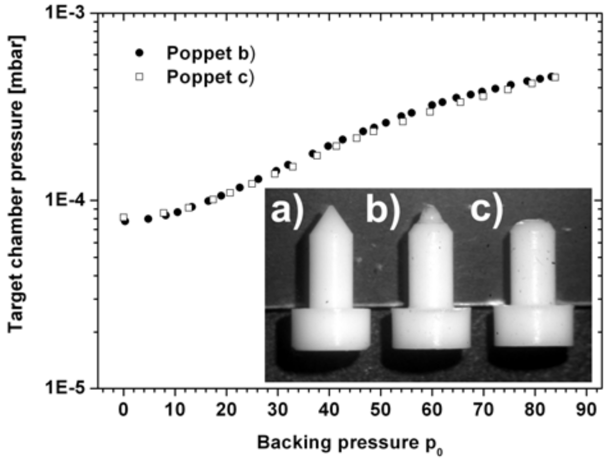

Figure 2. The inset shows pictures of sealing poppet: a) new, b) after several hundred opening cycles and c) after subsequent modification. Flattening of the poppet tip significantly increases the flow while the leak rate in closed position is not affected.

As a reference a series 9 valve was connected to a Mach 3.5 nozzle with a throat diameter of 1 mm and an exit diameter of 2 mm as shown in Figure 3. Here a void volume of about 1cm^3 remains due to the connection.

Figure 3. Image of Mach 3.5 nozzle head connected to series 9 valve. The inset shows the modified head applied with a Mach 5.5 nozzle. The outer diameters of the nozzles are 4.05 mm and 2.1 mm, respectively.

To examine the temporal density evolutions using both valve-nozzle systems, time resolved interferograms of the gas jet were obtained using a modified Nomarski interferometer$^{4)}$. The nozzles were imaged with a resolution of 50 pixel per mm onto a gated high speed CCD camera (model 4 Quick E by Stanford Computer Optics) using an expanded 532 nm diode laser beam and an achromatic lens with f = 300 mm. The time resolution was 1 µs set by the gating interval and the target chamber was evacuated to about 10^{-1} mbar between the shots. The time evolution of the phase shift induced by neutral Argon atom density was evaluated and the density calculated by performing an Abel inversion$^{5)}$.

The result is shown in Figure 4. The backing pressure was 41 bars of Argon and the densities were evaluated 500 µm above the nozzle exit. The delay time until a stationary flow regime is obtained is about 30 ms in the case when a void volume is present. As shown in Figure 4 the maximum density could be doubled by modifying the poppet. The interferograms confirm that the shape of the flow profile is not affected. In contrast, with the modified flange body the delay is in the order of 3 ms. Note that a density of about $3 \cdot 10^{19}$ particles per cm^3 is obtained though the throat diameter is about 0.5 mm and a higher Mach number. This shows that the Mach 3.5 nozzle is still underperforming due to that the flow is chocked by the valve.

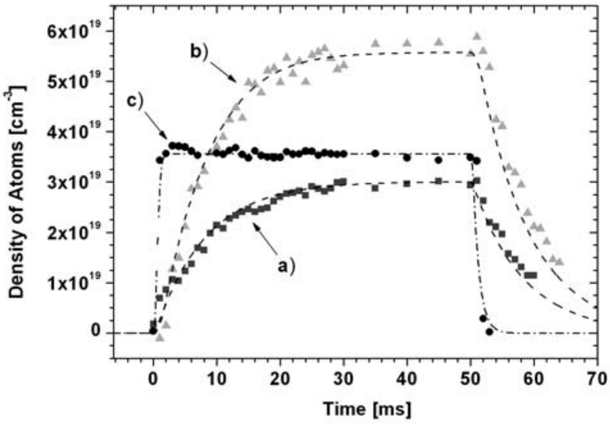

Figure 4. Measured and calculated history of atomic density at 500 µm above nozzle exit for a) M = 3.5 nozzle and using an unmodified poppet, b) same but using a modified poppet, c) M = 5.5 nozzle and modified head as well as flattened poppet.

Analysis and Result

For an analysis the dynamics was calculated by solving the governing differential equations for the mass flow through the valve on the one hand and the converging-diverging section given by the nozzle on the other, where both are connected by a given void volume. Therefore the valve was treated as converging duct with (time-dependent) effective annulus given by the poppet position and it was assumed that the poppet opens and closes linearly within 500 ms, respectively. Thus the effect of choking mass flow rate was fully included in this model. To extrapolate the densities at 500 µm above the nozzle exits, the density gradient obtained from the interferograms was used. Though the model of 1-dimensional isentropic flow completely neglects real gas effects, a good analogy to the dynamics measured could be observed as indicated by the dashed lines in Figure 4.

To summarize, using a series 9 valve the effective mass flow was measured using an orifice of 0.78 mm. It was found that the flow could significantly be increased by a modification of the sealing mechanics, especially the poppet. Hereby neither the flow profile nor the vacuum sealing capacities were reduced. Time resolved interferometry shows that in a nozzle-valve combination void volumes in between significantly increase the delay until a stationary flow regime is achieved. This could be reproduced using 1-dimensional modeling of the time-dependent flow. As an improvement a modified valve head is suggested that allows a simple exchange of the Mach number.

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