AASC12TM09

"A Novel Gas Jet for Laser Wakefield Acceleration"

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2 Project Objectives

Our Ph-II goals as stated in the proposal were:

- to improve upon the Ph-I prototype by delivering a faster valve to LOASIS/LBNL and other groups for tests with intense lasers
- to design and test linear nozzle arrays (as alternatives to the present slit nozzles) and show that such arrays of coaxial nozzles produce better gradient structures for future injectors for »GeV accelerators
- to test an innovative concept for a nozzle that produces a "hollow" density profile along the laser axis, to enhance the laser focal path
- to demonstrate fast injection of gas pulses into static capillary loads, for controlled enhancement of the wakefield gradients
- to make the valve/nozzle package robust, reliable and reproducible, for adoption by wakefield laser facilities
- to adapt the basic wakefield accelerator design for other gas jet/capillary applications such as Raman amplifiers, proton accelerators and intense x-ray sources.

2.1 Ph-II Tasks as listed in Ph-II proposal

The tasks to be completed in Ph-II as stated in our proposal were:

1. **Make improvements to the Ph-I prototype valve, by further reduction in opening and closing times.**
2. **Design and Test valve at AASC and at LOASIS/LBNL.**
3. **Design and test (first on the bench at AASC, then at LOASIS and possibly at other locations such as DIOCLES), a linear array of cylindrical nozzles with tailored density gradients to optimize the acceleration of electron bunches. Such an array would serve as a superior injector for further acceleration in capillary gas columns.**
4. **Design and test nozzle/wire or hollow nozzle combinations that produce a hollow density profile across the jet, to enhance laser guiding across the jet. This would permit longer acceleration lengths than are possible with standard nozzles whose gas flow has a maximum density on axis and a monotonic decay off axis.**
5. **Test the pulse-pulse stability of the gas flow and ensure that it meets LWFA injector specifications.**
6. **Design and test a fast valve to inject a tailored puff of gas into a capillary, to create well defined density profiles as specified by LWFA requirements.**
7. **Adapt the fast valve design for other applications in order to improve commercialization success. Such related applications include gas jet Raman amplifiers, proton accelerators, intense gamma sources and window-less XUV filters for flash x-ray machines or other accelerators**.

3 Project accomplishments

3.1 Task 1: Make improvements to the Ph-I prototype valve, by further reduction in opening and closing times.

The flyer-plate/spring system in our valve acts as a simple harmonic oscillator whose natural frequency determines the closing time. The opening time is determined by the electromagnetic force applied as well as the natural frequency. We found a vendor who could make machined springs for us: HELI-CAL products in Santa Maria, CA. HELI-CAL delivered several machined springs to AASC, with spring constants varying from 50-205N/mm. The advantage of the machined spring is that its flexure is linear (no torque as in coil springs), repeatable and predictable. This greatly improved the pulse-pulse reproducibility of valve opening, which is important for future Laser Plasma Accelerator (LPA) applications that would demand reproducible gas injection at rep-rates of 10-1000Hz.

Figure 1 shows a cross-section of the valve with the coil spring. Figure 2 shows a photograph of the machined spring.

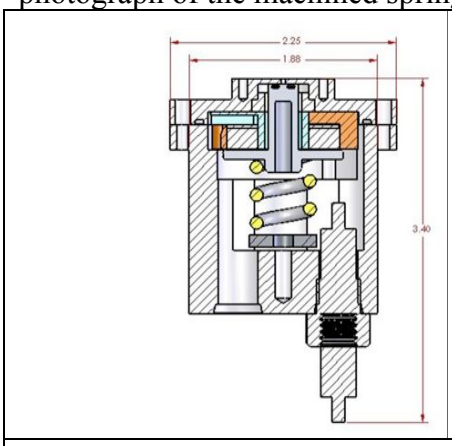

Fig. 1: Cross-section drawing of AASC fast valve with original coil spring

Fig. 2: Photograph of HELI-CAL machined spring that replaced coil spring shown in Fig. 1

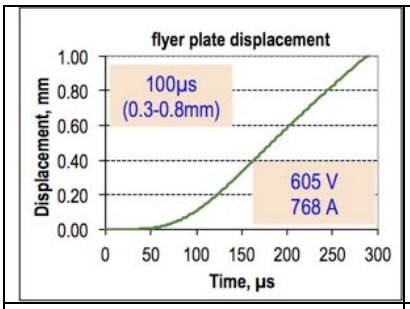

Fig. 3: 100µs opening time (details in text)

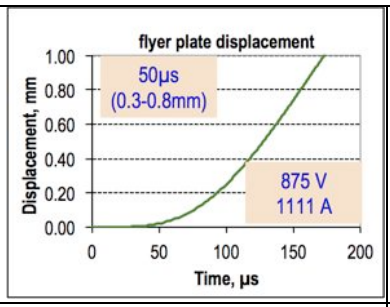

Fig. 4: 50µs opening time (details in text)

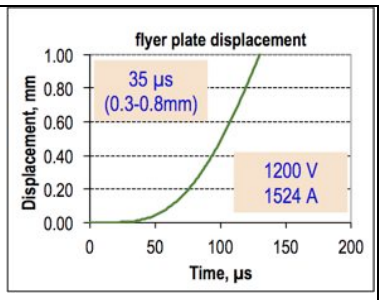

Fig. 5: 33µs opening time (details in text)

With the machined spring it was possible to design for different opening times. Three cases are shown in Figures 3-5. The legend insets indicate that for a fixed spring constant of 88N/mm and a fixed coil inductance of 35µH, as the charge voltage on the drive capacitor bank is increased, the peak coil current increases and the valve opening time is

reduced. We define opening time as the time taken by the flyer plate to move from -.3mm (the Viton O-ring's initial compression) to 0.8mm. A 0.5mm displacement of the flyer plate would more than suffice to fully choke the flow at the nozzle throat. By adjusting the spring constant, this opening could be varied as well. The coil inductance determines the peak current.

To control the opened time of the valve i.e. the duration of the flow, the spring constant is varied. Results are shown in Figures 6-9.

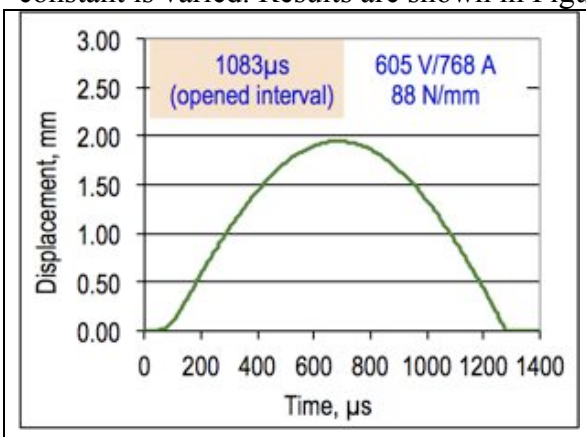

Fig. 6: 1083 µs "opened" duration of flow (voltage, peak current and spring constant shown in legend)

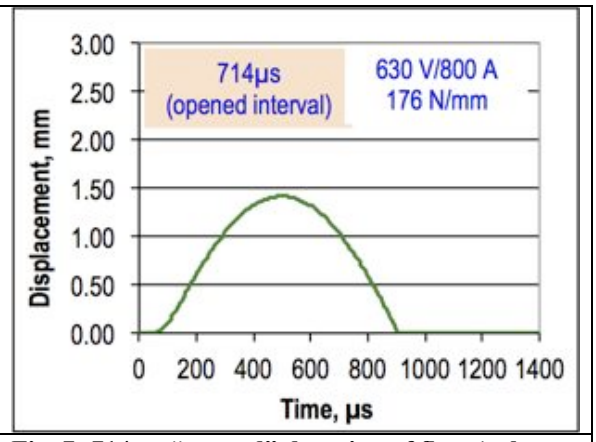

Fig. 7: 714 µs "opened" duration of flow (voltage, peak current and spring constant shown in legend)

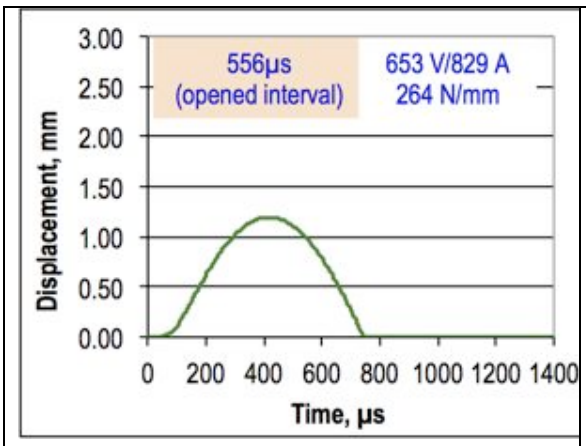

Fig. 8: 556 µs "opened" duration of flow (voltage, peak current and spring constant shown in legend)

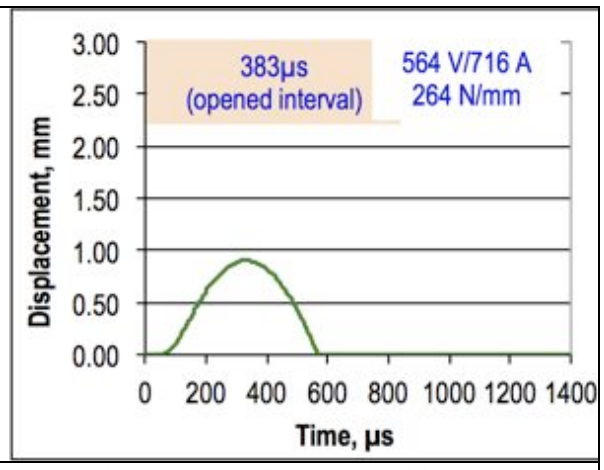

Fig. 9: 383 µs "opened" duration of flow (voltage, peak current and spring constant shown in legend)

For each operating condition, the opening time of the flow (defined as before as the time for the flyer plate to move from 0.3 – 0.8mm) was held constant at 100µs. It is observed that by using different machined springs the opened duration may be varied from ≈400 – 1100 µs, as needed.

3.2 Design and Test valve at AASC and at LOASIS/LBNL

After extensive testing in the vacuum chamber at AASC, the valve was delivered to LBNL, where it has been in use for the LOASIS (and later BELLA) LPA development.

Recently LBNL has requested a quotation from AASC to provide an advanced version of our valve (dubbed Mark-2). Once a Purchase Order has been received from LBNL, AASC will deliver such a valve with a nozzle to LBNL.

3.3 Design and test (first on the bench at AASC, then at LOASIS and possibly at other locations such as DIOCLES), a linear array of cylindrical nozzles with tailored density gradients to optimize the acceleration of electron bunches. Such an array would serve as a superior injector for further acceleration in capillary gas columns

Figure 10 shows a drawing of the Mark-2 valve with the linear nozzle array.

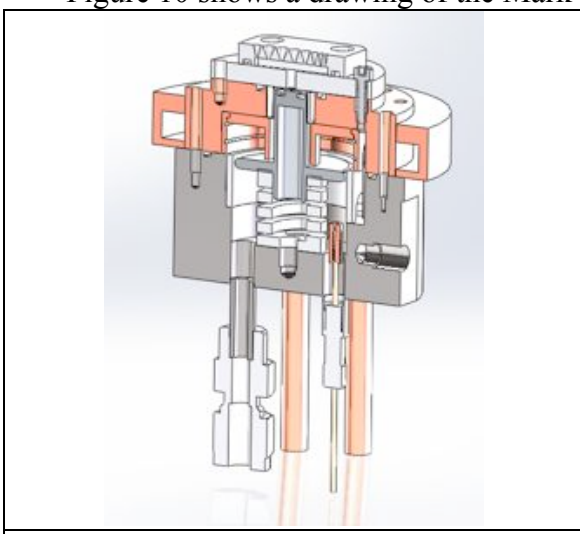

Fig. 10: Cross-section drawing of Mark-2 valve with linear nozzle array

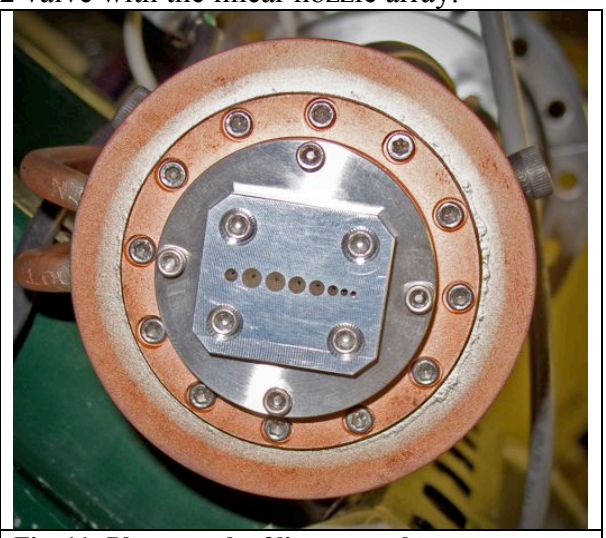

Fig. 11: Photograph of linear nozzle array mounted to Mark-2 valve

The design concept was that the separate cylindrical flows from each nozzle would merge at some distance beyond the nozzle face, to blend into a more uniform flow that has density gradients in it. If the throat apertures behind each nozzle were to be the same, then the Mach # of each flow varies (since the exit aperture is varied) and hence so does the exit density of the flow. Starting from the right of Fig. 11, the density would be highest, gradually decreasing as one moves towards the left. But notice that the left-most aperture is small once more. The idea was to create a sudden increase in density at the low density end. This would permit “down-ramp” injection, as suggested by Geddes et al [1].

Figure 12 shows an areal density map taken from the central four nozzles in the array. The nozzle flows create oblique shocks at their intersections as shown. The four nozzles create three oblique shocks and those shocks create two more followed by a last shock as the flow expands into vacuum. At first glance, these shocks would appear to make it impossible to create a smooth density profile across such a flow.

However, Figure 13 shows that a judicious choice of angle (see dashed red lines across the flow) permits fairly smooth profiles of areal density to be generated (see graph insets in figure).

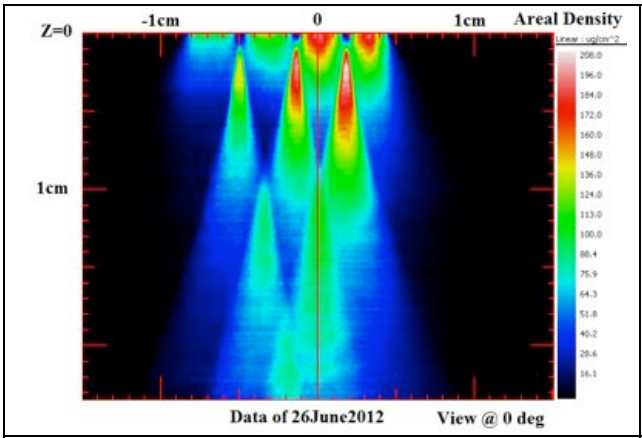

Fig. 12: Areal density measured from central 4-nozzle in the 8-nozzle array

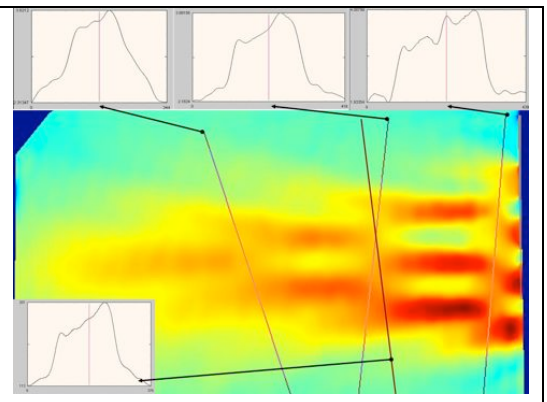

Fig. 13: Sample areal density profiles for slices at various angles (as shown) from 4-nozzle array

These graphs are of areal density. Since such flows are not axi-symmetric, Abel inversion is not possible to convert the areal density into density maps. A more elaborate procedure is required. First, the nozzle must be rotated and data gathered at several angles. The data set must then be analyzed using SART (Simultaneous Algebraic Reconstruction Techniques) to derive density profiles.

3.4 Design and test nozzle/wire or hollow nozzle combinations that produce a hollow density profile across the jet, to enhance laser guiding across the jet. This would permit longer acceleration lengths than are possible with standard nozzles whose gas flow has a maximum density on axis and a monotonic decay off axis

We have built a valve/nozzle combination that generates a hollow density profile. Figure 14 shows a SolidWorks image of the hollow gas jet. Figure 15 shows a photo of the machined parts in the final valve assembly. The valve has been pressurized and the cooling system integrated into the copper head. The valve was tested electrically and operated successfully.

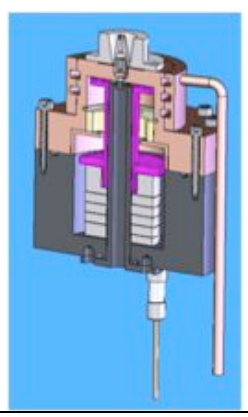

Fig. 14: SolidWorks image of cross-section of Hollow Wakefield Gas jet

Fig. 15: Photograph of assembled valve

Figure 16 shows a layout of internal parts for the head of the valve and in Figure 17 shows those parts assembled and inserted into the copper valve head. Figure 18 shows a

current trace from a Pearson coil integrated into the pulse diver used to test the valve. For this shot the valve was pressurized to 100 psia of Helium gas and the driver was charged to 1000V volts. The trace shows that the current reaches just over 2500 amps.

The tests with the hollow Wakefield jet were done with AASC's new rep-rated pulser with integrated power supply and energy recovery circuit. Figure 19 shows a photograph of this pulser with the lid off. The new pulser is capable of charge voltages greater than 1000V and rep rates of 10 Hz.

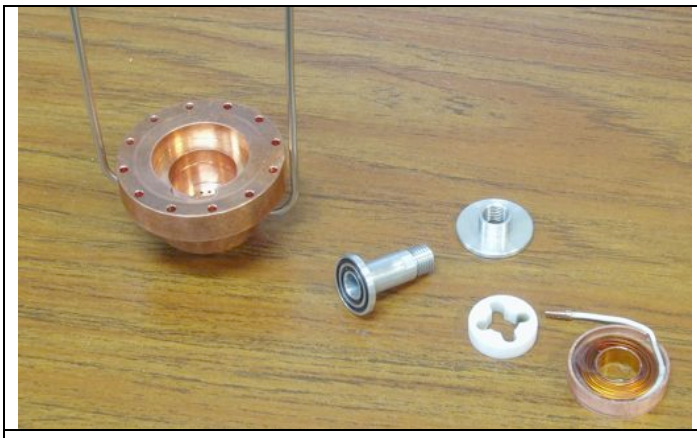

Fig. 16: Layout of internal parts

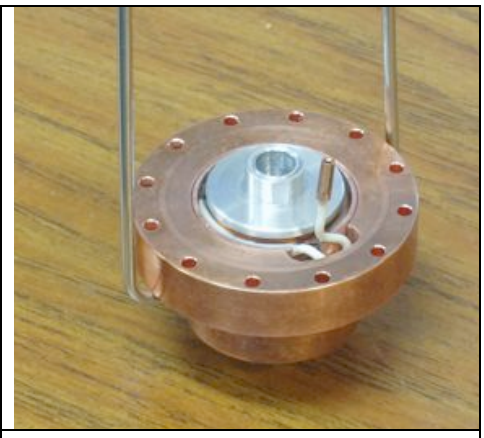

Fig. 17: Assembled internal parts

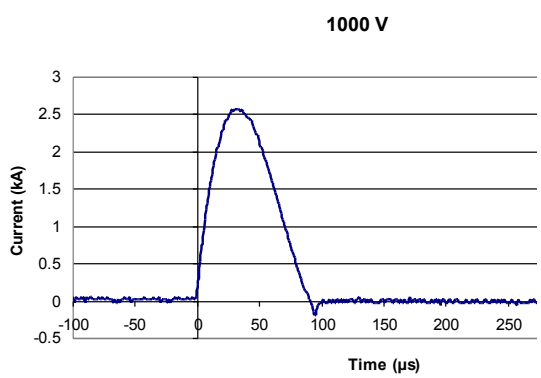

Fig. 18: Current trace of 1000V pulse fired through valve

Fig. 19: AASC's High Repetition Rate Pulser

Figure 20 shows the configuration used to scan the Piezo-resistive probe across the face of the hollow nozzle. Figure 21 shows the measured pressure data. As expected, there is a "hole" in the gas density (pressure) on and about the axis, as the hollow nozzle ends in solid metal in this region (see Fig. 14).

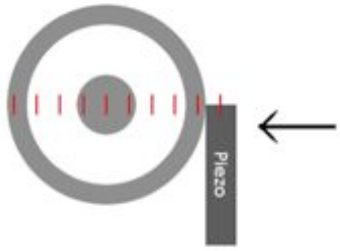

Fig. 20: Configuration of Piezo-resistive probe scan across the hollow gas jet

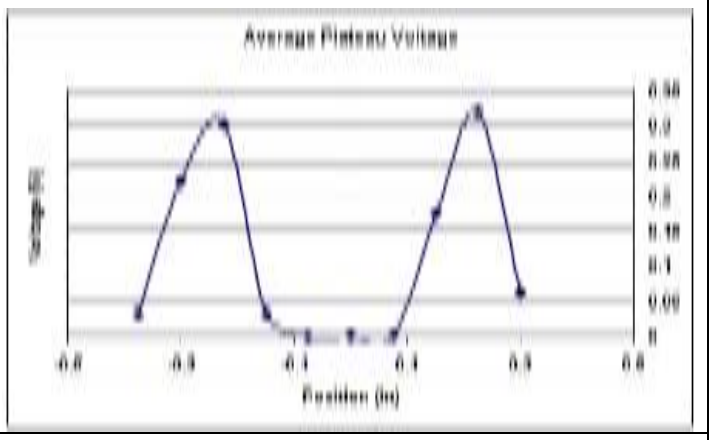

Fig. 21: Measured Piezo pressure signal across the hollow gas jet's diameter.

For this scan, the Piezo probe was placed just a few mm in front of the nozzle face. As the probe is moved farther away from the face, we would expect some filling in of the flow, since the supersonic gas diverges from the nozzle exit. By properly adjusting the diameter of the "stub" on axis (Fig. 14) and the tilt of the nozzle, we may control the manner in which the flow fills in the void on axis and hence create a suitable flow gradient in the radial direction, to collimate the laser.

A recent paper by a Munich group along with the LOASIS group [***Tapered plasma channels to phase-lock accelerating and focusing forces in laser-plasma accelerators;*** PHYSICS OF PLASMAS **17**, 063104, 2010] also suggests that a properly tailored axial gradient in the gas density might allow enhanced LPA interaction. In a nutshell, the problem of LPA optimization may be summarized as the need to mitigate the "three D's": diffraction, dephasing and depletion. A tailored radial density gradient (such as that offered by our hollow jet) can tackle diffraction, allowing the laser focal spot to persist over many Rayleigh ranges. Dephasing and depletion may be reduced by axial gradients in density. Curiously, a divergent gas nozzle provides such an increasing axial gradient as the gas flow merges on to the axis from the hollow nozzle exit. By varying the tilt of the nozzle, we may control the manner in which the gas converges on axis and hence the axial gradient.

Next we briefly describe a 2D laser interferometer that AASC has assembled Figure 22 shows the concept.

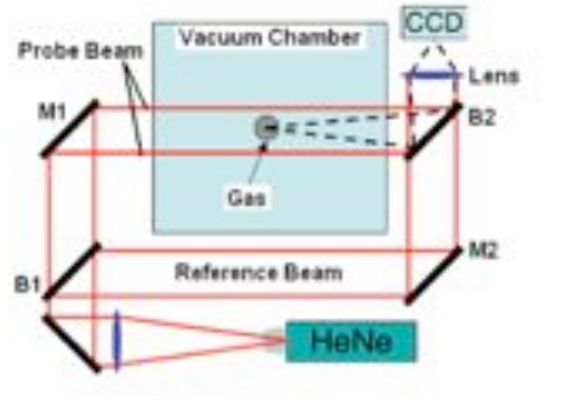

Fig. 22: 2D interferometer built at AASC to characterize nozzle flows

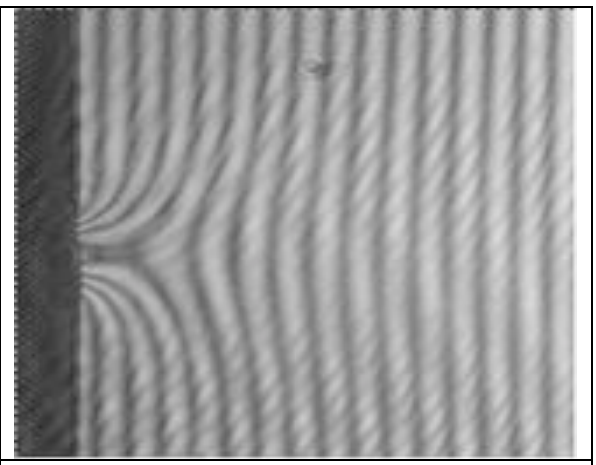

Fig. 23: Example 2D interferogram. A shadow of the nozzle is on the left with gas flow towards the right.

A frequency stabilized He-Ne laser is expanded and split into two paths as shown. The "probe" beam is modulated in phase by the gas flow that crosses the beam. Mirror M2 is adjusted to physically overlay the probe and reference beams. Then the beam-splitter B2 is tilted slightly, to create interference fringes. A typical fringe pattern is shown in Figure 23. The final lens in front of the CCD camera converges the mixed beams down to fit onto the CCD camera face. The dark shadow in the figure is the nozzle face. Fourier analysis methods convert the fringe curvature seen here into a 2D phase map. An Abel inversion procedure then gives the gas density profile in the 2D field of view. The optics are capable of roughly a 25x35mm field of view, so the 2 dimensional outflow from the Gas Jet may be imaged in a single shot.

Figures 24 and 25 show photographs of the interferometer as configured at AASC. The interferometer can map out the gas flow field from different gas jets. Estimates of the sensitivity of the instrument suggest that for a path length (across the gas jet) of ~ 10 mm, the "floor" density detectable above rms phase noise should be ~$4x10^{16}$ /cc. The typical peak density in the core nozzle flow will be ~10^{19} /cc. Thus we expect a dynamic range of ≈200:1. The present estimates of gas density needed in the hollow shell range from ≈10^{17} /cc to ≈$5x10^{17}$ /cc. Thus we expected to be able to measure the desired density gradients in the hollow jet using our interferometer.

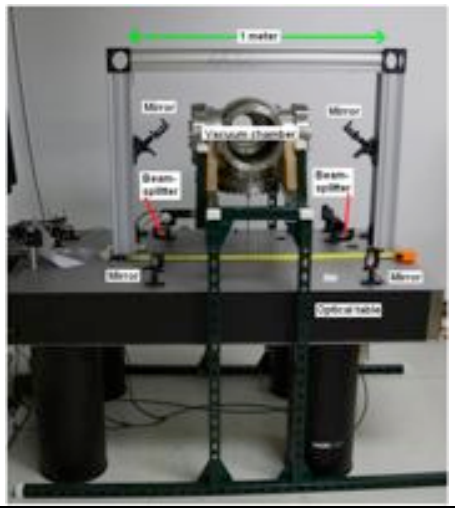

Fig. 24: One view of 2D interferometer with small vacuum chamber

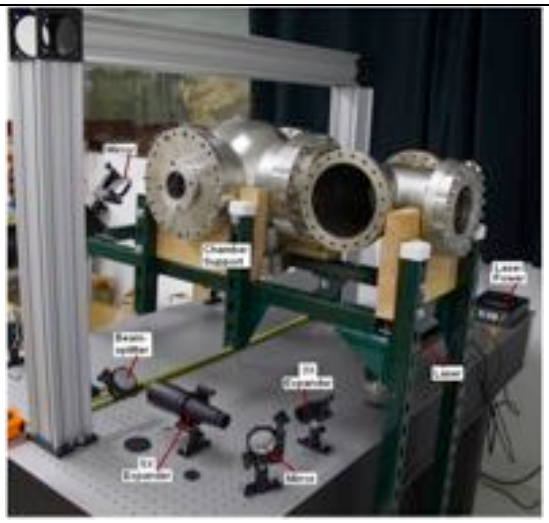

Fig. 25: Side view showing part of the interferometer beam path.

Figure 26 shows four interferograms taken from the hollow gas jet.

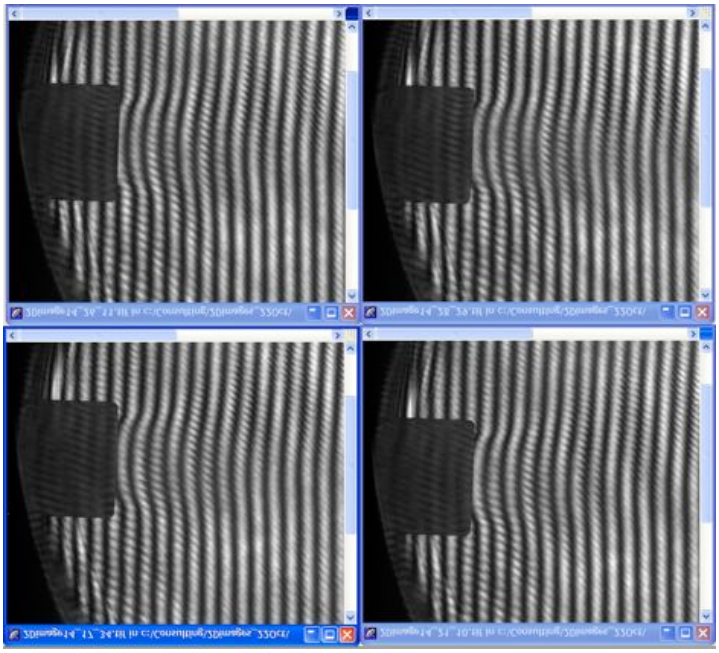

Fig. 26: Sample raw 2D interferometer images for a gas puff. The shot rate, about 1 per minute, was limited by the camera control software, not the puff valve or its driver.

3.5 Test the pulse-pulse stability of the gas flow and ensure that it meets LWFA injector specifications

Both Piezo-resistive pressure sensor and 2D interferometer data were analyzed to confirm that with the machined spring and better coil designs, our valve is reproducible (shot-shot) to better than ±5%. The improved coil design is shown in Figure 27. Instead of winding the coils in-house, we found a vendor who was capable of winding coils to tight specification of ID/OD and free-space inductance.

Fig. 27: Photograph of wire would coil as received from vendor

Fig. 28: Photograph of coil after potting at AASC using Master-bond epoxy

Figure 28 shows a photograph of the coil after it was potted at AASC using a specially purchased epoxy (from Master-Bond Inc.) that combines the attributes of good electrical isolation with excellent thermal conductivity.

The Mark-2 valve was fired at 500psia for a sequence of 10,000 pulses. The Piezo-resistive pressure transducer was used to measure the pressure vs. time at ~1cm from the nozzle exit at the start and then at the end of this long run. The pressure was found to be reproducible to ±5%.

3.6 Design and test a fast valve to inject a tailored puff of gas into a capillary, to create well defined density profiles as specified by LWFA requirements.

One copy of our Mark-2 valve was delivered to LBNL. Due to the size of the valve body, the 2.2mm exit aperture supersonic nozzle could not be placed directly next to the capillary discharge in use at LBNL. Hence the valve face was modified to allow a small diameter plastic tube to be connected from the valve to the nozzle that was built-in to the LBNL sapphire capillary, for gas injection. The valve has been in reliable use at LBNL for almost two years.

3.7 Adapt the fast valve design for other applications in order to improve commercialization success. Such related applications include gas jet Raman amplifiers, proton accelerators, intense gamma sources and window-less XUV filters for flash x-ray machines or other accelerators.

This SBIR project has allowed AASC to sell three complete fast valve/nozzle systems to various customers. While the total revenue generated from these sales (~$100K) is a small fraction of the $800K investment by the SBIR program, future sales might increase this fraction. One valve was sold to the University of Nebraska (DIOCELES) LPA program. A second system was sold to Prof. Roland Smith of Imperial College (IC), for use at Rutherford Appleton Lab. (RAL) and also internally at IC. Prof. Smith was particularly interested in the capability of our valve to produce clusters in the jet. AASC loaned a Mark-2 valve with a custom built 10-mm exit aperture nozzle to IC. This 10-mm nozzle was designed for the same Mach # (≈6) as the smaller 2.2-mm nozzle in use until then.

Figure 29 shows radial density profiles measured at various distances from the nozzle exit, using our 2D laser interferometer. The figure shows density (normalized) for 35 and 70Bar plenum pressure. The density was linear with plenum pressure and the small divergence of the M=6 flow causes slight expansion at the wings of the profiles as shown. The IC group under Prof. Smith used a powerful green laser and Rayleigh scattering to visualize the clusters in the flow. The data are shown in Figure 30. The laser is expanded by a cylindrical lens and fired at right angles to the flow in the plane of the paper into a beam dump. The Rayleigh scattered light is detected by a condenser lens into a CMOS camera at right angles to both the flow and the laser (out of the plane of the paper).

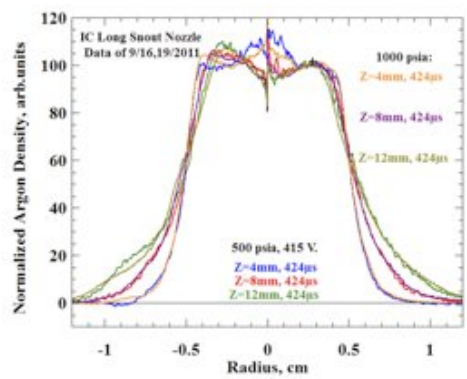

Fig. 29: Radial density profiles (derived using our 2D interferometer) from a 10-mm, M=6 nozzle designed for Prof. Roland Smith of IC

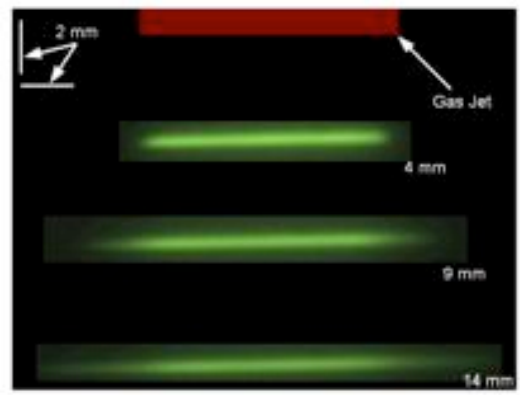

Fig. 30: Images of Rayleigh scattered light from Ar clusters in the expanding supersonic flow from the 10-mm nozzle at 50 Bar plenum pressure

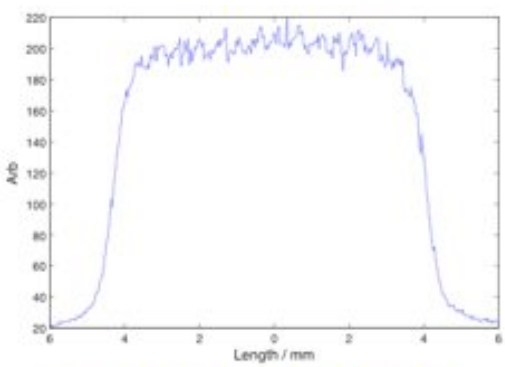

Fig. 31: Radial lineout across cluster flow

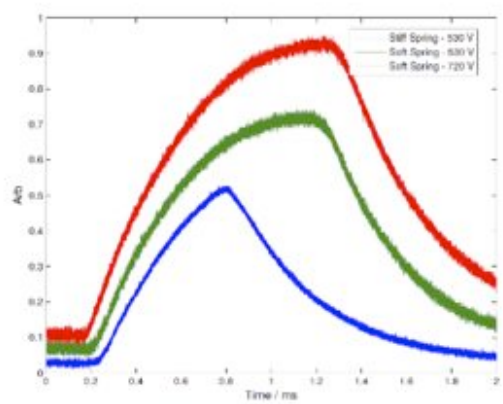

Fig. 32: Graph showing the difference in Rayleigh Scattering signal with the 1170 lb./in spring at 530 V and 585 lb./in at 530 V and 720 V. The signal levels are arbitrary , however the graphs shows a clear signal saturation suggesting a saturation of the clustering process, as desired

Figure 31 shows a radial lineout across the flow taken through the Rayleigh Scattering signal, 4 mm from the nozzle using the 585 lb./in spring. This gives a flat top

profile of for the Rayleigh scattered signal, which shows that the clusters occupy a large uniform volume.

Alternating between the stiff spring (at 1170 lb./in) and the soft spring (at 585 lb./in) produced the plateau in the scatter signal associated with saturation of the clustering process as shown in Figure 32. The region lasts for ~0.3 ms and ~0.4 ms for drive voltages of 530 V and 720 V respectively (Fig. 32). With the Modified Parker 99 valves that were typically used at IC, the nozzle must be open for ~4 ms for strong clustering to occur. Such long opening times are not an operational requirement of their experiments. However, reaching the saturation region improves the shot to shot stability. The soft spring did not cause the AASC valve to leak while under vacuum when tested up to 55 Bar of backing pressure. Based on the good results obtained using the AASC valve/nozzle, Prof. Smith ordered a custom built valve/nozzle from AASC that was delivered within 8 weeks.

M. Krishnan of AASC gave a talk at the AAC Conference in Austin TX in June 2012. A group from the Laser Particle Acceleration Division, Helmholtz-Zentrum Dresden-Rossendorf (HZDR) requested a quote from AASC and a Purchase Order was received for a 10-mm nozzle driven by a Mark-2 valve along with our energy recovery pulser.

Lastly, the BELLA group at LBNL has also ordered a Mark-2 valve with 2.2-mm nozzle and our lower rep-rate driver. A prospective future sale might be to Prof. Michael Downer, College of Natural Sciences Distinguished Professor, Physics Department, University of Texas at Austin. Prof. Downer has expressed an interest in collaborating with AASC in the future so that our gas jets might be used in his laser plasma accelerator experiments.

Another application of our fast jet was to the Laboratory Astrophysics research program at Blackett laboratory, Imperial College (IC), London. Several publications resulted from this interaction. The basic idea was to use our jet in an experimental investigation of the interaction of a supersonic, radiatively cooled plasma jet with argon gas on the MAGPIE facility at IC. The jet is formed by the ablation of an aluminum foil driven by a 1.4 MA, 250 ns current pulse in a radial foil Z-pinch configuration. The outflow consisted of a supersonic (Mach number~3−5), dense (ion density n_i~10^{18} cm^{-3}), highly collimated (half-opening angle ~2°- 5°) jet surrounded by a lower density halo plasma moving with the same axial velocity as the jet. The addition of argon above the foil led to the formation of a shock driven by the ablation of halo plasma, together with a bow-shock driven by the dense jet. Experimental data with and without the presence of argon were compared with three-dimensional, magneto-hydrodynamic simulations with the code GORGON. Details are in the PoP paper:

Interaction of a supersonic, radiatively cooled plasma jet with an ambient medium, F. Suzuki-Vidal, M. Bocchi, S.V. Lebedev, G.F. Swadling, G. Burdiak, S.N. Bland, P. de Grouchy, G.N. Hall, A.J. Harvey-Thompson, S. Patankar, L. Pickworth, J. Skidmore, R. Smith and J.P. Chittenden**,** M. Krishnan, R.E. Madden, K. Wilson-Elliot**,** A. Ciardi**,** A. Frank, Phys. Plasmas 19, 022708 (2012); doi: 10.1063/1.3685607. A related paper is:

Interaction of a Supersonic Plasma Jet With an Argon Ambient Using Laser Interferometry, Francisco Suzuki-Vidal, Sergey V. Lebedev, George Swadling, Philip

de Grouchy, Matteo Bocchi, Guy Burdiak, Simon N. Bland, Gareth N. Hall, Adam J. Harvey-Thompson, Essa Khoory, Louisa Pickworth, Jonathan Skidmore, Jeremy P. Chittenden, Mahadevan Krishnan, Kristi Wilson Elliot, Robert Madden, and Andrea Ciardi, IEEE TRANSACTIONS ON PLASMA SCIENCE, VOL. 39, NO. 11, NOVEMBER 2011.

In the absence of an ambient gas, the jets produced by MAGPIE are highly collimated, with an aspect ratio (jet length to jet radius) exceeding 20 and a half-opening angle of 2 –5 degrees . Measurements of the jet velocity and plasma temperature using optical Thomson scattering showed that the jet is supersonic, but the internal Mach number is much smaller (M~3–5) than would be expected (M~20) from the observed small opening angle of the jet. The jet is surrounded by a low-density halo plasma which moves with the same velocity as the jet, but the thermal pressure of this plasma is not sufficient to explain the observed level of jet collimation. 3-D resistive MHD simulations of the jet formation showed that the toroidal magnetic field diffuses through the heated foil and plays a role in the jet collimation. The JxB force associated with this toroidal magnetic field re-directs the flow of plasma ablated from the foil towards the axis, and the ram pressure of this converging flow is responsible for the collimation of the central, dense part of the jet. In simulations, the half-opening angle of the dense part of the jet was found to be larger than observed experimentally (half-opening angle ~6 degrees versus ~2 degrees in the experiments). It is suggested that for the chosen initial conditions, the code underestimates the level of current (and thus magnetic field) present in the outflow.

In the case where argon was present above the foil, both the formation and propagation of the jet were affected, leading to the formation of several shock features. It is interesting that some of the plasma dynamics observed in this configuration are similar to those seen in laser-jet experiments performed in conditions with an ambient gas present in the laser-target interaction region. It is very much possible that some of the shocks observed in those experiments, especially the conical shock extending to large diameters, were driven by the material ablated from the target and are similar to the ablation shock seen in our experiments.

The novel feature observed in our experiments is the formation of a bow-shock structure propagating ahead of the ablation shock. This bow-shock is driven by re-direction and acceleration of the flow produced by a “nozzle-like” structure formed at the tip of the ablation shock. Simulations indicate that the flow exiting this nozzle is supersonic (internal Mach number M≈8) and moves faster than the ablation flow and the ablation shock. This secondary high Mach number flow interacts with the undisturbed argon ambient, resulting in a working surface structure similar to those described by authors modeling propagation of astrophysical jets (e.g., Refs. 47 and 49). The shape of the bow-shock is initially a smooth curved, approximately hemispherical surface, which later evolves into a more elongated shape and develops several smaller-scale structures at the shock front. The interaction of the secondary supersonic flow with an undisturbed ambient medium is very promising for detailed investigations of the effects of radiative cooling on the properties of forming working surfaces. First estimates combining experimental and simulation results show that the cooling parameter in the bow-shock

(assuming it is made purely of argon) is $\chi \ll 1$. In addition, estimates of the Reynolds and Peclet numbers result in values $\gg 1$ ($R_e \sim 10^6$ and Pe ~40-250, respectively) ensuring that these outflows are relevant to the modeling of astrophysical jets with similar dimensionless numbers.

The IC group has also expressed interest in purchasing a valve from AASC in the future.

4 Recapitulation of Phase II Accomplishments

- AASC has completed all tasks established at the time of the Ph-II proposal.
- We have sold versions of our valve/driver/nozzle hardware to the Univ. of Nebraska, Imperial College/London, Helmholtz-Zentrum Dresden-Rossendorf (HZDR), and LBNL/BELLA.
- Two other groups at IC have included budgets in recent proposals to purchase valves from AASC in 2013.
- Our valve/nozzle has been used in diverse applications, including as gas jets in LPAs, as cluster jets in LPAs, and as controlled supersonic targets for laboratory astrophysical plasma interactions.
- Our expertise in gas valves developed via the SBIR program has also allowed us to sell larger versions of our gas jets to Sandia National labs. as a load for the 18MA Z-driver.

5 References

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