Tailored supersonic gas jet targets for Laser-Plasma Accelerators (LPAs)*

Mahadevan Krishnan

Alameda Applied Sciences Corporation, San Leandro, CA, USA

Laser Plasma Targetry Workshop

Le Réfectoire des Cordeliers

Université Pierre et Marie Curie

15 rue de l'Ecole-de-Médecine 75006 Paris

• This research was supported by a DOE SBIR Grant #DE-SC0011366

Outline

- Role of Gas Jets in LPA development
- Challenges for Gas Jets (Jets v. Capillary targets)
- AASC's Gas Jet Development
- Future Plans

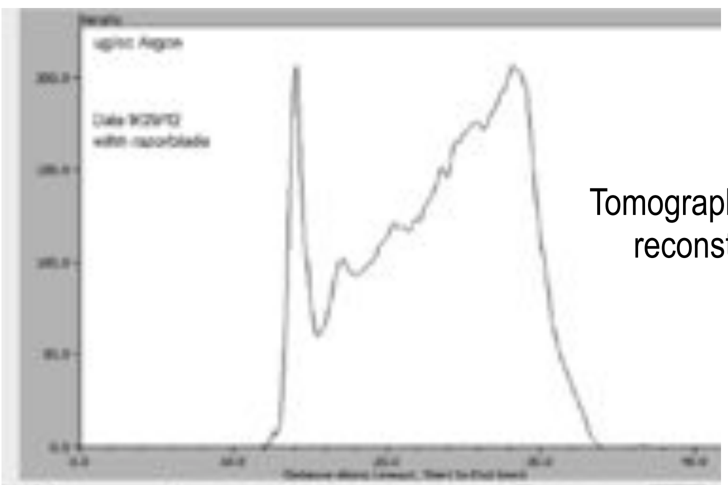
AASC Gas Jets at LBNL/BELLA

- LBNL/BELLA has used several AASC built gas jets in their LPA development
- Recently, a 20-mm rectangular jet was used on BELLA to study pointing stability of electron bunches from a 16J/360TW LPA interaction
- The following three slides were provided to AASC by LBNL:
  - Wim Leemans
  - Danny Mittelberger
  - Tony Gonsalves
  - Kei Nakamura
  - Han-Shin Mao

W. P. Leemans, A. J. Gonsalves, H.-S. Mao, K. Nakamura, C. Benedetti, C. B. Schroeder, Cs. Tóth, J. Daniels, D. E. Mittelberger, S. S. Bulanov, J.-L. Vay, C. G. R. Geddes, and E. Esarey, “Multi-GeV Electron Beams from Capillary-Discharge-Guided Sub-petawatt Laser Pulses in the Self-Trapping Regime”, Phys. Rev. Lett. 113, 245002 – Published 8 December 2014

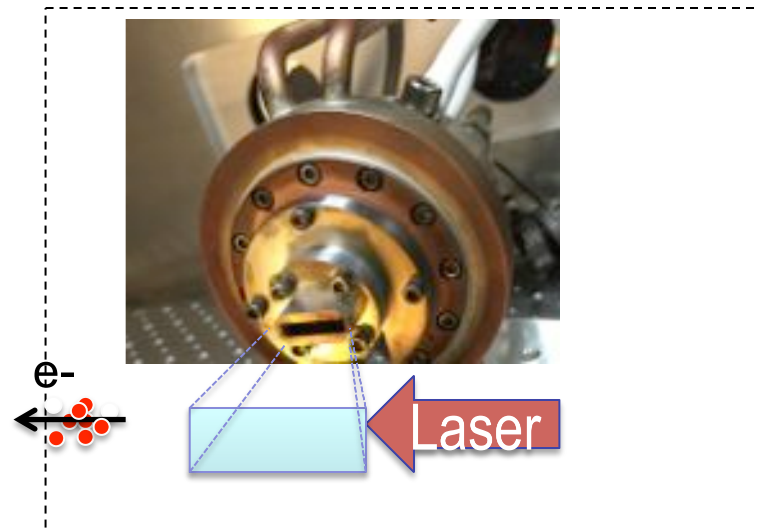
Carl B. Schroeder, Eric Esarey, Carlo Benedetti, Wim Leemans, “Control of focusing forces and emittances in plasma-based accelerators using near-hollow plasma channels”, arXiv:1304.7299 [physics.plasm-ph]

AASC Gas Jets at BELLA

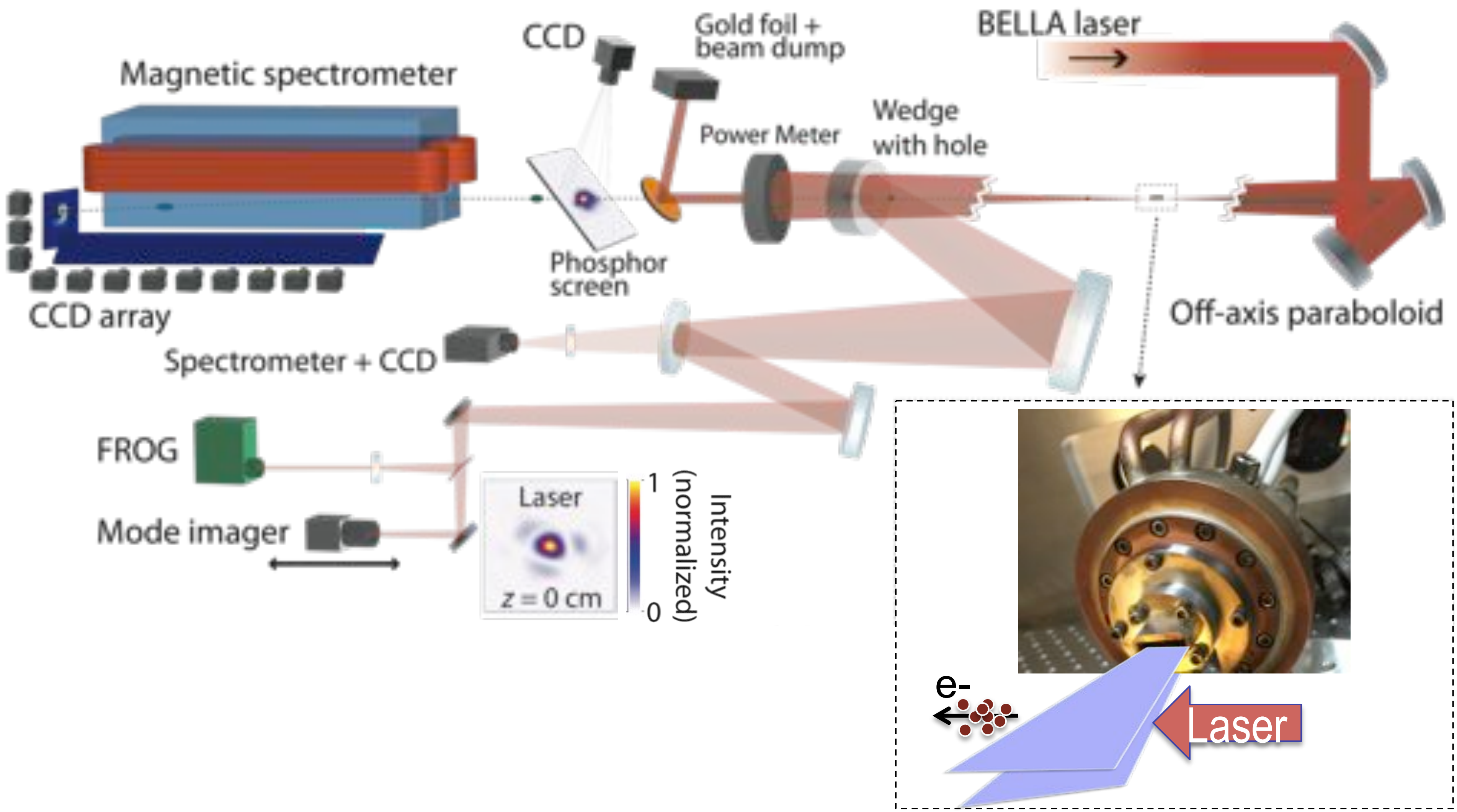


Tomographic density reconstruction

Density profile of a 20mm long region with sharp entrance gradient and linear density ramp (for LPA laser at BELLA)



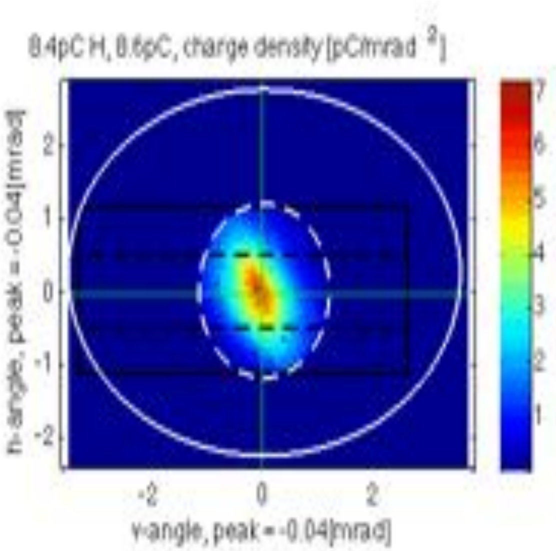
Experiments at BELLA with
2cm AASC Jet as Acceleration Target



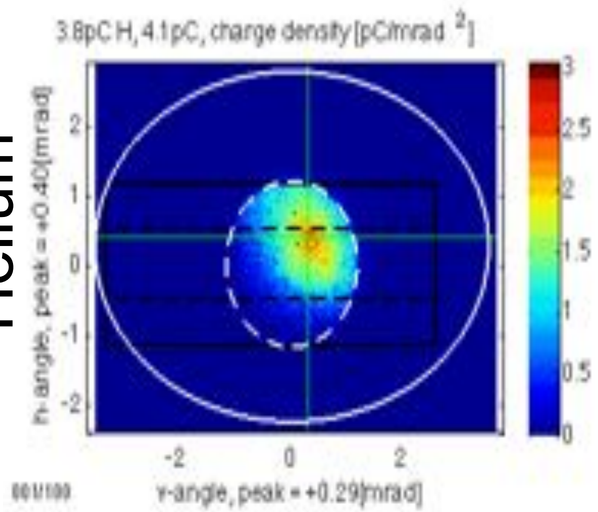
This 20-mm long gas target was tested by Wim Leemans' group on BELLA (it gave ~2GeV bursts)

Excellent Electron Beam Quality & Pointing Stability from Recent BELLA Experiments

Hydrogen



Helium



- ◆Laser: 16 J, 360 TW
- ◆Clear aperture for e-beam is limited to ±1.2mrad
- ◆Target 3D density profile characterized at AASC

◆Hydrogen with 5×10^{17} atoms/cm^3

- ❖ pointing stability 0.21 mrad (1-sigma)
- ❖ mean charge 4.3 pC (sigma =3.4)
- ❖ mean energy ~ 650 MeV, tail out to 1 GeV
- ❖ More charge possible with higher density with larger pointing jitter

◆Helium with 2.5×10^{17} atoms/cm^3

- ❖ pointing stability 0.18 mrad (1-sigma)
- ❖ mean charge 4.6 pC (sigma =1.9)
- ❖ mean energy ~ 500 MeV

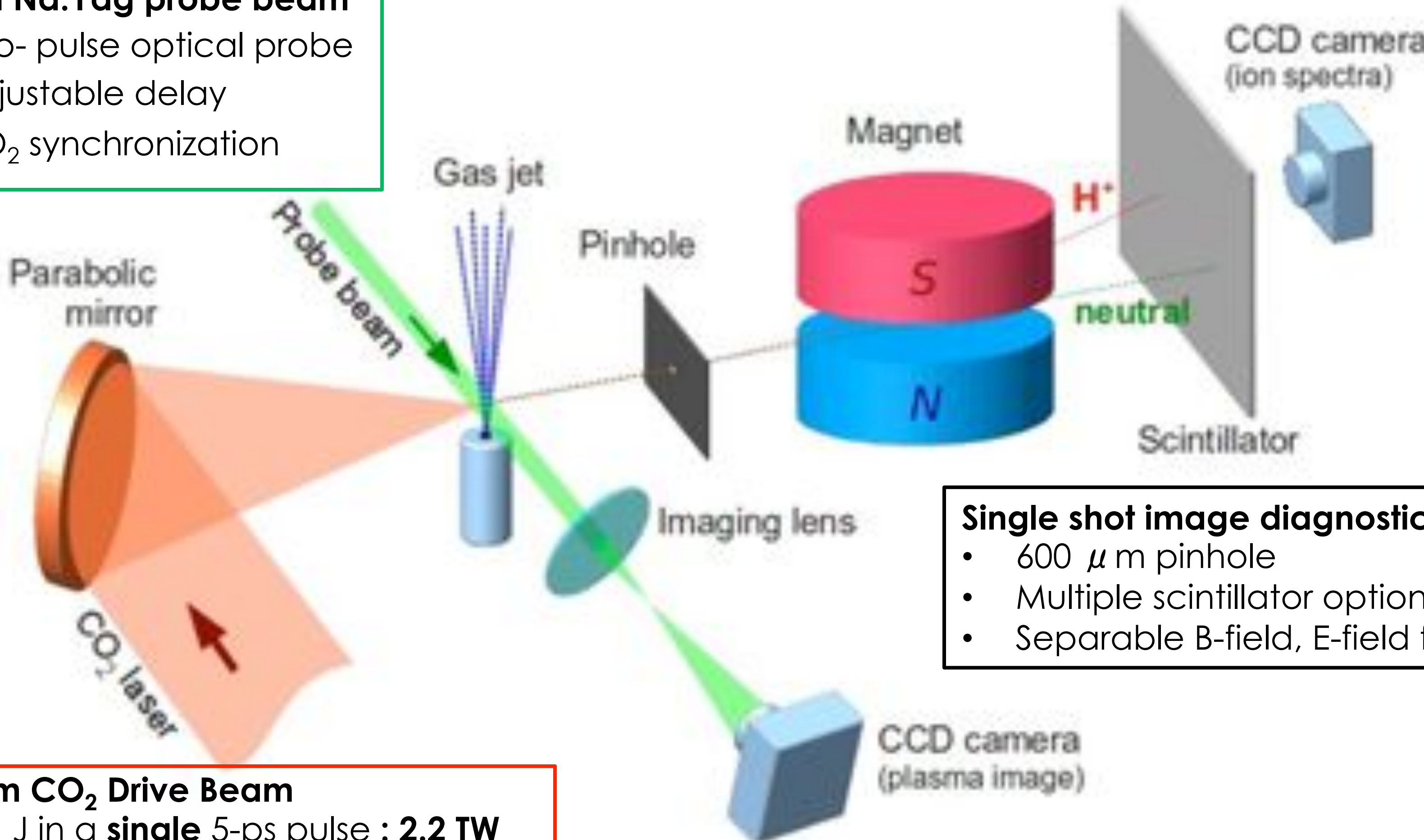
Gas Jets at ATF (BNL)

- The group at BNL has demonstrated an innovative approach to shaping gas targets to create the sharp gradients required for ion acceleration
- This group has achieved reproducible shock acceleration of >1MeV He+ and quasi-monoenergetic H+ ions using the ATF CO_2 laser and optically shaped gas targets
  - A low energy laser pre-pulse (~100mJ, I~10^{14} Wcm^{-2}) is used to drive a blast wave inside the gas target to create a steepened density profile
  - After a delay of ~25ns to allow the steepened profile to develop, the high intensity CO_2 laser pulse (I~10^{16} Wcm^{-2}) produces an electrostatic, collisionless shock
  - Upstream ions can be reflected off the shock to create ions that are accelerated to twice the velocity of the driving shock
- The following two slides were provided to AASC by Nathan Cook of BNL: collaborators: Igor Pogorelsky, Peter Shkolnikov (Stony Brook), Zulfikar Najmudin (Imperial)

(1) N. Cook, O. Tresca, N.P. Dover, C. Maharjan, M.N. Polyanskiy, Najmudin, P. Shkolnikov, I. Pogorelsky, "Hydrodynamic shaping of gas jets for laser driven shock acceleration of helium ions," Advanced Accelerator Concepts Workshop 2014, San Jose, CA.
(2) Tresca, O, Cook, N., Dover N.P., Maharjan, C.M., Najmudin, Z., Pogorelsky, I., Polyanskiy, M.N., Shkolnikov, I. (2014). "Spectral modification of shock accelerated ions using a hydrodynamically shaped gas target." submitted to PRL

Gas Jet at ATF (BNL)

532 nm Nd:Yag probe beam
- Two- pulse optical probe
- Adjustable delay
- CO_2 synchronization

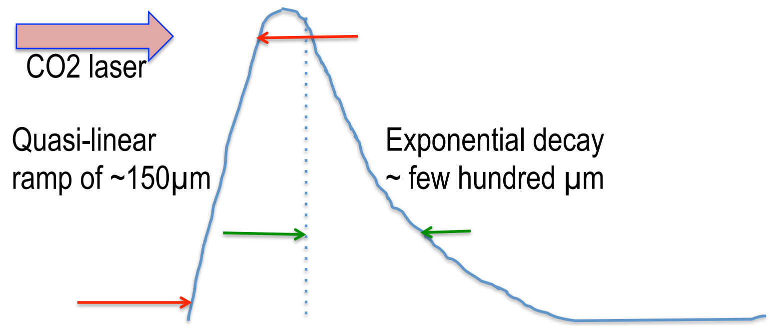


Single shot image diagnostic
- 600 μm pinhole
- Multiple scintillator options
- Separable B-field, E-field filters

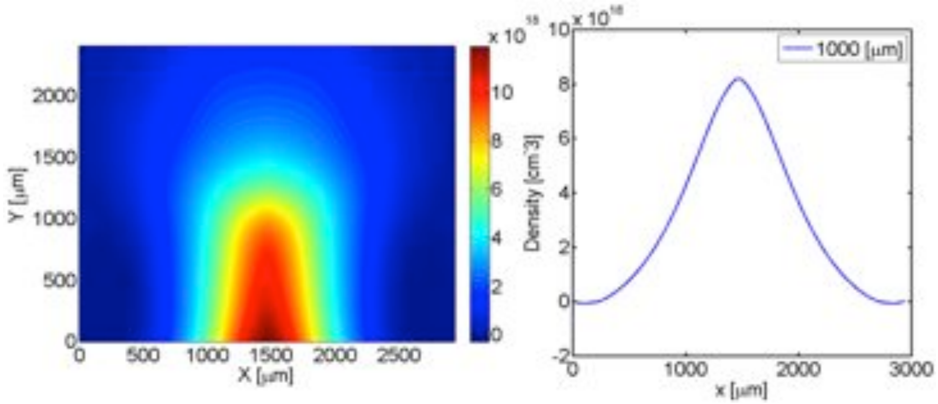
10.3 μm CO_2 Drive Beam
- <11 J in a **single** 5-ps pulse **: 2.2 TW peak power**
- 65 μm spot-size: for >**2×10^{16} W/cm^2**
- 0.05 Hz rep rate
- Adjustable 5 ps pre-pulse

ATF Gas Jet Targets

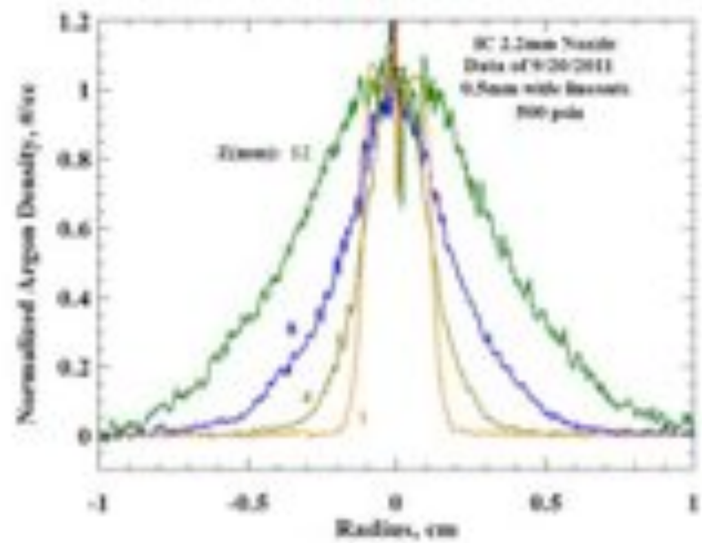
- Gas jet is a flexible target
  - Reusable, high rep-rate operation
  - High purity, variety of species
  - Vary backing pressure, focal position to obtain different density profile
- 1 mm diameter nozzle with circular aperture produces triangular profile
- 800 µm ~linear ramp in density
- 0.8 x10^{19} cm^{-3} peak neutral density @12 bar



required density profile for proton acceleration

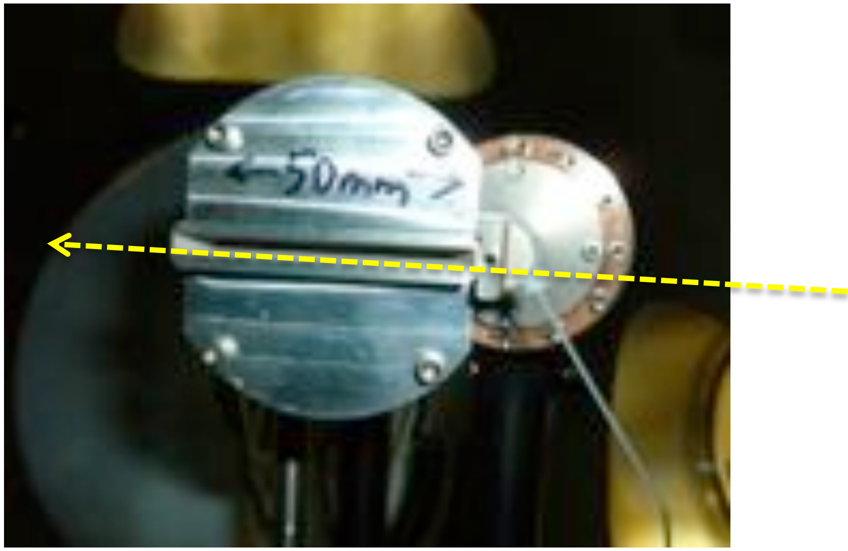


Transverse neutral density profile of He gas jet from 1 mm nozzle

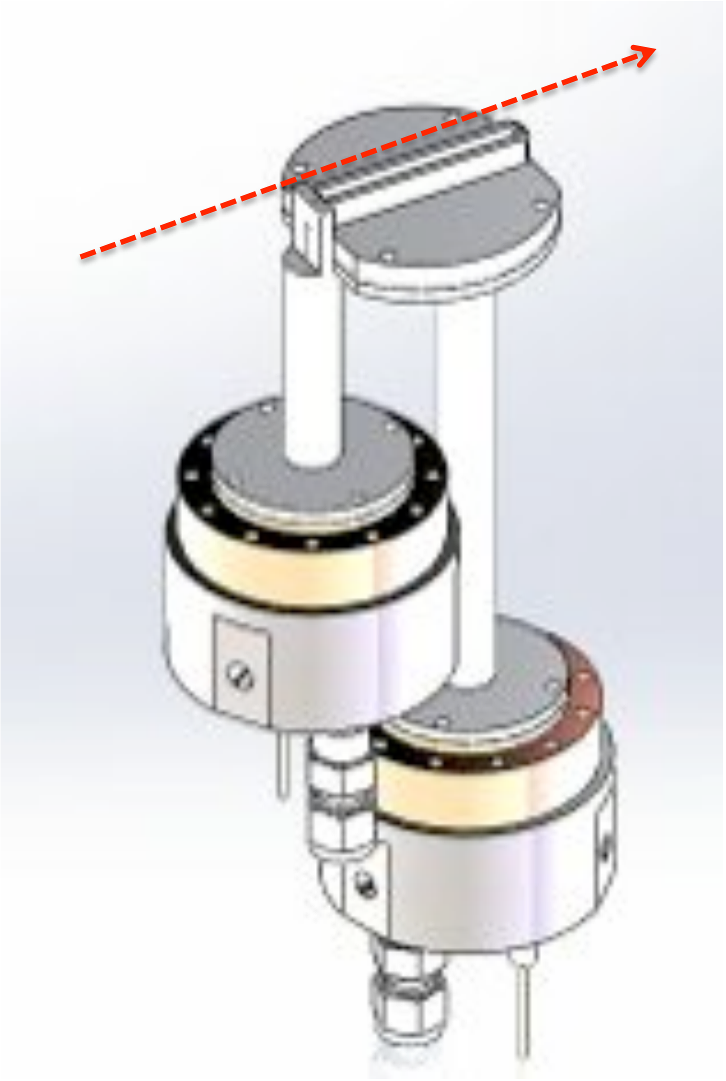


Density profiles from an AASC high density gas jet

UT-Austin Dual Gas-Jet Nozzle: independent valves give flexibility

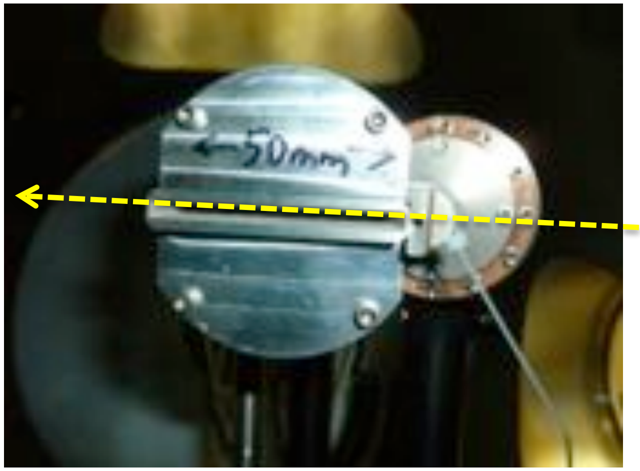


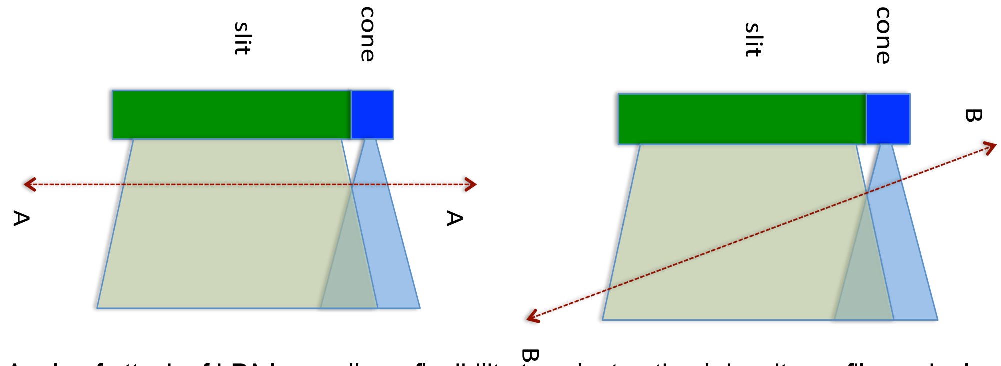
Rectangular nozzle and conical nozzle are driven by separate valves allowing *independent* control of density and gas species, e.g. N_2 doped hydrogen cone, pure hydrogen slit



Dual valve assembly – Isometric view

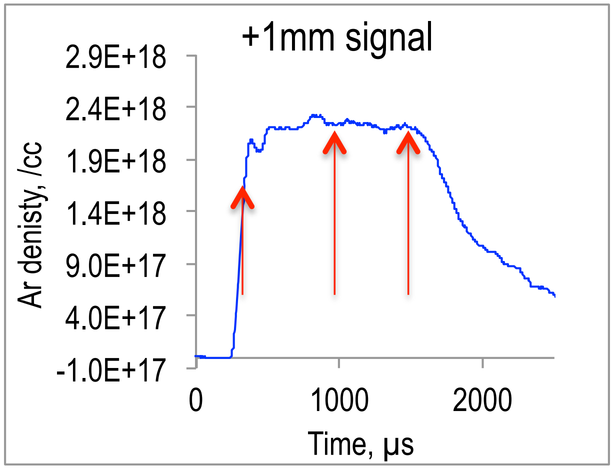
Dual Gas-Jet Nozzle: angle of attack & firing time flexibility





Angle of attack of LPA laser allows flexibility to select optimal density profile: a single pair of plenum pressures allows wide variation in density profiles

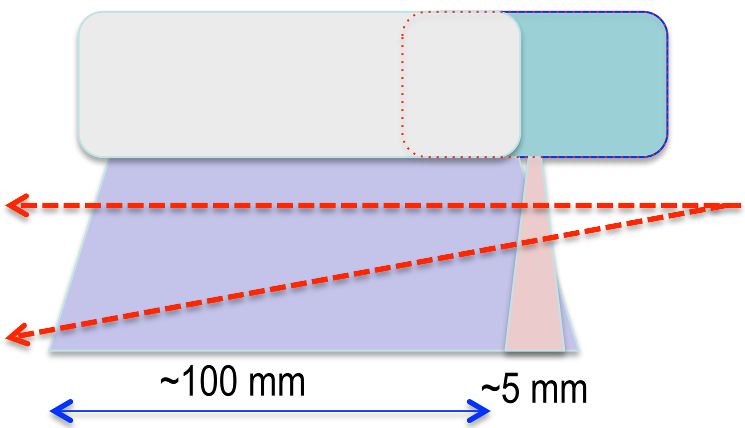
Dual Gas-Jet nozzle was measured at UT-Austin and will be tested on the Texas PW laser soon

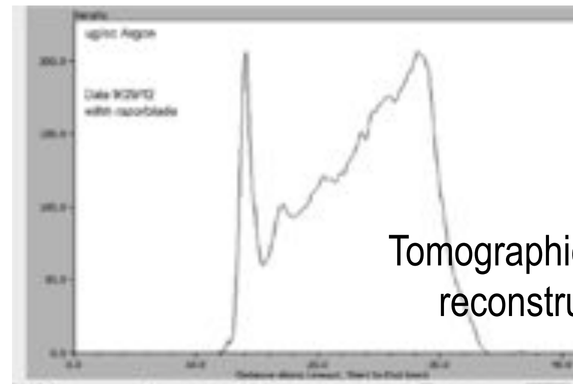


Changing the firing time allows flexibility as well

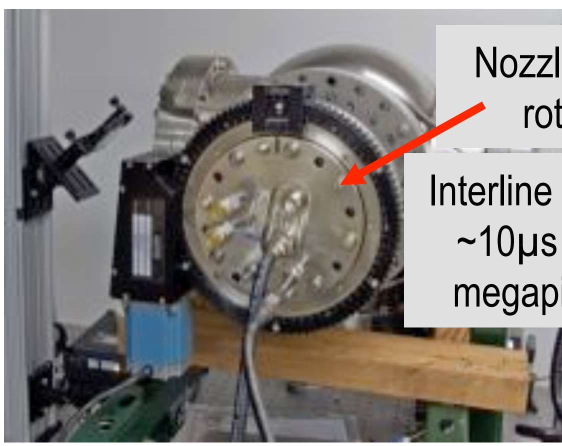
Gas Jets v. Capillaries

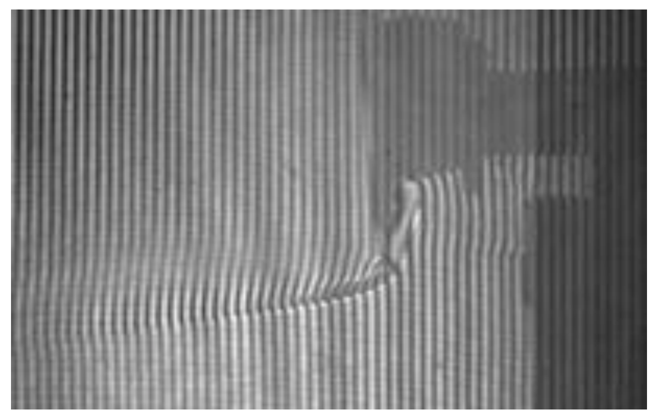
The goal of AASC is to demonstrate freely expanding gas jets as complements/ alternatives to capillary gas loads





Density profile of a 20mm long region with sharp entrance gradient and linear density ramp (for LPA laser at BELLA)

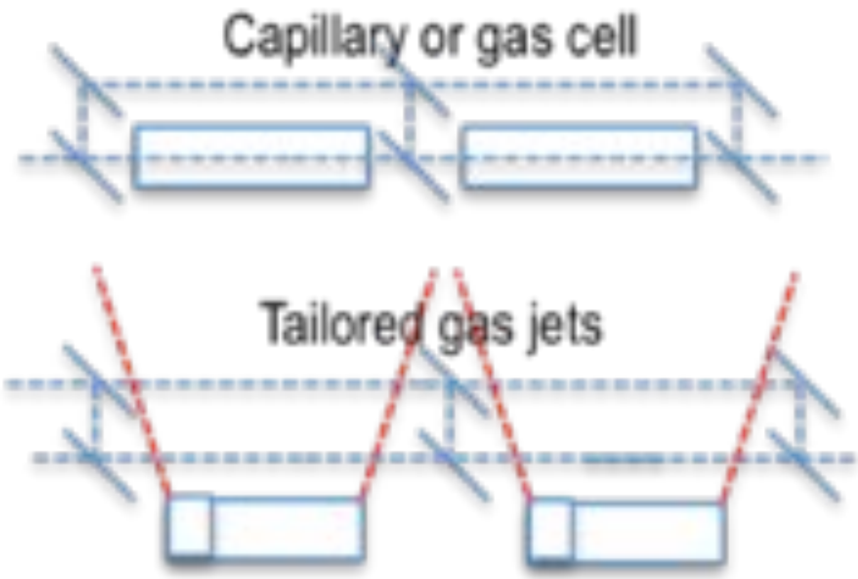




Raw phase map of razor blade/slit nozzle flow

Tomographic ("ART") Methods: IEEE-ICOPS 2012, Edinburgh, Scotland, Philip Coleman, M. Krishnan, B. Bures, K. Wilson-Elliott and R. E. Madden, Alameda Applied Sciences, 12 July 2012

Gas Jets v. Capillaries



Segmented capillary and gas jet targets for LPAs)

- Can a freely expanding supersonic jet be configured to give ~100 mm long gas jets?
- Gas Jets provide flexibility (density profiles, timing control, gas mixtures); capillaries are less flexible in this regard
- Gas Jets require laser pre-ionization for laser guiding; capillaries use a discharge to create a waveguide
- Freely expanding gas jets avoid wall interactions (capillaries can be damaged)
- Fast opening/closing gas jets reduce load on vacuum pumps

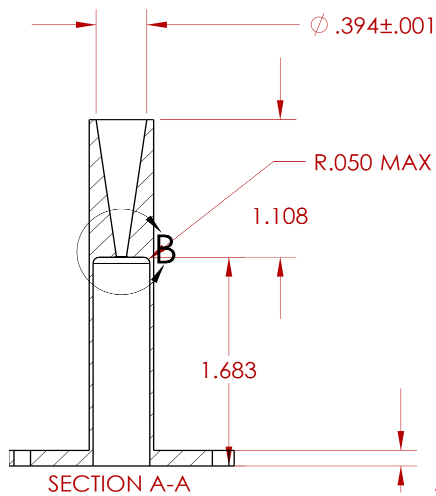
Fast Valve With Many Nozzle Geometries

Valve with simple conical nozzle

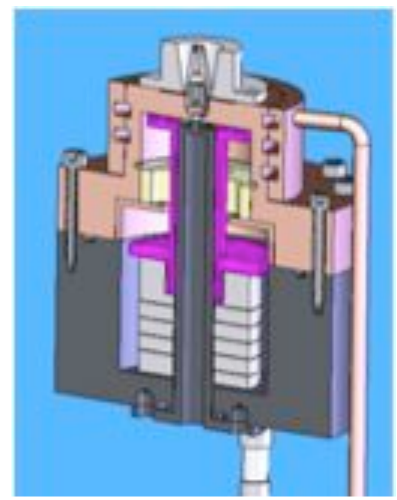
Valve with “snout” nozzle

Valve with “hollow” nozzle

2.2mm conical nozzle cross-section

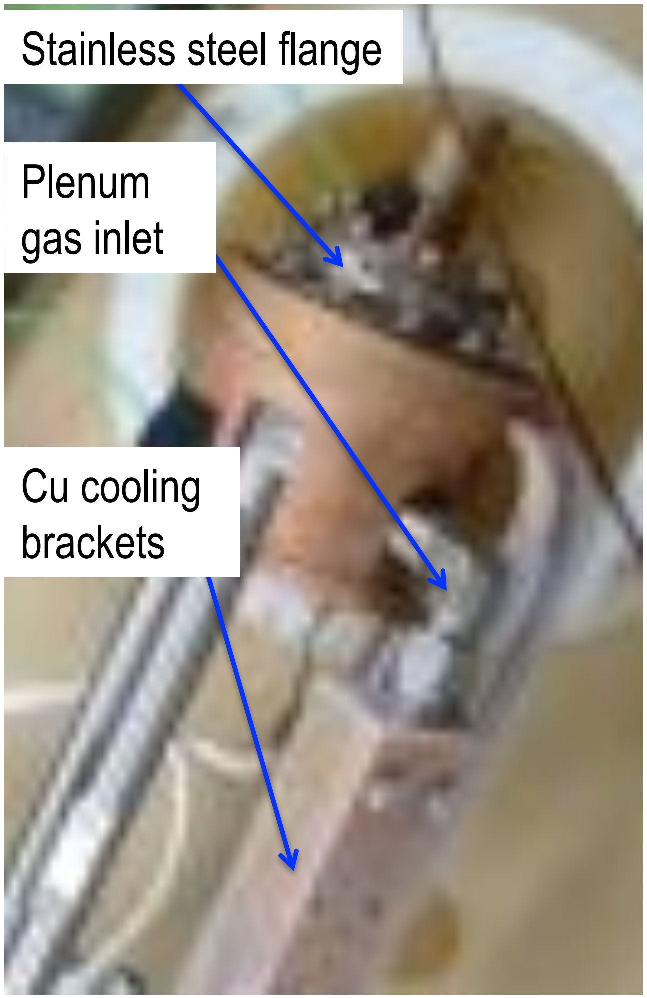


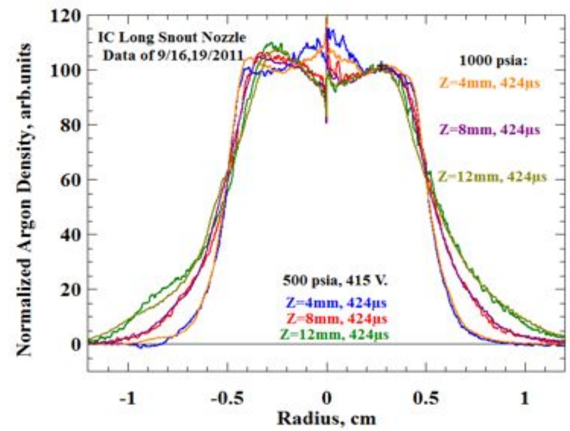
10mm conical nozzle cross-section



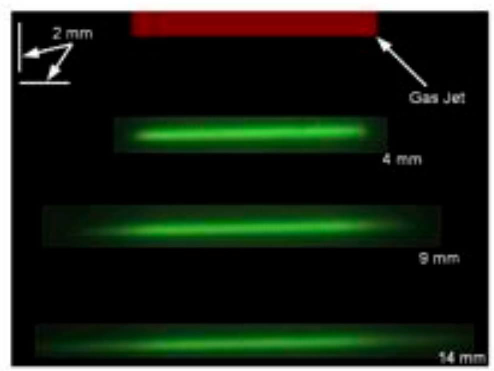
Hollow nozzle

AASC cooled valve for clusters

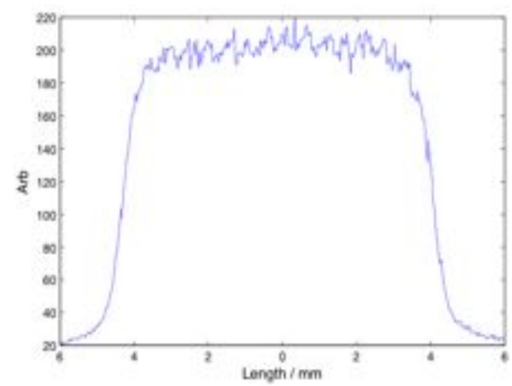




Radial density lineouts (10mm nozzle)



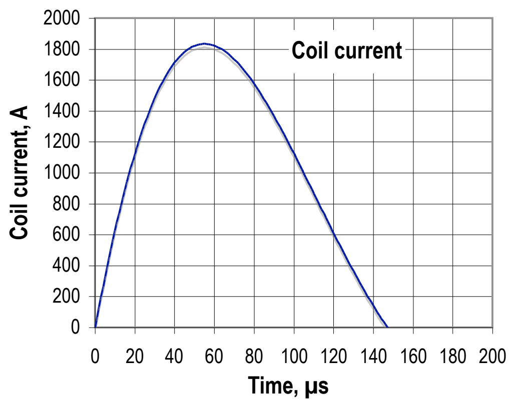
Rayleigh scattered images of Ar clusters



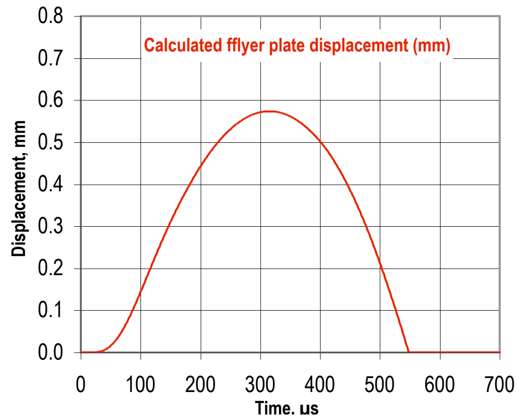
Radial lineout across clusters

Images and analysis of Argon clusters provided by Prof. Roland Smith and Stefan Robbie Olsson, Imperial College, London

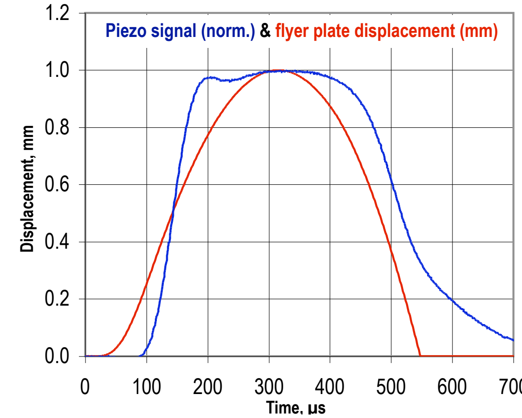
Valve Dynamics, Nozzle Designs



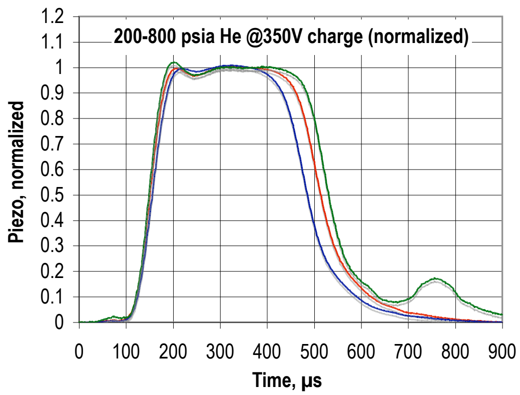
Coil current v. time



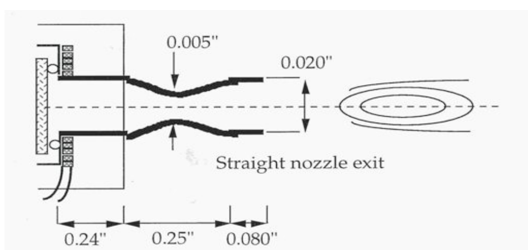
Flyer plate displacement v. time

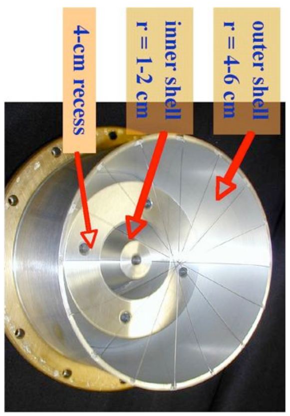


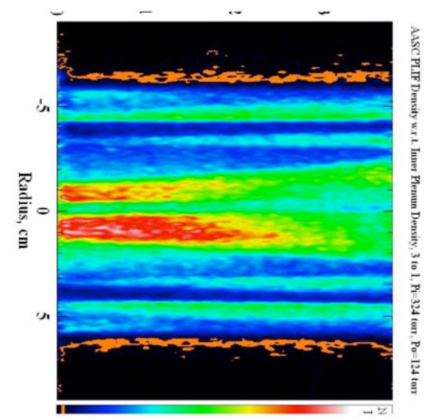
Piezo sensor v. model



Piezo signals at 350Vcharge voltage and different pressures







M. Krishnan, K. Wilson-Elliott, C. G. R. Geddes, R. A. van Mourik, W. P. Leemans, H. Murphy and M. Clover, "Electromagnetically driven, fast opening and closing gas jet valve," Physical Review Special Topics: Accelerators and Beams, vol. 14, no. 3, p. 033502, 2011.

AASC’ s nozzles span the size range from <1mm up to 200mm; opened durations from ~50μs up to ~1ms; pressure up to 70Bar

Status of Valve/nozzle development

- AASC has been supported by DOE (via SBIR grants) to develop supersonic gas jets for Laser Plasma Accelerator (LPA) applications
- A fast valve that opens in <100µs and closes in <500µs has been delivered to various LPA groups:

Lead End-User	Customer	Research purpose
Dr. Donald Umstadter	University of Nebraska, USA	Laser wakefield acceleration
Dr. Roland Smith	Imperial College, UK	Laser-matter shock interactions
Dr. Arie Irman	HZDR Lab, Germany	LPA solid foil target research
Dr. Wim Leemans	Lawrence Berkeley National Lab, USA	LPA research - LOASIS facility
Dr. Wim Leemans	Lawrence Berkeley National Lab, USA	LPA research - BELLA facility

- The nozzle has been used to demonstrate cluster formation in krypton and argon; a cooled version was built for hydrogen clusters (but needs some work)
- We have developed dual gas-jet nozzles suitable for LPAs at LBNL/BELLA (Wim Leemans) and at UT-Austin (Mike Downer)
- We have plans to develop sharp edged gas jets for the ATF at BNL

The goal of our research is to demonstrate freely expanding gas jets as complements/alternatives to capillary gas loads

Gas Jet requirements for the future

- LPAs have recently demonstrated energy gains[1] up to 4.25 GeV, beam emittances comparable to state of the art conventional photo-injectors, and energy spreads below 1% RMS.
- In order to develop applications of laser plasma accelerators ranging from high energy physics research to compact gamma ray sources for nuclear detection, we require precise control over focusing of the charged particle beam and the laser driver. This requires gas targets with precise, reproducible density profiles and (eventually) high rep-rates
- A ~1kHz rep-rate laser demands a ~1kHz rep-rate gas jet; the AASC design allows an "opened" duration of <50µs; this reduces the vacuum loading by 20x versus operating at steady flow
- Schroeder[2] et al. describe a near-hollow plasma channel, in which the low density in the channel contributes to the focusing forces, while the accelerating fields are determined by the high density in the channel walls. The channel also guides the intense laser pulses used for wakefield excitation and mitigates emittance growth due to Coulomb scattering for high-energy physics applications

(1) W.P. Leemans, A.J. Gonsalves, H.-S. Mao, K. Nakamura, C. Benedetti, C.B. Schroeder, Cs. Tóth, J. Daniels, D.E. Mittelberger, S.S. Bulanov, J.-L. Vay, C.G.R. Geddes, and E. Esarey, "Multi-GeV Electron Beams from Capillary-Discharge-Guided Sub-petawatt Laser Pulses in the Self-Trapping Regime", Phys. Rev. Lett. 113, 245002 – Published 8 December 2014

(2) Carl B. Schroeder, Eric Esarey, Carlo Benedetti, Wim Leemans, "Control of focusing forces and emittances in plasma-based accelerators using near-hollow plasma channels", arXiv:1304.7299 [physics.plasm-ph]

Future Plans: Advanced Gas Jet Designs

- The same need for hollow channels applies to beam-driven plasma wakefield accelerator (PWFA[1,2]) concepts or compact LPA-based Thomson[3] light sources

AASC's high rep rate cluster gas jet is a key component in development of a new type of particle accelerator, the LPA-driven compact gamma ray source for cargo inspection.

LPAs have the potential to advance the fields of high energy particle physics, compact photon sources, plasma physics, and hydrodynamics.

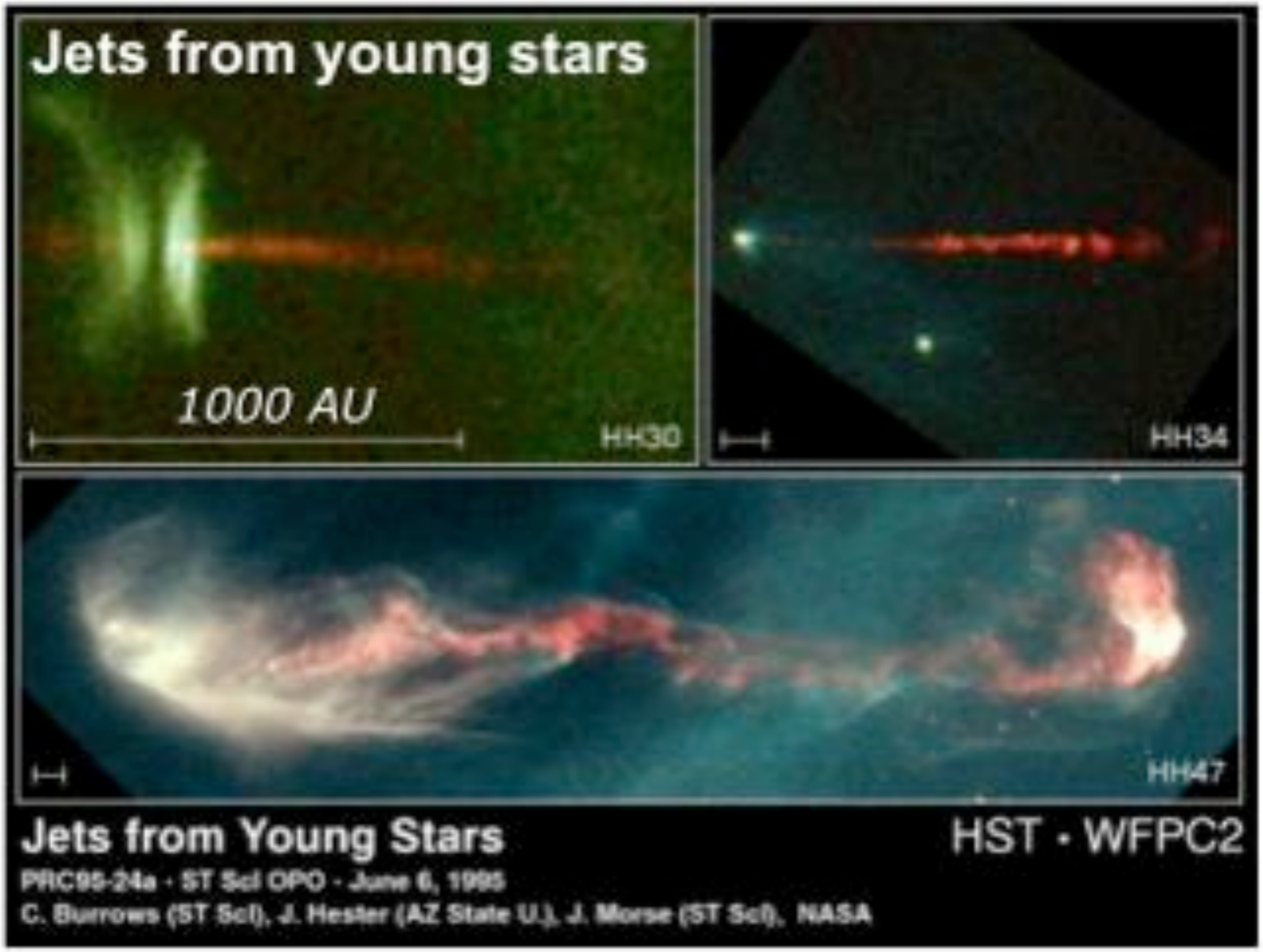
Since LPA technology requires much less space than conventional Radiofrequency Accelerator (RFA) technology, it has the potential to revolutionize the accelerator industry. Experiments that required miles of track can now be performed in a standard lab space, or for photon source applications may be of truck or small room scale.

(1) Erik Adli, Jean-Pierre Delahaye, Spencer J. Gessner, Mark J. Hogan, Tor Raubenheimer, Weiming An, Chan Joshi, Warren Mori, "A Beam Driven Plasma-Wakefield Linear Collider: From Higgs Factory to Multi-TeV", arXiv.org > physics > arXiv: 1308.1145

(2) M.J. Hogan et al.NewJ.Phys.12,055030(2010)

(3) S G Rykovanov, C G R Geddes, J-L Vay, C B Schroeder, E Esarey and W P Leemans, "Quasi-monoenergetic femtosecond photon sources from Thomson Scattering using laser plasma accelerators and plasma channels", J. Phys. B: At. Mol. Opt. Phys. 47 (2014) 234013 (22pp)

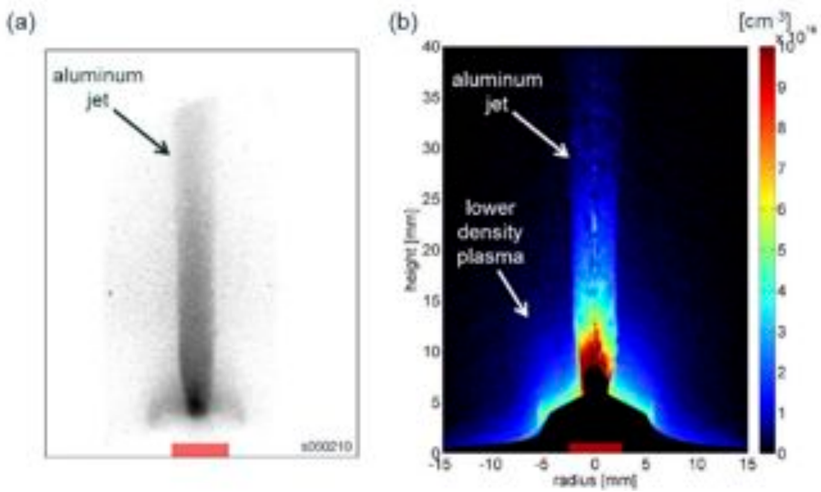
AASC's gas jets used in study of stellar plasma jets



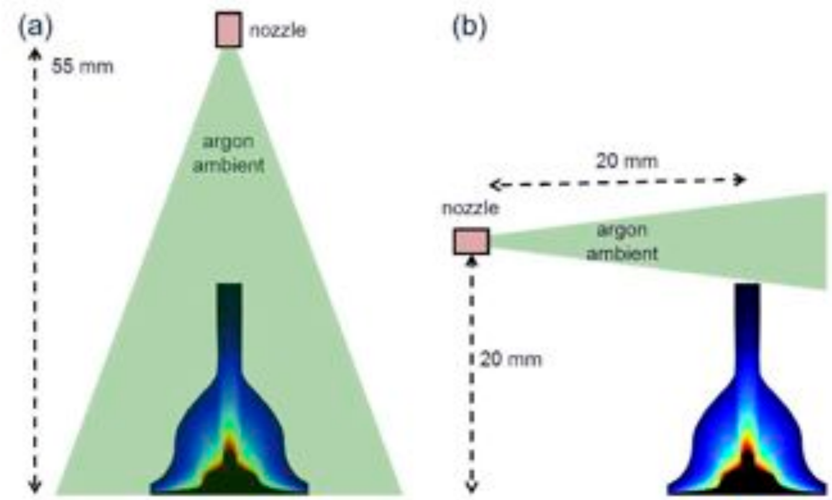
Nozzle used at Imperial College for Lab-Astro. Studies

Interaction of radiatively cooled plasma jets with neutral gases for laboratory astrophysics studies

F. Suzuki-Vidal, S. V. Lebedev, M. Krishnan, J. Skidmore, G. F. Swadling, A. J. Harvey-Thompson, S. Patankar, M. Bocchi, M. Bennett, S. N. Bland, G. C. Burdiak, J. P. Chittenden, P. de Grouchy, G. N. Hall, E. Khoory, L. Pickworth, R. A. Smith, S. J. P. Stafford, L. Suttle, A. Ciardi, A. Frank, R. Madden, K. Wilson-Elliot, P. Coleman (submitted for publication)



XUV image and simulated image of Al plasma jet produced by 1.4MA/250 ns pulse

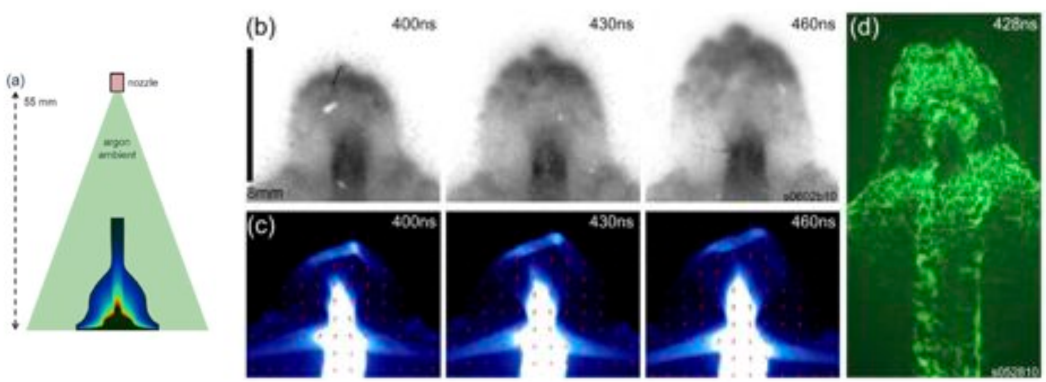


AASC gas nozzle used to inject gas against and across plasma jet

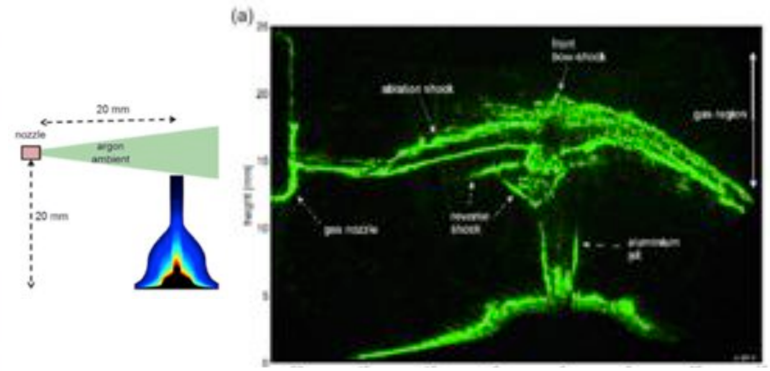
Interaction of a supersonic, radiatively cooled plasma jet with an ambient medium

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, E. Khoory, S. Patankar, L. Pickworth, J. Skidmore, R. Smith, J. P. Chittenden, M. Krishnan, R. E. Madden, K. Wilson-Elliot, A. Ciardi, and A. Frank, PHYSICS OF PLASMAS 19, 022708 (2012)

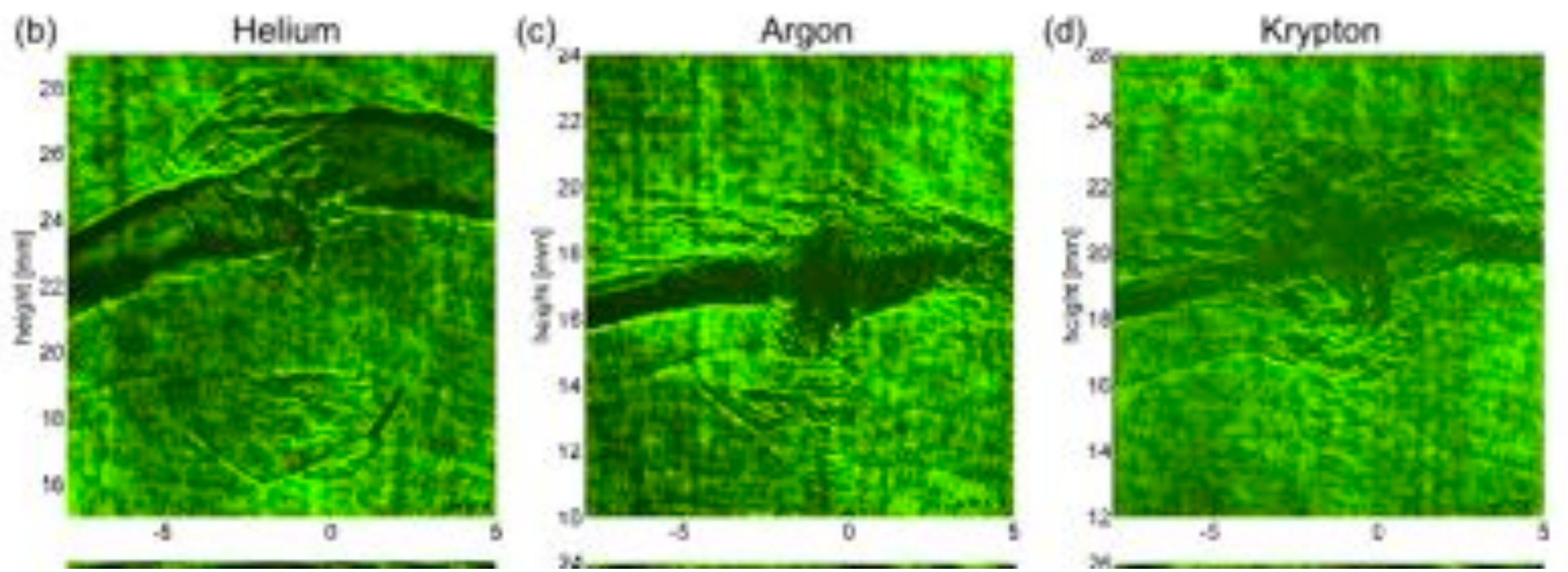
Imperial College Plasma Jets Interact With Nozzle Flows



Al plasma jet forms bow shock in Ar gas



Al plasma jet collides with Kr gas to form radiative shocks



Al plasma jet forms radiative shocks in He, Ar and Kr gas