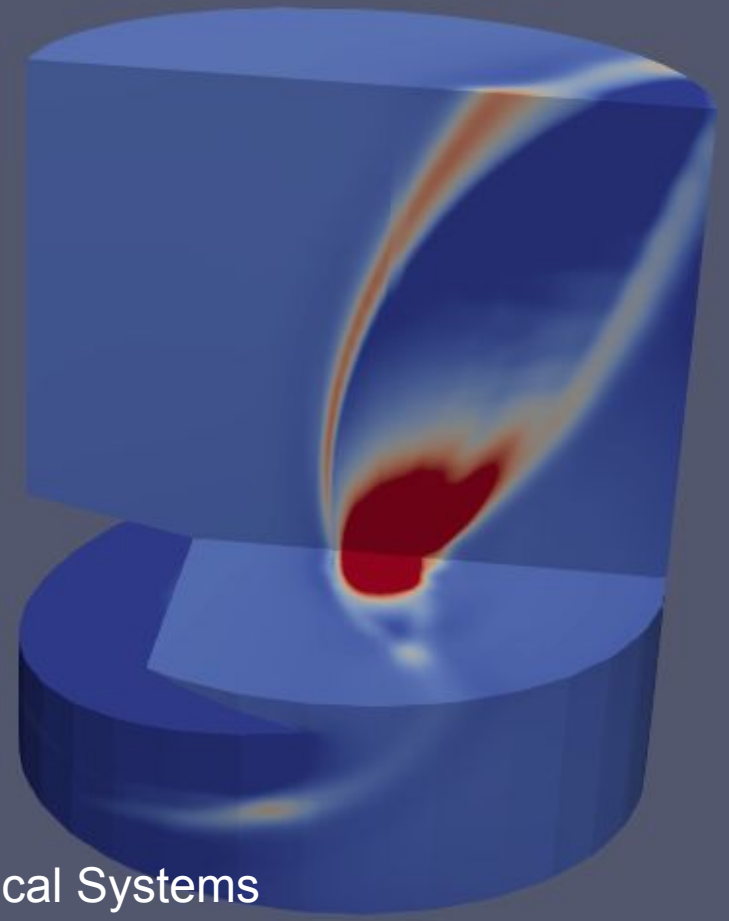
Structure of Supersonic Flows Impinged on by Thin Blades for Laser Plasma Accelerators



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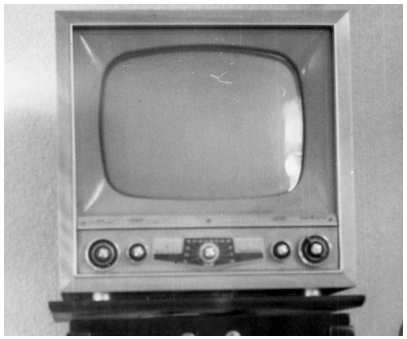
August 13, 2019
PPPL GSS

Work supported by DOE-HEP, NSF, Varian Medical Systems

Outline

- Laser Wakefield Accelerators
  - Next generation accelerators
- Controlled Electron Injection
  - Previous experiments
  - Simulations
  - Experimental verification of simulations

Accelerators are everywhere



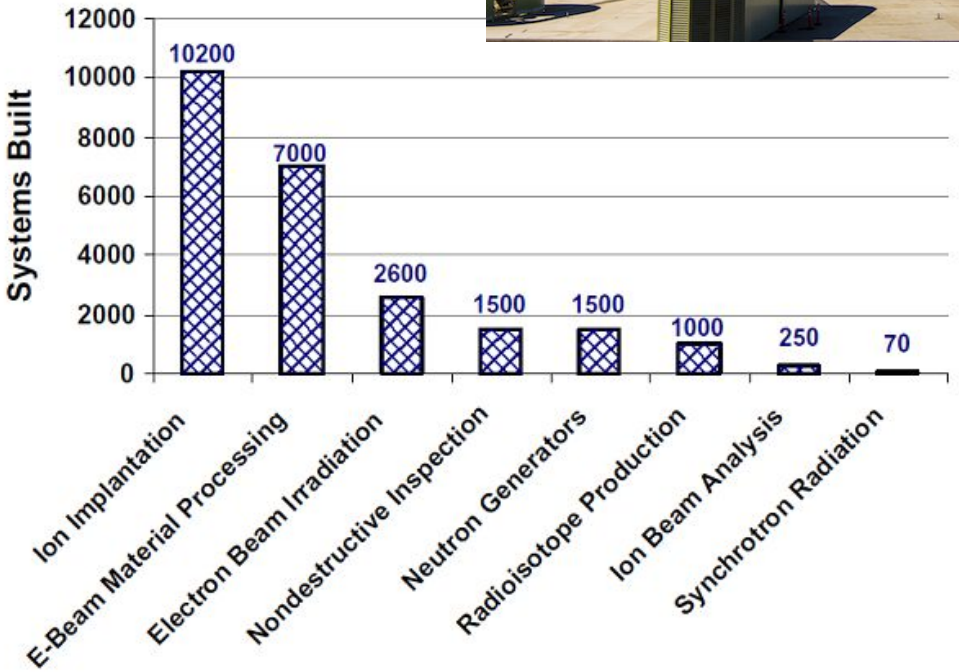
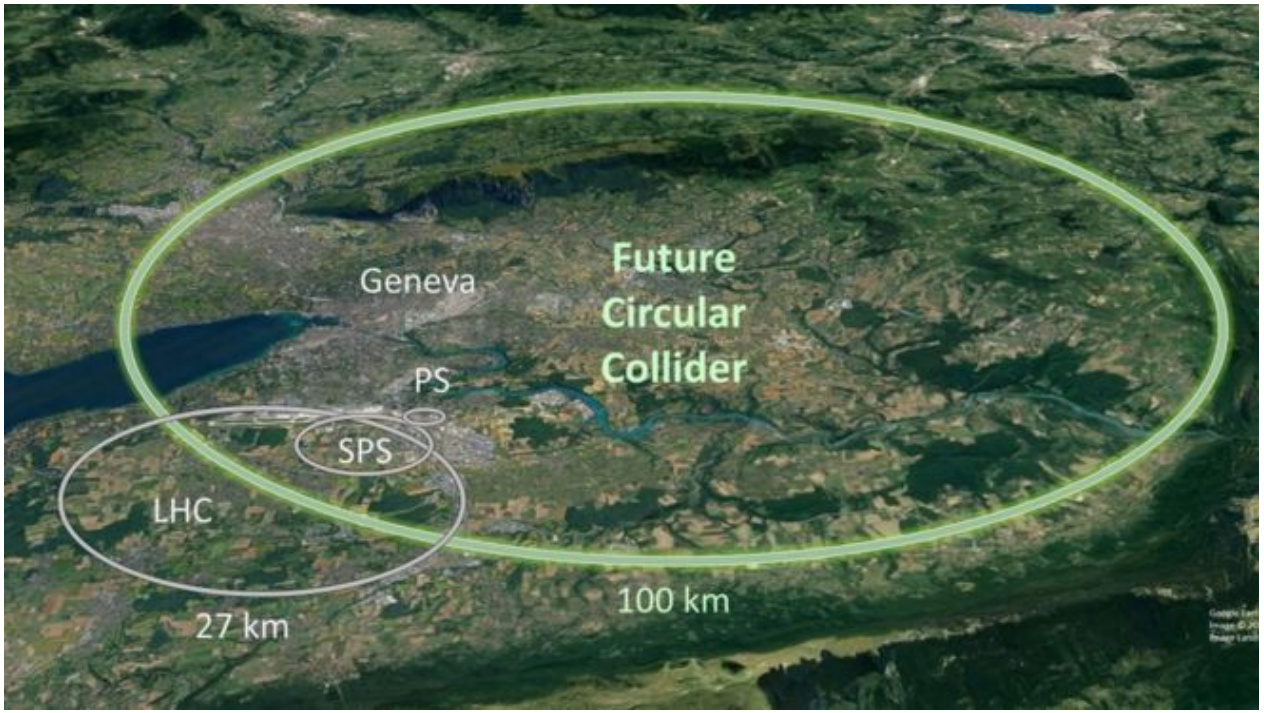


Image credits : Car, engine, wheels: 2007 Opel Astra GTC Hybrid concept by Studio Parsons for Adam Opel AG | Dashboard: Adam Opel AG | Car interior: Adam Opel AG | Suspension: 2CarPros.com

Accelerators have advanced very far

Ernest O. Lawrence
1931 4.5 in diameter cyclotron
1.8kV volts to accelerate hydrogen ions up to energies of 80keV.

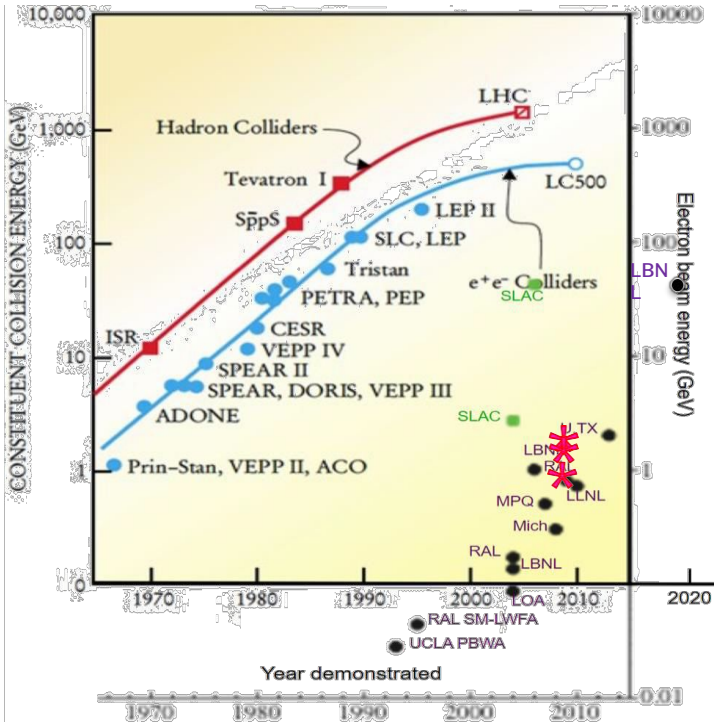


CERN - 6.5 TeV

Accelerators need a new technology

- Particle accelerators are approaching limits:
  - Space limited: LHC – 27 km circumference
  - Fundamental limit: dielectric breakdown
- LPA systems promise a solution
  - Smaller, more accessible, powerful
  - RF cavities ~ 100 MV/m
    vs LPA~ 100 GV/m

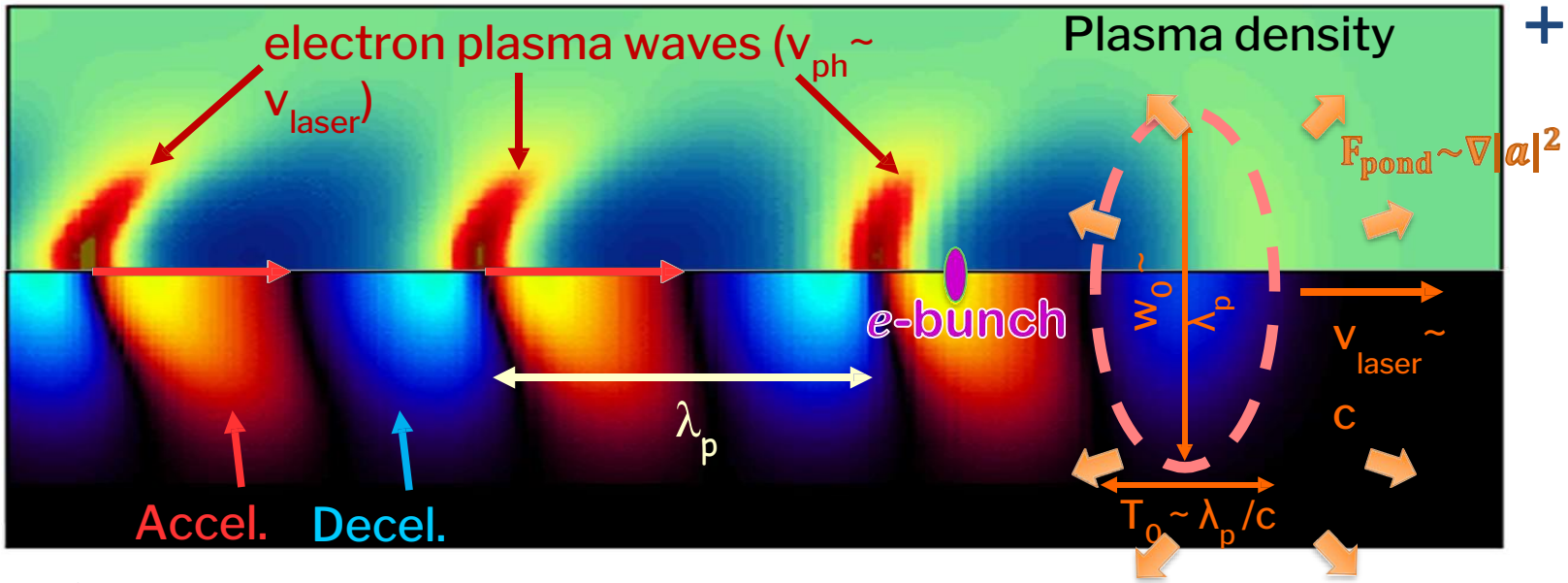
Livingston Plot*



*Tigner, M., *Phys. Today,* 2001 *Faure et al., *Nature,* 2004; Geddes et al., *Nature*, 2004; Mangles et al., *Nature,* 2004[3]

High-intensity lasers can be used to generate a plasma wake for electron bunch acceleration

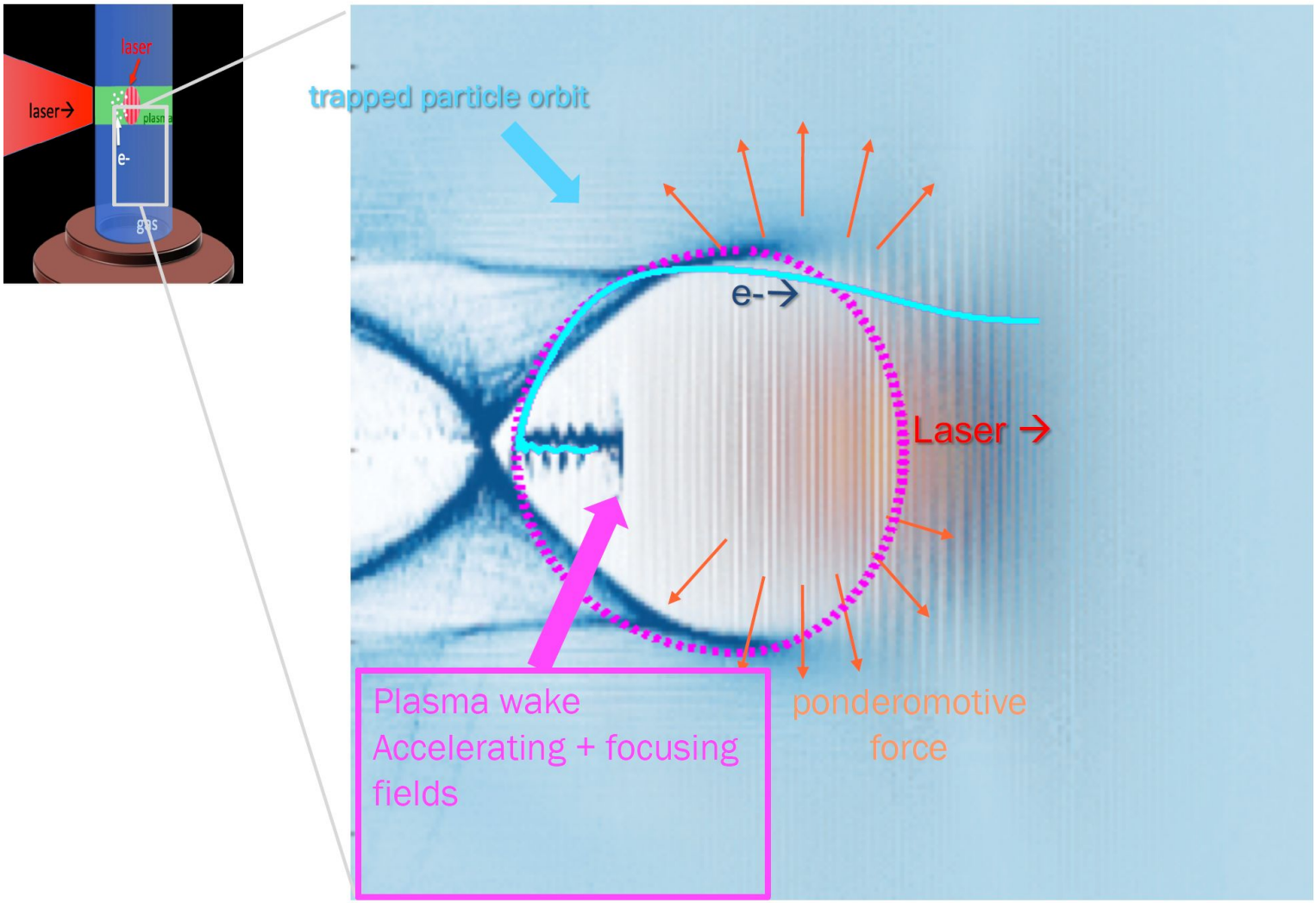
- Laser-Plasma Accelerator (LPA)
  - First proposed in 1979 by Dawson of UCLA*
  - Principle of operation:
    - Ultrashort laser pulse → electron plasma wave → accelerating E-field



*Tajima, T. & J.M. Dawson, *PRL*, 1979,

+Benedetti, C., *44th Conf. Plasma Phys.* – EPS, 2017

High-intensity lasers can be used to generate a plasma wake for electron bunch acceleration

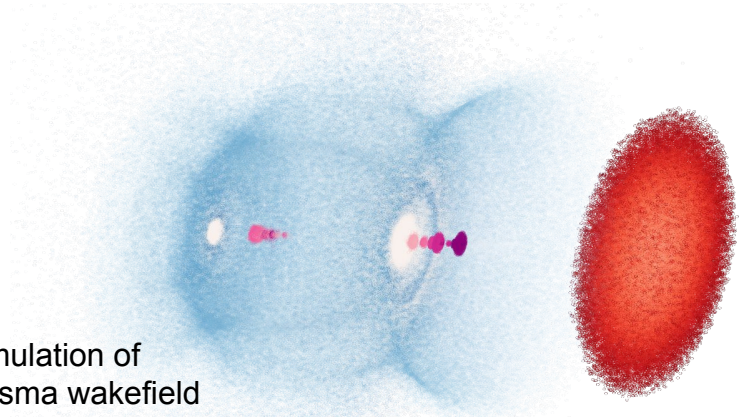


1: W.P. Leemans, Phys. Plasmas 1998, 2: C. Geddes et al., Nature 2004. 3: W.P. Leemans et al., PRL 2014, 4: S. Steinke et al., Nature 2016

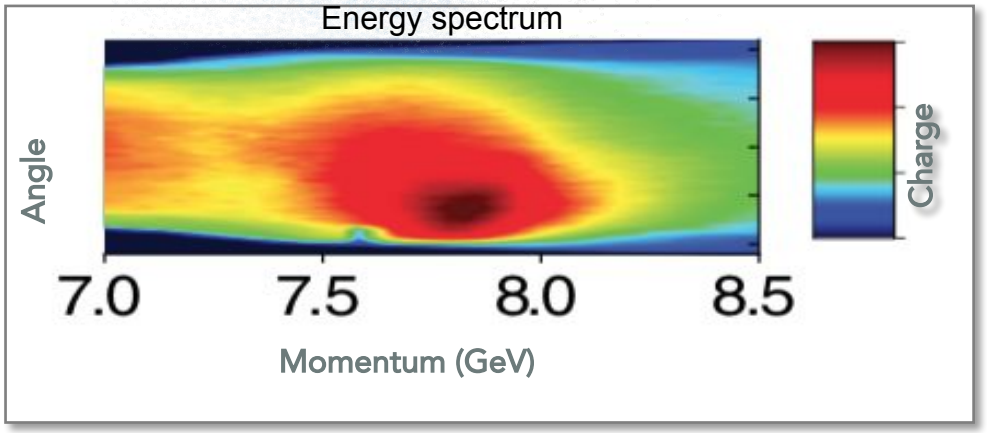
Energy record by LPAs is 8 GeV electron beams

Research highlight – 8 GeV electron beams[1]

- *In **20 cm** accelerating structure*
- *Using **0.85 PW** and **novel capillary***

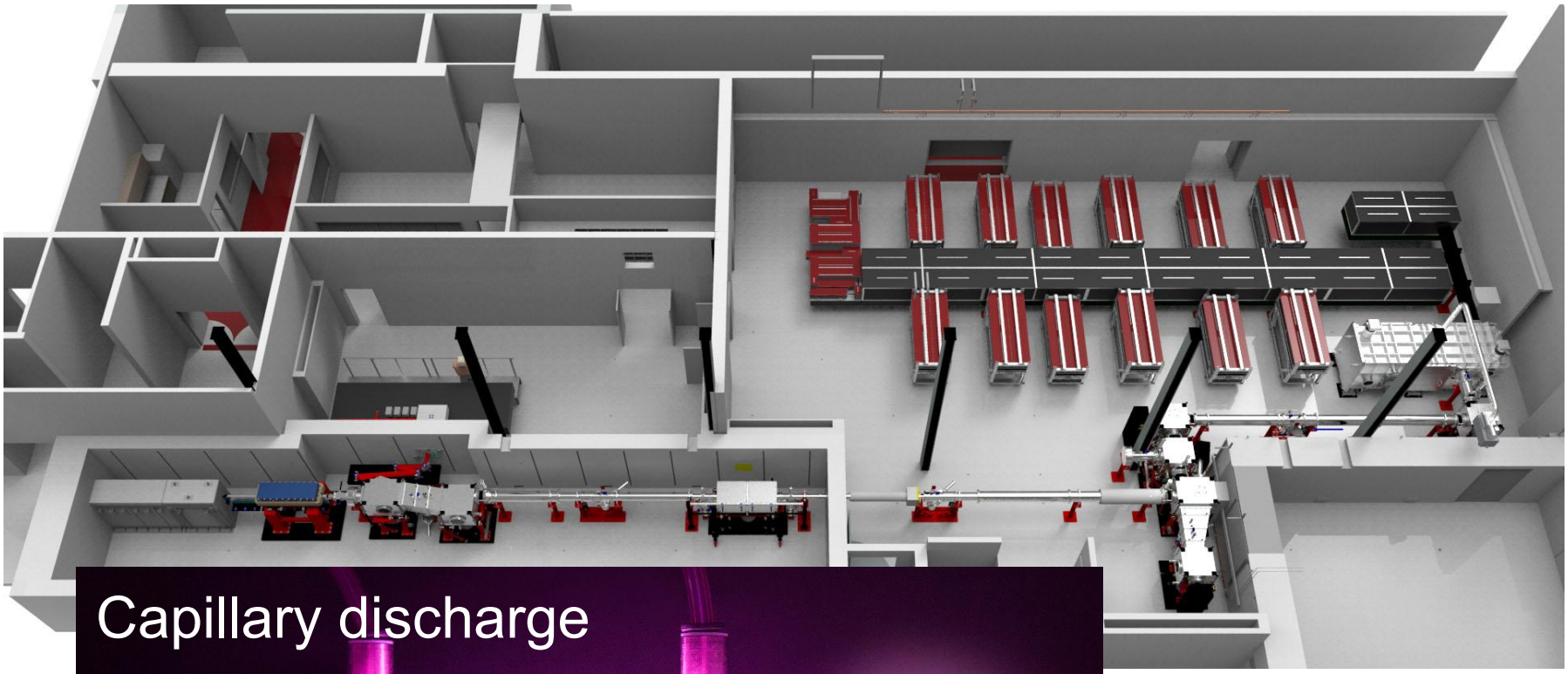


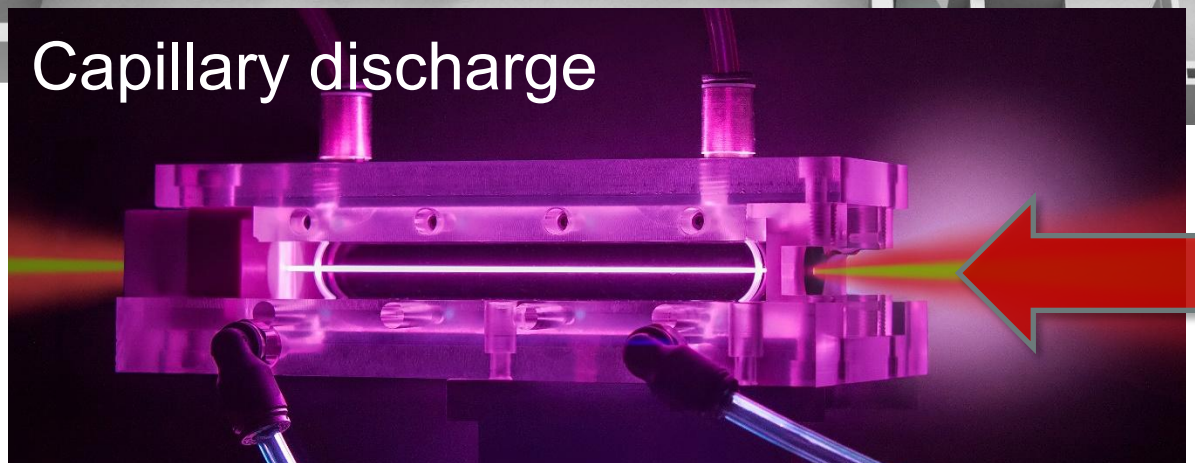
Simulation of plasma wakefield



[1]A.J. Gonsalves et al., Phys. Rev. Lett. **122** 084801 (2019);

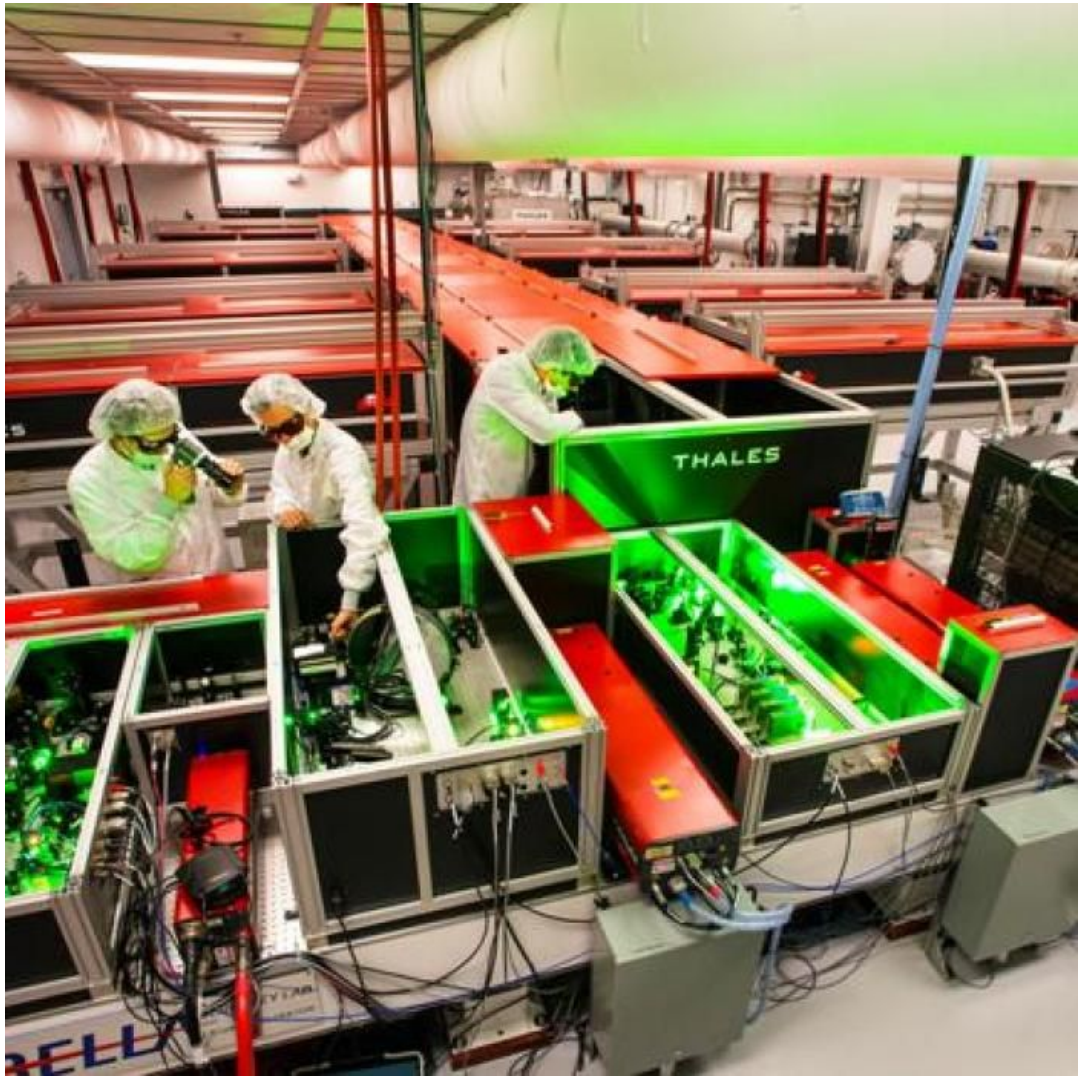
BELLA Laser bay and scalable accelerator





BELLA Laser - table top(s) accelerator

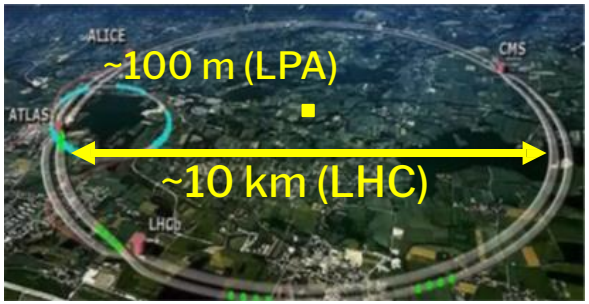
10 GeV equivalent to conventional accelerator at least **5 football fields** long



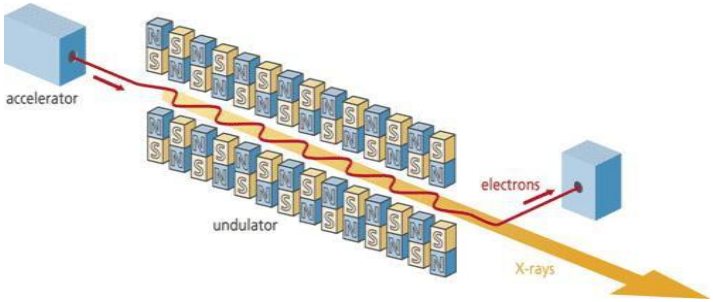
LPAs already have near term applications

Several Applications

HEP Collider

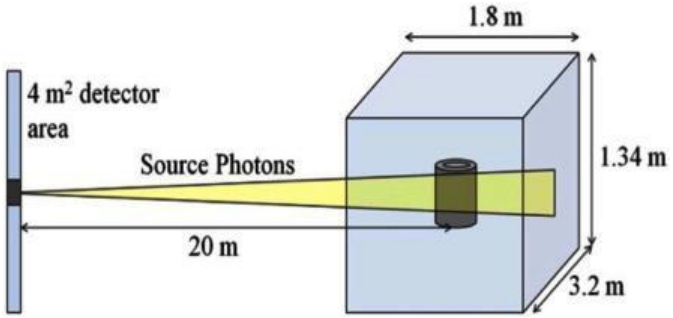


FEL X-Ray Source



Medical*

Security



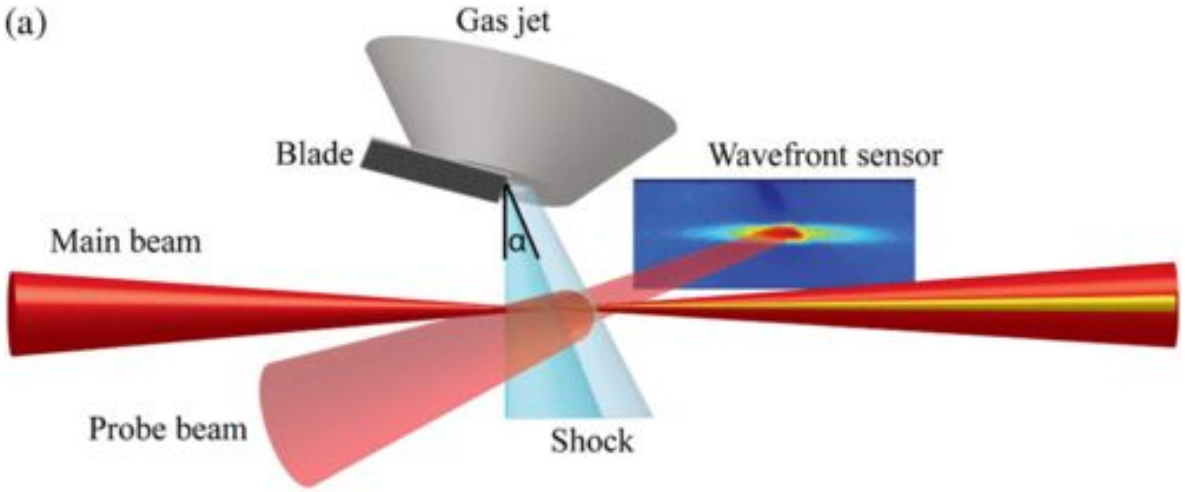
Outline

- Laser Wakefield Accelerators
  - Next generation accelerators
- → Controlled Electron Injection
  - Previous experiments
  - Simulations
  - Experimental verification

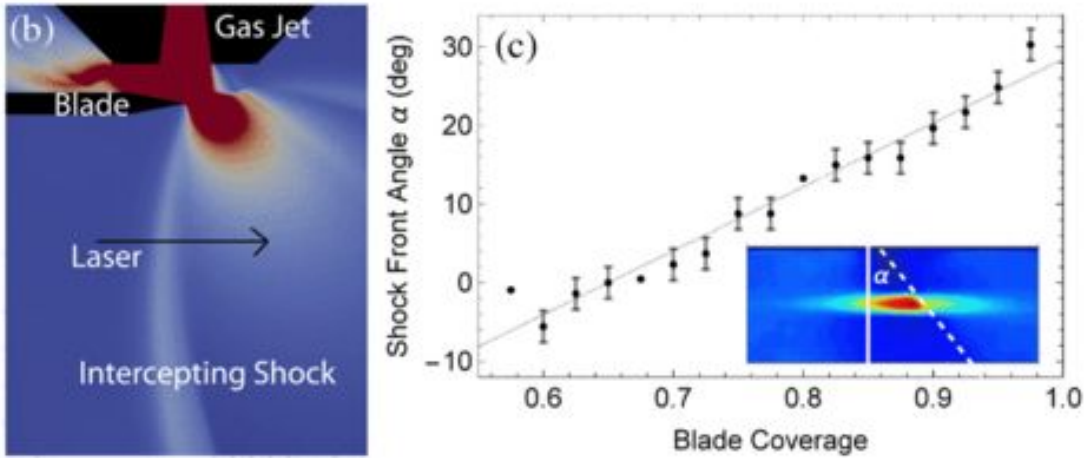
Control is required for reliable acceleration

Previous experiments shaped gas for quasi-monoenergetic beams

Gas profile can be shaped to control electron injection



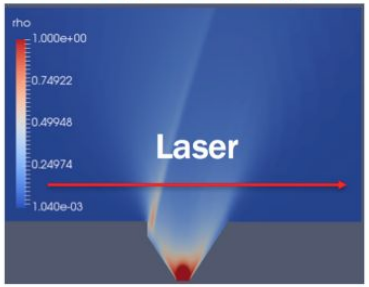
Simulated gas profile

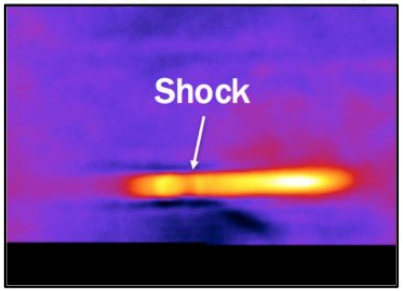


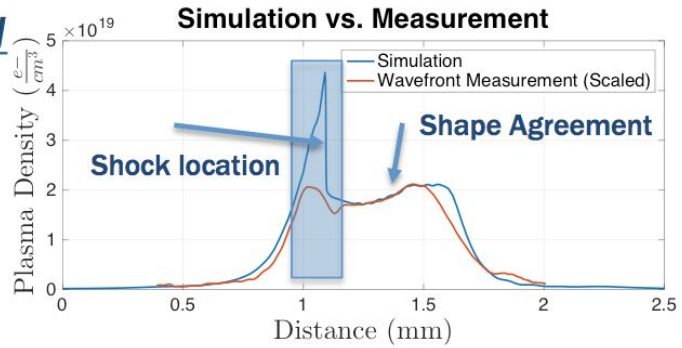
K. K. Swanson et al., Phys. Rev. Accel. Beams 20, 051301
H.-E. Tsai et al., AIP Conference Proceedings 1812, 040005 (2017); doi: 10.1063/1.4975852

Paradox: Phase images suggested flow upstream

Mini-LPA target designed* and experimentally validated





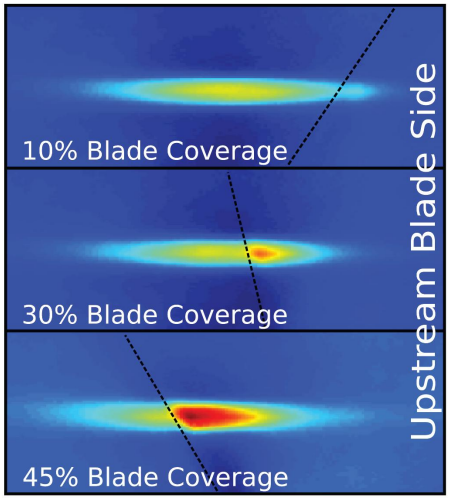


**Provisional Patent*

- Plasma column shows predicted shock
- Current diagnostics insufficient for this class of LPA

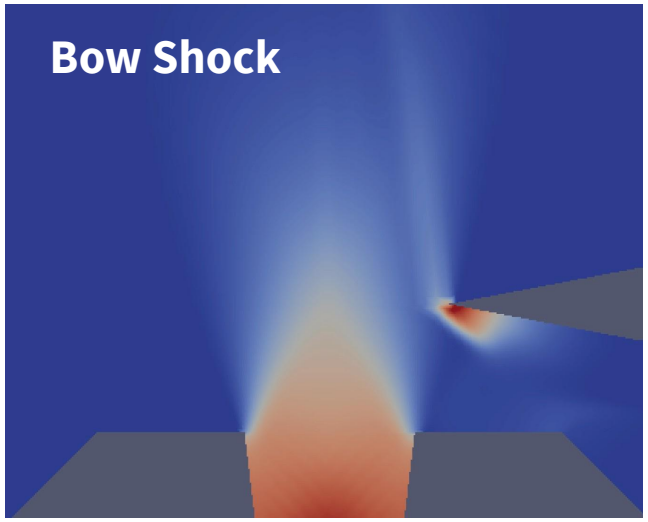
Slide excerpted from presentation by Hann Shin Mao Jan 5, 2018

Previous experiments showing control of tunable monoenergetic electron beams by injecting along a shock induced density downramp used line-of-sight gas jet diagnostic.

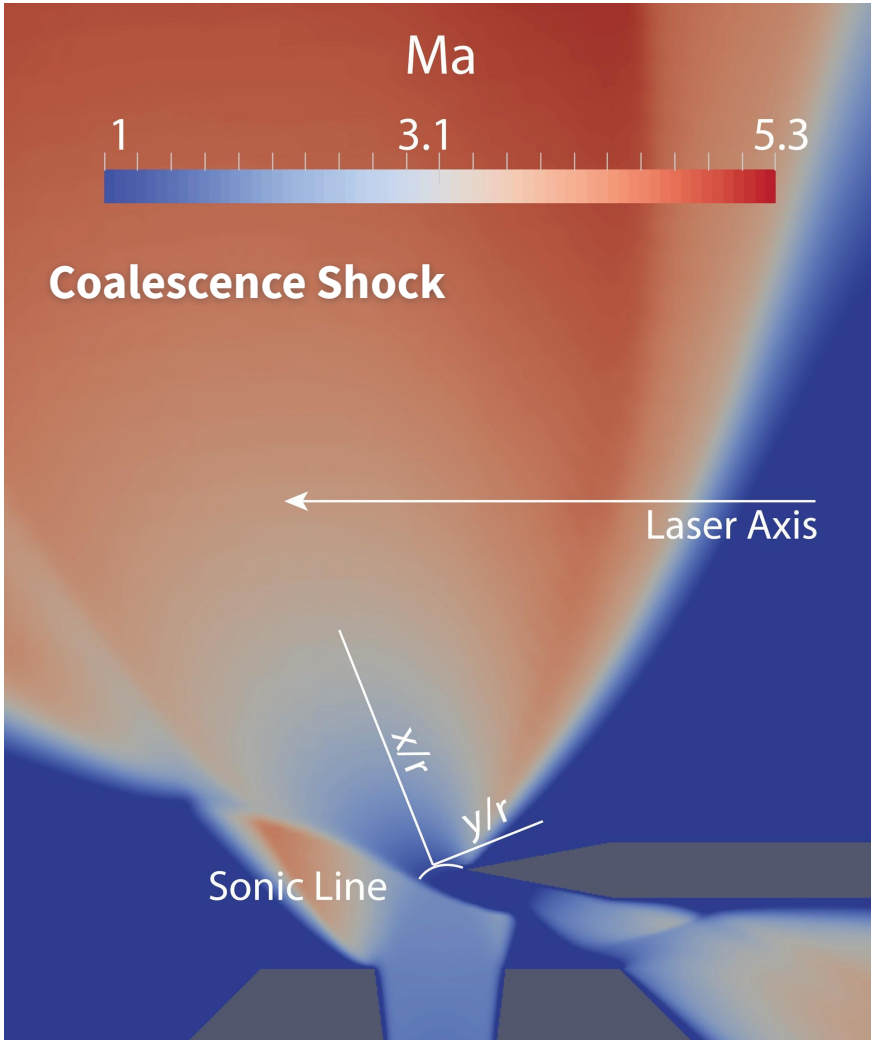


K. K. Swanson et al., Phys. Rev. Accel. Beams 20, 051301
H.-E. Tsai et al., AIP Conference Proceedings 1812, 040005 (2017); doi: 10.1063/1.4975852

Hypothesized that characteristic flow was changing



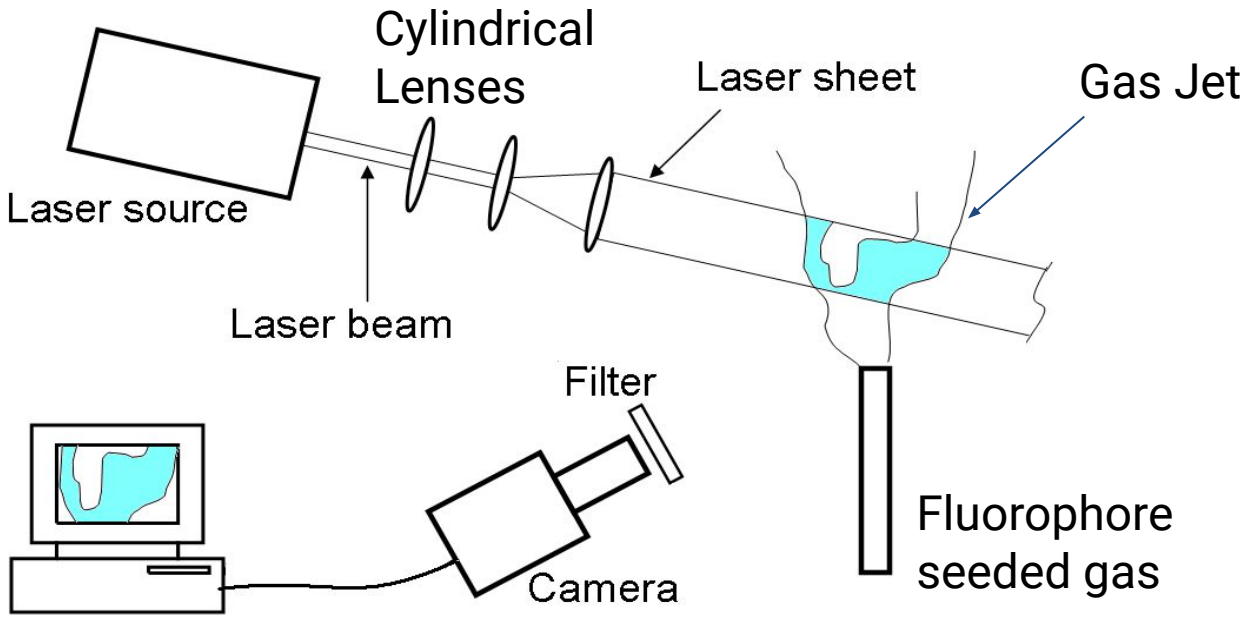
Bow shock would attach to blade. Hypothesized that blow shock becomes inaccessible. Only coalescence shock remains.



Used Planar laser-induced fluorescence to image asymmetric plume

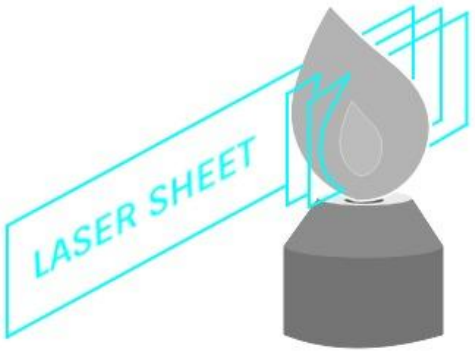
Planar Laser-Induced Fluorescence (PLIF)

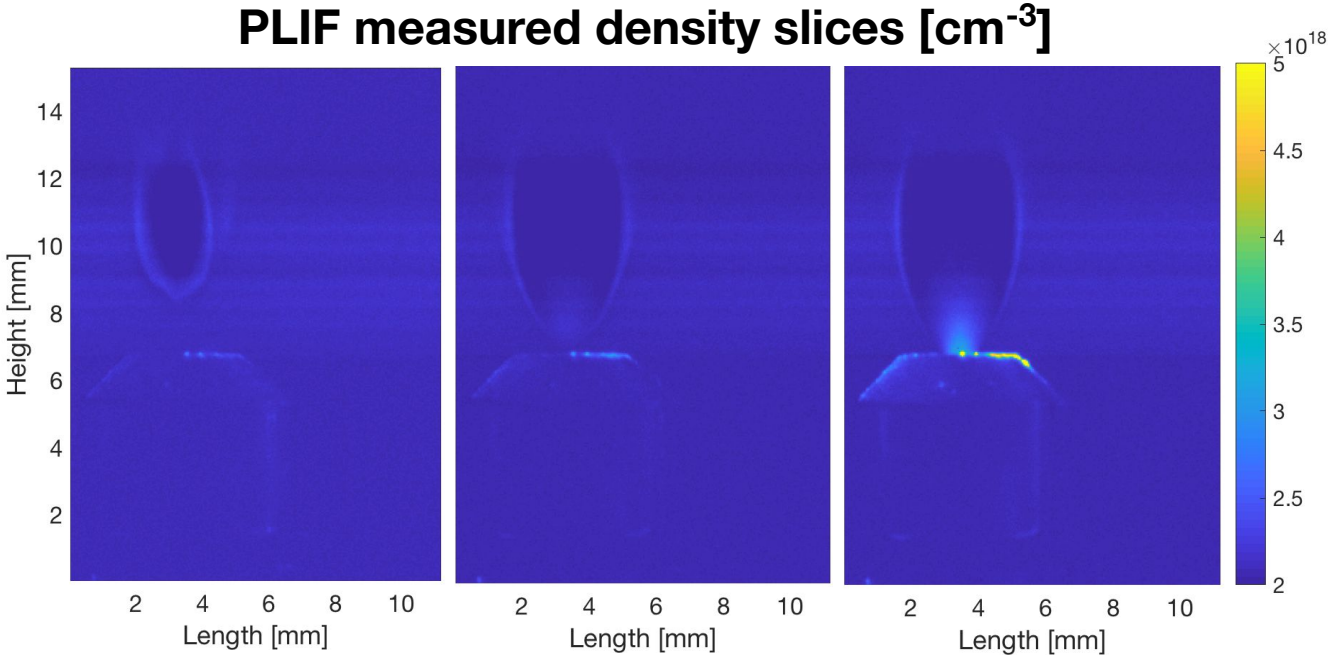
Commonly used in aerospace applications

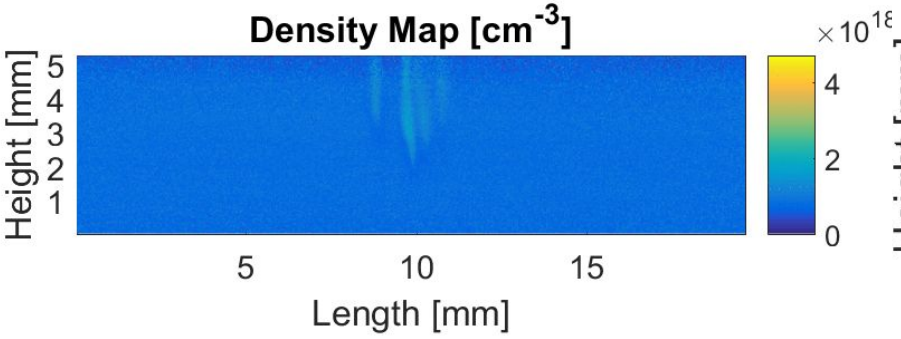


Epstein, A. H. 1974 Fluorescent gaseous tracers for three dimensional flow visualization. MIT Gas Turbine Lab Rep. 117

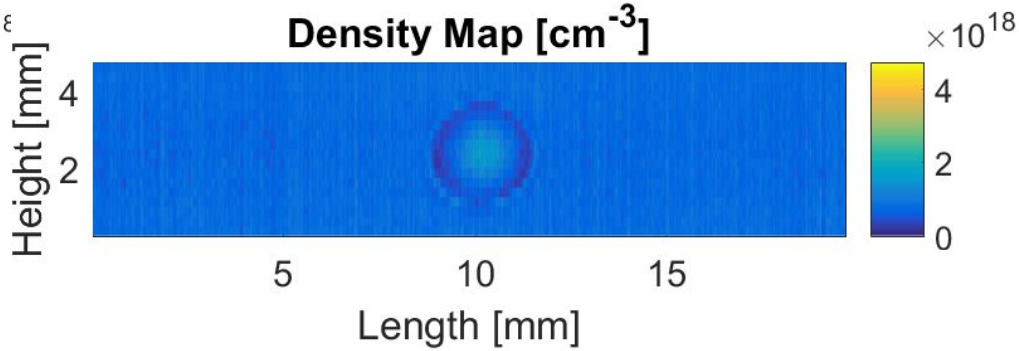
Translating laser sheet provides 3D density profiles





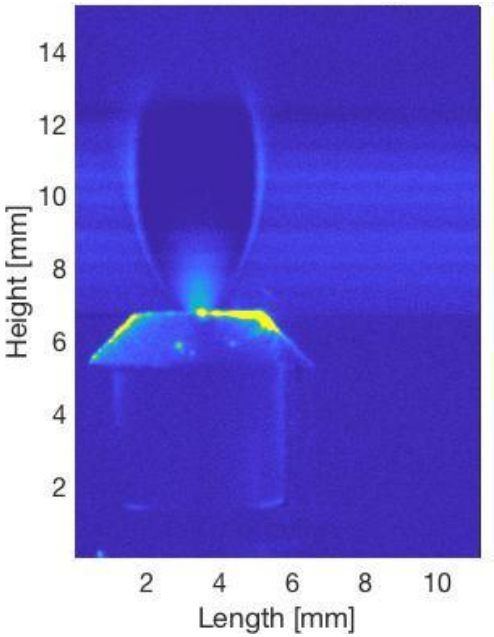


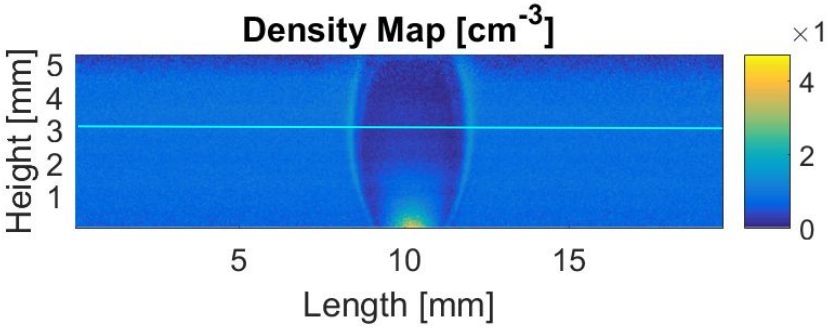
Side View



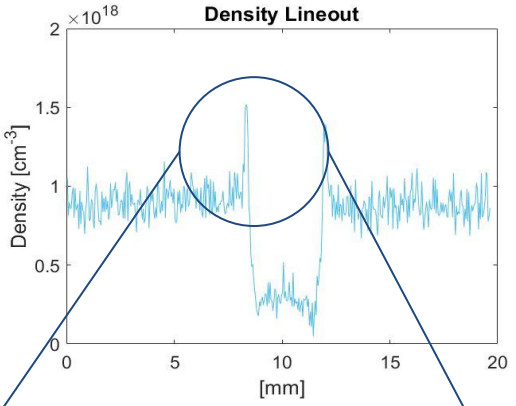
Top View

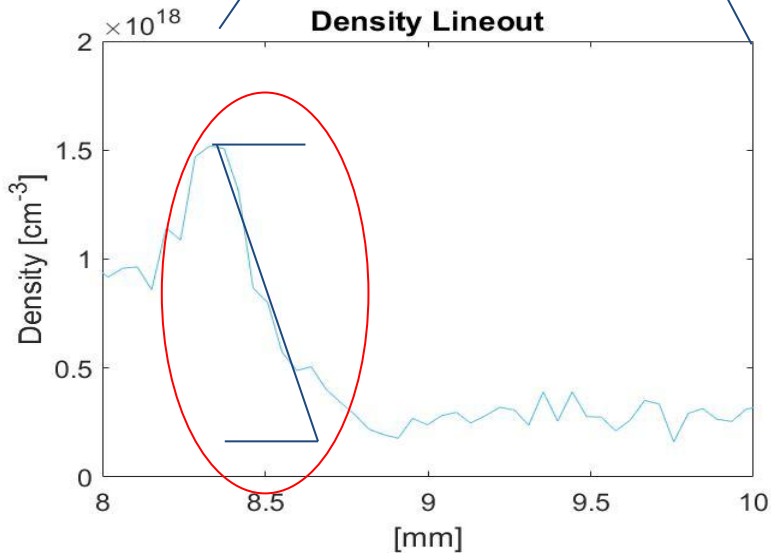
Experimental results show PLIF reveals sharp features in the flow





*44.5um / px (Camera Calibration)





Mean-free path

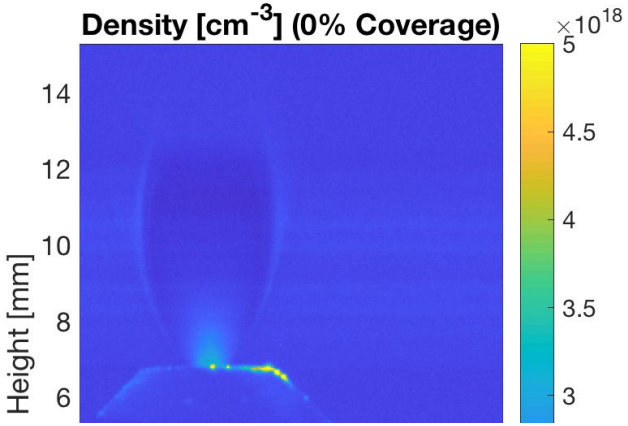
$$\lambda_{mfp} = (\sqrt{2}n\sigma)^{-1} = 32\mu m$$

for Ar at $n = 2 \times 10^{17} cm^{-3}$

Density gradient thickness

$$\bar{x} = \frac{n_{max} - n_{min}}{(dn/dx)_{max}} = 130um$$

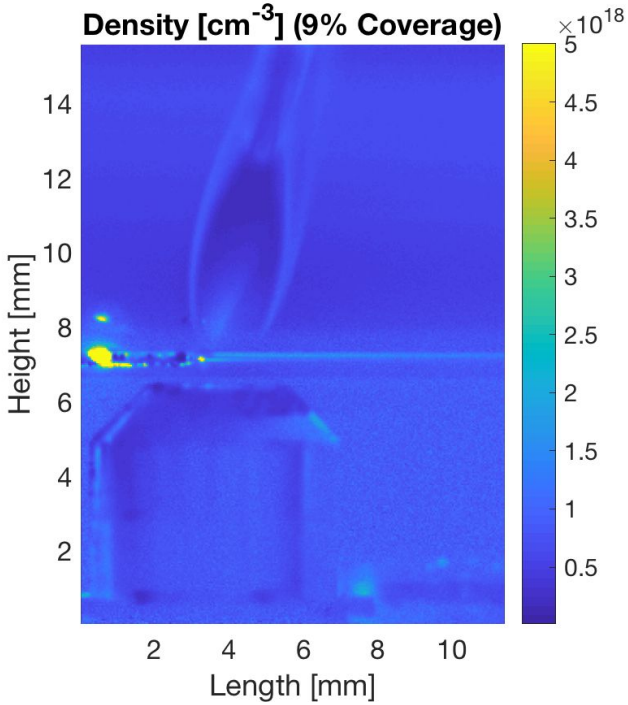
Measurements show jets with different characteristic flow properties

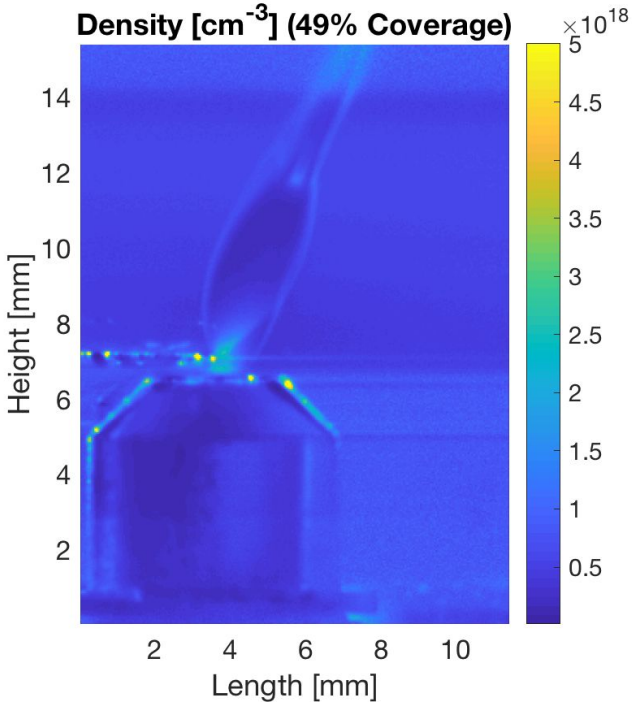


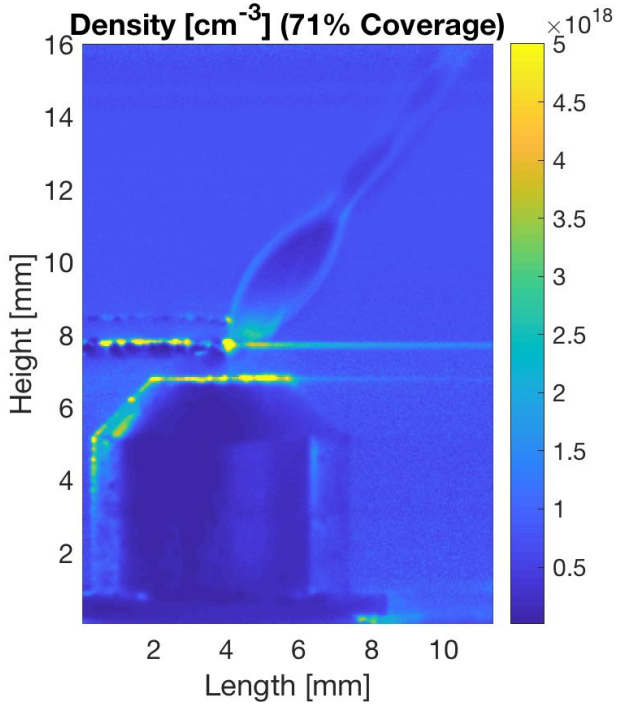
Measurements at uncovered, 9%, 49% and 71% blade coverage were taken with PLIF. It was found that:

- angle of gas jet axis deflects with blade coverage
- pressure ratio jet/background pressure decrease with blade coverage. Mach number is decreased.
- Interference of shocks

* bottle pressure was maintained at 25psi for all.

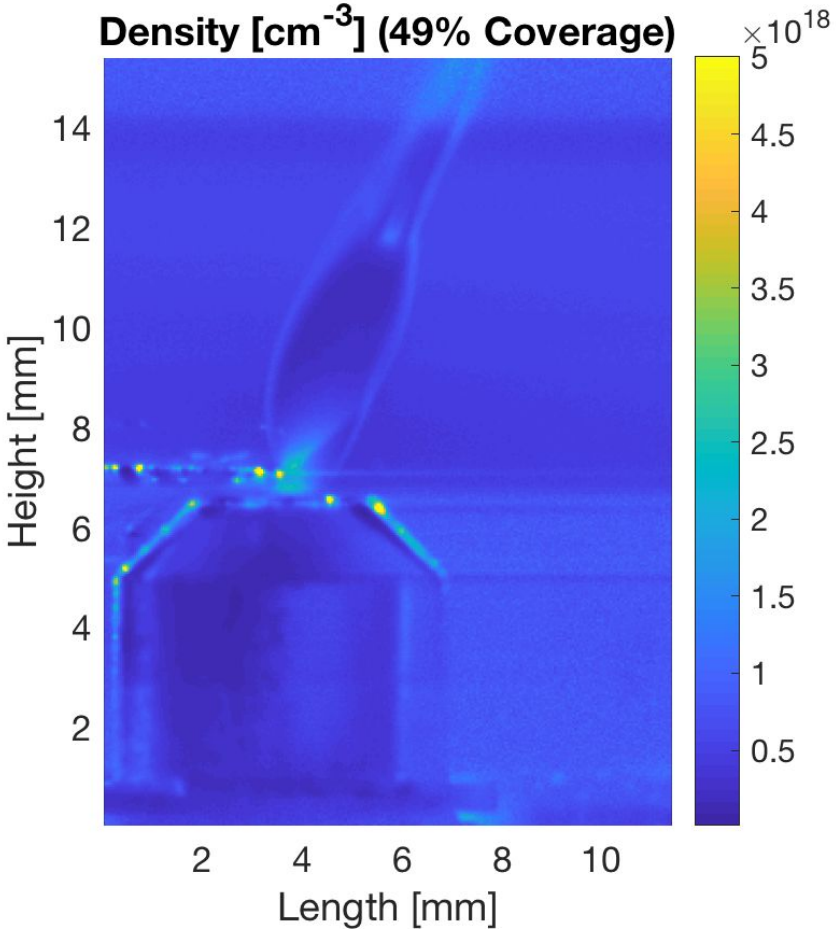


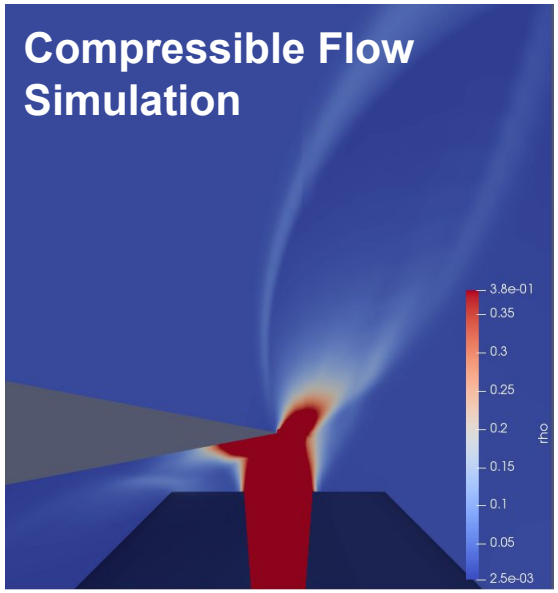




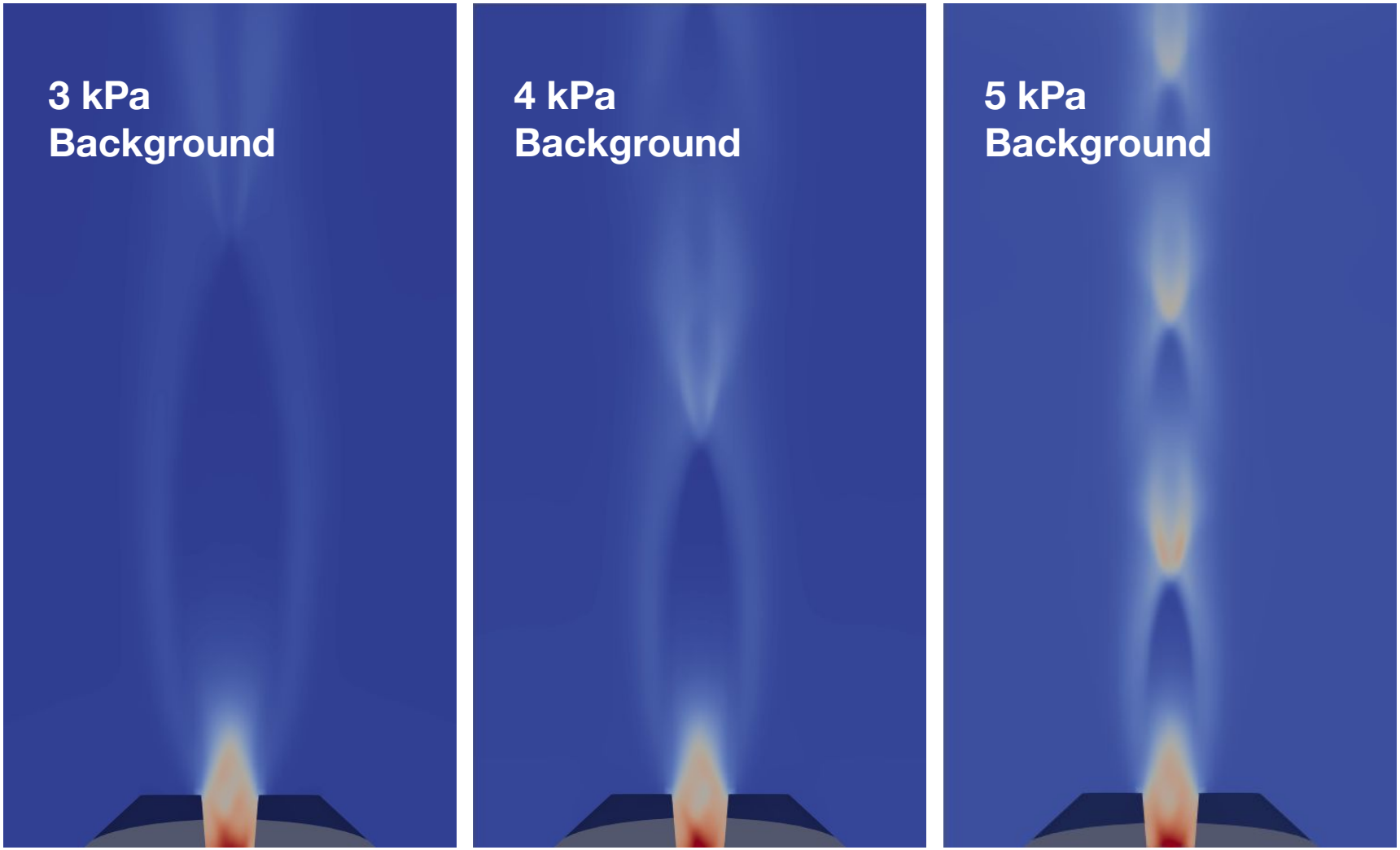
Simulations had shown jet would be deflected

Simulations show that the entire jet, not just the shock next to the blade, is shifted, suggesting that an entirely new jet is formed.





Three different background pressures



Summary and Next Steps

Summary

- Laser plasma accelerators are next generation accelerators
- PLIF diagnostic imaged low density and asymmetric gas jets with unprecedented resolution
- Fluid dynamical insights were gained to improve injection methods

Next Steps

- Conduct parametric study of accelerator variables, timing, pressure, blade distance to optimize for beam production
- Compare results with previous and ongoing electron acceleration experiments

ACKNOWLEDGEMENTS This work was supported by the Director, Office of Science, Office of High Energy Physics, of the U.S. Department of Energy under Contract No.DE-AC02-05CH11231, NSF and the Varian Medical Systems/LBNL Strategic Partnership