Measurement of turbulent dissipation with advanced laser diagnostics

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Los Alamos National Lab (Dr. John Charonko)

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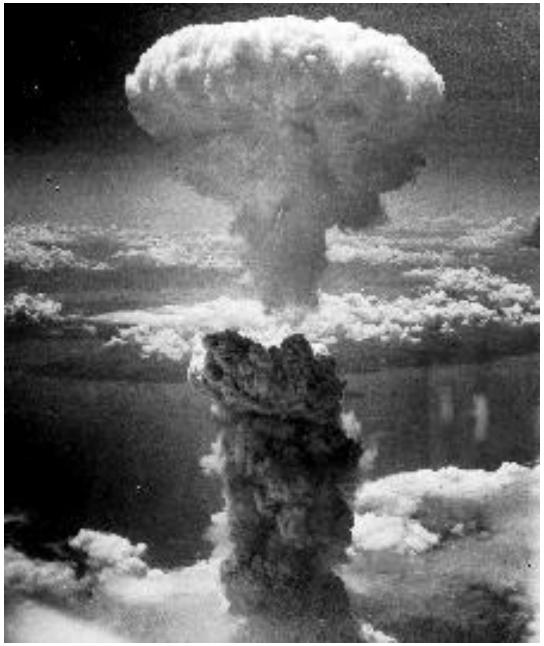
Introduction



Informing numerical models of buoyancy driven flows requires fully resolved velocity gradients and kinetic energy measurements

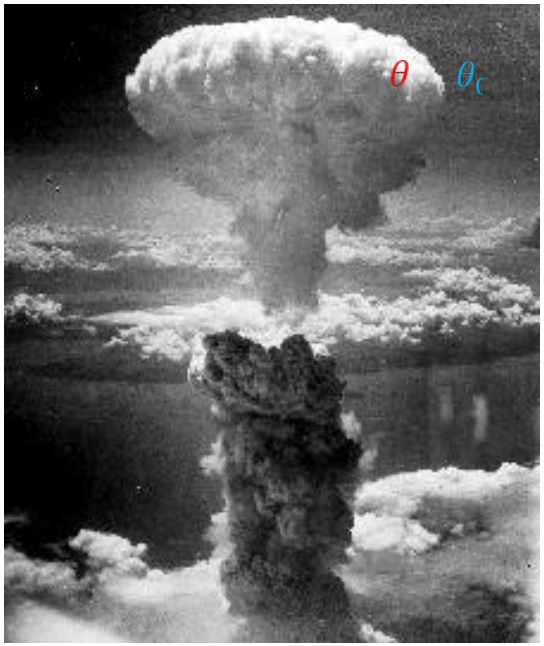
Department and University: The George Washington University, *Department of Mechanical and Aerospace Engineering*
Academic Advisor: Philippe M. Bardet
NSSC Research Focus Areas: Nuclear Engineering
Planned Graduation Date: *N/A*

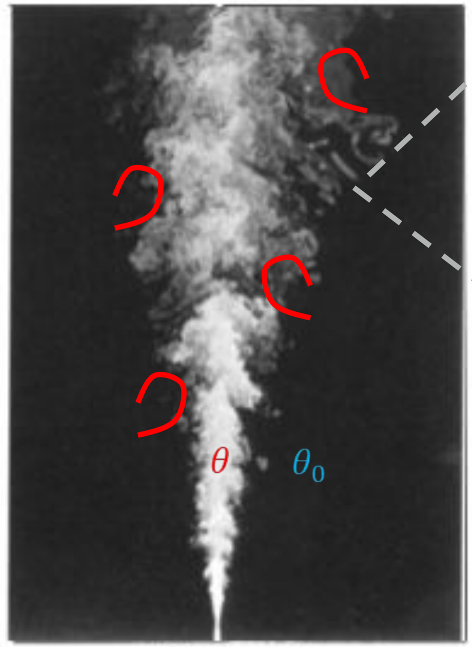
Lab Mentor and Partner Laboratory: Dr. John Charonko, LANL

Mission Relevance of Research:

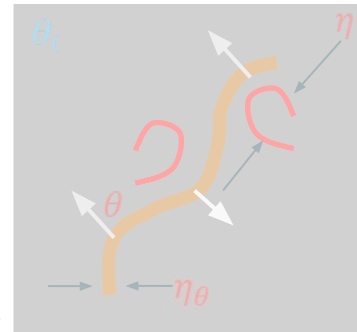
In the case of a global nuclear detonations, detection and disaster mitigation can be accomplished by simulating the rise height and fall out of the resulting buoyant plume. To properly parameterize these simulations, **it is imperative to provide the direct measurement of small scale velocity gradients in a turbulent flow**. This quantity is necessary to determine the rate at which the turbulence dissipates energy and is a fundamental in developing realistic models of turbulent flows. This research supports the NNSA security mission of nuclear detonation forensics by providing CFD models with data inputs with minimal assumptions regarding the resolved scales of the measurement.

Emergency Response to extreme Events





(b) Re $\simeq 10^4$



Kolmogorov scale

$\eta = (\nu^3/\epsilon)^{1/4}$

Batchelor scale (air)

$\eta_\theta = \eta\, Sc^{-3/4}$

Schmidt number

$Sc = \nu/D = 0.7$

Mixing occurs when **small-scales** of plume are *similar* to those of turbulence

Strong need for:

- Experimental determination of k & ϵ
- Experimental determination of potential forcing terms in RANS models

Prediction efforts begin with a RANS $k-\epsilon$ model

$$\frac{Dk}{Dt} = \mathcal{P}_k + \frac{\partial}{\partial x_j}\Big[\Big(\nu + \frac{\nu_t}{\sigma_k}\Big)\frac{\partial k}{\partial x_j}\Big] - \epsilon + \mathcal{F}_k^b$$

$$\frac{D\epsilon}{Dt} = C_{\epsilon 1}\frac{\epsilon P_k}{k} + \frac{\partial}{\partial x_j}\Big[\Big(\nu + \frac{\nu_t}{\sigma_\epsilon}\Big)\frac{\partial \epsilon}{\partial x_j}\Big] - C_{\epsilon 2}\frac{\epsilon^2}{k} + \mathcal{F}_\epsilon^b$$

Buoyancy contributions to **TKE** and **dissipation**

$$\mathcal{F}_k^b = -\rho\beta g_i \overline{u_i\theta}$$

$$\mathcal{F}_\epsilon^b = C_\epsilon \frac{\epsilon}{k}\mathcal{F}_k^b$$

Emergency Response to extreme Events

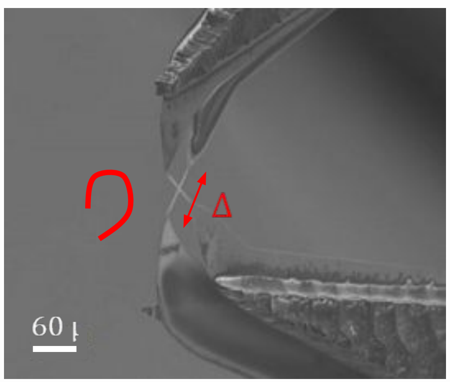
"The problem of <u>spatial resolution</u> is simply the fact that the sensing element cannot truly respond to scales smaller than its dimensions"
Örlu & Alfredsson, 2010

Dissipation rate: $\epsilon = \nu \langle \frac{\partial u_i}{\partial x_j} \frac{\partial u_i}{\partial x_j} \rangle$

Deliverables:

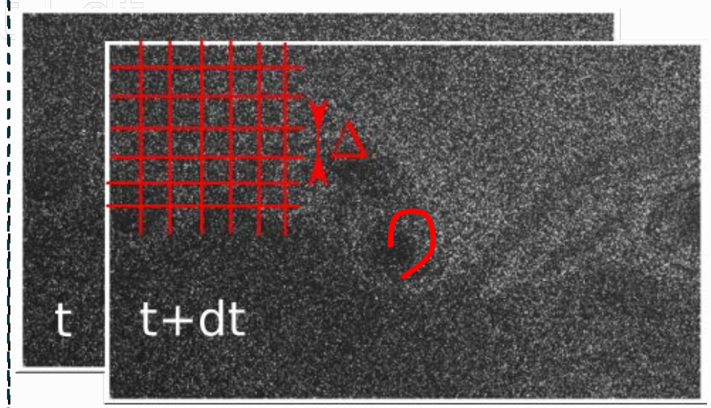
- Develop a compact velocimeter that measures velocity gradients with sufficient resolution to determine ε
- Test method in flow configuration where the velocity gradients are known (stagnation point flow)

Hot-wire anemometry



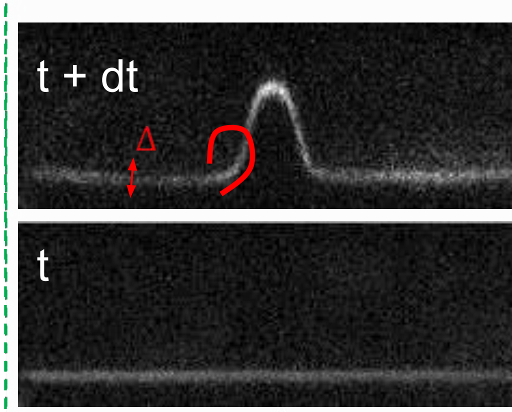
- Spatial filtering of data when wire length $\Delta/\eta \gg 1$
- Indirect measurement velocity gradient

PIV



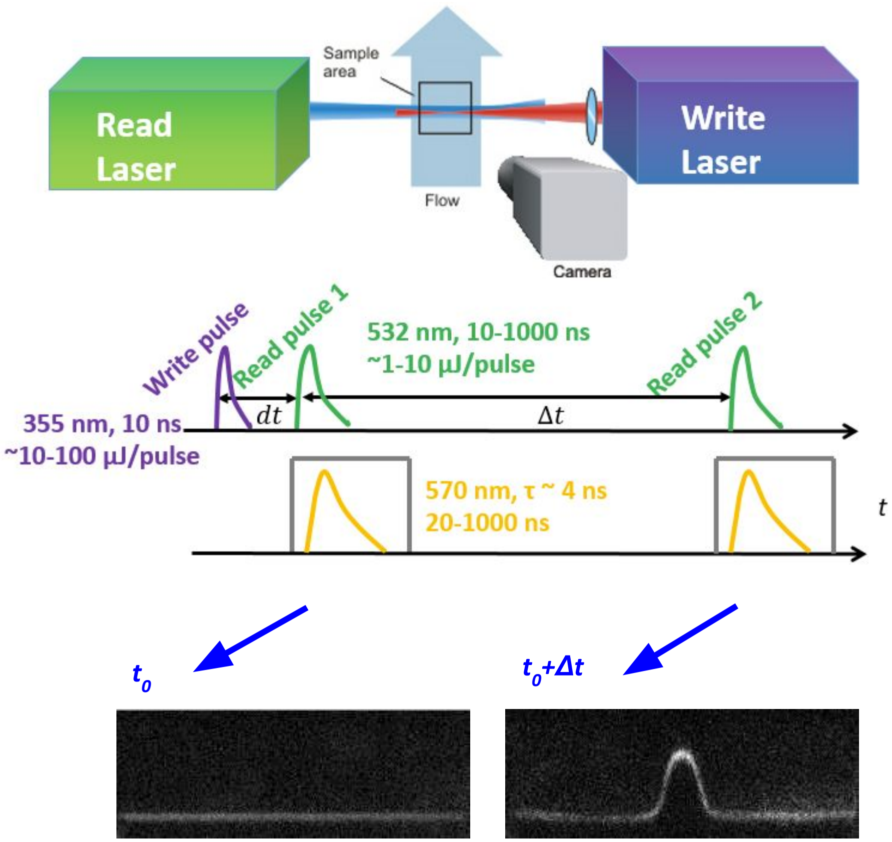
- Interrogation window (Δ) limits resolution of velocity derivative
- Velocity gradient amplifies noise in the dissipation measurement

MTV



- Beamlet width (Δ) limits resolution of probe
- Velocity derivative encoded in the time of flight measurement

Microscopic Molecular Tagging Velocimetry (μ-MTV)



Operating Principles of μ-MTV

•**Spectroscopy** of molecular tracers (seeded or naturally present)

•**Tracer activation** (tagging) with a first laser (***write***)

•**Time of flight** of tagged pattern with a 2nd laser (***read***)

Spectroscopic determination of thermodynamic state variables:

- **Pressure** (in gas) : *Basu et. al., Exp. Fluids (2010)*
- **Temperature** (in gas) : *Matthew et. al., AIAA (2015)*
- **Temperature** (in liquid) : *Natrajan and Christensen, Meas. Sci. Technol. 2009*

Simultaneous Concentration/Velocity Temperature/Velocity measurements :

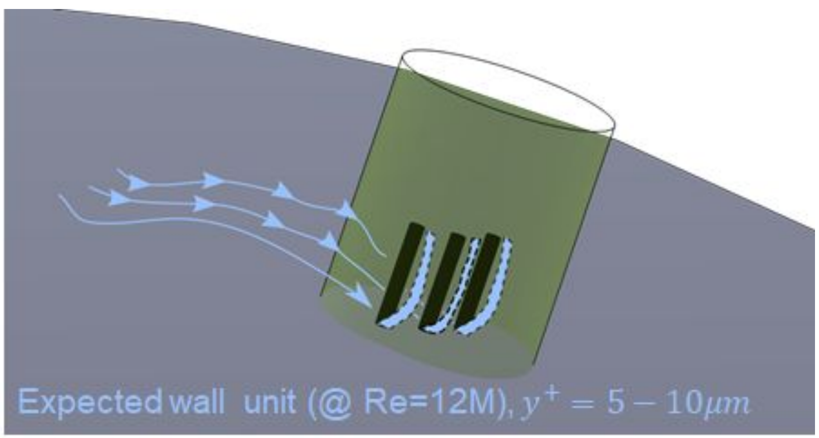
Koochesfahani et. al. Meas. Sci. Technol. 2000

Structured Illumination gives a uniform pattern along the optical axis

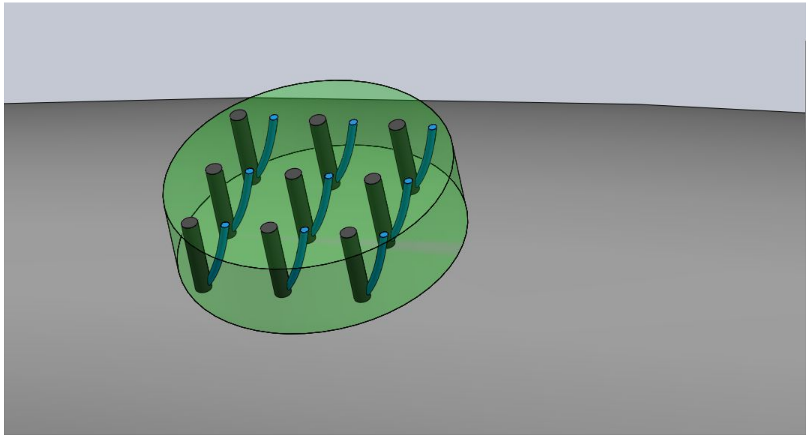
Talbot Effect Structured Illumination

<u>Goal:</u> Instantaneous 3D-2C Velocity measurements at a solid interface

Fort et al., *Exp Fluids* (2020a)



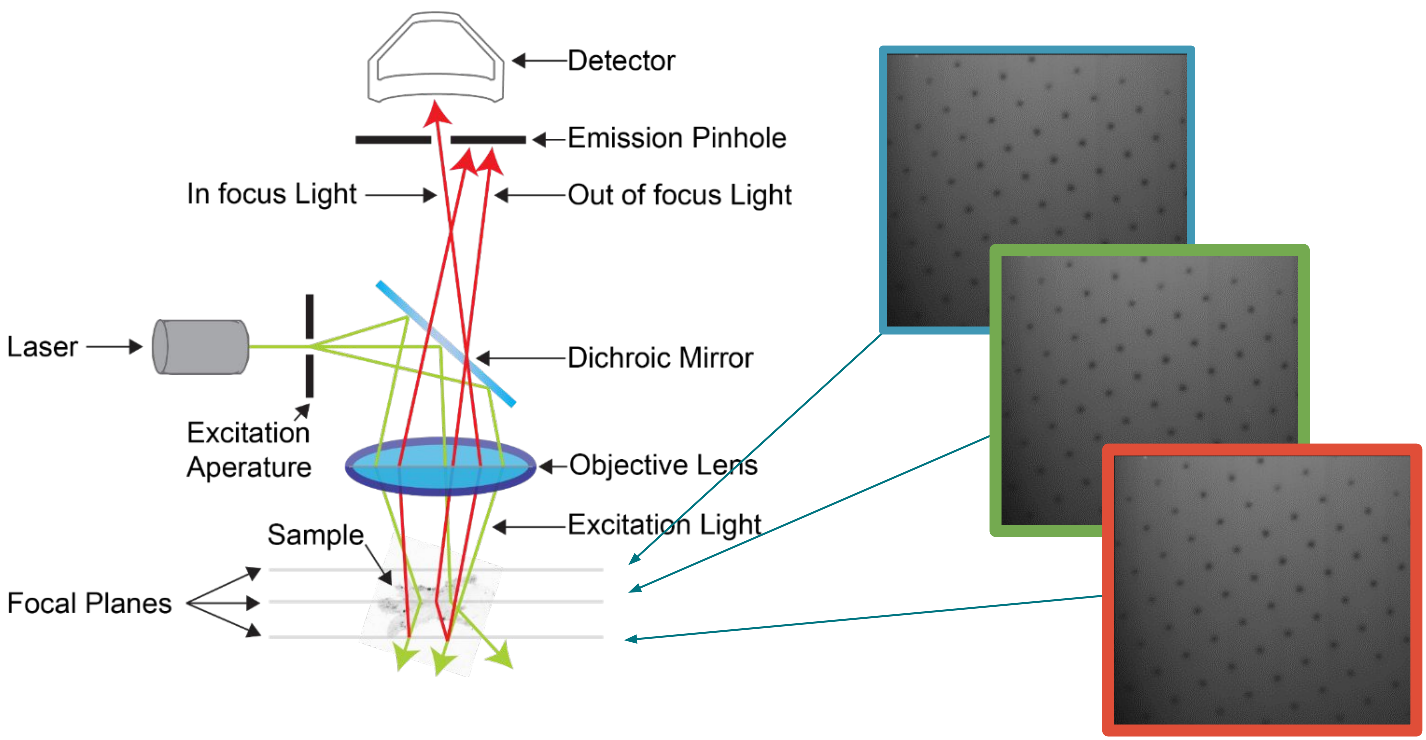
Tagged pattern (black) is deformed (blue) by the fluid flow



Optical sectioning provides in focus images at different depths

Principle of Microscopic Integral Velocimetry (MIV)

<u>Confocal Microscopy:</u> "Emission Pinhole" permits fine optical sectioning at focal planes



<u>Velocimetry (μPIV, $Shake\ The\ Box$)</u>

2 Camera Microscopy & Velocimetry

Kim et. al., Exp. Fluids (2011)

Resolution: $R_{xy} = 32\ \mu m$

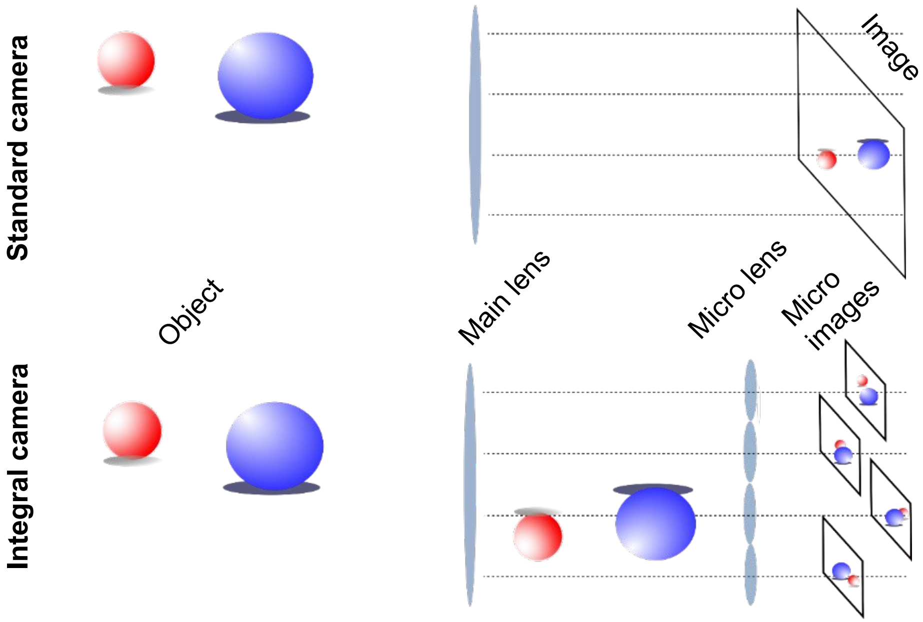
6 Camera Tomography – 4D PTV "Shake the Box"

Schroëder et. al., Flow Turbulence Combus (2015)

Reslution: $R_{xy} = 93\ \mu m$

Operational Principles of Integral Imaging

Levoy (2005)



<u>Applications</u>

- Optical aberration, temperature, and density variation characterization
Clifford et. al. , AIAA (2017)
Wilson, Mon. Not. R. Astron. (2002)

- Sensor fusion – synthetic aperture:
Levoy et al. ACM Trans. (2004)

- Optically assisted surgery:
Le et. al., Chin. Opt. Lett (2017)

<u>Design Tradeoffs:</u>

Reduce spatial resolution
Increased angular resolution

Microscopic Integral Velocimetry (MIV) Resolution

Design Criteria

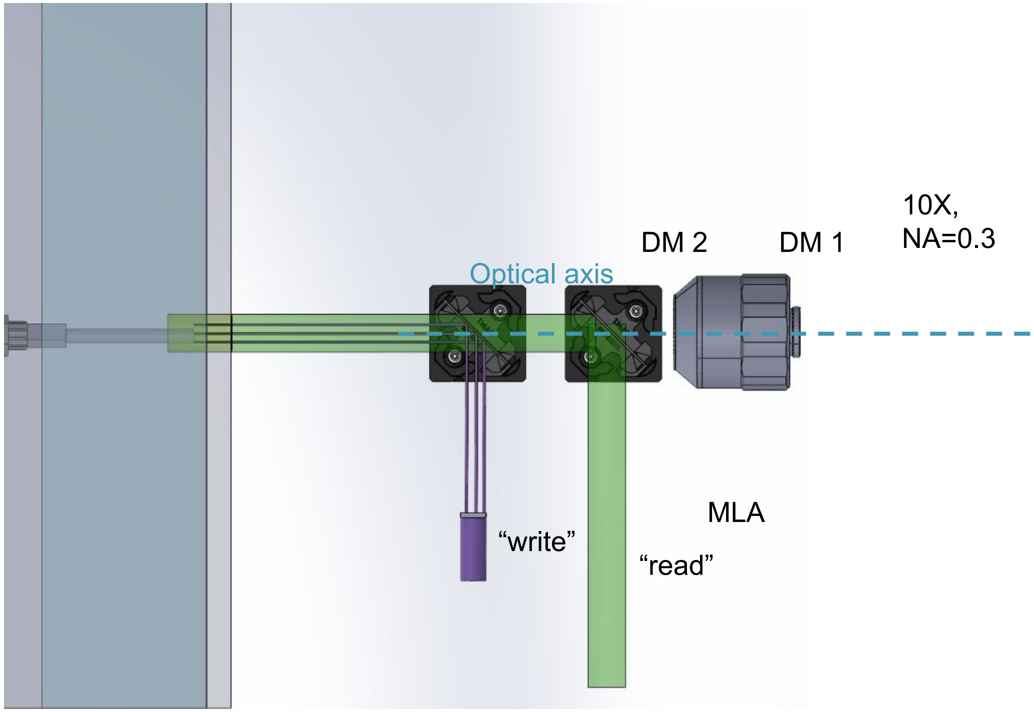
$\boldsymbol{l_\nu}(\boldsymbol{\mu}\mathbf{m}) \in [\mathbf{5}, \mathbf{11}]$ **: viscous length scales**

$t_\nu(\mu s) \in [25{,}120]$: viscous temporal scales

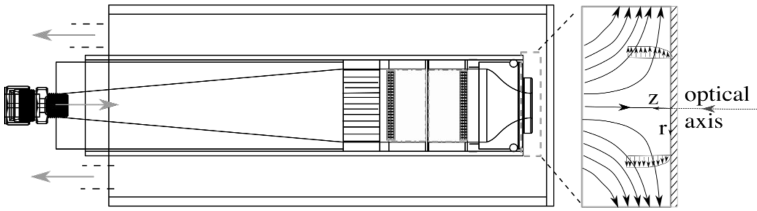
$f_s(\mathrm{kHz}) = 2(t_\nu)^{-1}$: sampling frequency $\in [16, 80]\ kHz$

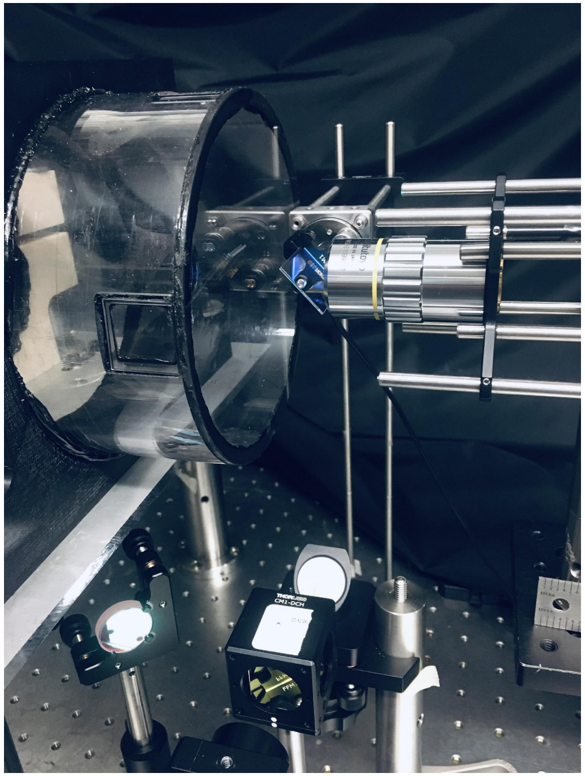
type			
Confocal M=20X NA=0.4			
FIMic M=20X NA=0.4			

Optical implementation in a newly designed facility



Stagnation Jet Facility





Validate Schlichting Theory for Axisymmetric Stagnation Jet

<u>*Similarity Solution*</u> $f''' + 2ff'' + 1 - f'^2 = 0$

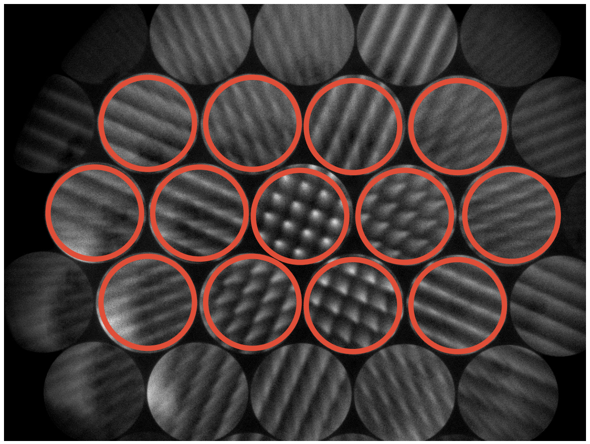
<u>*Velocity Profile*</u> $u/(\alpha r) = f'(\eta)$

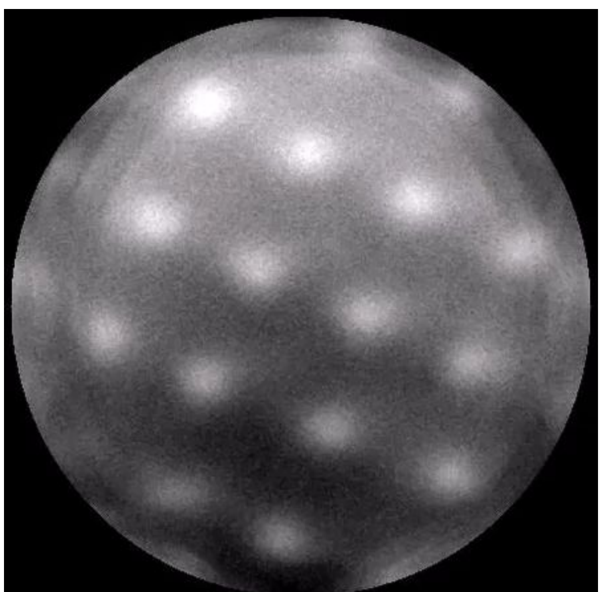
Validate Prediction for Boundary Layer Thickness

<u>*Boundary Layer Height*</u> $\delta = 2.8\sqrt{\nu/\alpha}.$

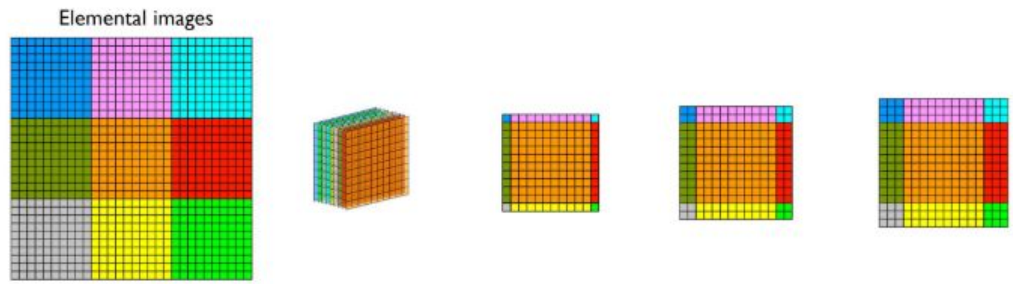
Raw (background subtracted/inverted) images

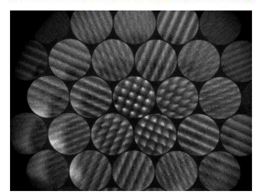
13 “mini cameras”

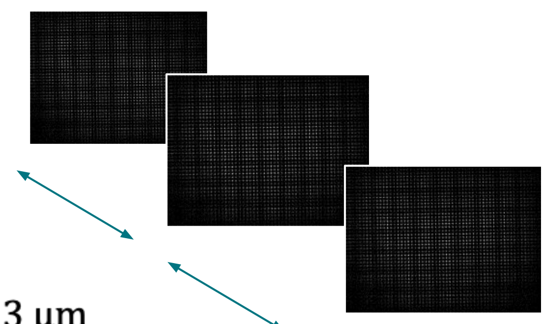




Back projection of EIs into physical space (& sum)





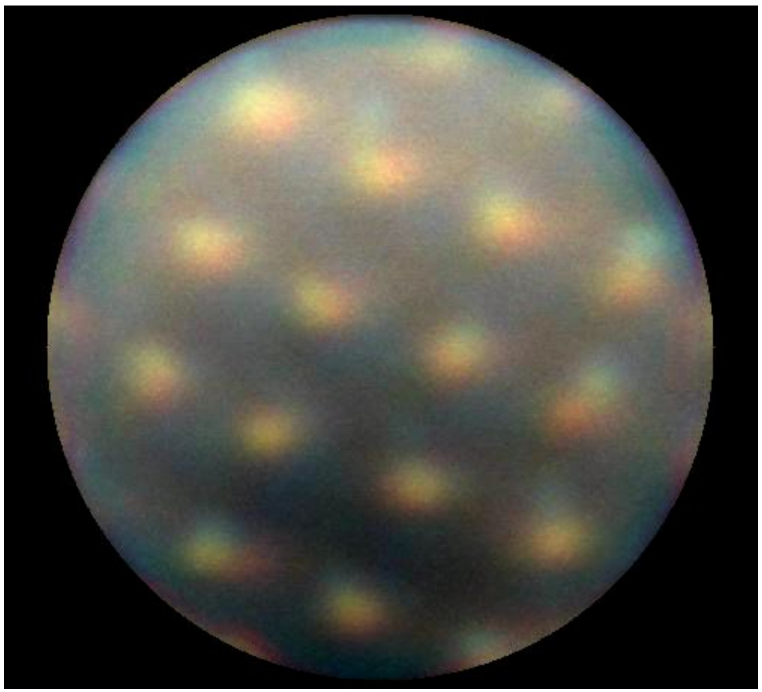


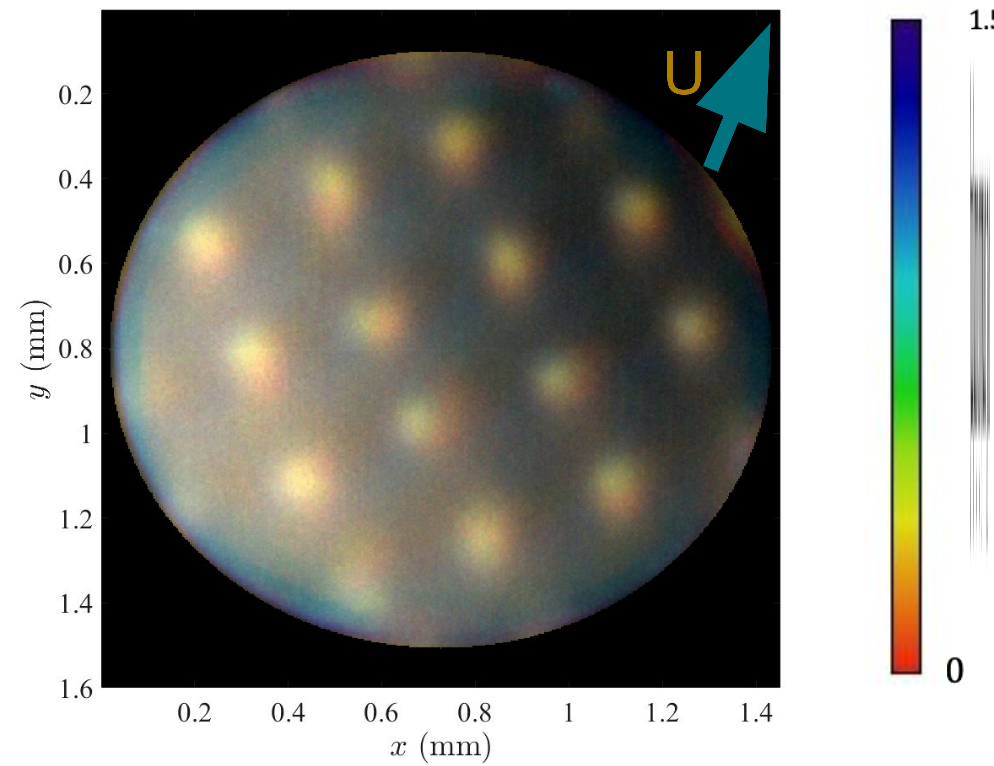
$$R_{zF} = \left(\frac{f_{MO} f_2}{f_1}\right)^2 \frac{p}{f_{MLA} D} = 33\ \mu\mathrm{m}$$

(10X , NA=0.28)

First approach to rendering

$t = 70\ \mu s$



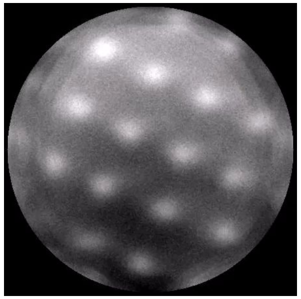


Theoretical Depth of Field $\Delta_{zF} = 260\mu m$

Theoretical Axial Resolution $R_{zF} = 33\mu m$

3D-2C Instantaneous Velocimetry

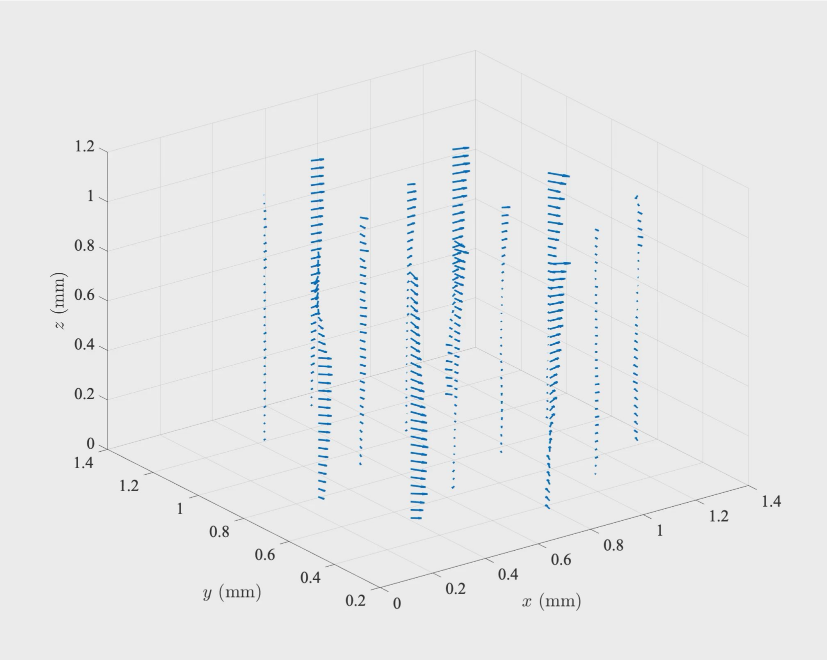
- Vertical resolution (33 μm), smooth gradients
- Lateral resolution (300 μm), probe
- Probe resolution (30 μm)
- 3D structures apparent



Huck et. al. , NURETH 19, 2022.

***Huck** et. al.*, International Symposium on Applications of Laser and Imaging Techniques to Fluid Mechanics Lisbon, 11-14 July 2022

Huck et. al. , Symposium Naval Hydrodynamics 2022.



The NSSC Experience

NSSC involvement has broadened my scientific culture and opened up doors professionally.

- ”Non-destructive testing”. NSSC conference series, Dr. Steve Glenn, LLNL.

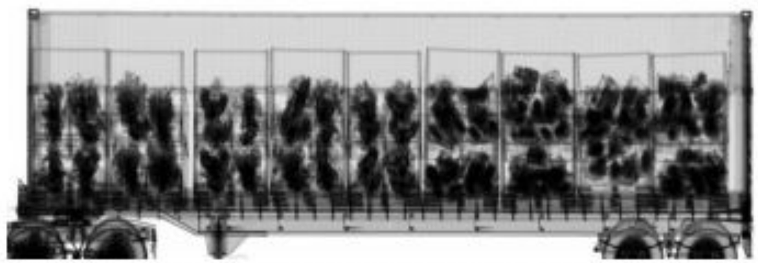


Fig. 3. Example cargo radiograph from a Smiths Detection HCVP NII system.

Martz et. al., IEEE Transactions Nuclear Science, 2016

- Networking and gained understanding of role of hydrodynamics in National Laboratory Research

Phoenix APS DFD 2021 November 21-23

Los Alamos NATIONAL LABORATORY

- Under consideration for ”*Experimental Physicist Position*” , Lawrence Livermore National Lab

WCI WEAPONS AND COMPLEX INTEGRATION

Lawrence Livermore National Laboratory

Acknowledgements

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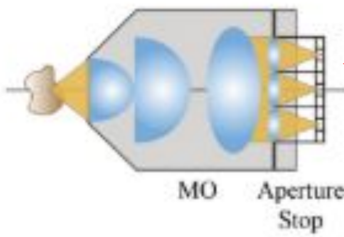
The geometry of Fourier Integral Microscopy (FIMic)

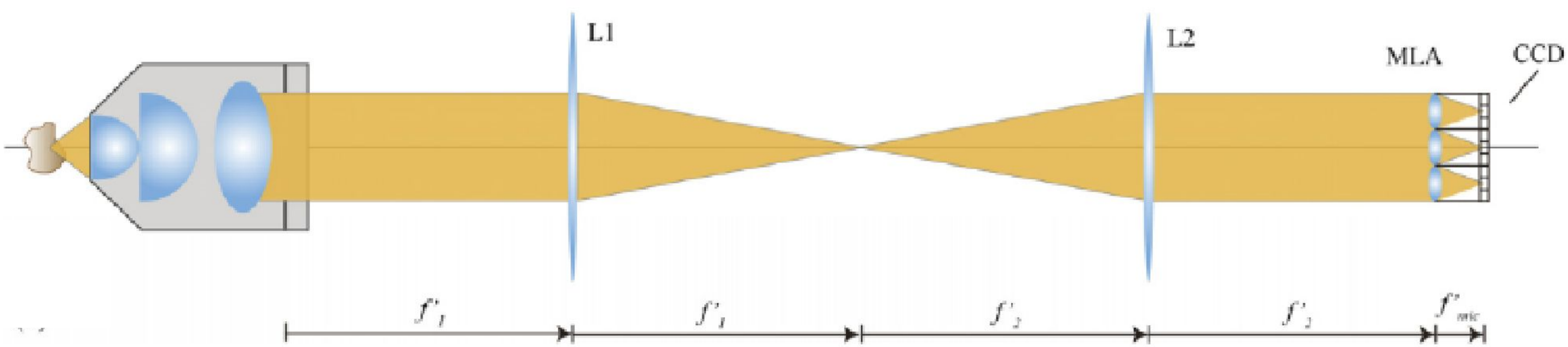
Principle

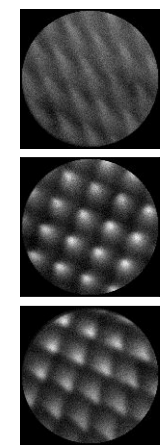


N microlenses (in diagonal) subsample the aperture (of Fourier) plane of the microscope objective

$$NA_{FIMic} = \frac{NA_{MO}}{N}$$

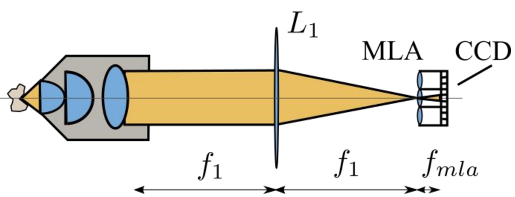
Practical implementation





Three approaches to Integral Microscopy

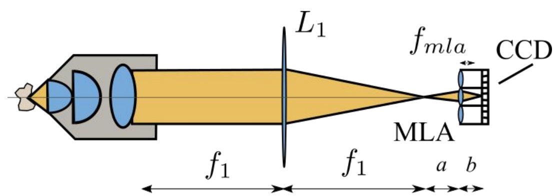
Plenoptic 1.0



- High angular (depth) resolution
- Low spatial (lateral) resolution

Plenoptic 2.0

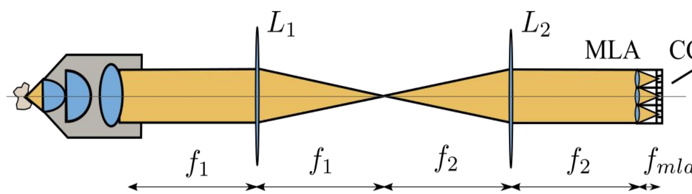
***Huck** et. al. , NURETH 19, 2022.*



- High spatial resolution
- Extended depth of field
- Long Working Distance
- Low angular resolution
- Black box post-processing
- High Resolution (>25MP) cameras (low acquisition rate)

Fourier Integral Microscopy - FIMic

***Huck** et. al. , Provisional Patent - Wall Shear Stress Optical Probe, 2022.*



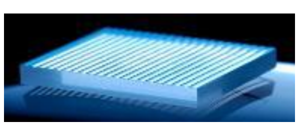
- Higher spatial resolution
- Flexible design and operation. Active community (open source)
- Modest Resolution (~5-16MP) cameras (high acquisition rate)
- Restricted depth of Field. Small working distance

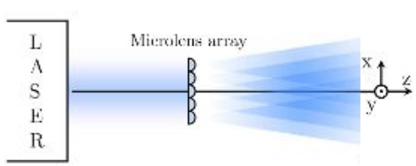
Talbot-effect structured illumination (TESI) generates fine and flexible laser patterns

<u>Structured Illumination</u>: **intensity *modulation*** of excitation light in the spatial domain.

Device	Reference	p (mm)	w (mm)
Beam blockers	Roetmann et. al. (2008)	0.48	0.16
Ronchi gratings	Charogiannis et. al. (2019)	0.2	0.1
Beam Dividers	Chu and Liao (1992)	2	0.15
Micro lens array	Sheng et. al. (2017)	0.5	0.3
Talbot Effect	Fort et. al. (2020)	0.038	0.017

<u>TESI</u>: **Interferometric** technique for flexible Creation of small-scale patterns





Talbot distance:

$$z_T = \frac{p_0^2}{\lambda}$$

Pattern periodicity varies along **z**

$$p\left(z = \frac{M}{N} z_T\right) = \frac{p_0}{N}$$

<u>Further uses:</u>

- Sub probe-volume resolution in LDV :

Konig et. al. , Meas. Sci. Technol. (2017)

- Vibration monitoring and profilometry :

Agarwal et. al., Opt. Eng. (2018)

Spagnolo et. al., J. Opt. A. Pure Appl. Opt. (2002)

- Extreme UV Lithography :

Isoyan et. al., J. Vac. Sci. Technol. , (2009)