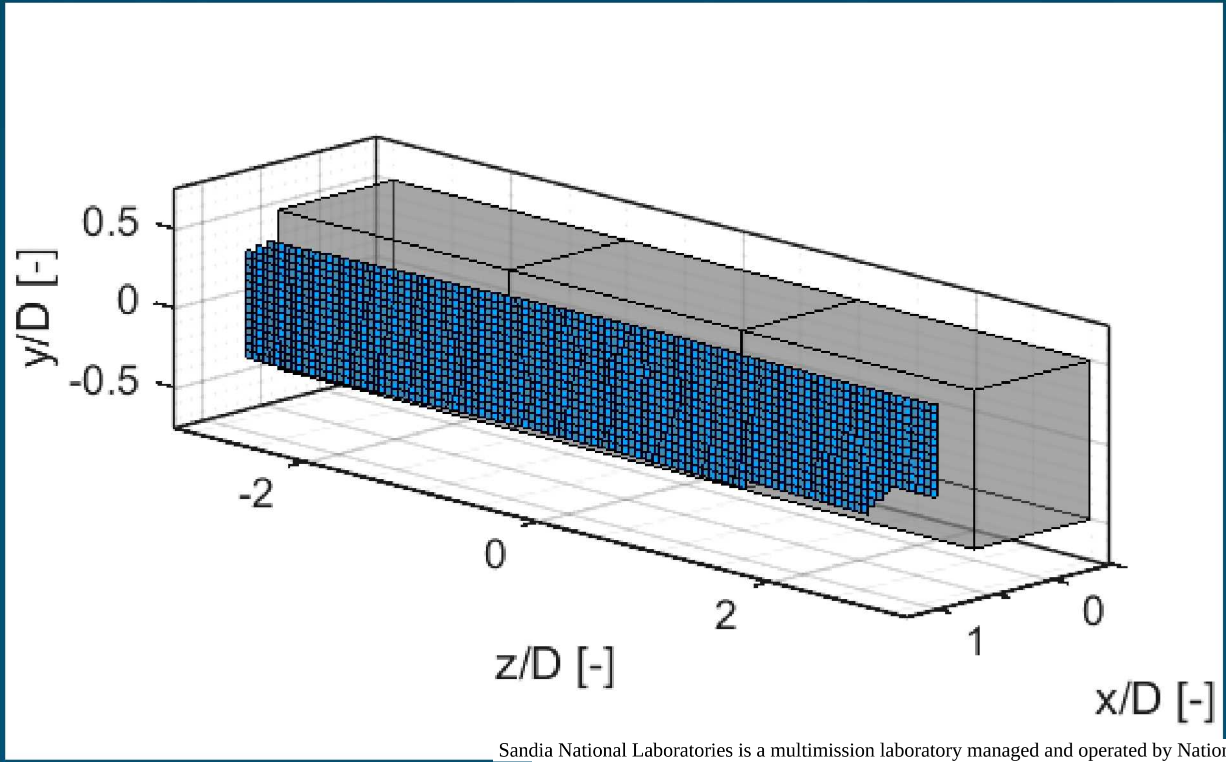
This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

Sandia National Laboratories

SAND2019-12661C

Investigation of fluid-structure interactions in a shock tube using digital image correlation



Elizabeth M. C. Jones
Kyle P. Lynch
Enrico C. Quintana
Phillip L. Reu
Jeremy W. James
Benjamin R. Halls
Justin L. Wagner

Sandia National Laboratories, Albuquerque, NM, USA

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tland, OR

Acknowledgements

Paul Farias, Seth Spitzer, Tom Grasser

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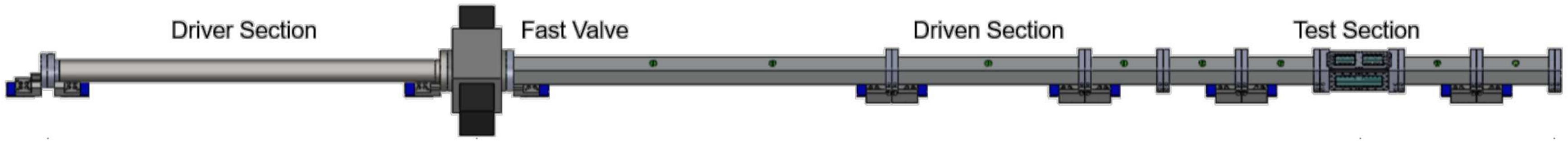
Sandia National Laboratories

Why are Fluid-Structure Interactions (FSI) important?

Tacoma Narrows Bridge destruction caused by FSI

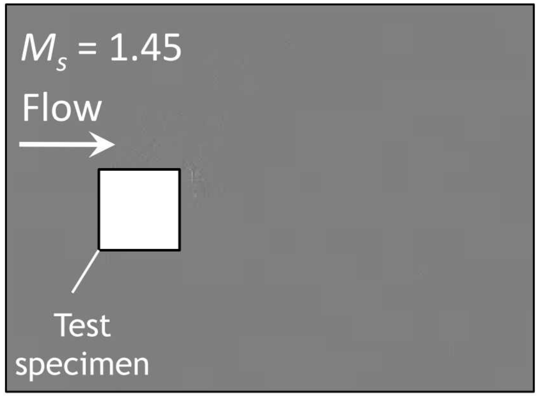
https://en.wikipedia.org/wiki/Tacoma_Narrows_Bridge_(1940)

A canonical experiment was designed in a shock tube, to develop diagnostics for FSI measurements.



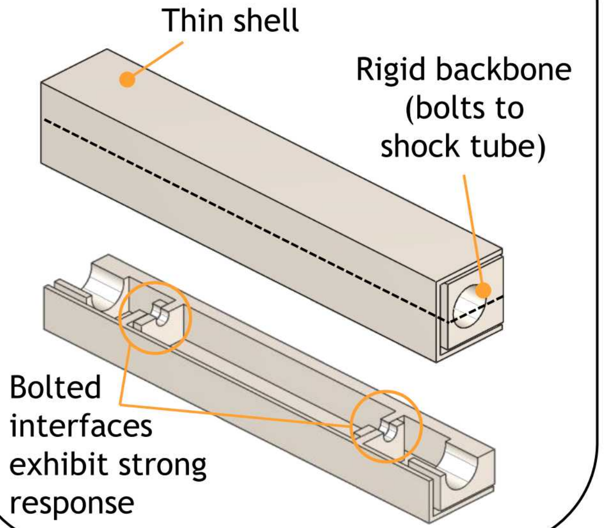
Shock tube creates impulsive start and periodic vortex shedding loads → **Fluid loads a jointed beam structure** → **DIC is used to measure the response of the structure**

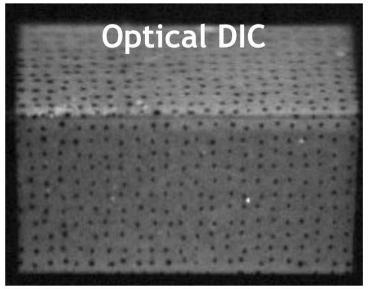
Schlieren video of wake behind test specimen

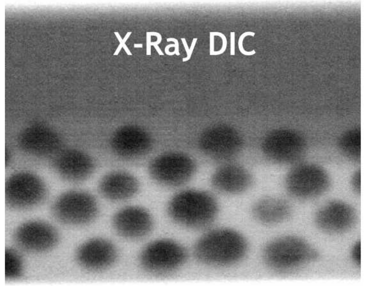


Schlieren imaging shows density gradients in the fluid.

Test specimen: Stainless steel bolted beam



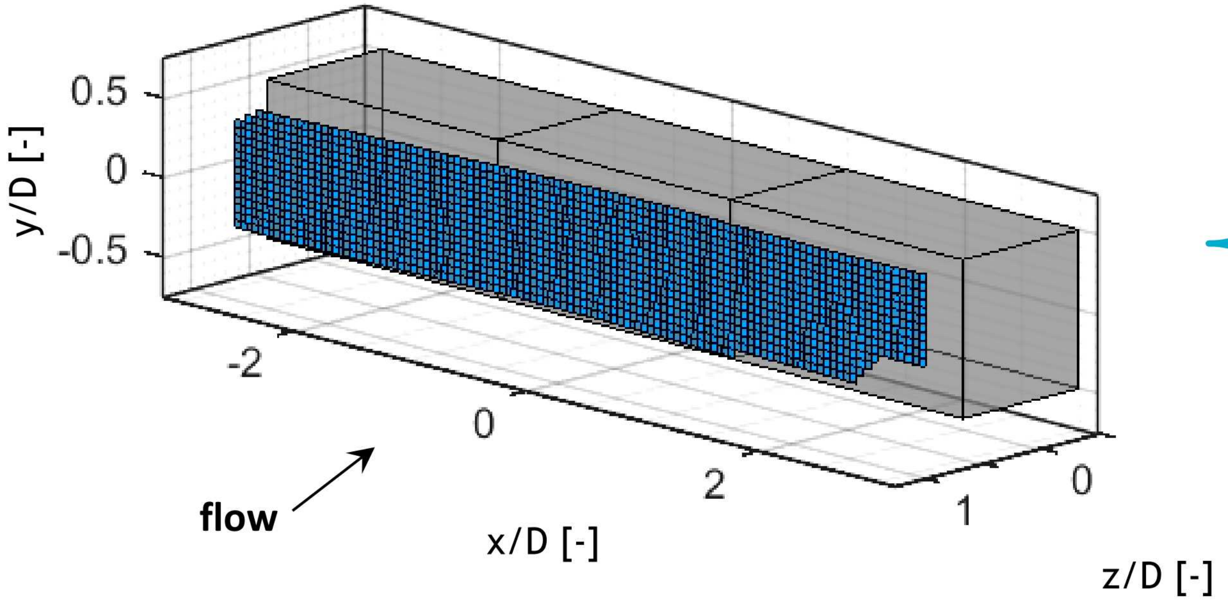




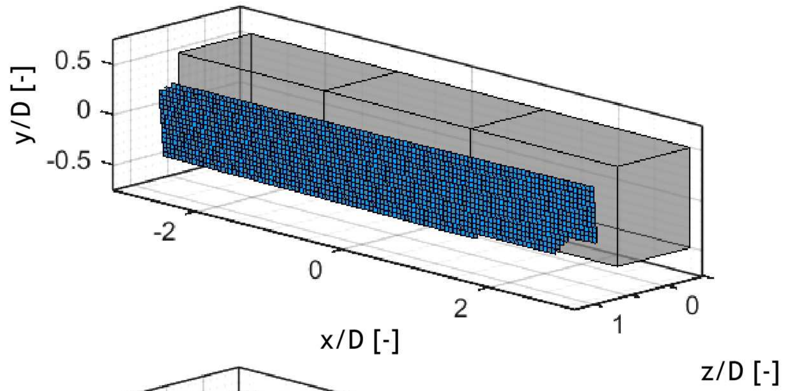
Primary goal: measure the input fluid loading and output structural response, to test the predictivity of constitutive models on jointed structures, under real fluid dynamic loading.

Spoiler Alert!

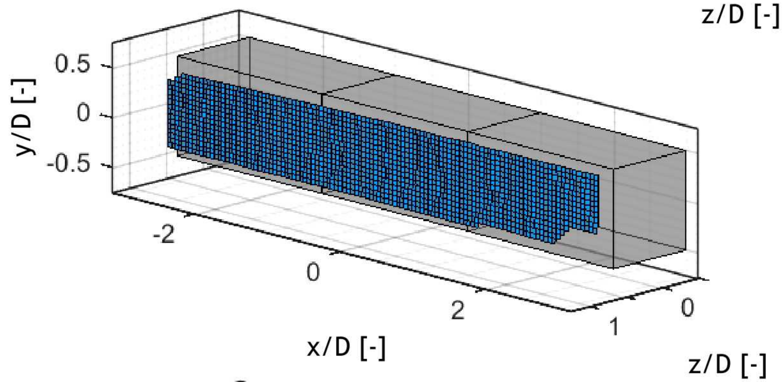
Motion of the front surface of the beam.



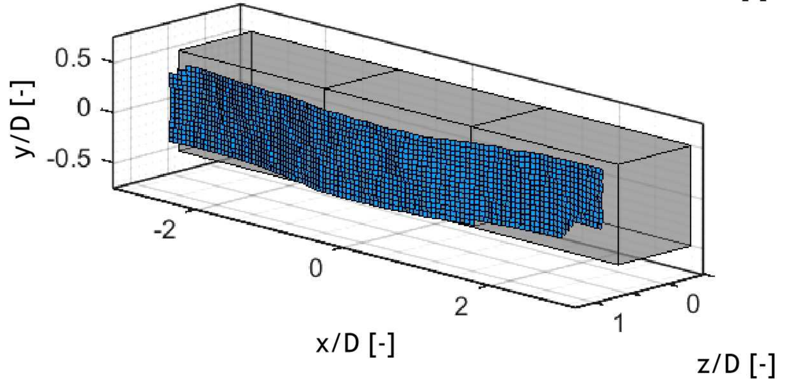
Actual magnitude of displacement is approximately 5-50 μm.



Mode 1: "Rocking"



Mode 2: "Impact"



Mode 3: "Bending"

Higher order terms

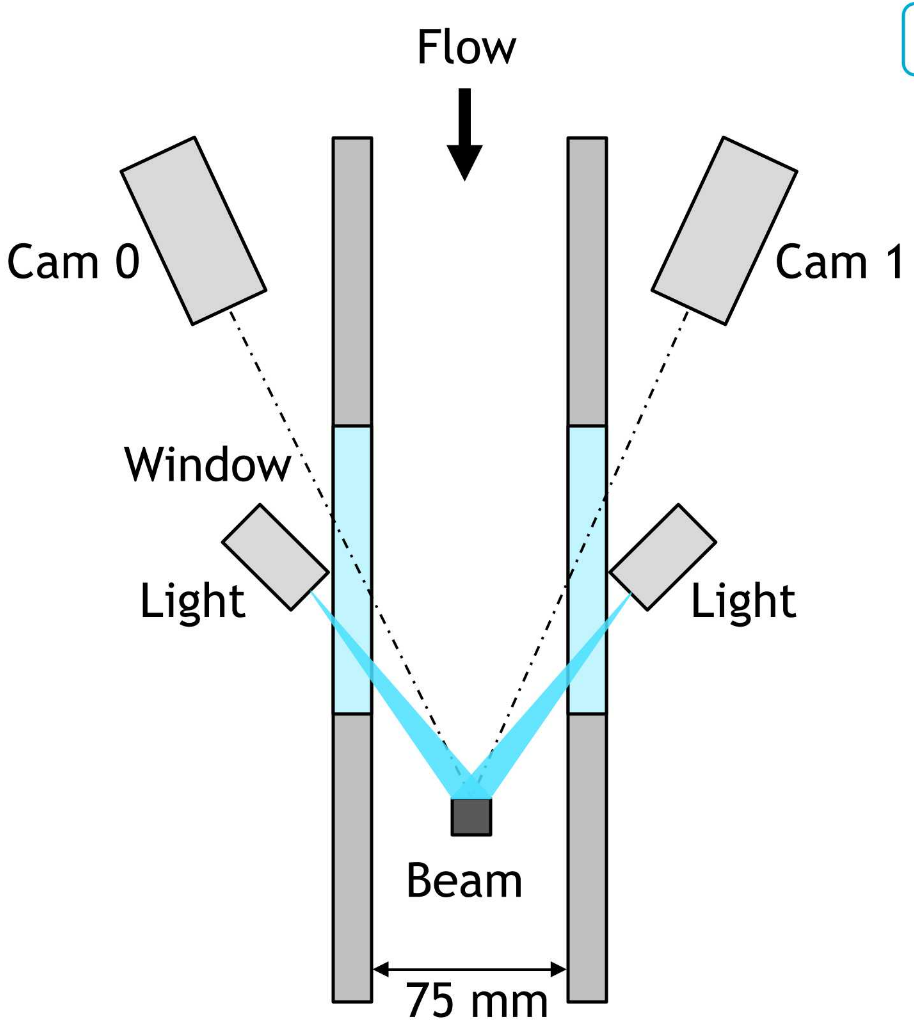
- Higher-order bending modes
- High spatial frequency bias errors from refraction

Optical and X-Ray DIC were both developed to measure the beam motion.

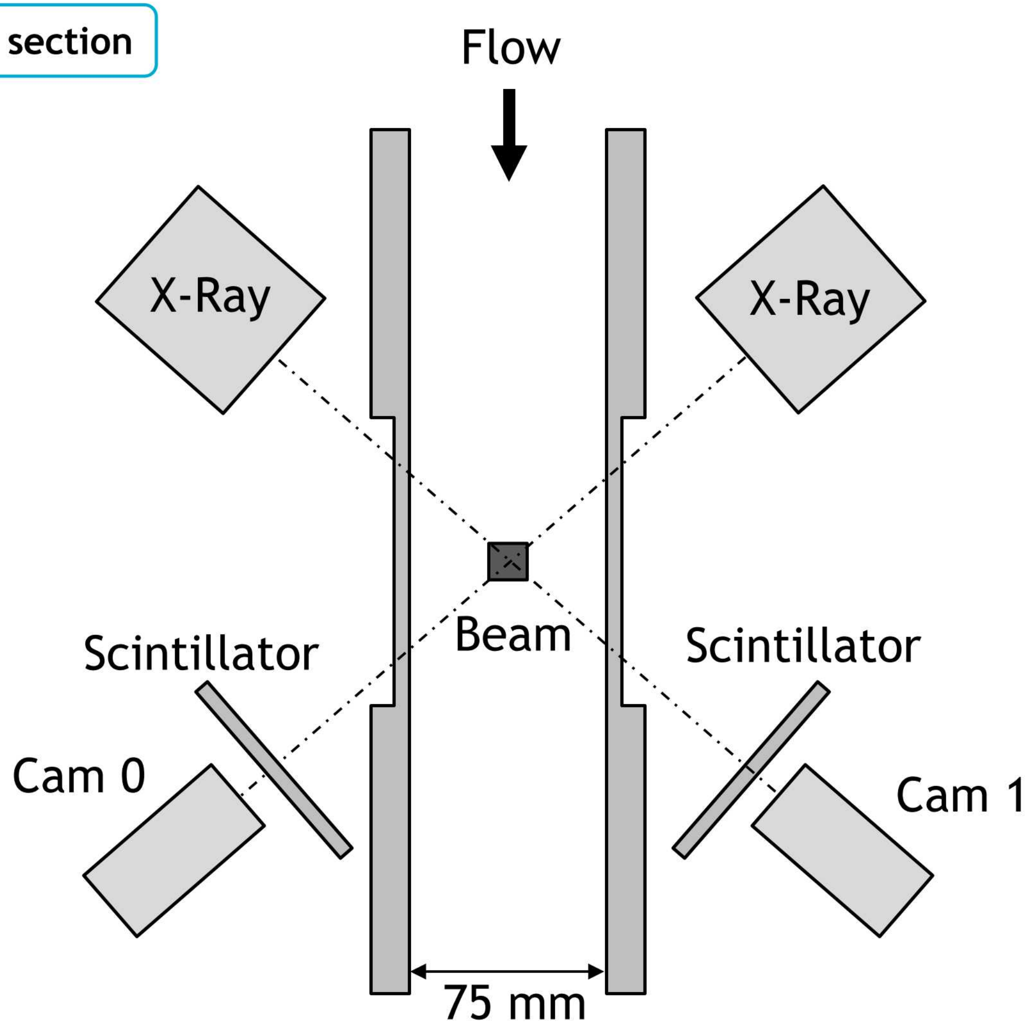
Top-view of test section

Optical DIC

(combined with pressure sensitive paint)

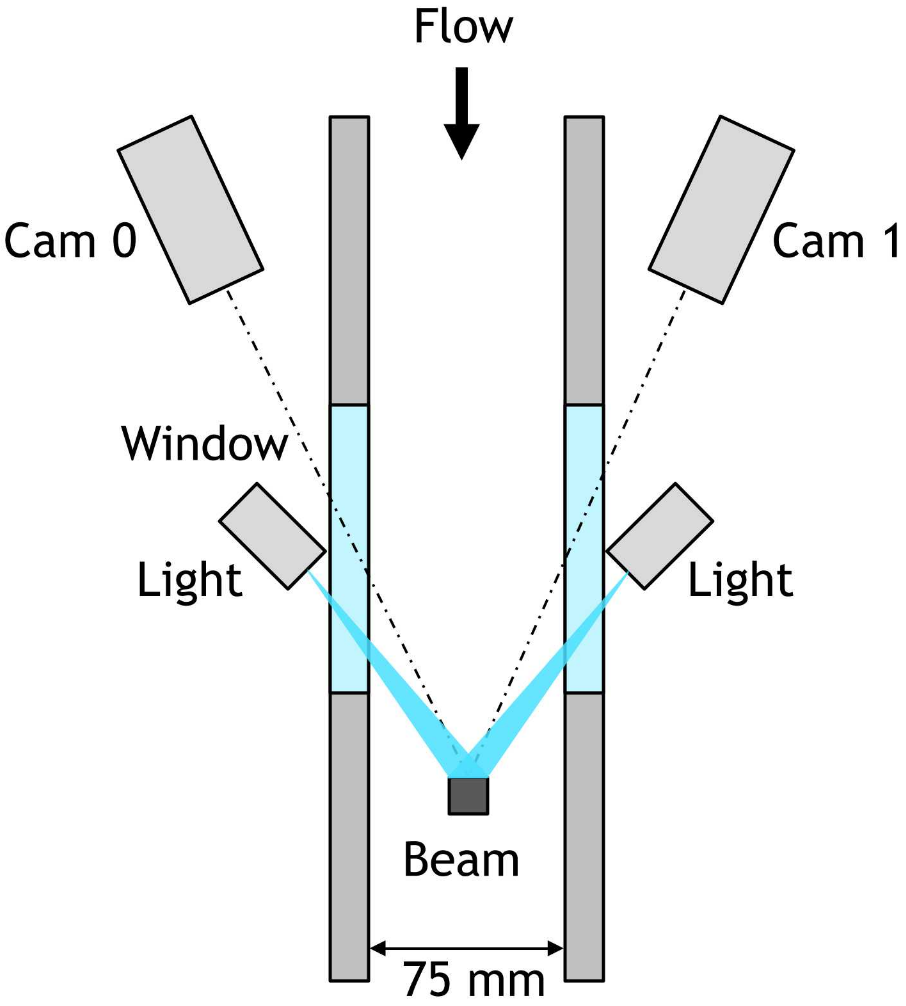


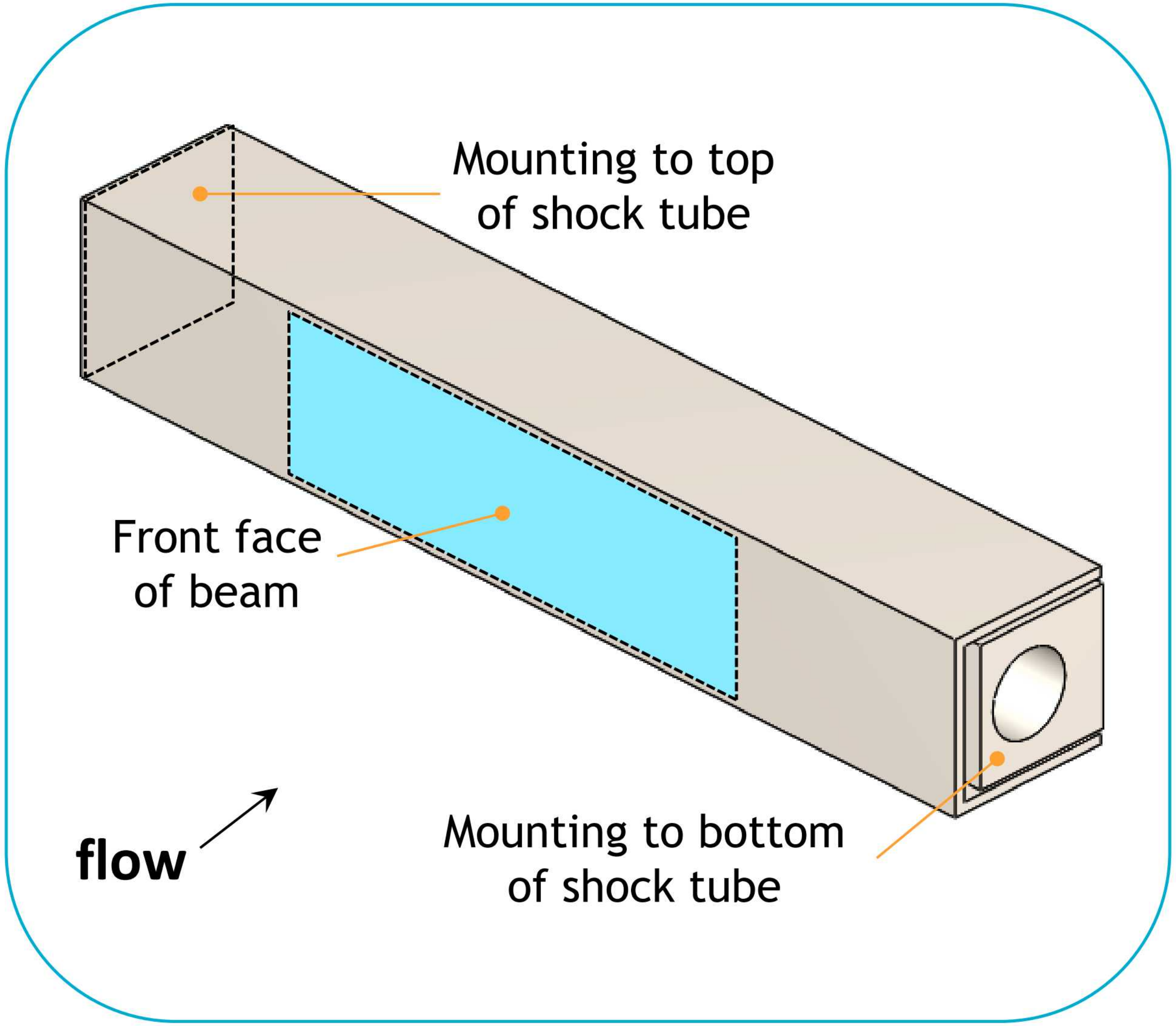
X-Ray DIC



Optical and X-Ray DIC were both developed to measure the beam motion.

Optical DIC
(combined with pressure sensitive paint)



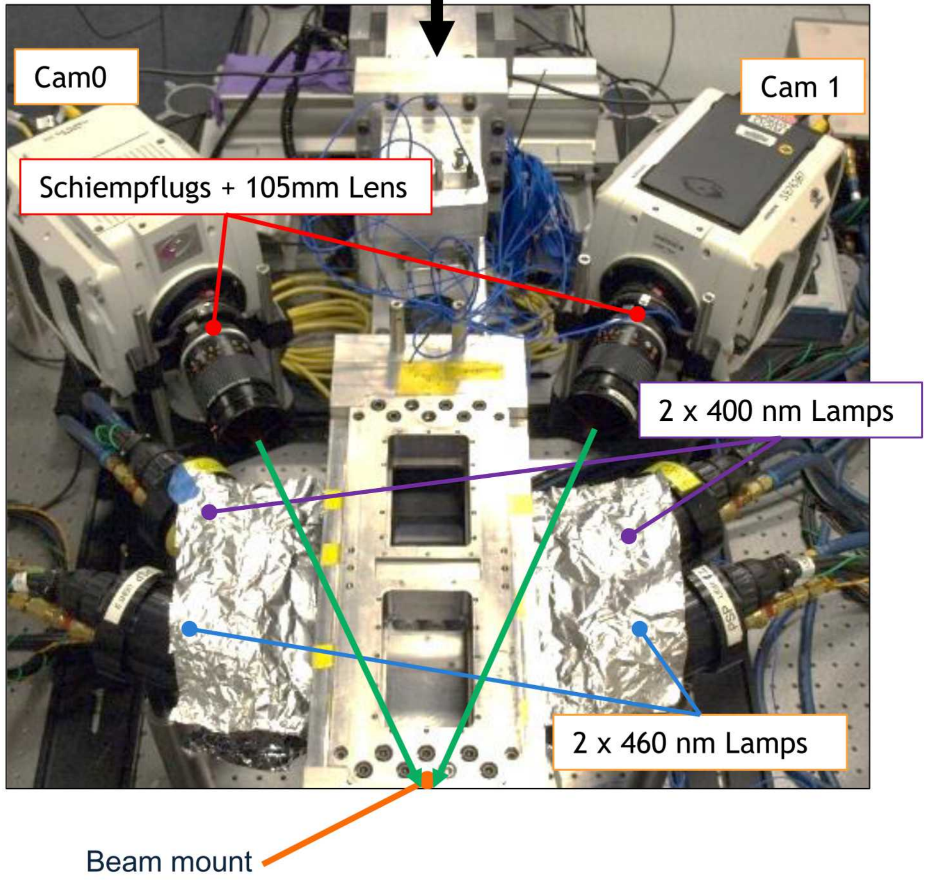


Optical and X-Ray DIC were both developed to measure the beam motion.

Optical DIC

(combined with pressure sensitive paint)

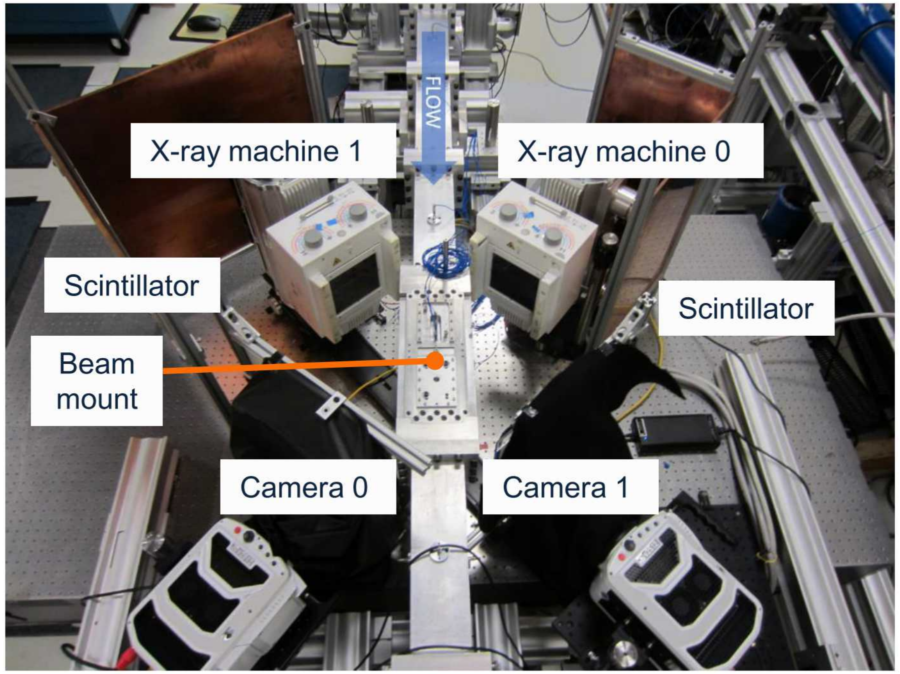
Flow



20 kHz image acquisition

X-Ray DIC

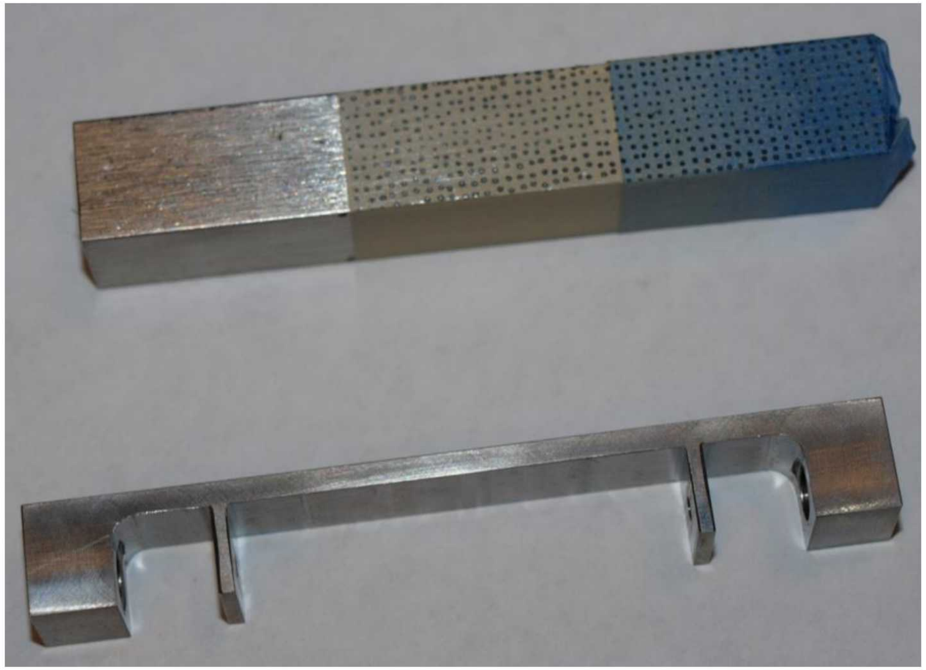
Flow



10 kHz image acquisition

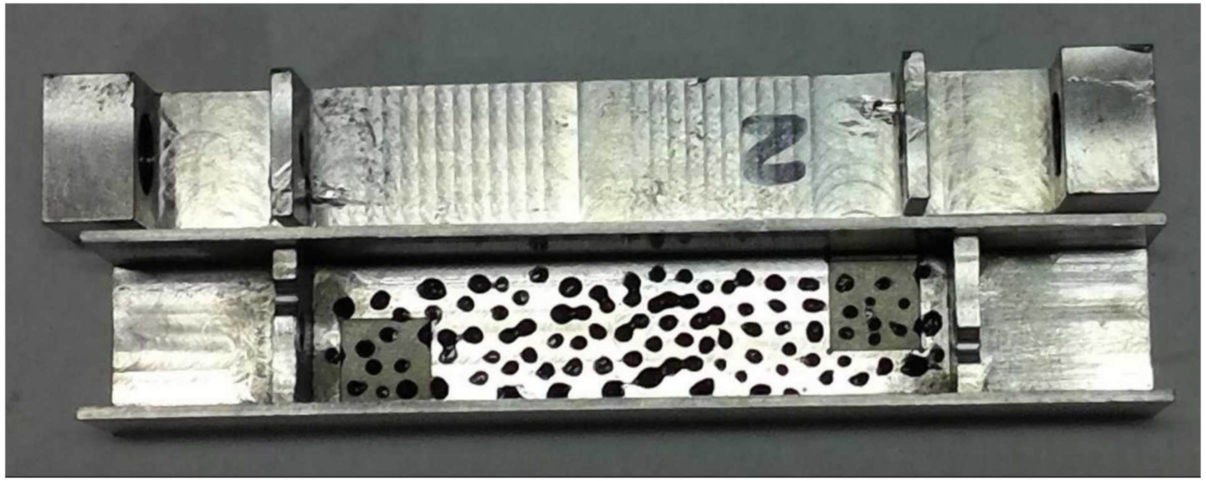
Specialized DIC patterns were applied to the beam.

Optical DIC
(combined with pressure sensitive paint)



- Base layer of pressure sensitive paint
- Sparse pattern applied with ink stamp
- Pattern applied on front face of C-shell
- Central 25 mm patterned

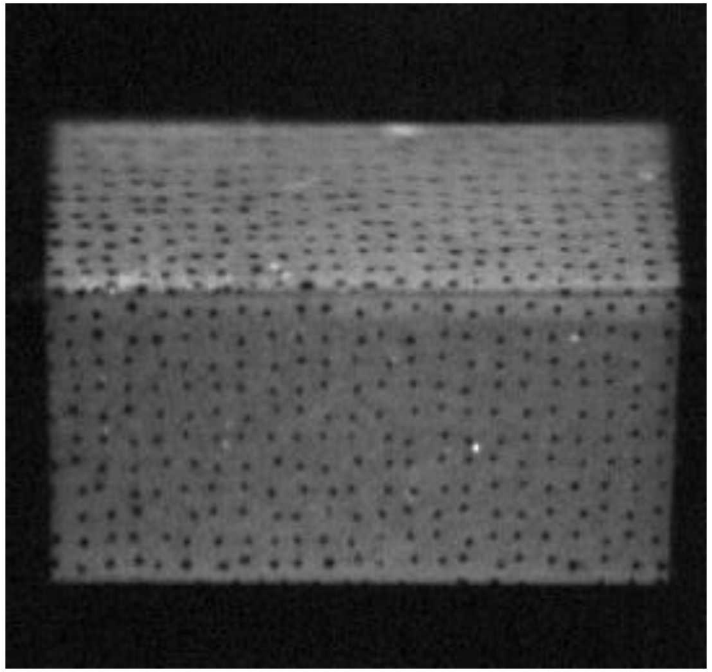
X-Ray DIC



- Ta powder mixed with epoxy
- Dots applied by hand (can be optimized)
- Pattern applied on *interior* of C-shell
- Central 50 mm patterned

Specialized DIC patterns were applied to the beam.

Optical DIC
(combined with pressure sensitive paint)



- Base layer of pressure sensitive paint
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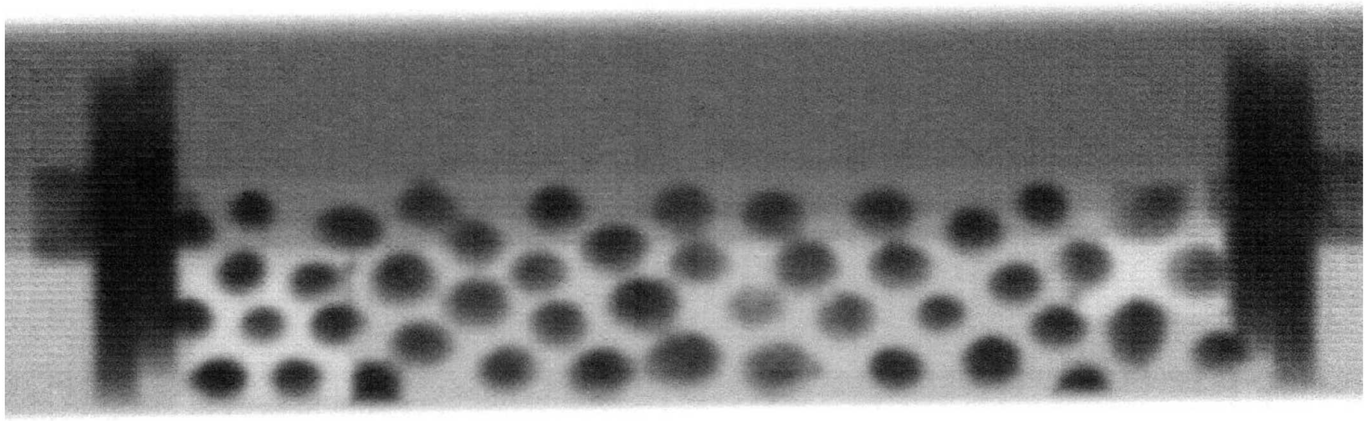
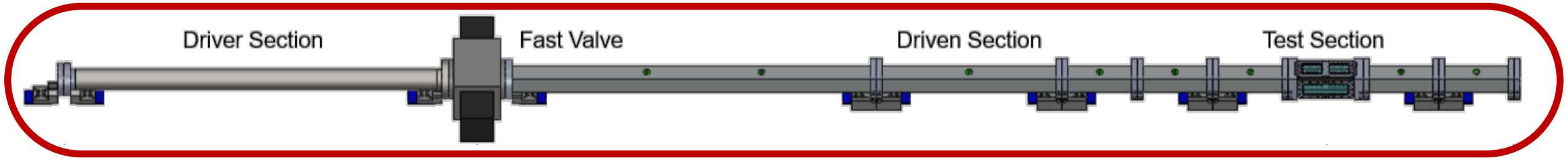
X-Ray DIC

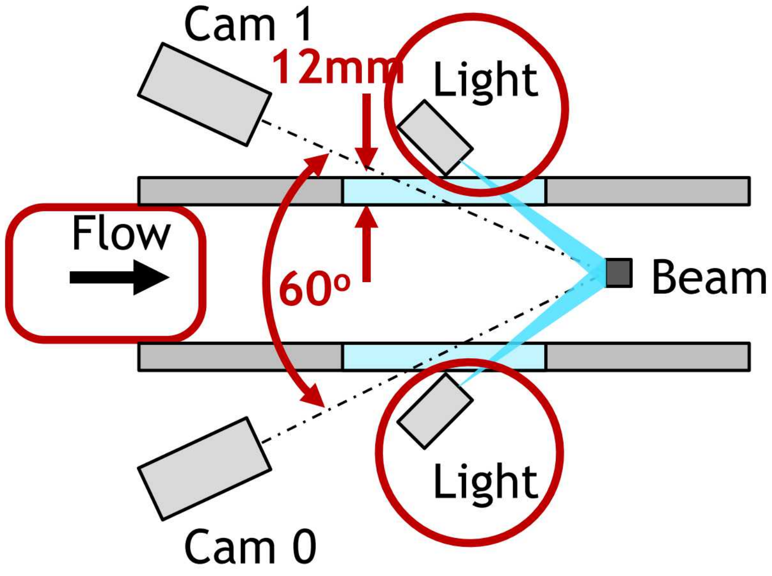


- Ta powder mixed with epoxy
- Dots applied by hand (can be optimized)
- Pattern applied on *interior* of C-shell
- Central 50 mm patterned

Many challenges must be overcome to obtain accurate and precise optical DIC measurements of the beam.



Top view of test section

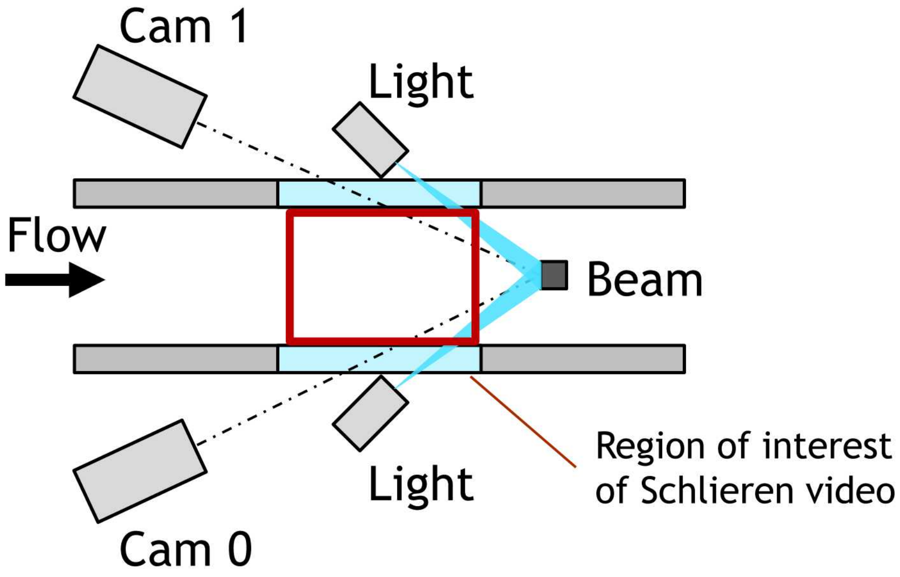


Challenges:

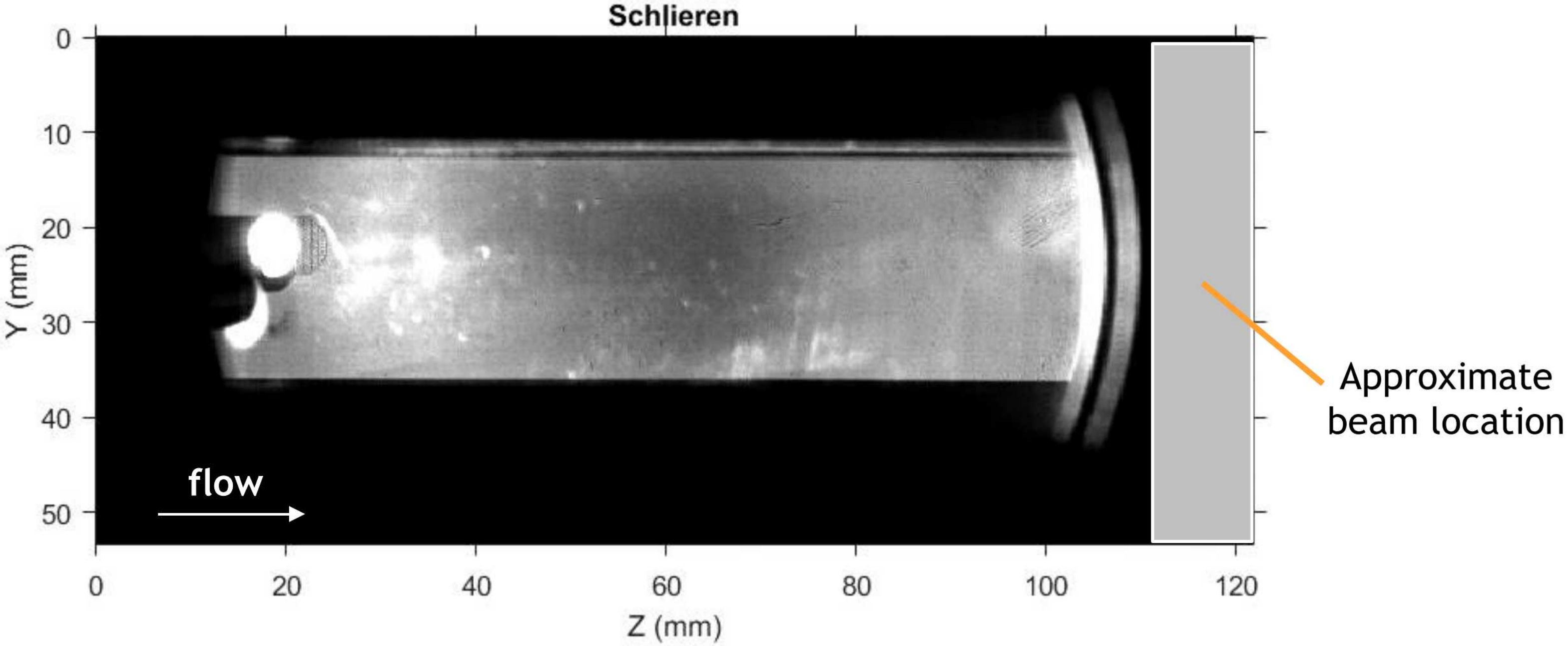
1. Severe astigmatism distortions
2. Refraction and diffraction due to time-varying wavelength of lights
3. Low-frequency shock tube recoil
4. Refraction through fluid density gradients

Schlieren imaging shows density gradients in the fluid, from the initial shock front, reflected shocks, and turbulence.

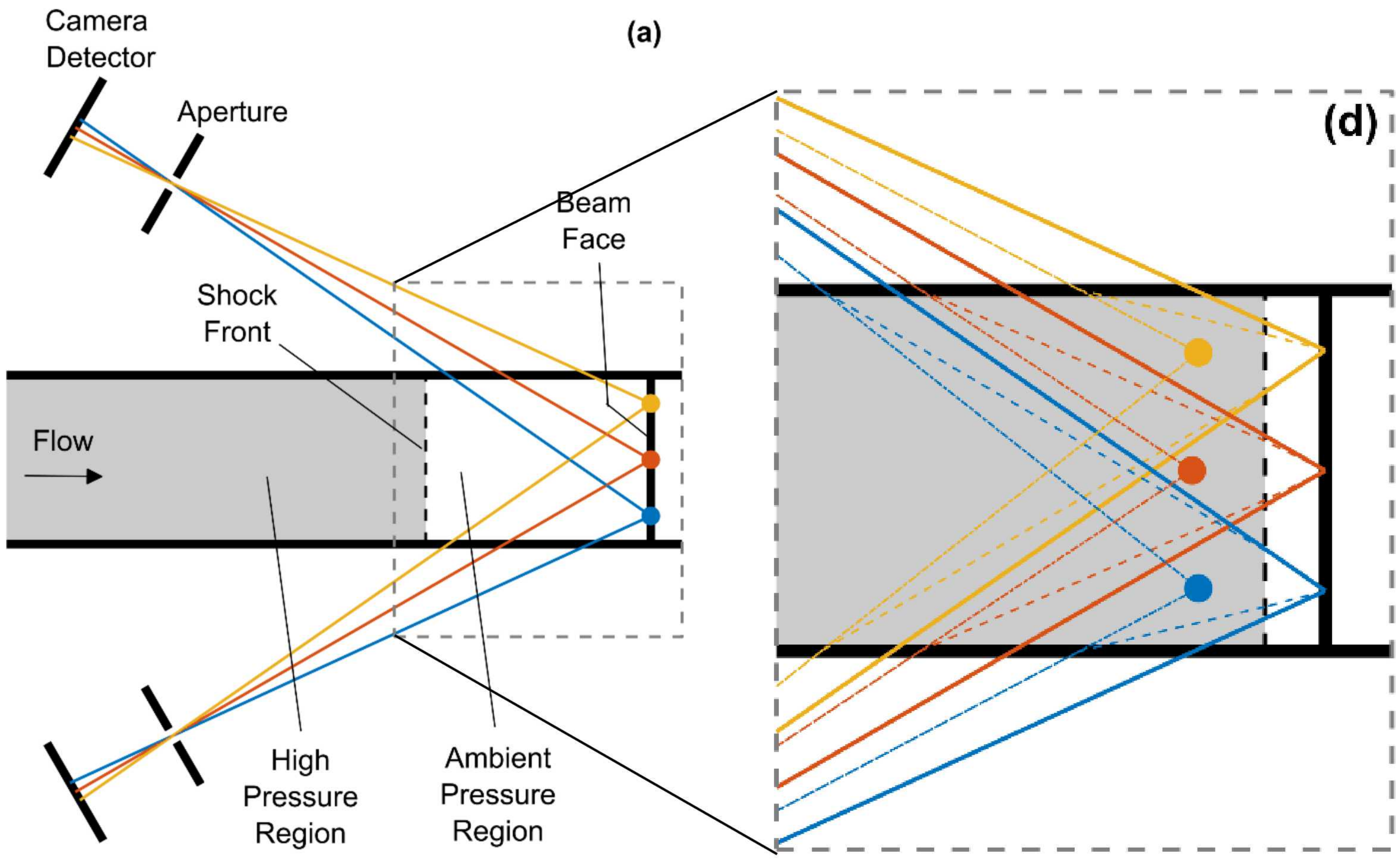
Top View



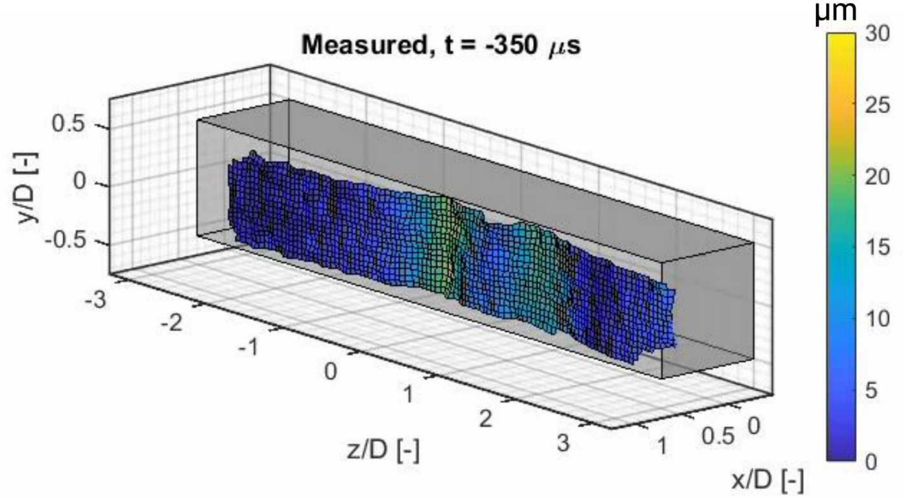
Side View

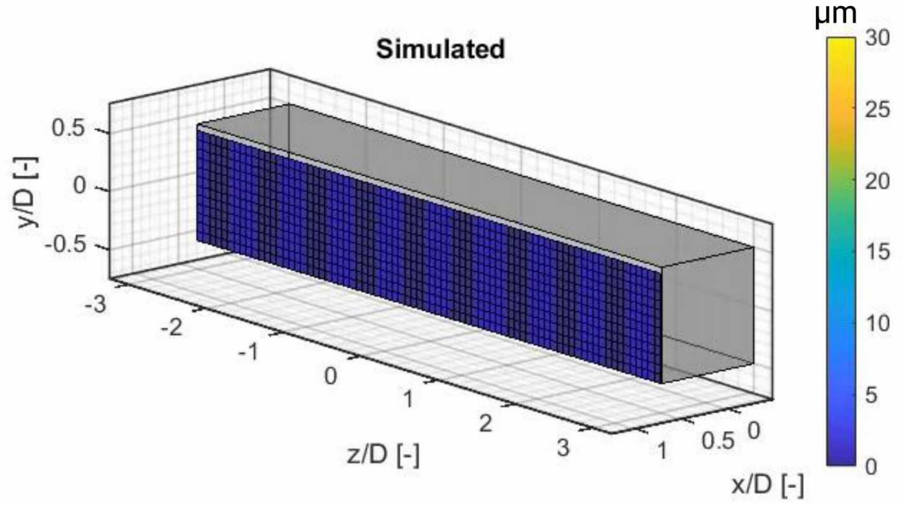


False displacements from shock front are explained through a simple ray-tracing model.



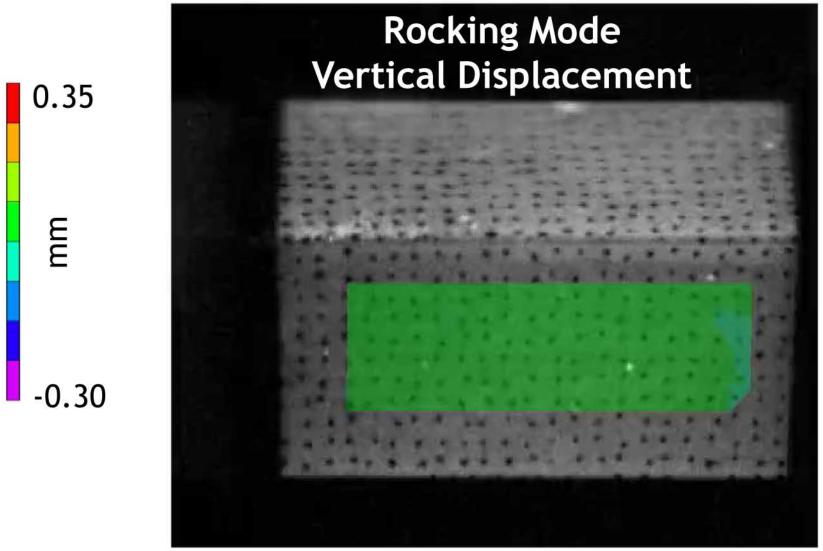
Displacement error due to refraction through shock front

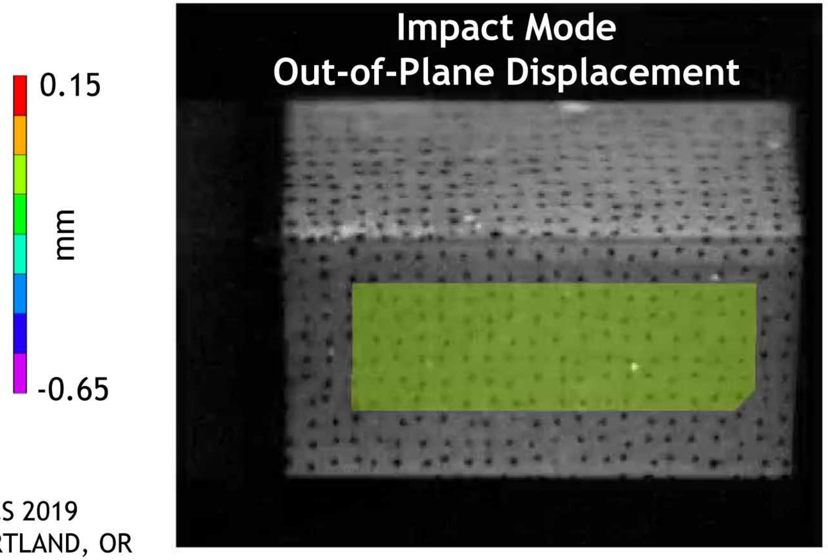




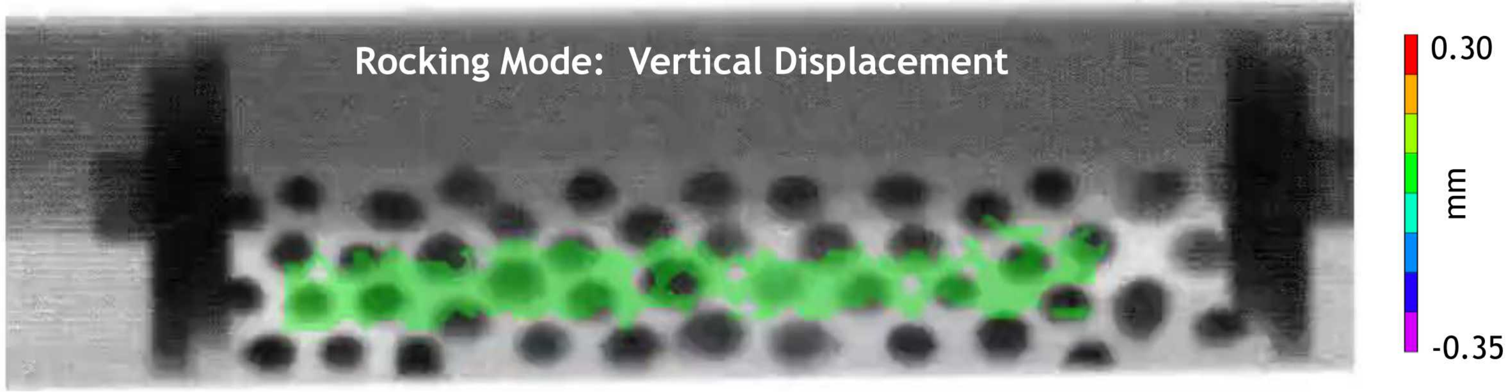
Optical and X-ray DIC were applied to measure beam motion in the shock tube.

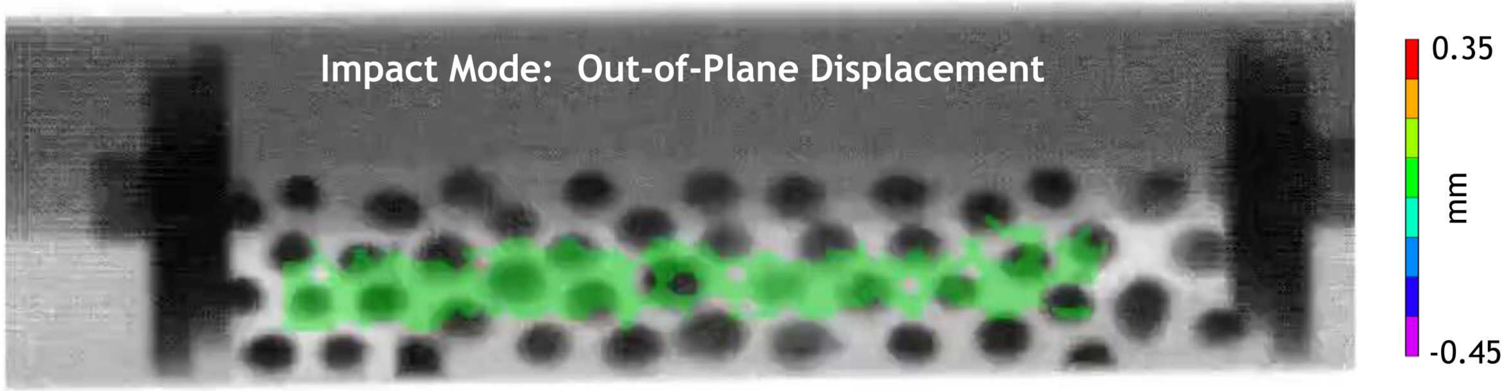
Optical DIC Results

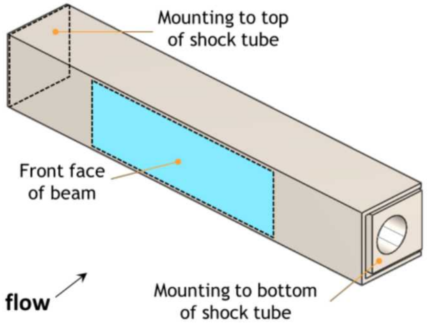




X-Ray DIC Results



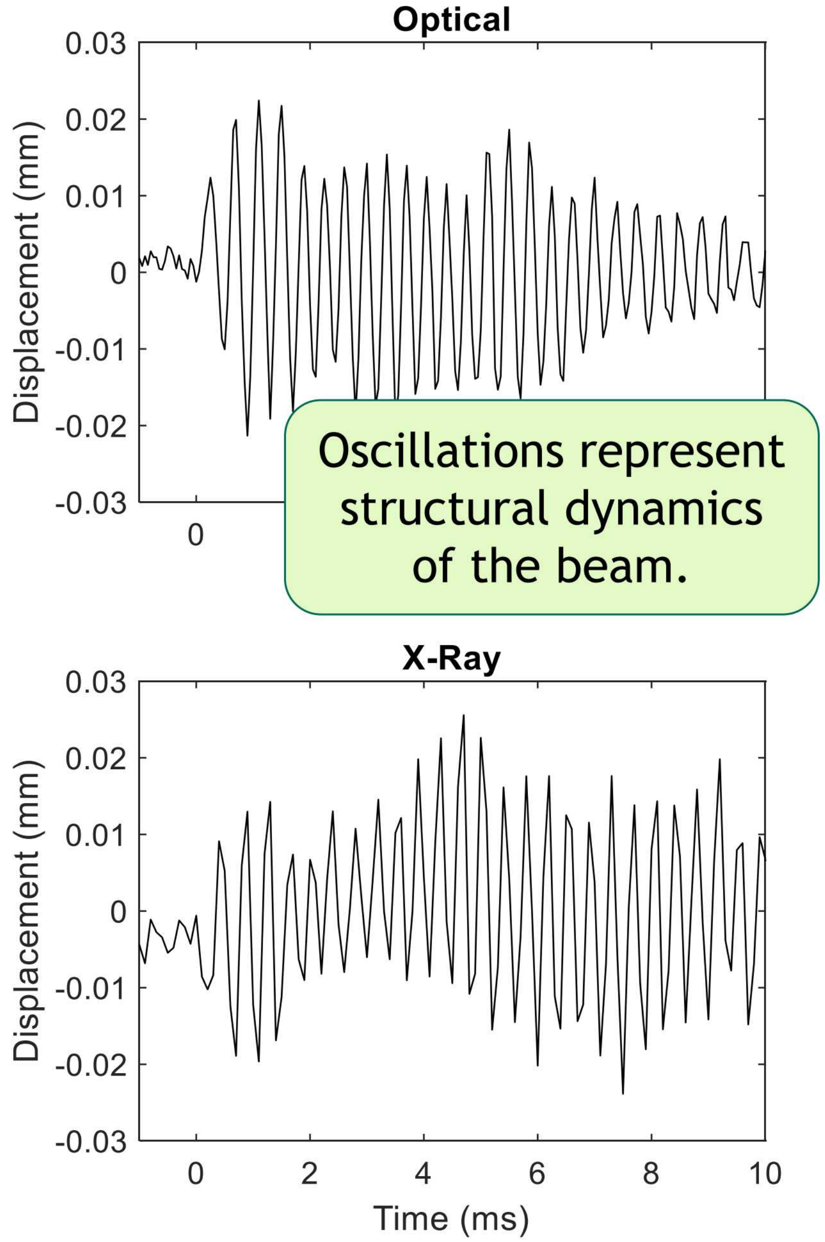




X-ray DIC elucidates beam motion that was previously obfuscated by bias errors in optical DIC.

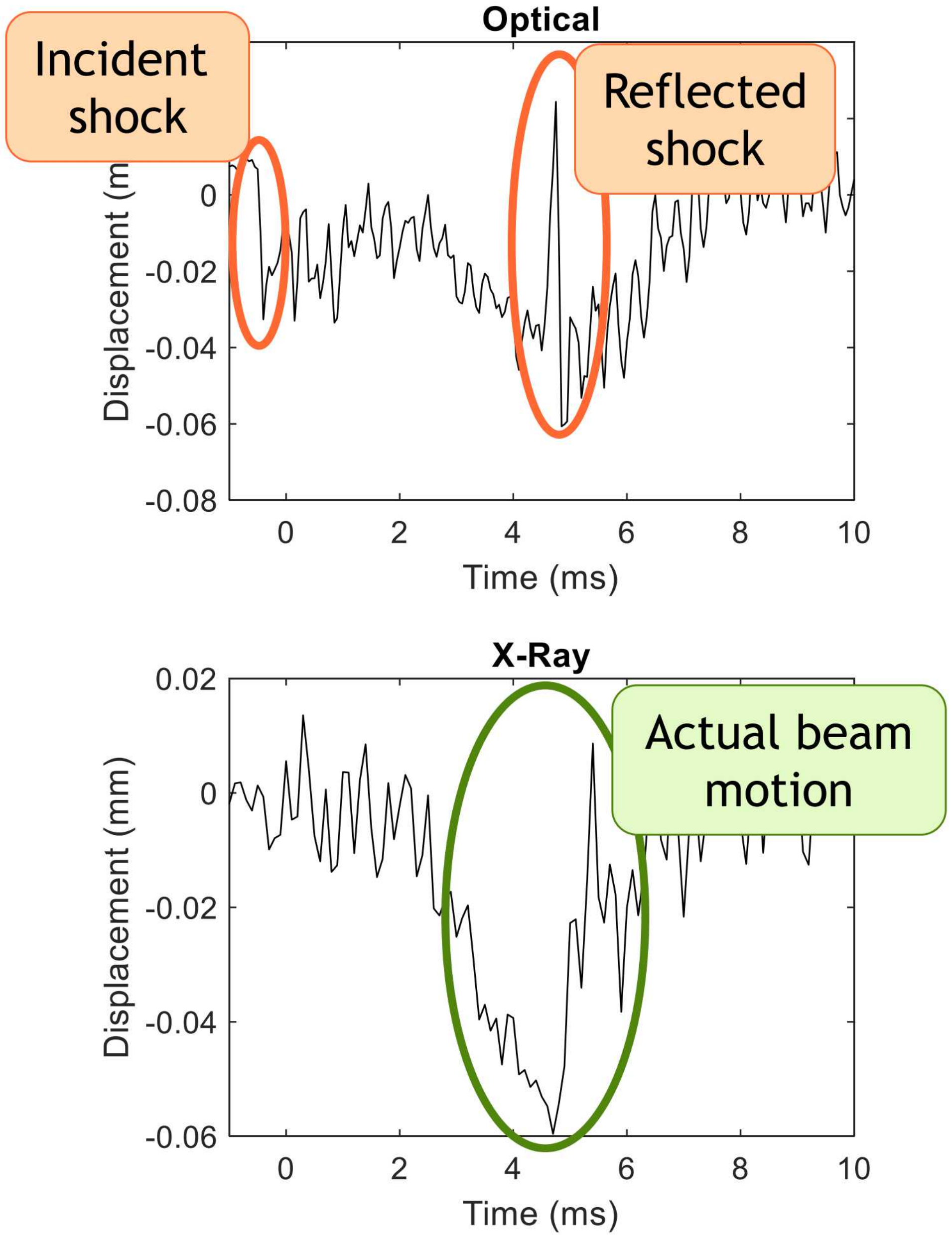
Rocking Mode

Vertical Displacement



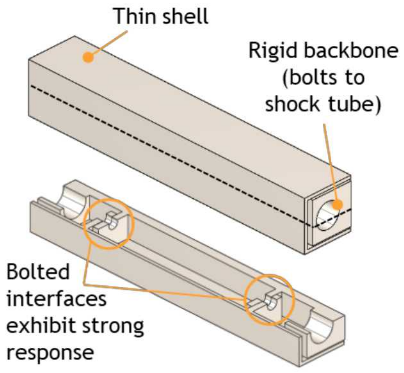
Impact Mode

Out-of-Plane Displacement

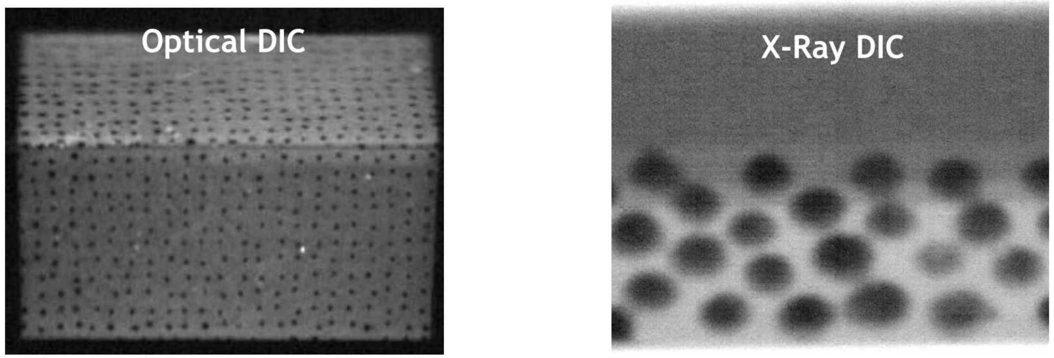


Elizabeth Jones, Sandia National Laboratories

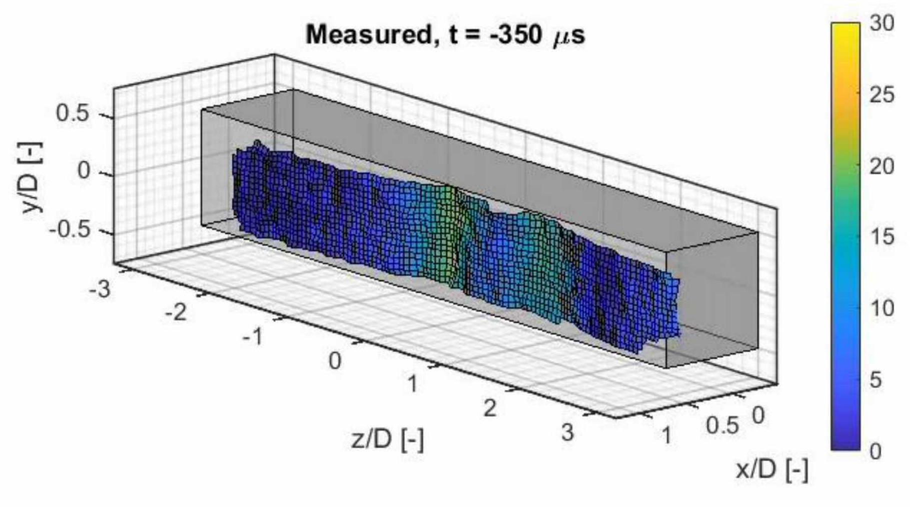
Fluid-structure interactions were studied with a canonical beam in a shock tube.



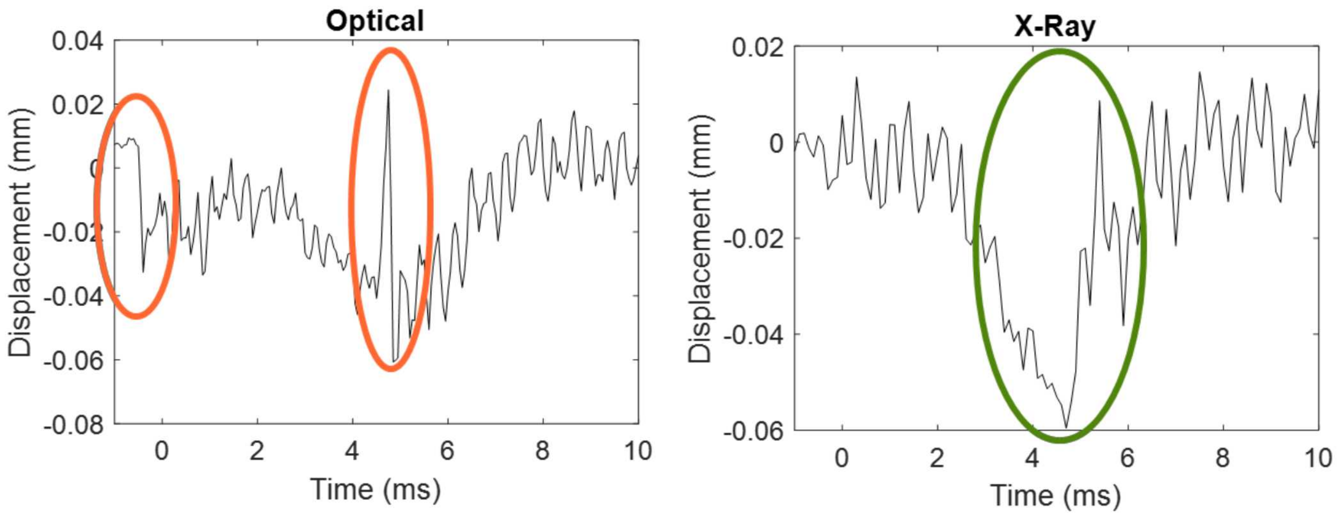
Optical and X-ray DIC were both developed to measure structure motion.



Optical DIC suffered from bias due to density gradients in the flow.



X-ray DIC elucidated beam motion on the interior of the structure that was obfuscated in the optical DIC measurements.

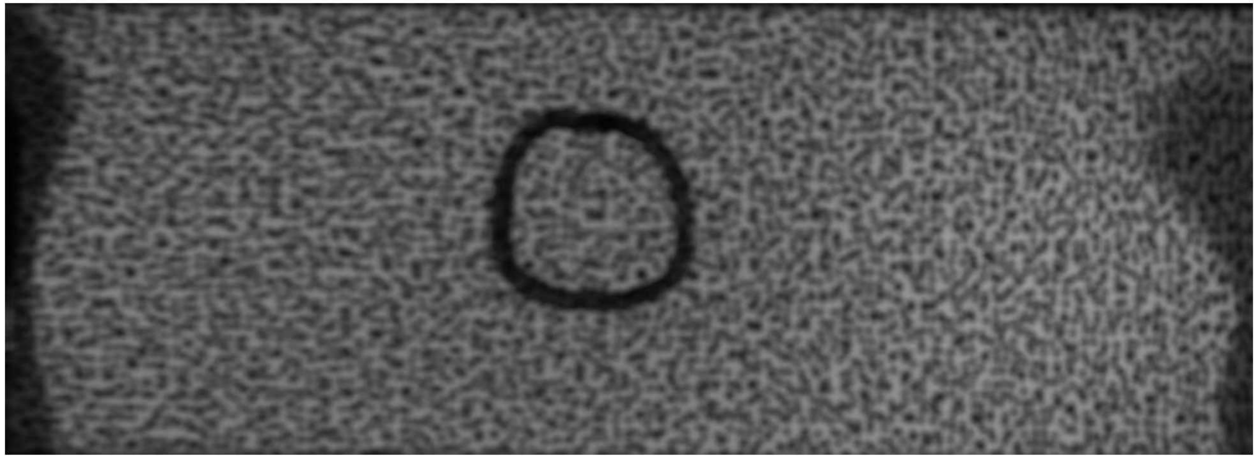


More info on X-ray stereo DIC: EMC Jones, EC Quintana, PL Reu, JL Wagner (2019) *Exp. Tech.*

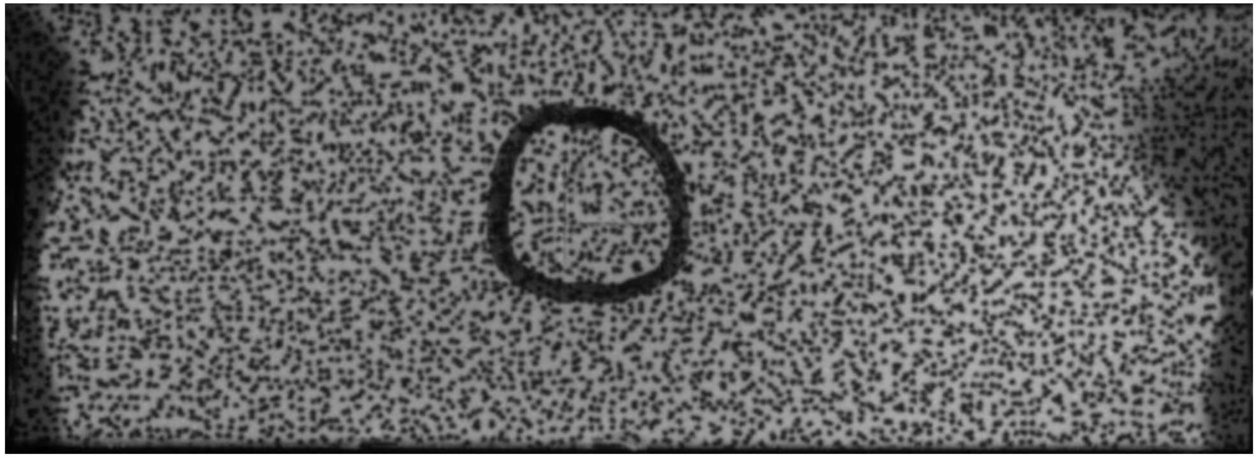
BACK-UP SLIDES

Challenge 1: Thick windows and a glancing view angle cause significant astigmatism distortions.

F/2.8 (large aperture), ~ 0.4 ms exposure



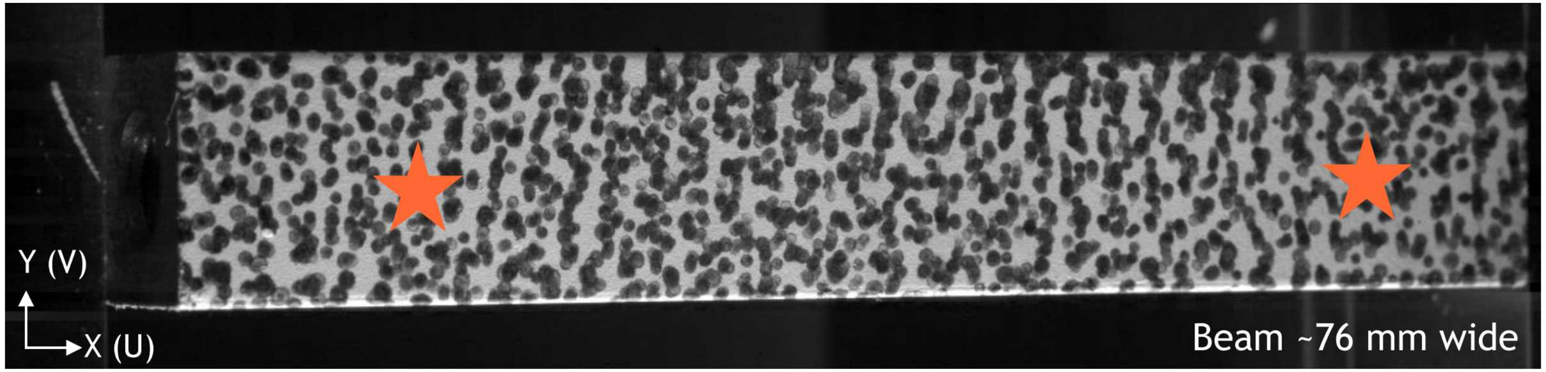
F/32 (small aperture), 40 ms exposure

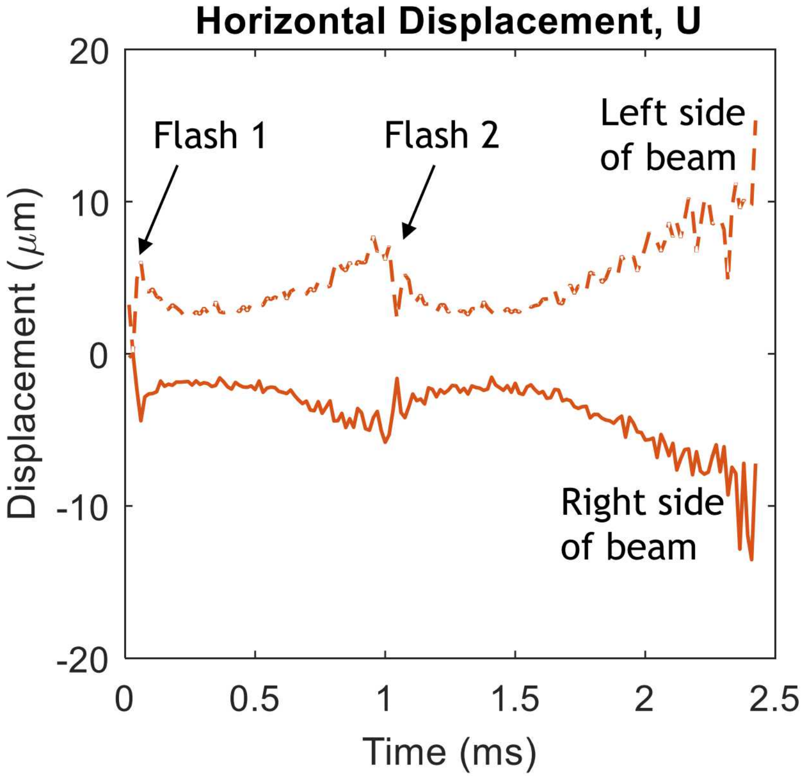


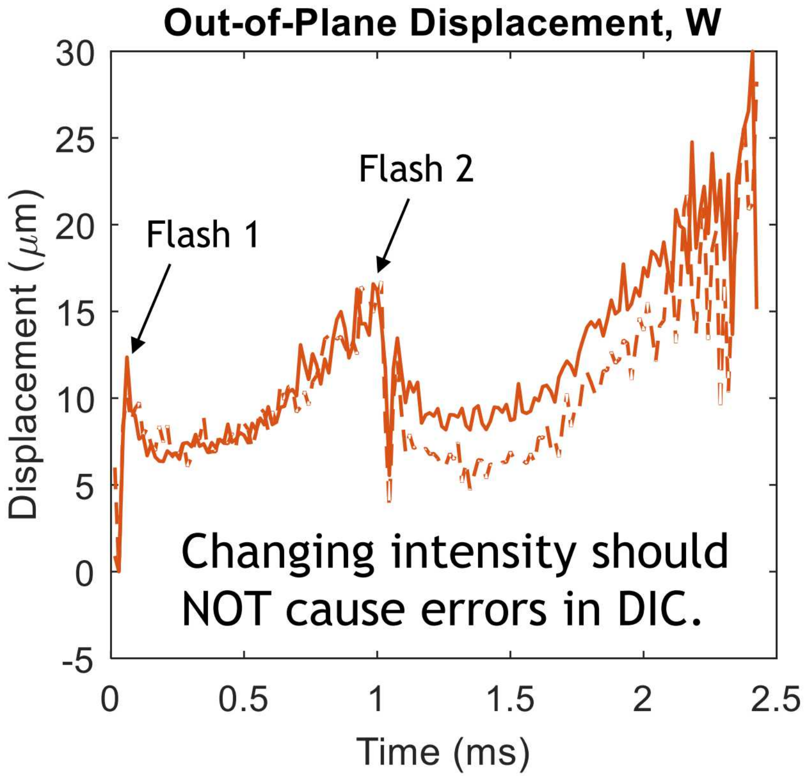
Solution: Decrease aperture. But, requires ~100x light!

High-intensity Xenon flash lamps are required to have sufficient light for high-speed imaging with small apertures.

Static beam illuminated with two sequential Xenon flash lamps

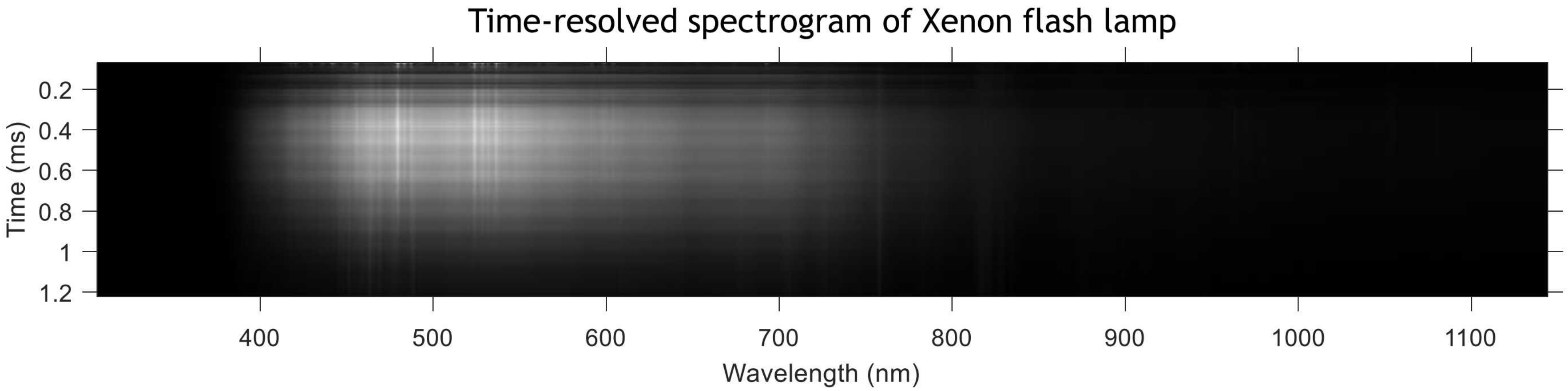


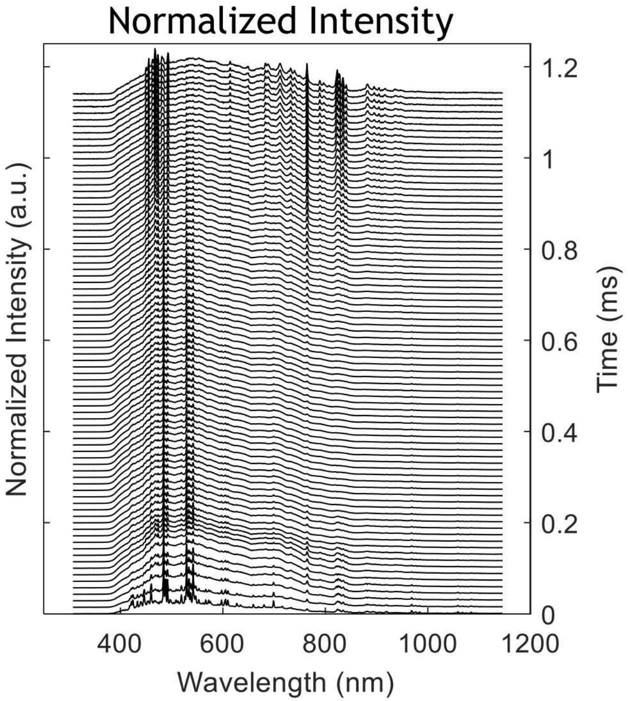




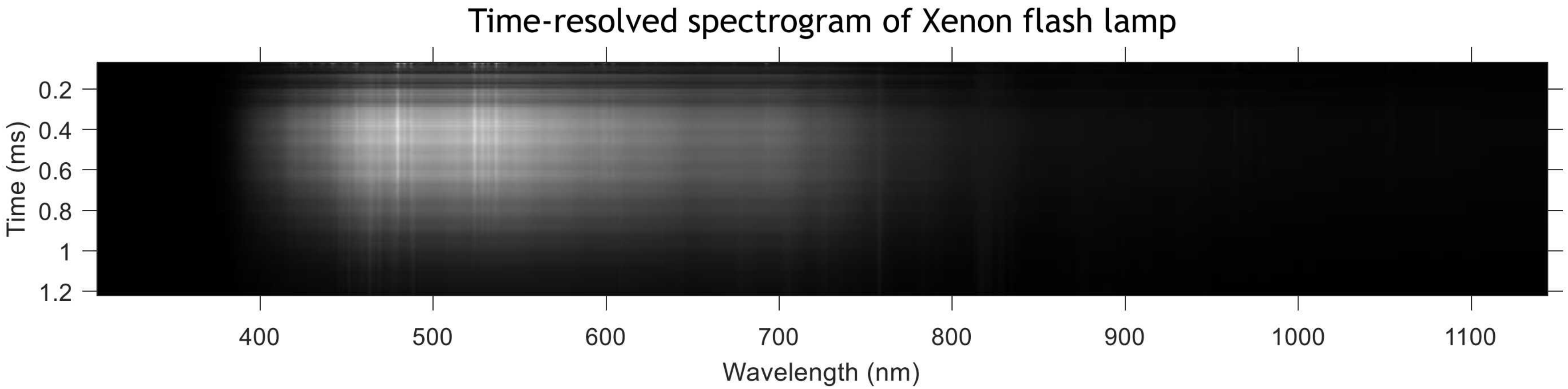
Changing intensity should NOT cause errors in DIC.

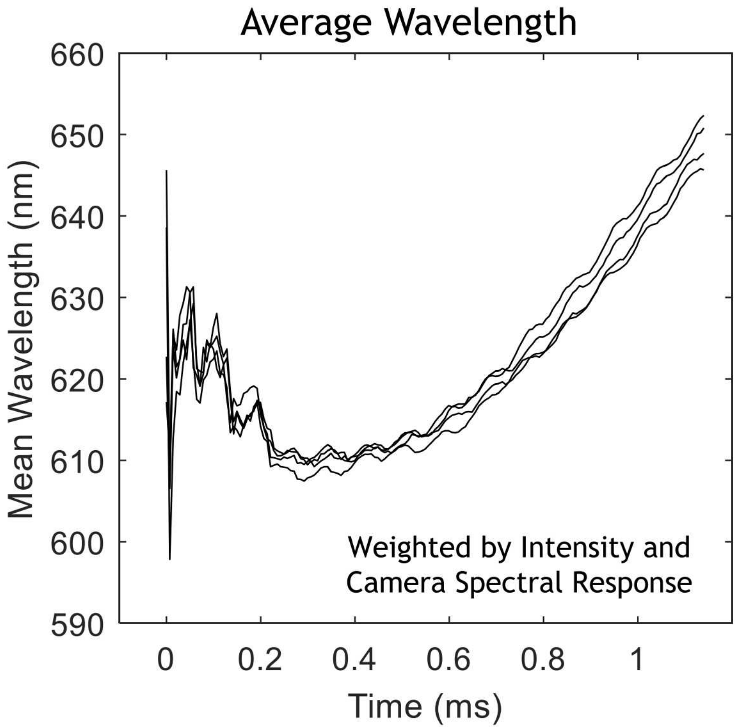
Challenge 2: Time-varying wavelength of flash lamp causes refraction and diffraction errors.

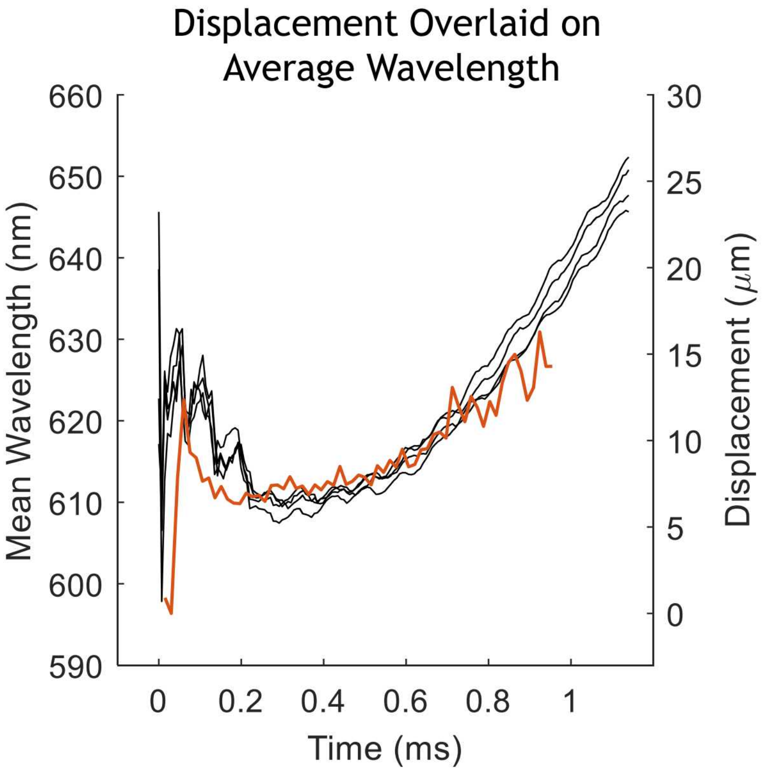




Challenge 2: Time-varying wavelength of flash lamp causes refraction and diffraction errors.



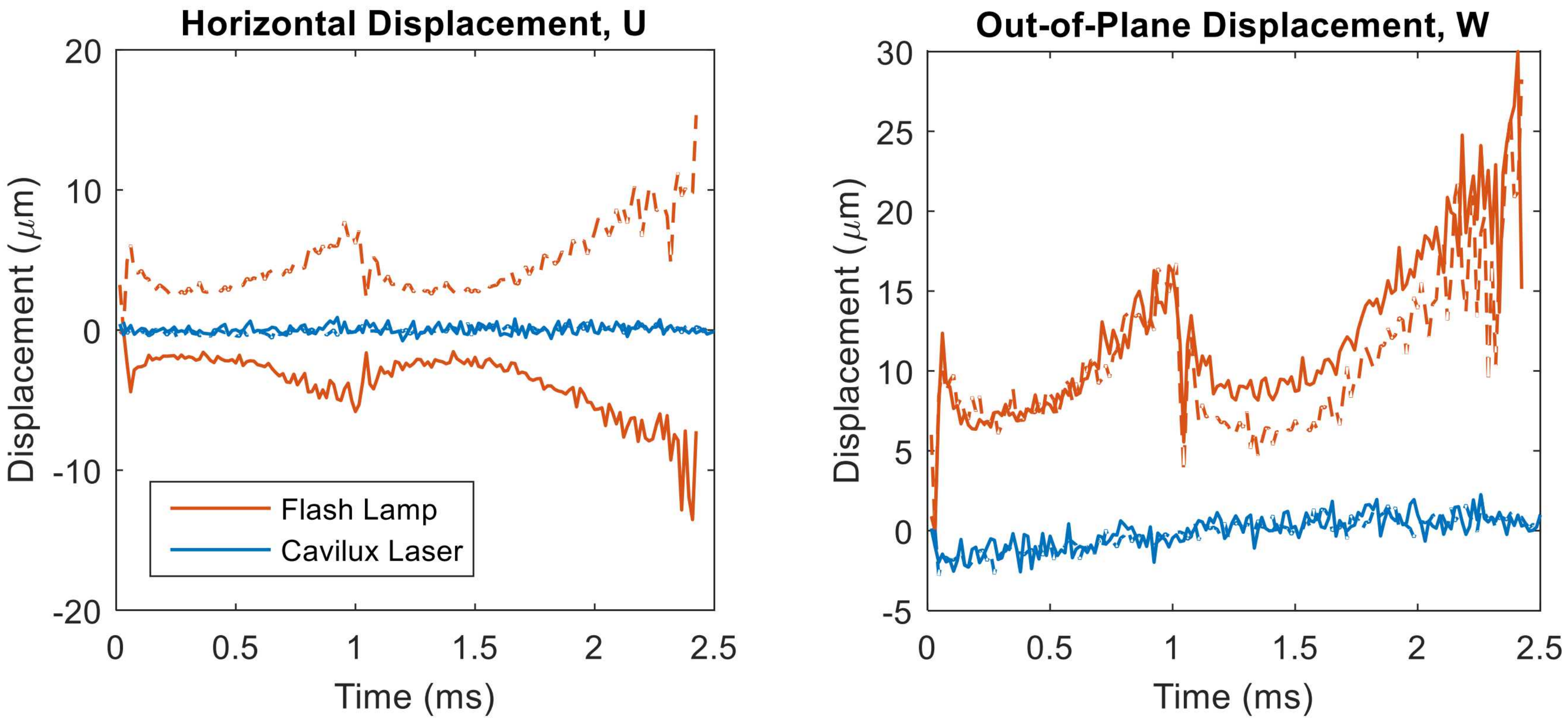




Challenge 2: Time-varying wavelength of flash lamp causes refraction and diffraction errors.

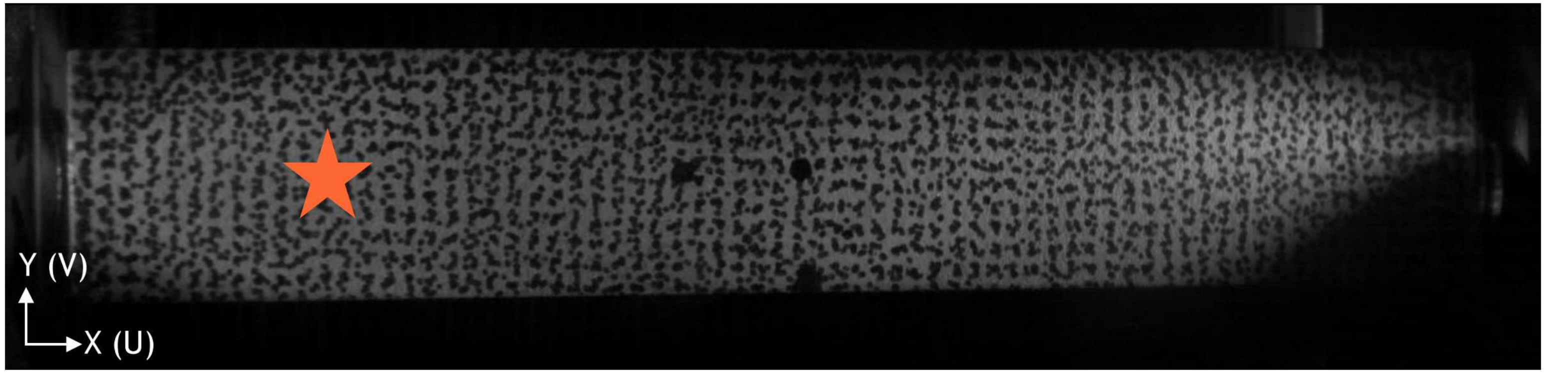
Refraction through window and lens, and diffraction, all depend on wavelength!

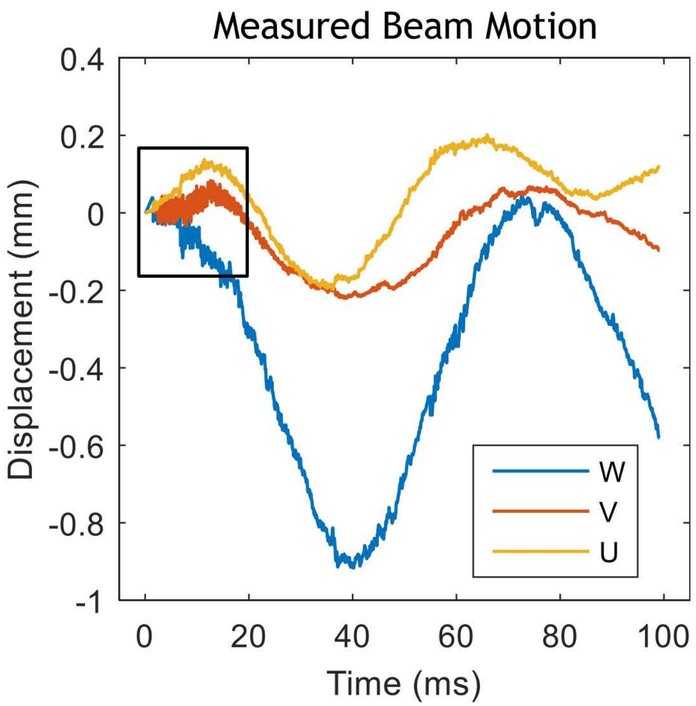
Solution: Cavilux laser provides high-intensity light, with a constant wavelength.

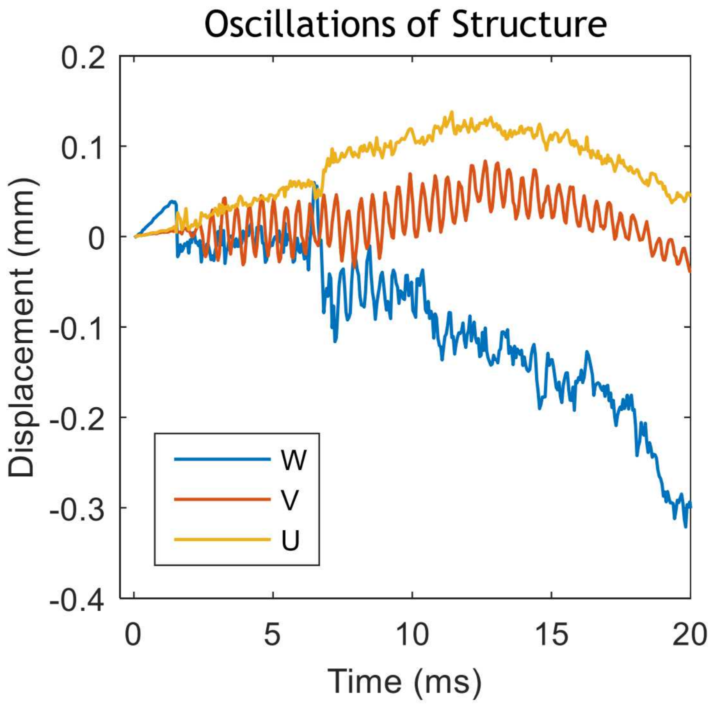


Challenge 3: Shock tube recoils when fired.

Beam subjected to fluid loading in shock tube.







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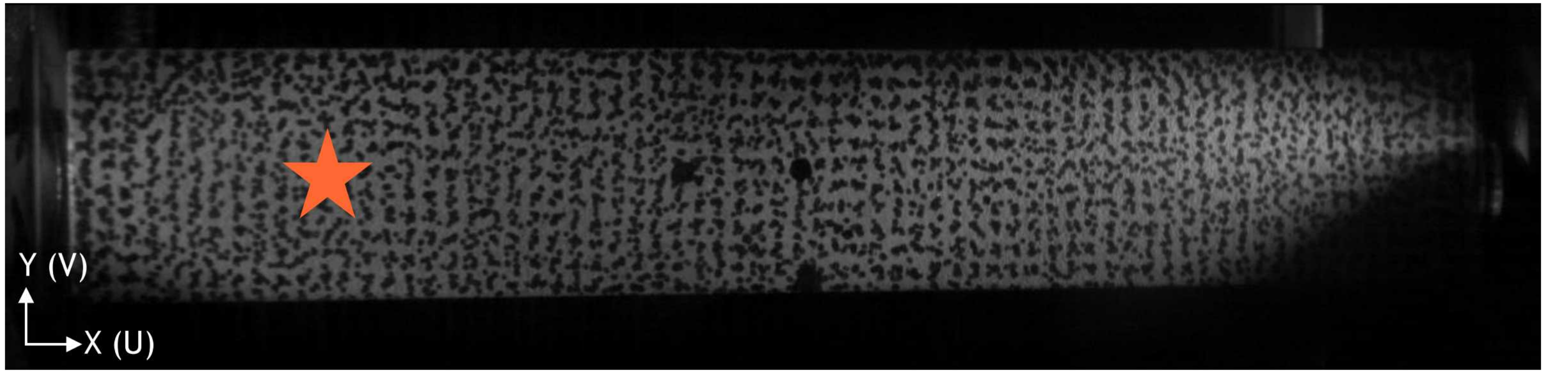
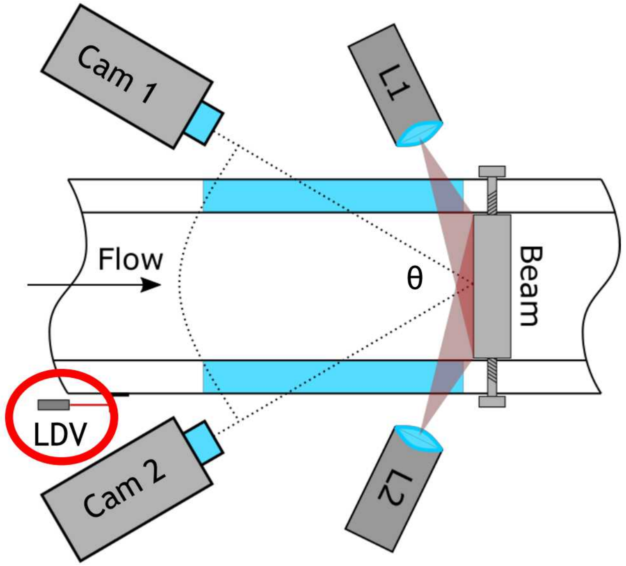
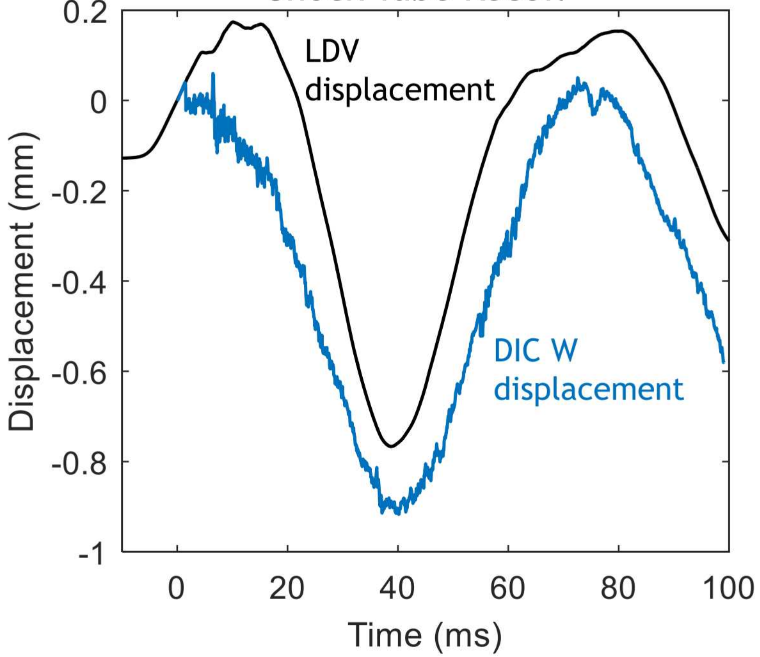




LDV = Laser Doppler Vibrometer

Independent Measurement of Shock Tube Recoil



Challenge 3: Shock tube recoils when fired.

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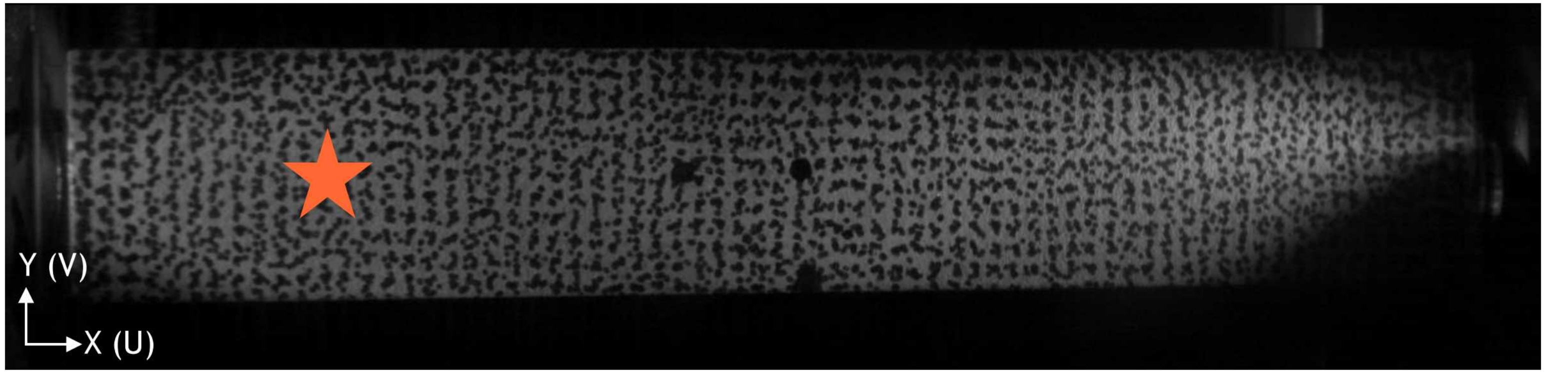
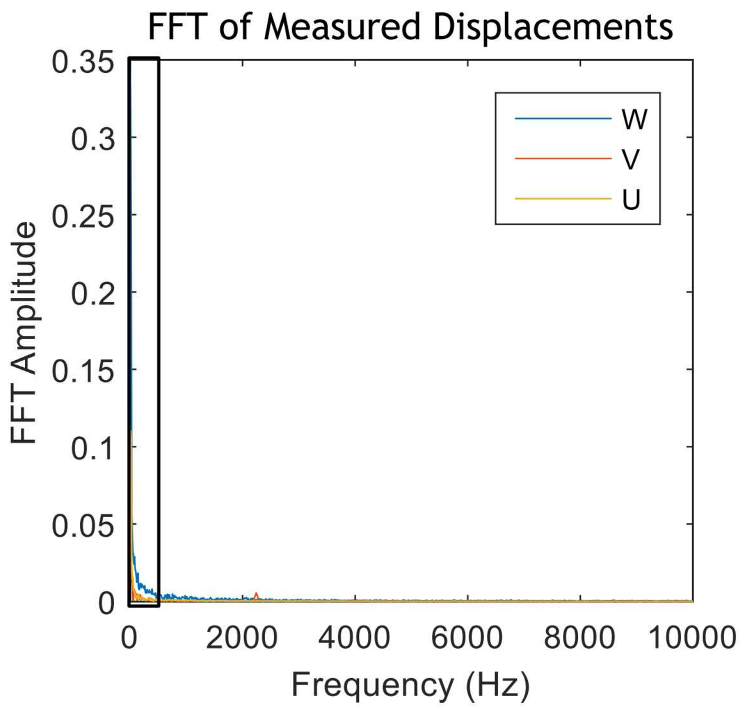
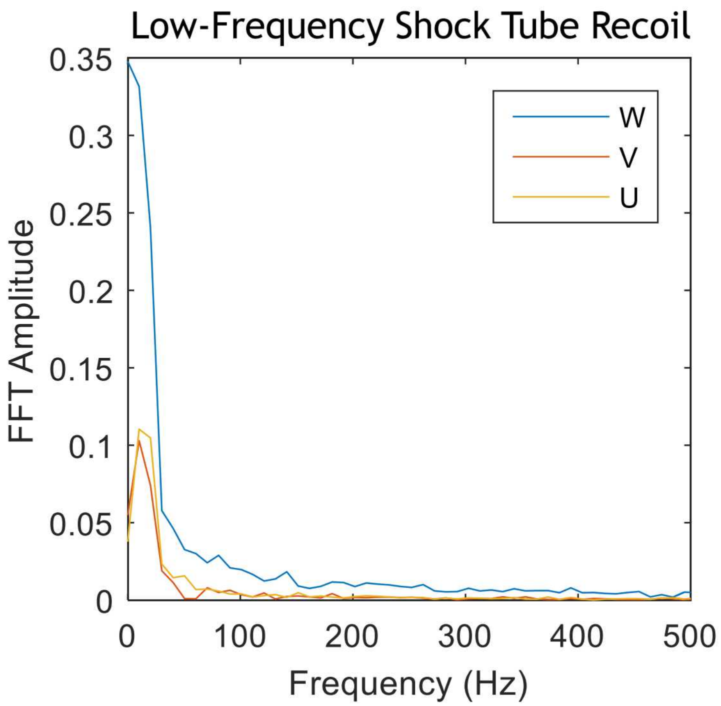
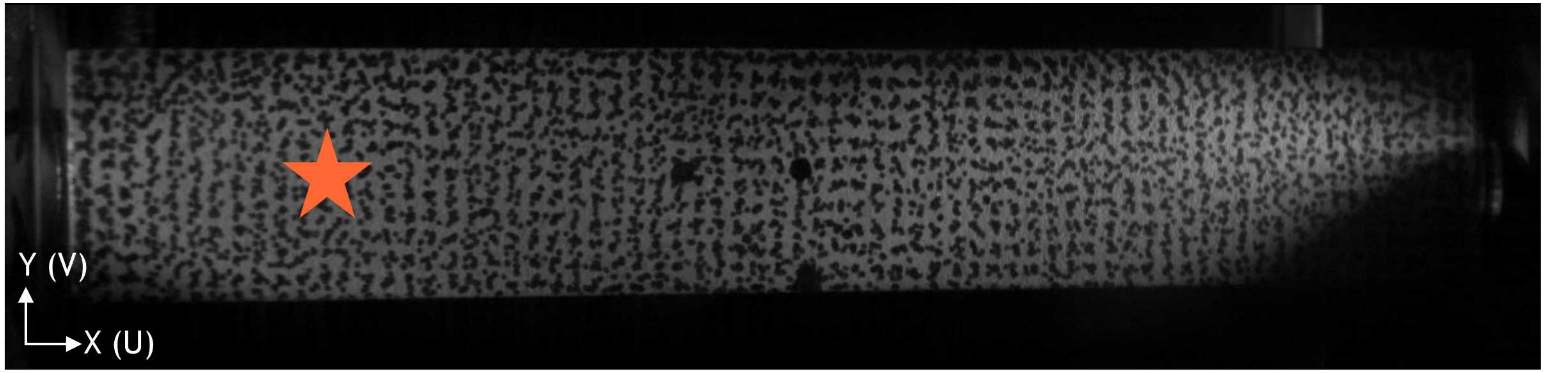


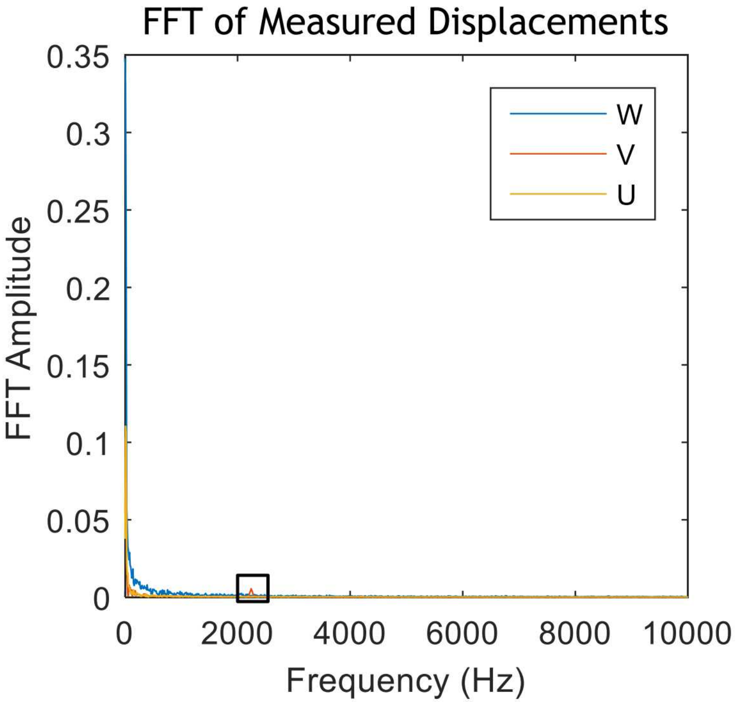


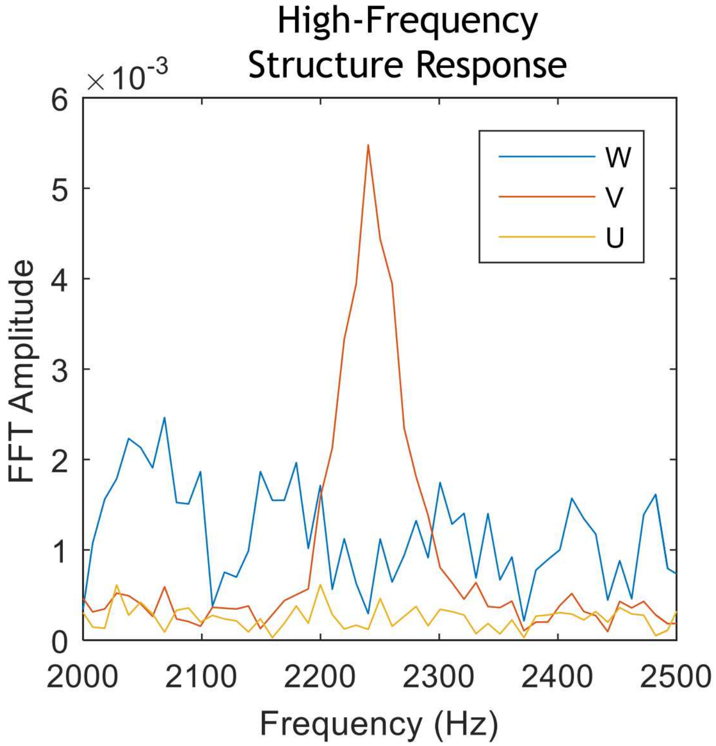


Challenge 3: Shock tube recoils when fired.

Beam subjected to fluid loading in shock tube.

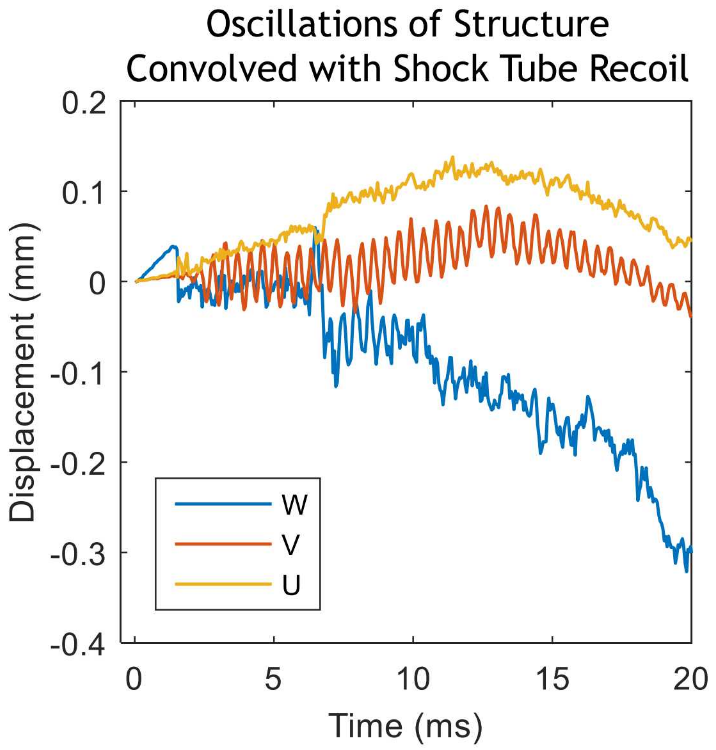


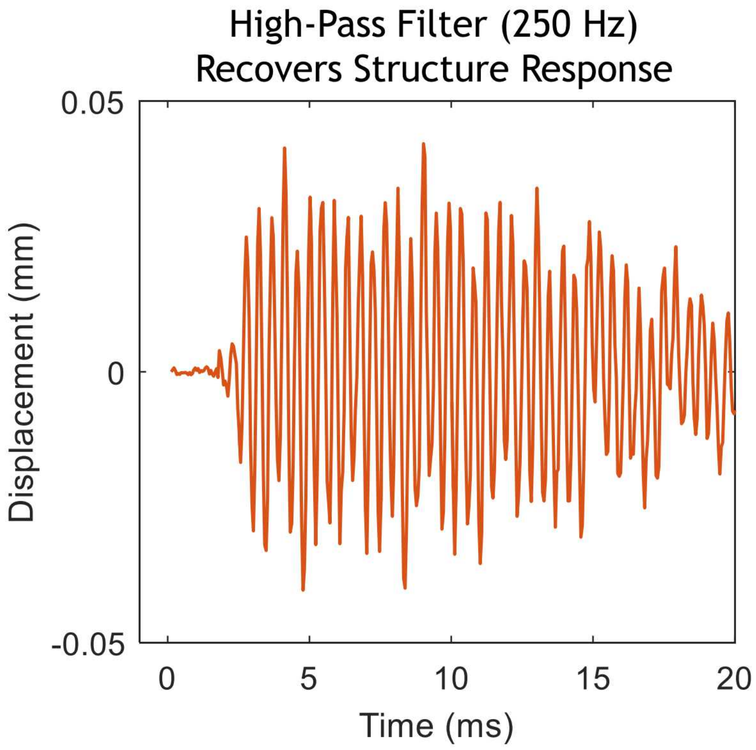




Challenge 3: Shock tube recoils when fired.

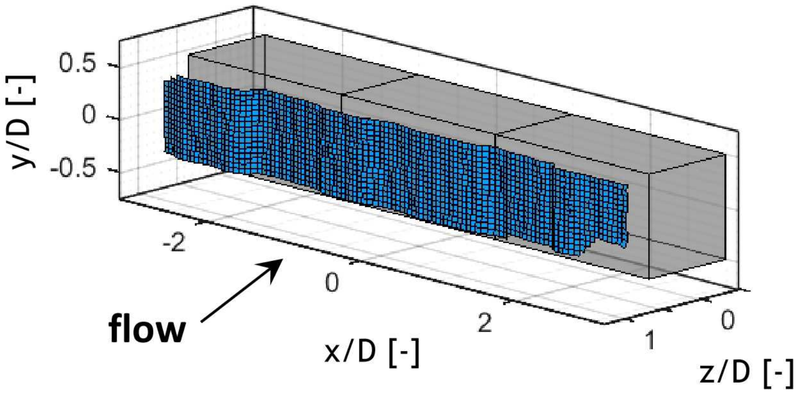
Solution: High-pass filter deconvolves shock tube recoil from structure response.





Solution: Principal Component Analysis (PCA) separates beam motion from refraction through fluid.

Raw DIC Movie (displacements x 10)

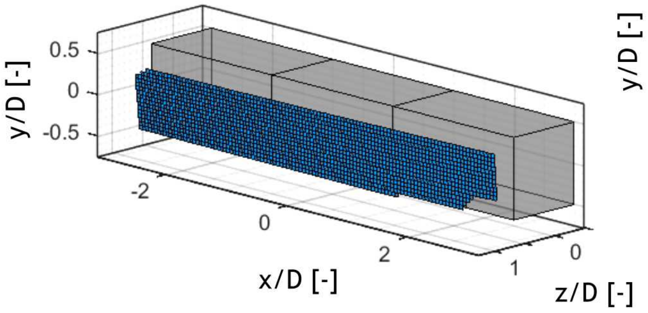


- Goal: decompose displacements ***d*** into modes $\boldsymbol{\phi}$ with amplitudes *a:*

$$\boldsymbol{d}(\boldsymbol{x},t) - \overline{\boldsymbol{d}(\boldsymbol{x})} = \sum_m a_m(t)\boldsymbol{\phi}_m(\boldsymbol{x})$$

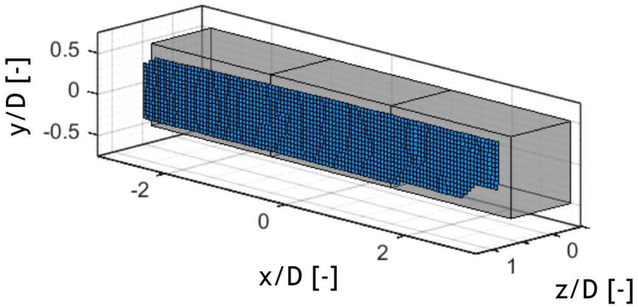
d *= {u, v, w}* is displacement, a vector quantity
x is the spatial coordinate
$a_m(t)$ are the *time-dependent* modal amplitudes
$\boldsymbol{\phi}_{\boldsymbol{m}}(\boldsymbol{x}) = \{u, v, w\}$ are *spatially-dependent* mo
shapes

Mode 1



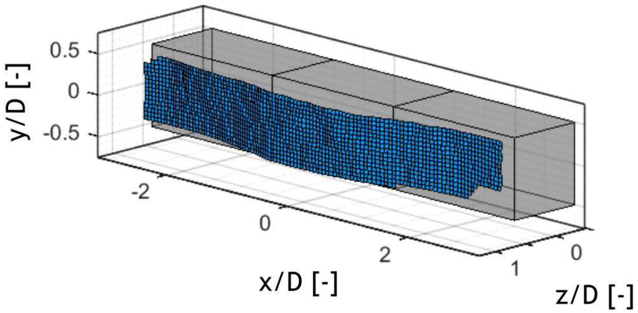
'Rocking'

Mode 2



'Impact'

Mode 3

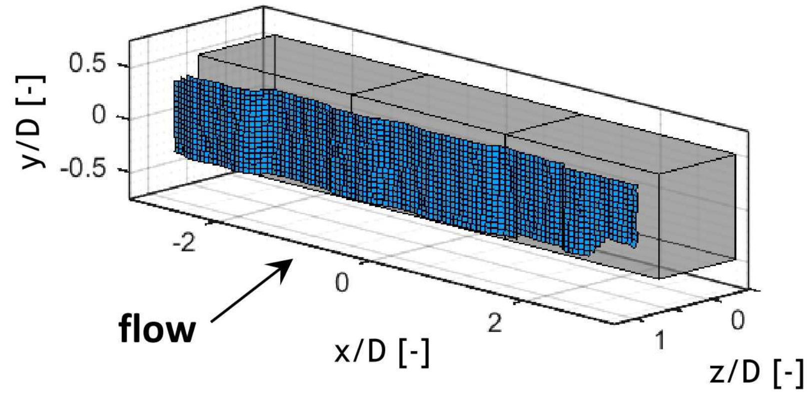


'Bending'

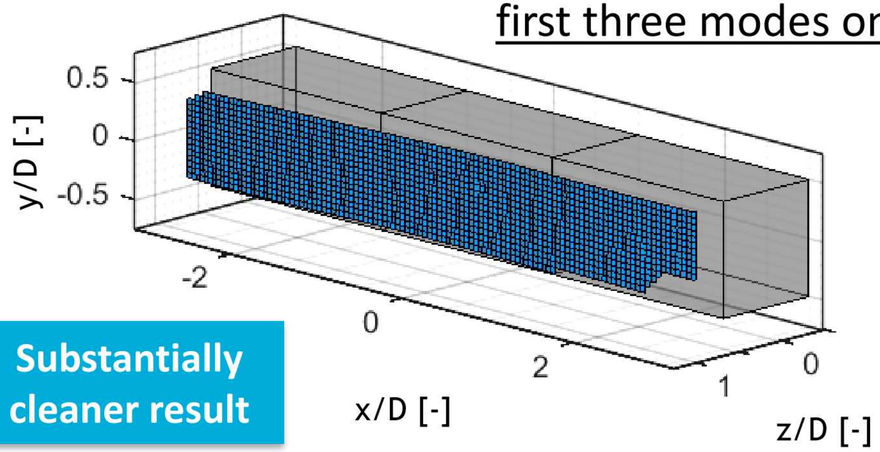
First three modes comprise 80% of total energy.

Solution: Principal Component Analysis (PCA) separates beam motion from refraction through fluid.

Raw DIC Movie (displacements x 10)

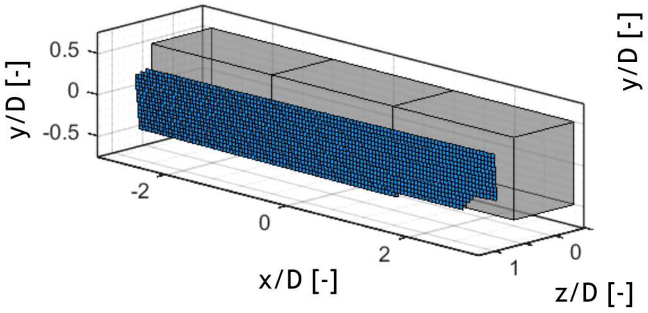


Reconstruction with first three modes only



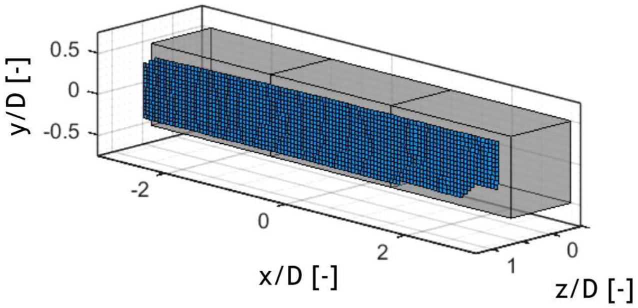
Substantially cleaner result

Mode 1



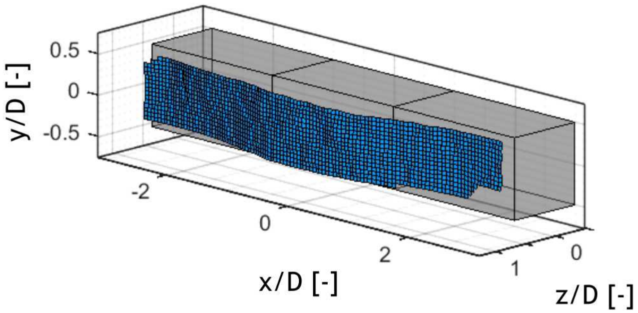
'Rocking'

Mode 2



'Impact'

Mode 3



'Bending'

First three modes comprise 80% of total energy.

Left Camera

Right Camera

Image Acquisition Rate: 20 kHz
Total Duration: ~0.1 sec
Beam width: 3 inches

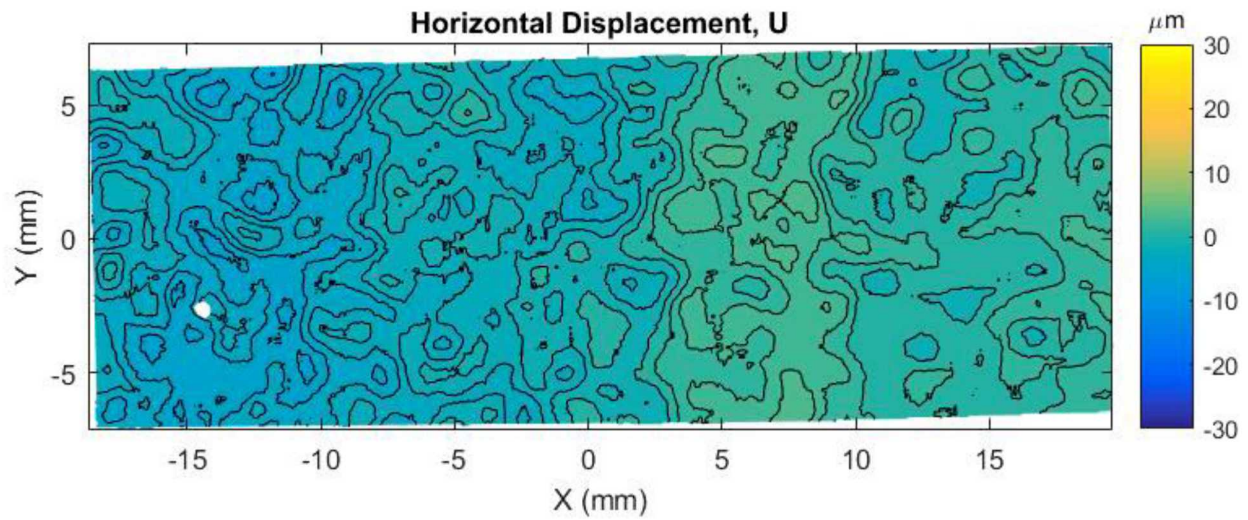

U [mm]
0.3
0.2
0.1
0
-0.1
-0.2
-0.3


V [mm]
0.13
0.0866667
0.0433333
0
-0.0433333
-0.0866667
-0.13

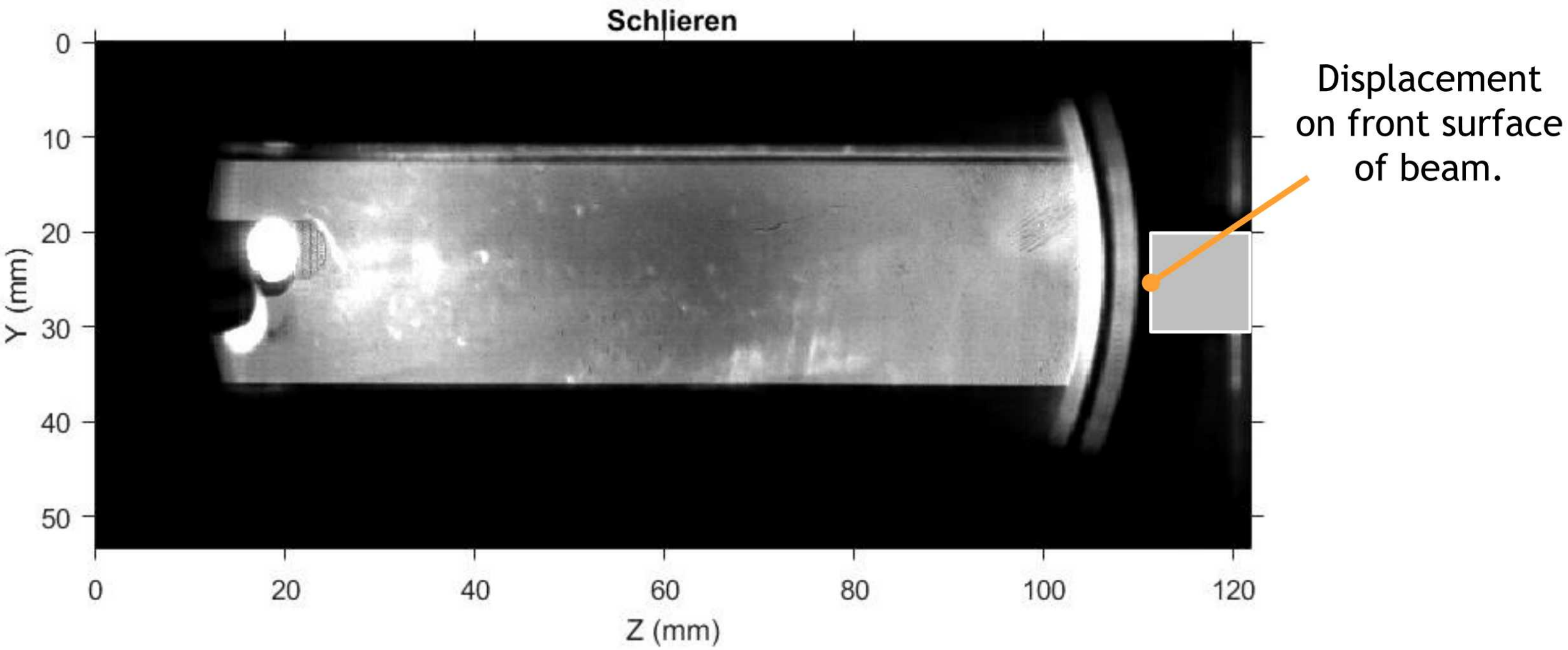

W [mm]
0.1
-0.0333333
-0.166667
-0.3
-0.433333
-0.566667
-0.7

Refraction through shock front cause beam steering and false DIC displacements.

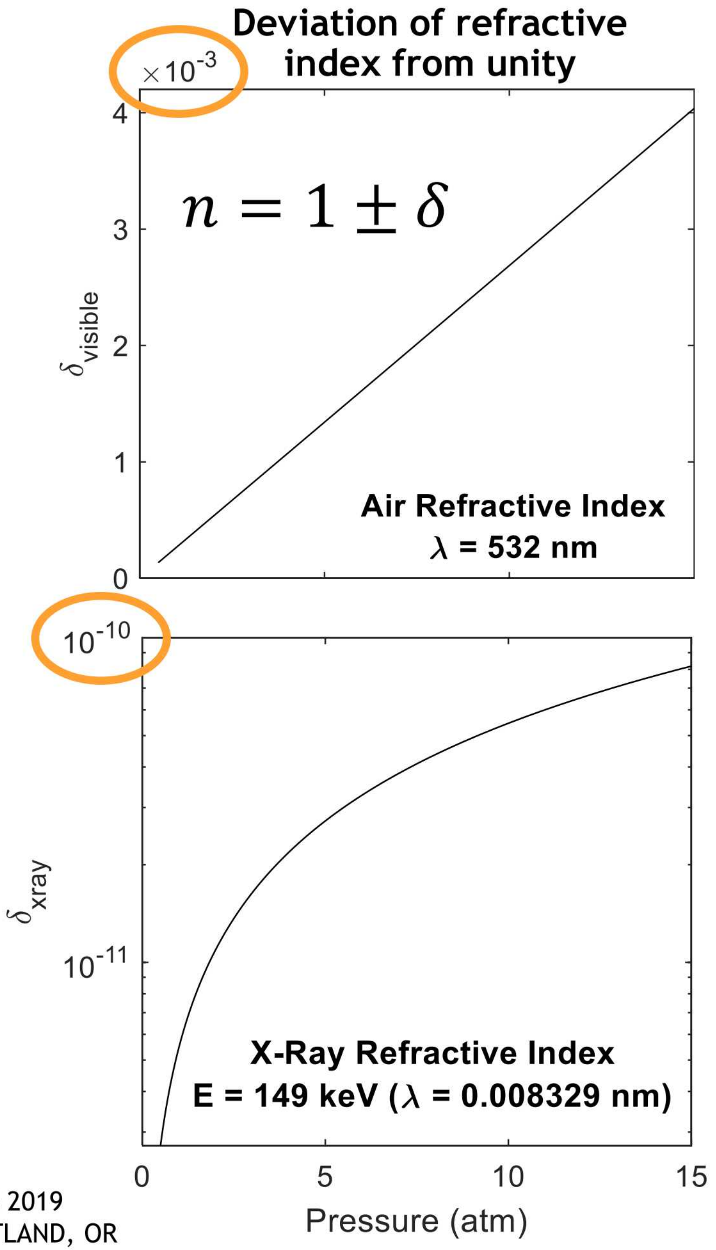
Front View

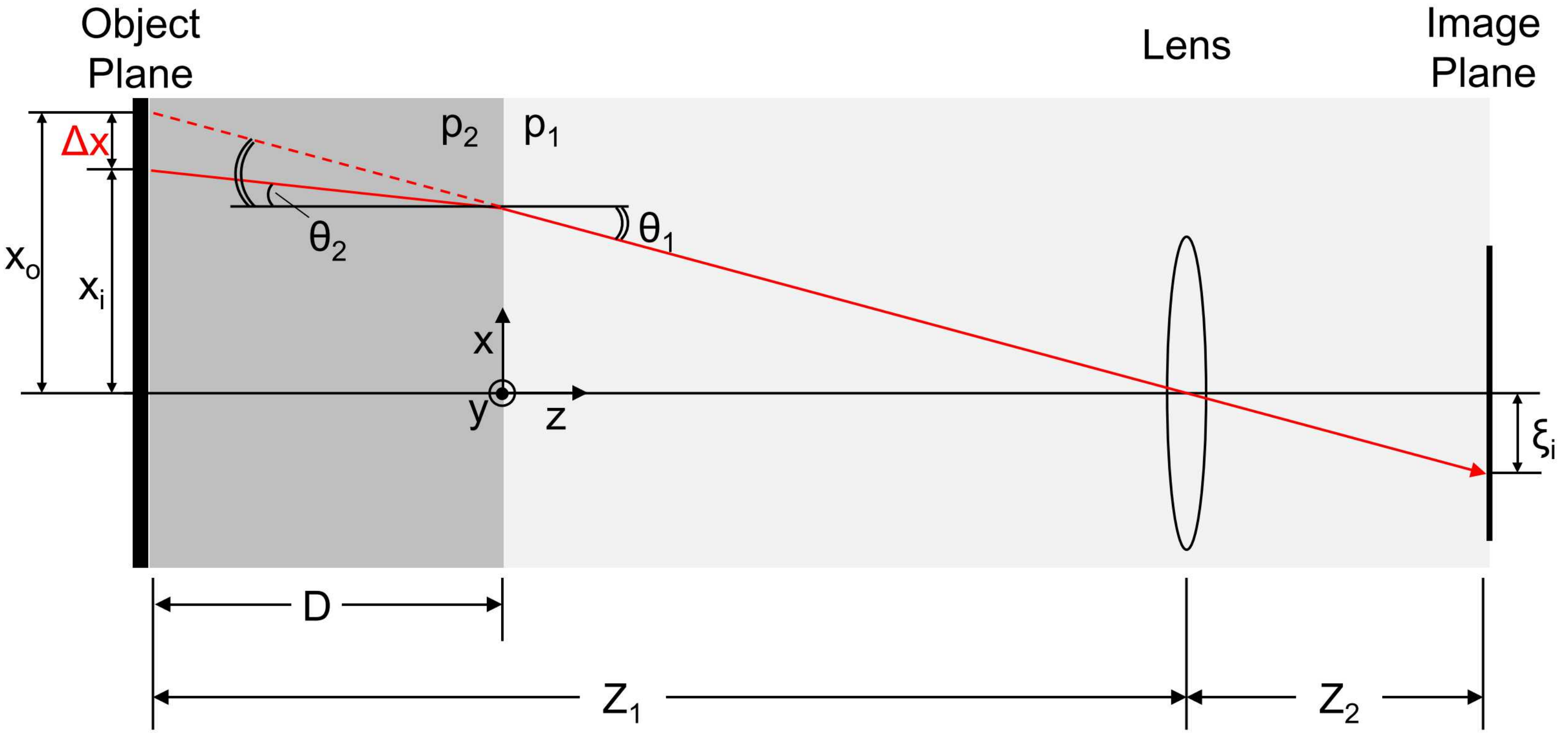


Side View



X-rays do not refract significantly through density gradients in air.





Illustrative example:

p_1 = 1 atm
p_2 = 10 atm
D = 100 mm
θ_1 = 10°

Optical error:

n_1 = 1 + 2.679e-4
n_2 = 1 + 2.688e-3
Δx = 44 μm

X-ray error:

n_1 = 1 - 5.455e-12
n_2 = 1 - 5.455e-11
Δx < 1 pm