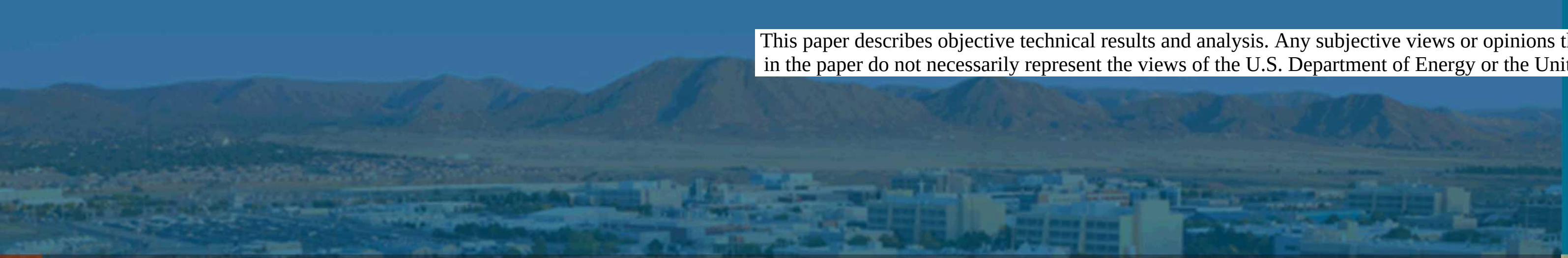
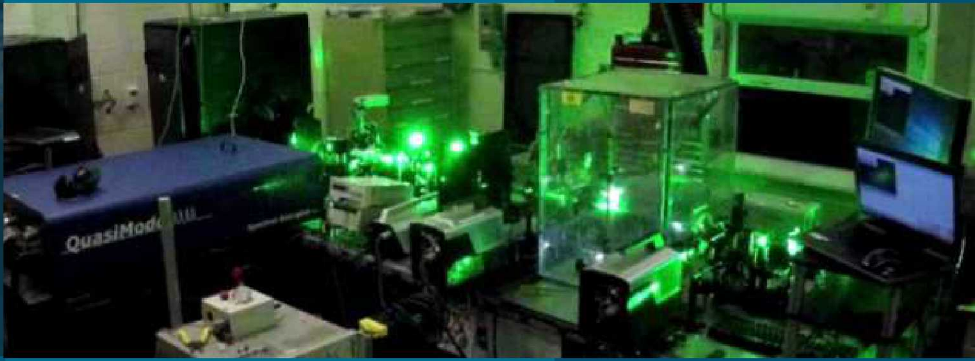
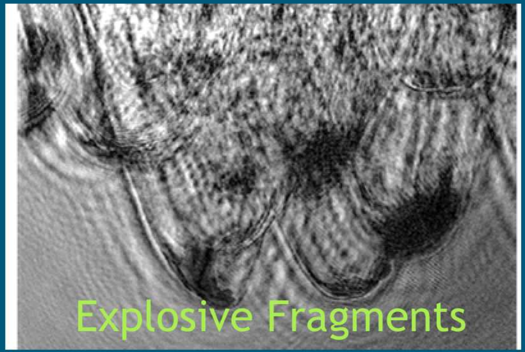
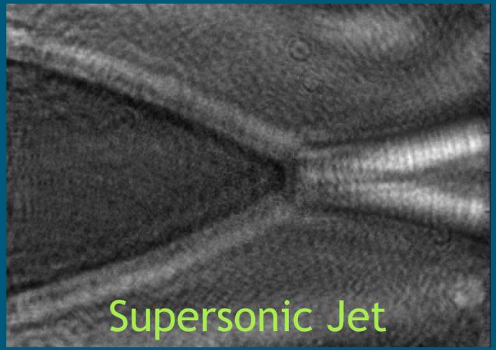


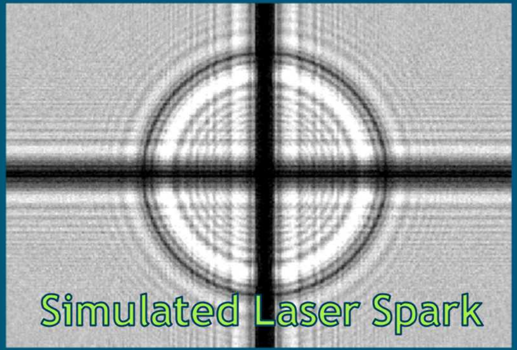
SAND2018-14200C

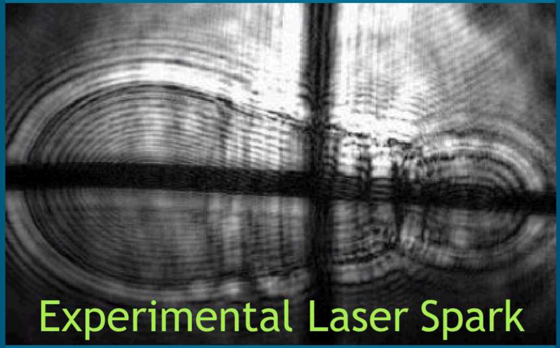
Ultra-high-speed Pulse-burst Phase Conjugate Digital-Inline Holography for Imaging through Shock-wave Distortions











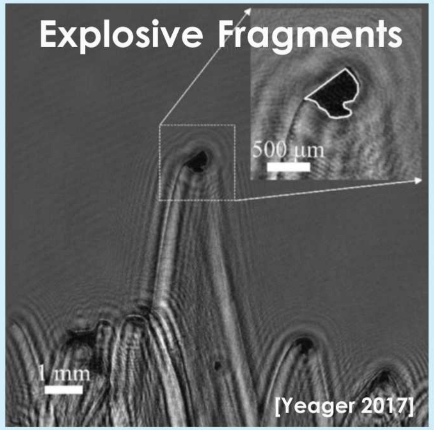
Ellen Yi Chen, Jeffery D. Heyborne, Daniel R. Guildenecher, Michael E. Smyser and Mikhail N. Slipchenko

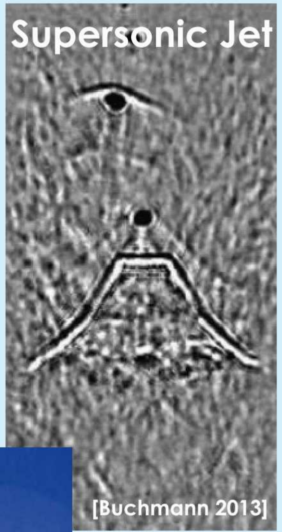
AIAA SciTech
San Diego, California, January 7th-11th, 2018

Motivation

Problem Statement

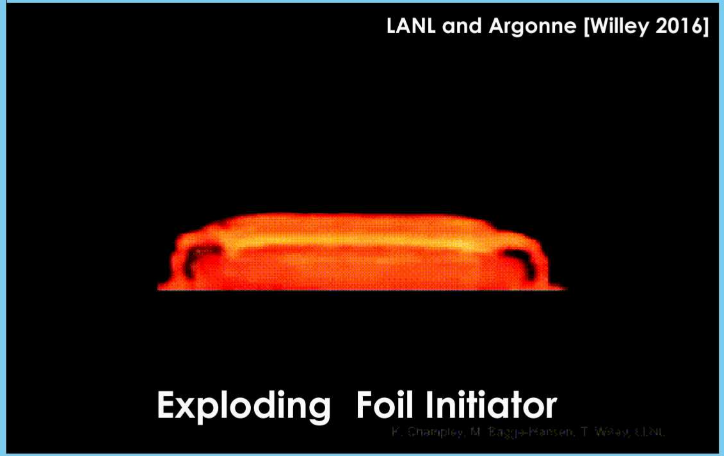
- Shock-wave distortions prevent accurate 3D interrogation in supersonic, hypersonic, and explosive environments
- Ultra-high-speed acquisition is desired for time-resolved measurements

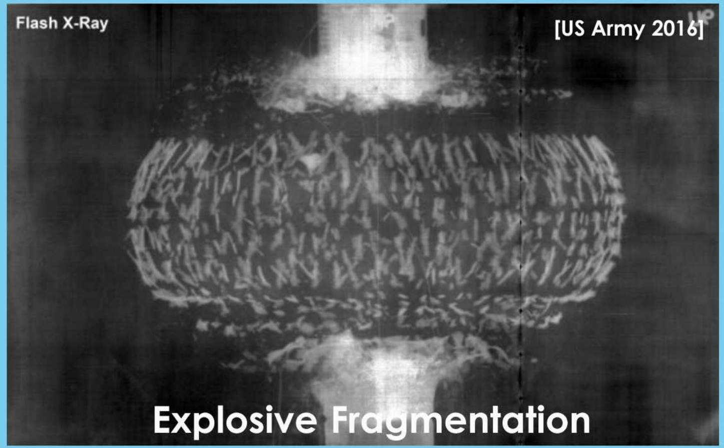




Existing Approaches

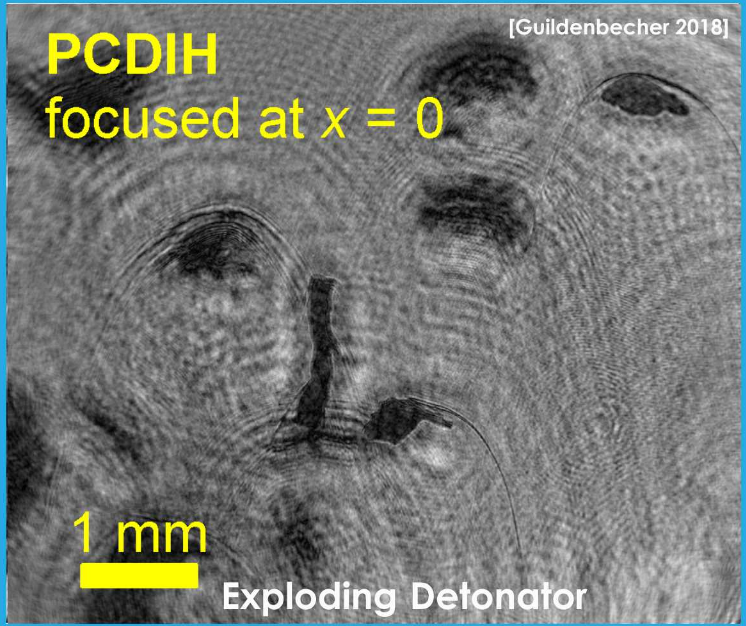
- Testing in vacuum
- Synchrotron x-rays and experimental repetition





Proposed Solution

- Cancelling the distortion using phase conjugate digital in-line holography (PCDIH)



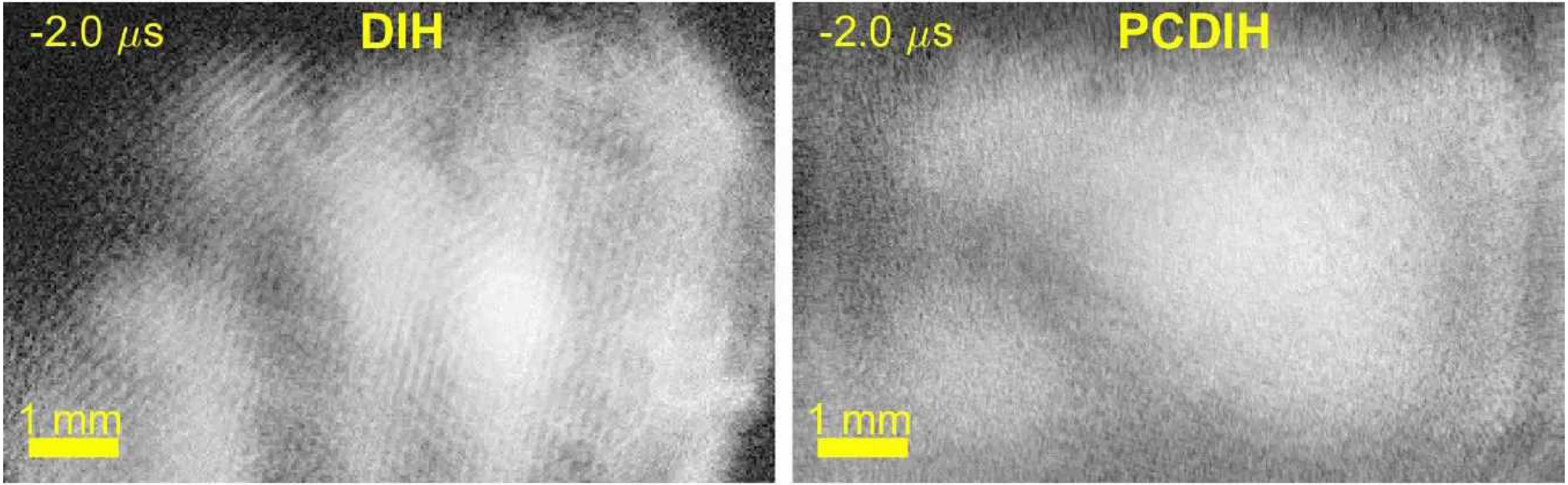
- Previous work limited to 10 to 20 Hz due to peak power requirements→ one image per experiment
- Implementing the method with a pulse burst laser and ultra-high-speed cameras for time-resolved measurements.

Goals

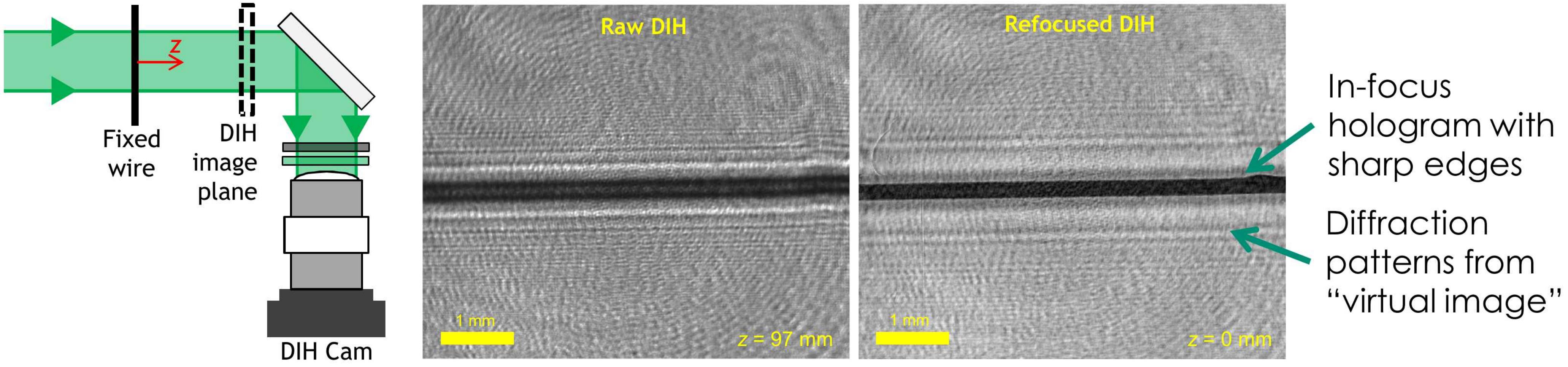
- Track hypersonic fragments from an explosive detonator in 3D through shock-wave distortions
- Increase acquisition from 10 to 20 Hz → 2 to 5 MHz (increase by > 5 orders of magnitude)
- Understand the physical mechanisms that produce unknown features in DIH and PCDIH images

DIH versus PCDIH

2 MHz Holograms



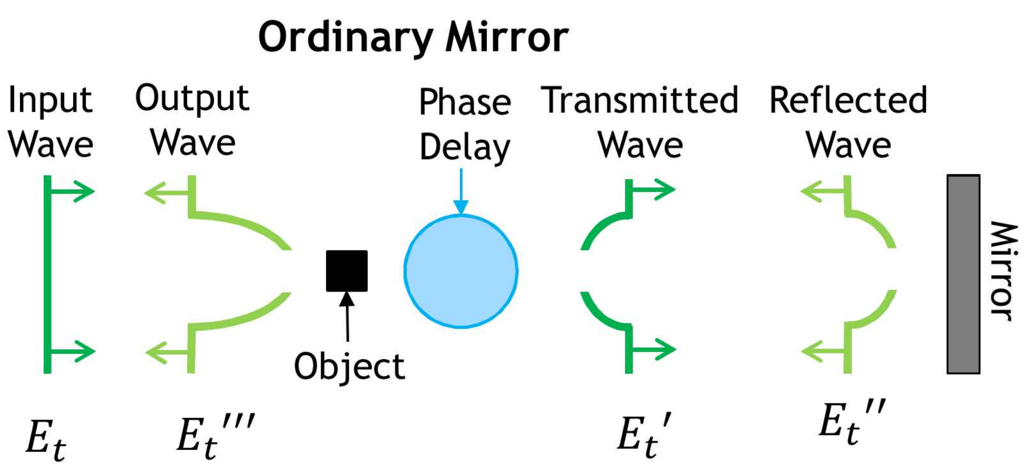
Digital In-line holography

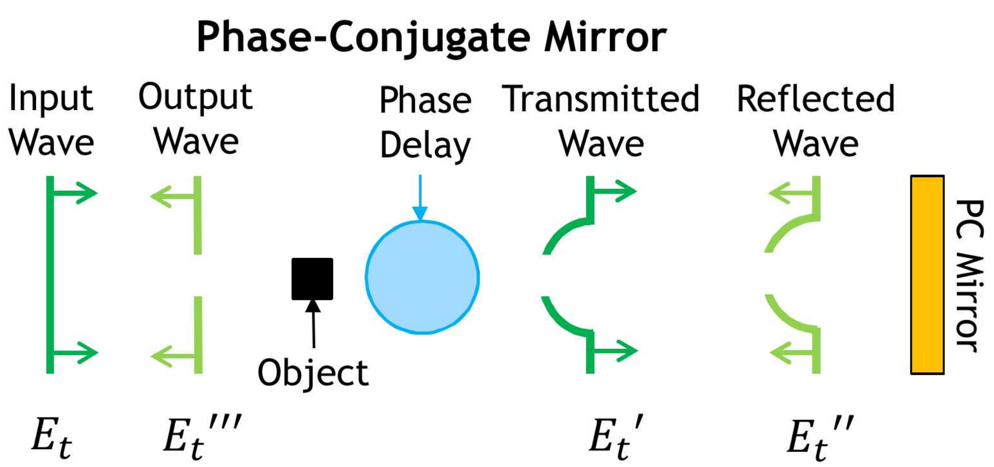


- Digital In-line holograms (Gabor 1948) are collected out-of-focus and are later numerically refocused
- Holograms are collected at the image plane z_h as $h(x,y) = |E_t(x,y,z_h)|^2$
- Holograms are numerically refocused using $E_h(x,y,z) = [h(x,y)E_r^*(x,y)] \otimes g_b(x,y,z)$

  where $g_b = FT^{-1}(G^*)$ and $G = e^{\frac{2\pi i z}{\lambda}\sqrt{1-(\lambda x)^2-(\lambda y)^2}}$
- The amplitude is determined from $A_h = |E_h|$
- In-focus z-planes are determined using maximum edge sharpness and minimum amplitude criteria.
- Tracking across multiple frames gives 3D velocity
- How do phase-distortions affect this process?

Phase Conjugate Mirror for Distortion Cancellation





Ordinary Mirror

Transmitted Wave

$$E_t' = E_t(x,y,z)e^{i\phi_s(x,y)}$$

Reflected Wave

$$E_t'' = R_m E_t(x,y,z)e^{i\phi_s(x,y)}$$

Output Wave

$$E_t''' = R_m E_t(x,y,z)e^{i\phi_s(x,y)+i\phi_s(x,y)}$$

Doubled phase delay

Phase-Conjugate Mirror

Transmitted Wave

$$E_t' = E_t(x,y,z)e^{i\phi_s(x,y)}$$

Reflected Wave

$$E_t'' = R_{pc} E_t(x,y,z)e^{-i\phi_s(x,y)}$$

Conjugate phase

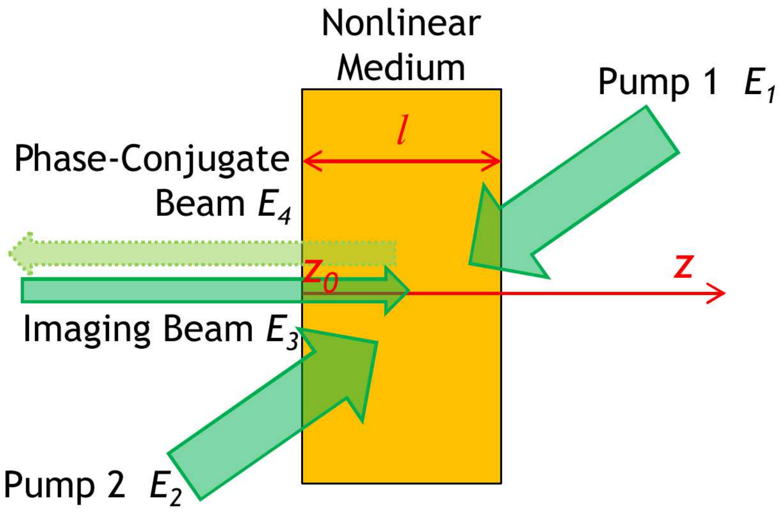
Output Wave

$$E_t''' = R_{pc} E_t(x,y,z)e^{-i\phi_s(x,y)+i\phi_s(x,y)} = R_{pc} E_t(x,y,z)$$

Cancelled phase delay

Phase Conjugation via Degenerate Four-Wave-Mixing

- Phase-conjugate beam needs to be generated quickly and at high repetition rates
- Degenerate four-wave-mixing: 1 imaging beam and 2 pump beams produces a 4th beam
- Phase-matching → 4th beam travels in opposite direction as imaging beam
- Solving nonlinear coupled wave equations → 4th beam is conjugate of imaging beam
- Phase conjugate mirror reflectivity is a function of tan^2



Electric Fields

$$E_1 = A_1(r)e^{ik_1\cdot r - i\omega t}$$

$$E_2 = A_2(r)e^{ik_2\cdot r - i\omega t}$$

$$E_3 = A_3(x,y,z)e^{ik_3 z - i\omega t}$$

$$E_4 = A_4(x,y,z)e^{ik_4 z - i\omega t}$$

Phase Matching

$$k_1 + k_2 = k_3 + k_4$$

$$k_1 = -k_2$$

Nonlinear Coupled Wave Equations

$$\frac{dA_3^*(z)}{dz} = i\gamma^* A_4(z)$$

$$\frac{dA_4(z)}{dz} = i\gamma A_3^*(z)$$

$$\gamma = \frac{\omega}{2cn_0(\omega)}\chi_e^{(3)} A_1 A_2$$

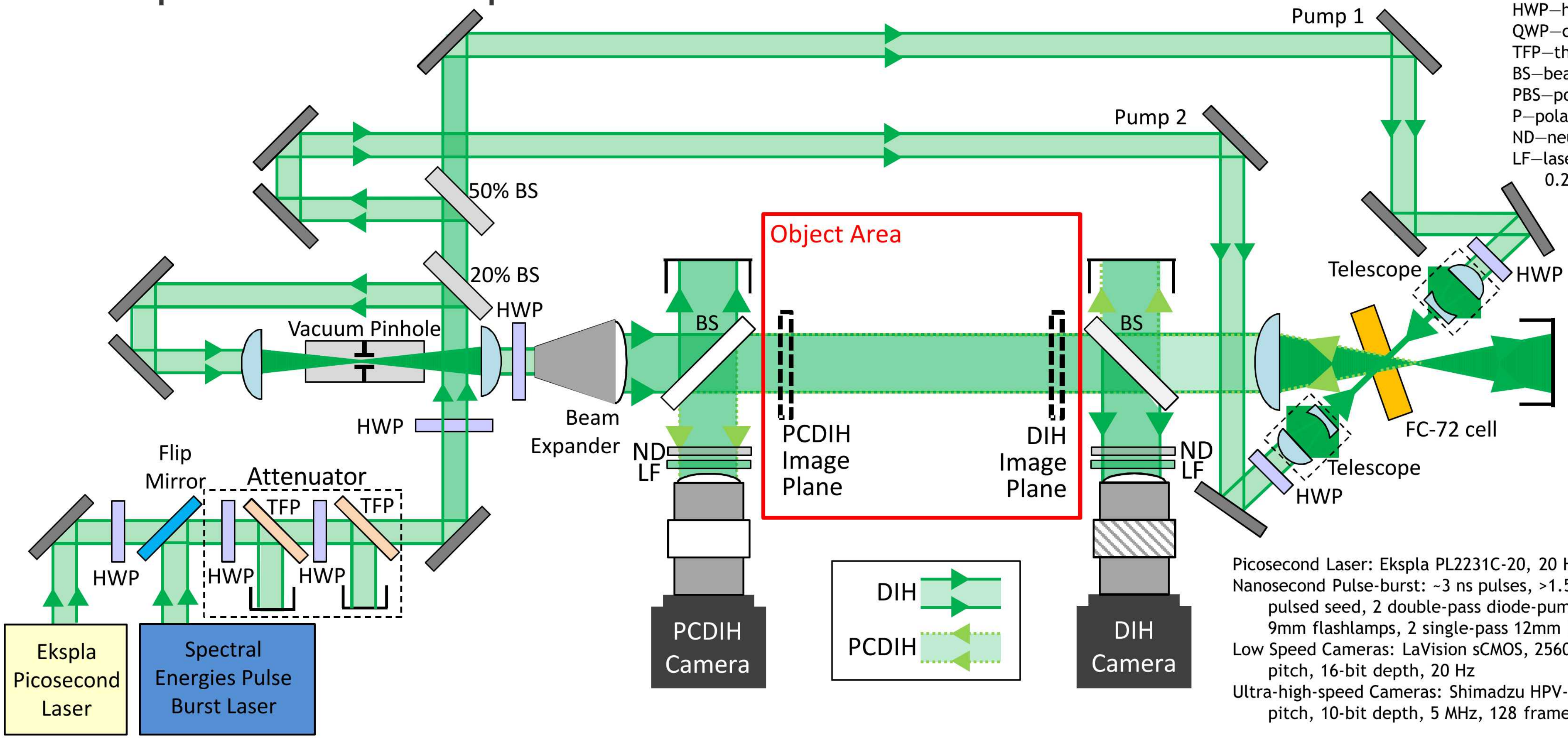
Phase-conjugate Beam

$$A_4(z_0) = -i\frac{\gamma}{|\gamma|}\tan(|\gamma| l)A_3^*(z_0)$$

Phase Conjugate Mirror Reflectivity

$$R_{pc} = \frac{|A_4|^2}{|A_3|^2} = tan^2\left(\left|\frac{\omega}{2cn_0(\omega)}\chi_e^{(3)} A_1 A_2\right| l\right)$$

Experimental Setup: Picosecond or Nanosecond PCDIH

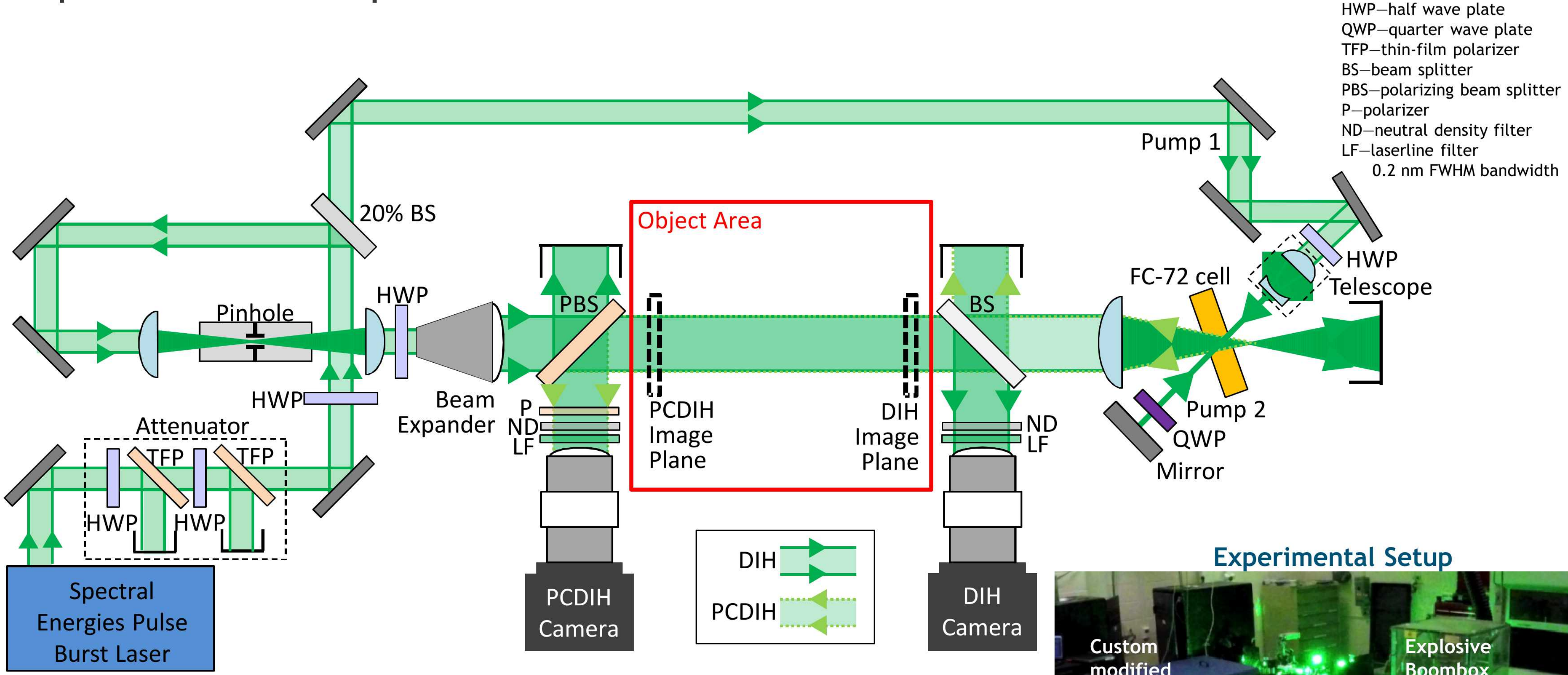


HWP—half wave plate
QWP—quarter wave plate
TFP—thin-film polarizer
BS—beam splitter
PBS—polarizing beam splitter
P—polarizer
ND—neutral density filter
LF—laserline filter
0.2 nm FWHM bandwidth

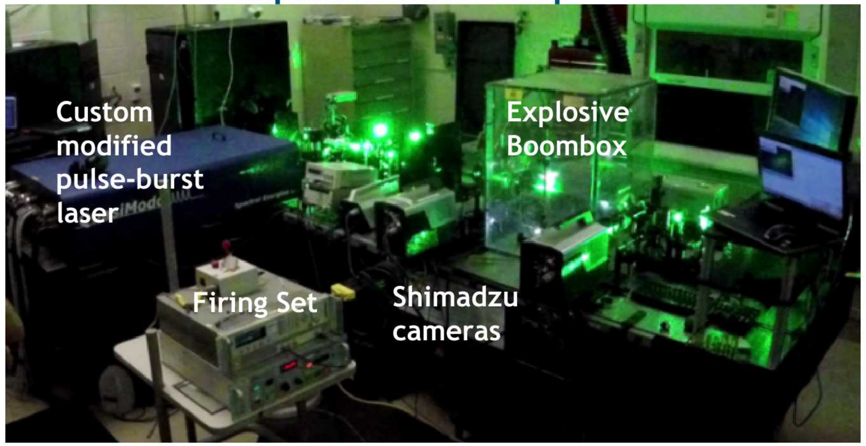
Picosecond Laser: Ekspla PL2231C-20, 20 Hz, 60 ps, 532 nm, >15 mJ/pulse
Nanosecond Pulse-burst: ~3 ns pulses, >1.5 ms burst, 12 s between bursts, pulsed seed, 2 double-pass diode-pumped amplifiers, 2 double-pass 9mm flashlamps, 2 single-pass 12mm flashlamps, 30 mm LBO crystal
Low Speed Cameras: LaVision sCMOS, 2560 x 2160 pixels, 6.5 μm pixel pitch, 16-bit depth, 20 Hz
Ultra-high-speed Cameras: Shimadzu HPV-X2, 400 x 250 pixels, 32 μm pixel pitch, 10-bit depth, 5 MHz, 128 frames max

- Laser split into 3 beams, 1 imaging and 2 pump beams
- Capable of simultaneous measurement with traditional DIH and PCDIH
- Polarizations: pump1 → p, pump2 → s, imaging → p, phase conjugate → s
- Configuration works for both picosecond and nanosecond lasers

Experimental Setup: Nanosecond Pulse Burst PCDIH

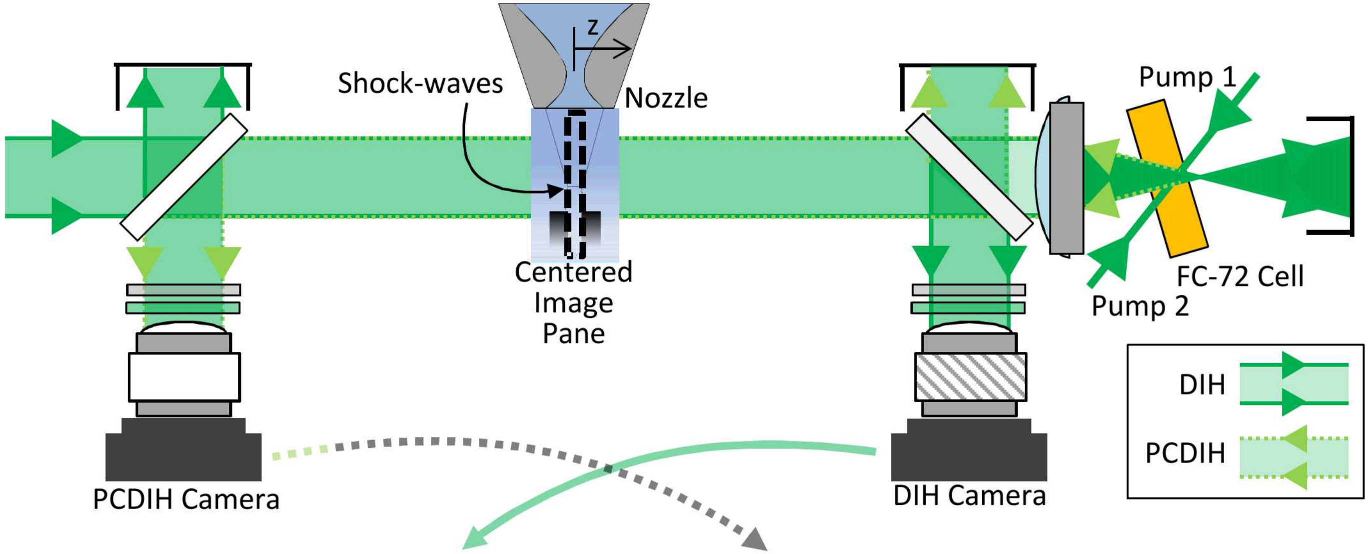


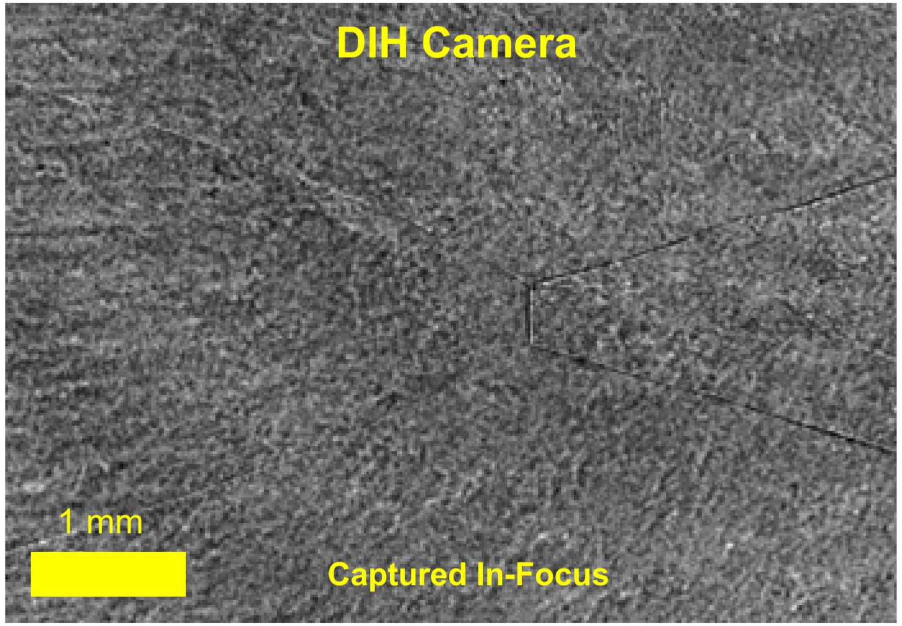
Experimental Setup

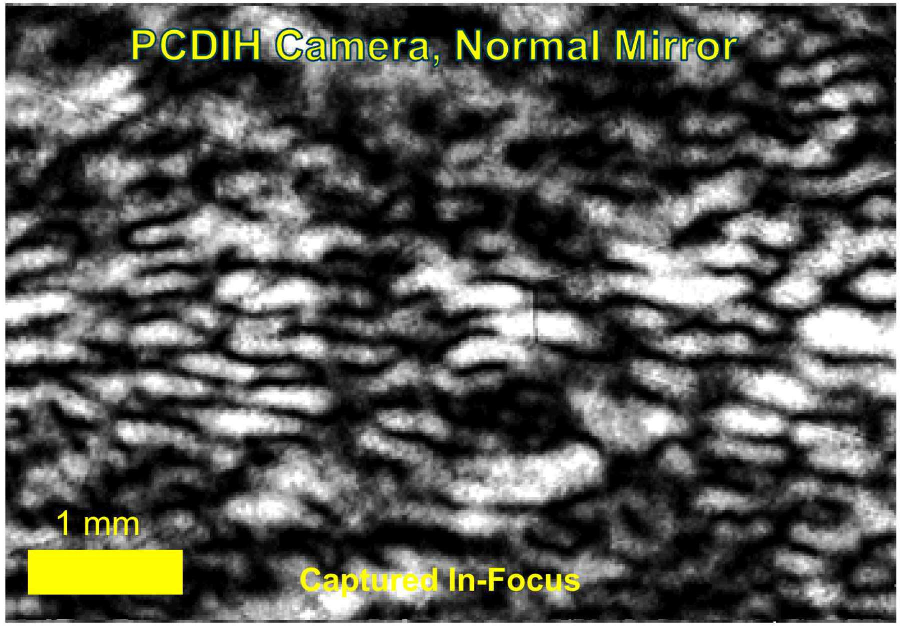


- More efficient design for nanosecond lasers
- Fewer optical components and easier to align
- 1 imaging and 1 pump beam (reflected for second pump beam)
- Inherent optical isolation in the pump beams

Stationary Supersonic Shock-waves (picosecond laser)



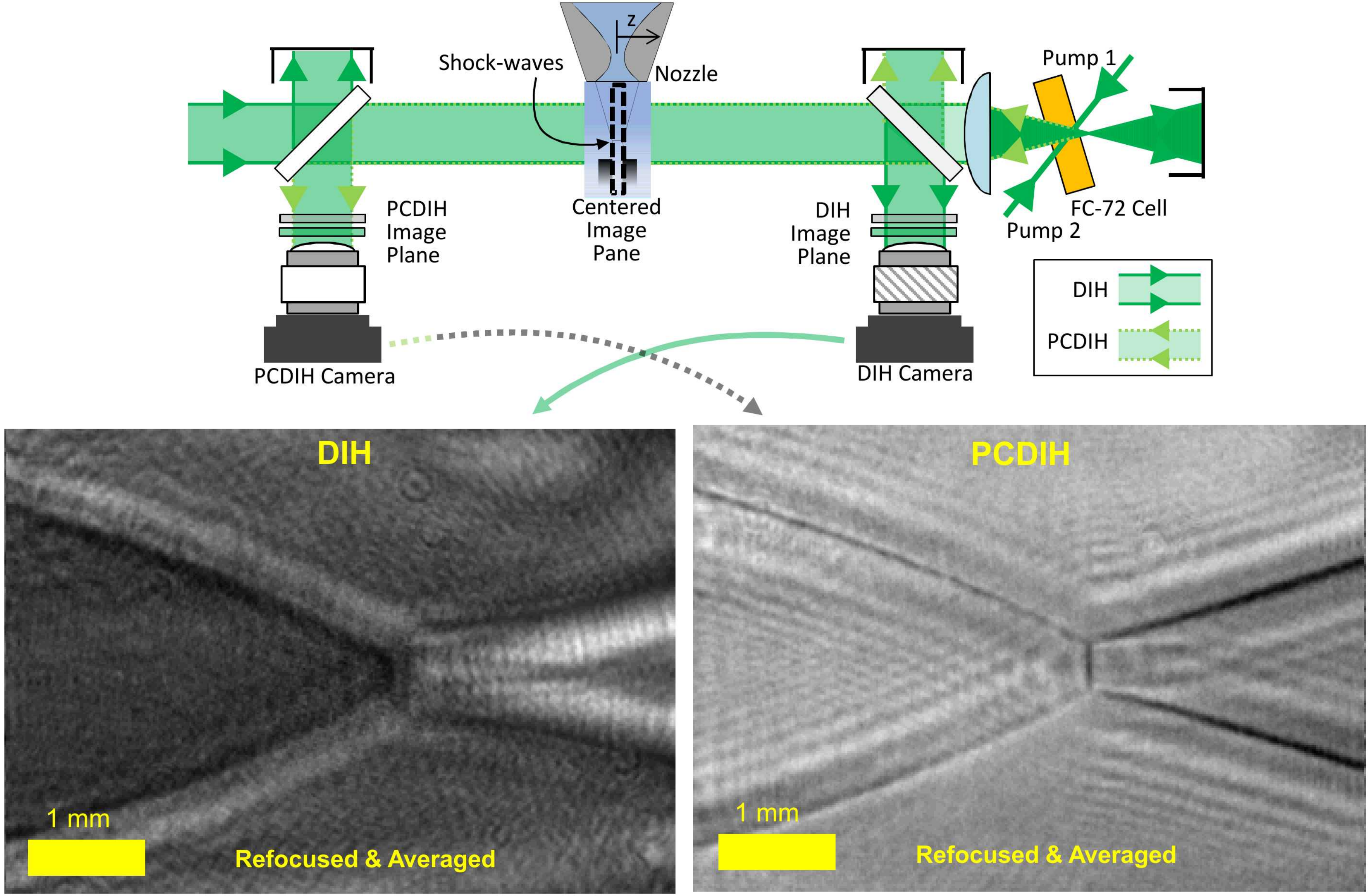




- Supersonic jet allows us to study <u>stationary</u> shock-waves
- Start by investigating <u>in-focus normal imaging</u>
- DIH camera shows clear shock-wave edges & some turbulence
- <u>Shock-wave edges are visible due to refraction</u>
- PCDIH camera shows shadows from acceptance angles of the PC mirror
- PCDIH camera with ordinary mirror shows out-of-focus diffraction patterns from the first pass and shock-wave edges from second pas

over-expanded jet
design Mach number of 3.7
6.35 mm nozzle outlet
stagnation pressure 4.3 Mpa
atmospheric pressure 84 kPa

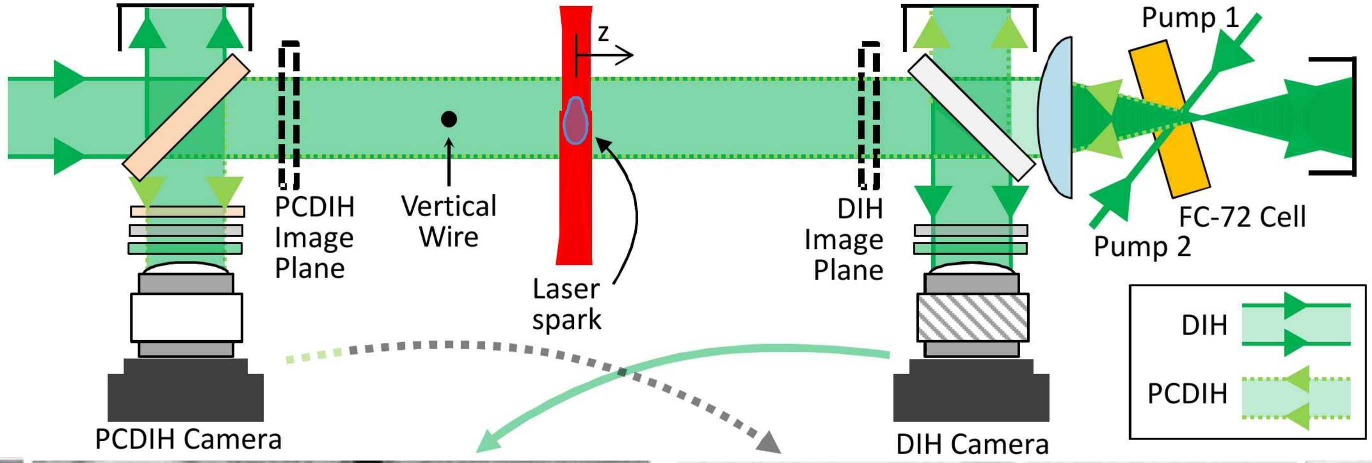
Stationary Supersonic Shock-waves (picosecond laser)



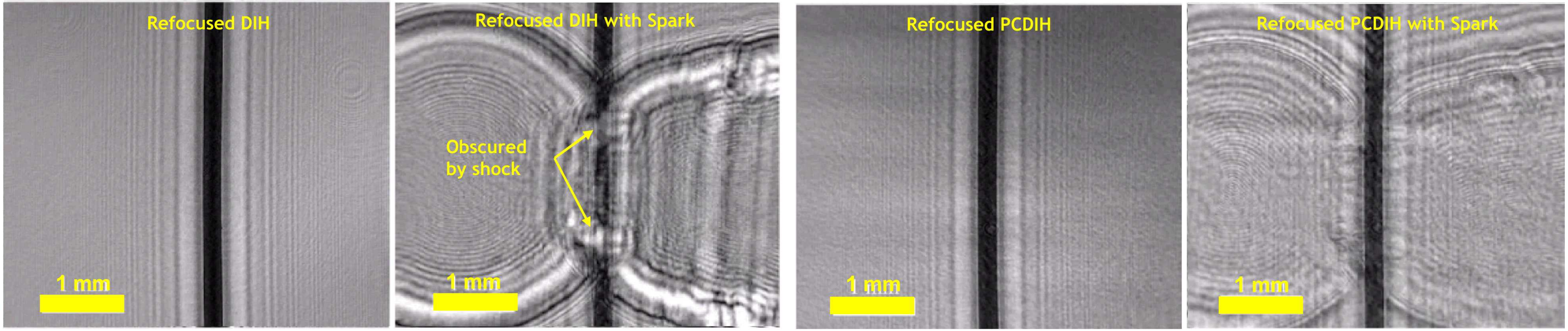
- Focal planes are next moved back for in-line holography
- Holograms are numerically refocused to the focal plane of the shock-wave.
- Single-shot DIH does not numerically refocus to any edges
- Single-shot PCDIH does refocus to shock-wave edges
- Averaging 500 holograms removes turbulence effects
- The DIH hologram does not refocus due to shock-wave distortions
- The PCDIH image refocuses successfully

Laser-spark plasma-generated shock-waves (picosecond laser)

Guildenbecher et al., Optics Letters, 2018



200 µm diameter wire
Continuum Surelite III focused laser
10 Hz, 1064 nm, 5 ns pulse duration
operating at 400 mJ per pulse



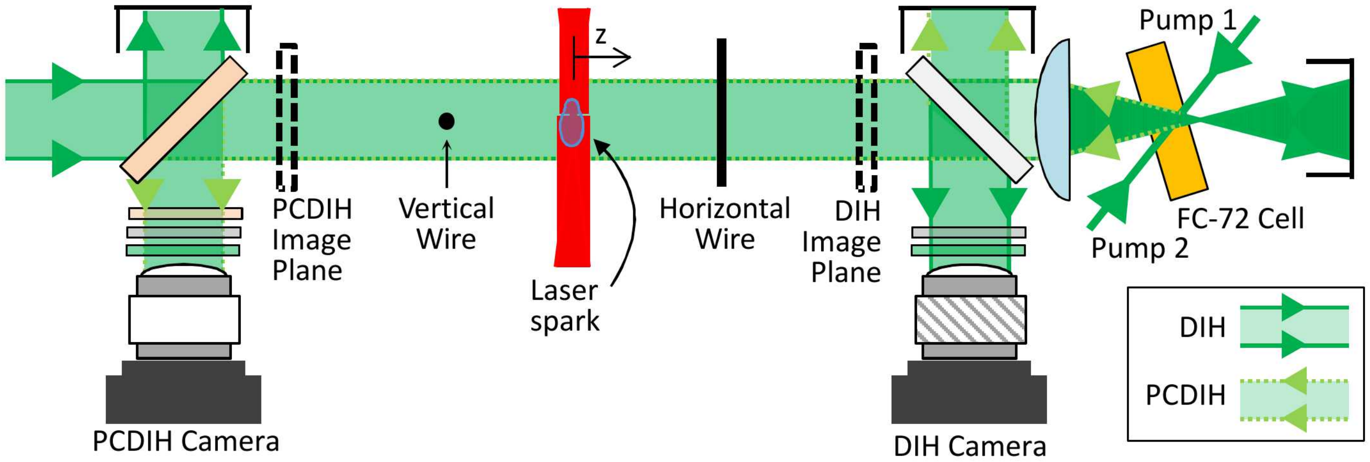
- PCDIH successfully cancels distortions generated by shockwaves that are obscured in DIH images
- Does the order of the wire and phase distortion matter?
- What does the shock-wave phase distortion look like as a function of time?

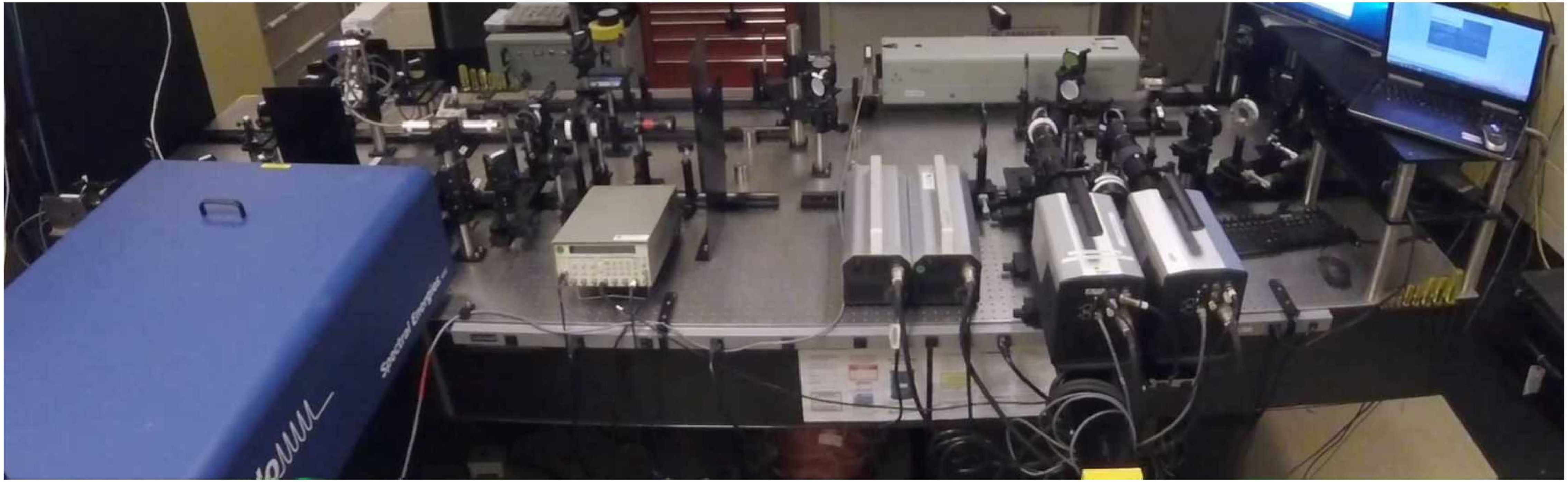
Pulse-burst Experiment

- Why do the shock-waves come into focus in DIH and PCDIH?
- What is the source of the remaining interference patterns in PCDIH if phase is cancelled?

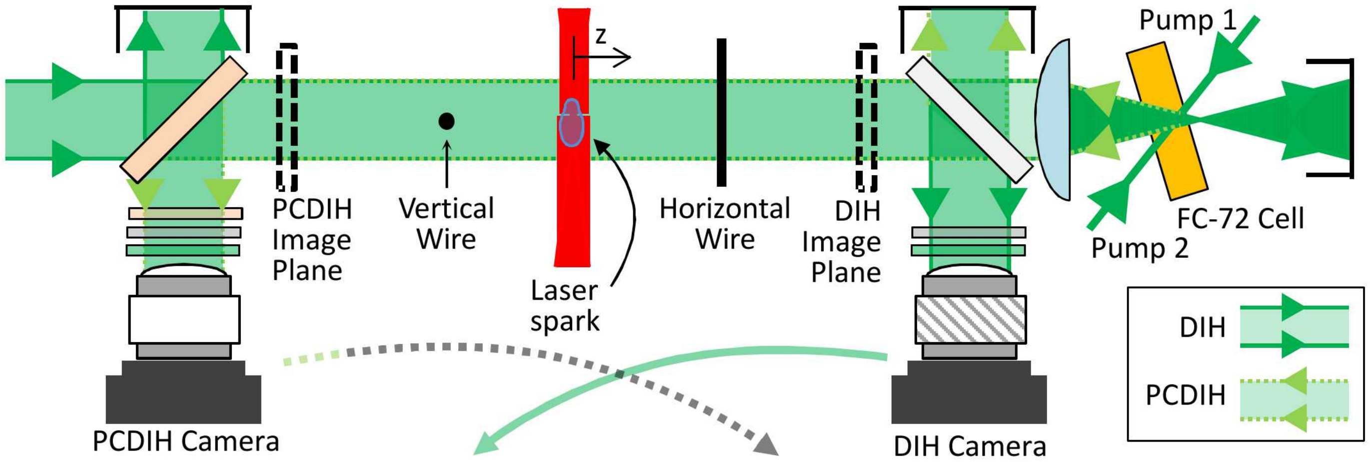
Numerical Simulation

Laser-spark plasma-generated shock-waves (nanosecond pulse burst)

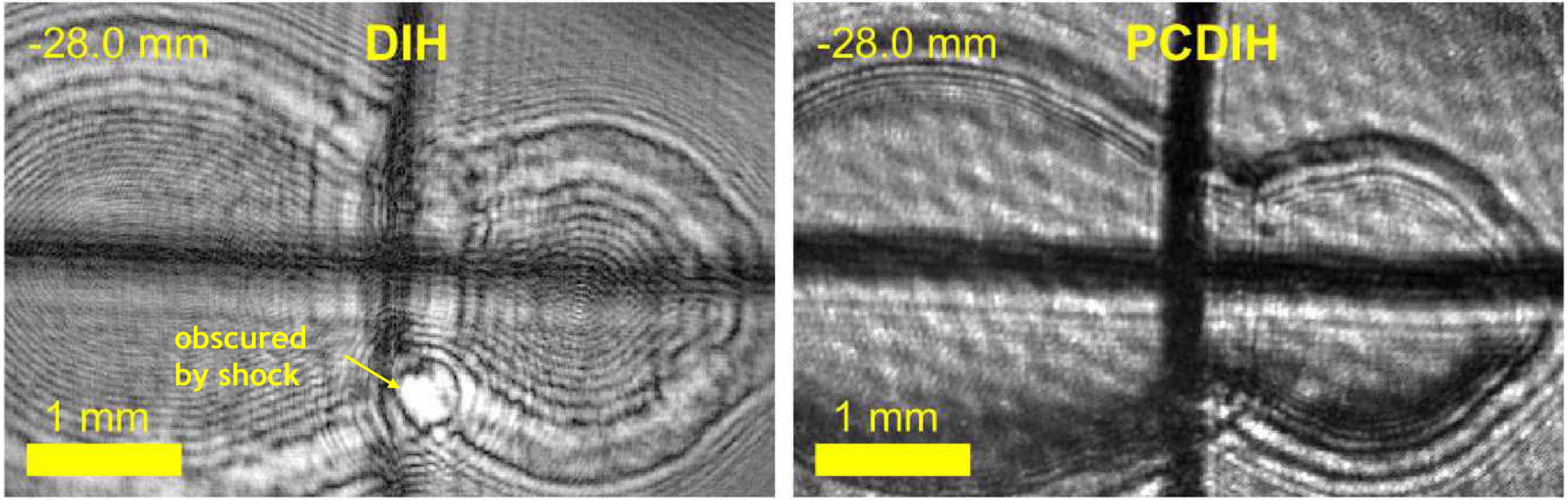




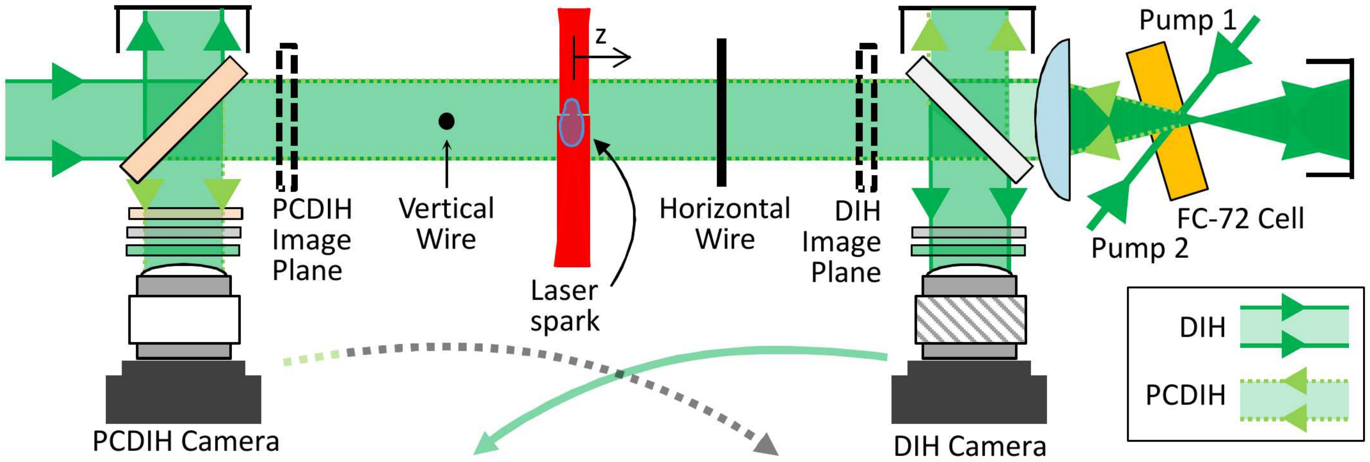
Laser-spark plasma-generated shock-waves (nanosecond pulse burst)



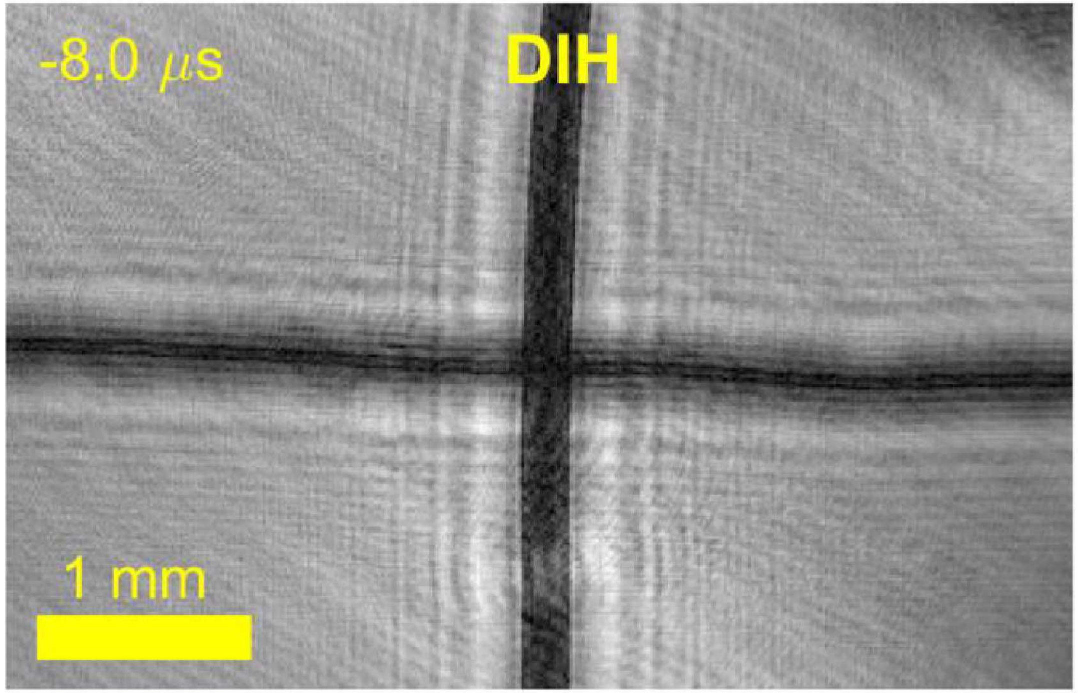
Numerical Refocusing

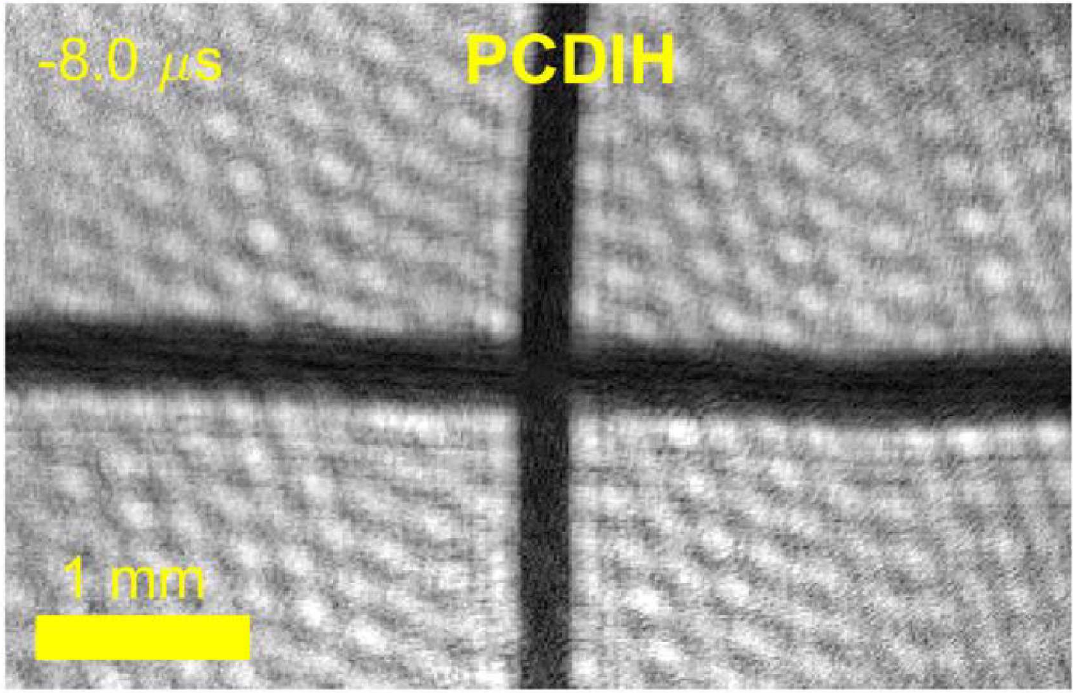


Laser-spark plasma-generated shock-waves (nanosecond pulse burst)

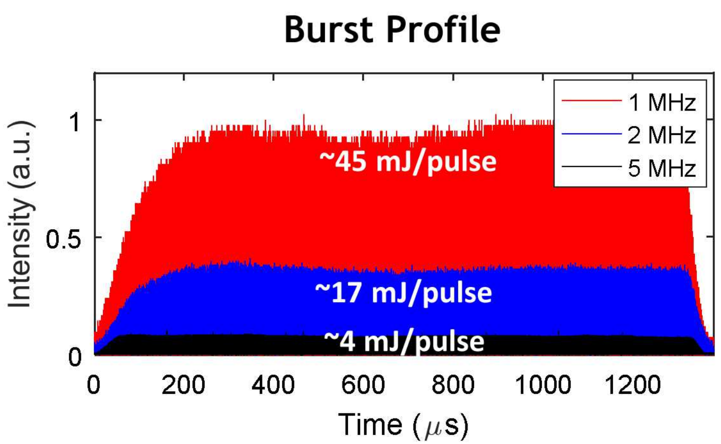


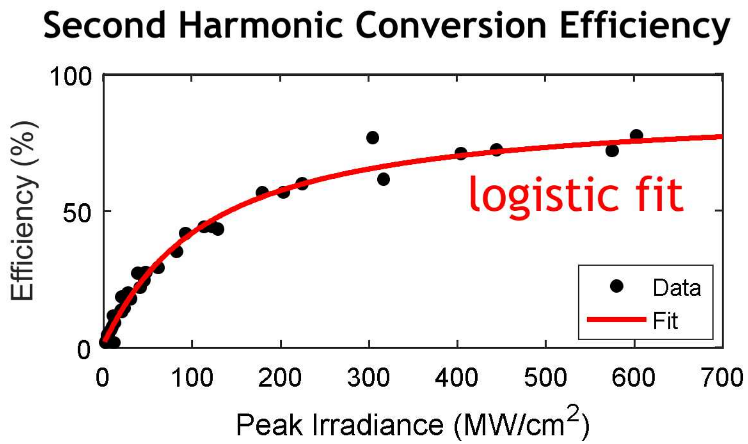
500 kHz Acquisition

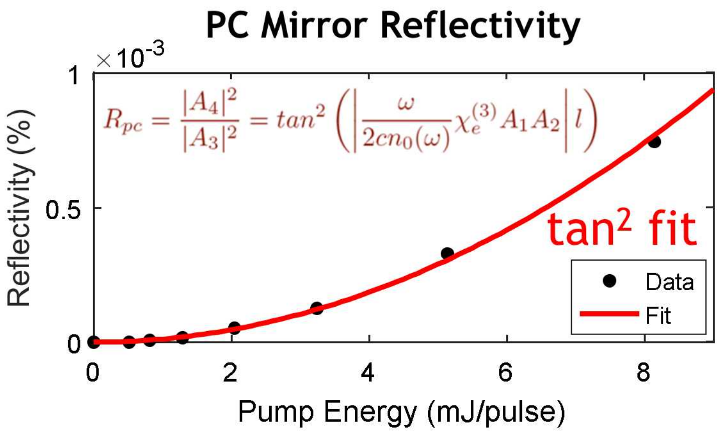




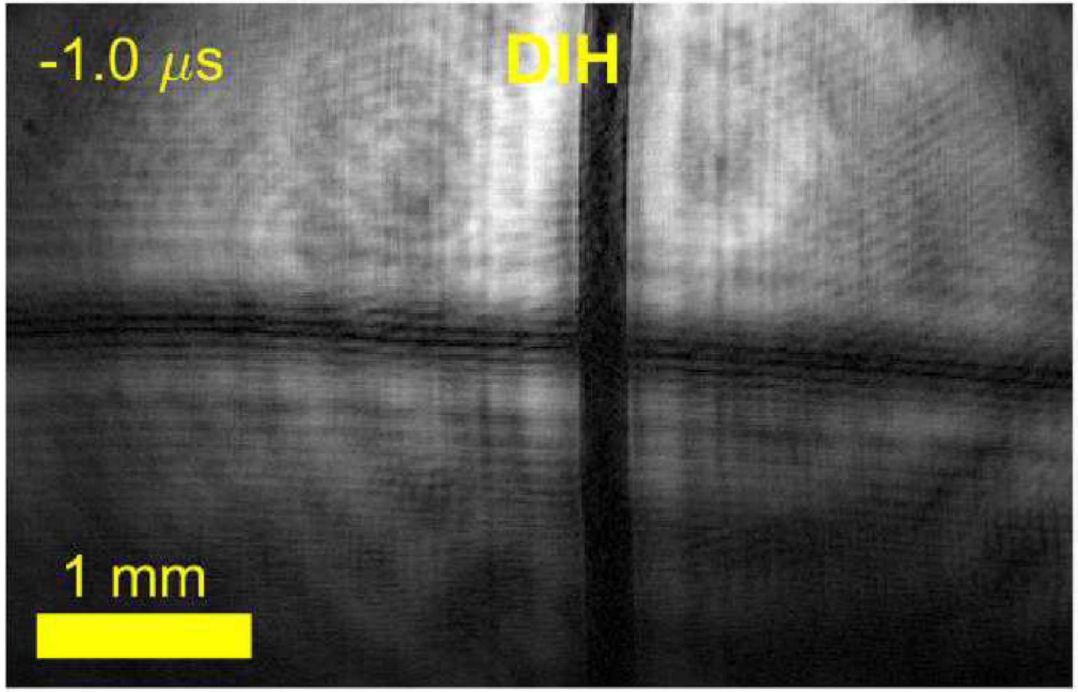
Laser-spark plasma-generated shock-waves (nanosecond pulse burst)

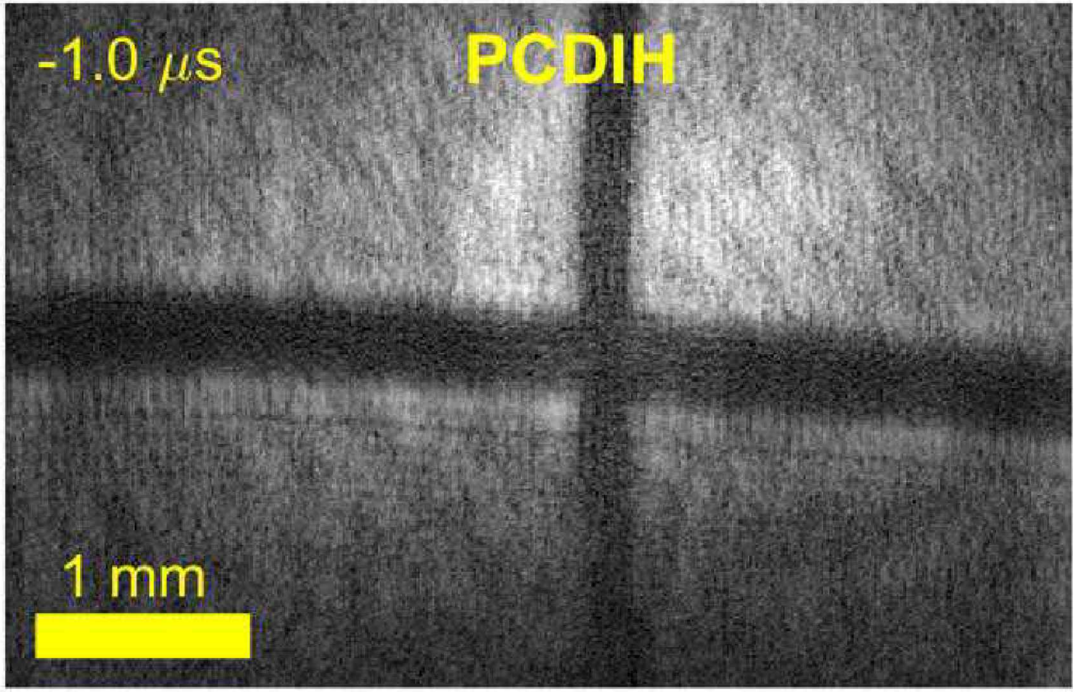




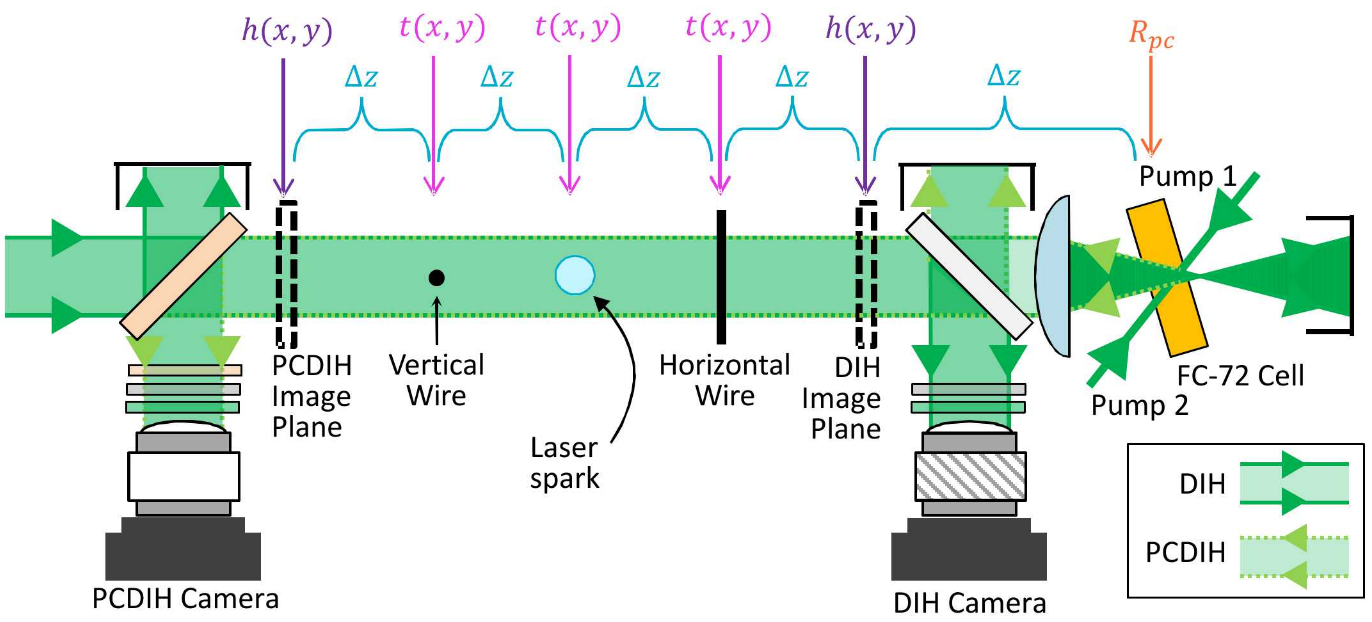


5 MHz Acquisition





Shockwave simulations



Coherent light $E_r(x,y) = A_r(x,y)e^{ikz-i\omega t}$

Interaction with object $t(x,y) = e^{-a(x,y)+i\phi(x,y)}$

Diffraction Propagation $E_t(x,y,z) = (E_r(x,y)\cdot t(x,y)) \otimes g_f(x,y,z)$,

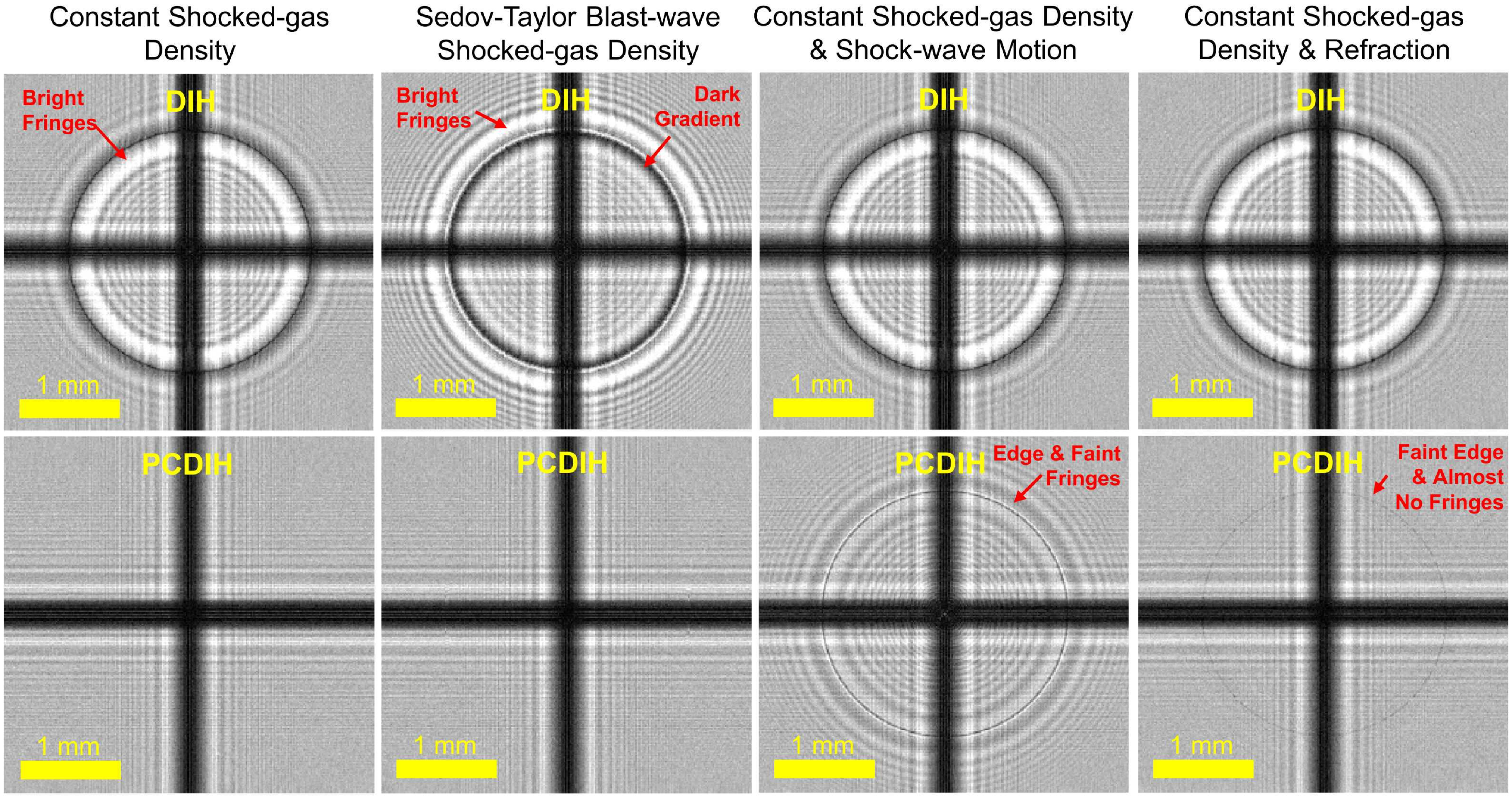
where i$g_f = FT^{-1}(G)$ and $G = e^{\frac{2\pi iz}{\lambda}\sqrt{1-(\lambda x)^2-(\lambda y)^2}}$

Spherical shock-wave phase delay $\phi(x,y) \approx 2\pi R(n_{gas} - n_{air})/\lambda\sqrt{1-z^2/R^2}$

Hologram collected at the image plane z_h as $h(x,y) = |E_t(x,y,z_h)|^2$

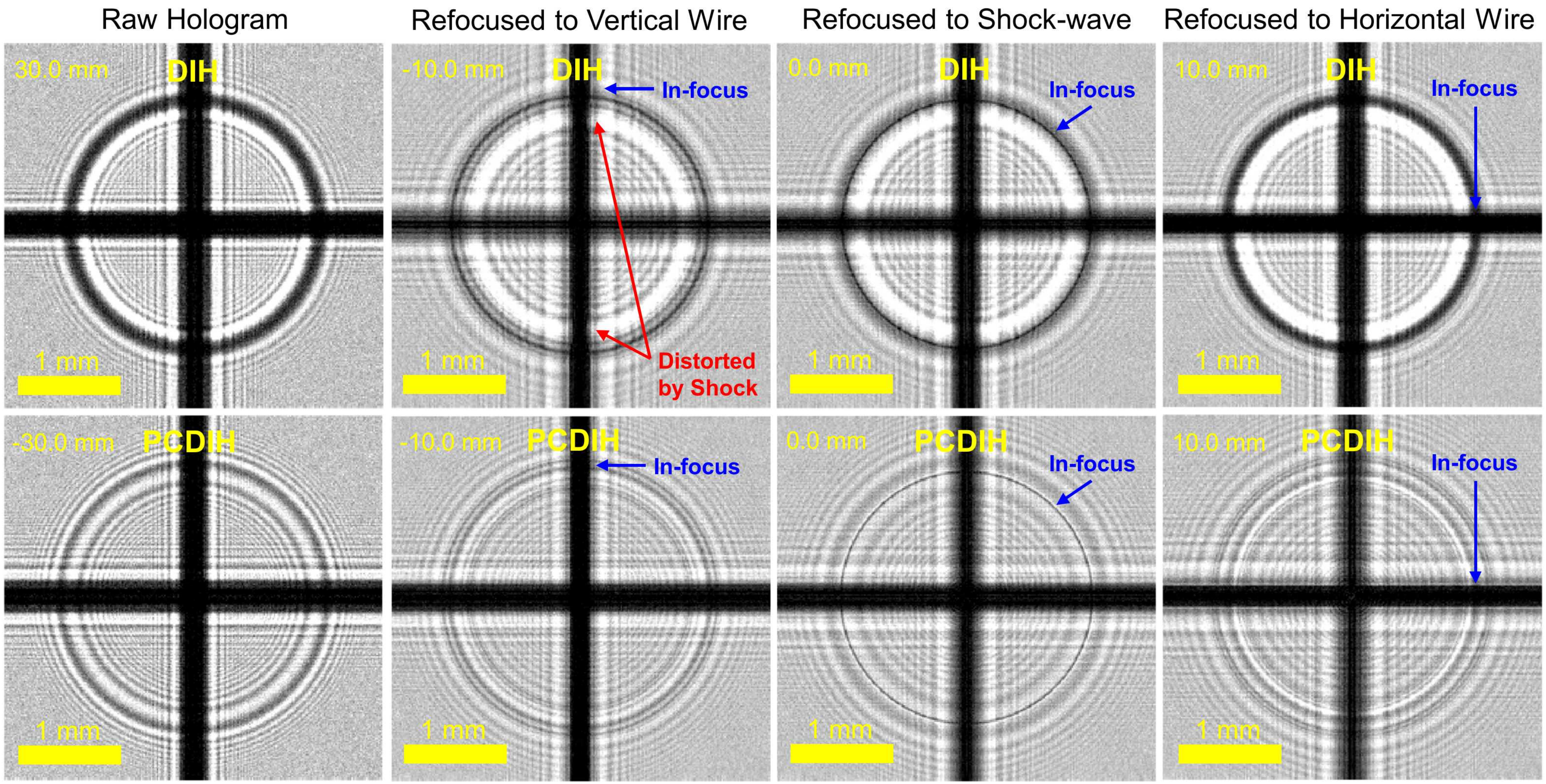
Phase conjugate mirror reflection $E_t'' = R_{pc}E_t^*(x,y,z)$

Shockwave simulations: Interference pattern sources



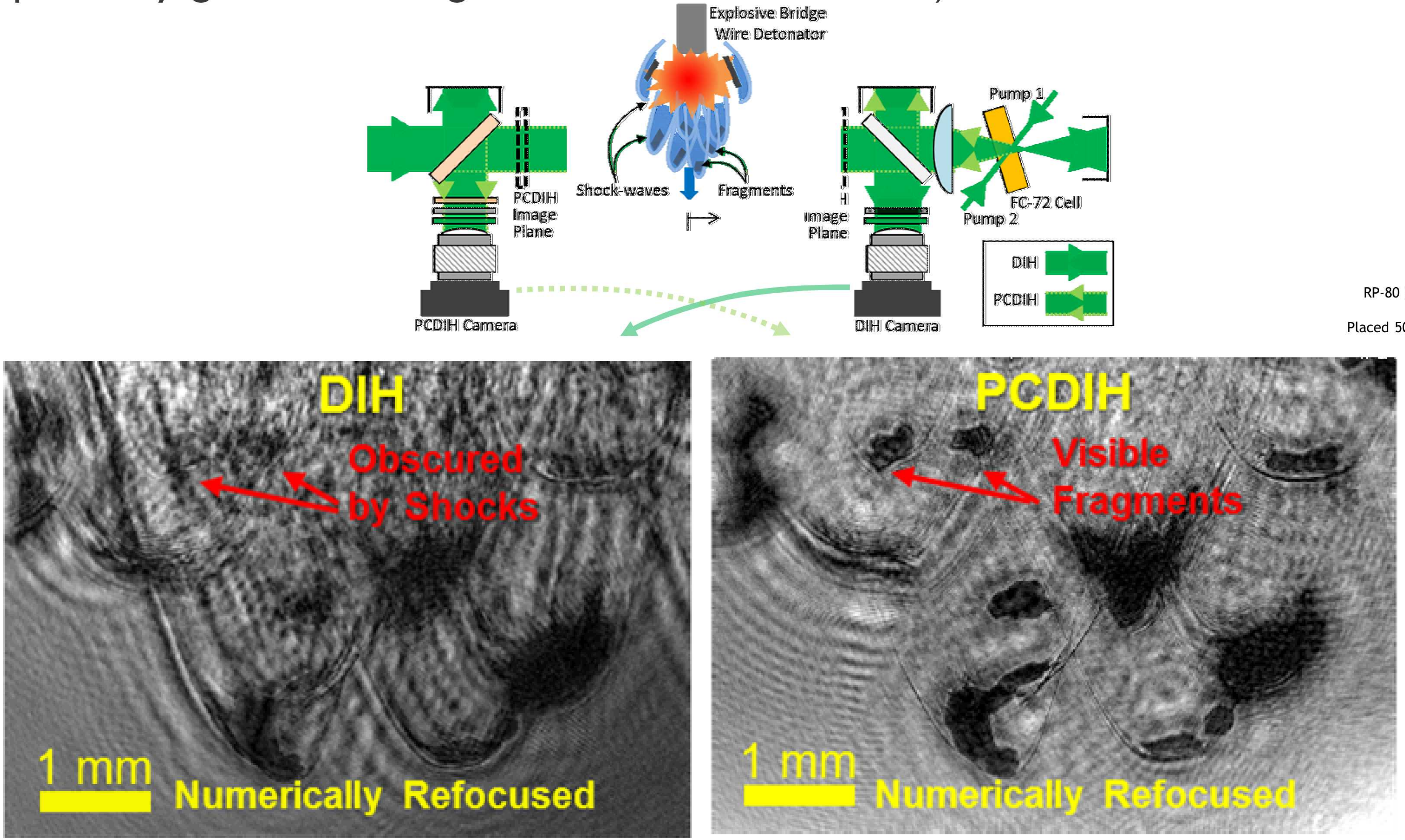
- Shock-wave motion during laser beam time-of-flight (6.8 to 12.8 μm) produces faint fringes
- Small misalignments or beam divergence can cause similar features
- From stationary supersonic shock-wave experiment, we know refraction also plays a role

Shockwave simulations: Refocusing of features



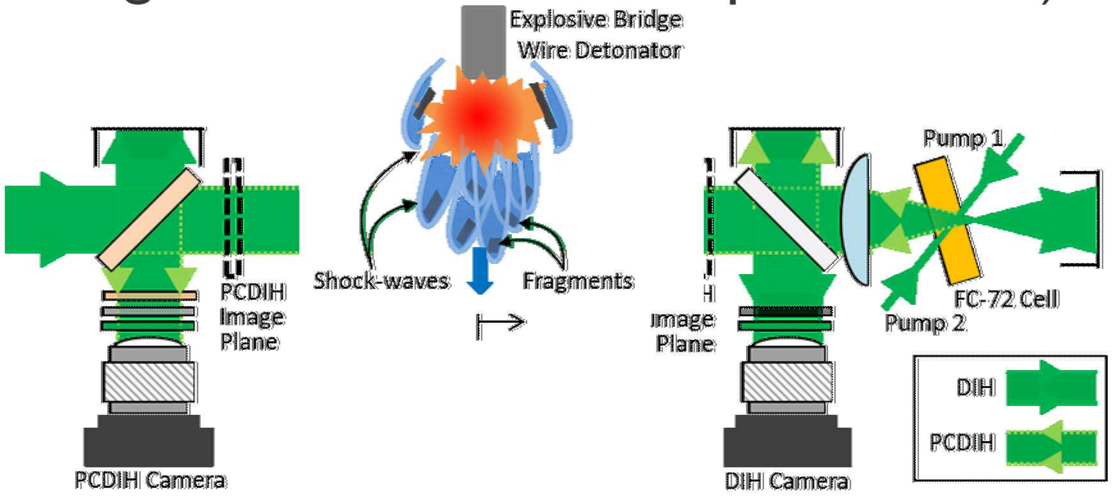
- Combining all the features, we get simulations that are very similar to experimental data
- Refocusable shock-wave edges in DIH and PCDIH
- Wire distortions (mostly on the vertical wire) from shock-wave phase delay due to order of objects

Explosively generated fragments (picosecond laser)



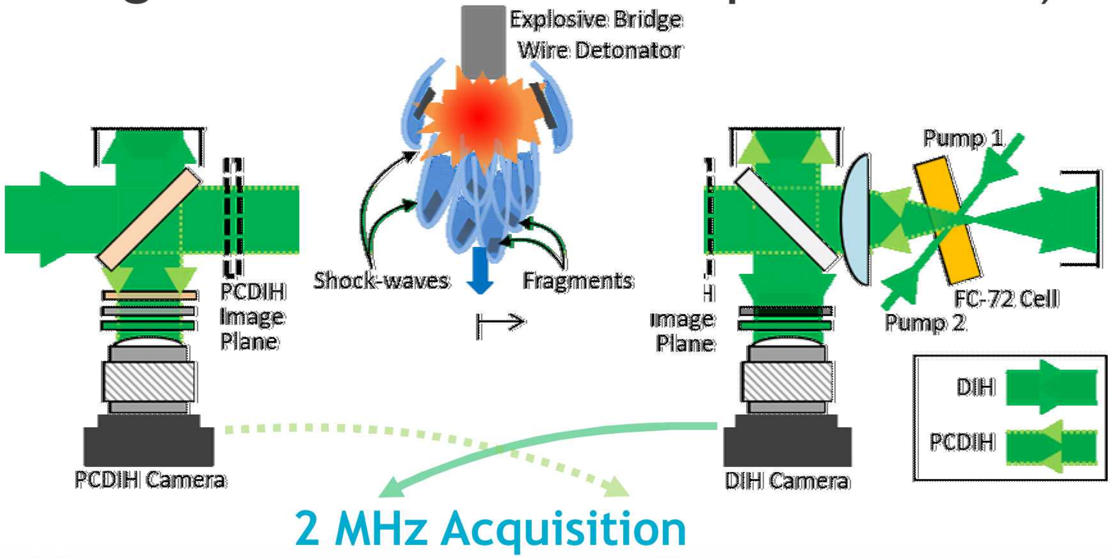
RP-80 EBW from Teledyne RISI
custom aluminum cap
Placed 50 mm from field-of-view

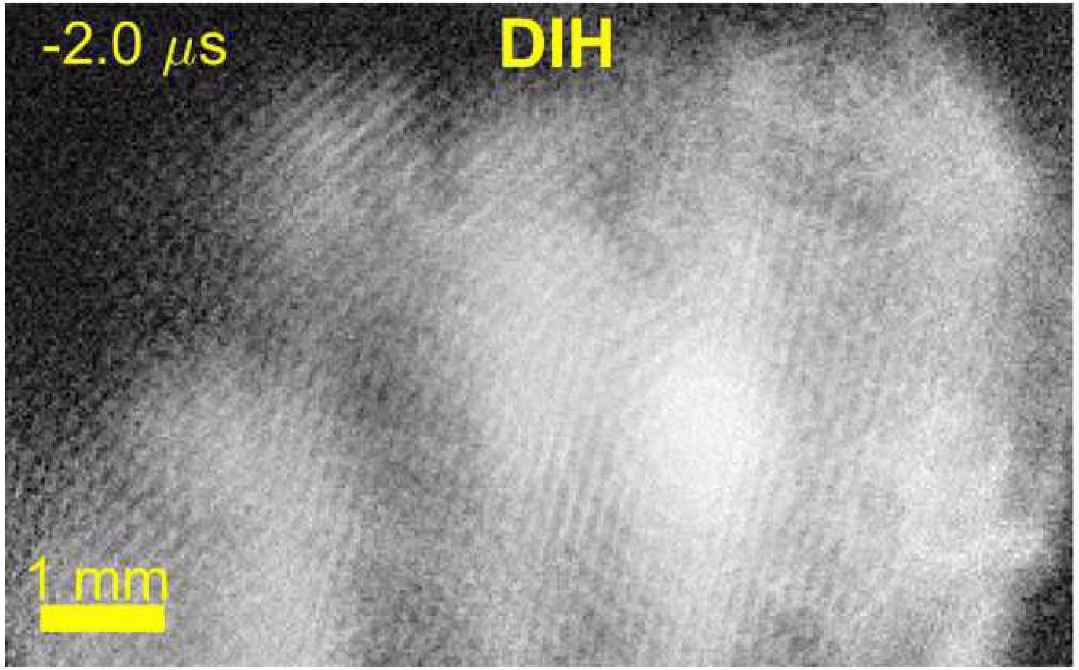
Explosively generated fragments (nanosecond pulse burst)

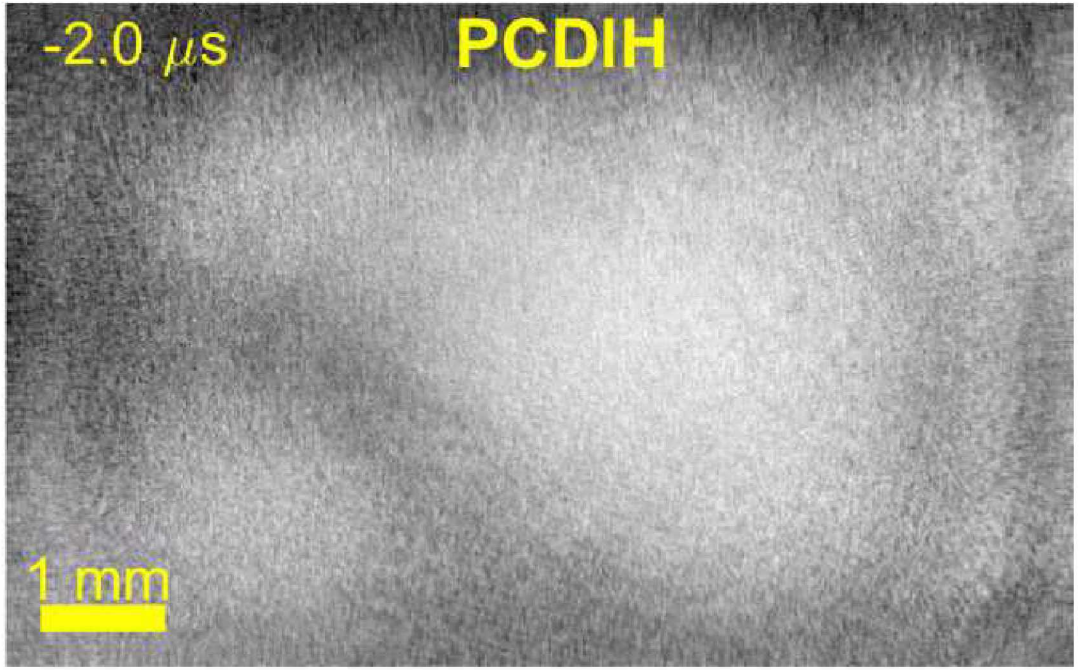


RP-80 EBW from Teledyne RISI
custom 180 μm thick brass cap
Placed 50 mm above field-of-view
facing downward

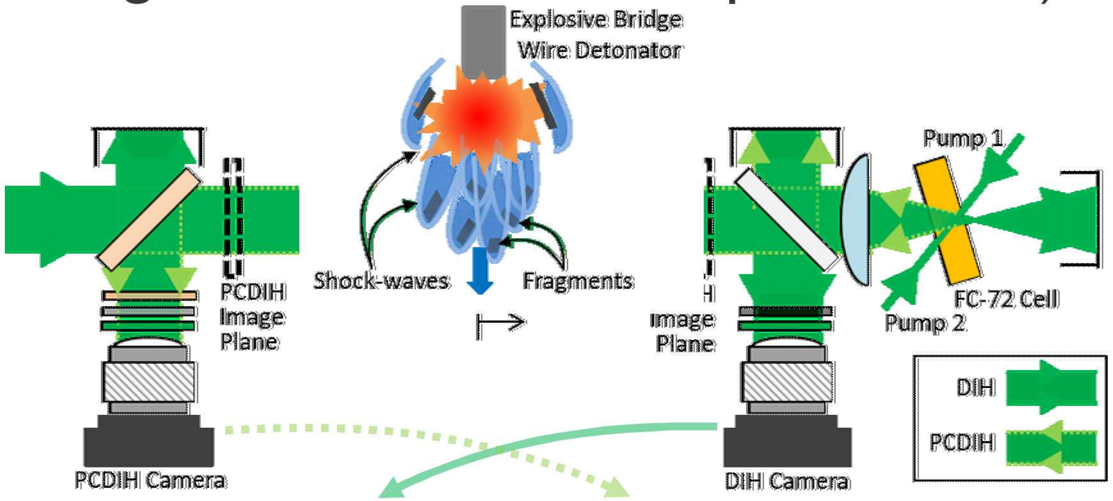
Explosively generated fragments (nanosecond pulse burst)





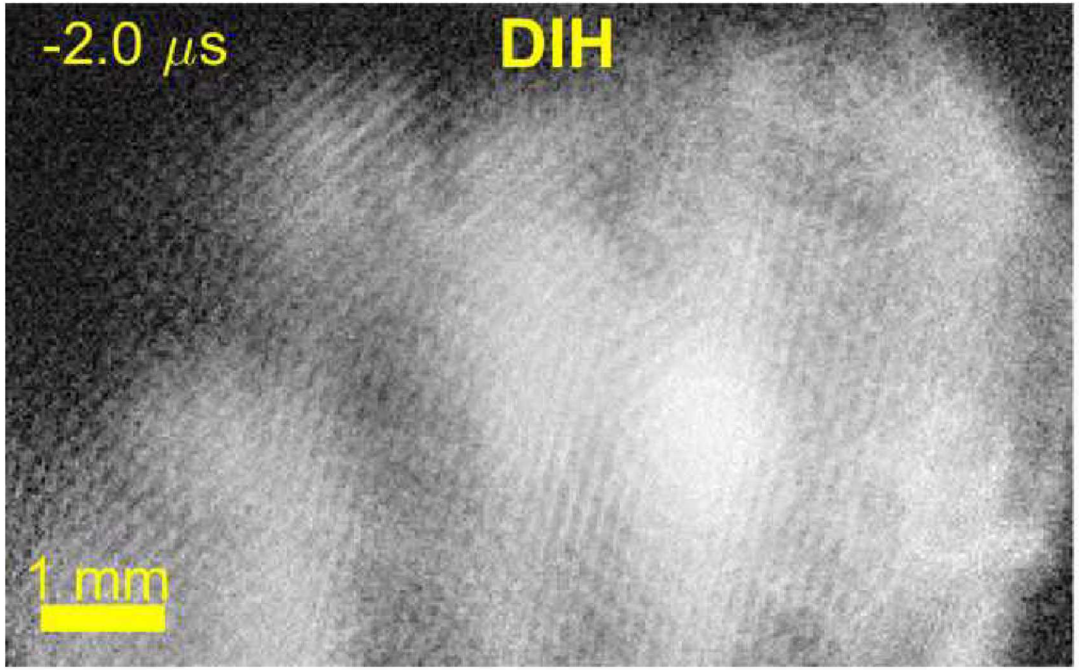


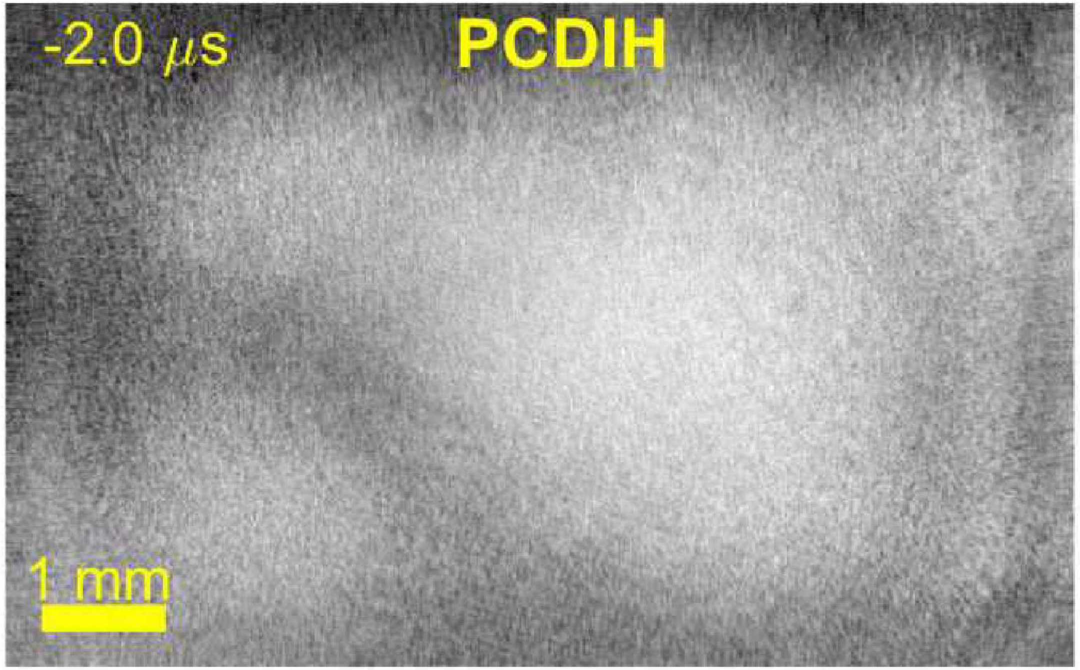
Explosively generated fragments (nanosecond pulse burst)



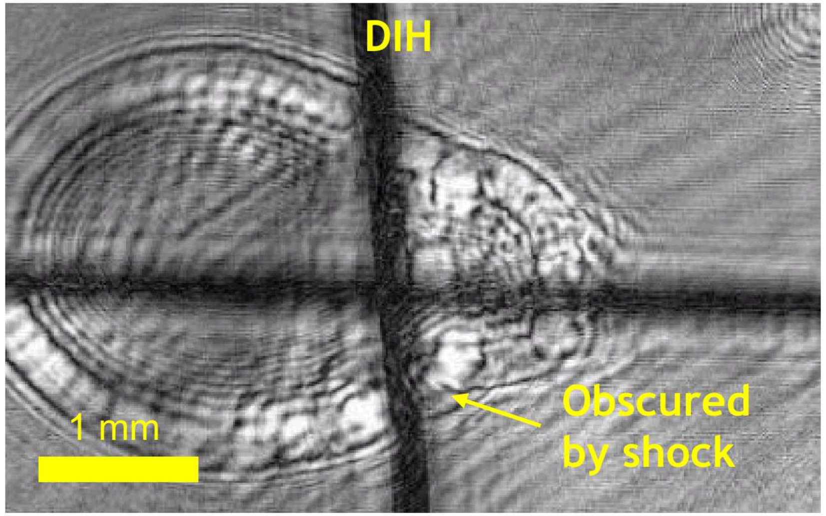
2 MHz Acquisition

Fragment Speeds:
2.34 to 2.83 km/s
Mach 6.8 to Mach 8.2





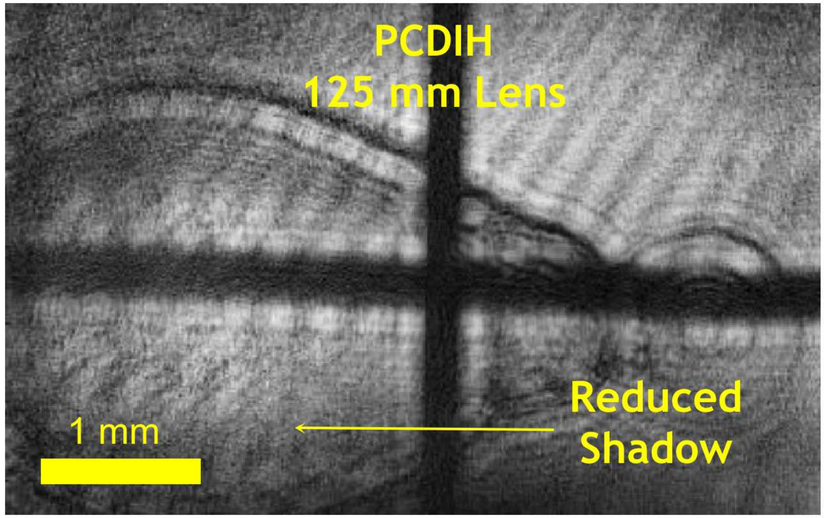
Shock-wave edge enhancement (nanosecond pulse burst)



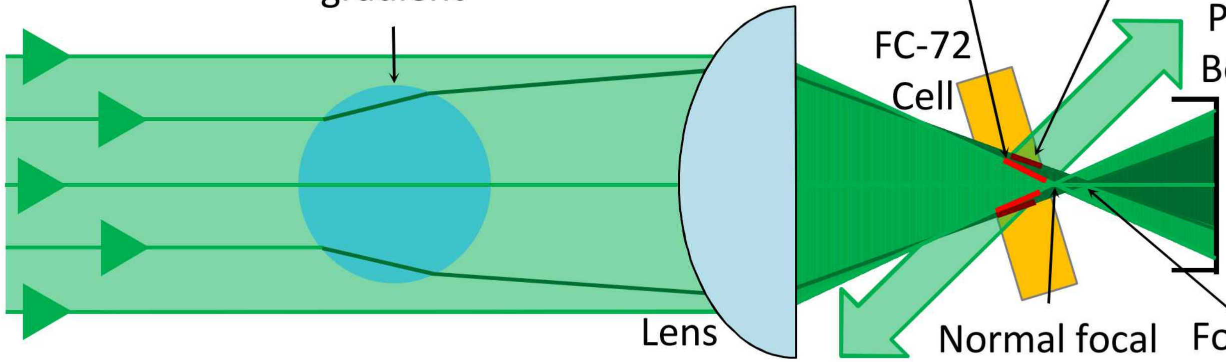
PCDIH
300 mm Lens

1 mm

Shockwave Shadow

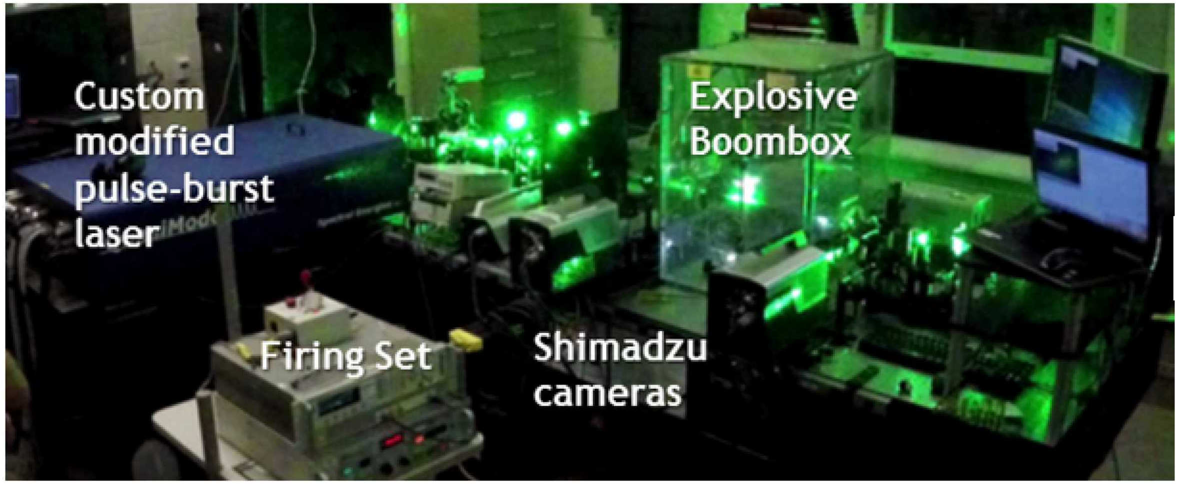


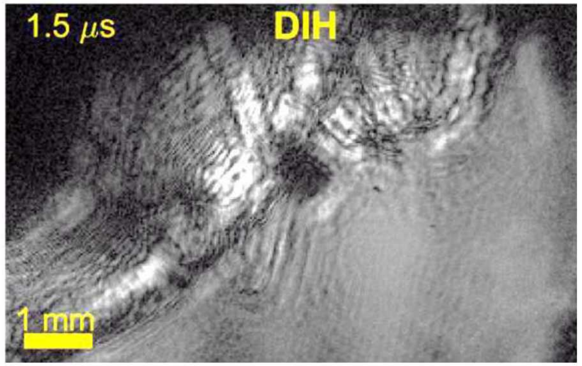
- Shock-wave edges can be enhanced depending on the geometry of the phase conjugate mirror
- Edge enhancement effect is similar to Schlieren or Shadowgraphy <u>except:</u>
    - Effect is nonlinear
    - Shock-wave edge locations can be refocused to find z-position

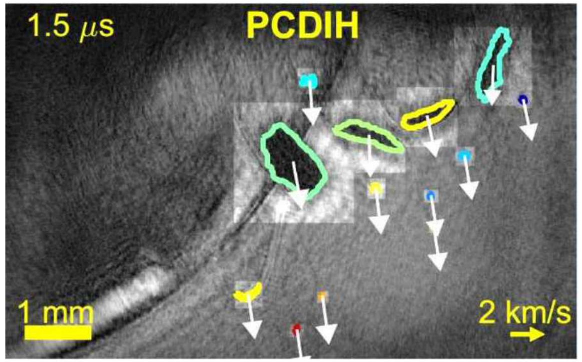


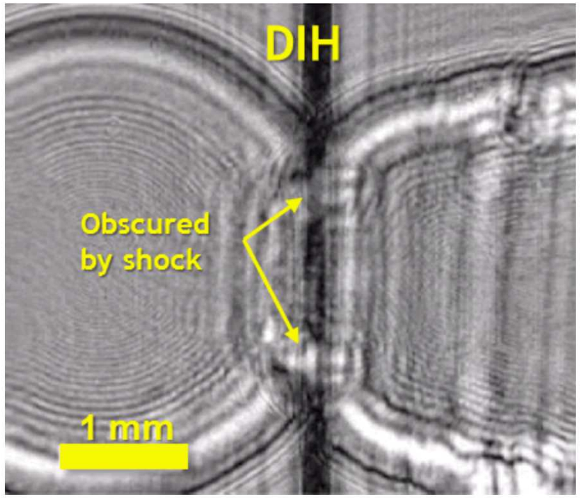
Conclusions

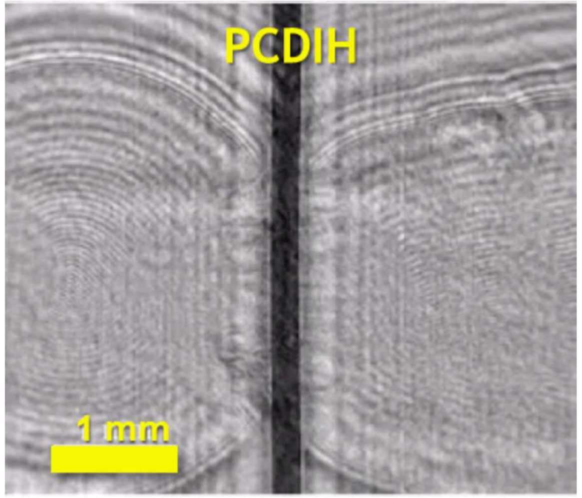
- Shock-wave phase distortions prevent 3D time-resolved holographic imaging
- We introduce ultra-high-speed PCDIH for phase-distortion canceled 3D imaging and object tracking using only one line of sight
- Custom modified nanosecond pulse-burst laser and ultra-high-speed cameras were used
- Demonstrated up to 5 orders-of-magnitude increase in speed from 10-20 Hz up to 5 MHz
- Fastest digital in-line holograms collected to date
- Experiments were conducted on:
  - Stationary supersonic shock-waves
  - Laser-spark plasma-generated shock-waves
  - Explosively generated fragments
- Simulations show that:
  - Object and phase delay order determines degree of distortion
  - Shock-wave edges are visible and refocusable in PCDIH due to shock-wave motion and refraction











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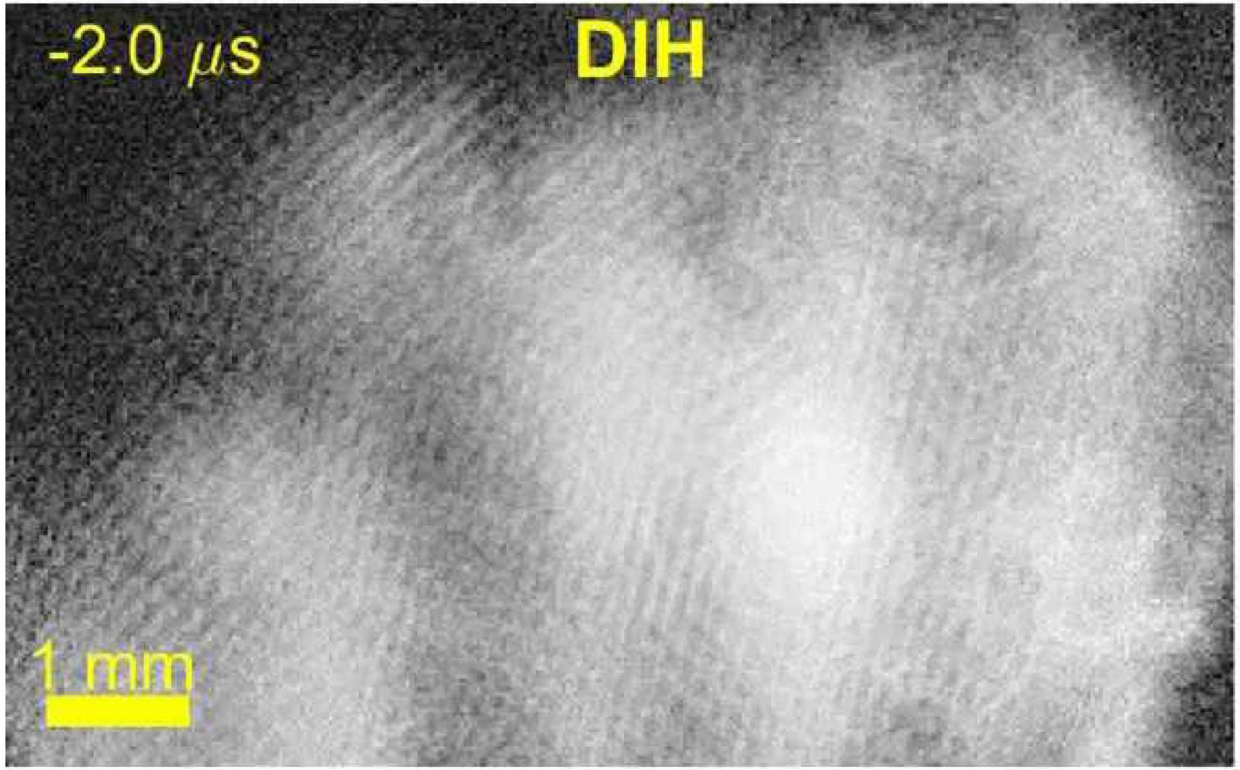
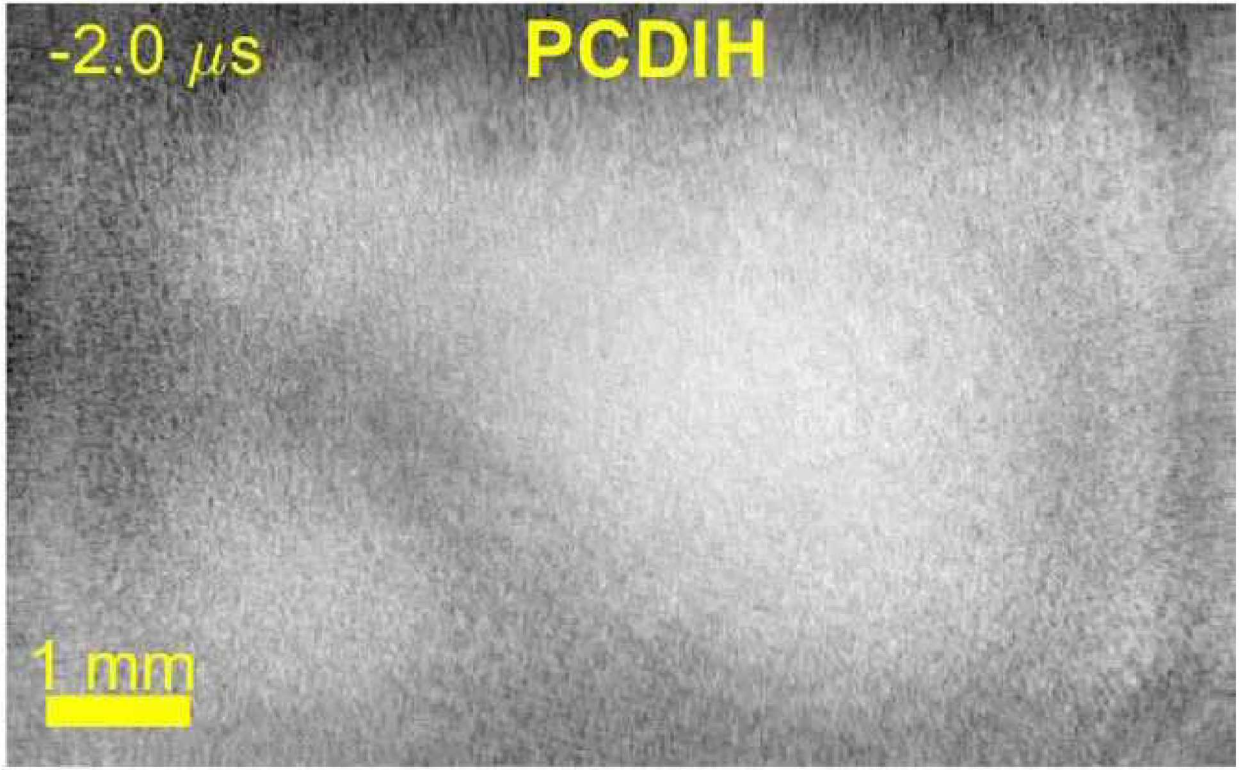
Questions?

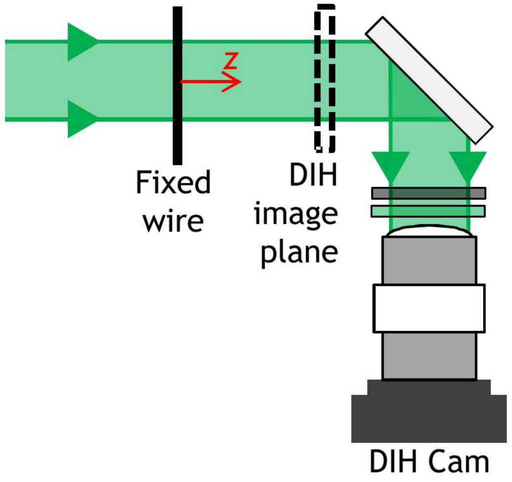
DIH versus PCDIH

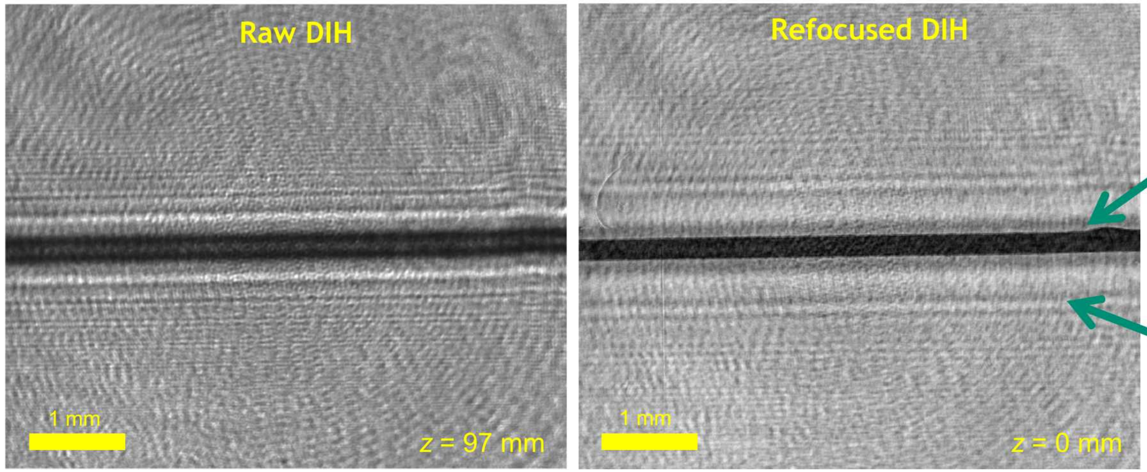




Additional Backup Slides

Digital In-line holography





In-focus hologram with sharp edges

Diffraction patterns from "virtual image"

- Digital In-line holograms (Gabor 1948) are collected out-of-focus and are later numerically refocused

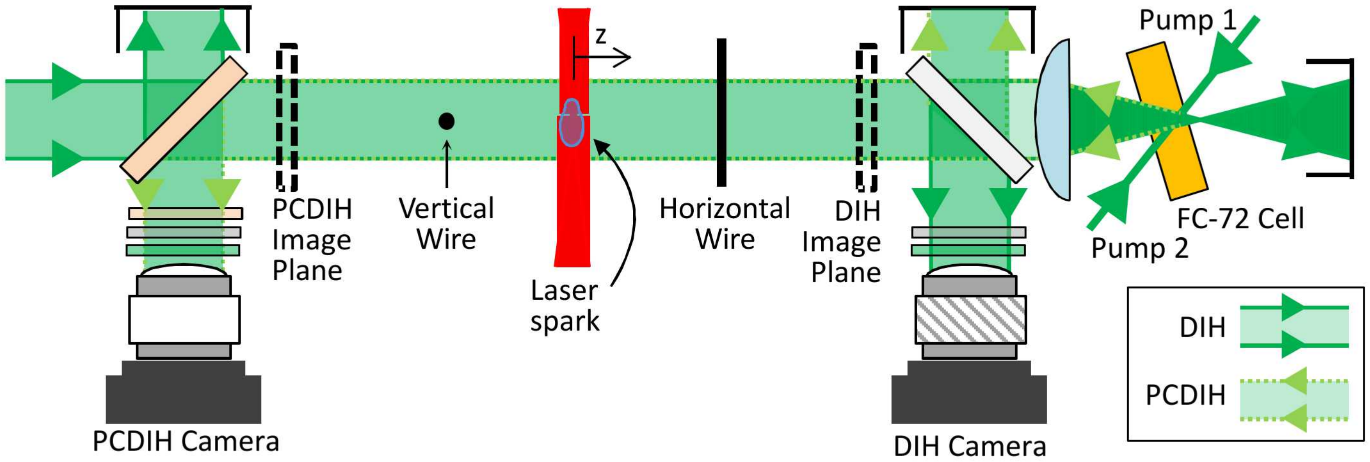
Hologram Generation Process

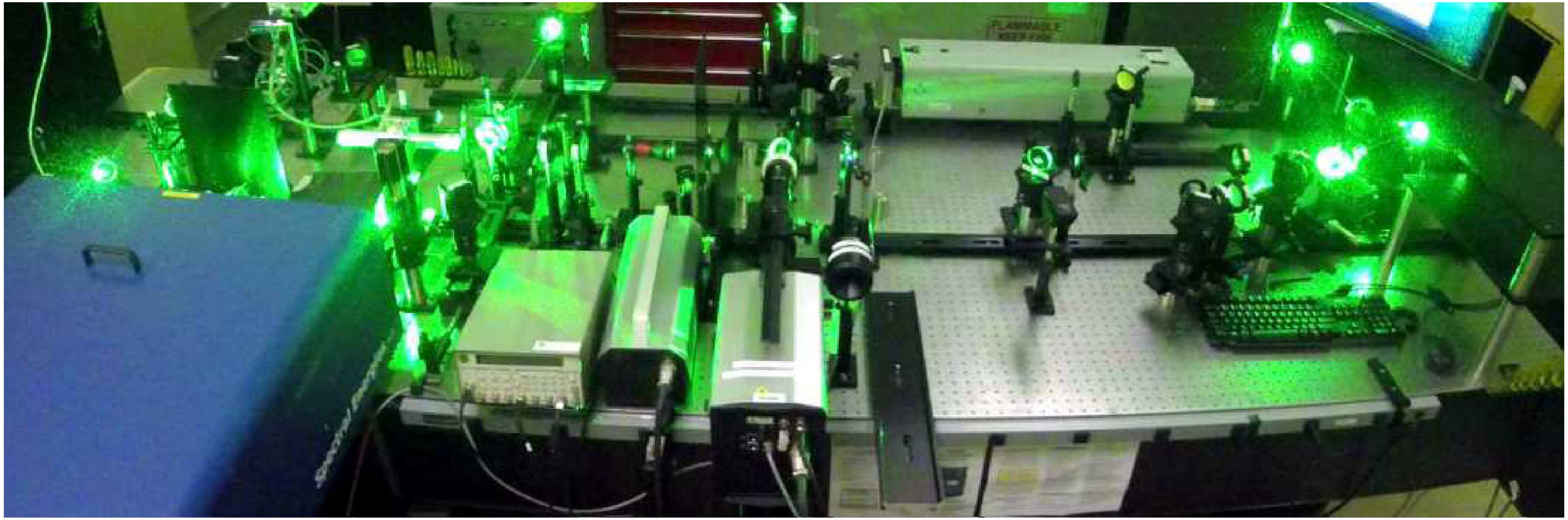
- Holograms are generated
  - When coherent light $E_r(x, \mathrm{y}) = \mathrm{A_r(x,y)e^{ikz-i\omega t}}$ passes over a diffractive object with transmission $t(x,y) = e^{-a(x,y)+i\phi(x,y)}$
  - Fresnel-Kirchhoff diffraction can be using as $E_t(x,y,z) = \left(E_r(x,y)\cdot t(x,y)\right) \otimes, g_f(x,y,z)$
  - Where the diffraction kernel is $g_f = FT^{-1}(G)$ where $G = e^{\frac{2\pi i z}{\lambda}\sqrt{1-(\lambda x)^2-(\lambda y)^2}}$
- Holograms are collected at the image plane z_h as $h(x,y) = |E_t(x,y,z_h)|^2$

Hologram Refocusing Process

- Holograms are numerically refocused
  - Using $E_h(x,y,z) = [h(x,y)E_r^*(x,y)] \otimes g_b(x,y,z)$ where $g_b = FT^{-1}(G^*)$
  - The amplitude is determined from $A_h = |E_h|$
  - In-focus z-planes are determined using maximum edge sharpness and minimum amplitude criteria.

Laser-spark plasma-generated shock-waves (nanosecond pulse burst)





5 MHz Laser-spark plasma-generated shock-wave Mach stems