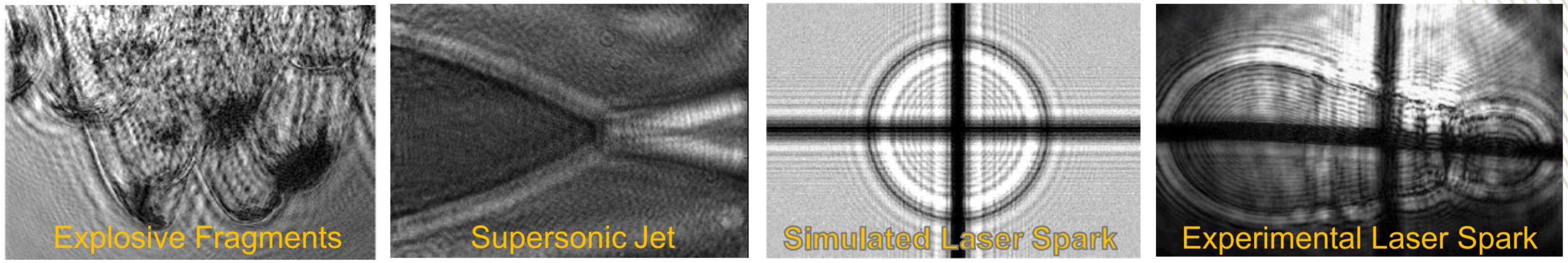
SAND2019-6962C

Shock-wave Distortion Cancellation using Ultra-high-speed Phase-conjugate Digital In-line Holography



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Gordon Research Conference
Laser Diagnostics in Energy and Combustion Science
Les Diableret, Switzerland, June 23rd -28th, 2019

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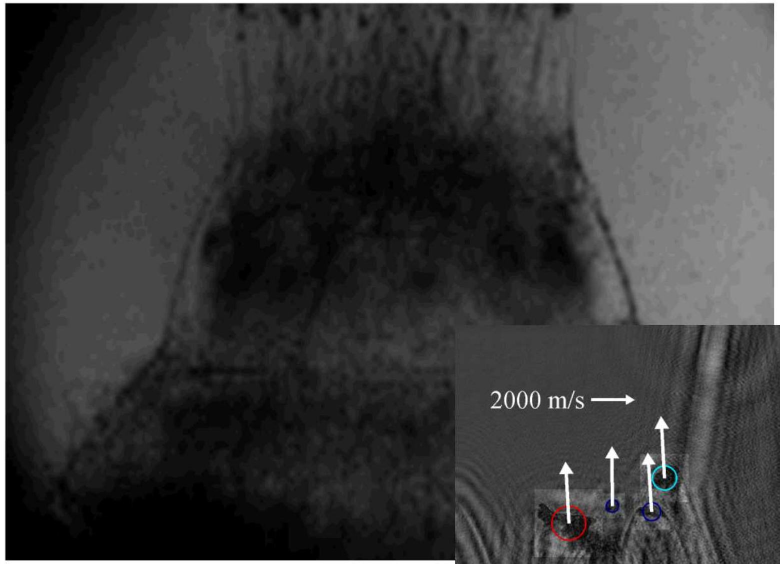
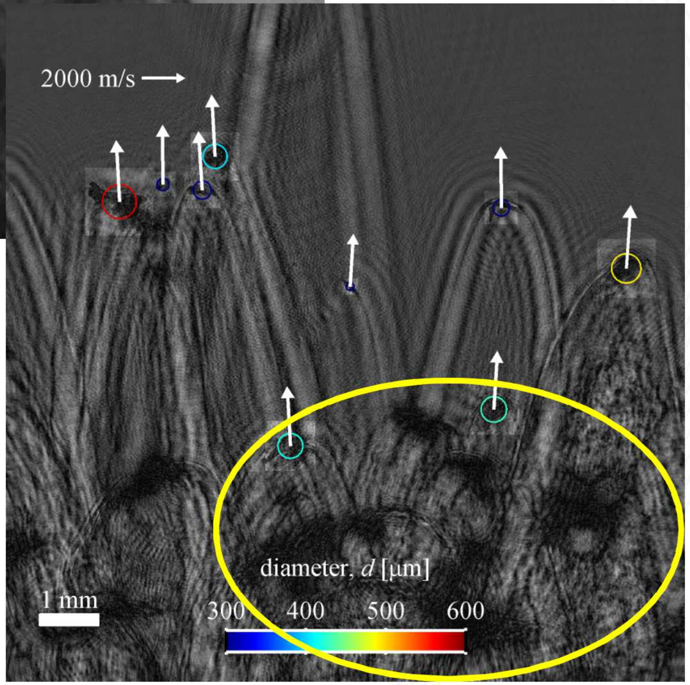
Motivation

Problem

- <u>Shock-wave phase distortions</u> prevent accurate <u>3D</u> interrogation in supersonic, hypersonic, and explosive environments.

Shadowgraphy of Exploding Detonator





Digital In-line Holography
Fragments Obscured by Shock-Waves

Motivation

Problem

- Shock-wave phase distortions prevent accurate 3D interrogation in supersonic, hypersonic, and explosive environments.
- Shock-wave motion often requires ultra-high-speed acquisition for time-resolved measurements.

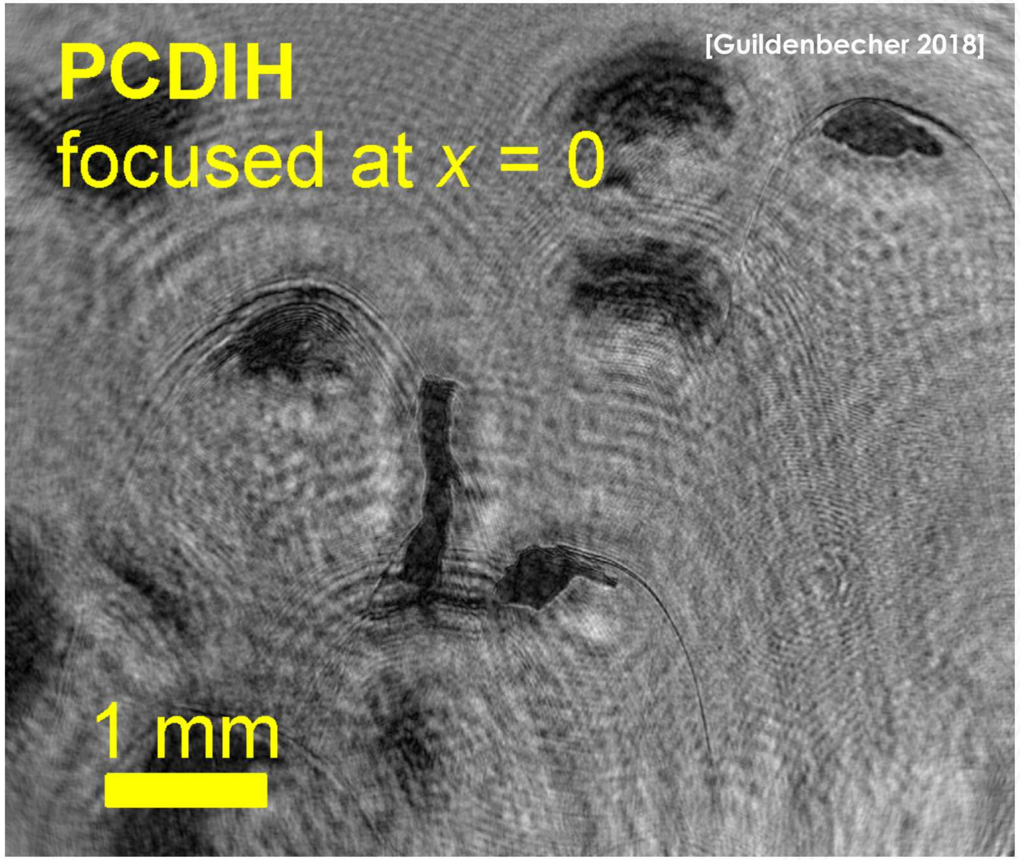
Existing Approaches

- Testing in vacuum changes the environmental conditions.
- Synchrotron x-ray testing requires experimental repetition to get 3D information [Willey 2016].

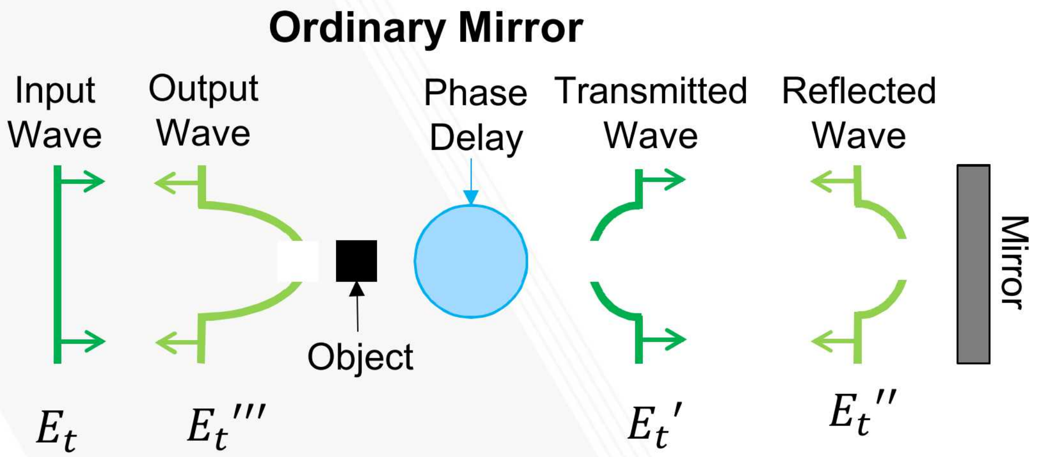
Proposed Solution/Objectives

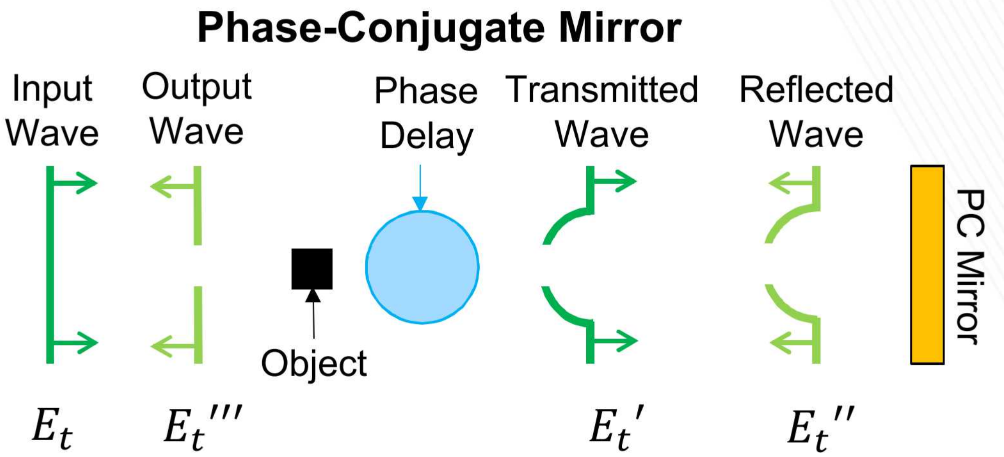
- Cancelling the distortion using phase-conjugate digital in-line holography (PCDIH)
- Track hypersonic fragments in 3D from an explosive detonator through shock-wave distortions
- Acquire data at 2 to 5 MHz (increase of 5 orders of magnitude from 20Hz) using pulse burst laser.
- Understand the physical mechanisms that produce unknown features in DIH and PCDIH images

Fragments from Exploding Detonator
Single-shot hologram from 20 Hz Picosecond Laser



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

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

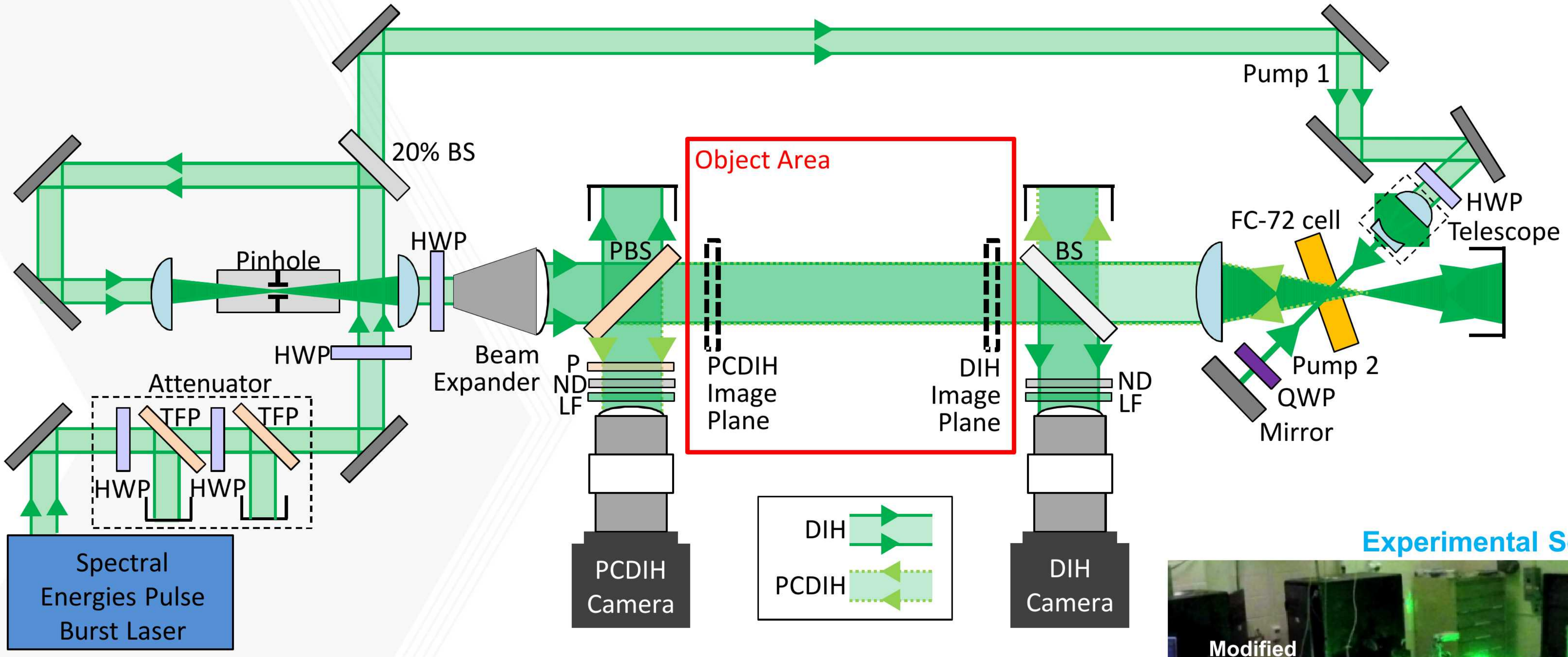
Conjugate phase

Output Wave

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

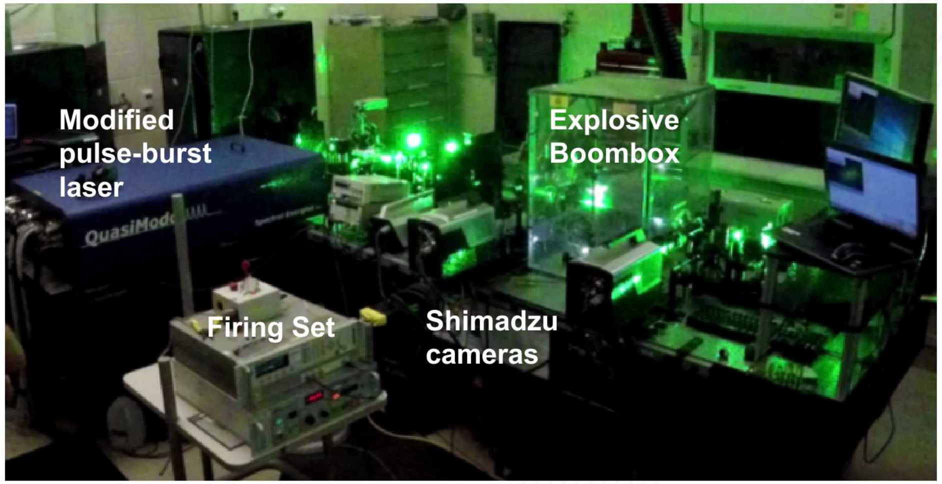
Cancelled phase delay

PCDIH with Nanosecond Pulse Burst Laser



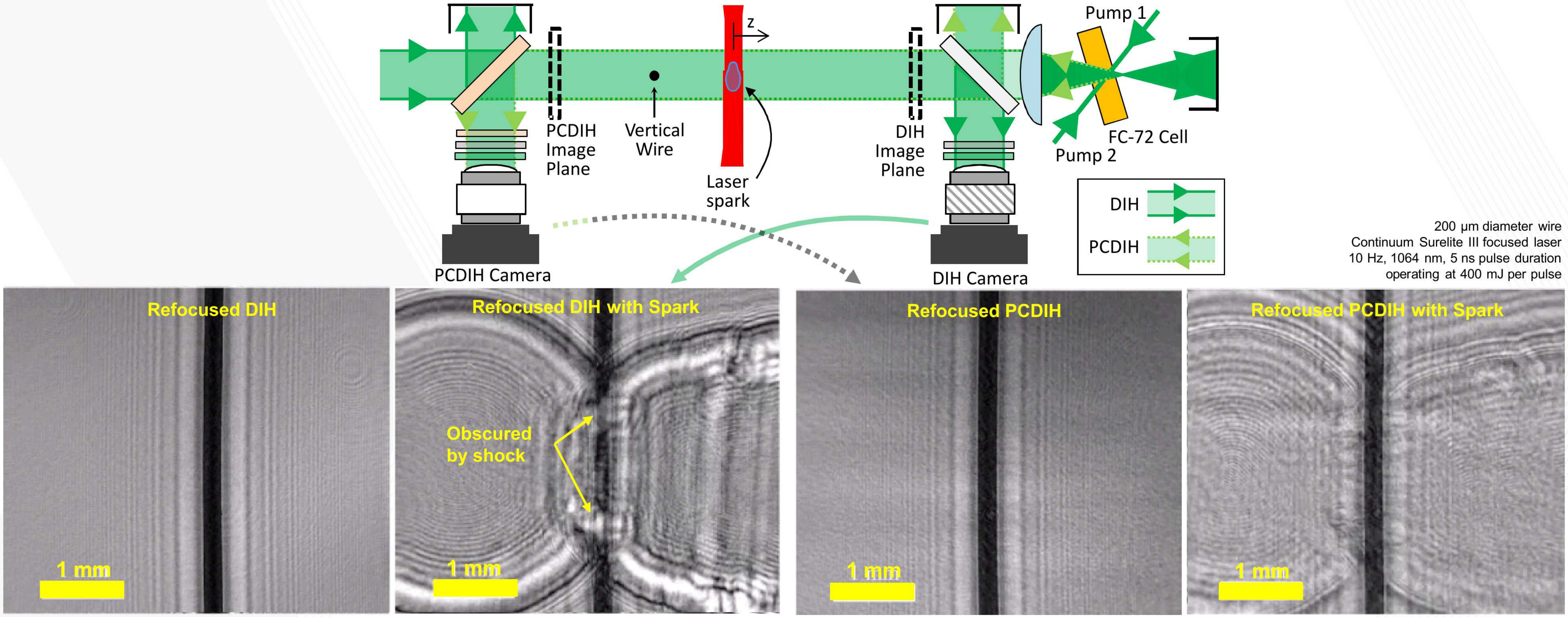
- HWP—half wave plate
- QWP—quarter wave plate
- TFP—thin-film polarizer
- BS—beam splitter
- PBS—polarizing beam splitter
- P—polarizer
- ND—neutral density filter
- LF—laserline filter, 0.2 nm FWHM
- Nanosecond Pulse-burst: ~3 ns pulses, >1.5 ms burst, 12 s between bursts, pulsed seed, 2 double-pass diode-pumped amplifiers, 2 double-pass 9mm flashlamps, 2 single-pass 12mm flashlamps, 30 mm LBO crystal
- Ultra-high-speed Cameras: Shimadzu HPV-X2, 400 x 250 pixels, 32 μm pixel pitch, 10-bit depth, 5 MHz, 128 frames max
- Polarizations: pump1 → p, pump2 → s, imaging → p, phase conjugate → s

Experimental Setup



- Custom modified Spectral Energies pulse burst to operate up to 5 MHz
- 2 Shimadzu ultra-high-speed cameras operating up to 5 MHz
- 1 imaging & 2 pump beams (1 reflected for improved efficiency & alignment)
- Simultaneous DIH and PCDIH measurements.
- Phase conjugate mirror made via degenerate four-wave mixing in a liquid cell.
- Inherent optical isolation in the pump beams

Laser-spark plasma-generated shock-waves



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

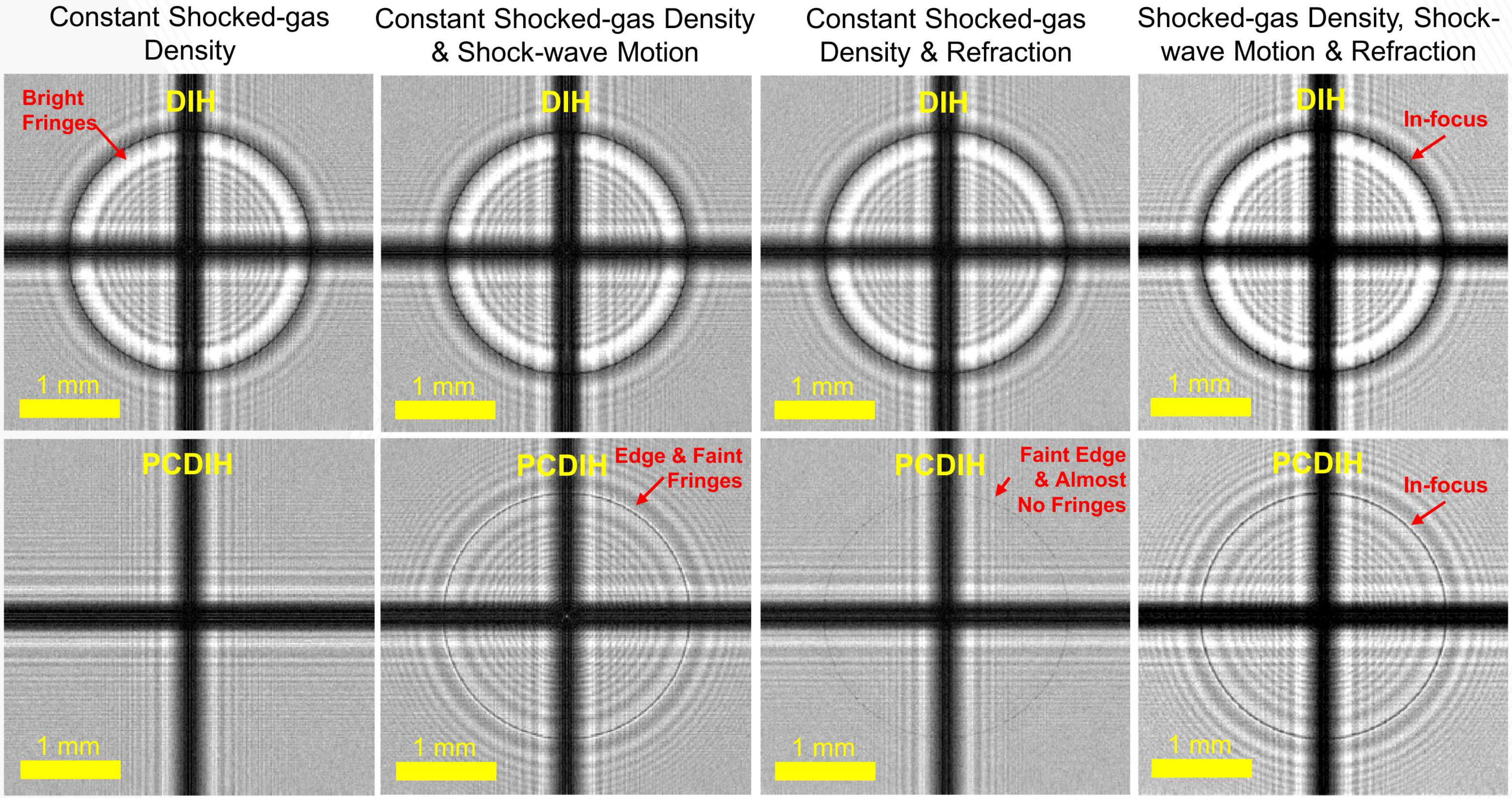
- PCDIH successfully cancels distortions generated by shockwaves
- What is the source of the remaining interference patterns in PCDIH if phase is cancelled?
- Why do the shock-waves come into focus in DIH and PCDIH?

Numerical Simulation

- 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

Shockwave simulations: Interference pattern sources



- DIH interference patterns are due to the phase discontinuity
- Shock-wave motion during laser beam time-of-flight (6.8 to 12.8 μm) produces faint fringes
- From stationary supersonic shock-wave experiment, we know refraction also plays a role

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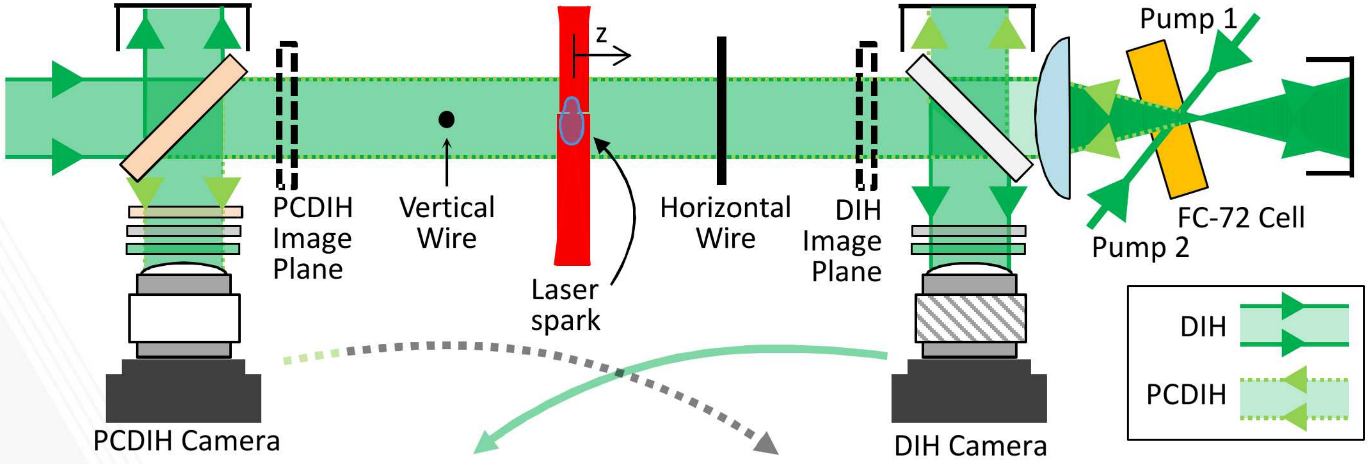
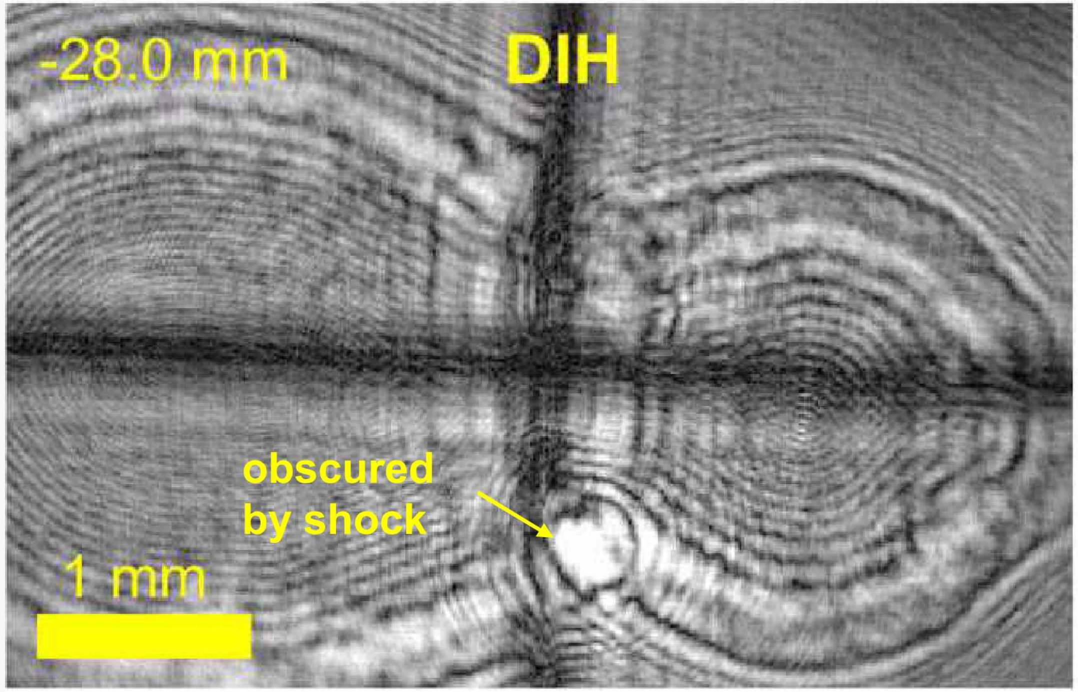
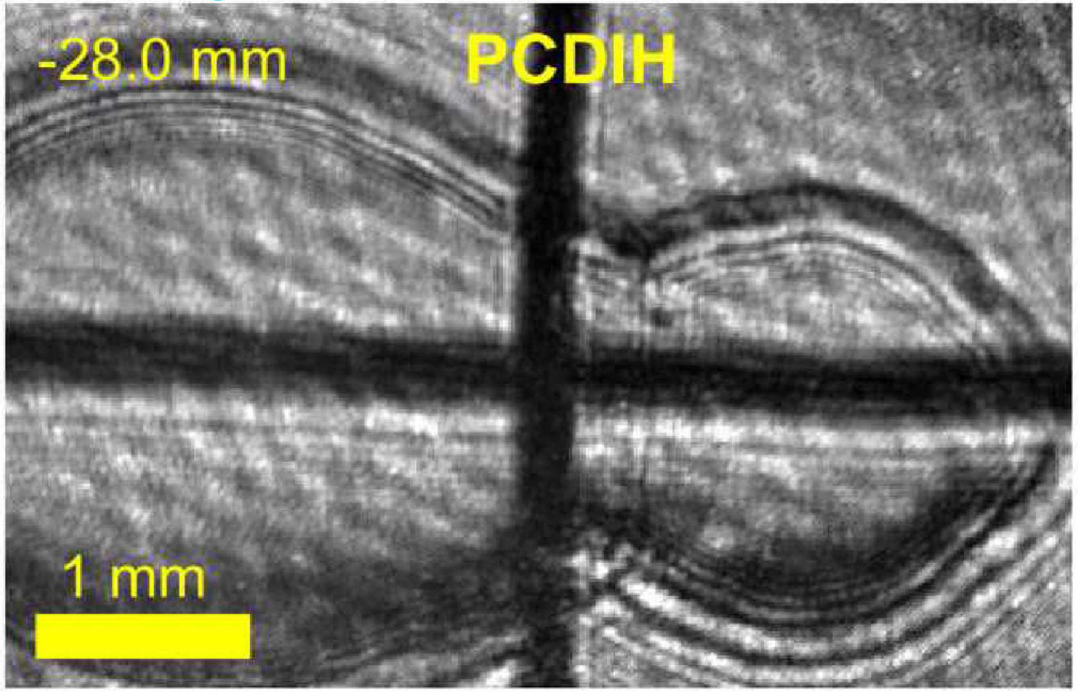
Laser-spark plasma-generated shock-waves

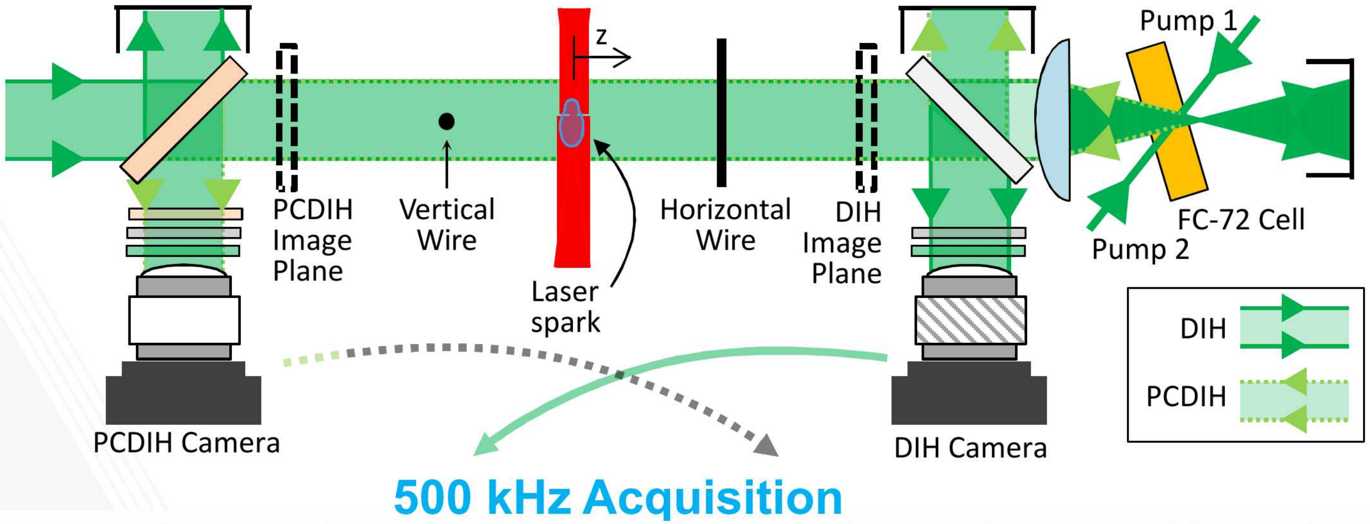


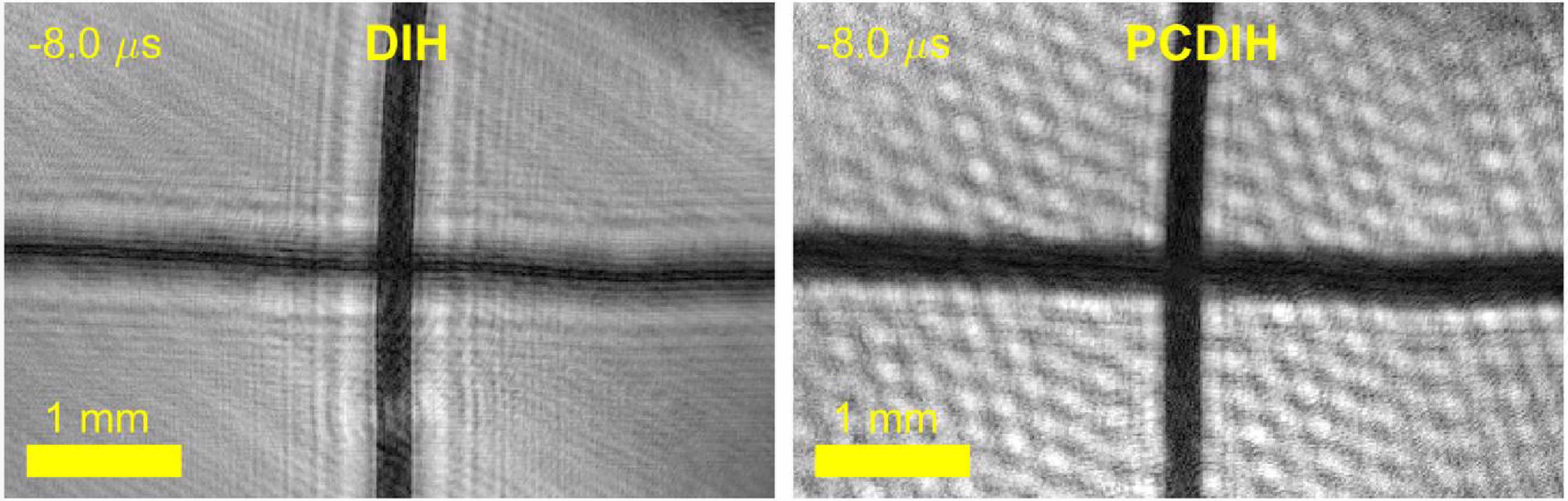
Numerical Refocusing



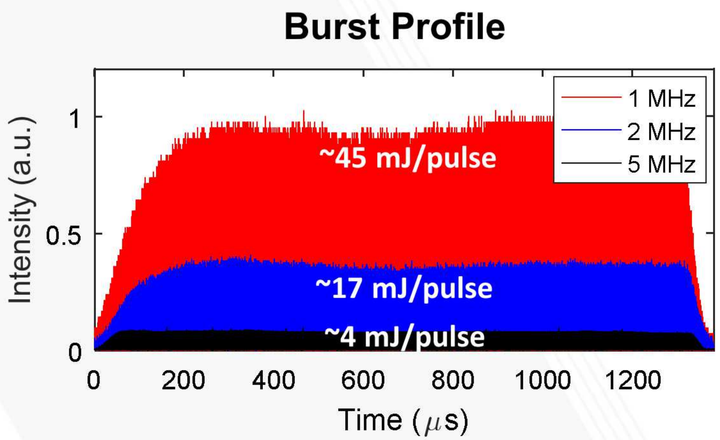


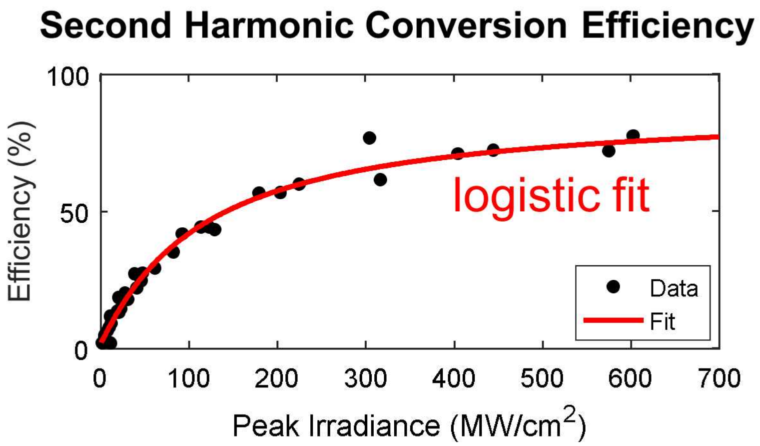
Laser-spark plasma-generated shock-waves

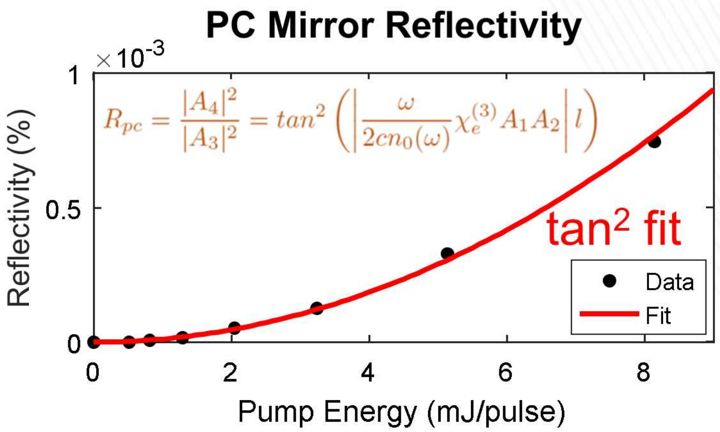




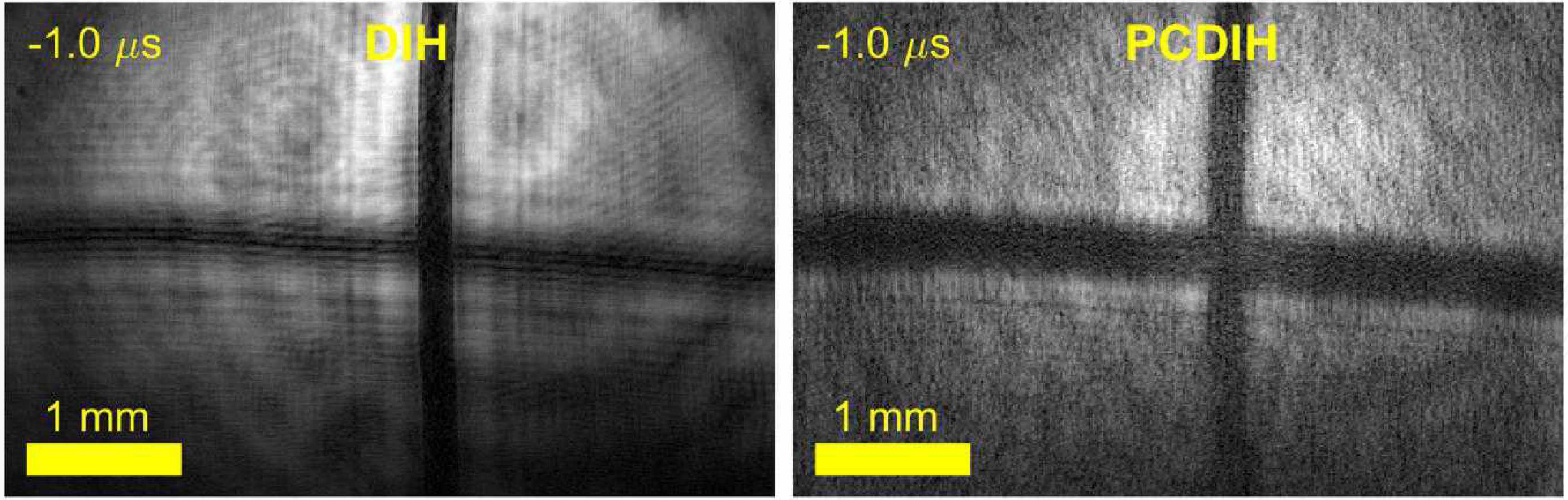
Laser-spark plasma-generated shock-waves



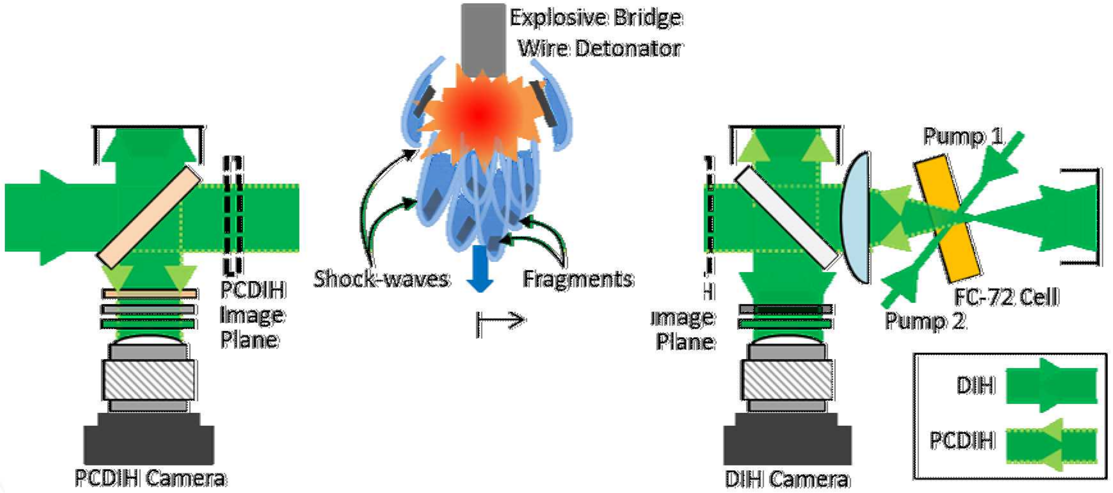




5 MHz Acquisition

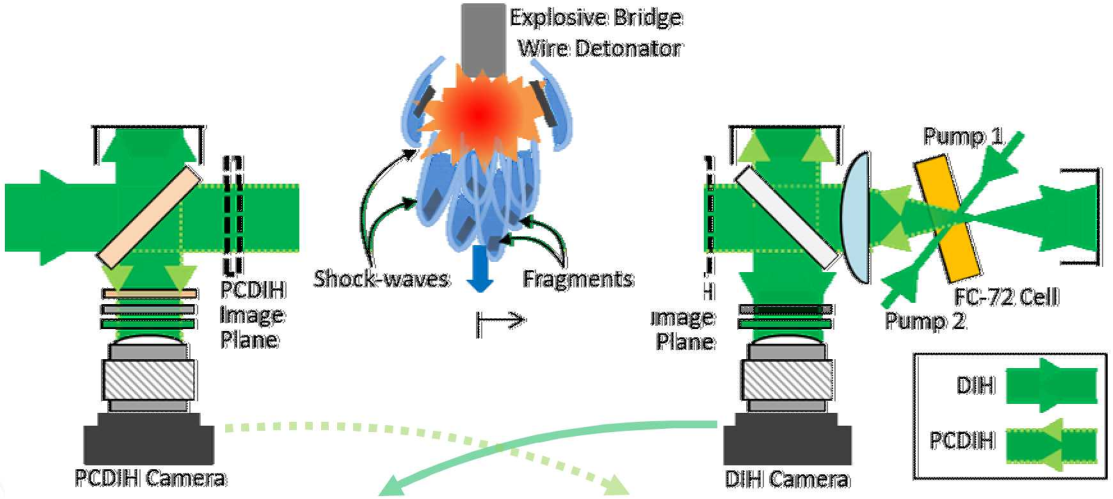


Explosively generated fragments

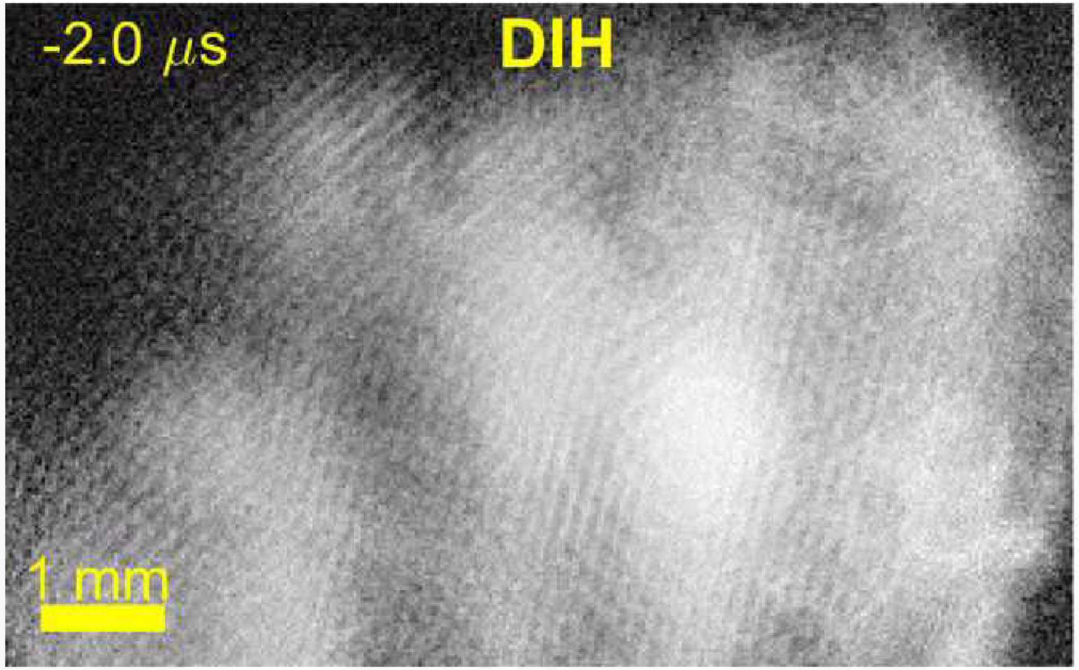


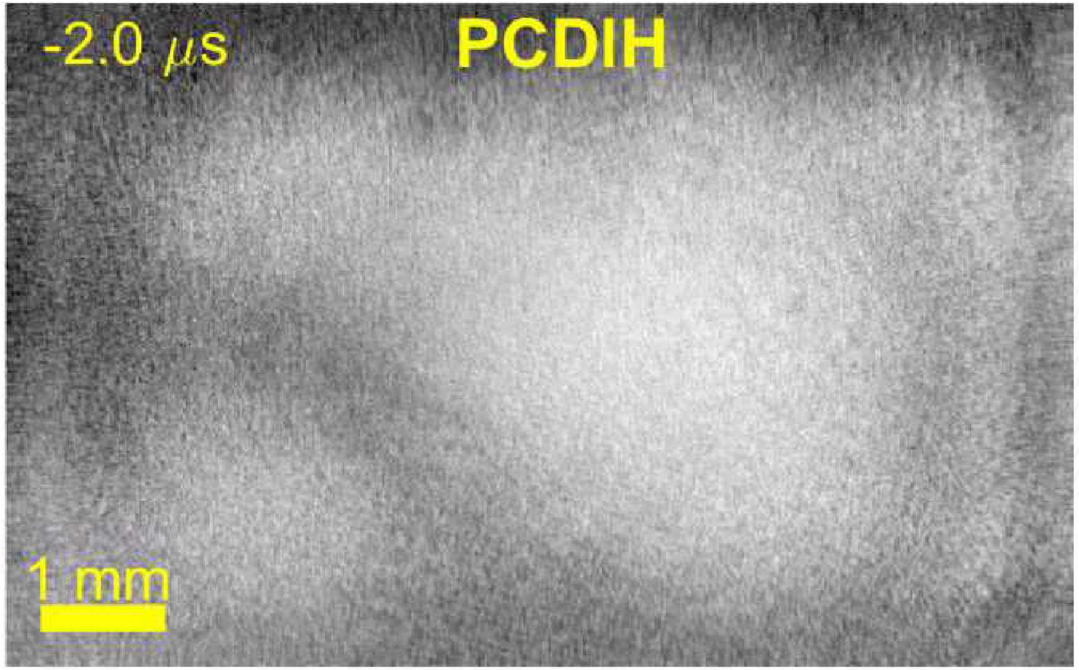
RP-80 EBW from Teledyne RISI
custom 180 μm thick brass cap
Placed 50 mm above field-of-view
facing downward

Explosively generated fragments

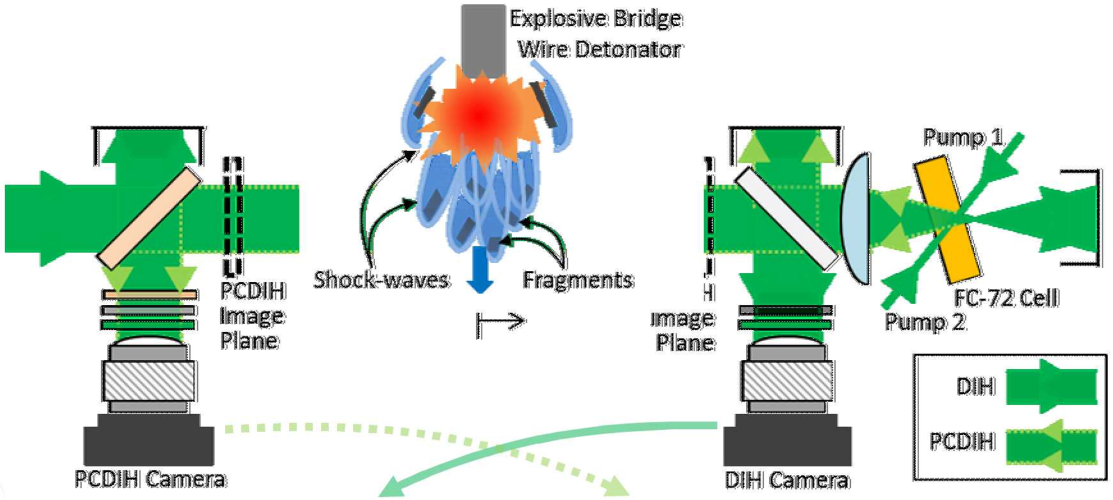


2 MHz Acquisition



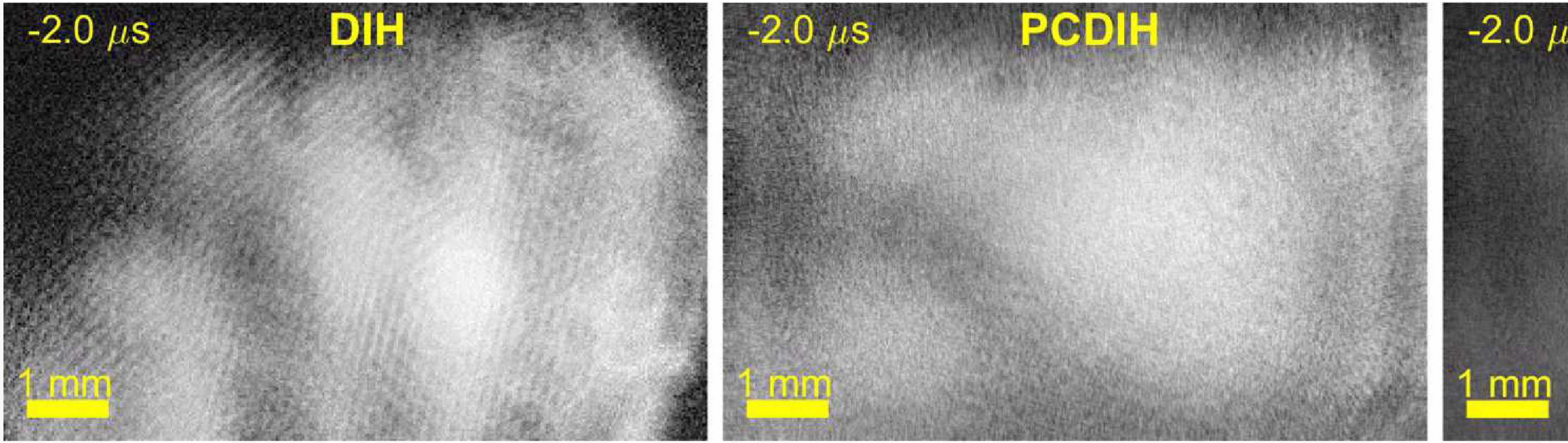


Explosively generated fragments



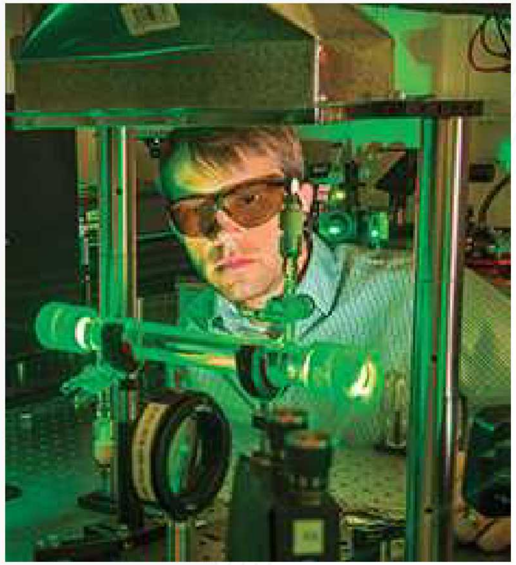
Fragment Speeds:
2.34 to 2.83 km/s
Mach 6.8 to Mach 8.2

2 MHz Acquisition

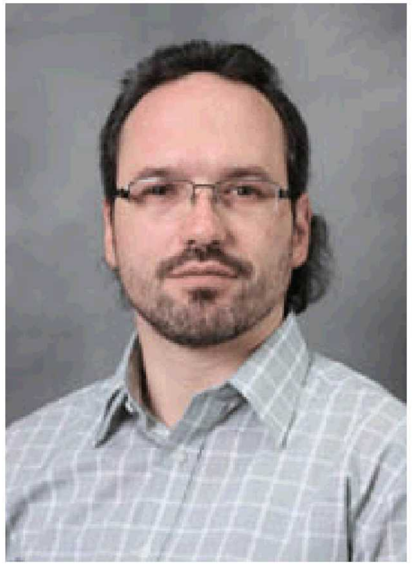


Conclusions and Future Work

- We introduce an ultra-high-speed PCDIH technique for phase-distortion cancellation for 3D imaging.
- Custom modified pulse-burst laser and new optical design for improved alignment are utilized.
- Demonstrated > 5 orders-of-magnitude increase in speed from 20 Hz up to 5 MHz.
- This work represents the fastest digital in-line holograms collected to date.
- Simulations show that shock-wave edges are visible and in PCDIH due to shock-wave motion and refraction.
- Future work aims to improve PC mirror efficiency with different optical designs and PC mirror materials.


Daniel R. Guildenbecher


Mike E. Smyser


Mikhail N. Slipchenko

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