High Speed Digital Holography for PFC Erosion Measurements

August 11, 2011

C. E. (Tommy) Thomas Jr.
Third Dimension Technologies
L. R. Baylor, S. K. Combs,
S. J. Meitner, D. A. Rasmussen
Oak Ridge National Lab

E. M. Granstedt, R. P. Majeski, R. Kaita
Princeton Plasma Physics Laboratory

Outline

- Motivation
- Intro To Digital Holography
- Phase II SBIR System at ORNL/PPPL
- Digital Holography Measurements at ORNL/PPPL
- Discussion

Motivation

- Measure in-situ erosion for PFC components
- ITER Divertor Erosion Measurement Requirements
  (P. Andrew, Nov. 2008)

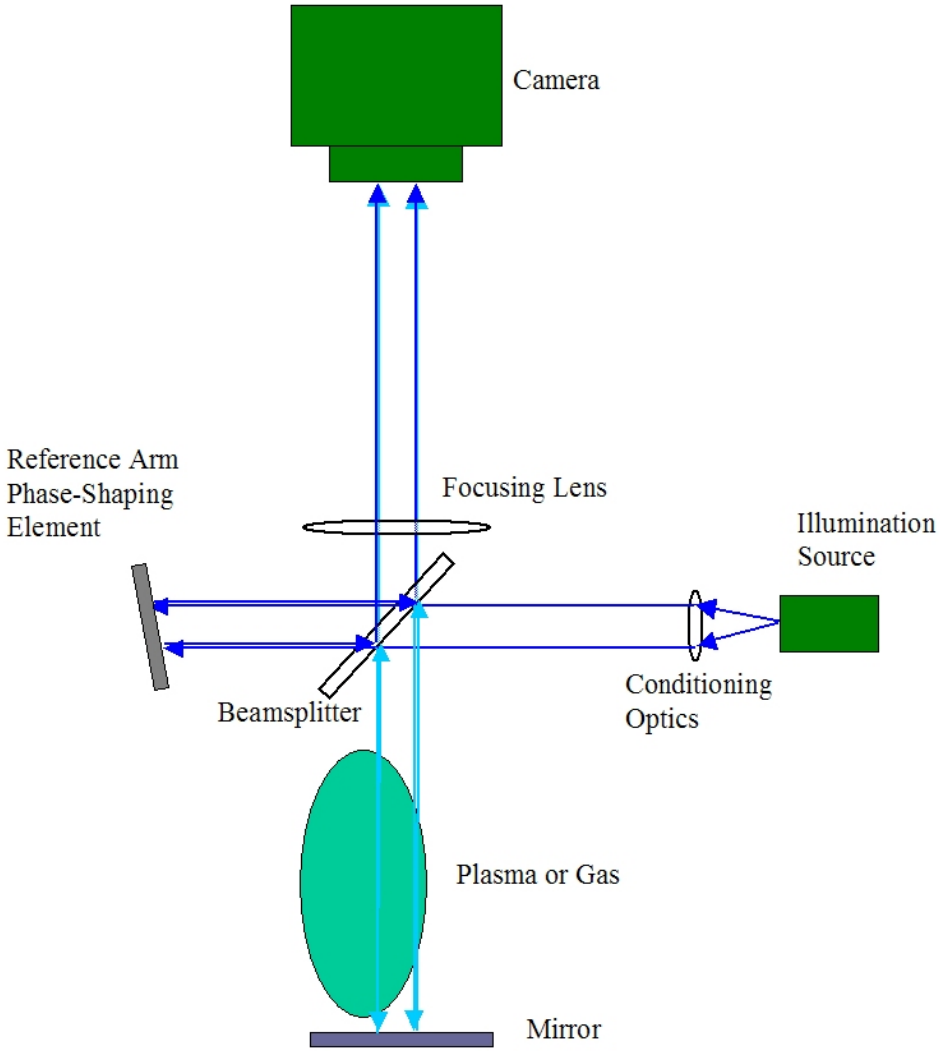
MEASUREMENT	PARAMETER	CONDITION	RANGE or COVERAGE	RESOLUTION		ACCURACY
				Time or Freq.	Spatial or Wave No.	
16. Divertor Operational Parameters	Erosion rate		$1 - 10 \times 10^{-6}$ m/s	2 s	10 mm	30 %
	Net erosion		0 – 3 mm	Per pulse	10 mm	12×10^{-6} m

Nominal CO2 Laser Digital Holography Capabilities

- Frame rates from 500 Hz (256 x 256 pixels) to 1.5 kHz (128 x 128 pixels), or even 3 kHz (64 x 64 pixels), or faster
- x,y Resolution ~9.1μ x F/#, e.g., 1mm @ F/100 lens
- z-Range—100 nm to 1 cm (single-frame) with dual-laser (two-color) system
- Time Response: Frame rate, e.g. 2ms for 500Hz
- Camera—FLIR SC4000 or SC6000 QWIP or HgCdTe; self-contained; Mil-Spec reliability; similar CEDIP or Sofradir available (30Hz uncooled Photon camera?)

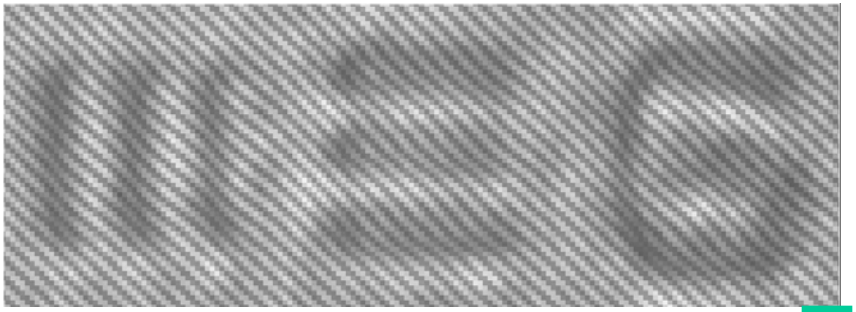
Simple Shearless Digital Holography Measurement System with Michelson Geometry

- **Simple Michelson geometry schematic for Shearless Digital Holography illustrating unsheared beams (no angle between the beams, U.S. Patent 79289253). The reference arm phase-shaping element can be a stepped optical element and mirror or a diffractive or holographic optical element.**



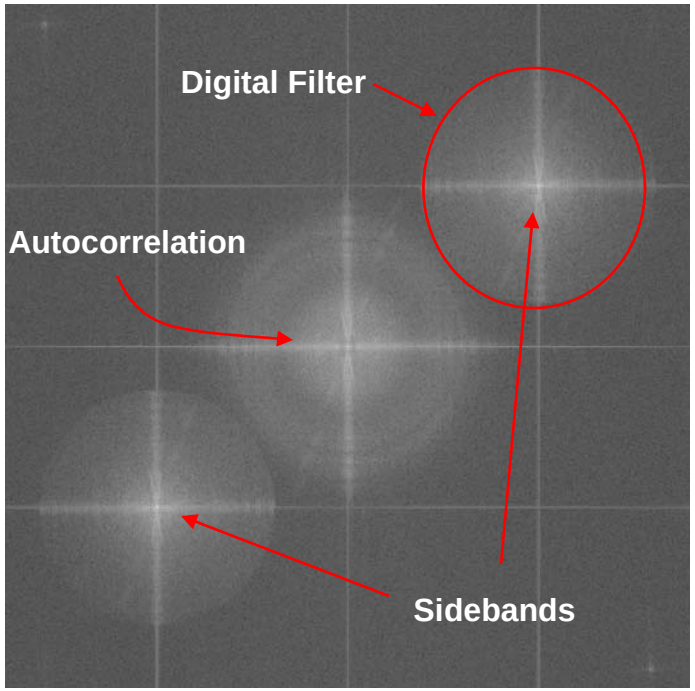
Fourier domain processing enables the extraction of the complex wavefront

Raw Digital Hologram Input intensity image



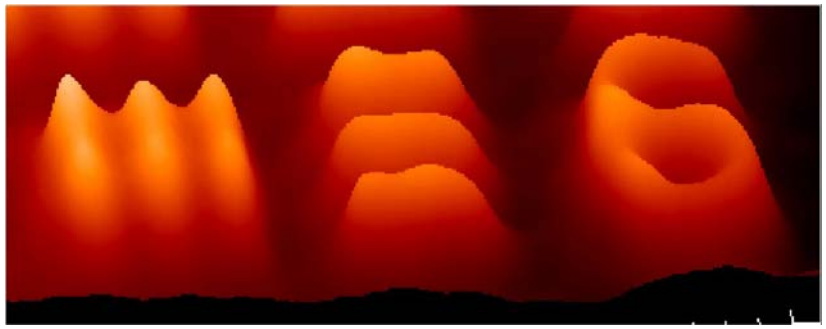
~Two-Micron Feature Sizes
~300 nm Height

Spatial 2-D FFT



2-D IFFT of
filtered & centered sideband

Output phase



Heterodyne Recording Draws much of the Energy from the Reference Beam

- The energy in the hologram is:

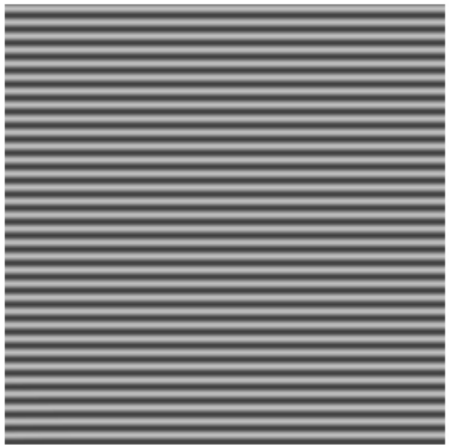
$$W \sim E_1 E_2^*$$

where E_1 and E_2 are the electric fields

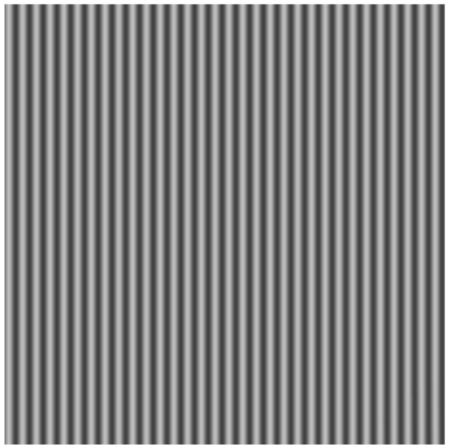
- An object beam energy I_1 that is 1% of the reference beam energy is adequate to form a hologram (note--E_1~(I_1)^0.5~10%).
- In fact, great care must be taken in system design to avoid reflections (slightly wedged windows, high quality AR coats, de-centered lenses)—unwanted reflections are significant noise sources.

Two Digital Holograms Can Be Recorded Simultaneously—Same Camera Frame

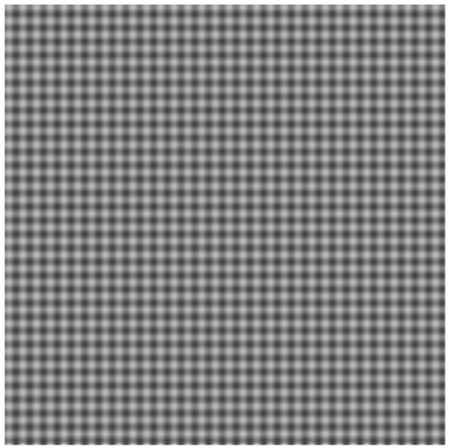
- **For the object beam two beams at two different wavelengths/ colors are combined and traverse an identical optical path**
- **Digital hologram 1 at wavelength/color 1 is recorded with horizontal fringes (reference beam at a vertical angle to the object beam).**
- **Digital hologram 2 at wavelength/color 2 is recorded with vertical fringes (reference beam at a horizontal angle to the object beam**
- **A single forward FFT and two inverse FFT's with different axis translation and filters process the holograms**



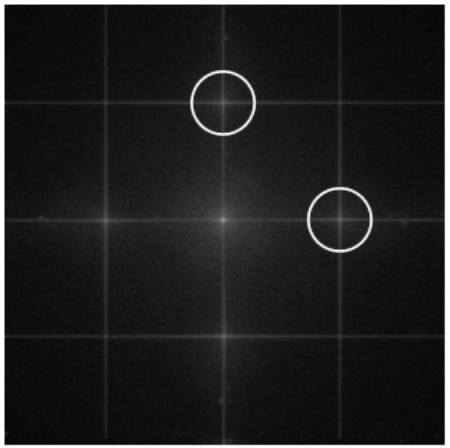
A) Horizontal Fringes—Color 1



B) Vertical Fringes—Color 2



C) Simultaneously Exposed Horizontal and Vertical Fringes—Both Colors



D) 2-D FFT of Hologram in C)

Dual Wavelength—slide 2

- The complex (phase and amplitude) Image 1 is divided, pixel by pixel, by the complex Image 2.
- Division results in subtraction of the two phases

$$\exp[i(\phi_1 - \phi_2)]$$

- This effectively forms a phase image with a synthetic wavelength, much longer than the original wavelengths:

$$\lambda_s = (\lambda_1\lambda_2)/(\lambda_1 - \lambda_2)$$

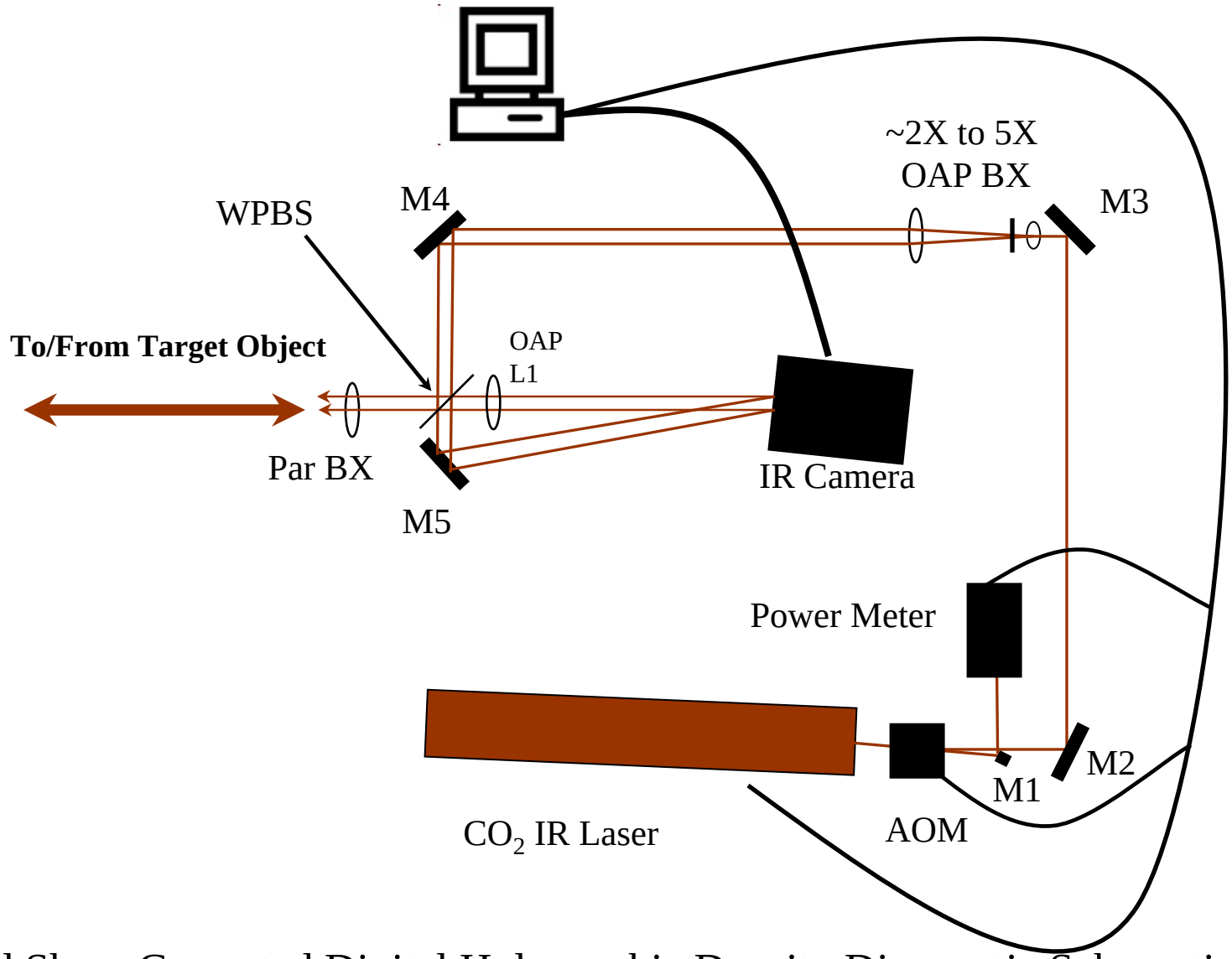
- For instance, if the two wavelengths are CO2 lines separated by 10nm, then the synthetic wavelength is:

$$\lambda_s = 1\text{cm}$$

Pulsed Laser PFC Measurement

- A CW CO2 laser and Ge crystal AOM can provide pulses down to ~600 ns, at 1 MHz, with ~92% efficiency (measured efficiency on two TDT systems)
- Required laser power ~20W
- Infrared cameras up to 640 x 512 pixels and sensitive to CO_2 are available up to ~40 kHz @ 64 x 4 pixels (Window/Region of Interest measurement at frequencies over ~200 Hz)
- Nominal camera of interest is 320 x 256 at ~400 Hz. Frame-rate increases as number of pixels is decreased up to 40 kHz, FLIR SC4000 LWIR. SC6000 640x512 also available, similar frame rates
- Typical camera frame rates:

  200Hz@ 640 x 512 pixels
  400Hz@ 320 x 256 pixels
  500Hz @ 256 x 256 pixels
  1500Hz@ 128 x 128 pixels
  3kHz @ 64 x 64 pixels
  43kHz @ 64 x 4 pixels



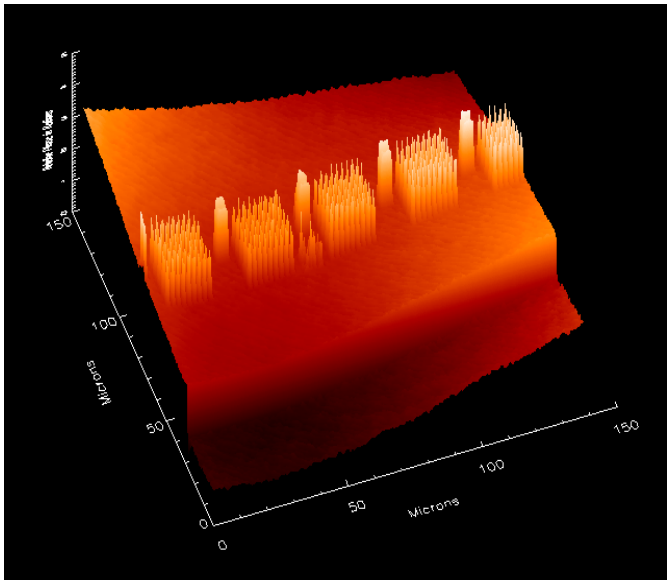
Simplified Shear Corrected Digital Holographic Density Diagnostic Schematic

Minimum Theoretical Noise Level for Digital Holography

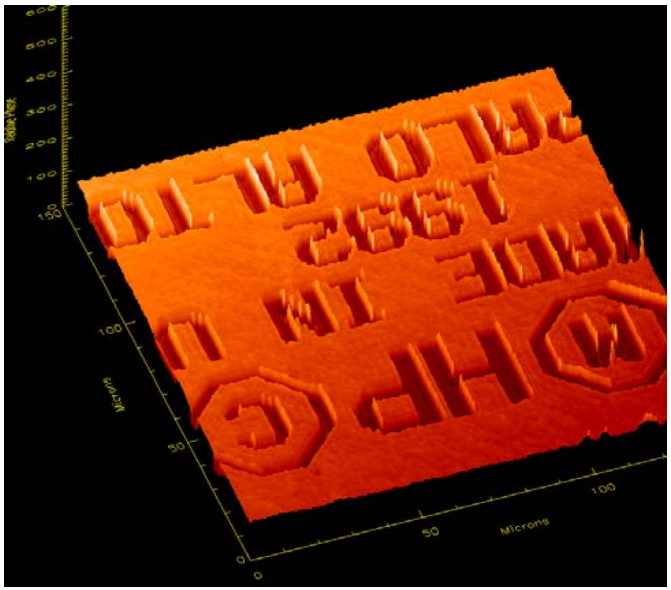
- Photon Statistics is the ultimate theoretical noise limit—for typical numbers of detected IR laser photons per pixel ~1/10,000'th of a wavelength is the photon noise limit (estimating ~10 pixels involved in the measurement)
- Thermal, laser, vibrations, or amplifier noise may (will probably ;-)) limit sensitivity before the photon statistics limit is reached

Flat-Field Correction For Removal of Systematic (Repetitive) Noise/Distortion

- 3D image of photoresist on silicon, with no flat-field correction (HeNe laser example)
- Demonstrates the effect of no flat-field correction. Curvature of field from left to right can be noticed.



- A reference image can be subtracted from phase and amplitude to flat-field correct the object wave (e.g., image made before start of ITER shot flat-field corrects the in-shot images)
- Flat-Field Correction has taken out the field curvature in this phase image of copyright on a silicon wafer (note that diagonal steps are ~700 nm, again a HeNe laser example).



Example Phase II IR Hologram Noise Level ~8nm Measured on TMC Table, FLIR SC4000 Camera, Access Lasy-20S Laser

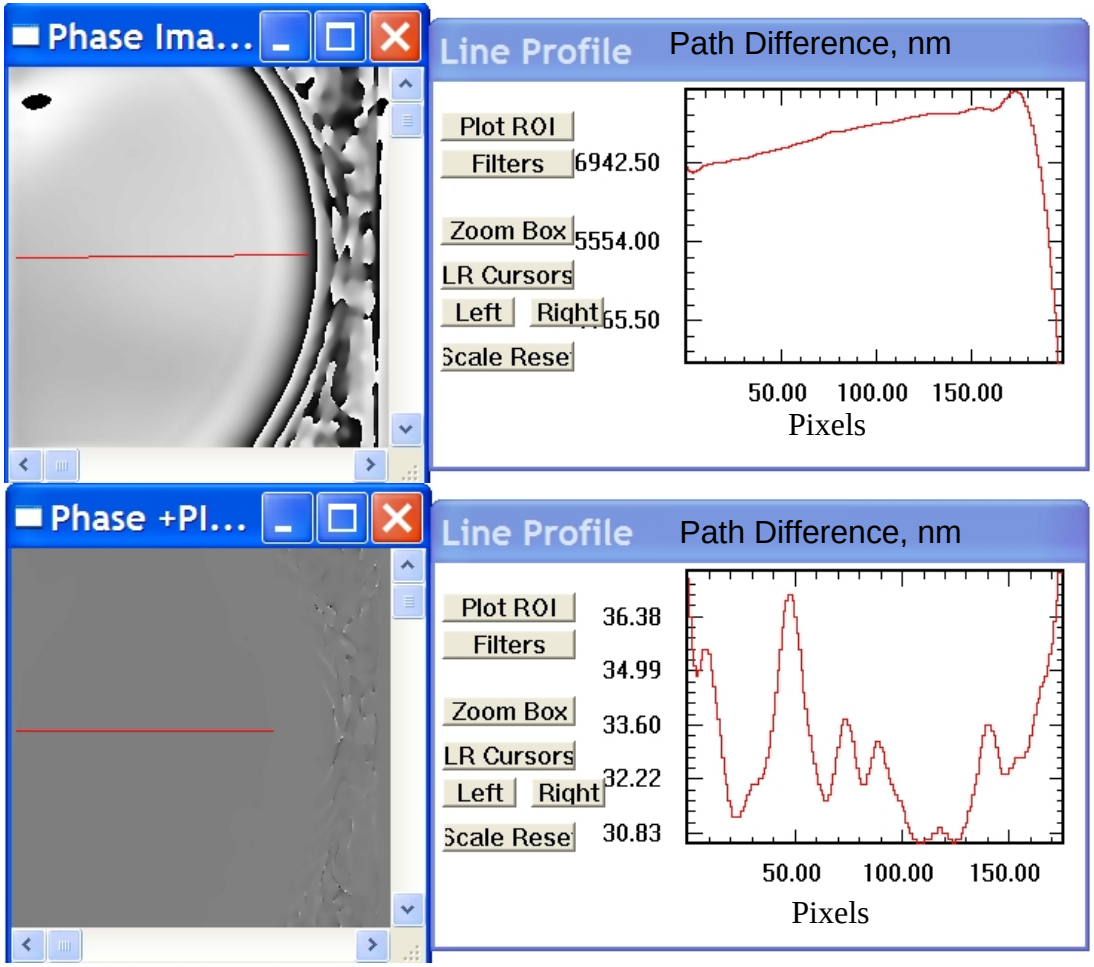


Image: 256 x 256 pixels
Surprise Aperture
SC4000, 256x256 ROI
No Flat Field
Reliable Data
~165Wx256H pixels

SC4000, 256x256 ROI
With Flat Field
Reliable Data
~165Wx256H pixels

~8nm noise, 0.0009 frng

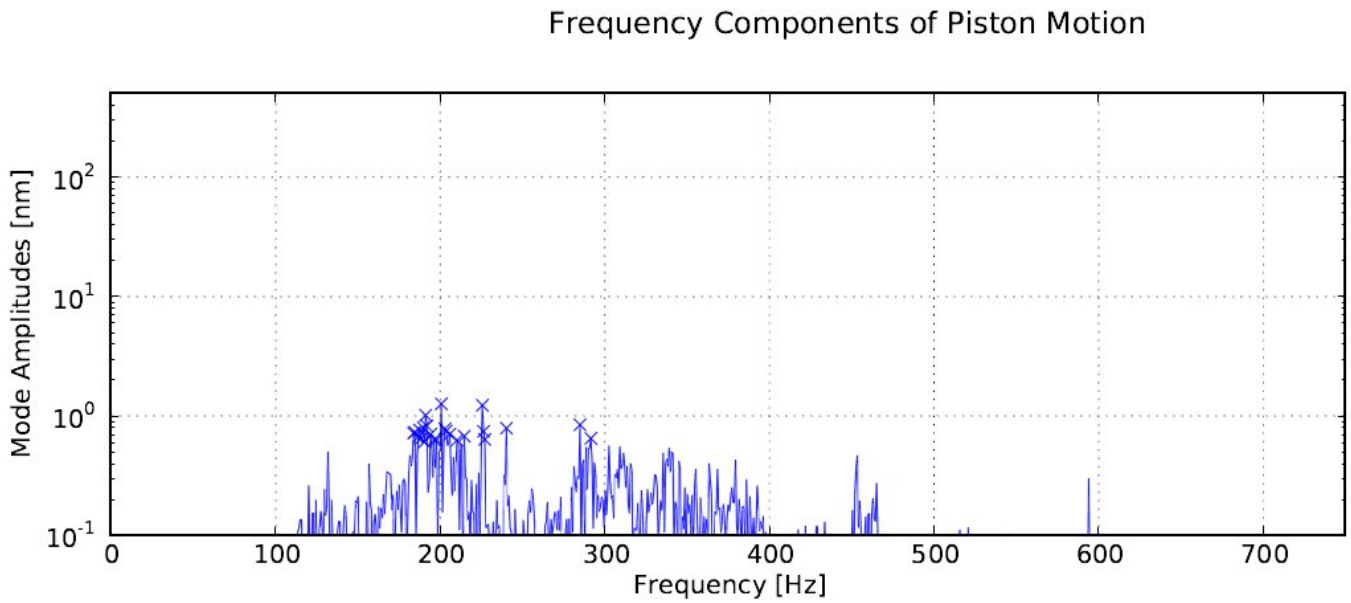
- Digital Holography Phase Image, note SC4000 camera internal aperture
- First Hologram Flat-Fielded by Second Same-Conditions Shot, 0.0009 fringes of noise

Vibrational Noise Removal

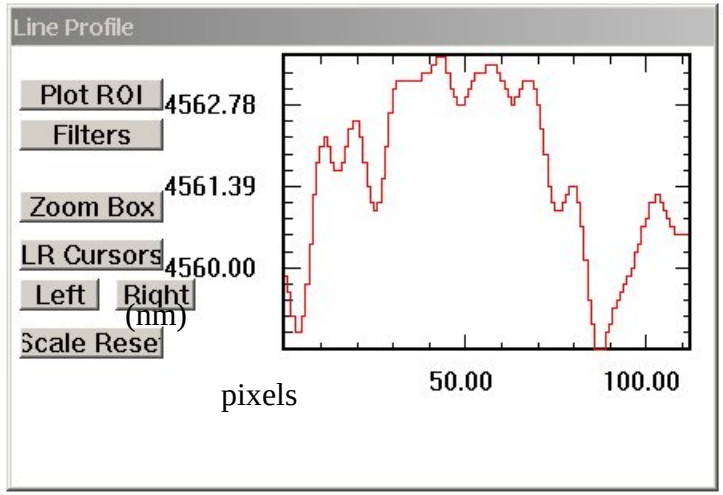
- To first order, no vibration occurs during a ~100ns up to ~20 microsecond laser pulse (motion is stopped—typical vibrations are kHz)
- To second order vibration between frames can show up as wedge (planar tilt) in the hologram, or path length change
- Tilt can be removed in software by fitting a plane and forcing the tilt to zero
- Higher Order vibrational modes create frame to frame noise (all diagnostics will see this--averages out for tiles).
- The diagnostic can follow frame to frame changes up to 1cm with a dual-wavelength system, or frame to frame changes up to 10.6μ with a single-laser system

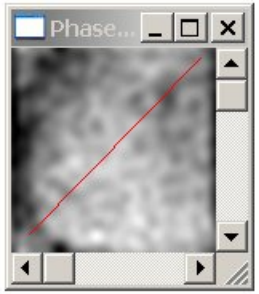
Vibration Noise August 5, 2011

Noise with 90 Hz high-pass filter, nm/Hz

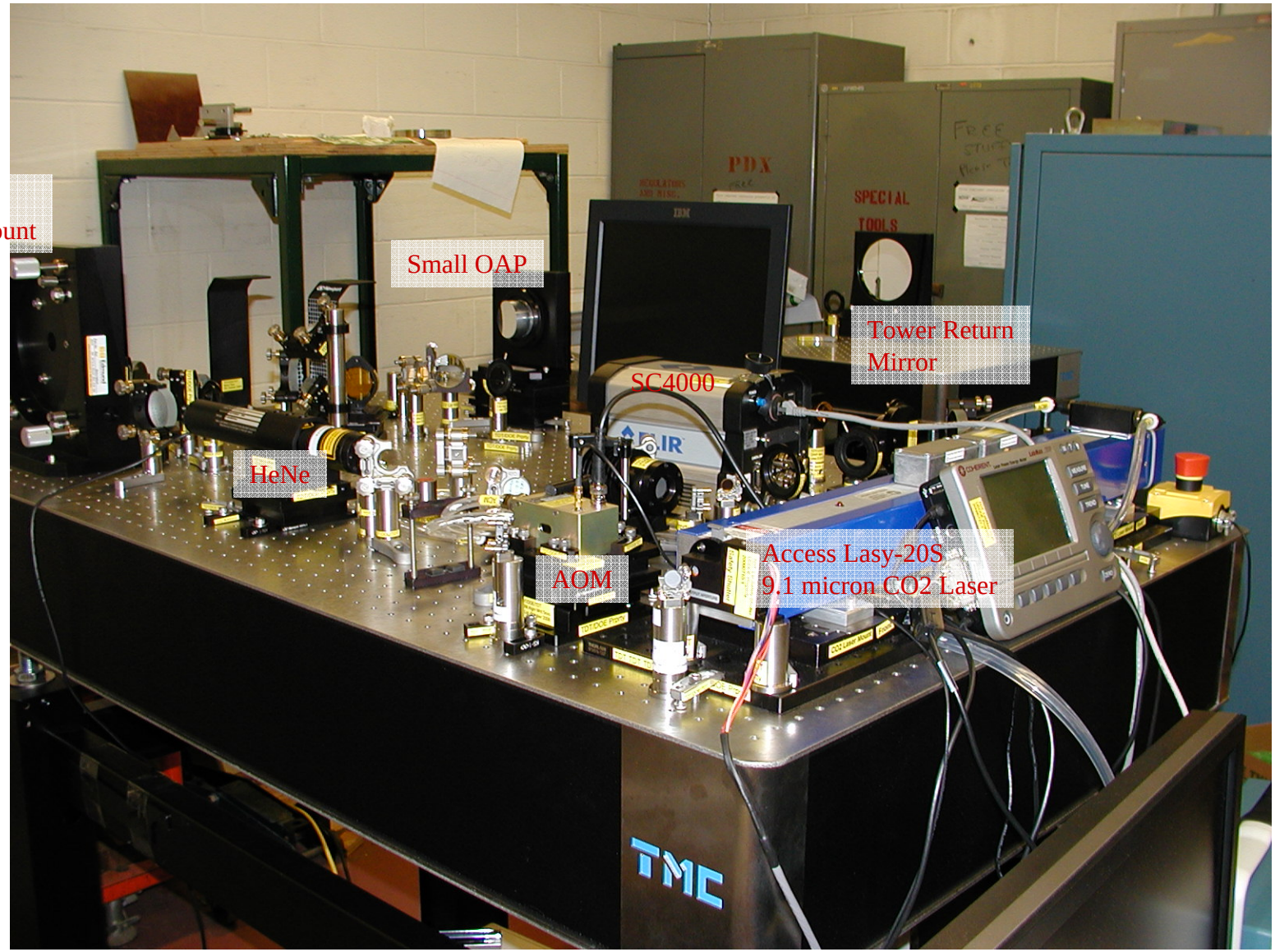


Frame to frame noise (phase image from one frame subtracted from the next frame) is about 4 nm for 128 x 128 pixels

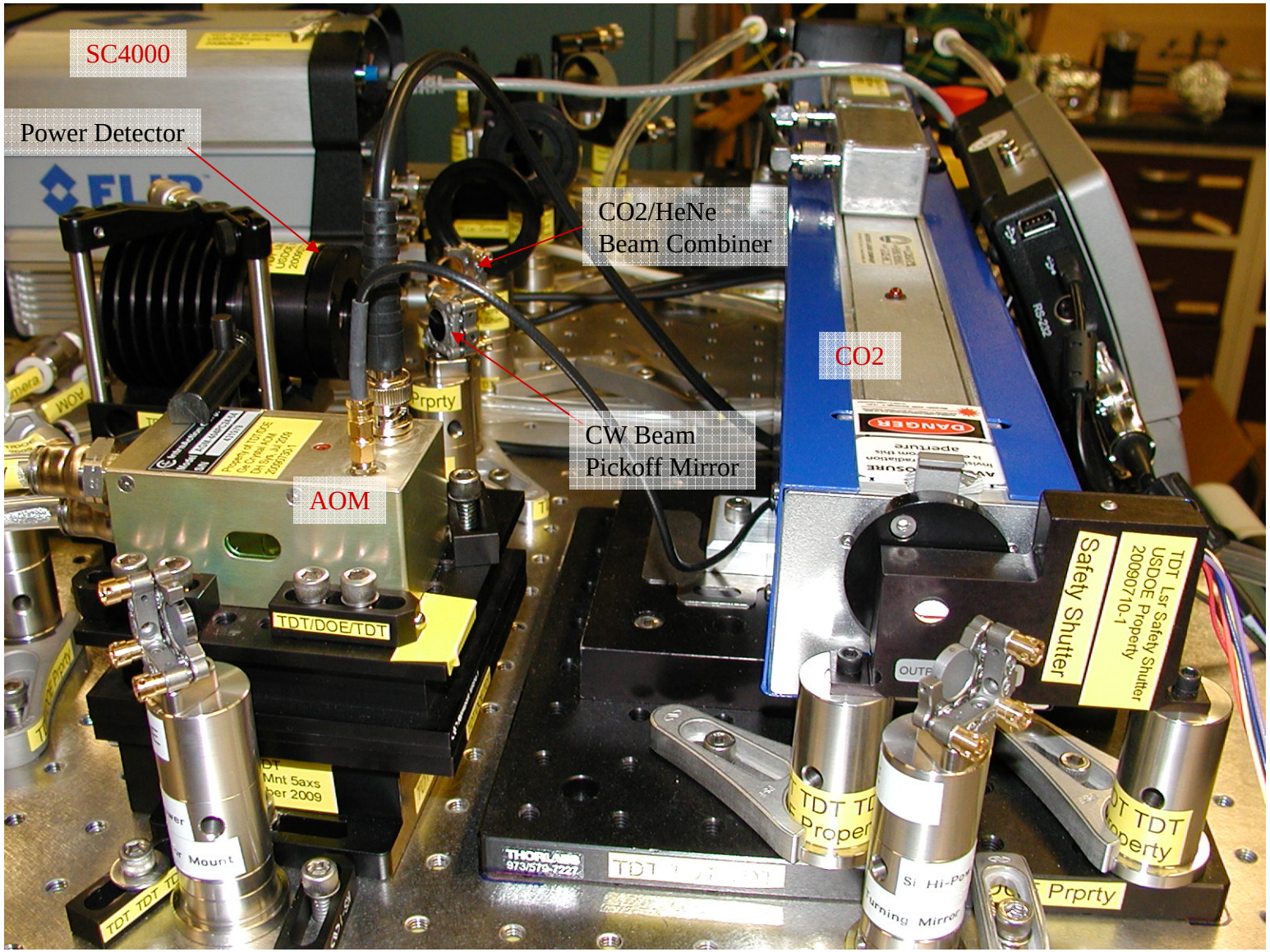




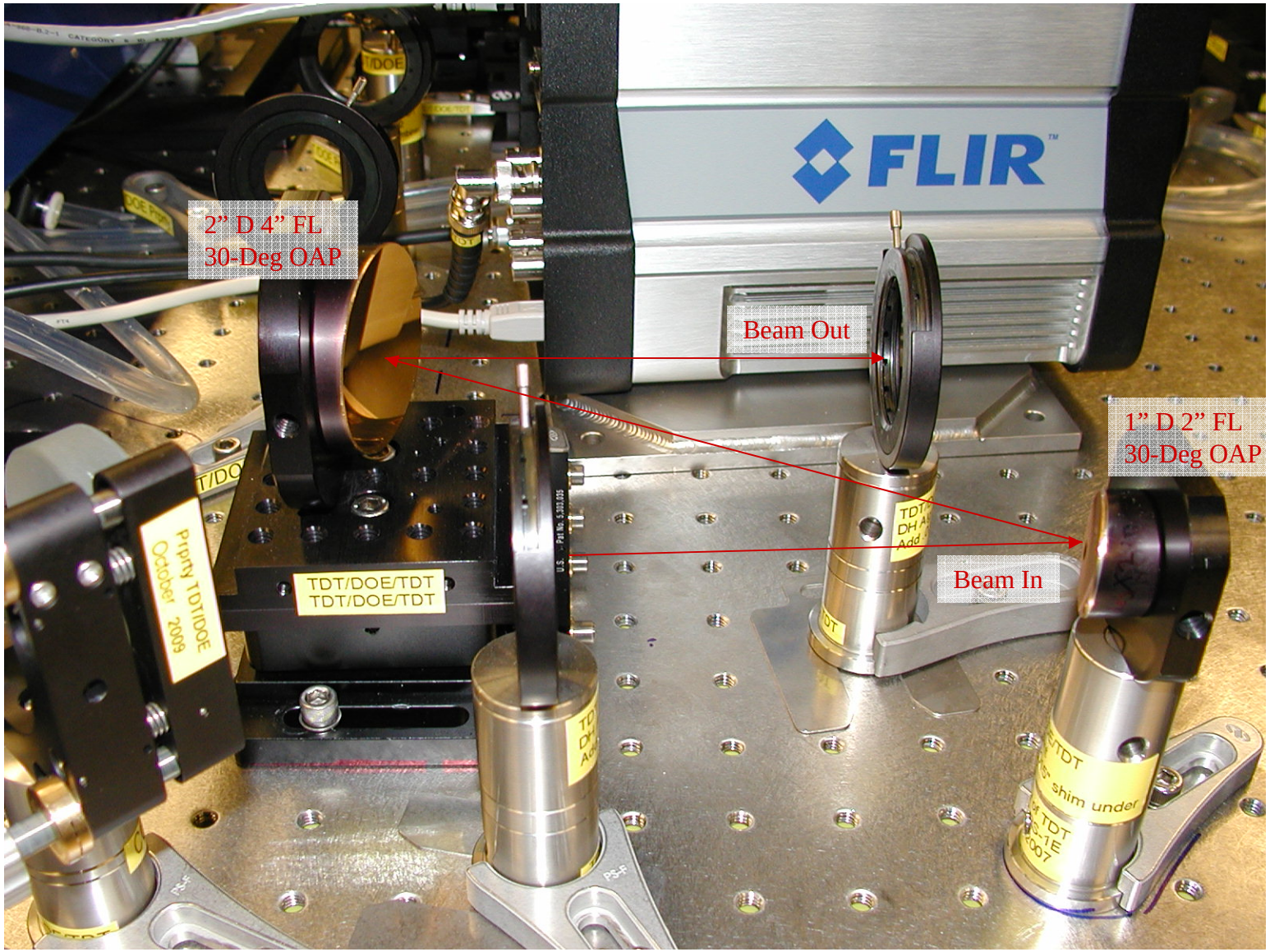
CO2 Laser Digital Holography System at PPPL



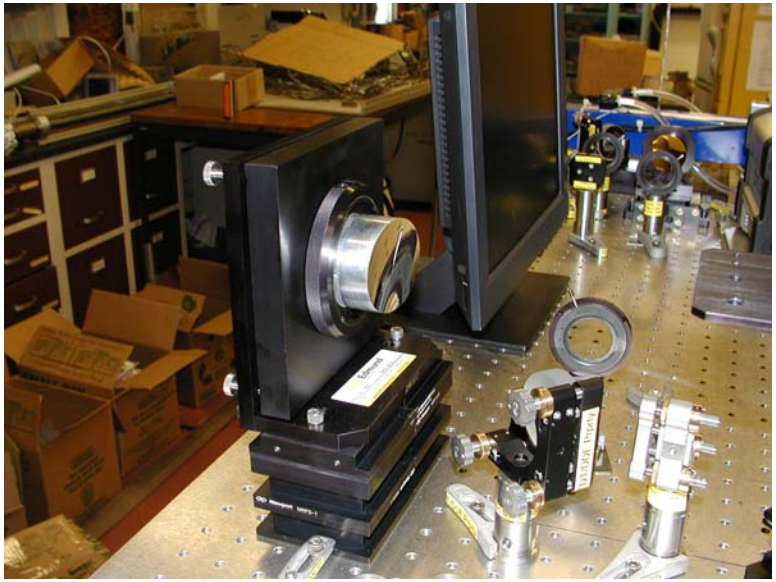
CO2 Laser Digital Holography System At PPPL, View 2

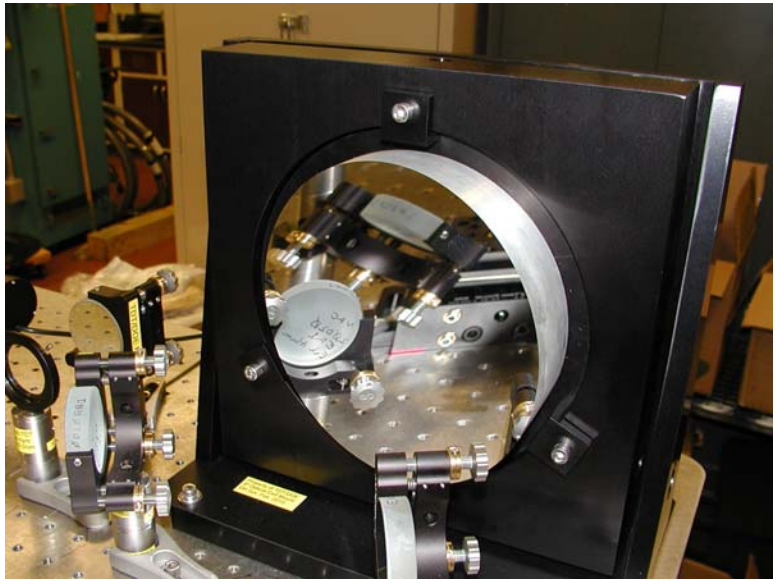


A 2X OAP Pair Beam Expander, At PPPL Expands The Beam To ~Camera Image Size



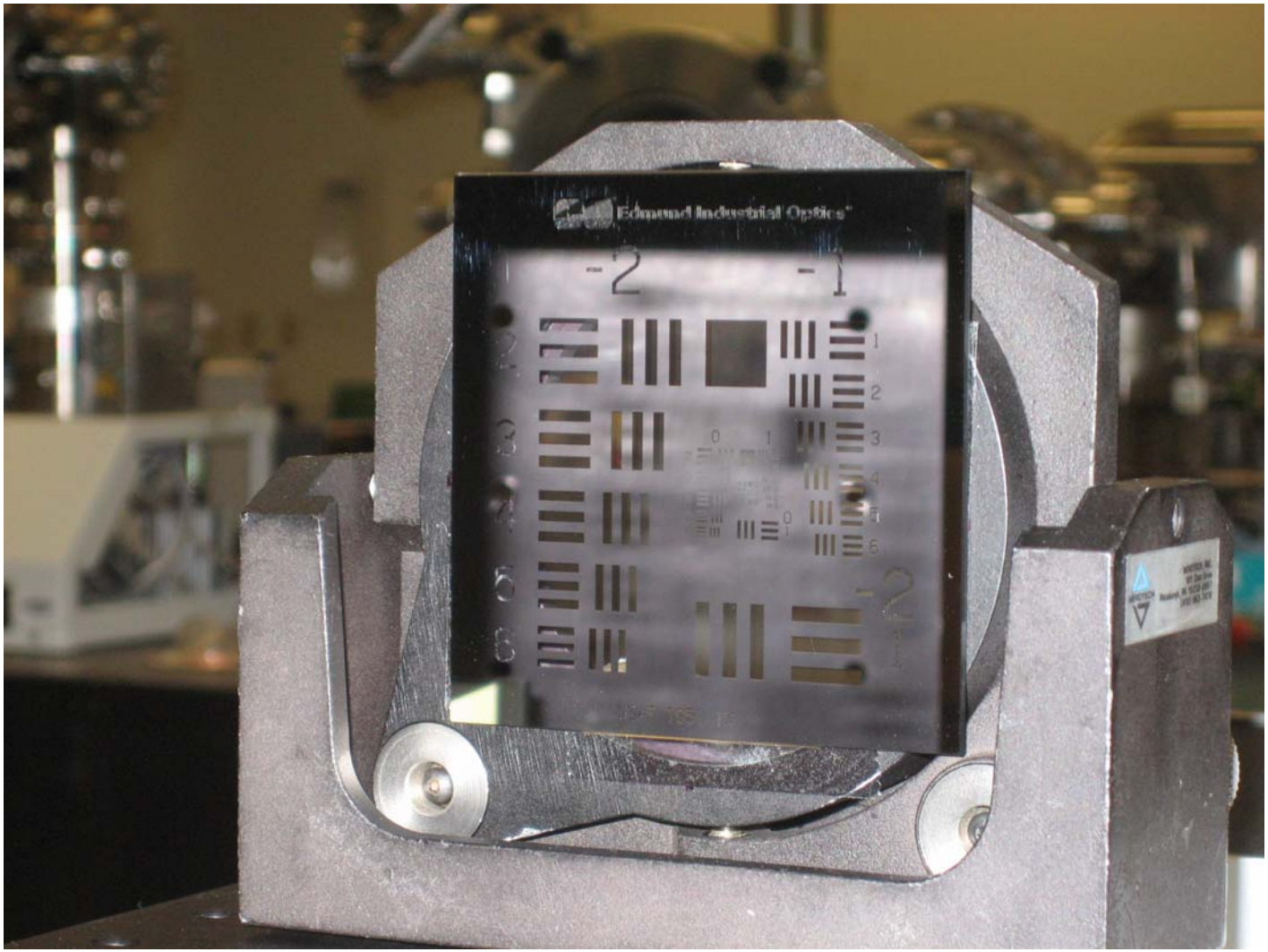
Parabolic Mirror Pair Expands Beam Up To 7”





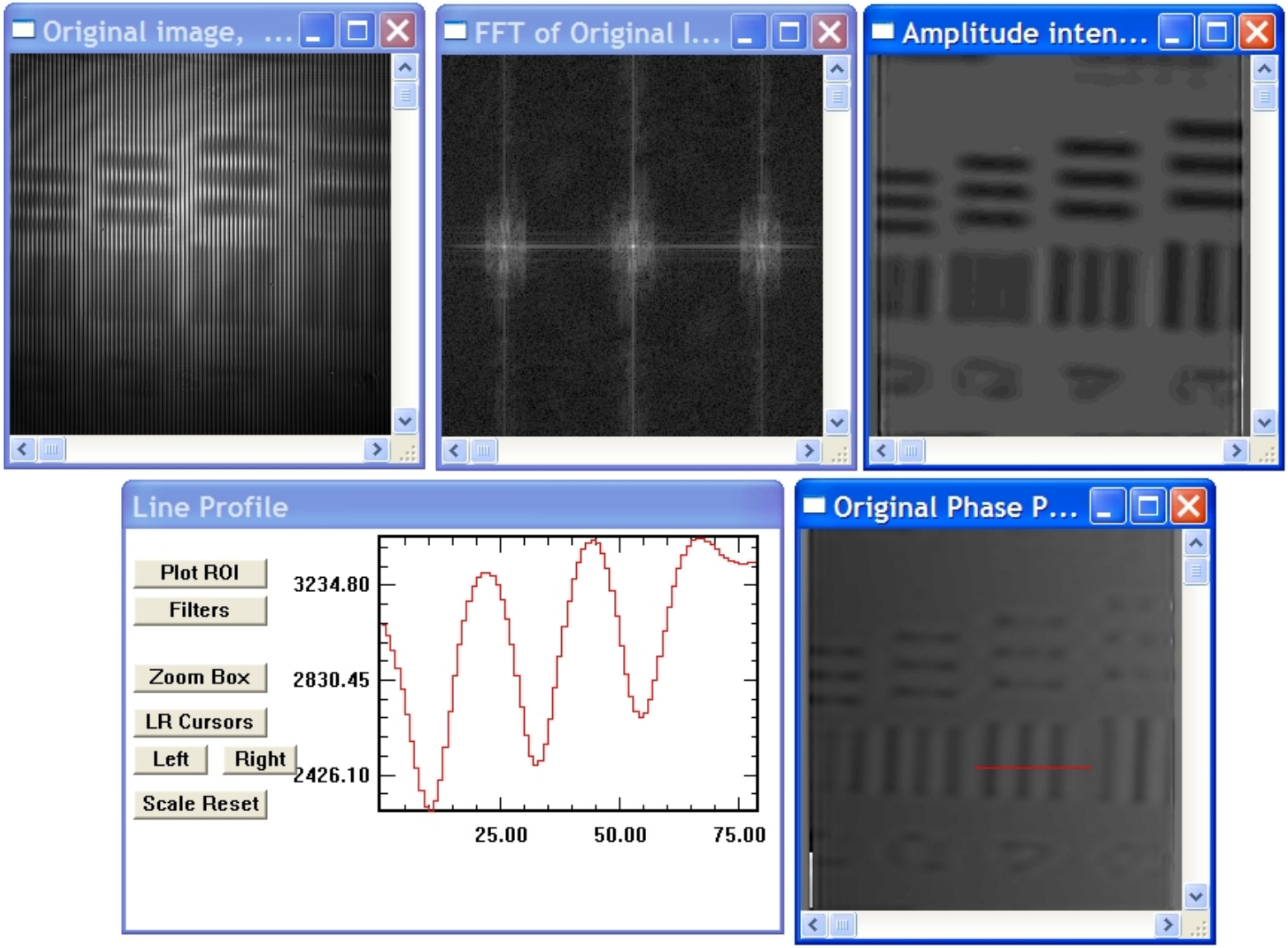
- Off-axis Parabolic Mirrors expand beam to as much as 7”
- Expander small OAP on left, collimator large OAP on right
- As assembled and mounted at PPPL, expansion is ~6.2X
- Parabolic Beam Expander Design and Mirrors Courtesy Dr. Don Hutchinson (ORNL, retired)

Chrome On Glass USAF Test Target



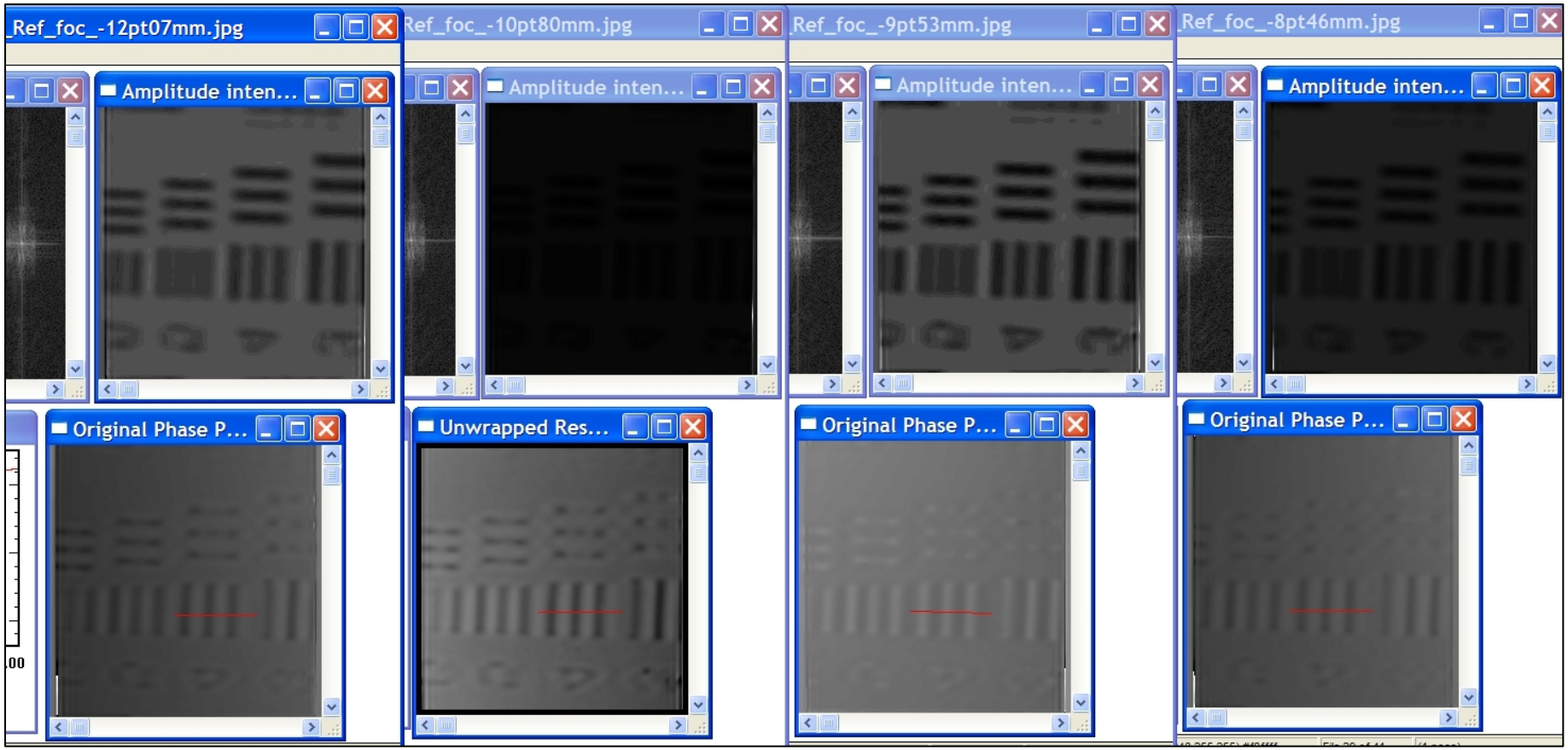
- 3” chrome on glass USAF test target
- Target is very flat—reflections cause the mottled appearance
- Note Group 0 test elements 2, 3, 4, 5, 6 at center left

Phase I Hologram of Chrome On Glass USAF Test Target



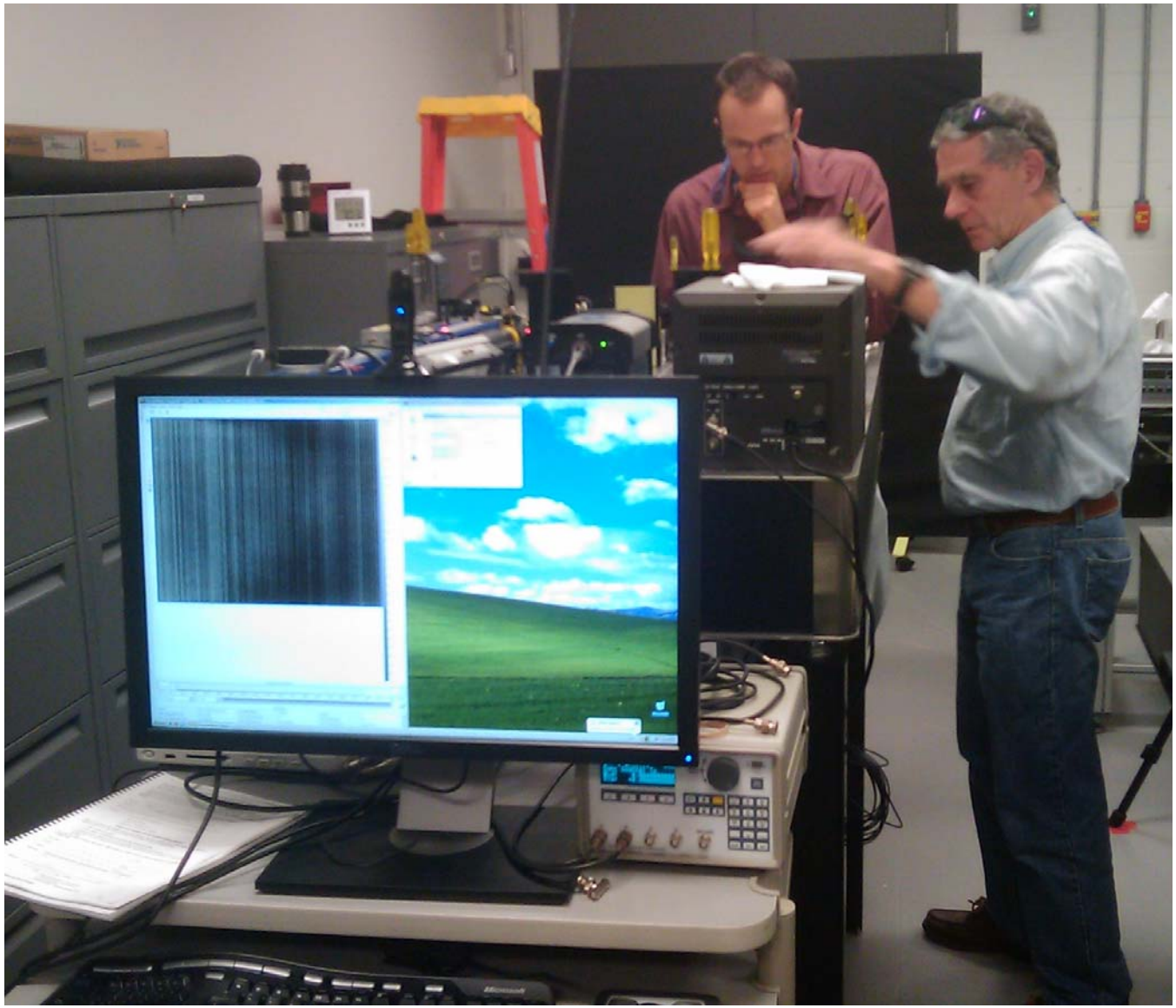
- Elements 3, 4, 5, and 6 from Group 0 of USAF Target (1.26 to 1.78 lp/mm) ~F/26
- Line Profile in nm (divide by two for height/depth)

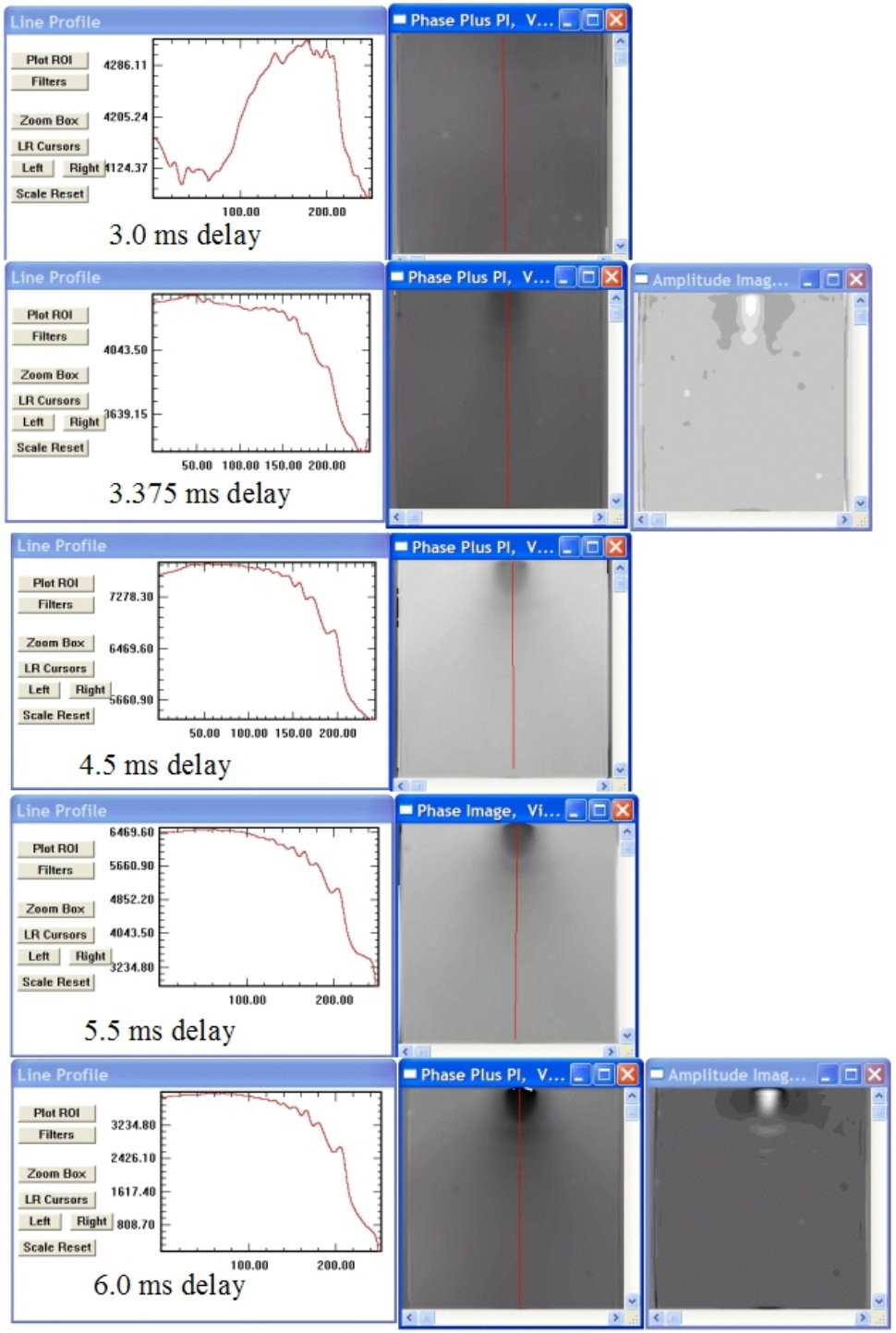
Phase I Focus Series of Chrome On Glass USAF Test Target



- Elements 3, 4, 5, and 6 from Group 0 of USAF Target
- Camera focal positions are ~1.27 mm (0.05 in) apart, so ~4 mm range

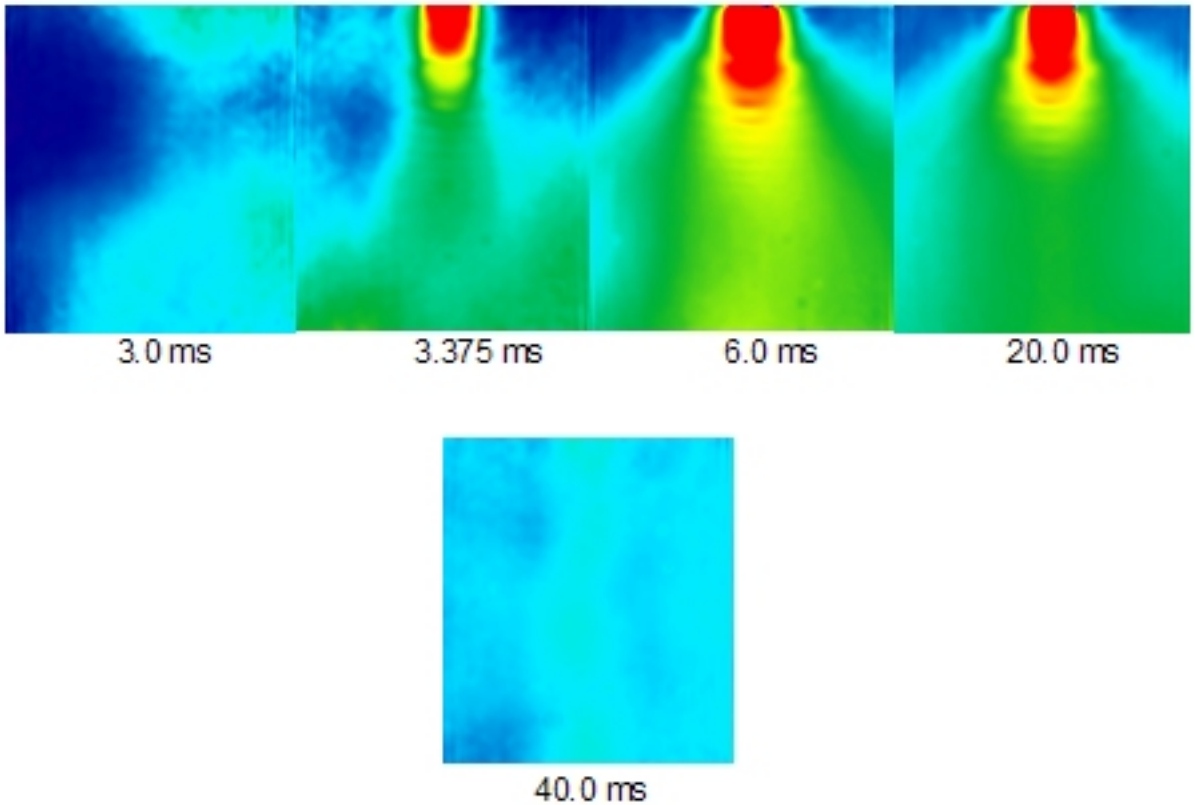
Two of the Authors
(actually working on Phase II System ;-))





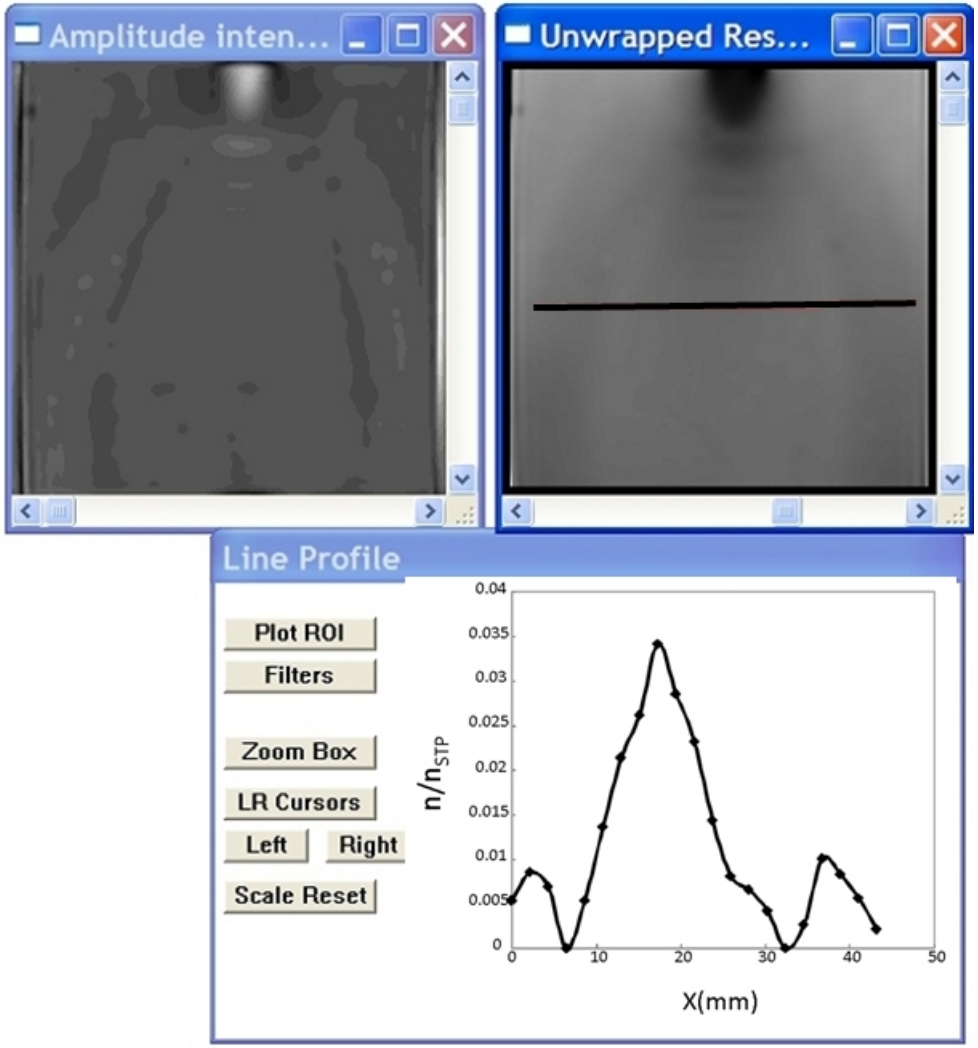
- **Phase I System Data**
- **Time sequence of phase and amplitude images of plume from fast gas valve expanding into the test stand.**
- **No flow at 3 ms after trigger and fully developed flow at 6 ms after trigger**
- **Missing amplitude images represent a software opportunity**

Color-Coded Phase Images of Fast-Gas-Valve Plume



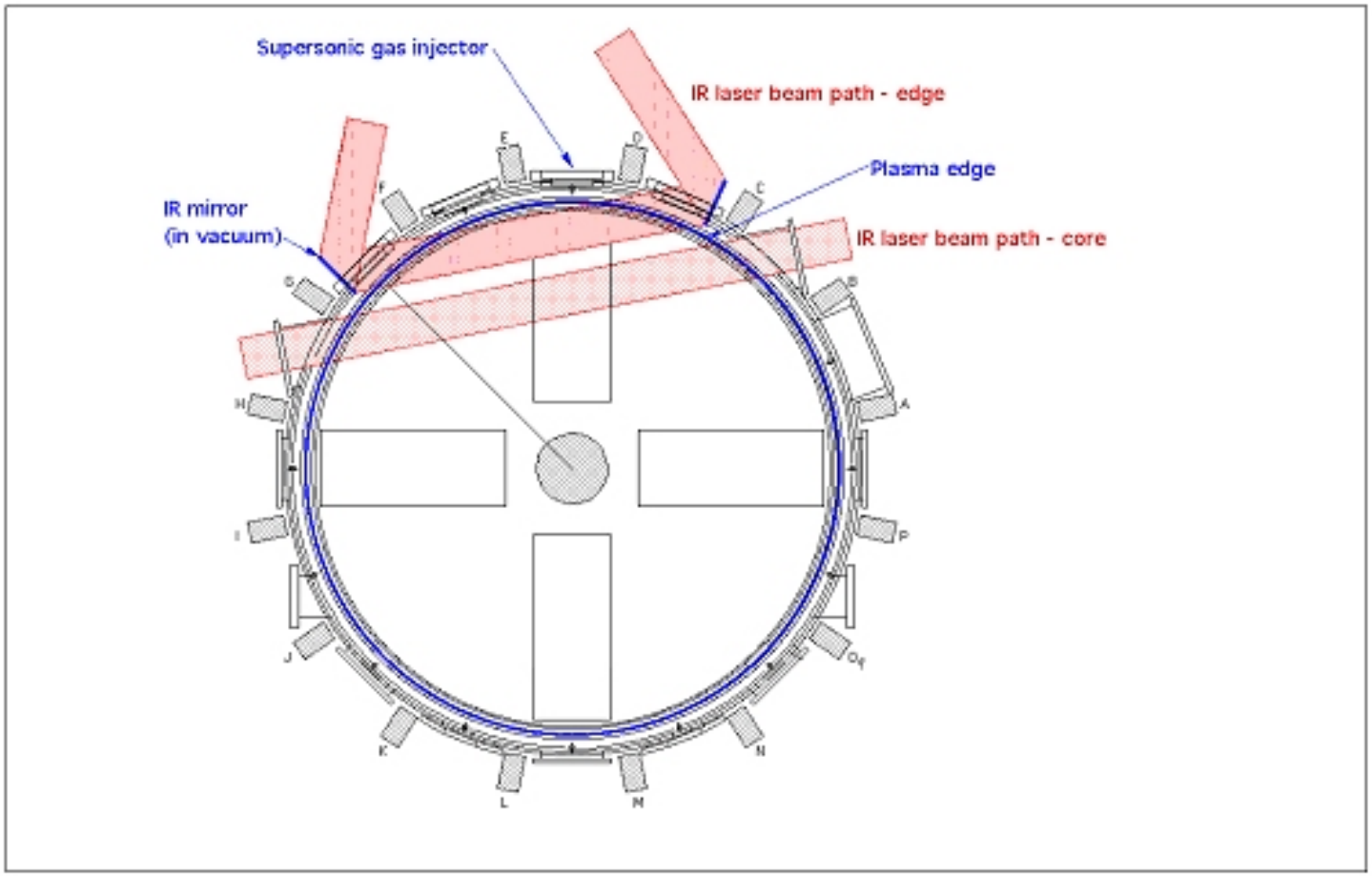
- Time-series of gas-plume images with colors assigned to phase-difference levels
- This can also be presented as a 3-D plot of Ar line-density vs. position, or unfolded into a 3D density dataset by assuming symmetry

Line Plot of n/n_{stp}



Noise level is less than 0.001 atmospheres Ar

The Phase II high-speed system will install on LTX very soon (E. Granstedt, R. Majeski, R. Kaita)



Discussion

- A very inexpensive system could be built with:
  - Single 20Watt 10.6μ laser (~$30k)
  - AOM (~$5k)
  - Photon (or new generation) uncooled 30Hz 320x256 IR camera (~$12k)
  - Balance of optics & table (~$20k)
  - Recirculating closed-loop chiller (~$3k)
  - Fast computer (~$4k)
  - Pulse generator & oscilloscope (~$4k)
  - Nominal total ~$100k
- Would be capable of measuring erosion at 300 μ/sec
- Dual lasers (for large steps, ~1cm, on measurement area) would increase this by $40k—still only requires one camera
- A high-speed dual laser-system (up to 3kHz at 64x64 pixels) would add ~$400k to the cost of the system

References

- Gabor, D., Proc. Roy. Soc. London Ser. A A197, p. 459 (1949).
- Leith, E., and Upatnieks, J., *J. Opt. Soc. Am*. **52,** p. 1123 (1962).
- Leith, E., and Upatnieks, J., *J. Opt. Soc. Am*. **53**, p. 1377 (1963).
- Heflinger, L. O., Wuerker, R. F., and Brooks, R. E., *J. App. Phys*, **37,** p. 643 (1966).
- Thomas, C. E., Baylor, L. R., Hanson, G.R., Rasmussen, D. A., et al., Direct to Digital Holography and Holovision, June 20, 2000, U.S. Patent 6,078,392.
- Thomas, C. E., and Hanson, G. R., Acquisition and replay systems for direct-to-digital holography and holovision, February 25, 2003, U.S. Patent 6,525,821.
- Thomas, C. E., et al., Off-axis illumination direct-to-digital holography, June 8, 2004, U.S. Patent 6,747,771.
- Thomas, C. E., System and Methods For Shearless Hologram Acquisition, October 30, 2007, U.S. Patent 7,289,253.
- Hanson, G. R., Bingham, P.R., Simpson, J. T., Karnowski, T. P., Voelkl, E. “Two-Wavelength, Spatial-Heterodyne Holography”, December 25, 2007, U.S. Patent 7,312,875.
- Invited Refereed Paper: Thomas, C.E., et. al., "Direct To Digital Holography for Semiconductor Wafer Defect Detection And Review", SPIE Conference on Process Control and Diagnostics in IC Manufacturing, Proceedings of SPIE Volume 4692, Jul 2002, SPIE Press, Bellingham, WA.
- Invited Refereed paper: Thomas, C. E., et. al., “Direct To Digital Holography For High Aspect Ratio Inspection of Semiconductor Wafers”, 2003 International Conference on Characterization and Metrology for ULSI Technology, March 24-28, 2003, American Physical Society.
- Acedo, P., Lamela, H., Sánchez, M., Estrada, T., and Sánchez, J., “CO2/He–Ne two-color laser interferometry for low and medium electron density measurements in the TJ-II Stellarator”, Rev. Sci. Inst., **75,** No. 11, p. 4671, November 2004.

TDT Coordinates

- C. E. (Tommy) Thomas Jr.
- Third Dimension Technologies LLC
  11020 Solway School Road
  Knoxville, TN 37931
- Phone: 865-896-0032
- Email: thomasce2@att.net