Characterization of an X-ray Radiographic System for Measuring the Evolution of Broadband Imprint in Laser-Driven Planar Targets

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X-ray face-on radiography has long been used as one of the most powerful tools for quantitative measurements of 3-D mass perturbations on laser-accelerated targets in various ICF experiments. Typically these systems employ pinholes and microchannel plates that limit the ultimate spatial resolution and introduce noise; therefore, to reliably interpret images of target nonuniformities, the experimental system must be properly characterized. To extend the capabilities of our present system configuration, making it more suitable for our new series of experiments, we introduced some changes in the experimental setup. We present results that demonstrate the spatial resolution and sensitivity as well as the new signal-to-noise ratio of a system that uses ~1.3-keV backlighter x rays and a framing camera as a detector. The optical response of the system has been characterized and used to construct a Wiener filter, further applied to increase the signal-to-noise ratio in the spectra of the radiographic images. A discussion of this technique and its effects on the interpretation of the data is presented. This work was supported by the U.S. Department of Energy Office of Inertial Confinement Fusion under Cooperative Agreement No. DE-FC03-92SF19460, UR, and NYSERDA.

Characterization of an X-ray Radiographic System for ICF Hydrodynamic Stability Experiments

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Abstract

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Summary

A characterization of our radiographic system was done for three different conditions in search of an optimal configuration

- We varied the magnification (8× and 12×) and pulse duration (2 ns and 3 ns) of the backlighter in three cases and compared system performance.
- System response is improved by increasing backlighter intensity and choosing higher magnification.
- From the three considered cases, 12× magnification with the 2-ns-long backlighter had the best sensitivity and resolution.
- The results will be applied to future series of experiments requiring higher sensitivity.

Introduction

X-ray radiography is the primary tool for observation of hydrodynamic instabilities in ICF targets

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- With improved uniformity the OMEGA laser challenges our diagnostics since the imprint signal approaches film noise.
- The imprinted mass perturbations possess broadband spectra with wavelengths ranging from 2 mm up to ~200 μm. Those in the range of 200 and 100 μm are of particular interest.
- Data analysis involves significant image processing.
- Detailed knowledge of the resolution and noise of the imaging system is required.

Backlighter x rays traverse the target and are imaged on a framing camera by a pinhole array

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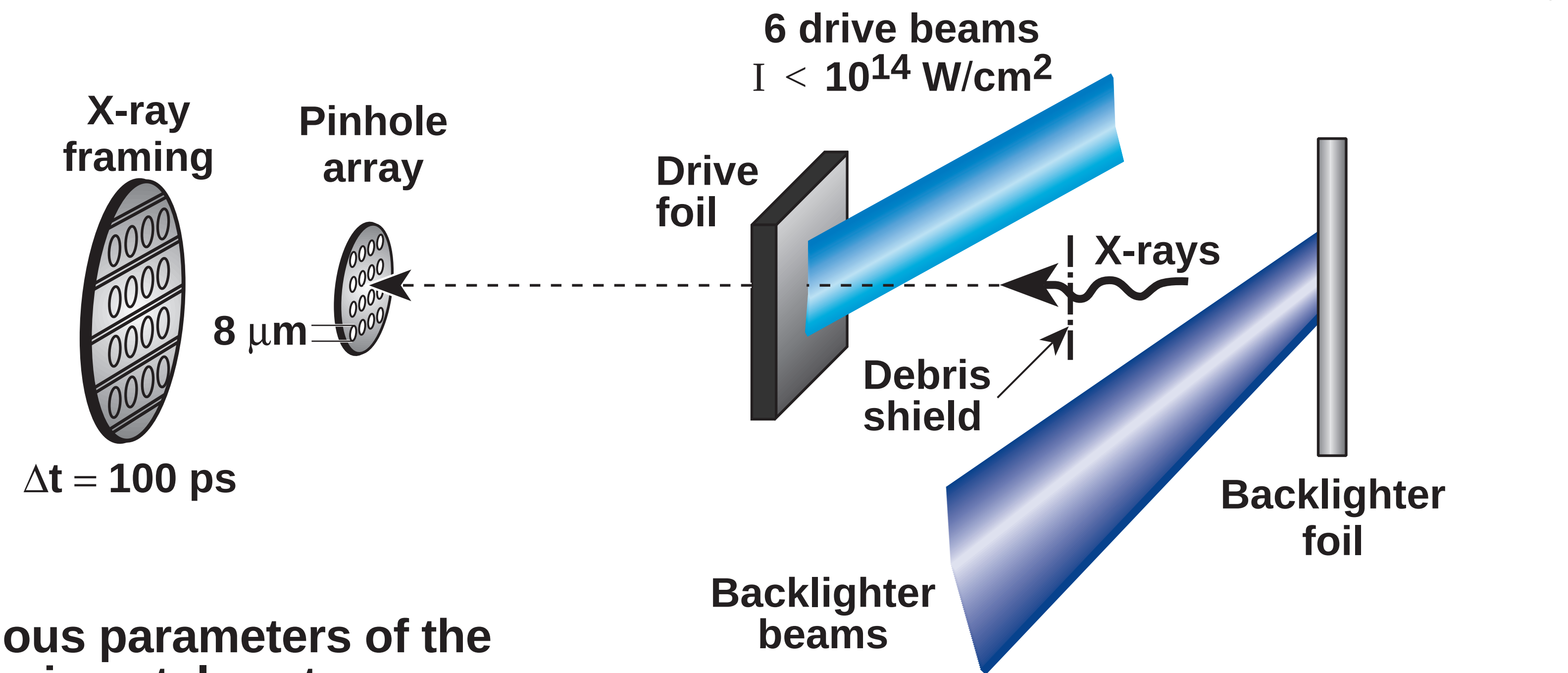

- Various parameters of the experimental system:

Magnification	Backlighter pulse duration (ns)	Target-pinholes distance (mm)	Spatial resolution (µm)	Spatial field-of-view (µm)	Temporal resolution (ps)
8×	3	25.5	~ 13	350	80
12×	2	25.0	~ 8	500	150
12×	3	24.8	~ 9	500	150

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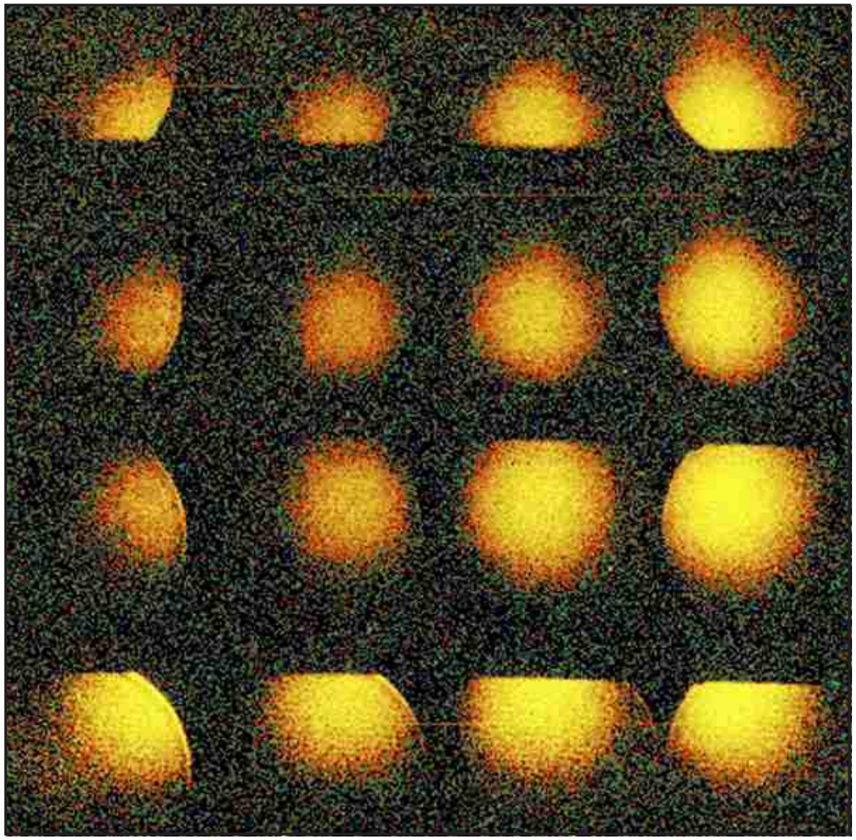
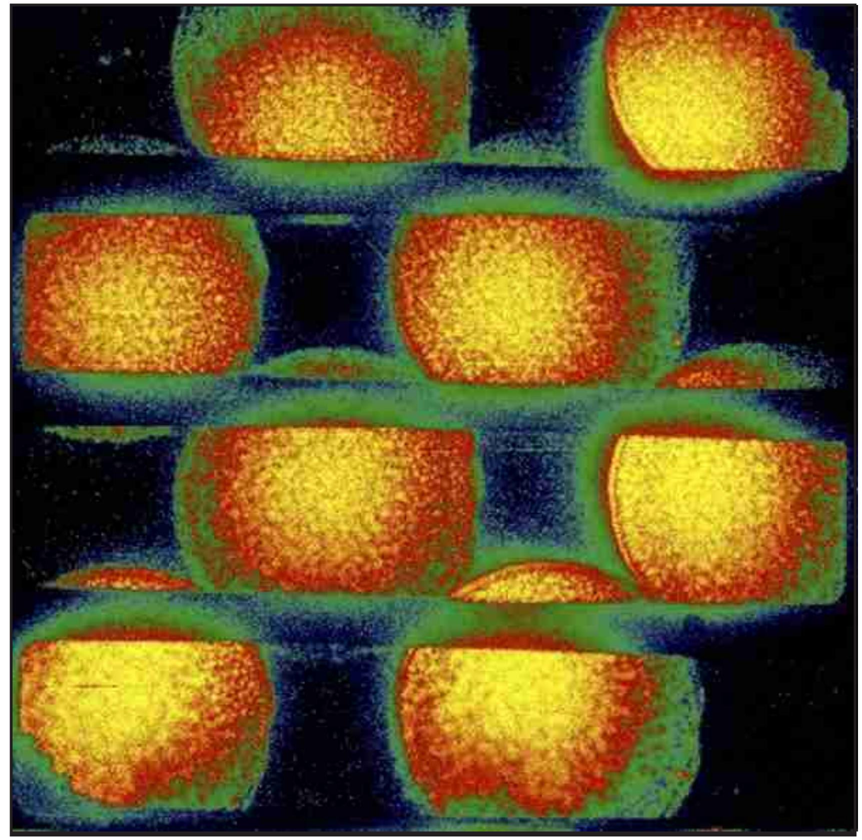
Typical radiographic images (of a planar ICF target) taken under 8× and 12× magnification respectively





The non-ideal response of the diagnostic and digitizing equipment is assumed to be linear

- The linear response of the system is good assumption since the modulation in the target optical density is small:

$$D_0(r,t) << 1$$

- Speckle and noise in raw data are uncorrelated

$$\left|I(k_x,k_y)\right|^2 = \left|I_s(k_x,k_y)\right|^2 + \left|I_n(k_x,k_y)\right|^2;$$

their spectral power components add in quadrature

$$\sigma_{rms}^2 + \sigma_s^2 + \sigma_n^2.$$

- The broadband spectrum of the imprint can be distinguished from the detector noise.

- Nonlinear effects such as coupling of modes and harmonics generation are negligible as simulations show for even greater than the routinely measured modulation amplitudes.[1]

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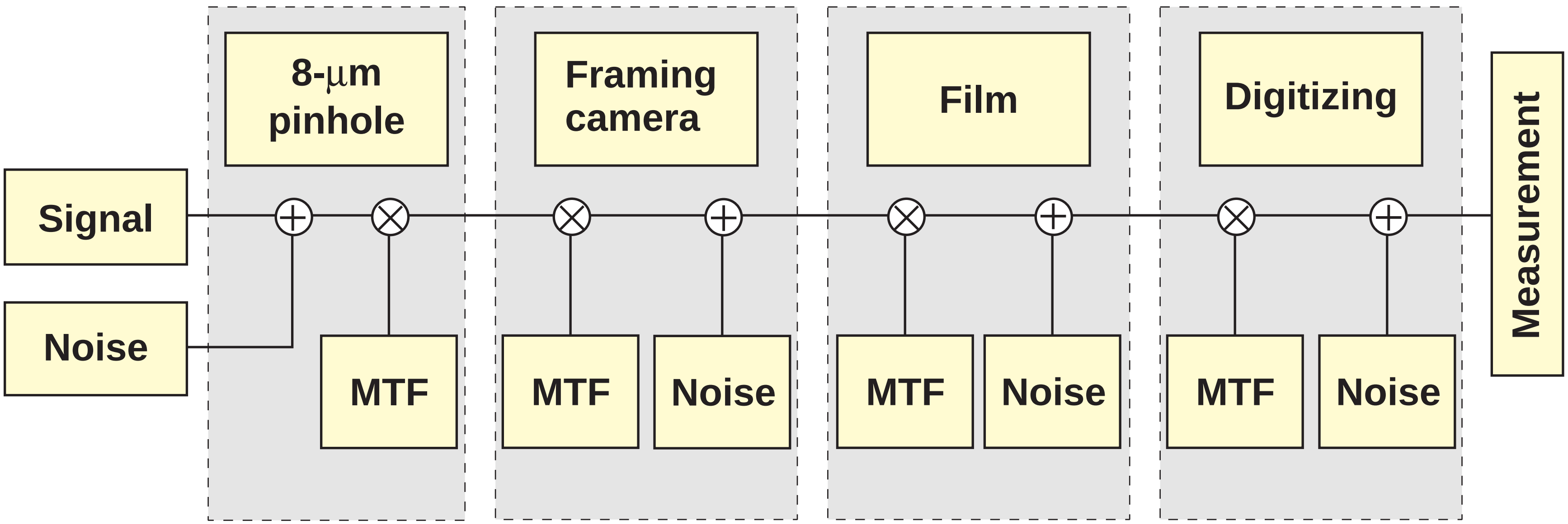
[1]V. A. Smalyuk *et al*., Rev. Sci. Instrum. 70, 647 (1999).

Optical response of the diagnostic system's components can be expressed in frequency space as multiple operators acting on the initial signal

$$MTF_{TOT} = \prod_i MTF_i$$



- The system resolution is limited by the pinhole camera (PHC) and the microchannel plate (MCP).
- The noise is predominantly determined by photon statistics of the backlighter x rays.[2]

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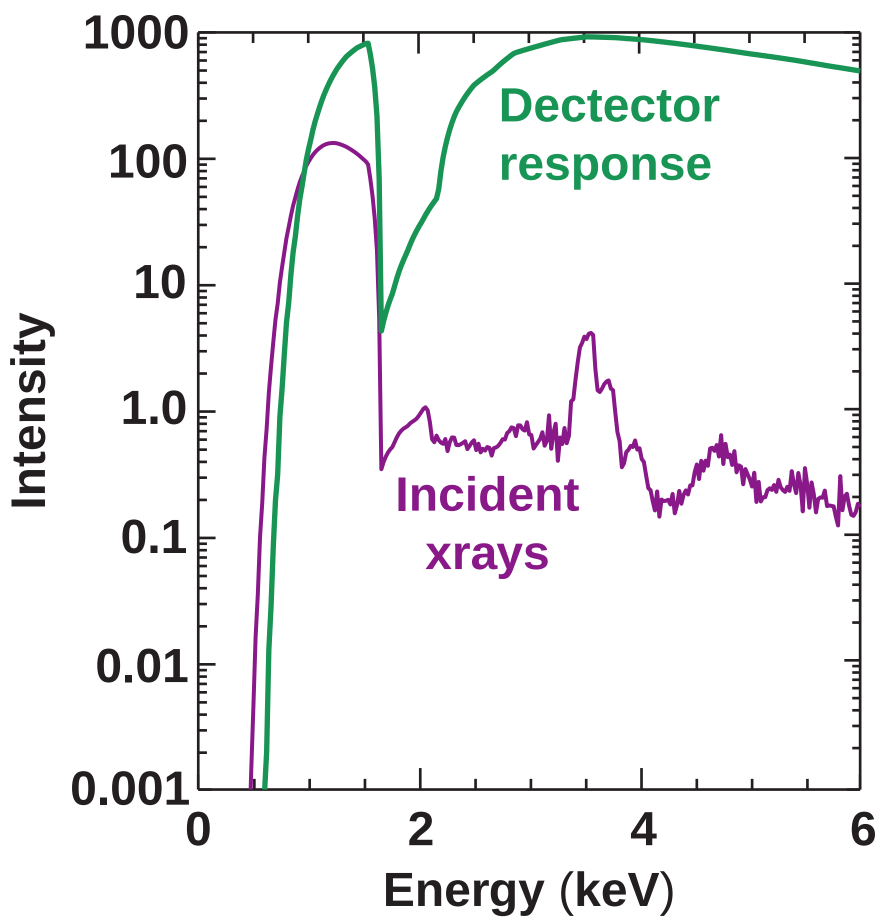
[2] V. A. Smalyuk *et al.*, Rev. Sci. Instrum. 70, 647 (1999).

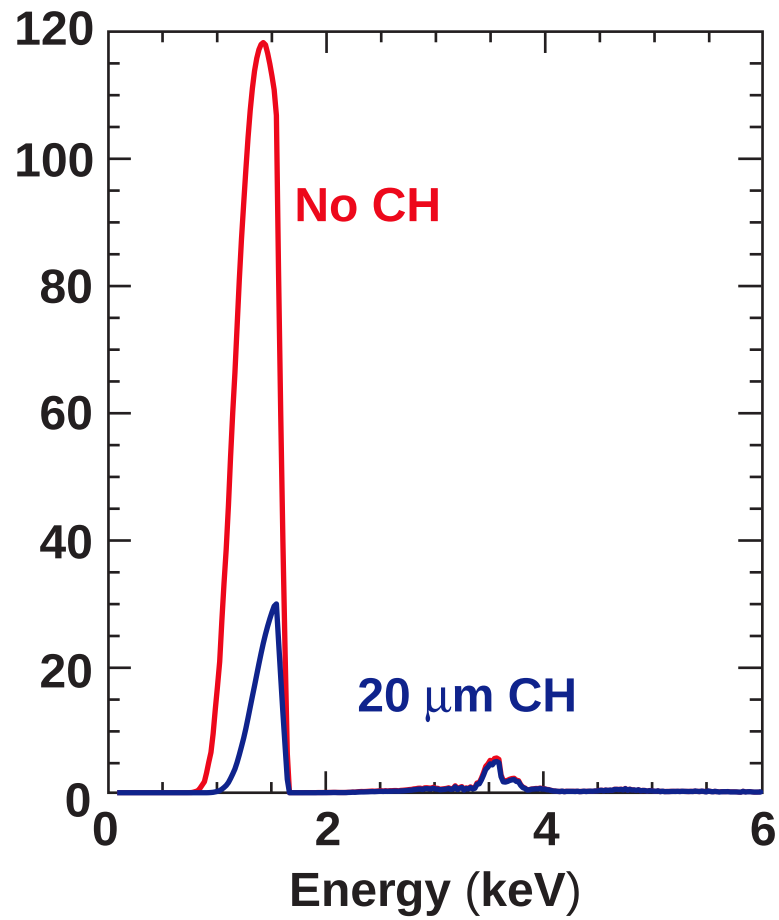
The signal-to-noise ratio for this system is moderate-to-low; hence, noise reduction techniques are required

- The primary objective is to recover the amplitude of the perturbation at the ablation surface using the measured optical-depth modulations. A Wiener filter accounts for noise and system resolution.

- The steps involved are
  - Measurements of the noise from
    - detector
    - film
    - digitization process
  - Model of the modulation transfer function (MTF),
  - Determination of the sensitivity by measuring the spectrally weighed attenuation length of an undriven target,
  - Construction of a Wiener filter and its application to the raw data.

The uranium n-band emission has dominant contribution to the spectrally weighted attenuation length λ_x of the CH target





- The high energy m-band emission at 3.5 keV reduces contrast of the images.

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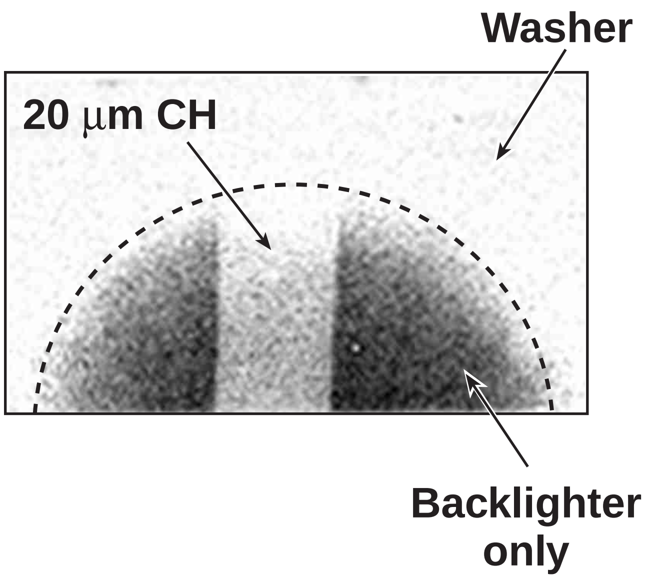
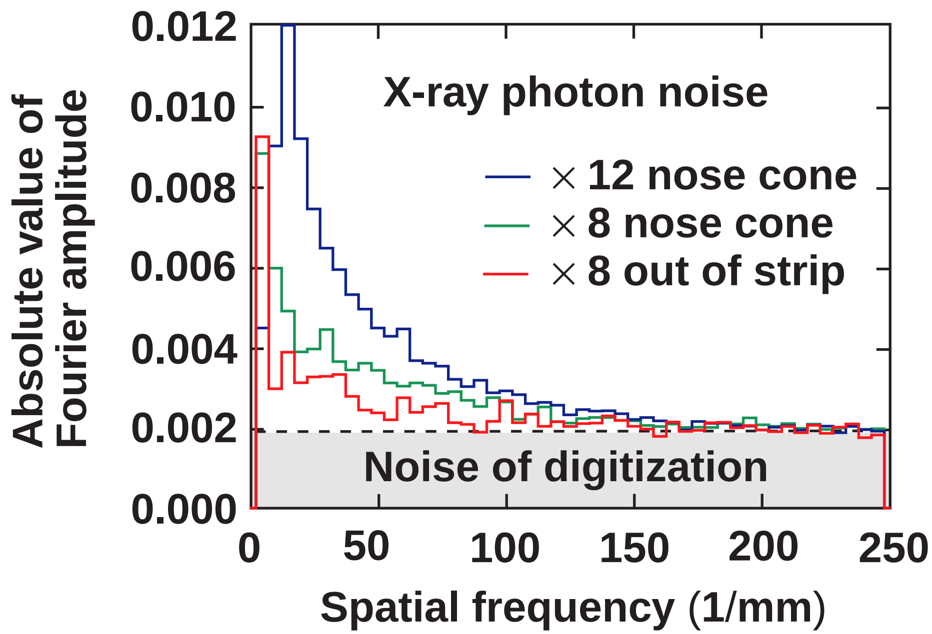
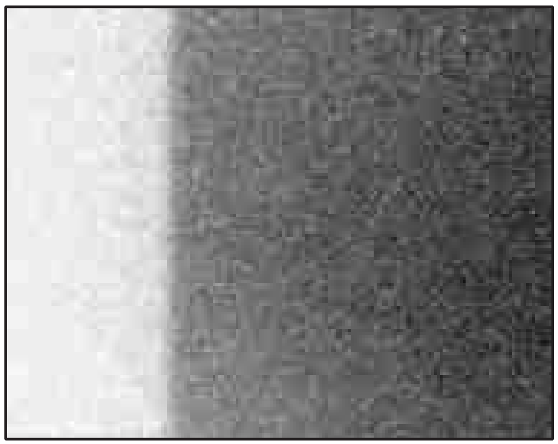
The noise spectrum is measured from images of an undriven “band” target



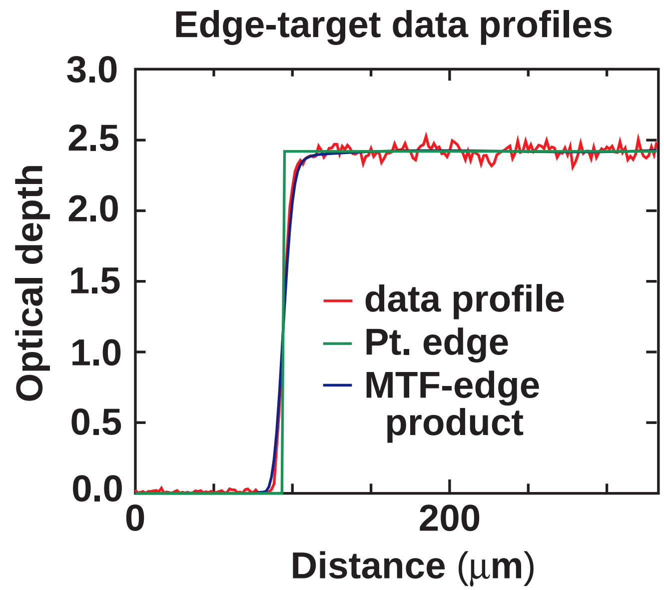


- **The signal-to-noise ratio is high for the 8× magnification case but at the cost of lower spatial resolution.**

The MTF of the entire imaging system is evaluated using edge-target data



Fragment of a target image; Pt edge shown.



$$\mathrm{MTF} = Ae^{-(\sigma_1 f)^2} + (1 - A)\, e^{-(\sigma_2 f)^2}$$

The product in Fourier space of the MTF and the ideal edge profile fits very well the raw data profile.

- Curve fitting by nonlinear optimization using a modified Levenberg-Marquardt algorithm. A two-Gaussian curve models the MTF.

$A = 0.12$,	$\sigma = 91.7$ µm,	$\sigma = 30.8$ µm	(12×, 2-ns backlighter)
$A = 0.18$,	$\sigma = 104.5$ µm,	$\sigma = 24.3$ µm	(12×, 3-ns backlighter)
$A = 0.41$,	$\sigma = 53.2$ µm,	$\sigma = 20.0$ µm	(8×, 3-ns backlighter)

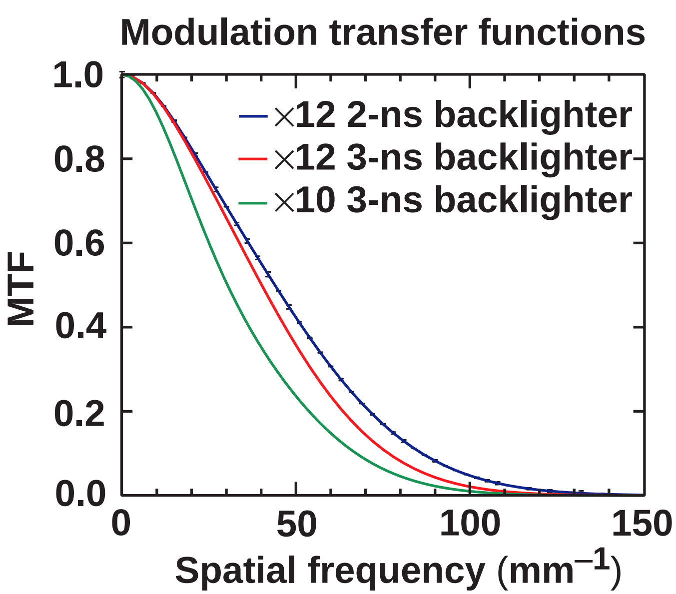
A Wiener filter is constructed from the response characteristics of the system (noise and MTF)

- C(f) – measured noisy signal
- R(f) – restored signal
- MTF(f) – total system MTF
- $|N(f)|^2$ – Wiener noise spectrum
- $|S(f)|^2$ – signal with noise subtracted in quadrature

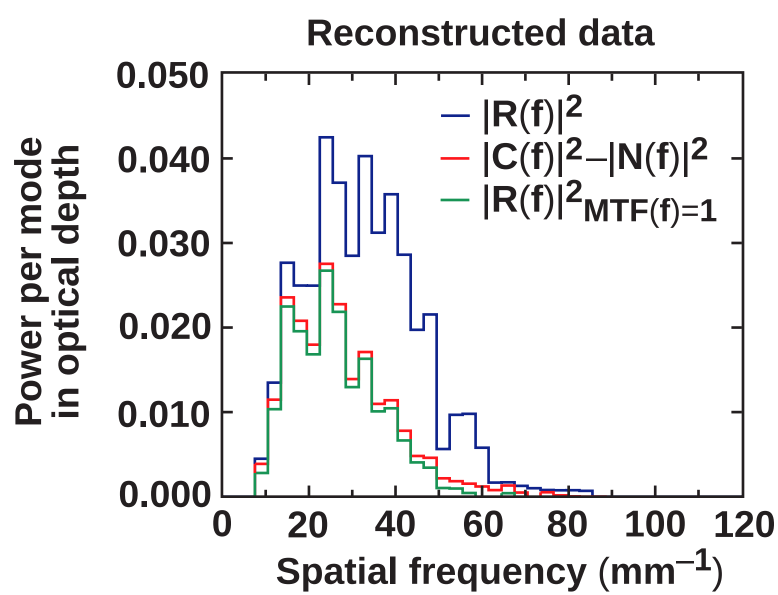
$$R(f) = \frac{C(f)}{MTF(f)} \, \frac{|S(f)|^2}{|S(f)|^2 + |N(f)|^2}.$$

$$|S(f)|^2 = |C(f)|^2 - |N(f)|^2, \mathrm{K}\, |C(f)| > 2|N(f)|$$

$$|S(f)|^2 = 0, \mathrm{K}\, |C(f)| < 2|N(f)|$$



Two-Gaussian fits for the modulation transfer function of the entire system.



Power per mode of a target-image spectra before and after the Wiener.

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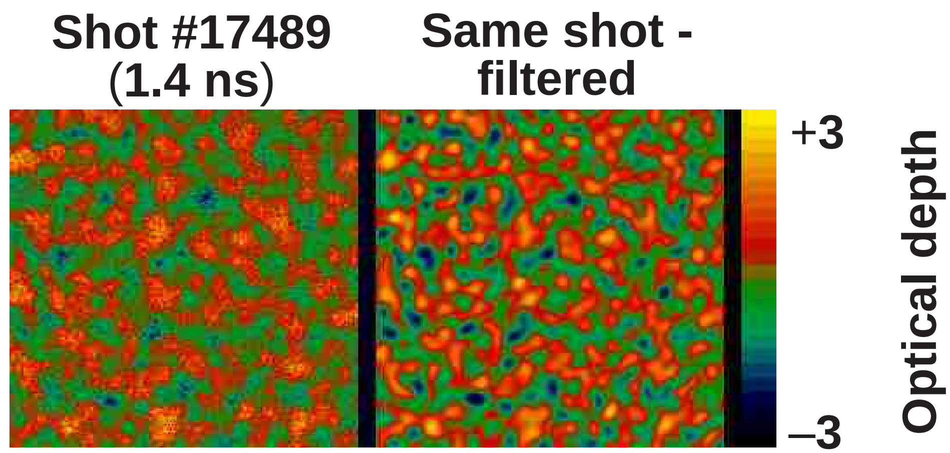
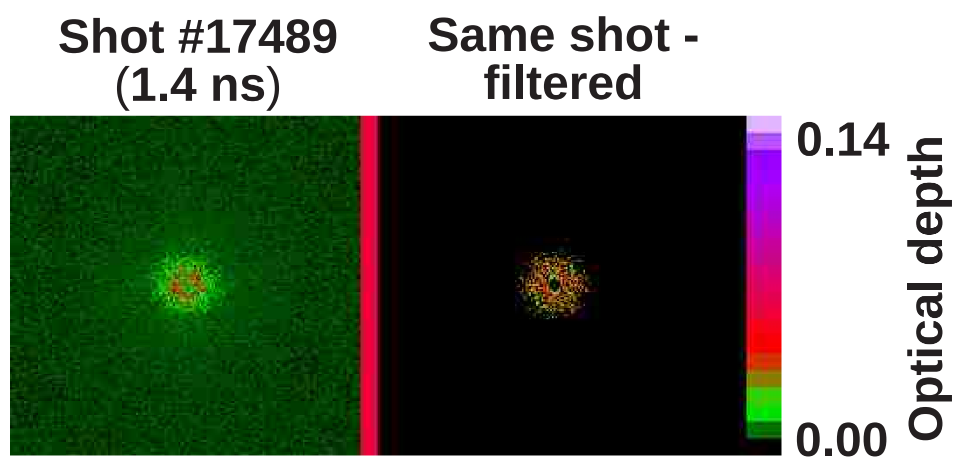
The Wiener filter reduces the high-frequency noise and improves overall image quality

- **Effect of the Wiener filter**
  - The image enhancement is done in frequency space since it is more convenient to work with the Wiener spectrum and MTF rather than with their real-space counterparts—the autocorrelation function and PSF.



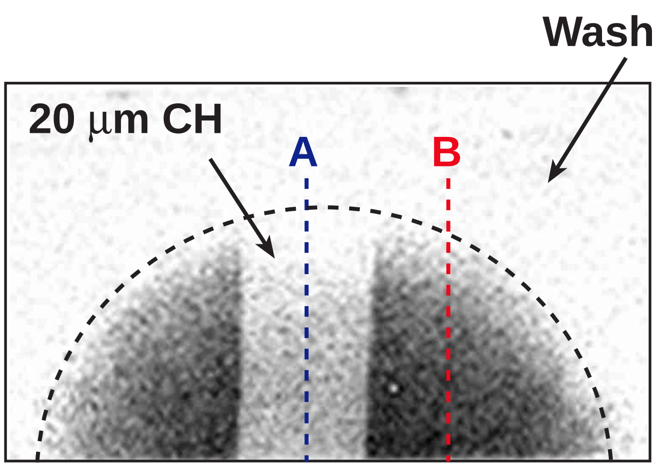
Shot #17489 DPP only

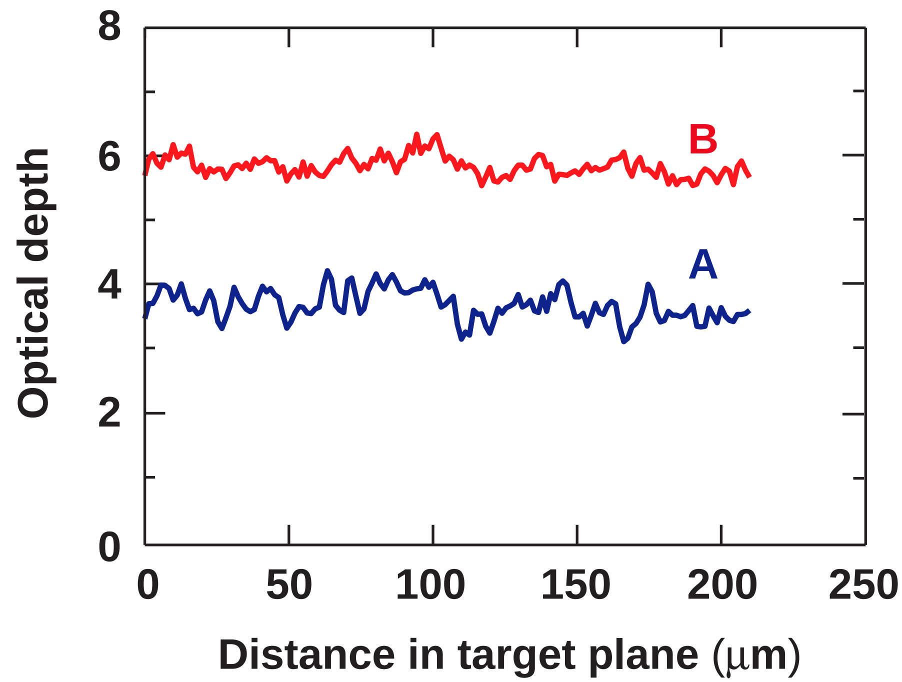


Fourier amplitudes in OD

The spectrally weighted attenuation length is measured to determine the system sensitivity

- To measure the spectrally weighted attenuation length, the optical depth in and out of strip is necessary. (see figure)





- ξ (r,t) = D (r,t) λ_{CH}, where $\lambda_{CH} = \lambda_x/Cp$
- Measured $\lambda_x = 10 \pm 1$ μm (12×)
- Measured $\lambda_x = 11 \pm 1$ μm (8×)

- $I(x) = I_0(x) \exp[-t(x)/\lambda_x]$
- λ_x is the attenuation length of the material.

E10144

Conclusions

- System response is improved by increasing backlighter intensity and choosing a higher magnification.
- From the three considered cases, 12× magnification with the 2-ns-long backlighter had the best resolution, thus making it suitable for broadband imprint experiments.
- Lower-magnification configurations are more suitable for single-mode perturbation growth measurements given the better sensitivity of the 8× case.
- The results along with the improved image-processing apparatus will be applied to future series of experiments requiring higher sensitivity and resolution.