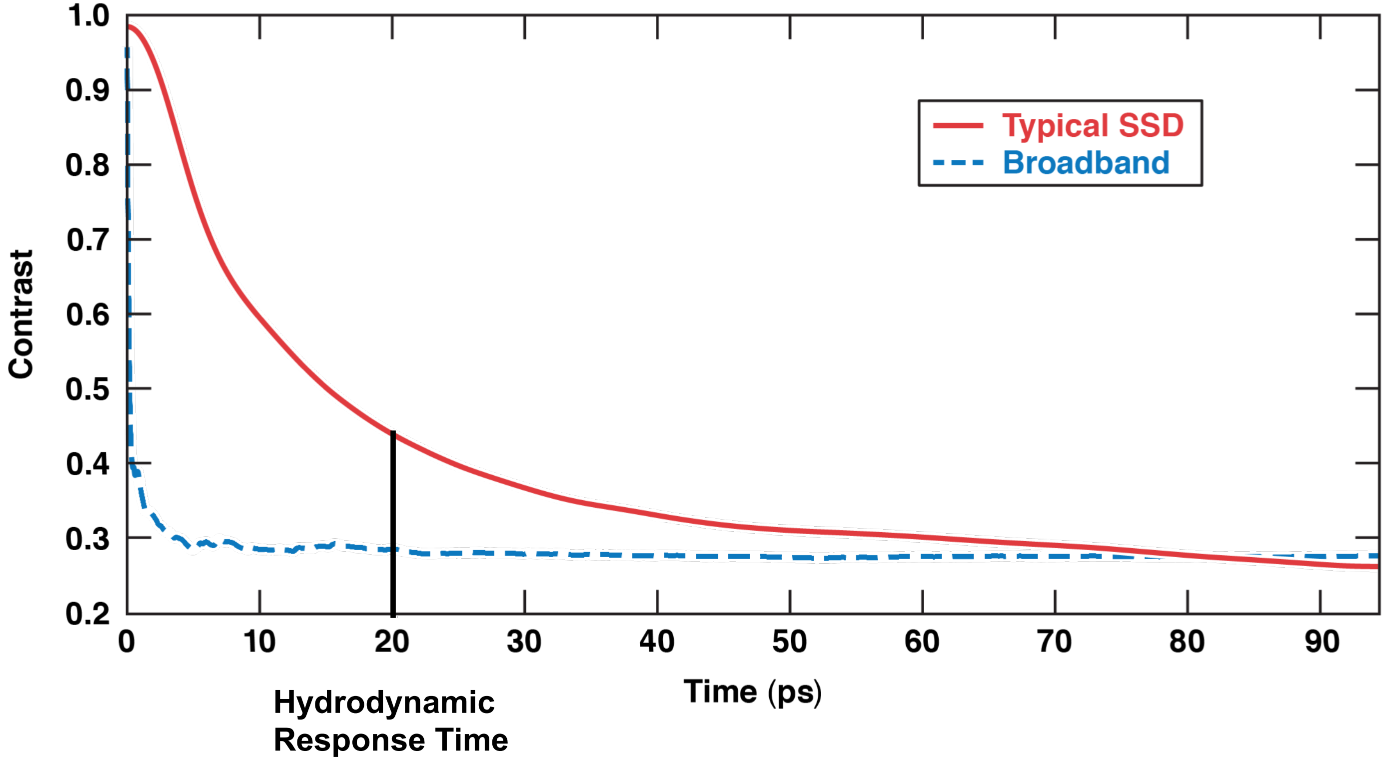
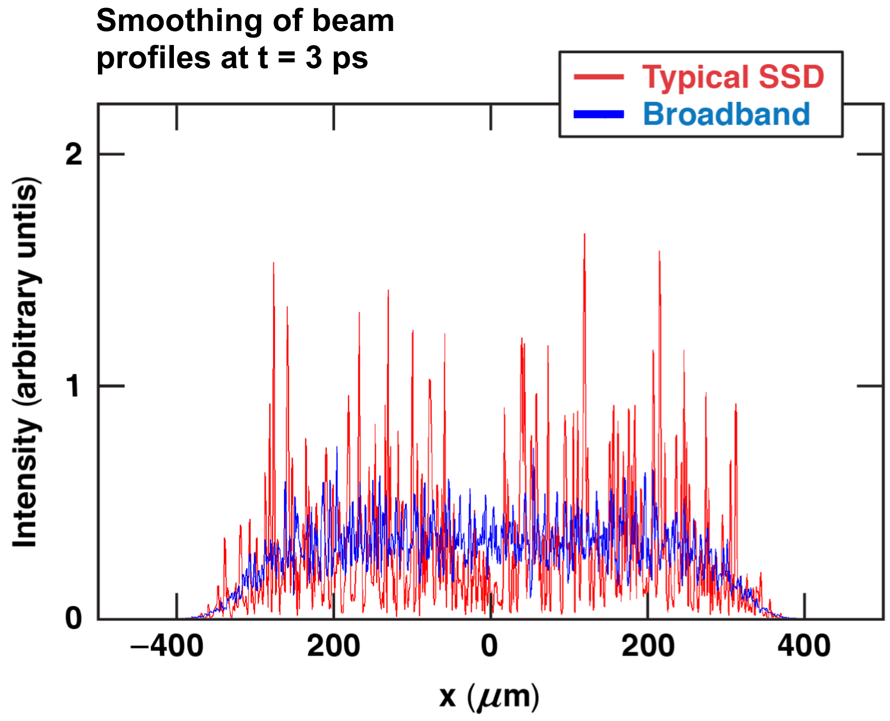
Broadband Smoothing of Laser Pulses for Imprint Reduction in Direct-Drive Inertial Confinement Fusion





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Division of Plasma Physics
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Summary

Broad-bandwidth lasers can smooth much faster than existing smoothing by spectral dispersion (SSD)

- LLE is developing a prototype broad bandwidth (13 THz) ICF driver (FLUX)

- Broad-bandwidth lasers can mitigate imprint by rapidly moving speckle patterns, smoothing intensity non-uniformities faster than the capsule surface hydrodynamically evolves

- Calculations predict that the rapid smoothing of the FLUX laser reaches a comparable asymptotic contrast to typical SSD

Collaborators

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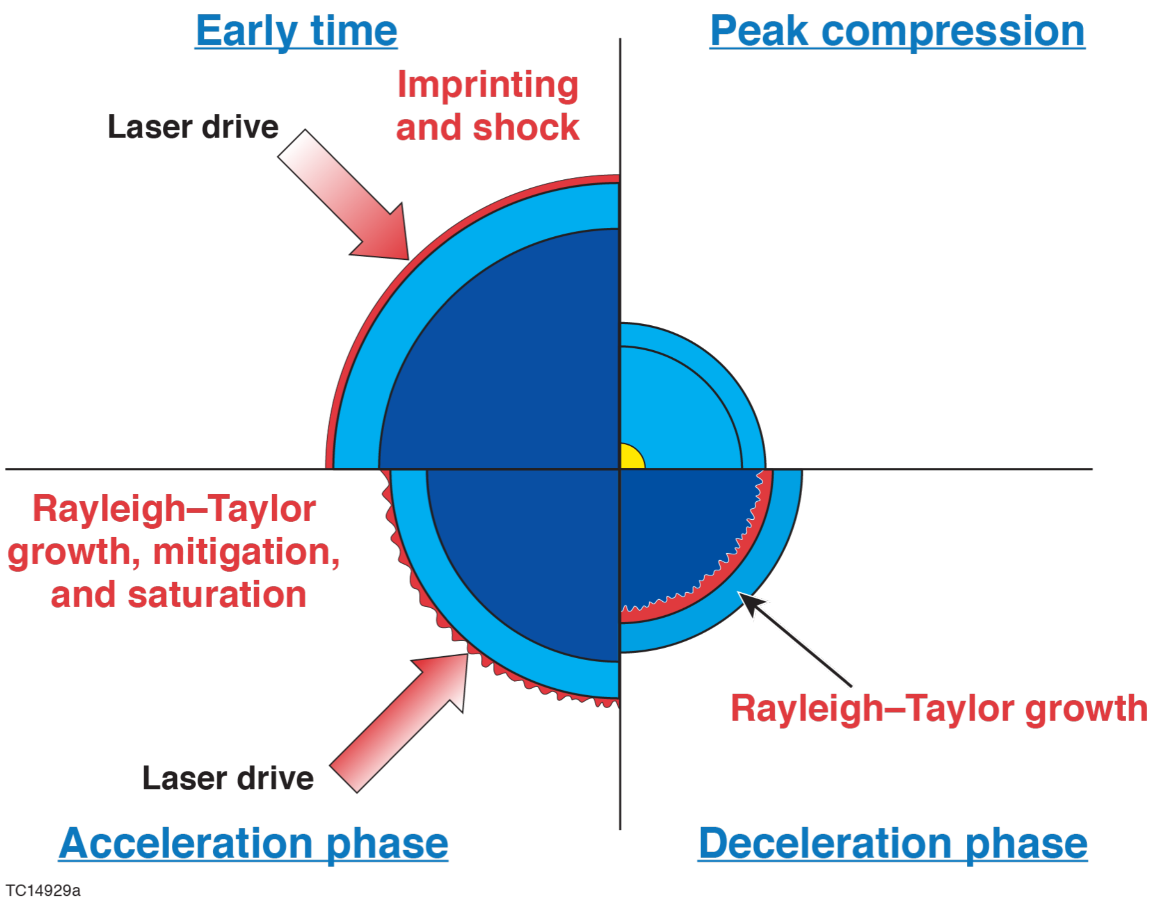
In direct-drive inertial confinement fusion (ICF), an ensemble of laser beams drive the compression of a deuterium–tritium fuel capsule

- **Intense speckles locally heat the ablation surface, imprinting small-scale density nonuniformities**

- **The nonuniformities seed hydrodynamic instabilities—a major limiting factor on performance**

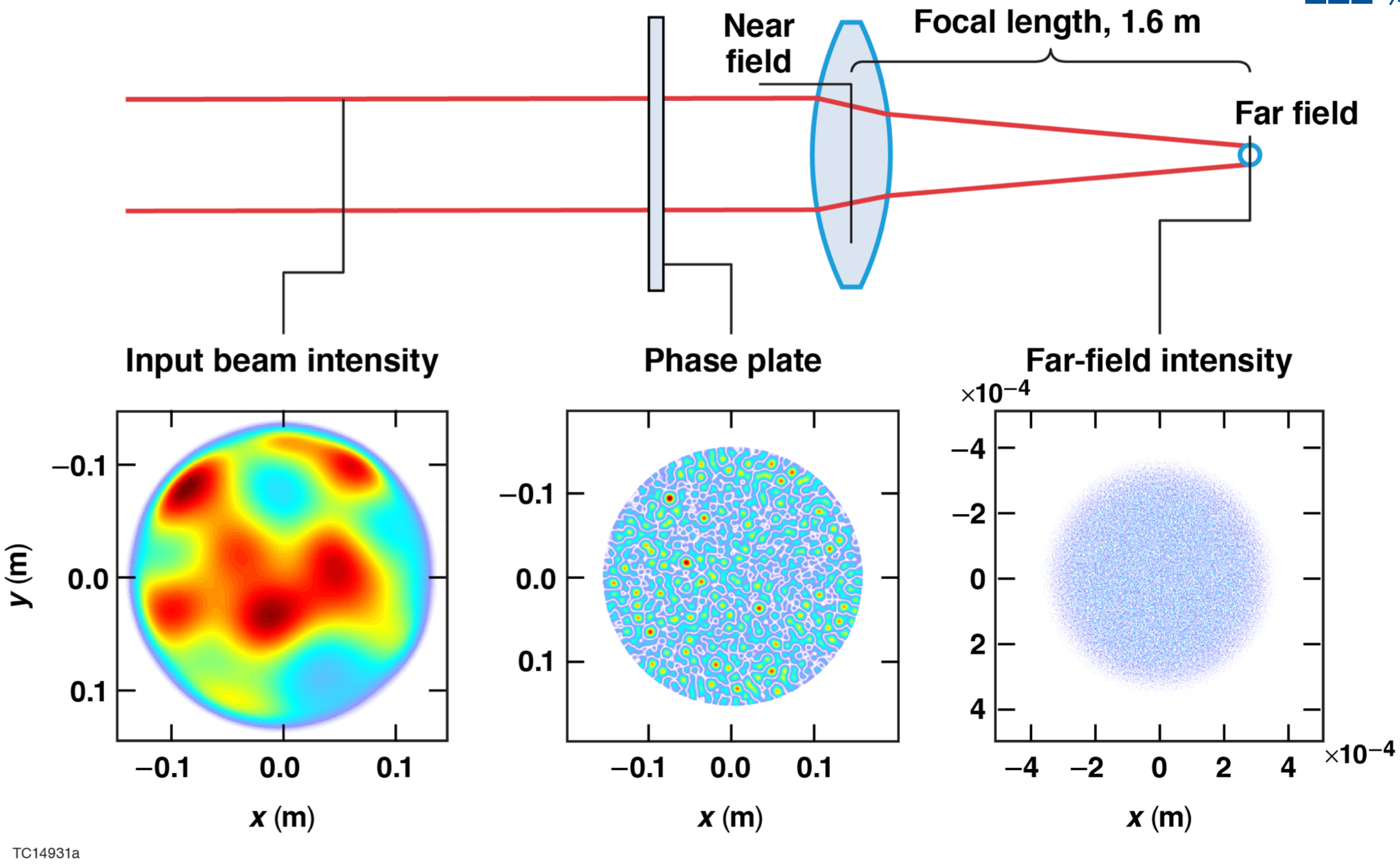


R. S. Craxton *et al.*, Phys. Plasmas 22, 110501 (2015).

The smoothing of large scale nonuniformities introduces small-scale spatial nonuniformities

- Large-scale nonuniformities can
  - seed laser filamentation
  - preclude a symmetric implosion

- Phase plates smooth large-scale nonuniformities, but introduce small-scale speckles



Large scale

Small scale

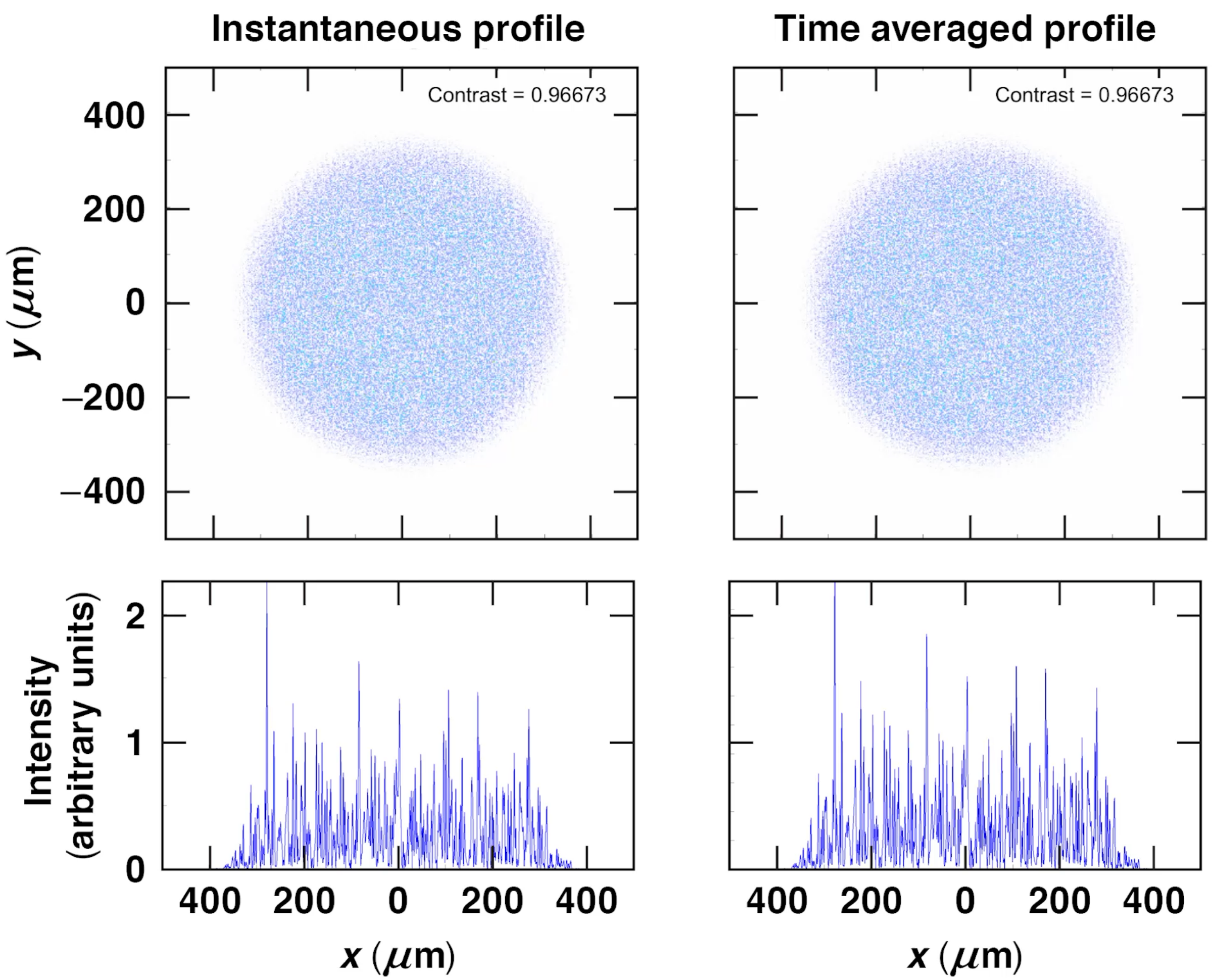
Temporal smoothing can prevent small-scale nonuniformities from imprinting on the capsule

- **The shell experiences the intensity non-uniformities convolved over the hydrodynamic response time**

- **Rapidly moving the speckle pattern effectively smooths the non-uniformities**

Contrast = $\frac{\sigma_I}{\langle I \rangle}$ σ_I **= standard deviation**
$\langle I \rangle$ **= average intensity**

$\sigma_{rms} = 100 \cdot$ **Contrast**



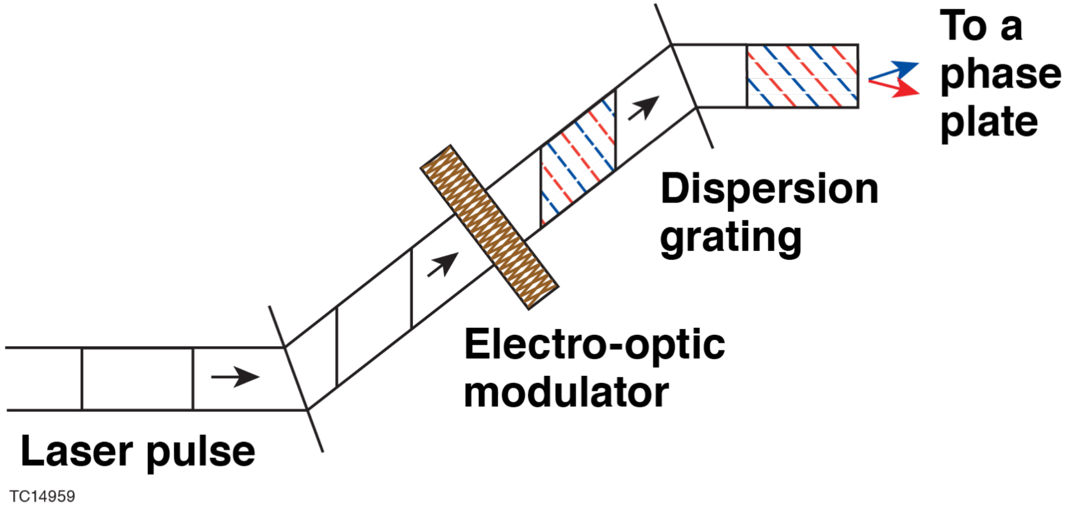
TC15217

Currently the Laboratory for Laser Energetics uses traditional SSD* to temporally smooth OMEGA pulses

- Traditional SSD uses dispersion and frequency modulation to impose temporally varying phase-front modulations across the beam

- Here, we consider 1D multi-frequency-modulated SSD has a bandwidth of 0.066 THz, and is modeled by three frequency modulations

$$\omega(t) = \omega_0 + \sum_{m=1}^{3} \delta_m \, \omega_m \cos(\omega_m t)$$



* S. Skupsky *et al.*, Journal of Applied Physics 66, 3456

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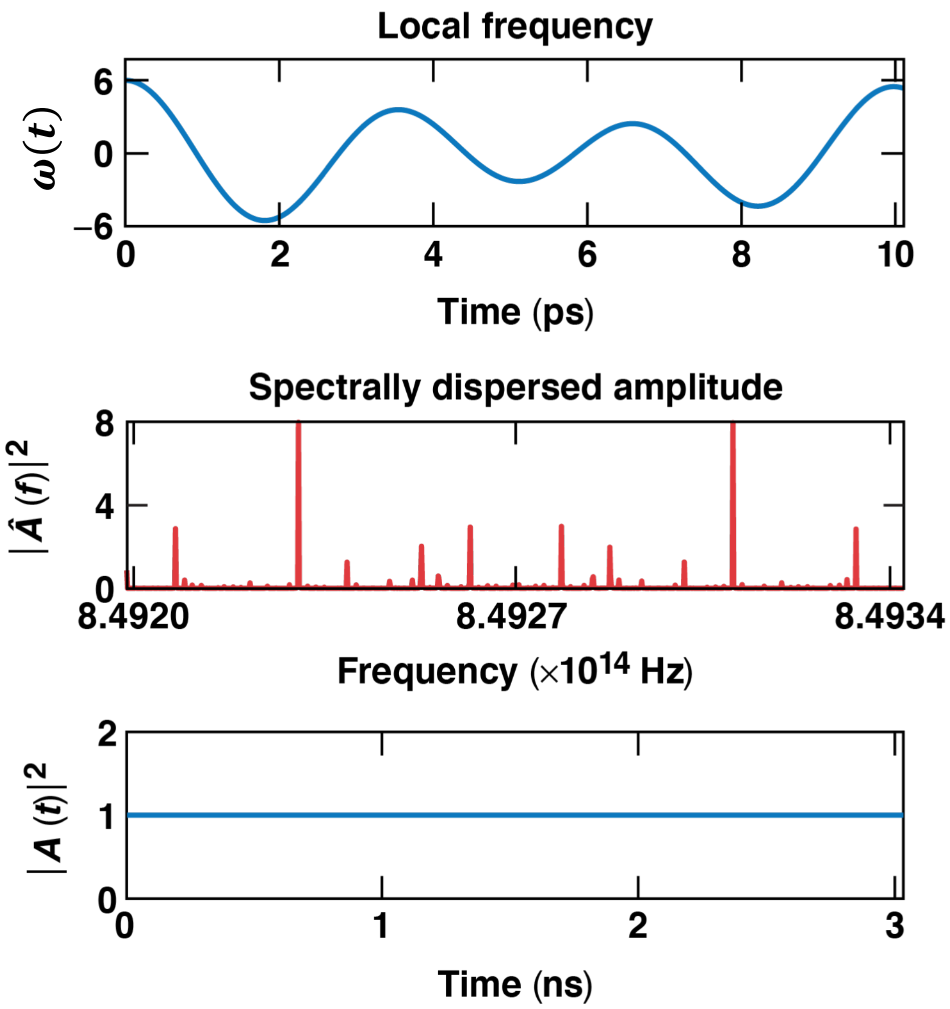
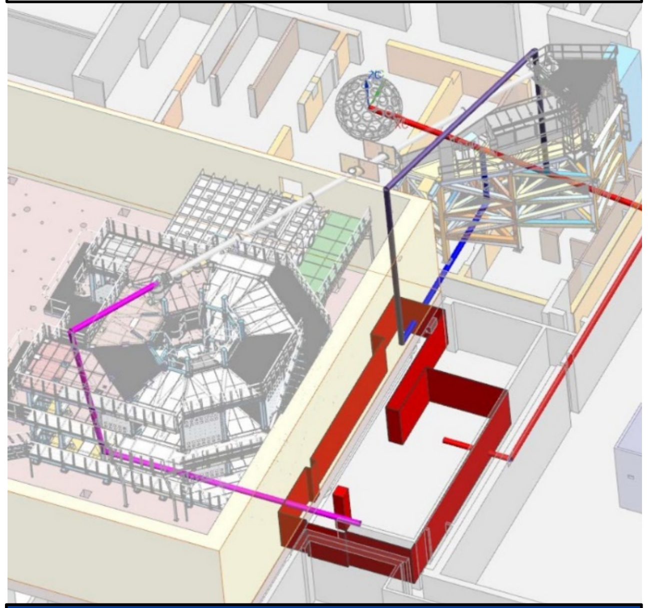


High-bandwidth technologies developed to support short-pulse lasers are being used at LLE to build the next-generation driver for ICF

- **The Fourth-generation Laser for Ultra-broadband eXperiments (FLUX) aims to demonstrate laser technologies that would scale to full OMEGA.**

- **Modeling predicts high-bandwidth will mitigate:**
  - **Laser plasma instabilities**
  - **Laser imprint**

The FLUX laser will feed the OMEGA LPI Platform



FLUX-p9 experiments will validate ICF modeling with bandwidth

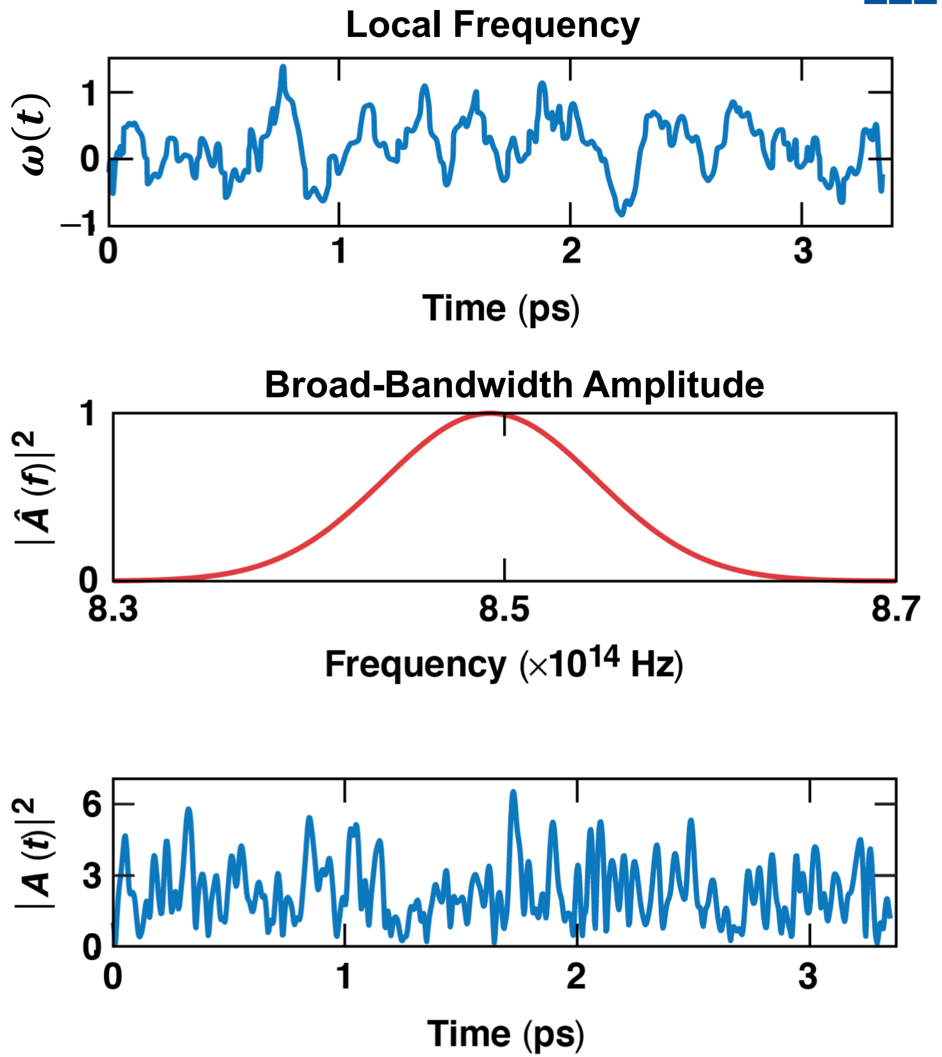
FLUX will use broad-bandwidth light with a bandwidth of 13 THz

- FLUX was modeled by a Gaussian spectrum with with random spectral phase

$$\hat{A}(\omega) = A_0 \exp\left[-\frac{(\omega - \omega_0)^2}{2\Delta\omega^2} - i\phi(\omega)\right]$$

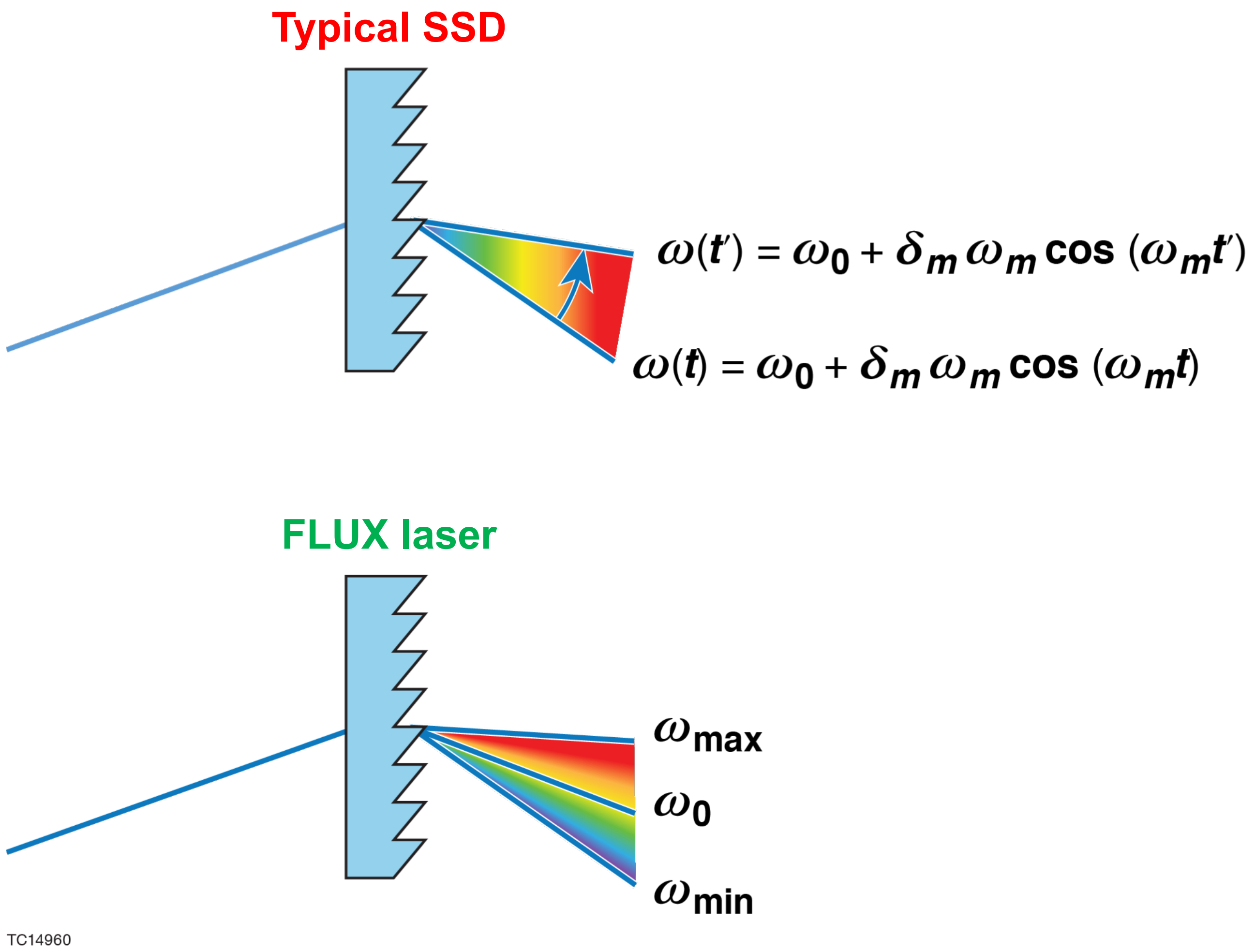
- All frequencies are present at all times; both the amplitude and phase are modulated in time

- Smoothing requires spatial separation of each frequency in the far-field

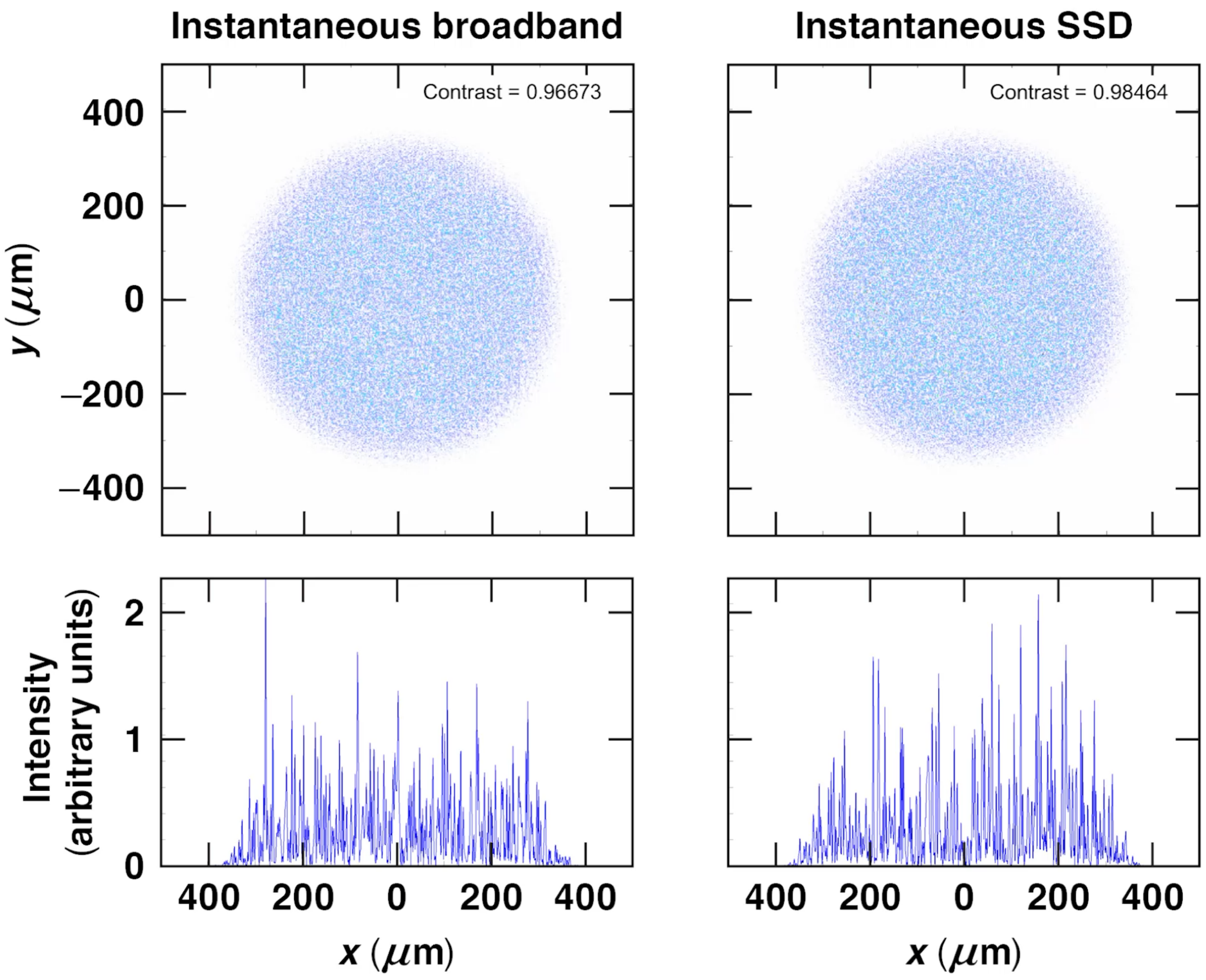


Angular dispersion spatially separates each frequency, moving the speckle pattern in the far field

- **Wavelengths initially overlapped in space undergo differential refraction and focus to different transverse locations in the far field**
- **For typical SSD, the frequencies cycle across the beam**
- **For the FLUX laser, the frequencies have a fixed location across the beam**



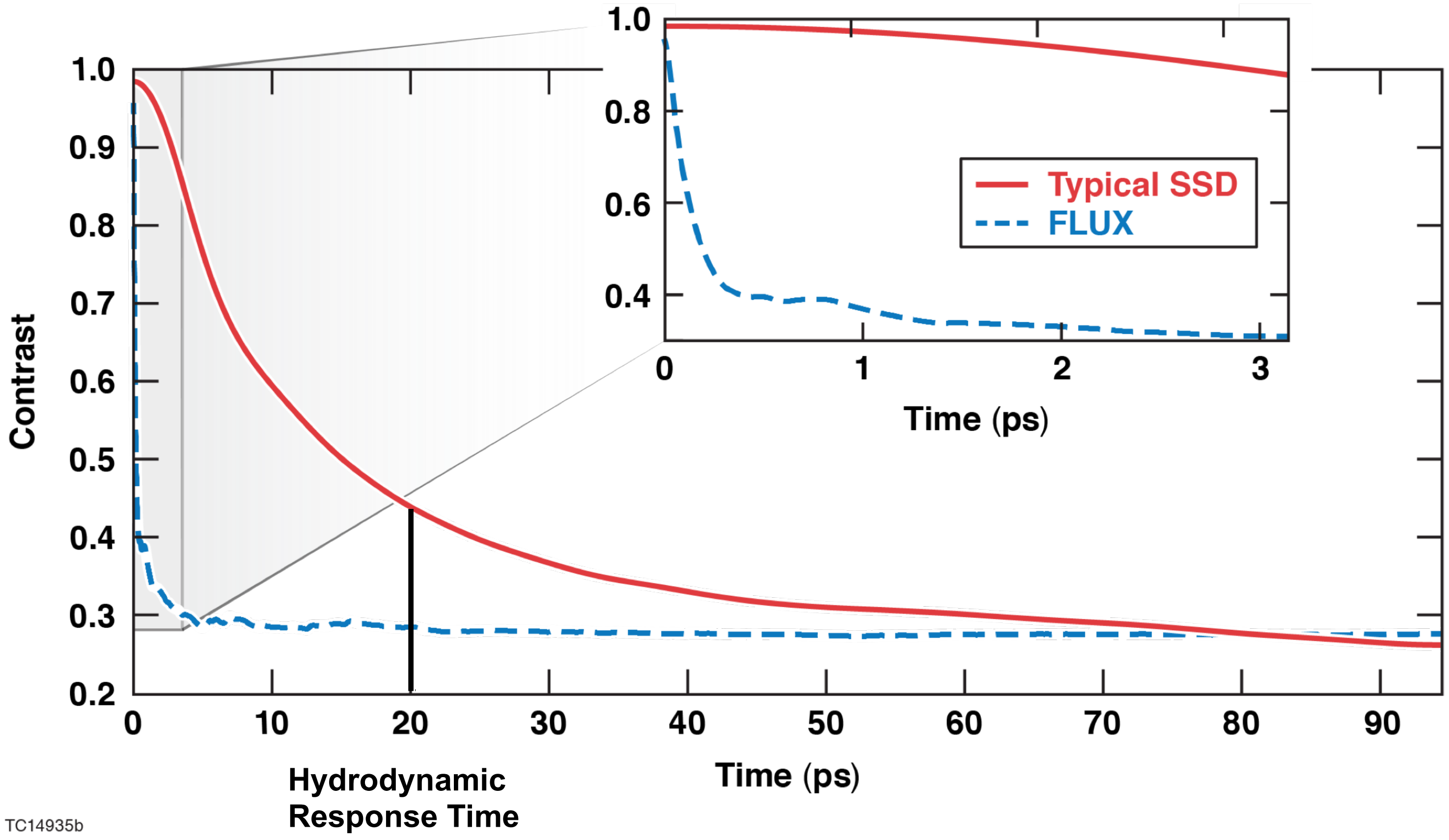
The broad bandwidth of the FLUX laser smooths much faster than typical SSD

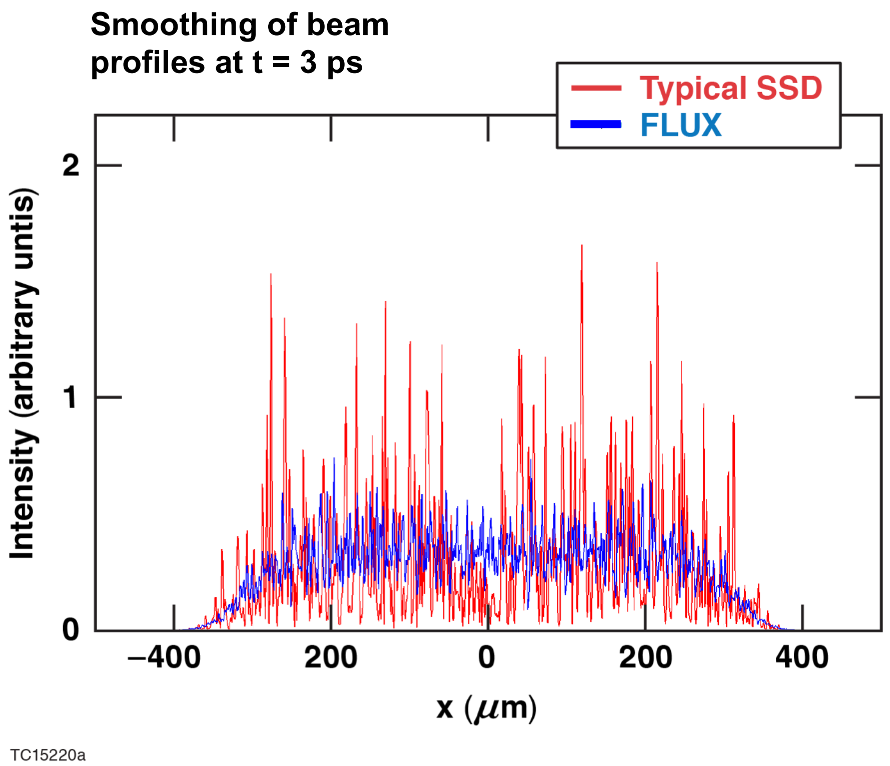


1-s runtime = 0.3349 ps simulated

TC15218

Calculations predict that the rapid smoothing of the FLUX laser reaches a comparable asymptotic contrast to typical SSD





Broad-bandwidth lasers can smooth much faster than typical smoothing by spectral dispersion (SSD)

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- **Broad-bandwidth lasers can mitigate imprint by rapidly moving speckle patterns, smoothing intensity non-uniformities faster than the capsule surface hydrodynamically evolves**
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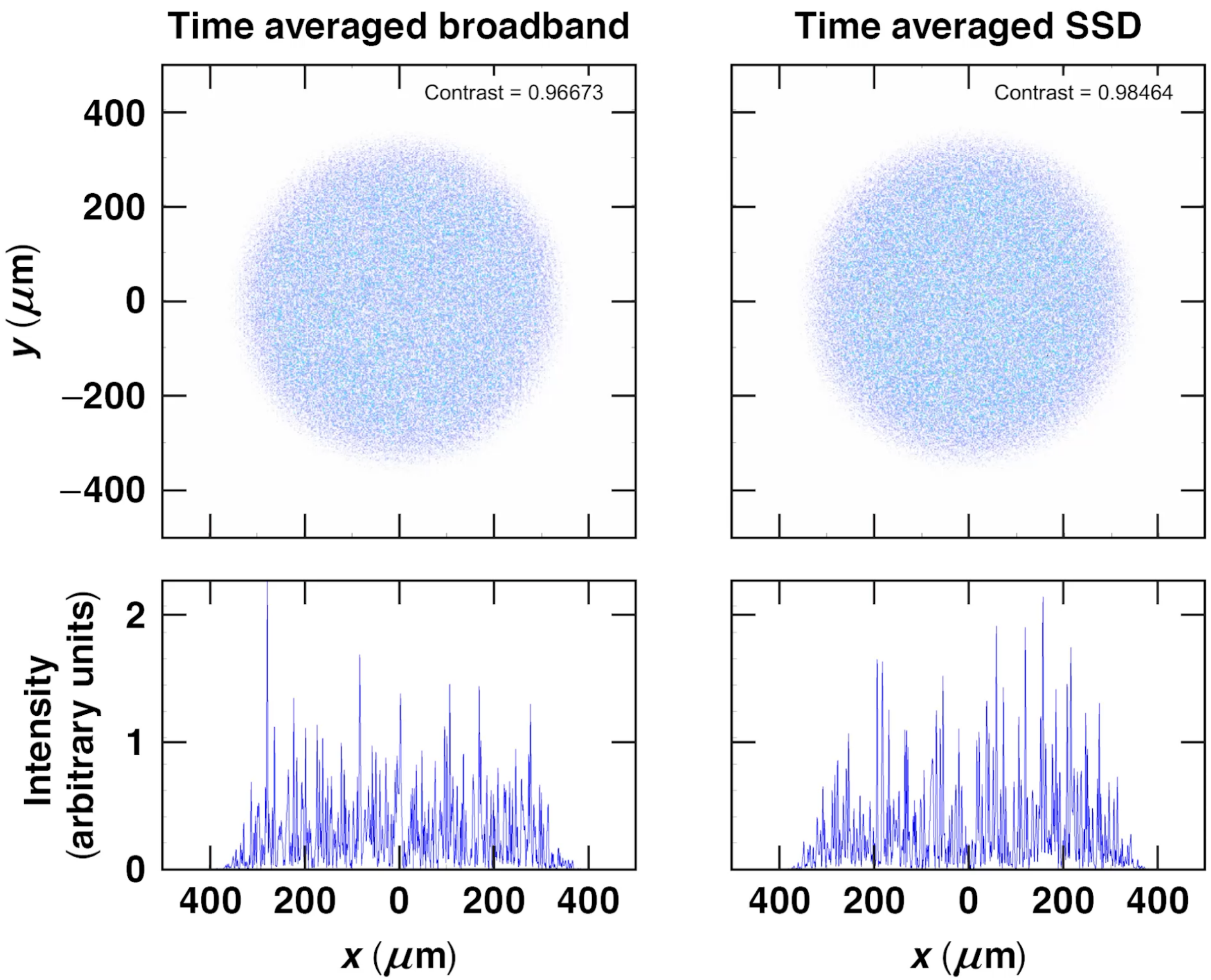
Extra slides

The broad bandwidth of the FLUX laser smooths much faster than typical SSD



1-s runtime = 0.3349 ps simulated

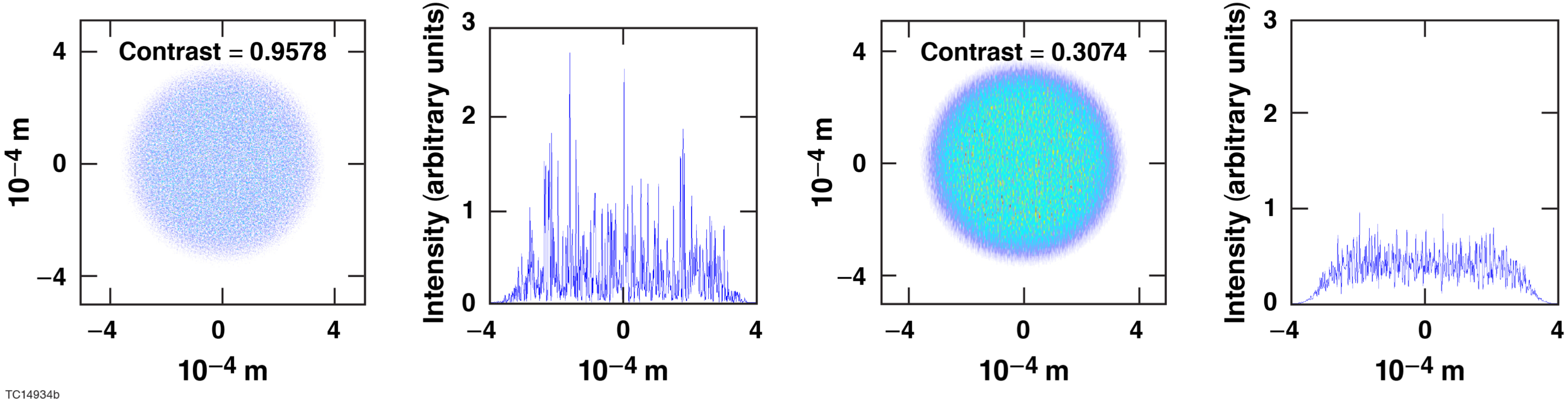
TC15219

Decreasing contrast on a time scale shorter than the hydrodynamic response time can prevent the seeding of hydrodynamic instabilities

- Contrast qualifies the uniformity of the laser profile

$$\text{Contrast} = \frac{\sigma_1}{\langle I \rangle} \qquad \begin{aligned} \sigma_1 &= \text{standard deviation} \\ \langle I \rangle &= \text{average intensity} \end{aligned}$$

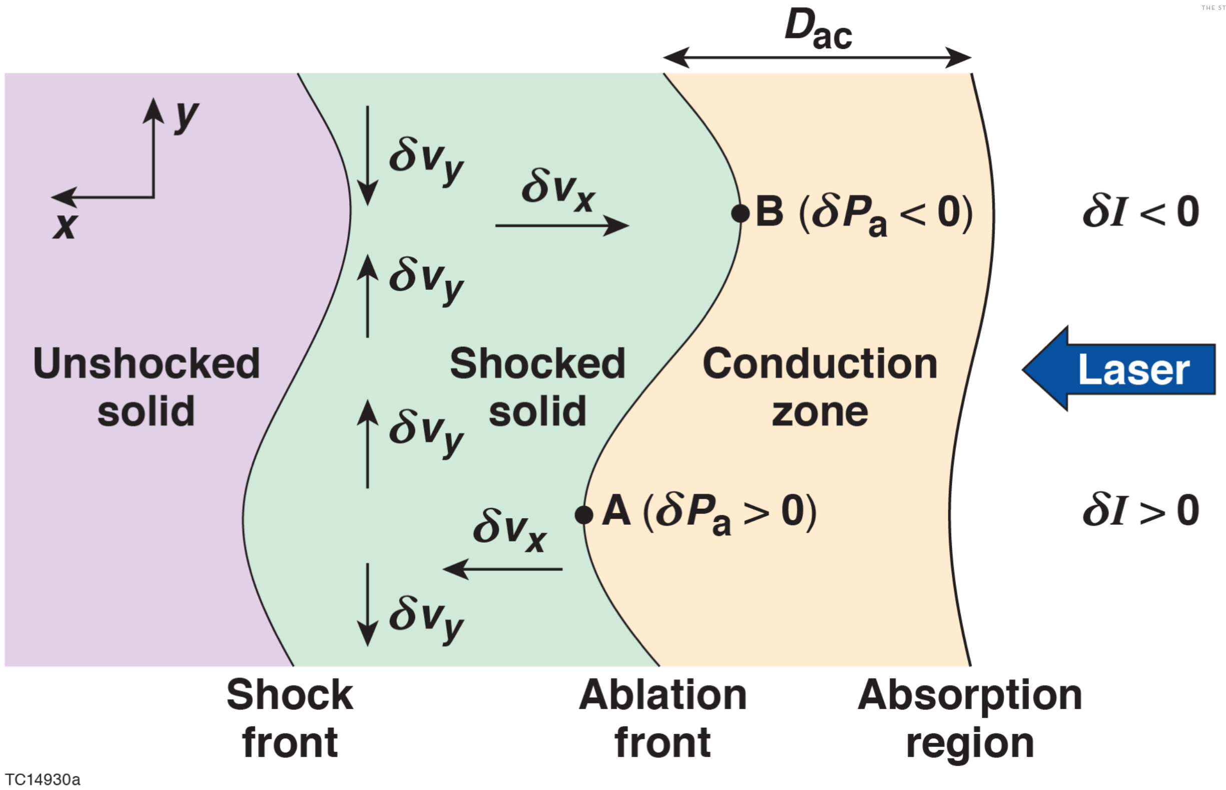
- A smooth beam has a contrast of zero. A higher contrast is indicative of higher relative differences of the laser profile; the faster the contrast is lowered for a beam profile, the faster a beam is smoothed and imprinting is prevented



TC14934b

Perturbations on the laser create a modulated ablation/shock front seeding

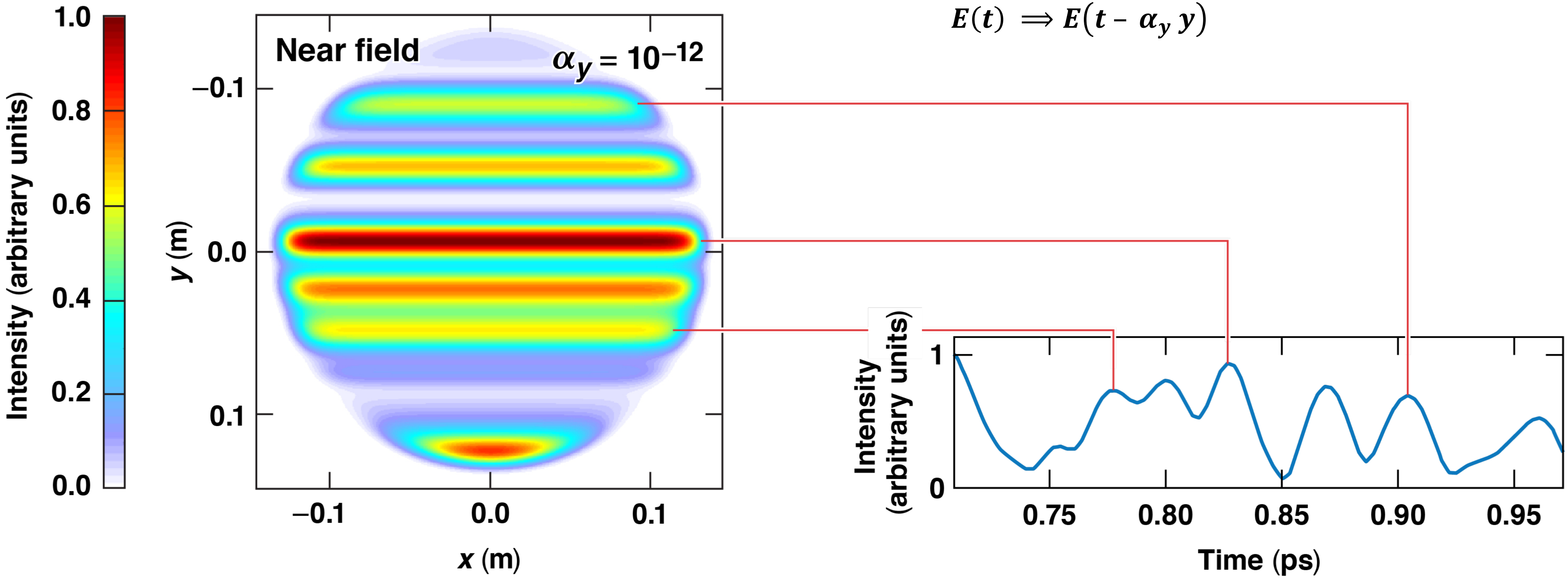
- High-intensity speckles drive higher-pressure shocks, which translates to a variation in sound speed across the shock front
- Pressure deficiencies form behind the fast parts of the shock, while excess pressure builds behind the slow parts
- The resulting transverse pressure gradient causes acceleration modulations that grow the ablation front ripple



R. S. Craxton *et al.*, Phys. Plasmas 22, 110501 (2015).

Angular dispersion leads to a spatially dependent temporal shift

$$\phi = \alpha_y y\,(\omega - \omega_0)$$
$$E(t) \Rightarrow E(t - \alpha_y y)$$



TC14933a