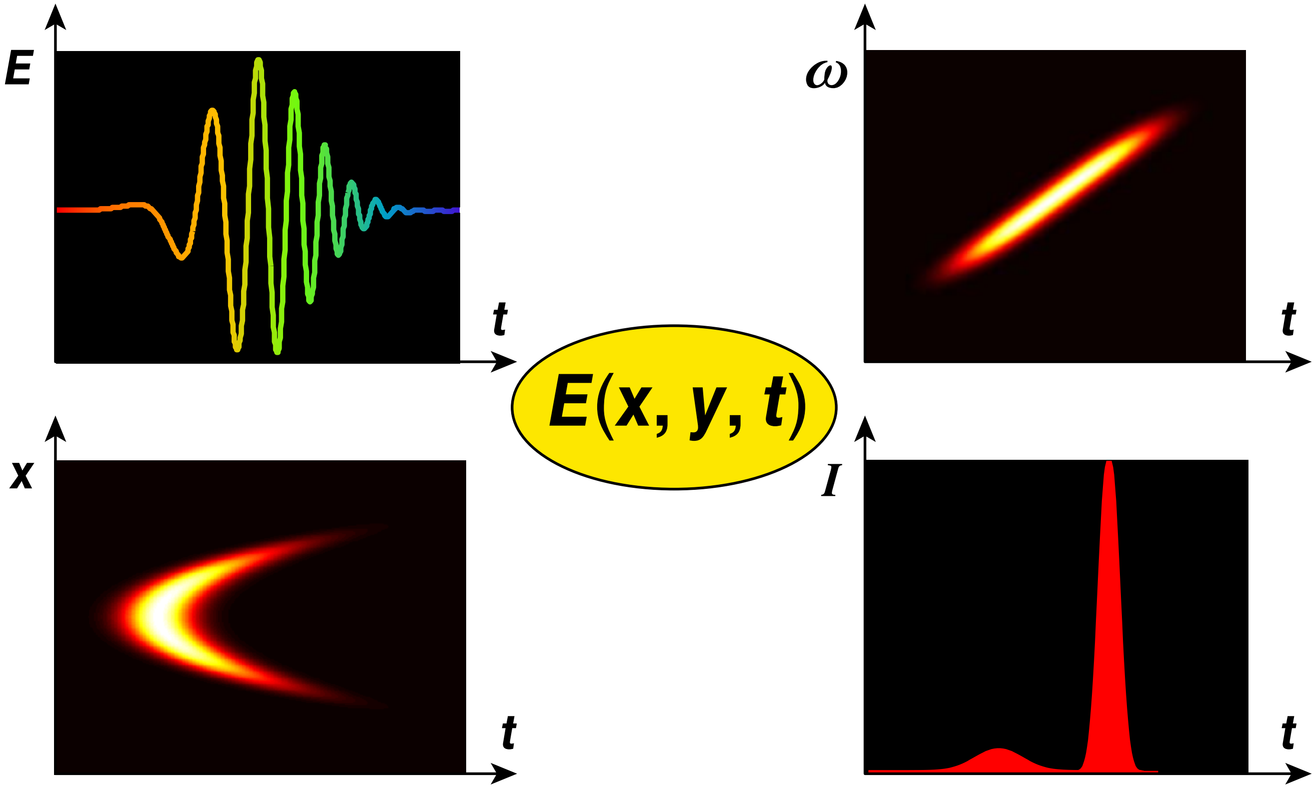
Temporal Characterization Diagnostics for Ultrahigh-Intensity Laser Systems



C. Dorrer
University of Rochester
Laboratory for Laser Energetics

ICUIL Conference
Watkins Glen, NY
26 September – 1 October 2010

Summary

Temporal characterization diagnostics are paramount to the development and operation of high-intensity laser systems

- The temporal characterization of high-intensity laser systems is a multifaceted challenge

- Temporal characterization is required to develop these laser systems and understand target physics
  - measurements of the on-target power/intensity
  - characterization of space–time coupling
  - temporal contrast measurement

- Various concepts and diagnostics for temporal characterization are reviewed

If you cannot measure it, you cannot improve it (Lord Kelvin).

Acknowledgments and references

- Acknowledgments
  - I. A. Walmsley, Oxford University
  - J. Bromage, Laboratory for Laser Energetics
  - C. Haefner, Lawrence Livermore National Laboratory

- References
  - I. A. Walmsley and C. Dorrer, Adv. Opt. Photon. 1, 308 (2009).
  - And 369 references therein

Measuring the electric field $E\ (x, y, t)$ is the goal of optical pulse characterization

- Other physical quantities of interest can equivalently be measured

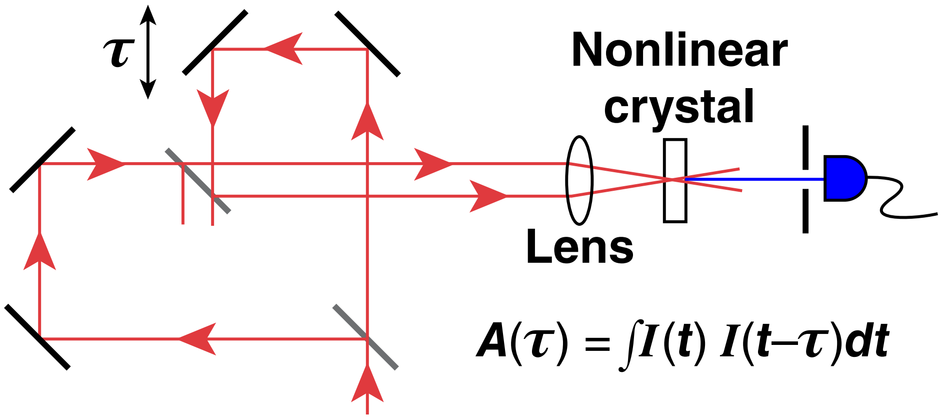
$$\begin{tikzcd}
E\,(x, y, t) \arrow[r, leftrightarrow] \arrow[d, leftrightarrow] \arrow[dr, phantom, "\text{Fourier transforms}"] & \bar{E}\,(k_x, k_y, t) \arrow[d, leftrightarrow, "{(t, \omega)}"] \\
\tilde{E}\,(x, y, \omega) \arrow[r, leftrightarrow, "{(k, x)}"'] & \bar{\tilde{E}}\,(k_x, k_y, \omega)
\end{tikzcd}$$

- In many cases, an “averaged” $E\ (t)$ is measured, which might not be a good description of the pulse interacting with the target
- Measuring $E\ (t)$ requires temporal resolution
  - electronics (fast photodetection or modulation)
  - nonlinear optics

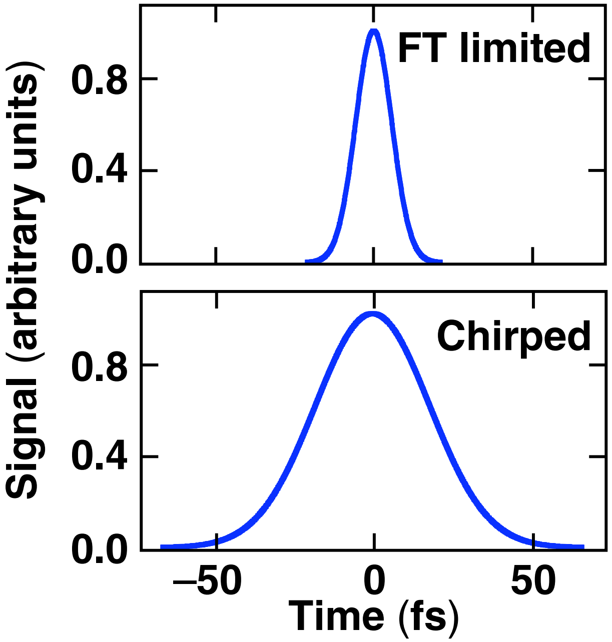
There are many challenges to the temporal characterization of high-intensity laser sources

- The repetition rate is low in some cases, ~1 shot per hour
- The bandwidth can be very wide, ~200 nm for all OPCPA systems at 910 nm
- The pulse can be far from Fourier-transform limited
- Spatial properties can be impaired by architecture and components, making fiber coupling or nonlinear interactions difficult
  - near field: scattering, clipping, grating tiling
  - far field: aberrations (large-scale beamlines, thermal load, large optics)
- Residual space–time coupling might prevent accurate characterization

The second-order autocorrelation only provides indirect temporal information

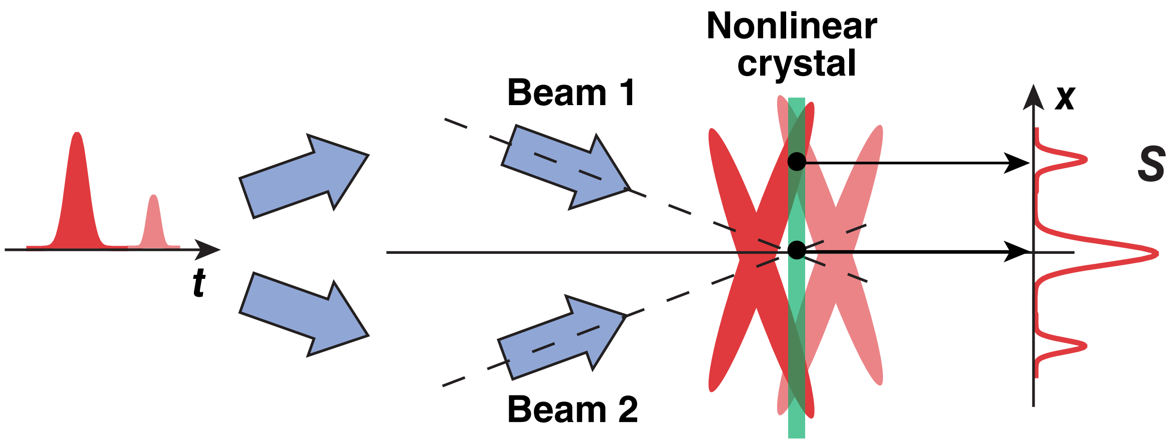


$$A(\tau) = \int I(t)\, I(t-\tau)\,dt$$



- Intensity autocorrelations measure how concentrated the energy is around $t = 0$
- Still the work-horse of temporal diagnostics, even with significant drawbacks
  - symmetric
  - very different pulses might have undistinguishable autocorrelations

Single-shot temporal gating can be obtained with time-to-space encoding



$$S(x) = \int I(t)\, I[t - \tau(x)]\, dt$$

- Noncollinear nonlinear interaction, possibly using pulse-front-tilt from a diffraction grating, leads to time-to-space mapping for single-shot autocorrelators
- Various implementations of this concept
  - time-expanded single-shot autocorrelator (LLE) uses pulse-front-tilt to cover a 50-ps temporal range
  - contrast diagnostics*
  - single-shot SHG-FROG**
- Might be degraded by beam profile and wavefront

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*J. Collier *et al*., Laser Part. Beams 19, 231 (2001), I. Jovanovic, presented at the CLEO/QELS Conference, Baltimore, MD, 6–11 May 2007 (Paper JThD137)

**C. Haefner, this conference (Paper TP2).

The theoretical framework of pulse characterization is well established*

- Techniques measuring *E* (*t*) without assumption require a time-stationary (e.g., a spectrometer) and time-nonstationary (e.g., a nonlinear interaction) element
    - necessary but not sufficient condition
    - autocorrelators only have a time-nonstationary element
- Pulse-characterization strategies classified according to the order and type (phase/amplitude) of the stationary/nonstationary elements
    - eight classes of techniques
    - FROG-like techniques: temporal modulation + spectrometer
    - SPIDER-like techniques: linear temporal phase modulation + spectral interference

There are many pulse-characterization concepts and implementations, but only a few have prevailed in practice.

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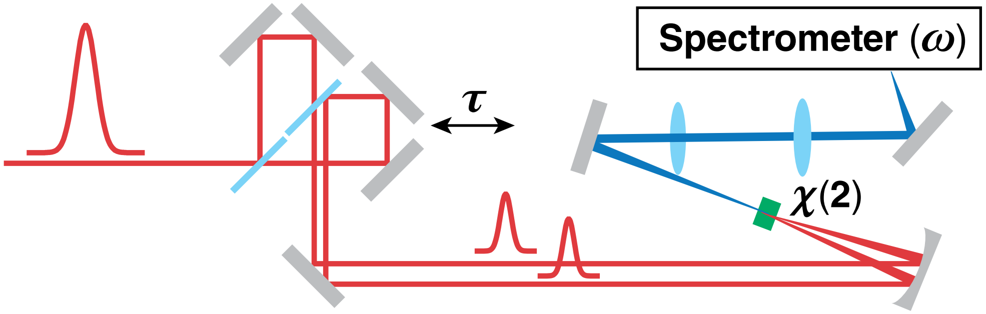
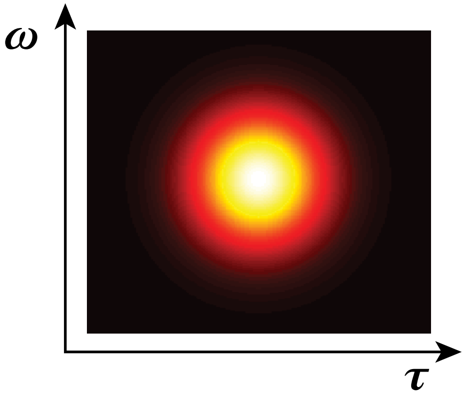
*I. A. Walmsley and V. Wong, J. Opt. Soc. Am. B 13, 2453 (1996).

Frequency-resolved optical gating (FROG) is based on phase retrieval from a nonlinear spectrogram



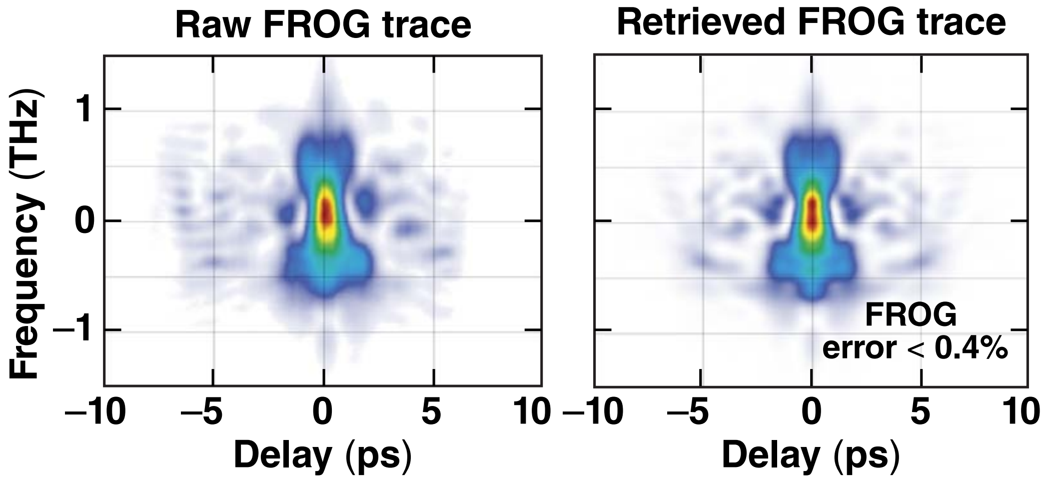


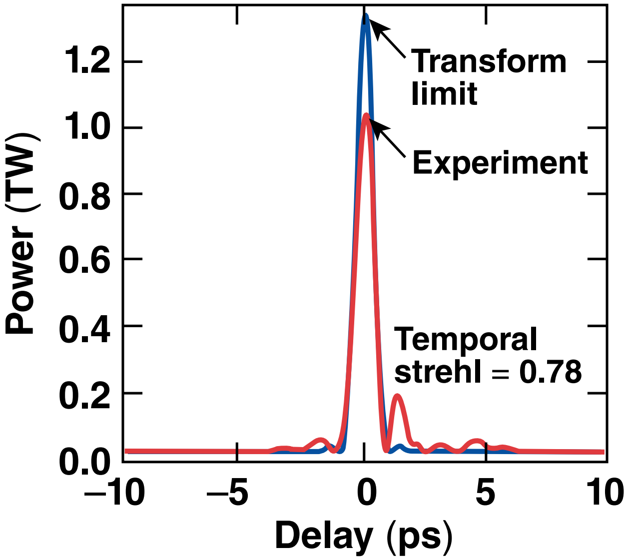
- FROG measures a time-frequency representation of the pulse using a nonlinear interaction

$$S(\omega,\tau) = \left|\int E(t)\, g(t-\tau)\, \exp(i\omega t)\, dt\right|^2 \xrightarrow{\text{Phase-retrieval algorithm}} E(t)$$

- Can be operated in single shot with time-to-space encoding
  - sensitivity to input-beam profile
  - hard to get long temporal range

A single-shot SHG FROG device with large temporal range has been used on the prototype NIF-ARC front end



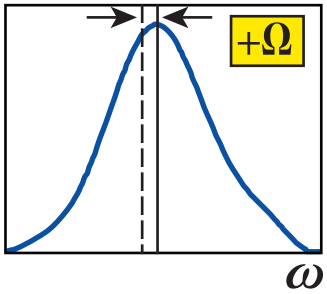
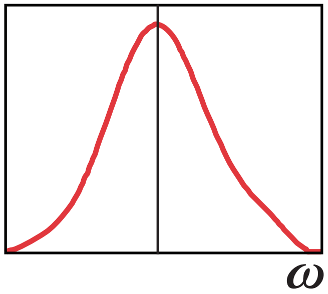
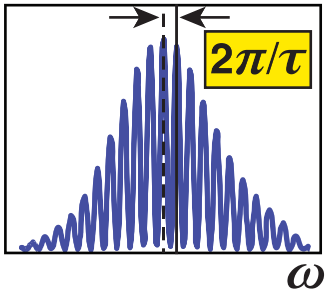
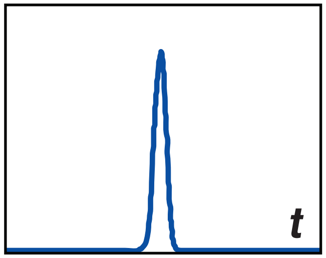
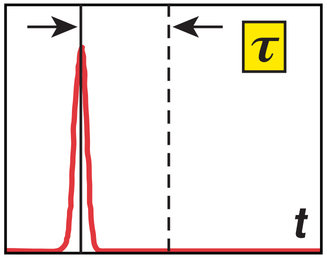
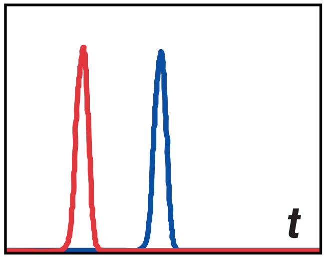


⇨ **Peak power ~1 TW, FWHM = 0.9 ps**

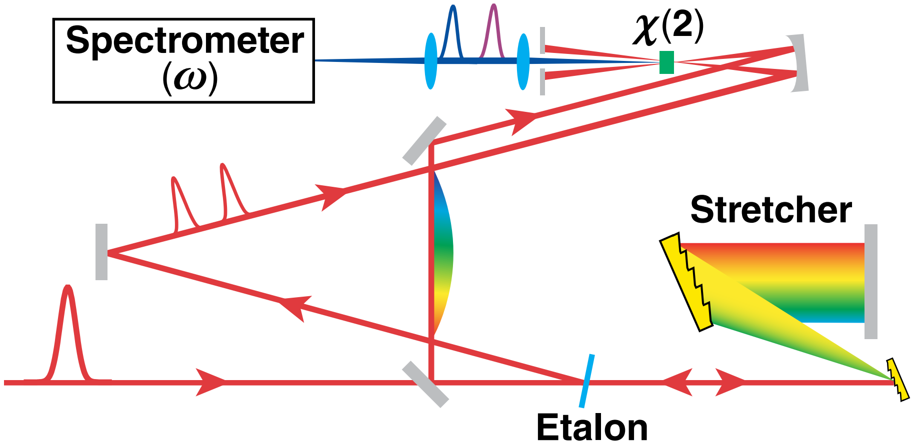
- 20-ps temporal window (up to ~6-ps pulse duration)

Data courtesy of C. Haefner, this conference (Paper TP2).

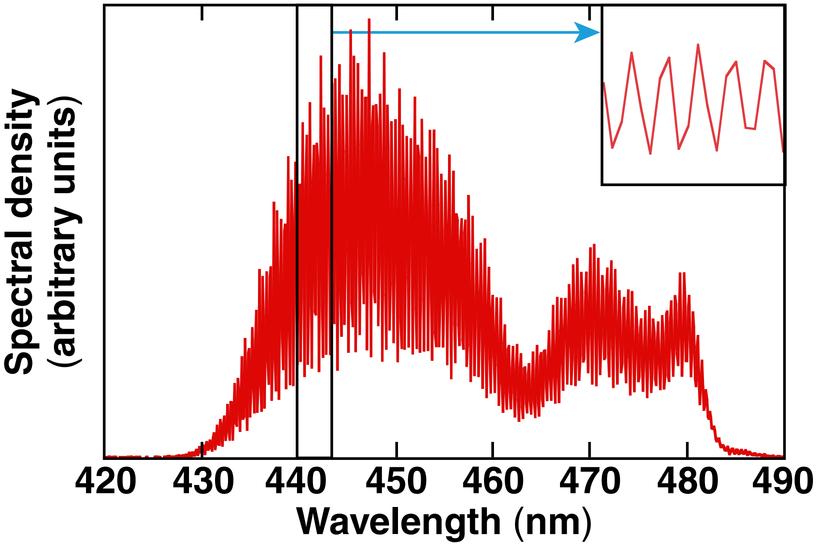
Spectral-shearing interferometry directly measures the spectral phase of the test pulse

	Pulse 1: spectral shift	**Pulse 2: time delay**	**Interference phase**
Spectral field	$\tilde{E}_1(\omega)=\sqrt{\tilde{I}(\omega-\Omega)}\times\exp[i\varphi(\omega-\Omega)]$	$\tilde{E}_2(\omega)=\sqrt{\tilde{I}(\omega)}\exp[i\omega\tau]\times\exp[i\varphi(\omega)]$	$\varphi(\omega)-\varphi(\omega-\Omega)+\omega\tau$ $\Rightarrow$ $\varphi(\omega)$
Spectrum			
Intensity			

SPIDER uses a nonlinear interaction with a chirped pulse to generate a relative spectral shear

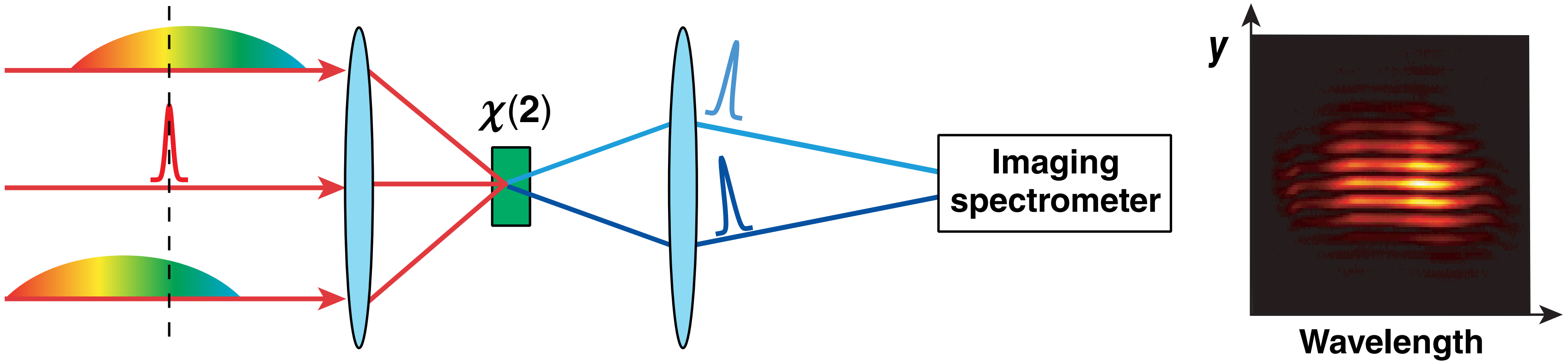


910-nm broadband NOPA characterization



- Spectral shearing using nonlinear optics with a chirped pulse
  - stretched pulse has linear time-to-frequency relation
  - nonlinear interaction of two replicas of the main pulse
  - interferometric signal encoded in spectral fringes
- Variants of SPIDER for very broadband operation
  - encoding of interferometric signal in spatial fringes
  - zero-delay operation

A zero-delay version of SPIDER uses encoding in spatial fringes

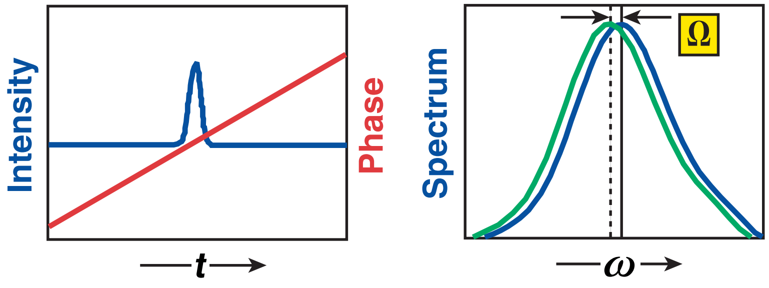


- Two noncollinear chirped pulses interact with a single pulse under test
  - no need to replicate pulse under test
  - simple calibration by setting the delay between chirped pulses to zero

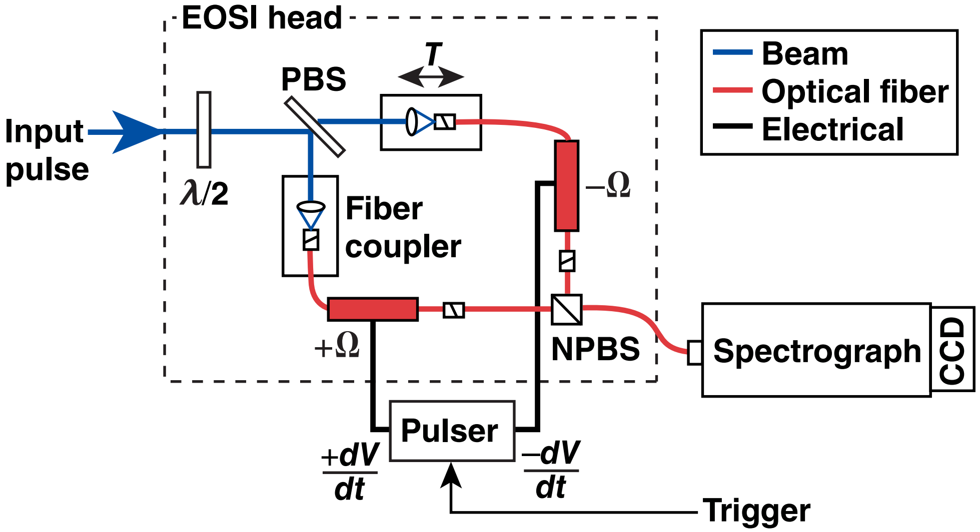
Spatial fringes decrease the spectral-resolution requirement for the spectrometer.

E. M. Kosik *et al.*, Opt. Lett. 30, 326 (2005).
A. S. Wyatt *et al.*, Opt. Lett. 31, 1914 (2006).

Linear electro-optic spectral-shearing interferometry (EOSI) allows for sensitive versatile pulse characterization*



$$E'(t) = E(t)\exp(i\Omega t) \Longleftrightarrow \tilde{E}'(\omega) = \tilde{E}(\omega-\Omega)$$



- Spectral-shear equivalent to linear temporal-phase modulation
- Linear temporal-phase modulation obtained from electro-optic phase modulator driven by linear voltage
  - high single-shot sensitivity (~1 nJ)
  - time window limited by voltage linearity (~100 ps)

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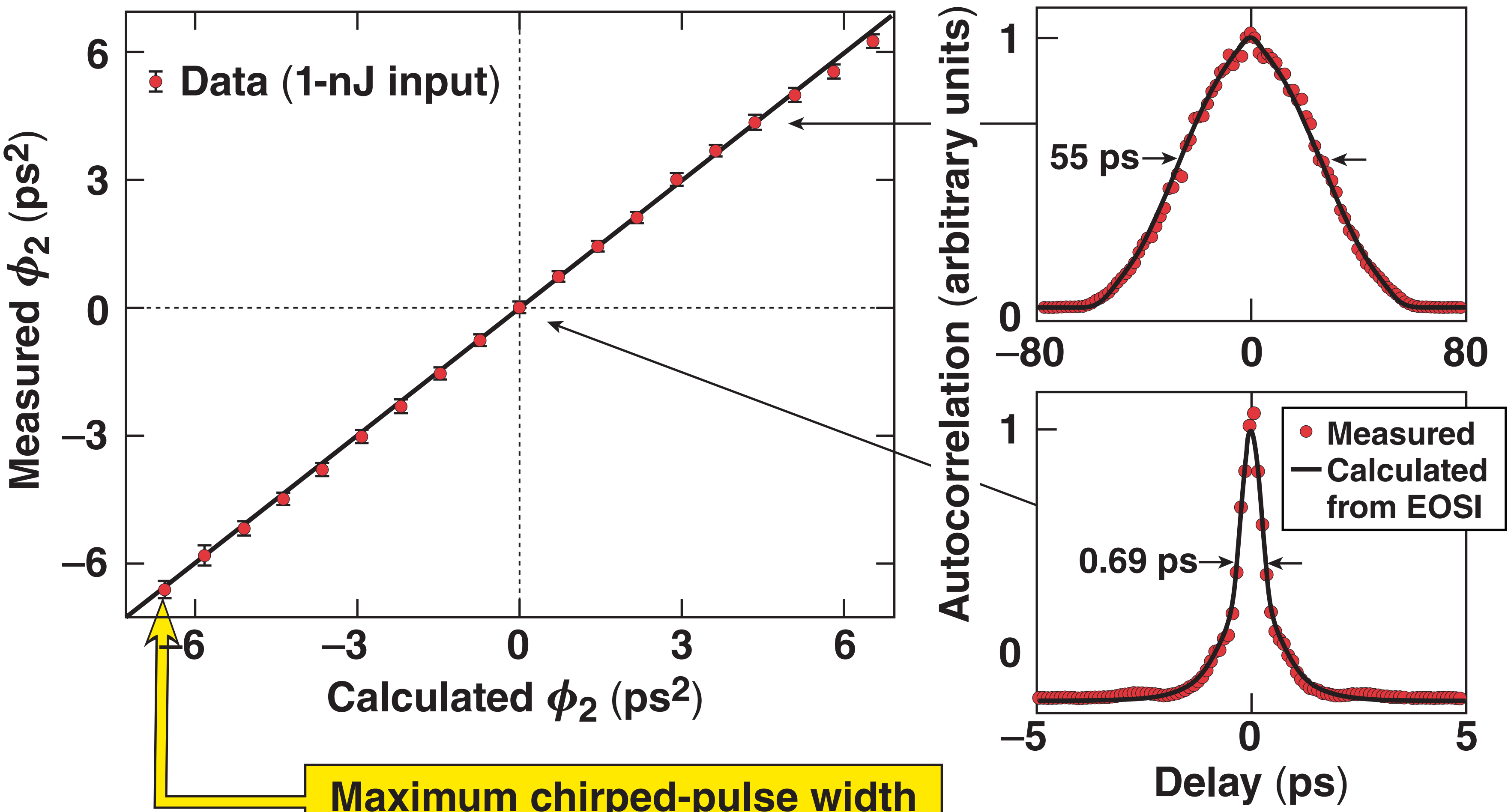
*J. Bromage *et al.*, Opt. Lett. 31, 3523 (2006).

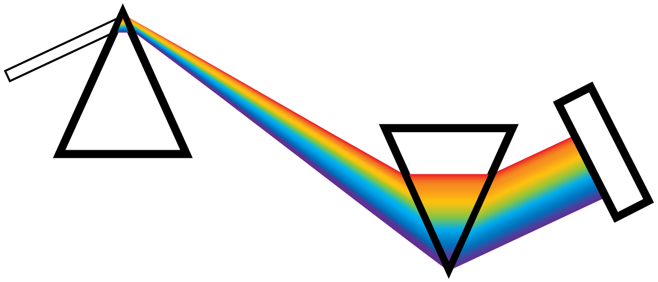
EOSI can characterize pulses with duration over 100× their Fourier-transform limit



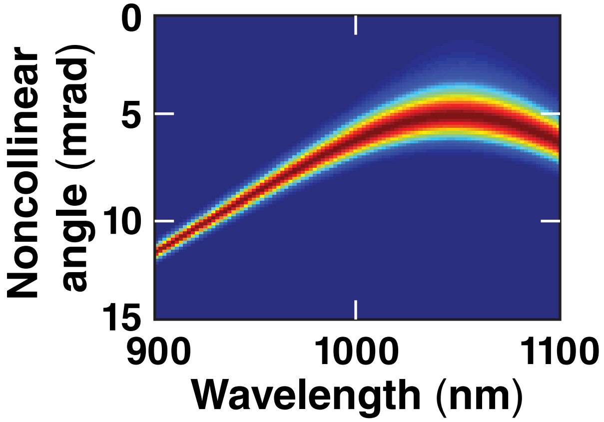
Maximum chirped-pulse width of 85 ps (200× transform limit)

High-intensity lasers rely on components having spectrally varying spatial properties

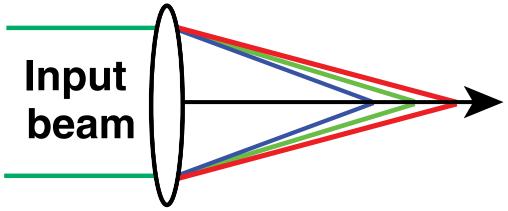
Stretcher/compressor



Parametric gain

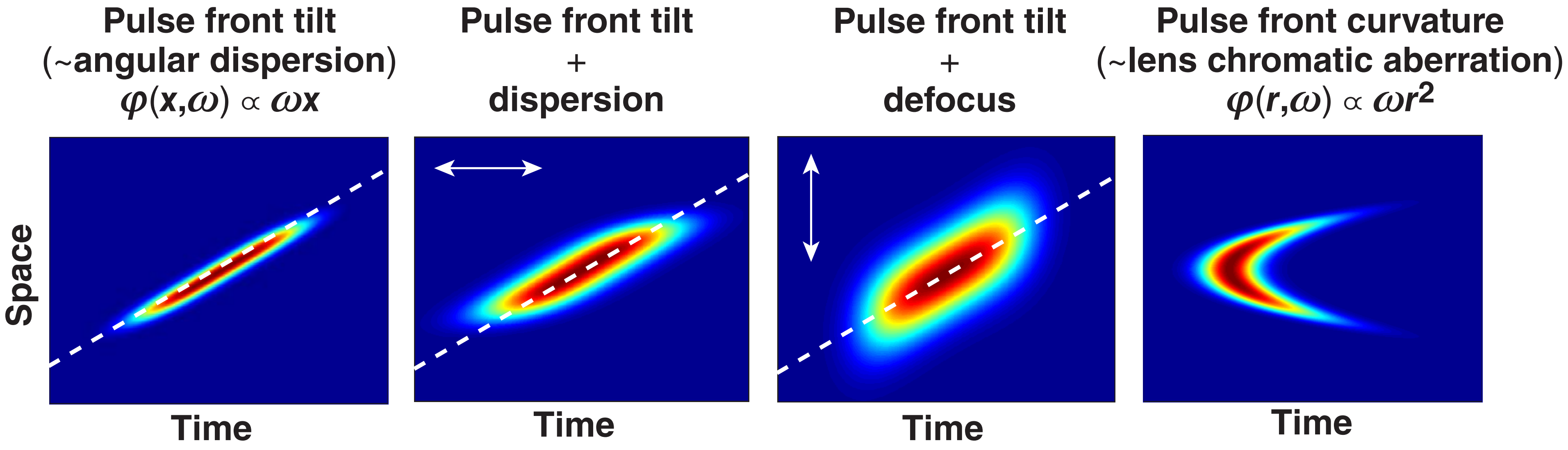


Single lens



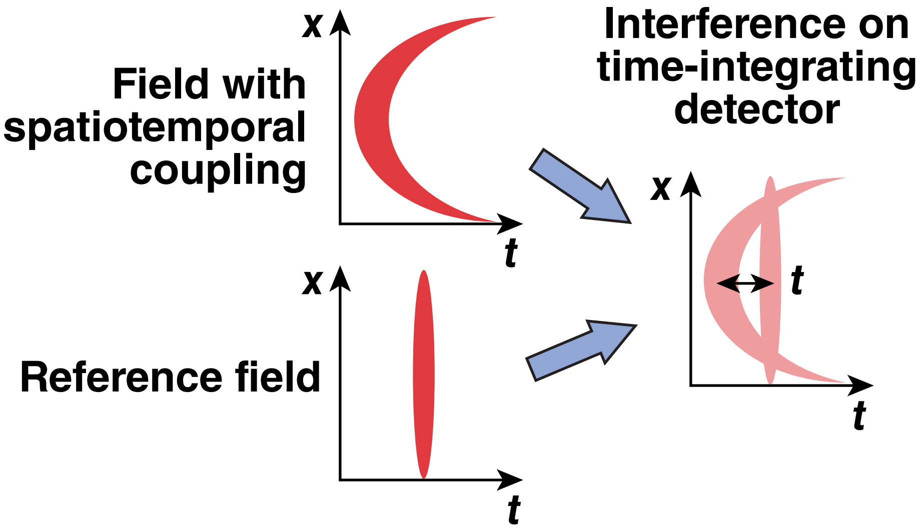
- Measuring the on-shot electric field $E(x,y,t)$ is the ultimate goal, although simpler endeavors have high payoff
  - – independent characterization of individual optical components
  - – characterization with high-repetition-rate low-energy seed source

Space–time coupling can be characterized interferometrically with a reference pulse



- In most cases, the electric field $E(\vec{r}, \omega)$ is measured relative to an unknown space-time-coupling-free reference
- No requirement for
  - dispersion conpensation (ω only)
  - adaptive optics ($\vec{r}$ only)

Spatial variations of the group delay can be mapped out directly with spatially resolved photodetection*

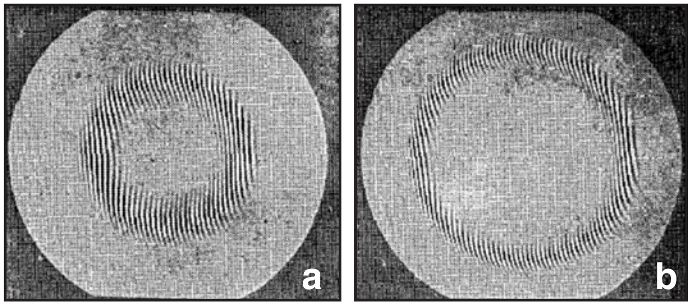


Field with spatiotemporal coupling

Reference field

Interference on time-integrating detector

Interference fringes observed for two different relative delays between the fields*



- Combination of two fields leads to spatial fringes where the relative delay is smaller than the source coherence time
- Spatial group delay in the test field is mapped out by scanning the relative delay
- Extracting higher-order spatiotemporal terms is difficult in the time domain

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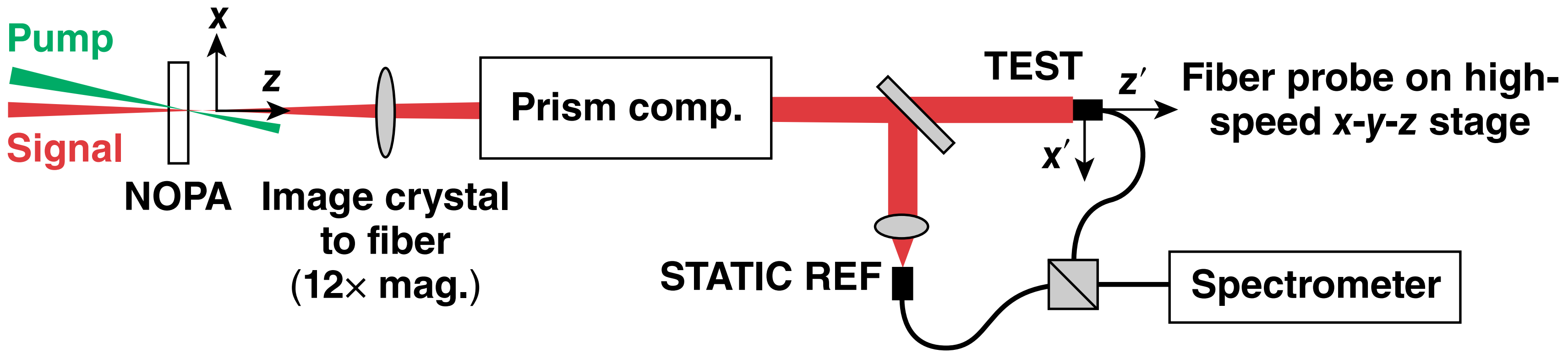
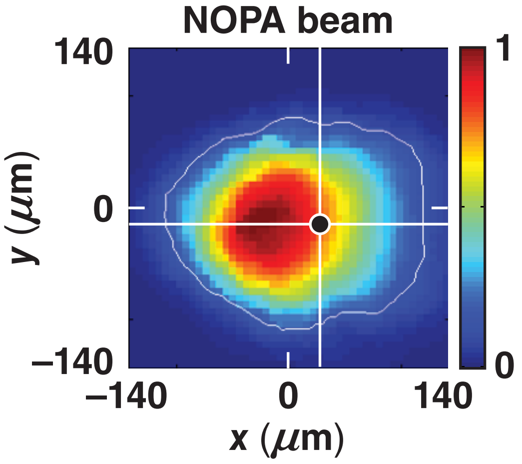
*Z. Bor, Z. Gogolak, and G. Szabo, Opt. Lett. 14, 862 (1989).

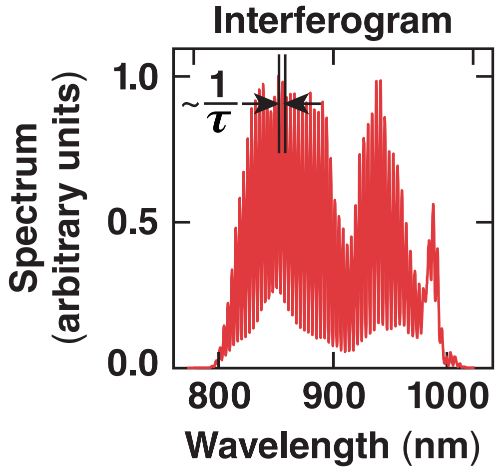
Spectral interferometry with a reference field allows the measurement of spatiotemporal coupling



Pump
Signal
x
z
NOPA
Image crystal to fiber (12× mag.)
Prism comp.
TEST
z′
x′
Fiber probe on high-speed *x-y-z* stage
STATIC REF
Spectrometer



NOPA beam



Interferogram

$$\Phi_{\text{MEAS}}(x,y,\omega)=\phi_{\text{NOPA}}(x,y,\omega)-\phi_{\text{REF}}(\omega)-\omega\tau$$

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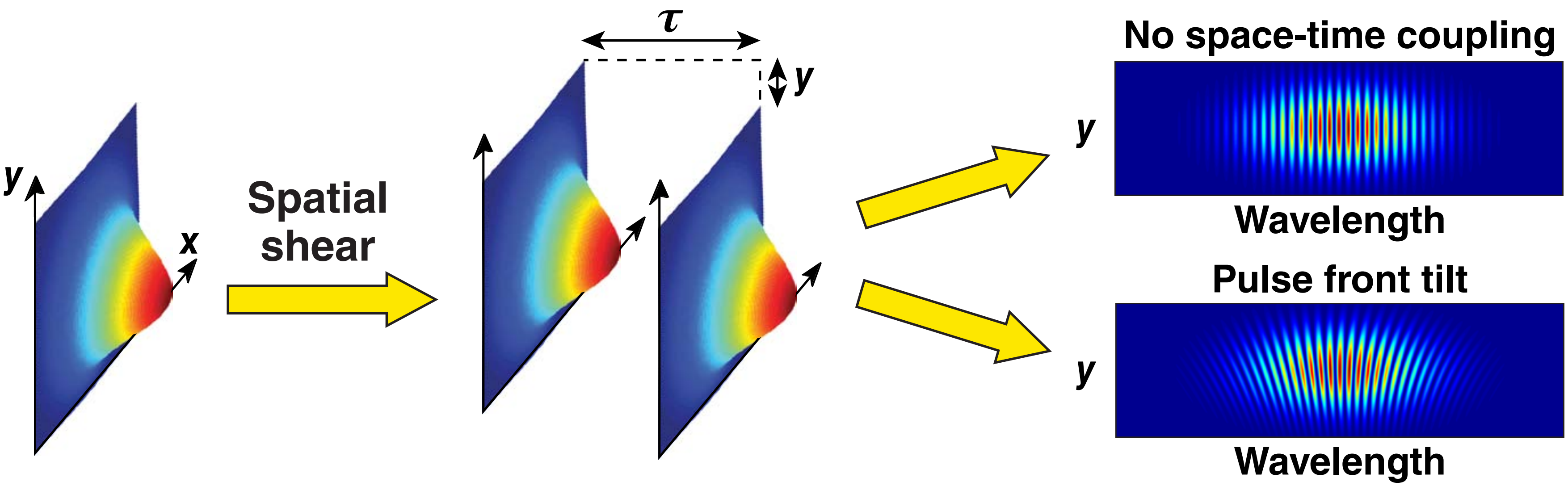
*J. Bromage, C. Dorrer, and J. D. Zuegel, this conference (Paper MO2).
P. Bowlan, P. Gabolde, and R. Trebino, Opt. Express 15, 10,219 (2007).

A spectrally resolved spatial shearing interferometer measures space-time coupling without a reference pulse



- **A spectrally resolved spatial-shearing interferometer measures the spatiospectral phase up to an unknown spectral function**

$$\Delta\varphi(y,\omega) = \varphi(y+Y,\omega) - \varphi(y,\omega) + \omega\tau \quad \Longrightarrow \quad \varphi(y,\omega) + \Gamma(\omega)$$

Delay removal from calibration
Integration along *y* for each ω

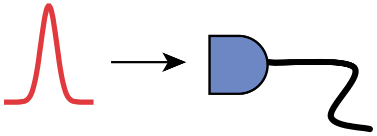
C. Dorrer and I. A. Walmsley, Opt. Lett. 27, 1947 (2002).
C. Rouyer *et al.*, Opt. Express 15, 2019 (2007).

High-dynamic-range measurements are crucial for the development of high-intensity laser sources

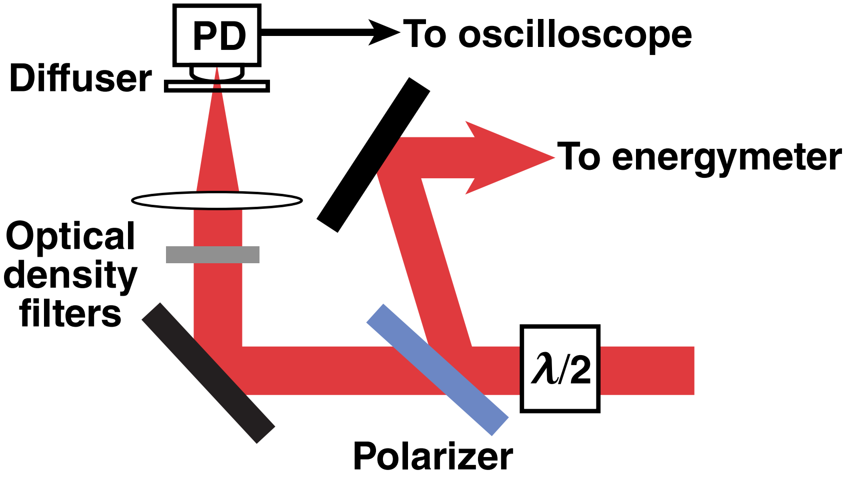
- Coherent and incoherent light before the main pulse can negatively impact the laser–target interaction
  - prepulses from seed laser and regenerative amplifiers
  - laser and parametric fluorescence
  - spectral modulations from stretcher (mostly phase) and from pump noise in OPCPA (mostly amplitude)
  - incomplete pulse recompression and/or sharp spectral clipping
- The dynamic and temporal ranges requirements are beyond the capabilities of conventional pulse-characterization devices
  - dynamic range ~10^{12}
  - temporal range ~1 ns to 1 μs
- Dedicated contrast diagnostics have been developed to achieve these goals

The nanosecond temporal contrast is measured with calibrated fast photodetection

Concept

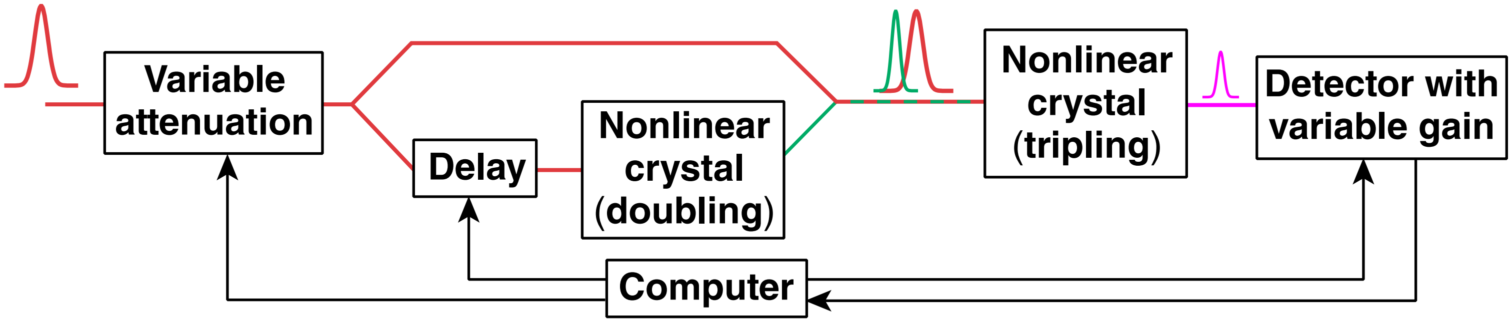


Example of implementation



- Fast photodetection provides long range power measurements with adequate temporal resolution
  - temporal resolution limited by components and detection bandwidth, ~200 ps
  - temporal range set by oscilloscope memory, ~1 μs
  - dynamic range set by photodiode damage threshold

High-resolution contrast measurements use nonlinear optics



- Instantaneous nonlinear response can be used to gate optical pulses
  - generation of high-contrast gating pulse at 2ω by SHG
  - gating of pulse under test at 1ω by 2ω pulse
  - variable attenuation, variable gain, background-free detection at 3ω ensure high dynamic range
  - temporal resolution ~ fraction of input-pulse duration
  - temporal range set by translation stage
- Single-shot implementations have been demonstrated using time-to-space encoding* or pulse replication**

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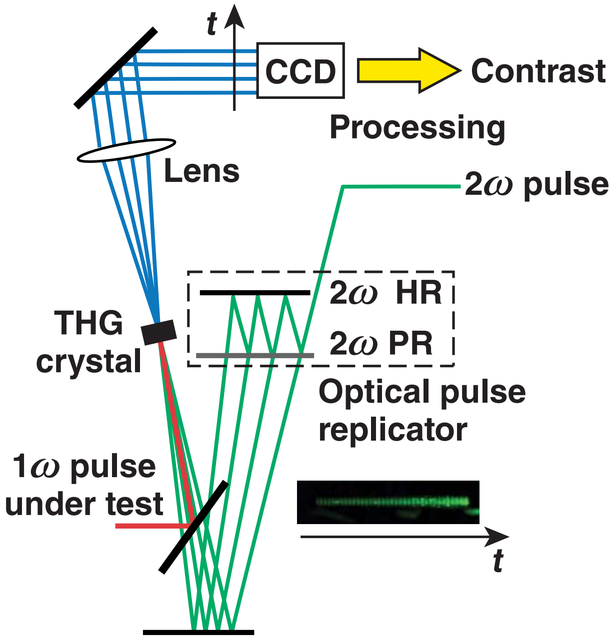
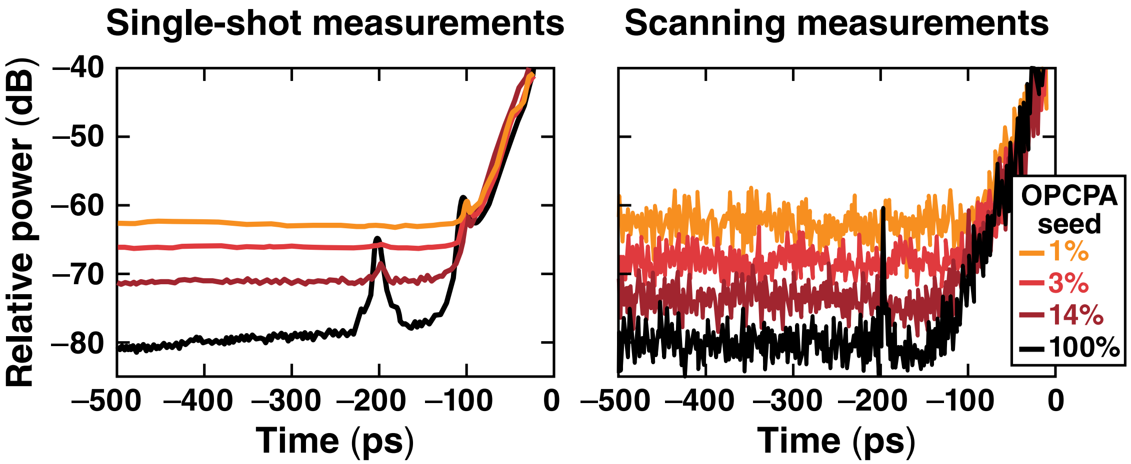
* J. Collier *et al*., Laser Part. Beams 19, 231 (2001), I. Jovanovic *et al*., presented at the CLEO/QELS Conference, Baltimore, MD, 6–11 May 2007 (Paper JThD137).

**C. Dorrer, J. Bromage, and J. D. Zuegel, Opt. Express 16, 13,534 (2008).

Optical-pulse replication allows for single-shot correlation measurements over a large temporal range





- Replication of the 2ω gating pulse is a discrete version of time-to-space encoding
  - sequence of temporally delayed and spatially displaced gating pulses
  - 3ω signal measured with a CCD, with time-to-space calibration
- All gating beams have similar properties, which should decrease the sensitivity of the diagnostic-to-input spatial properties

Summary/Conclusions

Temporal characterization diagnostics are paramount to the development and operation of high-intensity laser systems

- The temporal characterization of high-intensity laser systems is a multifaceted challenge

- Temporal characterization is required to develop these laser systems and understand target physics
  - measurements of the on-target power/intensity
  - characterization of space–time coupling
  - temporal contrast measurement

- Various concepts and diagnostics for temporal characterization are reviewed