Spectral Phase Modulation and chirped pulse amplification in High Gain Harmonic Generation

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- **Optical Compression and and Shaping coherent FEL output**
- **Measuring Spectral Phase**
  - SPIDER technique
  - Application at 266nm for picosecond laser pulses
- **Measurements HGHG**
  - Unchirped, narrow bandwidth
    - Near transform limit
  - Chirping and Compressing

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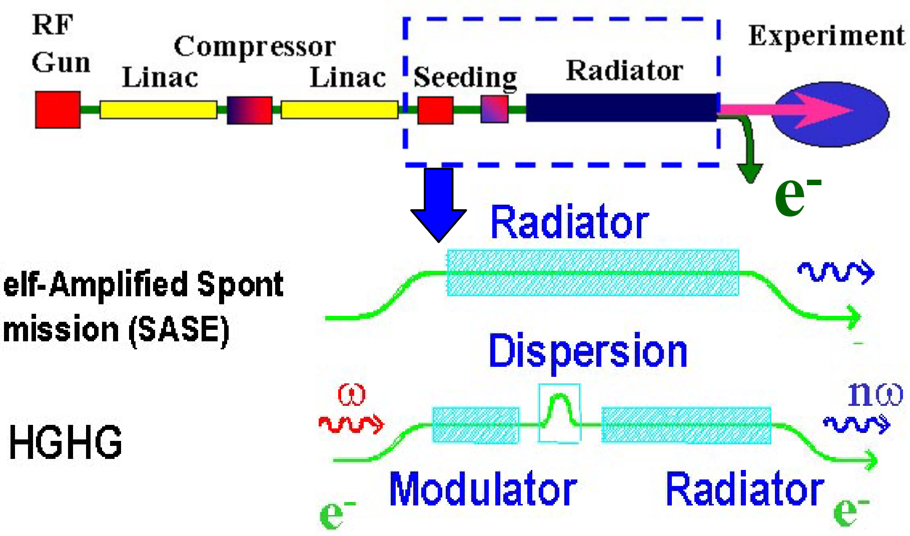
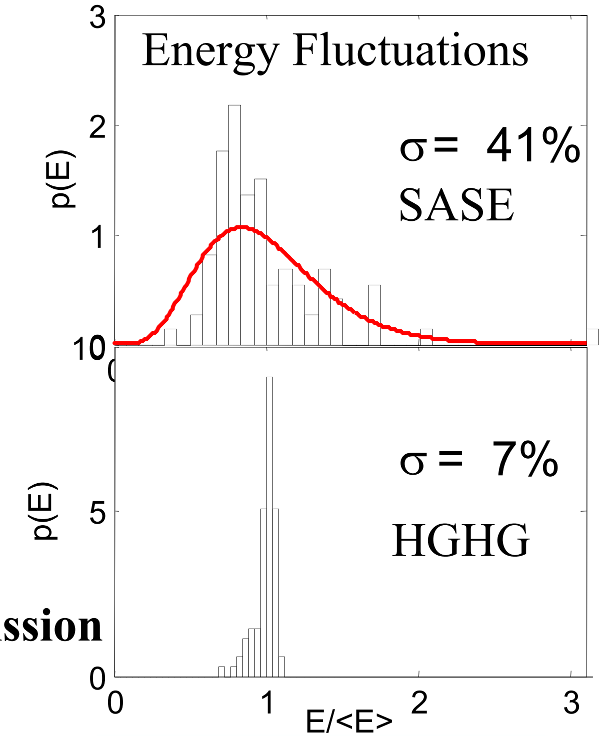
High Gain Harmonic Generation (HGHG)





- **Self amplified Spontaneous Emission (SASE)**

Spontaneous emission ⇨ microbunching ⇦⇨ enhanced emission

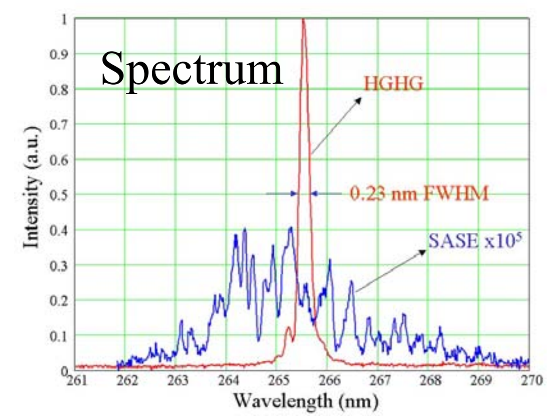
- **Noisy**
- **Broad Bandwidth**
- **Not longitudinally coherent**

- **HGHG**

Seed modulates e^- energy

⇨coherent microbunching ⇦⇨emission

- **Short wavelength : tune radiator to harmonic of seed**
- **Stable**
- **Narrow bandwidth, higher brightness**
- **Longitudinal coherence**



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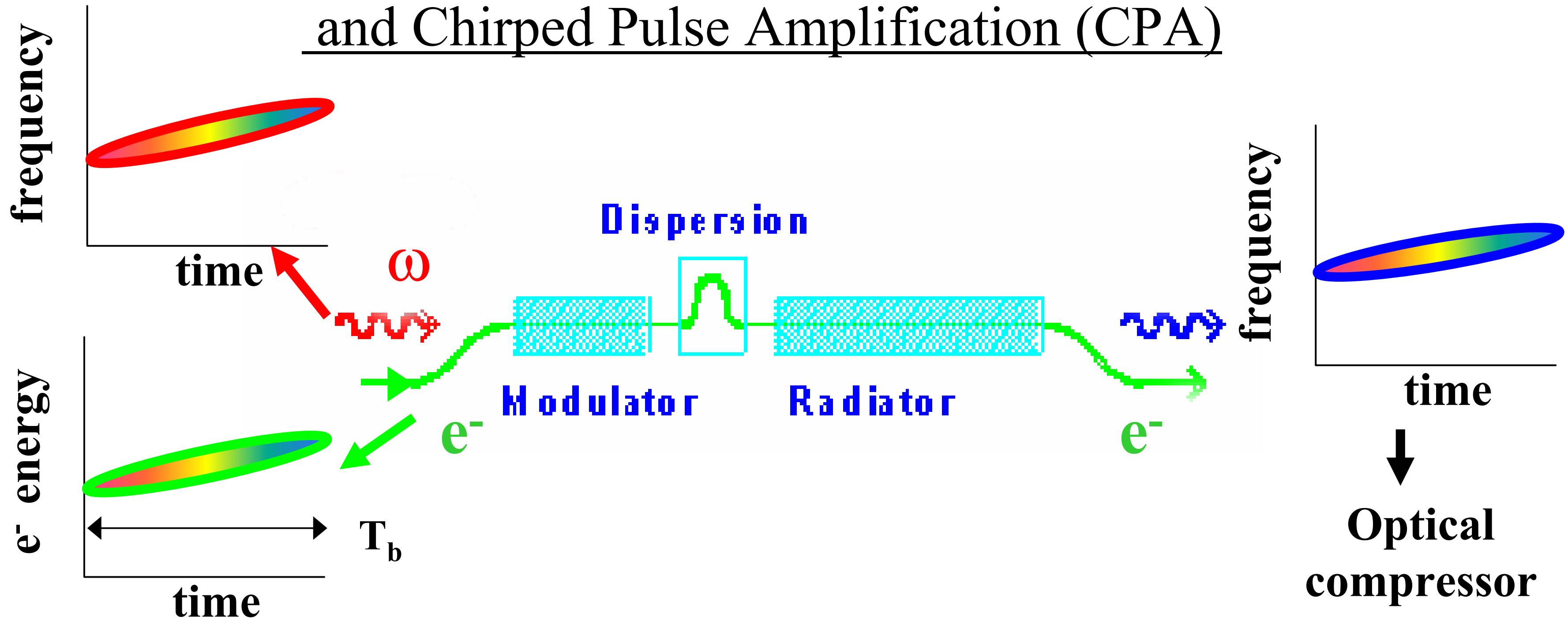
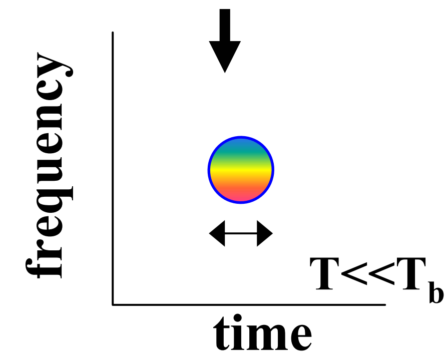
High Gain Harmonic Generation (HGHG) and Chirped Pulse Amplification (CPA)





- Match optical seed chirp to electron energy chirp
  - Resonant frequency in modulator matches seed at each moment in the bunch
- Output pulse is also chirped
  - Longitudinal coherence permits optical compression to transform limit
    - femtosecond pulses
- Sensitive to spectral phase distortion
- Li Hua Yu et al Phys Rev E 49, 4480 (1994)

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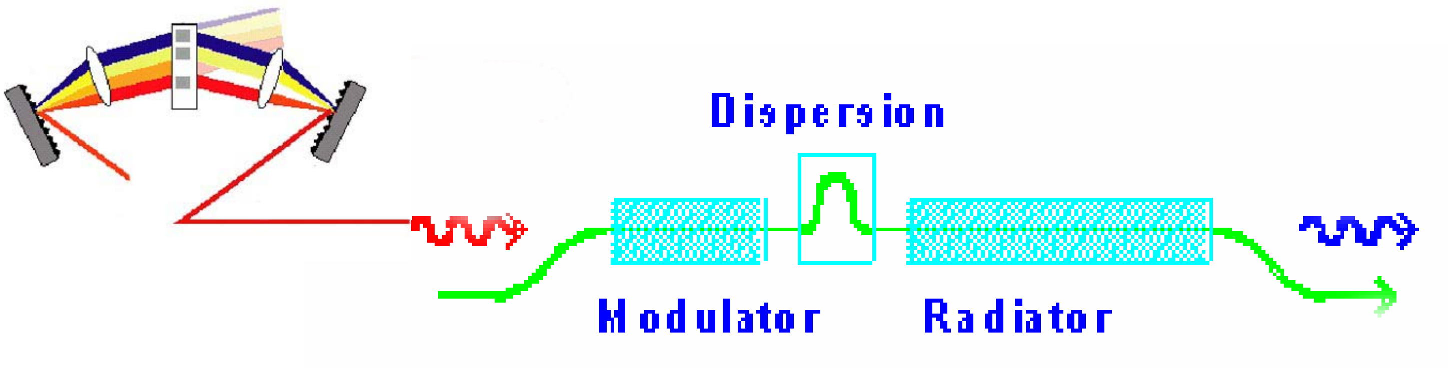
Shaping HGHG



- Coherent control at short wavelengths
- For both chirping and shaping, the question is:

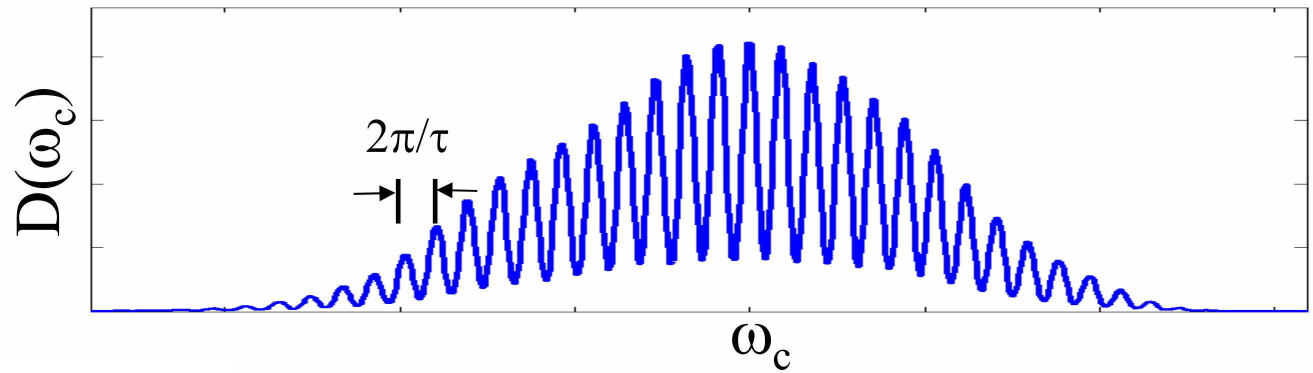
How will phase modulation in the seed transfer to HGHG?

- Can distortions be used as a probe of e^- beam and radiator dynamics

Potential Problems / Interesting Questions

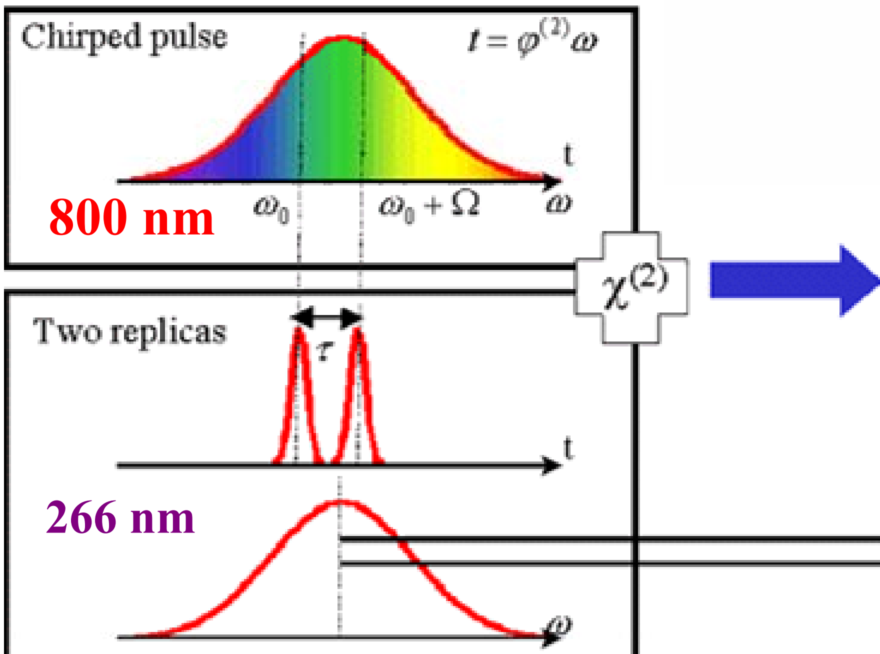
- **synchronization jitter**
- **stability**
- **noise & harmonics**
- **optical field is bipolar, electron density is not.**

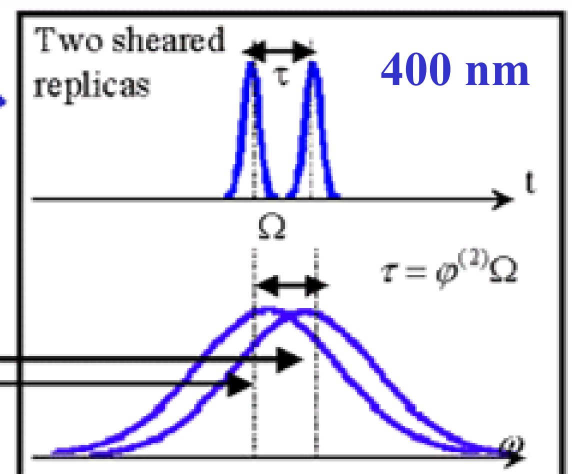
Measuring the spectral phase: SPIDER
(Spectral Interferometry for Direct Electric-Field Reconstruction)



$$D(\omega_c) = |\tilde{E}(\omega_c - \Omega)|^2 + |\tilde{E}(\omega_c)|^2 + 2|\tilde{E}(\omega_c - \Omega)\tilde{E}(\omega_c)| \cos[\phi_\omega(\omega_c - \Omega) - \phi_\omega(\omega_c) - \tau\omega_c].$$

(Walmsley group, Oxford)





C. Iaconis and I. A. Walmsley, **Opt. Lett**. 23, 792–794 (1998).

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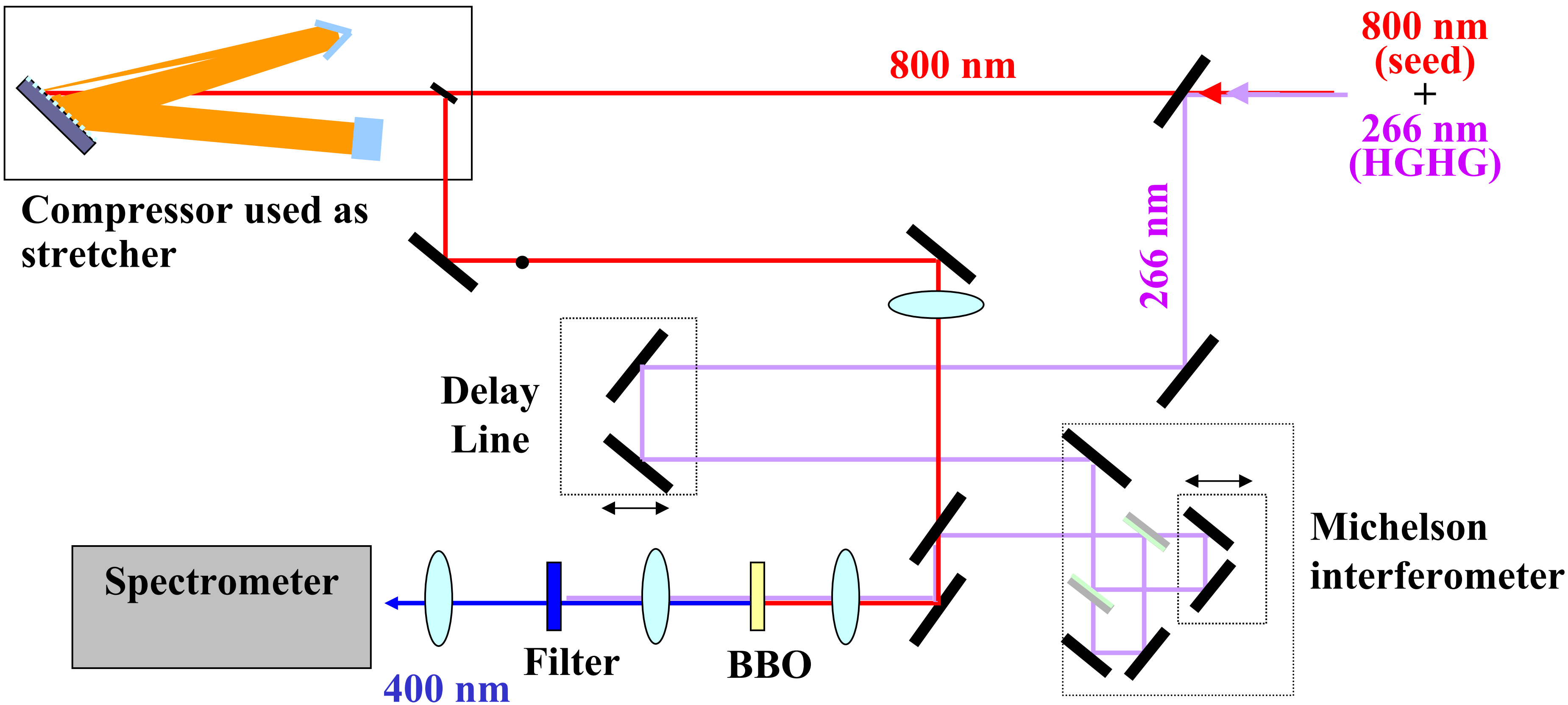
DOWNCONVERSION SPIDER LAYOUT



- Separate seed pulse (800 nm) and HGHG
- stretch seed to 60 psec
- make 2 HGHG pulse replicas in interferometer and separate by τ=3.5 psec
- Downconvert to 400 nm in BBO
- frequency shift is Ω=0.2 THz
- set spectrometer to λ_c=800 nm
- measure 400 nm SPIDER trace in 2nd order
- block seed, remove filter and measure 266 nm calibration trace in 3rd order

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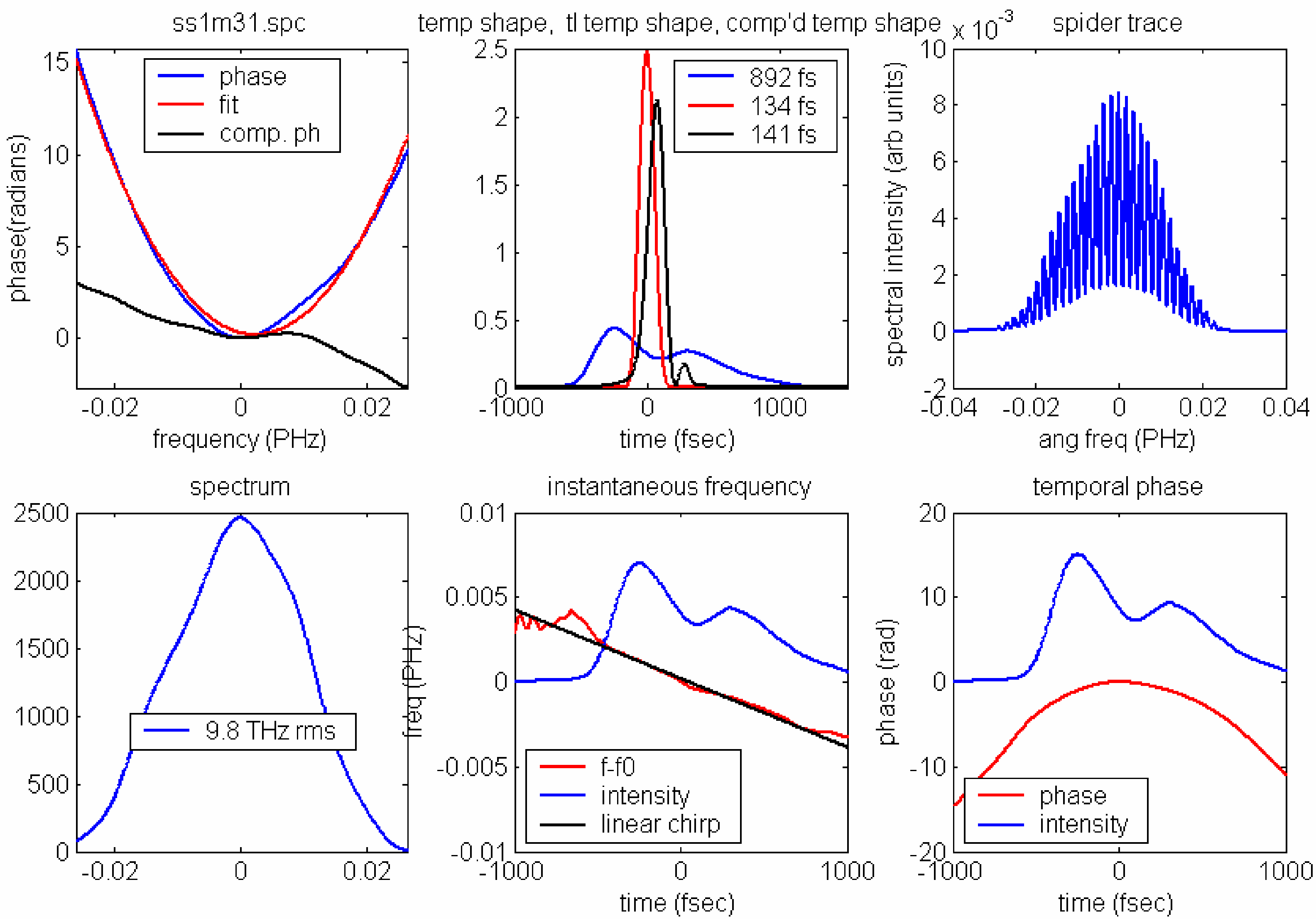

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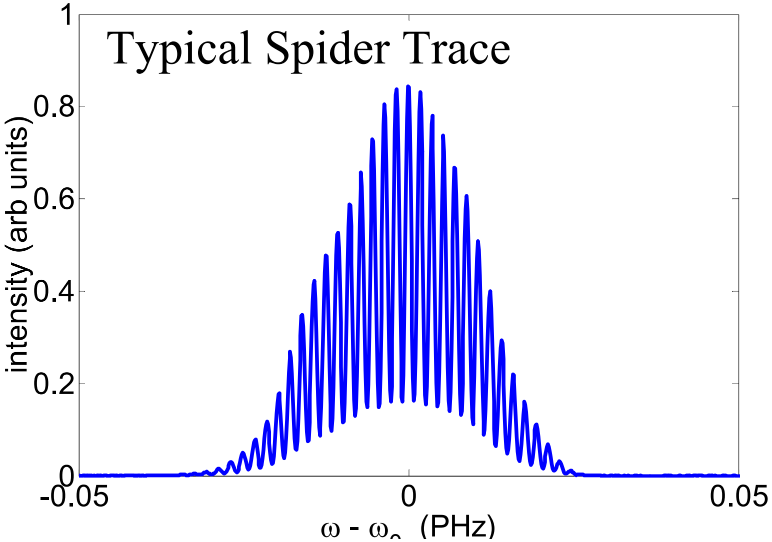
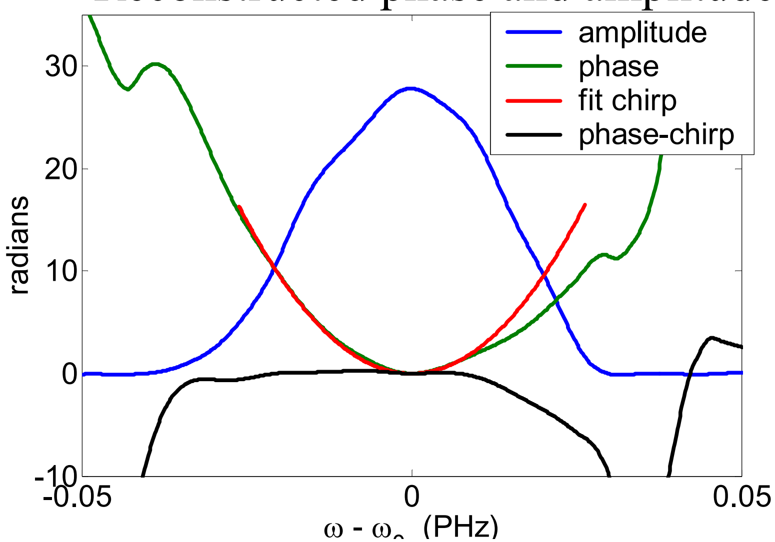
Spidering a laboratory 266 nm source

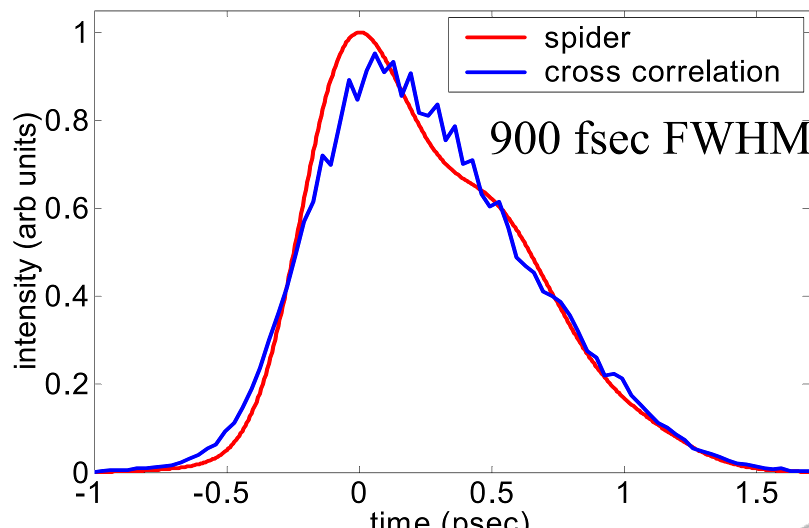


- stretch a 100 femtosecond 800 nm Ti:Sapph chirped-pulse-amplification system
- Frequency-triple in BBO to 266 nm(spoil phase matching to create an asymmetry in the time profile)
- Compare scanning multishot x-correlation of the 266 nm and a short 800 nm pulse with the average reconstruction, convolved with 250 fsec resolution of the x-correlator

Reconstructed phase and amplitude



Comparison with x-correlation



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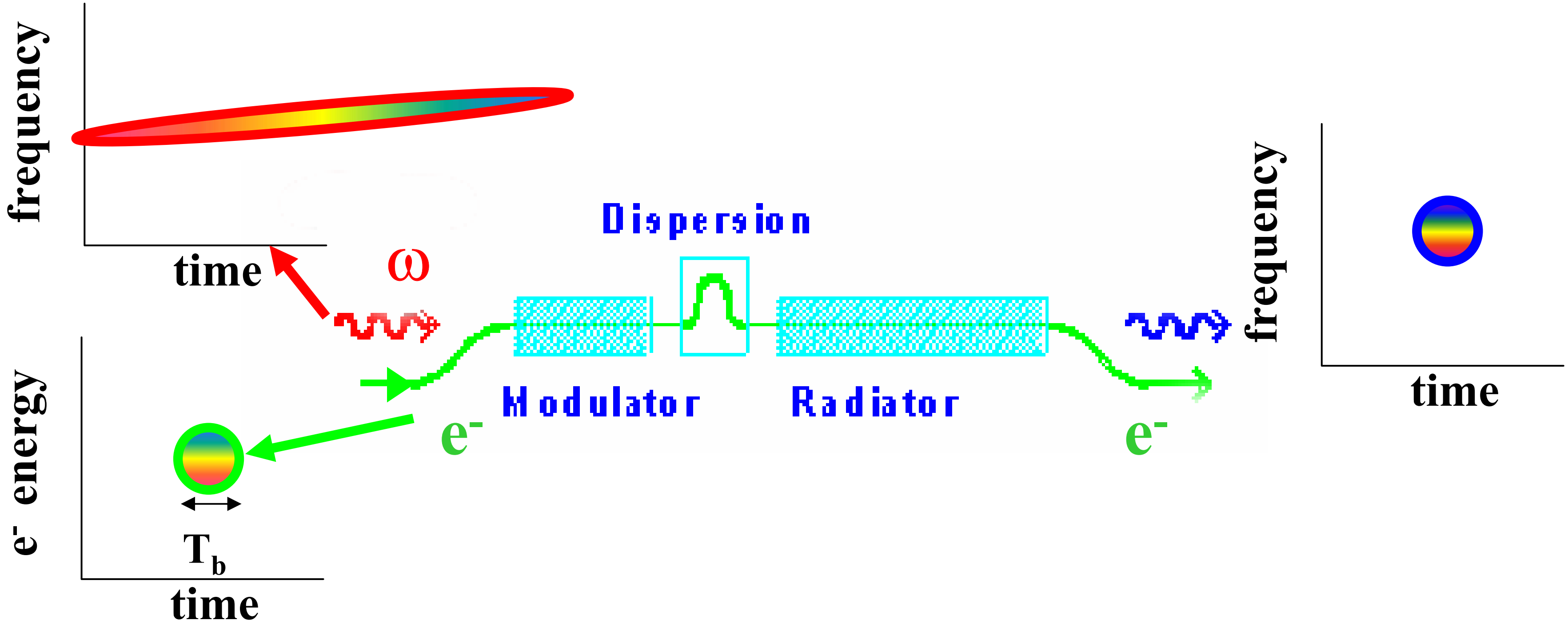
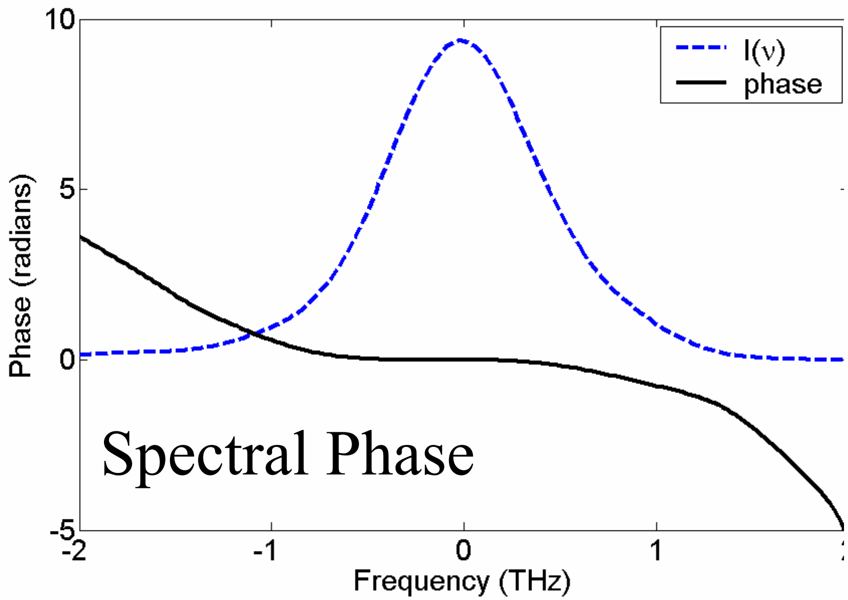
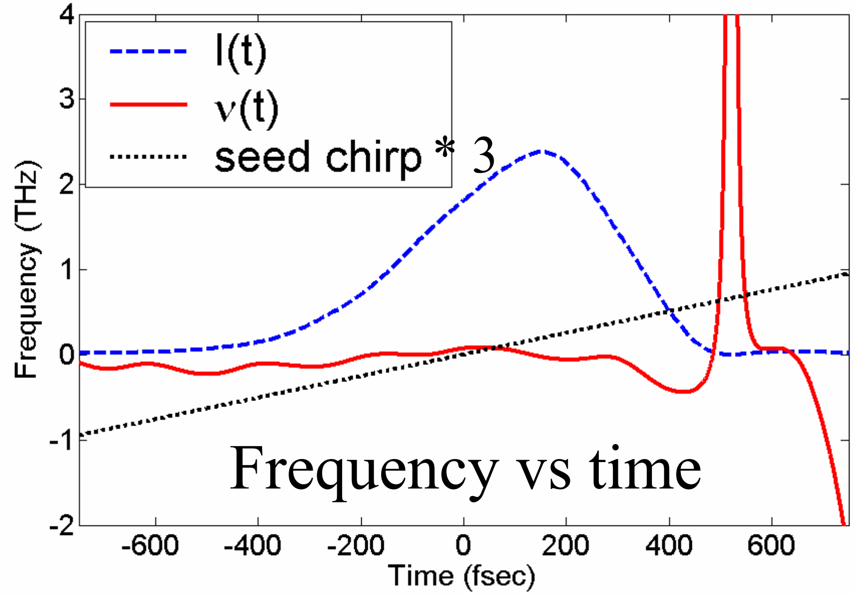
UNCHIRPED HGHG

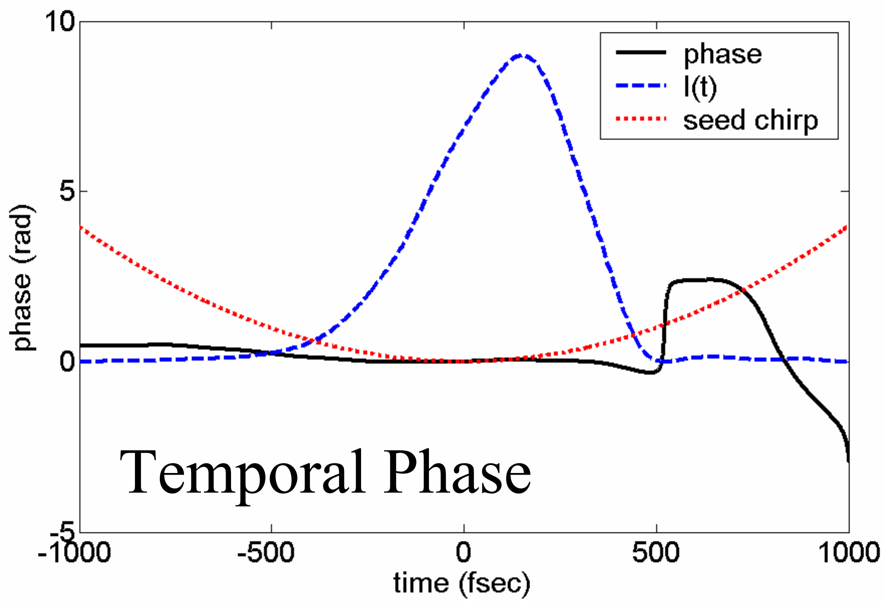


- Stretch seed to 6 psec
- optimize compression / minimize e$^-$ energy chirp
- minimize output bandwidth

UNCHIRPED HGHG







- flat phase across the pulse
- residual seed chirp not visible
- frequency vs time constant

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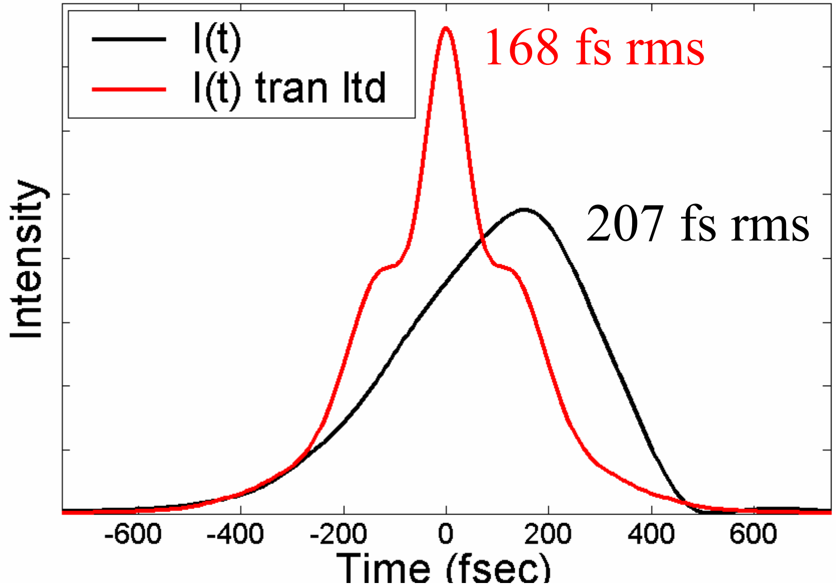
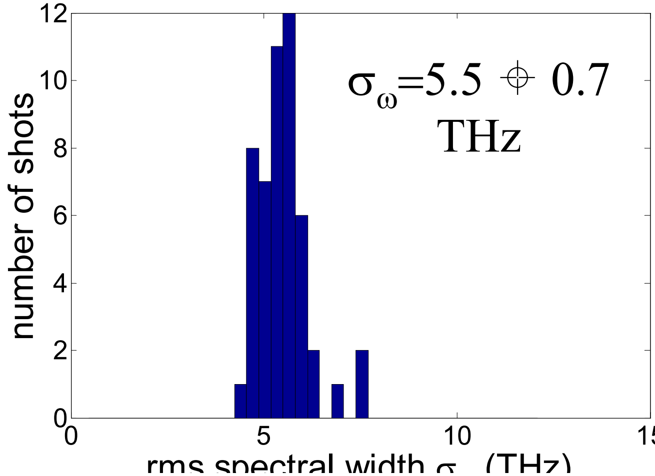
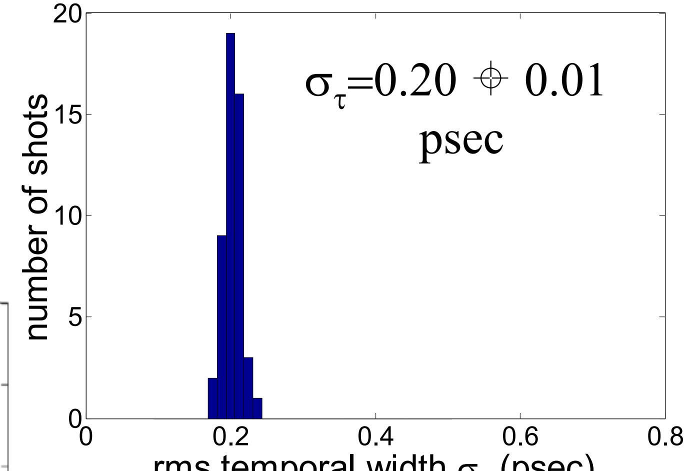
UNCHIRPED HGHG



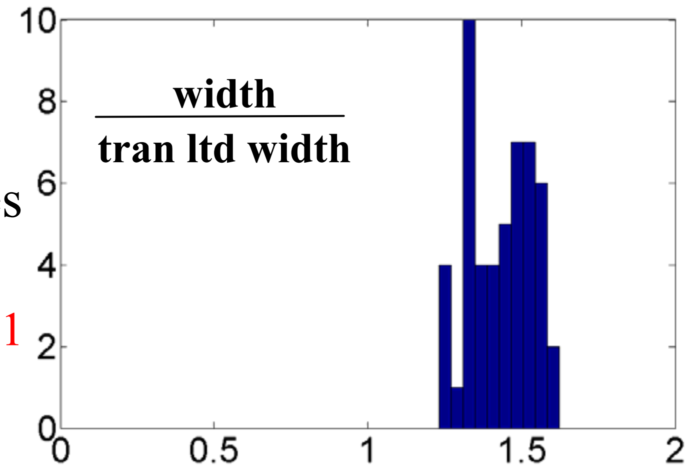
50 shots





- $\sigma_\omega\sigma_\tau$ = 1.1, twice transform limit for a Gaussian pulse
- FWHM = 440 ⊕ 80 fsec
- pulses are not Gaussian

- Define transform limit as the pulse when spectral phases are set to zero.
- pulses are 1.4 ⊕ 0.1 times transform limit



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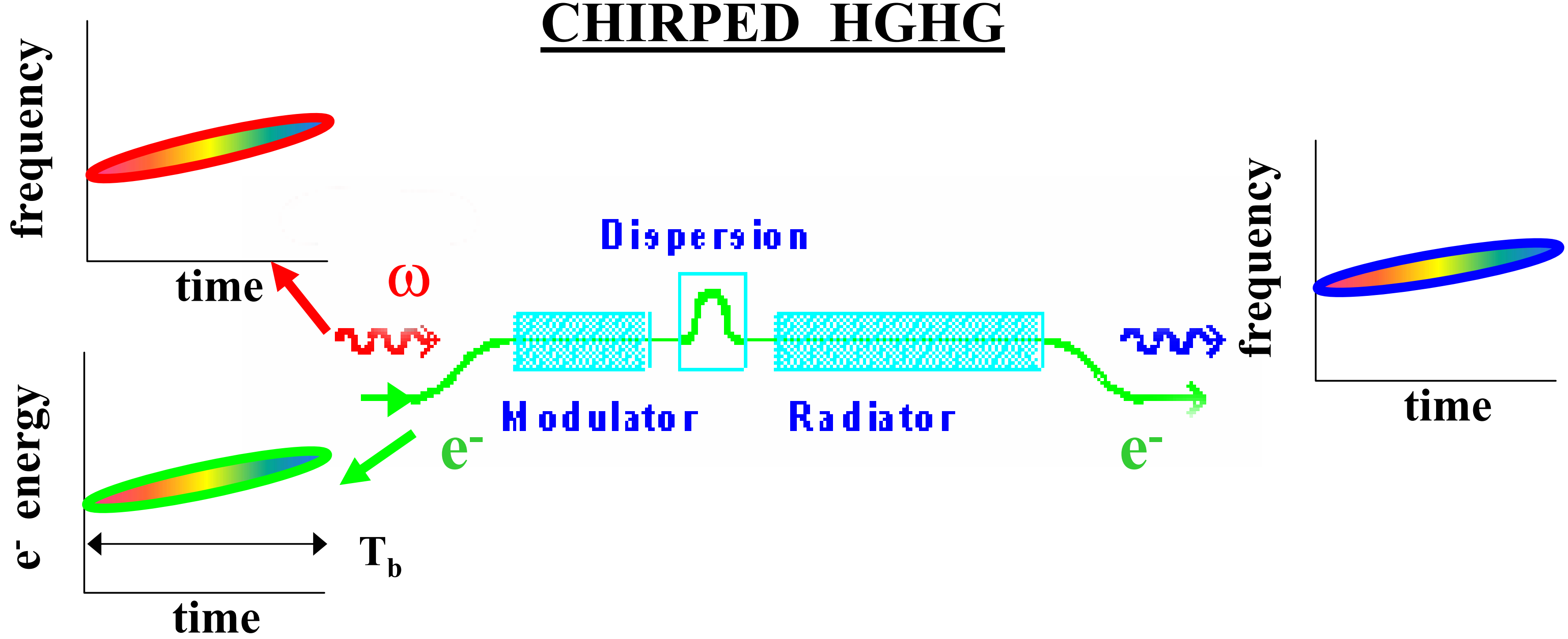
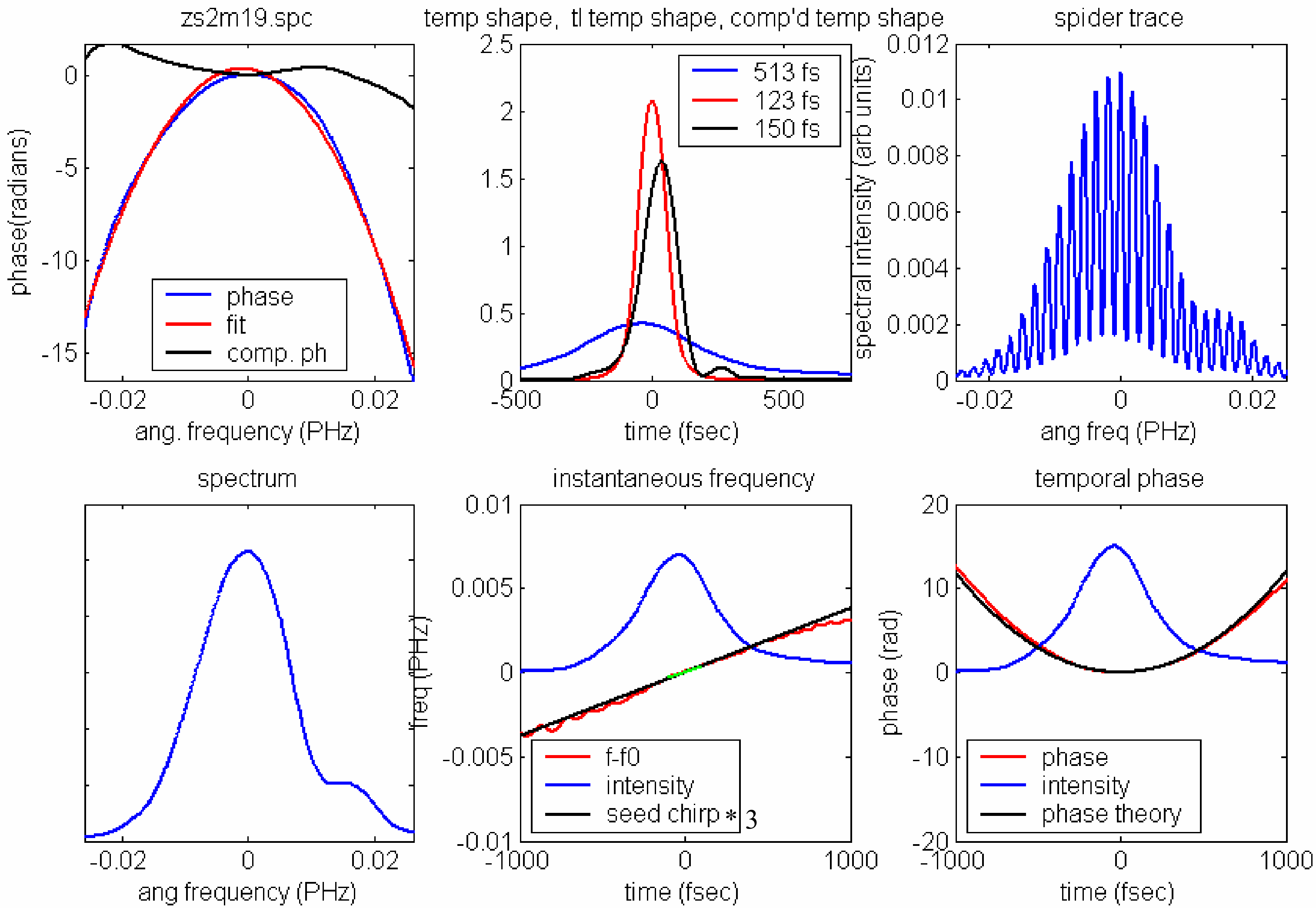
CHIRPED HGHG



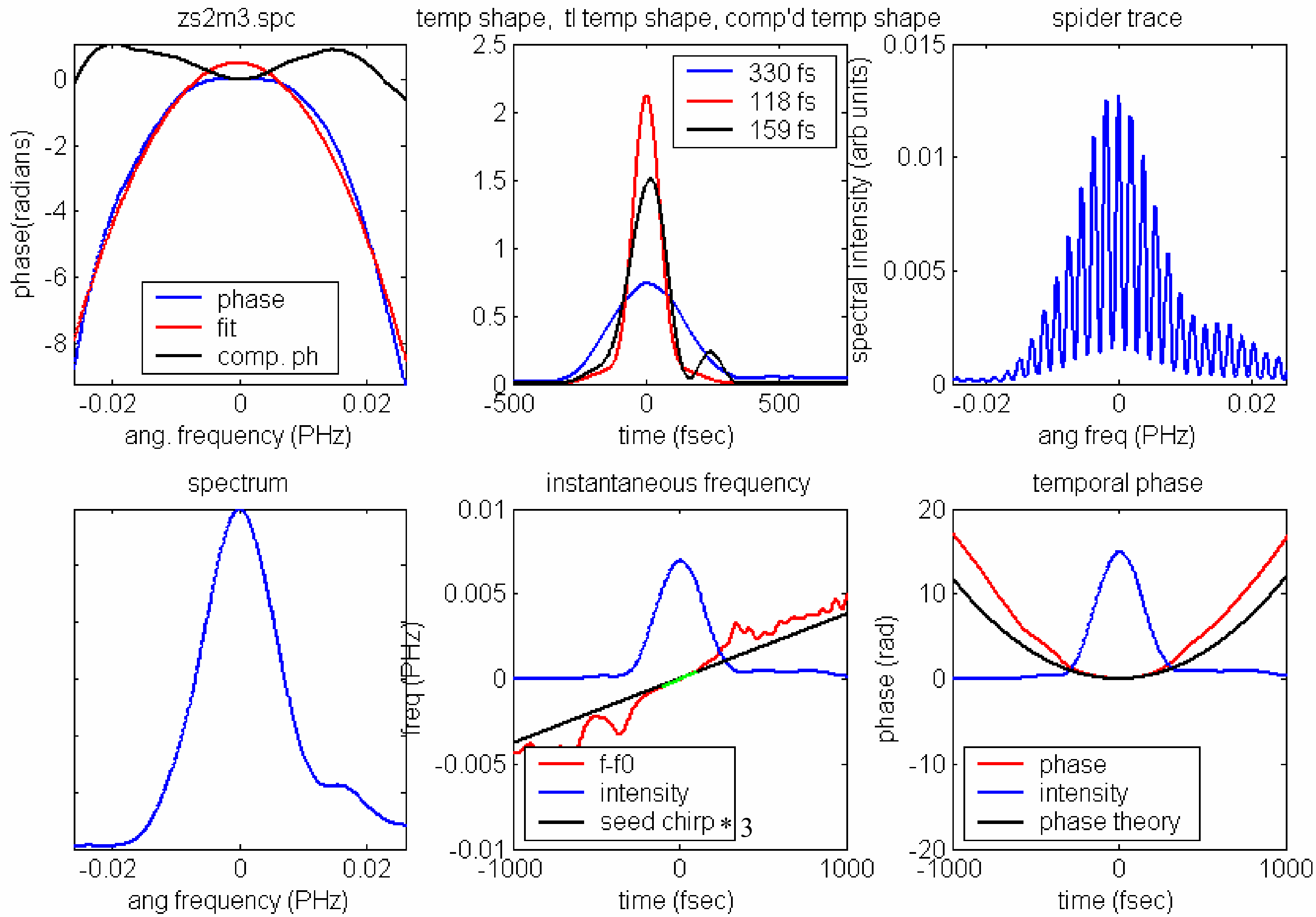
- Chirp e⁻ bunch and optical seed together
- optical seed: 3.8 THz/psec
- e⁻ bunch: 2.7 THz/psec (resonant frequency)
- broader bandwidth already observed

  Doyuran et al PRST AB 7, 050701 (2004)

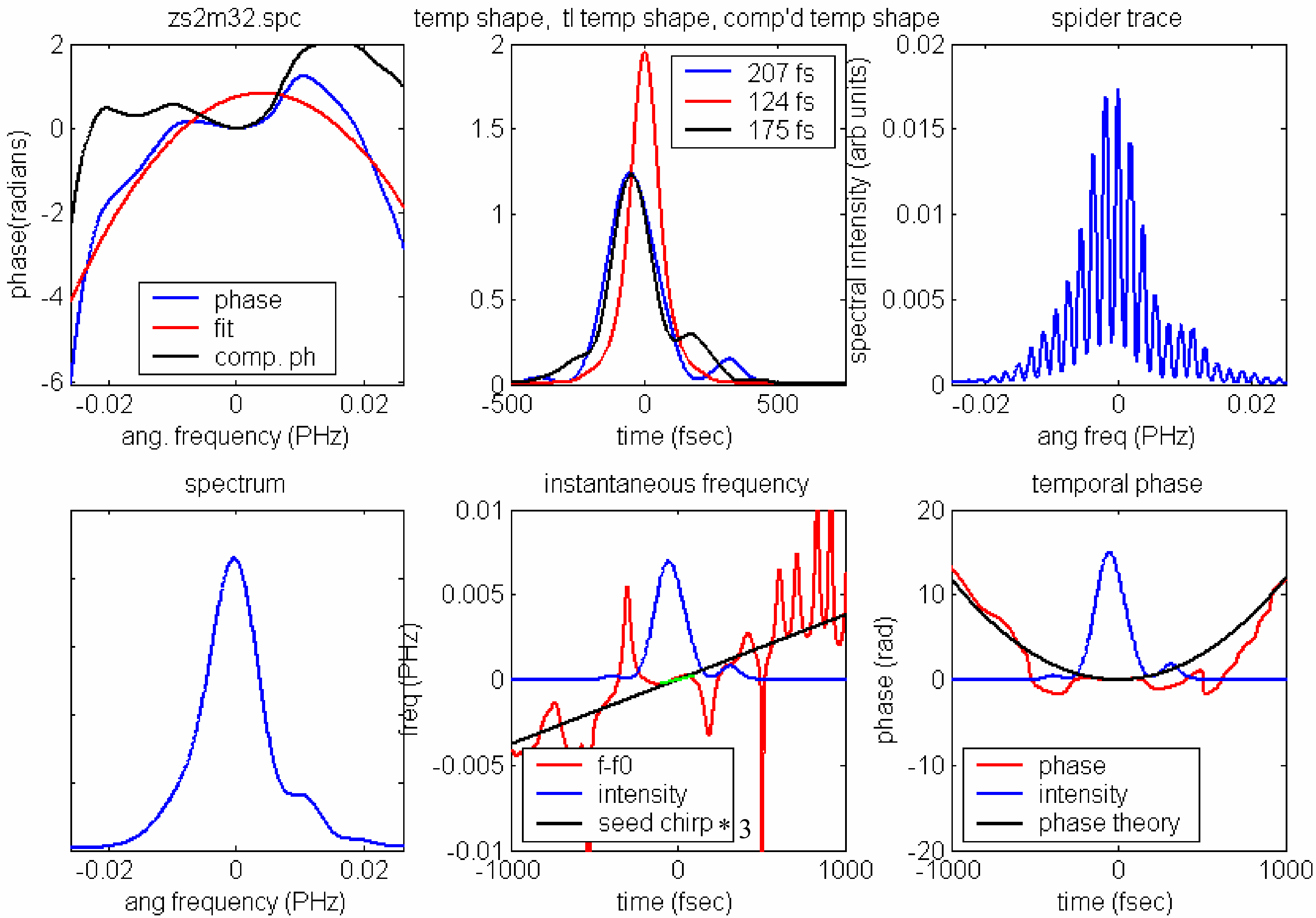
CHIRPED HGHG



CHIRPED HGHG



CHIRPED HGHG



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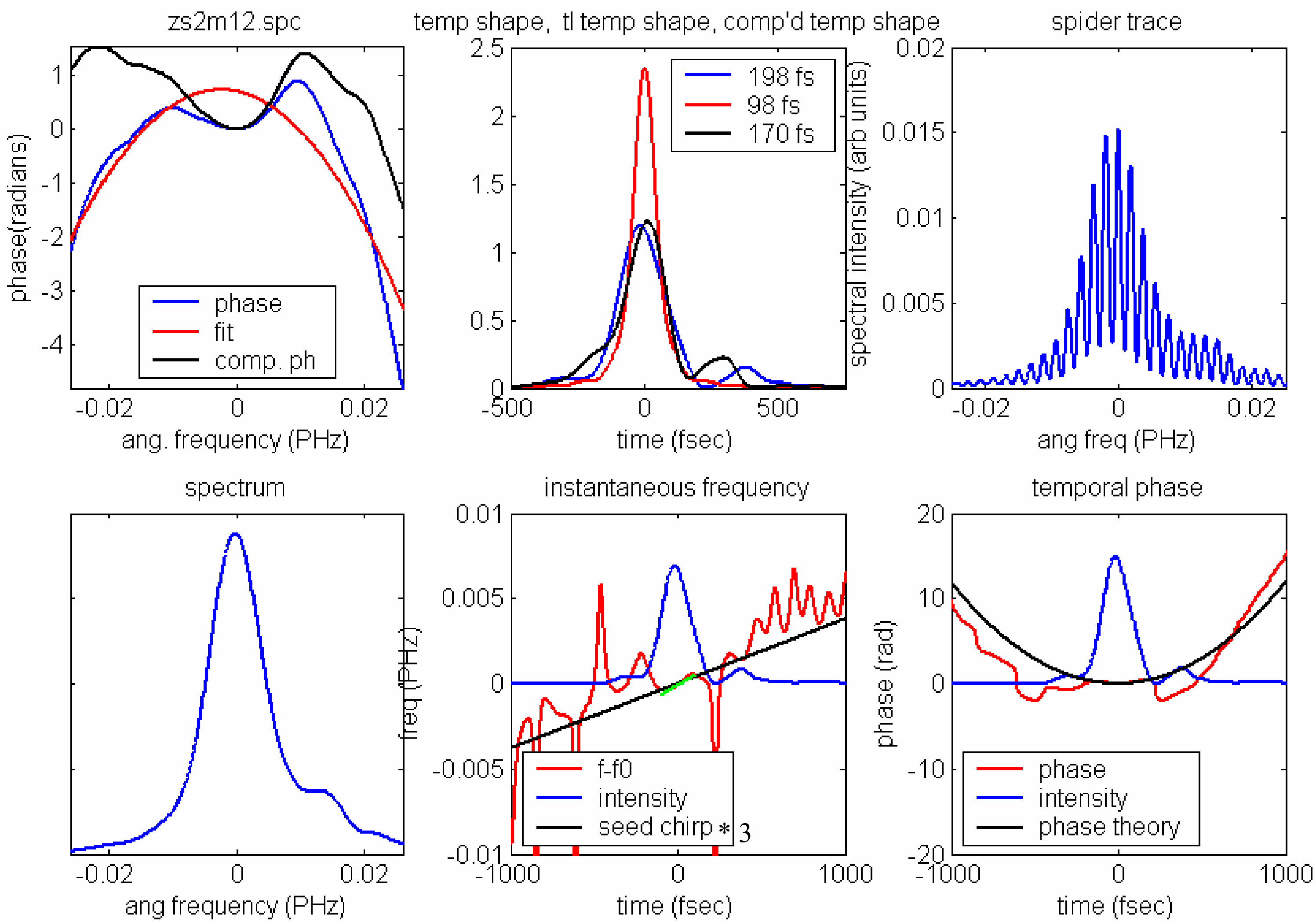
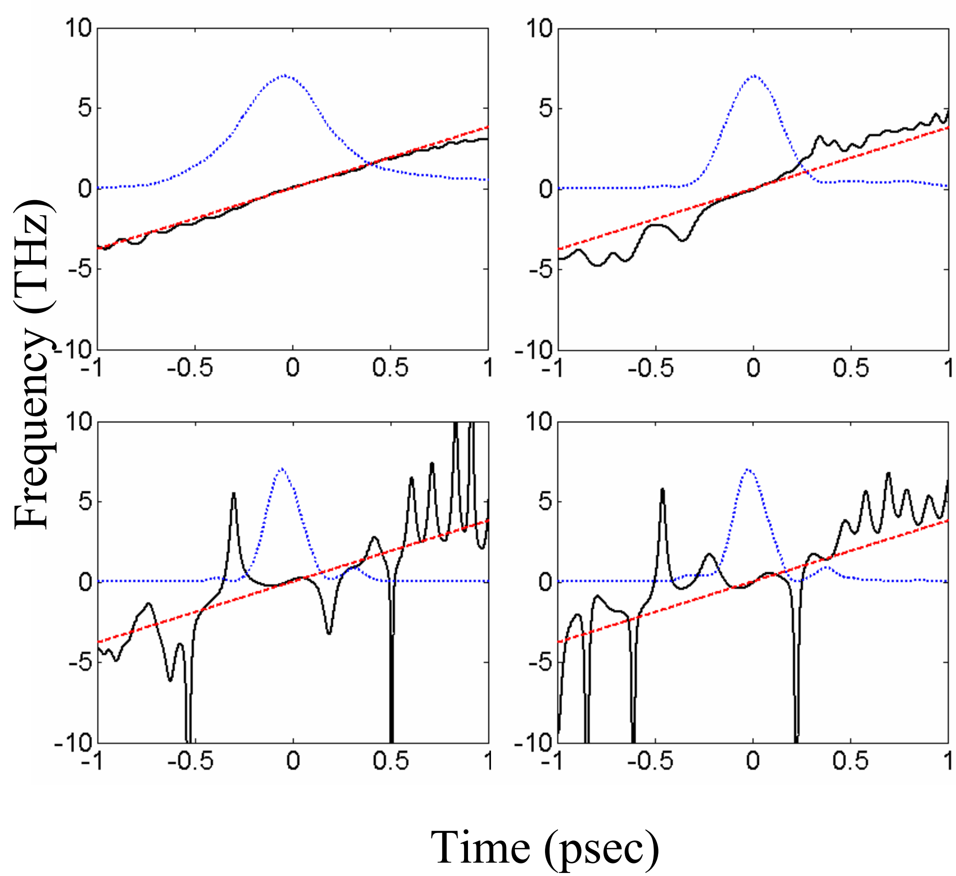
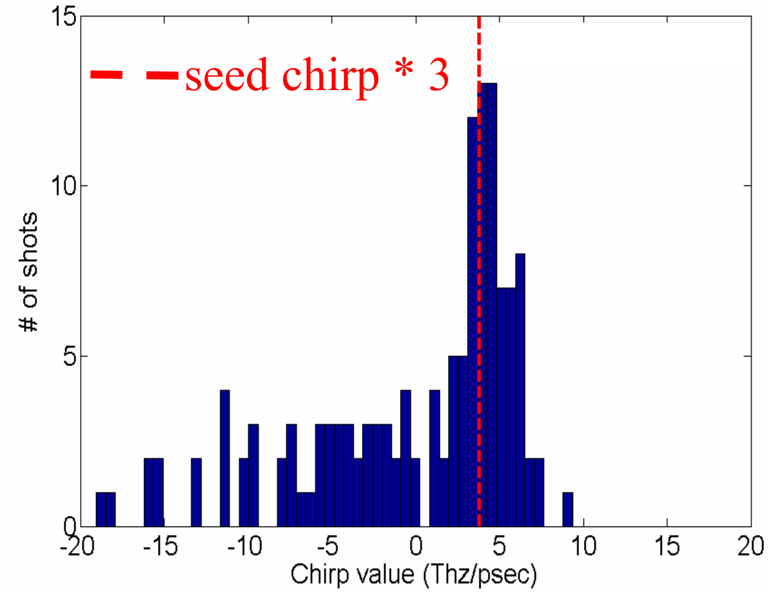
CHIRPED HGHG



CHIRPED HGHG



Distribution of chirps fit over a 200 fs window around peak center



- Sources of instability
  - optical chirp / e^- chirp mismatch
  - synchronization (150 fsec rms)
  - compression instability
  - rf curvature

•The seed chirp is clearly observed in the HGHG output over part of the pulse

• distortion in the pulse wings deteriorates compressibility

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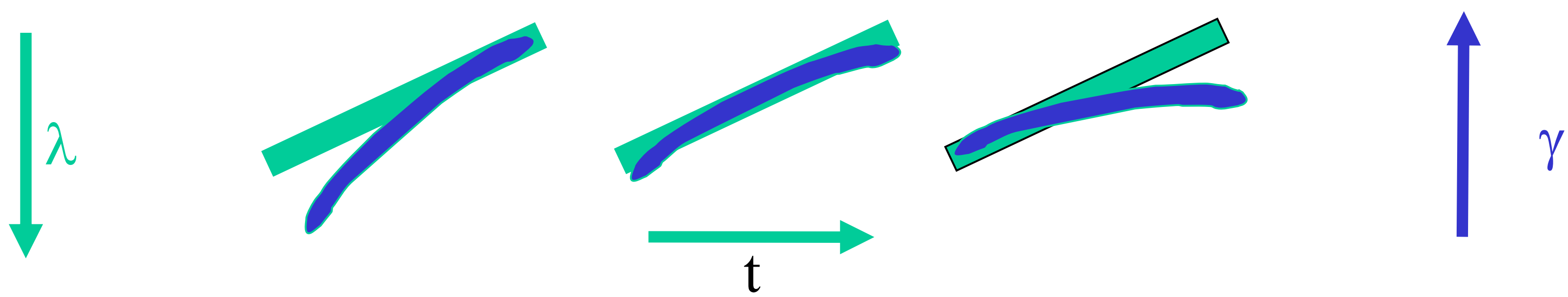
Matching Electron and Optical Chirp

Optical Beam

Electron Beam



- Electron beam has curvature due to sinusoidal acclerating field
- If chirp is not matched, resonance occurs only over a short portion of the electron bunch
- Mismatched is more sensitive to synchronization jitter.

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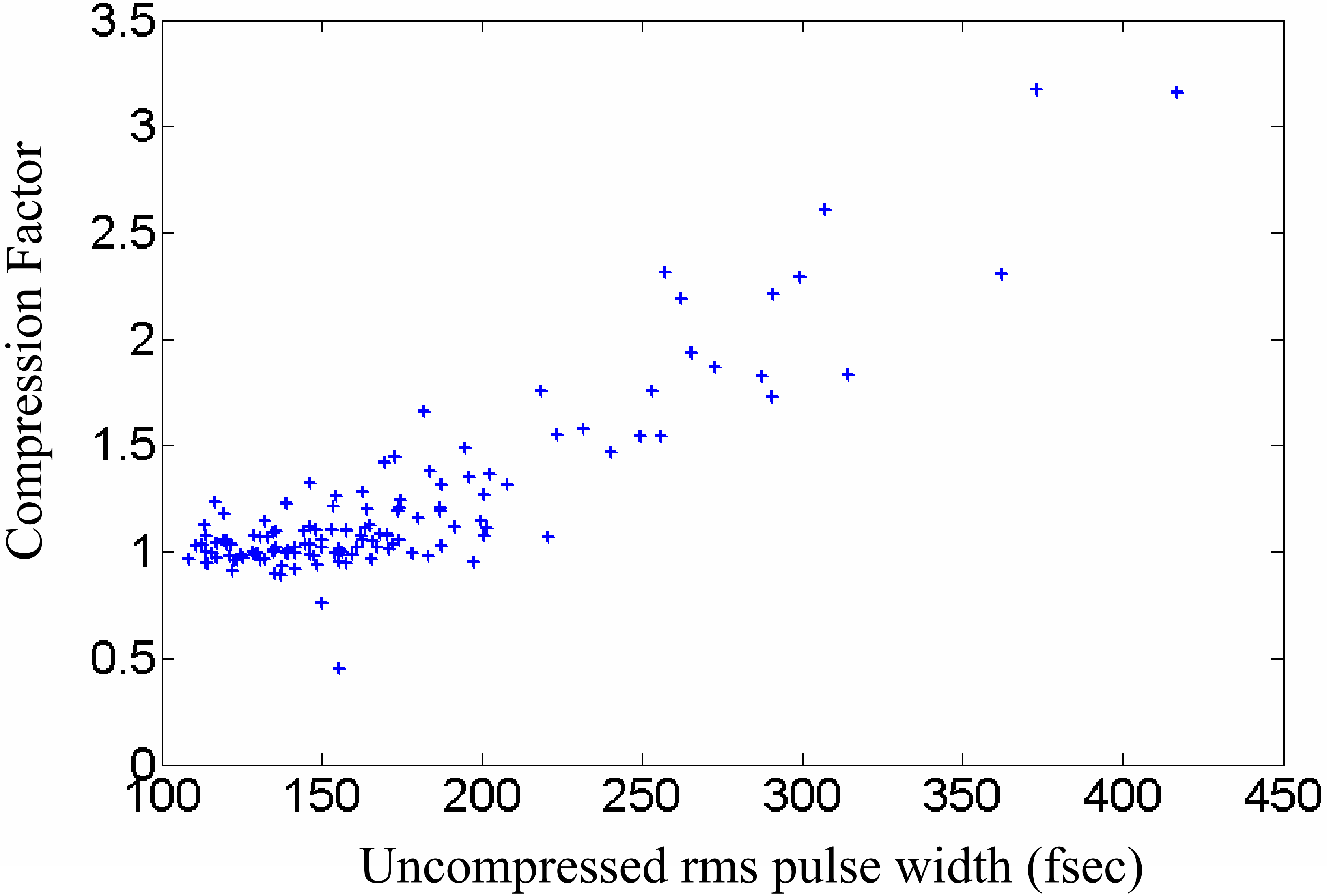

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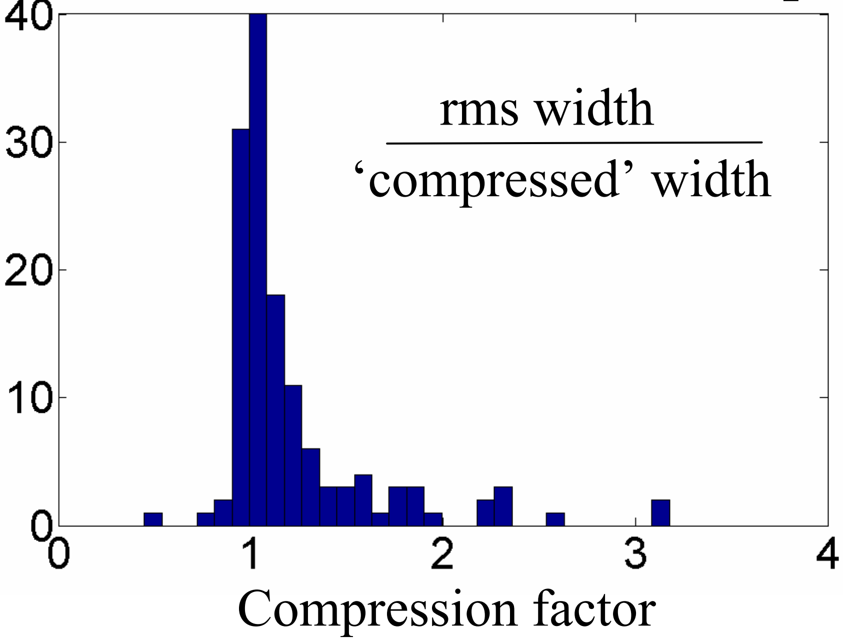
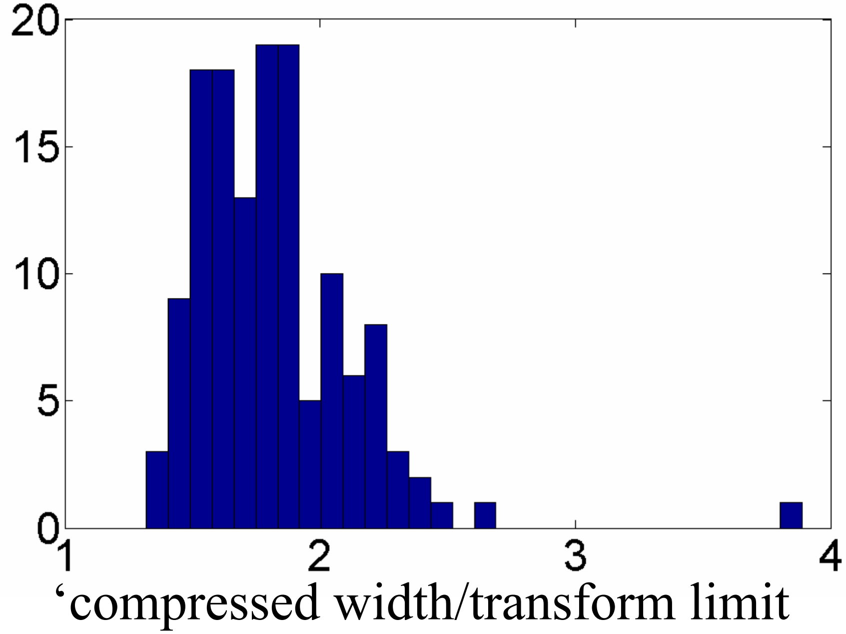
Fit b for each shot and 'compress':





- most pulses compressible in principle to ~ twice transform limit
- quadratic spectral phase (defines compressor) not determined only by chirp
- a 'reasonable' fixed compressor compresses only 15% of pulses

Summary

• Successfully demonstrated SPIDER at shortest wavelength and longest pulse lengths reported.

• Characterized spectral phase of High Gain Harmonic Generation
  - • near transform limited

• Chirped Pulse Amplification
  - • Imparted positive chirp commensurate with seed chirp
  - • poorly matched electron chirp
  - • sensitivity to other factors still unclear

• shown the viability of CPA and potential for more complex pulse shaping

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