Effect of Seed Laser Phase on Harmonic Seeding

D. Ratner, A. Fry, G. Stupakov, W. White
Outline

1. What is laser phase?
2. Laser phase effects on harmonic seeding
   - High Gain Harmonic Generation (HGHG)
   - Echo-Enabled Harmonic Generation (EEHГ)
3. Measuring and controlling phase in the UV
Laser Phase Errors in Harmonic Seeding

Laser Phase

Spectral domain:

\[ \tilde{E}(\omega) = e^{-\frac{(\omega - \omega_0)^2}{4\sigma_w^2}} e^{i\left[\frac{\phi_2}{2}(\omega - \omega_0)^2 + \frac{\phi_3}{6}(\omega - \omega_0)^3 + \ldots\right]} \]

Time domain:

\[ E(t) = e^{-\frac{t^2}{4\sigma_t^2}} e^{-i[\omega_0 t + \theta_2 t^2]} \]
Laser Phase Errors in Harmonic Seeding

Laser Phase

Time domain:

\[ E(t) = e^{-\frac{t^2}{4\sigma_t^2}} e^{i\left[\omega_0 t + \frac{\theta_2}{2} t^2\right]} \]

\[ \phi(t) \]

\[ \omega(t) = \frac{d\phi(t)}{dt} = \omega_0 + \theta_2 t \]

Linear Chirp \( \Rightarrow \) Quadratic Phase!
Laser Phase Errors in Harmonic Seeding

Transform Limited Pulses

![Time Domain Graph](image)

![Frequency Domain Graph](image)

Time Bandwidth Product = $\Delta T \Delta \omega$

Flat Phase $\Rightarrow$ Minimal TBP*

* For the given spectrum!
Effect of finite pulse length and laser frequency chirp on HGHG and EEHG seeding

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November 16, 2011

Analytical studies of constraints on the performance for EEHG FEL seed lasers

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aEuropean XFEL GmbH, Hamburg, Germany

bDeutsches Elektronen-Synchrotron (DESY), Hamburg, Germany

Laser phase errors in seeded free electron lasers

D. Ratner, A. Fry, G. Stupakov, and W. White

SLAC, Menlo Park, California 94025, USA

(Received 7 December 2011; published 12 March 2012)

\[ \tilde{E}(\omega) = e^{-\frac{(\omega - \omega_0)^2}{4 \sigma_w^2}} e^{i \left[ \frac{\phi_2}{2} (\omega - \omega_0)^2 + \frac{\phi_3}{6} (\omega - \omega_0)^3 + \ldots \right]} \]
Laser Phase Errors in Harmonic Seeding

Transverse Laser Modes

TOLERANCES FOR ECHO-SEEDING IN THE FLASH ORS SECTION
Kirsten Hacker, TU Dortmund, Holger Schlarb, DESY Hamburg

Profile Monitor CAMR:IN20:186 26 Jun 2012 09:26:55

LCLS Drive Laser

Sensitivity of Bunching Factor to Seed Wavefront Distortion

Bunching Suppression Factor

RMS Wavefront Distortion [nm]
Laser Phase Errors in Harmonic Seeding

Model for HGHG Seeding

Electron phase space copies laser E-field

X-ray output determined by electron density spikes

- Bunching factor

$$B_k = \sum_j e^{ikz_j}$$
Laser Phase Errors in Harmonic Seeding

Model for HGHG Seeding

Electron phase space copies laser E-field

X-ray output determined by electron density spikes
- Bunching factor

\[ B_k = \sum_j e^{ikz_j} \]
Laser Phase Errors in Harmonic Seeding

Flat-top Laser

\[ \frac{\lambda}{H} + \frac{\Delta \lambda}{H} \]

Harmonic number

\[ \frac{\Delta f_1}{f_1} = \frac{\Delta f_H}{f_H} \]

\[ \Rightarrow \Delta f_H = H \Delta f_1 \]

Bandwidth increases LINEARLY with harmonic number, NOT as \( H^2 \)!
Electron Bunching Phase

\[ \tilde{E}(\omega) = e^{-\frac{(\omega - \omega_0)^2}{4 \sigma_w^2}} e^{i \left[ \frac{\phi_2}{2} (\omega - \omega_0)^2 + \frac{\phi_3}{6} (\omega - \omega_0)^3 + \ldots \right]} \]

Laser Spectral Phase: \( \varphi(\omega) \)

Electron Spectral Phase

\[ b(k) \equiv \frac{1}{N} \sum_{j=1}^{N} e^{-i k \bar{z}_j} \]

\[ \varphi_e^{-}(k) = \text{Arg}[b(k)] \]
Laser Phase Errors in Harmonic Seeding

Electron Bunching Phase

\[ b(k) \equiv \frac{1}{N} \sum_{j=1}^{N} e^{-i k \bar{z}_j} \]

Electron Spectral Phase

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$b(k) \equiv \frac{1}{N} \sum_{j=1}^{N} e^{-ik\bar{z}_j}$

Electron Spectral Phase

$\varphi_{e^{-}}(k) = \text{Arg}[b(k)]$

Simulation

Analytical
Laser Phase Errors in Harmonic Seeding

Electron Bunching Phase

\[ b(k) \equiv \frac{1}{N} \sum_{j=1}^{N} e^{-i k z_j} \]

Electron Spectral Phase

\[ \varphi_{e^-}(k) = \text{Arg}[b(k)] \]

[Graph showing electron spectral phase vs. frequency, with annotations for fundamental and 10th harmonic.]
Laser Phase Errors in Harmonic Seeding

Gaussian Laser Profile

- Fundamental
- 2nd Harmonic
- 10th Harmonic

Laser Profile

Electron Bunching Factor

Longitudinal Position (z/λ)

RMS Pulse Length

H⁻¹/³ scaling

Simulation
Phase Errors in HGHG

**Higher Order phase**

No analytical solution ➔ use simulation

---

**Third Order Phase Example**

- **Laser Profile**
- **Fundamental**
- **10th Harmonic**
- **Laser Phase**

**Graph Details:**
- **Y-axis:** Electron Bunching Factor
- **X-axis:** Longitudinal Position ($z/\lambda$)
- **Range:**
  - Y-axis: 0 to 0.5
  - X-axis: -100 to 100
Phase Errors in HGHG

**Higher Order phase**

No analytical solution ➔ use simulation

Odd order phase has weaker effect on bandwidth of harmonics!
Laser Phase Errors in Harmonic Seeding

FERMI Experimental Results
(Preliminary)

Seed laser pulse length FWHM: $\Delta_{\text{seed}} = 150$ fs
Seed laser harmonic number: $N$
FEL bandwidth FWHM: $\Delta E$
FEL pulse length FWHM: $\Delta FEL = \Delta_{\text{seed}} / \sqrt{N}$
Transform limit (Gaussian pulse): $1840$ meV fs

<table>
<thead>
<tr>
<th>Lambda (nm)</th>
<th>$\Delta E$ (meV)</th>
<th>$N$</th>
<th>$\Delta FEL$ (fs)</th>
<th>$\Delta E \times \Delta FEL$</th>
<th>$\frac{(\Delta E \times \Delta FEL)}{TL}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>26</td>
<td>61.8</td>
<td>10</td>
<td>47.4</td>
<td>2929</td>
<td>$\approx 1.6$</td>
</tr>
<tr>
<td>32.5</td>
<td>50.1</td>
<td>8</td>
<td>53</td>
<td>2655</td>
<td>$\approx 1.44$</td>
</tr>
<tr>
<td>43.3</td>
<td>33.8</td>
<td>6</td>
<td>61.2</td>
<td>2069</td>
<td>$\approx 1.12$</td>
</tr>
<tr>
<td>52</td>
<td>31.8</td>
<td>5</td>
<td>67.1</td>
<td>2134</td>
<td>$\approx 1.16$</td>
</tr>
<tr>
<td>65</td>
<td>28.8</td>
<td>4</td>
<td>75</td>
<td>2160</td>
<td>$\approx 1.17$</td>
</tr>
</tbody>
</table>

$I_1^{st}/I_3^{rd} \approx 160$

Allaria, Fawley, Ferrari, Spezzani + FCT + PADReS + CR people

C. Svetina, N. Mahne
Laser Phase Errors in Harmonic Seeding

Echo Enabled Harmonic Generation

\[ R_{56}^{(1)} \]

\[ R_{56}^{(2)} \]
Laser Phase Errors in Harmonic Seeding

Echo Enabled Harmonic Generation

First stage decreases bunching

Second stage increases bandwidth

Laser 1

Laser 2

\( R_{56}^{(1)} \)

\( R_{56}^{(2)} \)

e^-

Modulator 1

Modulator 2

Electron Bunching Factor (arb. units)

Harmonic Number

Simulation, No Phase

Analytical, No Phase

Simulation, \( f_2 \) on Laser 1

Analytical, \( f_2 \) on Laser 1

Simulation, \( f_2 \) on Laser 2

Analytical, \( f_2 \) on Laser 2
Laser Phase Errors in Harmonic Seeding

Practical Example

<table>
<thead>
<tr>
<th>Measured Laser Pulse</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Central Wavelength</td>
<td>800 nm</td>
</tr>
<tr>
<td>Bandwidth (FWHM)</td>
<td>73 nm</td>
</tr>
<tr>
<td>Pulse Duration</td>
<td>22 fs</td>
</tr>
<tr>
<td>Second Order Phase (GDD)</td>
<td>0.5 fs²</td>
</tr>
<tr>
<td>Third Order Phase (TOD)</td>
<td>2.4 × 10³ fs³</td>
</tr>
<tr>
<td>Fourth Order Phase (FOD)</td>
<td>−4.6 × 10⁴ fs⁴</td>
</tr>
<tr>
<td>Fifth Order Phase (5OD)</td>
<td>−1.2 × 10⁶ fs⁵</td>
</tr>
</tbody>
</table>

Legend Elite USX

Pulse Intensity vs. Longitudinal Position (z/λ)

Zero phase equivalent
Pulse with Measured Phase

TBP ≡ ΔTΔf

TBP, Measured phase
TBP, flat phase
Laser Phase Errors in Harmonic Seeding

Phase Measurement Methods
What are prospects for measuring phase in the UV?

Frequency Resolved Optical Gating (FROG)

Figures from A. Monmayrant, S. Weber, and B. Chatel
Phase Measurement Methods
What are prospects for measuring phase in the UV?

Spectral Phase Interferometry for Direct Electric-field Reconstruction (SPIDER)

Characterization of sub-6-fs optical pulses with spectral phase interferometry for direct electric-field reconstruction

L. Gallmann, D. H. Sutter, N. Matuschek, G. Steinmeyer, and U. Keller

Ultrafast Laser Physics Laboratory, Institute of Quantum Electronics, Swiss Federal Institute of Technology,
ETH Hönggerberg-HPT, CH-8093 Zurich, Switzerland

C. Iaconis and I. A. Walmsley

The Institute of Optics, University of Rochester, Rochester, New York, 14627

A. Monmayrant, S. Weber, and B. Chatel

I. Walmsley and C. Dorrer
Phase Measurement Methods
What are prospects for measuring phase in the UV?

Challenges for extending techniques to short wavelengths:
• Need high intensities for nonlinear effects
• Few nonlinear materials
• Spectrometers more challenging
Laser Phase Errors in Harmonic Seeding

Measurements in the UV

High Harmonic XUV Spectral Phase Interferometry for Direct Electric-Field Reconstruction


DSM-DRECAM-Service des Photons, Atomes et Molécules, CEA Saclay, 91191 Gif-sur-Yvette Cedex, France

(Received 8 December 2004; published 5 May 2005)

Frequency-Resolved Optical Gating of Isolated Attosecond Pulses in the Extreme Ultraviolet


Institute for Solid State Physics, University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa 277-8581, Japan

(Received 20 June 2006; published 27 December 2006)
Summary

1. Laser phase affects both EEHG and HGHG
2. Time-bandwidth product scales linearly or sub-linearly
3. Even order phase has greater effect than odd order
4. Need to develop new techniques for measuring and controlling UV laser phase

Thanks for Listening!
Laser Phase Errors in Harmonic Seeding

Gaussian Laser Profile

How does time domain change effect of laser phase?

Averaged Bunching Factor

\[ b(k) \equiv \frac{1}{N_T} \sum_{j=1}^{N_T} e^{-i k \bar{z}_j} \]

Slice Bunching Factor

\[ b_{\text{slice},k}(\bar{z}) \equiv \frac{1}{N_{\text{slice}}(\bar{z})} \sum_{j=1}^{N_{\text{slice}}(\bar{z})} e^{i k \bar{z}_j} \]
Phase Measurement Methods
What are prospects for measuring phase in the UV?

Multipulse Intrapulse Interference Phase Scan (MIIPS)

Use known phase to control AND correct phase

\[ \phi''(\Delta) = -f''(\Delta) \]

Pulse phase  Known phase

Fig. 1. Experimental setup of the MIIPS.
Laser Phase Errors in Harmonic Seeding

Practical Example

| Measured Laser Pulse |  
|----------------------|---
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| Fourth Order Phase (FOD) | $-4.6 \times 10^4$ fs⁴  
| Fifth Order Phase (5OD) | $-1.2 \times 10^6$ fs⁵  

Legend Elite USX

Spectral Power/Phase

Frequency (w/w₀)

Spectral Power
Spectral Phase

Pulse Intensity

Pulse with Measured Phase

Zero phase equivalent
Laser Phase Errors in Harmonic Seeding

Practical Example

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\[ TBP \equiv \Delta T \Delta f \]

TBP, Measured phase

TBP, flat phase

Electron Bunching Factor

Legend Elite USX