Effect of Seed Laser Phase on Harmonic Seeding

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

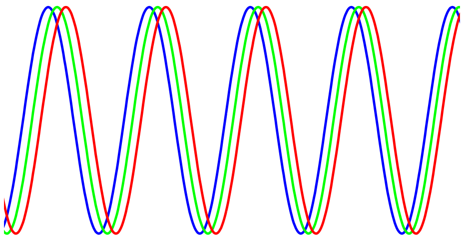
U.S. DEPARTMENT OF ENERGY Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

Outline

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

Laser Phase



Spectral domain:

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

Time domain:

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

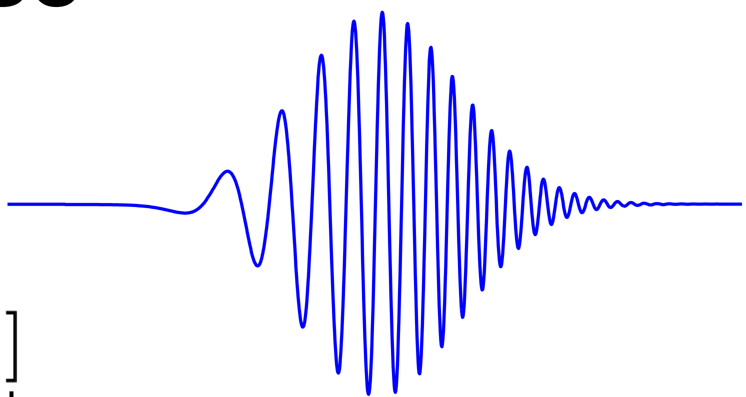
Laser Phase

Time domain:

Carrier frequency

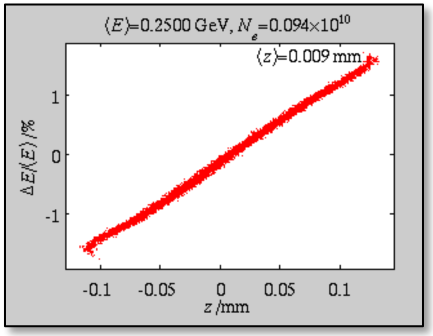
Chirp

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



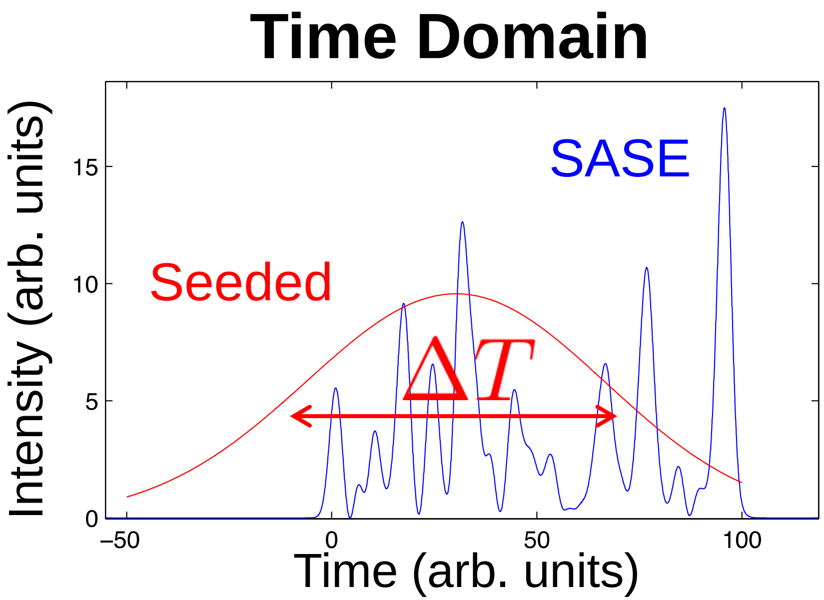
$$\omega(t) = \frac{d\phi(t)}{dt} = \omega_0 + \theta_2 t$$

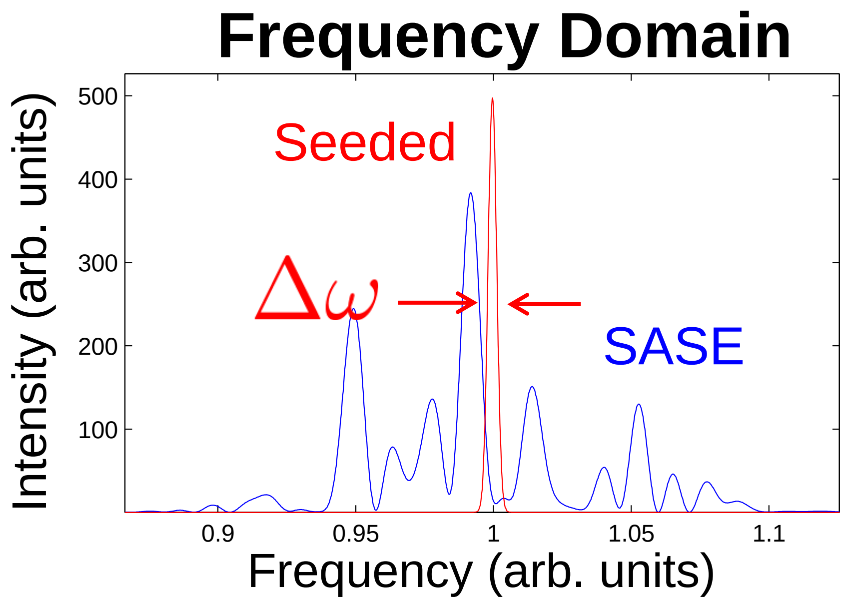
Linear Chirp ➔ Quadratic Phase!



LiTrack, LCLS parameters

Transform Limited Pulses





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

Flat Phase ➔ Minimal TBP*

* For the given spectrum!

Laser Phase Studies

Effect of finite pulse length and laser frequency chirp on HGHG and EEHG seeding

G. Stupakov

SLAC National Accelerator Laboratory, Stanford University, Stanford, CA 94309

November 16, 2011

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

Gianluca Geloni,[a,1] Vitali Kocharyan[b] and Evgeni Saldin[b]

[a]*European XFEL GmbH, Hamburg, Germany*

[b]*Deutsches Elektronen-Synchrotron (DESY), Hamburg, Germany*

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **15**, 030702 (2012)

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)

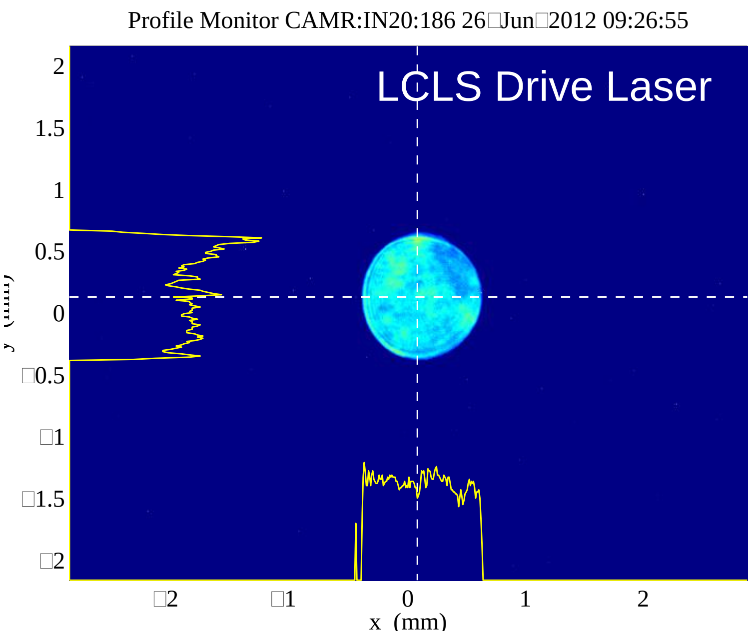
$$\tilde{E}(w) = e^{-\frac{(\omega-\omega_0)^2}{4\,\sigma_w^2}} e^{i[\frac{\phi_2}{2}(\omega-\omega_0)^2+\frac{\phi_3}{6}(\omega-\omega_0)^3+\dots]}$$

Transverse Laser Modes

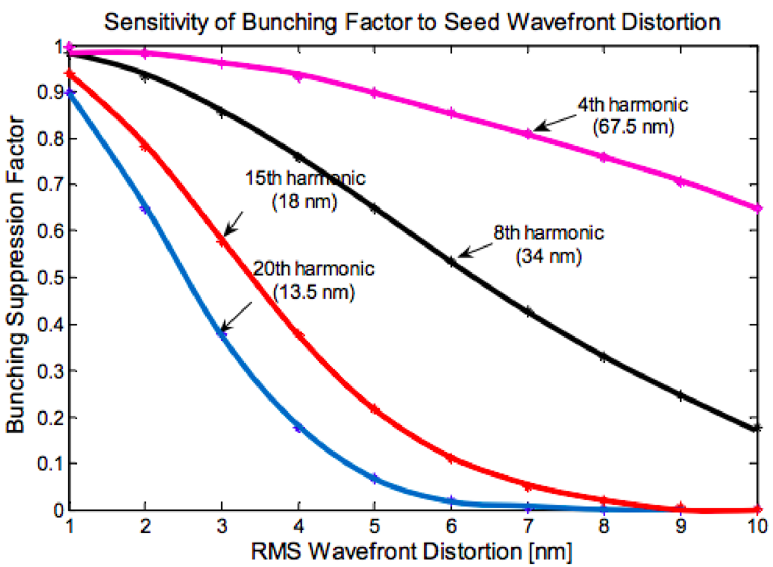
TESLA-FEL 2011-05

TOLERANCES FOR ECHO-SEEDING IN THE FLASH ORS SECTION

Kirsten Hacker, TU Dortmund, Holger Schlarb, DESY Hamburg

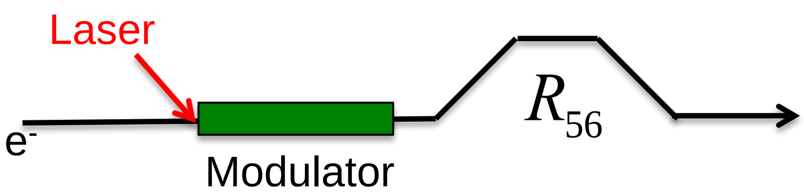


LCLS physics e-log

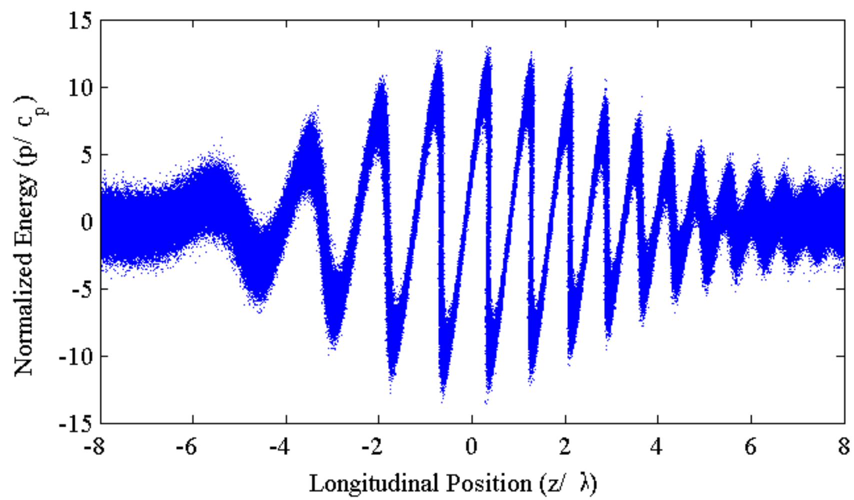


K. Hacker, T. Dortmund and H. Schlarb

Model for HGHG Seeding



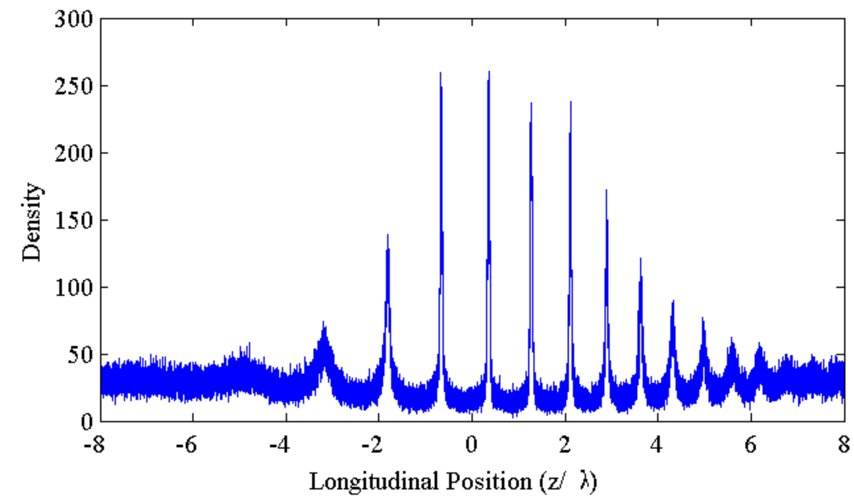
Electron phase space copies laser E-field



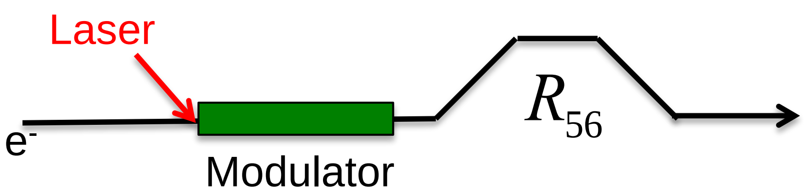
X-ray output determined by electron density spikes

- Bunching factor

$$B_k = \Sigma_j e^{ikz_j}$$



Model for HGHG Seeding



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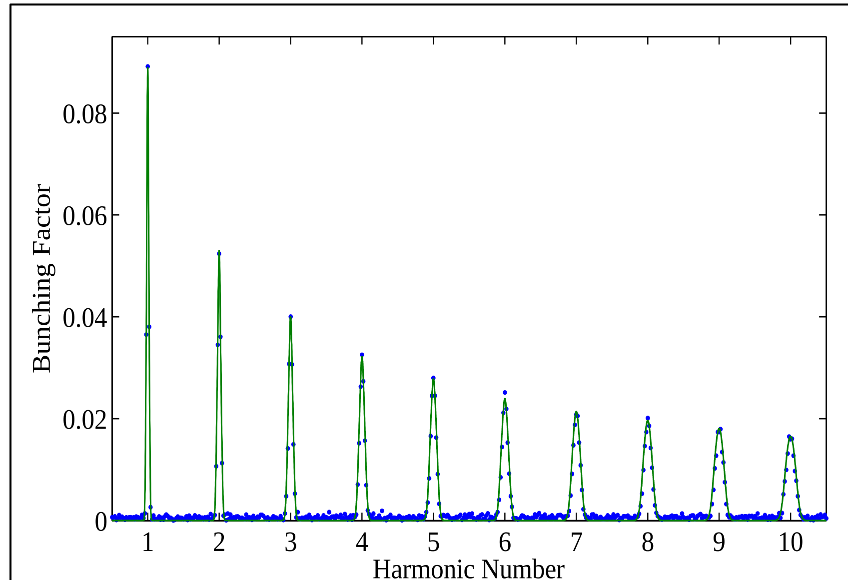

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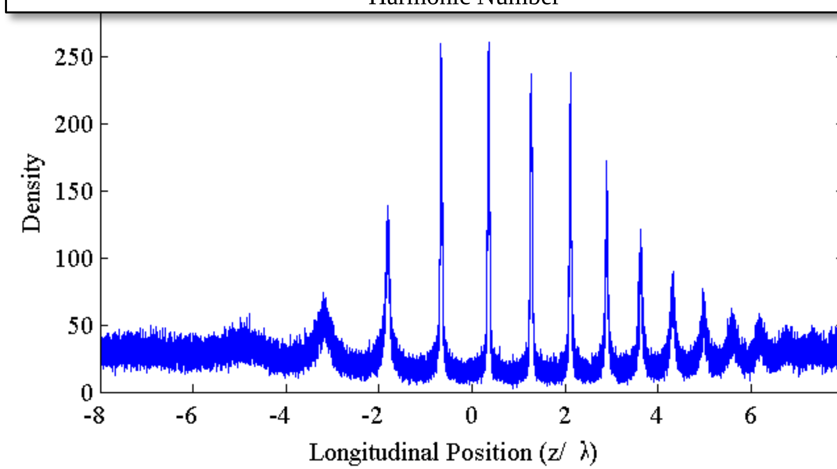
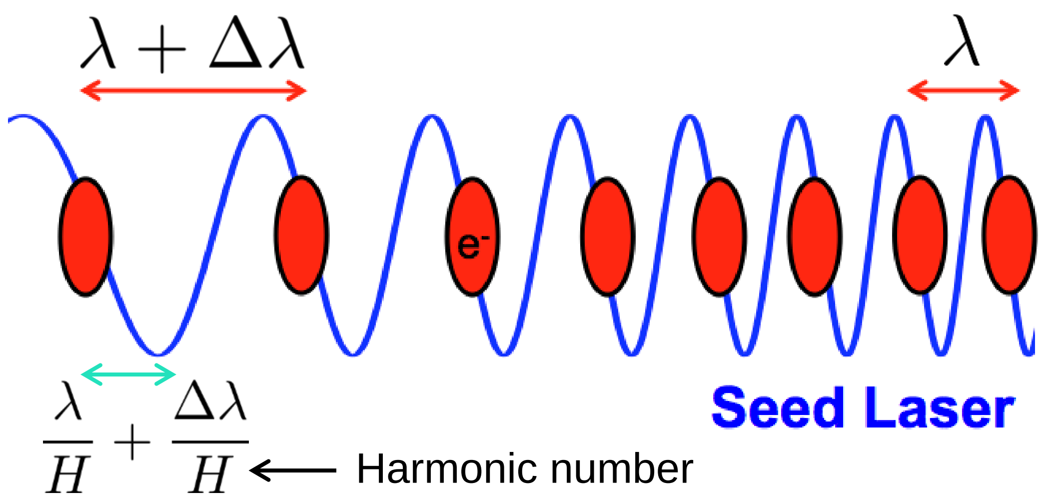


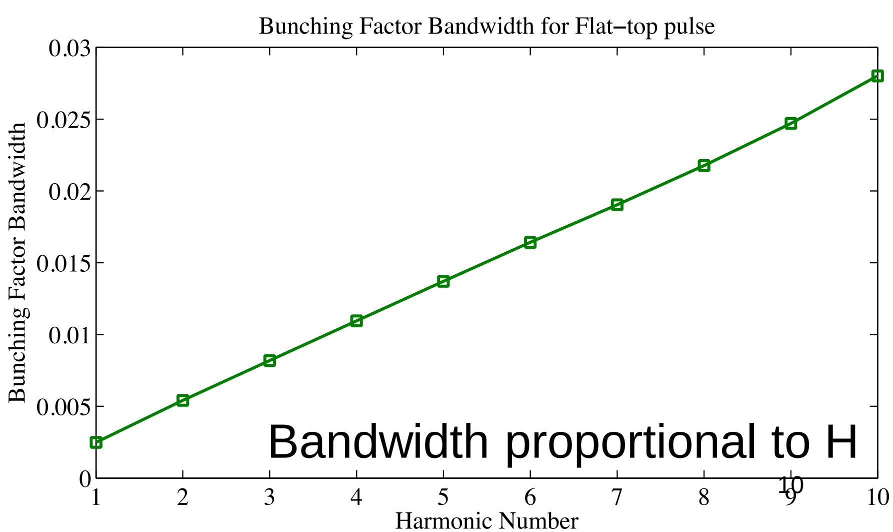
Laser Phase Errors in Harmonic Seeding

Flat-top Laser



$$\frac{\Delta f_1}{f_1} = \frac{\Delta f_H}{f_H}$$

$$\Rightarrow \Delta f_H = H \Delta f_1$$



Bandwidth increases LINEARLY with harmonic number, NOT as H^2!

Electron Bunching Phase

$$\tilde{E}(w) = e^{-\frac{(\omega-\omega_0)^2}{4\sigma_w^2}} e^{\underbrace{i\left[\frac{\phi_2}{2}(\omega-\omega_0)^2+\frac{\phi_3}{6}(\omega-\omega_0)^3+\ldots\right]}_{\text{Laser Spectral Phase: } \varphi(\omega)}}$$

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

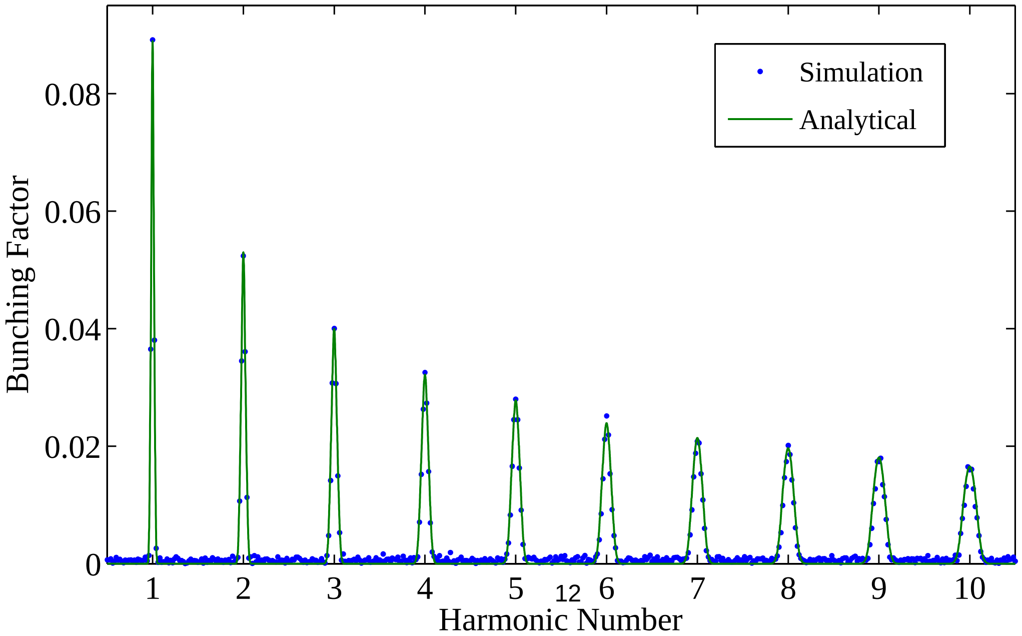
Electron Spectral Phase

$$b(k) \equiv \frac{1}{N}\sum_{j=1}^{N} e^{-ik\bar{z}_j} \Rightarrow \varphi_{e^-}(k) = \mathrm{Arg}[b(k)]$$

Electron Bunching Phase

Electron Spectral Phase

$$b(k) \equiv \frac{1}{N}\sum_{j=1}^{N} e^{-ik\bar{z}_j} \quad \Rightarrow \quad \varphi_{e^-}(k) = \mathrm{Arg}[b(k)]$$



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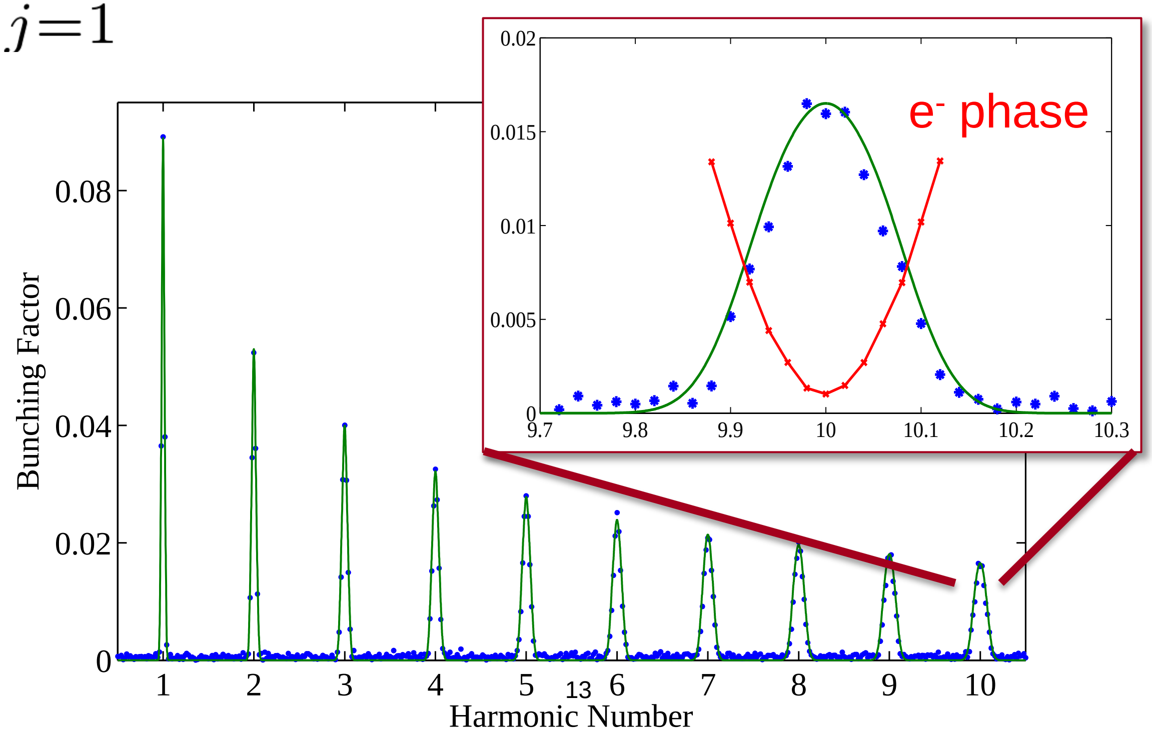

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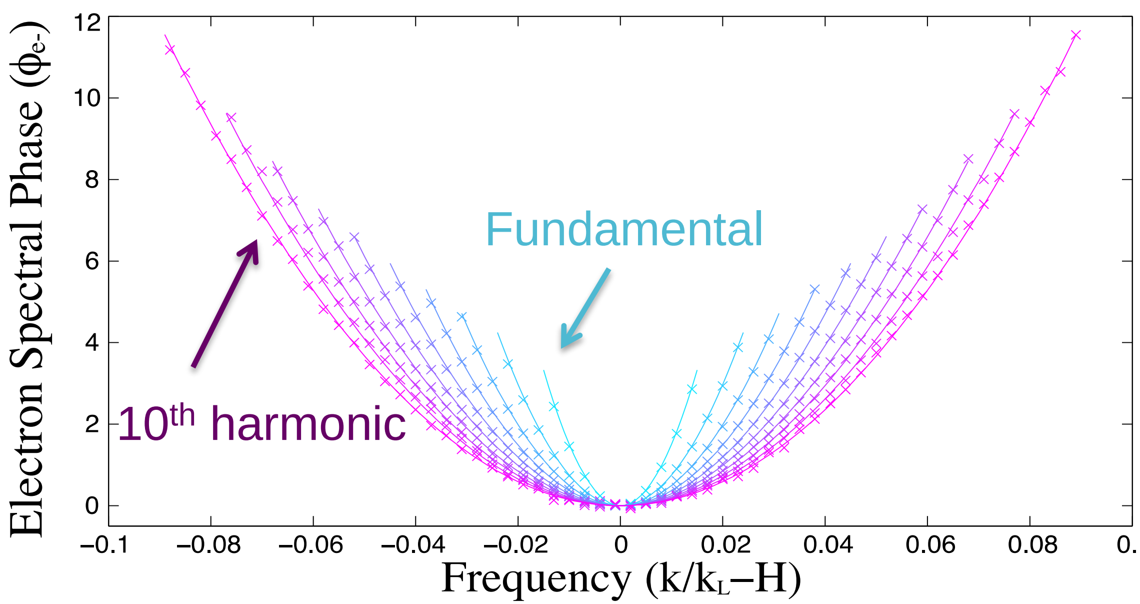
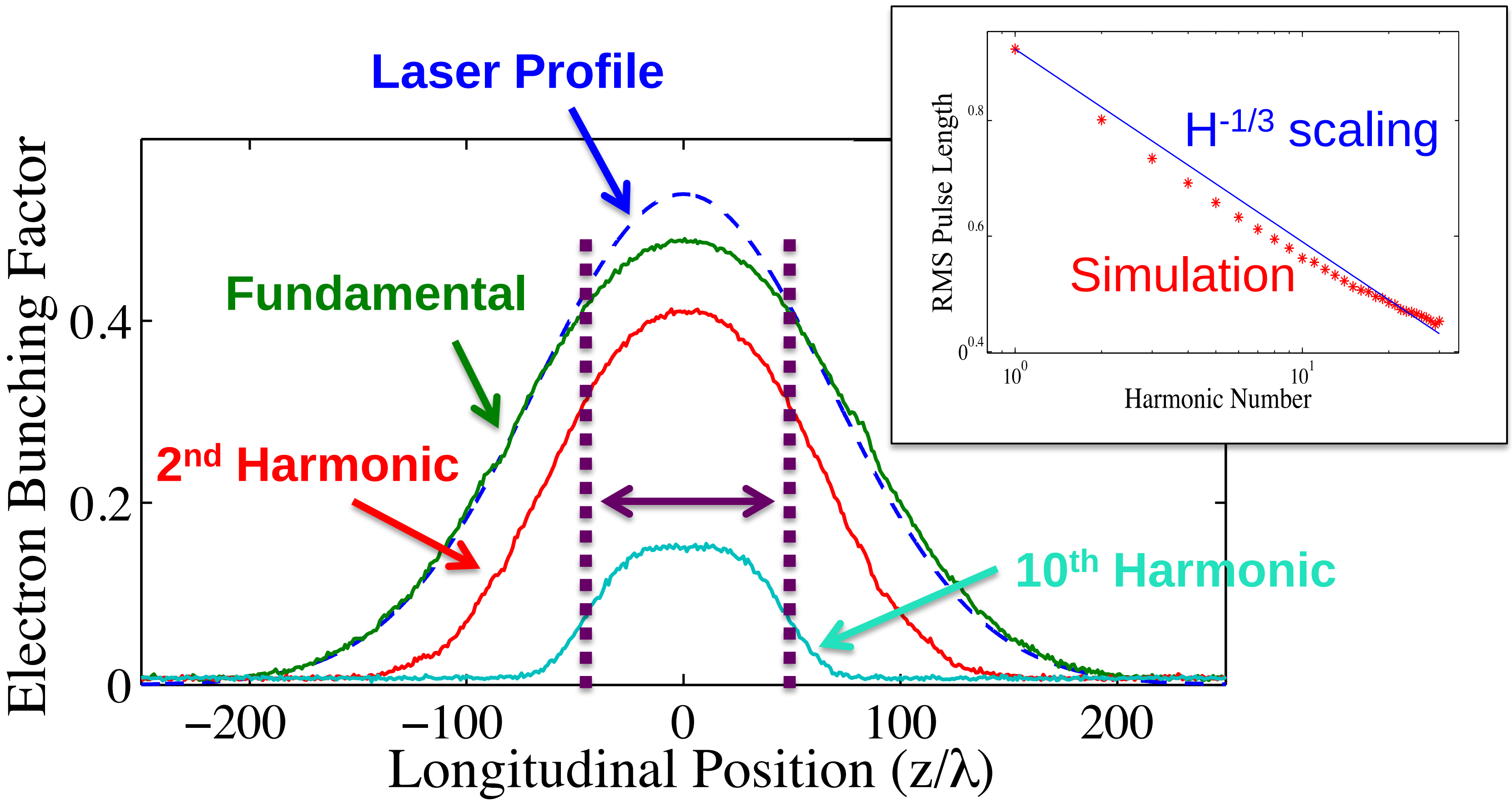
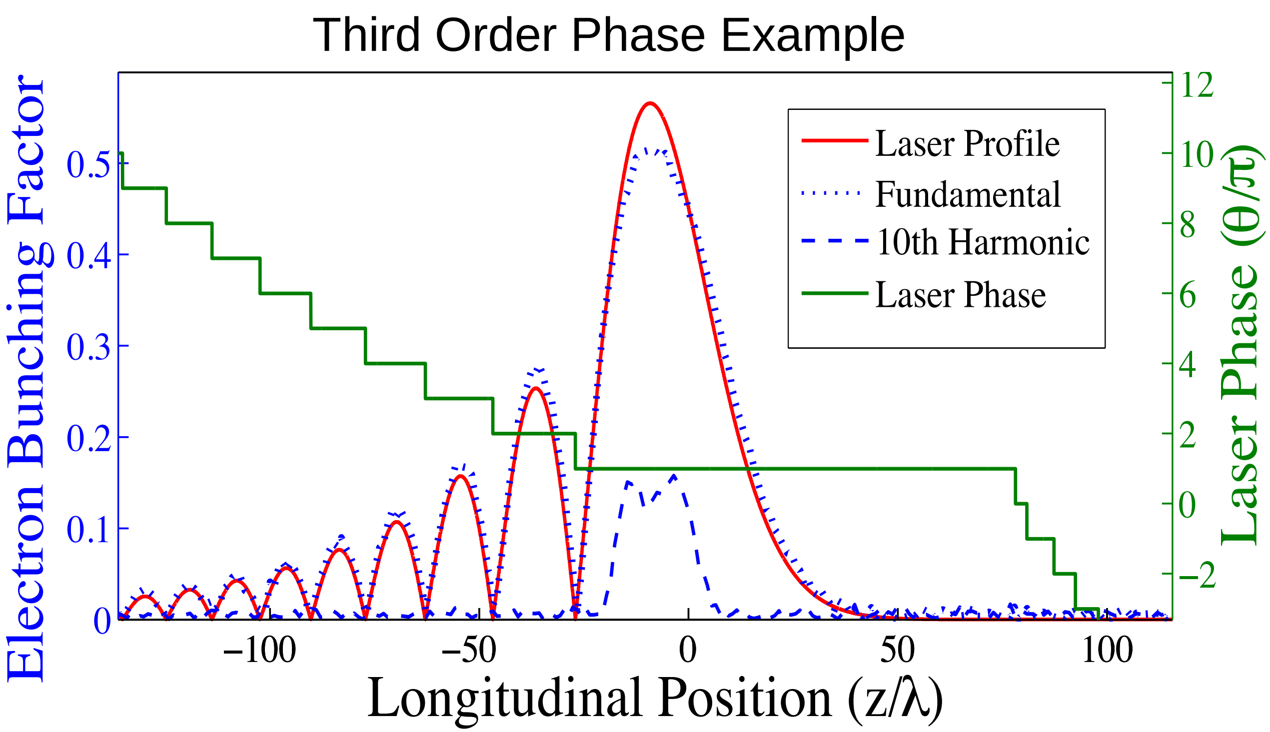


Gaussian Laser Profile



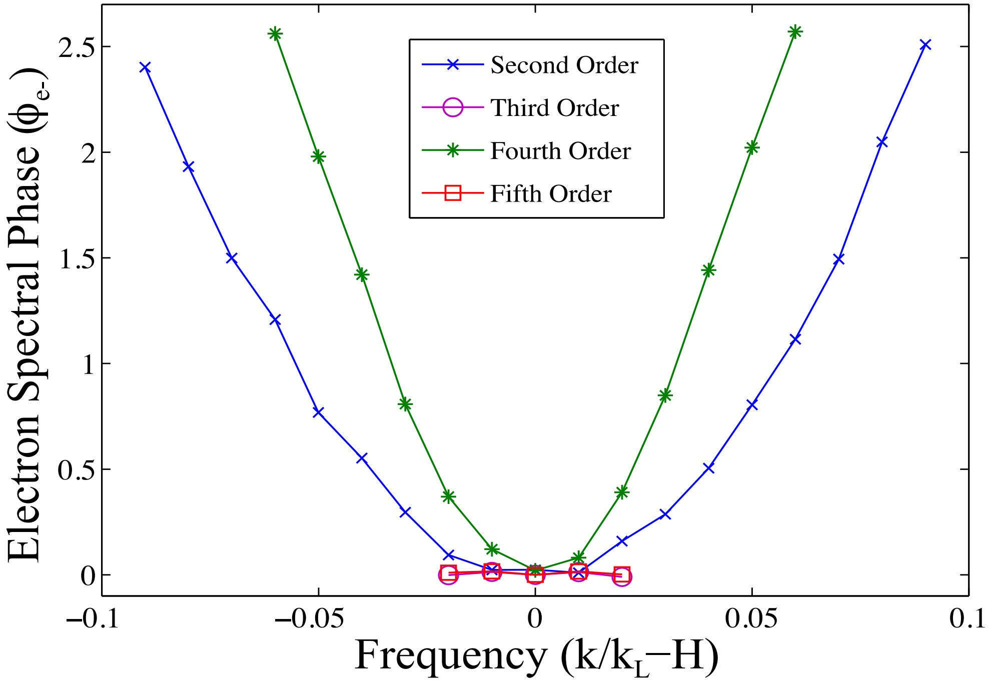
Higher Order phase

No analytical solution ➔ use simulation



Higher Order phase

No analytical solution ➔ use simulation



Odd order phase has weaker effect on bandwidth of harmonics!

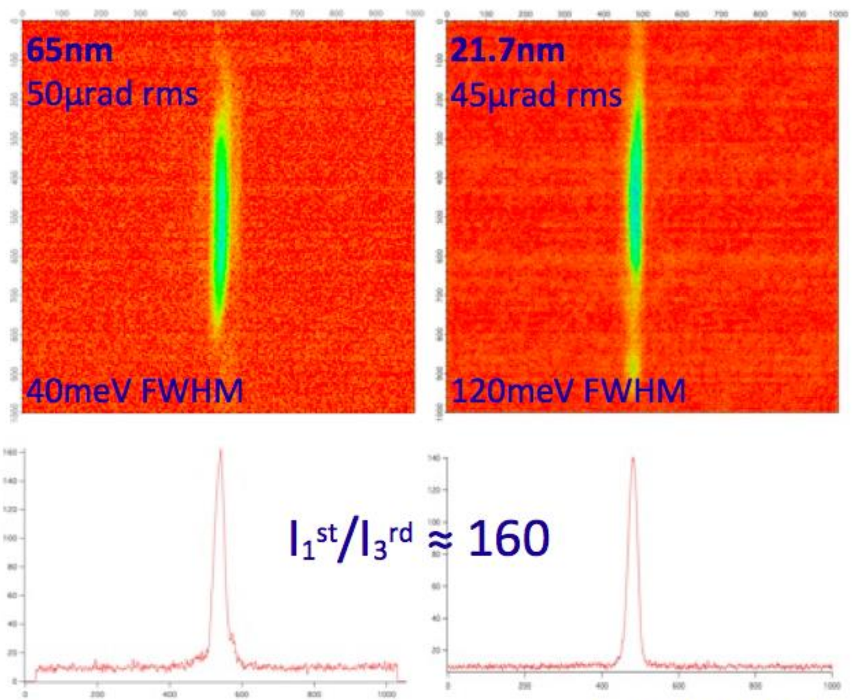
FERMI Experimental Results

(Preliminary)

Seed laser pulse length FWHM: Δseed=150fs
Seed laser harmonic number: N
FEL bandwidth FWHM: ΔE
FEL pulse length FWHM: ΔFEL=Δseed / √N
Transform limit (Gaussian pulse):1840 meV fs

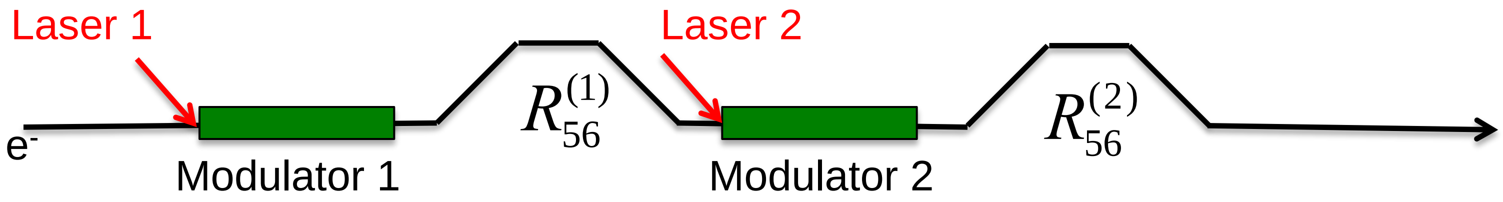
Lambda (nm)	ΔE (meV)	N	ΔFEL (fs)	ΔE x ΔFEL	(ΔExΔFEL) / TL
26	61.8	10	47.4	2929	≈1.6
32.5	50.1	8	53	2655	≈1.44
43.3	33.8	6	61.2	2069	≈1.12
52	31.8	5	67.1	2134	≈1.16
65	28.8	4	75	2160	≈1.17

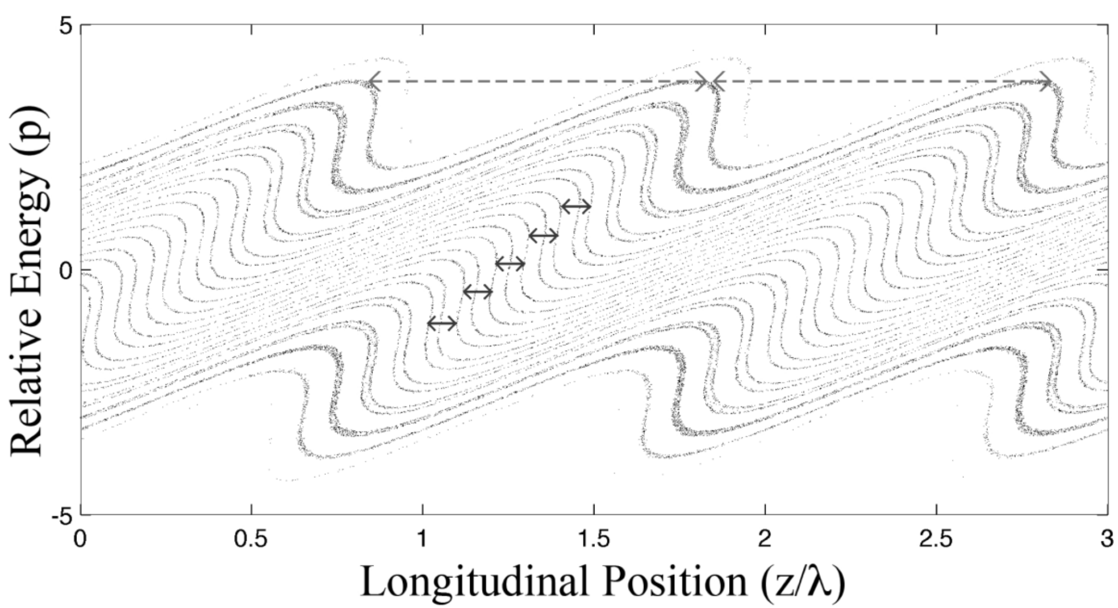
Allaria, Fawley, Ferrari, Spezzani + FCT + PADReS + CR people



C. Svetina, N. Mahne

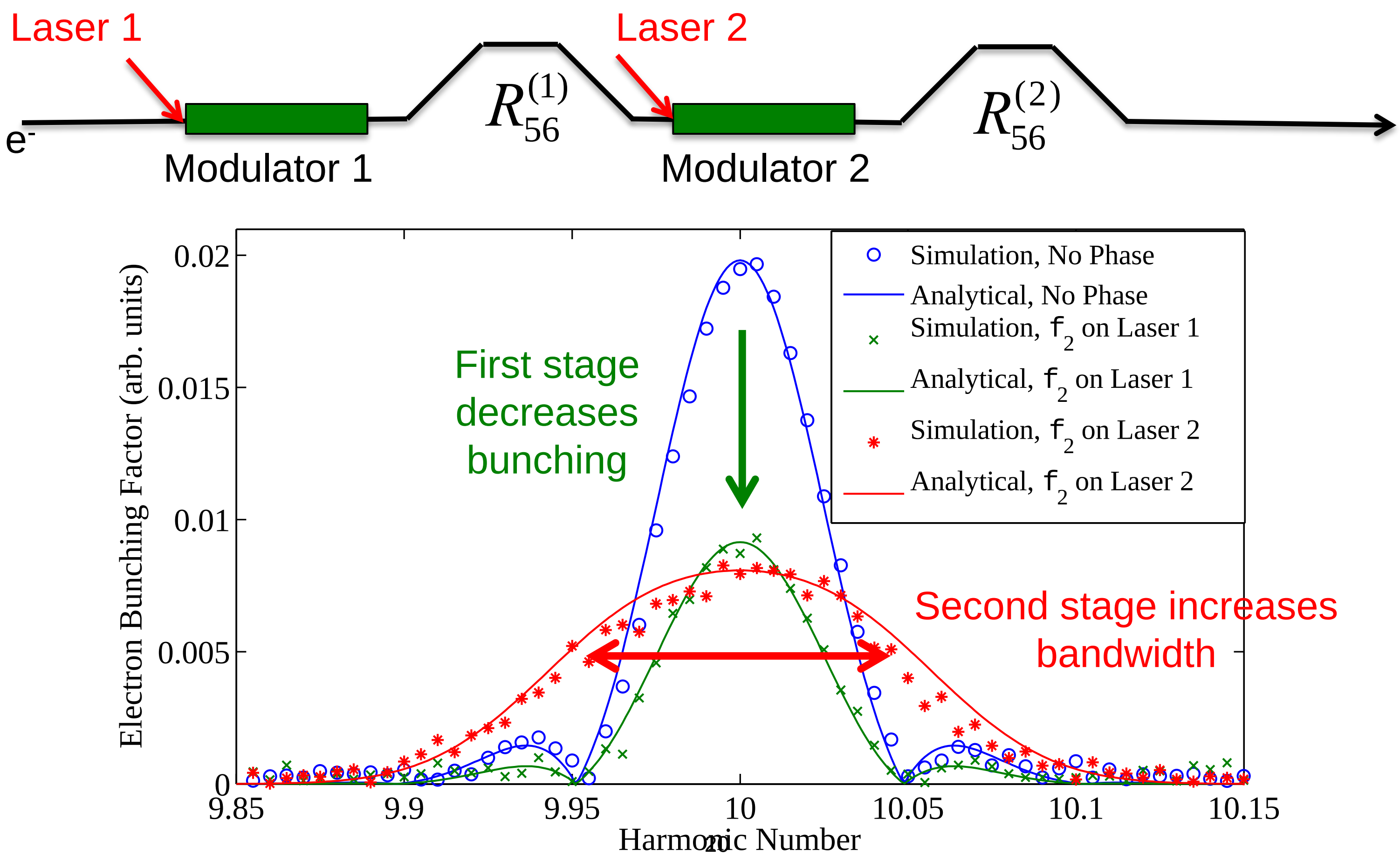
Echo Enabled Harmonic Generation





Laser Phase Errors in Harmonic Seeding

Echo Enabled Harmonic Generation



Practical Example

Measured Laser Pulse	
Central Wavelength	800 nm
Bandwidth (FWHM)	73 nm
Pulse Duration	22 fs
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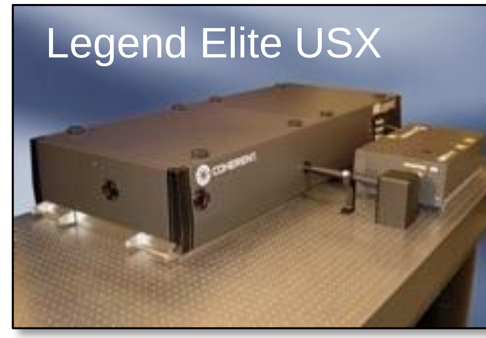
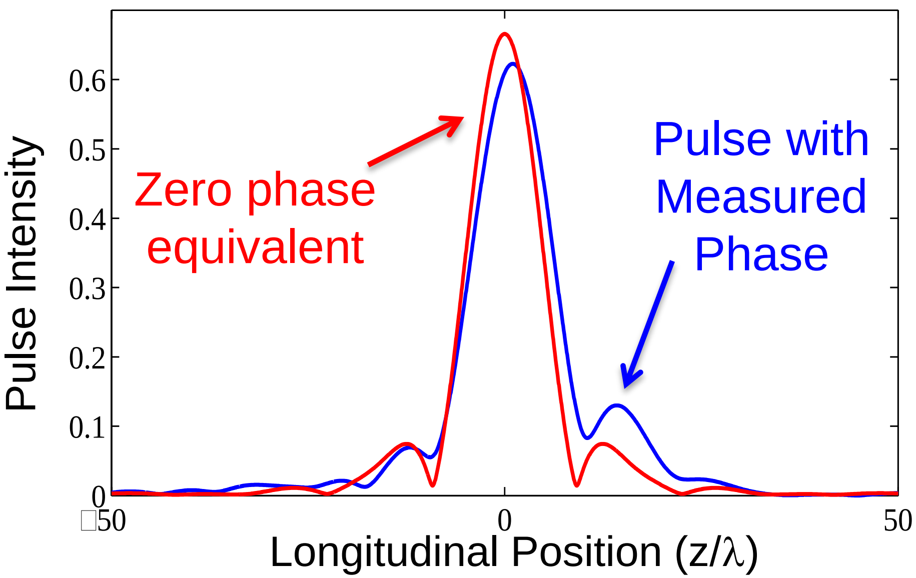
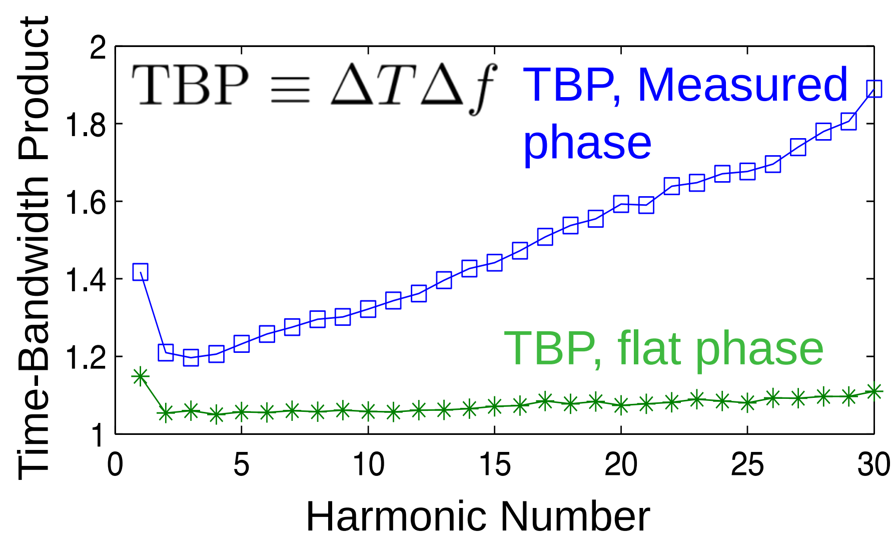






Phase Measurement Methods

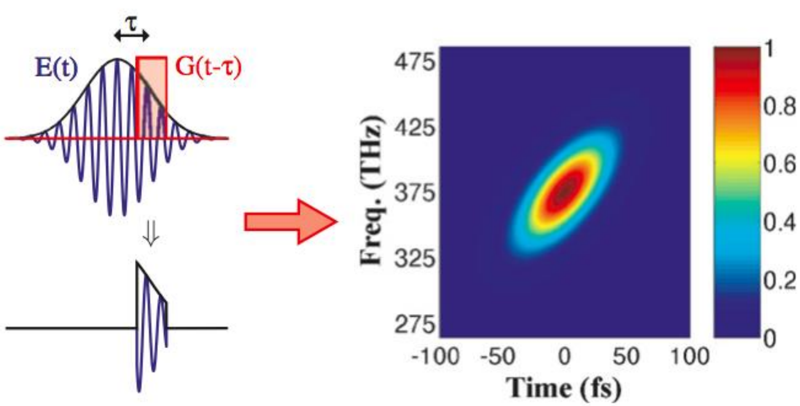
What are prospects for measuring phase in the UV?

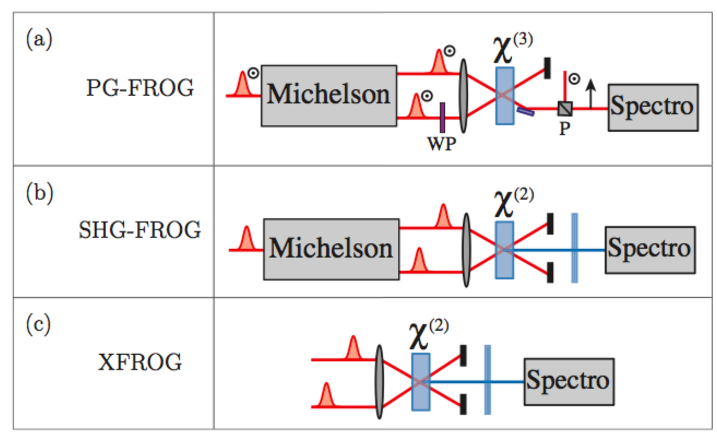
Frequency Resolved Optical Gating (FROG)


AIP | Review of Scientific Instruments

Measuring ultrashort laser pulses in the time-frequency domain using frequency-resolved optical gating

Rick Trebino, Kenneth W. DeLong, David N. Fittinghoff, John N. Sweetser, Marco A. Krumbügel et al.





 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)

1314 OPTICS LETTERS / Vol. 24, No. 18 / September 15, 1999

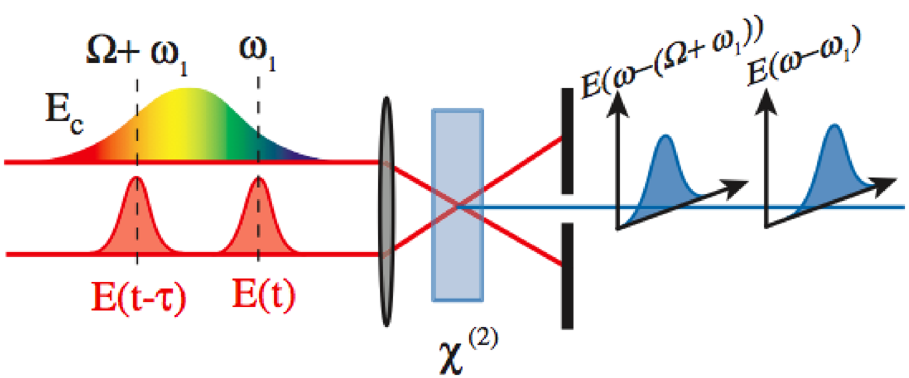
Characterization of sub-6-fs optical pulses with spectral phase interferometry for direct electric-field reconstruction

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

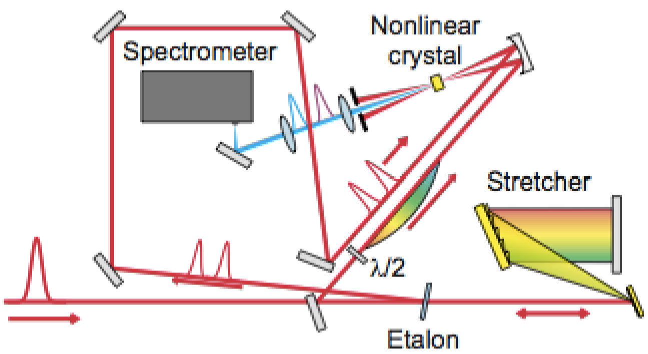
Ultrafast Laser Physics Laboratory, Institute of Quantum Electronics, Swiss Federal Institute of Technology, ETH Hönggerberg-HPT, CH-8093 Zürich, Switzerland

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

VOLUME 90, NUMBER 7 PHYSICAL REVIEW LETTERS week ending 21 FEBRUARY 2003

Attosecond Spectral Shearing Interferometry

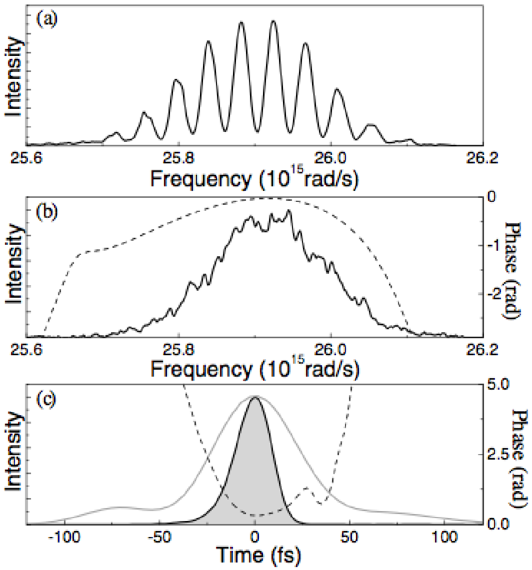
F. Quéré,* J. Itatani, G. L. Yudin, and P. B. Corkum
Steacie Institute for Molecular Sciences, National Research Council of Canada, Ottawa, Ontario, Canada K1A 0R6
(Received 18 December 2001; published 21 February 2003)

Measurements in the UV

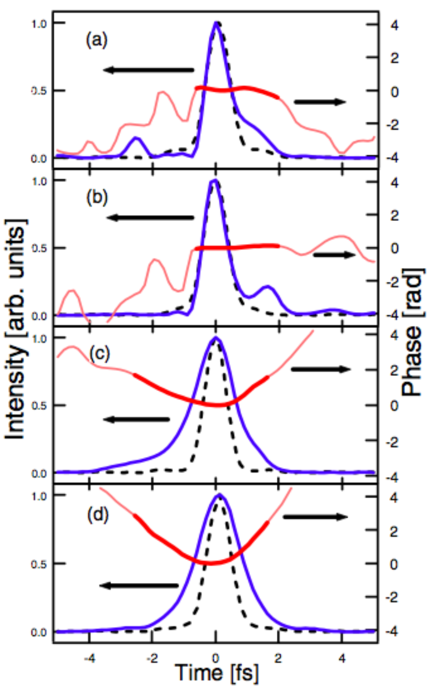
PRL **94,** 173903 (2005) PHYSICAL REVIEW LETTERS week ending 6 MAY 2005

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

Y. Mairesse, O. Gobert, P. Breger, H. Merdji, P. Meynadier, P. Monchicourt, M. Perdrix, P. Salières, and B. Carré
DSM-DRECAM-Service des Photons, Atomes et Molécules, CEA Saclay, 91191 Gif-sur-Yvette Cedex, France
(Received 8 December 2004; published 5 May 2005)



SPIDER



FROG

PRL **97,** 263901 (2006) PHYSICAL REVIEW LETTERS week ending 31 DECEMBER 2006

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

A. Kosuge, T. Sekikawa, X. Zhou, T. Kanai, S. Adachi, and S. Watanabe
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

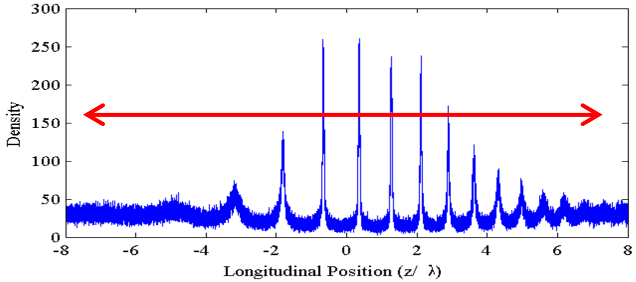
Thanks for Listening!

Gaussian Laser Profile

How does time domain change effect of laser phase?

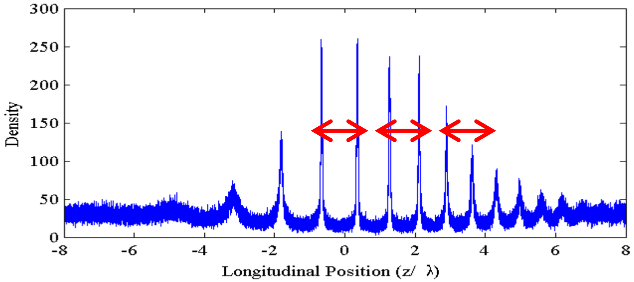
Averaged Bunching Factor

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



Slice Bunching Factor

$$b_{\mathrm{slice,k}}(z) \equiv \frac{1}{N_{\mathrm{slice}}(z)} \sum_{j=1}^{N_{\mathrm{slice}}(z)} e^{ik\bar{z}_j}$$



Phase Measurement Methods

What are prospects for measuring phase in the UV?

Multipulse Intrapulse Interference Phase Scan (MIIPS)

April 1, 2004 / Vol. 29, No. 7 / OPTICS LETTERS 775

Multiphoton intrapulse interference. IV. Ultrashort laser pulse spectral phase characterization and compensation

Vadim V. Lozovoy, Igor Pastirk, and Marcos Dantus

Department of Chemistry and Physics, Michigan State University, East Lansing, Michigan 48824-1322

Use known phase to control AND correct phase

$$\phi''(\Delta) = -f''(\Delta)$$

Pulse phase Known phase

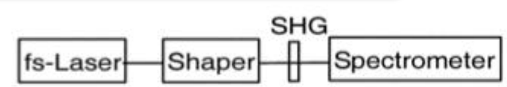
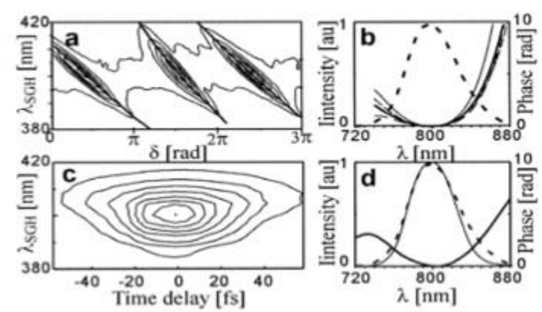


Fig. 1. Experimental setup of the MIIPS.



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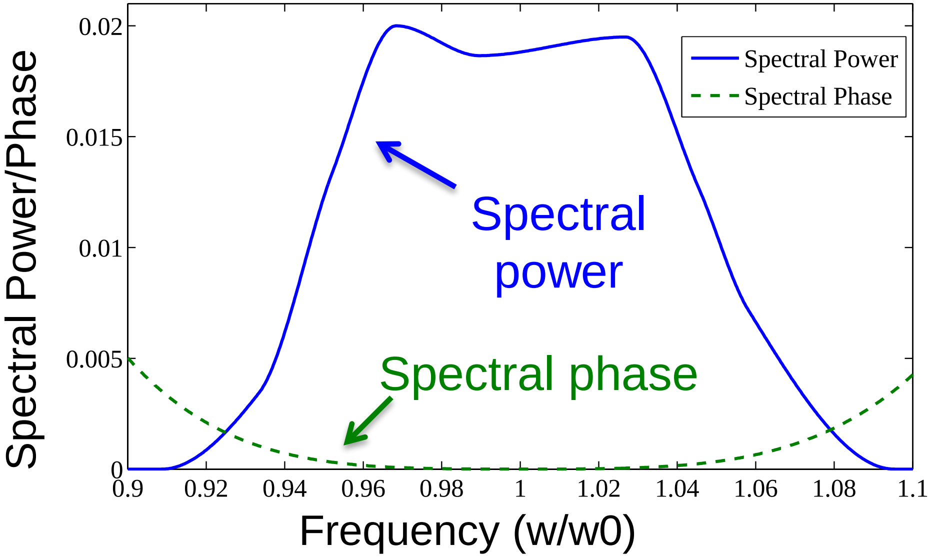

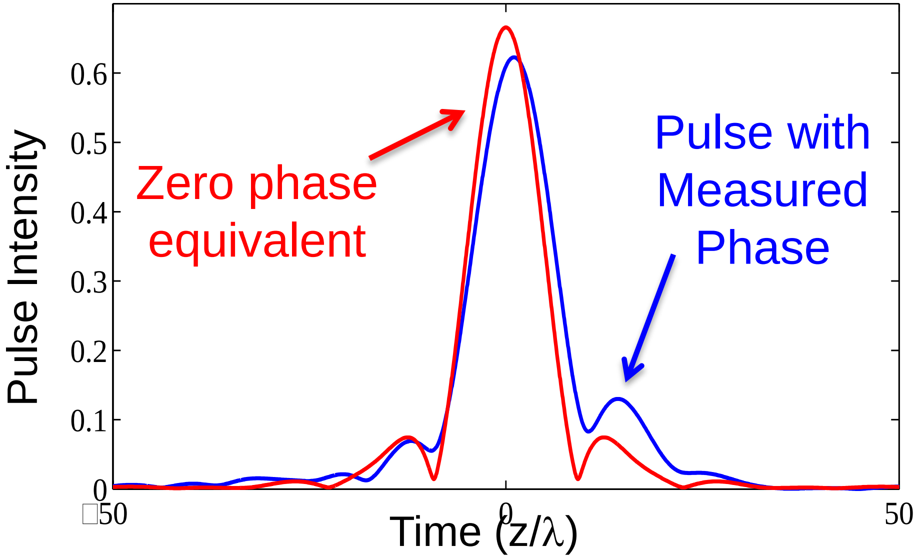

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