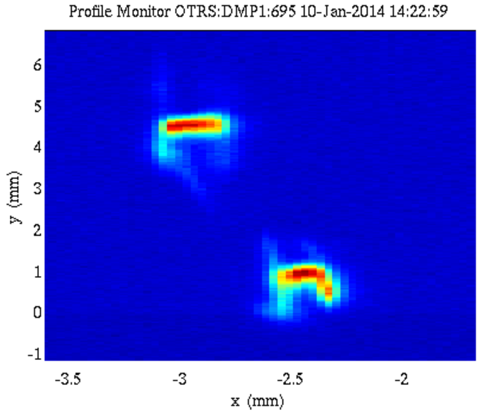

Double Bunch Operation for High Intensity Two-Color X-Rays

Agostino Marinelli

SLAC

International Free-Electron Laser Conference

Aug 28, 2014

Basel

U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

Outline of the Talk

1) Two Color FEL Operation at LCLS

2) Double Bunch FEL

3) Experimental Demonstration and User Operation

4) Conclusions

2 Color Free-Electron Lasers

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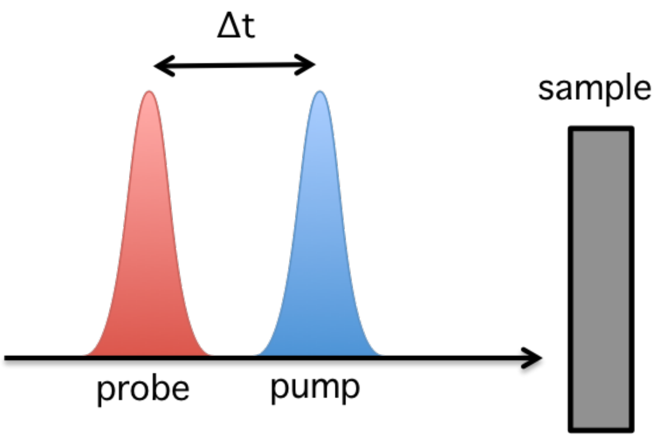

$$\lambda_{1,2} = \lambda_w \frac{1+K_{1,2}^2}{2\gamma^2}$$

$$\lambda_{1,2} = \lambda_w \frac{1+K^2}{2\gamma_{1,2}^2}$$

2 pulses with

-tunable energy difference

-tunable arrival time

Many applications!

- x-ray pump/x-ray probe
- 2 color diffraction imaging

PRL 110, 134801 (2013) PHYSICAL REVIEW LETTERS week ending 29 MARCH 2013

Experimental Demonstration of Femtosecond Two-Color X-Ray Free-Electron Lasers

A. A. Lutman, R. Coffee, Y. Ding,* Z. Huang, J. Krzywinski, T. Maxwell, M. Messerschmidt, and H.-D. Nuhn
SLAC National Accelerator Laboratory, Menlo Park, California 94025, USA
(Received 13 December 2012; published 25 March 2013)

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Multicolor Operation and Spectral Control in a Gain-Modulated X-Ray Free-Electron Laser

A. Marinelli,[1,*] A. A. Lutman,[1] J. Wu,[1] Y. Ding,[1] J. Krzywinski,[1] H.-D. Nuhn,[1] Y. Feng,[1] R. N. Coffee,[1] and C. Pellegrini[2,1]

ARTICLE

Received 8 Sep 2013 | Accepted 12 Nov 2013 | Published 4 Dec 2013 DOI: 10.1038/ncomms3919

Two-colour hard X-ray free-electron laser with wide tunability

Toru Hara[1], Yuichi Inubushi[1], Tetsuo Katayama[2], Takahiro Sato[1,†], Hitoshi Tanaka[1], Takashi Tanaka[1], Tadashi Togashi[2], Kazuaki Togawa[1], Kensuke Tono[2], Makina Yabashi[1] & Tetsuya Ishikawa[1]

PRL 110, 064801 (2013) PHYSICAL REVIEW LETTERS week ending 8 FEBRUARY 2013

Chirped Seeded Free-Electron Lasers: Self-Standing Light Sources for Two-Color Pump-Probe Experiments

Giovanni De Ninno,[1,2] Benoît Mahieu,[1,2,3] Enrico Allaria,[2] Luca Giannessi,[2,4] and Simone Spampinati[2]

ARTICLE

Received 24 May 2013 | Accepted 21 Aug 2013 | Published 18 Sep 2013 DOI: 10.1038/ncomms3476 OPEN

Two-colour pump-probe experiments with a twin-pulse-seed extreme ultraviolet free-electron laser

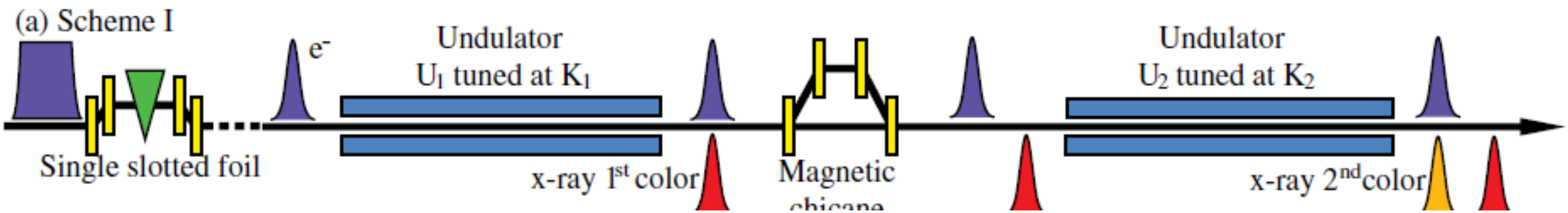
E. Allaria[1], F. Bencivenga[1], R. Borghes[1], F. Capotondi[1], D. Castronovo[1], P. Charalambous[2], P. Cinquegrana[1],

PRL 111, 114802 (2013) PHYSICAL REVIEW LETTERS week ending 13 SEPTEMBER 2013

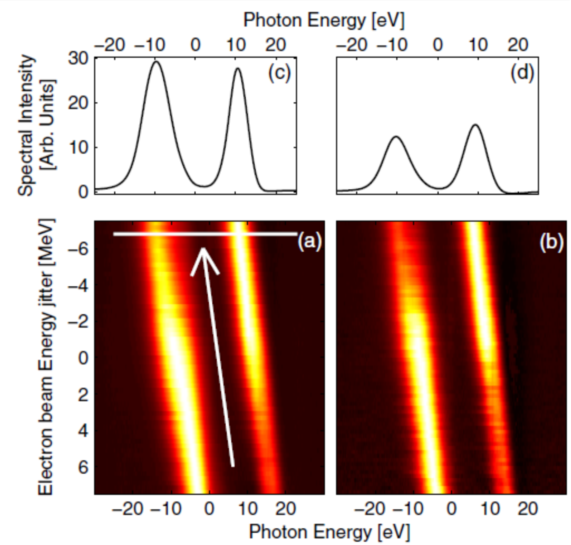
Observation of Time-Domain Modulation of Free-Electron-Laser Pulses by Multipeaked Electron-Energy Spectrum

V. Petrillo,[1] M. P. Anania,[2] M. Artioli,[3] A. Bacci,[1] M. Bellaveglia,[2] E. Chiadroni,[2] A. Cianchi,[4] F. Ciocci,[3] G. Dattoli,[3] D. Di Giovenale,[2] G. Di Pirro,[2] M. Ferrario,[2] G. Gatti,[2] L. Giannessi,[3] A. Mostacci,[5] P. Musumeci,[6] A. Petralia,[3] R. Pompili,[4] M. Quattromini,[3] J. V. Rau,[7] C. Ronsivalle,[3] A. R. Rossi,[1] E. Sabia,[3] C. Vaccarezza,[2] and F. Villa[2]

Split Undulator Scheme



$$\lambda_{1,2} = \lambda_w \frac{1+K_{1,2}^2}{2\gamma^2}$$



Split undulator in 2 parts.

Use magnetic chicane to introduce delay

Easy to tune!

~1/10 to 1/5 of SASE power

Controllable delay up to 40 fs.

PRL 110, 134801 (2013) PHYSICAL REVIEW LETTERS week ending 29 MARCH 2013

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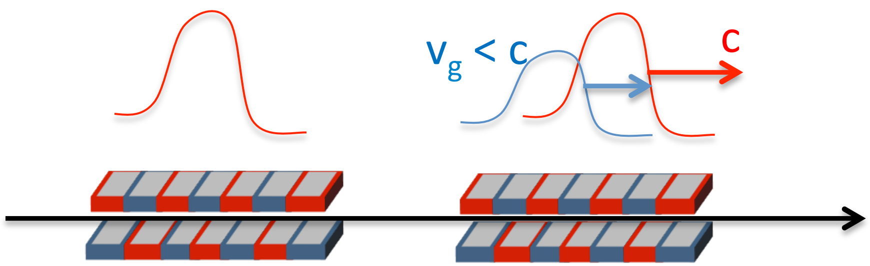
Gain-Modulation

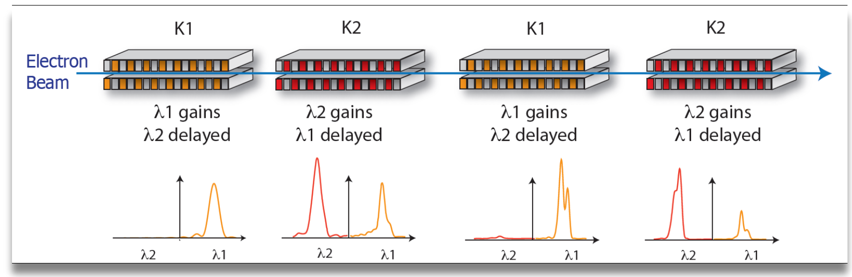
Split undulator yields minimum delay of 2/3 slippage length



At soft x-rays that's ~ a few fs

For short pulse applications it's a real problem!

Solution: discretely modulate undulator



2 colors catch up to each other -> 0 delay!

$$\lambda_{1,2} = \lambda_w \frac{1 + K_{1,2}^2}{2\gamma^2}$$

PRL **111,** 134801 (2013) PHYSICAL REVIEW LETTERS week ending 27 SEPTEMBER 2013

Multicolor Operation and Spectral Control in a Gain-Modulated X-Ray Free-Electron Laser

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Limiting Factors

$$\lambda_{1,2} = \lambda_w \frac{1+K_{1,2}^2}{2\gamma^2}$$

1) In either scheme both colors emitted by one bunch:
CAN'T REACH SATURATION!

2) Each color uses half undulator:
At HXR pulse energy is limited to ~100 μJ

How Can We Improve?

SLAC

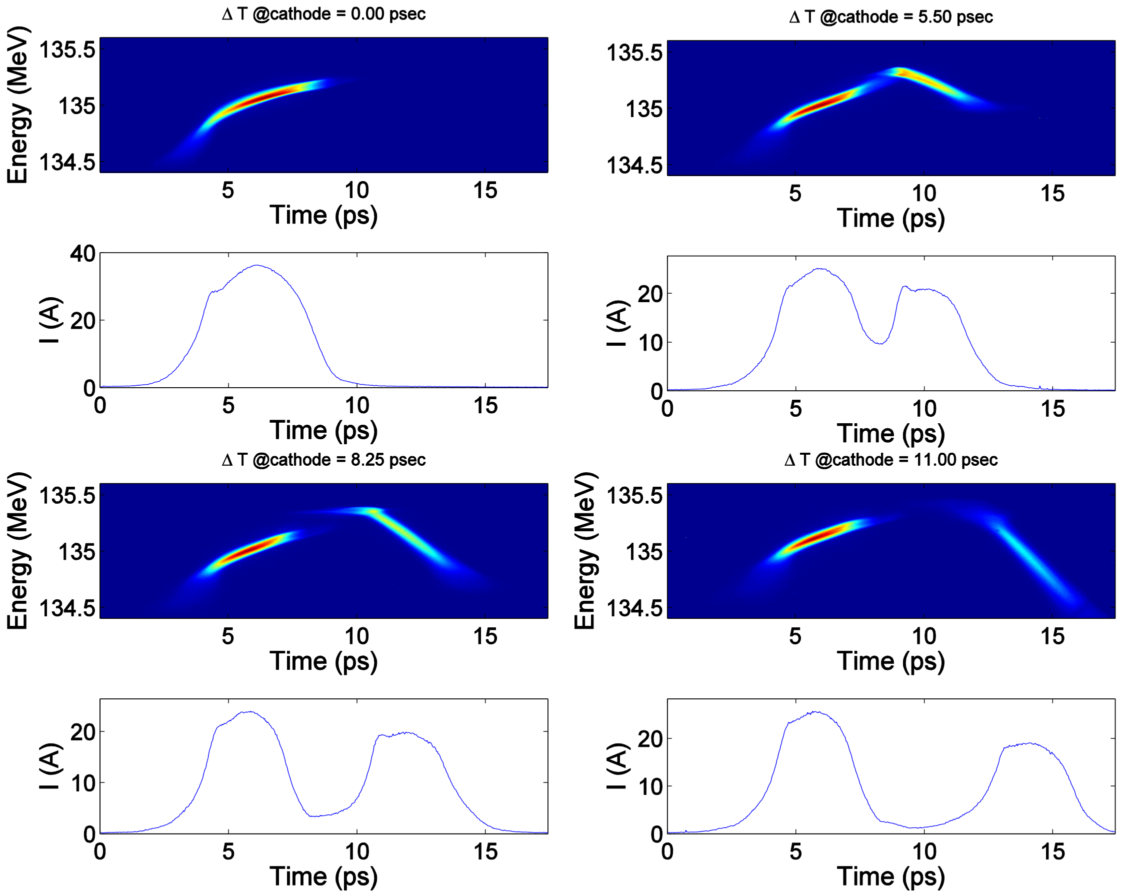
$$\lambda_{1,2} = \lambda_w \frac{1 + K^2}{2\gamma_{1,2}^2}$$

If we generate a beam with two energy bands and send it down the undulator:

1) Each color can saturate

2) Each color uses the whole undulator (improvement by a factor ~ 20 at HXR!)

Longitudinal Phase Space in Injector



Total charge 150 pC

Bunches separate around 6 ps delay

Projected emittance 0.4 um after solenoid and correction quad tuning

(comparable to standard operation…)

Unspoiled Phase-Space

Figure removed pending publication

Compressed to ~5 kA

Time delay ~ 35 fs

$\Delta E = 70$ MeV

Lasing

SLAC

Figure removed pending publication

Peak power ~ 60 GW

Time separation
ΔT = 35 fs

Individual duration
dT = 10 fs

E_{pulse} = 1.2 mJ

IMPROVEMENT OF 1 ORDER OF MAGNITUDE OVER STATE OF THE ART @HXR

Spectral Properties

Figure removed pending publication

Figure removed pending publication

90 eV Separation
10-15 eV bandwidth

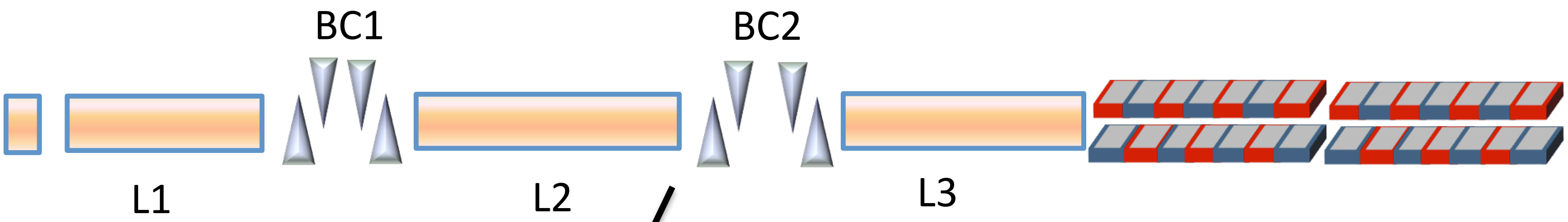
Seeded Spectra

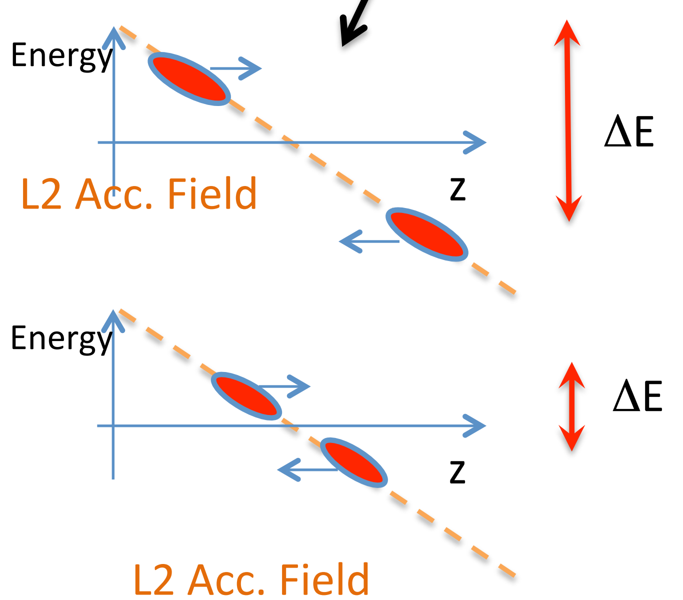
Figure removed pending publication

Figure removed pending publication

Pulse energy down to 130 uJ
Spectral brigthness x 2!

Spectral Control





Stronger BC1 compression

↓

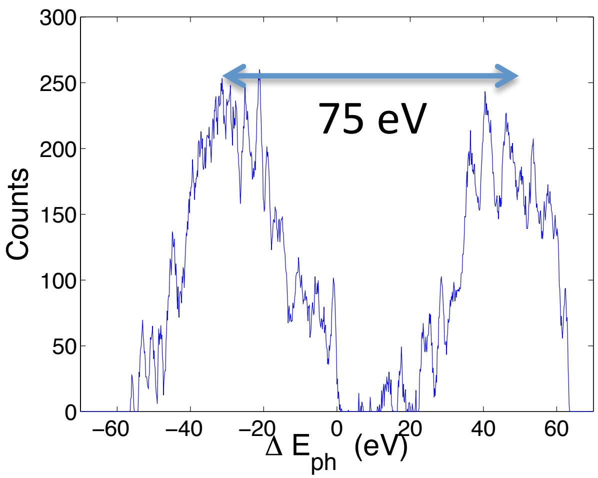
Two bunches are closer in phase in L2

↓

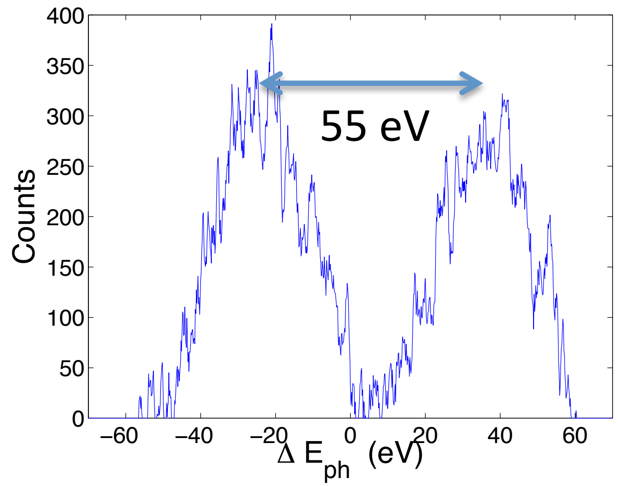
Smaller energy separation

Spectral Control

L1 phase = -21.5



L1 phase = -23



Energy separation is controlled by L1 phase

(non-binned average spectra)

Time Delay Tunability

Time delay is tunable
INDEPENDENTLY of
-energy separation
-compression

Time Delay range
10 – 150 fs

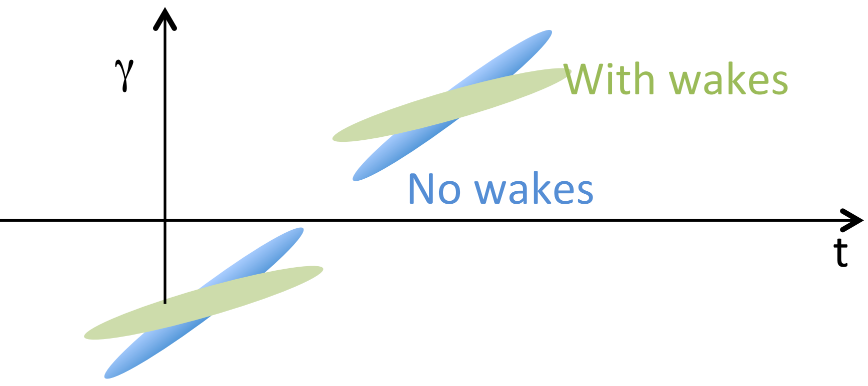
Note: at HXR and 150 pC
High energy pulse comes first!

(not true at lower charge OR
lower energy)

Figure removed pending publication

Figure removed pending publication

Why and How



ΔE at compressor entrance

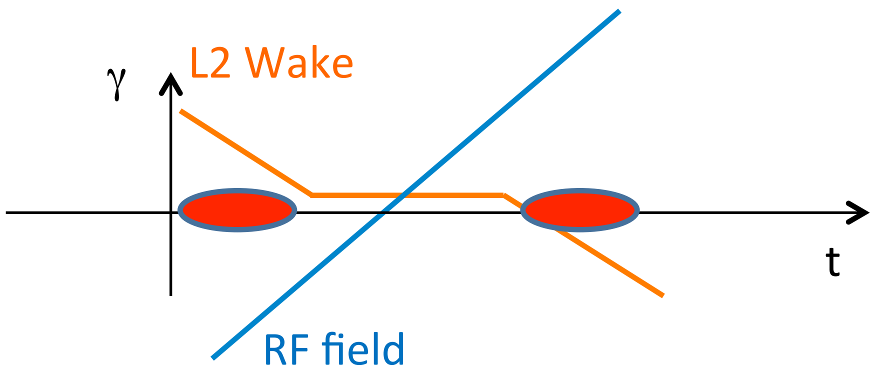
IS NOT chirp x ΔT

Because wakes remove the chirp of each bunch

BUT

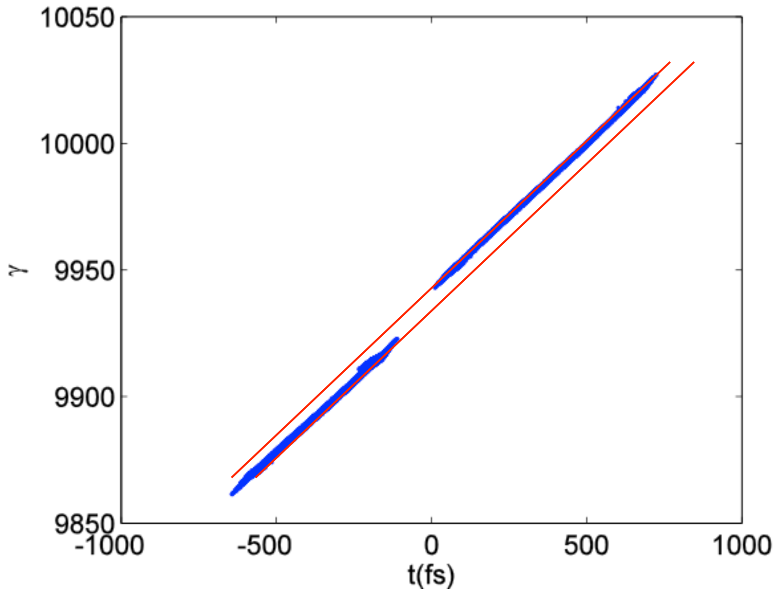
do not grow between the two bunches

(i.e. they have little effect on DE)



Why and How

@BC2 entrance



Elegant simulation

ΔE at compressor entrance

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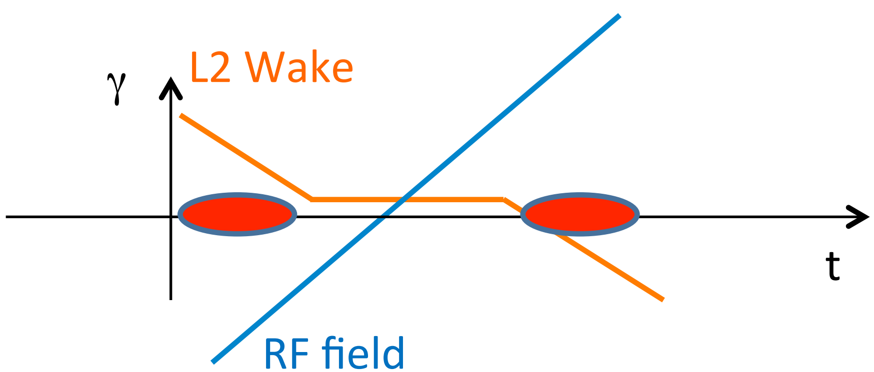

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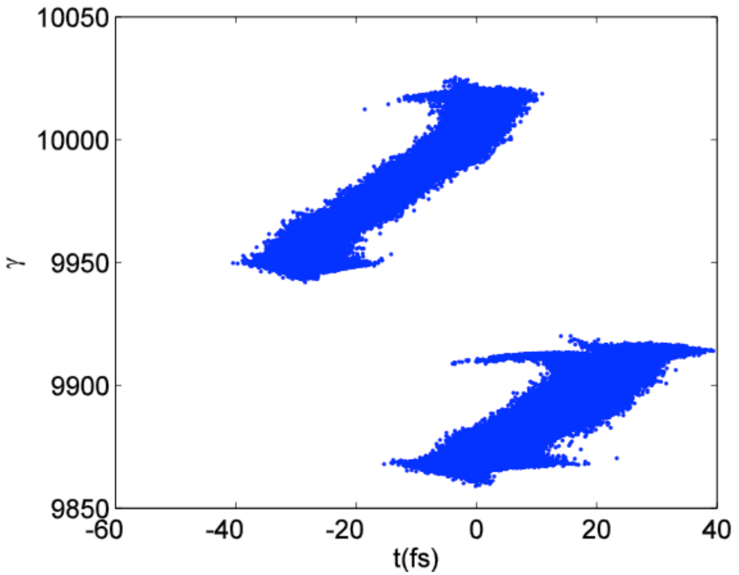


Elegant simulation

Bunches go through time overlap
UNDER-COMPRESSED

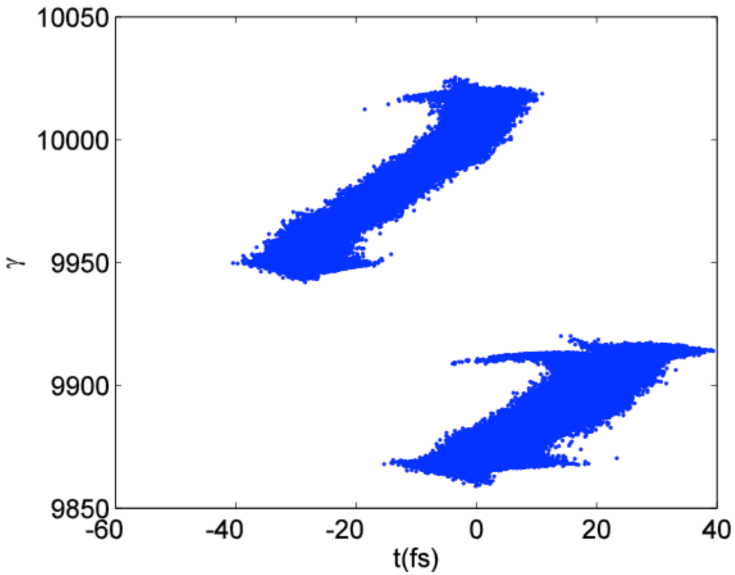
(note: in the absence of wakes
0 delay <---> full compression)

For each compression stage:

$$\Delta T_{final} = \frac{\Delta T_{initial}}{C_{factor}} + \Delta T_{GAP} \times \frac{1}{E}\frac{dE}{dt}_{wakes} \times \frac{R56}{c}$$

Final time delay depends on:
- -Initial delay
- -Total compression
- -Intermediate compression

Why and How



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Wake-induced delay

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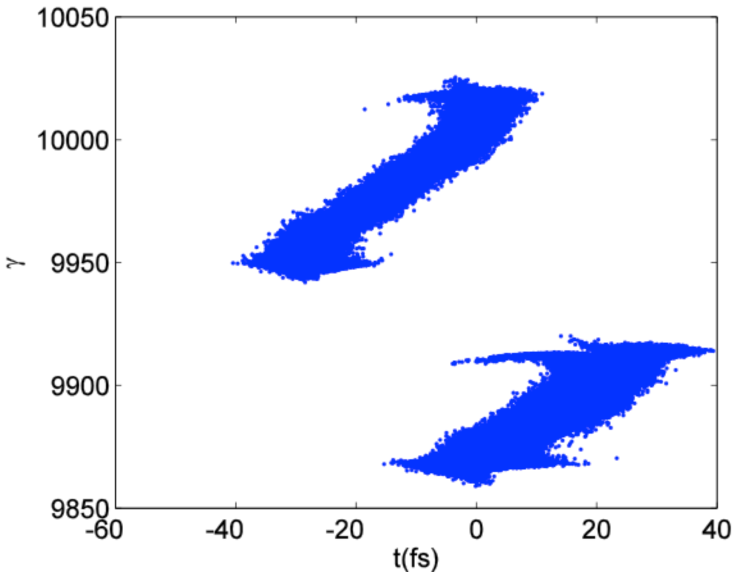

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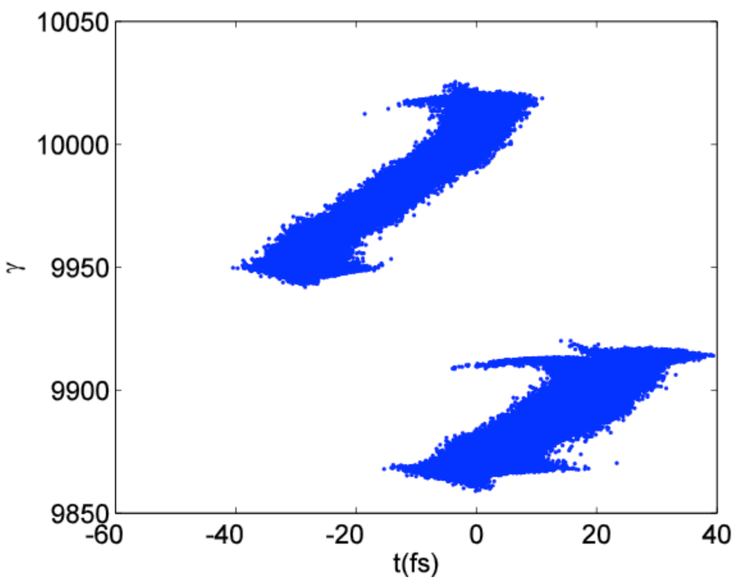
Why and How

SLAC



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- -Intermediate compression

Recipe for Delay Tuning

Increase cathode delay

↓

Compensate energy separation by increasing BC1 compression

↓

Compensate for overall compression by varying BC2 compression

↓

Larger delay in undulator

6-10 ps range at cathode

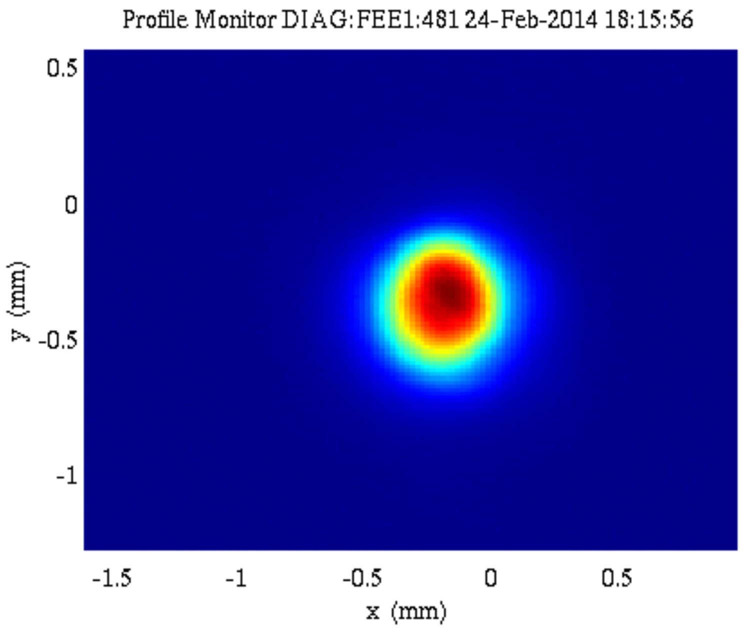
≈

10-100 fs range in undulator

CAN BE EXTENDED TO NEGATIVE DELAYS BY TUNABLE CHICANEWITH R56<0 (currently under study!)

Figure removed pending publication

Transverse Overlap



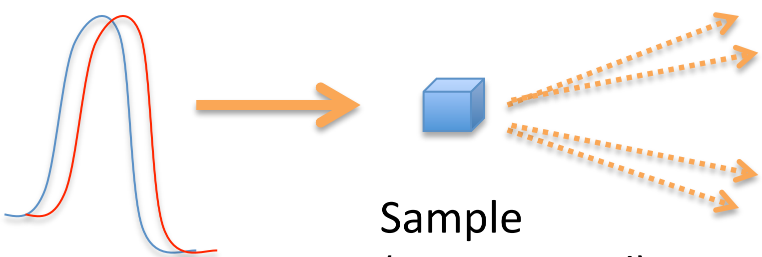
Good transverse overlap easily achievable.

(tweaking 1 dispersion quad and orbit in x-band linearizer does the trick!)

Good overlap is also observed in user hutches after transport!

Two Color X-FELs: Multi-Wavelength Anomalous Dispersion

Two pulses ~ simultaneous



Sample
(nano-crystal)

Figure removed pending publication

Diffraction
Pattern

1st pulse: tuned above absorption edge -> Does not diffract off of heavy atoms

2nd pulse: below absorption-edge -> Diffracts off of all atoms

De novo phase reconstruction from the two split diffraction patterns…

Operational Experience with Users

4 User Experiments Already Successfully Performed

~1-2 hours of initial tuning for SASE
~2-3 hours for self-seeding

Changing time delay takes ~ 30 min for large delays, few mins for small delays

Typically achieve OVER 1 mJ of SASE for 5 days straight.

Conclusions

SLAC

- 2-Bunch Operation has been successfully demonstrated at HXR:
  - High Power (1.3 mJ / 50-60 GW) 2 Color SASE improves performance by a factor 20 at HXR
  - 2 Color Self-Seeding on a large bandwidth enables new imaging and pump-probe experiments!
  - Single-shot non-destructive diagnostic of double pulse using x-tcav.
- Already delivered to users…Performance expected to improve as more experience is acquired

Acknowledgements

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