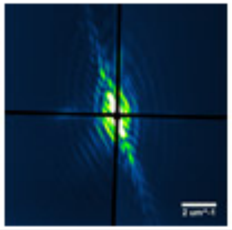
A proposal for a mode-locked hard x-ray free-electron laser

Ryan Lindberg and Alexander Zholents
Argonne National Laboratory

SSSFEL12



Seeding and Self-seeding at New FEL Sources
ICTP, Adriatico Guesthouse / Trieste, Italy / 10-12 December 2012

X-ray FELs enable new science

LETTER

Femtosecond X-ray protein nanocrystallography

PRL 104, 253002 (2010) PHYSICAL REVIEW LETTERS week ending 25 JUNE 2010

Ultraintense X-Ray Induced Ionization, Dissociation, and Frustrated Absorption in Molecular Nitrogen

M. Hoener,[1,2] L. Fang,[1] O. Kornilov,[3] O. Gessner,[3] S. T. Pratt,[4] M. Gühr,[5] E. P. Kanter,[4] C. Blaga,[6] C. Bostedt,[7] J. D. Bozek,[7] P. H. Bucksbaum,[5] C. Buth,[5,8] M. Chen,[9] R. Coffee,[7] J. Cryan,[5] L. DiMauro,[6] M. Glownia,[5] E. Hosler,[10] E. Kukk,[11] S. R. Leone,[3,10] B. McFarland,[5] M. Messerschmidt,[7] B. Murphy,[1] V. Petrovic,[5] D. Rolles,[12] and N. Berrah[1,*]

[1]Western Michigan University Physics Department, Kalamazoo, Michigan 49008, USA
[2]Advanced Light Source, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA
[3]Ultrafast X-ray Science Laboratory Chemical Sciences Division Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA
[4]Argonne National Laboratory, Argonne, Illinois 60439, USA
[5]The PULSE Institute for Ultrafast Energy Science, SLAC National Accelerator Laboratory, Menlo Park, California 94025, USA
[6]The Ohio State University, Department of Physics, Columbus, Ohio 43210, USA
[7]Linac Coherent Light Source, SLAC National Accelerator Laboratory, Menlo Park, California 94025, USA
[8]Department of Physics, Louisiana State University, Baton Rouge, Louisiana 70803, USA
[9]Lawrence Livermore National Laboratory, Livermore, California 94550, USA
[10]Department of Chemistry and Physics University of California, Berkeley, California 94710, USA
[11]Department of Physics and Astronomy, University of Turku 20014 Turku, Finland
[12]Max Planck Advanced Study Group, CFEL, 22761 Hamburg, Germany
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High-Resolution Protein Structure Determination by Serial Femtosecond Crystallography
Sébastien Boutet et al.
Science 337, 362 (2012);
DOI: 10.1126/science.1217737

High-Resolution Protein Structure Determination by Serial Femtosecond Crystallography

nature

Vol 466 | 1 July 2010 | doi:10.1038/nature09177

ARTICLES

Femtosecond electronic response of atoms to ultra-intense X-rays

L. Young[1], E. P. Kanter[1], B. Krässig[1], Y. Li[1], A. M. March[1], S. T. Pratt[1], R. Santra[1,2], S. H. Southworth[1], N. Rohringer[3], L. F. DiMauro[4], G. Doumy[4], C. A. Roedig[4], N. Berrah[5], L. Fang[5], M. Hoener[5,6], P. H. Bucksbaum[7], J. P. Cryan[7], S. Ghimire[7], J. M. Glownia[7], D. A. Reis[7], J. D. Bozek[8], C. Bostedt[8] & M. Messerschmidt[8]

LETTER

Single mimivirus particles intercepted and imaged with an X-ray laser

Time-resolved pump-probe experiments at the LCLS

James M. Glownia, J. Cryan, J. Andreasson, A. Belkacem, N. Berrah, C. I. Blaga, C. Bostedt, J. Bozek, L. F. DiMauro, L. Fang, J. Frisch, O. Gessner, M. Gühr, J. Hajdu, M. P. Hertlein, M. Hoener, G. Huang, O. Kornilov, J. P. Marangos, A. M. March, B. K. McFarland, H. Merdji, V. S. Petrović, C. Raman, D. Ray, D. A. Reis, M. Trigo, J. L. White, W. White, R. Wilcox, L. Young, R. N. Coffee, and P. H. Bucksbaum

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(C) 2010 OSA 16 August 2010 / Vol. 18, No. 17 / OPTICS EXPRESS 17620

Selected for a Viewpoint in Physics

PRL 109, 065002 (2012) PHYSICAL REVIEW LETTERS week ending 10 AUGUST 2012

Direct Measurements of the Ionization Potential Depression in a Dense Plasma

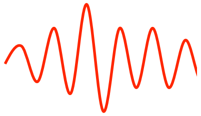
O. Ciricosta,[1] S. M. Vinko,[1] H.-K. Chung,[2] B.-I. Cho,[3] C. R. D. Brown,[4] T. Burian,[5] J. Chalupský,[5] K. Engelhorn,[3] R. W. Falcone,[3,6] C. Graves,[7] V. Hájková,[5] A. Higginbotham,[1] L. Juha,[5] J. Krzywinski,[7] H. J. Lee,[7] M. Messerschmidt,[7] C. D. Murphy,[1] Y. Ping,[8] D. S. Rackstraw,[1] A. Scherz,[7] W. Schlotter,[7] S. Toleikis,[9] J. J. Turner,[7] L. Vysin,[5] T. Wang,[7] B. Wu,[7] U. Zastrau,[10] D. Zhu,[7] R. W. Lee,[7] P. Heimann,[3] B. Nagler,[7] and J. S. Wark[1,*]

[1]Department of Physics, Clarendon Laboratory, University of Oxford, Parks Road, Oxford OX1 3PU, United Kingdom
[2]Atomic and Molecular Data Unit, Nuclear Data Section, IAEA, P.O. Box 100, A-1400, Vienna, Austria
[3]Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, California 94720, USA
[4]Plasma Physics Department, AWE Aldermaston, Reading, United Kingdom
[5]Institute of Physics ASCR, Na Slovance 2, 18221 Prague 8, Czech Republic
[6]Department of Physics, University of California, Berkeley, California 94720, USA
[7]SLAC National Accelerator Laboratory, 2575 Sand Hill Road, Menlo Park, California 94025, USA
[8]Lawrence Livermore National Laboratory, 7000 East Avenue, Livermore, California 94550, USA
[9]Deutsches-Elektronensynchrotron DESY, Notkestrasse 85, 22603 Hamburg, Germany
[10]IOQ, Friedrich-Schiller-Universität Jena, Max-Wien-Platz 1, 07743 Jena, Germany

… and this proposal seeks adding to XFELs new functionality customary for atomic lasers.

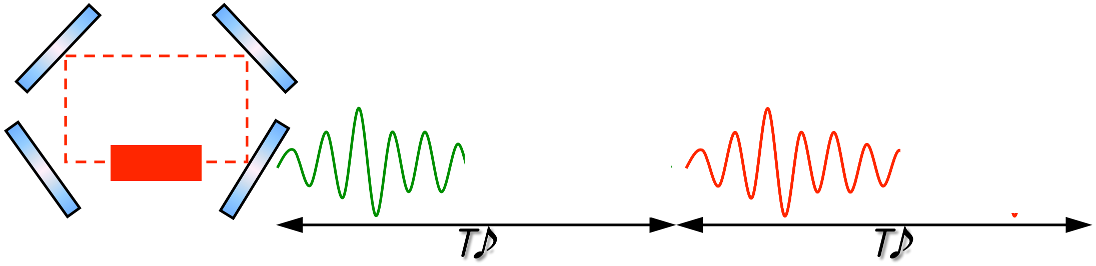
Cavity modes and frequency comb*

Single pulse♪



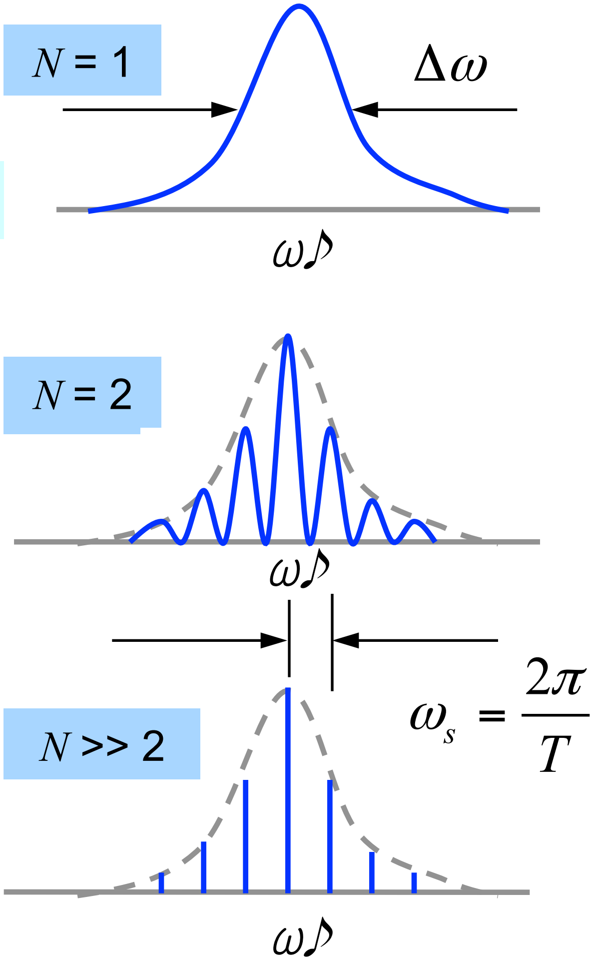
- $\Delta\omega$ is defined by atomic linewidth or gain bandwidth

Cavity with a round trip time = T♪



A repeated waveform generates a spectral comb

- Mode spacing $\omega_s=2\pi/T$
- Number of modes: $M = \Delta\omega/\omega_s$
- Linewidth of a mode ~ 1/N



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* A. E. Siegman, *Lasers* (University Science Books, Sausalito, USA, 1986). See Chap. 27.

Courtesy B.W.J. McNeil

Signal

$$\varepsilon^{(N)}(t) = \sum_{n-0}^{N-1} \varepsilon(t - nT)$$

Spectral intensity

$$I^{(N)}(\omega) \sim \left|\tilde{\varepsilon}^{(N)}(\omega)\right|^2$$

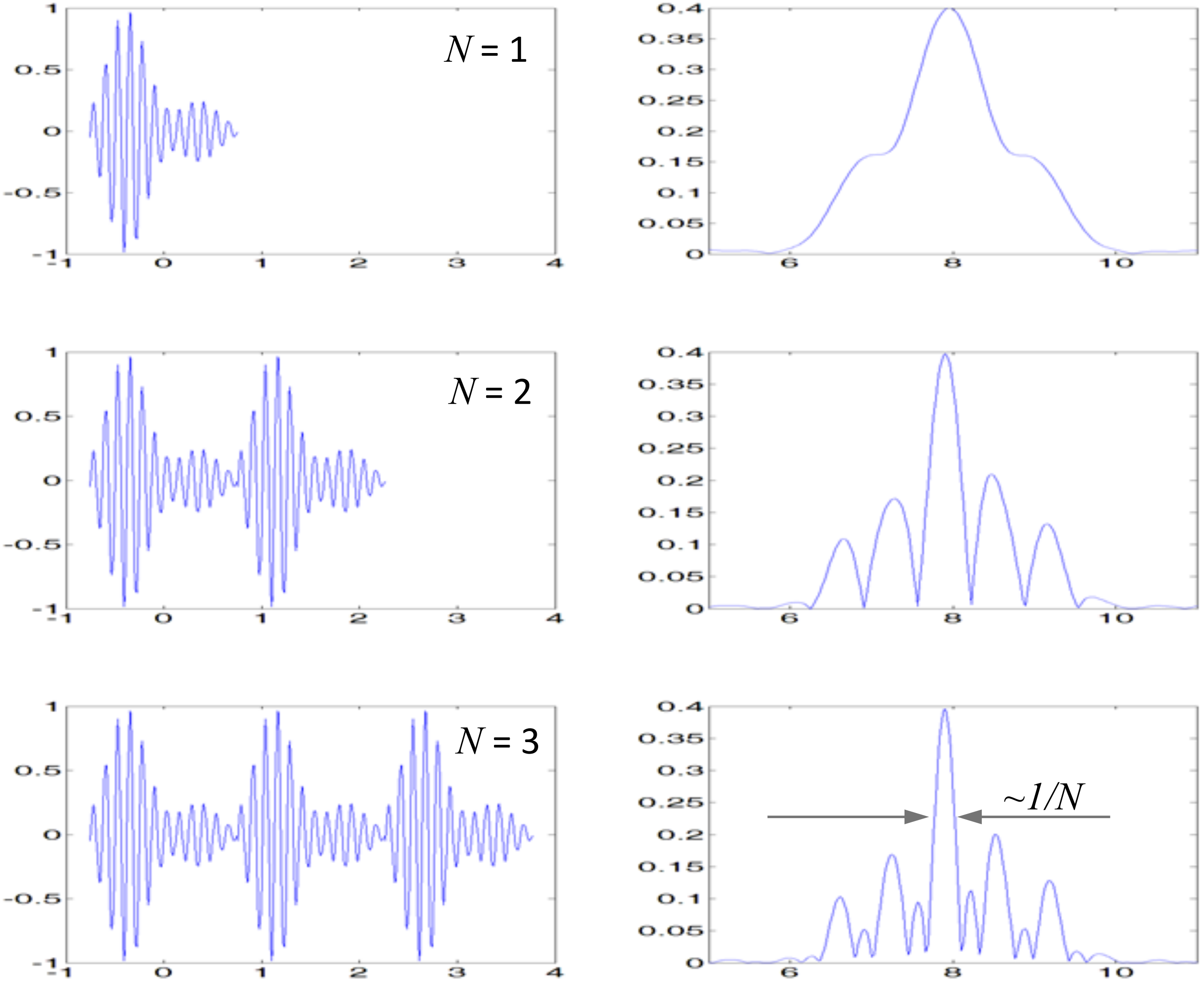
Applying Fourier time shifting identity and summation

$$F\{\varepsilon(t - nT)\} = e^{-in\omega T} F\{\varepsilon(t)\} \qquad \sum_{n=0}^{N-1} e^{in\omega T} = (1 - e^{iN\omega T}) / (1 - e^{i\omega T})$$

One obtains:

$$I^{(N)}(\omega) = \left(\frac{\sin(N\omega T / 2)}{\sin(\omega T / 2)}\right)^2 I^{(0)}(\omega)$$

$$I^{(N)}(\omega) = \left(\frac{\sin(N\omega T/2)}{\sin(\omega T/2)} \right)^2 I^{(0)}(\omega)$$

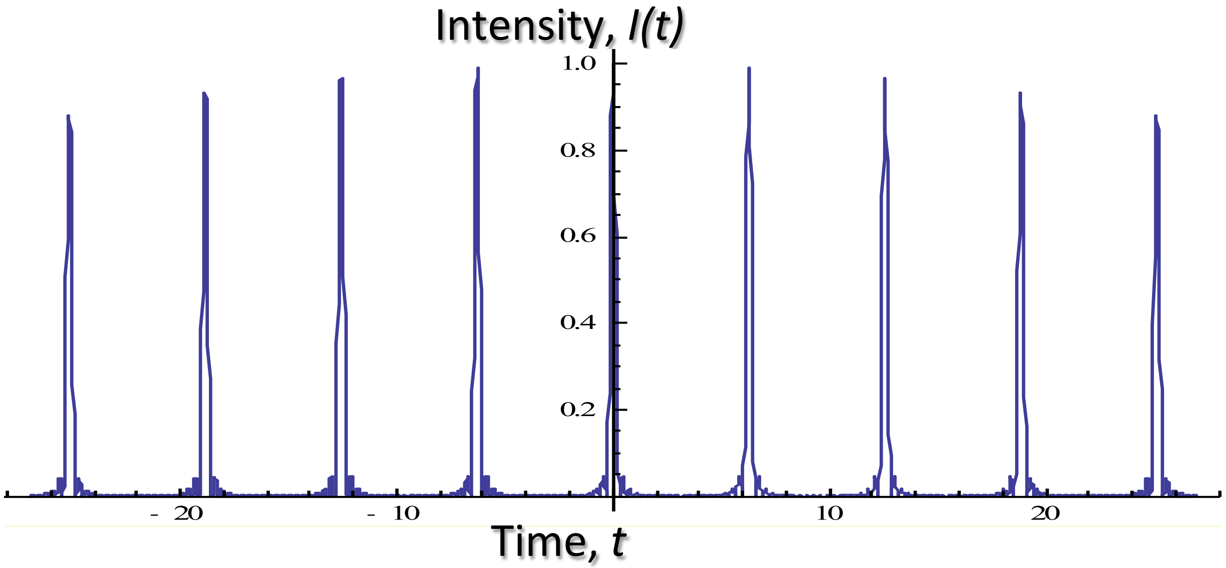


When the axial modes are all in phase, then the time-domain signal has a pulsed pattern, closely resembling the comb structure of the frequency domain:

$$\varepsilon^{(N)}(t) = \varepsilon_0 \sum_{n=0}^{N-1} e^{-i(\omega_0 + n\omega_s)t} = \varepsilon_0 e^{-i\omega_0 t} \frac{1-e^{-iN\omega_s t}}{1-e^{-i\omega_s t}}$$

(equal field amplitudes are assumed for simplicity)

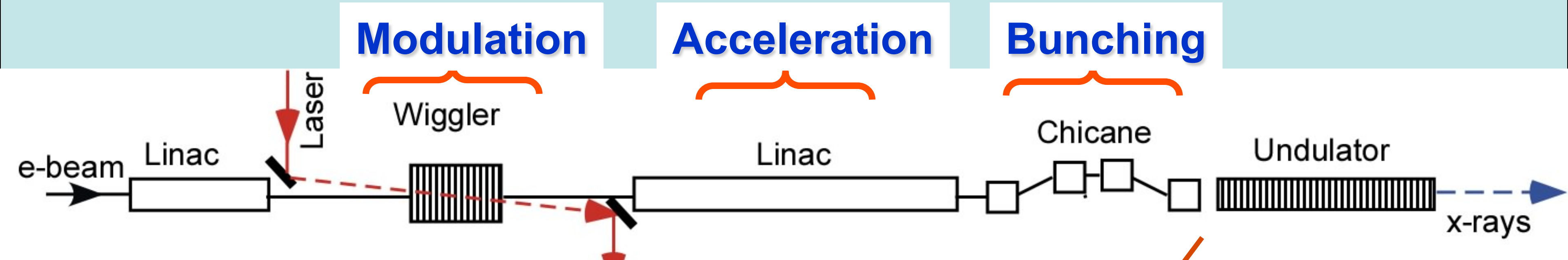
$$I^{(N)}(t) = \left(\frac{\sin(N\omega t/2)}{\sin(\omega t/2)}\right)^2 I^{(0)}(t)$$

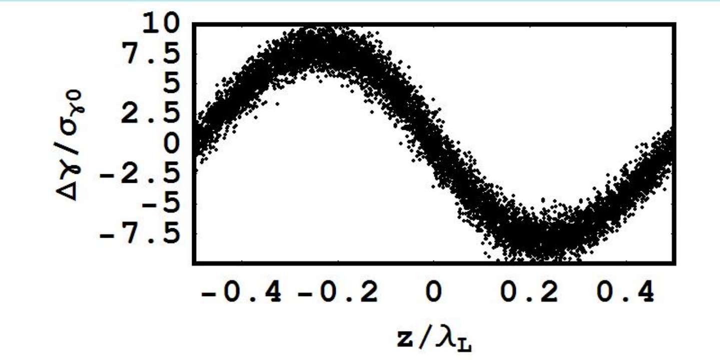


Modulation at round trip frequency or gain modulation causes mode-locking. A periodic pulse structure of sufficiently short pulses can be obtained when mode phase lock. Often locking only neighboring modes is sufficient.

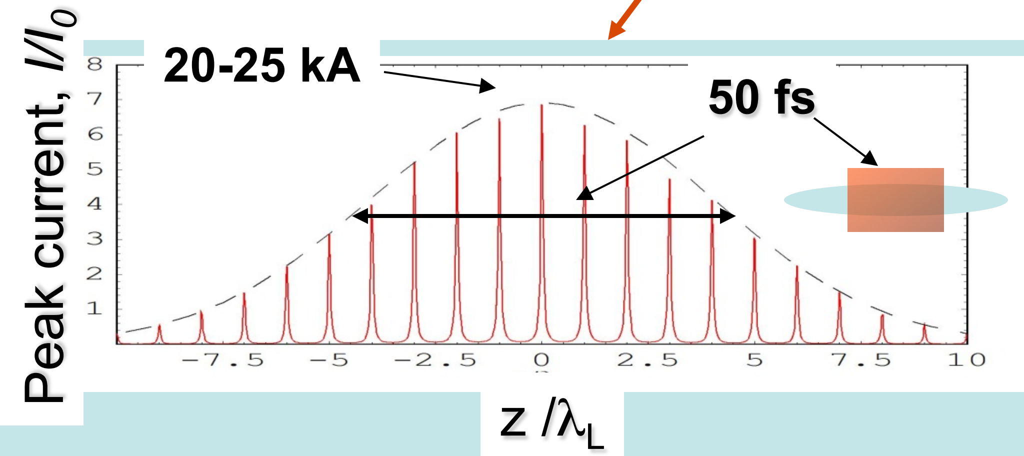
FEL gain modulation through peak current modulation*

Optical manipulation of electrons to obtain a “train” of microbunches



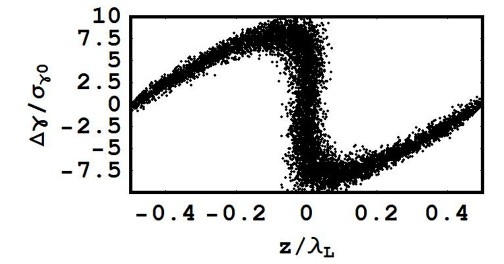


Only one optical cycle is shown



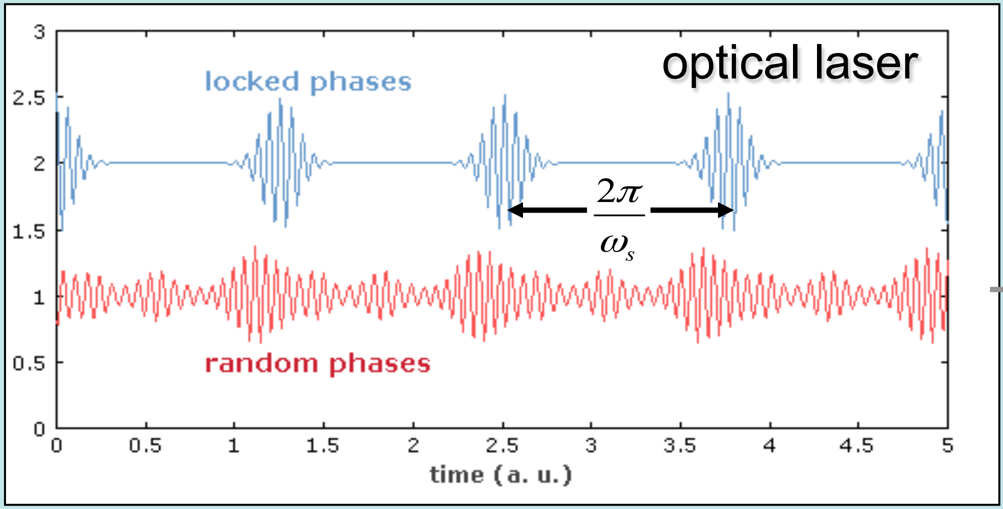
- Electron beam after bunching at optical wavelength

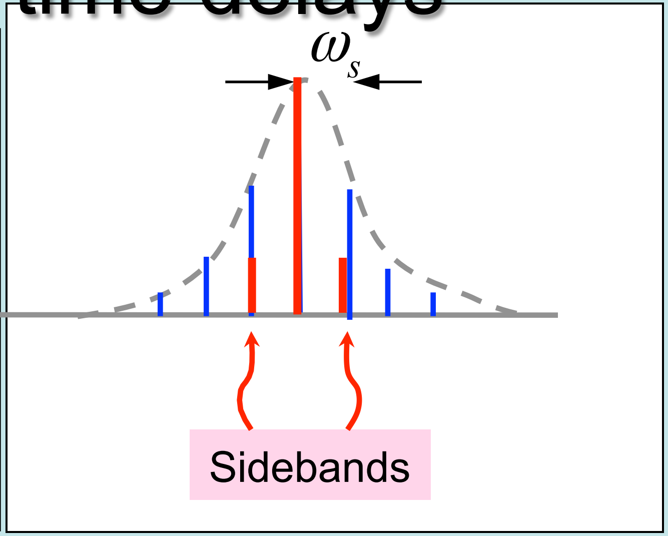
Region with large peak current gives the dominant x-ray radiation synchronized to laser source

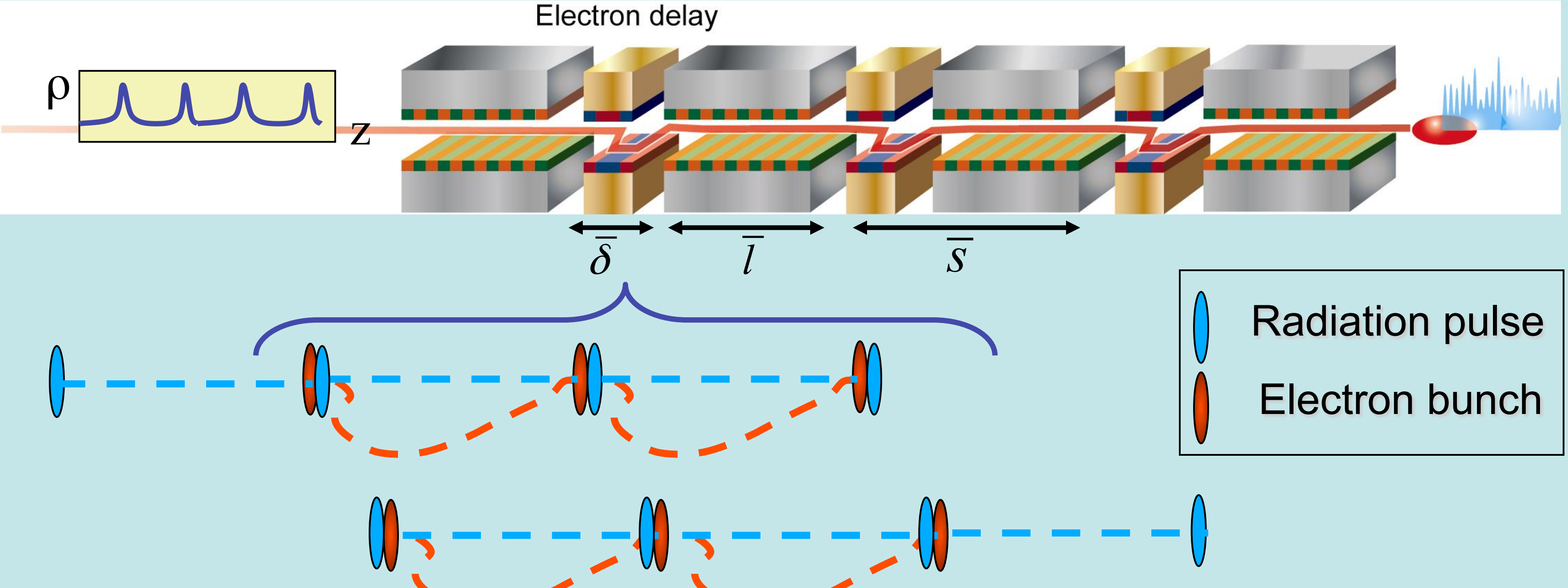


* A. Zholents, PRST-AB, **8**, 040701(2004).

Mode-locked FEL with electron time delays*







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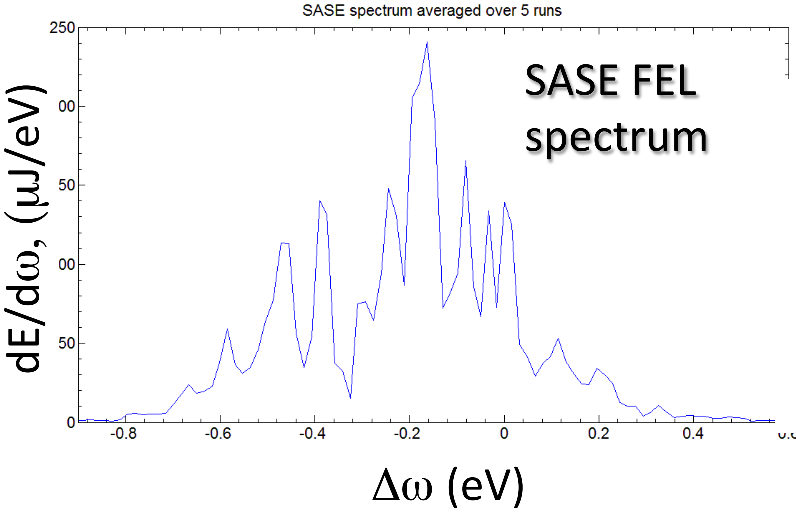
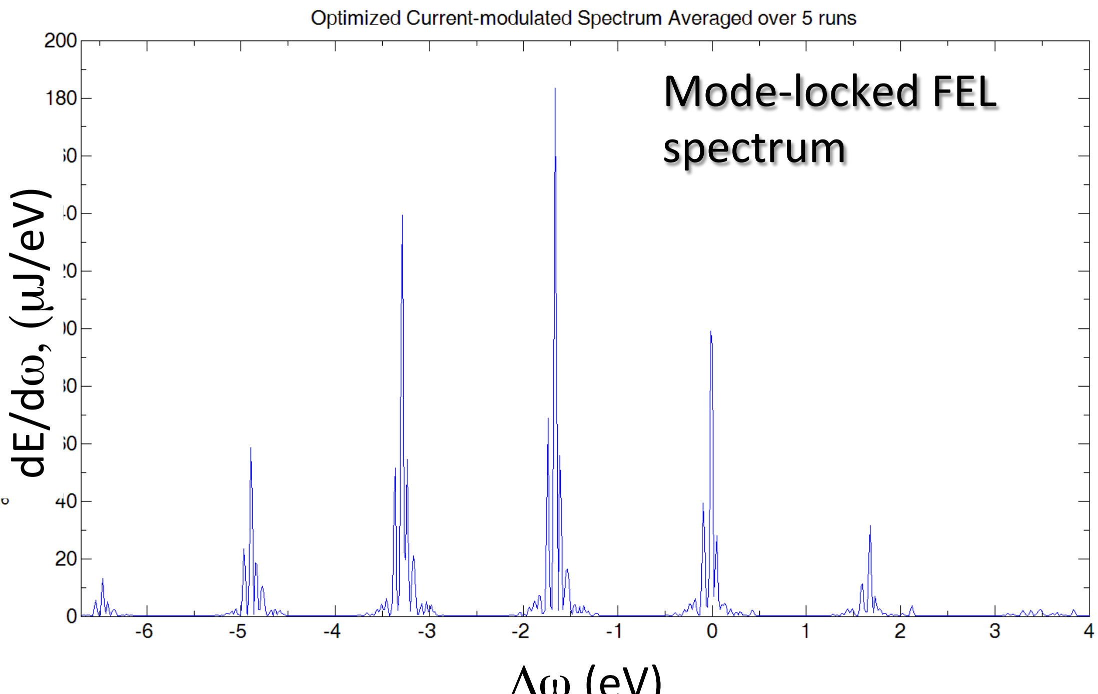
* N.R.Thompson and B.W.J.McNeil, PRL, 100, 203901(2008);
E. Kur, et al., New Journal of Phys., 13, 063012(2011);
C. Feng, et al., Phys. Rev. ST – AB, 15, 080703(2012).

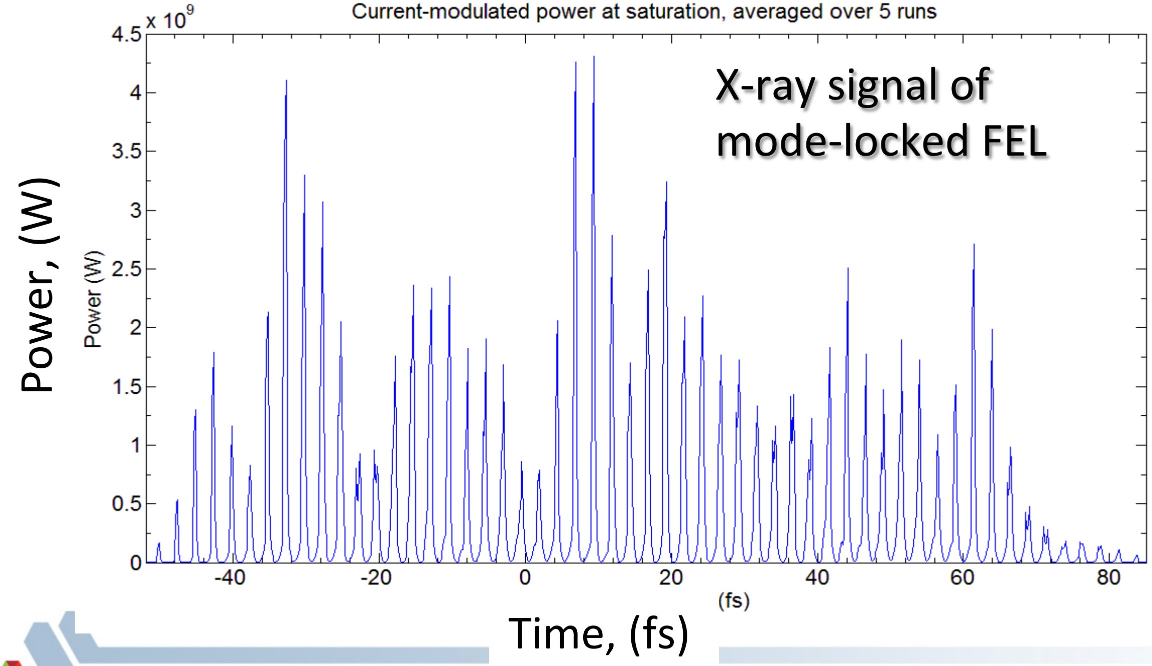
Courtesy B.W.J. McNeil



SASE FEL spectrum



Mode-locked FEL spectrum

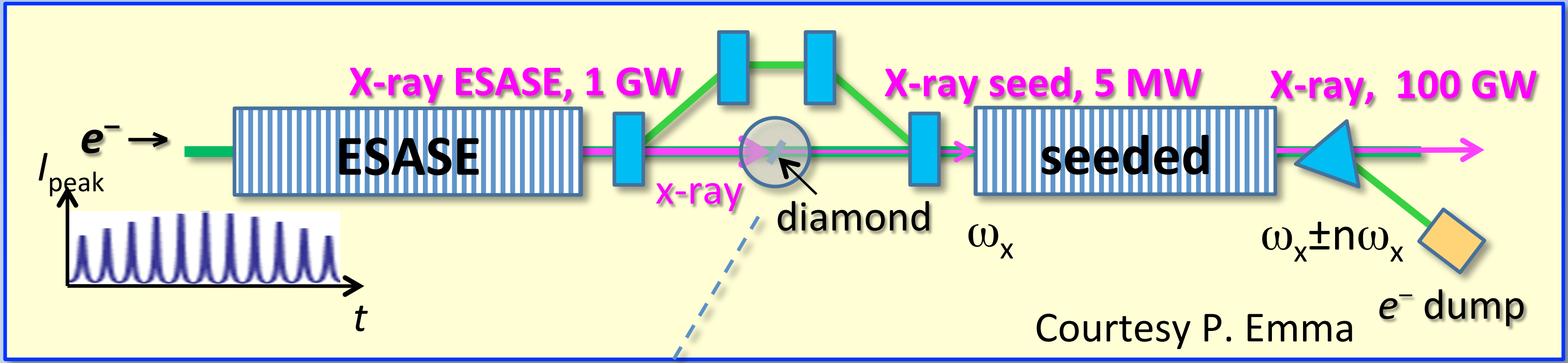


X-ray signal of mode-locked FEL

Generation of multiple frequency lines may enhance the capability of FELs in some specific applications:

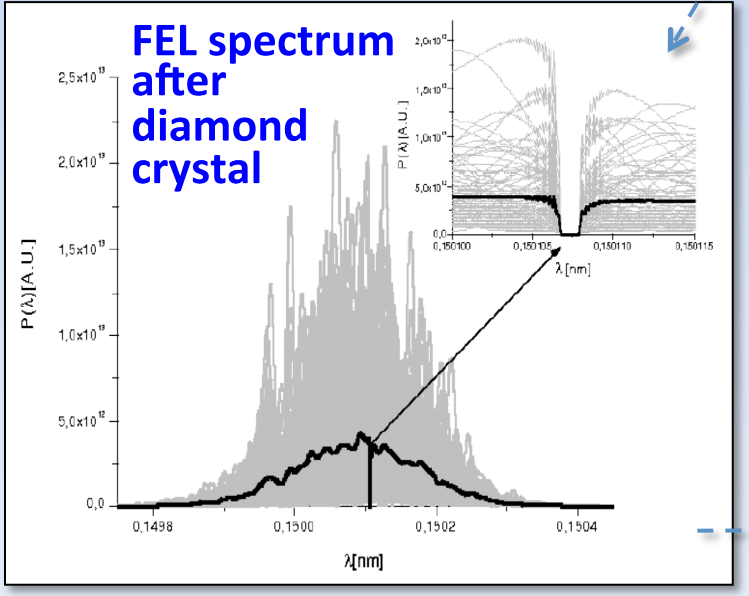
a) transmission and reflectivity spectra of various materials;
b) resonant inelastic x-ray scattering (RIXS);
c) ab-initio phasing of nanocrystals.

Self-seeding is a new path to a mode-locked FEL*



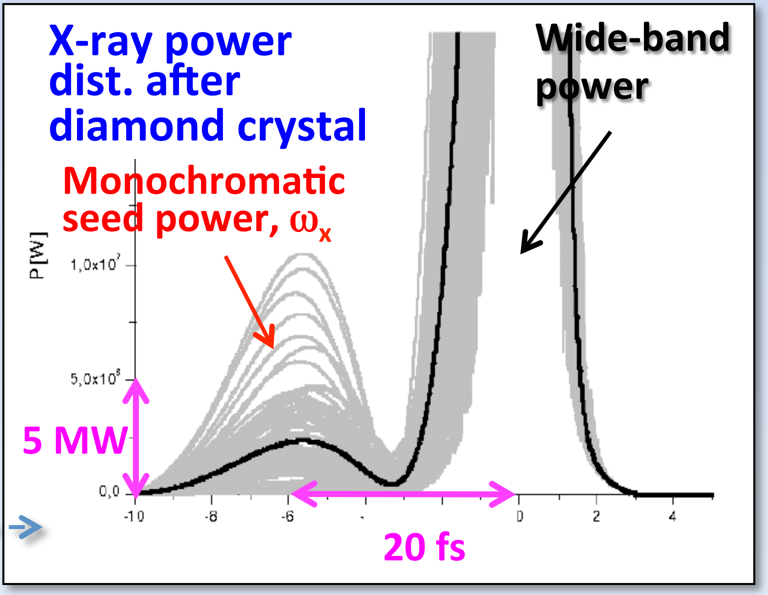
Courtesy P. Emma

*) self-seeding idea by Geloni, Kocharyan, Saldin



FEL spectrum after diamond crystal

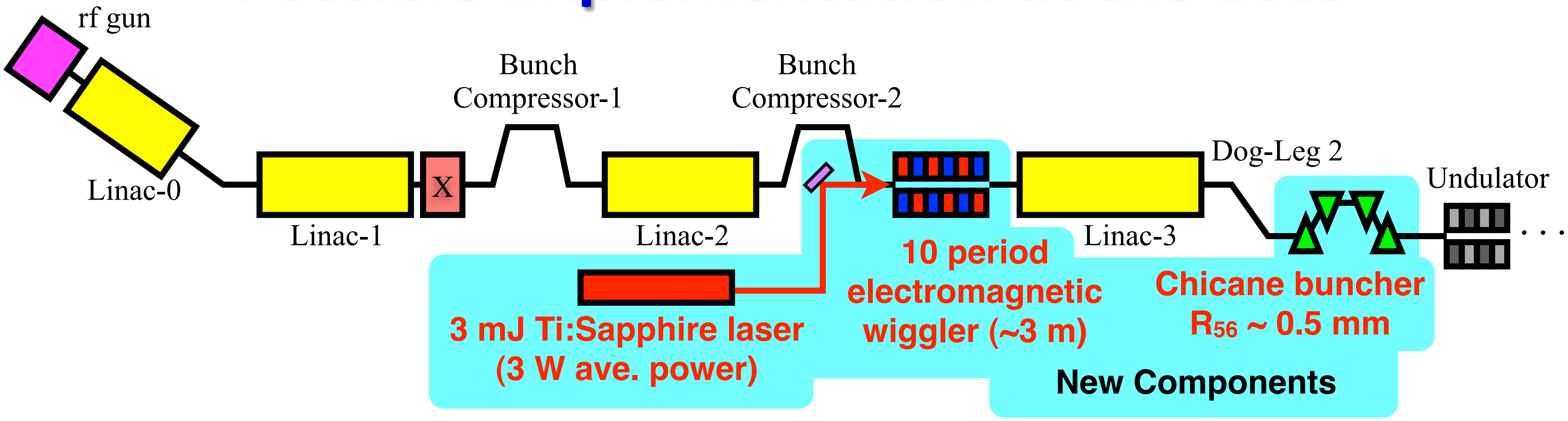
Use short, low-charge bunch to self-seed at 1.5 Å (20-40 pC)



X-ray power dist. after diamond crystal

*D. Xiang, et al., Phys. Rev. ST-Accel. Beams, 1050707(2012).

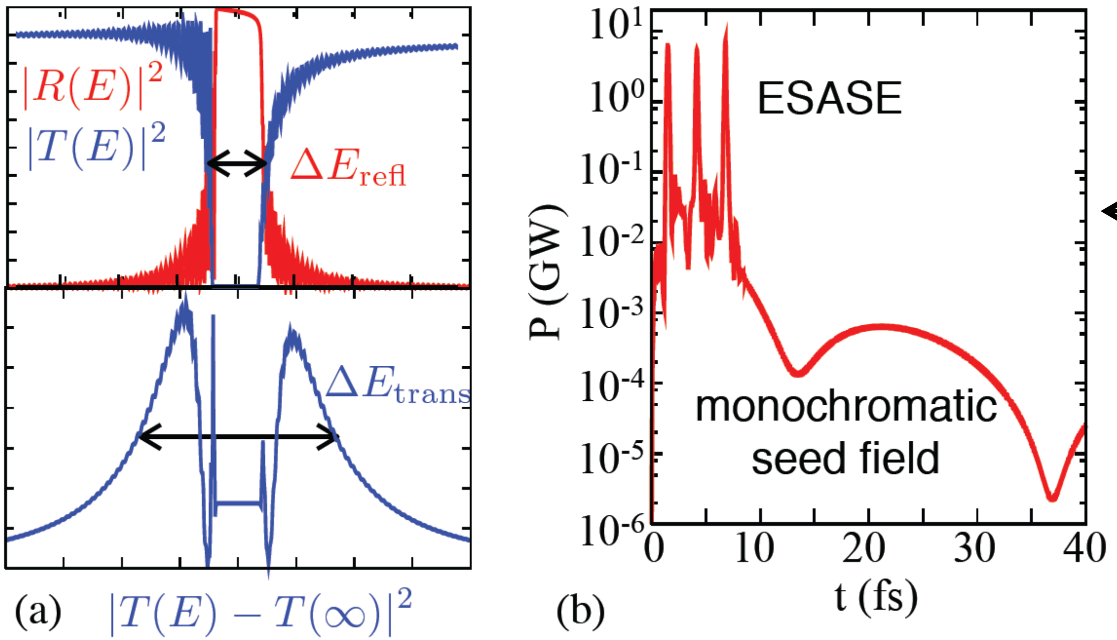
Possible implementation at the LCLS



Schematic of equipment additions within current LCLS layout.
Items highlighted in cyan are the new components.

Bragg backward scattering

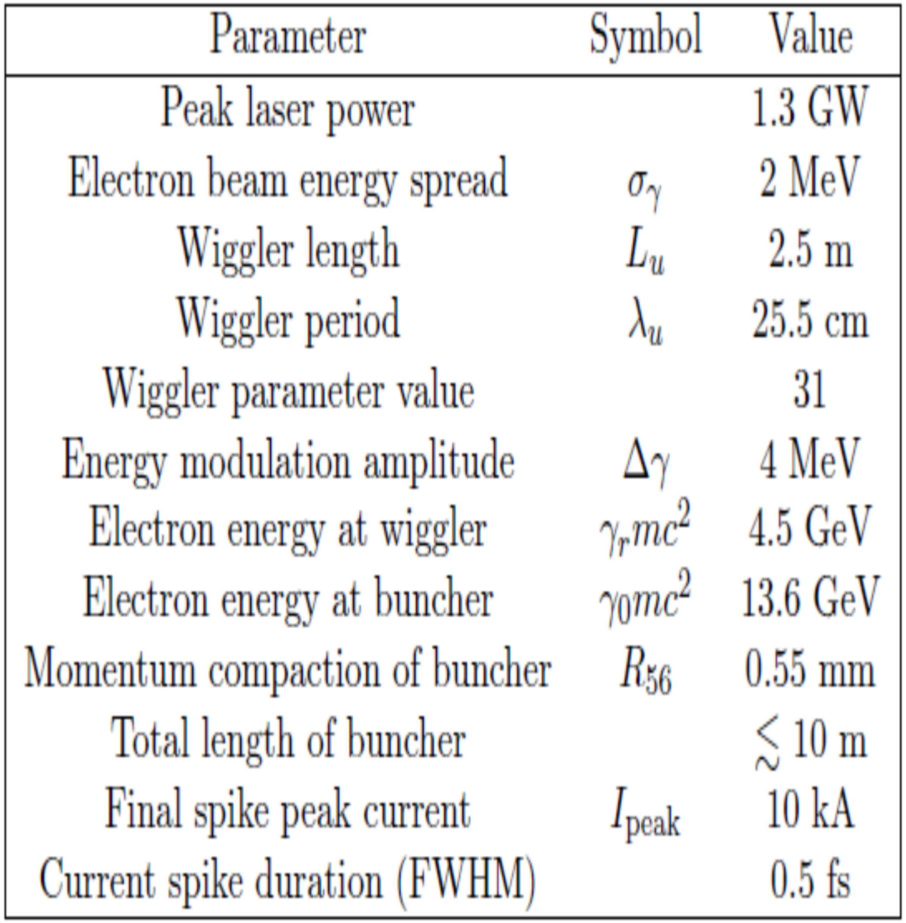
Bragg forward scattering



Example of the seeding field for the proposed system

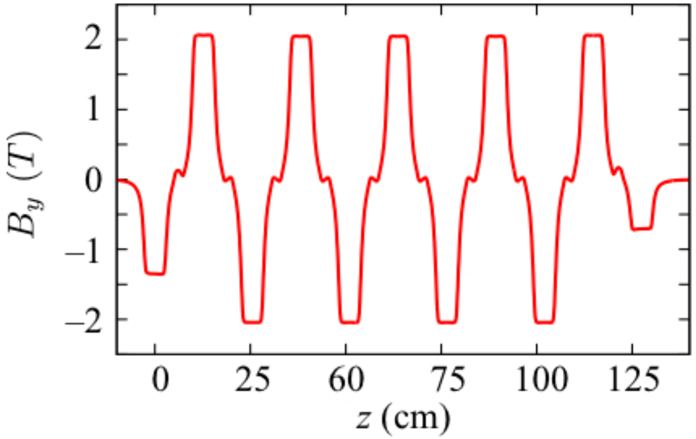
Possible implementation at the LCLS (2)

Nominal parameters used in simulations

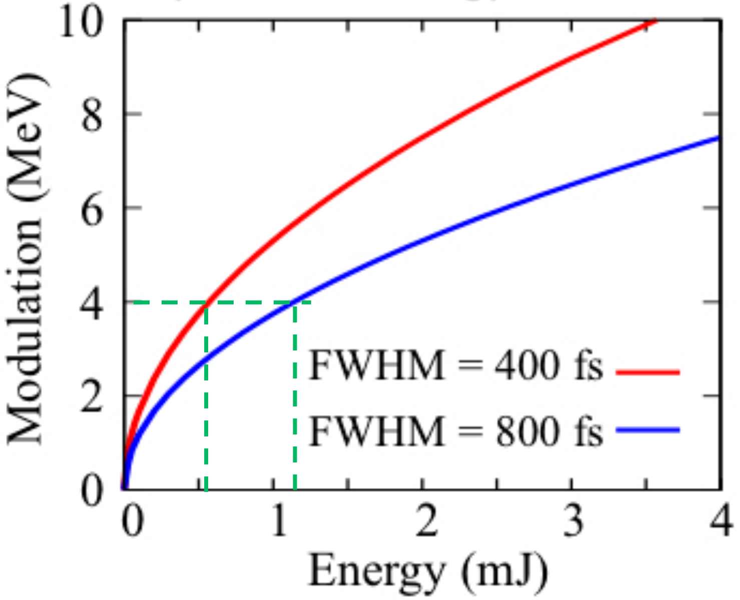


Parameter	Symbol	Value
Peak laser power		1.3 GW
Electron beam energy spread	σ_γ	2 MeV
Wiggler length	L_u	2.5 m
Wiggler period	λ_u	25.5 cm
Wiggler parameter value		31
Energy modulation amplitude	$\Delta\gamma$	4 MeV
Electron energy at wiggler	$\gamma_r mc^2$	4.5 GeV
Electron energy at buncher	$\gamma_0 mc^2$	13.6 GeV
Momentum compaction of buncher	R_{56}	0.55 mm
Total length of buncher		$\lesssim 10$ m
Final spike peak current	I_{peak}	10 kA
Current spike duration (FWHM)		0.5 fs

Wiggler magnetic field



Amplitude of energy modulation



Possible implementation at the LCLS (3)

Bragg reflection condition from the (004) atomic planes of diamond

Length over which the field is reflected from the crystal ~ 23 μm

Bragg angle ~ 54°, 8 keV x-ray

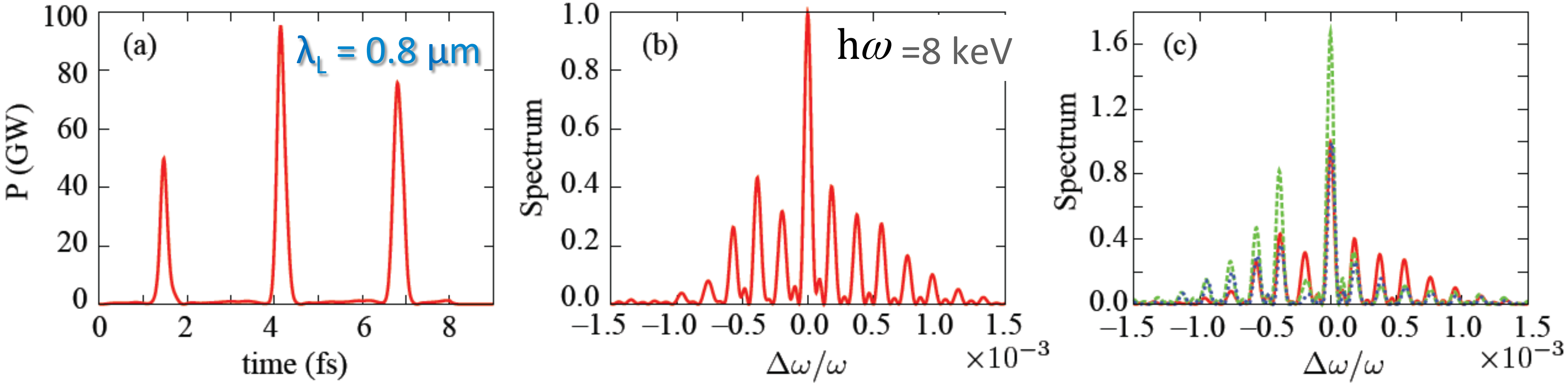
$$\Delta t_{wake} \sim \frac{\Lambda^2 \sin\theta}{cd} \approx 15\ \mathrm{fs}$$

Diamond crystal thickness, 100 μm

Duration of the "wake"

Possible implementation at the LCLS (4)

Simulation results



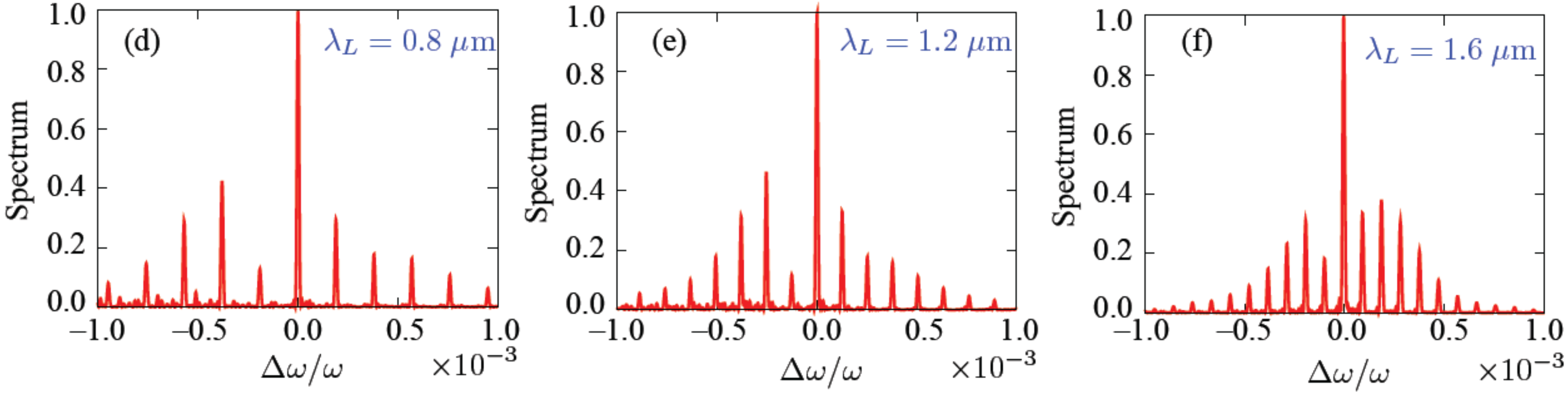
Single shot x-ray power profile

Single shot x-ray spectrum

Three statistically independent trials showing the fluctuation level due to SASE

Possible extension to a better mode-locked FEL

Using reflection from 331 atomic planes in diamond for 7.6 keV x-rays leads to a seeding wake structure ≥ 50 fs and ≥ 40 fs long bunch train*



Single shot x-ray power profile as before, but with 5 times narrower spikes

Changing laser modulation frequency allows control over spike separation

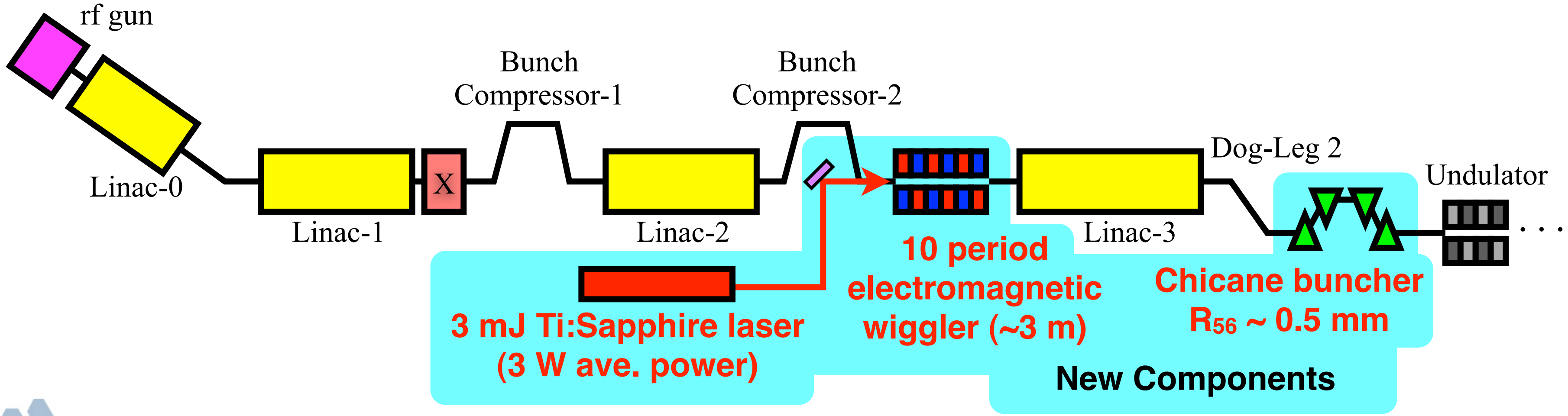
* longer delay chicane than is presently available at the LCLS self-seeding monochromator is required

Summary

1)

ESASE + self-seeding = mode-locked FEL

2) Implementation of mode-locking at LCLS is possible with minimal perturbation to current operation



3 mJ Ti:Sapphire laser (3 W ave. power)

10 period electromagnetic wiggler (~3 m)

Chicane buncher R_{56} ~ 0.5 mm

New Components

Thank you for your attentio