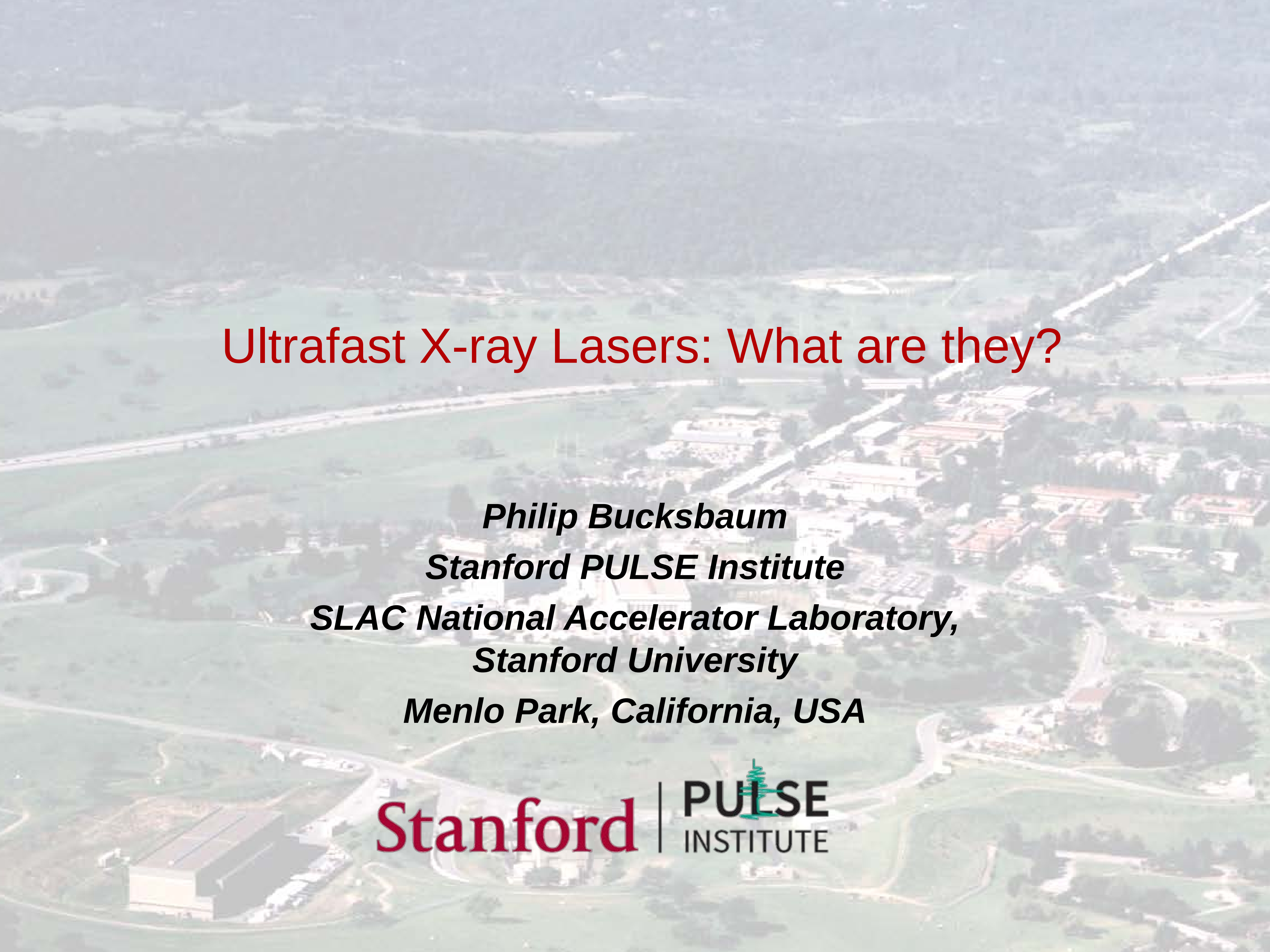


Ultrafast X-ray Lasers: What are they?

Philip Bucksbaum

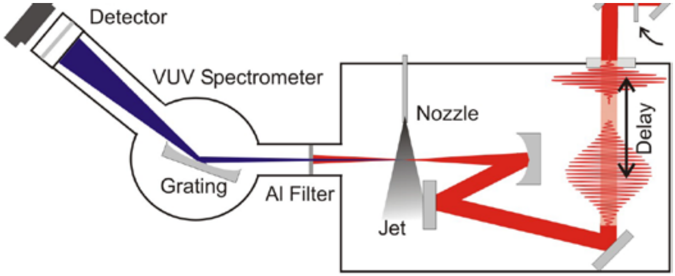
Stanford PULSE Institute

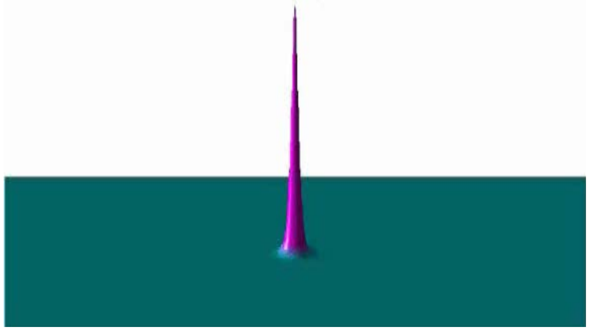
SLAC National Accelerator Laboratory,
Stanford University

Menlo Park, California, USA

Sources of ultrafast short wavelength coherent light:

HHG

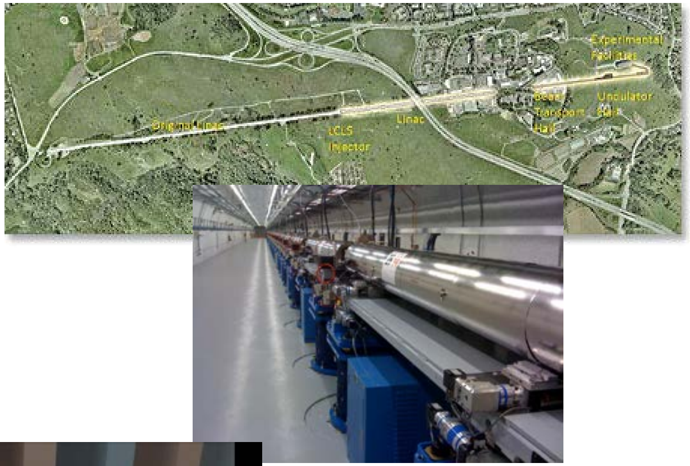


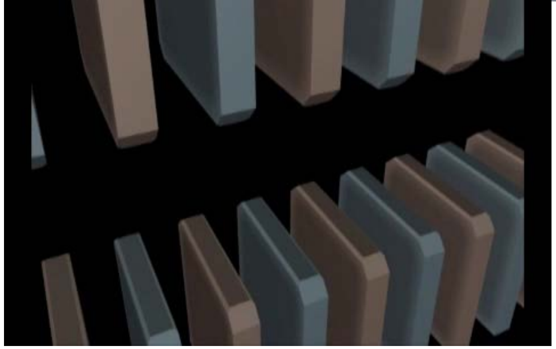


$$\lambda_{\substack{HHG \\ MAX}} = hc\left[\frac{3.17F^2}{4m\omega_L^2} + I_P\right]^{-1} \sim 15-50nm$$

~10nJ

SASE-FEL





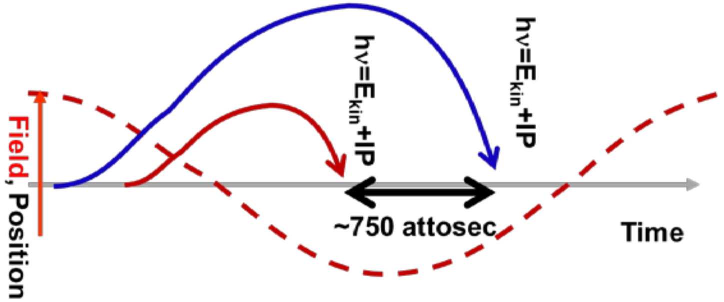
- Electron energy= γmc^2
- Wavelength = λ
- Undulator period $=\lambda_u$
- Maximum deviation angle of the electrons = $K/\ \gamma$

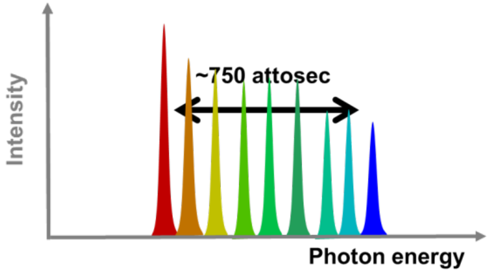
$$\lambda_{FEL} = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right) \sim 0.1-4nm$$

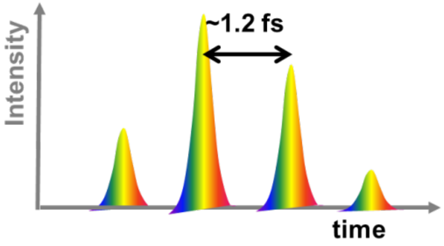
~0.5 mJ

Attosecond sources: Strong fields, HHG and X-ray FELs

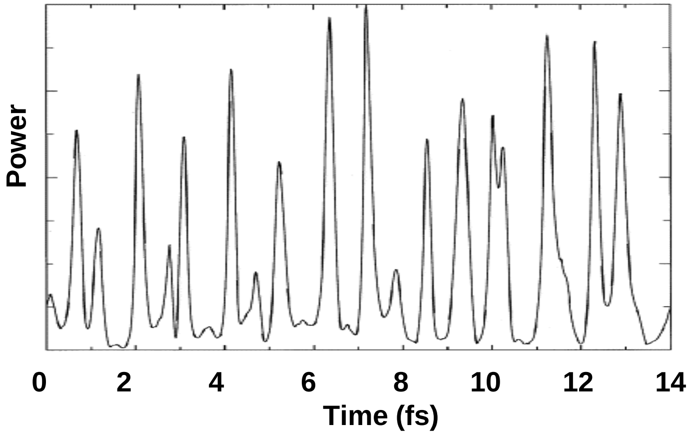
HHG and strong field ionization:
Attosecond pulse trains, attochirp

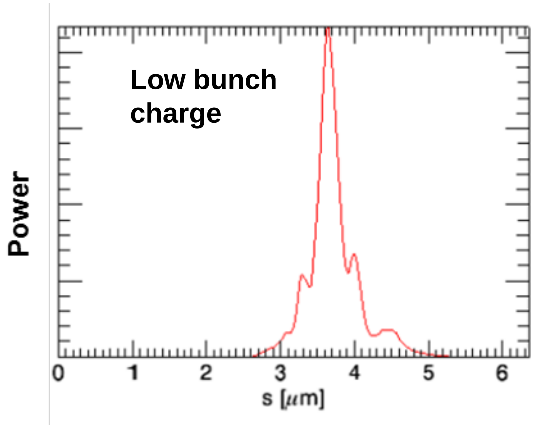






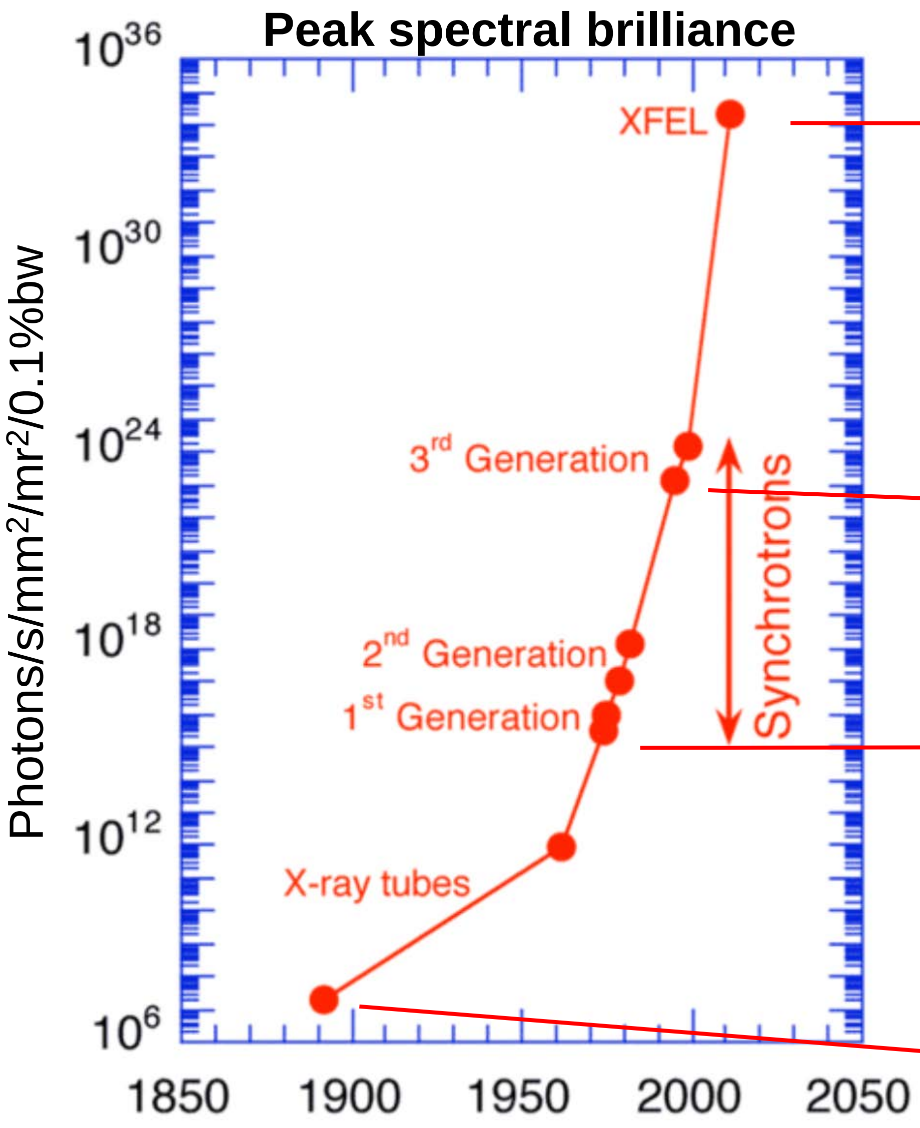
LCLS:
Sub-fs spikes, SASE

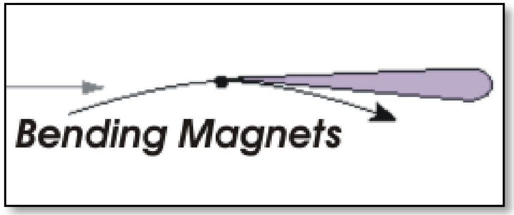




Nuhn, NIM A 429, 249 (1999)
Y. Ding, PRL 102, 254801(2009)

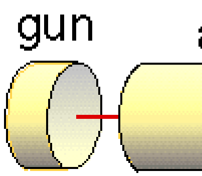
What’s the big deal with x-ray FELs?

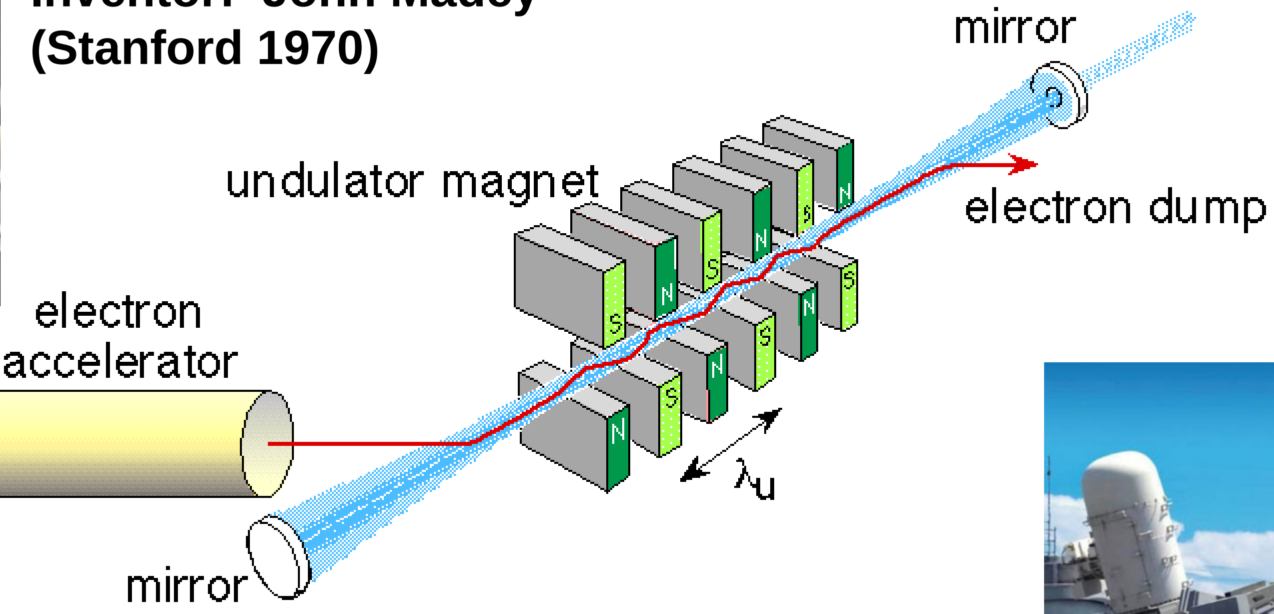




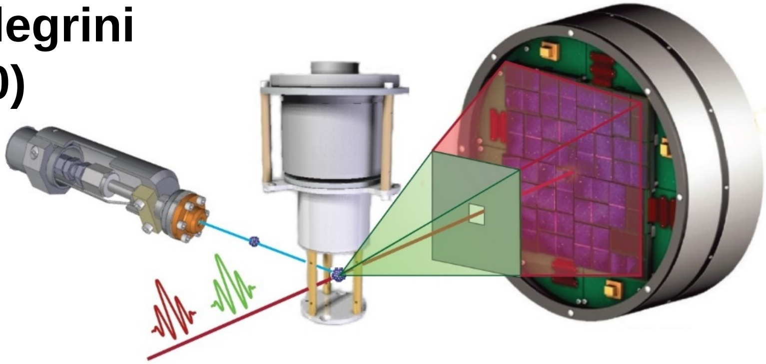
FEL: Free Electron Laser

Inventor: John Madey
(Stanford 1970)





Claudio Pellegrini
(SASE, 1990)

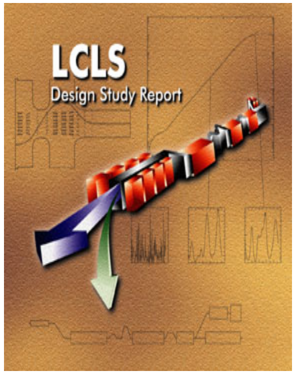


Applications…

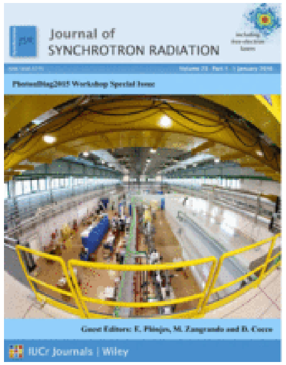
Outline

- Undulators: How x-rays are produced by magnetic fields and relativistic electrons?
- Free electron laser basics
- LCLS, and the growing list of x-ray FELs
- Timing, pulse duration, jitter.

References



LCLS Conceptual Design Report   SLAC-R-593, UC-414
http://www-ssrl.slac.stanford.edu/lcls/cdr/
Chapter 4 is a good FEL tutorial



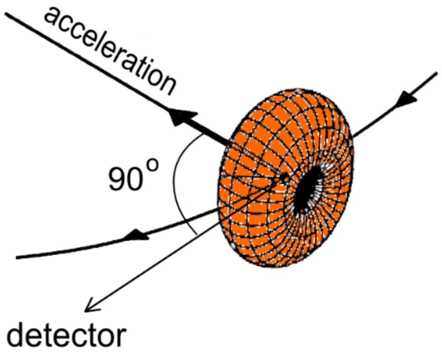
Margaritondo, G. & Rebernik Ribic, P.
A simplified description of X-ray free-electron lasers. *J Synchrotron Rad, J Synchrotron Radiat* 18, 101–108 (2011).

Huang, Z. & Kim, K.-J.
Review of x-ray free-electron laser theory.
***Physical Review Special Topics - Accelerators and Beams* 10, (2007).**

Also acknowledge: Neil Thompson, Daresbury; Zhirong Huang, Jerry Hastings, Nick Hartmann, SLAC

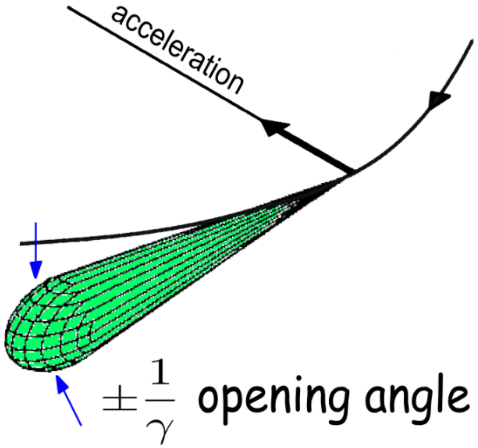
Synchrotron radiation comes from electrons accelerated in a circle.

Rest frame:



$$\frac{1}{\gamma} = \frac{m_o c^2}{E} = \sqrt{1-(\frac{v}{c})^2}$$

Lab frame:



Very powerful at high energy

$$P = \frac{2}{3}\frac{q^2}{4\pi\varepsilon_0}a^2$$

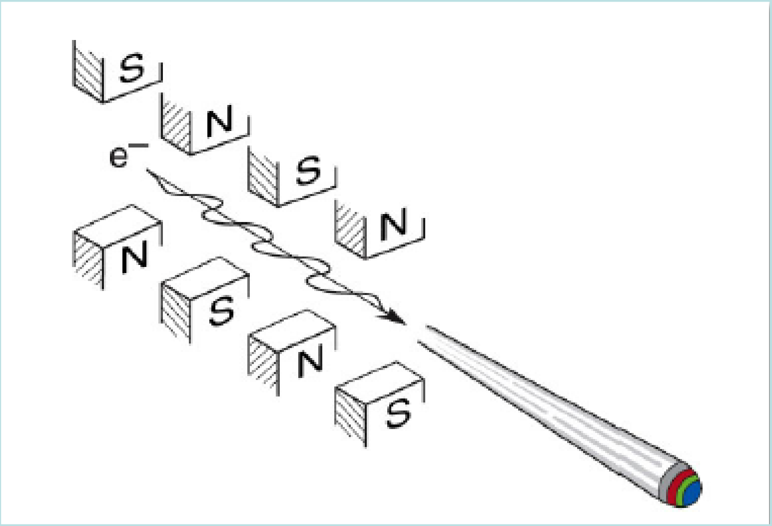
$$P = \frac{2}{3}\frac{q^2}{4\pi\varepsilon_0}\left[\gamma^2\frac{v^2}{r}\right]^2$$

$$\sim\boldsymbol{\gamma^4}$$

Electrons emit with random phase ➔ radiation intensity $\propto N$
(γ is Lorentz factor; number of electrons ~10^9)

Periodic Magnetic Structures

A relativistic electron beam and synchrotron radiation co-propagating through an oscillating magnetic field



Relevant parameters:

- Electron energy= γmc^2
- Wavelength = λ_r
- Undulator period =λ_u
- Number of periods = N
- Peak Magnetic field = B_0

$$B(z) = B_0 \cos(2\pi z/\lambda_u)$$

$$K = eB_0\lambda_u / 2\pi mc = 0.934\lambda_u\,[\mathrm{cm}]\,B_0[\mathrm{T}]$$

Is the normalized angular deflection.
(Max deflection angle = K/γ)

K>1: Wiggler, P ~ N
K<1: Undulator, P ~ N^2

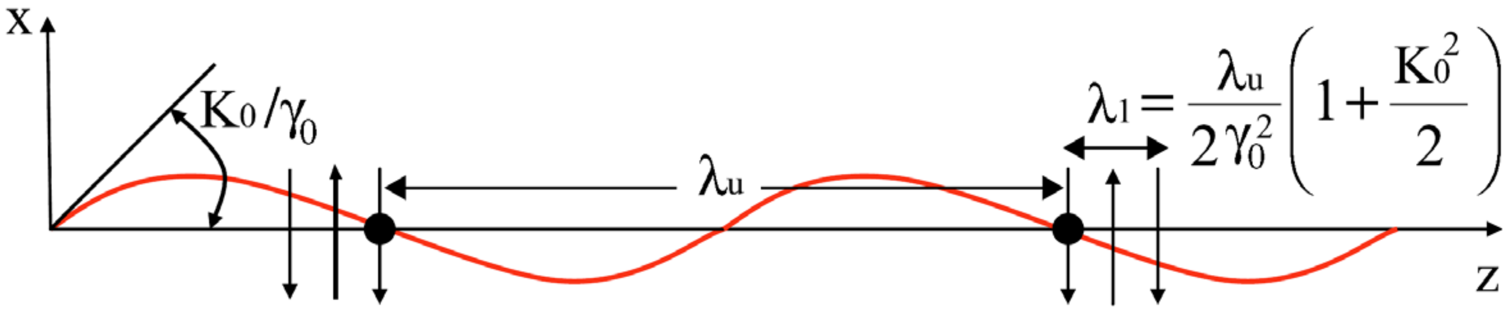
Electrons and light in resonance in an undulator

- **The relativistic electrons and the light are traveling together, but the electrons don’t go as fast, or in a straight line**
- **Resonance occurs when the electrons slip one optical wavelength λ_r (or λ_1) after each undulator period λ_u:**

$$\lambda_1 = \frac{\lambda_u}{2\gamma^2}\left(\boxed{1}+\boxed{\frac{K^2}{2}}\right)$$

Slippage because v<c

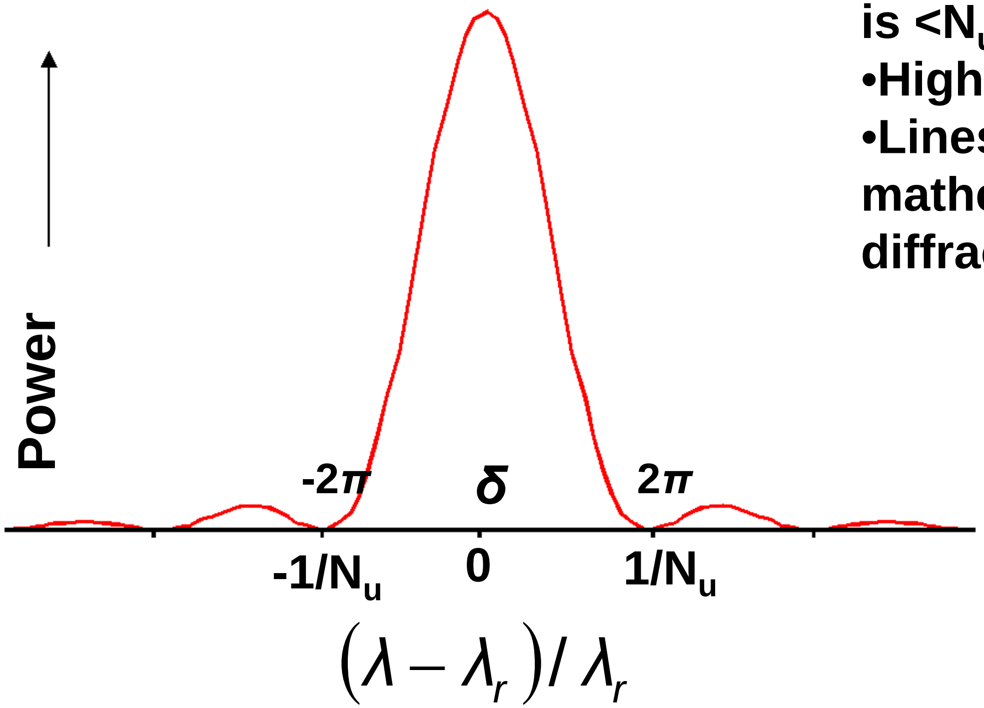
Slippage from wiggling



Undulator spontaneous emission linewidth

It's basically a diffraction grating equation…

- **Electron slips one cycle per undulator period, so the length of a coherent pulse is <N_u cycles**
- **Highest field if $\lambda=\lambda_r$.**
- **Lineshape vs. detuning is mathematically similar to single-slit diffraction pattern.**



Detuning parameter
$\delta=2\pi N(\Delta\lambda/\lambda)$

http://www.rijnh.nl/n4/n3/n2/FELbasics.htm

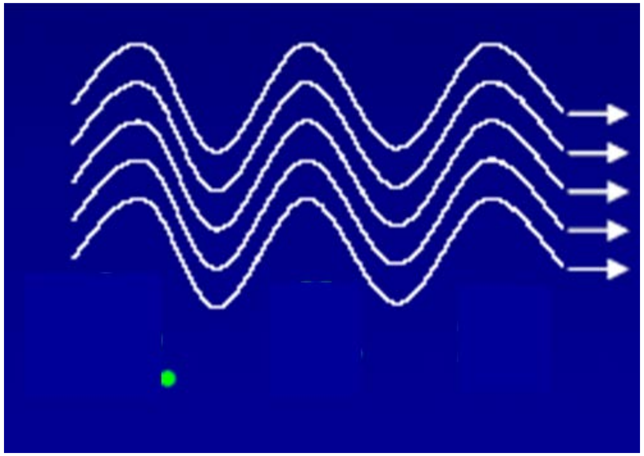
The light comes from synchrotron radiation

- **The undulator resonance condition is the same as the FEL resonance**
- **Undulator bandwidth $\Delta\omega/\omega = 1/N_u$**
- **Photons are diffraction-limited: divergence x source size ~ $\lambda_r/4\pi$**

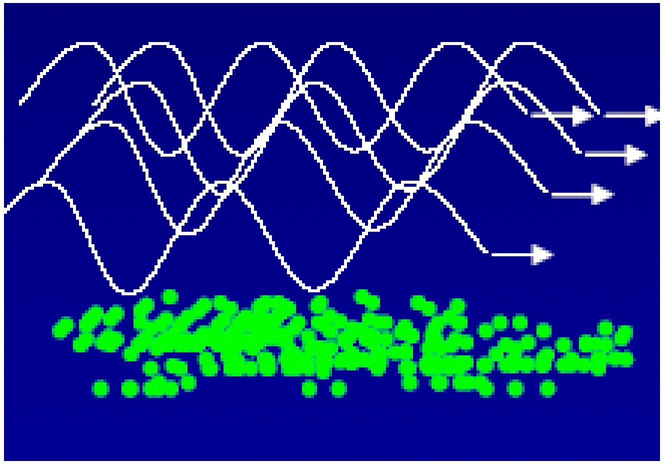
- **So, what's different in an FEL?**

A question of coherence

Undulator conditions:



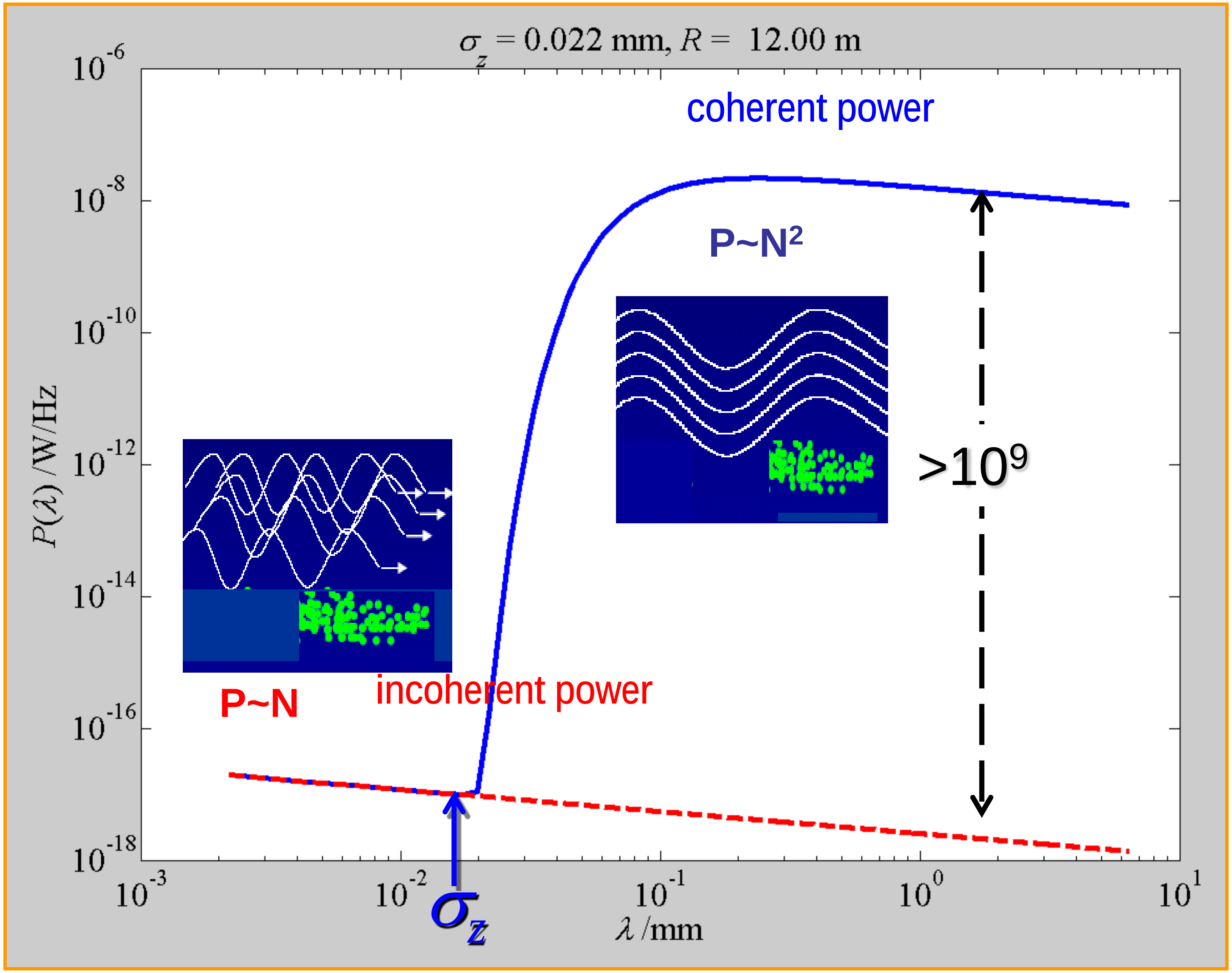
Photons produced on different undulator bends, but from the same electron, are *in phase*. (longitudinal or temporal coherence)



Photons from different electrons are out of phase

Undulators are weak radiators: photons per electron ~ 0.01

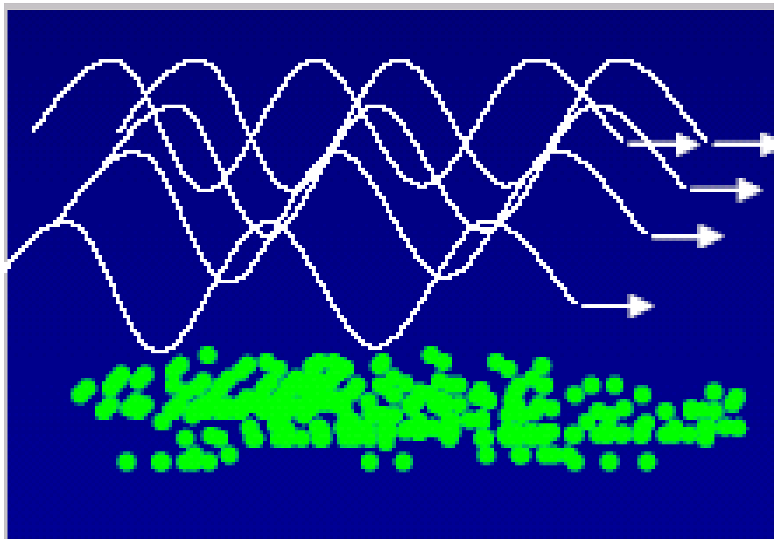
Temporal coherence

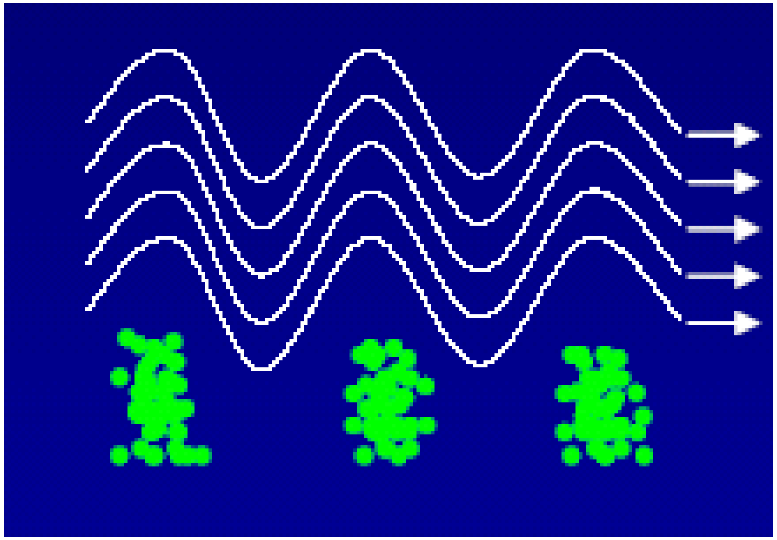


Power

Wavelength

Bunching turns an undulator into an FEL

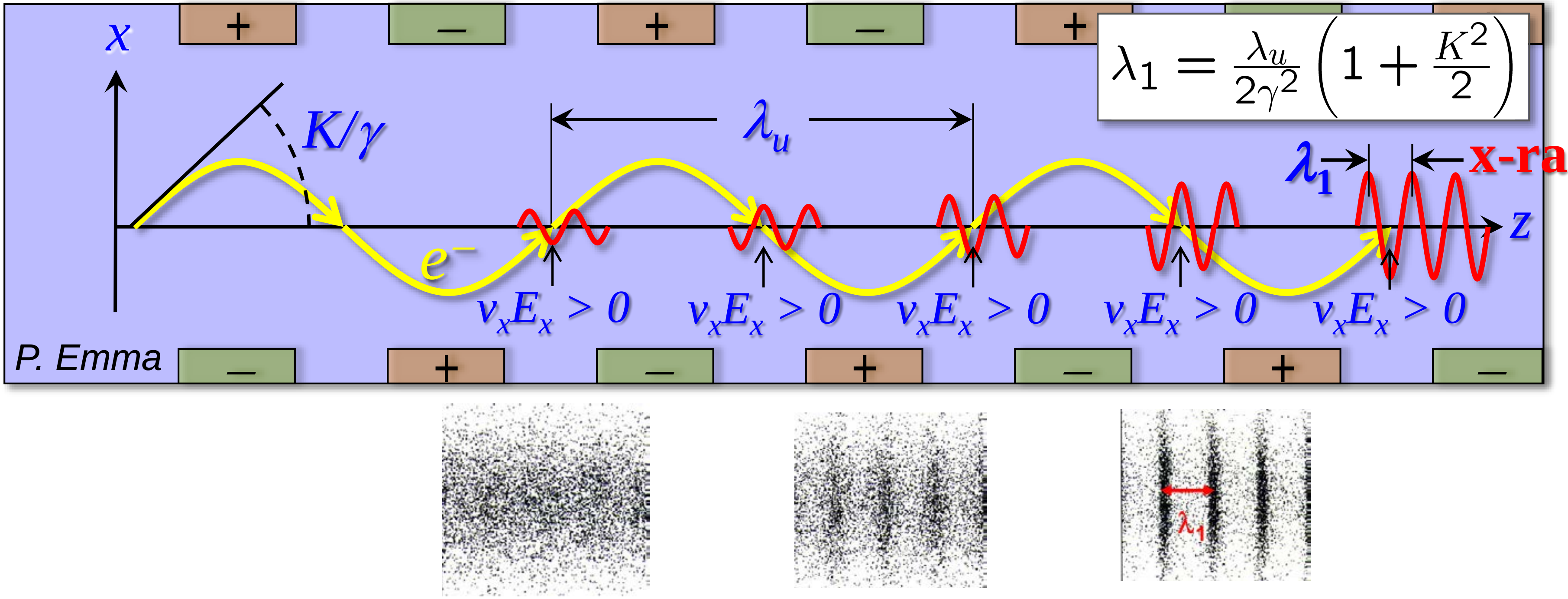




But how?

Microbunching happens ***by itelf*** when electrons begin to feel their own radiation

- **Electrons slip behind EM wave by λ_1 per undulator period (λ_u)**

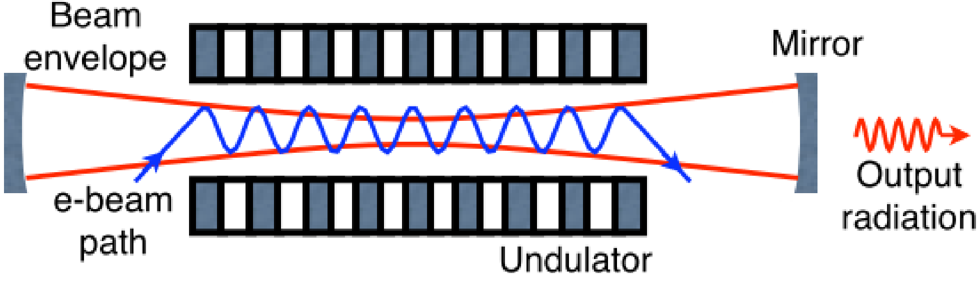


$$\lambda_1 = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

- Some e^-‘s lose energy, others gain ➔
- e^- losing energy lag, and e^- gaining energy lead ➔ (microbunching)
- Microbunched beam radiates coherently at λ_1, ➔ exponential growth of radiation power

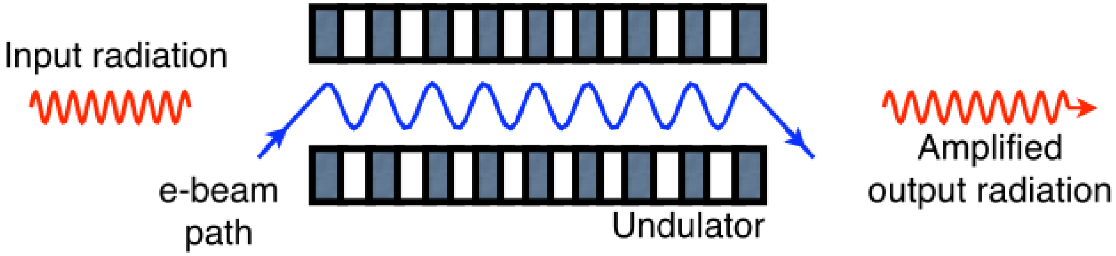
Three FEL modes

FEL OSCILLATOR



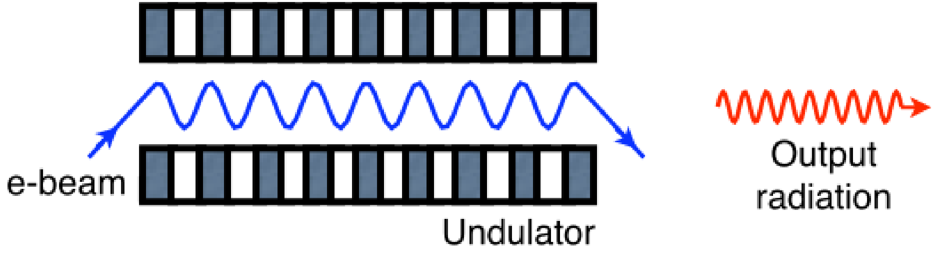
NOTE: Requires mirrors

SEEDED FEL AMPLIFIER



NOTE: Requires input radiation at desired wavelength

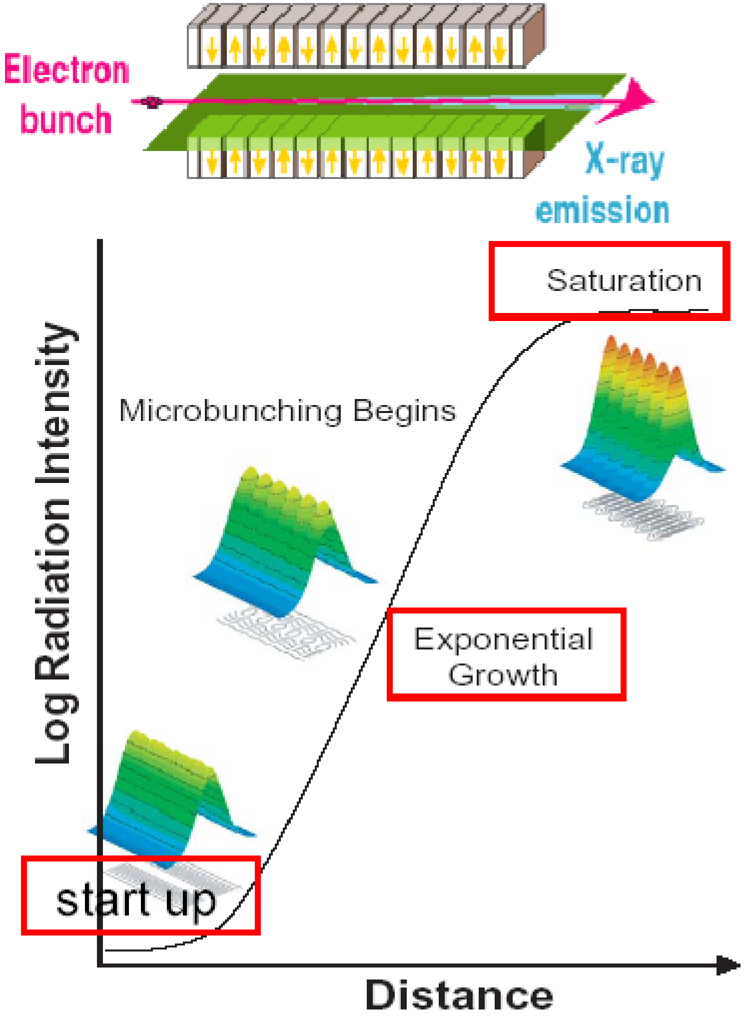
SELF_AMPLIFIED SPONTANEOUS EMISSION (SASE) FEL



NOTE: Does not requires input radiation or mirrors

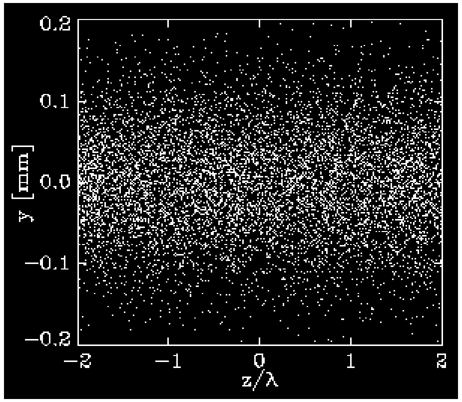
SASE FEL's

- Undulator radiation starts up from noise to interact with the e-beam
- Energy modulation ➔ density modulation at λ (microbunching) ➔ coherent radiation at λ ➔ exponential growth (L_G)
- At sufficiently high power, electrons fully microbunched with large energy spread ➔ reach saturation (P_{sat})

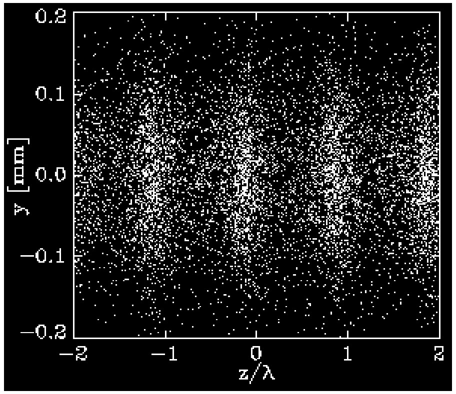


Microbunching through SASE Process

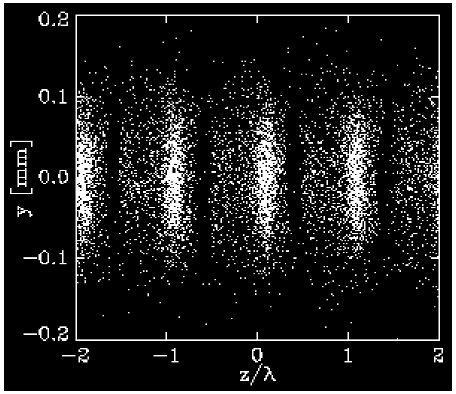
undulator entrance



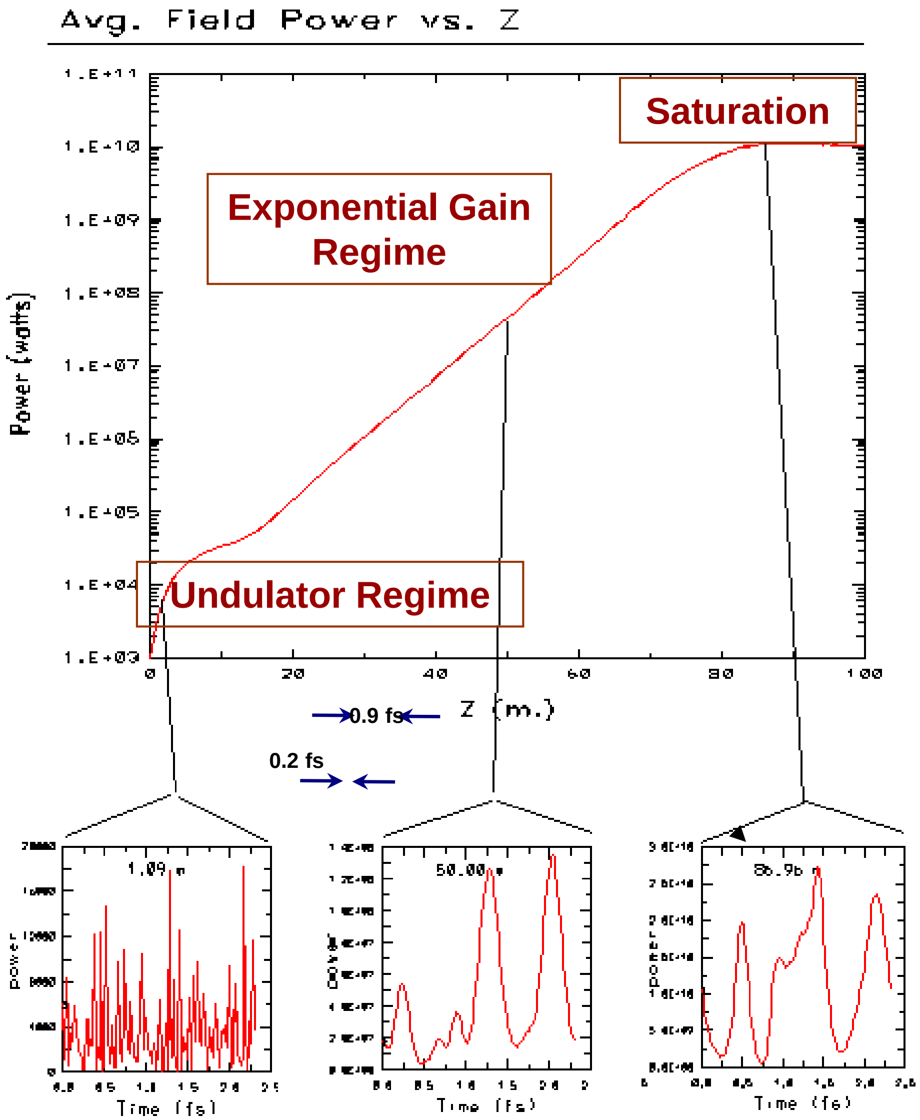
half-way saturation



full saturation



***GENESIS* -**
simulation for TTF parameters
Courtesy - Sven Reiche (UCLA)



Saturation

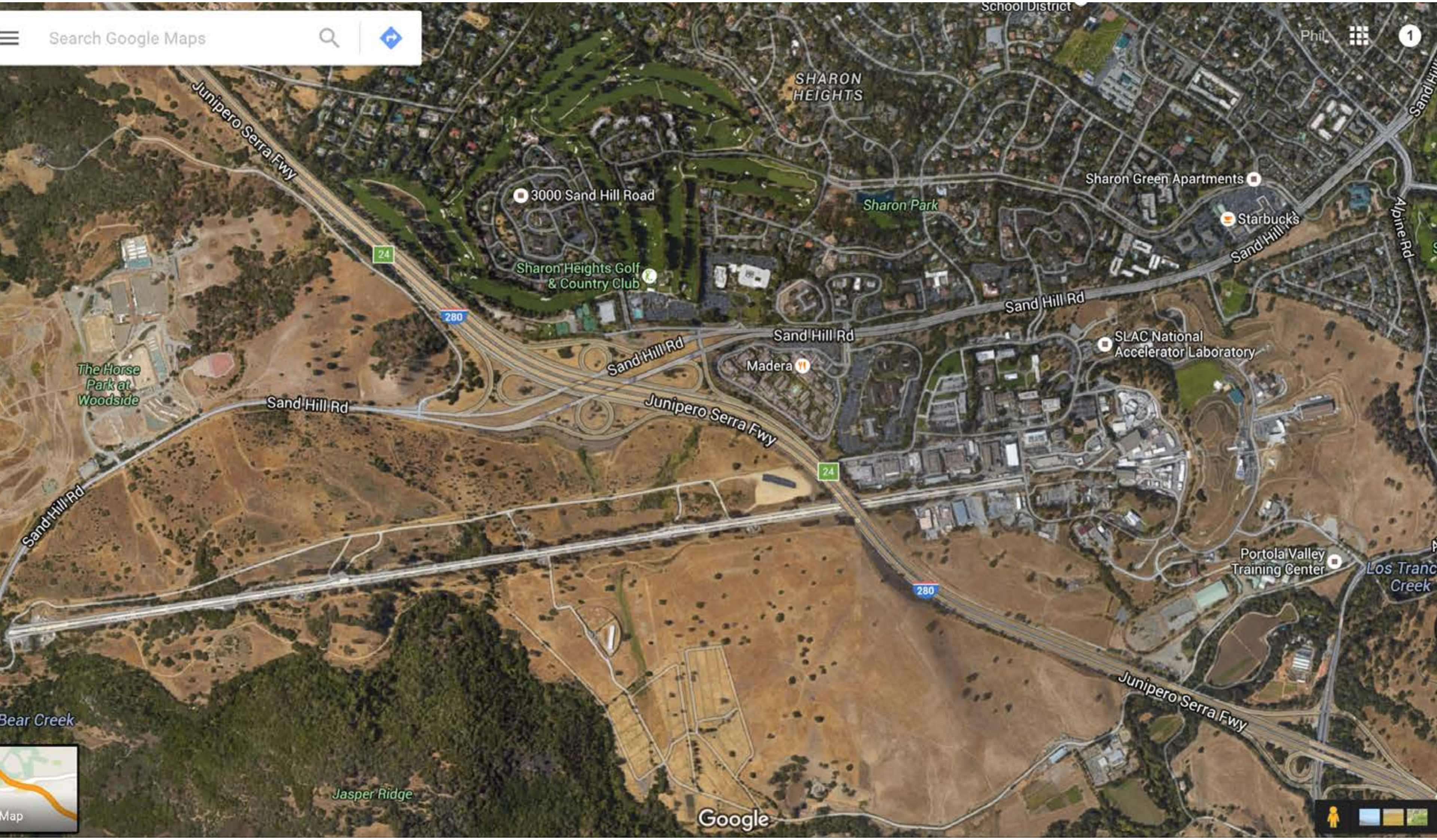
Exponential Gain Regime

Undulator Regime

0.9 fs

0.2 fs

SLAC


Search Google Maps
School District
Phil
1
SHARON HEIGHTS
Junipero Serra Fwy
3000 Sand Hill Road
Sharon Park
Sharon Green Apartments
Starbucks
Sand Hill Rd
Alpine Rd
24
Sharon Heights Golf & Country Club
280
Sand Hill Rd
Sand Hill Rd
SLAC National Accelerator Laboratory
Madera
The Horse Park at Woodside
Sand Hill Rd
Junipero Serra Fwy
24
Sand Hill Rd
Portola Valley Training Center
Los Tranc
Creek
280
Junipero Serra Fwy
Bear Creek
Jasper Ridge
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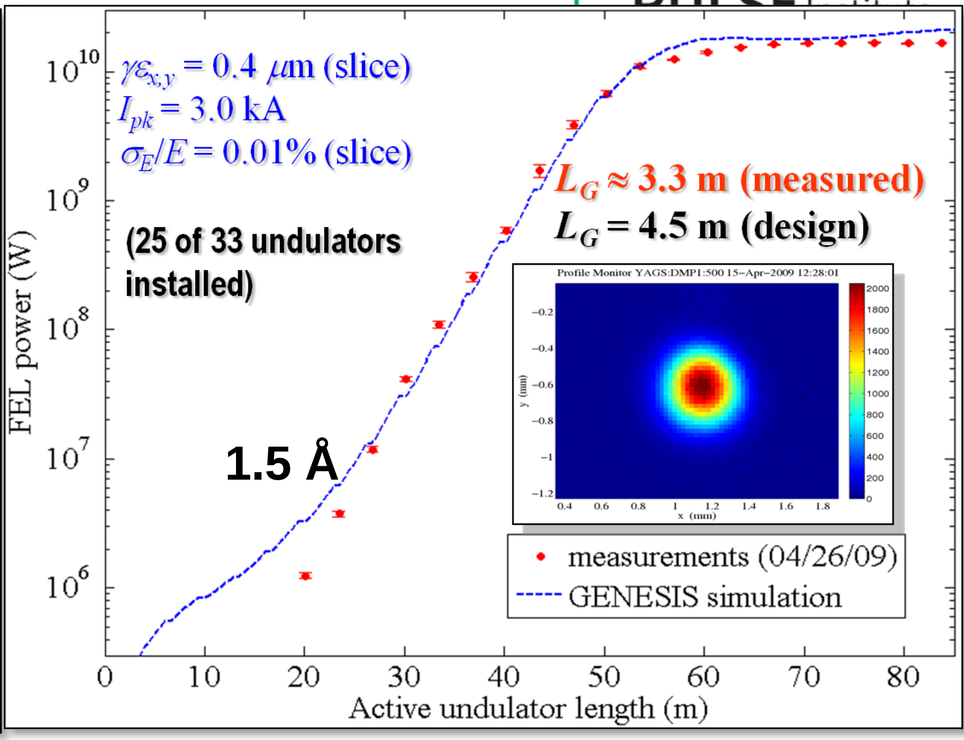
Map

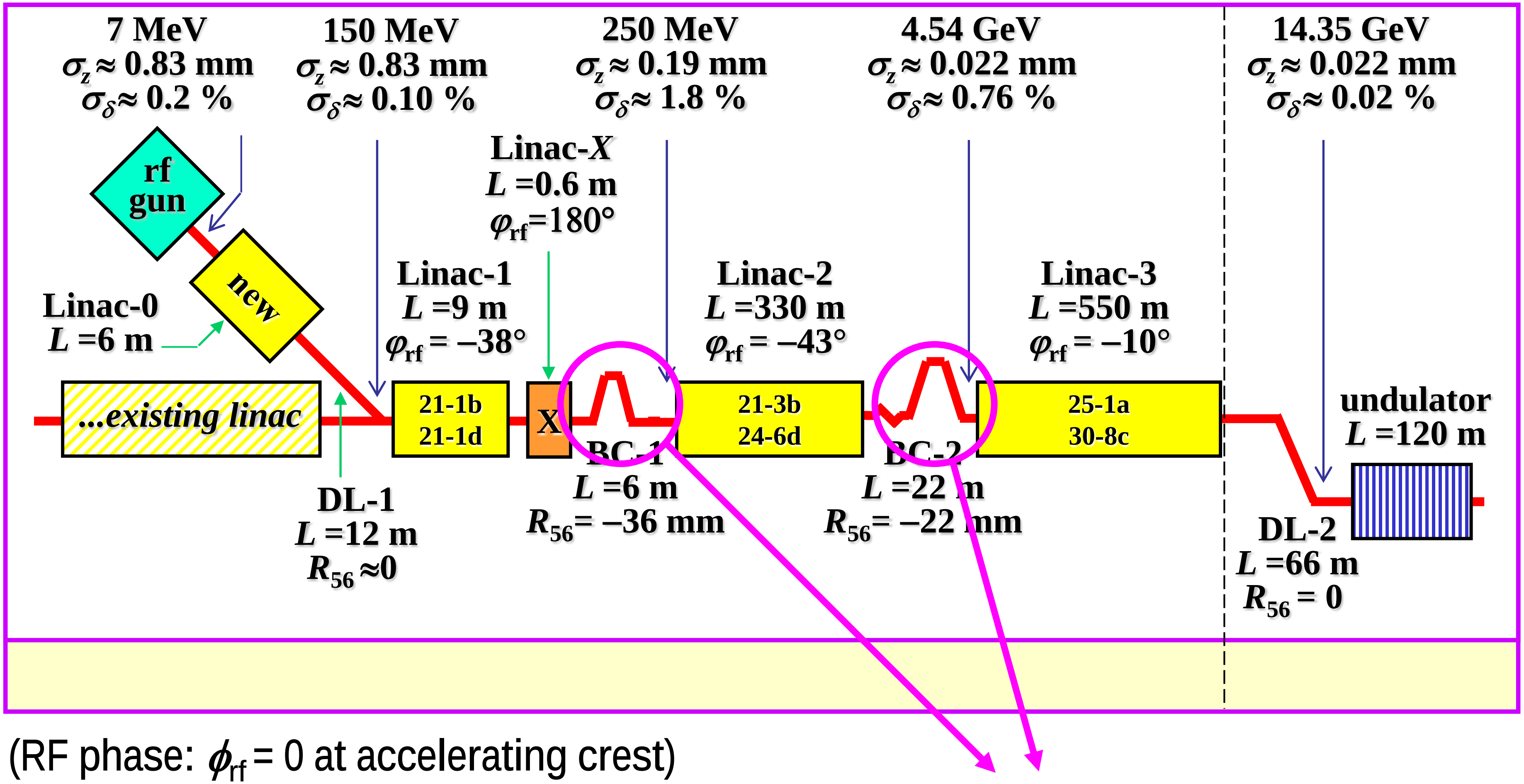
LCLS: world’s first hard x-ray FEL



- **SASE wavelength range: 30 – 1.2 Å**
- **Photon energy range: 0.4 - 10 keV**
- **Pulse length FWHM 5 – 100 fs (5- 500 fs for SXR only)**
- **Pulse energy up to 4 mJ**
- **~95% accelerator availability**

LCLS Linac Parameters for 1.5-Å FEL

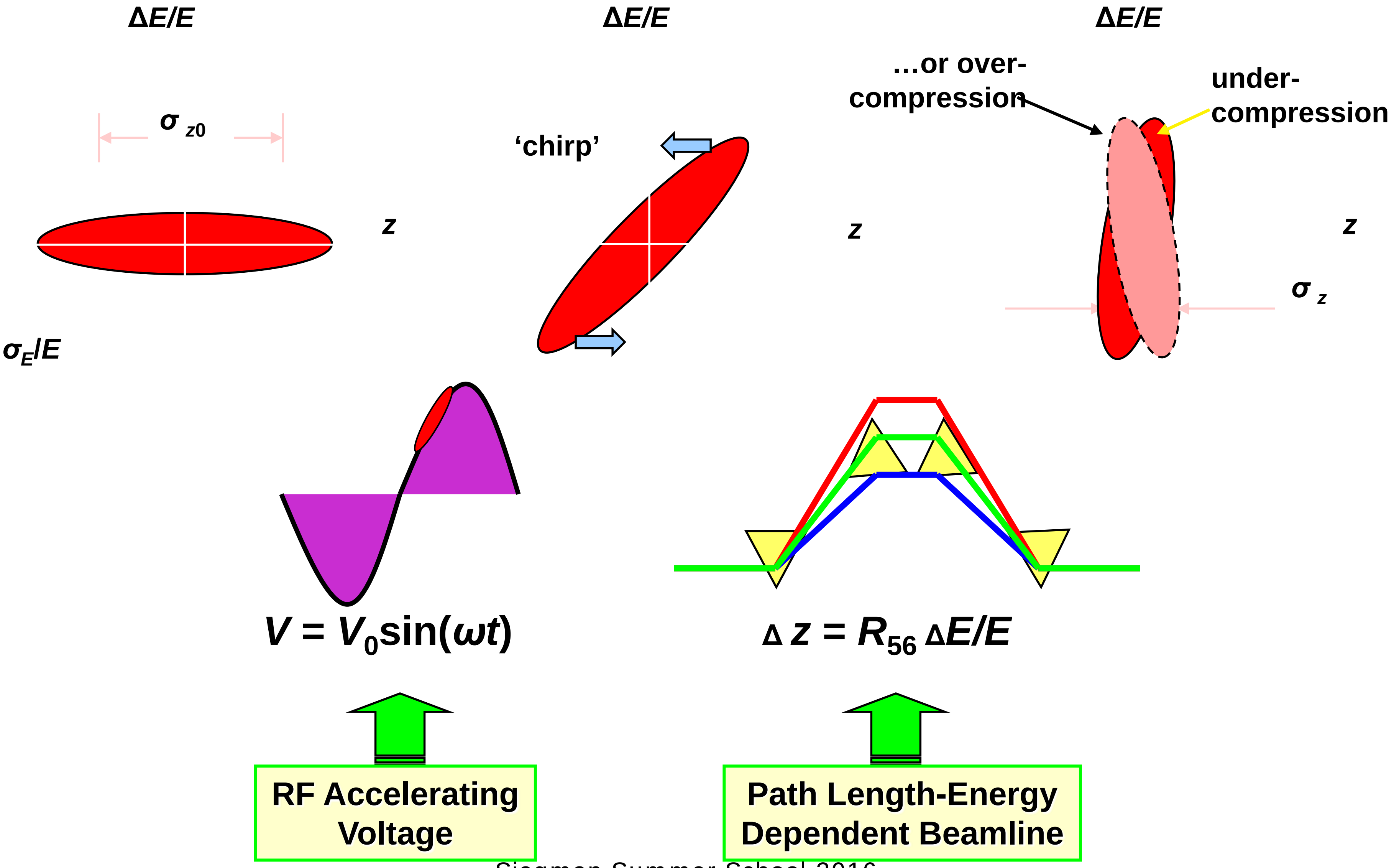
single bunch, 1-nC, 120-Hz



(RF phase: ϕ_{rf} = 0 at accelerating crest)

Two stages of bunch compression

FEL for x-rays: Electron bunch compression



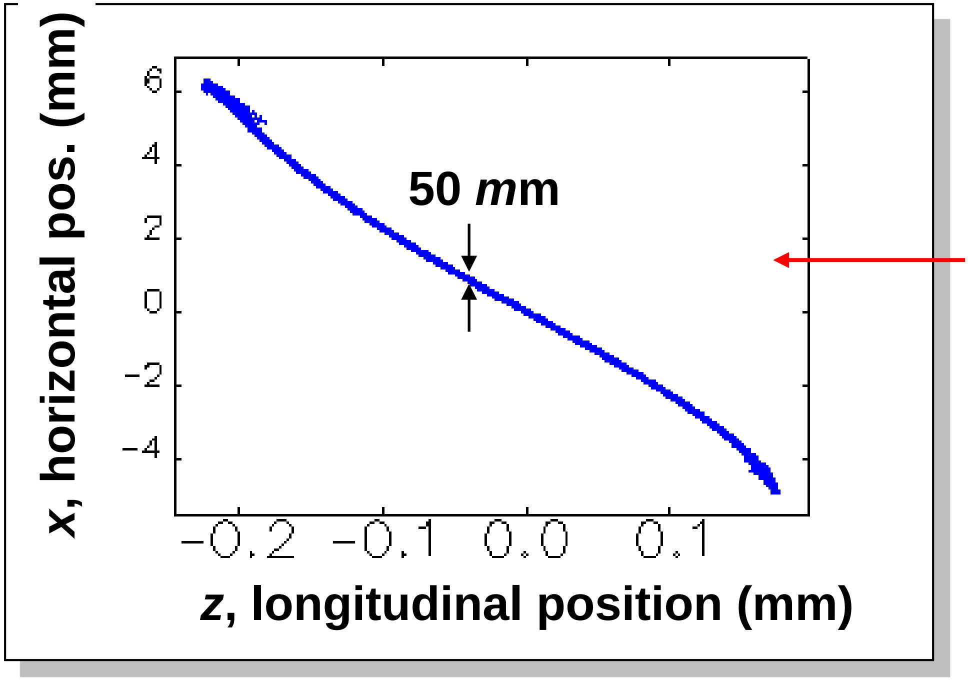
$V = V_0 \sin(\omega t)$

$\Delta z = R_{56}\, \Delta E/E$

RF Accelerating Voltage

Path Length-Energy Dependent Beamline

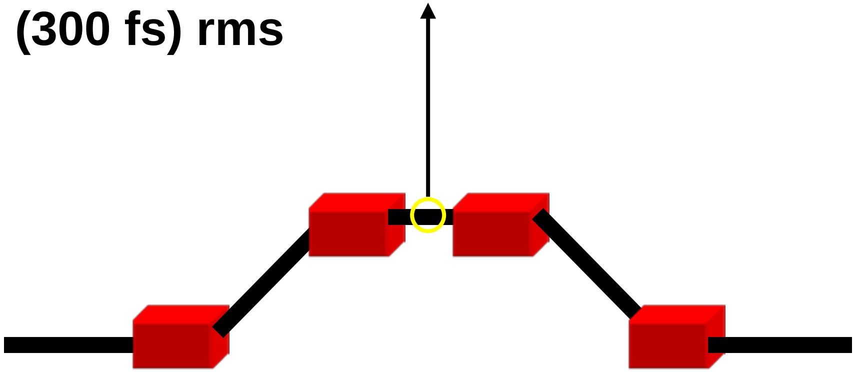
The chicane can also shape pulses



2.6 mm rms

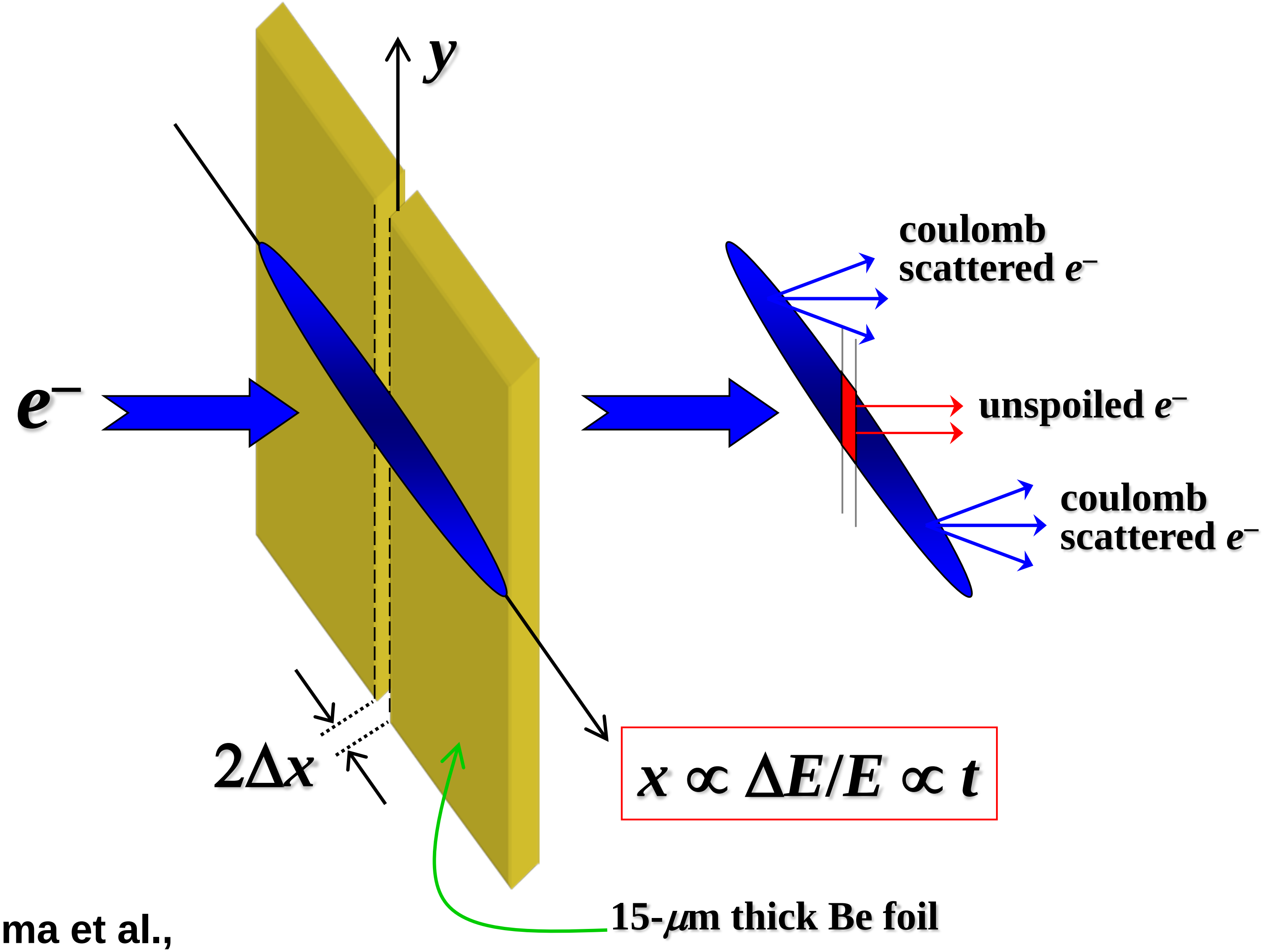
Easy access to *time* coordinate along bunch

0.1 mm (300 fs) rms



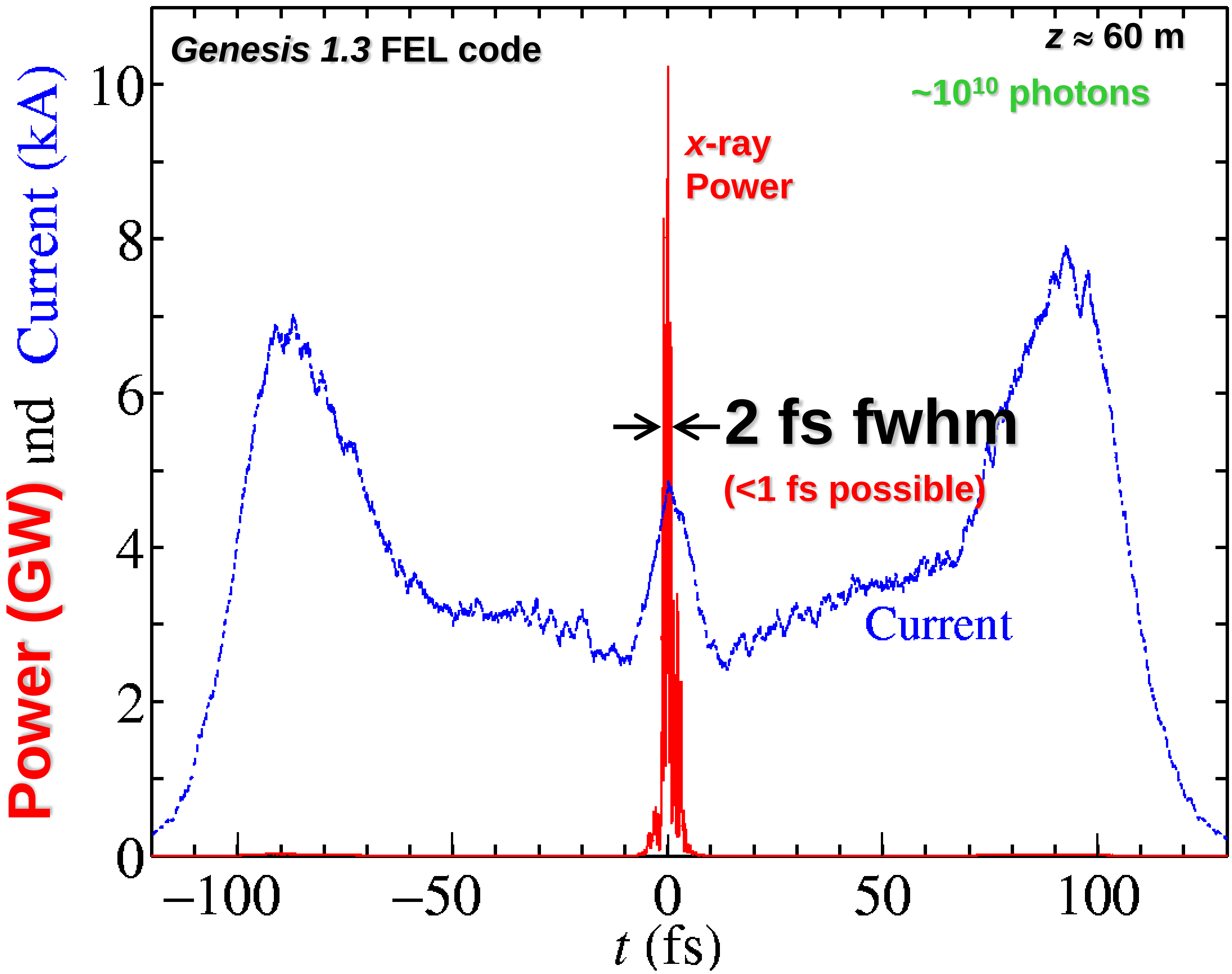
***LCLS* BC2 bunch compressor chicane**

Add thin slotted foil in center of chicane

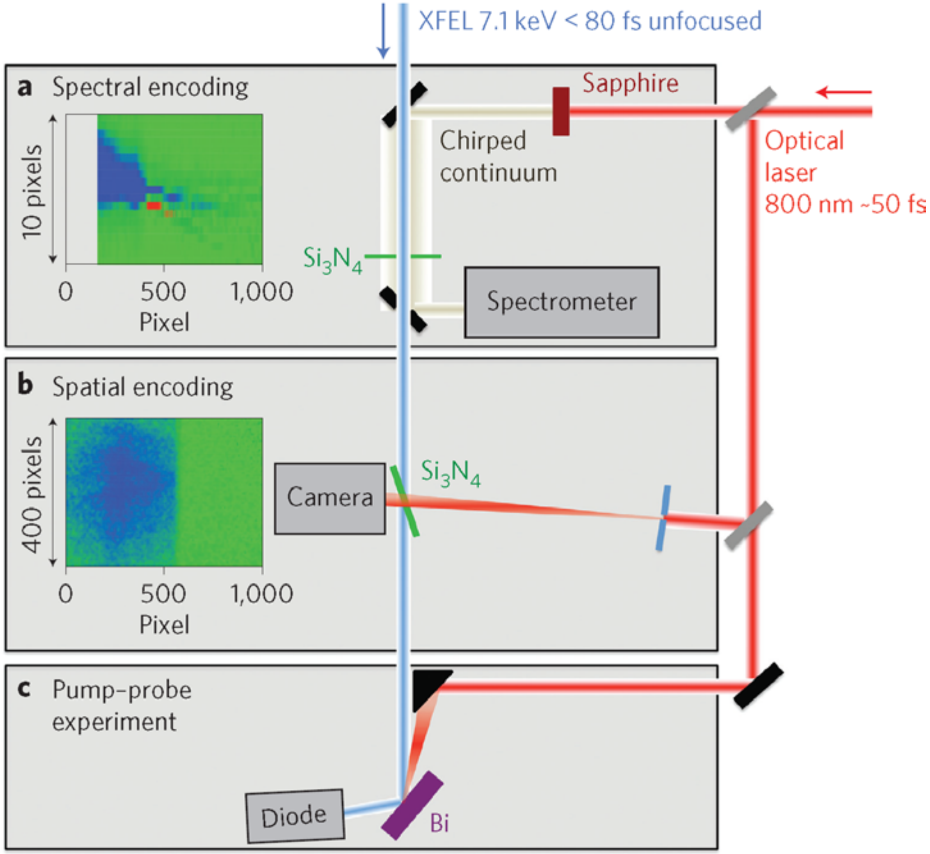


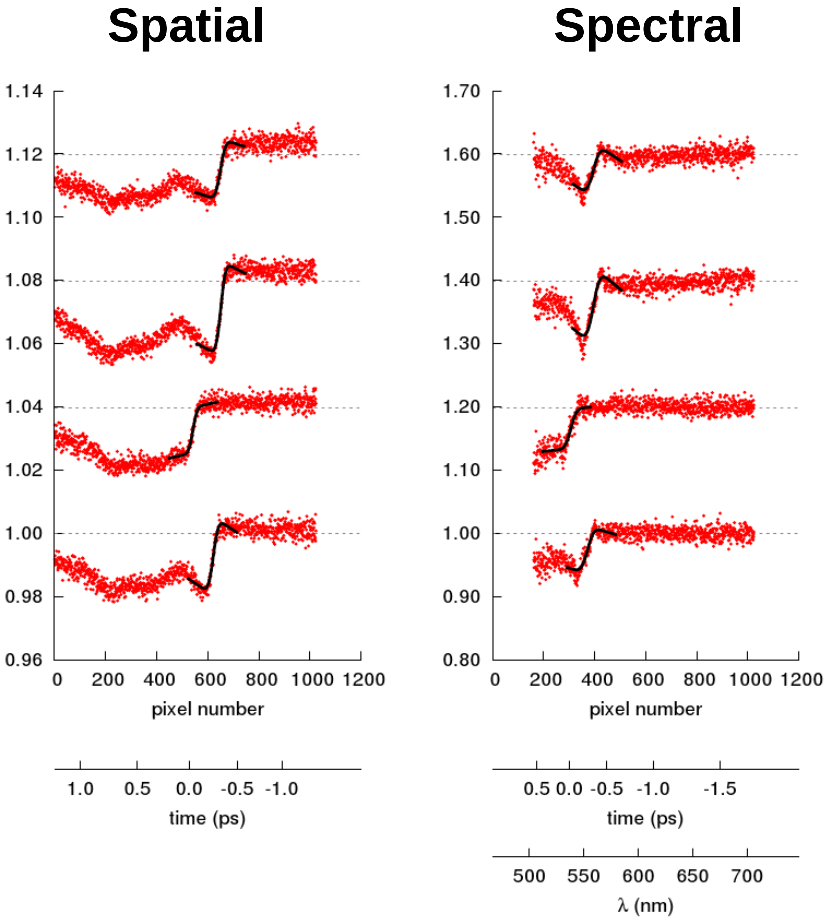
$$\boxed{x \propto \Delta E/E \propto t}$$

Emma et al.,
***PRL* 92, 074801 (2004).**


Genesis 1.3 FEL code
z ≈ 60 m
~10^{10} photons
x-ray Power
2 fs fwhm
(<1 fs possible)
Current
Power (GW) and Current (kA)
0
2
4
6
8
10
−100
−50
0
50
100
t (fs)

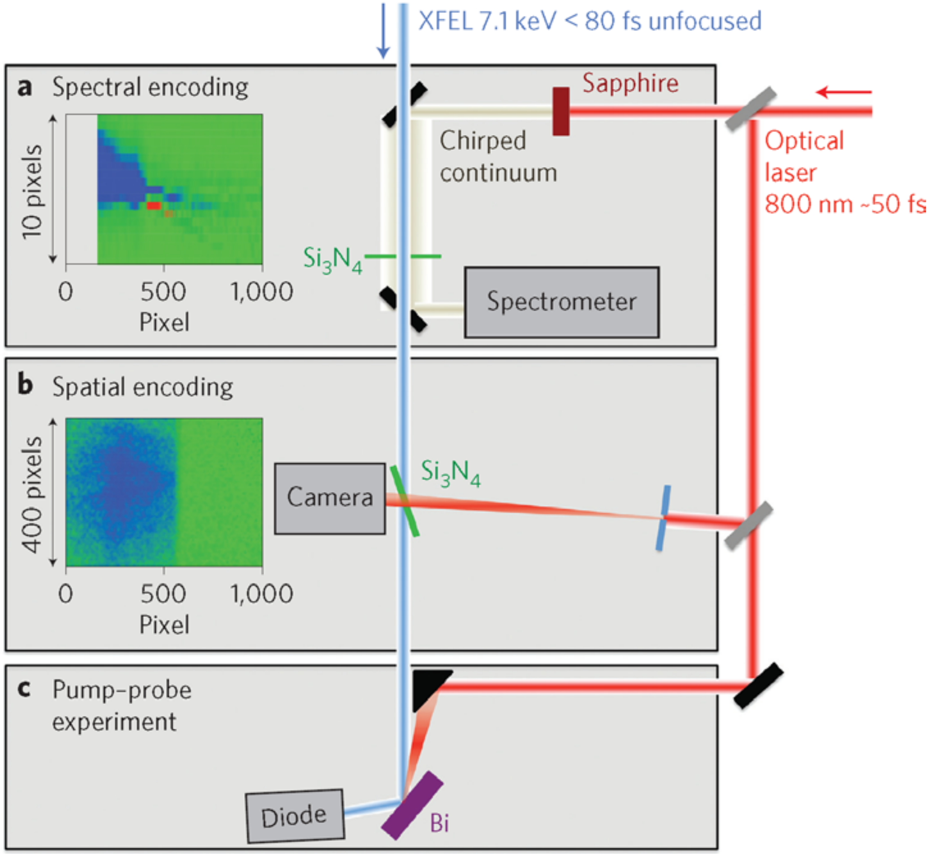
Timing by single-shot time-sorting



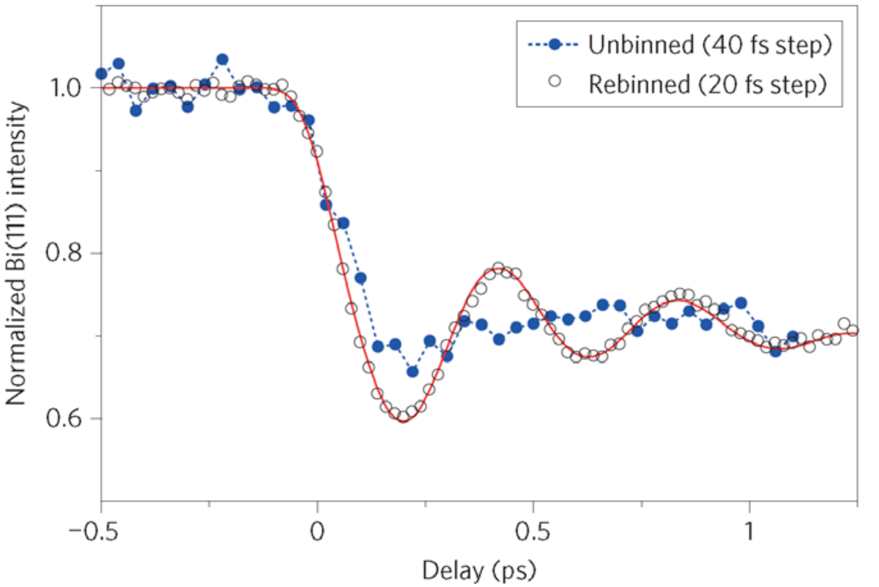


M Harmand, R. Coffee, M. Bionta, et al., Nature Photonics 2013 doi: 10.1038/NPHOTON.2013.11

Timing by single-shot time-sorting

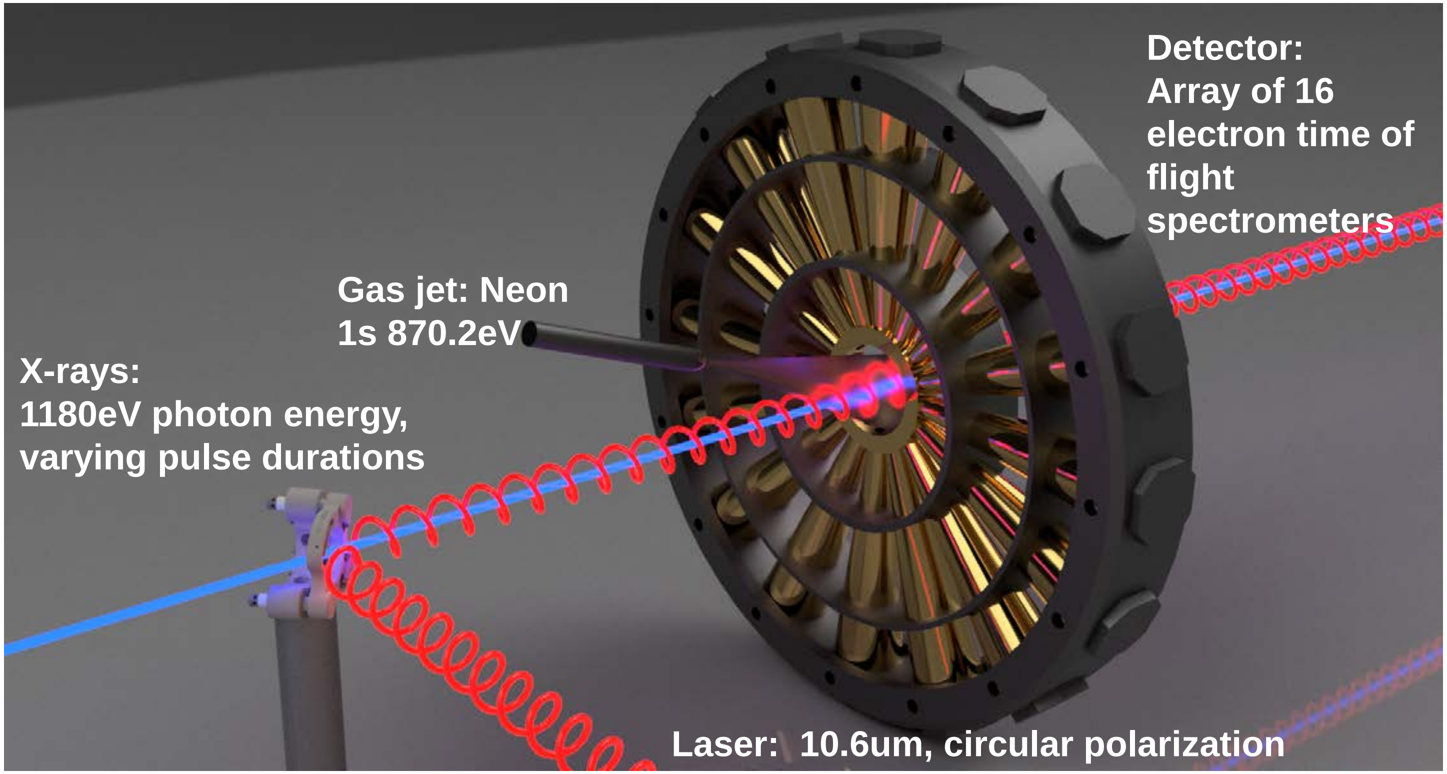


Bi optical phonons



M Harmand, R. Coffee, M. Bionta, et al., Nature Photonics 2013 doi: 10.1038/NPHOTON.2013.11

Angular streaking for ultrafast X-ray pulse characterization at free-electron lasers

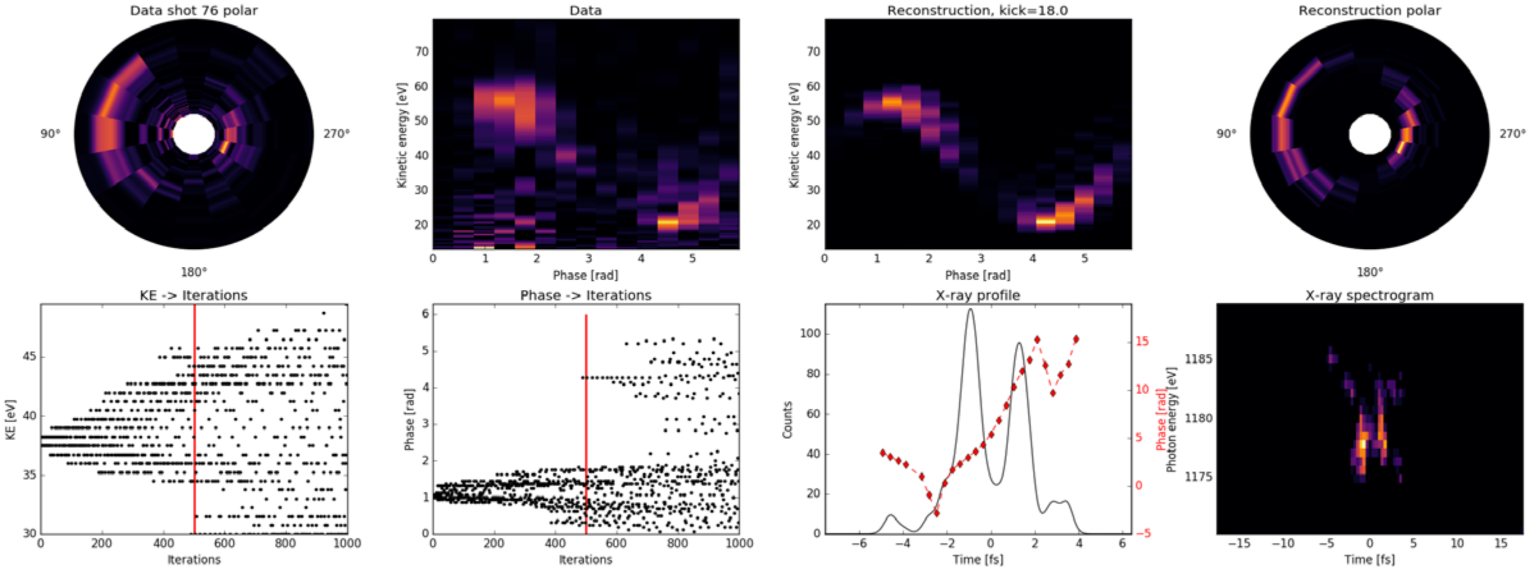


N. Hartmann, C. Benko, C. Bostedt, J. Buck, J. Gruenert, G. Hartmann, R. Heider, M. Ilchen, J. Krzywinski, A. Lindahl, J. Liu, A. Lutman, A. Marinelli, T. Maxwell, A. Miahnahri, S. Moeller, M. Planas, J. Robinson, M. S. Wagner, J. Viefhaus, T. Feurer, R. Kienberger, R. N. Coffee, W. Helml, in preparation

Angular streaking for ultrafast X-ray pulse characterization at free-electron lasers

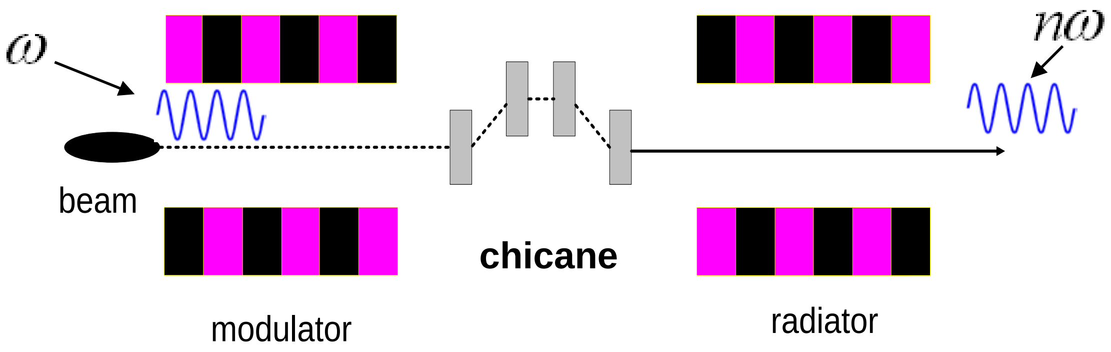
- **Single-shot and reference-free time/frequency characterization of ultrafast X-ray pulses**
- **Time-domain phase estimate based on instantaneous frequency (no CEO-phase information**
- **Insensitive to X-ray arrival timing jitter, capable of measuring X-ray/optical arrival time**
- **Time resolution scales with streaking wavelength deep into the attosecond regime**

Example SASE X-ray shot (single slotted spoiler, ~7fs) :

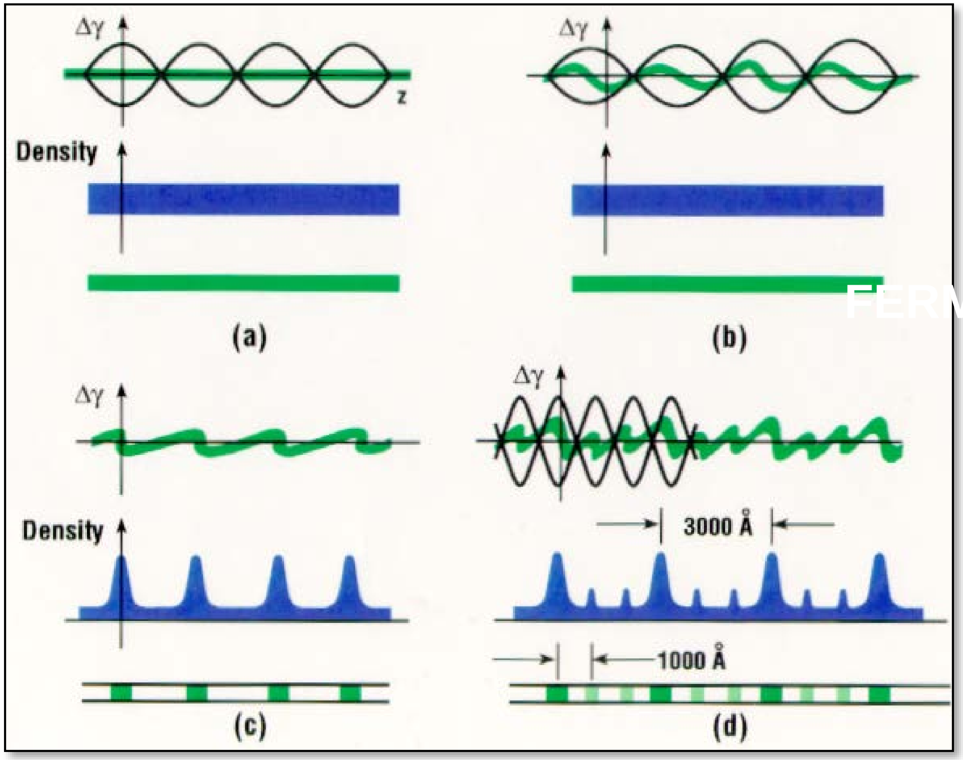


High Gain Harmonic Generation (HGHG)

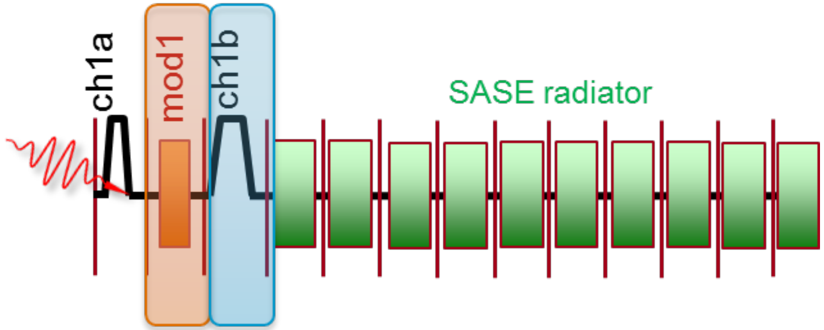
L.-H. Yu, PRA, 1991

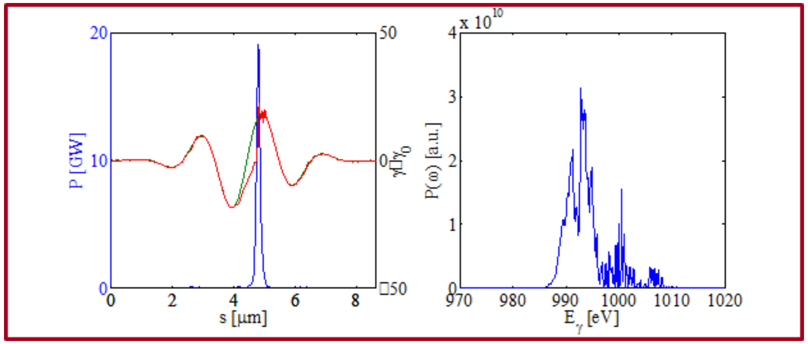


BNL 2003

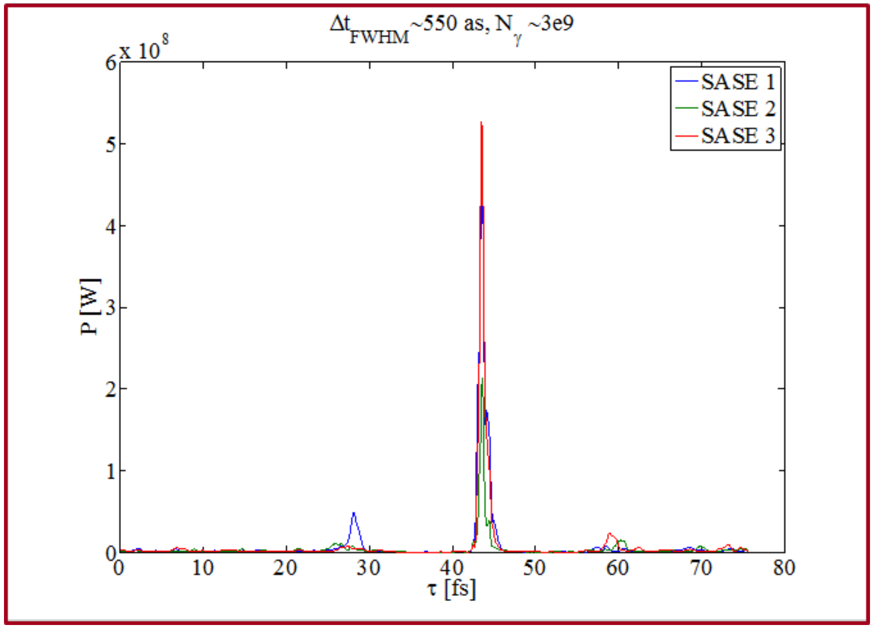


Here’s what higher stability could buy us:





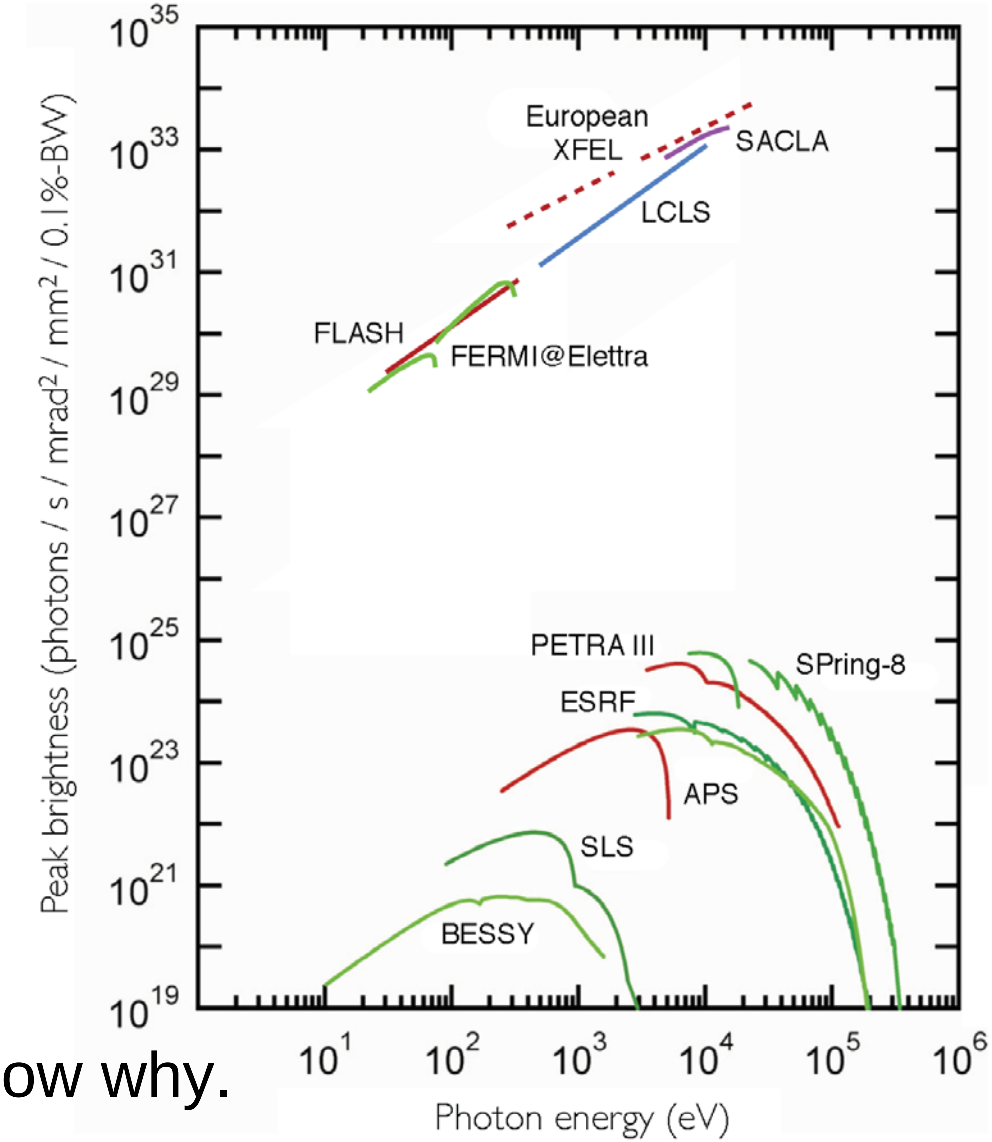
NGLS-like parameters



Current enhanced SASE yields stable femtosecond pulses…(G. Marcus)
Also Zolents PRSTAB 8, 040701 (2005)


FLASH 2005
XFEL 2015
LCLS II 2017
SACLA 2012
LCLS 2009
FERMI 2010
PAL-XFEL 2015
SwissFEL 2017

Summary: Peak Brilliance of FEL’s



Now you know why.