X-ray Free Electron Lasers

Daniel Ratner, June 27, 2013

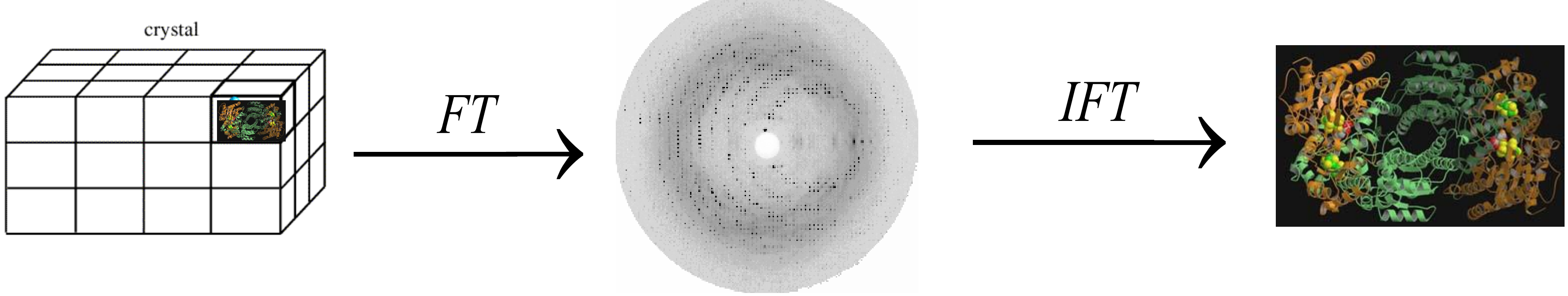
Outline

1. Why you should care about FELs
2. How FELs work
3. How FELs *should* work

Motivation

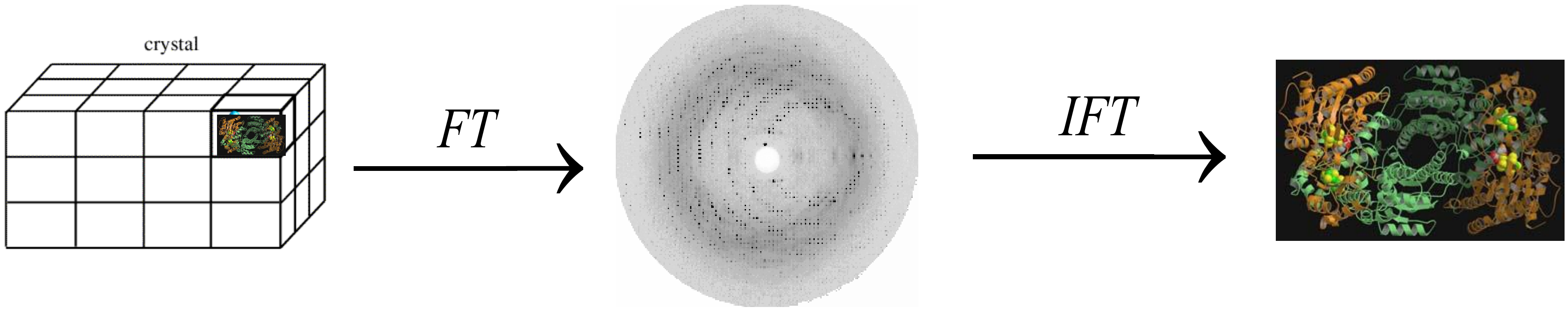
Structural biology in 4 steps:

- Isolate and make protein
- Crystallize protein
- Measure diffraction pattern from crystal
- Recover structure from diffraction data



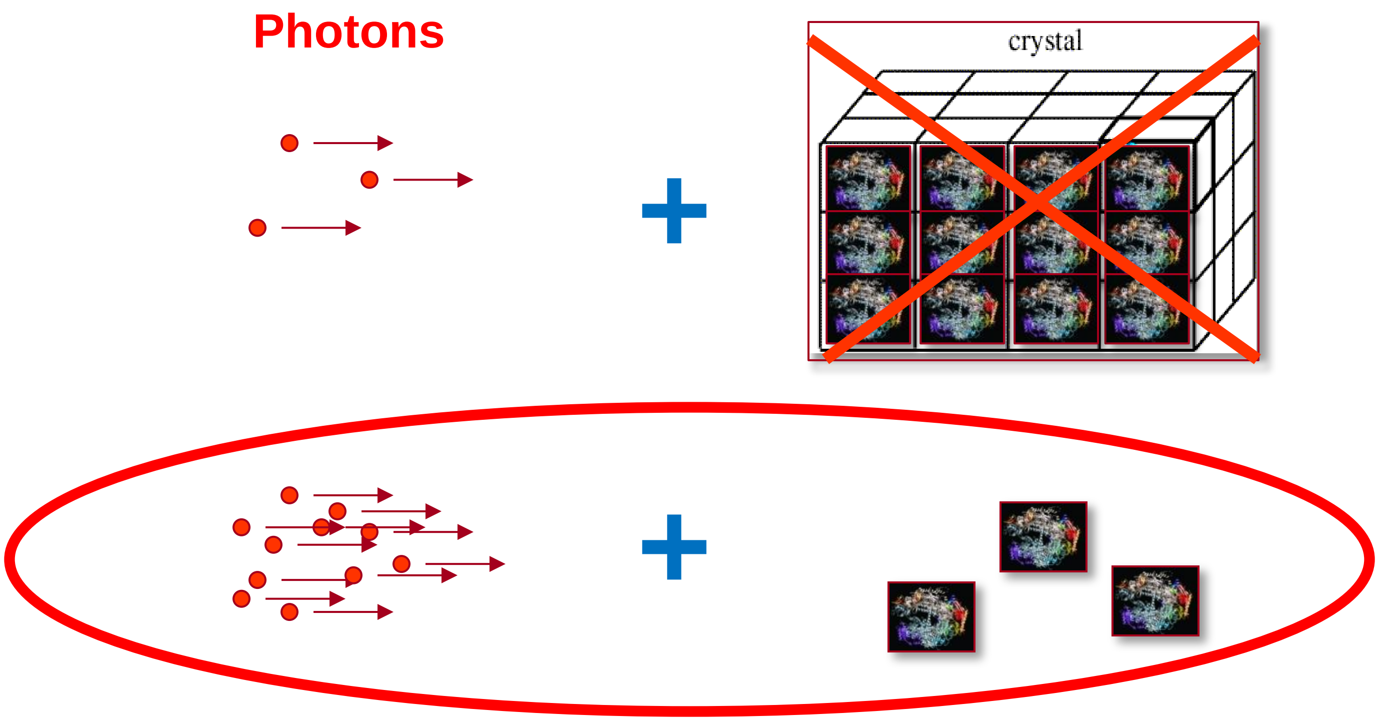
Structural biology in 4 steps:

- Isolate and make protein
- Crystallize protein – Can we avoid bottleneck?
- Measure diffraction pattern from crystal
- Recover structure from diffraction data



Motivation

Two paths to molecular image:

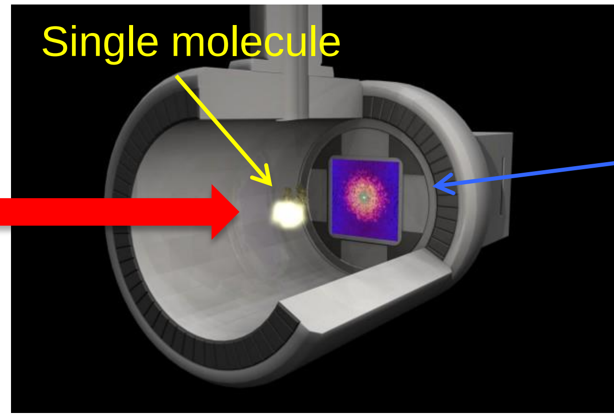


Only possible with an X-ray laser!

Motivation

SLAC

Single molecule imaging!



… or at least really really small crystals: **nanocrystallography**

Simultaneous Femtosecond X-ray Spectroscopy and Diffraction of Photosystem II at Room Temperature

Jan Kern,[1,2] Roberto Alonso-Mori,[2] Rosalie Tran,[1] Johan Hattne,[1] Richard J. Gildea,[1]

Science AAAS

Natively Inhibited Trypanosoma brucei Cathepsin B Structure Determined by Using an X-ray Laser
Lars Redecke *et al.*
Science **339**, 227 (2013);
DOI: 10.1126/science.1229663

LETTER doi:10.1038/nature09750

Femtosecond X-ray protein nanocrystallography

Henry N. Chapman[1,2], Petra Fromme[3], Anton Barty[1], Thomas A. White[1], Richard A. Kirian[4], Andrew Aquila[1], Mark S. Hunter[3],

LETTER doi:10.1038/nature09748

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

M. Marvin Seibert[1]*, Tomas Ekeberg[1]*, Filipe R. N. C. Maia[1]*, Martin Svenda[1], Jakob Andreasson[1], Olof Jönsson[1], Duško Odić[1],

Motivation

SLAC

And many many more fields…

Science AAAS

Real-Time Observation of Surface Bond Breaking with an X-ray Laser
M. Dell'Angela *et al.*
Science **339**, 1302 (2013);
DOI: 10.1126/science.1231711

Sciencexpress

Ultrafast Three-Dimensional Imaging of Lattice Dynamics in Individual Gold Nanocrystals

J. N. Clark,[1*] L. Beitra,[1] G. Xiong,[1] A. Higginbotham,[2] D. M. Fritz,[3] H. T. Lemke,[3] D. Zhu,[3] M. Chollet,[3] G. J. Williams,[3] M. Messerschmidt,[3] B. Abbey,[4] R. J. Harder,[5] A. M. Korsunsky,[6,7] J. S. Wark,[2] I. K. Robinson[1,7]

LETTER doi:10.1038/nature10721

Atomic inner-shell X-ray laser at 1.46 nanometres pumped by an X-ray free-electron laser

Nina Rohringer[1]†, Duncan Ryan[2], Richard A. London[1], Michael Purvis[2], Felicie Albert[1], James Dunn[1], John D. Bozek[3], Christoph Bostedt[3], Alexander Graf[1], Randal Hill[1], Stefan P. Hau-Riege[1] & Jorge J. Rocca[2]

LETTER doi:10.1038/nature11627

An unexpectedly low oscillator strength as the origin of the Fe XVII emission problem

S. Bernitt[1], G. V. Brown[2], J. K. Rudolph[1,3], R. Steinbrügge[1], A. Graf[2], M. Leutenegger[4,5], S. W. Epp[1,6], S. Eberle[1], K. Kubiček[1]†, V. Mäckel[1]†, M. C. Simon[7], E. Träbert[2], E. W. Magee[2], C. Beilmann[1], N. Hell[2,8], S. Schippers[3], A. Müller[3], S. M. Kahn[9], A. Surzhykov[10,11], Z. Harman[1,12], C. H. Keitel[1], J. Clementson[2], F. S. Porter[4], W. Schlotter[13], J. J. Turner[13], J. Ullrich[1]†, P. Beiersdorfer[2] & J. R. Crespo López-Urrutia[1]

ARTICLES — nature photonics
PUBLISHED ONLINE: 11 NOVEMBER 2012 | DOI: 10.1038/NPHOTON.2012.261

Ultra-efficient ionization of heavy atoms by intense X-ray free-electron laser pulses

Benedikt Rudek, Sang-Kil Son, Daniel Rolles *et al.**

PRL **109,** 245003 (2012) PHYSICAL REVIEW LETTERS week ending 14 DECEMBER 2012

Resonant $K\alpha$ Spectroscopy of Solid-Density Aluminum Plasmas

B. I. Cho,[1,*] K. Engelhorn,[1] S. M. Vinko,[2] H.-K. Chung,[3] O. Ciricosta,[2] D. S. Rackstraw,[2] R. W. Falcone,[1,4] C. R. D. Brown,[5] T. Burian,[6] J. Chalupský,[6] C. Graves,[7] V. Hájková,[6] A. Higginbotham,[2] L. Juha,[6] J. Krzywinski,[7] H. J. Lee,[7] M. Messersmidt,[7] C. Murphy,[2] Y. Ping,[8] N. Rohringer,[9] A. Scherz,[7] W. Schlotter,[7] S. Toleikis,[10] J. J. Turner,[7] L. Vysin,[6] T. Wang,[7] B. Wu,[7] U. Zastrau,[11] D. Zhu,[7] R. W. Lee,[7] B. Nagler,[7] J. S. Wark,[2] and P. A. Heimann[7]

PRL **108,** 217402 (2012) PHYSICAL REVIEW LETTERS week ending 25 MAY 2012

Ultrafast Transitions from Solid to Liquid and Plasma States of Graphite Induced by X-Ray Free-Electron Laser Pulses

S. P. Hau-Riege,[1,*] A. Graf,[1] T. Döppner,[1] R. A. London,[1] J. Krzywinski,[2] C. Fortmann,[1] S. H. Glenzer,[1] M. Frank,[1] K. Sokolowski-Tinten,[3] M. Messerschmidt,[2] C. Bostedt,[2] S. Schorb,[2] J. A. Bradley,[1] A. Lutman,[2] D. Rolles,[4,5] A. Rudenko,[4,6] and B. Rudek[4,6]

PRL **108,** 253006 (2012) PHYSICAL REVIEW LETTERS week ending 22 JUNE 2012

Transient X-Ray Fragmentation: Probing a Prototypical Photoinduced Ring Opening

Vladimir S. Petrović,[1,2,*] Marco Siano,[3] James L. White,[2,4] Nora Berrah,[5] Christoph Bostedt,[6] John D. Bozek,[6] Douglas Broege,[2,4] Max Chalfin,[1,2] Ryan N. Coffee,[6] James Cryan,[1,2] Li Fang,[5] Joseph P. Farrell,[1,2] Leszek J Frasinski,[3] James M. Glownia,[2,4] Markus Gühr,[2] Matthias Hoener,[5] David M. P. Holland,[7] Jaehee Kim,[1,2] Jonathan P. Marangos,[3] Todd Martinez,[2,8] Brian K. McFarland,[2,4] Russell S. Minns,[9] Shungo Miyabe,[2,8] Sebastian Schorb,[6] Roseanne J. Sension,[10] Limor S. Spector,[1,2] Richard Squibb,[3] Hongli Tao,[2,8] Jonathan G. Underwood,[9] and Philip H. Bucksbaum[1,2,4]

The Free Electron Laser

John Madey, 1971

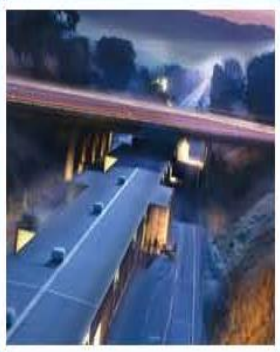
JOURNAL OF APPLIED PHYSICS VOLUME 42, NUMBER 5 APRIL 1971

Stimulated Emission of Bremsstrahlung in a Periodic Magnetic Field

JOHN M. J. MADEY
Physics Department, Stanford University, Stanford, California 94305

(Received 20 February 1970; in final form 21 August 1970)

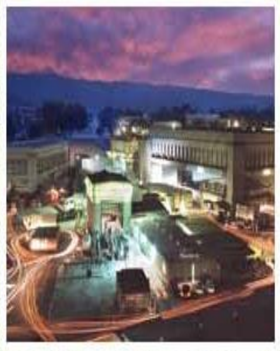
The Weizsäcker–Williams method is used to calculate the gain due to the induced emission of radiation into a single electromagnetic mode parallel to the motion of a relativistic electron through a periodic transverse dc magnetic field. Finite gain is available from the far-infrared through the visible region raising the possibility of continuously tunable amplifiers and oscillators at these frequencies with the further possibility of partially coherent radiation sources in the ultraviolet and x-ray regions to beyond 10 keV. Several numerical examples are considered.

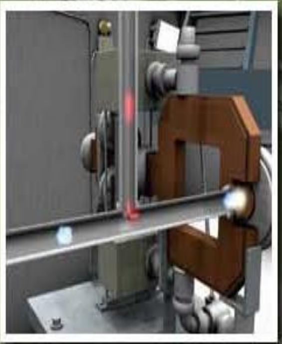


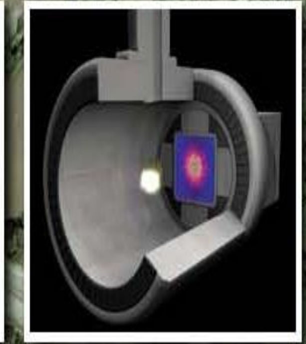
LCLS

The Linac Coherent Light Source (LCLS) is transforming the face of SLAC. For more than 40 years, SLAC's two-mile long linear accelerator has produced cutting edge physics.

Now, scientists will continue this tradition of discovery using the final third of SLAC's linac to create an entirely new kind of laser.





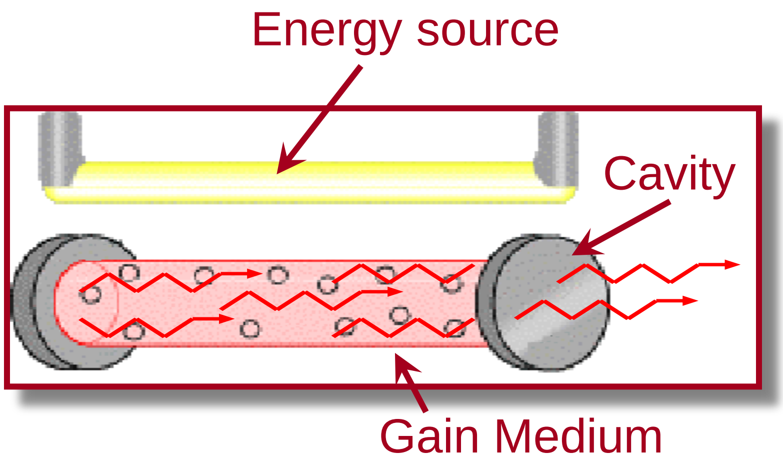


The World's First Hard X-ray Free-Electron Laser

Laser Components

SLAC

1. Energy Source (e.g. flashlamp)
2. Radiation Source (electronic transition)
3. Wavelength Selection (gain medium):
4. Gain (oscillator cavity)



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Free Electron Laser Basics:
FEL Components

SLAC

Energy source: SLAC Linac

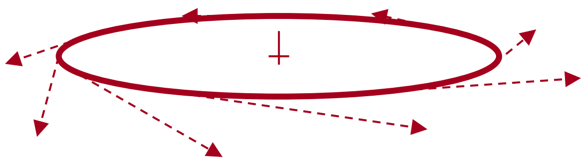
1 km can produce ~15 GeV beam ~ TW peak power

XFEL extracts less than 0.1% as radiation

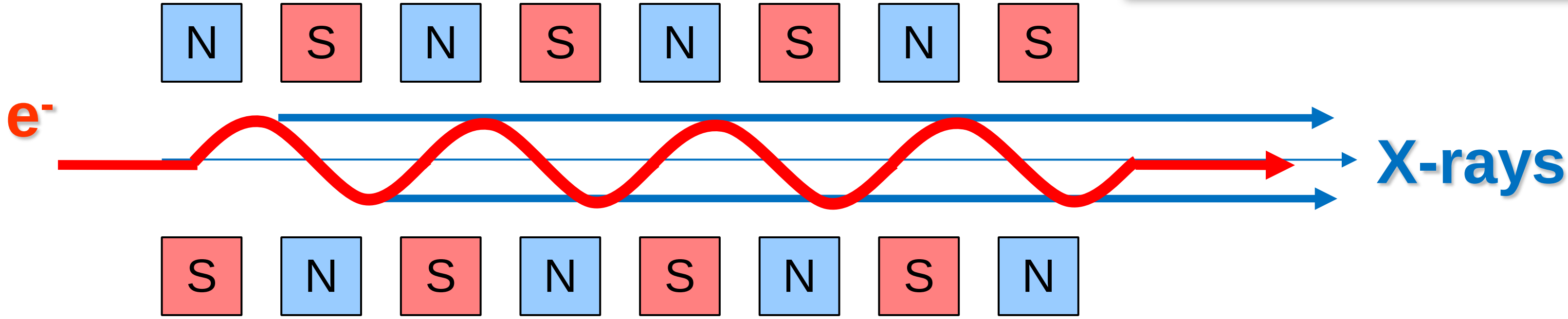
Free Electron Laser Basics:
Radiation Source

SLAC

Bending high energy electrons ➔ X-rays



Modern light sources use Undulators:

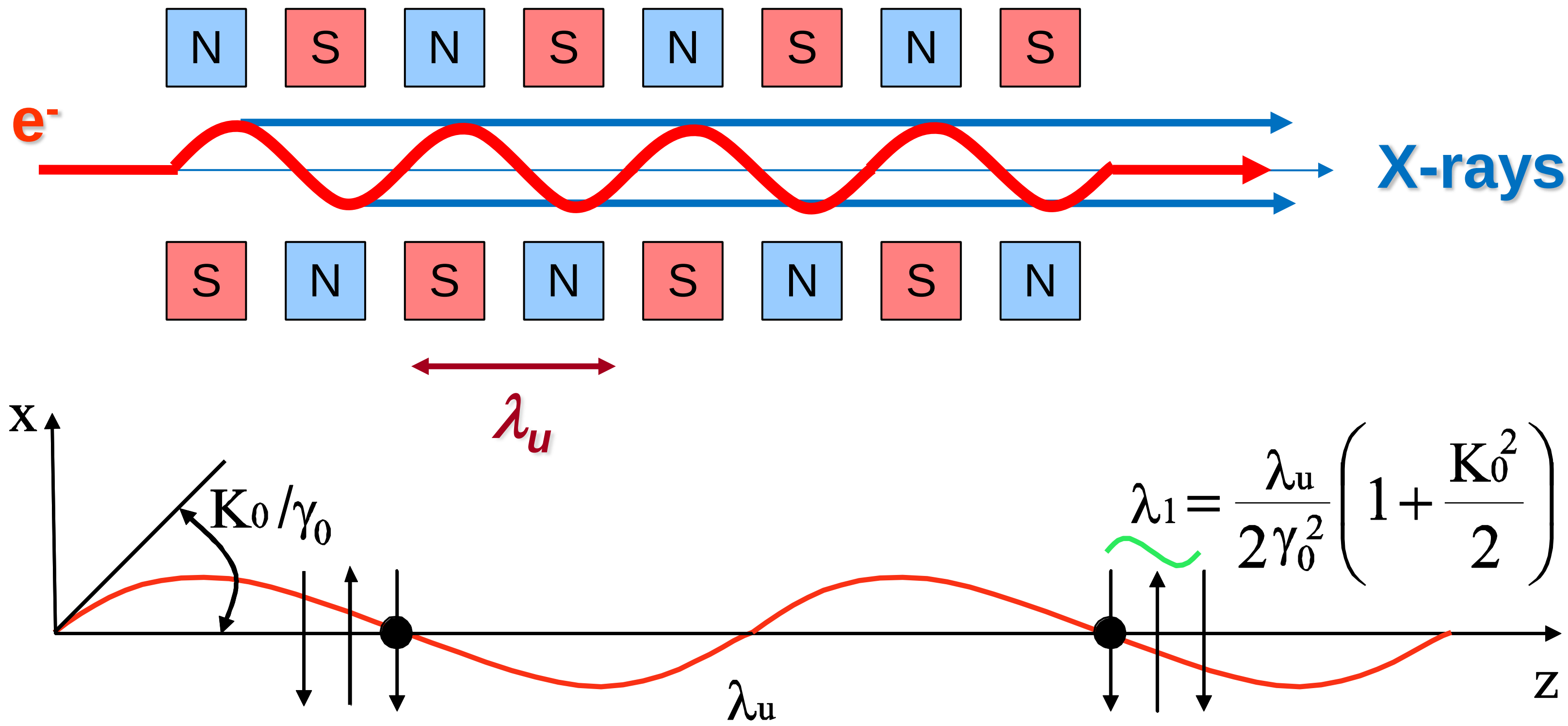


Free Electron Laser Basics: Resonant Condition

SLAC

Electrons travel farther than photons

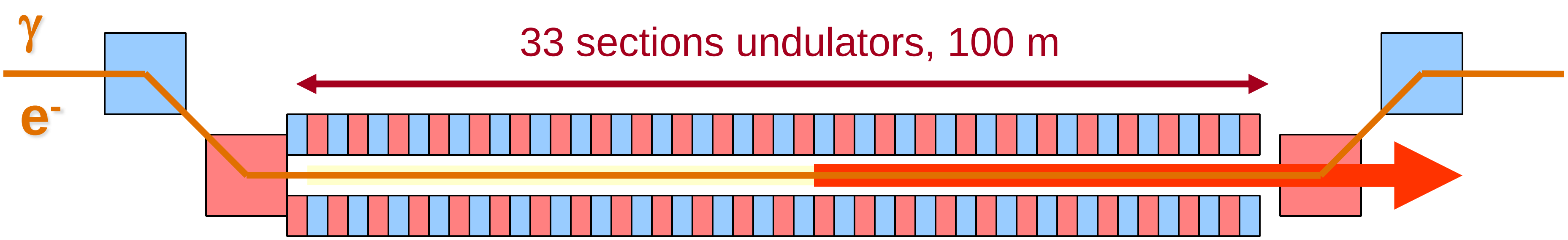
- Match slippage to exactly one radiation wavelength
- Only resonant wavelength is amplified

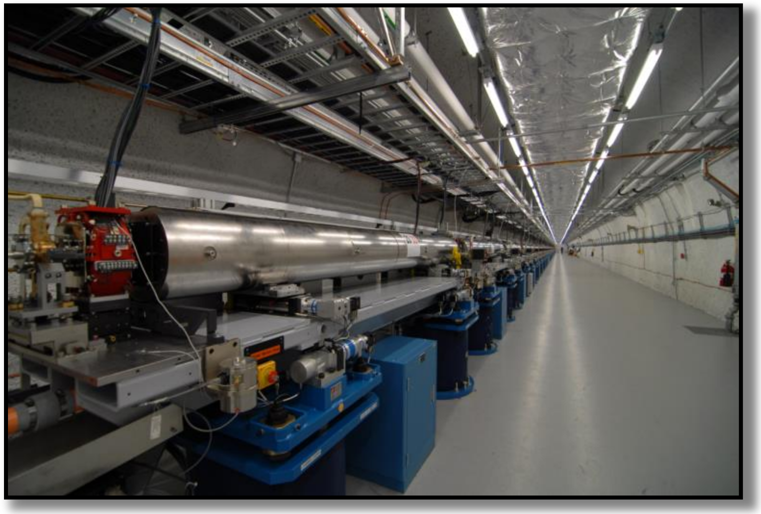


Free Electron Laser Basics:
Gain

High Gain FEL: single pass for electrons

- No mirrors, no cavity
- LCLS uses ~3000 periods





1D FEL Theory

Define new variables

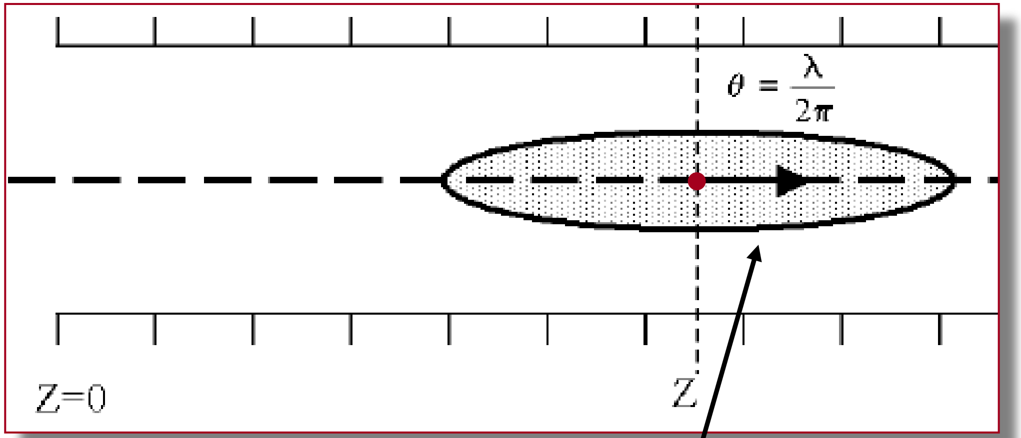
energy $\eta=(\gamma-\gamma_0)/\gamma_0$

phase $\theta=(k_r+k_u)z-\omega_r t$

radiation wavenumber

undulator wavenumber

arrival time at undulator distance



Electron phase, θ, is longitudinal position relative to radiation phase

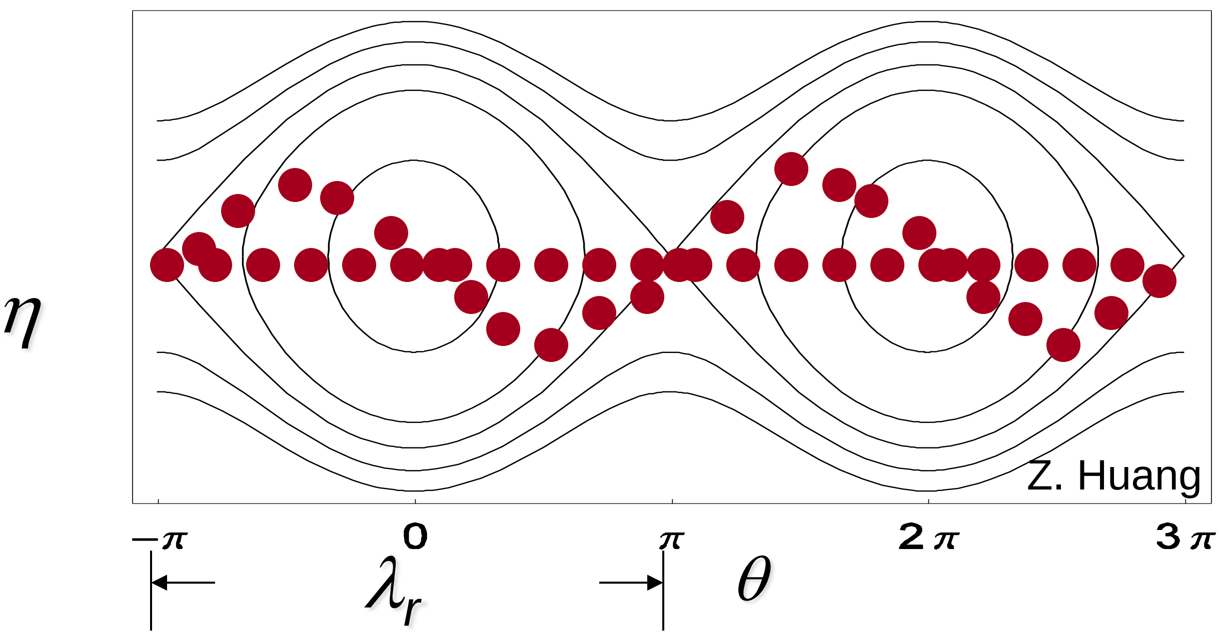
Intro to FEL Theory

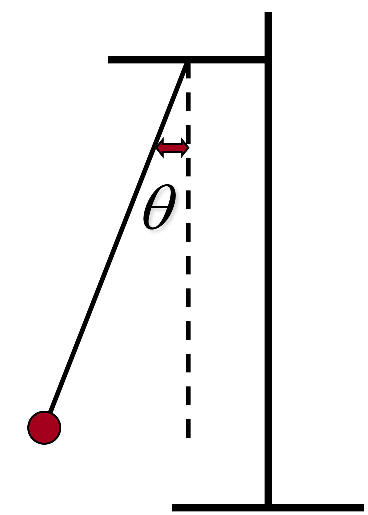
$$\frac{dq}{dz} = 2hk_u, \quad \frac{dh}{dz} = c_1\left(\tilde{E}e^{iq} + \tilde{E}^* e^{-iq}\right)$$

field amplitude

$$\chi_1 = \frac{eK[\mathrm{JJ}]}{(2\gamma_0^2 mc^2)} \qquad [\mathrm{JJ}] = J_0\left(\frac{K^2}{4+2K^2}\right) - J_1\left(\frac{K^2}{4+2K^2}\right)$$ (planar undulator)

$$K = eB_0/(mck_u) = 0.94 B_0[\mathrm{Tesla}]\lambda_u[\mathrm{cm}]$$





Radiation scales as e⁻ bunching: $\frac{d\tilde{E}}{dz} \propto \left\langle e^{-i\theta_j} \right\rangle_{Slice} \equiv b$

e⁻ bunching

Combining 3 coupled equations

$$\frac{d\theta}{dz} = 2\eta k_u, \quad \frac{d\eta}{dz} = c_1\left(\tilde{E}e^{i\theta} + \tilde{E}^* e^{-i\theta}\right), \quad \frac{d\tilde{E}}{dz} \propto \left\langle e^{-i\theta_j} \right\rangle_{Slice}$$

$$\rightarrow \quad \frac{d^3\tilde{a}}{d\bar{z}^3} \propto i\tilde{a} \qquad \bar{z} = 2k_u \rho z, \quad \tilde{a} = \frac{c_1}{2k_u\rho^2}\tilde{E} \qquad \rho \equiv \left[\frac{I}{8\pi I_A}\left(\frac{K[JJ]}{1+K^2/2}\right)^2 \frac{\lambda_1^2}{\Sigma_A}\right]^{1/3}$$

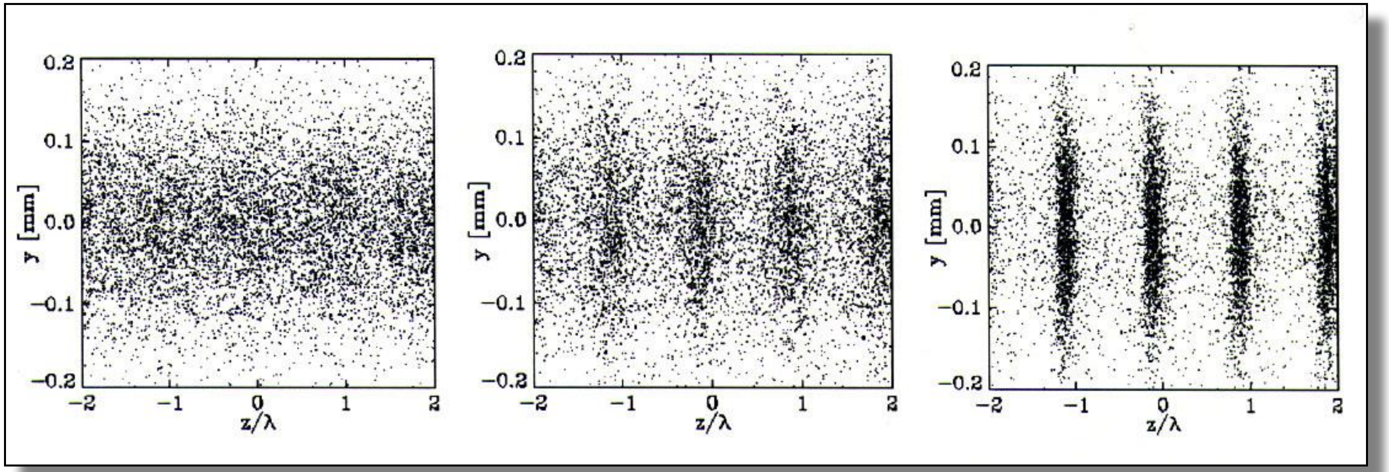
Alfven current   beam cross section

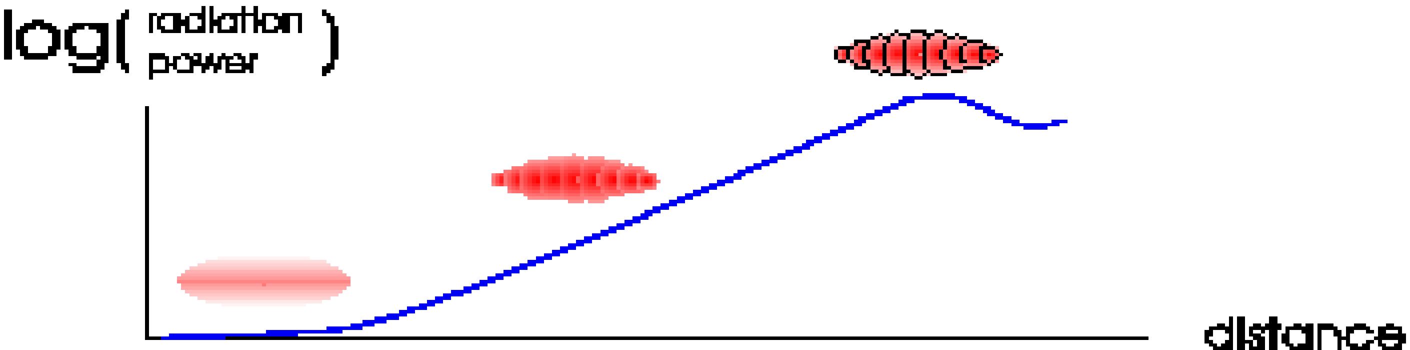
And finally exponential radiation growth

$$\tilde{A}(\bar{z}) \approx \frac{1}{3}\left(\tilde{A}(0) - i\frac{b(0)}{\mu_3} - iP(0)\mu_3\right)e^{-i\mu_3\bar{z}}, \quad \mu_3 \equiv \frac{-1+\sqrt{3}i}{2}$$

Radiation   Bunching   Momentum

X-ray FELs start from shot noise

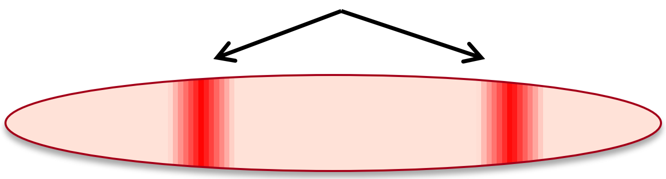




SLAC

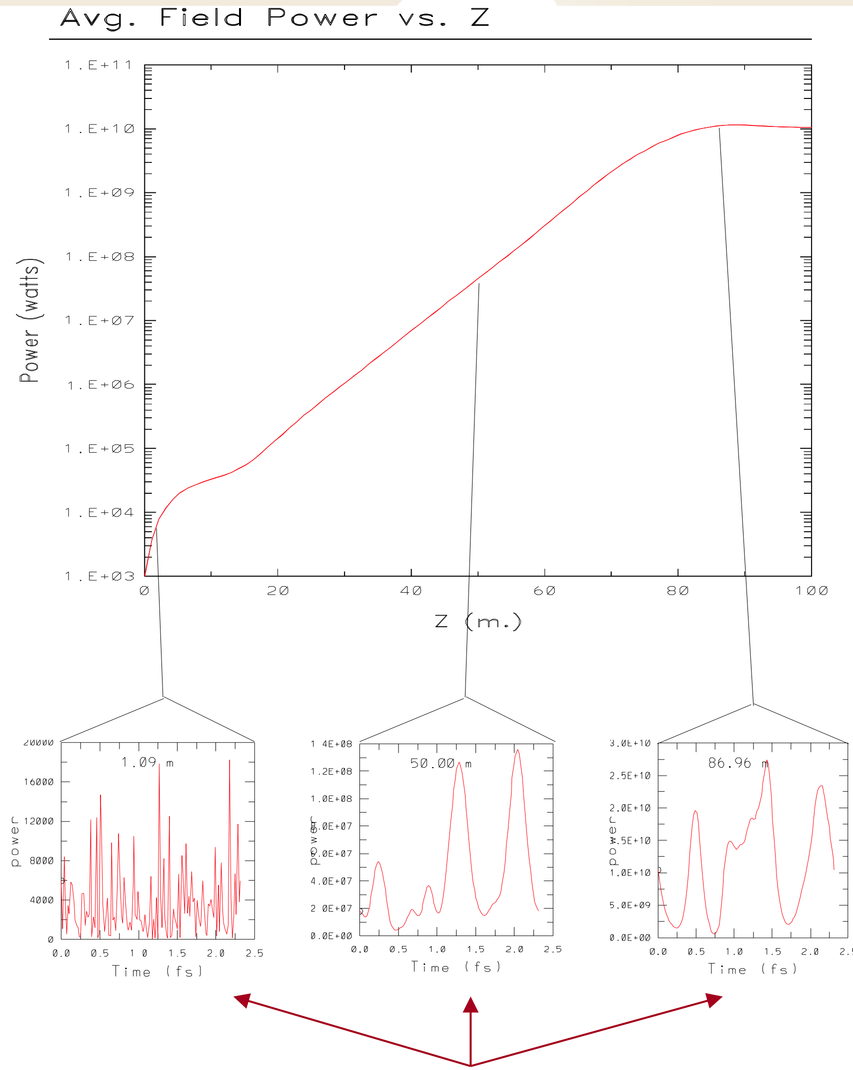
Implications of shot noise:

Different slices don't communicate



➡ Each slice lases independently!

Upshot: SASE FELs have complicated temporal structure



W. Fawley

1 % of X-Ray Pulse Length

LCLS Parameters

LCLS accelerator parameters:

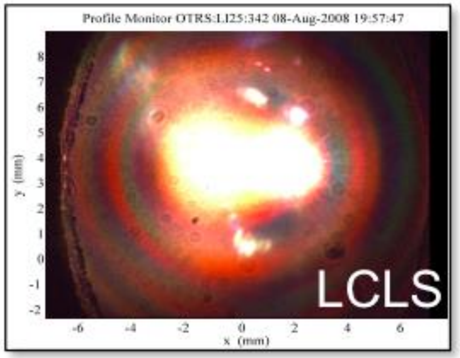
Parameter	Value
Electron energy range	2.5-15.8 GeV
Electron charge	20-250 pC
Slice emittance (normalized)	0.2-0.4 um
Electron pulse length	~5-500 fs
Peak current	1-3 kA
Initial slice energy spread	1-2 MeV
Electron energy jitter	0.04-0.07 %
Undulator period	3 cm
Number of undulator periods	3000
Gain length	1.5-3 m

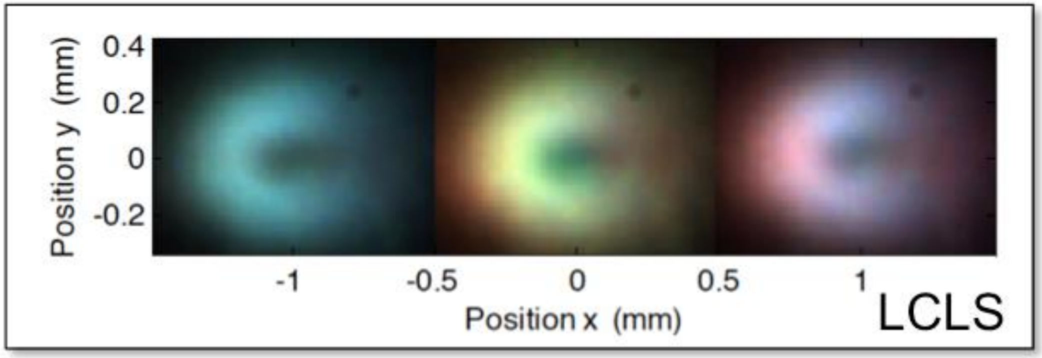
SLAC

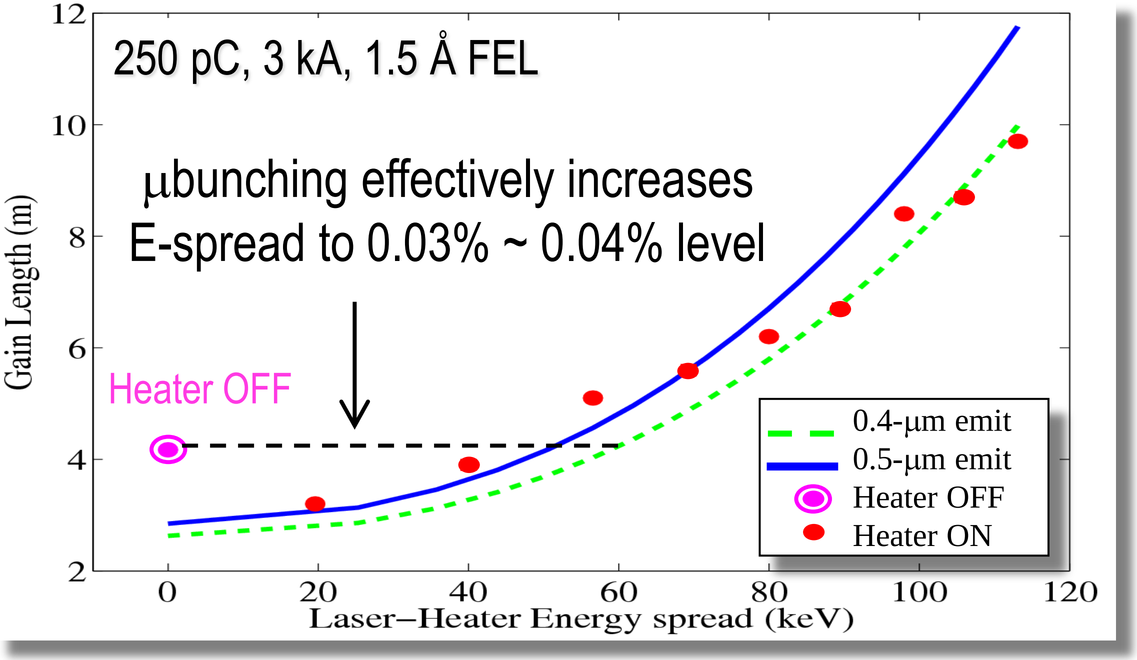
LCLS X-ray performance:

Parameter	Value
Photon energy range (fundamental)	0.3-11.2 keV
Photon wavelength range	0.11-4 nm
Typical pulse energy	2 mJ
Typical number of photons	$10^{12} – 10^{13}$
Bandwidth (non-seeded)	0.1-0.5 %
Pulse length	<10-400 fs

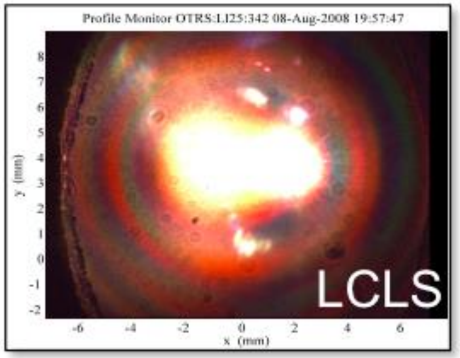
Microbunching Instability

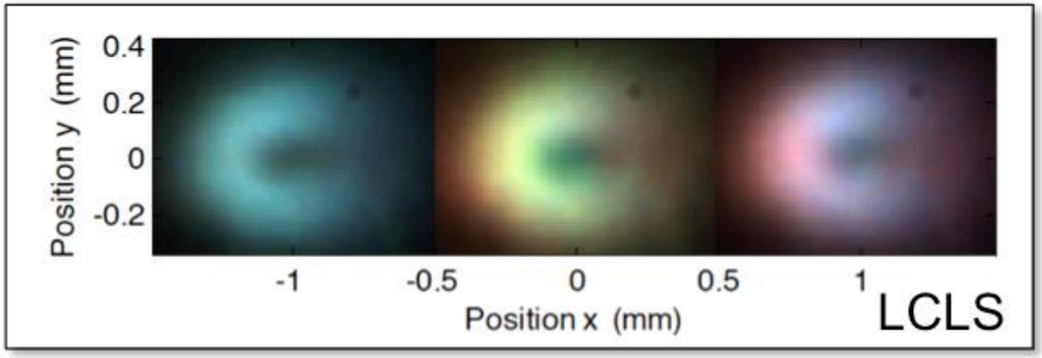


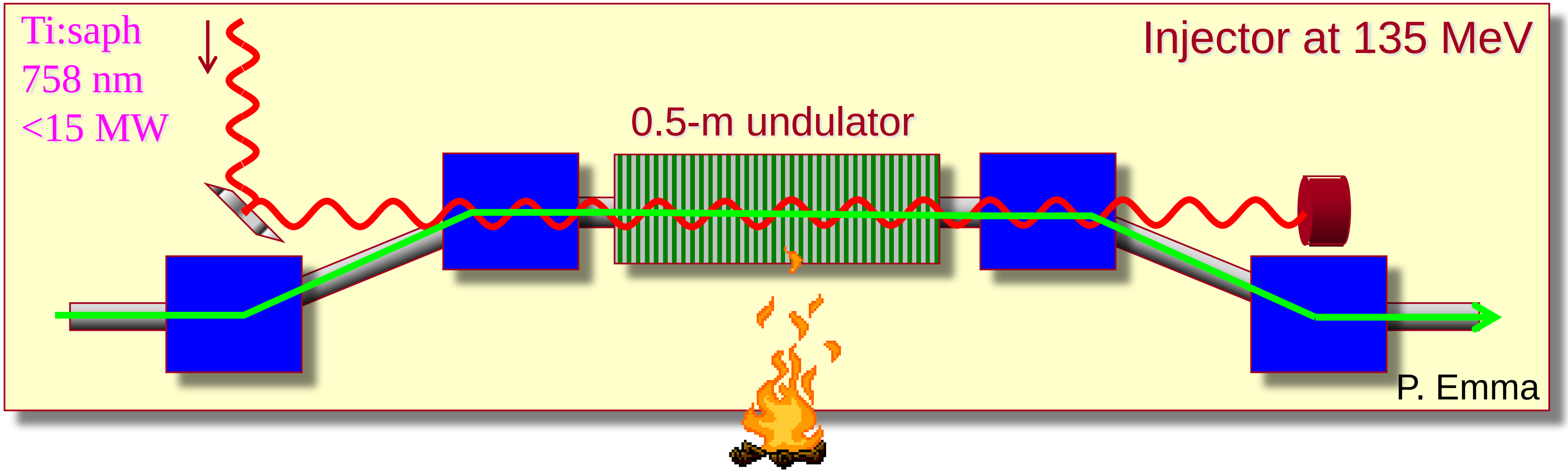




Microbunching Instability



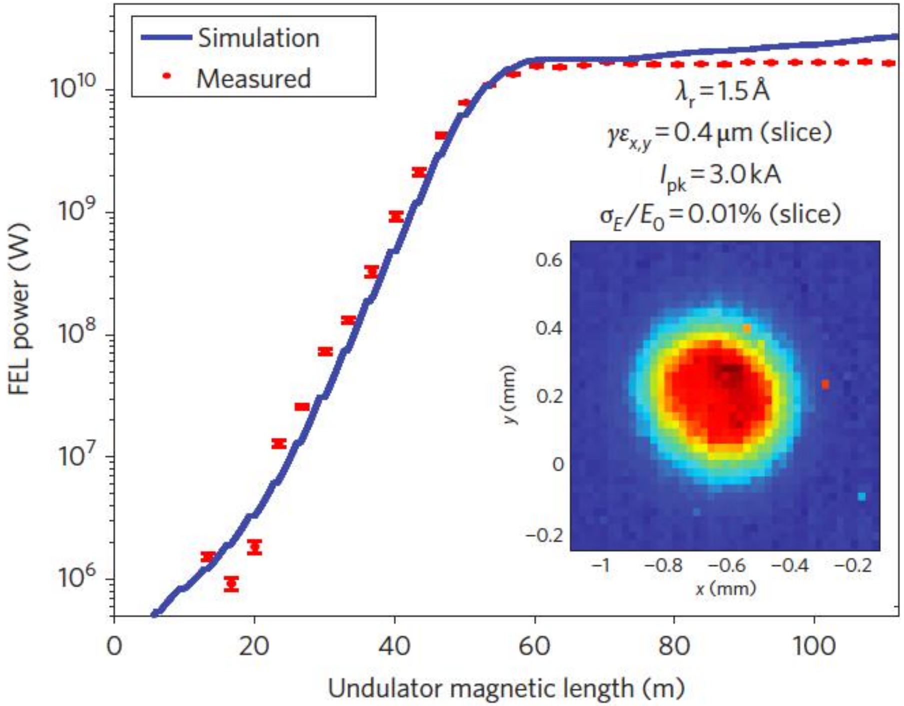


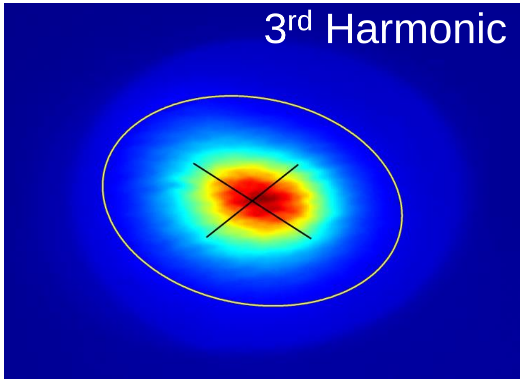


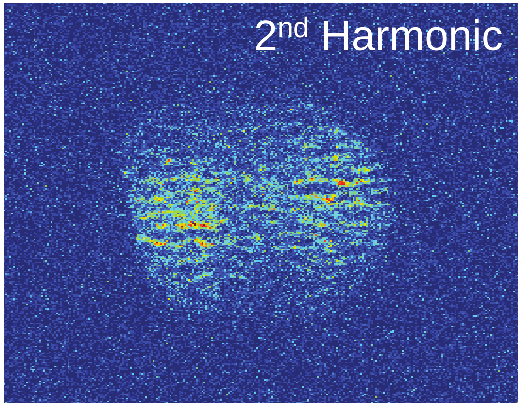
'Laser heater' suggested by Saldin et al., NIMA, 2004; independently by J. Galayda

LCLS design study: Z. Huang et al., PRST 2004 (chicane suggested by T. Smith)

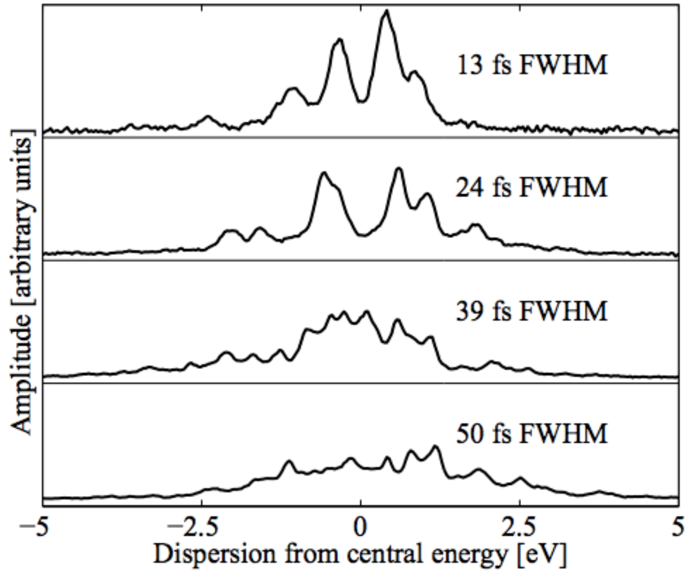
LCLS data: Transverse structure







LCLS data: Longitudinal structure



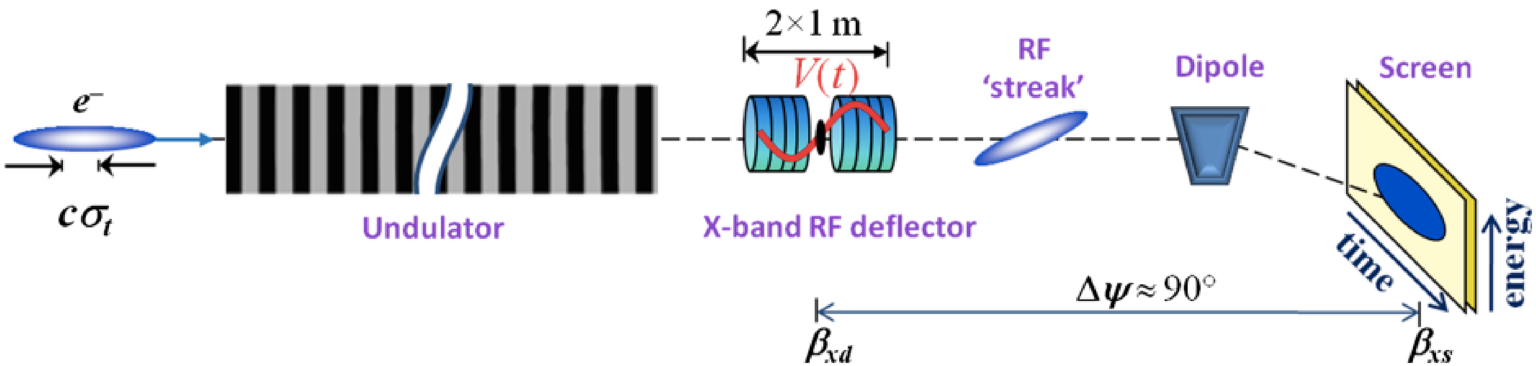
PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **15**, 030705 (2012)

Femtosecond x-ray free electron laser pulse duration measurement from spectral correlation function

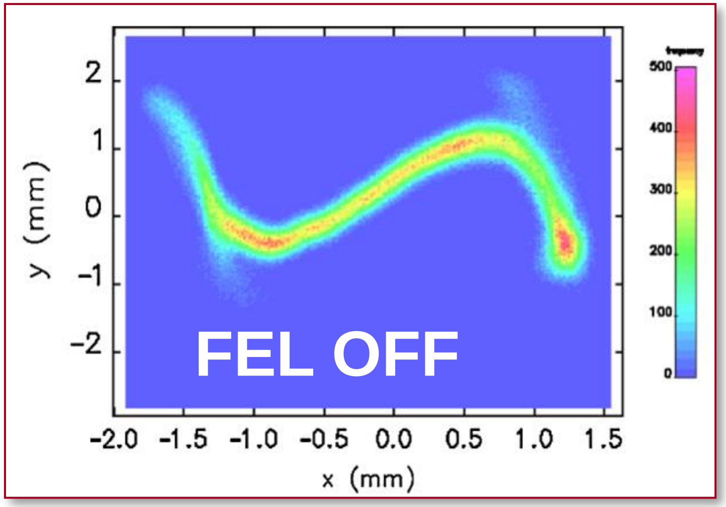
A. A. Lutman,* Y. Ding, Y. Feng, Z. Huang, M. Messerschmidt, J. Wu, and J. Krzywinski

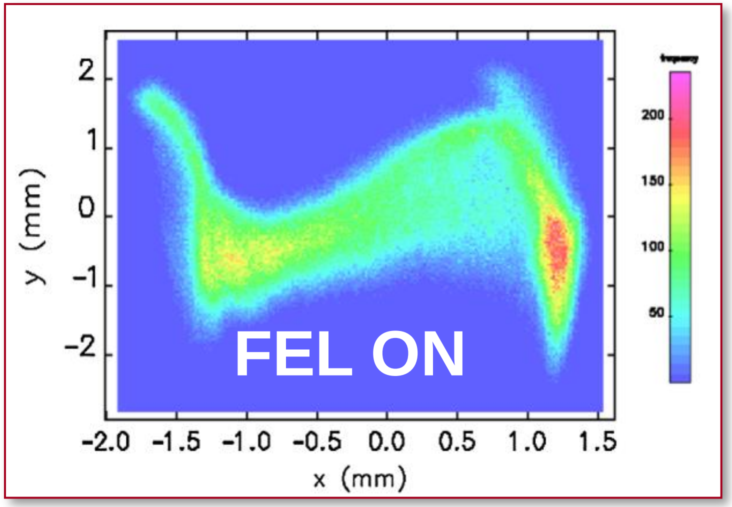
Measurements

X-Band Transverse Cavity



Energy





Time

Y. Ding et al., PRSTAB 2011

Moving Beyond the Vanilla FEL

Baseline modern X-ray FEL:

- High power (GW) in the X-ray regime
- Good transverse coherence, poor longitudinal coherence
- Need ~1km and ~$1 billion to build

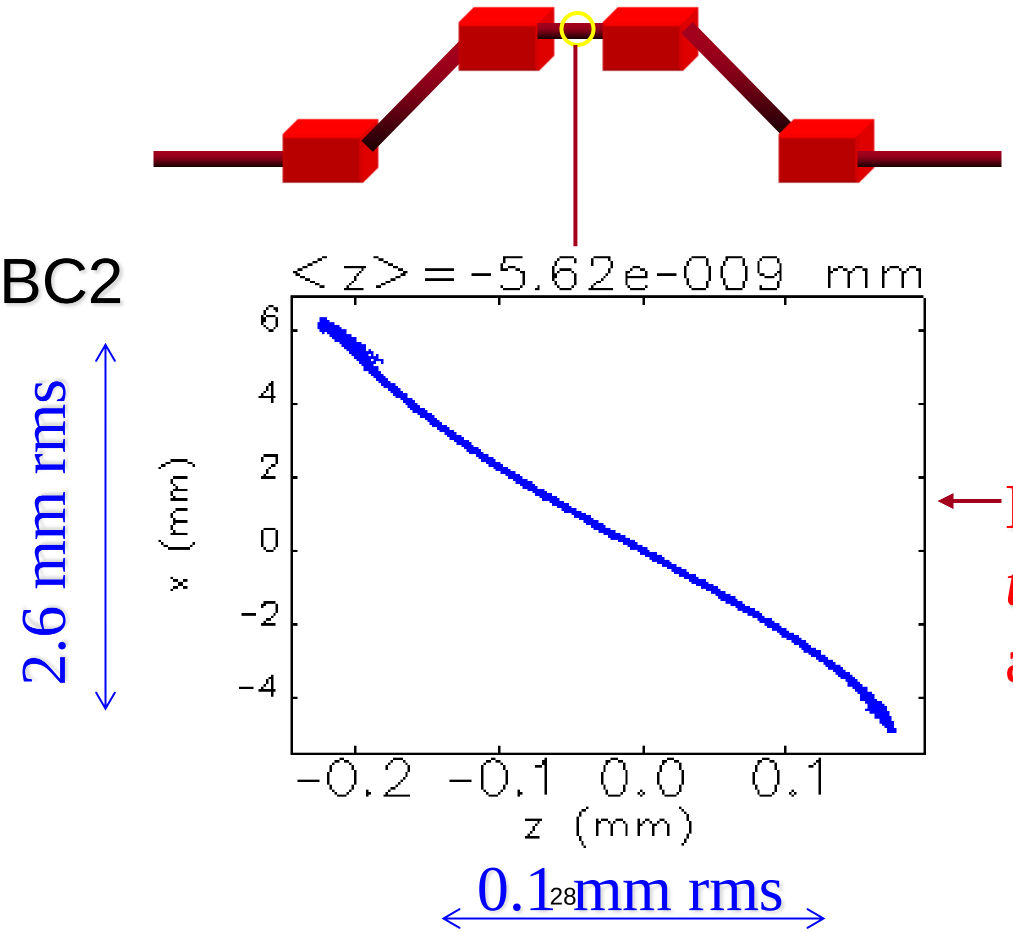
Looking towards the future:

- Shorter pulses/higher power
- More energy per pulse
- Coherent control
- Smaller and cheaper!

Slotted-spoiler

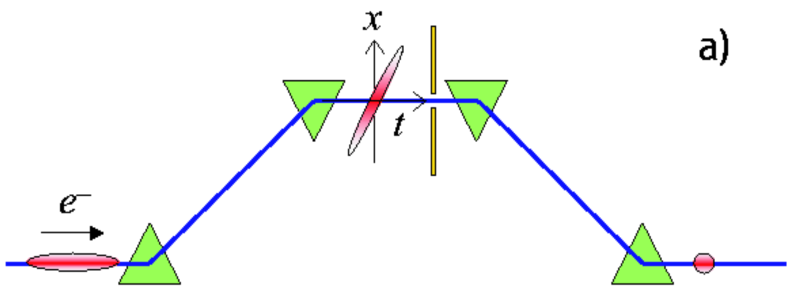
Large x-z correlation inside a bunch compressor chicane

LCLS BC2

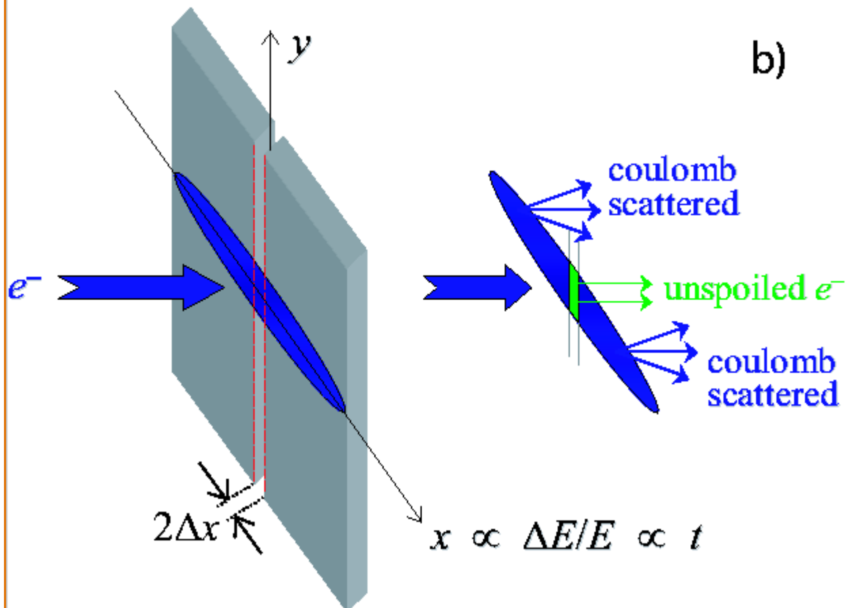


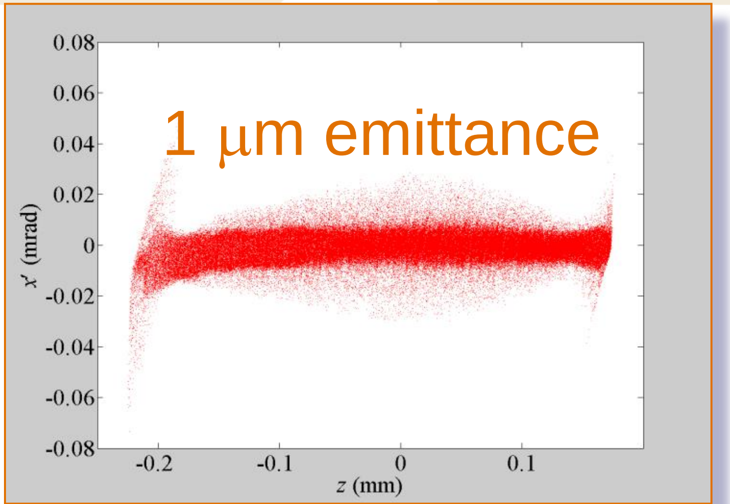
Easy access to *time* coordinate along bunch

Slotted-spoiler

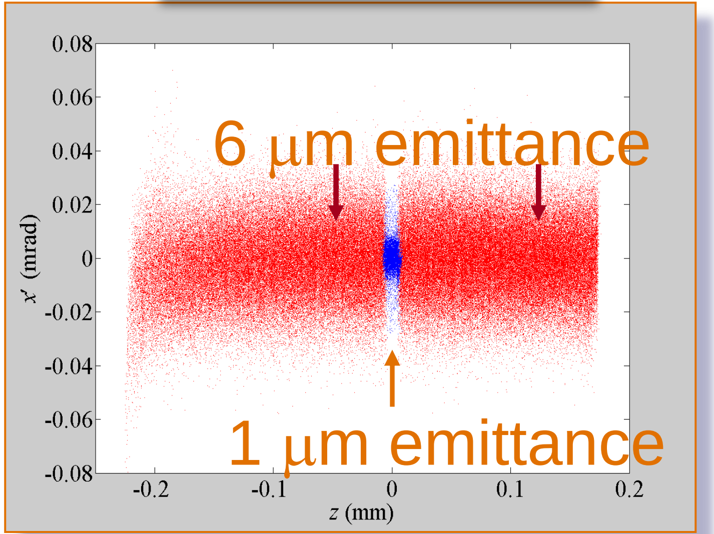


P. Emma et al. PRL92, 074801 (2004)





15-μm Be foil



Low charge mode

➔ **Short pulse, low emittance**

nominal: 150-250 pC

low charge mode: 10-40 pC

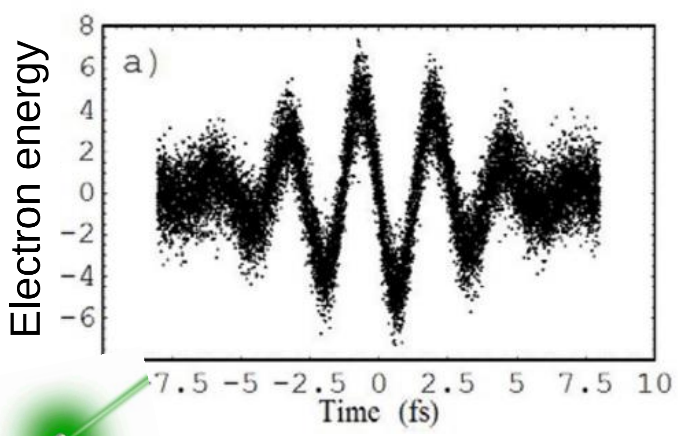
PRL **102,** 254801 (2009) PHYSICAL REVIEW LETTERS week ending 26 JUNE 2009

Measurements and Simulations of Ultralow Emittance and Ultrashort Electron Beams in the Linac Coherent Light Source

Y. Ding, A. Brachmann, F.-J. Decker, D. Dowell, P. Emma, J. Frisch, S. Gilevich, G. Hays, Ph. Hering, Z. Huang, R. Iverson, H. Loos, A. Miahnahri, H.-D. Nuhn, D. Ratner, J. Turner, J. Welch, W. White, and J. Wu

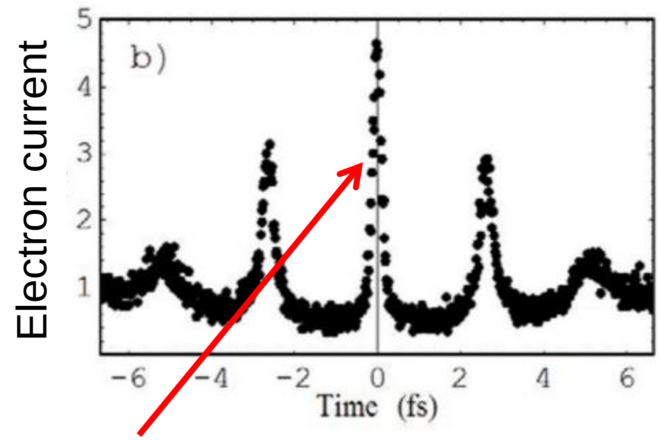
enhanced-SASE (eSASE)

Energy modulation from laser



Dispersion

Density modulation



Only current spike makes X-rays

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **8**, 040701 (2005)

Method of an enhanced self-amplified spontaneous emission for x-ray free electron lasers

Alexander A. Zholents

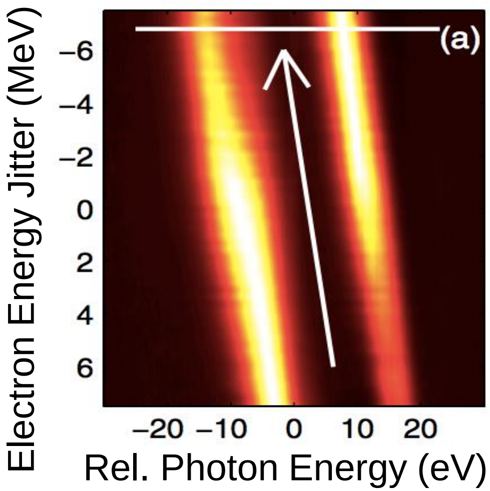
Coherent Control

Two Color:

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



Polarization Control:

Nuclear Instruments and Methods in Physics Research A 347 (1994) 83–86

Analyses for a planar variably-polarizing undulator

Shigemi Sasaki

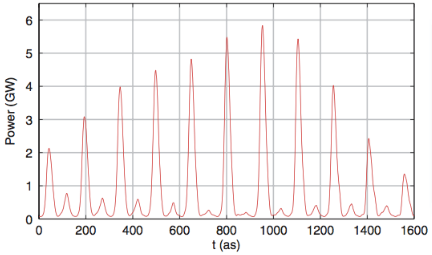
APPLE-II, BESSY

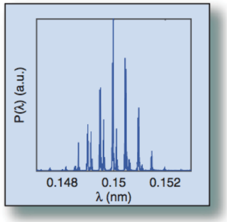
Modelocking:

PRL **100,** 203901 (2008) PHYSICAL REVIEW LETTERS week ending 23 MAY 2008

Mode Locking in a Free-Electron Laser Amplifier

N. R. Thompson[1,2,*] and B. W. J. McNeil[1,†]





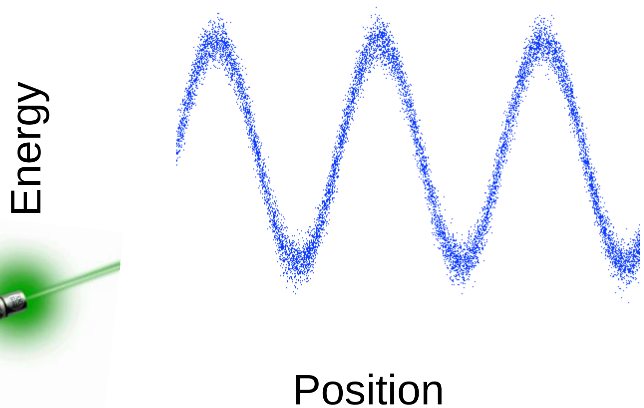
Seeded FELs

SASE FEL: Start from shot noise

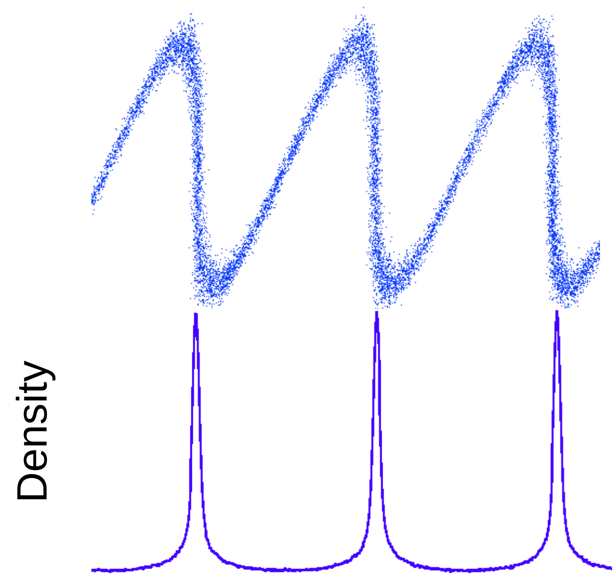
Seeded FEL: Start from radiation

$$\tilde{a}(\bar{z}) \approx \frac{1}{3}\left(\tilde{a}(0) - i\frac{b(0)}{\mu_3} - iP(0)\mu_3\right)e^{-i\mu_3\bar{z}}$$

Radiation Bunching Momentum



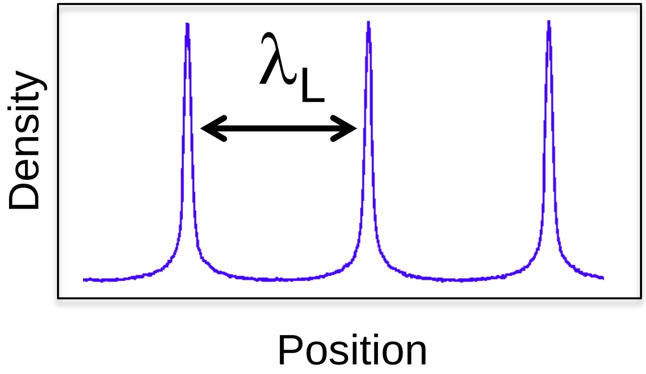
Dispersion



Seeded FELs

Seeded FEL: Start from radiation

$$\tilde{a}(\bar{z}) \approx \frac{1}{3}\left(\tilde{a}(0) - i\frac{b(0)}{\mu_3} - iP(0)\mu_3\right)e^{-i\mu_3\bar{z}}$$



Short-wavelength seeding:

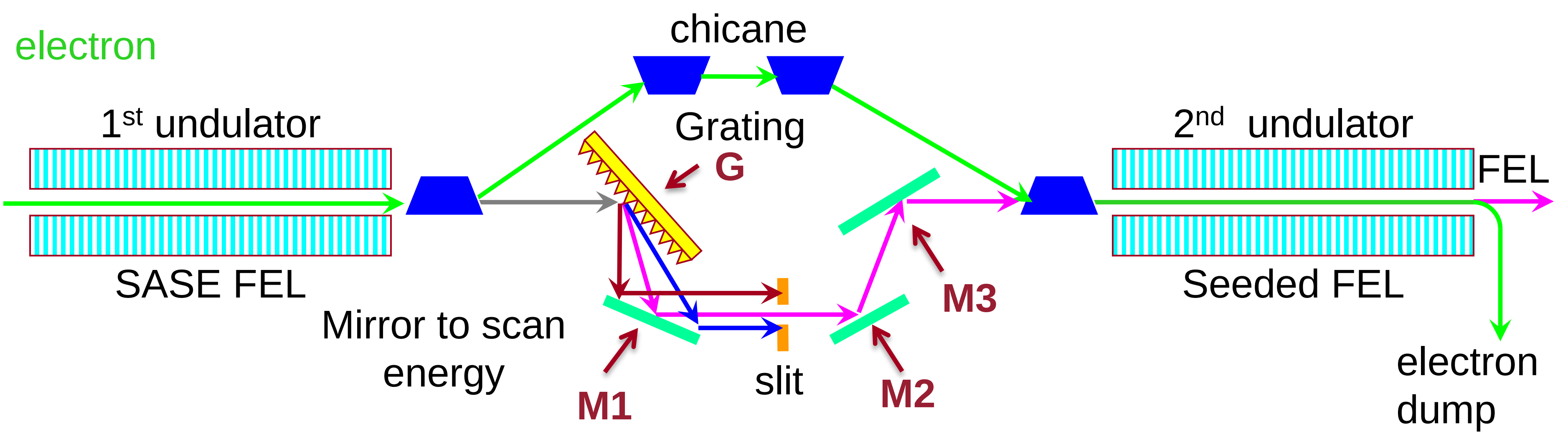
1. High Harmonic Generation (HHG): small λ_L
2. Harmonic seeding: $\lambda_L \rightarrow \lambda_L/H$
   High Gain Harmonic Generation (HGHG)
   Echo-enabled Harmonic Generation (EEHG)
3. Self-seeding: use λ_{FEL}

Self-Seeding: First half of FEL seeds second half

Two components:

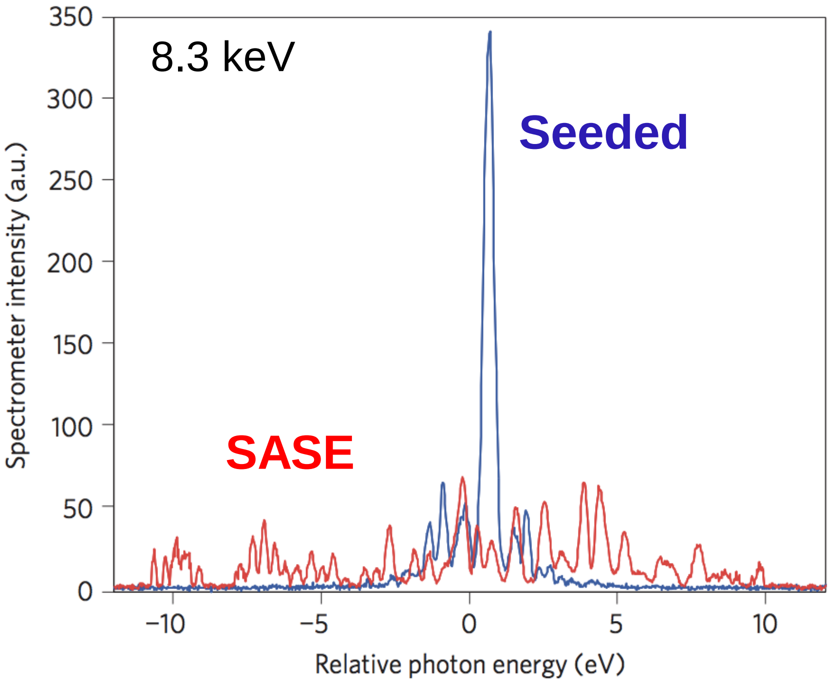
a) Monochromator makes narrow-bandwidth seed
b) Chicane resets electron bunch

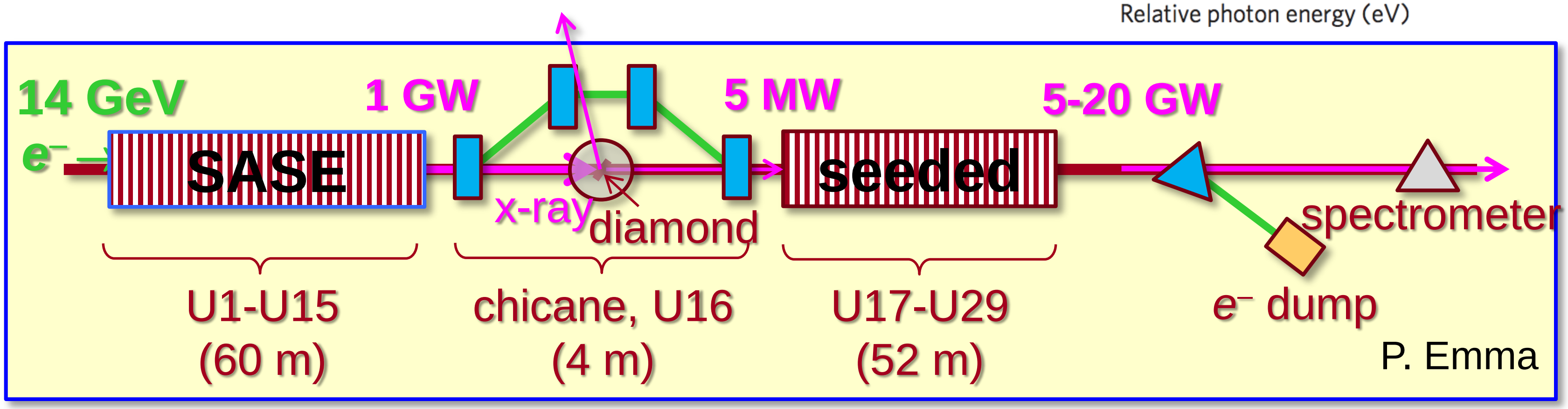
Soft X-ray Self-Seeding Design



Self-Seeding: Hard X-rays

Diamond Bragg reflection produces monochromatic wake

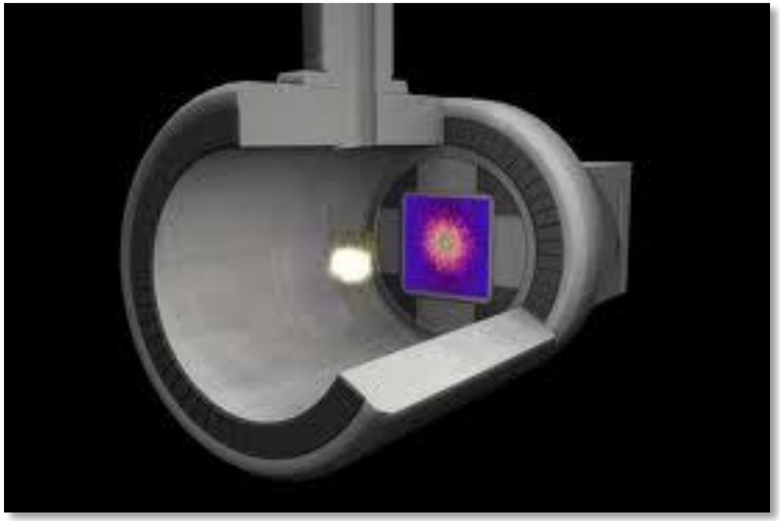




TW FELs

XFEL dream:
Single molecule imaging

…but need TW FEL!!



LCLS currently saturates around 10 GW

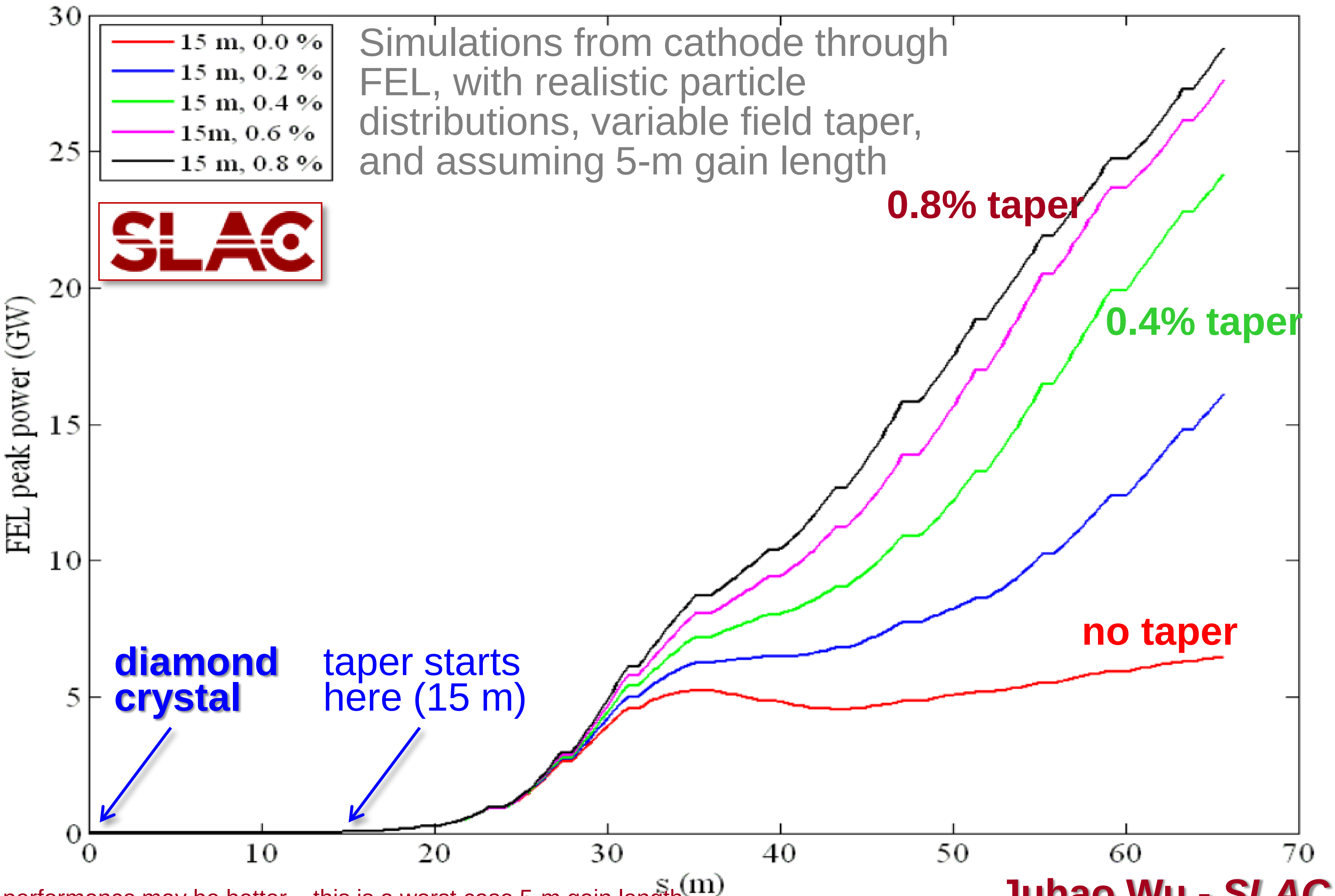
1. Bunching maximal
   ➔ exponential growth ends
2. e- energy drops
   ➔ Resonant frequency changes

Offset with drop in K

$$\lambda_{sat} = \lambda_u \frac{[1 + K^2/2]}{2(\gamma_0 - \Delta\gamma)^2} > \lambda_1$$

Energy drops

Start-to-End HXRSS Simulations (U17-U33)

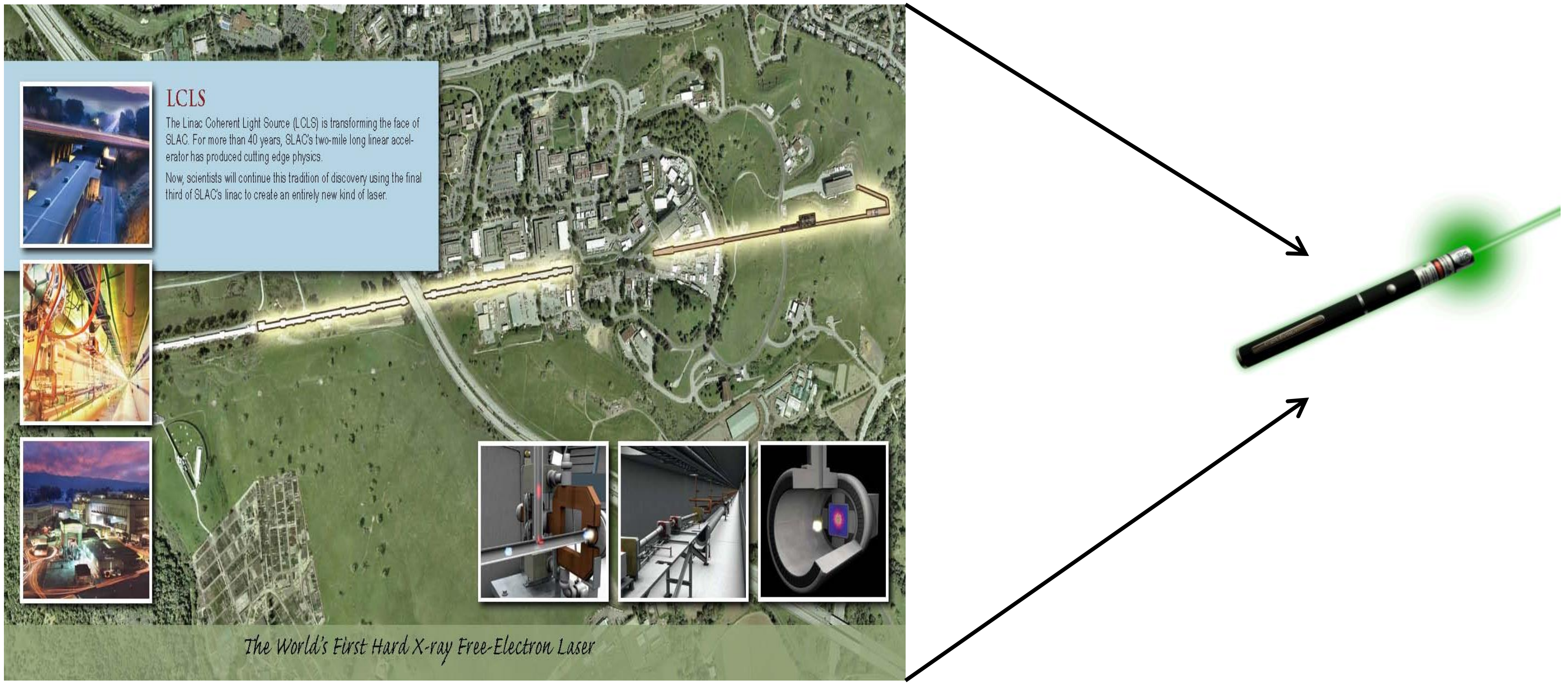


performance may be better – this is a worst case 5-m gain length

Juhao Wu - *SLAC*

Compact FELs

Grand challenge in FELs:
Miniaturize the X-ray laser!

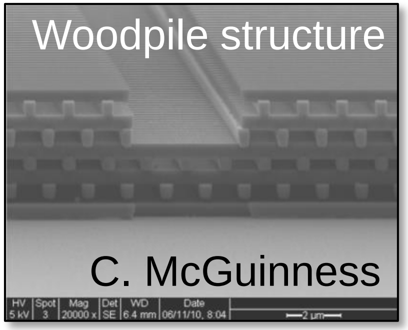


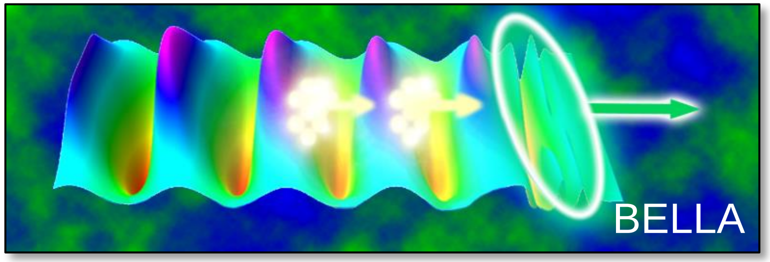
Path to a Miniature X-ray FEL: Miniaturize the Accelerator

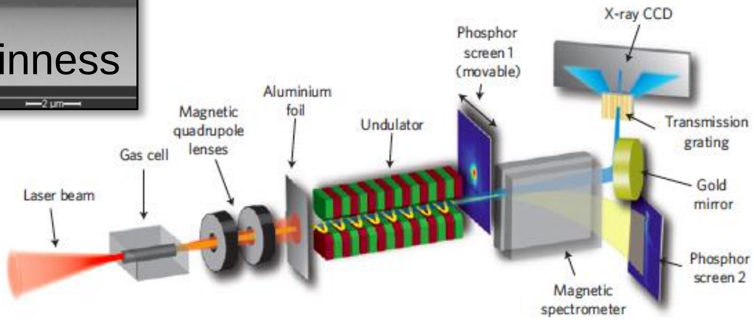
Small step:
X-band guns, accelerators

Big step:
Novel acceleration methods

e.g. Laser wakefield
and dielectrics:



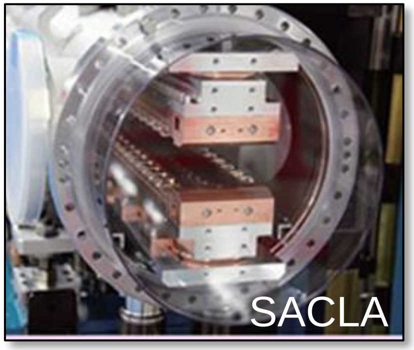




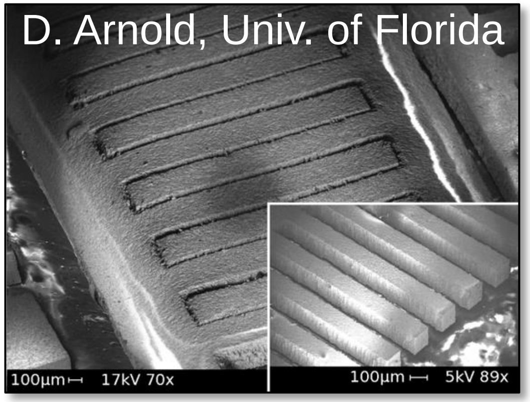
M. Fuchs et al., Nature 2009

Path to a Miniature X-ray FEL: Miniaturize the Undulator

Smaller periods:

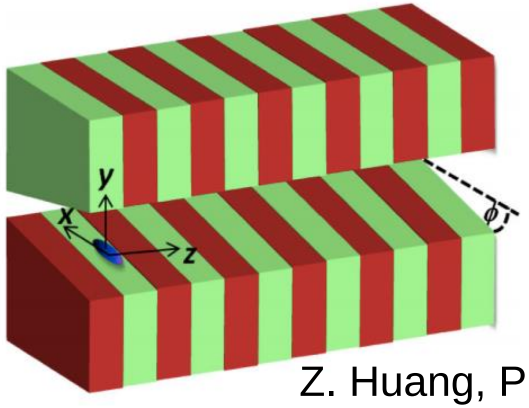


In vacuum



Micromachining

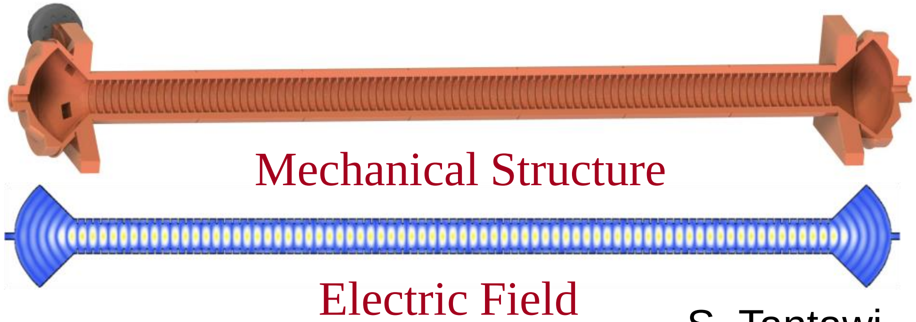
Undulators for compact accelerators:



Z. Huang, PRL 2012

Transverse Gradient Undulator

Electromagnetic undulators



S. Tantawi

Compact FELs

Path to a Miniature X-ray FEL: Miniaturize the Accelerator
Miniaturize the Undulator

It’s up to you to put them together!

FEL References

SLAC

References:

K.-J. Kim and Z. Huang, FEL lecture note, available electronically upon request (zrh@slac.stanford.edu)

Saldin, Schneidmiller, Yurkov, The Physics of Free Electron Lasers (Springer, 1999), more SASE but much more technical

Thanks for help with figures from Y. Ding, B. Fawley, Z. Huang, C. Limborg, S. Reiche, J. Wu