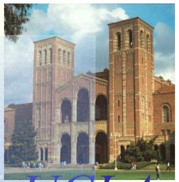


Challenges of 4^{th} Generation LightSources

C. Pellegrini

SLAC, National Accelerator Laboratory

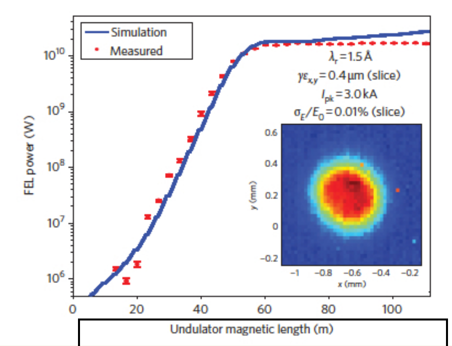
UCLA, Department of Physics and Astronomy

The 4th generation:1992-2011

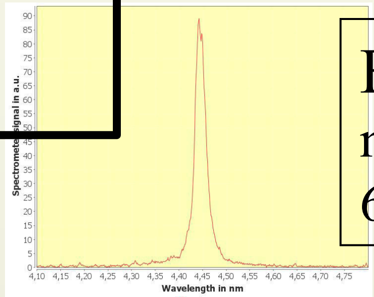
A 4 to 0.1 nm FEL Based on the SLAC Linac$_t$
C. Pellegrini, UCLA, March 2, 1992

Abstract

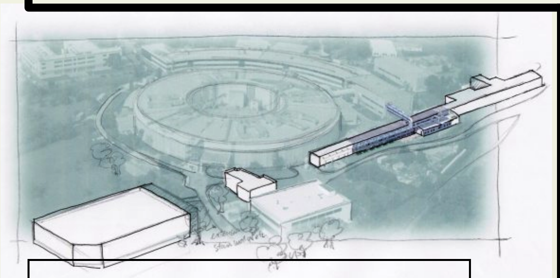
We show that using existing electron gun technology and a high energy linac like the one at SLAC, it is possible to build a Free Electron Laser operating around the 4 nm water window. A modest improvement in the gun performance would further allow to extend the FEL to the 0.1 nm region. ..with a brightness many order of magnitude above that of any synchrotron radiation source, …in the multi gigawatt region and subpicosecond pulse length. ..



LCLS, 1.5 Å, 4/2009, 1-3 mJ



Flash: 4.45 nm, 0.3 mJ, 6/2010



Fermi@Elettra, 43nm,12/2010

SACLA, 0.8 Å, 6/2011

New projects: XFEL (2014), LCLS-II, Swiss X-FEL, Shangai, Korea, NGLS ….

X-ray FELs, generate coherent electromagnetic radiation at ~1Å, 1 fs, atomic phenomena characteristic length and time scales, with high peak power and brightness, giving us new, unprecedented capabilities to study the structure and dynamics of atomic and molecular systems, for biology, physics and chemistry, complex materials, matter under extreme conditions.

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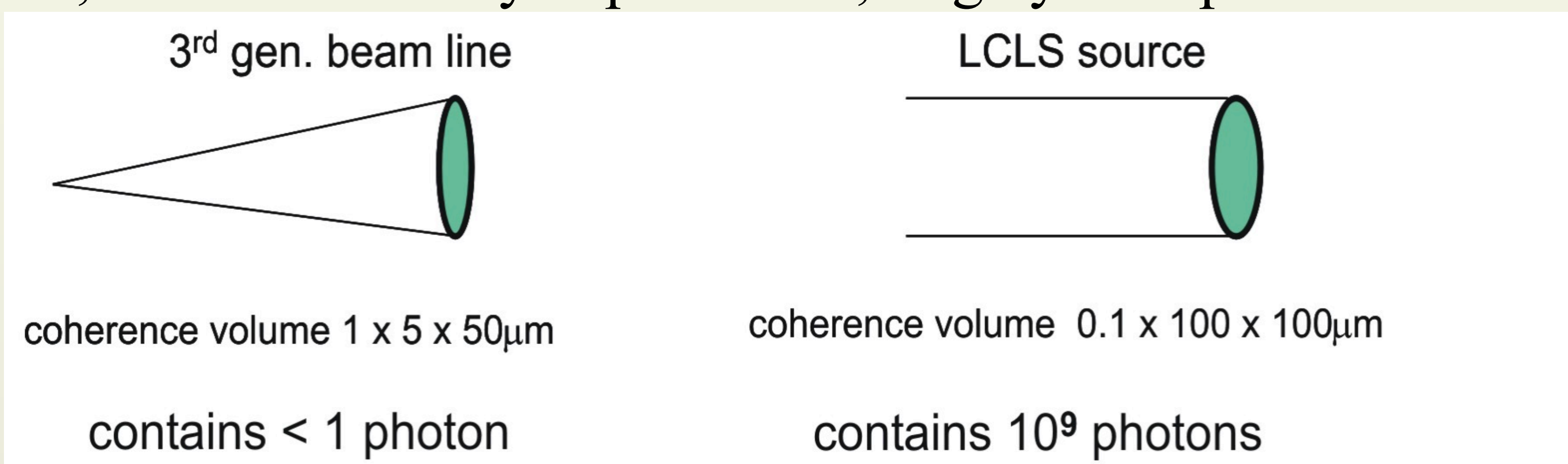
The X-ray FEL radiation: ~10^9 photons in a coherence volume compared to less than 1 for spontaneous radiation. This property allows studies of coherent diffraction imaging, multi-photons excitations, non-linear X-ray experiments, largely unexplored areas of science.



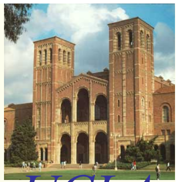
Outline

- Present status
- Next steps and next generations
- The Terawatt X-ray FEL
- Electron beam physics challenges
- Laser/plasma/wake-fields accelerators
- Conclusions

Disclaimer: X-ray FELs are today a very active field of research, development and construction. I cannot even try to cover it all in 30 minutes. I have made some choices reflecting my own bias. FLASH, SACLA, Fermi@Elettra have already been discussed in papers presented at this conference and I will mostly refer to LCLS data.

Present status: LCLS, long pulse case*

*P. Emma et al., Nature Photonics, DOI: 10.11038 2010.176



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Electrons

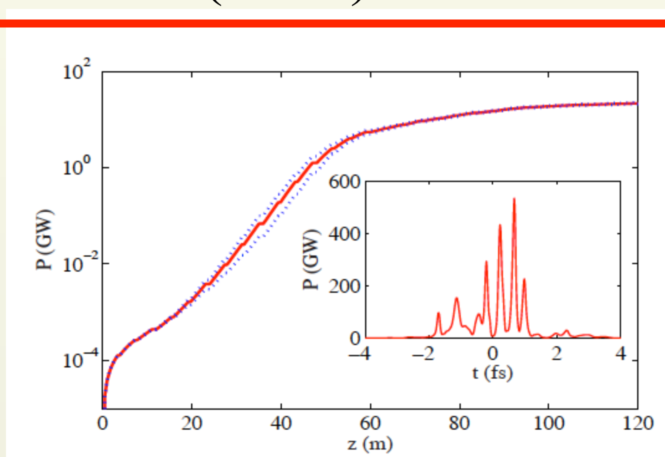
Charge/bunch, nC	0.25	0.25
Beam energy, GeV	13.6	3.5–6.7
Slice emittance (injected), µm	**0.4**	0.4
Projected emittance, µm	0.5–1.2	0.5–1.6
Peak current, kA	2.5–3.5	0.5–3.5

Xrays

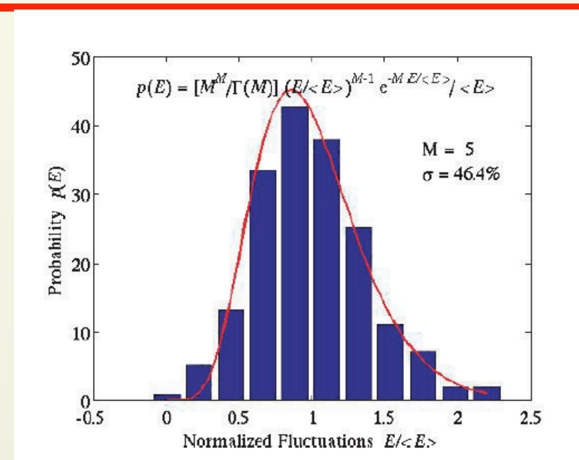
Radiation wavelength, Å	**1.5**	**6–22**
FEL gain length, m	3.5	1.5
Photons per pulse x 10^{12}	1.0–2.3	10–20
Peak X-ray power, GW	15–40	3–35
Pulse length (FWHM), fs	70–100	70–500
Bandwidth (FWHM), %	0.2–0.5	0.2–1.0

Low charge LCLS, 20pC

LCLS operation at, 20 pC. Bunch length too short to measure until now. Estimated < 10fs. Peak power at 1.5Å and saturation ~60 GW, ~ 10^{11} coherent photons/pulse. Y. Ding et al., Phys. Rev. Lett., 102, 254801 (2009).



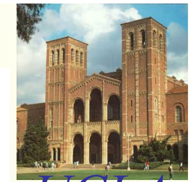
Peak power along the undulator and snapshot of typical 2fs FEL pulse at 100 m. Notice the characteristic SASE spikes.



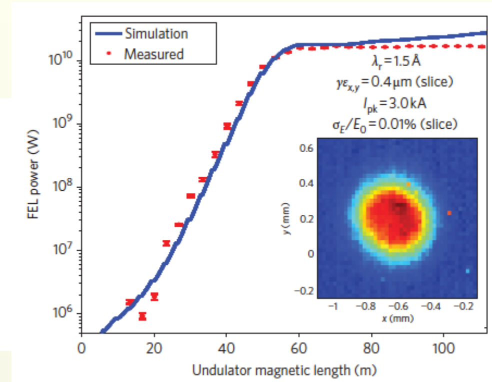
800 eV. SASE Intensity fluctuations, corresponding to about 5 longitudinal modes.

J. Wu et al., Proc. 2010 FEL Conf.

FEL Scaling



A high gain FEL is characterized by the FEL parameter, ρ, [R. Bonifacio, C. Pellegrini, and L.M. Narducci, Opt. Com-mun., 50, 373 (1984)] giving:



1. the exponential growth rate, $P=P_0\ exp(z/LG)$, where $L_G \sim \lambda_U/4\pi\rho$
2. The saturation power $P_{sat}=\rho I_{beam}\ E_{beam}$

$$\rho = \left(\frac{K}{4} \frac{\Omega_p}{\omega_U} \right)^{2/3}, \quad \Omega_p = \left(\frac{4\pi r_e c^2}{\gamma^3} n_e \right)^{1/2}, \quad \omega_U = \frac{2\pi c}{\lambda_U}$$

For LCLS: λ=1.5Å, $I_{bean} \sim 3\ k\ A$, $E_{bean} \sim 14\ GeV$, $\rho \sim 5x10^{-4}$, $P_{sat} \sim 20\ GW$, $N_{coh} \sim 10^{12}$ *in 100fs*. Typically $\rho \sim 10^{-3}$-10^{-4} for soft and hard X-rays

The number of coherent photons/pulse scales almost linearly with the pulse duration -~10^{12} at 100 fs, 10^{11} at 10fs for 8keV- and inversely with the photon energy.

Remarks on 4th generation

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- FLASH and LCLS have demonstrated outstanding capabilities, increasing by 7 to 10 orders of magnitude the photon peak brightness.
- The LCLS X-ray pulse duration and intensity can be changed from about 100 to a few femtosecond and 10^{13} to 10^{11} photons/pulse, over the wavelength range of 2.2 to 0.12 nm, by varying the electron bunch charge from 250 to 20 pC. **The X-ray pulse can be optimized for the experiment, not possible in storage ring sources**.
- Theory, simulations and experimental results are mostly in good agreement. Simulations tools have been developed and benchmarked to evaluate the electron beam properties and the X-ray pulse characteristics, from the electron source to the undulator exit. These tools can be used to design new, advanced FELs.
- We know that we can generate high energy electron beams with phase space density larger than what we expected until recently.

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Electron beam (The Lasing Medium) physics challenges

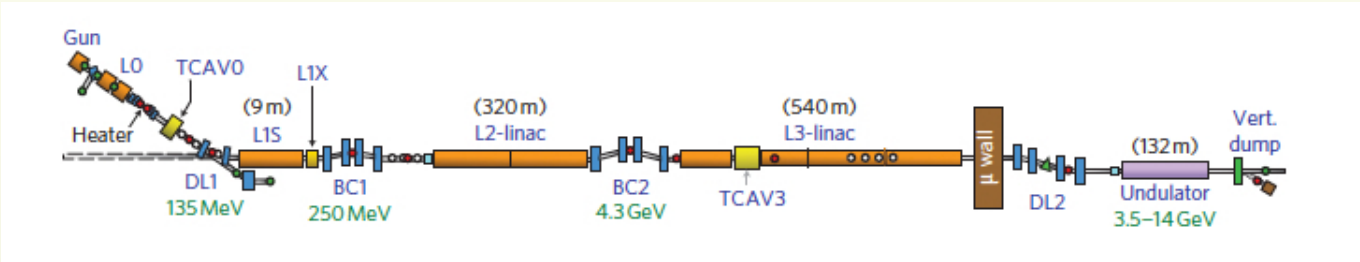
a) Beam noise and density modulation from electron gun generates large coherent transition radiation and coherent synchrotron radiation, limiting the bunch compression, beam peak current and the FEL gain and power. An effect not predicted in the design phase and not yet fully understood.

b) Limitations to electron bunch compression and peak current, non flat bunch current profile after compression (the double horn current profile), have an effect on the FEL performance and design.

Understanding and controlling these effects, generating a better lasing medium, leads to more powerful and more compact X-ray FEL.

Magnetic bunch compression

LCLS and other 4th generation FELs use magnetic compression with two chicanes as shown for LCLS.



Coherent synchrotron radiation (CSR) and space charge effects during the compression can increase the beam emittance and distort the phase space.

M. Borland et al., Nucl. Instr. And Methods A483, p. 268-272 (2002).
E. Saldin, E. Schneidmiller and M. Yurkov, Nucl. Instr. and Meth. A490, p. 1 (2002); S. Heifets, G. Stupakov and S. Krinsky, Phys. Rev. ST Accel. Beams, 5, 064401 (2002); Z. Huang and K.-J. Kim, Phys. Rev. ST Accel. Beams, 5, 074401 (2002); G. Stupakov, Proc. 2003 Part. Acc. Conf., Portland, Oregon (2003).

Magnetic bunch compression

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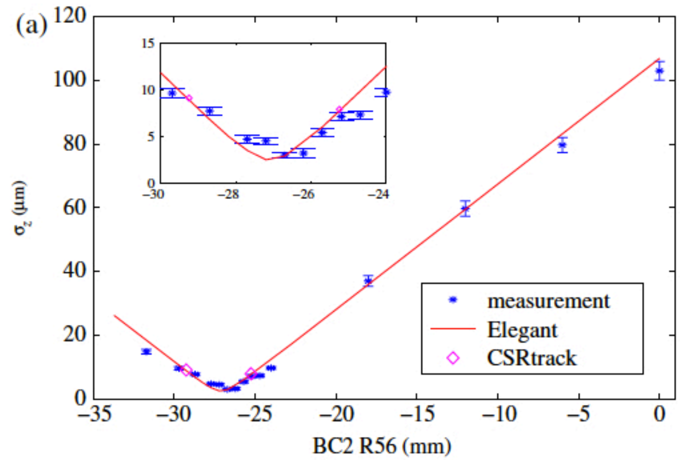
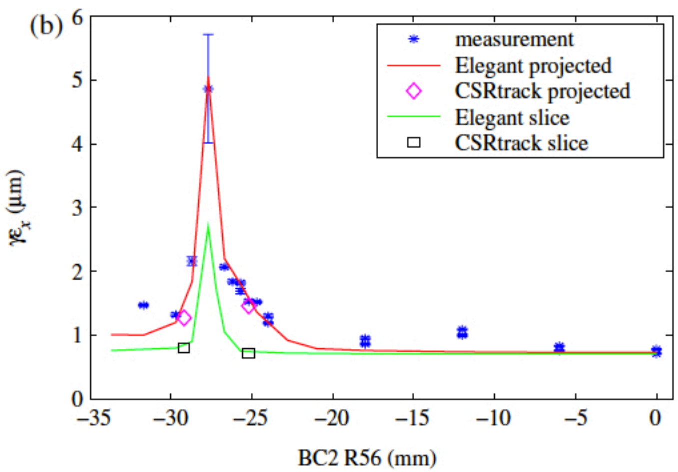


Compressed bunch length after BC2 at 250 pC.



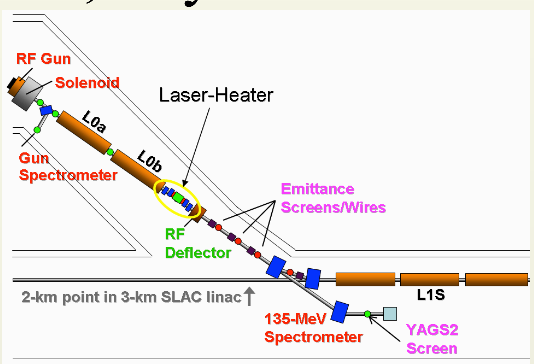
Horizontal emittance after BC2 at 250 pC.

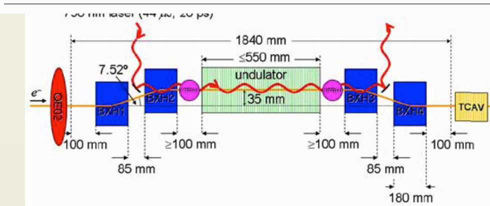
LCLS measurements of emittance and compression at 250 pC. Coherent synchrotron radiation (CSR) blows up the emittance for large compression. The effect is larger at large charge.

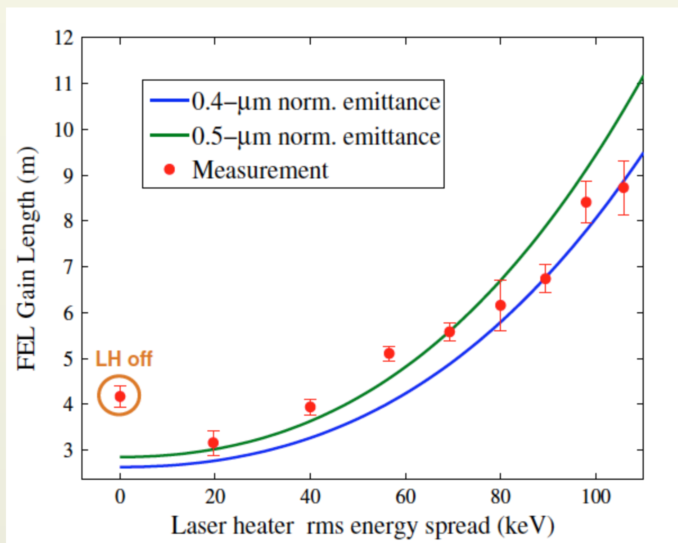
Laser heater

A "Laser Heater" has been developed and used in LCLS to increase the beam energy spread, and control these effects, yielding larger X-ray pulse power at 250 pC.

Z. Huang et al., Phys. Rev. ST AB 7, 074401 (2004); J. Galayda, private communication; P. Emma et al, Proc. PAC 2009, Huang et al., Phys. Rev. ST AB 13, 020703 (2010).

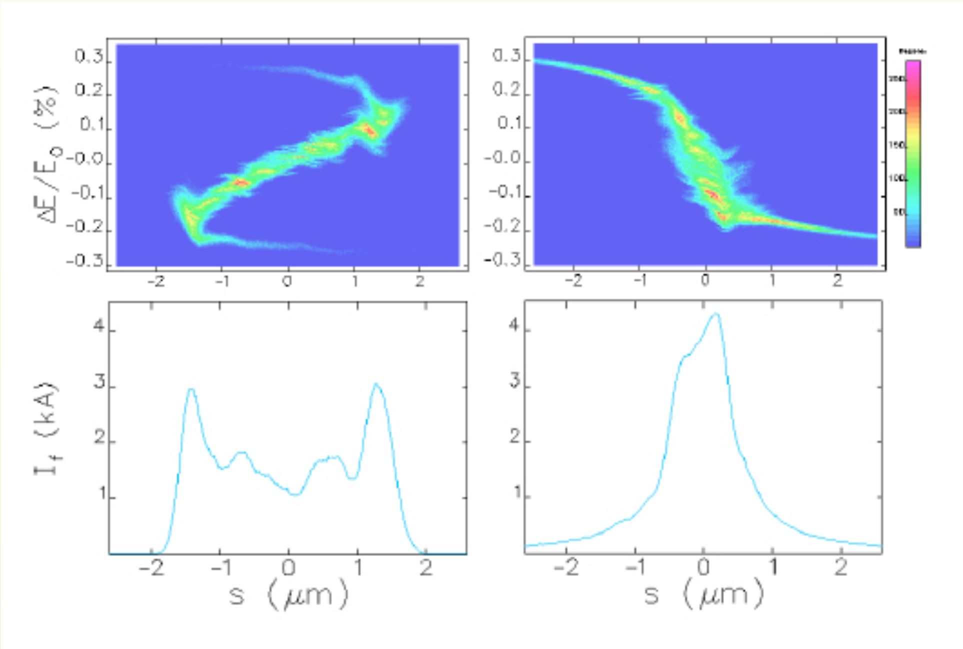






Laser heater decreases gain length.

Longitudinal emittance

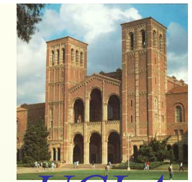


Longitudinal emittance ~6keVps

Longitudinal phase space measurements after the second bunch compressor, and before the final acceleration. Under-compression and over-compression phase space and current profile. Beam energy ~4 GeV. The bunch head to the left.

Y. Ding et al. Phys. Rev. Lett., 102, 254801 (2009).

Transverse slice emittance scaling with charge



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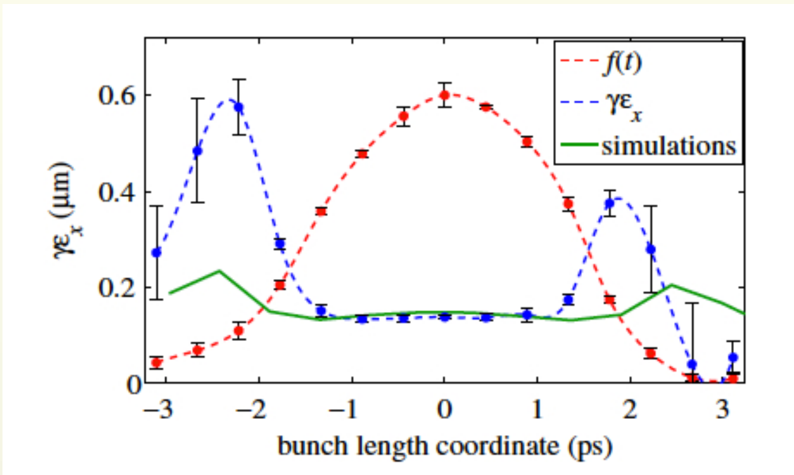
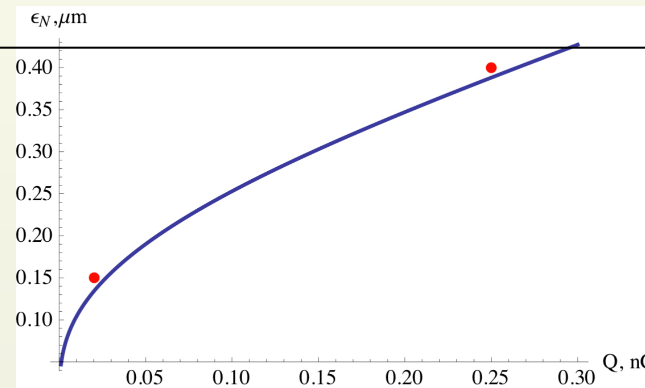


LCLS results at 20 pC: slice emittance <0.2μm. Y. Ding et al., Phys. Rev. Lett. 102, 254801 (2009)



Emittance scaling. ε_N in μm, Q nC For Q <0.3 nC the RF term is negligible. Ferrario et a., Nucl. Instr. And Meth. A57, 98 (2006).

The red dots are LCLS experimental results. The empirical factor 1.4 indicates a thermal emittance larger than theoretical value.

Thermal Space charge RF

$$\varepsilon_N = 1.4\sqrt{0.111Q^{2/3} + 0.18Q^{4/3} + 0.18Q^{8/3}}$$

Another method to generate short pulses: the slotted emittance spoiler system.

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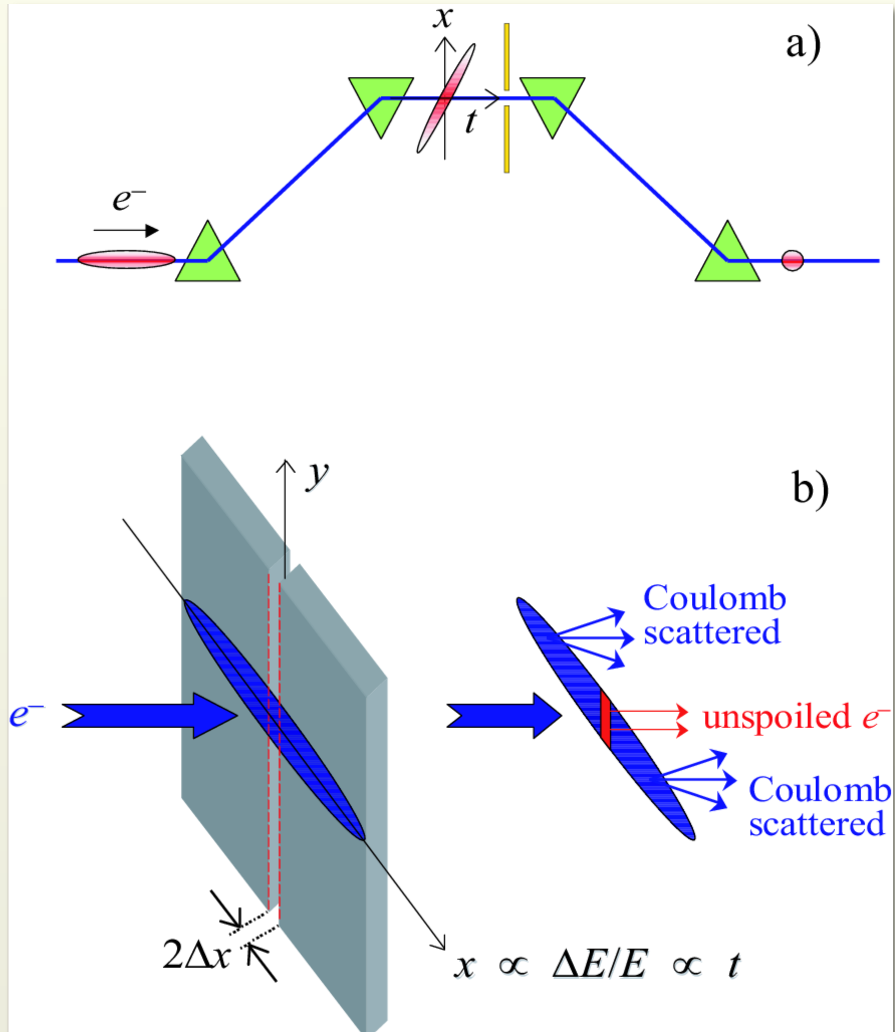
Concept introduced in 2004, P. Emma, et al., Phys. Rev. Lett. **92**, 074801 (2004).

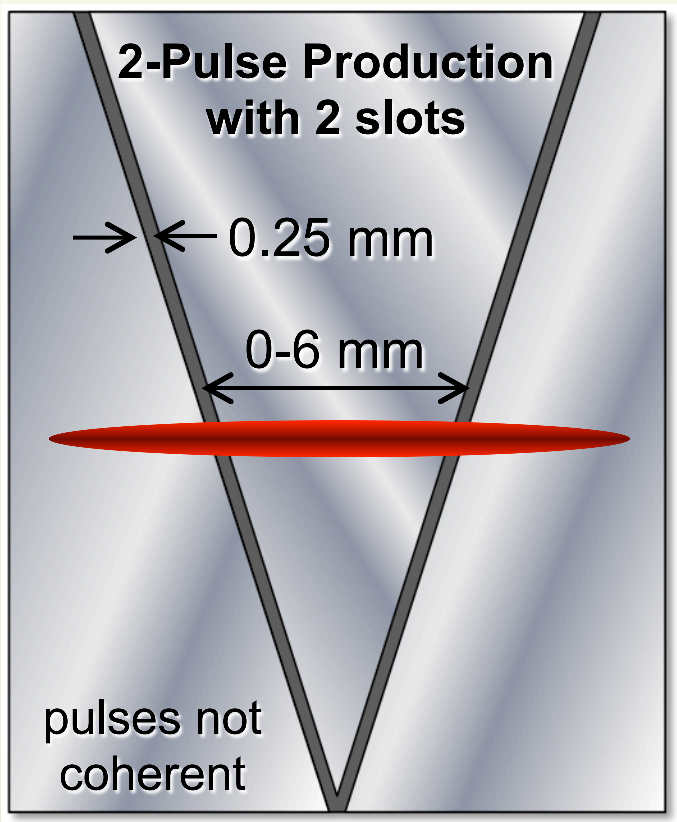
Successfully used to generate few fs pulses at LCLS.

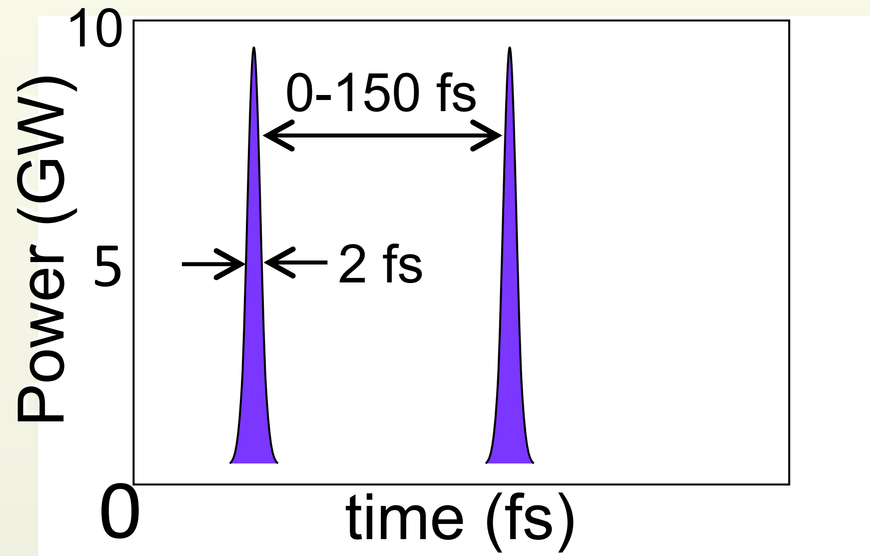
Courtesy P. Emma



Double X-Ray Pulses from a Double-Slotted Foil

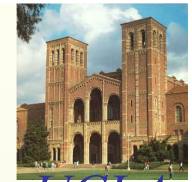
Controlled time delay between x-ray pump and x-ray probe pulses.





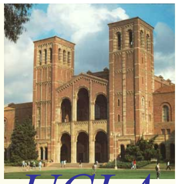
Courtesy P. Emma

What next?



Photon energy, keV	0.1-100
Pulse repetition rate, Hz	10^2-10^6
Pulse duration, fs	<1-1000
Coherence, transverse	Diffraction limited
Coherence, longitudinal	Transform limited
Coherent photons/pulse	10^9-10^{14}
Peak (Average) brightness, ph/s mm^2 mrad^2 0.1% bandwidth	10^{32}-10^{36} (10^{21}-10^{29}) LCLS->2×10^{33} (10^{22})
Peak (Average) power, TW (kW)	>1 (>1)
Polarization	Variable, linear to circular
Multicolor pulses	Two λs from one e-bunch

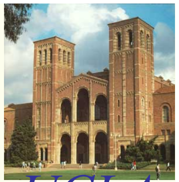
Wish list remarks



Different, specialized FELs will be needed to satisfy these requests.

Example 1. An **X-ray FEL oscillator** is a very good candidate to produce a nearly transform limited pulse, with a line width a small as 10^{-6}-10^{-7} (K.-J. Kim, Y. Shvydko, S. Reiche, Phys. Rev. Lett. 100, 244802 (2008)). Reaching the same line-width in an amplifier is practically impossible, even with seeding. The oscillator would generate a small number of coherent photons per pulse in a long pulses, 0.1 to 1ps, at high, MHz, repetition rate, using a CW superconducting linac. The X-ray oscillator would use low emittance, low charge, ~50 pC, electron bunches. Challenges: low loss mirrors in the Ångstrom to nanometer region; high repetition rate, one to a few MHz, electron guns with the required emittance and linear longitudinal phase space distribution.

Wish list remarks



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Example 2. Single molecule imaging requires a large number of photons, $>10^{13}$ in about 10 fs or less, ~1 TW peak power, leading to a very different FEL optimization. Measurements are done in a single shot, blowing up the sample. Matching the sample preparation time and the FEL repetition rate is important.

Example 3. Reaching into the **femtosecond/attosecond** region reduces the number of photons and the charge per bunch that is required. The sample is not destroyed by the X-ray pulse and the amount of data/shot is limited. A high FEL repetition rate, up to MHz, becomes very desirable. The beam energy can be reduced using the low emittance obtained at small charge/bunch.

Femtosecond X-ray protein nanochrystallography
H. N. Chapman et al., Nature 470, 73 (2011).

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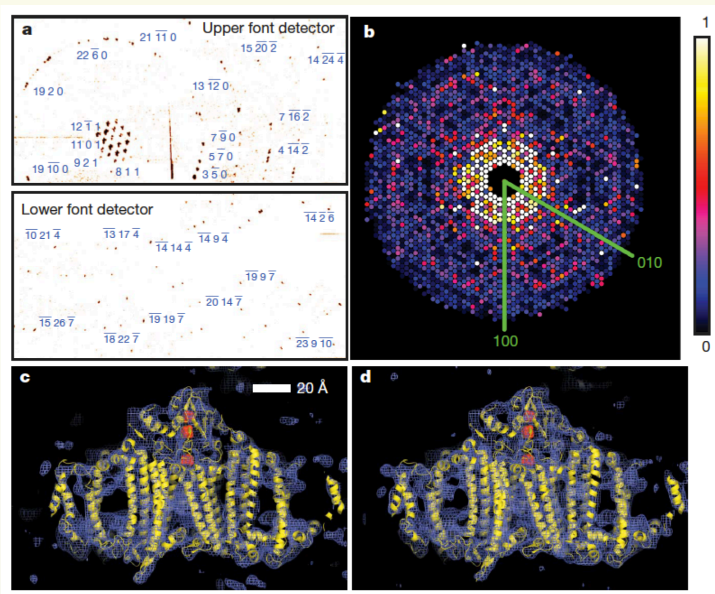
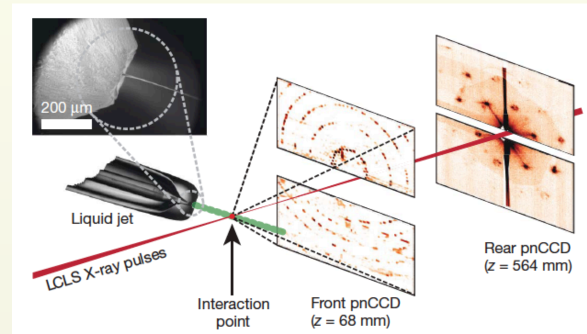
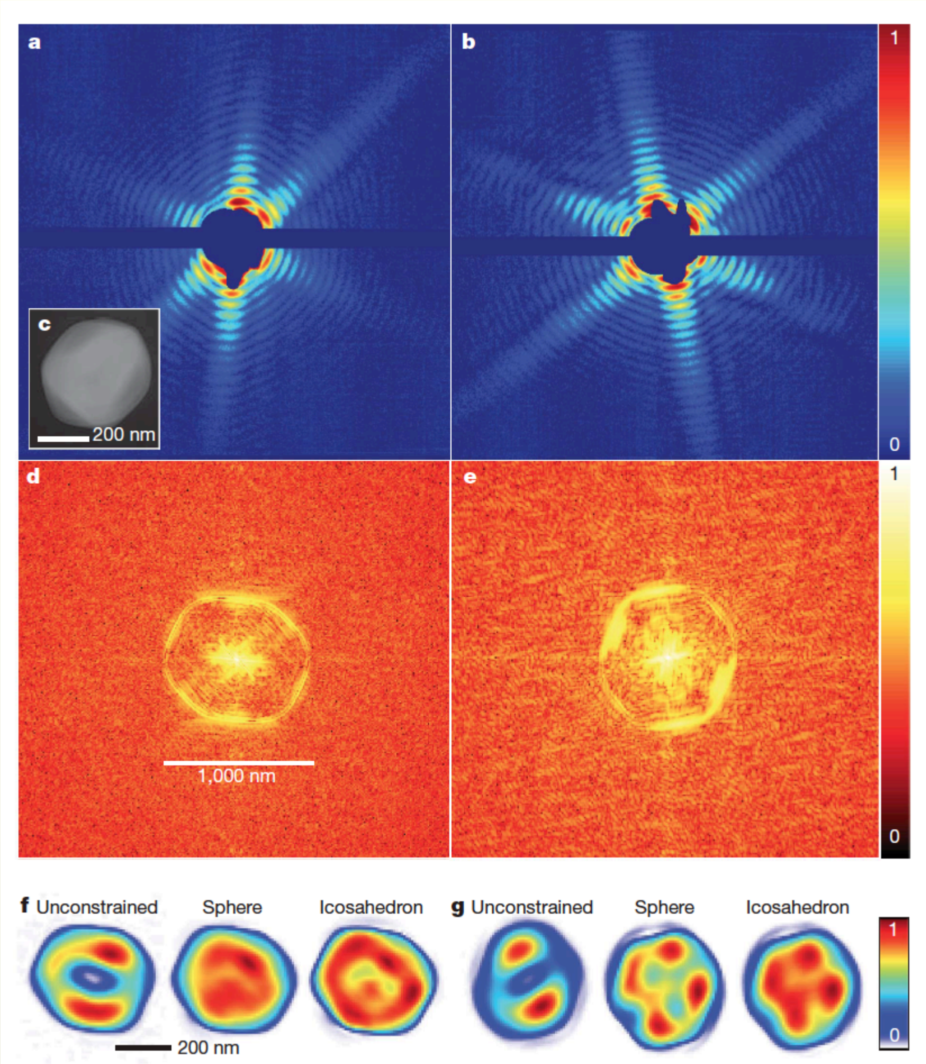


E_{photon}=1.8 keV
$N_{photons}$~1012/pulse
T_{pulse}~70fs



a) Diffraction intensity with single 70 fs pulse; resolution 8.5 Å
b) pattern of the [001] zone obtained from merging data from >15,000 nano-crystal;
c) electron density of photosystem I from LCLS data and
d) from synchrotron data with a resolution of 8.5 Å.

Mimivirus



The 2nd experiment [M.M. Seibert et al., Natire 470, 78 (2011)] shows that high quality diffraction data can be obtained from a single X-ray pulse on a non-crystalline biological sample, a single mimivirus particle. 7Å, 70 fs, 10^{12} photons.

Nano-crystallography and more ….

The nano-crystal imaging experiment used 70 fs long pulses of about 10^{12} photons of 1.8 keV. Resolution about 8.5Å. Reducing the pulse duration to 10 fs or less, increasing the number of photons to 10^{13} and the energy to 8 keV, allows single shot measurements of single molecules with a few Å resolution, a great breakthrough. **To reach this goal we are studying the feasibility of a 1 TW, 10 fs X-ray FEL at 1.5 A, using LCLS electron beam parameters.**

Examples of TW FELs other applications : splitting the X-ray pulse for 3D imaging with multiple orthogonal beams; non-linear electrodynamics, like multi-photon creation of electron-positron pairs, imaging matter in disordered states.

TW feasibility studies

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Existing hard X-ray FELs, like LCLS, operate in high gain SASE mode, starting from longitudinal density noise in the electron beam and reaching saturation. The saturation power is ~30-40GW.

Kroll, Rosenbluth and Morton [N.M. Kroll, P.L. Morton, and M.N. Rosenbluth, IEEE J. Quantum Electronics, QE-17, 1436 (1981)] proposed to increase the energy transfer from the electron to the photon beam by adjusting the undulator magnetic field to compensate for the electron energy losses, a “tapered” undulator.

A tapered undulator in combination with self-seeding can be used to reach the 1 TW level.

TW X-ray FELs: two studies for XFEL & LCLS

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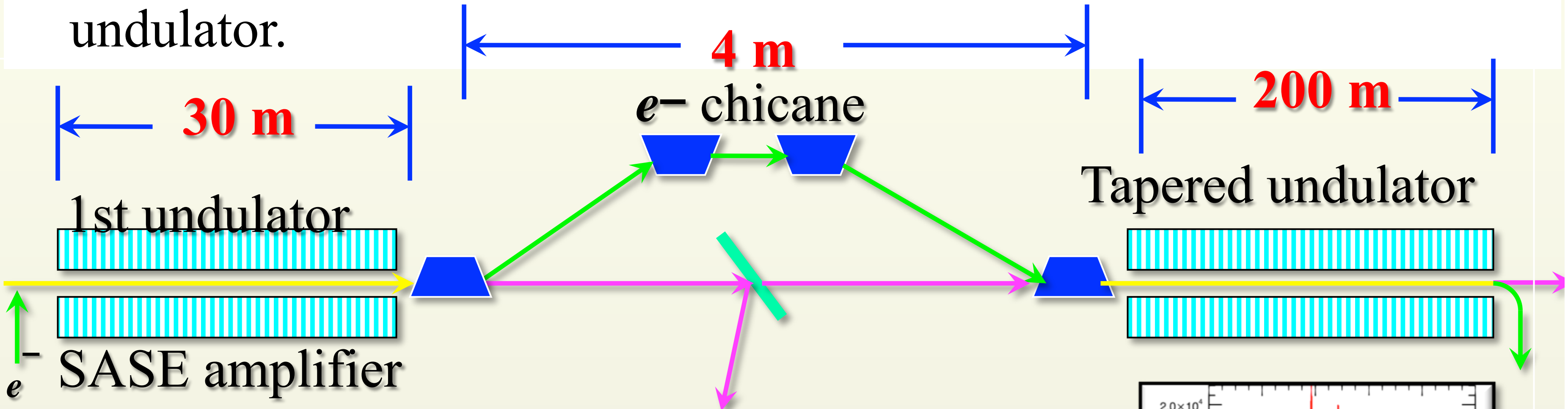
Tapering for TW XFEL studied by G. Geloni, V. Kocharian and E. Saldin, arXiv:1007.2743v1, 2010 and arXiv:1006.2045v1.

Terawatts Hard X-ray FELs for LCLS-II, W.M.Fawley, J. Frisch, Z. Huang, Y. Jiao, H.-D. Nuhn, C. Pellegrini, S. Reiche, J. Wu, 33rd FEL Conf., Shanghai, 2011.

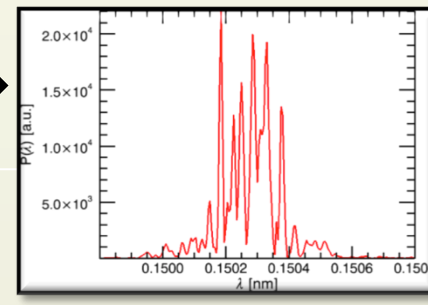
- The system consists of a SASE amplifier, followed by a "self-seeding" crystal monochromator, and a long tapered undulator.
- Results for LCLS and XFEL show that **TW-level** output power at 8 keV is **feasible.** For LCLS we have a total undulator length below 200 m for a **10 fs**, **40 pC** bunch charge, normalized transverse emittance **0.3-mm-mrad**, peak current **4 kA**, electron energy **13.6 GeV**.

TW SELF-SEEDED FEL

- Start with a SASE FEL, followed by a monochromator and a tapered undulator. Simulations for the LCLS-II variable gap undulator.



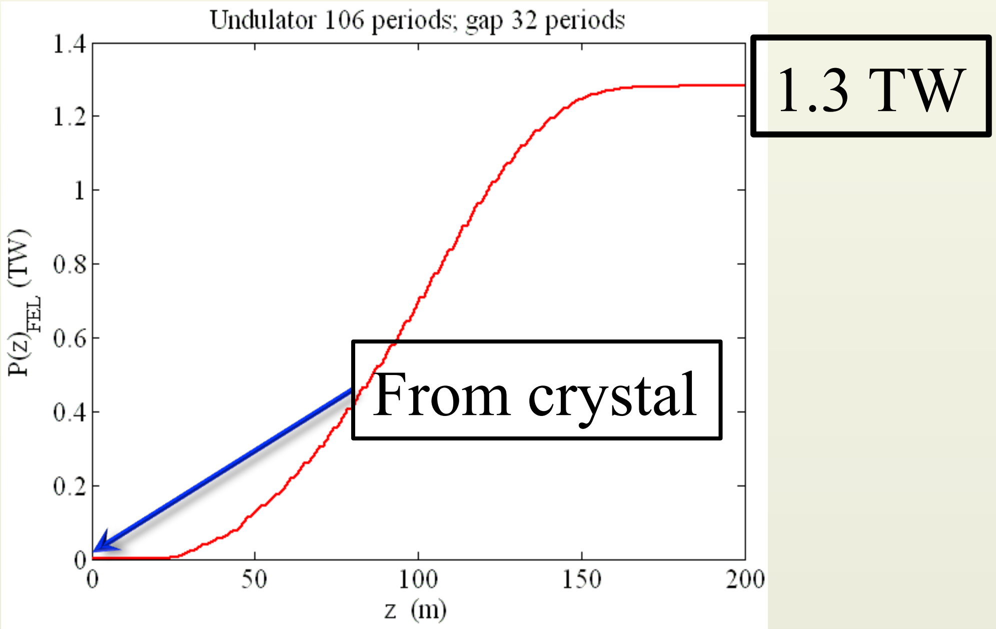
SASE undulator power ~20 GW. Spectrum ➔

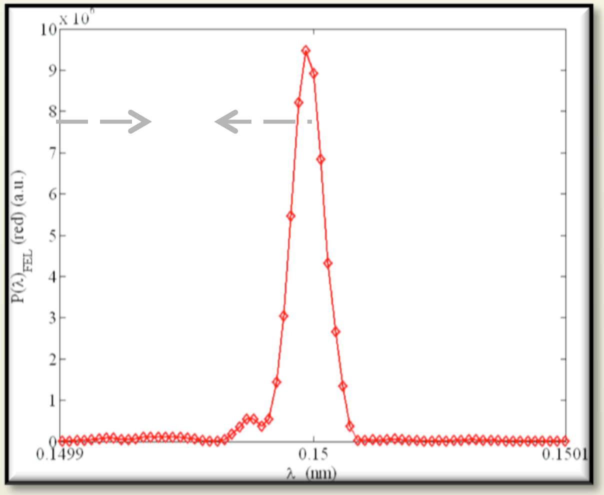


Self-seeding with single crystal monochromator proposed by G. Geloni, V. Kocharyan and E. Saldin, DESY 10-053 (2010). It can also be done with a 4 crystals monochromator and/or a double (fresh) bunch scheme.

TW FEL: LCLS-II case

- 8.3 keV -- 1.5 Å (13.64 GeV)
- 40-pC; 4-kA peak current; 10 fs FWHM; emittance 0.3-μm
- Quadratic tapered field decreasing 13 % to 200 m.
- λ_U= 3.2 cm, undulator sections 3.4 m, 1 m break; $<\beta>$= 20 m
- Longitudinal: close to transform limited
- X-ray pulse brightness increases by 10^3

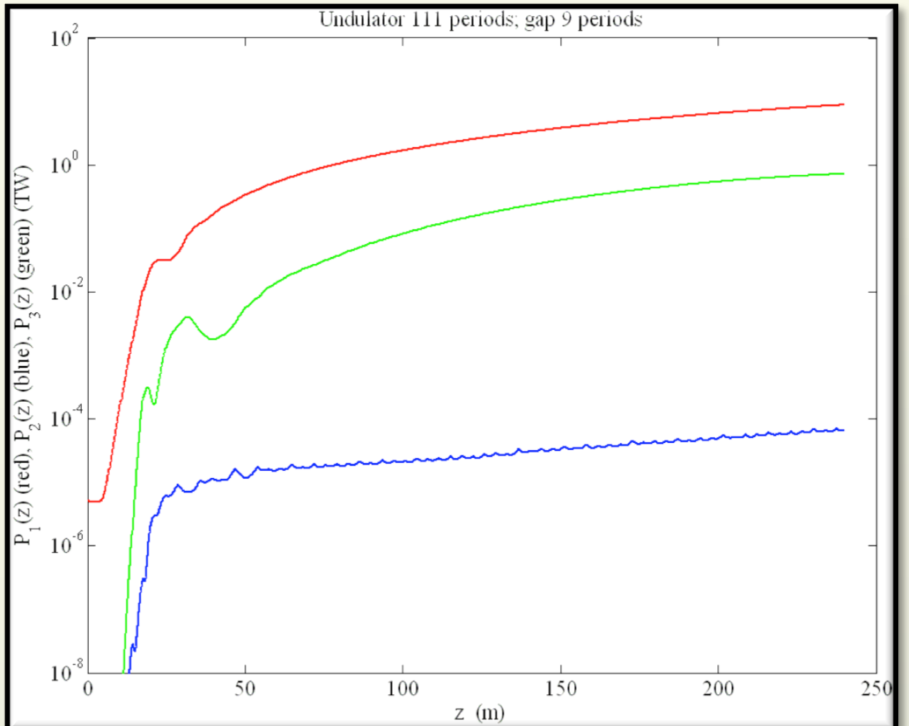


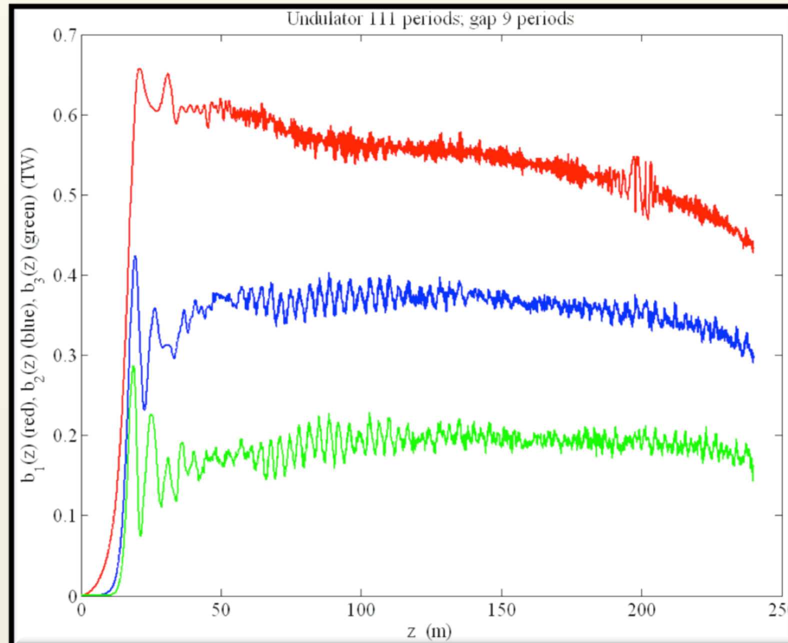


$\Delta\lambda/\lambda=10^{-4}$ FWHM

Large harmonics in the TW FEL

The bunching remains high in the long tapered undulator and harmonics are large. For a tapered planar undulator the third harmonic at 24 keV is about 100GW.





Fundamental (red); Second harm. (blue); Third harm. (green)

Some general considerations: fs and meV

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X-ray FELs can be designed to generate very short, fs to as, pulse duration τ, or to pulses with very small line-width and small photon energy ΔE_{ph}. In the two cases the connection between charge and emittance leads to very different optimization.

$$Q_{Bunch} = IL_{Bunch} / c,\ L_{Bunch} = \lambda / (\Delta\lambda / \lambda),$$

$$Q_{Bunch} = \frac{I}{c}\frac{\lambda^2}{\Delta\lambda} = \frac{Ih}{\Delta E}$$

Short pulse➔low charge
SmallΔE➔high charge

Fs pulse duration and 1 kA current gives a charge of about 1pC and an emittance 0.03 µm.
At 1nm and ΔE=1 meV, we need 3nC for a current of 1kA and the emittance is 2µm. CSR and other collective effects will strongly distort the beam phase space. A high gain amplifier becomes complicated and a low gain oscillator system should be considered.

Beam physics and the next generation of FELs

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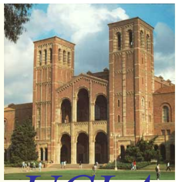
Using the beam properties already obtained we can already reduce the size and cost of X-ray FELs. With new possible advances we will be able to produce electron beams with even higher phase-space density, and better characteristics as an FEL lasing medium.

Lower emittance → Lower beam energy for given λ → Compact, cheaper FEL with same X-ray beam

Better compression → Larger peak current → Compact, cheaper FEL with same X-ray beam

Short list of new advances

Some new results and concepts to improve the “lasing medium”



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- **Photo-injector blow out regime, J. T. Moody, et al., Phys. Rev ST AB 12, 070704 (2009).**
- **Velocity bunching, with emittance preservation, Ferrario et al., Phys. Rev. Lett. 104, 054891 (2010).**
- **Seeding** and self seeding
- **ECHO, a new idea for seeding, D. Xiang et al., Phys. Rev. Lett. 105, 114801 (2010).**
- ESASE: A. Zholents, Phys. Rev. ST Accel. Beams 8, 040701 (2005)

Some new results and concepts to improve the "lasing medium"

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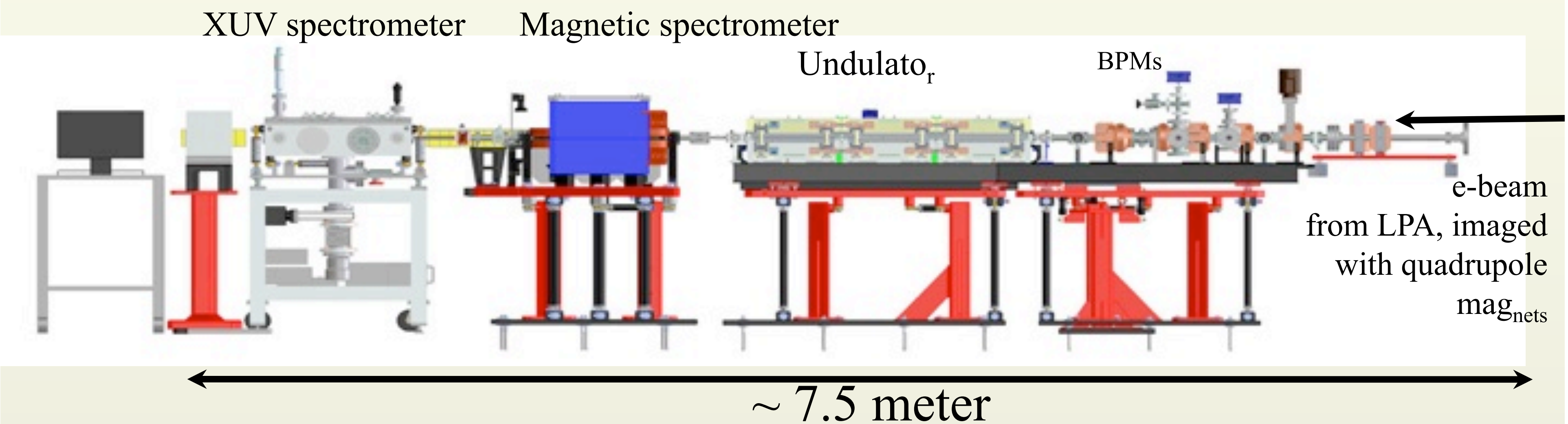
- Controlling the bunch current profile in a photo-injector to reduce wake-field effects M. Cornacchia et al., ST/F-TN-06/06
- Split compressor, J. Frisch and Y. Ding, private comm.
- Single SASE spike, fully coherent. J. Rosenzweig et al., Nucl. Instr. And Meth.A593, 39 (2008); S. Reiche et al., Nucl. Instr. And Meth.A593, 45 (2008).

First step towards a TableTop FEL: undulator based diagnostic of LPA beams

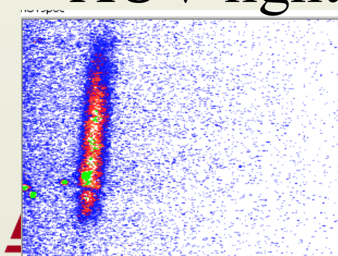
Courtesy W. Leemans

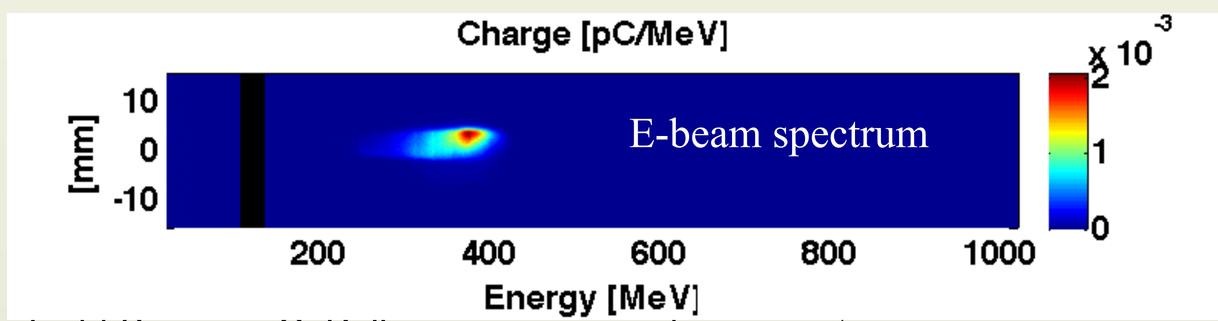
*: A.J. Gonsalves et al. Nature Physics 2011

- Uses combined gas jet + capillary discharge based LPA*
- Beam imaging with permanent quadrupoles onto undulator entrance ~4.5 meter away: observed first light at LOASIS/LBNL



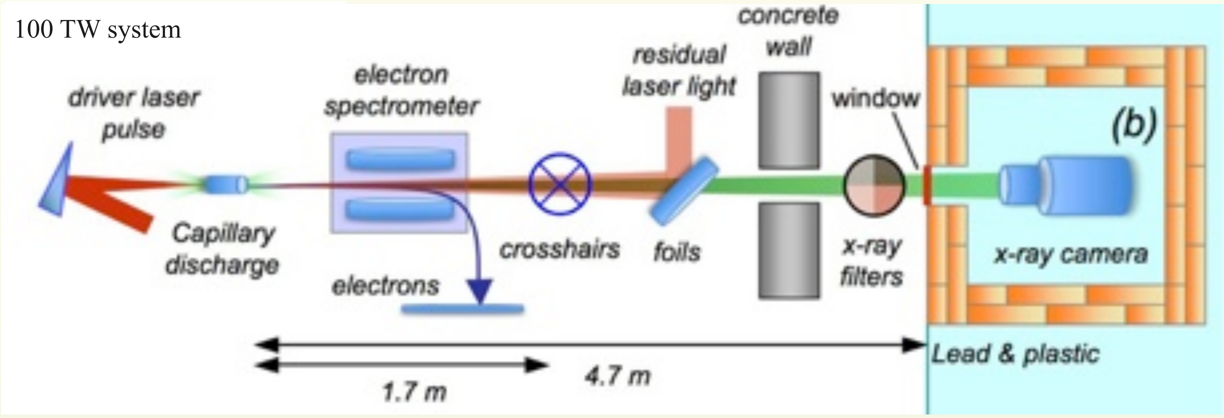
XUV light





Ultra-low emittance measured using x-ray spectroscopy of betatron radiation of laser plasma accelerator beams

100 TW system



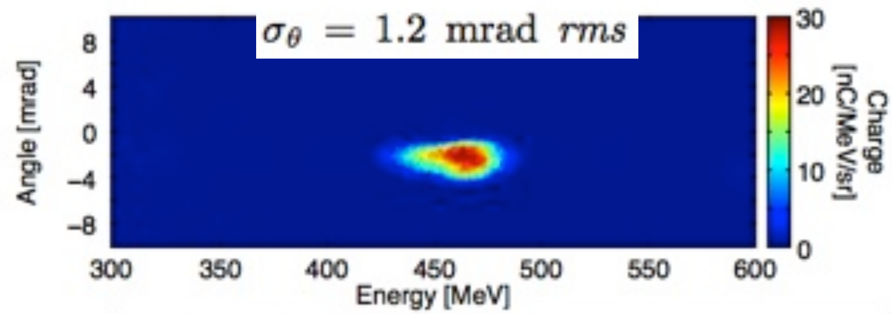
Single shot x-ray image

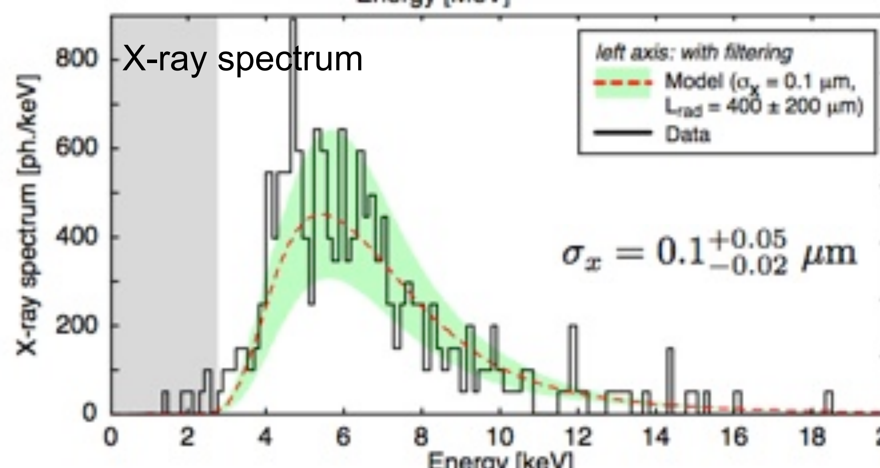
- X-ray spectrum provides measure of beam size inside accelerator:
- 0.1-0.15 micron
- Simultaneous divergence and beam energy measurement provides normalized emittance

$$\epsilon_x \approx \gamma \sigma_x \sigma_\theta$$

$\boxed{\text{0.1-0.2 mm-mrad - normalized}}$

- Value consistent with simulations





G. R. Plateau et al., submitted (2011)

Conclusions

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1. X-ray FELs can be developed to fulfill most of our requirements: femto- to atto-second pulse duration, very small line width, ultra-high, TW, peak power, opening new windows in many areas of science.
2. Utilizing the extraordinary brightness of low-charge bunches it is possible to reduce the size and cost of the accelerator, particularly so for short pulses and using new short period undulators.
3. Longitudinal coherence can be pushed near the transform limit using single spike, self seeding, seeding, or an X-ray oscillator.
4. Developments in understanding beam physics and manipulation may enable more compact future hard x-ray FEL facilities.
5. Research on laser/plasma/wakefield accelerators and new electron sources can lead to compact, university scale, X-ray FELs.