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5th Generation light sources

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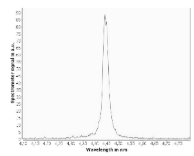
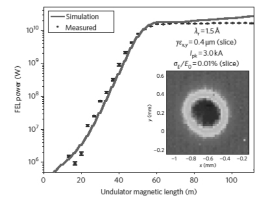
Outline

- Present status
- Where do we go from here? Wish list
- How to make the wish list a reality, using dedicated FEL sources
- Conclusions

Notice: I will not try to give a general and comprehensive overview, but will select some results and future developments that in my own opinion are interesting and important.

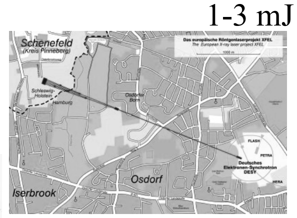
The 4th generation:1992-2010

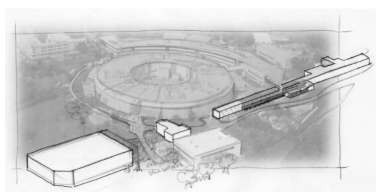




LCLS, 1.5 Å, April 2009, 1-3 mJ at 13.8 GeV

Flash: 0.3 mJ at 4.45 nm, 1.2 GeV, June 2010





European XFEL, 2013

SCSS, 2011

Fermi@Elettra, 2011

New projects: Switzerland, Shangai, Korea, LCLS-II, NGLS …

Present status: LCLS, long pulse case*

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

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

4th generation: LCLS, long pulse case

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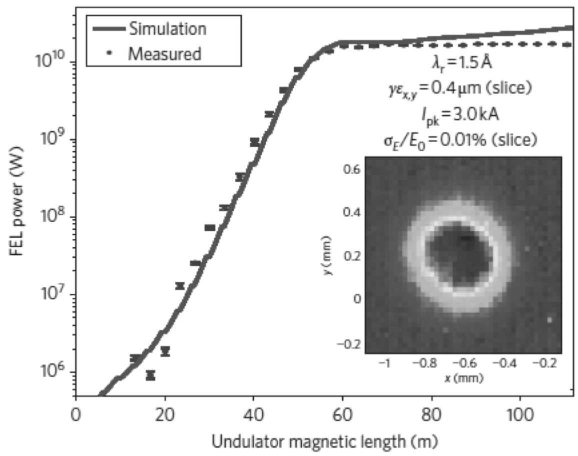

The peak power and number of photons are the value at saturation, at the end of the exponential growth.

Low charge LCLS, 20pC

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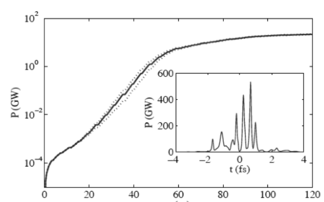
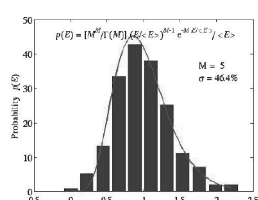
LCLS operation at, 20 pC. Bunch length too short to measure until now. Estimated < 10fs. Peak power at 1.5Å and saturation ~60 GW, ~ 10^{11} coherent photons/pulse. Y. Ding et al., Phys. Rev. Lett., 102, 254801 (2009).



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.

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 agree quite well. We have developed and benchmarked excellent simulations tools to predict the electron beam properties and the X-ray pulse characteristics from the electron source to the undulator. We can use these tools 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 (more later).

Where do we go from here? Wish list for 5th generation.

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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 brightness, ph/s mm^2 $mrad^2$ 0.1% bandwidth	10^{30}-10^{34}
Average Brightness, same units	10^{18}-10^{27}
Polarization	Variable, linear to circular
Multicolor pulses	Two λs from one e-bunch

Wish list remarks

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Different, specialized FELs will be needed to fully satisfy all 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 becomes important. This type of experiments were discussed at a recent, and exciting, workshop at LBL on FEL and Biology. (More to follow).

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.

Classifying FEL regimes

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	E-bunch charge	E-beam energy	Ph/pulse	Longitudinal coherence
Short pulse, fs or< fs,	Small, few-10s pC	Low	Low	Single SASE spike, self-seeding or external laser seeding
Long pulse, 0.1-1ps	Medium to large, 0.1-1nC	High	High	self-seeding, external laser seeding, oscillator
Very high peak power, >1TW, ~10fs	Medium? Large?	High	Very high	Self-seeding, seeding needed for tapering

Other recent results: Transverse emittance scaling with charge

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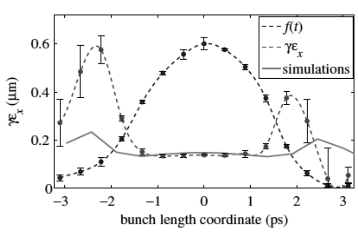
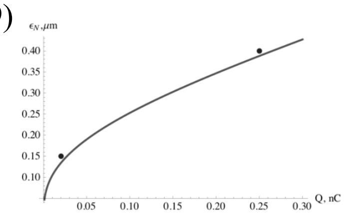


LCLS results at 20 pC: slice emittance <0.2μm. Y. Ding et al., Phys. Rev. Lett. 102, 254801 (2009)



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).

Thermal Space charge RF

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

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

Longitudinal emittance

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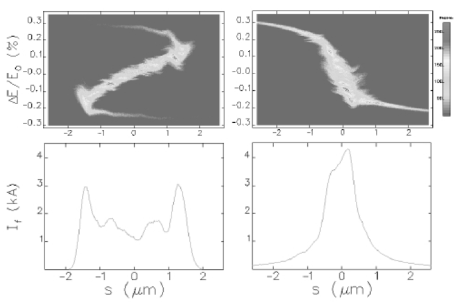

Longitudinal emittance ~6keVps

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).

Photo-injector blow-out regime

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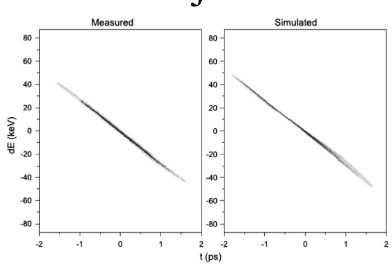

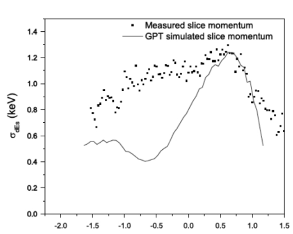

Longitudinal emittance < 1 keV ps

A laser pulse < 100 fs illuminates the cathode. Space charge forces change the electron charge distribution from a pancake-like shape to a nearly ideal, uniformly filled, ellipsoidal distribution. Beam self-fields, beam dynamics and phase space are approximately linear.
J. T. Moody, et al., Phys. Rev ST AB 12, 070704 (2009)

Magnetic and velocity bunch compression

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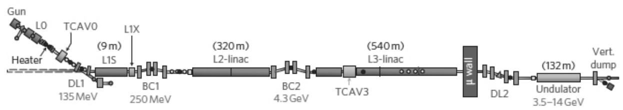
LCLS and other 4th generation FELs use magnetic compression with two chicanes as shown for LCLS.



Coherent synchrotron radiation 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. of the 2003 Particle Acc. Conf., Portland, Oregon (2003).

Laser heater

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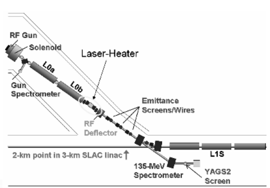
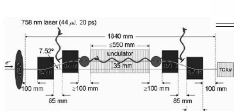
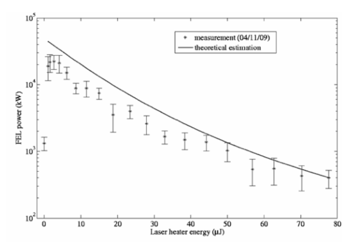
A “Laser Heater” has been developed and used at LCLS to increase the beam energy spread, and control these effects, yielding larger X-ray pulse power at 250 pC.

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).







More on Laser Heater at 1.5 Å

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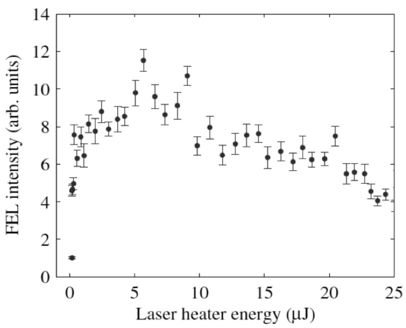

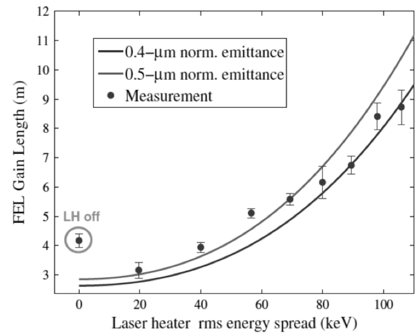

Magnetic and velocity bunch compression

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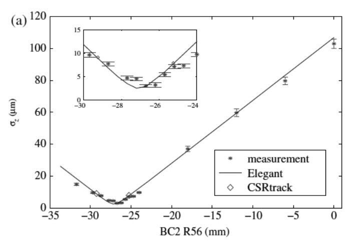
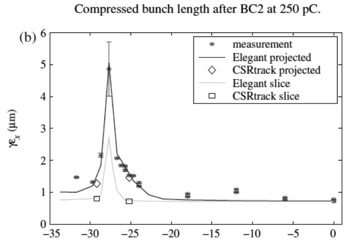


Compressed bunch length after BC2 at 250 pC.

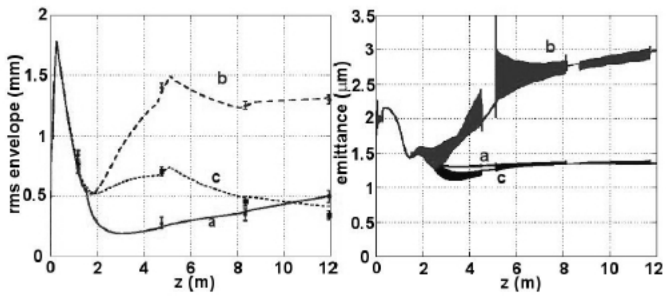


Horizontal emittance after BC2 at 250 pC.

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

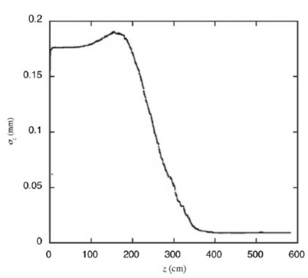
Magnetic and velocity bunch compression

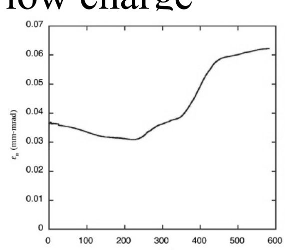
Velocity bunching, with emittance preservation, demonstrated recently at SPARC, can help reduce the problem. Ferrario et al., Phys. Rev. Lett. 104, 054891 (2010).



Left: measured envelopes and PARMELA simulations. Right: PARMELA simulations of the emittance along the linac,. No compression (curves a), compression with solenoids off (curves b), same compression with solenoids at 450 G (curves c).

Magnetic and velocity bunch compression at low charge





Simulations, Frascati, UCLA collaboration, Rosenzweig et al., Nucl. Instr. Amnd Meth. A 593, 39 (2008)

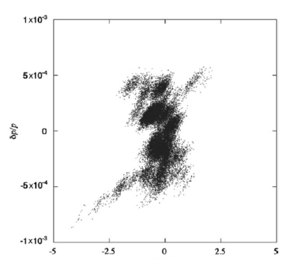


Fig. 3. Longitudinal phase space at SPARX undulator entrance.

SPARX S-band photo-injector: 1 pC charge; bunch length compression 175 µm-> 9 µm; injector energy 17.9 MeV. Transverse normalized emittance growth-> 0.03 to 0.06 mm. The phase space is single spike, slice, distribution. Longitudinal emittance 0.12 ps keV.

Wavelength and energy scaling with charge: reducing the beam energy at low charge

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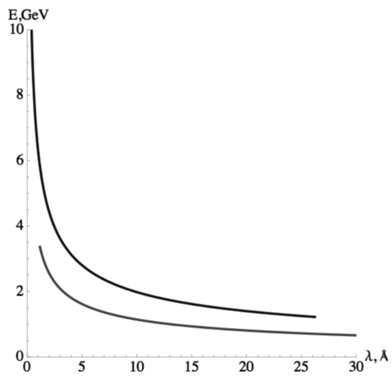
Satisfying the transverse phase space matching, $\varepsilon_N/\gamma<\lambda/4\pi$, requires a smaller beam energy at low charge.



Using a shorter undulator period reduces the beam energy needed for a given wavelength.

Electron energy vs λ: 1.5 cm period, K=1 undulator (red line); 0.5 cm period, K=1 undulator (black line). As λ changes the charge is adjusted in the range 1 to 250 pC, to satisfy the phase space matching condition

Examples: a 1nm, short pulse FEL

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Energy Gev	Charge pC	λ_U, cm /K	λ, nm	σ_L, fs	L_G,m/ρ x103	P GW	N_{pho}/ pulse 10^9	N_{spikes}
1.17	1	0.7/1	1	1	0.26/1.7	0.7	3.4	1.3
1.17	10	0.7/1	1	4	0.21/1.9	2.2	44	6.3
1.7	1	1.5/1	1	1	0.5/2	1	4.5	1.4
1.7	10	1.5/1	1	4	0.4/2	3.2	63	7.2
7.2	1	4.1/4.3	1	1	1.7/2.2	2.7	14	1.1
7.2	10	4.1/4.3	1	4	1.2/2.5	11	230	6

Short period undulators

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A short period undulator, λ_U~<1.5 cm, K~1, can reduce the size and cost of the FEL. Undulator with 1.5 cm, K-1 gap 5 mm exist.

A 9 mm period undulator using a cryogenically cooled Pr-SmCo-Fe hybrid cooled to 30 ^{o}K, field >2 T/m (*K*=2.2), is being tested at UCLA and at HZ-Berlin as part of a project to develop table top FELs using a plasma accelerator. OShea, F. H. et al., Phys. Rev. ST Accel. Beams 13, 070702 (2010).

An LBNL group is investigating sub-centimeter period, K=1, gap 4-5 mm, superconducting undulators using Nb3Sn superconducting material, which gives a larger peak field than NbTi. R. Schlueter, et al. Synchrotron Radiation News, 17, 33 (2010).

X-band RF undulators can give periods<1cm,K~1, large gaps. Tantawi et al

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Pulse duration and intensity control

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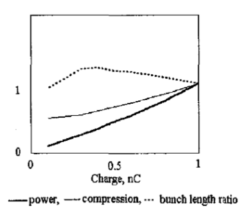
Control of the X-ray pulse intensity and length by changing the electron bunch charge and the bunch compression was studied as far back as 1999 *.



One of the important results obtained by the LCLS team** is the demonstration that it is possible to do it

*C. Pellegrini, X. Ding, J. Rosenzweig, Proc. *1999* Part. Accel. Conf., New York, *1999;*
**P. Emma et al., Nature Photonics, DOI: 10.11038 2010.176;

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Power and pulse length control

Optimizing the number of photons/fs for LCLS, optimum at 100 pC.

Table 1: Simulated 1.5 Å FEL performance at 4 charges*.

Bunch charge (pC)	20	50	100	250
I_p (kA)	3.5	5	5	3
Final slice emittance (μm)	0.3	0.3	0.35	0.6
FEL pulse, fwhm, (fs)	2	4	10	60
FEL photons (10^{11})	1	3	10	2x10
Energy/pulse, mJ	0.13	0.4	1.3	2.6
Peak power, GW	70	100	130	40

*Y. Ding et al., Part. Acc. Conf. (2009)

Seeding and self seeding

Seeding with an external laser, modulating the beam energy and generating higher harmonic of bunching combined with high gain, the HGHG system was proposed by L.-H. Yu and others. There has been much work in this area and I will not try to cover it. There is an agreement that this can be important for the soft X-ray region, but becomes very difficult for hard X-ray.
Laser seeding and harmonic generation demonstrated at a few labs. Most recently at SPARC, L. Giannessi et al. Proc. 2010 FEL Conf., seeding at 401 nm (2nd Harmonic of TiSA). Seeded amplifier, saw disappearing of SASE spikes, HGHG.

ECHO, a new idea for seeding. First experimental results experiment

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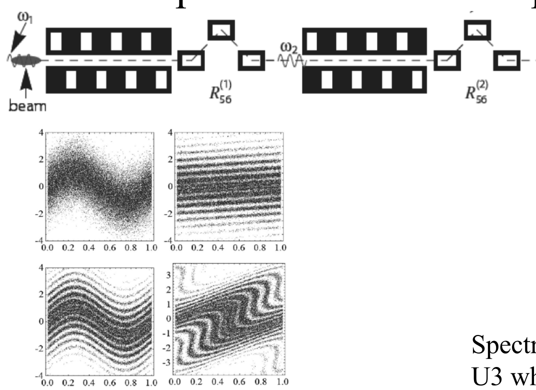
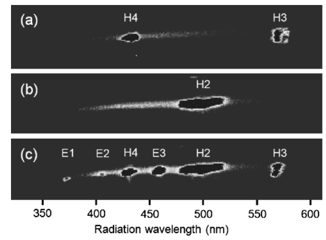


Phase space after the first and Second modulator-chicane systems. G. Stupakov, Phys. Rev. Lett. 102, 074801 (2009);



Spectrum of the radiation at the exit of U3 when the beam has considerable energy chirp: (a) only the 1590 nm laser is on; (b) only the 795 nm laser is on; (c) both lasers are on. D. Xiang et al., Phys. Rev. Lett. 105, 114801 (2010).

Single crystal self-seeding

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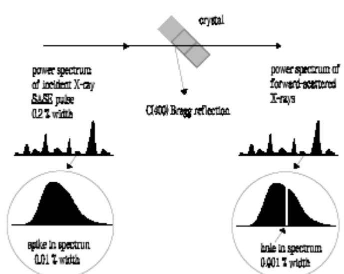
Self seeding can be effective in the hard X-ray region. First proposed to reduce the line-width by J. Feldhaus et al., Optics. Comm. 140, 341 (1997), inserting a 4 crystals monochromator and sending the beam through a bypass in a SASE undulator. More recently a single crystal system for the Å region has been proposed, offering a useful practical advantage (Geloni et al. arXiv:1004.4067v1 (2010) .



System schematic. The X-ray pulse delay is in the 10 fs region, shorter than in the 4-crystal scheme, reducing the bypass length.

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Ultra-short, fs/as, pulses.

One important direction of FEL development. Many options: single spikes, electron bunch chirping and/or laser or optical manipulation … I will consider a few cases.

In all cases we either use a small number of electrons selected from a long bunch, or start directly the FEL process with a short bunch and low charge.

Single SASE spike

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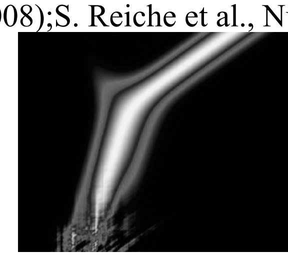
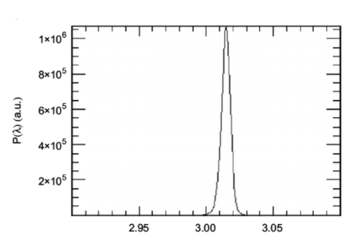
The UCLA/Frascati group proposed to use a very short electron bunch, 1 μm or less, to generate a short FEL pulse. The bunch charge is few pC -> small emittance. Large peak current, ~1 kA, obtained with velocity and magnetic compression. The result is a single SASE spike, fully coherent. J. Rosenzweig et al., Nucl. Instr. And Meth.A593, 39 (2008);S. Reiche et al., Nucl. Instr. And Meth.A593, 45 (2008)



SPARX, λ=3nm, 1 pC, radiation temporal profile, horizontal axis, along the undulator, vertical axis.



Same case, spectrum at saturation.

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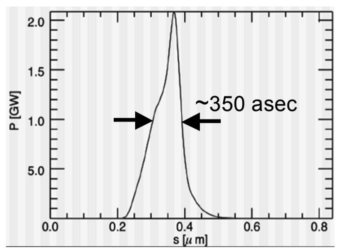
Single SASE spike

- For LCLS at 1 pC, 0.15 nm, one can obtain almost a single spike, in the as range.



Pulse length, FWHM, 0.1 μm, 300 as

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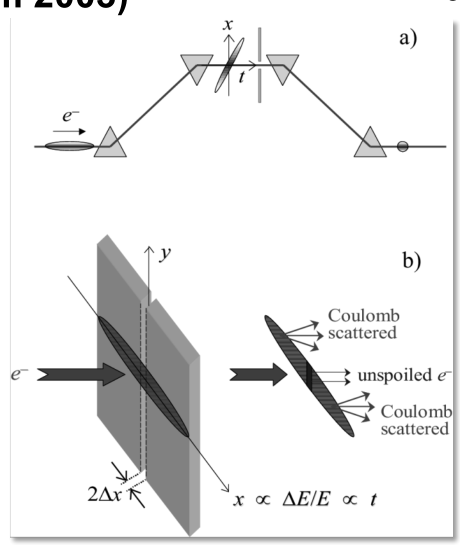
Slotted spoiler initial results. Concept (idea from 2003)

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

Courtesy P. Emma



Estimate X-ray Pulse Length for 3 kA at 250 pC

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$$\Delta\tau \approx \frac{2.35}{|\eta h| c}\sqrt{\eta^2\sigma_{\delta_0}^2 + (1 + hR_{56})^2\left[\Delta x^2/3 + \epsilon\beta\right]}$$

η = 363 mm (BC2 peak dispersion)
R_{56} = –24.7 mm (BC2)
$h = \sigma_{\delta 2}/\sigma_{z1}$ = (0.315%)/(84.4 µm) = 37.3 m (chirp),
$(\varepsilon\beta)^{1/2}$ = 44 µm (non-dispersed x beam size).
With I_{pk} = 3 kA and laser heater at 7 µJ we have:
$\sigma_{\delta 0}$ = 0.003% (sliced rms energy spread entering BC2),
and for $2\Delta x$ = 220 µm (larger full slot width)…

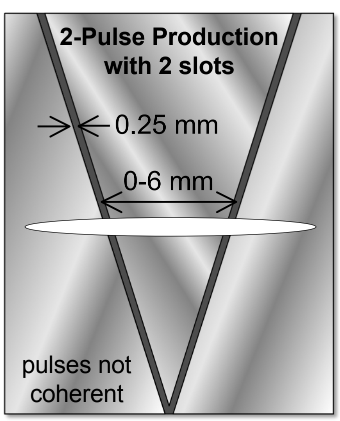
$\Delta\tau$ = 7 fs FWHM (3 fs, if laser heater is OFF)
(almost same for smaller 125 µm slot width)

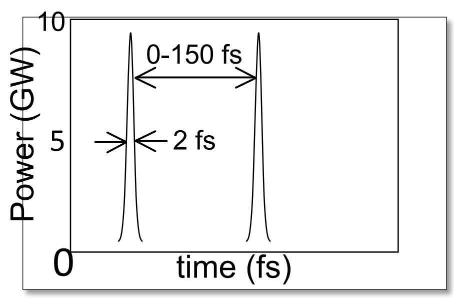
Chirp is least well known and ±10% uncertainty will change $\Delta\tau$ by a factor of 2

Double X-Ray Pulses from a Double-Slotted Foil

UCLA

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





Courtesy P. Emma

Optical manipulations techniques (1)

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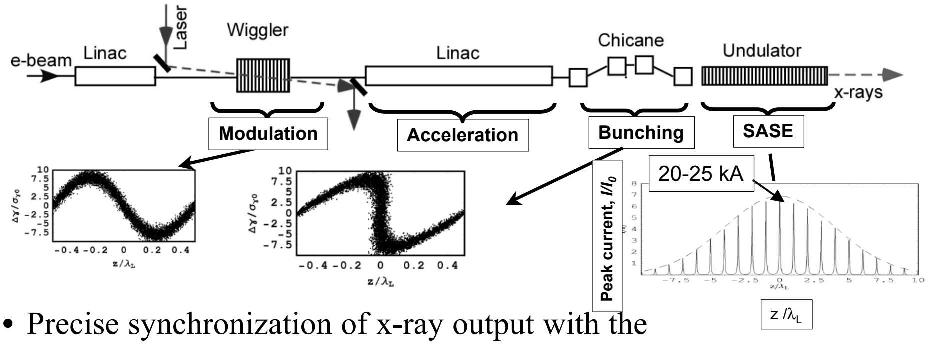
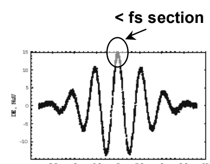
ESASE: A. Zholents, Phys. Rev. ST Accel. Beams 8, 040701 (2005)



- Precise synchronization of x-ray output with the modulating laser
- Variable output pulse train duration
- Increased peak current and shorter x-ray undulator
- Solitary ~100-attosecond duration x-ray pulse



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Optical manipulations techniques (2): HHG laser seed

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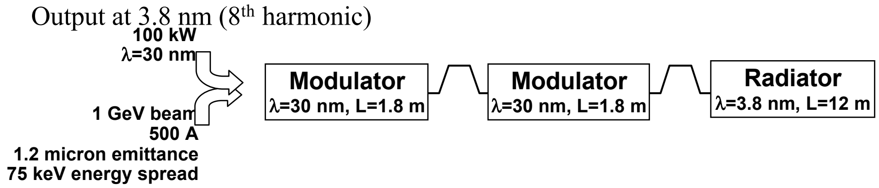
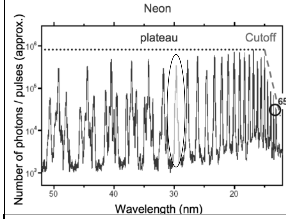
Example with seed at 30 nm, radiating in the water window

First stage amplifies low-power seed with "optical klystron". More initial bunching than could be practically achieved with a single modulator

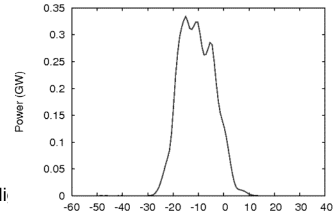
Output at 3.8 nm (8th harmonic)





Lambert et al., FEL04

300 MW output at 3.8 nm (8th harmonic) from a 25 fs FWHM seed



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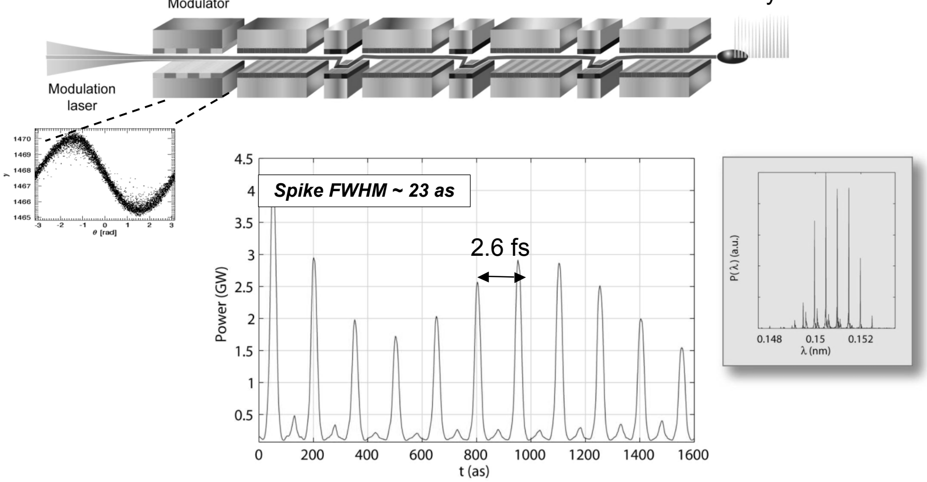
X-ray SASE FEL with mode-locking: attosecond pulse train

B.W.J.McNeil, N.R.Thompson, PRL, 100, 203901(2008)

UCLA

courtesy B. McNeil



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Coherent Diffraction imaging

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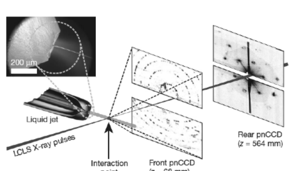
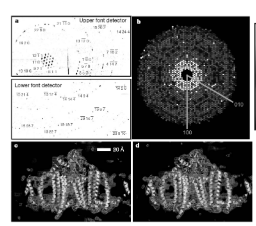
Two recent experiments at LCLS demonstrate that the concept of diffraction before destruction operates at sub-nanometer resolution. One [H. Chapman et al., Nature 470, 73 (2011)] uses the membrane protein photosystem-I as a model system, and establish an approach to structure determination based on X-ray diffraction data from a stream of nanocrystals. Experiments done at ~7Å, 70 fs, 10^{12} ph/pulse.





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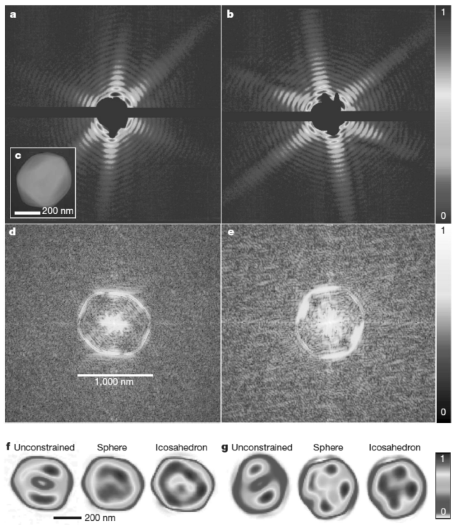
Mimivirus

UCLA



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.

Ultra-high peak power FELs: What do we want for single molecule imaging in biology?

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- The answer given by Henry Chapman and others at a January 2010 workshop at LBL:
  The optimal X-ray source is that of highest pulse power
- We would like to go from the present 30 GW level to ~1TW, with a pulse duration of about 10fs. Can we do it?
- We would also like higher pulse repetition rate, up to 10kHz, for a Structural Proteomics Center with an X-FEL
- We would like better intensity and spectral stability in the X-ray pulse.

FEL power and intensity scaling

UCLA

For a constant period and magnetic field undulator the efficiency of energy transfer from the electron beam to the photon beam at saturation is given by the FEL parameter ρ, a function of electron beam energy, density and undulator parameters (Bonifacio, Pellegrini and Narducci, Opt. Comm. 50 (1984)). The FEL peak power at saturation, P_L, the energy in the X-ray pulse, E_L, and the number of coherent photons per electron, $N_{C,e}$.

$$P_L = \rho E_B I_{B,P}\,,\ E_L = \rho E_B Q_B\,,\ N_{C,e} = \rho E_B / \hbar\omega_R$$

Typical values for LCLS or other X-ray FELs, assuming ρ~0.001, E_B=15 GeV, $I_{B,P}$~3kA, Q_B~0.3 nC, t~100fs, 10 keV photons:

P_L=40 GW, E_L= 4 mJ, $N_{C,e}$=1.5 10^3, $N_{C,T}$=2 10^{12}.

Scaling

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

For X-ray FELs ρ is typically of the order 10^{-4}-10^{-3}.

It is interesting to notice that Ω_P, the beam plasma frequency, scales as $1/\gamma$. The product $K\lambda_U$ increases with γ for a fixed wavelength, so the value of the FEL parameter is weakly dependent on the beam energy, but the peak power increases with beam energy.

a. Overall, the peak power at saturation is in the range of 10 to 50 GW for X-ray FELs at saturation.

b. The number of coherent photons scales almost linearly with the pulse duration, and is ~10^{12} at 100 fs, 10^{11} at 10fs.

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Options for increasing peak power

- 1. Chirped pulse amplification
- 2. Undulator tapering after saturation

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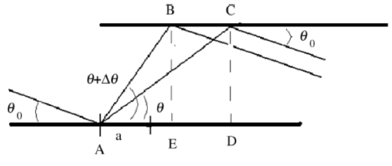
Chirped pulse amplification and fs pulses*

Amplify to saturation, using a long electron bunch, with large charge, and chirp the electron energy along the bunch, to a value given by the FEL bandwidth, $\sim\rho$, times half the number of spikes in the X-ray pulse. Compress the chirped X-ray pulse, with two diffraction gratings, as in CPA lasers, to reduce the pulse duration to about 10 fs. Can increase the peak power by about 10 for lossless gratings.

Challenges: losses in gratings; transport of large, few %, energy chirped beam through the linac-undulator system.



*C. Pellegrini, Nucl. Instr. And Methods A445,124-127 (2000)

Tapering

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Initial work by Kroll, Morton and Rosenbluth, IEEE J. Quantum Electr., QE-17, 1436 (1981).

The basic idea of tapering is to change the undulator period and/or magnetic field to compensate the electron energy loss to the radiation and continue to satisfy the resonance condition

$$\lambda = \frac{\lambda_U (1+K^2)}{2\gamma^2}$$

During the exponential growth, and before saturation, the relative electron energy loss is smaller than ρ, and can be neglected.

Tapering

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Near the saturation point, start changing the undulator period and magnetic field along the undulator length to adjust to the energy of a reference electron

$$\lambda = \frac{\lambda_U (z)[1+K(z)^2]}{2\gamma_R(z)^2}$$

The electron energy loss depends on the amplitude, A, and phase of the radiation field

$$\frac{d\gamma_R}{dz} = \frac{eA(z)}{mc}\frac{K(z)}{\gamma_R(z)}\sin\Psi_R$$

The phase can be kept constant. The rate of energy change and the undulator tapering must be adjusted for maximum energy transfer from the electrons to the radiation.

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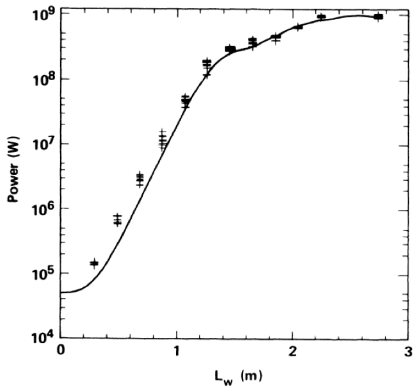
First demonstration of tapering at 30 GHz*



The experiment was done at LLNL by a LLNL/LBL group led by D. Prosnitz, with a seeded 10 cm wavelength FEL and a tapered undulator.

* T.J. Orzechowski et al. Phys. Rev. Lett. 57, 2172-2175 (1986)

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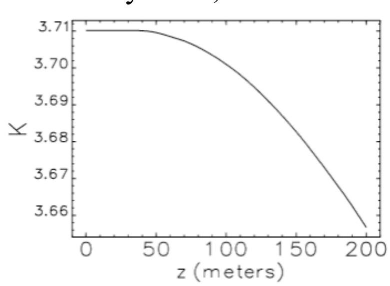
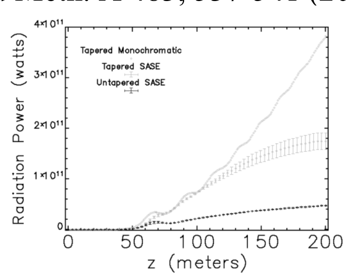
Example of tapering: LCLS

W. Fawley et al., Nucl. Instr. And Meth. A 483, 537-541 (2002)





Effect of tapering LCLS at 0.15 nm,1nC, 3.4kA. The saturation power at 70 m ~20 GW. A 200m, untapered undulator doubles the power. Tapering for a monochromatic, seeded, FEL brings the power to 380 GW, corresponding to 4 mJ in 10 fs (2x10^{12} photons at 10 keV). The undulator K changes by ~1.5%.

Remarks on tapering

1. Tapering a SASE pulse works poorly because of the large change in field amplitude across the bunch, the SASE spiking.
2. Spiking can be eliminated with seeding, or with self-seeding, greatly improving the peak power obtained with tapering.
3. The previous case is based on "old" LCLS parameters. With the present beam properties we can start from a larger power at saturation and reach a larger final output power. Optimizing the choice of charge we can be near to 1 TW for a 200 m tapered undulator.
4. Self-seeding can be done in an effective way at Å wavelengths using a single crystal (G. Geloni, V. Kocharian, E. Saldin, arXiv:1004.4067v1 **)**, but the system has to be tested. A two crystal system would also work.

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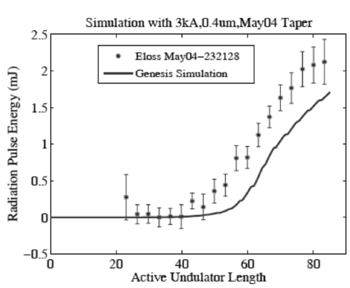
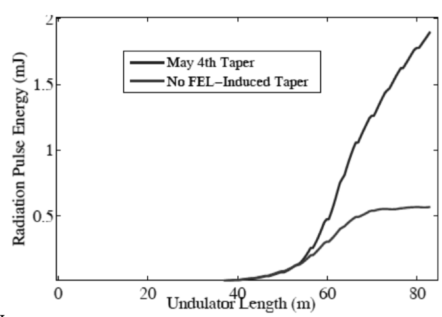
Tapering for a SASE pulse has already been tested at LCLS.

LCLS measurements with tapering at 1.5 A
D. Ratner et al., Proc.2009 FEL Conf. Liverpool, p. 221-224.





Good confirmation of theory.

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LCLS taper

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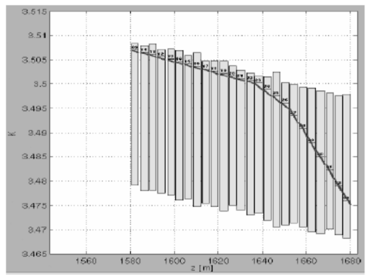
The LCLS undulator allows limited tapering. A new tapering section would be needed for high peak power operation.



Experimentally-optimized undulator taper (red line) that yielded an FEL-induced average electron energy loss of nearly 9 MeV. Yellow boxes show available range of taper for each undulator.

Tapered European XFEL

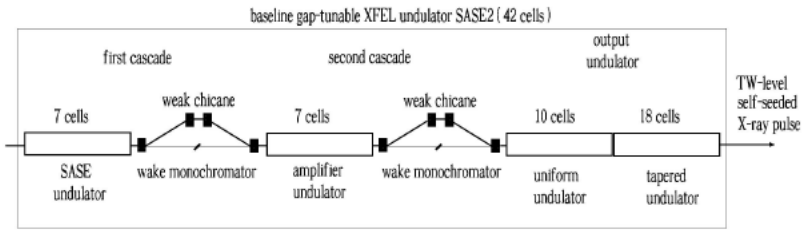
UCLA

A study of tapering for XFEL, by G. Geloni, V. Kocharian and E. Saldin, arXiv:1007.2743v1, 2010.

Electron Beam Parameters

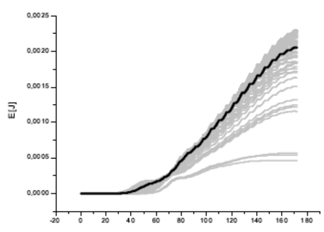
Undulator period, mm	48
K parameter (rms)	2.516
Wavelength, nm	0.15
Energy, GeV	17.5
Charge Bunch, pC	25
Bunch length (rms), μm	1
Normalized emittance, mm mrad	0.4
Energy spread, MeV	1.5

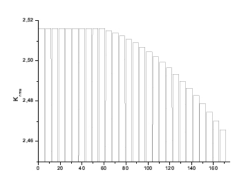
XFEL proposed tapered undulator

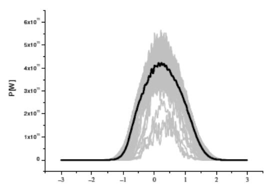


Undulator for self-seeding and tapering.

Power evolution along the undulator





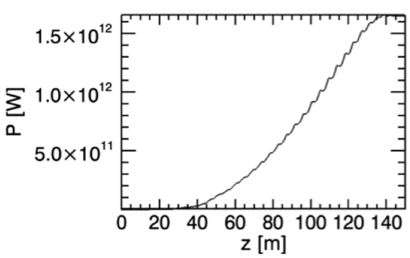


Power distribution in the X-ray pulse, showing large pulse to pulse fluctuations. Black line: average over 100 pulses.

At 180 m one has about 2 mJ in a 1mm long bunch, near to 1TW. Notice the large fluctuations.

LCLS-II tapering: Very preliminary results
J. Wu, W. Fawley, Z. Huang, C. Pellegrini

Energy 13.5 GeV, λ=1.5 Å;
Electron Charge 40 pC, peak current 4 kA, FWHM 10fs; 0.2 *m*rad emittance;
LCLS-II Undulator, λ_U = 3.2 cm; beta-function ~ 20 m



Tapering starts at 20 m; quadratic tapering; 8.5454 % from 20 m to 150 m

Beam power~50 TW
About 3% power transfer

High repetition rate room temperature linacs for X-ray FELs

A paper studying the use of an X-band (~ 12 GHz) room temperature linacs operating at 1 kHz was presented by C. Pellegrini and S. Tantawi at the Basic Energy Science light source workshop on 9/14-17/2009.

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Most existing linacs have been designed to produce the maximum beam energy in the shortest possible distance. This approach has led to a linac structure design that maximizes the accelerating field.

However, to produce the field, the accelerating structures must be filled with electromagnetic energy. The average power needed is proportional to the repetition rate, *f*, the pulse duration τ and filling time, the structure volume *V*, and the square of the accelerating field, *E*:

$$P_{Ave} \sim f \tau E^2 V$$

To minimize the power requirement, and increase *f,* we minimize *V* by using high frequency RF -X-band linac-, reducing the pulse duration and the accelerating voltage.

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Conclusion of the BES paper

- With recent advances on X-band accelerator structures and related RF systems, it is possible to think of an “efficient” room temperature high repetition rate low gradient linacs.
- Reduced accelerating field “easily” allows designs with gradients of 10-15 MV/m at repetition rates of 1 kHz
- System optimization may allow us to think of higher repetition rates, say 10 kHz.

Linacs and electron guns

Laser/plasma/dielectric wake-field based accelerators are being developed. They could become available for light sources in the future and decrease the accelerator length to a small fraction of its present size. One example is the HZ project at Berlin to develop tabletop sources. Other projects to develop high gradient laser/plasma based accelerators as future linac to drive light sources and high energy physics colliders are being developed at Berkeley by Wim Leemans and coworkers, at SLAC/UCLA by C. Joshi and coworkers, and in Europe within the framework of the European Extreme Light Infrastructure. The dielectric wakefield accelerators is another interesting option.

Leemans, W.P. et al., IEEE Trans. On Plasma Science 33, 8 (2005).
I. Blumenfeld et al., Nature 445, 05538 (2007).
http://www.extreme-light-infrastructure.eu/

Linacs and electron guns

Tesla and LCLS electron guns are working very well. The LCLS gun has generated record breaking high brightness beams.

A new RF electron gun for very high repetition rate, 0.1 to a few MHz, X-ray FELs, is being developed at LBNL with the cathode inserted in a low frequency, 75MHz, normal conducting cavity. J. W. Staples et al., in Proceedings of Part. Acc. Conf., Albuquerque, New Mexico, 2990 (2007).

S-band and superconducting linacs are well established.

A C-band linac, with larger accelerating gradient, is used for SCSS, reducing the accelerator length. X-band linacs could be used. Both C band or X-band linacs could also be used at low accelerating gradient to increase the linac repetition rate, up to 1-10 kHz.

Conclusions

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X-ray FELs can be developed to fulfill most of the wish list: femto-second to atto-second pulse duration, very small line width, MHz repetition rates, ultra-high peak power. 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 when coupled to new short period undulators. Longitudinal coherence can be pushed near to the transform limit using single spike, self seeding, seeding, or with an X-ray oscillator. Such high-power, ultra-short x-ray pulses will open up new applications in many areas of science. In addition, the achieved beam brightness may enable a more compact design of a future hard x-ray FEL facility, where a lower-energy linac than the LCLS and a shorter-period undulator can be envisioned to drive a hard X-ray FEL.

Conclusions

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Peak power of about 1 TW for 10 fs can be generated at Å wavelength using self-seeding and tapering.
The number of coherent photons/pulse and other characteristics can be tailored to the experiments to explore biological, physical and chemical phenomena in a novel way.
Systems providing only a subset of these characteristics, in particular short pulses, can be built at lower cost. Ongoing research on laser/plasma/wakefield accelerators, high frequency, high repetition rate linacs and electron beam injectors can lead in the future to very compact, university scale, X-ray FELs. Support for accelerator and FEL research and student training is of great importance to realize the full potential of future FEL light sources.