X-ray free-electron lasers physics
and
ultra-fast science at the
atomic and molecular scale.
Part 1

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1

OUTLINE

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1. Introduction
2. FEL physics and basic properties of the radiation
3. Present state of the art: results obtained until now.
4. X-ray FELs parameters
5. Future developments
6. Conclusions

2

Introduction: X-Ray FELs

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The interest in X-ray FELs is motivated by their characteristics of tunability, coherence, high peak power, short pulse length. They can explore matter at the length <u>and</u> time scale typical of atomic and molecular phenomena: Bohr atom radius, about 1 Å, Bohr period of a valence electron, about 1 fs.

Introduction: X-ray FELs

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The large number of photons per pulse allows to determine the structures of complex molecules or nano-systems in a single shot; to study non linear phenomena; to study high energy density systems.

The transverse coherence gives new possibilities of imaging at the nano and sub-nano scale. Using fast, single shot imaging, one can follow the dynamics of these phenomena.

Using all these properties we can explore matter with unprecedented time-space resolution.

X-ray FEL Main Characteristics

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- Peak power, about 10 Gigawatt or more
- Pulse length, about 100 femtosecond or shorter
- Transversely coherent, diffraction limited
- Line width < 0.001
- Tunable from 15 to 0.5Å

The X-ray FEL is a powerful tool to explore matter and fundamental physics.

5

FEL Physics

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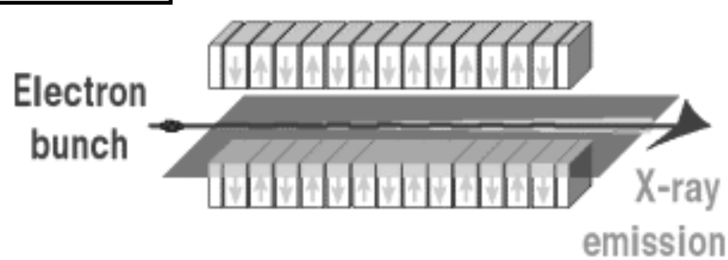

An electron beam, moving through an undulator magnet, executes an oscillation transverse to the direction of propagation. Each electron radiates an electromagnetic field. The radiation acts on other electrons, establishing a collective interaction. Under proper conditions, the interaction produces a transition of the beam to a novel states, in which the electron distribution consists of micro-bunches separated by the radiation wavelength, and the radiation emitted is coherent and has larger intensity.

6

FEL PHYSICS: RADIATION FROM ONE ELECTRON

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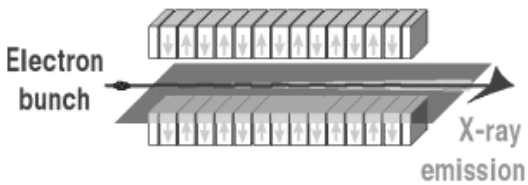
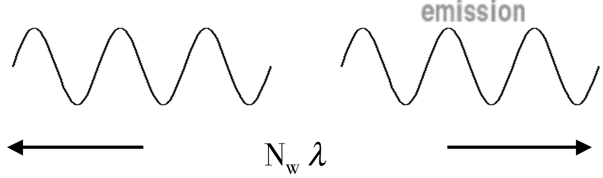


Undulator with N_w periods.



$\Delta\lambda/\lambda=1/N_w$

Each electron emits a wave train with N_w waves

$\lambda=\lambda_w(1+K^2/2+\gamma^2\theta^2)/2\gamma^2$

$K=eB_w\lambda_w/2\pi mc^2$

For $\gamma=3\times10^4$, $\lambda_w=3$ cm, K=3, $N_W\sim3300$:

$\lambda\sim0.1$ nm, $\Delta\lambda/\lambda\sim3\ 10^{-4}$, $N_w\lambda\sim0.3\,\mu$m.

7

FEL PHYSICS: RADIATION FROM ONE ELECTRON

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Because of dependence of the wavelength on the emission angle, the "coherent angle", corresponding to $\Delta\lambda/\lambda<1/N_w$, is

$$\theta_c=(\lambda/N_w\lambda_w)^{1/2}$$

the effective, diffraction limited, source radius is

$$a_c=(\lambda N_w \lambda_w)^{1/2}/4\pi$$

with $a_c\theta_c=\lambda/4\pi$. For the X-ray FEL $\theta_c\sim1\ \mu$rad, $a_c\sim10\ \mu$m.

The average number of coherent photons/electron in $\Delta\Omega=\pi\theta_c^2/2$, $\Delta\lambda/\lambda=1/N_w$ is

$$N_{ph}=\pi\alpha K^2/(1+K^2)\sim0.01,$$

a small number.

8

SASE: A BEAM SELF-ORGANIZATION EFFECT.

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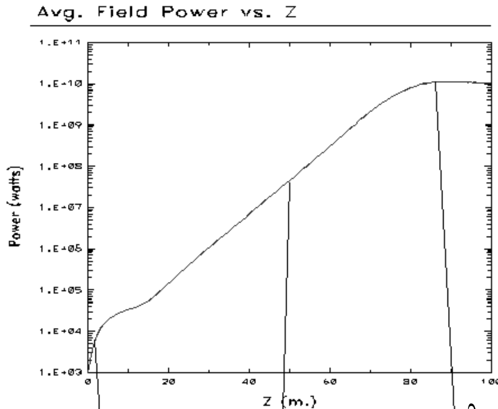
Evolution of power along the undulator from spontaneous radiation to FEL amplified radiation.

In the initial state the electrons have a random longitudinal position. The wave train from the electrons superimpose with random phase (spontaneous radiation).



The interaction produces an ordered distribution in the beam, like a 1-D crystal.

9

FEL Collective Instability

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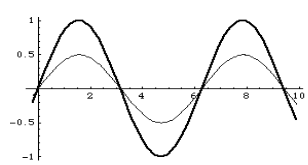
I. e-beam+undulator +EM field (initially spontaneous radiation)-> electron energy modulation, scale λ;

$$\frac{d\gamma}{dt} \sim eE \bullet V_T \cos\Phi$$

$$\Phi = \frac{2\pi}{\lambda}(z-ct) + \frac{2\pi}{\lambda_w} z$$

Φ is the relative phase of the field and electron oscillation.

II. energy modulation + undulator -> electron bunching, scale λ;



$$\frac{d\Phi}{dt} \sim \gamma - \gamma_0$$

III. larger bunching factor B->higher EM field intensity ->go back to step I

10

A PICTURE OF THE WAVE TRAINS EMITTED BY MANY ELECTRONS

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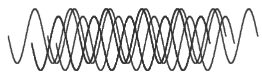

Initial state, disordered state-
Intensity ~ N_e

Final state, ordered state-
Intensity ~ N_e^2

11

FEL COLLECTIVE INSTABILITY: MAIN CHARACTERISTICS

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All key characteristics are given by one universal FEL parameter: $\rho=\{(K/4\gamma)(\Omega_p/\omega_w)\}^{2/3}$
($\omega_w=2\pi c/\lambda_w$, Ω_p=beam plasma frequency).

- Gain Length: $L_G=\lambda_w/4\pi\rho$,
- Saturation: $P\sim\rho\, I_{beam}\, E$
- Saturation length: $L_{sat}\sim 10L_G \sim\lambda_w/\rho$
- Line width: $1/N_w\sim\rho$

Number of photons/electron at saturation: $N_{ph} \sim \rho E/E_{ph}$. For E_{ph}=10keV, E=15 GeV, $\rho=10^{-3}$, $N_{ph}\sim10^3$, a gain of 5 orders of magnitude.

12

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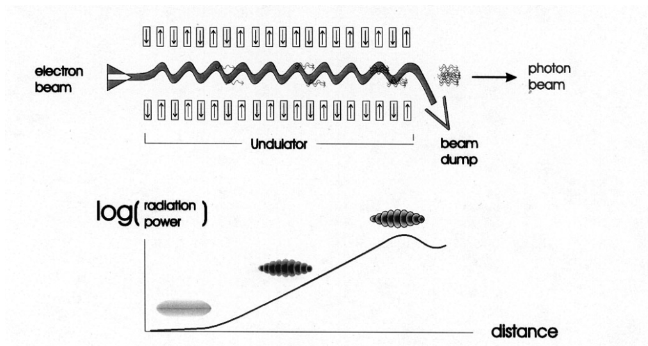

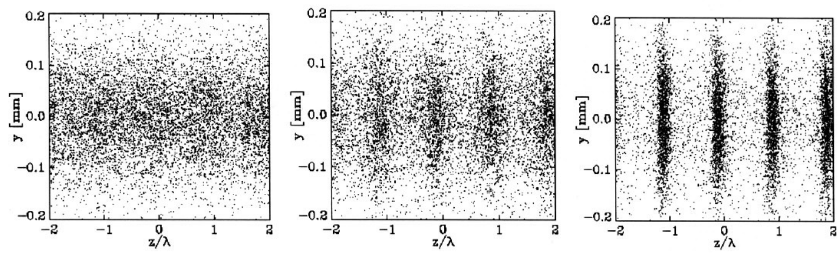

13

FEL Collective Instability: electron beam conditions

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The exponential growth occurs if

$\sigma_E < \rho$ (cold beam)

$\varepsilon \sim \lambda/4\pi$ (Phase-space matching) To satisfy this condition we use a large beam energy.

$Z_R/L_G > 1$ Diffraction losses from the beam less than the gain

The beam Rayleigh range is $Z_R = 2\pi a/\lambda$, where a is the beam transverse radius.

14

FEL Collective Instability: causality

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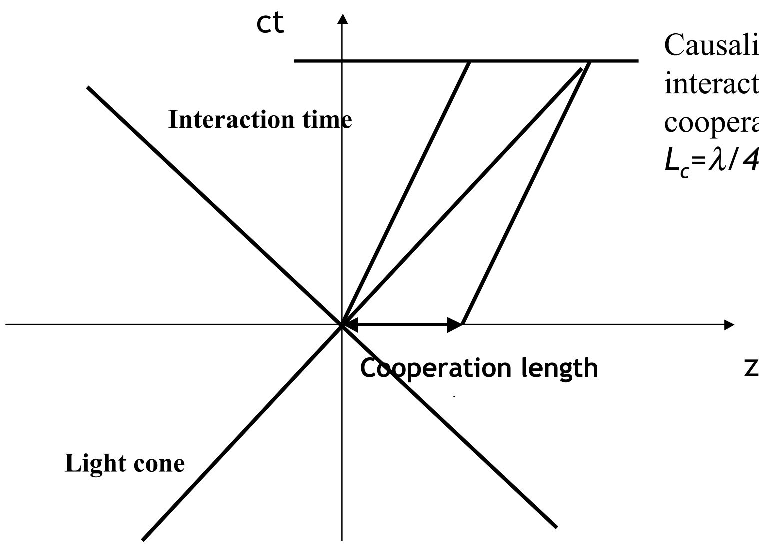

Causality limits the interaction to the cooperation length: $L_c = \lambda / 4\pi\rho$.

15

Slippage, Cooperation Length, Time Structure

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- The radiation propagates faster than the electron (it "slips" by λ per undulator period); thus electrons communicate with the ones in front only if their separation is less than the total slippage $S = N_w \lambda$.
- Cooperation length (slippage in one gain length)

$$L_c = \lambda / 4\pi\rho$$

- The local intensity in a SASE radiation pulse is proportional to the initial random bunching within a cooperation length, leading to the formation of "spikes", with independent intensity.
- Number of "spikes" in an X-ray pulse: bunch length/$2\pi L_c$.

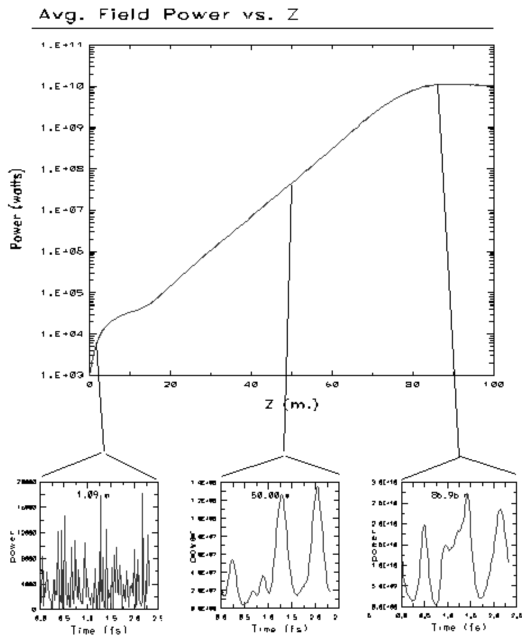
(R. Bonifacio, C.Pellegrini, et al., Phys. Rev. Lett. 73, 70 (1994)).

16

The spiky nature of SASE-FEL

LCLS: L_c=0.04 µm
The full spike length is
~ 0.24 µm or 0.8 fs
$\Delta\lambda/\lambda$=3x10^{-4}

The number of spikes is about 250.



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17

X-rays Coherence properties

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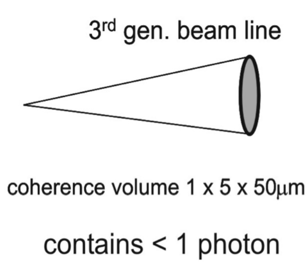
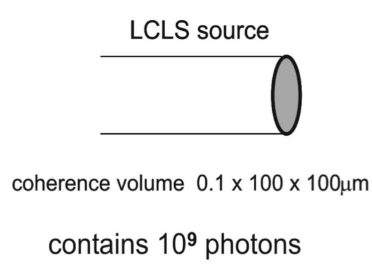
The X-ray FEL radiation has unprecedented coherence, about 10^9 photons in the coherence volume. The energy of coherent photons can be pooled to create multi-photons excitations and carry out non-linear X-ray experiments. This is a largely unexplored area of science.





18

Experimental verifications of theory

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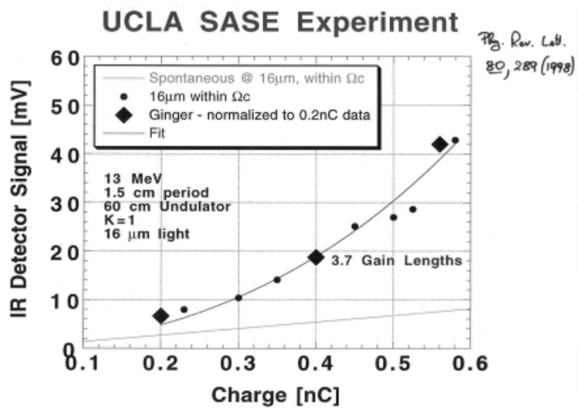
UCLA/Kurchatov

M. Hogan et al. Phys. Rev. Lett. 80, 289 (1998).



19

The BNL-SLAC-UCLA photoinjector electron source

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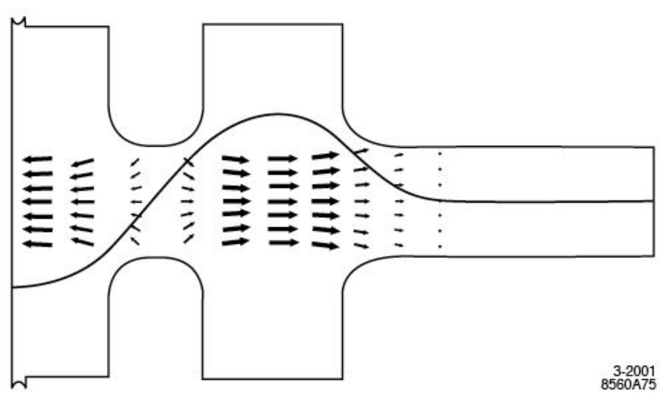

Field lines in the RF gun, for the π mode of operation.

20

The BNL-SLAC-UCLA photoinjector electron source

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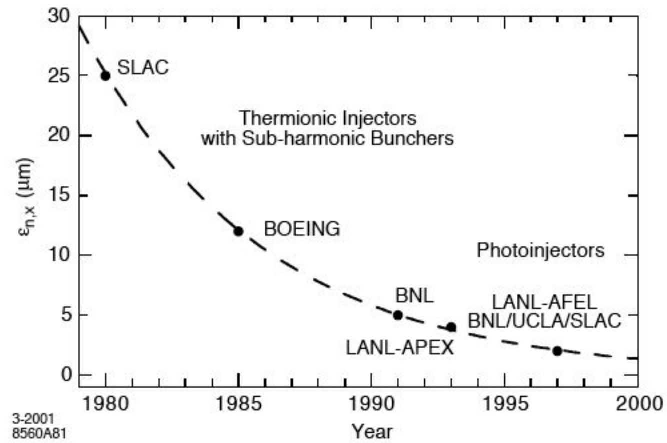

Progress in emittance value using photoinjectors

21

Experimental verifications of theory

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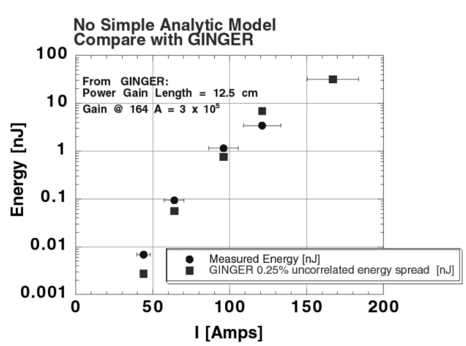
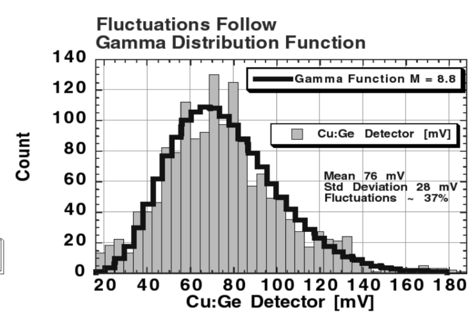
UCLA/Kurchatov/LANL/SSRL

Gain of 3x105 at 12 mm. Demonstration of fluctuations and spikes, good agreement with theory.

M. Hogan et al. Phys. Rev. Lett. 81, 4897 (1998).





22

Experimental verifications of theory

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UCLA/Kurchatov/LANL/SSRL
Direct measurement of microbunching using coherent transition radiation.
A. Tremaine et al., Phys. Rev. Lett. 81, 5816 (1998).

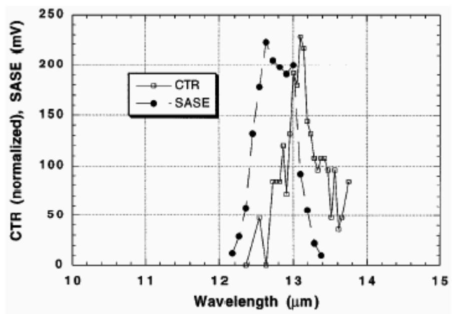

FIG. 3. SASE and CTR signals as a function of wavelength, with CTR scaled to SASE amplitude.

23

LEUTL, APS

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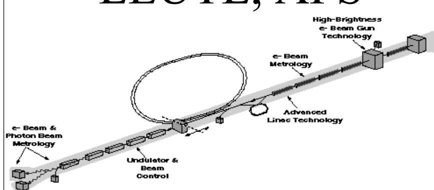

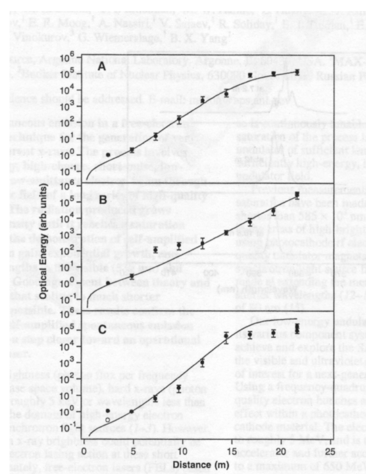

LEUTL exponential gain and saturation at 530 nm, A &B, and 385 nm, C. The gain reduction for case B was obtained by reducing the peak current.

Milton et al., Science*express*, May 17, 2001.

24

http://www.aps.anl.gov/aod/mcrops/leutl/Steve.html

Visible to Infrared SASE Amplifier

BNL-LLNL-SLAC-UCLA

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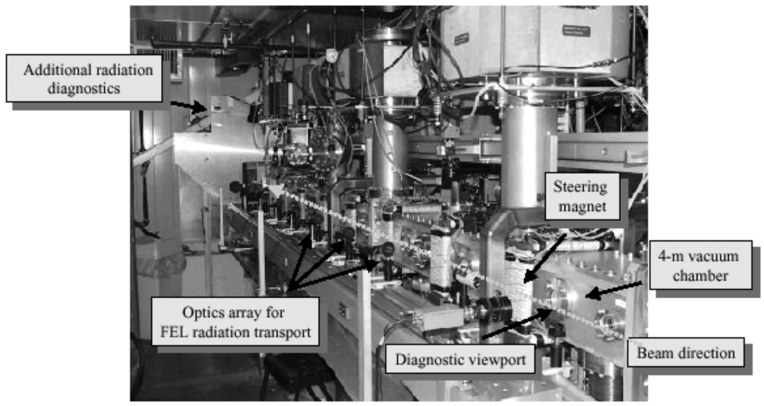

VISA:Visible to Infrared SASE Amplifier

BNL-SLAC-LLNL-UCLA

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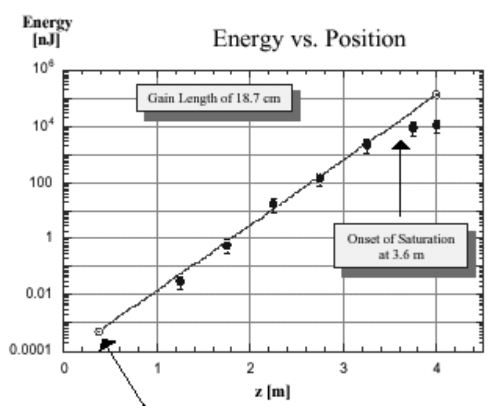

Wavelength 830nm
Average Charge:170 pC
Gain Length 18.5 cm
Equivalent Spontaneous Energy: 5 pJ
Peak SASE Energy:10 μJ
Total Gain: 2×10^7

Visible to Infrared SASE Amplifier

BNL-LLNL-SLAC-UCLA

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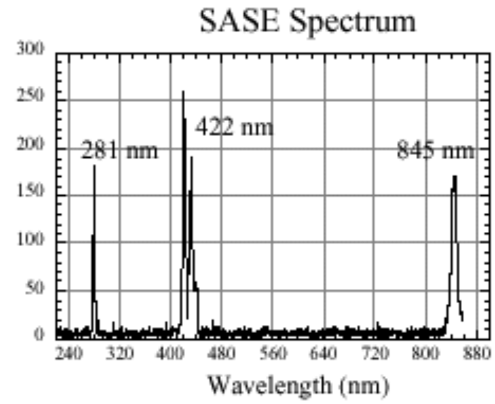

27

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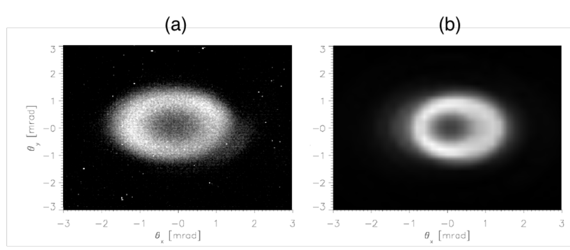
Measured and simulated angular distribution at saturation in VISA



Simulation done with Genesis use the Parmela-Elegant output.

28

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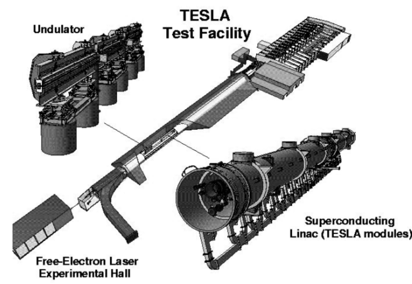
FLASH at DESY: a UV-soft X-ray FEL

- 1 GeV – 6 nm
- Norm. emittance: 2 mm mrad
- FWHM FEL pulse length: ca. 100 fs
- Peak current 2500 A
- Linac rep. rate 10 Hz
- Max. pulse rate 72 000



Courtesy J. Rossbach, Desy

29

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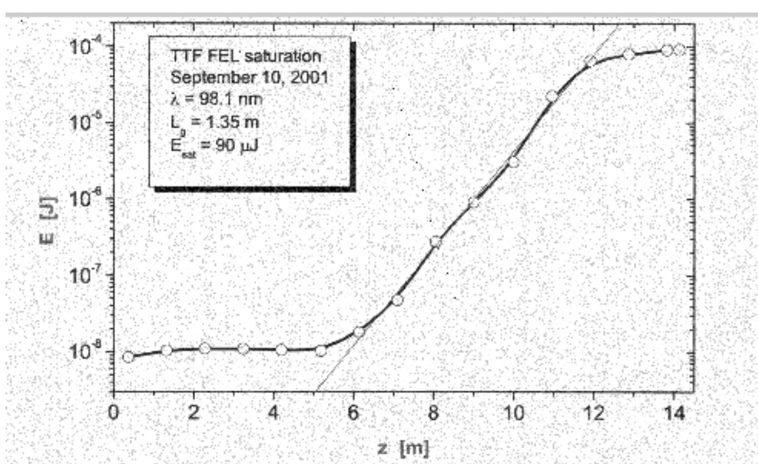
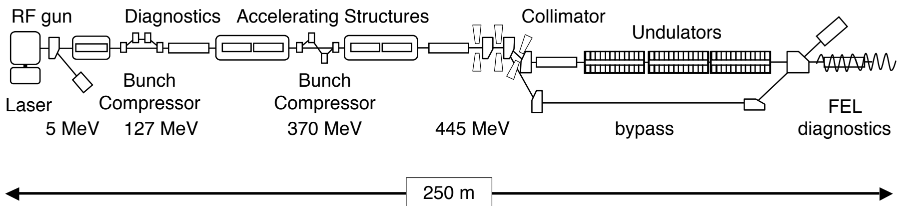


30

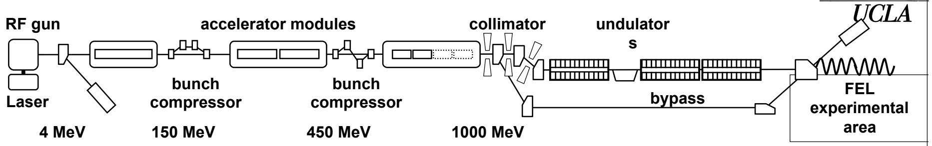
Present Layout of the VUV-FEL



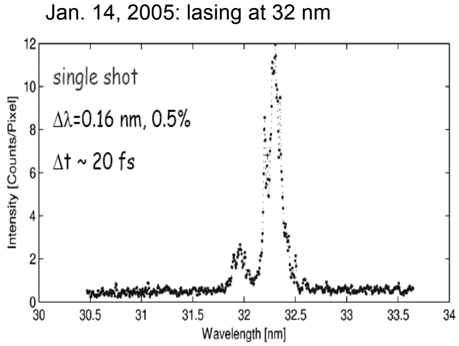
Courtesy J. Rossbach, Desy

VUV-FEL → FLASH

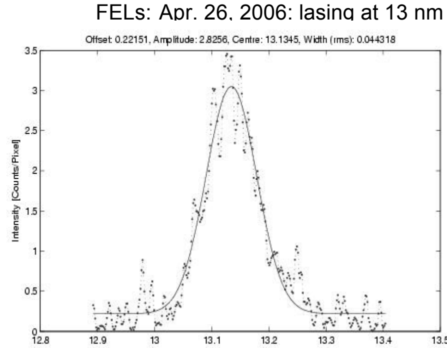
Free Electron LASer in Hamburg



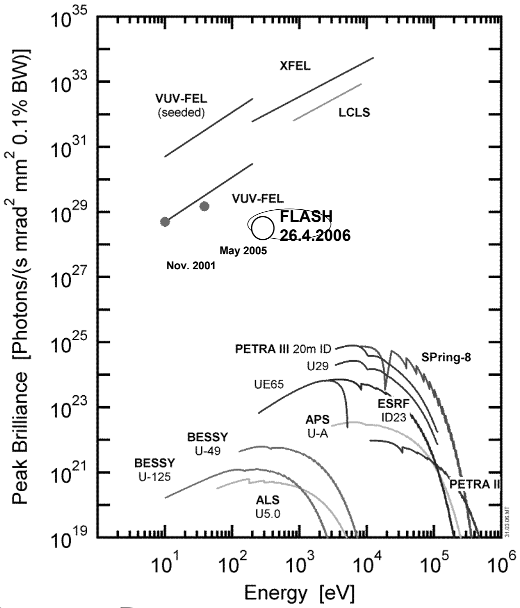
Jan. 14, 2005: lasing at 32 nm



Latest wavelength record for SASE FELs: Apr. 26, 2006: lasing at 13 nm



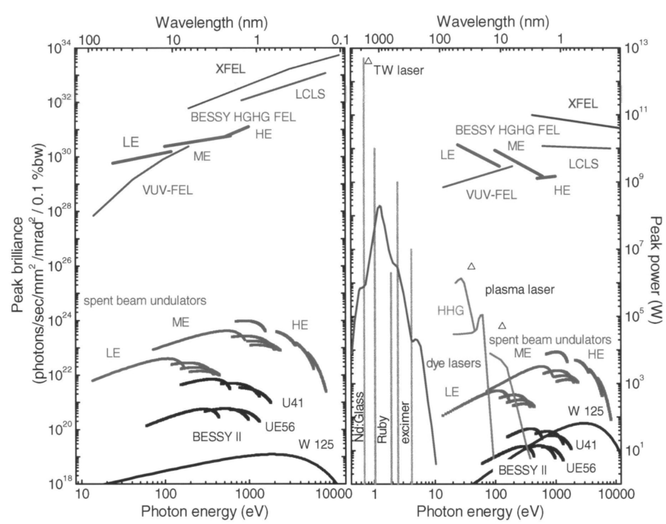
Courtesy J. Rossbach, Desy



Courtesy J. Rossbach, Desy

33

Comparison of some radiation sources



From the Bessy CDR

34

FEL Collective Instability: short history

The theoretical derivation of the existence of imaginary solutions of the FEL dispersion relation goes back to the late 70, early 80s.

Ref: N.M. Kroll and McMullin,Phys.Rev.A17,300 (1977); A.M. Kondratenko and E.L. Saldin, Dokl. Aka. Nauk SSSR 249, 843 (1979); P. Sprangle and R.A Smith, Phys. Rev. A21, 293 (1980); ..

A complete 1-D theory of a SASE-FEL including saturation was given in 1984 by R. Bonifacio, C. Pellegrini and L. Narducci, Optics Comm.50, 313 (1984). This theory introduced the universal FEL parameter **r**, which gives all the basic FEL properties.

35

FEL Collective Instability: short history

- First proposal to use the instability to produce IR radiation starting from noise A.M. Kondratenko and E.L. Saldin, Part. Acc.10, 207 (1980).
- First proposal to use the instability for a soft X-ray FEL starting from noise J.B. Murphy and C. Pellegrini, J. Opt. Soc. Am. B2, 259 (1985), using a bypass in a storage ring.
- First proposal to use the instability for a 1 Å X-ray FEL starting from noise and using the SLAC linac C. Pellegrini, Proc. of the Workshop on 4th Generation Light Sources, Stanford 1992.

36

FEL Collective Instability: short history

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- Reaching 1 Å was made possible by the development of a novel electron source, the photoinjector, by J.S. Fraser, R.L. Sheffield, and E.R. Gray, Nucl. Instr. and Meth. in Phys. Res., 250, 71, (1986).

37

Production of ultra-short radiation pulses in the VUV FEL

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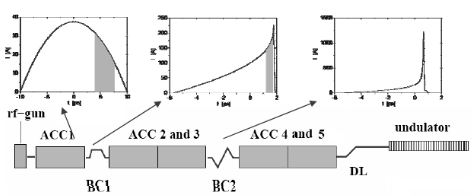
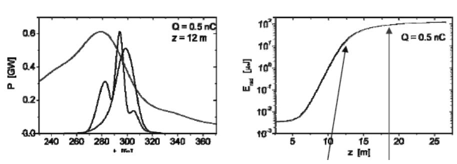
An ultra-short current spike (50-100 fs FWHM) with peak current 1-2 kA is formed in the nonlinear bunch formation system of the VUV FEL



Strong energy chirp along current spike leads to significant shortening of the radiation pulse. Minimum pulse length occurs in the end of the linear regime.



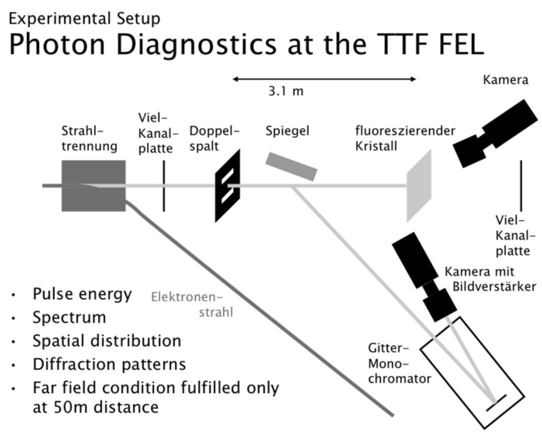
The VUV FEL is capable to produce short, down to 20 fs radiation pulses with GW-level peak power and degree of contrast 80 %:

$$C(\tau) = \frac{\int_{-\tau/2}^{\tau/2} P(t)\,\mathrm{d}t}{\int_{-\infty}^{\infty} P(t)\,\mathrm{d}t} .$$

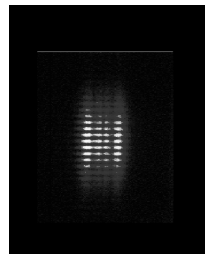
Courtesy M. Yurkov et al.

38

Transverse coherence measurement
R. Ishebek et al.



Double slit diffraction.
λ=100nm.Average of 100 shots



Courtesy R. Ishebek

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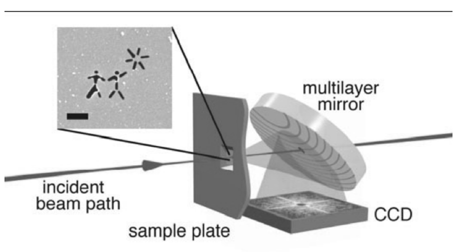
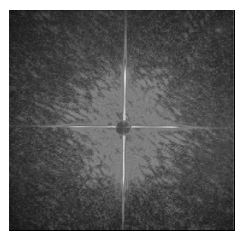
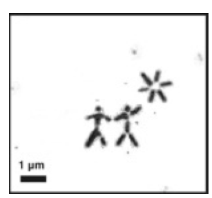
39





Ultrafast Coherent Diffractive Imaging at FLASH, H.N. Chapman et al. Nature Physics 2, 839 (2006).

(a) Coherent diffraction pattern recorded from a single 25 fs pulse. (b) Reconstructed X-ray image, which shows no evidence of the damage caused by the pulse.



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40

X-Ray FELs

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After many years of research and development an X-ray free-electron laser (FEL) operating in the Å spectral region, the LCLS, first proposed in 1992, is now being built and will be completed by 2008. Another X-ray FEL operating at the same wavelength is being developed at DESY as a European project. Other similar projects are being developed in Japan, China and Korea. Several FELs operating in the few nanometer region, or in the 10 t0 100 nm region, are being developed and built in Europe, the US and Asia.

41

LCLS

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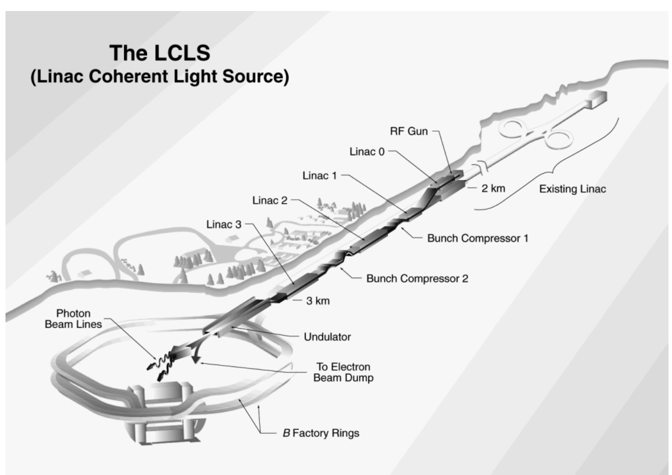

42

LCLS SCHEMATIC

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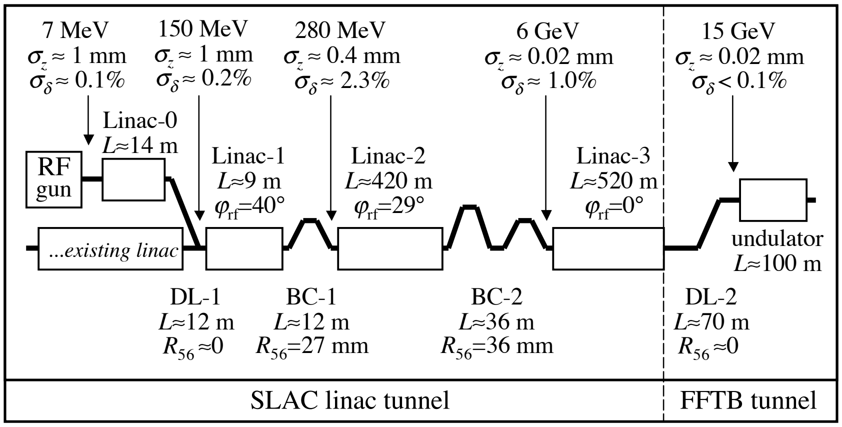

43

The LCLS electron injector

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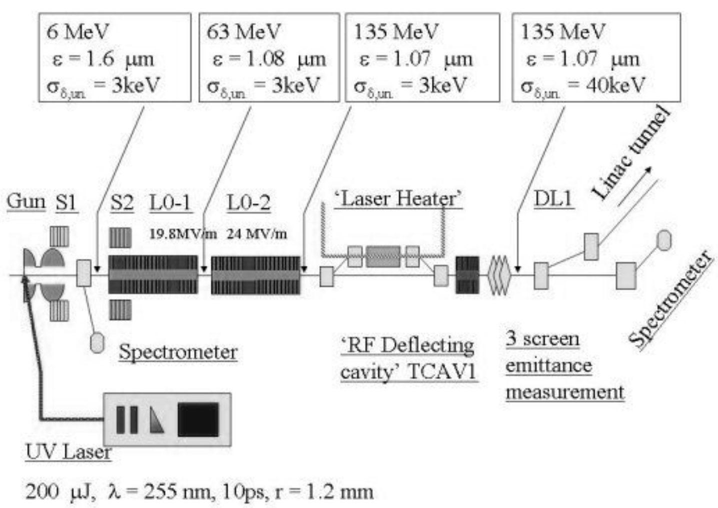

44

Electron Beam	**λ=15 nm**	λ= 0.15	nm
Electron energy	4.313	13.64	GeV
Normal. Emittance, slice	2	1.2	mm mrad
Charge	0.2-1	0.2-1	nC
Peak current	1920	3400	A
Pulse form, long. flat top, trans. Gaussian			
RMS bunch duration	136	73	fs
Energy spread, slice rms	0.03	0.01	%
Energy spread, Proj. rms	0.09	0.03	%

45

FEL			
Wavelength (fundamental)	1.5	0.15	nm
FEL parameter	8.5	4.2	
Power gain length	2.6	5.1	m
Peak saturation power	4	8	GW
Average saturation power	0.23	0.23	W
Cooperation length	280	57	nm
Photons per pulse	10.6	1.1	x 10^{12}
Peak brightness	0.28	15	x 10^{32*}

46

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Spontaneous radiation			
Wavelength (fundamental)	1.5	0.15	nm
Peak power	4.1	73	GW
DE/E, spontaneous rad.	0.048	0.15	%
DE/E, wake fields	0.03	0.1	%
Average saturation power	0.23	0.23	W
Cooperation length	280	57	nm
Photons per pulse	10.6	1.1	x 10^{12}
Peak brightness	0.28	15	x 10^{32*}

47

Some LCLS Radiation Characteristics

For LCLS: ***L_c=0.06 μm~0.2 fs***

$\Delta\lambda/\lambda = 4x10^{-4}$

N_S=250, L_P ~100 fs, rms

The line-width is about 100 times the Fourier transform line-width for a 100 *fs* long pulse.

In SASE operation the pulse to pulse intensity fluctuates by about 7% (the fluctuation level can be increased by system fluctuations).

48

X-ray free-electron lasers physics and ultra-fast science at the atomic and molecular scale. Part II

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UCLA

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1

Reducing the LCLS Pulse Length

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FEL characteristics that can be used to reduce the pulse length:

1. The large gain bandwidth;
2. The dependence of the wavelength on the electron energy;
3. The dependence of the pulse length on the electron bunch length (they are about equal);
4. Chirping the electron beam energy and the radiation pulse wavelength;
5. Local increase of the electron bunch emittance and/or energy spread.

2

Reducing the LCLS Pulse Length

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The reduction of the electron bunch length is limited to about a factor of 2, for the charge design values, and using present type of electron gun.

A larger reduction can be obtained by producing from the linac a "chirped" electron bunch, with energy dependent on the longitudinal position. This gives a "chirped" X-ray pulse, with a correlated frequency spread larger than the "natural" LCLS spread. Chirped bunches and pulses can be used in many ways.

3

Enhanced SASE. A. Zholents, LBNL55938 and PRL

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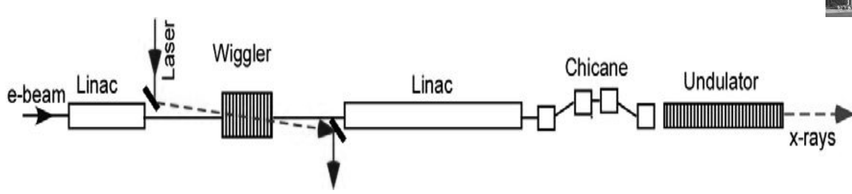

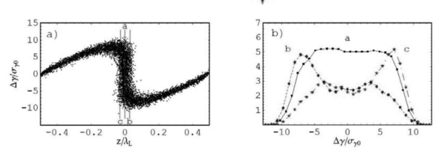

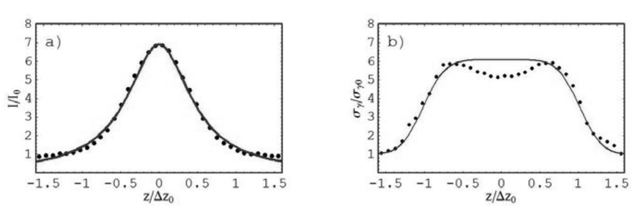

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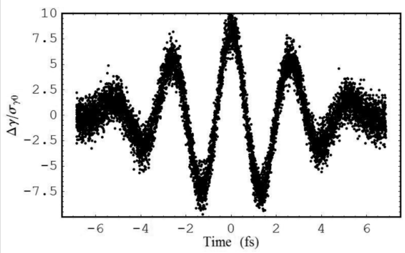
ESASE at LCLS (Zholents)



Modulating Laser at wavelength 2.2 mm, power 6 GW

Modulator magnet with ten periods, 16 cm long, field 2T (K=29),at E=2GeV..

FEL parameter, of modulated beam 8x10^{-4},twice as large as the non modulated beam.

FEL radiation at 0.15 nm, with Peak power of 230 GW and pulse length of 0.2 fs.

5

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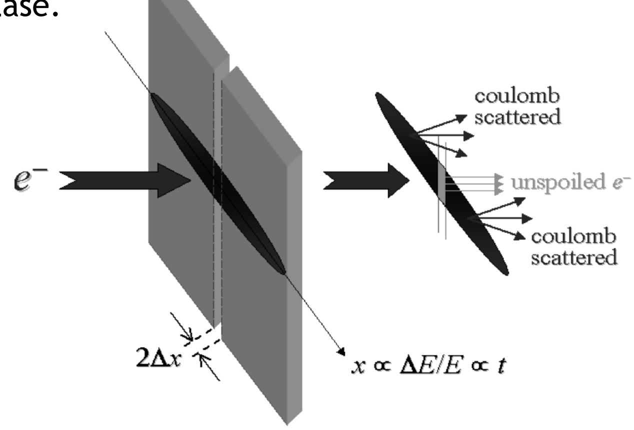
Slotted spoiler method to produce femtosecond pulses. P. Emma, Z. Huang, et al., Ph. Rev. Lett. 2004

Slotted spoiler at the center of a chicane leaves a narrow, un-spoiled beam center, which has small emittance and will lase. The rest of the bunch has emittance too large to lase.



6

Two-Stage Chirped-Pulse Seeding in LCLS

C. Schroeder, J. Arthur, P. Emma, S. Reiche, and C. Pellegrini, JOSA B 19,, 1782-1789, (2002). Virtual Journal of Ultrafast Science 8/2002.

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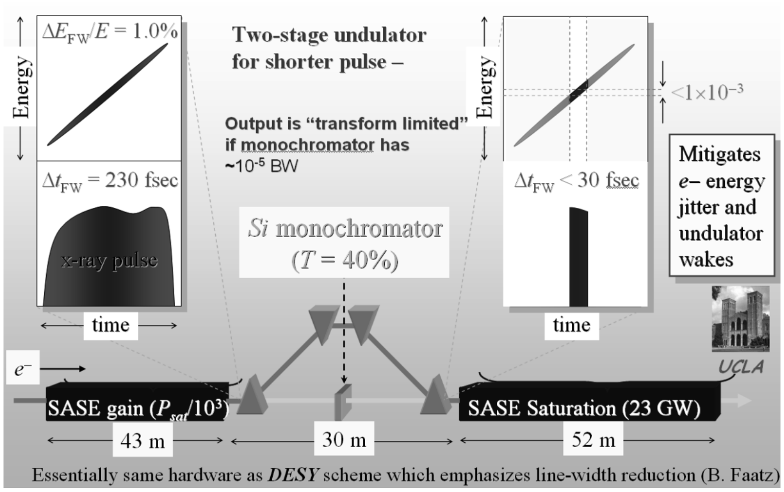

7

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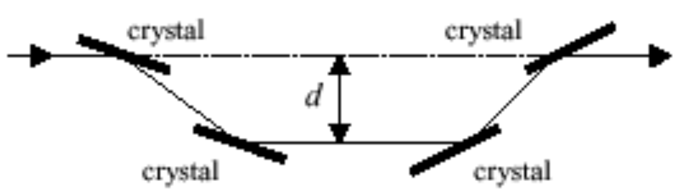
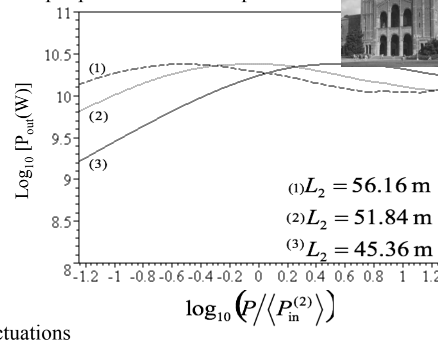
Bragg diffraction in crystals is the method of bandwidth selection. For example,one can consider a Si(111)crystals, with a FWHM bandwidth of 1 .3×10^{-4} , or a Ge(111) crystals, with a FWHM bandwidth of 3.1× 10^{-4} .



Shot-to-shot fluctuations:

Dependence of output power on input power for FEL amplifier



Radiation Probability Distribution after Monochromator:

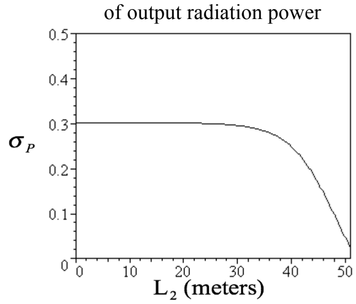
Negative Binomial Distribution

$$p(P) = \frac{\Gamma(P+M)}{\Gamma(P+1)\Gamma(M)} \frac{\left(1+\frac{M}{\langle P_{in}^{(2)}\rangle}\right)^{-P}}{\left(1+\frac{\langle P_{in}^{(2)}\rangle}{M}\right)^{-M}}$$

Standard deviation of radiation power into second undulator:

$$\sigma_P = \frac{1}{\sqrt{M}} \approx \sqrt{\frac{2\pi\sigma_c}{L_p}}$$

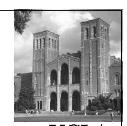
Relative rms fluctuations of output radiation power

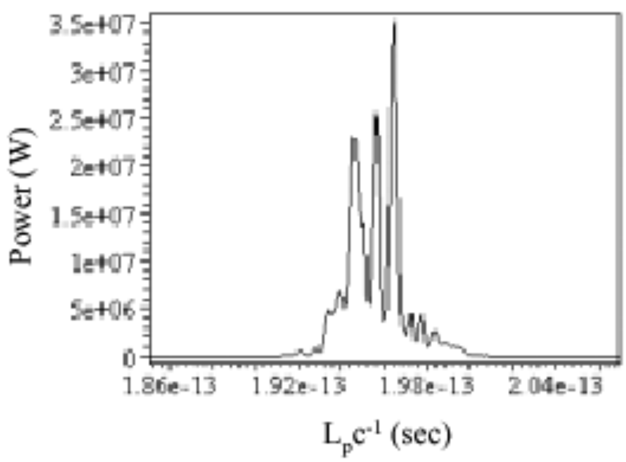


Shot-to-shot fluctuations of output radiation power are reduced by operating the FEL amplifier in the non-linear regime.

9

Pulse shape at 2nd undulator exit





10

Second undulator

INPUT ELECTRON BEAM:

PEAK CURRENT 3.9 KA

BUNCH DURATION,FWHM 200 FS

UNCORRELATED ENERGY SPREAD 0.008%

BEAM SHOT NOISE POWER 6.3 KW

Input radiation:

Pulse duration,FWHM 3.4 fs

Mean peak radiation power 2.5MW

Bandwidth,FWHM 1 .3 $\times 10^{-4}$

Power fluctuations,rms 44%

Output radiation:

Pulse duration,FWHM 3.4 fs

Mean peak power 23 GW

Bandwidth,FWHM 1 .3 $\times 10^{-4}$

Power fluctuations,rms 7%

Transverse rms size 31 μm

Transverse rms divergence 0.5μrad

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11

Visible to Infrared SASE Amplifier

BNL-LLNL-SLAC-UCLA

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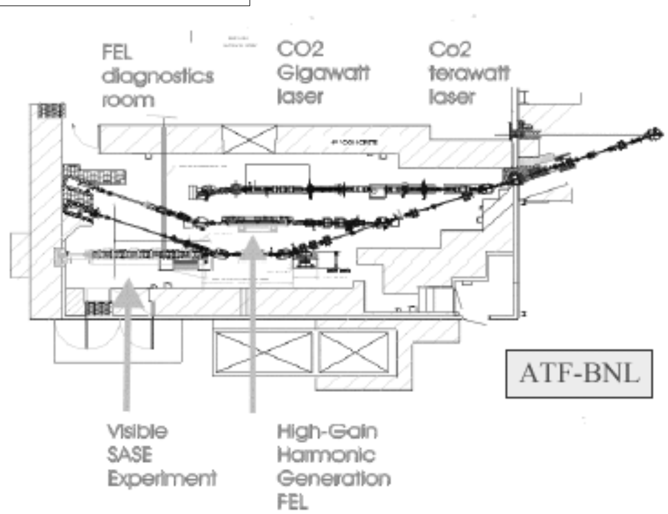

12

X-ray FEL Developments: short pulses and reduced line width

A High Gain FEL has a large gain bandwidth. When starting from noise, as in a SASE-FEL, the large gain bandwidth produces spikes in the intensity temporal profile.

Spike length at saturation, rms, is given by L_c , the cooperation length, $L_c=\lambda/4\pi\rho$, where ρ is the FEL parameter.

13

Conclusions

- The progress in the physics and technology of particle beams, and the exploitation of the FEL collective instability, has made possible to design and build a powerful X-ray FELs in the 1Å spectral region.
- The unique characteristics of the X-ray pulse will open new areas of research in physics, chemistry and biology.
- R&D work needs to be done in areas like X-ray optics, synchronization of the X-ray probe pulse with a pump pulse, short fs pulses, higher peak power to enhance the future potential of the system.

14

Focusing and high fields

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•The X-ray beam radius at the undulator exit is about 30mm, with a peak power of about 10 GW. The power density and peak electric field are 3×10^{14} W/cm^2, and 4 $\times10^{10}$ V/m.

•If one could focus to a radius of 10Å the power density and field would be 3×10^{23} W/cm2, and 1×10^{15} V/m. The last value is about 1/10 of the Schwinger critical field, opening interesting possibilities for the study of nonlinear QED or other phenomena.

•Focusing 10^{12} photons on a small spot size is also important for single molecule studies, to obtain structural information in a single shot.

Other Properties and Options

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Many types of undulators and wigglers can be used:

1. helical undulator: no harmonics on axis, circularly polarized

2. planar undulator: rich harmonics content, the third harmonic is amplified

3. short undulator or wigglers to produce only spontaneous radiation

Other Properties and Options

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1. The wavelength is tunable by changing the beam energy; 10-20% tunability from pulse to pulse; 1.5 to 0.05 nm total

2. The peak power can be controlled by changing the electron bunch charge

3. In normal SASE operation there is a time structure in the pulse with spikes about 1 fs long, and pulse to pulse intensity fluctuation of about 7%

17