Status and Development of SASE-FELs

C. Pellegrini

UCLA Department of Physics and Astronomy

Outline

1. Status of SASE-FELs theory and recent experimental results
2. New experiments in preparation
3. Status and development of the X-ray SASE-FEL (XFEL) → POWER, LINEWIDTH, PULSE LENGTH CONTROL

SASE-FEL Theory

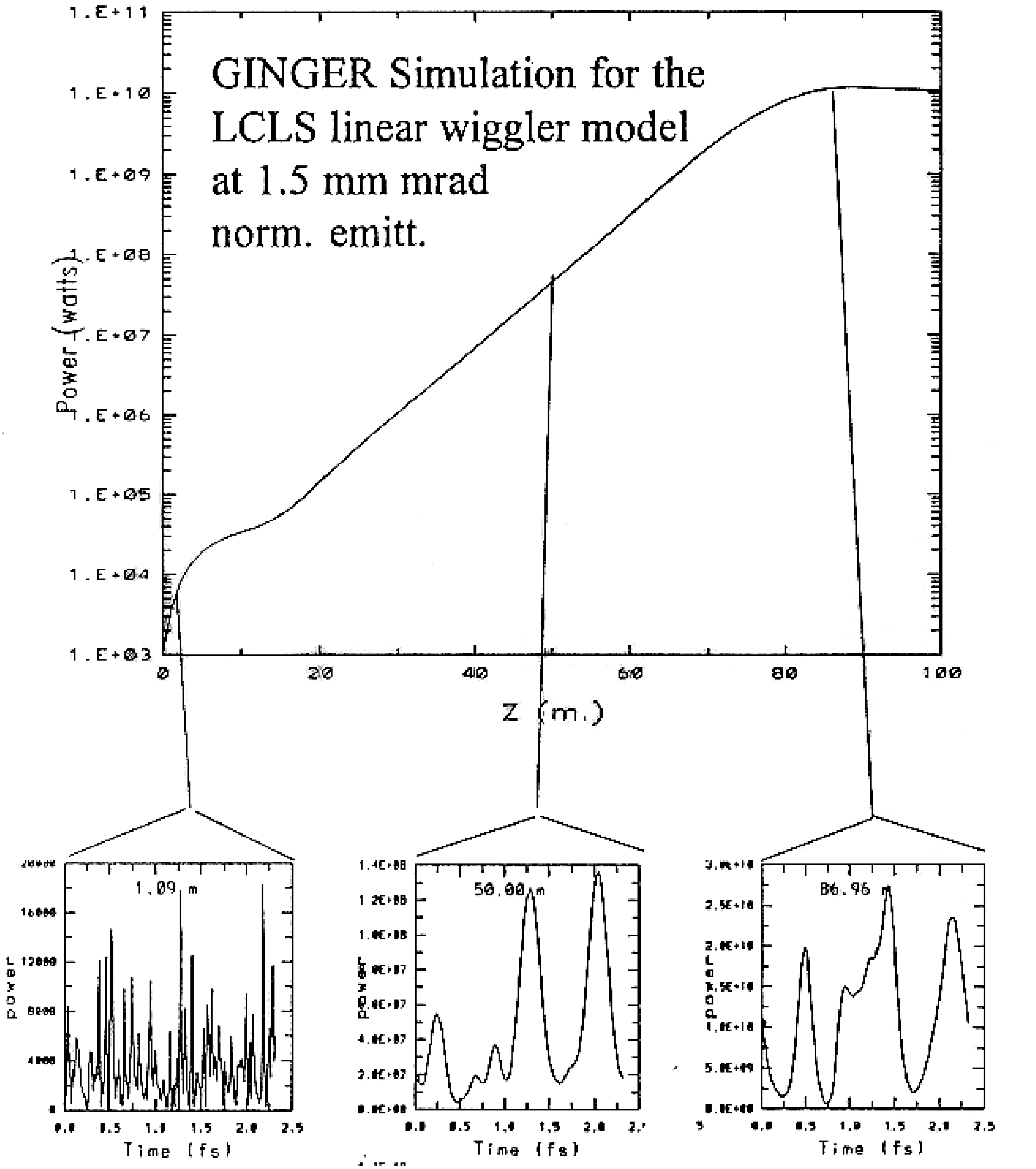
The theory of SASE-FELS has been developed starting in the 80s. Key theoretical results:

1. Gain length, and its dependence on beam emittance, current and energy spread, and including diffraction and slippage effects;
2. Radiation pulse time and spectral structure (spikes) and intensity fluctuations;
3. Saturation.

LCLS: Superradiant Spikes

Peak Current 3400 A
Wavelength 0.15 nm

Avg. Field Power vs. Z



Slices are 0.9 % of FWHM bunch length.

Heinz-Dieter Nuhn

SASE-FEL experimental status

Points 1 and 2 have been verified by experiments over a wavelength range 0.5 to 16 μm, a gain as large as 3×10^5, and with observation of intensity fluctuations.

Good agreement of theory and experiments.

Saturation has not yet been tested in experiments.

Results already obtained

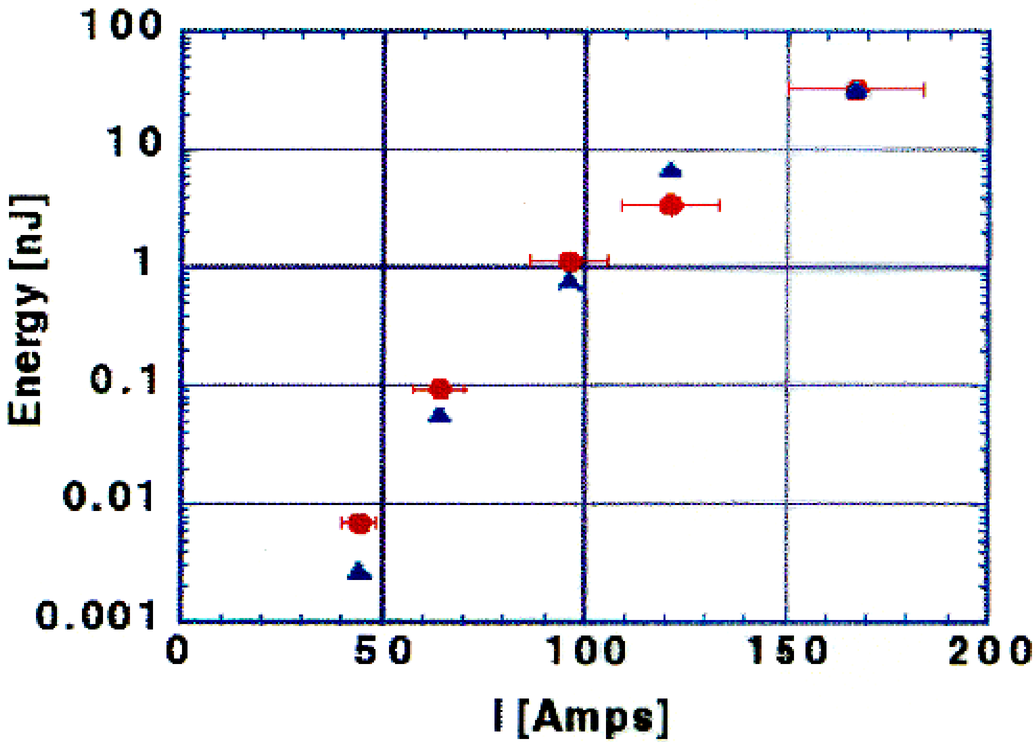
Observed SASE in the IR down to the visible in experiments at BNL, Orsay, Los Alamos, UCLA

Measured intensity gain larger than 100,000 in the UCLA-LANL experiment

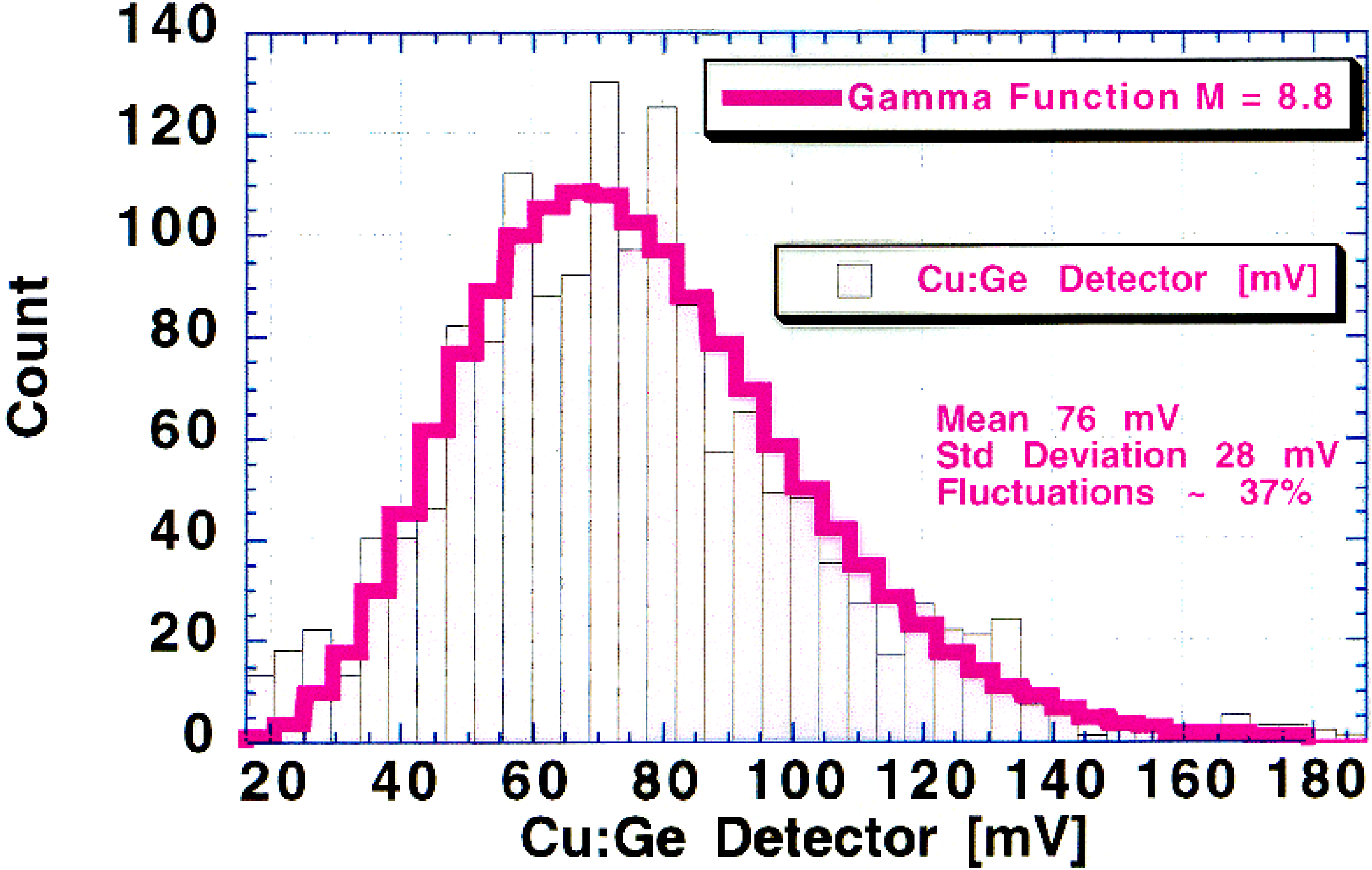
Observed SASE intensity fluctuations at BNL, UCLA, and UCLA-LANL. UCLA and UCLA-LANL experiments have demonstrated agreement with a Γ distribution function predicted by theory.

UCLA-LANL 12 μm SASE-FEL

Phys. Rev. Lett. 81, 4867 (1998)



Fluctuations Follow Gamma Distribution Function



New SASE experiments

A new round of experiments is now in advanced state of preparation. They are aimed at extending the wavelength range and study saturation and additional properties

1. VISA

A BNL-LANL-LLNL-SLAC-UCLA collaboration is preparing VISA, at a wavelength between 0.8 and 0.6 μm, using the ATF linac, with a beam energy of 70 to 90 MeV, and a four-meter long undulator. The undulator has strong focusing quadrupole system distributed along it, with a beta function of 30cm.

New SASE experiments

VISA is designed to reach saturation and study in details the pulse time and frequency structure, dependence of output intensity on electron parameters and undulator length, and the angular distribution of the radiation.

Another goal is to Benchmark SASE-FEL codes like Ginger, TDA3D, etc.

Saturation for VISA requires a normalized beam emittance of 2mm mrad and 200A peak current, using the 1.6 cell photonjector. These conditions are near to those required for a XFEL like LCLS.

Results from VISA are expected in 1999.

New SASE experiments

2. BNL-SDL

The BNL group is also using the ATF linac to study SASE and harmonic generation. The initial studies are again done in the infrared to visible region, and the plan is to extend them to the UV region using the 230 MeV SDL linac.

New SASE experiments

3. TESLA-FEL

A Desy group is preparing a series of experiments using the TESLA Test Facility superconducting linac . The Phase 1 experiment will be done at an energy of 390 MeV, with a 15 m undulator, at a wavelength of 42nm, and is expected to be ready in 1999.

In Phase 2, scheduled for 2002, the linac energy will be increased to 1000 MeV, reaching a wavelength of 6 nm, with a 30 m long undulator.

New SASE experiments

4. APS-LEUTL

A group at Argonne is preparing a UV SASE-FEL experiment using the APS injector linac with an upgraded photoinjector, a beam energy of about 600 MeV and a 25 m long undulator. The goals are again to study SASE-FELs and extend the wavelength region to the UV. The schedule for the beginning of the experiment is 1999.

UCLA

Physics and Astronomy

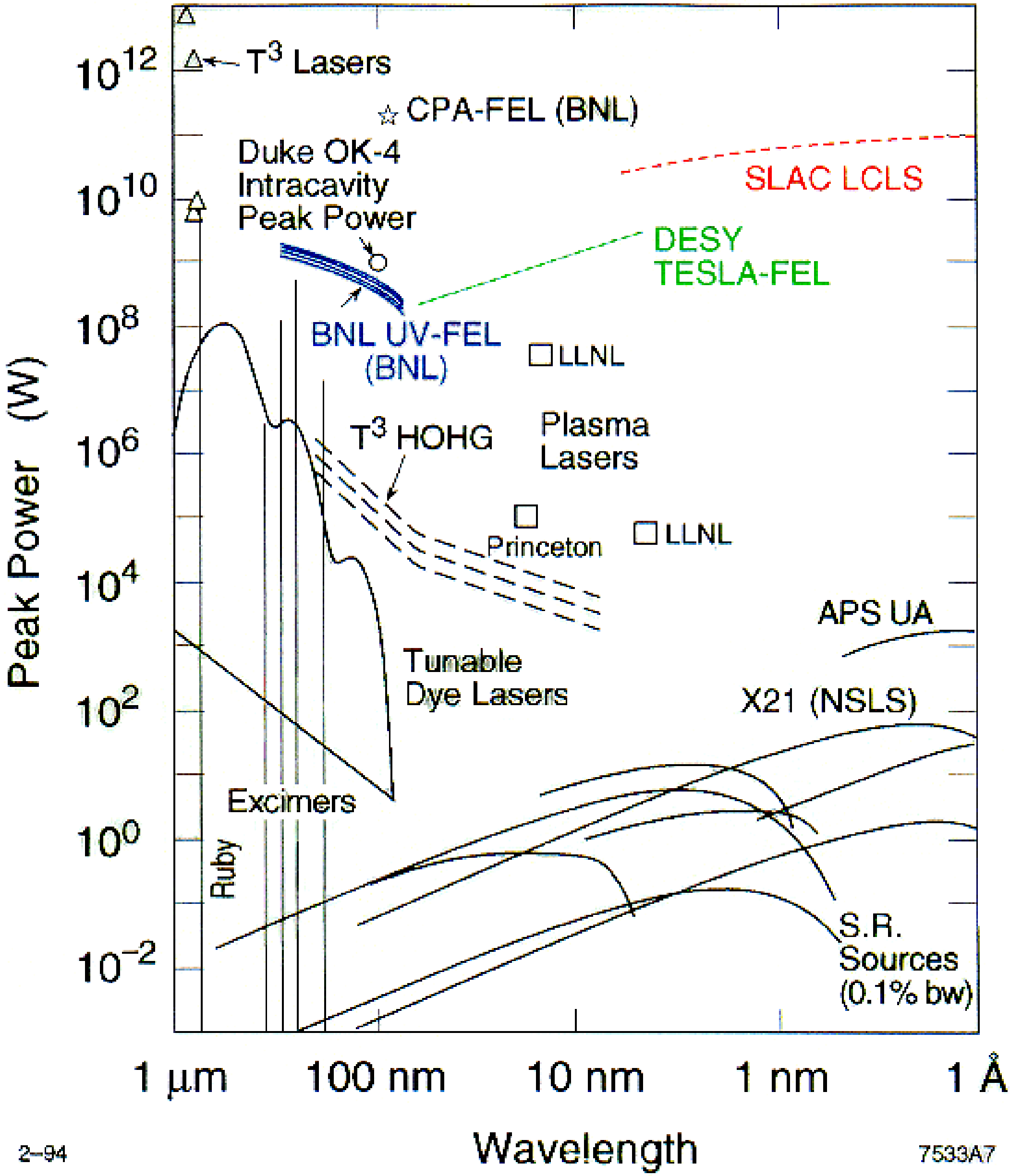
New SASE experiments

5. LCLS

The LCLS is the SLAC project to develop a 1Å XFEL based on the SLAC linac, in collaboration with APS/LLNL/LANL/UCLA.

The LCLS is described in the LCLS design study group REPORT (1998), and the system is feasible using available technology.

Based on present design the LCLS can be completed by 2005.



Peak Power (W)
10^{12}
10^{10}
10^8
10^6
10^4
10^2
10^0
10^{-2}
T^3 Lasers
CPA-FEL (BNL)
Duke OK-4 Intracavity Peak Power
SLAC LCLS
DESY TESLA-FEL
BNL UV-FEL (BNL)
LLNL
T^3 HOHG
Plasma Lasers
Princeton
LLNL
APS UA
Tunable Dye Lasers
X21 (NSLS)
Excimers
Ruby
S.R. Sources (0.1% bw)
1 µm
100 nm
10 nm
1 nm
1 Å
Wavelength
2–94
7533A7

LCLS

	Electron
Electron energy, GeV	14.3
Emittance, nm rad	0.05
Peak current, kA	3.4
Energy spread, %	0.02
Bunch length, fs	67
Undulator	
Period, cm	3
Field, T	1.32
K	3.7
Gap, mm	6
Total length, m	100
Radiation	
Wavelength, nm	0.15
FEL parameter, ρ	5×10^{-4}
Field gain length, m	11.7
Bunches/sec	120
Average brightness	4×10^{22}
Peak brightness	10^{33}
Peak power, GW	10^{9}
Intensity fluctuations, %	8

$\lambda = 1.5 - 0.5 Å$

$P_p = 10\,GW$

$\tau \sim 150\,fs$

$\frac{\Delta\omega}{\omega} \sim 5\times10^{-4}$

2.6 mJ/pulse

$\rightarrow 10^{12}$ ph/pulse

LCLS Parameters. Energy spread, pulse length, emittance are rms values. Brightness is in photons/s/(mm mrad)^2/0.1% bandwidth. The energy spread is the local energy spread in a cooperation length. A correlated energy chirp of 0.1% is also present along the bunch.

XFEL radiation pulse manipulation

The XFEL-LCLS can produce coherent X-rays with large power and brigthness, and subpicosecond pulses, as required for a 4th generation light source.

The already unique experimental opportunities offered by LCLS can be extended even more by:

0. USING PLANAR OR HELICAL UNDULATORS
1. Controlling the output power
2. Reducing the line width
2. Producing fs pulses
3. Reducing the fluctuation level

These characteristics can be obtained by manipulation of the radiation pulse, and/or the electron beam.

XFEL Power output control

C. Pellegrini, X. Ding and J. Rosenzweig, presented at PAC99

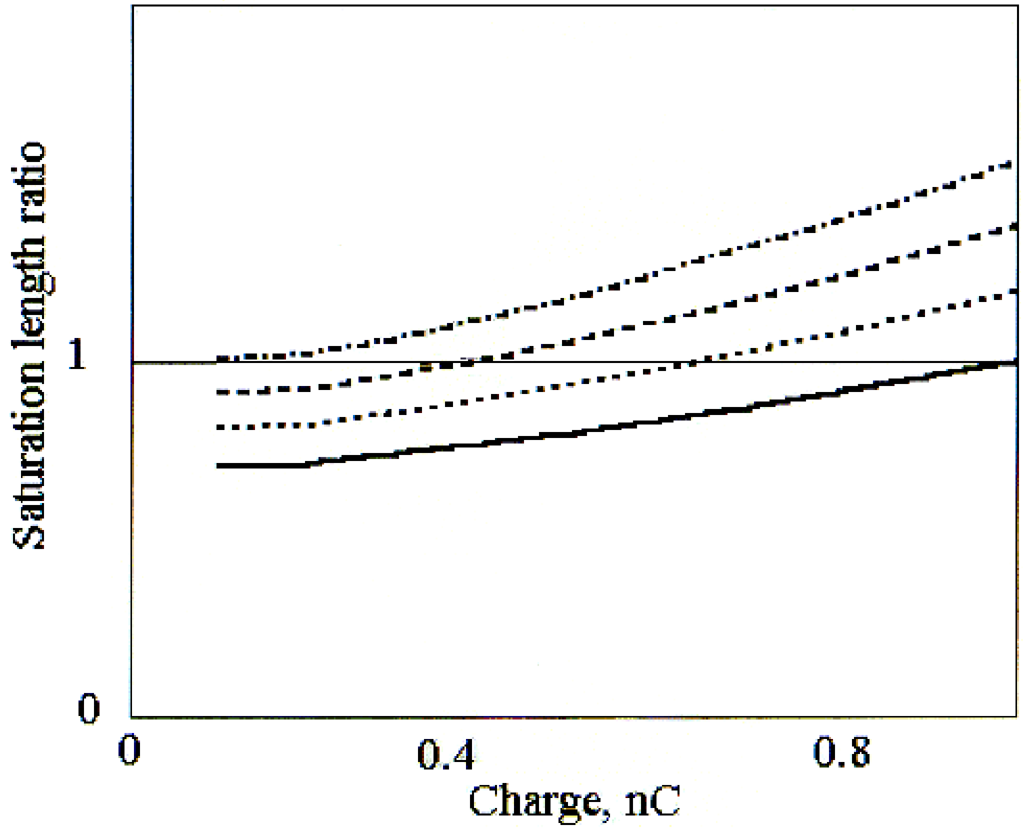
The photoinjector offers the possibility of producing electron bunches of variable charge, emittance and pulse length. Scaling laws (Rosenzweig and Colby, Proc. Conf. Advanced Accel. Concepts, AIP vol.335, p. 724 (1995); J. Rosenzweig et al., "Comparison of split and integrated photoinjector performance", presented at PAC99):

$$\varepsilon = 1.45 \times 10^{-6}(0.38Q^{4/3} + 0.095Q^{8/3})^{1/2},$$

$$\sigma_L = 0.63 \times 10^{-3} Q^{1/3}$$

XFEL Power output control

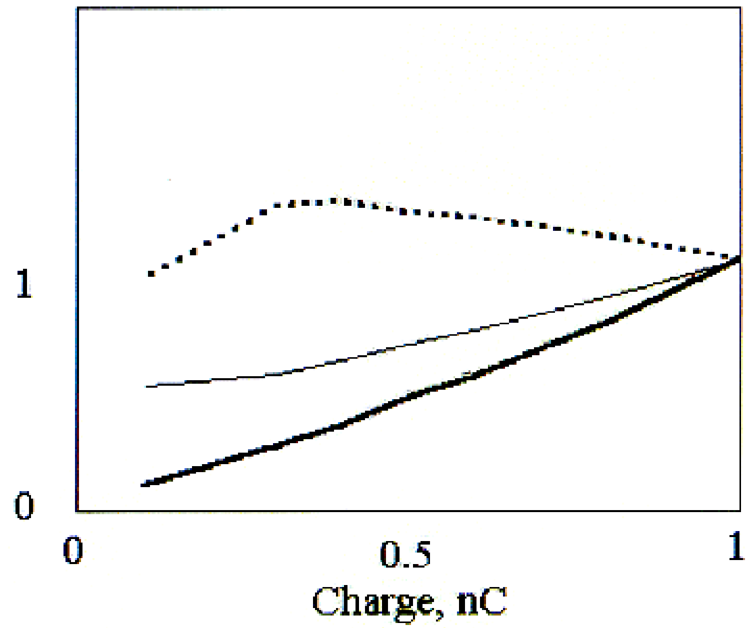
C. Pellegrini, X. Ding and J. Rosenzweig, presented at PAC99



— Cf=20, ···· Cf=15, ---- Cf=12, -·-·- Cf=10.

XFEL Power output control

C. Pellegrini, X. Ding and J. Rosenzweig, presented at PAC99



—— power, —— compression, --- bunch length ratio

XFEL development: time and spectral structure

The possibility of using harmonic generation has been studied by several authors, more recently at BNL. (SEE TALK BY LI-HUA YU)
Several ideas to reduce the line width for SASE schemes have been introduced by the DESY and LANL groups, using schemes to filter the radiation and/or using a regenerative amplifier.
Another example is the Two Bunch Scheme. (WINICK, PELLEGRINI)

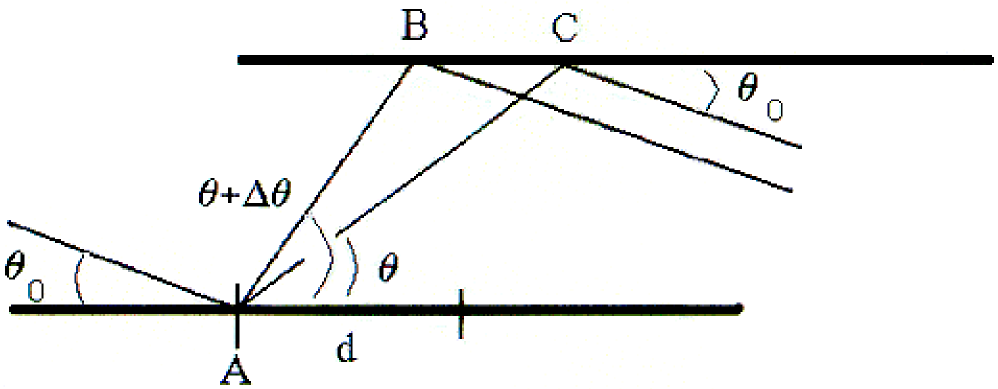
Pulse length compression

The SASE-FEL line-width is defined by the gain width, or equivalently the spike length. This property can be used to reduce the pulse length to that of a single spike, by chirping the frequency distribution and compressing in a diffraction grating pair (C. Pellegrini).

This will allow to obtain femtosecond long pulses, with very high peak power, and reduced fluctuation level.

Combining the pulse compression and the two bunch scheme one can produce radiation with smaller line width and reduced intensity fluctuations (C. Pellegrini).

Pulse length compression



LCLS

$\lambda = 1.4 \times 10^{-10}$ m

$L_c = 3.4 \times 10^{-7}$ m

$\frac{\Delta\lambda}{\lambda} = \frac{\lambda}{L_c} \sim 5 \times 10^{-4}$

$\tau_c \sim 1.1$ fs

$N_s = 150$

P_p (comp.) ~ 1-2 TW

$$2d[\cos(\theta_0)-\cos(\theta)]=n\lambda$$
$$C_f=AC-AB-BC\cos(\theta_0)$$
$$BC=AC\cos(\theta)-AB\cos(\theta+\Delta\theta)]$$

Particle Beam Physics Laboratory
UCLA

Other Properties and Options

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 5%

Physic & Performance of X-ray SASE-FEL

Other Properties and Options

Particle Beam Physics Laboratory
UCLA

4. With double pulses, filtering and regenerative systems we can control the line width, and the spiking

5. We can produce chirping and use it to reduce the pulse length or other pulse manipulation

Other Properties and Options

5. Many types of undulators and wigglers can be used:

5.1 helical undulator: no harmonics on axis, circularly polarized

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

5.3 short undulator or wigglers to produce only spontaneous radiation

Conclusions

1. Combining electron bunch manipulation techniques and laser pulse manipulation techniques we can extend the capability of the XFEL to the femtosecond and the terawatt region, or we can reduce of the line-width.

2. The LCLS will provide the opportunity to develop these new capabilities and test them in a real experimental situation.

3. All these ideas depend on the existence of the FEL gain at 1Å, as predicted by the theory and confirmed at long wavelength; measuring the gain at 1Å is the first step in any development plan for the XFEL.