Development of high gain X-ray FELs

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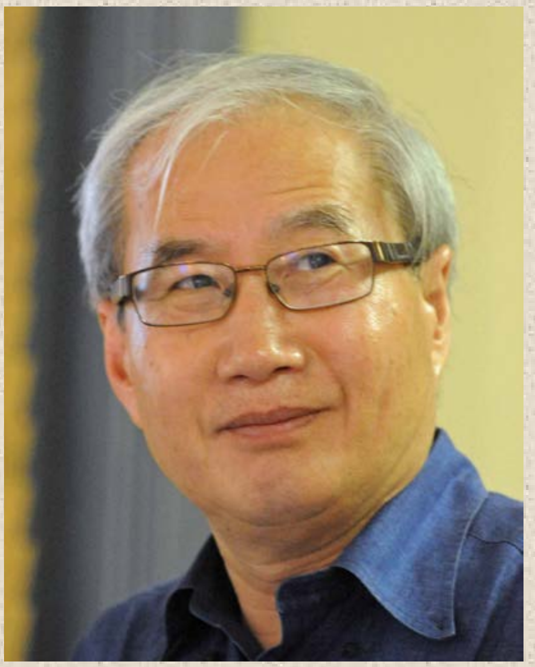


Kwang-Je Kim Symposium on "Coherence in particle and photon beams: past, present and future," March 15, 2018.

SLAC NATIONAL ACCELERATOR LABORATORY

Outline

- The development of X-ray free-electron lasers (FELs)
- The physics and present status of X-ray FELs
- Some experimental results at LCLS and future developments

Why X-ray lasers?

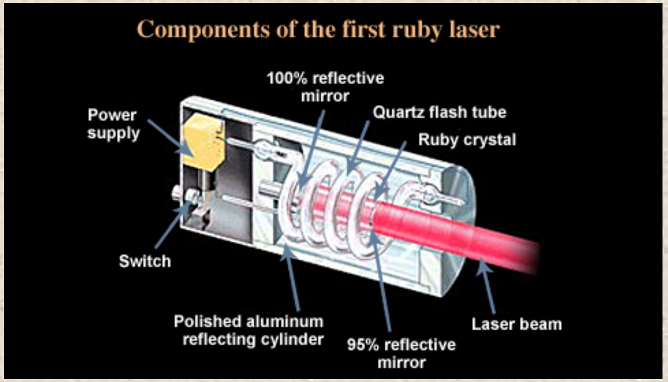
Coherent, high intensity, X-ray photons at Ångstrom wavelength and femtosecond pulse duration -the characteristics time and space scale for atomic and molecular phenomena- allow imaging of periodic and non periodic systems, non crystalline states, studies of dynamical processes and systems far from equilibrium, nonlinear science, opening a new window on atomic and molecular phenomena of interest to biology, chemistry, material sciences and physics.

The hydrogen Bohr radius is about 0.5 Å. The Bohr period of a valence electron is approximately 1 femtosecond. Atomic electric field $5x10^{11}$ V/m.

Niels Bohr, 1885-1962

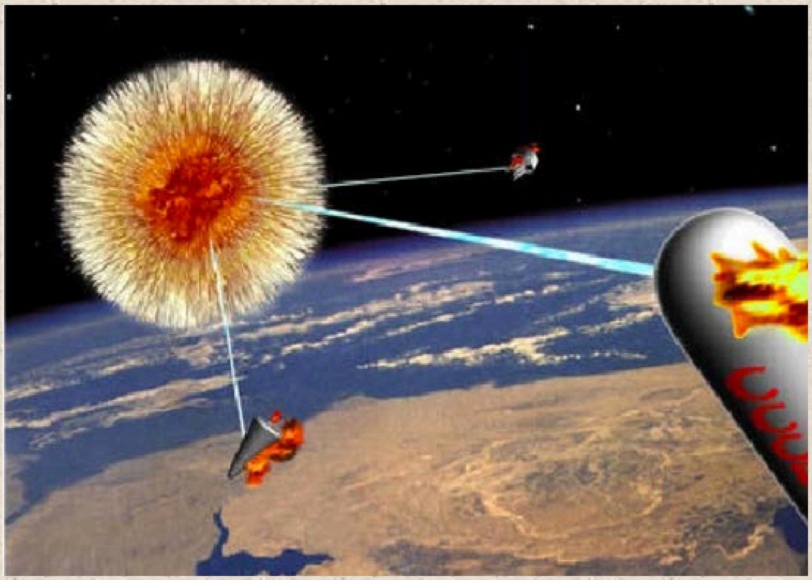
Early work on X-ray lasers

Almost from the time the first ruby laser was built in 1960, developing an X-Ray laser, generating coherent, high power, X-ray beams, has been a major goal in laser physics. In the atom-based, population inversion laser approach this task is extremely difficult, because of the very short lifetime of excited atom-core quantum energy levels. George Chapline and Lowell Wood of Lawrence Livermore National Laboratory estimated the radiative lifetime of an X-ray laser transition would be about 1 fs times the square of the wavelength in angstroms.
*Chapline G. and L. Wood,1975, Physics Today **40**, 8.*
The short lifetime and large energy needed to excite inner atomic levels, 1 to 10 KeV compared to about 1 eV for visible lasers, require very large pumping power to attain population inversion, too large for practical purposes.
Building low loss optical cavities for X-ray laser oscillators is also difficult.



The first Ruby laser, 1960, and its builder Ted Maiman.

Early work on X-ray lasers



But not to be discouraged: scientists at LLNL, driven by Edwards Teller, proposed to use a nuclear weapon to drive an X-ray laser. They tried the concept in the Dauphin experiment, apparently with success, in 1980.
Hecht J., 2008, The History of the X-ray Laser, Optics and Photonics News, 19 (2008)
During the Cold War X-ray lasers based in space, the Excalibur Project, were considered to destroy incoming enemy missiles.

From Joseph Nilsen, "Legacy of the X-ray Laser Program," Lawrence Livermore National Laboratory Report, also Energy and Tech. Rev. Nov. 1994

Atom bomb driven X-ray lasers, even if they work, are not a very practical research instrument.

Early work on X-ray lasers

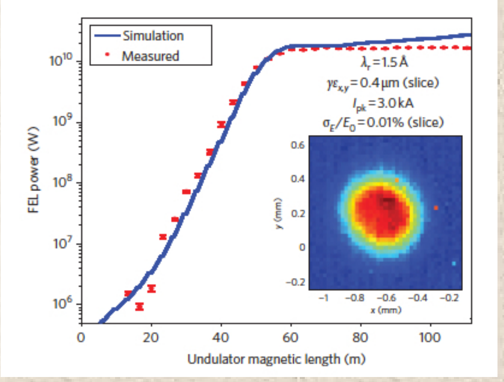
The development of high peak power, short pulse, visible light lasers made possible another approach: pumping cylindrical plasmas, in some cases also confining the plasma with magnetic fields. These experiments led to X-ray lasing around 18 nm with gain of about 100 in1985 (Matthews *et al*., 1985; Suckewer *et al*., 1985). More work has been done from that time and lasing has been demonstrated at several wavelengths in the soft X-ray region, however with limited peak power and tunability. A review of the most recent work and developments with this approach is given in (Suckewer and Jaeglé, 2009)

Matthews D.L. et al., 1985, Physics Review Letters ***54****, 110.*
Suckewer S. et al., 1985, Physics Review Letters ***55****, 1753.*
Suckewer S. and P. Jaeglé, 2009, Laser Physics Letters ***1****, 411 (2009).*

An alternative solution, paradigm change

Self amplified spontaneous emission free-electron lasers (SASE FELs), generating X-rays from high brightness relativistic electron beams, provide the way out of this difficult situation. A 1992 paper (*C. Pellegrini, 1992 Proc. of the Workshop on 4th generation light sources, SSRL/SLAC Rep. 92/02*) proposing to build an X-ray FEL using a 15GeV high brightness beam from the SLAC linac, lead to the design and construction of LCLS. In 2009 LCLS successfully lased at 1.5 Å (*P. Emma et al., 2010 Nat. Phot.* ***4****, 641*) with characteristics similar or better than originally proposed.

A detailed history of this development is found in C. *Pellegrini, X-ray free-electron lasers: from dreams to reality, Physica Scripta* ***T169****, 014004 (2016).*

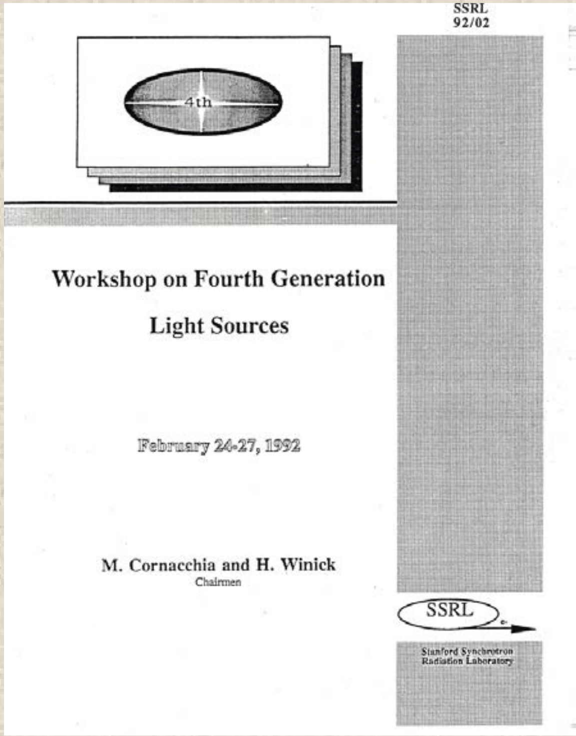


LCLS saturates: 1.5 Å, 4/2009, 1-3 mJ.

The proposal was based on: 1. High gain FEL theory; 2. A new high brightness electron source, the RF photoinjector. Next, we will discuss both points.

A 4 to 0.1 nm FEL Based on the SLAC Linac*.

C.Pellegrini
UCLA Physics Department, 405 Hllgard Avenue, Los Angeles CA 90024
March 2, 1992


SSRL 92/02

4th

Workshop on Fourth Generation Light Sources

February 24-27, 1992

M. Cornacchia and H. Winick
Chairmen

SSRL

Stanford Synchrotron Radiation Laboratory

1.Introduction

The progress in RF linacs and electron sources due to the recent work on linear colliders and FELs, makes now possible to combine these technologies to design and build a FEL in the soft X-ray region, capable of producing power in the GWatt range with subpicosecond pulses. Such a system, with a wavelength extending from 4nm down to 0.1 nm, thus covering the water window and the crystal structure region, offers unique and exciting new capabilities in areas as x-ray microscopy of biological samples, and holography of crystals.

Date: Tue, 03 Mar 1992 12:32:32 -0700 (PDT)
From: WINICK%SSRL01@SSRL.SLAC.STANFORD.EDU
Subject: 1-40A FELs using the SLAC Linac
To: A@SSRL.SLAC.STANFORD.EDU,
HODGSON@SSRL.SLAC.STANFORD.EDU

Art; Together with John Seeman of SLAC and Claudio Pellegrini at UCLA, we are working on the basic design parameters and layouts of 1-40A FELs that would use parts or all of the SLAC linac equipped with a low emittance gun such as is being developed at several places. I hope to have something to show you about this soon, possibly by the end of this week. Pellegrini has agreed to come to Stanford on March 18 for a follow up meeting. I briefed Keith on this today and also told him about Burt's request that we convene a meeting with Paul Berg to discuss biological applications of such a source. Is it possible to arrange for a first meeting at the end of this week? I am gone most of next week. Herman

SLAC NATIONAL ACCELERATOR LABORATORY

Date: Thu, 16 Apr 1992 18:38:03 -0700 (PDT)
From: WINICK%SSRL01@SSRL.SLAC.STANFORD.EDU
Subject: Notes on 4/16/92 FEL meeting; send comments/corrections to H. Winick

Attendees: Karl Bane, Max Cornacchia, Klaus Halbach, Kwang-je Kim, Phil Morton, Heinz-Dieter Nuhn, Claudio Pellegrini, Don Prosnitz, Tor Raubenheimer, David Robin, Ted Scharlemann, John Seeman, Roman Tatchyn, Herman Winick, Dandan Wu

This was a follow up meeting to the meeting of March 18. The next meeting will be at noon on Tuesday, May 19. Lunch will be provided.

The following was discussed at this meeting:

1. Several examples of 40 A and 1 A FELs were presented by Kim, Pellegrini, and Tatchyn. Each of these was requested to send a write-up on their work, particularly on the 40 A case, to Winick for distribution to others.
2. Seeman showed layouts and photographs of the possible locations for the FEL and experimental area.
3. Morton gave information about measurements taken at Los Alamos with their photocathode gun.
4. Raubenheimer reviewed the work done by him & Bane on pulse compression, wake fields & emittance degradation.
5. It was agreed that we would prepare a paper on this project for the International FEL meeting in Japan, Aug. 24-28.

ABSTRACT FOR THE INTERNATIONAL FEL CONFERENCE IN JAPAN IN AUGUST, 1992

A 4 nm High Power FEL on the SLAC Linac*

C. Pellegrini, J. Rosenzweig, UCLA

A. Bienenstock, K. Hodgson, H.-D. Nuhn, P. Pianetta, R. Tatchyn, H. Winick, SSRL

K. Bane, P. Morton, T. Raubenheimer, J. Seeman, SLAC

K. Halbach, K.-J. Kim, LBL

J. Kirz, SUNY Stony Brook

We discuss the characteristics and performance of a 4 nm SASE FEL, using a photoinjector to produce the electron beam, and the SLAC linac to accelerate it to an energy up to 10 GeV. One longitudinal bunch compression at an intermediate energy will increase ten fold the peak current to a value of 2 kA, while reducing the bunch length to the sub-picosecond range. The saturated output power of the FEL is in the multi-gigawatt range, producing about 10^{14} coherent photons with a bandwidth of about 0.5% (1 standard deviation) in a radiation pulse of several millijoules. At a 120 Hz repetition rate the average power is about 1 W. The system performance is optimized for x-ray microscopy in the water window around 4 nm, and will permit imaging a biological sample in a single sub-picosecond pulse. Details of biological applications and the planned experimental layout will be presented.

* Support provided by DOE Offices of Basic Energy Sciences and High Energy and Nuclear Physics

High gain FEL theory

In Madey's quantum theory the FEL gain does not depend on Planck's constant. A classical small signal gain theory, giving the same gain value, was developed by Colson.

Colson, W.B. 1977. One-body electrodynamics in a free electron laser. Phys. Lett. A 64, 190.

The small signal gain theory, and the lack of good optical cavities, precludes the possibility of pushing FELs to X-ray wavelengths.

The possibility of a high gain regime, an important step, was studied and developed in the 70s and 80s:
Kroll and Mc Mullin, 1978; Sprangle and Smith, 1980; Kondratenko and Saldin, 1980; Gover and Sprangle, 1981; Dattoli et a., 1981; Bonifacio, Casagrande and Casati, 1982; Bonifacio, Pellegrini and Narducci, 1984; Gea-Banacloche, Moore and Scully, 1984; Sprangle, Tang and Roberson, 1985; Jerby and Gover, 1985; Kim 1986; Wang and Yu, 1986; Bonifacio, Casagrande and Pellegrini, 1987.

FEL Collective Instability: main characteristics

Universal FEL parameter $\rho = \left(K\Omega_p / 4\gamma\omega_U\right)^{2/3}$

Gain Length $L_G = \lambda_U / 4\pi\rho,$

Saturation power $P_{sat} \simeq \rho P_{beam}$

Saturation length $L_{sat} \simeq 10 L_G$

Line width $\Delta\omega / \omega \simeq \rho$

Number of coherent photons/electron $N_{ph} \simeq \rho E_{beam} / E_{ph}$

Scaling: ρ scales as $\sqrt{\lambda}$, good result.

For the results to be valid we must have

$\sigma_{e,r}\sigma_{e,r} \leq \lambda_r / 4\pi,$ — phase space matching

$\sigma_{e,E} < \rho,$ — line width matching

$L_G < Z_R$ — Gain>diffraction losses

→ Very important conditions on electron beam phase space density

FEL physics as a collective instability. A self organization effect starting from noise.

COLLECTIVE INSTABILITIES AND HIGH-GAIN REGIME IN A FREE ELECTRON LASER, BONIFACIO, R., PELLEGRINI, C. and L.M. NARDUCCI, 1984, Optics Communication ***50,*** *373.*

The **instability can start from noise** and leads from an initial state with a random initial distribution of the electron longitudinal position to a state with a beam consisting of micro-bunches about 1/10 of the wavelength long and separated by a wavelength, a sort of 1-dimensional relativistic crystal.

The theory is formulated with universal variables and only one parameter, the FEL parameter ρ, describes the physics of the system. In this form the theory does not depend explicitly on the radiation wavelength. A test of the theory in the visible is good also at X-ray wavelengths.

Using this theory we can consider single pass (no optical cavity) FELs starting from noise, a SASE FEL, operating in the X-ray region.

Notice that this theory is one dimensional. Diffraction and betatron oscillation effects can only be included in a heuristic way.

VOLUME 57, NUMBER 15 PHYSICAL REVIEW LETTERS 13 OCTOBER 1986

Three-Dimensional Analysis of Coherent Amplification and Self-Amplified Spontaneous Emission in Free-Electron Lasers

Kwang-Je Kim
Center for X-Ray Optics, Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720

The growth and saturation of spontaneous emission and coherent radiation in a long undulator are studied by use of the 3D Maxwell-Klimontovich equation. Electron correlation, transverse radiation profiles, spectral features, transverse coherence, and intensity characteristics are discussed. The results, which agree with recent microwave experiments, are applied to proposed schemes for generation of short-wavelength coherent radiation.

PHYSICAL REVIEW A VOLUME 46, NUMBER 10 15 NOVEMBER 1992

Three-dimensional theory of the small-signal high-gain free-electron laser including betatron oscillations

Yong Ho Chin, Kwang-Je Kim, and Ming Xie

Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720

(Received 19 May 1992)

We have developed a three-dimensional free-electron laser (FEL) theory in the small-signal high-gain regime based upon the Maxwell-Vlasov equations including the effects of the energy spread, the emittance, and the betatron oscillations of the electron beam. The radiation field is expressed in terms of the Green's function of the inhomogeneous wave equation and the distribution function of the electron beam. The distribution function is expanded in terms of a set of orthogonal functions determined by the unperturbed electron distributions. The coupled Maxwell-Vlasov equations are then reduced to a matrix equation, from which a dispersion relation for the eigenvalues is derived. The growth rate for the fundamental mode can be obtained for any initial beam distribution including the hollow-beam, the water-bag, and the Gaussian distribution. Comparisons of our numerical solutions with simulation results and with other analytical approaches show good agreements except for the one-dimensional limit. We present a handy interpolating formula for the FEL gain of a Gaussian beam, as a function of the scaled parameters, that can be used for a quick estimate of the gain. The present theory can be applied to the beam-conditioning case by a few modifications.

Short Wavelength Coherent Radiation: Generation and Applications

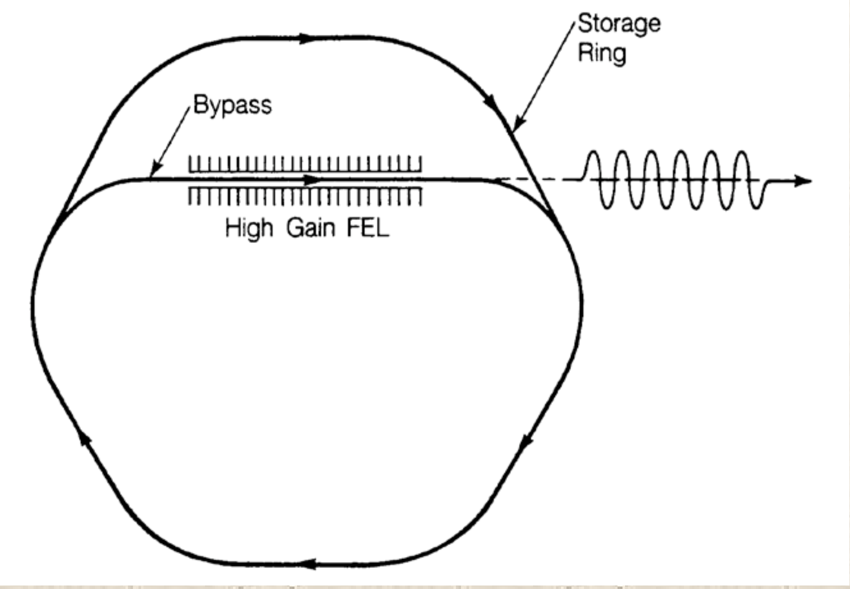
Conference date: 24-26 March 1986
Location: Monterery, CA, USA
ISBN: 0-88318-346-3
Editors: D. T. Attwood and J. Bokor
Volume number: 147
Published: Sep 10, 1986

HIGH-GAIN FREE ELECTRON LASERS AS GENERATORS OF SHORT WAVELENGTH COHERENT RADIATION*

Kwang-Je Kim
Lawrence Berkeley Laboratory
University of California,
Berkeley, California 94720

Claudio Pellegrini
Brookhaven National Laboratory
Upton, New York 11973

The development of coherent radiation in high-gain free electron lasers, either from initial noise or from low-power input radiation, is analyzed in terms of three-dimensional Maxwell-Klimontovich equations. Exponential growth and saturation, transverse radiation profiles, transverse coherence and spectral features are discussed. Two possible systems of high-gain free electron lasers, one based on a storage ring and by-pass, another based on a linac and damping ring, are considered for the generation of 400 ~ radiation.

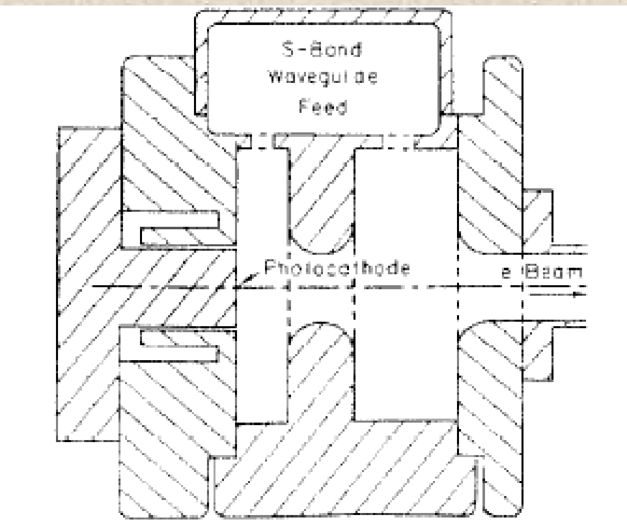


Linacs are more compact than storage rings. However, the emittances and energy spread of electron beams in linacs tend to be larger than those in storage rings. The drawback is removed if the electron beams from a linac are routed to a damping ring, which is basically a compact storage ring whose sole function is to decrease the beam emittances and the energy spread by radiation damping. A system consisting of a linac, a damping ring, and a long undulator offers another approach to a high-gain FEL.

Photo-injector development: satisfying the emittance criterion.

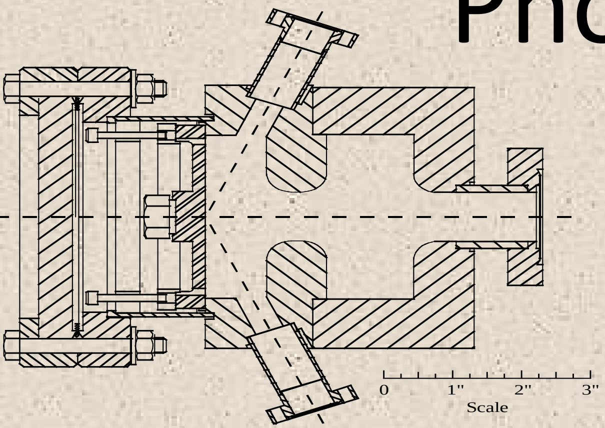
The Los Alamos photo-injector was developed in L-band for high average power FELs as part of the Star Wars program, and promised a much higher electron beam brightness. .An S-band version of the Los Alamos gun, optimized for high peak power, small emittance, and application in laser acceleration and FELs, was designed at Brookhaven at the Center for Accelerator 1986-87. Some updated version of this gun is now used in almost all X-ray FELS.

Batchelor, K., H. Kirk, K. McDonald, J. Sheehan and M. Woodle. 1988. Development of a High Brightness Electron Gun for the Accelerator Test Facility at Brookhaven National Laboratory. Proc. of the 1988 European Particle Accelerator Conf., Rome, pp. 54–958.



The gun development continued with a UCLA, SLAC (gun test facility) and Brookhaven collaboration leading to the LCLS gun.

Photocathode RF gun



RF AND SPACE-CHARGE EFFECTS IN LASER-DRIVEN RF ELECTRON GUNS

Kwang-Je KIM

Accelerator and Fusion Research Division, Lawrence Berkeley Laboratory, University of California, Berkeley, CA 94720, USA

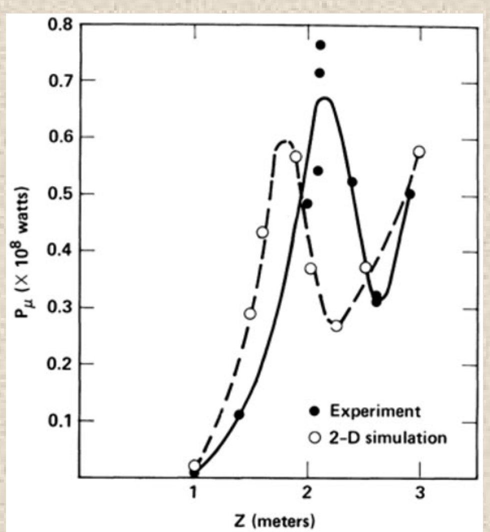
Received 9 September 1988

Nuclear Instr. and Meth. A275, 201 (1989).

The evolution of the electron-beam phase space distribution in laser-driven rf guns is studied by taking into account both the time variation of the rf field and space-charge effects. In particular, simple formulas are derived for the transverse and longitudinal emittances at the exit of the gun. The results are compared and found to agree well with those from simulation.

First experiments: LLNL high gain experiment

A high gain FEL was built and operated at Livermore in 1984-86 by a joint LLNL-LBL group at about one cm wavelength using a 5 MeV, 10 kA induction linac and an electromagnetic planar undulator. The electron beam dynamics is dominated by space charge effects. The FEL is also operating in a regime where space charge forces are important, in addition to the interaction of the electrons through the electromagnetic waves they emit.

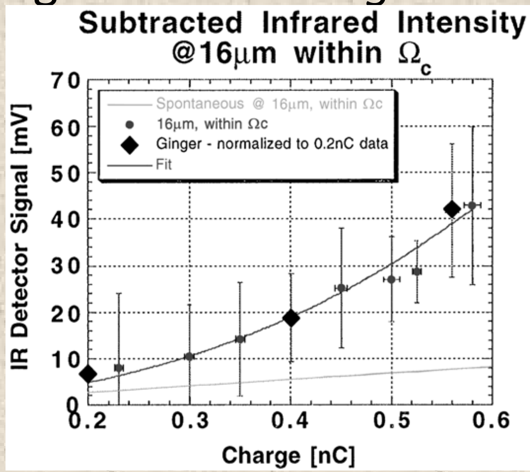


Amplified signal output as a function of length along the undulator. The FEL operates at a frequency of 34.6 GHz, and the input signal, provided by a magnetron, is about 50 kW. From reference [Orzechowski, et al., 1985].

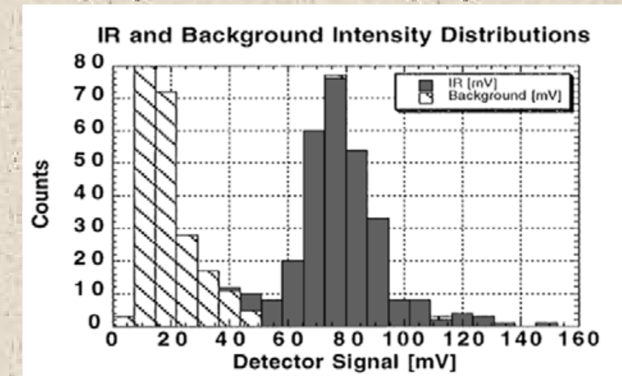
Orzechowski, T. et al.,1985, Physics Review Letters ***54****, 889*

SASE theory verification : UCLA 16 μm FEL, 1997-98

UCLA-Kurchatov group, using the UCLA 20 MeV linac, a photoinjector and a 60 cm long undulator. *Hogan M. J. et al., 1998, Physics Review Letters* ***80****, 289.*



Coherent IR intensity vs charge. Vertical bars: standard deviation of intensity fluctuations. Beam charge and radius uncertainties 9%. Straight line: calculated spontaneous emission intensity. Curved line: data fit $I=1.85Q\exp(4.4Q^{1/3})$, and Ginger simulations.

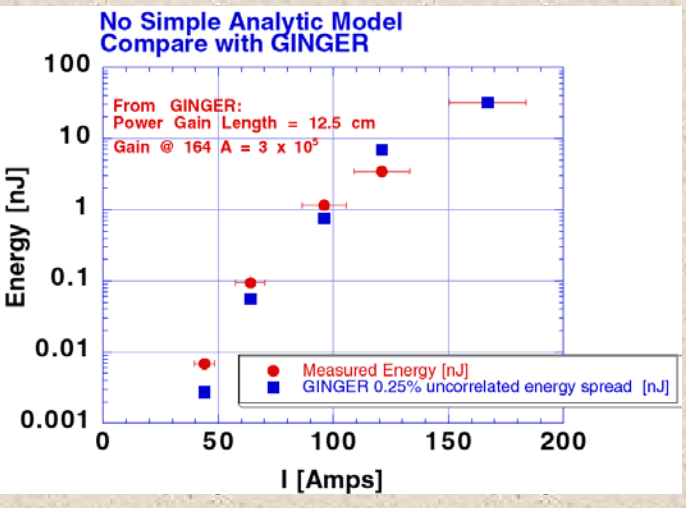


Intensity distribution of the IR and background signals for a mean charge Q =0.56 nC, standard deviation of 0.007 nC, IR mean = 78 mV, standard deviation = 14.3 mV; background mean = 18.7 mV, standard deviation = 9.1 mV

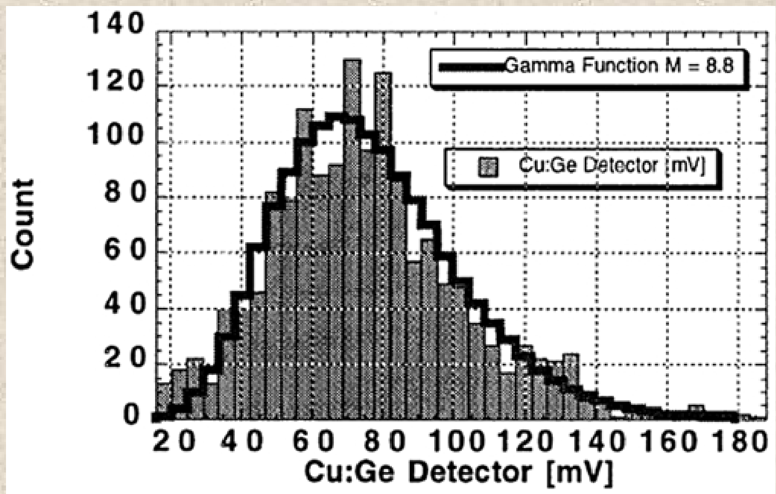
60 cm long undulator used in the experiment. C. Pellegrini, The history of X-ray free-electron lasers, EPJ H, **37**, 659 (2012)

Experimental verification of SASE theory: UCLA 12 μm FEL, 1998.

12 μm FEL, UCLA/Kurchatov/LANL/SSRL group. Gain larger than 3×10^5. *M. Hogan et al. Phys. Rev. Lett.* *81, 4897 (1998).*



Photon pulse intensity as a function of peak current.

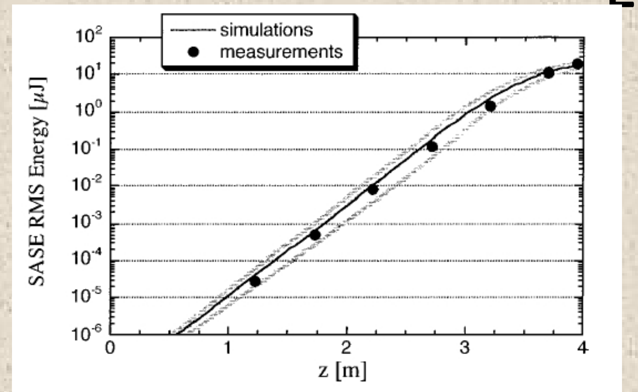


Intensity fluctuations for individual 2 nC micropulses compared with theory.

This result came just in time to be presented to the Leone Panel, that gave the first support for funding LCLS.

Other experiments at shorter wavelengths:

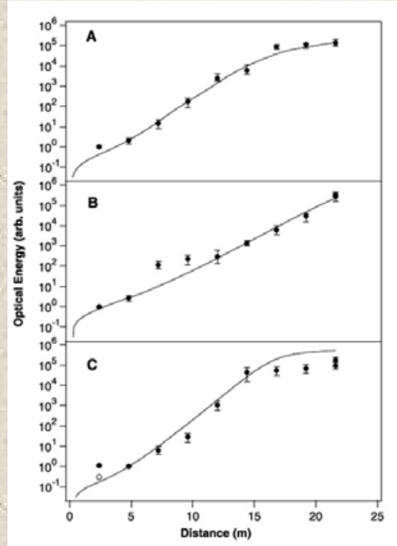
LEUTL, VUV FEL, VISA



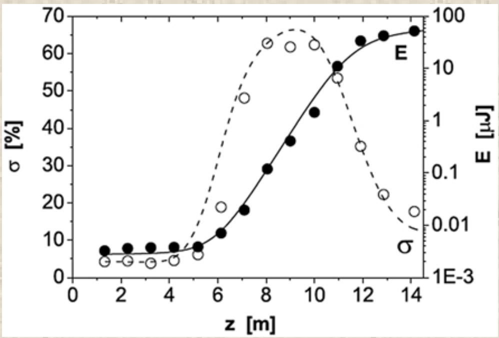
Measured SASE intensity vs undulator length and numerical simulations (gray lines are the rms boundaries of the set of GENESIS runs). The amplification curve yields a power gain length of 17.9 cm and saturates near the undulator exit.

λ=

Reference Murokh et al., 2003.

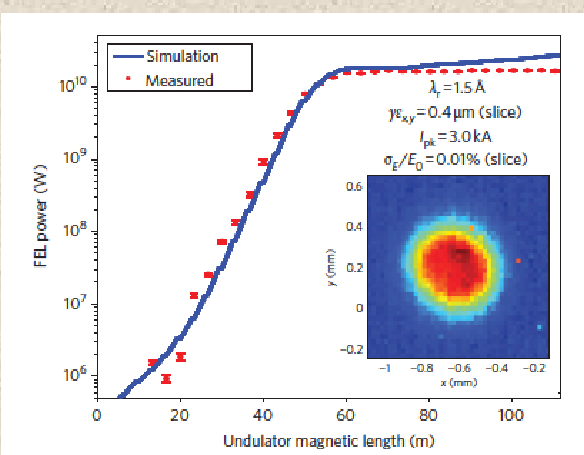


Intensity vs undulator length for various electron beam conditions. (A) 530-nm saturated conditions. (B) 530-nm unsaturated conditions. (C) 385-nm saturated conditions. Solid curves: GINGER simulation results. Reference Milton et al., 2001.



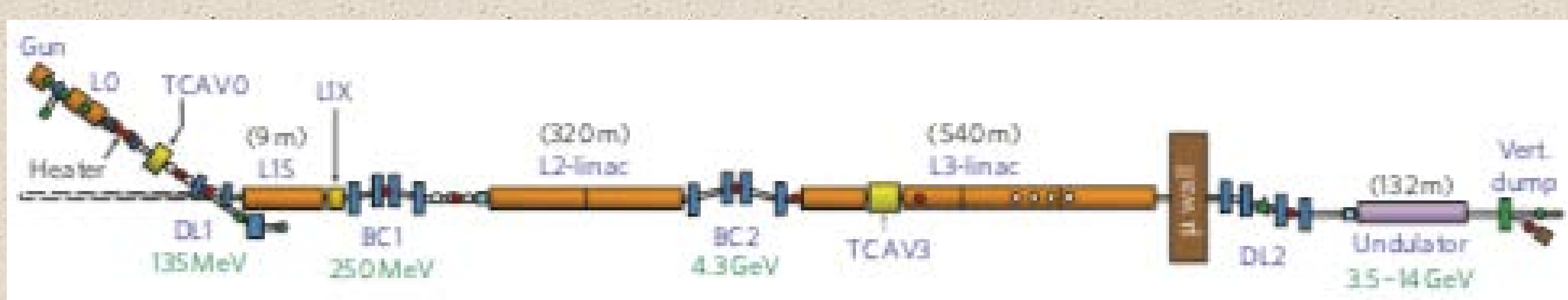
Average radiation pulse energy (solid circles) and rms energy fluctuations in the radiation pulse (empty circles) as a function of undulator length. Wavelength 98 nm. Circles: experimental results. Curves: numerical simulations. Reference Ayvazyan et al. 2002.

LCLS, 2009, 1.5Å



Beam energy, 13.6 GEV
Peak current, 3 kA
Peal X-ray power, 40 GW
Pulse length, 70-100 fs
Undulator period,3 cm
Gain Length, 4.4 m

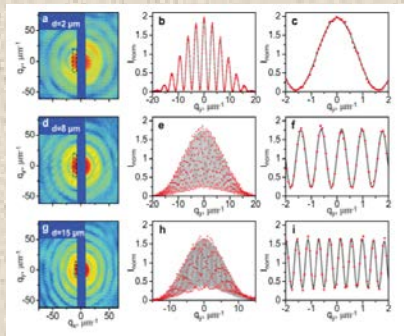
P. Emma et al., 2010 Nat. Phot. ***4****, 641*



Schematic of accelerator system and undulator.

Coherence properties of X-ray FEL

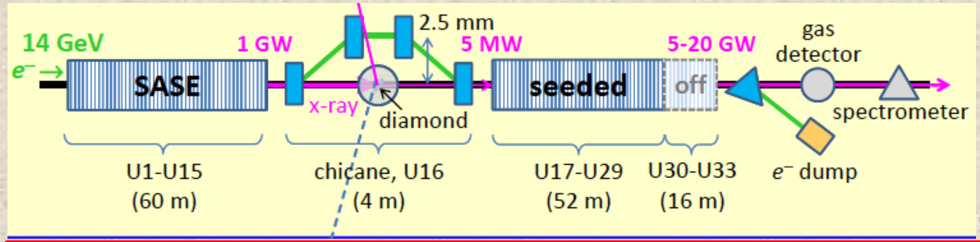
Transverse coherence: good.

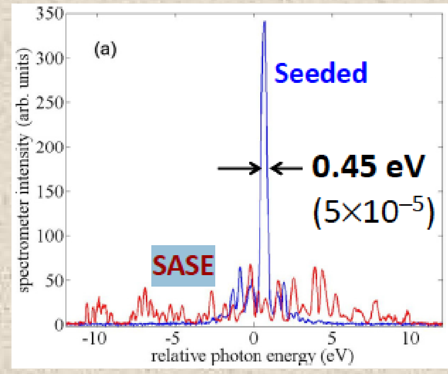


Coherence properties of individual femtosecond pulses of an X-ray FEL, I. A. Vartanyants et al., 2011, Phys. Rev. Lett. 107, 144801.

Improving LCLS temporal coherence: Self-seeded spectra

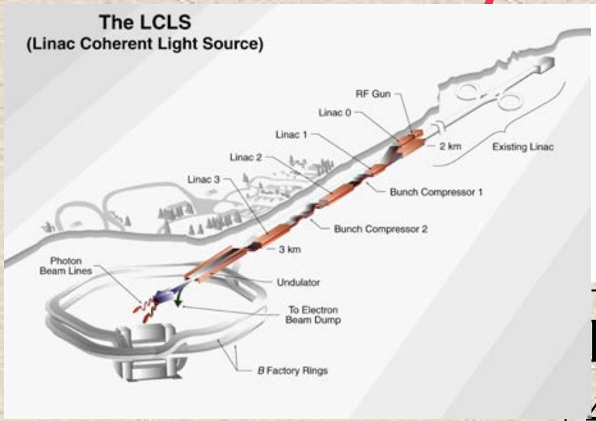
In a SASE FEL the spectrum is wide and fluctuates. Bonifacio, Pellegrini et al., Phys. Rev. Lett. 1994, **73**,70. Self-seeding is a way to improve the spectrum and reduce the line-width using the transmission around the stop band of a Bragg reflection in a diamond crystal, Geloni, G., V. Kocharyan and E. Saldin, 2011, J. of Mod. Opt. **58,** 16.

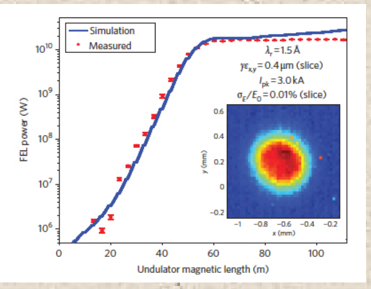




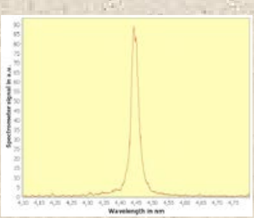
The concept as been demonstrated at LCLS , J. Amann, et al. Nature Photonics, DOI: 10.1038/NPHOTON 2012.180

X-ray Free-electron Lasers today



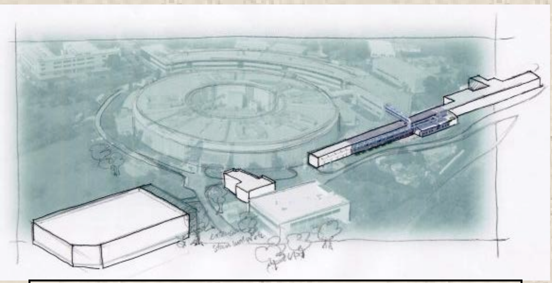


LCLS, 1.5 Å, 4/2009, 1-3 mJ



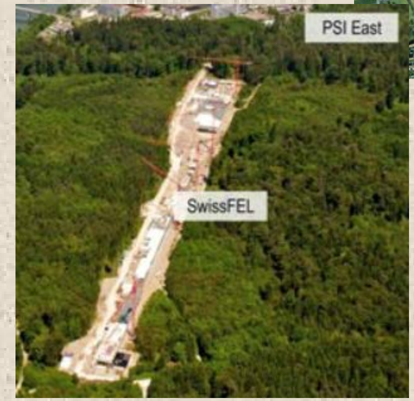
Flash: 4.45 nm, 0.3 mJ, 6/2010

SACLA 0.8 Å, 6/2011



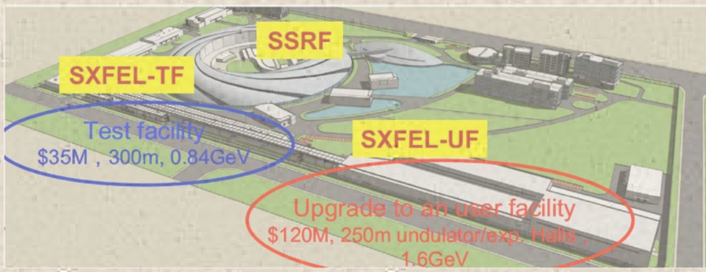
Fermi@Elettra, 43nm,12/2010

European XFEL, 2018



Swiss FEL 2017

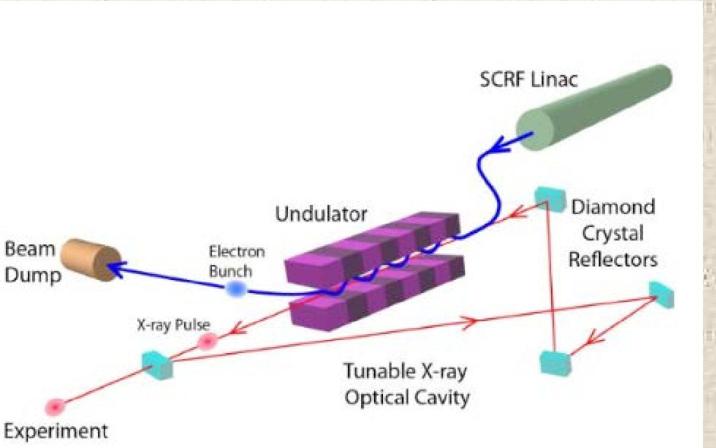
PAL XFEL Korea



Shanghai SXFEL

… and the future

XFELO



K.-J. Kim, Y. Shvyd'ko, and S. Reiche, "A proposal for an x-ray free-electron laser with an energy-recovery linac" Phys. Rev. Lett. **100**, 244802 (2008).

Attosecond

TW peak power

A coherent and bright vision of the future for X-ray FELS