Nobel Symposium on Free Electron Laser Research

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X-Ray FELs:
from dream to reality

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Outline

1. The past: A short history of X-ray free-electron lasers (FELs) development
2. The present: Today's status of X-ray FELs and work in progress

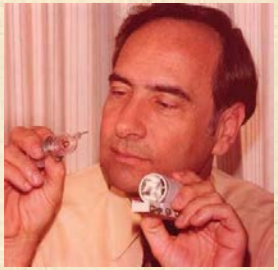
Early work on X-ray lasers

The development of an X-Ray lasers, generating coherent, high power, X-ray beams, has been a major goal in laser physics almost from the time the first laser was built in 1960.

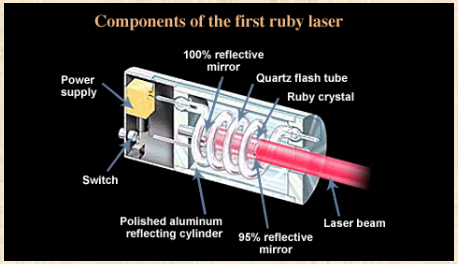
A history of laser development can be found in:

Bertolotti, M., 2005, History of the laser, Institute of Physics Publishing, Bristol.

Zinth, W., A. Laubereau and W. Kaiser, 2011, Eur. Physics J. H ***36****, 153.*



Ted Maiman (25 years after first Ruby laser)



Why x-ray lasers?

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

Early work on X-ray lasers

In the conventional atom-based 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 the 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.*

Together with the large energy needed to excite inner atomic levels, 1 to 10 KeV compared to about 1 eV for visible lasers, this leads to a requirement for very intense pumping levels to attain population inversion, too large for practical purposes.

Building low loss optical cavities for X-ray laser oscillators is also difficult, in fact beyond the present state of the art.

But not to be discouraged: Scientists at LLNL proposed to use a nuclear weapon to drive an X-ray laser. They tried this concept in the Dauphin experiment, apparently with success, in 1980.

Early work on X-ray lasers

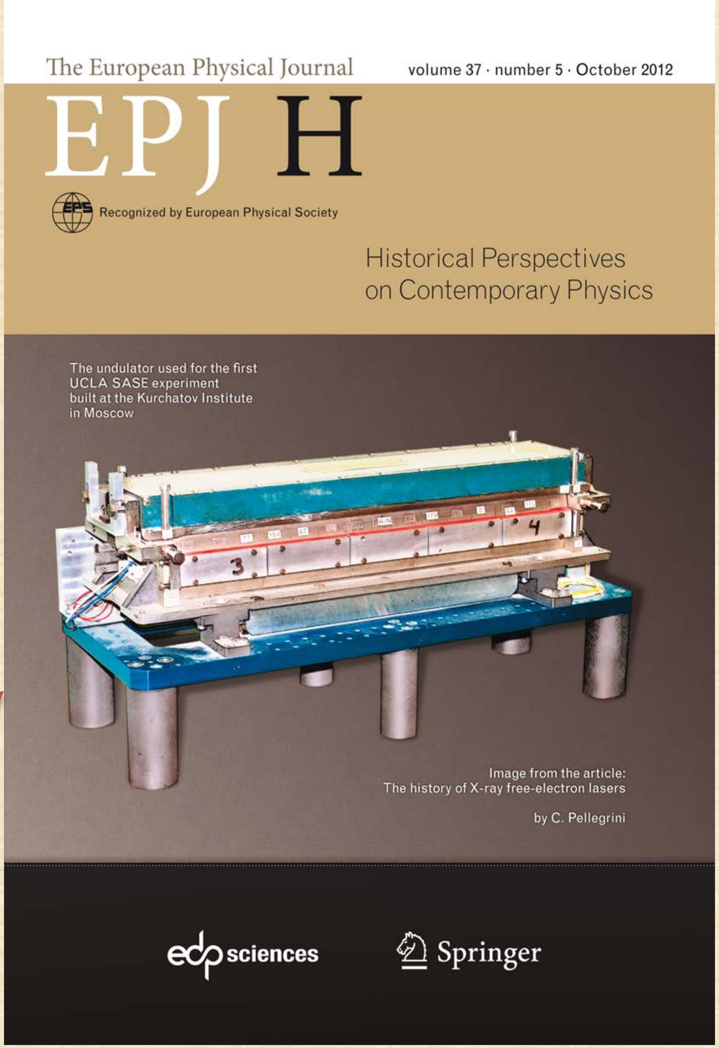
The experiment was part of the Star Wars Defense Initiative: generate an X-ray beam in space, exploding an atomic bomb, to kill incoming missiles. The program was terminated at the end of Star Wars (Hecht 2008).
The development of high peak power, short pulse, visible light lasers made possible another 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)

Hecht J., 2008, The History of the X-ray Laser, Optics and Photonics News, 19 (2008);
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

The way out of this difficult situation was offered by the generation of electromagnetic waves from relativistic electron beams and the FEL.

A history of this development is found in *Pellegrini, C., 2012, History of the X-ray free-electron laser, European Physics Journal H 37, 659.*



60 cm long undulator used for the first UCLA SASE FEL at 16 μm. Period 1.5 cm, K=1, gap 5mm.

Varfolomeev, A.A., Pellegrini, C., et al., 1992, Large-field-strength short-period undulator design, Nucl. Instr. and Meth. A ***318****, 813.*

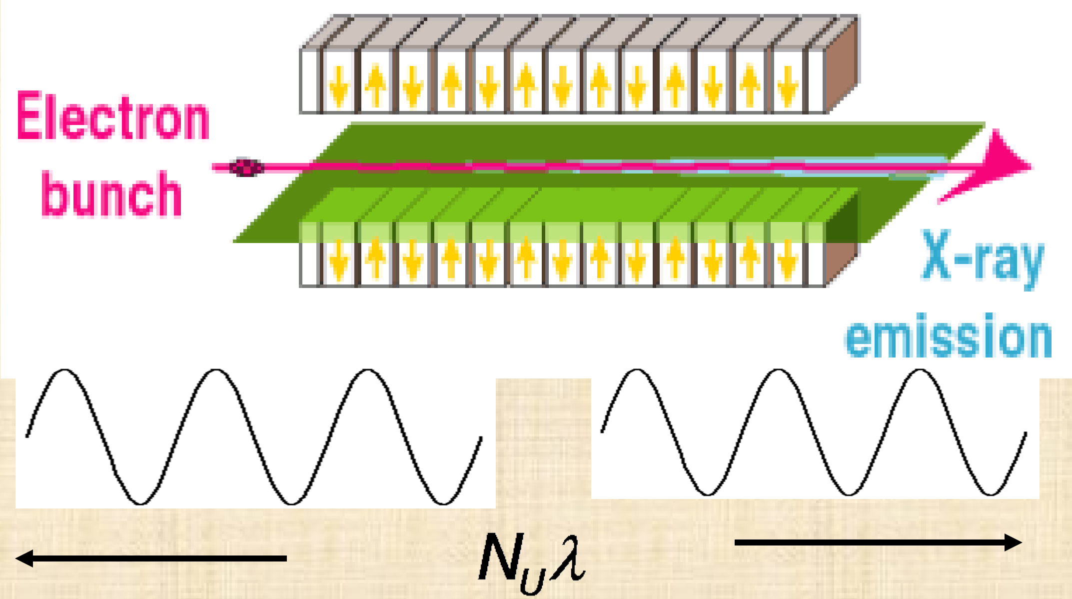
Important steps for the X-ray FEL development: undulator radiation

Hans Motz observed coherent radiation at Stanford at millimeter wavelength in 1953 using a planar undulator with 4 cm period and 3 to 5 MeV electron beam genrated by a linac with a bunch length shorter than the radiation wavelength. At 100 MeV he observed incoherent radiation. Using his words: " the mm wave generation might have some practical importance. In this case it is possible to bunch the electron beam so that groups of electrons radiate coherently. It was shown that the power level may be higher by a factor of the order of a million compared to non coherent radiation …" *Motz, H, W. Thon and R. N. Whitehurst, 1953,"Experiments on radiation by fast electron beams", J. Appl. Phys.* ***24****, 826.*

Can we do the same at wavelength of about 1Å? The answer is no, we do not know how to generate an electron beam with all electrons squeezed within $\lambda/10$ or separated by λ .

But in this case nature is kind to us. Under proper conditions, using an FEL the electron beam can go through a self-organization process and do just that, as we will see later.

X-ray FEL physics: Undulator radiation



Undulator with N_U periods and magnetic field on axis B_U. The electron has a sinusoidal trajectory around the axis.

$$\lambda = \lambda_U (1-\beta_z)/\beta_z$$

$$\approx \lambda_U \frac{1+K^2/2}{2\gamma^2}$$

One electron emits a wave train with N_U wave fronts

$$E = mc^2\gamma$$

Line width $\Delta\omega/\omega \approx 1/N_U$

$$K = eB_U\lambda_U/2\pi mc^2 \approx 1-3$$

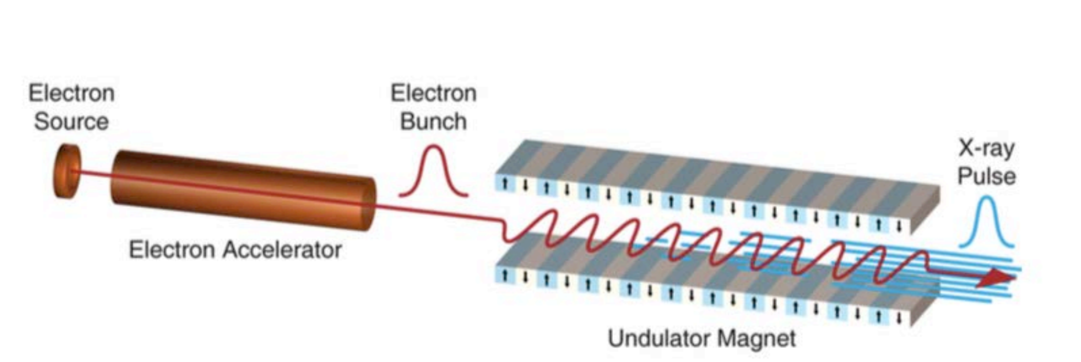
For a case like LCLS:

$$\gamma \approx 3\times 10^4,\ \lambda_U \approx 3cm,\ K \approx 3,\ N_U \approx 3500$$

$$\lambda = 0.1nm,\ \Delta\omega/\omega \approx 3\times 10^{-4},\ \lambda N_U = 0.3\mu m (1\,fs)$$

Free-electron lasers

Free-electron lasers (FELs) add an electromagnetic wave to the electron beam and the undulator magnet and thus open new possibilities. They combine the physics and technology of particle accelerator and lasers to generate electromagnetic radiation with very high brightness. John Madey introduced the initial FEL concept in 1971. *Madey, J.M.J. 1971, J. Appl. Physics* ***42,*** *1906*.



JOURNAL OF APPLIED PHYSICS VOLUME 42, NUMBER 5 APRIL 1971

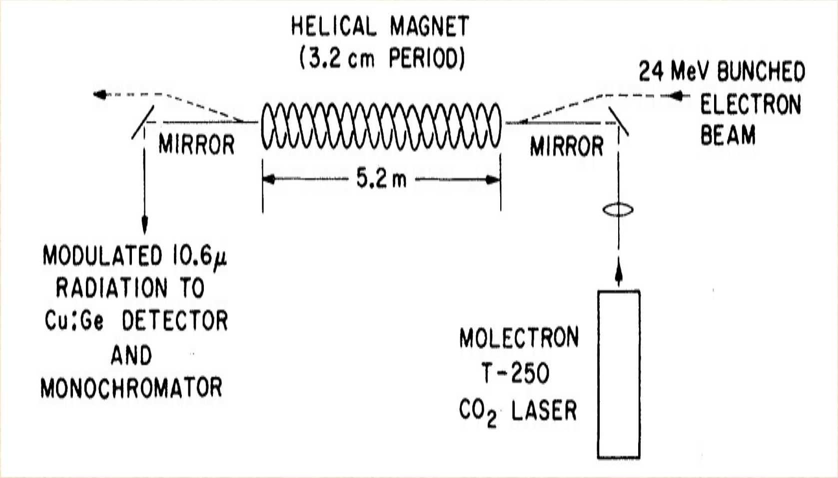
Stimulated Emission of Bremsstrahlung in a Periodic Magnetic Field

JOHN M. J. MADEY

The Weizsacker-Williams method is used to calculate the gain due to the induced emission of radiation into a single electromagnetic mode parallel to the motion of a relativistic electron through a periodic trans verse de magnetic field. Finite gain is available from the far-infrared through the visible region raising the possibility of continuously tunable amplifiers and oscillators at these frequencies with the further possibility of partially coherent radiation sources in the ultraviolet and x-ray regions to beyond 10 keV. Several numerical examples are considered.

“The dependence of the gain on the square of the final state wavelength probably precludes the development of steady-state oscillations in the region beyond the ultraviolet. …”

Madey's group two first FEL experiments: amplifier and oscillator at 10.6μm, gain up to 7%/pass.



Elias, L. et al. 1976. Observation of stimulated emission of radiation by relativistic electrons in a spatially periodic transverse magnetic field,. Phys. Rev. Lett. ***36****: 717-720*

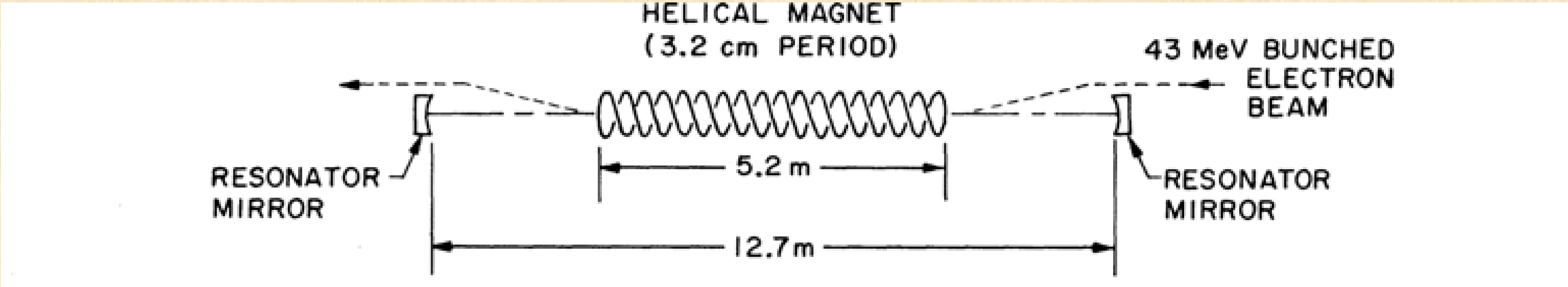


FIG. 1. Schematic diagram of the free-electron laser oscillator. (For more details see Ref. 6.)

Deacon, D.A.G. et al. 1977. First operation of a free-electron laser. Phys. Rev. Lett. ***38****, 892.*

Next steps:1

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, still precluded the possibility of pushing FELs to X-ray wavelengths

The high gain theory, the first next step, was developed in the 70s and 80s by many people:

- 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 1986a; Wang and Yu, 1986; Bonifacio, Casagrande and Pellegrini, 1987.

Next step: 2

The paper by Saldin and Kondratenko (1980) is an important contribution. In this paper it was considered, for the first time, the possibility of using the high gain regime, starting from spontaneous radiation, to reach saturation in a single pass infrared FEL, using low energy electron beams (a few to 10 MeV), eliminating the need of an optical cavity. In a second paper (Derbenev, Kontratenko and Saldin, 1982] they again discussed the case of infrared FELs and considered the possibility of increasing the beam energy to about 1 GeV, using a storage ring, to produce soft X-rays.

Kondratenko, A.M. and E.L. Saldin. 1980. Generation of coherent radiation by a relativistic electron beam in an undulator. Part. Accel. 10, 207.

Derbenev, Y.S., A.M. Kondratenko and E.L. Saldin. 1982. On the possibility of using a free electron laser for polarization control in a storage ring. Nucl. Instr. Meth. A 193, 415.

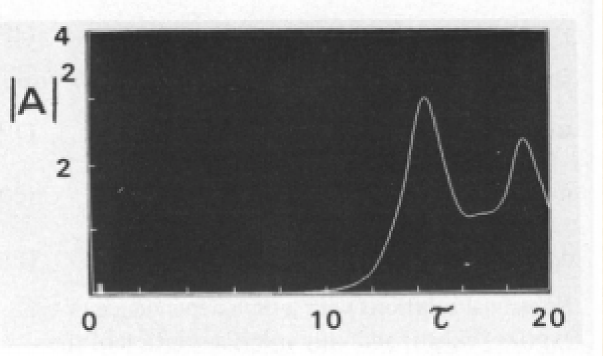
Next Step: 3

FEL physics as a collective instability. A self organization effect.

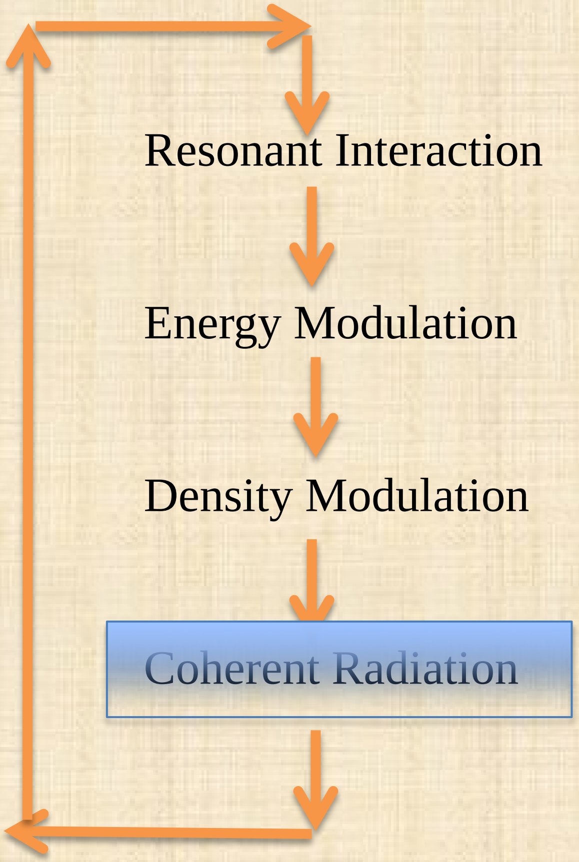
COLLECTIVE INSTABILITIES AND HIGH-GAIN REGIME IN A FREE ELECTRON LASER, BONIFACIO, R., PELLEGRINI, C. and L.M. NARDUCCI, 1984, Optics Communication ***50,*** *373.*

Abstract We study the behavior of a free electron laser in the high gain regime, and the conditions for the emergence of a collective instability in the electron beam-undulator-field system. Our equations, in the appropriate limit, yield the traditional small gain formula. In the nonlinear regime, numerical solutions of the coupled equations of motion support the correctness of our proposed empirical estimator for the build-up time of the pulses, and indicate the existence of optimum parameters for the production of high peak-power radiation.

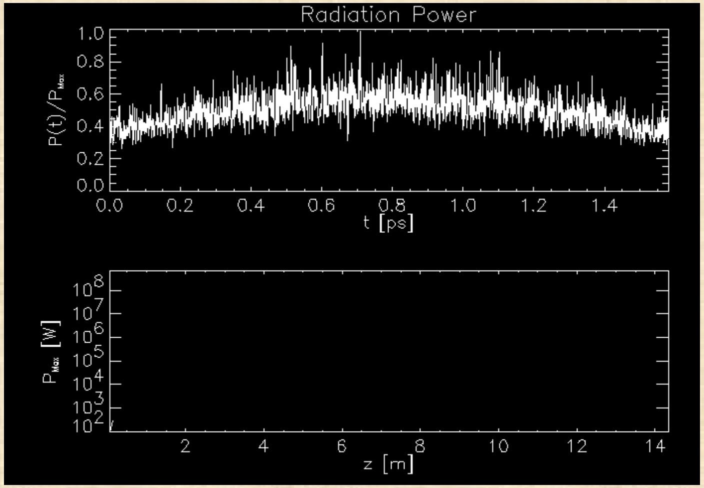
The instability can start from noise and leads from an initial state with a random initial distribution of the electron longitudinal position to a state with a beam consisting of micro-bunches about 1/10 of the wavelength long and separated by a wavelength, a sort of 1-dimensional relativistic crystal.



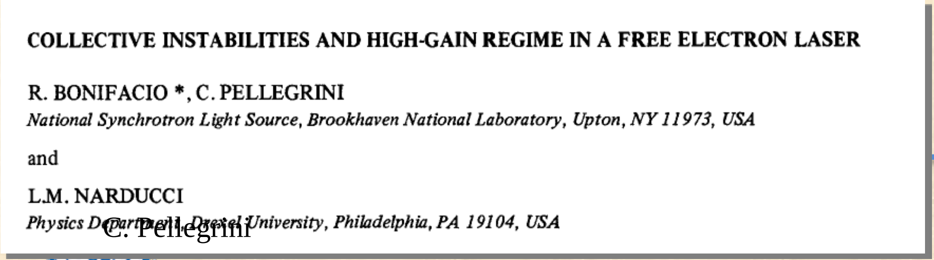
Collective instability physics



Process is unstable, leading to exponential growth of power until saturation is reached.



Can start from a coherent seed or by noise in electron distribution!


COLLECTIVE INSTABILITIES AND HIGH-GAIN REGIME IN A FREE ELECTRON LASER

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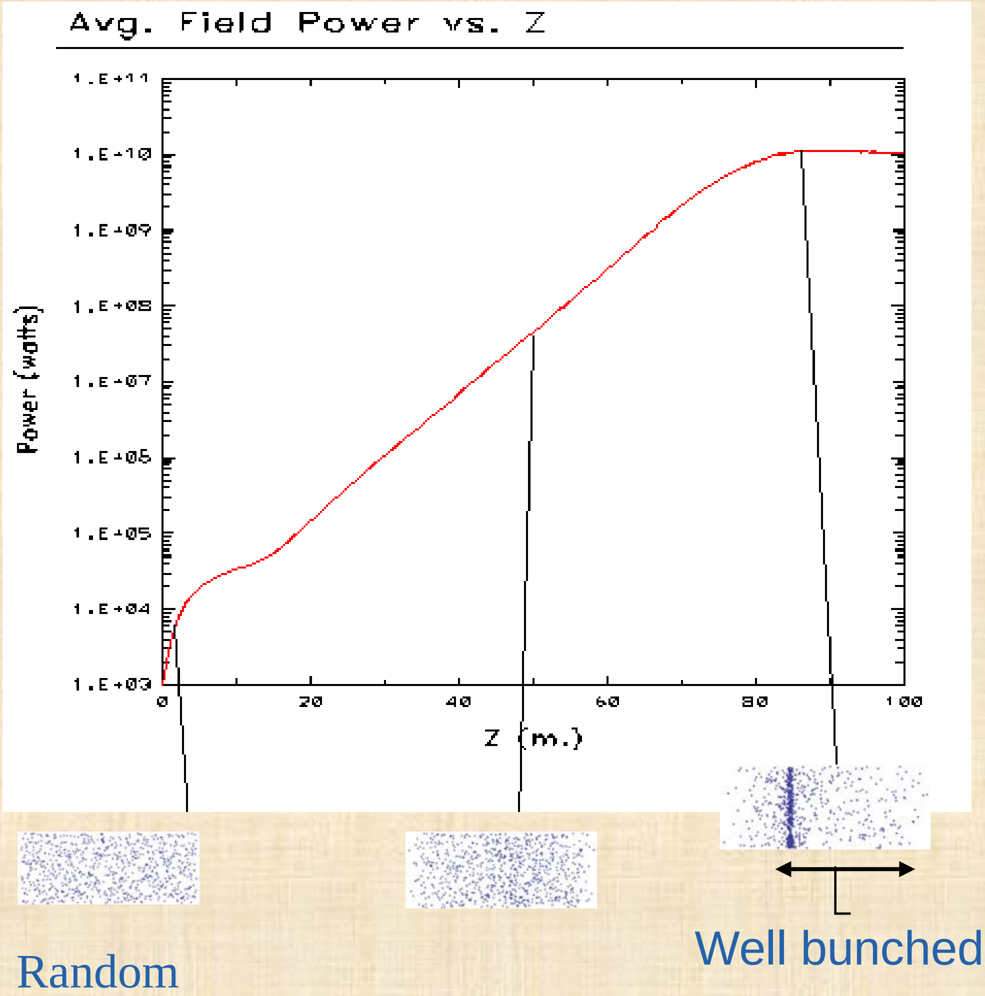
SASE: a beam self-organization effect.

Evolution of power and beam density along the undulator from spontaneous radiation to FEL amplified radiation. The exponential growth is characterized by the gain length, a function of the electron beam 6-D density and the undulator period.
The interaction produces an ordered distribution in the beam, a 1-dimensional relativistic quasi-crystal.



Next step: 3a

In the 1-D limit the FEL equations are written, using the length scale characteristic of the system, the gain length and the cooperation length, in a universal form, depending only on one parameter, ρ. It can be verified experimentally at any wavelength.

The most important quantity is the bunching, or order variable

$$B = \sum_{n=1}^{N_e} e^{i\Phi_n} / N_e$$

where Φ is the relative phase of the electron oscillation and the electromagnetic wave.

B=0 for a uniform electron distribution, *B<<1* for a random distribution, *B~1* for a SASE FEL at saturation. The intensity is proportional to $N_e^2 |B|^2$.

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	$N_{ph} \simeq \rho E_{beam} / E_{ph}$

For the results to be valid we must have

$\sigma_{e,r}\sigma_{e,r'} \le \lambda_r / 4\pi,$	$\sigma_{e,E} < \rho,$	$L_G < Z_R$
phase space matching	line width matching	Gain>diffraction losses

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

For E_{ph}=*10keV, E=15 GeV*, $\rho=10^{-3}$, $N_{ph} \sim 10^3$, compared to $\sim 10^{-2}$ for spontaneous radiation, a gain of 5 orders of magnitude.

3-D and time dependent effects

The next steps in the theoretical development were:

1. The high gain 3-D theory, establishing radiation focusing by gain guiding and by microbunching: Kondradenko and Saldin, 1980; Moore 1984; Moore 1985; Scharlemann, Sessler and Wurtele 1985; Kim1986b; Krinsky and Yu 1987; Yu, Krinsky and Gluckstern, 1990;

The beam can be approximated by a fiber with index of refraction

$$\mathrm{Re}\, n - 1 = \frac{1}{k_r}\frac{d\psi_r}{dz} \approx \frac{K}{\gamma E_r}\left\langle \cos\phi \right\rangle$$

Bunching factor

Scharlemann, E.T., A.M. Sessler and J.S. Wurtele, 1985, Physical Review Letters ***54****, 1925.*

The gain must overcompensate diffraction losses.

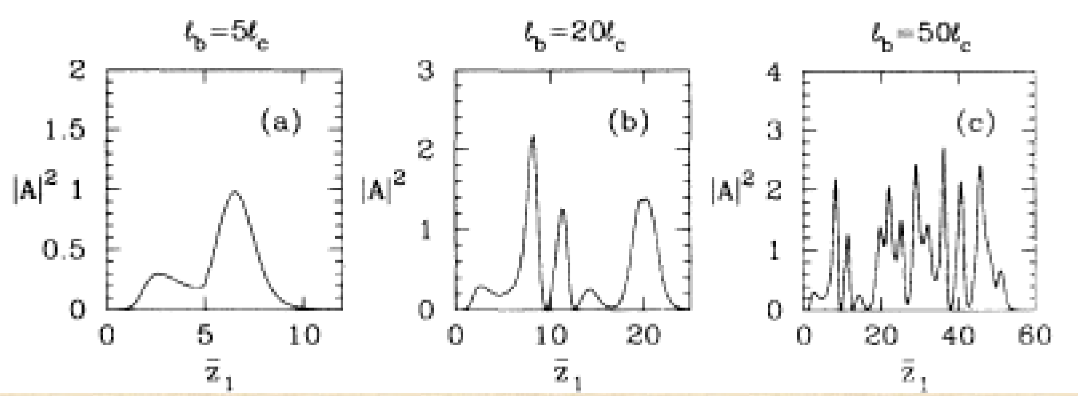
3-D and time dependent effects

Understanding the spectral/temporal properties of a SASE FEL and the spiky nature of the radiation: the cooperation length $L_c = \lambda_r / 4\pi\rho$

VOLUME 73, NUMBER 1 PHYSICAL REVIEW LETTERS 4 JULY 1994

Spectrum, Temporal Structure, and Fluctuations in a High-Gain Free-Electron Laser Starting from Noise

R. Bonifacio,[1,2] L. De Salvo,[1] P. Pierini,[2] N. Piovella,[1] and C. Pellegrini[3]



Temporal profile for different ratios of bunch length to cooperation length.

Statistical properties of the radiation from SASE FEL operating in the linear regime, E.L. Saldin, E.A. Schneidmiller, M.V. Yurkov, Nucl. Instr. and Meth. A407, 291 (1998)

Radiation energy probability distribution $$p(W) = \frac{M^M}{\Gamma(M)} \left(\frac{W}{\langle W \rangle} \right)^{M-1} \frac{1}{\langle W \rangle} \exp(-MW/\langle W \rangle)$$

From theory to working FELs: a second look at storage rings as FEL drivers.

Generation of high-intensity coherent radiation in the soft-x-ray and vacuum-ultraviolet region, J. B. Murphy and C. Pellegrini, J. Opt. Soc. Am. B, **2** (1985)

Abstract An electron beam can be made to interact with an undulator magnet so that a collective unstable mode is excited. In this mode, the beam generates coherent radiation whose wavelength is determined by the undulator period and the electron energy. By proper choice of the electron-beam energy, energy dispersion, and density, one can obtain coherent radiation in the soft-x-ray region with peak and average power of the order of hundreds of megawatts and hundreds of milliwatts, respectively. Larger peak powers, of the order of a gigawatt, can be expected for UV radiation with λ in the range of 500-2000 Å. We discuss the physical principles of these systems and give examples of how they might be built.

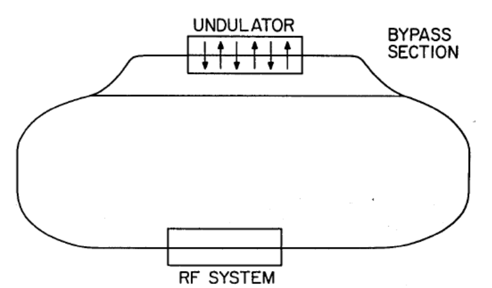
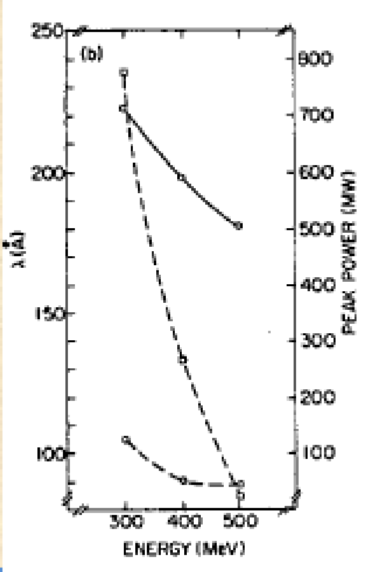


Fig. 4. Sketch of the storage ring and the bypass section.



Another breakthrough: the RF photo-injector electron source

- The analysis of Murphy and Pellegrini showed that using a storage ring to generate the electron beam limits the wavelength ≥50 nm.
- The limit comes from instability in rings, and a large, $\approx 10^{-3}$, electron energy spread.
- The way out of this is a linac with a new electron source, developed at Los Alamos as part of the Star Wars program: the RF photo-injector. *Fraser, J.S. and R.L. Sheffield. 1987. High-brightness injectors for RF-driven free-electron lasers. IEEE J. Quantum Electron. QE-23: 1489-1496.*
- This source could generate beams with 100 times better emittance and ten times smaller energy spread that the original SLAC linac thermo-ionic source.

PROGRESS TOWARD A SOFT X-RAY FEL

*C. PELLEGRINI, Nuclear Instruments and Methods A**272,** 364-367 (1988).*

Abstract: We review the FEL physics and obtain scaling laws for the extension of its operation to the soft X-ray region . We also discuss the properties of an electron beam needed to drive such an FEL, and the present state of the art for the beam production . [Use a linac and a photo-injector]

.. This approach uses Amplified Spontaneous Emission (ASE) to produce radiation starting from the beam noise, in a long undulator [we now call it a SASE FEL] and a photoinjector.

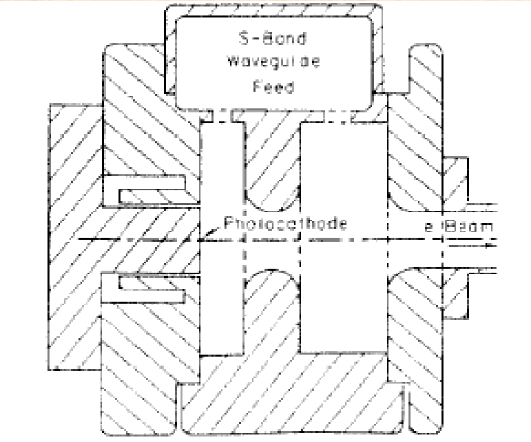
The conclusion is that using a linac and a photoinjector it is possible to reach the nm region at a beam energy of 1.5 GeV, with about 6 mJ/pulse starting from noise in an 11 m long undulator.

The same paper examined the FEL scaling law: the result, $\rho \approx \lambda^{1/2}$, is very favorable to push to even shorter wavelengths. In the small signal gain regime the scaling is like λ^2.

Photo-injector development

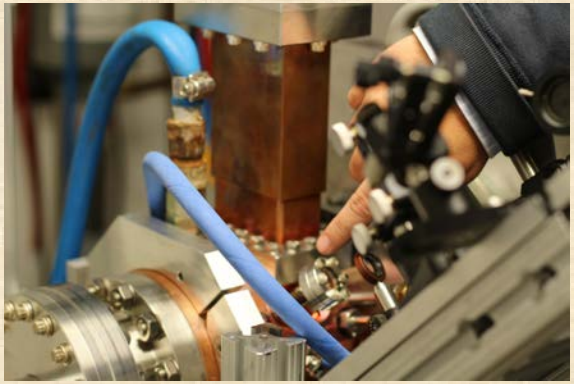
The Los Alamos photo-injector was developed in L-band for high average power FELs as part of the Star Wars program, and promised a much higher electron beam brightness. Robert Palmer and I, at the Center for Accelerator Physics at Brookhaven National Laboratory, decided in 1986-87 to develop this new technology for application in laser acceleration and FELs. An S-band version of the Los Alamos gun, optimized for high peak power and small emittance, was designed at Brookhaven.

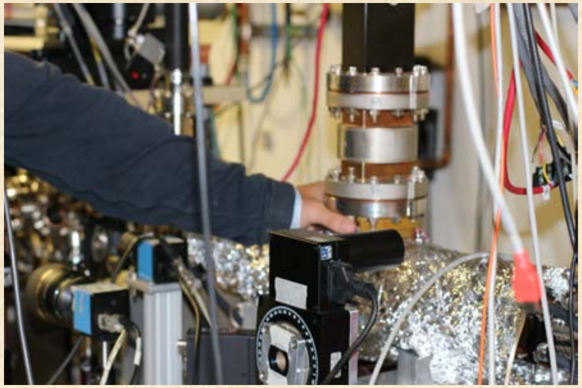
Batchelor, K., H. Kirk, K. McDonald, J. Sheehan and M. Woodle. 1988. Development of a High Brightness Electron Gun for the Accelerator Test Facility at Brookhaven National Laboratory. Proc. of the 1988 European Particle Accelerator Conf., Rome, pp. 54–958.



Later work on photo-injector development was done at UCLA and a program was started later at SLAC by Herman Winick, and continued with a BNL-SLAC-UCLA collaboration.

Experimental verification of SASE theory

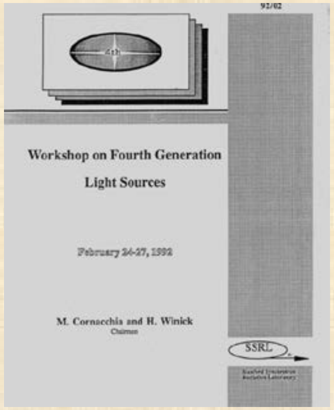




When I moved to UCLA in 1989 I started a program to verify the SASE theory at infrared to visible wavelength. The idea is that the basic 1-D theory depends only on the FEL parameter and there is no explicit dependence on wavelength, so a verification in the infrared to visible would be meaningful to establish the case for X-rays.

Together with Jamie Rosenzweig we built at UCLA an S-band photoinjector and a small, <1 m long, 15 MeV linac. A 60 cm long undulator was built by Alexander Varfolomeev from the Kurchatov Institute. Most of the work was done by graduate students and a post-doc, guided by Jamie Rosenzweig and myself. The photocathode laser was built by Chan Joshi and his students.

LCLS, a SASE X-ray FEL, proposed in 1992

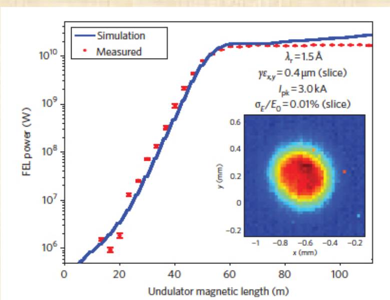


A 4 to 0.1 nm FEL Based on the SLAC Linac.

C. Pellegrini, UCLA Physics Department March 2, 1992

Abstract

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

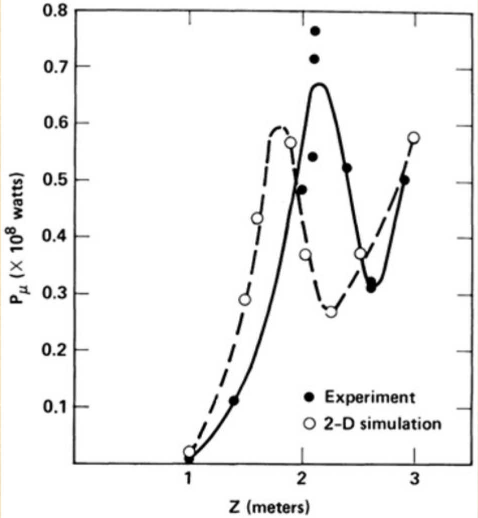


2009: it works!

The proposal was based on the photoinjector development and previous theoretical work: R. Bonifacio, C. Pellegrini and L. Narducci, Opt. Comm. 50, 373 (1984); J.B. Murphy and C. Pellegrini, J. Opt. Soc. Amer. B 2,259 (1985); C. Pellegrini, Nuclear Instruments and Methods A**272,** 364-367 (1988).

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.

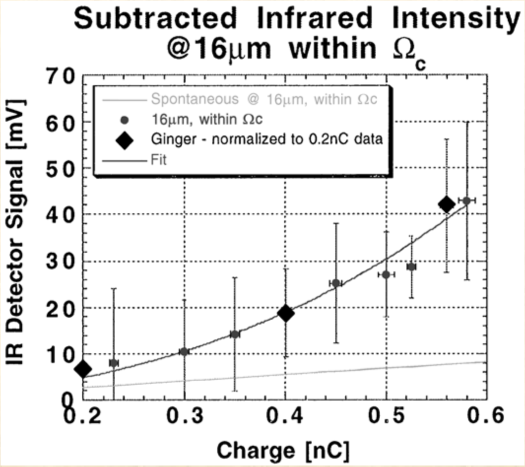


Amplified signal output as a function of length along the undulator. The FEL operates at a frequency of 34.6 GHz, and the input signal, provided by a magnetron, is about 50 kW. From reference [Orzechowski, et al., 1985].

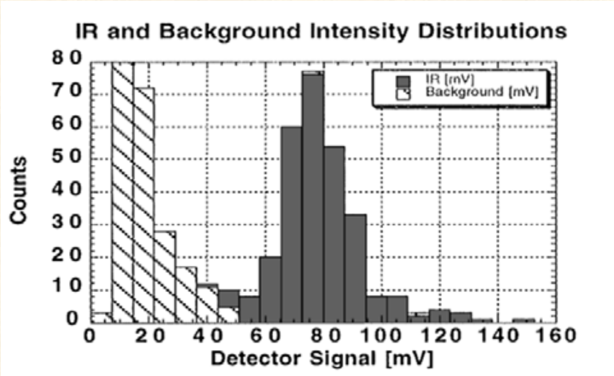
*Orzechowski, T. et al.,1985, Physics Review Letters **54**, 889*

Experimental verification of SASE theory: UCLA 16 μm FEL, gain >10, 1997-98

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



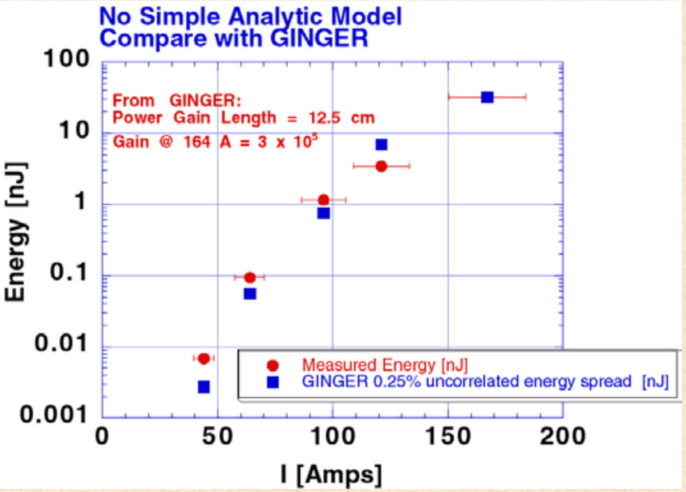
Coherent IR intensity versus charge. The vertical bars are the standard deviation for the intensity fluctuations. Beam charge and radius uncertainties are 9%, a standard deviation of 4 mV at 0.56 nC. Straight line: calculated spontaneous emission intensity. Curved line: data fit $I=1.85Q\exp(4.4Q^{1/3})$, and Ginger simulations.



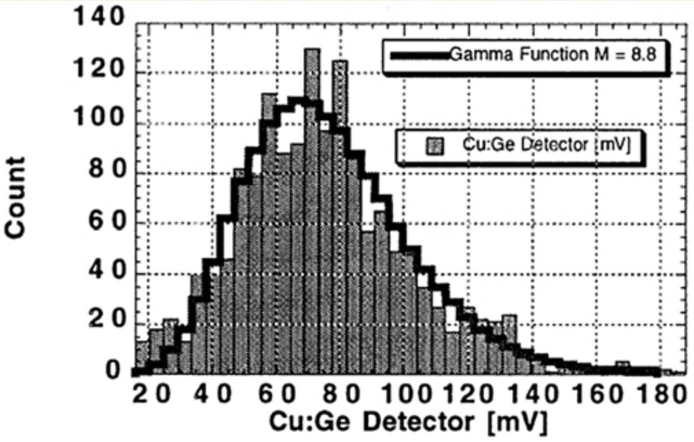
Intensity distribution of the IR and background signals for a mean charge Q =0.56 nC, standard deviation of 0.007 nC, IR mean = 78 mV, standard deviation = 14.3 mV; background mean = 18.7 mV, standard deviation = 9.1 mV

Experimental verification of SASE theory: 12 μm, gain > 10^5, SASE-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.



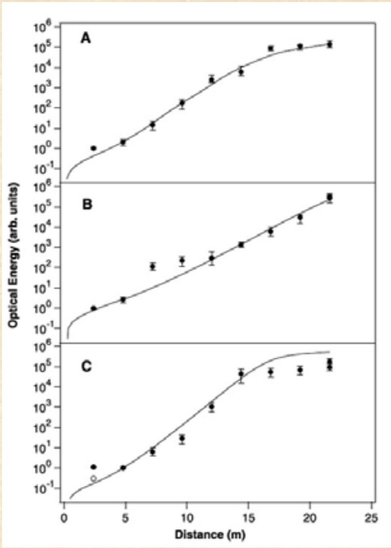
Intensity fluctuations for individual 2 nC micropulses compared with theory.

LCLS: 17 years from idea to first light

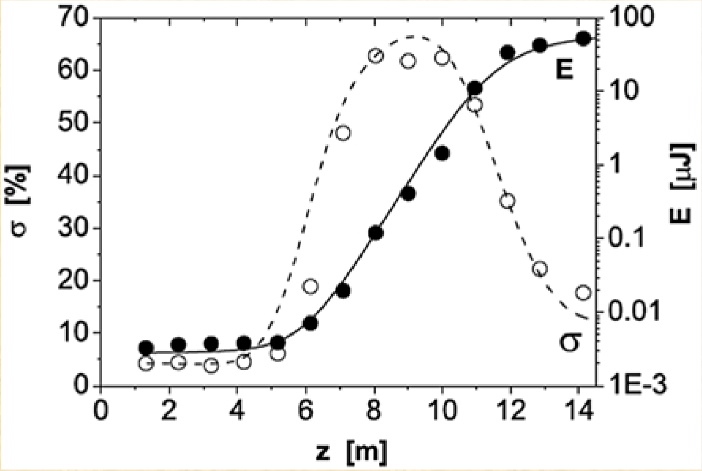
1992: Proposal (Pellegrini), Study Group(Winick)
1994: National Academies Report http://books.nap.edu/books/NI000099/html/index.html
1996: Design Study Group (M. Cornacchia)
1997: BESAC (Birgeneau) Report http://www.sc.doe.gov/production/bes/BESAC/reports.html
1998: LCLS Design Study Report SLAC-521
1999: BESAC (Leone) Report http://www.sc.doe.gov/production/bes/BESAC/reports.html
$1.5M/year, 4 years
2000: LCLS- the First Experiments (Shenoy & Stohr) SLAC-R-611
2001: DOE Critical Decision 0 – Permission to develop concept
2002: LCLS Conceptual Design
DOE Critical Decision 1 Permission to do Engineering Design
$36M for Project Engineering Design
2003: DOE Critical Decision 2A: accept estimate of
$30M in 2005 for Long Lead Procurements
2004: DOE 20-Year Facilities Roadmap
2005: Critical Decision 2B: Define Project Baseline
Critical Decision 3A: Long-Lead Acquisitions
2006: Critical Decision 3B: Groundbreaking
2009: First Light, 10 April 2009
2010: Project Completion

Courtesy J. Galayda

Other experiments at shorter wavelengths: LEUTL, VUV FELs

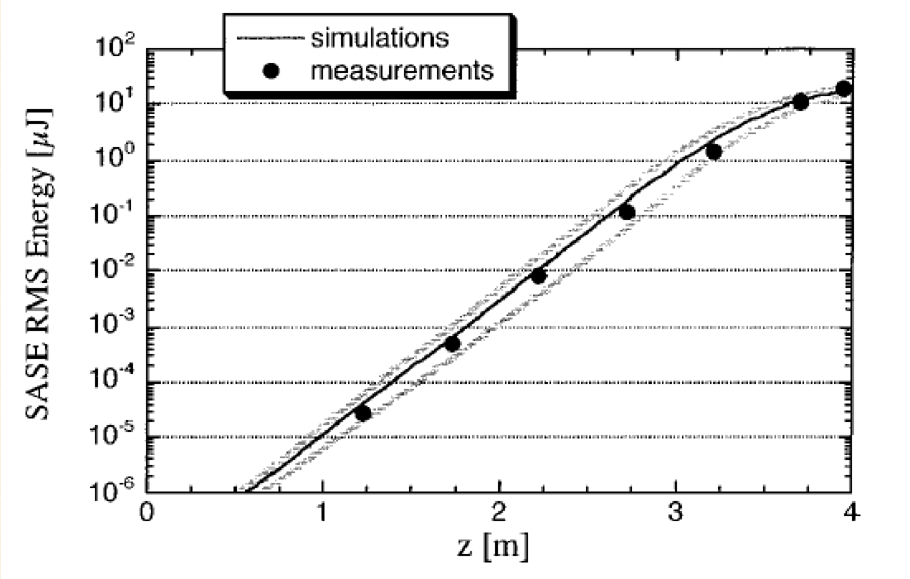


Intensity as a function of undulator length, under various electron beam conditions. (A) 530-nm saturated conditions. (B) 530-nm unsaturated conditions. (C) 385-nm saturated conditions. Solid curves: GINGER simulation results. Reference Milton et al., 2001.



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

UCLA-SSRL-BNL-LLNL VISA FEL at 800nm



Measured SASE intensity evolution along the 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. Reference Murokh et al., 2003.

Where are we today?

	LCLS	SACLA	European XFEL*	Korean X-FEL*	Swiss X-FEL*	LCLS-II Cu RF
Electron energy, GeV	2.15-15.9	5.2-8.45	8.5-17.5	4-10	2.1-5.8	2.5 - 15
Wavelength range, nm	0.11-4.4	0.275-0.063	5.1-0.04	0.6-0.1	7-0.1	1.2 – 0.05
X-ray pulse energy, mJ	1-3 for $0.1<\lambda<1.5$	0.2-0.4 for $0.08<\lambda<0.275$	0.67-8.5 for $0.04<\lambda<5.1$	0.81-1 for $0.1<\lambda<0.6$nm	0.5-1.3 for $0.1<\lambda<7$	1-4.5 for $0.05<\lambda<0.4$
Pulse duration, rms, fs	5-250 for $0.1<\lambda<1.5$	4.3 for $0.08<\lambda<0.275$	1.68-107 for $0.04<\lambda<5.1$	8.6-26 for $0.1<\lambda<0.6$nm	2-20 for $0.1<\lambda<7$	5-50
Line width, rms, % SASE	0.5-0.1 for $0.1<\lambda<1.5$	0.11-0.37 for $0.08<\lambda<0.275$	0.02-0.25 for $0.04<\lambda<5.1$	0.15-0.18 for $0.1<\lambda<0.6$nm	0.06-0.4 for $0.1<\lambda<7$	0.2-0.1
Line width, rms,% seeded	0.01-0.005 for $0.1<\lambda<1.5$	0.01-0.03* $0.08<\lambda<0.275$	0.04-0.005 for $0.04<\lambda<5.1$	0.002 -0.002 for $0.1<\lambda<0.6$nm	0.01-0.002 for $0.1<\lambda<7$	0.02

Characteristics of hard X-ray FELs in operation or under construction.

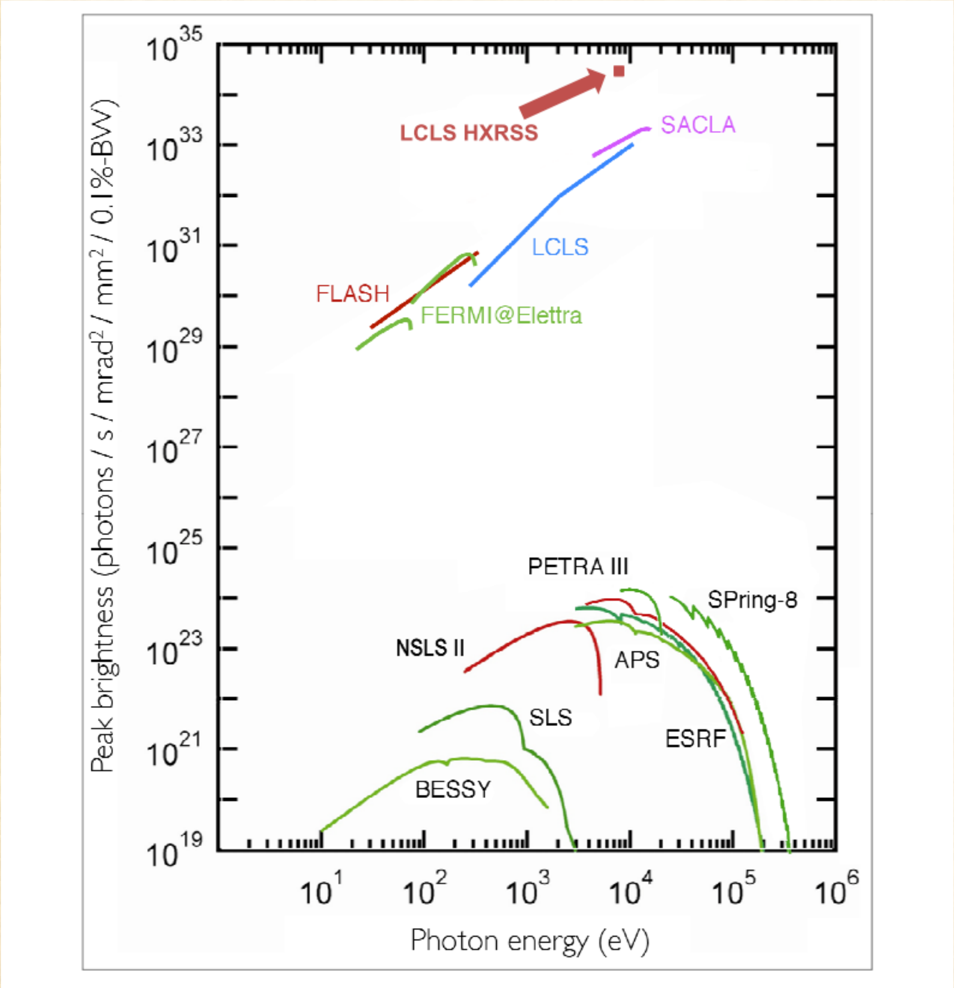
Characteristics of Soft X-ray FELs operating and under construction. LCLS-II has two undulators, SXR and HXR.

	FLASH	Fermi FEL-1	Fermi FEL-2	LCLS-II SXR Und.	LCLS-II HXR Und.
Electron energy, GeV	0.35-1.25	1.0 - 1.5		3.6 – 4.0	3.3 – 4.0
Wavelength range, nm	52-4.2	100-20	20-4	6 – 1.0	1.2 – 0.25
X-ray pulse energy, mJ	0.2 @ λ_{Max}, 0.5 @ λ_{min}	0.3 @ λ_{Max}, 0.1 @ λ_{min}	0.1 @ 10.8 nm, 0.01 @ λ_{min}	0.9 @ λ_{max}, 0.4 @ λ_{min}	1.1 @ λ_{max}, 0.02 @ λ_{min}
Pulse duration, rms, fs	15-100 @ λ_{Max} 15-100 @λ_{min}	Depending on seed pulse duration and harmonic order, typically 40-100		6 - 50	6 - 50
Line width, rms, % SASE	0.2 @ λ_{Max} 0.15 @λ_{min}			0.1	0.2 – 0.05
Line width,rms, % seeded		0.06 @λ_{Max} 0.03 @ λ_{min}	0.06@10.8nm,0.02@5.4nm,0.04@λ_{Min}	0.02	--

General characteristics of X-ray pulses can be summarized as follows:

➔Pulse energy hundreds of μJ to few mJ;
➔Line width in SASE mode about 10^{-3}, order of magnitude of the FEL parameter ρ; about ten times smaller than SASE when using self-seeding;
➔Pulse duration from a few to about 100 fs;
➔About 10^{3} photons/electron, at 1Å, compared to about 10^{-2} for spontaneous radiation; more at longer wavelengths.

Comparison of peak brightness



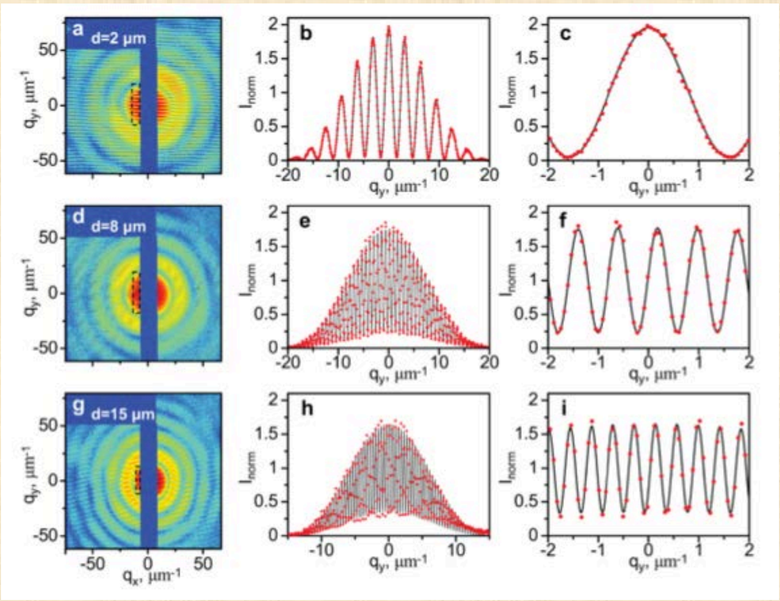
Courtesy H.-D. Nuhn, R. Hettel

Remarks on 4th generation

•FLASH, Fermi, SACLA and LCLS have demonstrated outstanding capabilities, increasing by 7 to 9 orders of magnitude the photon peak brightness.

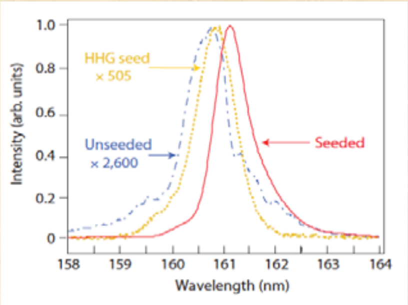
•The LCLS X-ray pulse duration and intensity can be changed from about 100 to a few femtosecond and 10^{13} to 10^{11} photons/pulse, over the wavelength range of 4 to 0.12 nm, by varying the electron bunch charge from 250 to 20 pC. **The X-ray pulse wavelength, intensity and duration can be optimized for each experiment, something not possible in storage ring sources**.

Characteristics of X-ray FELs radiation: Transverse coherence.

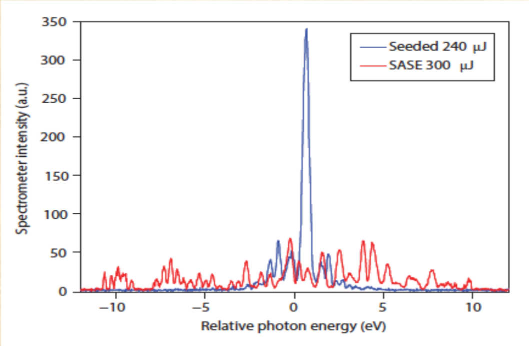


LCLS measurement of transverse coherence, *Vartanyants, I.A., et al., 2011, Physical Review Letters* ***107****, 144801.*

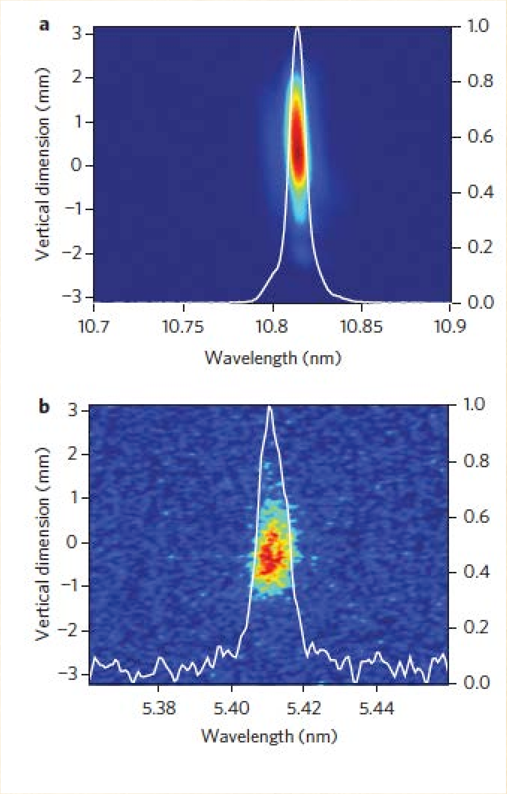
Longitudinal coherence



Spectra of seeded and SASE FEL at the SCSS Test Facility. The SASE spectrum scaled in amplitude. *Lambert G., et al., 2008, Nature Physics* ***4****, 296.*



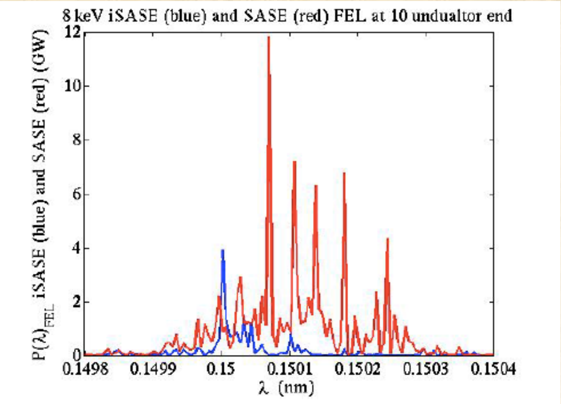
Self-seeding: Sample Spectra at LCLS for SASE, red, and self- seeded, blue, operation. *Amann, J., et al., 2012, Nature Photonics Articles* ***6,*** *693.*



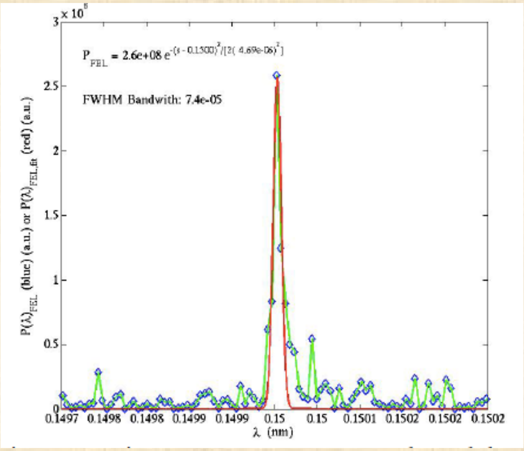
Fermi FEL Spectrum using two step cascaded HGHG. *Allaria, E., et al., 2012, New Journal of Physics* ***14,*** *113009.*

Longitudinal Coherence: iSASE

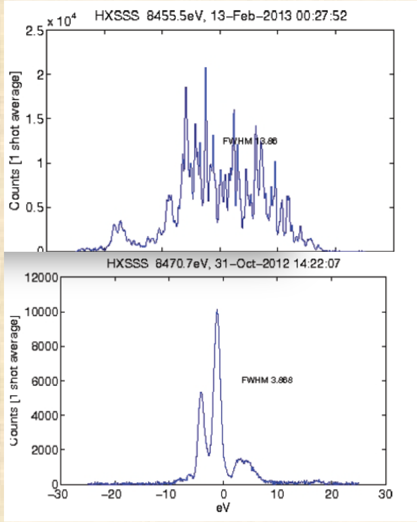
iSASE improves the longitudinal coherence by introducing a correlation between spikes by repeated electron bunch delays, respect to radiation pulse, of one or more cooperation lengths. The transform limit is obtained using a geometric series delays sequence, 1, 2, 4, …, 32 cooperation lengths. *J. Wu, A. Marinelli and C. Pellegrini, Generation of Longitudinally Coherent Ultra High Power X-Ray FEL Pulses by Phase and and Amplitude Mixing, Proc. FEL Conf. Nara, Japan, 2012, p. 237.*



iSASE (blue) and SASE (red) spectra after 10 LCLS undulator modules. FWHM 5.1E-05 vs. 1.5E-03

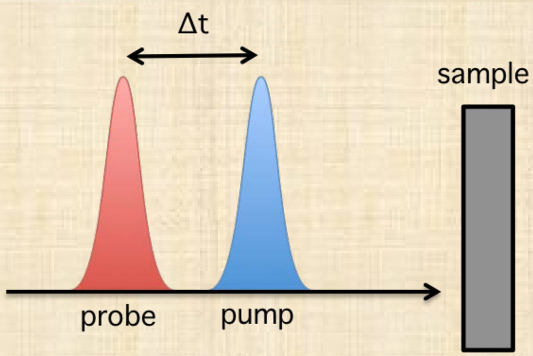


iSASE spectrum, tapered undulator end, close to transform limit, 0.6 TW.



LCLS proof of principle measurements. J. Wu et al., IPAC 2013 Shanghai, p. 2068

2 Color X-ray Free-Electron Lasers



$$\lambda_{1,2} = \lambda_w \frac{1+K^2}{2\gamma_{1,2}^2}$$

2 pulses with
-tunable energy difference
-tunable arrival time

$$\lambda_{1,2} = \lambda_w \frac{1+K_{1,2}^2}{2\gamma^2}$$

Many applications!
- x-ray pump/x-ray probe
- 2 color diffraction imaging

PRL 110, 134801 (2013) PHYSICAL REVIEW LETTERS week ending 29 MARCH 2013

Experimental Demonstration of Femtosecond Two-Color X-Ray Free-Electron Lasers

A. A. Lutman, R. Coffee, Y. Ding,* Z. Huang, J. Krzywinski, T. Maxwell, M. Messerschmidt, and H.-D. Nuhn
SLAC National Accelerator Laboratory, Menlo Park, California 94025, USA
(Received 13 December 2012; published 25 March 2013)

PRL 111, 134801 (2013) PHYSICAL REVIEW LETTERS 27 SEPTEMBER 2013

Multicolor Operation and Spectral Control in a Gain-Modulated X-Ray Free-Electron Laser

A. Marinelli,[1,*] A. A. Lutman,[1] J. Wu,[1] Y. Ding,[1] J. Krzywinski,[1] H.-D. Nuhn,[1] Y. Feng,[1] R. N. Coffee,[1] and C. Pellegrini[2,1]

ARTICLE
Received 8 Sep 2013 | Accepted 12 Nov 2013 | Published 4 Dec 2013 DOI: 10.1038/ncomms3919

Two-colour hard X-ray free-electron laser with wide tunability

Toru Hara[1], Yuichi Inubushi[1], Tetsuo Katayama[2], Takahiro Sato[1,†], Hitoshi Tanaka[1], Takashi Tanaka[1], ... Tono[2], Makina Yabashi[1] & Tetsuya Ishikawa[1]

ARTICLE
Received 16 Oct 2014 | Accepted 22 Jan 2015 | Published xx xxx 2015 DOI: 10.1038/ncomms7369 OPEN

High-intensity double-pulse X-ray free-electron laser

A. Marinelli[1], D. Ratner[1], A.A. Lutman[1], J. Turner[1], J. Welch[1], F.-J. Decker[1], H. Loos[1], C. Behrens[1,2], S. Gilevich[1], A.A. Miahnahri[1], S. Vetter[1], T.J. Maxwell[1], Y. Ding[1], R. Coffee[1], S. Wakatsuki[1,3] & Z. Huang[1]

PRL 110, 064801 (2013) PHYSICAL REVIEW LETTERS week ending 8 FEBRUARY 2013

Chirped Seeded Free-Electron Lasers: Self-Standing Light Sources for Two-Color Pump-Probe Experiments

Giovanni De Ninno,[1,2] Benoît Mahieu,[1,2,3] Enrico Allaria,[2] Luca Giannessi,[2,4] and Simone Spampinati[2]

PRL 111, 114802 (2013) PHYSICAL REVIEW LETTERS week ending 13 SEPTEMBER

Observation of Time-Domain Modulation of Free-Electron-Laser Pulses by Multipeaked Electron-Energy Spectrum

V. Petrillo,[1] M. P. Anania,[2] M. Artioli,[3] A. Bacci,[1] M. Bellaveglia,[2] E. Chiadroni,[2] A. Cianchi,[4] F. Ciocci,[3] G. Datto... D. Di Giovenale,[2] G. Di Pirro,[2] M. Ferrario,[2] G. Gatti,[2] L. Giannessi,[3] A. Mostacci,[5] P. Musumeci,[6] A. Petralia,[3] R. Pompili,[4] M. Quattromini,[3] J. V. Rau,[7] C. Ronsivalle,[3] A. R. Rossi,[1] E. Sabia,[3] C. Vaccarezza,[2] and F. Villa[2]

ARTICLE
Received 24 May 2013 | Accepted 21 Aug 2013 | Published 18 Sep 2013 DOI: 10.1038/ncomms3476 OPEN

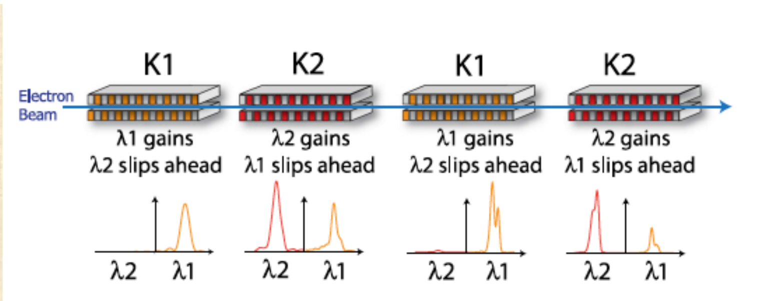
Two-colour pump-probe experiments with a twin-pulse-seed extreme ultraviolet free-electron laser

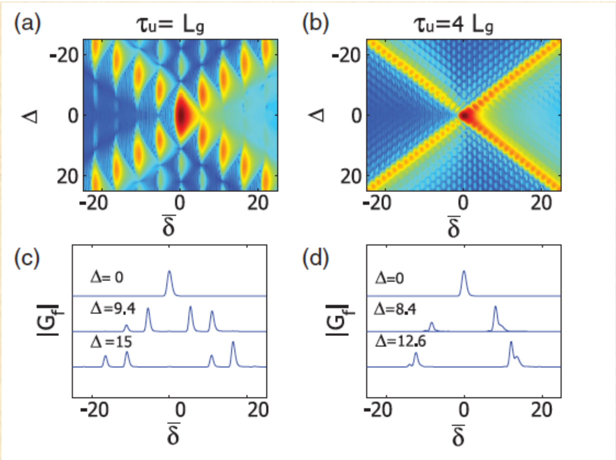
E. Allaria[1], F. Bencivenga[1], R. Borghes[1], F. Capotondi[1], D. Castronovo[1], P. Charalambous[2], P. Cinquegrana[1],

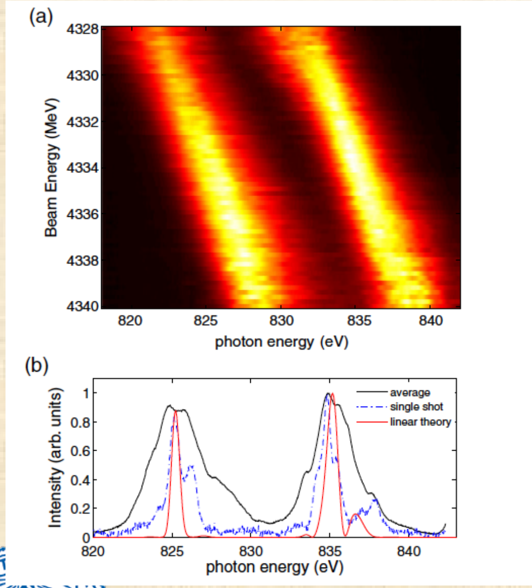
PRL 111, 134801 (2013) PHYSICAL REVIEW LETTERS week ending 27 SEPTEMBER 2013

Multicolor Operation and Spectral Control in a Gain-Modulated X-Ray Free-Electron Laser

A. Marinelli,[1,*] A. A. Lutman,[1] J. Wu,[1] Y. Ding,[1] J. Krzywinski,[1] H.-D. Nuhn,[1] Y. Feng,[1] R. N. Coffee,[1] and C. Pellegrini[2,1]

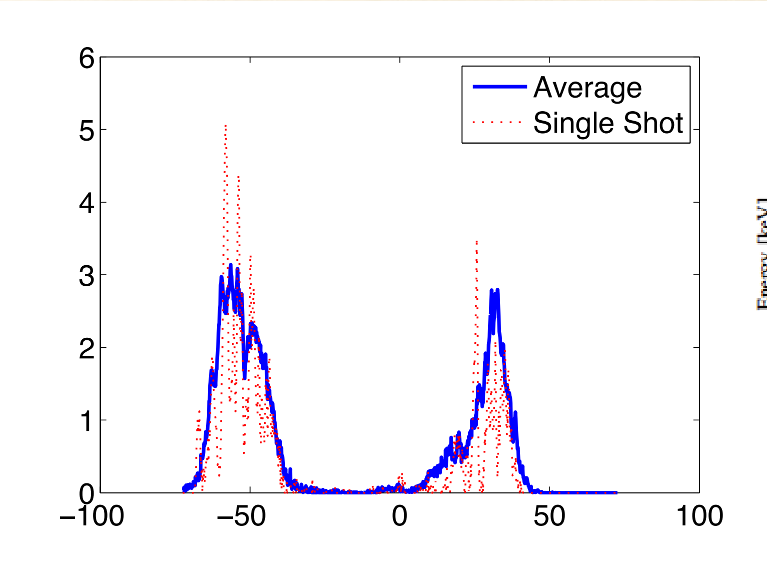


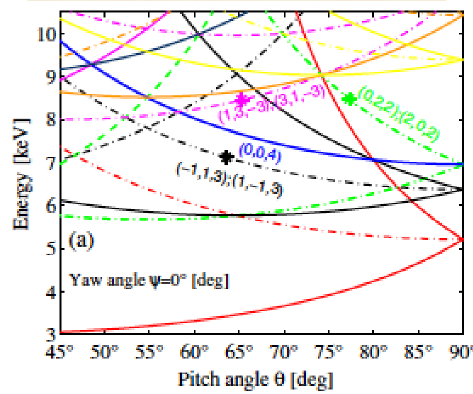


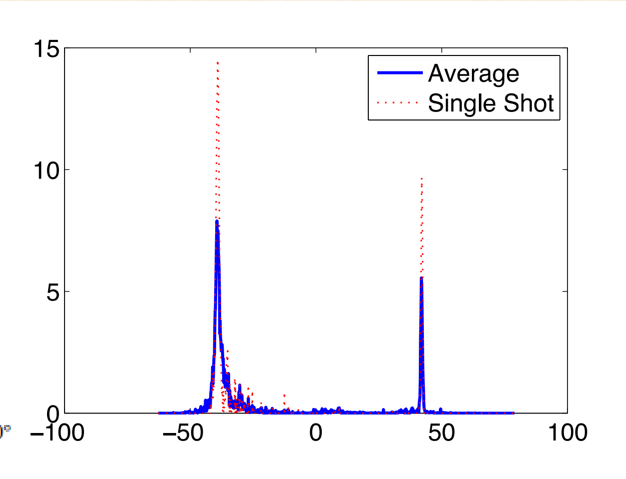


2 colors are simultaneous, important for stimulated emission. Line separation larger than bandwidth. Delay effect reduces bandwidth.

Spectral Properties







Seeded!
Pulse energy down to 130 uJ
Spectral brigthness x 2!

Max separation:
1% at HXR
3% at SXR
10-15 eV bandwidth

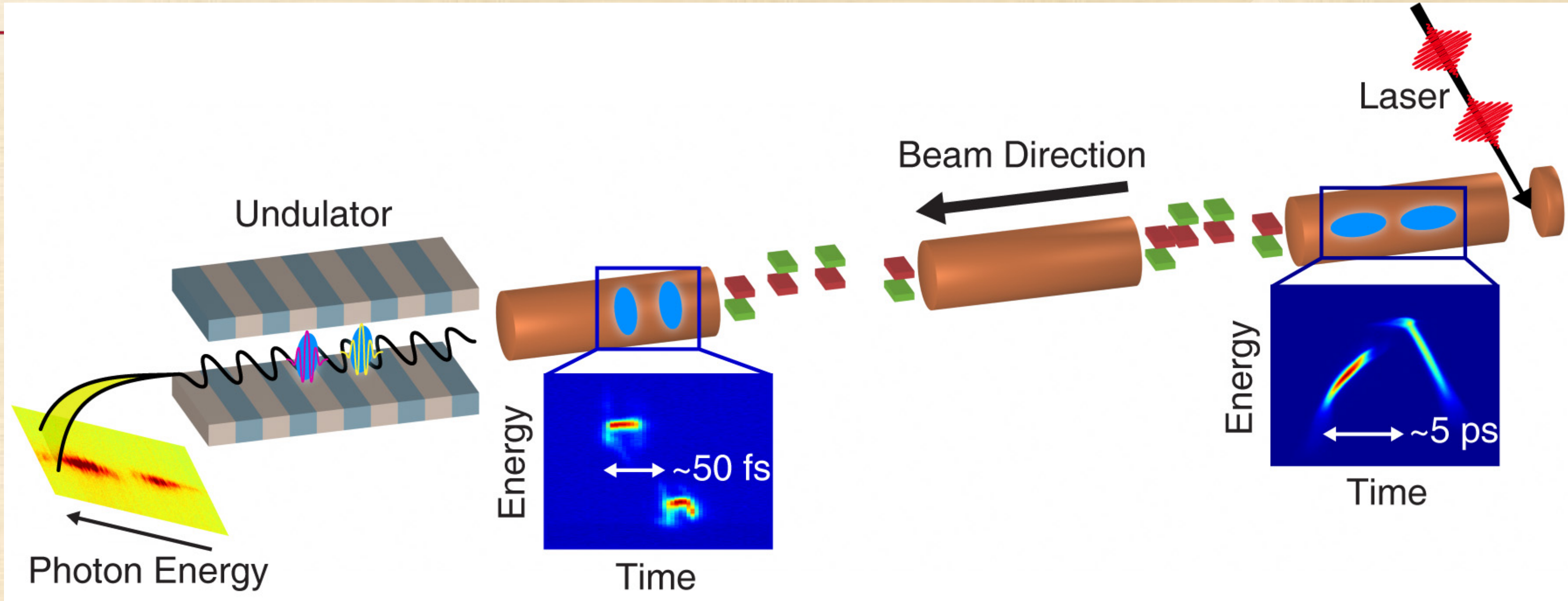
Important for
Multiwavelength
Anomalous Dispersion

PRL 113, 254801 (2014) PHYSICAL REVIEW LETTERS week ending 19 DECEMBER 2014

Demonstration of Single-Crystal Self-Seeded Two-Color X-Ray Free-Electron Lasers

A. A. Lutman,* F.-J Decker,† J. Arthur, M. Chollet, Y. Feng, J. Hastings, Z. Huang, H. Lemke, H.-D. Nuhn,
A. Marinelli, J. L. Turner, S. Wakatsuki, J. Welch, and D. Zhu

Twin-Bunch FEL



ARTICLE

Received 16 Oct 2014 | Accepted 22 Jan 2015 | Published 6 Mar 2015

DOI: 10.1038/ncomms7369

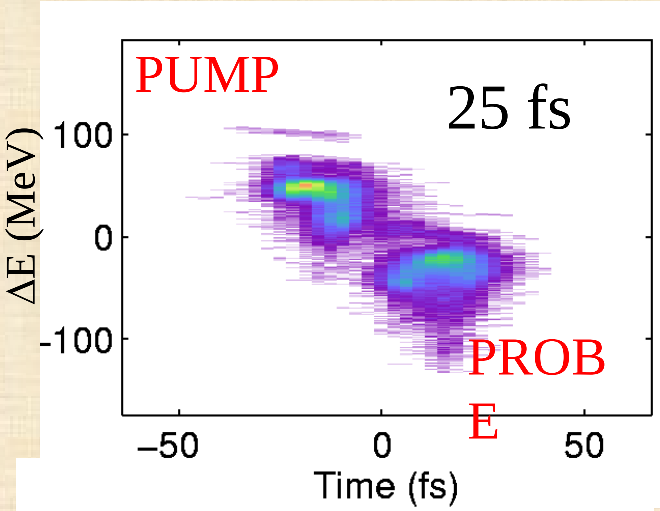
OPEN

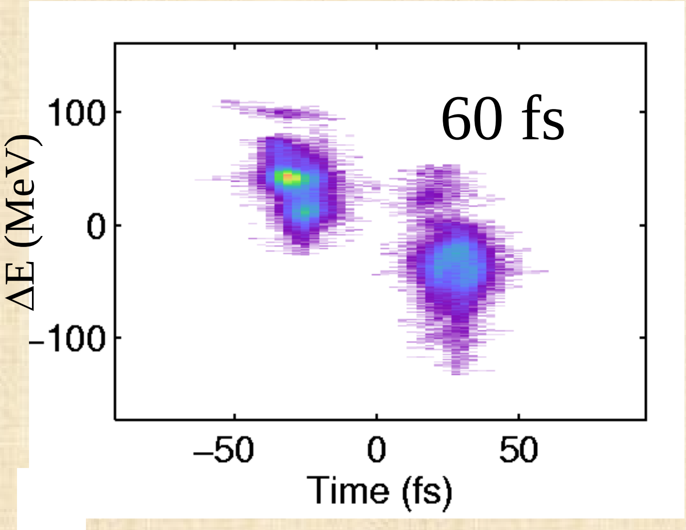
High-intensity double-pulse X-ray free-electron laser

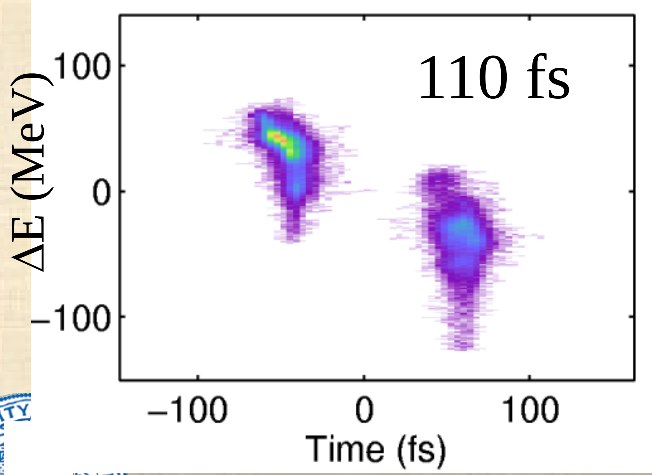
A. Marinelli[1], D. Ratner[1], A.A. Lutman[1], J. Turner[1], J. Welch[1], F.-J. Decker[1], H. Loos[1], C. Behrens[1,2], S. Gilevich[1], A.A. Miahnahri[1], S. Vetter[1], T.J. Maxwell[1], Y. Ding[1], R. Coffee[1], S. Wakatsuki[1,3] & Z. Huang[1]

nature COMMUNICATIONS

Time Delay Control for X-Ray Pump/X-Ray Probe Experiments





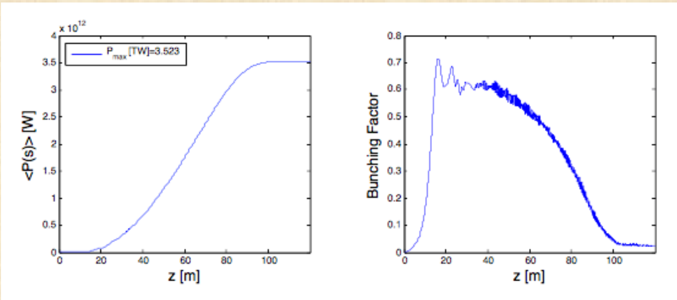


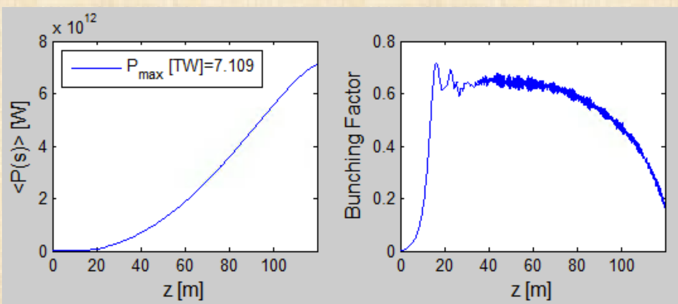
$$\Delta T_{final} = \frac{\Delta T_{initial}}{C_{factor}} + \Delta T_{GAP} \times \frac{1}{E}\frac{dE}{dt}_{wakes} \times \frac{R56}{c}$$

Twin-Bunch FEL

- Using the two-bunch two colors technique in a pump probe configurations with 0 to 100 fs variable delay, S. Boutet et al. have recently imaged in great detail molecular radiation damage. (S. Boutet, private communication)

TW FELs with the "super-undulator"





Work in progress: Claudio Emma, Juhao Wu, Claudio Pellegrini.

To maximize the peak power in a tapered FEL we use a helical superconducting undulator, 2 cm period, 1 m long modules, with superimposed quadrupole field to minimize the breaks between modules and diffraction losses. Using standard LCLS beam parameters -4 kA, 14 GeV, 1.5 Å, 0.4 mm-mrad emittance- we obtain 25 mJ in a 6 fs pulse, 3.5 TW, peak power and 7% energy transfer efficiency.

The lower plots show that by controlling the effect causing saturation we can almost double the efficiency and the intensity/pulse.

Conclusions

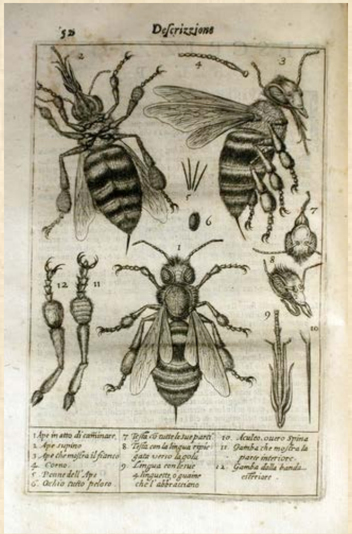
As we have seen in this symposium, X-ray FELs give us an unprecedented view of the structure and dynamics of matter at the Ångstrom-fs space-time scales. The flexibility of the system allows us to optimize the X-ray pulse intensity, time duration and spectral properties to the experiments being done.
Much has been learnt during the last six years, to improve the FEL characteristics, and generate scientific breakthroughs in physics, chemistry and biology. I am confident that in the years to come even more will be accomplished by our community.

Let me try to summarize how much has been done:

390 years of exploration of the microscopic world

Our only instrument for about 200,000 years. Resolution: ~0.1 mm, 0.1 sec

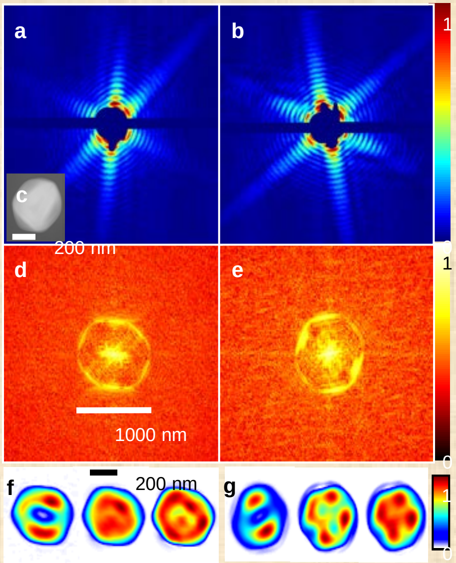
Galileian microscope, 1625.



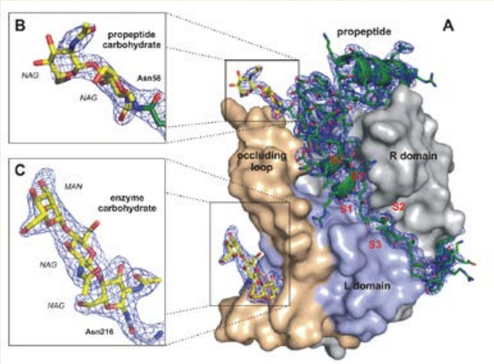
F. Stelluti, 1625

Resolution: ~0.01 mm, 0.1 sec

LCLS, 2009



Seibert et al, *Nature*, 470, 78 (2011)



Radecke et al, *Science* 339, 6116 (2012)

Resolution: ~few Å, few fs

Acknowledgements

I wish to express my gratitude to many friends and colleagues that have helped me during many years:

At SLAC: Herman Winick, Max Cormacchia, John Galayda, Paul Emma, Heinz-Dieter Nuhn, Tor Raubenheimer, John Arthur, Jo Stohr, Jerry Hastings and the many other scientists and engineers, too many to name them all, who transformed theoretical and small scale experimental results in the magnificent research tool that is LCLS today; Burt Richter, Artie Bienenstock, Keith Hodgson, who had the vision to support the project through difficult years.

At UCLA: Jamie Rosenzweig, Chan Joshi, David Cline and the many graduate and undergraduate students who did almost all the work, among them David Robin, Mark Hogan, Aaron Tremaine, Alex Murock; Joe Rudnick and Clarence Hall, chair and dean, who gave me the support I needed to setup my lab when I moved to UCLA.