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Cours/Lecture Series

2001/2002 ACADEMIC TRAINING PROGRAMME

LECTURES SERIES

SPEAKER	: R.P. Walker / Rutherford Laboratory, UK
TITLE	: **Introduction to free electron lasers**
TIME	: 15, 16, 17 May from 11:00 hrs to 12:00 hrs
PLACE	: Council room, bldg. 503 on 15 May, Auditorium, bldg. 500 on 16 and 17 May

ABSTRACT

The Free-electron laser (FEL) is a source of coherent electromagnetic radiation based on a relativistic electron beam. First operated 25 years ago, the FEL has now reached a stage of maturity for operation in the infra-red region of the spectrum and several facilities provide intense FEL radiation beams for research covering a wide range of disciplines. Several projects both underway and proposed aim at pushing the minimum wavelength from its present limit around 100 nm progressively down to the 1 Angstrom region where the X-ray FEL would open up many new and exciting research possibilities. Other developments aim at increasing power levels to the 10's of kW level. In this series of lectures we give an introduction to the basic principles of FELs and their different modes of operation, and summarise their applications and current state of development.

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Introduction to Free-Electron Lasers

Richard P. Walker, Diamond Light Source, U.K.

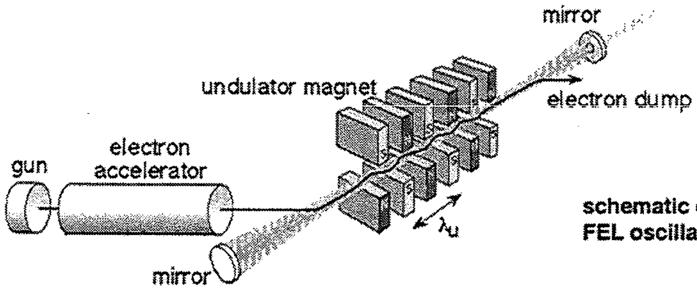
- ✻ Introduction
- ✻ Historical Background
- ✻ Basic FEL Physics
- ✻ Low-Gain FELs
- ✻ High-Gain FELs
- ✻ Technical Challenges for Short Wavelength SASE FELs
- ✻ Harmonics, Seeding and Short Pulse Generation

Scope of the Lectures

- Introductory
- Basic concepts and phenomena
- Very little maths
- Historical development
- Different FEL types
- Applications
- Technology
- World scene
- Future directions

So, what is a Free-Electron Laser ?

- a device which amplifies short-wavelength radiation by stimulated emission when the radiation and a relativistic electron beam propagate together through an "undulator" or "wiggler" magnet:

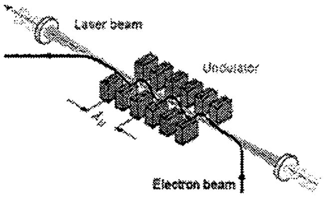


schematic of an FEL oscillator

Not a coventional laser ! - electrons are 'free' in the sense that they are not bound to atoms as in conventional lasers

(but not completey free since they are under the influence of magnetic forces which cause them to radiate)

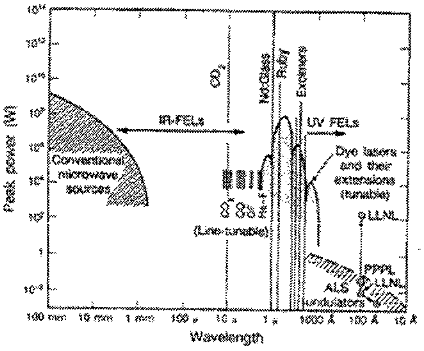
Main features of FELs



Unlike conventional lasers:

- the wavelength of the radiation depends on the electron beam energy and magnetic field strength and hence is **continuously tuneable**
- FELs are capable in principle of being extended to very **short wavelengths.** FELs have operated from the mm-wave regime through infra-red and visible and into the vacuum ultra-violet (100 nm) and various projects aim at 1Angstrom.
- no lasing medium, hence no breakdown problems;
  possibility of obtaining **high peak and average power levels**
- **flexible time structure** of the radiation: pulse length and repetition frequency is determined by that of the electron beam and hence can be manipulated relatively easily

Role of the FEL vs. Other Light Sources



Curent Status:

The main role for the FEL lies in the

- far-infrared (FIR) (10 μm - 1 mm) → mature technology; several user facilities
- vacuum ultra-violet (VUV) (200 - 10 nm) → Current R&D
- X-ray regions (10 nm - 0.1 nm) → Proposed future R&D

Applications of the FEL

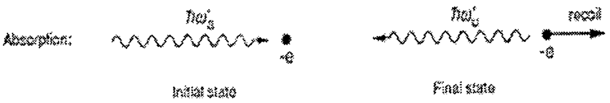
- Physics/Chemistry
  - IR : solid state physics, semiconductors, surface chemsitry etc.
  - VUV: electronic excitations, photochemistry etc.
  - Xray: atomic physics, structure determination etc.
- Biology
  - microscopy, DNA studies, cell response
- Medicine
  - surgery, ablation, photo-therapy (IR)
- Industrial
  - materials processing, microfabrication, photochemistry etc. (IR,UV)
- High power microwave applications
  - power beaming to satellites, plasma heating
  - remote atmospheric sensing etc.
- Accelerators
  - Inverse FEL, Two-beam accelerator
- Nuclear physics
  - gamma ray production by Compton backscattering
- Military (SDI/"Star Wars")

First Description of the FEL: Stimulated Compton Scattering

The undulator magnetic field is seen by the relativistic electron as an electromagnetic wave

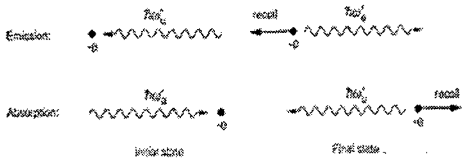
The electrons can either -
i) scatter an undulator "photon" in the forward direction and loose momentum (Emission) :

or,
ii) scatter a laser photon in the backward direction and gain momentum (Absorption) :



J.M.J. Madey, J. Appl. Phys., 42 (1971) 1906.

Stimulated Compton scattering

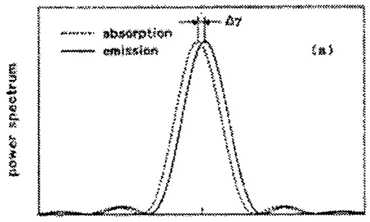


Because of electron recoil:

$$\hbar\omega'_e < \hbar\omega'_u \quad \text{and} \quad \hbar\omega'_a > \hbar\omega'_u$$

i.e. emission and absorption of a photon of a given frequency requires slightly different "undulator photon" energies, and hence different electron energies.

The probability curves for emission/absorption are therefore slightly shifted in energy:

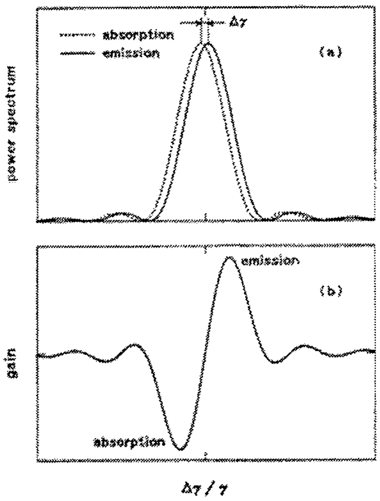


Stimulated Compton scattering

Thus, the "Gain Curve"
i.e. rate of (emission - absorption) is the derivative of the spontaneous emission curve :

"Madey's Theorem"

- a useful general result that allows the influence on the gain to be determined from the effect on the spontaneous emission spectrum (which is easier to calculate, and measure).



Stimulated Compton scattering

Madey's work is closely related to a proposal for Stimulated Compton scattering of a relativistic electron beam from microwave radiation

(Pantell et al., 1968):

itself following work going back to Kapitza and Dirac (1933)

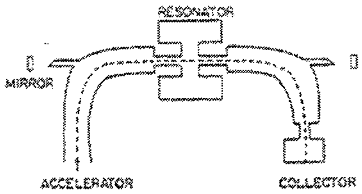


Fig. 1. Physical configuration for stimulated Compton scattering at infrared wavelengths.

e.g. E = 17.8 MeV, λ_0 = 10 cm, λ = 20 µm

"*The advantages of a Compton laser are that it is voltage tunable over a wide range and may provide intense, coherent radiation in portions of the spectrum where other sources are not readily available*"

The main difference of Madey's proposal with respect to earlier work is the use of a static magnetic field, rather than an electromagnetic one.

R.H. Pantell et al., IEEE J. Quantum Electr. QE-4 (1968) 905.

But is it a "Laser" ?

The first analysis of the FEL (Madey, 1971) was made using quantum theory, and the physical principles of FEL operation were considered different to those of earlier devices.

It was noted however that $\hbar$ cancelled out of the final equations and many doubts were expressed whether it was a 'true' laser ...

Later, a fully classical picture was developed* (Hopf et al., Colson, 1976):

> ***"the quantum theory of a free-electron laser is extremely tedious, and is neither desirable nor necessary"   Hopf et al., 1976***

The physical picture is of electrons **bunching** on the scale of the radiation wavelength and so emitting radiation coherently.

Slightly later a connection was made with earlier theoretical work showing that the FEL did indeed operate according to the same principles as earlier devices (Kroll et al., 1978)and so it eventually became clear that the FEL was essentially the latest in a long series of electron beam devices that generate coherent radiation.

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* *but also separately in R.B. Palmer, J. Appl. Phys. 43 (1972 3014.*

Bunching

For electrons having different longitudinal positions the Electric field of the emitted radiation depends on the phase with respect to the radiation wavelength: $\phi = 2\pi\, z/\lambda$

Electric field: $E = E_o \sum_{k=1}^{N_e} \exp(i\phi_k) = E_o B$ Intensity: $I = I_o |B^2|$

B → Bunching factor

1) **uniform distribution:** $B = 0, \quad I = 0$

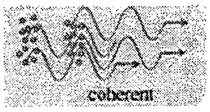
2) **random distribution:**

$\langle B \rangle = 0, \quad \langle |B^2| \rangle = N_e, \quad \boxed{I = I_o N_e}$

usual case:
spontaneous emission,
synchrotron radiation etc.
Intensity ~ N_e

3) **electrons all in phase:**

$\langle B \rangle = N_e, \quad \langle |B^2| \rangle = N_e^2, \quad \boxed{I = I_o N_e^2}$

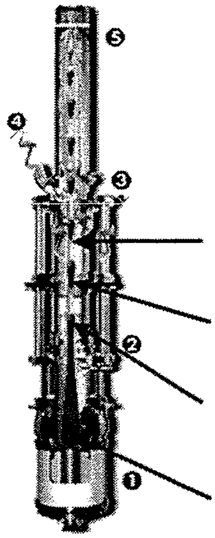


coherent emission:
Intensity ~ N_e^2

Historical Background to the FEL - the Klystron

In the first microwave devices (triode) a bunched beam was produced by direct modulation of the beam intensity.

In 1937 the klystron was invented capable of much higher frequency operation, using a new technique of <u>velocity modulation</u>:



output cavity - the bunched beam delivers power to the electromagnetic field

drift region - velocity modulation converts to density modulation

input cavity - r.f. voltage produces a velocity modulation

d.c. electron gun

The Travelling Wave Tube (Kompfner, 1947; Pierce, 1950)

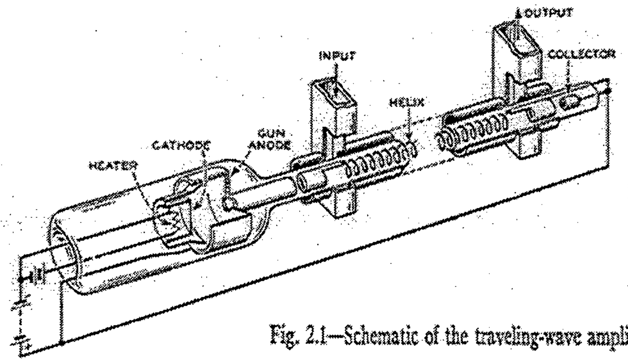
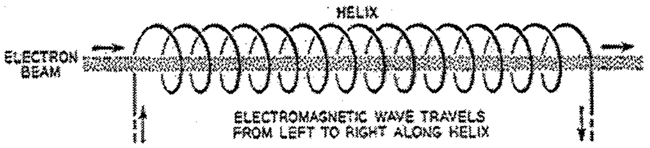


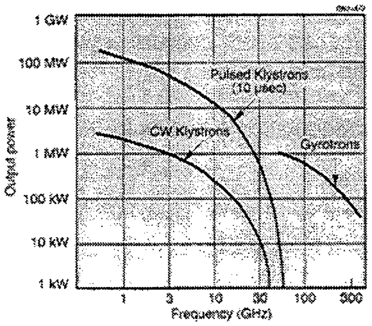
Fig. 2.1—Schematic of the traveling-wave amplifier.

the helix slows down the electromagnetic wave allowing synchronism with the electron beam

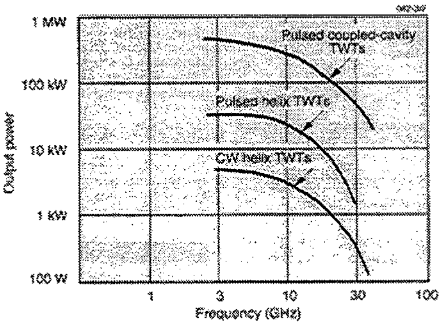


In these devices, the electromagnetic radiation is either contained in cavities (klystron, magnetron) or propagated along a loaded waveguide (TWT) to slow down the radiation to allow synchronism between radiation and electron beams ("slow-wave" structures).

The minimum wavelength is limited by the difficulty of fabricating small cavity and waveguide structures:



High-power Klystrons and Gyrotrons



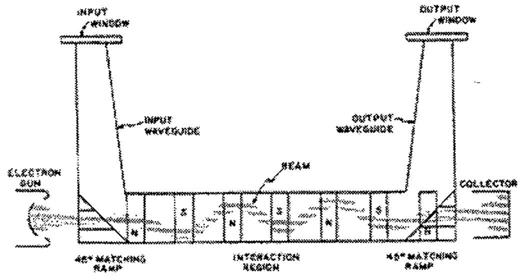
Traveling-wave tubes (TWTs)

The Ubitron

Undulating Beam Interaction

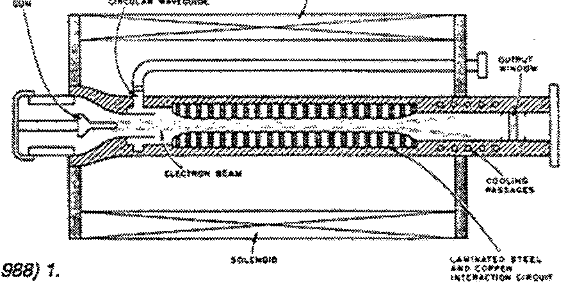
Invented in 1957 (Phillips).

A "fast wave" structure with a new interaction mechanism - undulation of the electron beam.



The first S-band Ubitron (3 GHz, λ ~ 10 cm)

both a microwave tube and a non-relativistic FEL amplifier.



V-band Ubitron,
54 GHz, λ ~ 5 mm
70 kV beam energy
150 kW output power

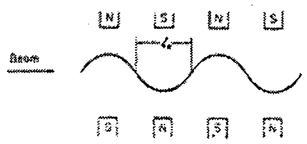
R.M. Phillips, Nucl. Instr. Meth. A272 (1988) 1.

The Undulator

Applications of the Radiation from Fast Electron Beams

H. Motz
Microwave Laboratory, Stanford University, California
(Received July 3, 1950)

Invented in 1951 by Motz as a means of producing coherent millimetre waves from a pre-bunched electron beam.

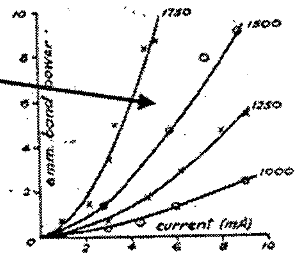


H. Motz,J. Appl. Phys. 22 (1951) 527.

Later experiments (1961) with a 3-5 MeV electron beam showed semi-coherent emission of 6-8 mm band radiation with

Intensity ~ (current)$^{1.7}$

indicating that the bunch length was about 10 mm.



Visible radiation was also generated using a 100 MeV electron beam (Motz, 1953)

H. Motz and D. Walsh, J. Appl. Phys. 33 (1962) 978.

The Undulator Amplifier

It was also shown (Motz, 1959) using the same analysis as for a TWT, that the undulator could be used to amplify a radiation beam - "***fast wave amplification***".

Essentially this was a relativistic FEL amplifier; the feeding back of the generated radiation to produce bunching at any wavelength was not however considered.

This could have been the start of the FEL development, but as Motz pointed out:

"*in the relativistic range amplification from undulating electrons leads to small gains .. radiation from pre-bunched electrons seems a more hopeful approach..*"

H. Motz and M. Nakamura, Symposium on Millimeter Waves, Brooklyn, 1959.

Historical Background to the FEL

In conclusion,

although the FEL follows on naturally from earlier work on stimulated compton scattering, it also has roots in both the Undulator Amplifier (a relativistic FEL amplifier) and Ubitron (a non-relativistic FEL amplifier) - both fast-wave structures - which themselves had close similarities with the Travelling Wave Tube (slow-wave structure).

FEL Operating Regimes

A. Low-gain (Compton)

single electron interaction; G~ z^3; gain per pass small (G<< 1)
usually are **oscillators**

B. High-gain (Compton)

collective interaction or "instability"; space-charge effects negligible; G ~ exp(z), G >> 1,

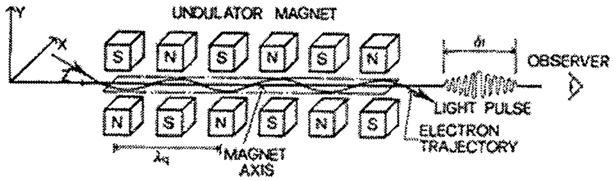
can be **amplifiers**, or build up from noise ("super-radiant" or "Self Amplified Spontaneous Emission", **SASE**)

C. High-gain (Raman)

"three-wave" device; electron beam is sufficiently dense, and low energy, that the collective interaction with space-charge (plasma) oscillations waves is dominant

can be **amplifiers**, **oscillators**, or **SASE**

Electron Motion in an Undulator



vertical sinusoidal field component: $B_y = B_o\cos(kz), \quad k = 2\pi/\lambda_o$

equation of motion from $\underline{F} = e(\underline{E}+\underline{v}\wedge\underline{B})$ $\quad \ddot{x} = -\frac{e}{\gamma m}\dot{z}B_y \quad \left\{\gamma = \frac{E}{mc^2} = \frac{E[MeV]}{0.511}\right\}$

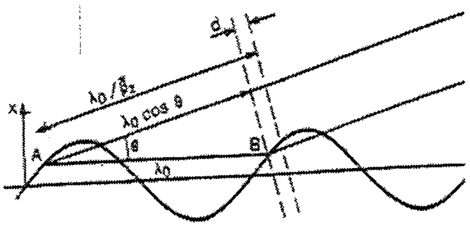
integrating gives the velocity: $\quad \dot{x} = -\frac{eB_o}{\gamma m}\frac{\cos(kz)}{k} \qquad \beta_x = \frac{\dot{x}}{c} = \frac{K}{\gamma}\cos(kz)$

where: $\quad K = \frac{eB_o\lambda_o}{2\pi mc} = 0.93\,B_o[T]\lambda_o[cm]$ (dimensionless)

since $\beta_x^2+\beta_z^2=\beta^2$ (= constant) $\quad \bar{\beta}_z \cong \beta\left(1-\frac{K^2}{4\gamma^2}\right) = 1-\frac{1}{2\gamma^2}-\frac{K^2}{4\gamma^2}$

NB] the average velocity along z is reduced due to the undulating motion

Interference Condition



distance between wavefronts emitted from points A and B $\quad d = \frac{\lambda_o}{\bar{\beta}_z} - \lambda_o\cos\theta$

constructive interference if $\quad d = n\lambda$

using the previous result $\quad \bar{\beta}_z = 1-\frac{1}{2\gamma^2}-\frac{K^2}{4\gamma^2}$

$$\boxed{\lambda = \frac{1}{n}\frac{\lambda_o}{2\gamma^2}\left(1+\frac{K^2}{2}+\gamma^2\theta^2\right)}$$

in the ideal case, on-axis, n = 1, 3, 5 etc.

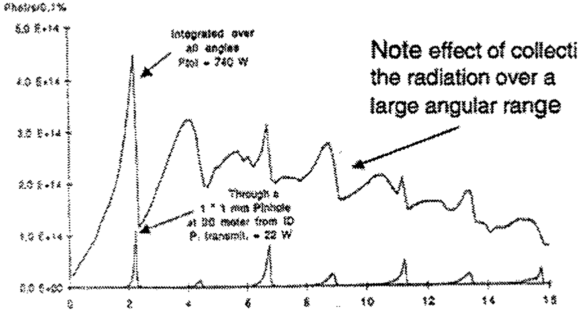
Spontaneous (Undulator) Radiation

$$\boxed{\lambda = \frac{1}{n}\frac{\lambda_o}{2\gamma^2}\left(1+\frac{K^2}{2}+\gamma^2\theta^2\right)}$$

The spontaneous radiation emitted in an undulator consists of a series of harmonics of a fundamental, which has a wavelength much smaller than the magnet period, λ_o ($\gamma >> 1$)

$$\left\{\gamma = \frac{E}{mc^2} = \frac{E[MeV]}{0.511}\right\}$$

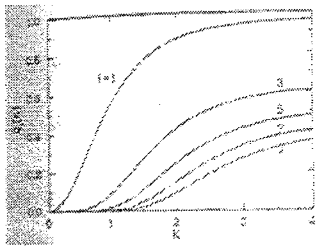
Typical undulator radiation spectra



Note effect of collecting the radiation over a large angular range

photon energy

Number of harmonics in the spectrum increases rapidly with K (~ K^3):



The Helical Undulator

$$\underline{B} = B_o\left(\cos(k_o z)\hat{x} + \sin(k_o z)\hat{y}\right) \quad k_o = 2\pi/\lambda_o$$

$$\underline{\beta} = -\frac{K}{\gamma}\left(\cos(k_o z)\hat{x} + \sin(k_o z)\hat{y}\right)$$

$$\beta_x^2 + \beta_y^2 + \beta_z^2 = \beta^2 \quad (= \text{constant})$$

$$\bar{\beta}_z = 1 - \frac{1}{2\gamma^2} - \frac{K^2}{2\gamma^2}$$

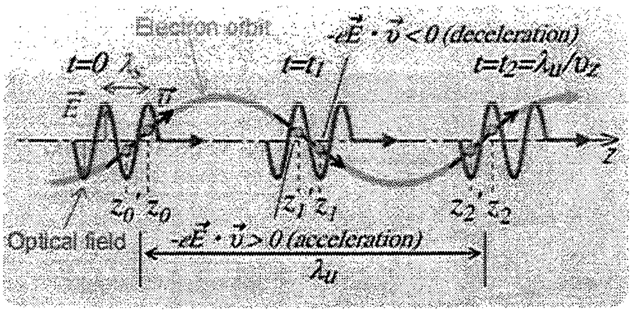
$$\boxed{\lambda = \frac{\lambda_o}{2\gamma^2}\left(1+K^2+\gamma^2\theta^2\right)}$$

NB] Higher symmetry results in only one harmonic on-axis

Resonance Condition

$$\boxed{\lambda = \frac{\lambda_o}{2\gamma^2}\left(1+\frac{K^2}{2}\right)}$$

The same equation gives also the condition for **synchronism** ("resonance condition") between an electron and an external radiation beam :
the electrons slip by one radiation wavelength for each magnet period.



Since:

$$\dot{\gamma} = \frac{e}{mc}\underline{\beta}\bullet\underline{E}$$

the transverse motion allows an energy exchange between the electron and radiation beams.

A systematic energy exchange can therefore take place, which depends on the initial phase of the electrons with respect to the radiation, resulting in an <u>energy modulation</u>, and hence <u>density modulation</u> (bunching) on the scale of the radiation wavelength.

The FEL Interaction

consider for simplicity a helical magnet:

$$\underline{B} = B_o\left(\cos(k_o z)\hat{x} + \sin(k_o z)\hat{y}\right) \quad k_o = 2\pi/\lambda_o$$

$$\underline{\beta} = -\frac{K}{\gamma}\left(\cos(k_o z)\hat{x} + \sin(k_o z)\hat{y}\right)$$

$$\underline{E} = E_o\left(\sin(kz-\omega t+\phi_o)\hat{x} + \cos(kz-\omega t+\phi_o)\hat{y}\right) \quad k = 2\pi/\lambda = \omega/c$$

$$\dot{\gamma} = \frac{e}{mc}\underline{\beta}\bullet\underline{E}$$

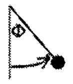
$$\dot{\gamma} = -\frac{eE_oK}{\gamma mc}\sin\Phi \qquad \Phi = (k+k_o)z - \omega t + \phi_o$$

$\Phi = \phi_o$ when $(k+k_o)z = \omega t$

i.e. $\gamma = \gamma_r$ with $\lambda = \dfrac{\lambda_o}{2\gamma_r^2}(1+K^2)$ same as the interference condition.

The FEL Interaction

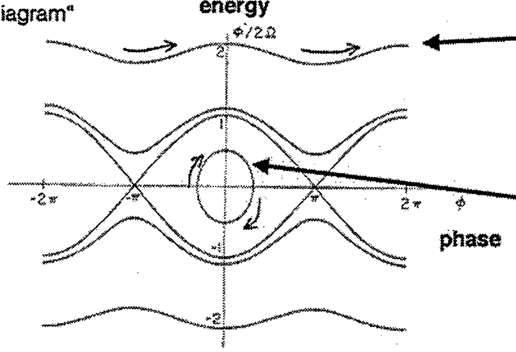
for small deviations from resonance define $\eta = (\gamma - \gamma_r)/\gamma_r$



$$\left.\begin{aligned} \eta &= -\frac{eE_oK}{\gamma_r^2 mc}\sin\Phi \\ \dot{\Phi} &= \frac{4\pi c}{\lambda_o}\eta \end{aligned}\right\} \ddot{\Phi} = -\Omega^2 \sin\Phi$$

= the motion of a simple pendulum; same as synchrotron motion in a storage ring

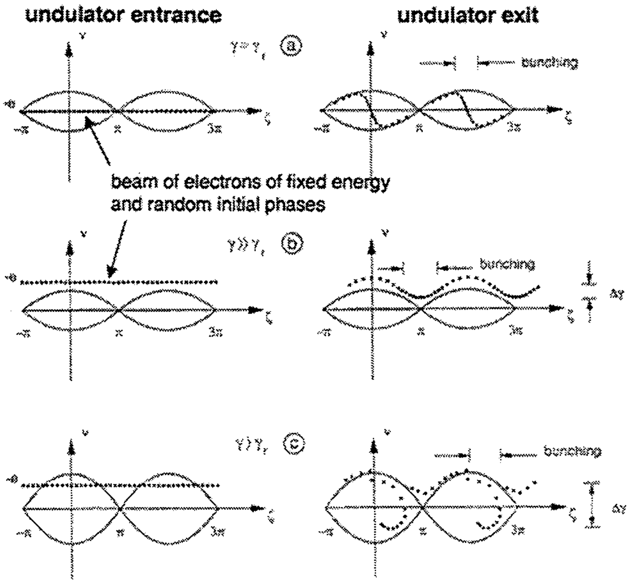
"phase space diagram"



for large Φ,electrons on open trajectories

for small Φ, electrons are "trapped" on closed trajectories (simple harmonic motion)

Motion in phase space



beam of electrons of fixed energy and random initial phases

On-resonance :

- **bunching**
- **no net energy exchange**

Far from resonance :

- **no electrons trapped**
- **some bunching**
- **small energy transfer**

Close to resonance :

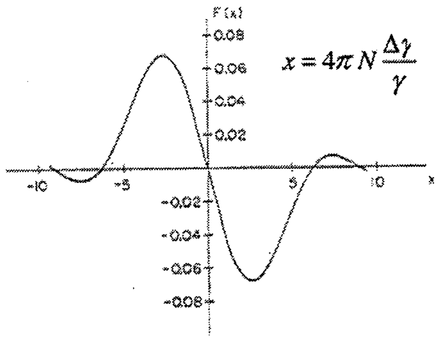
- **many electrons trapped**
- **strong bunching**
- **large induced energy spread**

Small Signal Gain

Averaging the energy loss/gain over all phases,and dividing by the radiation beam intensity results in the following expression for the Gain per pass:

$$G = -\frac{32\sqrt{2}\pi^2\lambda^{3/2}\lambda_o^{1/2}}{\Sigma}\frac{K^2}{(1+K^2)^{3/2}}\frac{I_{peak}}{I_A}N^3F(x)$$

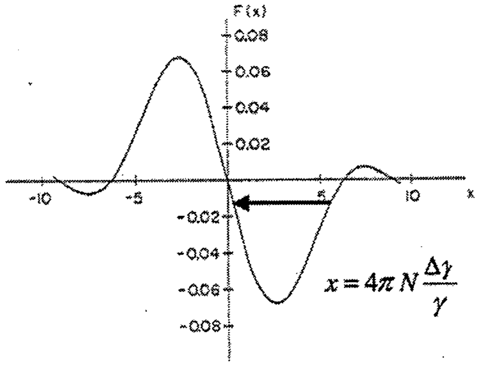
- depends linearly on peak current
- decreases with decreasing wavelength



$$x = 4\pi N\frac{\Delta\gamma}{\gamma}$$

NB] F(x) < 0 means gain !

The Gain Curve



$$x = 4\pi N\frac{\Delta\gamma}{\gamma}$$

- the maximum energy transfer from an electron to the radiation is

$$(\Delta\gamma)_{max}/\gamma \approx 1/2N$$

- the maximum power that can be extracted is therefore:

$$P_{laser} = (1/2N)\, I_b\, E$$

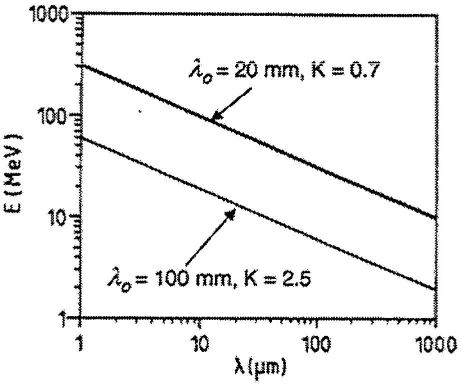
- the energy spread of the electrons must be less than this:

$$\sigma_\gamma/\gamma < 1/2N$$

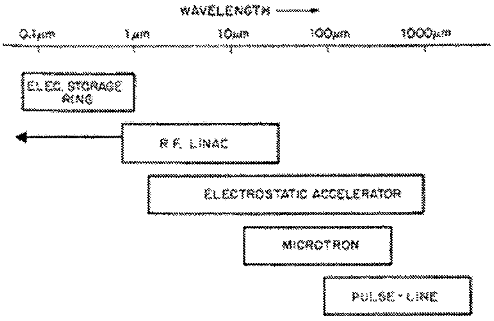
Electron beam energy and FEL wavelength

$$\lambda = \frac{\lambda_o}{2\gamma^2}\left(1+\frac{K^2}{2}\right) \qquad K = 0.93\,B_o[T]\,\lambda_o[cm]$$

Due to magnet technology reasons, as the period reduces, so does the field amplitude, and hence *K*



choice of electron source for different radiation wavelengths :



Electron Beam Quality

1) **small energy spread** $\sigma_\gamma/\gamma < 1/2N$

2) **small transverse sizes**

- for good overlap with the photon beam $\sigma_{x,y} < \Sigma$
- because focussing effects in the undulator cause position offsets to turn into angular offsets (and v.v.)

3) **small angular divergence:**

electrons travelling at an angle θ to the axis have effectively a lower velocity:

$$\frac{\Delta\gamma}{\gamma} = \frac{\gamma^2\theta^2}{2(1+K^2/2)}$$

and so to stay in resonance:

$$\left\langle \theta^2 \right\rangle^{1/2} \le \frac{(1+K^2/2)^{1/2}}{\gamma\sqrt{N}}$$

4) **high peak current**

Electron Beam Quality

Requirements on angular deviation and energy spread can be derived from the effect on the spontaneous radiation spectrum (Madey theorem):

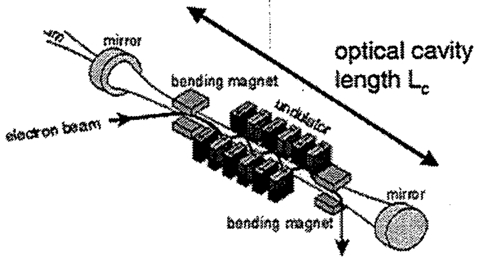
given: $$\lambda = \frac{1}{n}\frac{\lambda_o}{2\gamma^2}\left(1+\frac{K^2}{2}+\gamma^2\theta^2\right)$$

it follows: $$\frac{\Delta\lambda}{\lambda} = 2\frac{\Delta\gamma}{\gamma} \quad \text{and} \quad \frac{\Delta\lambda}{\lambda} = \frac{\gamma^2\theta^2}{1+K^2/2}$$

comparing to the natural linewidth $$\frac{\Delta\lambda}{\lambda} = \frac{1}{N}$$

gives as before $$\frac{\Delta\gamma}{\gamma} < \frac{1}{2N} \quad \text{and} \quad \left(\Delta\theta^2\right)^{1/2} < \frac{(1+K^2/2)^{1/2}}{\gamma\sqrt{N}}$$

Other Requirements



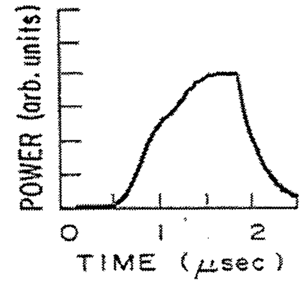
optical cavity length L_c

1) synchronism with the electron beam requires:

$$\frac{2L_c}{c} = \frac{1}{f_{rep.}}$$

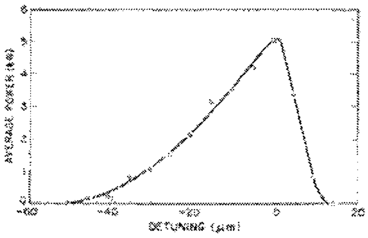
e.g. $L_c = 6.9$ m (LANL)
$f_{rep.} = 214$ MHz

2) sufficiently long macropulse to allow build-up to saturation:



Other Requirements

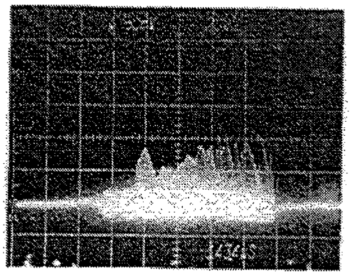
3) correct cavity length



Cavity length detuning curve for the LANL FEL

4) stable electron beam

LANL FEL expts. (1984)
$\lambda = 10\ \mu m$
E = 21 MeV
$I_{peak} = 40$ A
G = 25 %

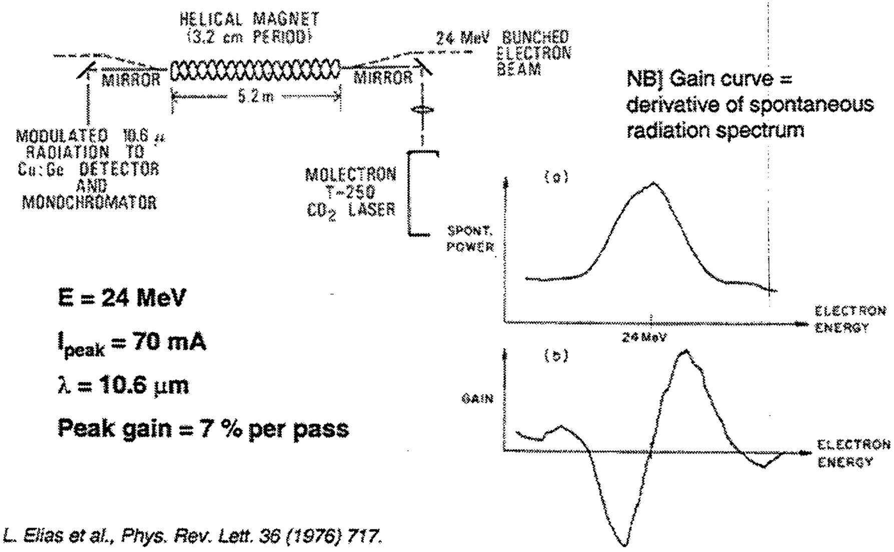


Fluctuations in laser intensity in the LANL FEL:

"Rocky Mountain" effect

due to gun and accelerator variations.

The First FEL Amplifier, Stanford 1976



NB] Gain curve = derivative of spontaneous radiation spectrum

E = 24 MeV

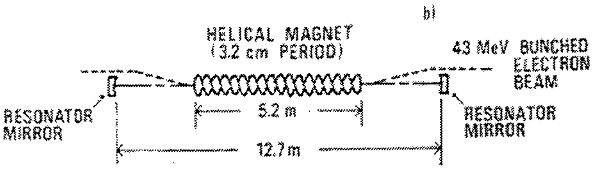
$I_{peak} = 70$ mA

$\lambda = 10.6\ \mu m$

Peak gain = 7 % per pass

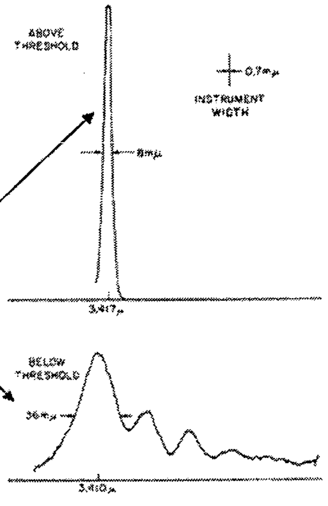
L. Elias et al., Phys. Rev. Lett. 36 (1976) 717.

The First FEL Oscillator, Stanford 1977



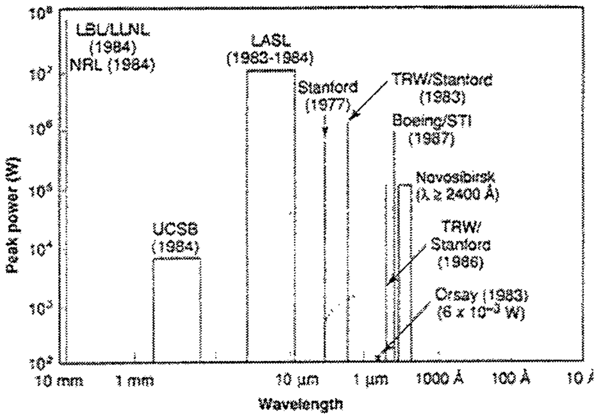
E = 43 MeV
I_{peak} = 2.6 A
λ = 3.4 μm
Average power = 0.36 W
Peak power = 7 kW

Increase in power 10^8



D. Deacon et al., Phys. Rev. Lett. 38 (1977) 892.

The subsequent years

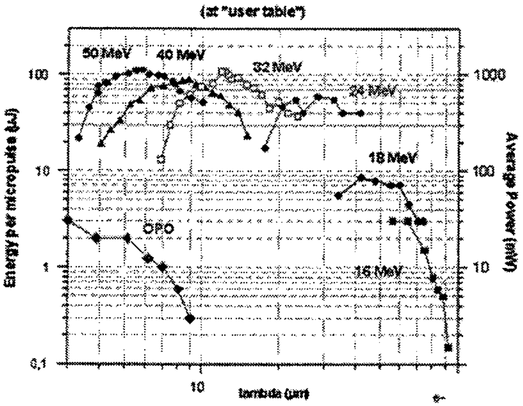


Facilities currently providing FEL radiation for research

Laboratory	Country	Wavelengths	Type
Univ. Duke (i) (ii)	USA	1.7 - 9.1 µm 193 nm - 400 nm	Linac Storage Ring
iFEL	Japan	230 nm - 100 µm	Linac
LURE (i,CLIO (ii)	France	3 - 90 µm 300 - 400 nm	Linac Storage Ring
Univ. Vanderbilt	USA	2.1 - 9.4 µm	Linac
Stanford	USA	3 - 65 µm	SC-linac
FELIX	Netherlands	3.1 - 250 µm	Linac
Jefferson Lab.	USA	3 - 6 µm	SC-linac
Science Univ, Tokyo	Japan	5 - 16 µm	Linac
UCSB	USA	30 µm - 2.5 mm	Electrostatic accelerator
ENEA	Italy	2.1 - 3.6 mm	Microtron

NB] all are low-gain FEL oscillators

CLIO (Orsay, France)



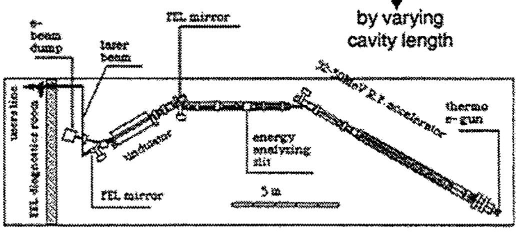
FEL Radiation

Wavelength:	3-90 µm
Max. av. power:	1 W
Max. peak power:	100 MW in 1 ps
Laser pulse length:	0.5 - 6 ps
Spectral width:	0.2 - 5 %

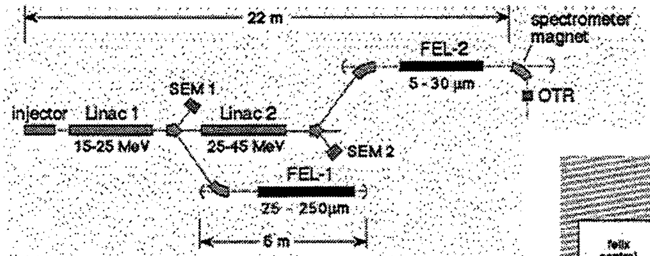
by varying cavity length

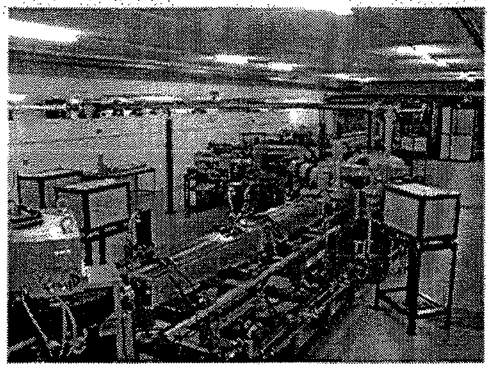
Linac

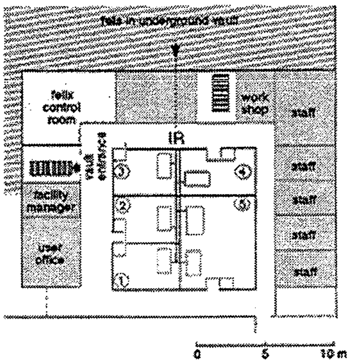
Energy:	16-50 MeV
Peak current:	70 A
Macropulse:	10 µs, 6.25-25 Hz
Micropulse:	10 ps FWHM



FELIX (Netherlands)

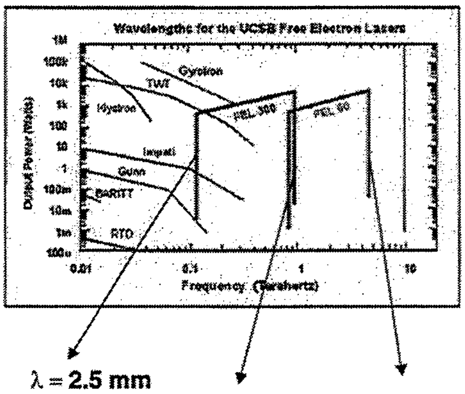






U.C. Santa Barbara

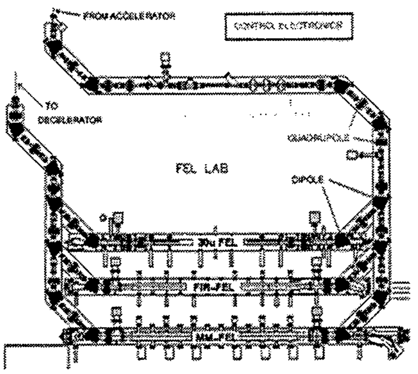
Center for Terahertz Science and Technology
University of California, Santa Barbara



λ = 2.5 mm

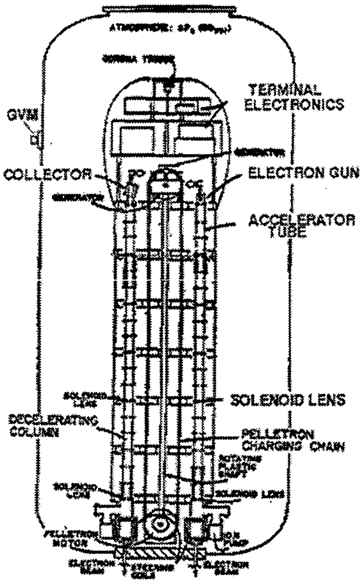
λ = 330 μm

λ = 60 μm



Center for Terahertz Science and Technology
University of California, Santa Barbara

ELECTRON-BEAM	
Energy	2.0 – 6.0 MeV
Current	2.0 A
Emittance	≈10π mm-mr
Energy spread	≈10^{-5}
Recirculation	99.7 %

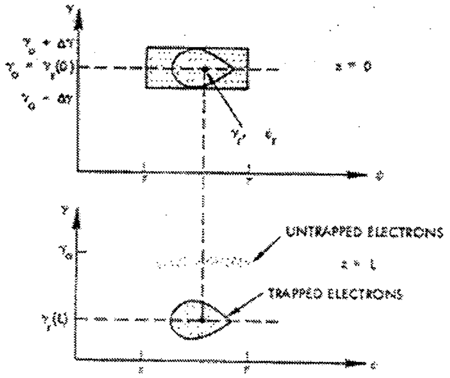


This accelerator uses 99.7 % recycled electrons.

Variations on a Theme - Tapering

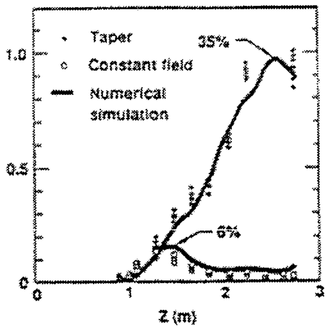
Variation ("tapering") of undulator field (and/or period) along its length to accommodate reduction in electron energy and hence increase output power.

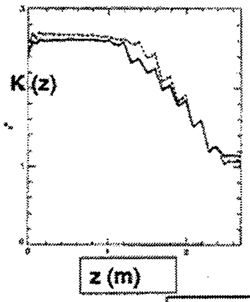
$$\lambda = \frac{\lambda_0(z)}{2\gamma(z)^2}\left(1+\frac{K(z)^2}{2}\right)$$



... trap the electrons in the bucket and then move the bucket down in energy

Tapering

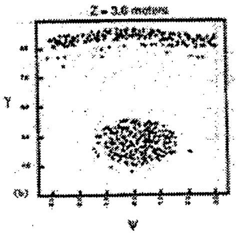




ELF experiment at LLNL (35 GHz), extraction increased from 6 % to 35 %.

other tapering experiments carried out at :
LANL, 10.6 μm, 5 %
Stanford, 1.6 μm, 1.2 %

simulation showing effect of trapping

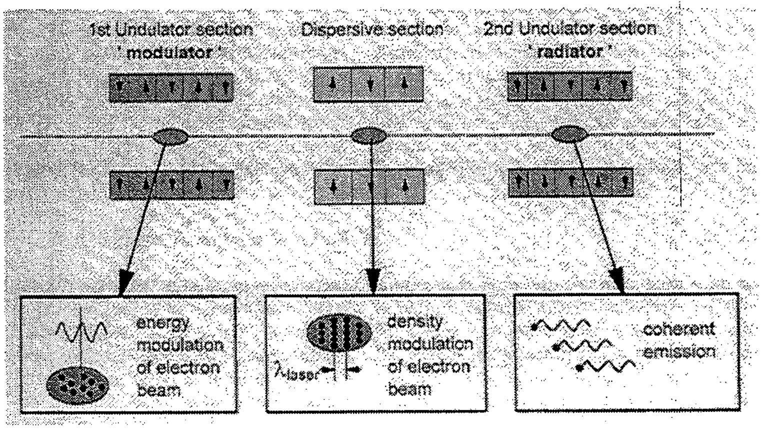


Useful increases in output power, but at the expense of lower gain.

Not sufficient in itself for very high power.

Variations on a Theme - Optical Klystron

A two-section undulator with a region of large dispersion in between - the analog of the microwave klystron (Vinokurov and Skrinsky, 1977):



1st Undulator section ' modulator '

Dispersive section

2nd Undulator section ' radiator '

energy modulation of electron beam

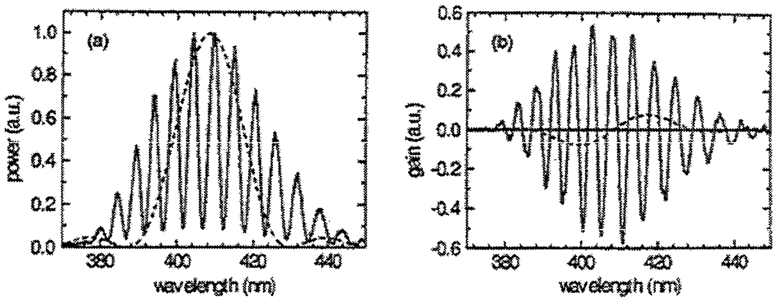
density modulation of electron beam

λ_{laser}

coherent emission

The Optical Klystron

The effect is introduce a modulation into the radiation spectrum and hence into the gain curve:



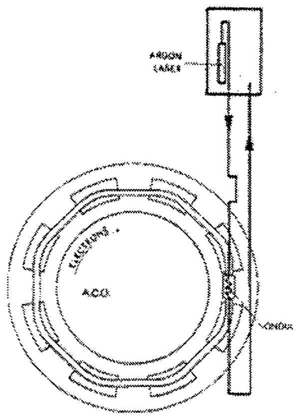
The peak gain is increased significantly but:
- increased sensitivity to electron beam energy spread
- lower extraction efficiency

Used in the majority of storage ring FEL experiments, where the high quality allows a higher gain.

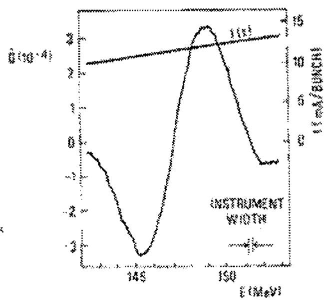
Storage Ring FELs

Because of the high energy, high beam currents and high beam quality, electron storage rings were once thought the key towards achieving high power and short wavelength ...

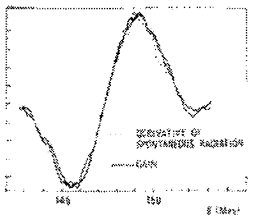
The first successful storage ring FEL was on ACO:



First gain measurements (1981)

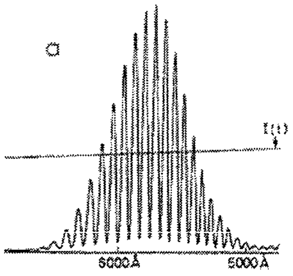


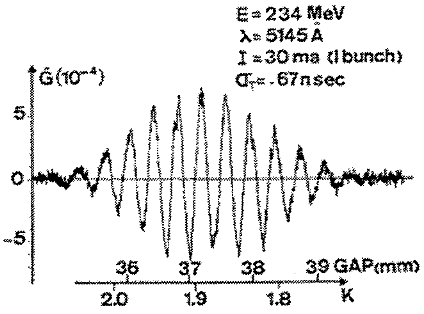
demonstration of the Madey Theorem:



The First Storage Ring FEL, ACO, Orsay

Later measurements using an optical klystron (1983):





First Oscillation June 1983	
Ring energy:	160 MeV
Peak current:	1-3 A
Wavelength:	650 nm
Mirror reflectivity:	99.965 %
Mirror transmission:	$3\ 10^{-5}$

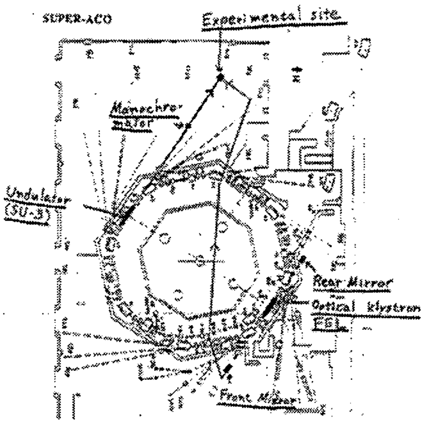
M. Billardon et al., Phys. Rev. Lett. 51 (1983) 1652.

Storage Ring Free-Electron Lasers

Ring	Country	First lasing	Energy (MeV)	λ range (nm)	Status
ACO	France	1983	160-240	655-463	Closed
VEPP-3	Russia	1988	350	690-240	Suspended
SuperACO	France	1989	600-800	690-300	Operating User expts.
TERAS	Japan	1991	231	598	Suspended
UVSOR	Japan	1992	430-600	488-238	Operating
NIJI-IV	Japan	1992	240-310	595-212	FEL dedicated
Duke Univ.	USA	1996	300-800	413-193	Operating User expts.
DELTA	Germany	1999	450-500	470-420	Suspended
ELETTRA	Italy	2000	0.9 - 1.3 GeV	356-189	Operating

Storage Ring FELs - state of the art

Shortest Wavelength	189 nm	ELETTRA
Minimum linewidth	$3\ 10^{-7}$ (rms)	VEPP3
Maximum gain	~ 20 %	ELETTRA, Duke
Maximum peak power	60 kW	VEPP3
Maximum average power	560 mW	ELETTRA
Maximum cw operation	10 h	SuperACO



first pump-probe experiments, FEL+SR, at Super-ACO

Storage Ring FEL Physics

Storage ring FELs are significantly different to single-pass FELs because of the coupling of the FEL and ring dynamics

- changes introduced by the FEL action (e.g. increase in energy spread) remain in the beam and are only damped by long-timescale radiation damping effects
- since at saturation the FEL is operating close to threshold (gain=losses) it is very sensitive to small instabilities and fluctuations in the electron beam (coupled bunch modes, 50 Hz noise etc.)

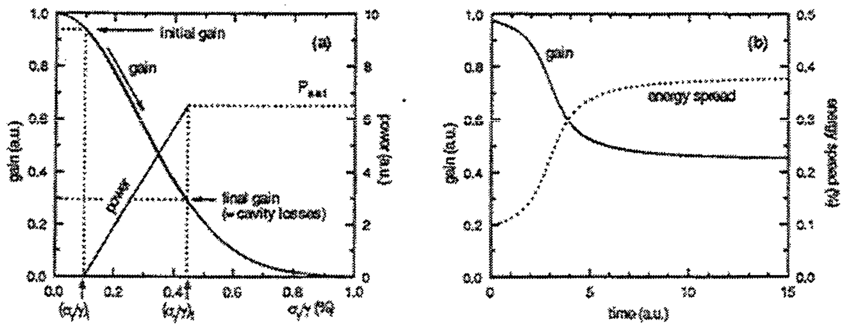
The maximum power of a storage ring FEL is limited by the increased energy spread, which can be related to the total synchrotron radiation power emitted in the whole ring (Renieri criterion) :

$$P_{FEL} \leq \left(\frac{\Delta E}{E}\right) P_{SR}$$

A. Renieri, Nuovo Cimento B53 1979 160.

Saturation in the Storage Ring FEL

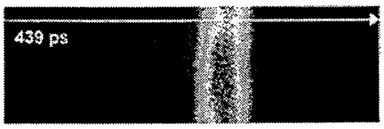
In reality, this limit is not reached because of the increased energy spread and bunch length reduce the gain:



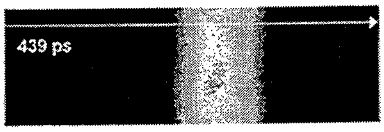
as power builds up,
the gain reduces due to increased energy spread
saturation occurs when gain=losses

Saturation in the Storage Ring FEL

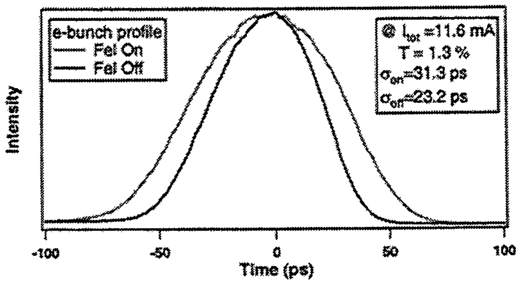
Bunch length measurements at ELETTRA using a double-streak camera:



FEL off



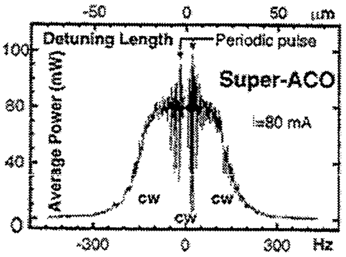
FEL on



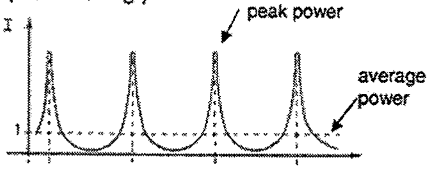
$\sigma_b^{on} / \sigma_b^{off} \approx 1.4$

Some features of SRFELS

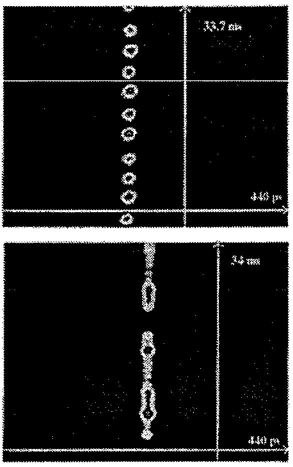
generally the cavity length detuning curve is quite complex



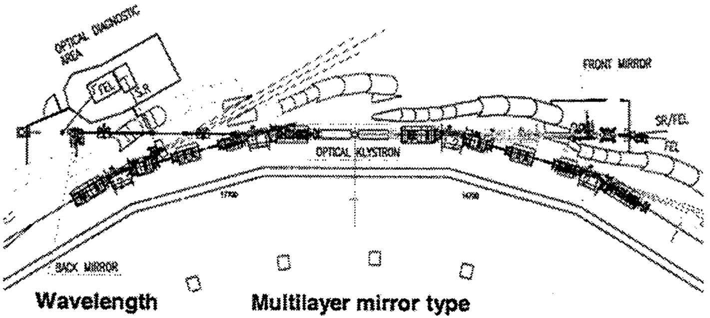
Higher peak power can be obtained by deliberately switching the FEL on/off ("Q-switching")

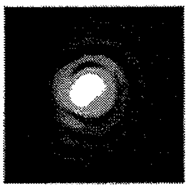


At ELETTRA no c.w. operation has yet been obtained due to small electron beam fluctuations. It is usually naturally pulsed, or random:

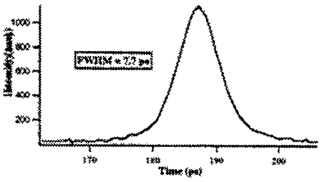


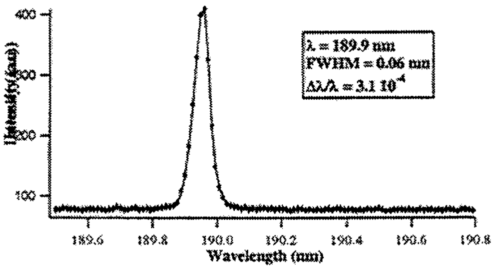
EUFELE - European Storage Ring FEL on ELETTRA



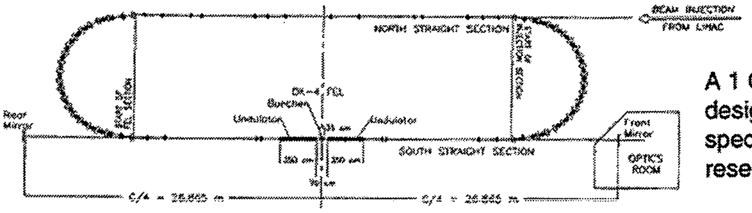


Wavelength	Multilayer mirror type
~ 350 nm	Ta_2O_5/SiO_2
250 - 268 nm	HfO_2/SiO_2
218 - 224 nm	Al_2O_3/SiO_2
189.7 - 200.3 nm	Al_2O_3/SiO_2



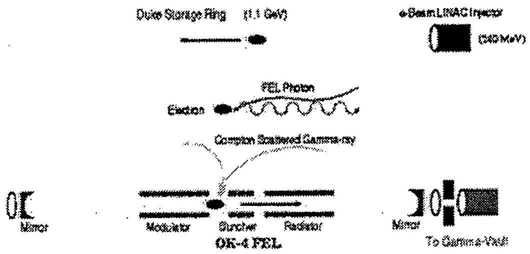


The Duke University Storage Ring FEL



A 1 GeV ring designed specifically for FEL research

A major use of the Duke FEL is for the production of gamma rays for nuclear physics experiments:



E(photon) ⟶ 3 eV - 12.5 eV

E(gamma) ∿ $4\gamma^2$ E(photon)

E(gamma) ⟶ 2.0 - 225 MeV

Advantages and Limitations of Storage Ring FELs

Advantages:

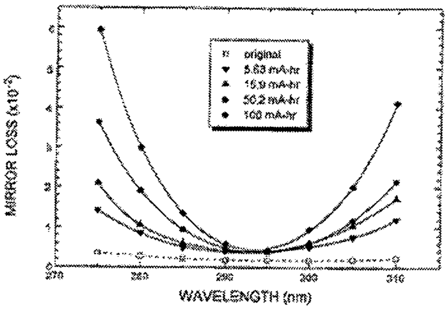
- Tunable in wavelength
- high average power, and photon flux compared to UV laser or SR
- continuous operation with MHz rep. rate
- Synchronised to synchrotron radiation
  (permitting two-beam, “pump-probe” experiments at high rep. rate)
- Small spectral linewidth (~ 10^{-4} “easy”, ~ 10^{-6} possible)
- "Cheap" addition to a Synchrotron Radiation user facility

Limitations:

- mainly due to the present performance of high reflectivity (> 95 %) multilayer mirrors, which limit the shortest wavelength achievable, as well as the range of tunability
- limited power ouput

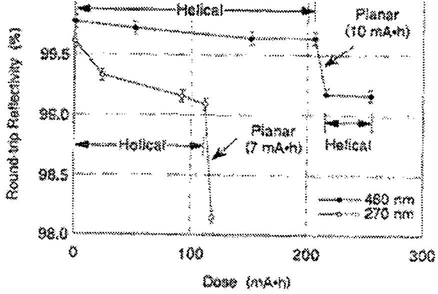
Mirrors for Storage Ring FELs

example of multilayer mirror degradation:



improvement from using a helical undulator at UVSOR

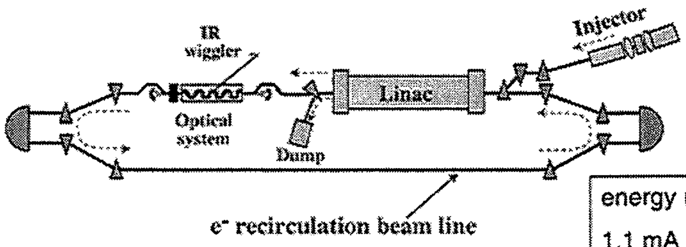
(used also at ELETTRA)



With higher gain (e.g. OK5 at Duke) it should be possible to use Aluminium mirrors to reach at least 150 nm with wide tunability.

Jefferson Lab. High Power FEL

High average FEL power achieved by means of high average current superconducting linac with energy recovery:



energy recovery ~ 75 %
1.1 mA no recovery
5 mA max. with recovery

$E = 48$ MeV
$I = 4.4$ mA
$\lambda = 3.1\ \mu$m
$P_L = 1.7$ kW

→ 210 kW electron beam power

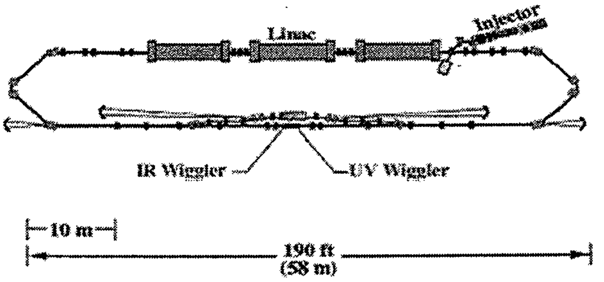
→ ~ 0.8 % efficiency

(1/2N = 1 %)

G.R. Neil et al., Phys. Rev. Lett. 84 (2000) 662.

Jefferson Lab. High Power FEL

Upgrade to 10 kW in progress:



E = 160 MeV
I = 10 mA
λ = 250 nm - 15 μm

Applications:

Polymer surface processing (e.g. clothing, carpets etc.)

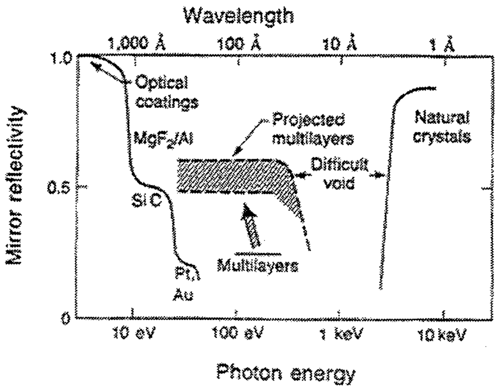
Metal surface processing (e.g. corrosion resistant materials with increased toughness)

Micromachining (mechanical and optical components)

Electronic materials processing (e.g. electronics for use in harsh conditions)

The FEL High Gain Regime - Why ?

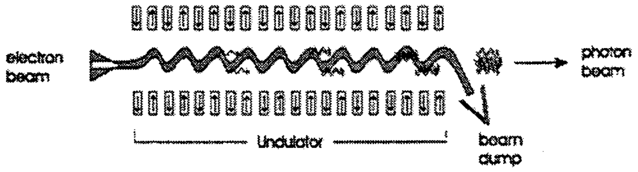
FEL oscillators are limited in wavelength by the availability of high reflectivity mirrors:

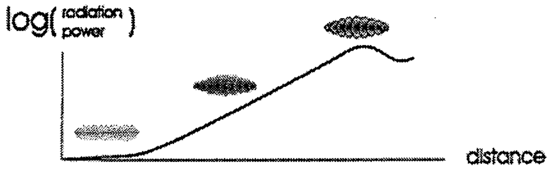


A different mechanism is therefore needed to approach short wavelengths.

The FEL High Gain Regime

The high-gain FEL regime with exponentially growing radiation was first analysed around 1977 (Kroll et al.), establishing a link between the FEL and the Travelling Wave Tube.





The use of this mechanism - with no resonator and with sufficiently long undulator that self-bunching can occur starting from random statistical fluctuations in intensity - as a source of coherent radiation was proposed in 1979 (Kondratenko and Saldin).

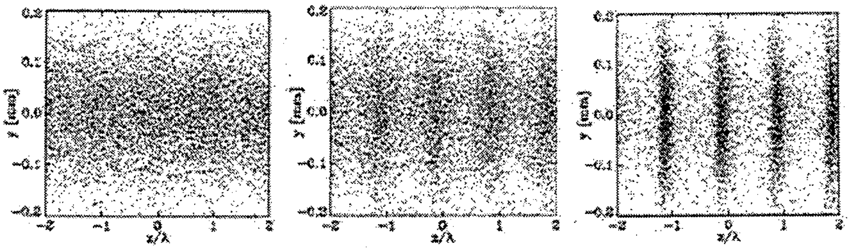
A.M. Kondratenko and E. Saldin, Sov. Phys. Dokl. 24 (1979) 986.

The FEL High Gain Regime

In this regime we refer to a collective "instability":

bunching - radiation - more bunching - more radiation ...

Calculation of micro-bunching in the TESLA XFEL:



undulator entrance

middle of exponential growth regime

undulator exit (saturation)

The FEL High Gain Regime

A simple theory which describes most of the physics with a single parameter (the Pierce parameter) was developed in 1984 (Bonifacio et al.):

$$\rho = \left(\frac{K}{4\gamma} \frac{\Omega_p}{\omega_o} \right)^{2/3}$$

Ω_p = plasma frequency
r_e = classical electron radius
n_e = electron density

$$\omega_o = 2\pi c / \lambda_o \qquad \Omega_p = \left(\frac{4\pi r_e n_e c^2}{\gamma} \right)^{1/2}$$

NB] neglecting space-charge forces implies : $\rho < 1$

For a long undulator the power grows as: $I \sim \frac{I_o}{9} \exp(z/L_G)$

where the gain lengths is: $L_G = \lambda_o / 4\sqrt{3}\pi\rho$

Saturation occurs in about 20 gain lengths: $L_{sat} \sim 20 L_G \sim \lambda_o / \rho$

with a saturation power: $P \sim \rho \, I_b \, E$

NOTE: power gain length = field gain length / 2

R. Bonifacio et al., Opt. Comm. 50 (1984) 373.

Electron Beam Requirements for SASE (1D model)

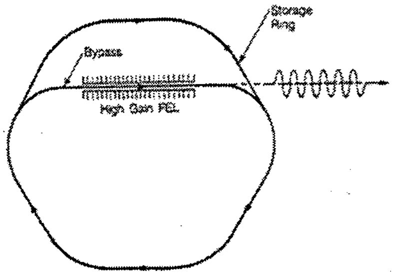
Small electron beam emittance $\varepsilon < \frac{\lambda}{4\pi}$ $\{\varepsilon_{x,y} = \sigma_{x,y} \sigma_{x,y}'\}$

Small electron beam energy spread $\sigma_E / E < \rho$

High peak current

Initial proposals to use the high-gain regime for short wavelength FELs assumed use of a storage ring, because of the possibility of creating high current, low emittance beams:

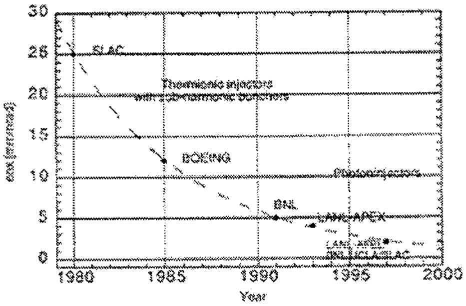
e.g. *Murphy and Pellegrini, 1985*



NB] this would involve switching the beam into the FEL bypass and back again, once each damping time

Electron Beam Requirements for SASE

Later, with the development of r.f. guns with low emittance, the direction switched to the use of linacs.



In a storage ring $\varepsilon \sim \gamma^2\, \theta_{\mathrm{bend}}^3$

In a linac $\varepsilon = \varepsilon_N / \gamma$

electron gun gives fixed normalised emittance (ε_N)

as linac energy increases, the geometric emittance (ε) decreases

First proposal for an X-ray FEL (0.1 - 4 nm) based on the SASE principle, using the SLAC linac, was in 1992

C. Pellegrini, 4'th Generation Light Source Workshop, Stanford, Feb. 1992.

The FEL as a "Fourth Generation" Light Source

With the increasingly real propsect of the FEL entering the short-wavelength domain of the synchrotron radiation sources, it is now considered to be the "fourth generation" of light source:

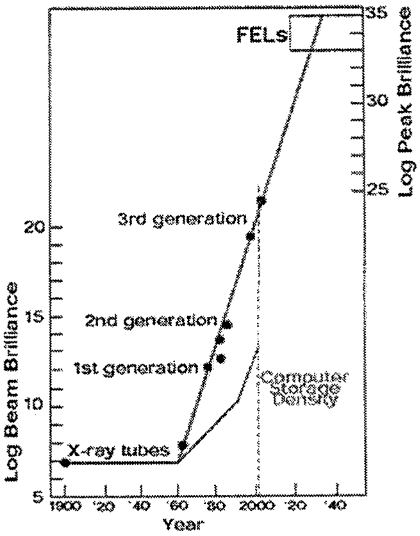
1st Generation: rings built originally for HEP and used parasitically for SR

2nd Generation: rings specially built for SR

3rd Generation: dedicated rings with a large number of undulator radiation sources

4th Generation: coherent radiation sources

NB] Not only is Brilliance important, but also the short radiation pulses, into the femtosecond region



SASE FEL Radiation Properties

Electrons communicate only with the electrons in front of them, at a distance no larger than the slippage distance = N λ

The main effect however takes place over the smaller "cooperation length", L_c - the slippage over one gain length:

$$L_c = \frac{\lambda}{\lambda_u} L_G = \frac{\lambda}{4\sqrt{3}\pi\rho}$$

At the undulator entrance the electron distribution - and hence the initial spontaneous radiation - is random on the scale of the radiation wavelength.

As amplification occurs each cooperation length evolves independently. The final radiation therefore consists of a number, *M*, of spikes whose intensity varies independently, where

$$M = \frac{L_{bunch}}{2\pi L_c}$$

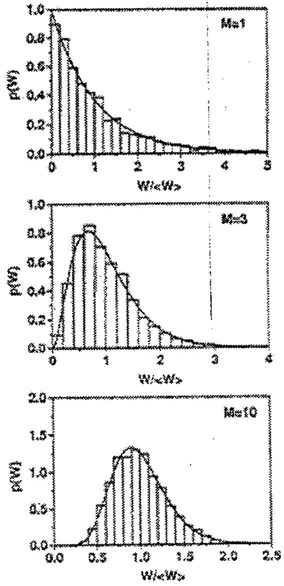
SASE FEL Radiation Properties

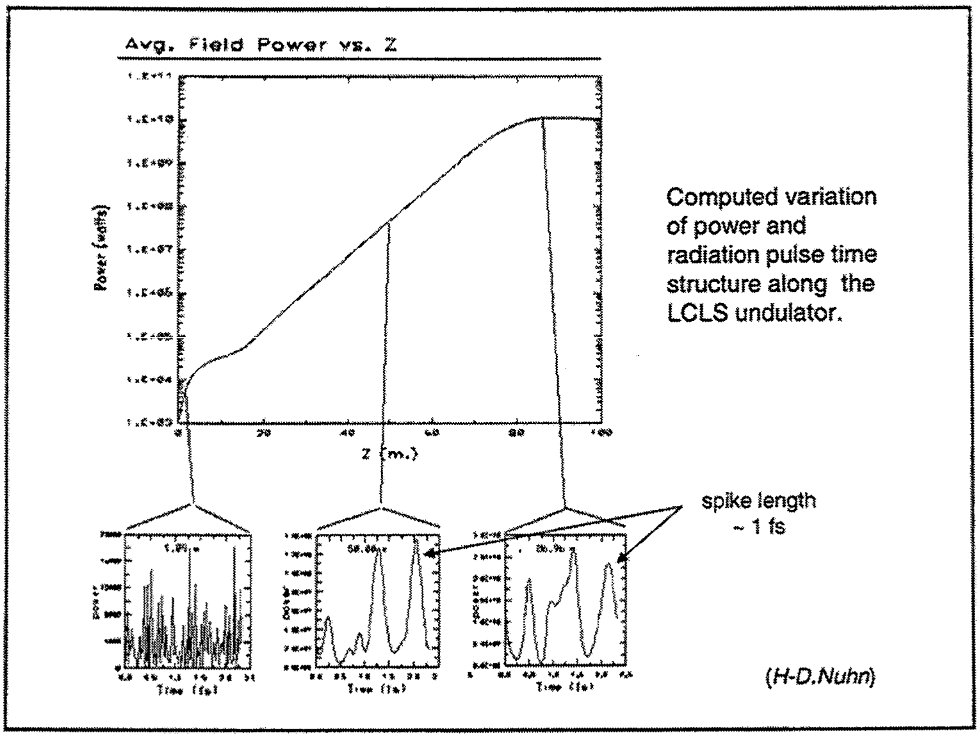
The total intensity of each pulse fluctuates from shot to shot, following a Gamma distribution with normalised rms variation = $1/\sqrt{M}$

The overall bandwidth of the radiation is relatively large, given by the temporal duration of one spike:

$$\frac{\Delta\lambda}{\lambda} = \frac{\lambda}{2\pi L_c}$$

i.e. the bandwidth is M times that of the Fourier Transmform limit of a single spike.





Computed variation of power and radiation pulse time structure along the LCLS undulator.

spike length ~ 1 fs

(*H-D.Nuhn*)

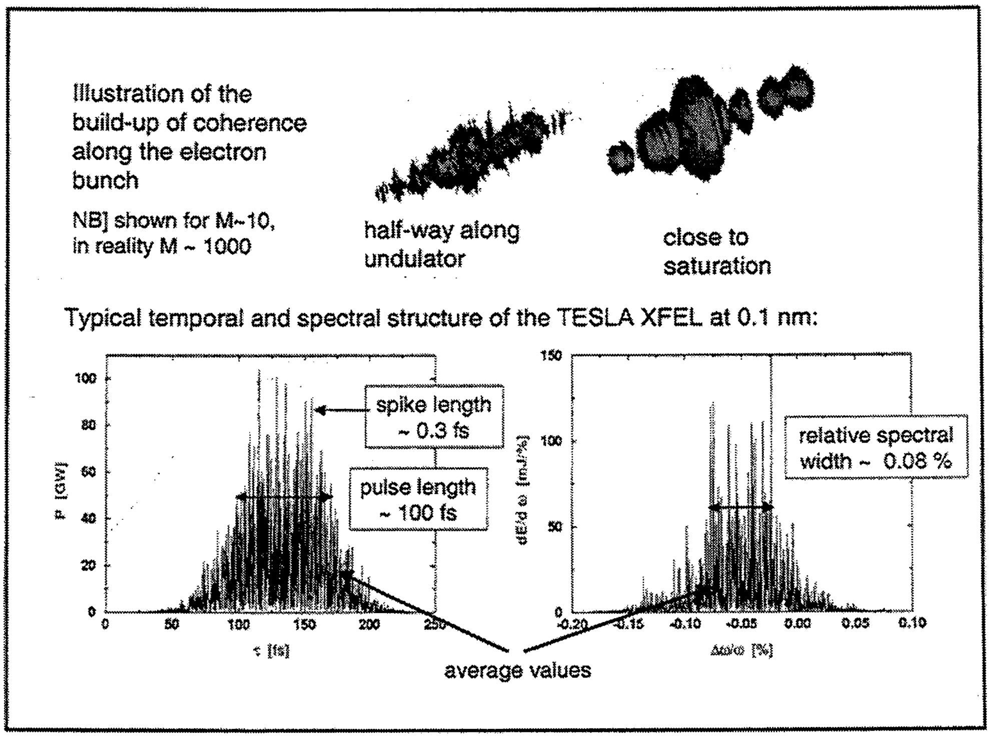


Illustration of the build-up of coherence along the electron bunch

NB] shown for M~10, in reality M ~ 1000

half-way along undulator

close to saturation

Typical temporal and spectral structure of the TESLA XFEL at 0.1 nm:

spike length ~ 0.3 fs

pulse length ~ 100 fs

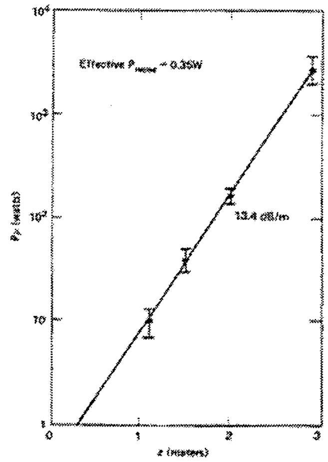
relative spectral width ~ 0.08 %

average values

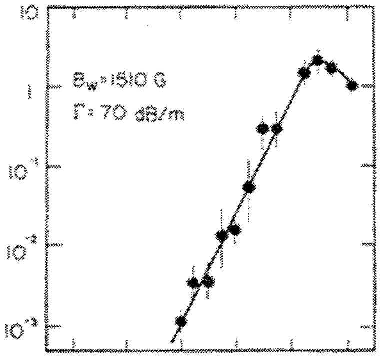
High-gain and SASE Experiments

Several amplifier and SASE tests in the mm-wave region in the USA in the mid-80's (LLNL, NRL) e.g.

ELF, Lawrence Livermore National Laboratory (1985)
35 GHz (8.7 mm); 3.6 MeV, 450 A beam

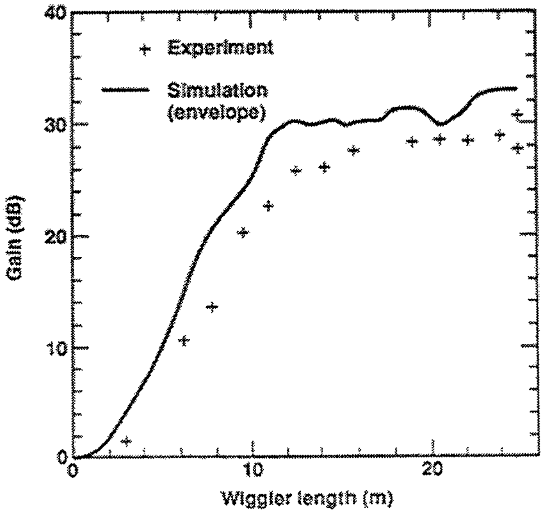


MIT (1988)
600 µm; 2 MeV, 900 A beam



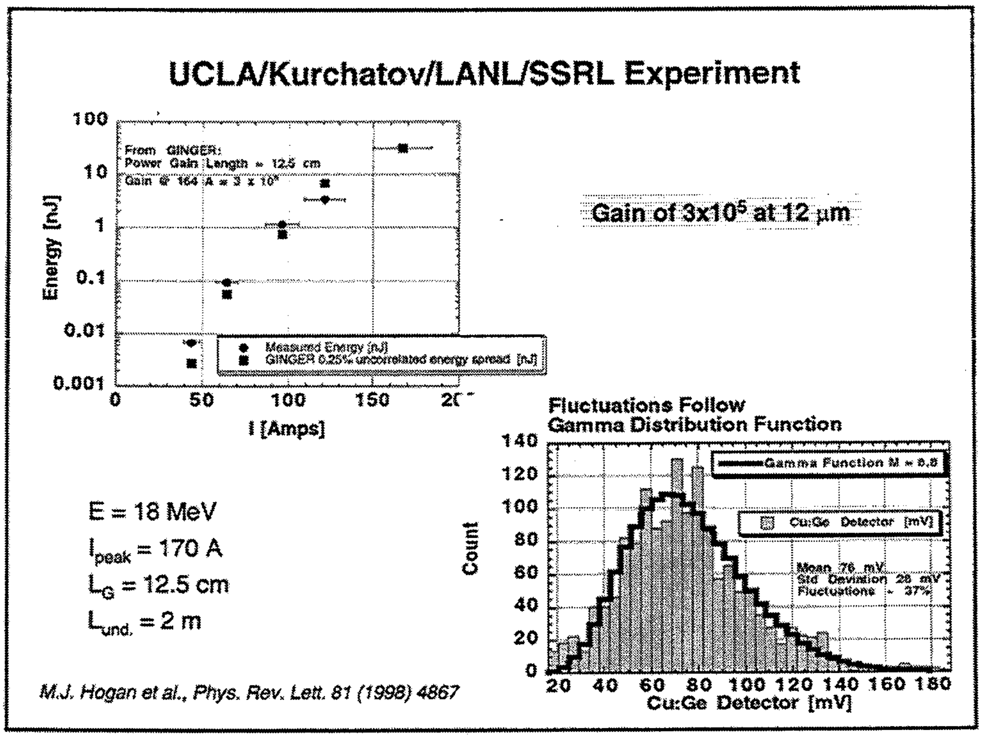
High-gain and SASE Experiments

PALADIN, Lawrence Livermore National Laboratory (1988/9)
10.6 µm Amplifier; Advanced Test Accelerator (ATA): 45 MeV, 800 A beam



14 MW output

18 kW input



UCLA/Kurchatov/LANL/SSRL Experiment

Gain of 3×10^5 at 12 μm

Fluctuations Follow Gamma Distribution Function

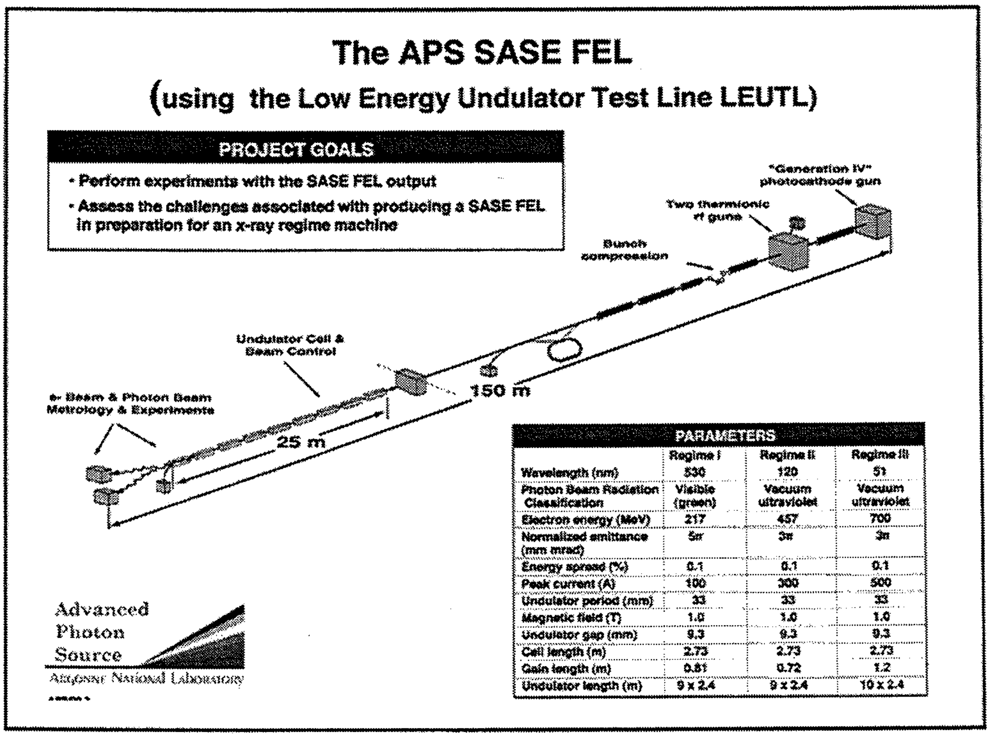
$E = 18$ MeV

$I_{peak} = 170$ A

$L_G = 12.5$ cm

$L_{und.} = 2$ m

M.J. Hogan et al., Phys. Rev. Lett. 81 (1998) 4867



The APS SASE FEL
(using the Low Energy Undulator Test Line LEUTL)

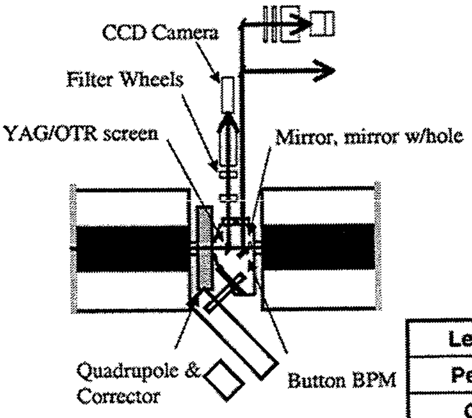
PROJECT GOALS

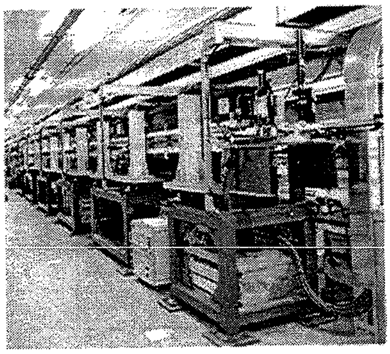
- Perform experiments with the SASE FEL output
- Assess the challenges associated with producing a SASE FEL in preparation for an x-ray regime machine

PARAMETERS	Regime I	Regime II	Regime III
Wavelength (nm)	530	120	51
Photon Beam Radiation Classification	Visible (green)	Vacuum ultraviolet	Vacuum ultraviolet
Electron energy (MeV)	217	457	700
Normalized emittance (mm mrad)	5π	3π	3π
Energy spread (%)	0.1	0.1	0.1
Peak current (A)	100	300	500
Undulator period (mm)	33	33	33
Magnetic field (T)	1.0	1.0	1.0
Undulator gap (mm)	9.3	9.3	9.3
Cell length (m)	2.73	2.73	2.73
Gain length (m)	0.81	0.72	1.2
Undulator length (m)	9 x 2.4	9 x 2.4	10 x 2.4

Advanced
Photon
Source
Argonne National Laboratory

APS SASE FEL: Undulator and Diagnostic Line



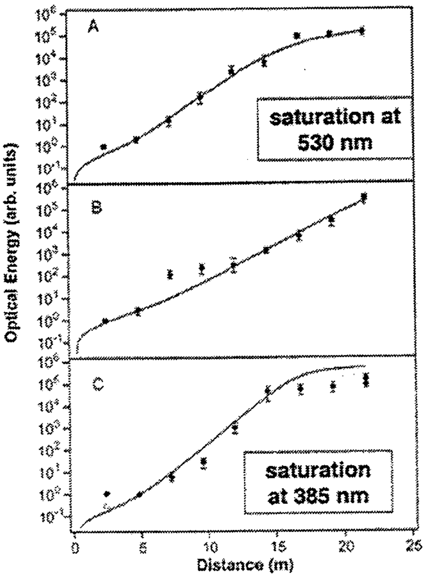


Length	9 x 2.4 m
Period	3.3 cm
Gap	9.4 mm
Field	1 T
K	3.1
Intermodule gap	33 cm

courtesy of S.V. Milton, APS

Advanced Photon Source
Argonne National Laboratory

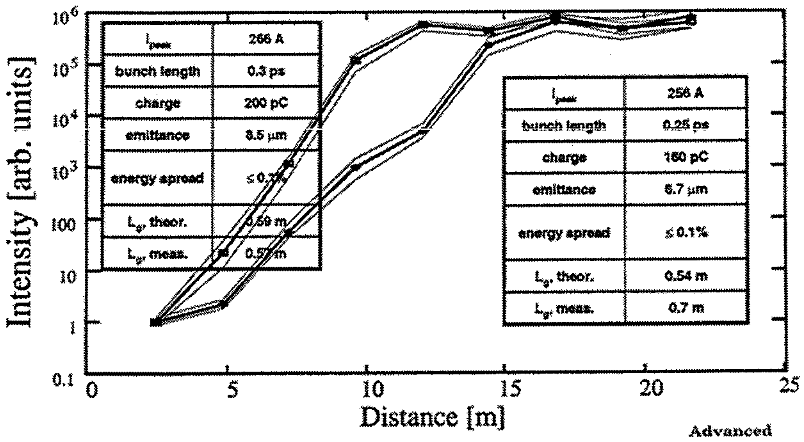
APS SASE FEL: Results



	A	B	C
Energy (MeV)	217	217	255
Wavelength (nm)	530	530	285
Charge (nC)	0.3	0.3	0.3
Bunch length (ps)	0.19	0.77	0.65
Peak curent (A)	630	171	184
Normalised Emittance (mm mrad)	8.5	8.5	7.1
Energy spread	0.4	0.2	0.1
Gain length (m)	1.0	1.4	0.8

S.V. Milton et al., Science 292 (2001) 203.

APS SASE FEL: Trajectory & Matching Effects



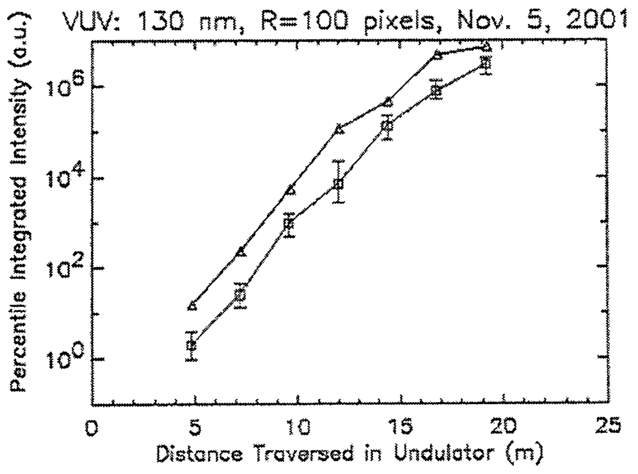
I_{peak}	256 A
bunch length	0.3 ps
charge	200 pC
emittance	8.5 µm
energy spread	≤ 0.1%
L_g, theor.	0.59 m
L_g, meas.	0.57 m

I_{peak}	256 A
bunch length	0.25 ps
charge	160 pC
emittance	5.7 µm
energy spread	≤ 0.1%
L_g, theor.	0.54 m
L_g, meas.	0.7 m

courtesy of S.V. Milton, APS

Advanced Photon Source
Argonne National Laboratory

APS SASE FEL: Recent Results at 130 nm



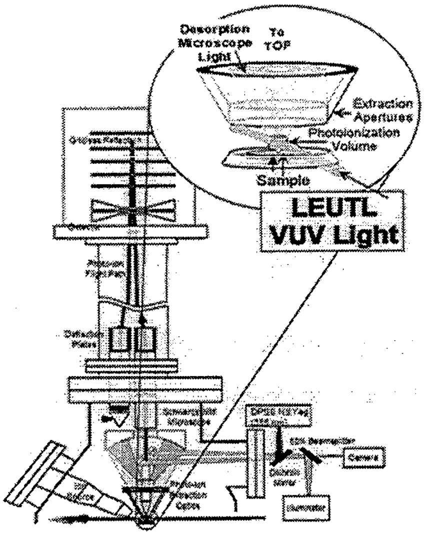
courtesy of S.V. Milton, APS

Advanced Photon Source
Argonne National Laboratory

APS SASE FEL: The First Experiment

Single Photon Ionization / Resonant Ionization to Threshold (SPIRIT)

M. Pellin MSD/ANL



planned in 2002

SPIRIT will use the high VUV pulse energy from LEUTL to uniquely study –

- **Trace quantities of light elements:**
  H, C, N, O in semiconductors with
  100 times lower detection limit
- **Organic molecules with minimal fragmentation**
  cell mapping by mass becomes feasible
  polymer surfaces
  modified (carcinogenic) DNA
  photoionization thresholds
- **Excited states of molecules**
  cold wall desorption in accelerators
  sputtering of clusters

courtesy of S.V. Milton, APS

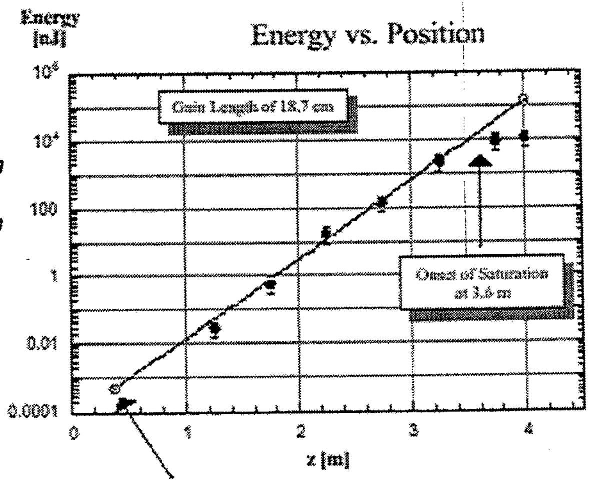
Advanced Photon Source
Argonne National Laboratory

VISA (Visible to Infrared SASE Amplifier)
(BNL-LLNL-SLAC-UCLA collaboration)

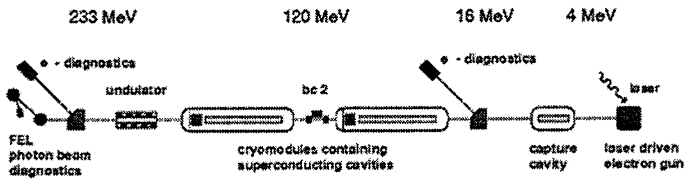
Brookhaven National Laboratory
Accelerator Test Facility

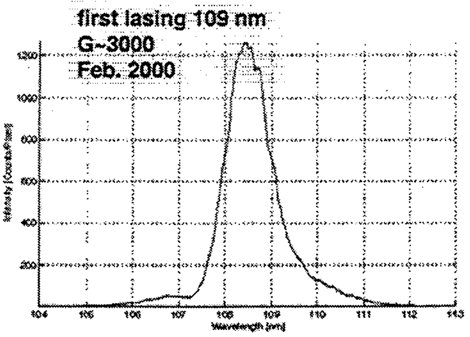
First saturation
March, 2001

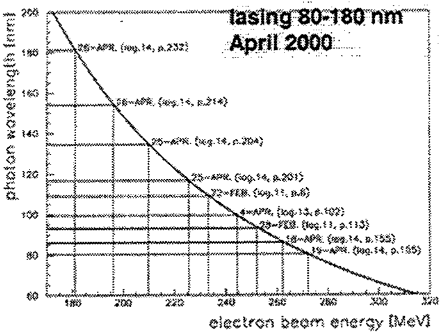
Wavelength:	*830 nm*
Average Charge:	*170 pC*
Gain Length	*18.5 cm*
SASE Energy:	*10 µJ*
Total Gain:	*2×10⁸*



TESLA TEST FACILITY (TTF)

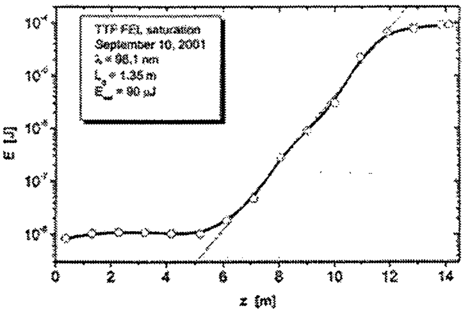



first lasing 109 nm
G~3000
Feb. 2000


lasing 80-180 nm
April 2000

J. Andruszkow et al., Phys. Rev. Lett. 85, (2000) 3825.

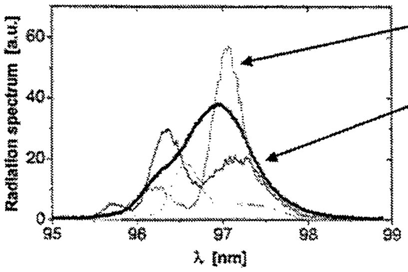
TESLA TEST FACILITY (TTF)



E = 240 MeV

I_{peak} = 1.3 kA

ε_N = 6 +/- 2 mm mrad



Measured single-shot spectra

Average spectrum

M ~ 2.5 implies radiation generated by only a fraction (50 fs) of the electron bunch

V. Ayvazyan et al., Phs. Rev. Lett. 88, (2002) 104802.

Future Short Wavelength SASE FELs

Extension of existing projects:

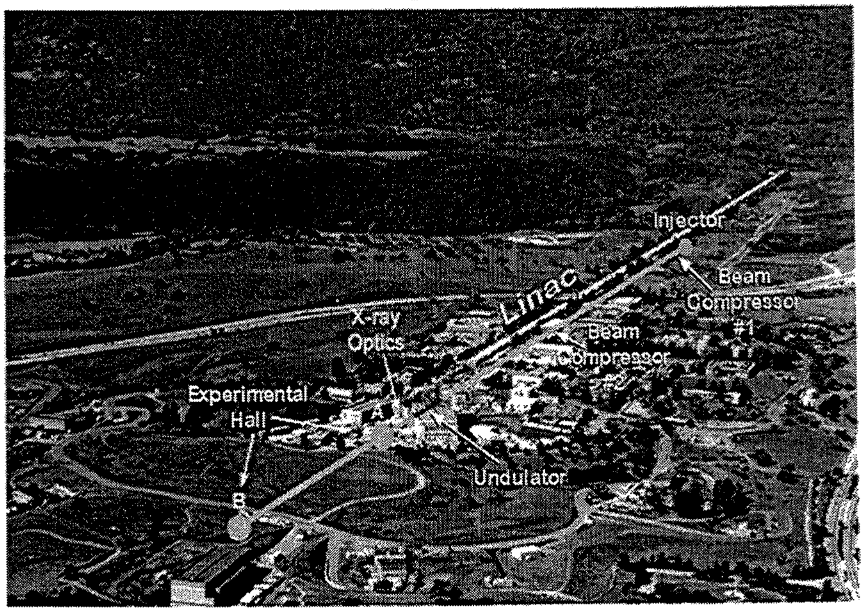
APS-FEL: extension to 50 nm

TTF-II: extension to 6 nm (1 GeV) underway; will become a user facility

New Projects:

Linac Coherent Light Source (LCLS)	1.5 Å	14.3 GeV	Linac
TESLA X-FEL	0.85 Å	50 GeV	SC linac
Spring-8 Compact SASE Source (SCCS)	3.6 nm	1 GeV	Linac
BESSY-FEL	1.2 nm	2.25 GeV	Linac
SPARX/FERMI (Italy)	1.2/1.5 nm	2.5/3 GeV	Linac
4GLS (UK)	12 nm	0.9 GeV	ERL

Linac Coherent Light Source - LCLS



LCLS Main Design Parameters

Fundamental FEL Radiation Wavelength	1.5	15	Å
Electron Beam Energy	14.3	4.5	GeV
Normalized RMS Slice Emittance	1.2	1.2	mm-mrad
Peak Current	3.4	3.4	kA
Bunch/Pulse Length (FWHM)	230	230	fs
Relative Slice Energy Spread @ Entrance	<0.01	0.025	%
Saturation Length	87	25	m
FEL Fundamental Saturation Power @ Exit	8	17	GW
FEL Photons per Pulse	1.1	29	10^{12}
Peak Brightness @ Undulator Exit	0.8	0.06	10^{33} *
Transverse Coherence	Full	Full	
RMS Slice X-Ray Bandwidth	0.06	0.24	%
RMS Projected X-Ray Bandwidth	0.13	0.47	%

* photons/sec/mm²/mrad²/ 0.1%-BW

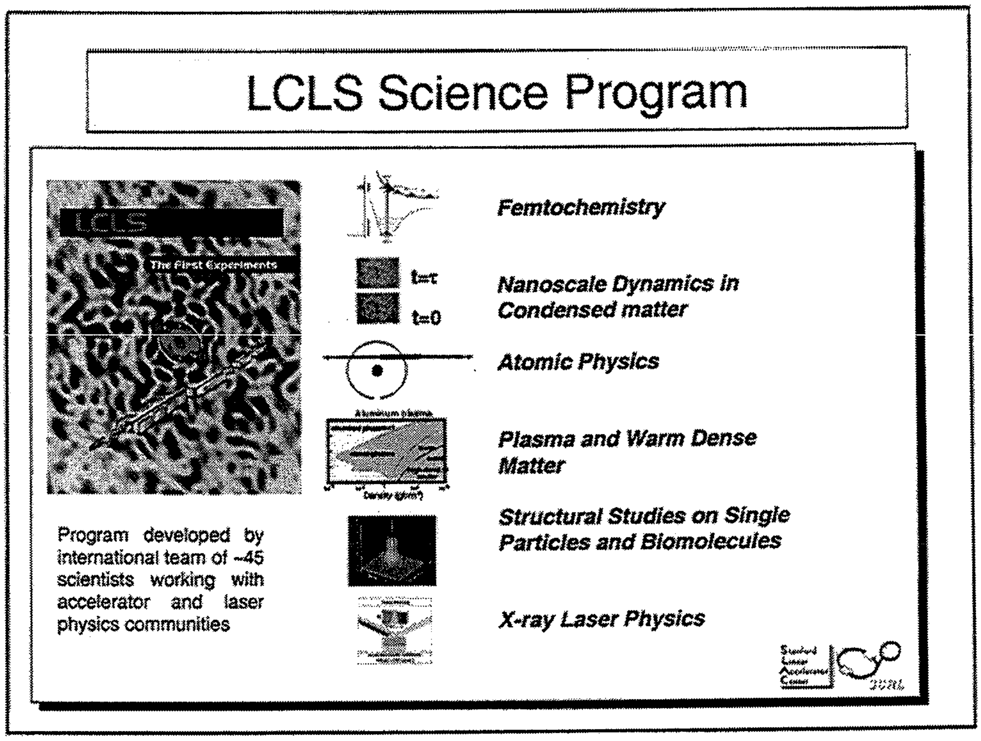
LCLS

Total Estimated Cost ($FY2002) $ 196.5 M

• Project Engineering and Design (direct)	$ 29.7 M
• Construction(direct)	$ 106.2 M
• Overhead	$ 23.1 M
• Contingency	$ 37.5 M

Timescales

May 2002	Projected DoE approval of preliminary project baseline (CD-1)
Jan. 2003	Projected DoE approval of performance project baseline (CD-2)
Mar. 2004	Projected DoE approval for start of construction (CD-3)
Oct. 2004	Start of Construction
Oct. 2007	Projected DoE approval for start of operation (CD-4)



LCLS Science Program

Femtochemistry

Nanoscale Dynamics in Condensed matter

Atomic Physics

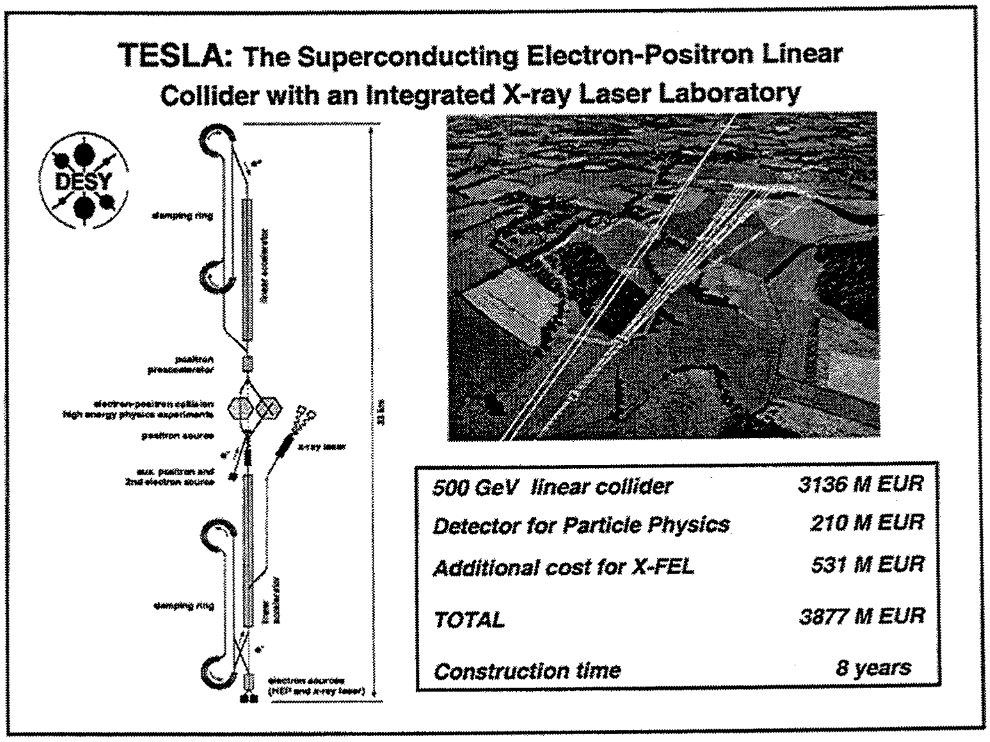
Plasma and Warm Dense Matter

Structural Studies on Single Particles and Biomolecules

X-ray Laser Physics

Program developed by international team of ~45 scientists working with accelerator and laser physics communities

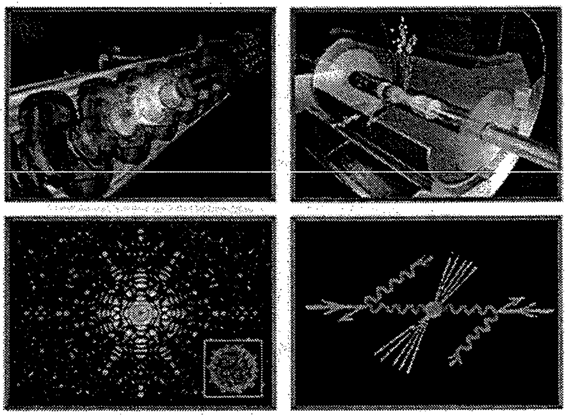
Stanford Linear Accelerator Center



TESLA: The Superconducting Electron-Positron Linear Collider with an Integrated X-ray Laser Laboratory

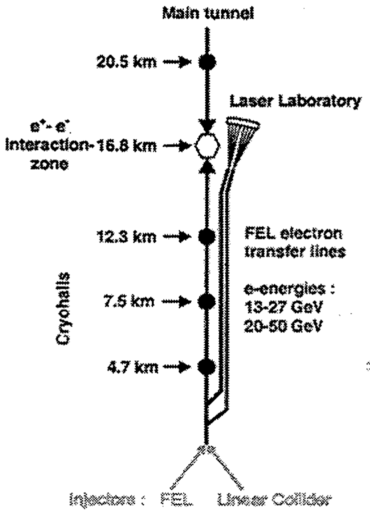
500 GeV linear collider	*3136 M EUR*
Detector for Particle Physics	*210 M EUR*
Additional cost for X-FEL	*531 M EUR*
TOTAL	*3877 M EUR*
Construction time	*8 years*

TESLA: The Superconducting Electron-Positron Linear Collider with an Integrated X-ray Laser Laboratory



Technical Design Report March 2001

TESLA XFEL: Integration with the Linear Collider



Main tunnel

20.5 km →

Laser Laboratory

e^+- e^- interaction-zone 16.8 km →

12.3 km →

FEL electron transfer lines

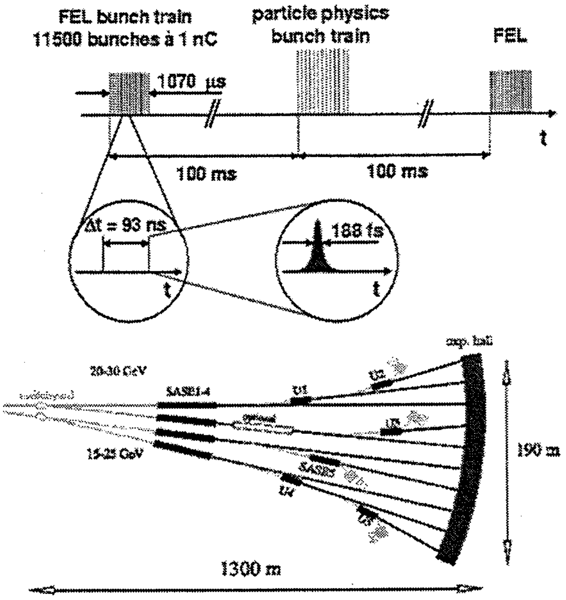
e-energies :
13-27 GeV
20-50 GeV

Cryohalls

7.5 km →

4.7 km →

Injectors : FEL Linear Collider



FEL bunch train
11500 bunches à 1 nC

particle physics bunch train

FEL

1070 µs

t

100 ms

100 ms

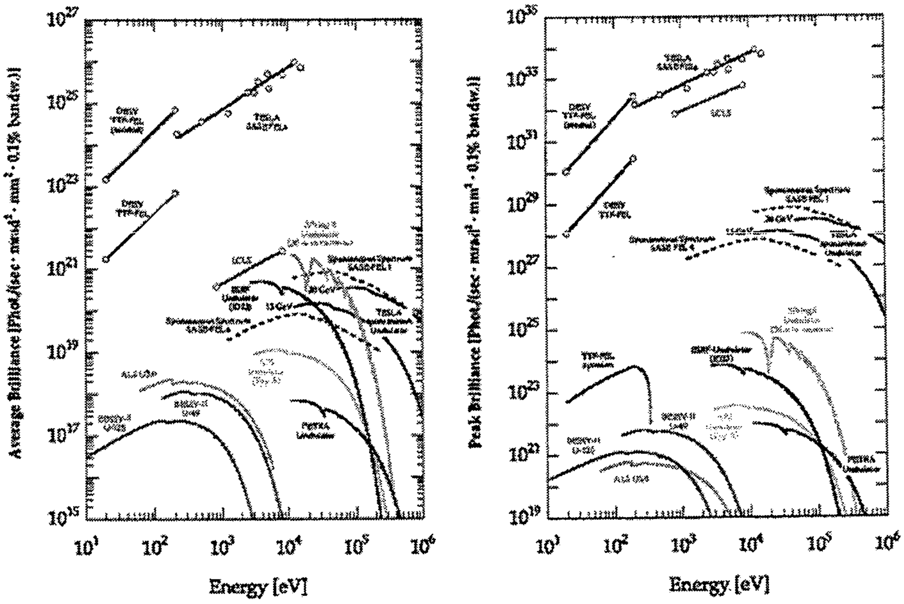
Δt = 93 ns

188 fs

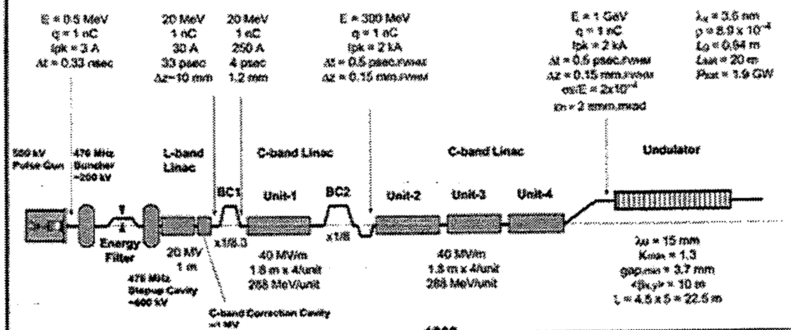
t

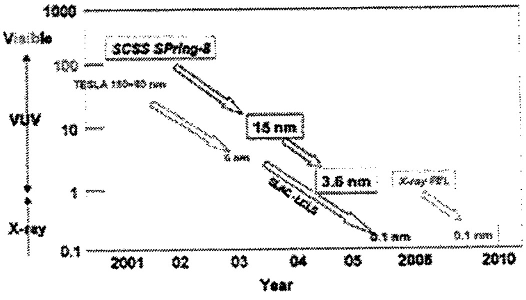
t

LCLS and TESLA XFEL Performance



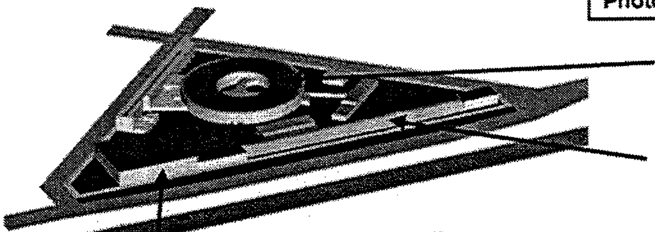
Spring-8 Compact SASE Source





The BESSY FEL

Wavelength: 60 - 1.2 nm
Photon energy: 20 eV - 1 keV

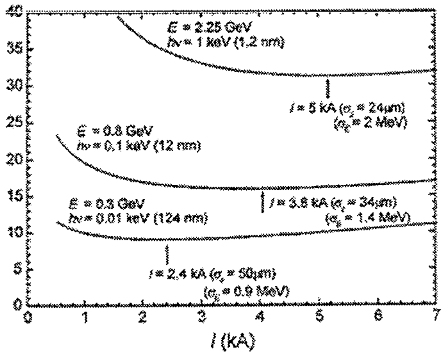


BESSY II 1.7/1.9 GeV storage ring

proposed 2.25 GeV superconducting linac

FEL (+SR) experimental hall

Charge:	**1 nC**
Bunch length:	**85 - 260 fs**
Peak current:	**1.5 - 5 kA**
Norm. emittance:	**1.5 mm mrad**
Energy spread:	**0.1 %**

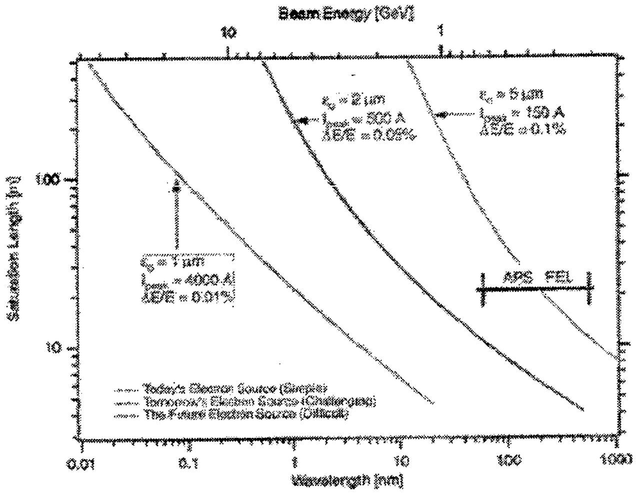


Initial cost estimate: 148 M EUR

Technical Challenges for Short Wavelength SASE FELs

- **Injector**
  - Low emittance
  - Stability
- **Compression and Acceleration**
  - Emittance preservation due to Coherent Synchrotron Radiation (CSR) and transverse wakefield effects
  - Stability (phase, amplitude)
- **Undulators**
  - Precise fabrication of long undulators
  - Trajectory alignment
  - Wakefields in the undulator (resistive wall, surface roughness, geometrical changes)
- **Photon beams handling**
  - optics, diagnostics etc.

Technical Challenges for Short Wavelength SASE FELs



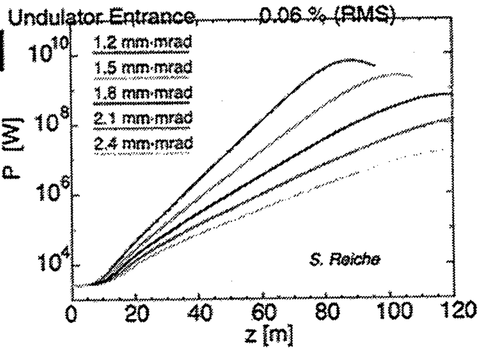
courtesy of S.V. Milton, APS

Parameter	Location	LCLS Goal Values*
Normalized Slice Emittance	Injector (@150 MeV)	1.0 mm mrad (RMS) Undulator Entrance 1.2 mm mrad (RMS)
Normalized Projected Emittance	Injector (@150 MeV)	1.2 mm mrad (RMS) Undulator Entrance 1.5 mm mrad (RMS)
Slice Energy Spread	Injector (@150 MeV)	<0.01 % (RMS) Undulator Entrance <0.01 % (RMS)
Projected Energy Spread	Undulator Entrance,	0.06 % (RMS)

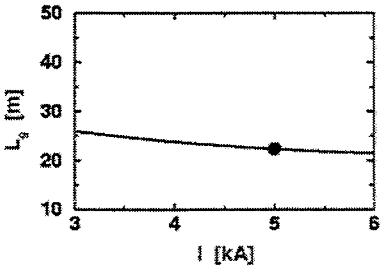
**At a peak current of 3400 A at the undulator*

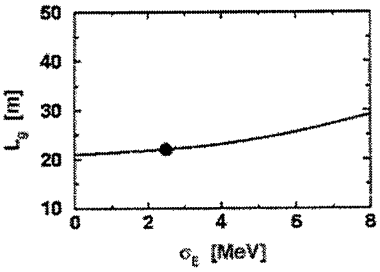
1.7 mm·mrad is the largest slice emittance, which allows saturation within the LCLS Undulator (120 m, including gaps between modules), assuming a local current of 3.4 kA.

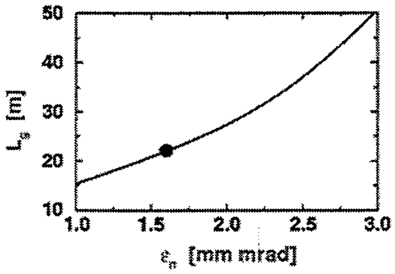
"slice emittance" is the local emittance over a cooperation length.



TESLA XFEL: Parameter sensitivity



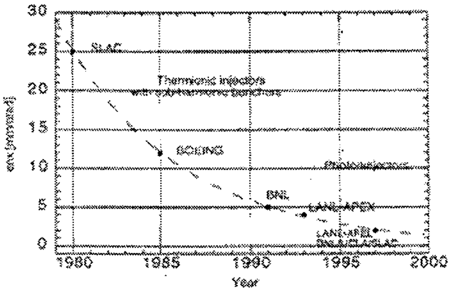


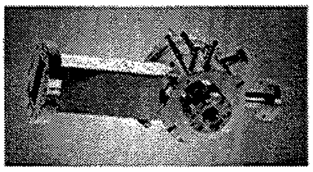


Nominal values are 5 kA
peak current with 1.6 μm
slice emittance

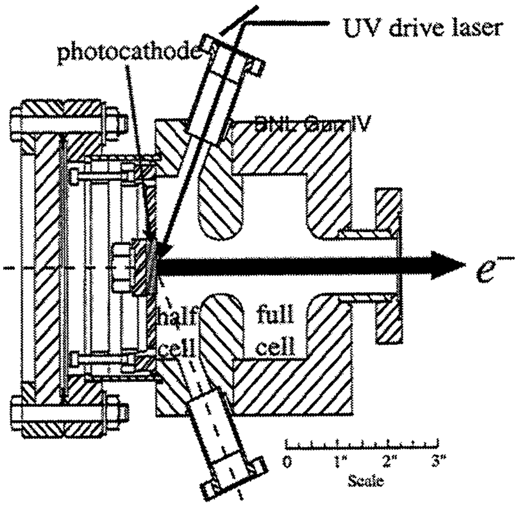
Photo-injectors

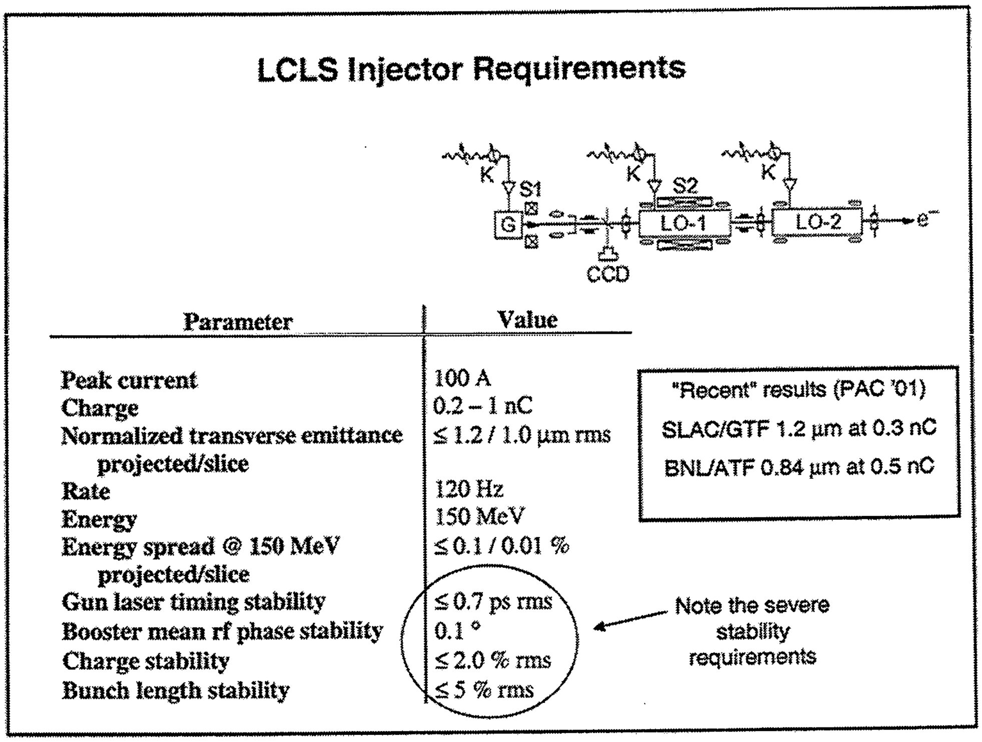
Improvement in beam emittance due to the development of thermionic, and later photo-cathode, r.f. cavity guns :





"Standard" 1.6 cell design:



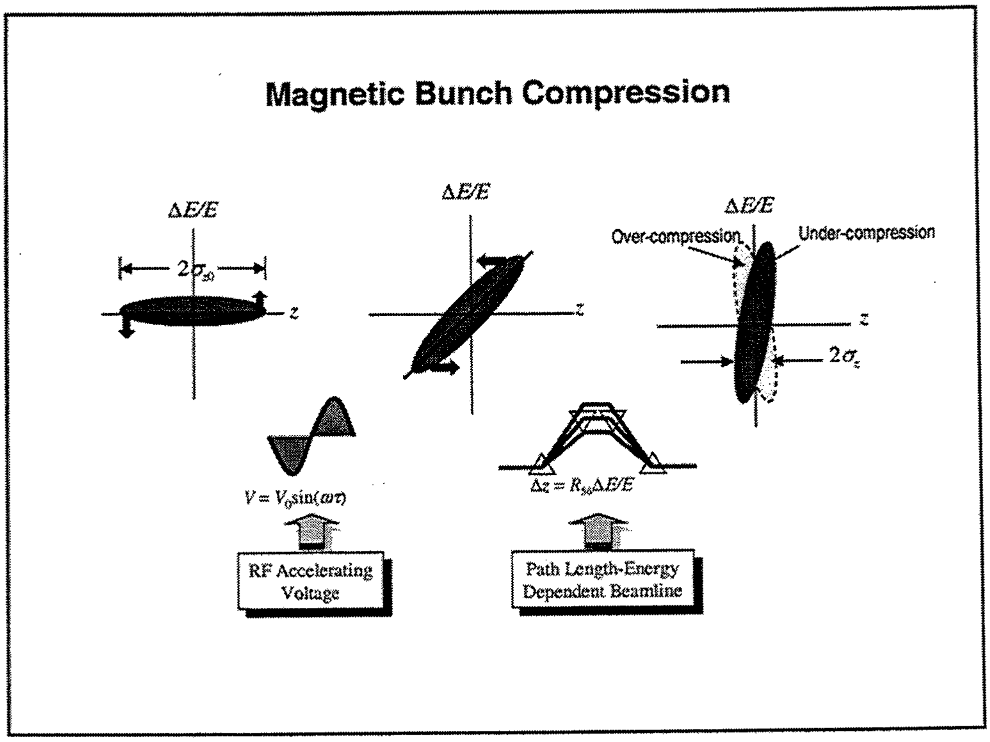


LCLS Injector Requirements

Parameter	Value
Peak current	100 A
Charge	0.2 – 1 nC
Normalized transverse emittance projected/slice	≤ 1.2 / 1.0 μm rms
Rate	120 Hz
Energy	150 MeV
Energy spread @ 150 MeV projected/slice	≤ 0.1 / 0.01 %
Gun laser timing stability	≤ 0.7 ps rms
Booster mean rf phase stability	0.1 °
Charge stability	≤ 2.0 % rms
Bunch length stability	≤ 5 % rms

"Recent" results (PAC '01)
SLAC/GTF 1.2 μm at 0.3 nC
BNL/ATF 0.84 μm at 0.5 nC

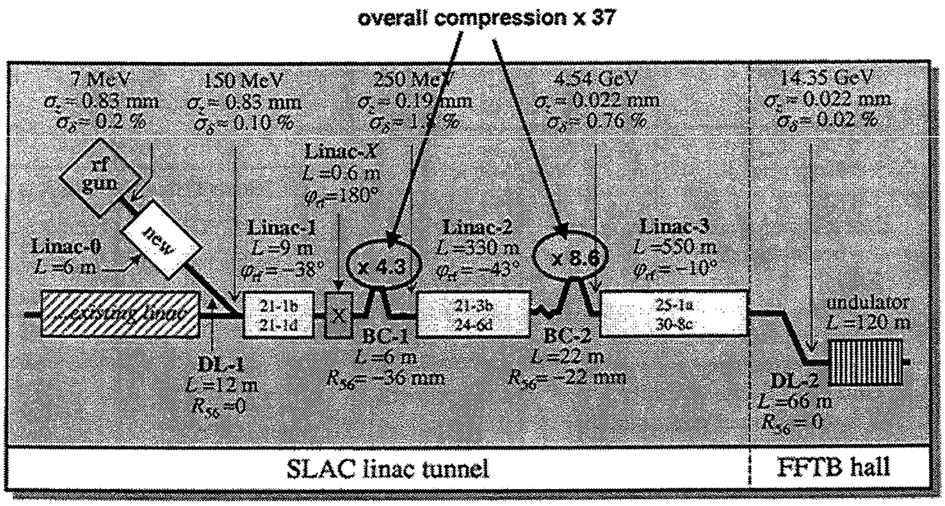
Note the severe stability requirements



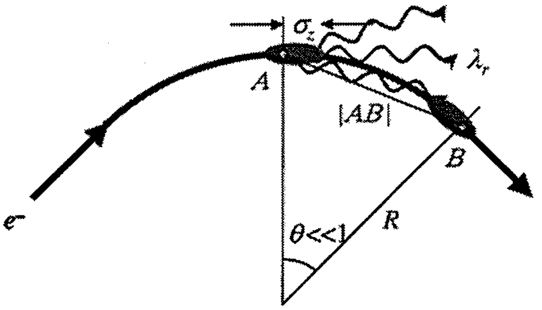
Magnetic Bunch Compression

Magnetic Bunch Compression

Magnetic compression is usually carried
out in more than one stage e.g. LCLS :



Coherent Synchrotron Radiation (CSR)



Coherent radiation for:
$\lambda_r >> \sigma_z$

Free space radiation from bunch tail at point ***A*** overtakes bunch head, a distance *s* ahead of the source, at the point ***B*** which satisfies...

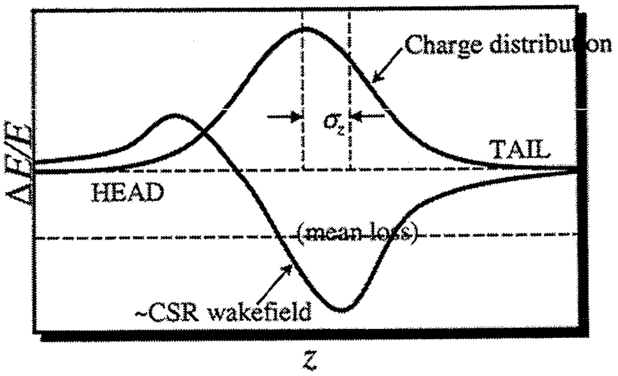
$$s = \mathrm{arc}(\boldsymbol{AB}) - |\boldsymbol{AB}| = R\theta - 2R\sin(\theta/2) \approx R\theta^3/24 = \sigma_z$$

i.e. when $L\theta^2 = 24\sigma_z$

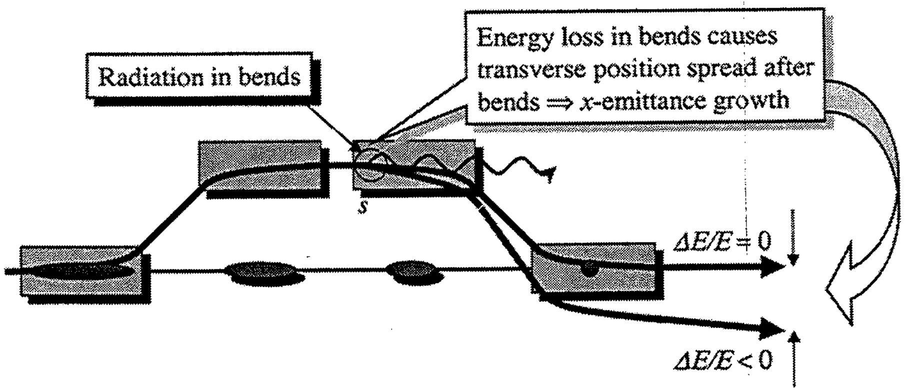
for LCLS: $\sigma_z = 22\ \mu m$, $L\theta^2 \sim 5\ 10^{-4}$

= 1 deg. bend, over 2 m

CSR → Energy Variation along the Bunch



CSR → Emittance Growth


Radiation in bends

Energy loss in bends causes transverse position spread after bends ⇒ *x*-emittance growth

Codes for "Start-end Simulations"

Gun
Parmela

→

Linac
Elegant

→

FEL
Genesis 1.3

Macro particles
External maps for E- and B-field
Space Charge

Macro particles
Tracking by matrix elements
Analytical model for CSR and wakefields

Macro particles and
Discritized radiation field
Analytical model for undulator wakefields

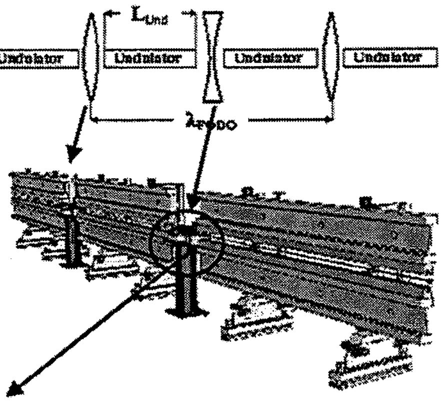
for LCLS ...

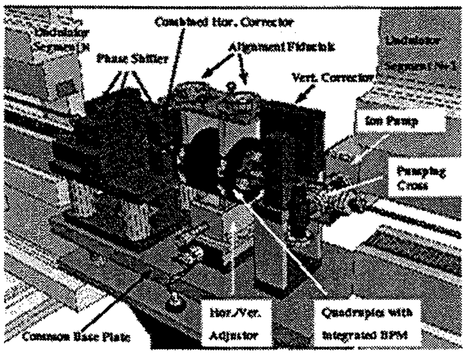
All four cases reach saturation

S. Reiche

Undulators

- Short wavelength FELs with long undulators need focussing along the length
- Undulator sections are interspersed with quadrupole focussing magnets (as well as other correction and diagnostic elements)





TESLA TDR, March 2001

TESLA XFEL Undulators

Main TESLA XFEL Undulator Parameters (SASE1)

Gap	*12*	*mm*
Period Length	*6*	*cm*
Peak On-Axis Field	*1.32*	*T*
K	*3.71*	
Segment Length	*5*	*m*
Number of Segments	*53*	
Undulator Magnet Length	*165*	*m*
Total Undulator Length	*323*	*m*

Total for 5 SASE Devices

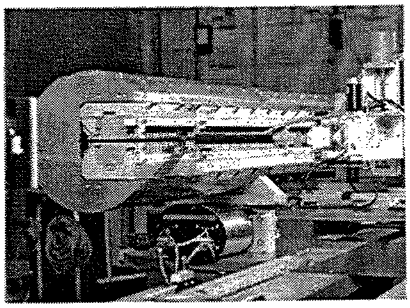
Total No. Segments	*231*	
Total Undulator Length	*1.1*	*km*

TESLA TDR, March 2001

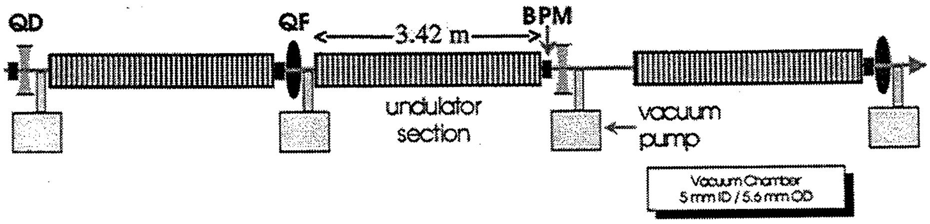
LCLS Undulator

Main LCLS Undulator Parameters

Gap	*6*	*mm*
Period Length	*3*	*cm*
Peak On-Axis Field	*1.32*	*T*
K	*3.71*	
Segment Length	*3.42*	*m*
Number of Segments	*33*	
Undulator Magnet Length	*112.8*	*m*
Total Undulator Length	*121.1*	*m*

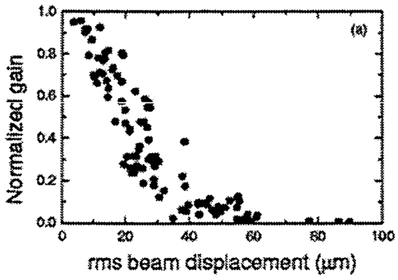


Prototype LCLS undulator under test

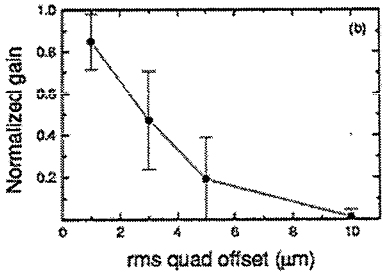


Undulator Quality and Alignment

Very high field quality, and precise alignment, is required to maintain the beam trajectory within tight tolerances, e.g. TESLA XFEL



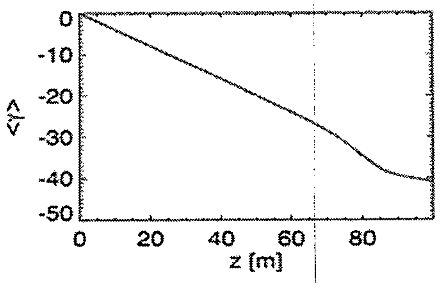
reduction in gain due to trajectory errors caused by random undulator field errors



reduction in gain due to random quadrupole misalignments, before correction

Effect of Spontaneous Radiation

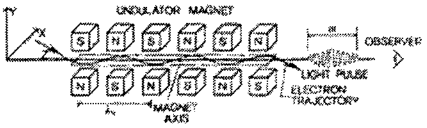
Weak taper of undulator field needed to compensate change in resonance condition due to energy loss caused by spontaneous emission :



for LCLS: $\frac{d}{dz}K = -1.5\cdot 10^{-5}\,\mathrm{m}^{-1}$

Harmonics

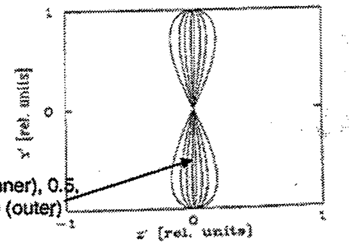
where do the harmonics come from in a planar undulator ?



$$\beta_x = \frac{K}{\gamma}\cos(kz) \qquad \beta_x^2 + \beta_z^2 = \beta^2 \quad (= \text{constant})$$

$$\beta_z \cong \beta\left(1 - \frac{K^2}{4\gamma^2} - \frac{K^2}{4\gamma^2}\cos(2kz)\right)$$

the velocity along the z-axis is modulated due to undulating motion



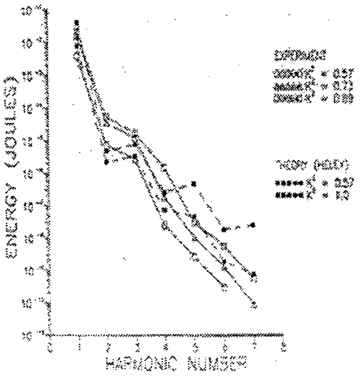
K=0.1 (inner), 0.5, 1.0, 10.0 (outer)

in the frame which moves with the average velocity along z, the electron performs a "figure-of-eight" motion, increasing with K value, giving rise to emission of harmonics.

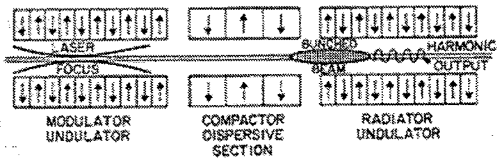
Harmonics in the low-Gain FEL

Lasing on the 3rd harmonic (and not on the fundamental) was first obtained in the Stanford Mark III FEL (Benson and Madey, 1989).

It was also shown that a FEL operating near saturation generates harmonics in excess of spontaneous radiation due to the harmonic content of the bunching (Bamford and Deacon, 1989).

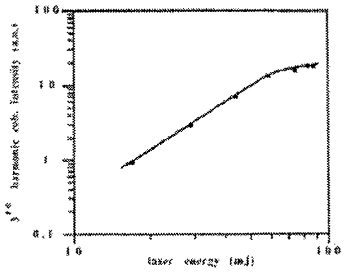


Coherent Harmonic Generation



First demonstrated on ACO, where the 3rd harmonic of an 1.06 µm Nd:YAG laser was generated with 10^2-10^3 enhancement over spontaneous emission (Girard et al. 1984).

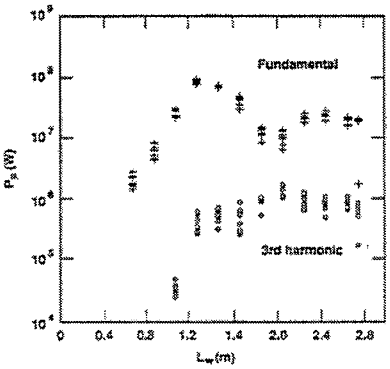
Later experiments at SuperACO have shown also the 5th harmonic.



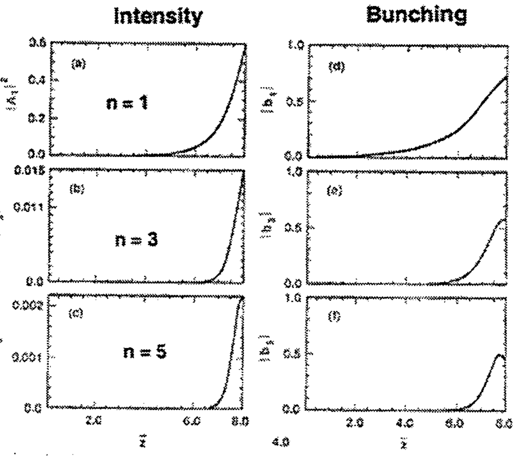
- requires very precise alignment of laser and electron beams
- average CHG output is limited by the laser repetition frequency (10-20 Hz in these experiments).

"Non-linear" Harmonic Generation

High gain regime experiments at ELF (35 GHz) showed a rapidly increasing signal at the 3rd harmonic:



This was later explained as being due to the exponential gain on the fundamental driving the harmonic bunching:



R. Bonifacio et al., Nucl. Instr. Meth. A293 (1990) 627.

"Non-linear" Harmonic Generation

This led to the proposal for:

Resonant Frequency Tripling

A two-stage FEL amplifier, with the second undulator tuned to the third (or higher) harmonic of the first.

- no mirrors

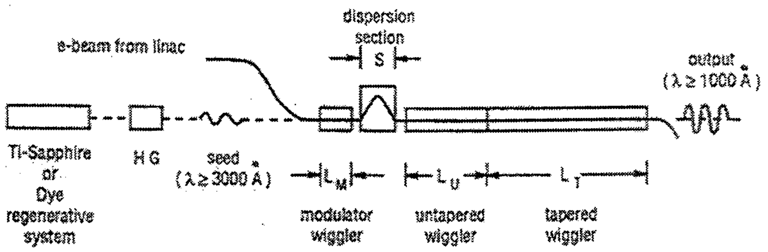
- advantages of an amplifier configuration (narrow linewidth)

- no seed required at the output frequency

R. Bonifacio et al., Nucl. Instr. Meth. A296 (1990) 787.

High Gain Harmonic Generation (HGHG)

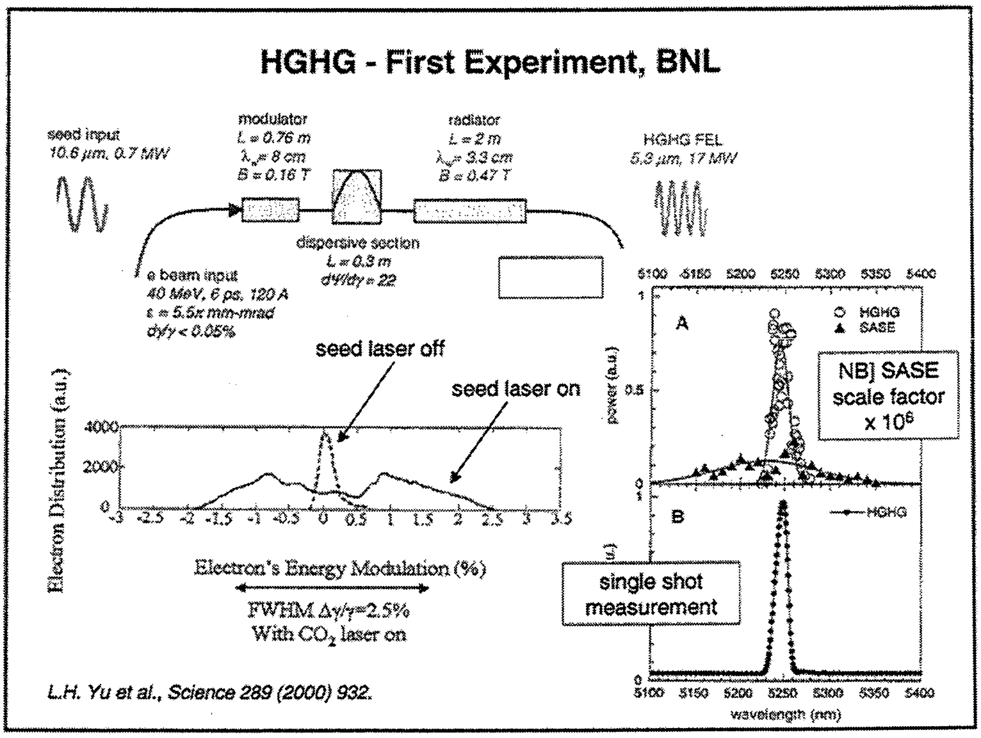
modified version of the the previous scheme, using a dispersion section to enhance the bunching:



Advantages of HGHG, compared to SASE:

- radiation is longitudinally coherent
- no spiking: smooth pulses in the temporal and spectral domains
- narrower linewidth
- wavelength stability provided by the seed laser
- adjustable pulse length by varying the seed laser pulse length
- shorter undulator

L.H. Yu, Phys. Rev. A44 (1991) 5178.



HGHG - First Experiment, BNL

seed laser off

seed laser on

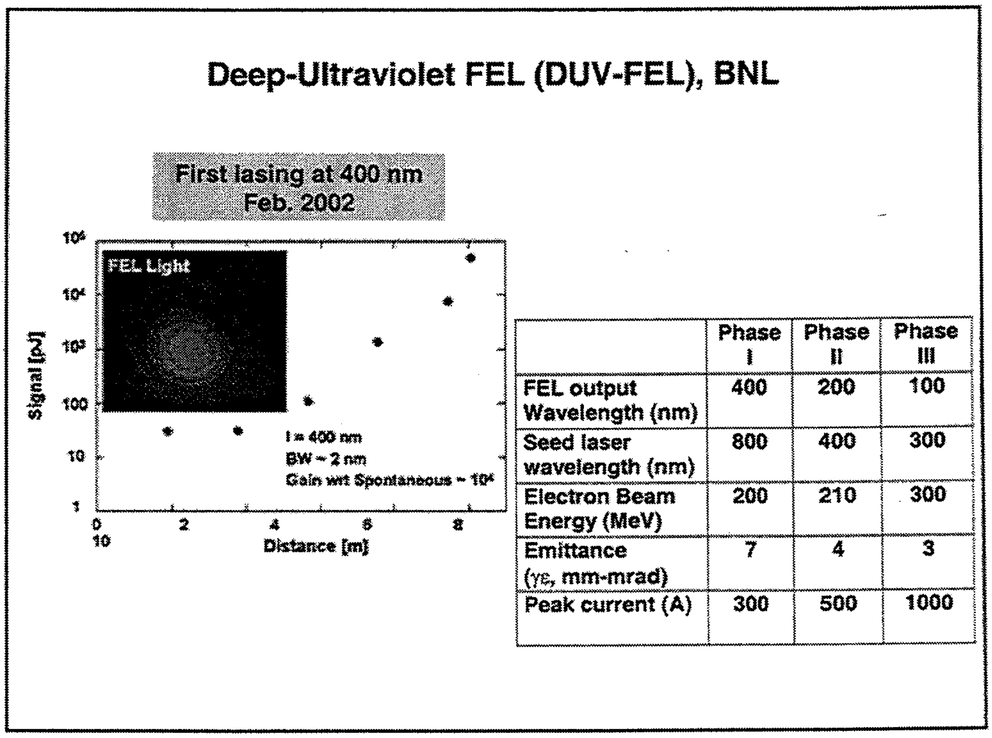
NB] SASE scale factor x 10^6

single shot measurement

Electron's Energy Modulation (%)

FWHM $\Delta\gamma/\gamma$=2.5%
With CO_2 laser on

L.H. Yu et al., Science 289 (2000) 932.



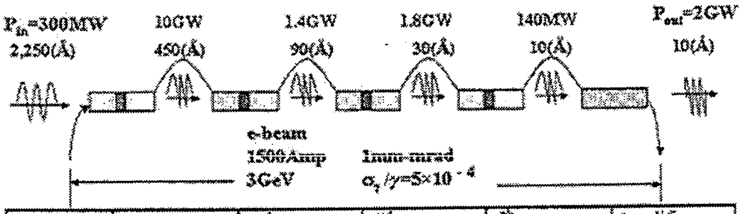
Deep-Ultraviolet FEL (DUV-FEL), BNL

First lasing at 400 nm
Feb. 2002

	Phase I	Phase II	Phase III
FEL output Wavelength (nm)	400	200	100
Seed laser wavelength (nm)	800	400	300
Electron Beam Energy (MeV)	200	210	300
Emittance ($\gamma\varepsilon$, mm-mrad)	7	4	3
Peak current (A)	300	500	1000

HGHG X-ray FEL

Cascaded HGHG using the 'fresh-part-of bunch' scheme :

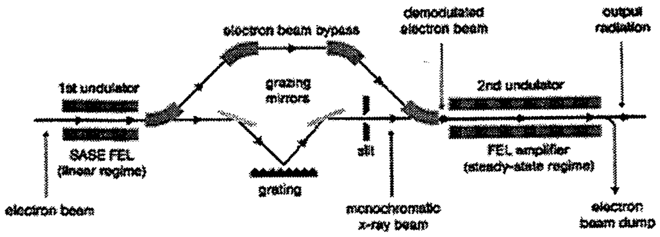


	1^{st} Stage		2^{nd} Stage		3^{rd} Stage		4^{th} Stage		Amplifier
λ(Å)	2250	450	450	90	90	30	30	10	10
λ_w(cm)	8.5	5.6	5.6	3.8	3.8	2.9	2.9	2.3	2.3
$d\psi/d\gamma$	0.4		0.1		0.1		0.1		
L_W(m)	4	9.5	1	4	2	8.5	1.5	5.5	10
L_G(m)	0.74	0.87	0.87	0.93	0.93	1.12	1.12	1.86	1.86

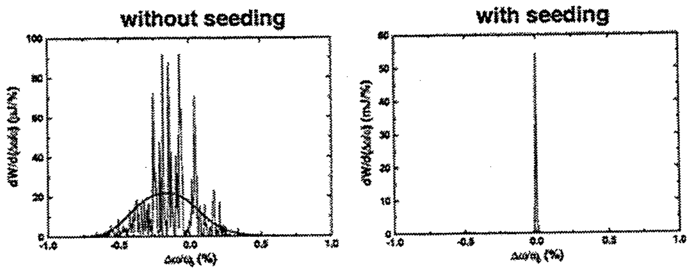
L_{total}=46m to reach 2 GW

J. Wu and L.H. Yu, Proc. PAC 2001

Two-stage SASE FEL



being implemented as part of TTF Phase II



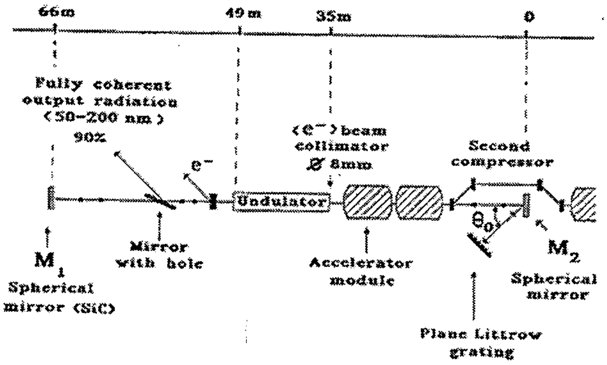
J. Feldhaus et al., Optics Comm. 140 (1997) 341.

Regenerative Amplifier FEL (RAFEL)

High-gain FEL with a small amount of feedback, to allow it reach saturation in a small number of passes. First developed and demonstrated at LANL *(Nguyen and Goldstein, 1997)*.

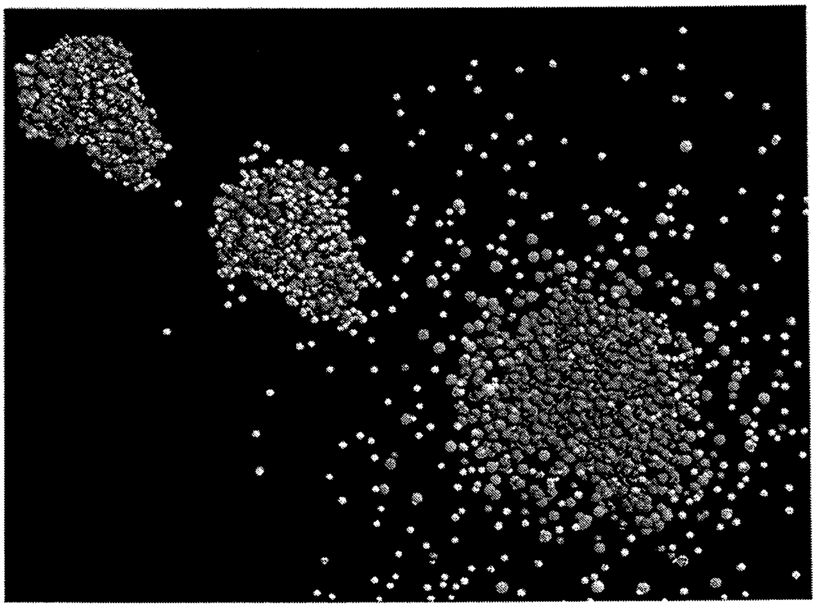
The concept was then modified to include monochromatization so that the seed radiation is longitudinally coherent. *(Faatz et al., 1999)*

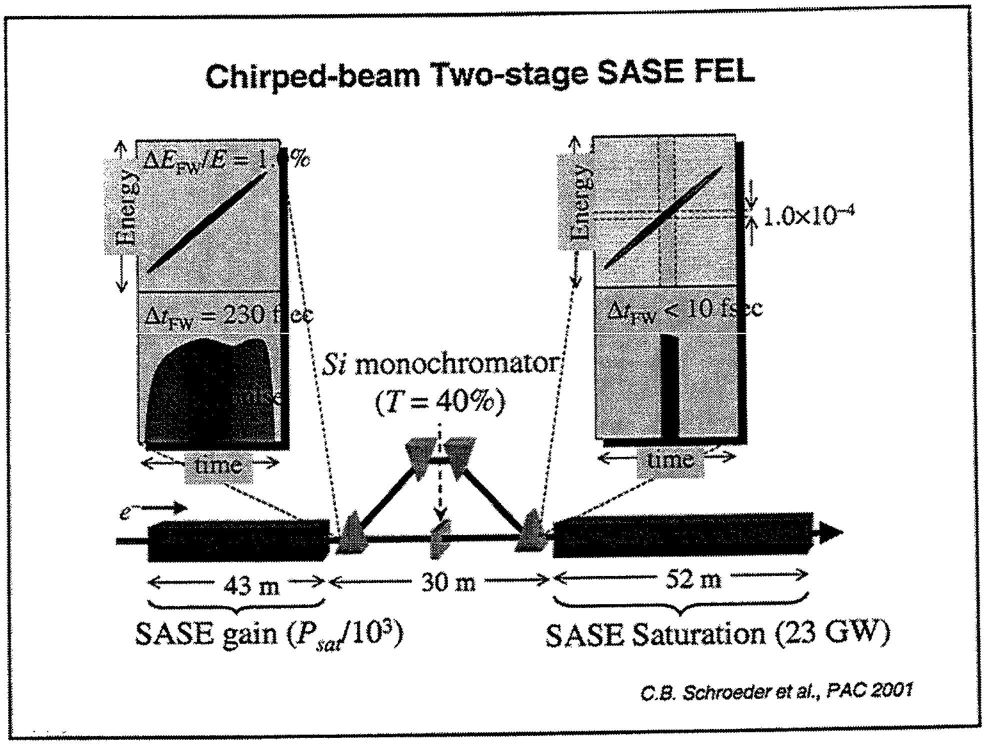
Experiment is currently being carried out at TTF-1:



66.4 m between the mirrors corresponds to 2 x distance between micropulses (9 MHz).

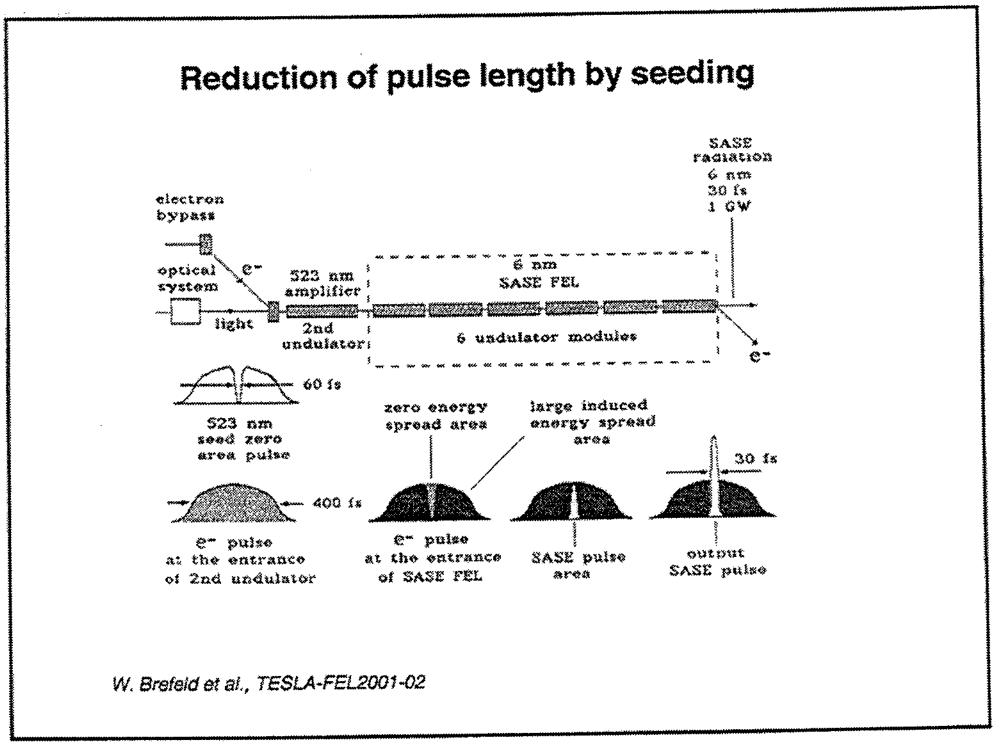
Motivation for Shorter Pulses: Radiation Damage





Chirped-beam Two-stage SASE FEL

C.B. Schroeder et al., PAC 2001

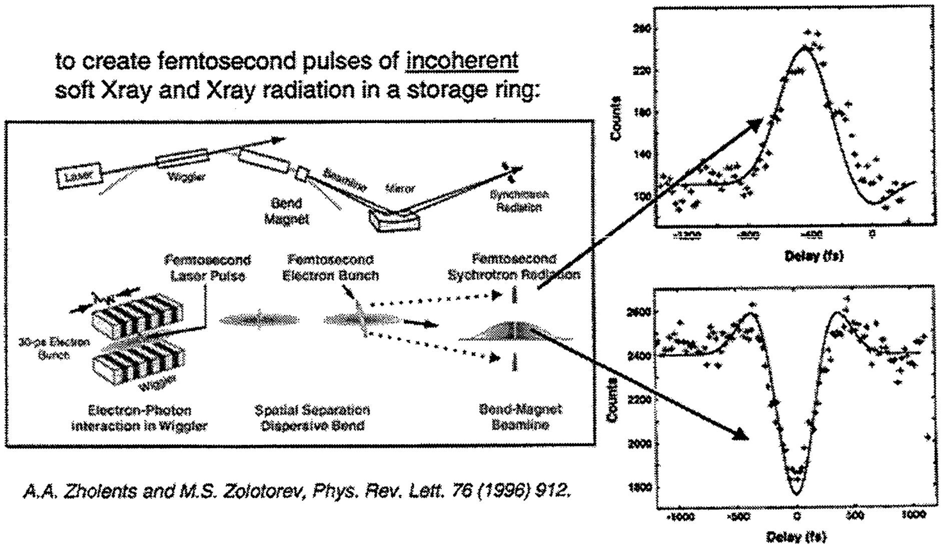


Reduction of pulse length by seeding

W. Brefeld et al., TESLA-FEL2001-02

"Pulse Slicing" using the FEL interaction

to create femtosecond pulses of <u>incoherent</u> soft Xray and Xray radiation in a storage ring:

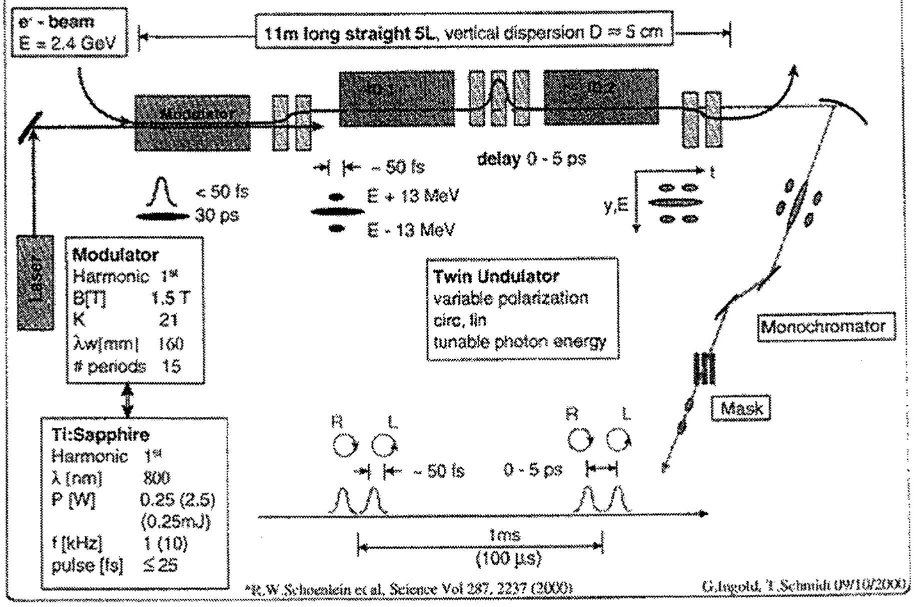


A.A. Zholents and M.S. Zolotorev, Phys. Rev. Lett. 76 (1996) 912.

R.W. Schoenlein et al., Science 287 (2000) 223.

PAUL SCHERRER INSTITUT — SLS

Femtosecond bunch slicing* in one straight: ~ 50 fs



Modulator	
Harmonic	1st
B[T]	1.5 T
K	21
λw[mm]	160
# periods	15

Ti:Sapphire	
Harmonic	1st
λ [nm]	800
P [W]	0.25 (2.5) (0.25mJ)
f [kHz]	1 (10)
pulse [fs]	≤ 25

*R.W.Schoenlein et al, Science Vol 287, 2237 (2000)

G.Ingold, T.Schmidt 09/10/2000

Conclusion

Since the first operation 25 years ago,
FELs have branched out in many different directions so that today there is a very wide range of FEL related activity.
(See for example the Proceedings of the Annual International FEL Conferences).

Many developments are underway, involving challenging accelerator physics and technological problems, particularly in the case of the short wavelength FELs

I hope these few lectures have stimulated some interest in this expanding and exciting field.