Future Short Wavelength SASE FELs

Extension of existing projects:

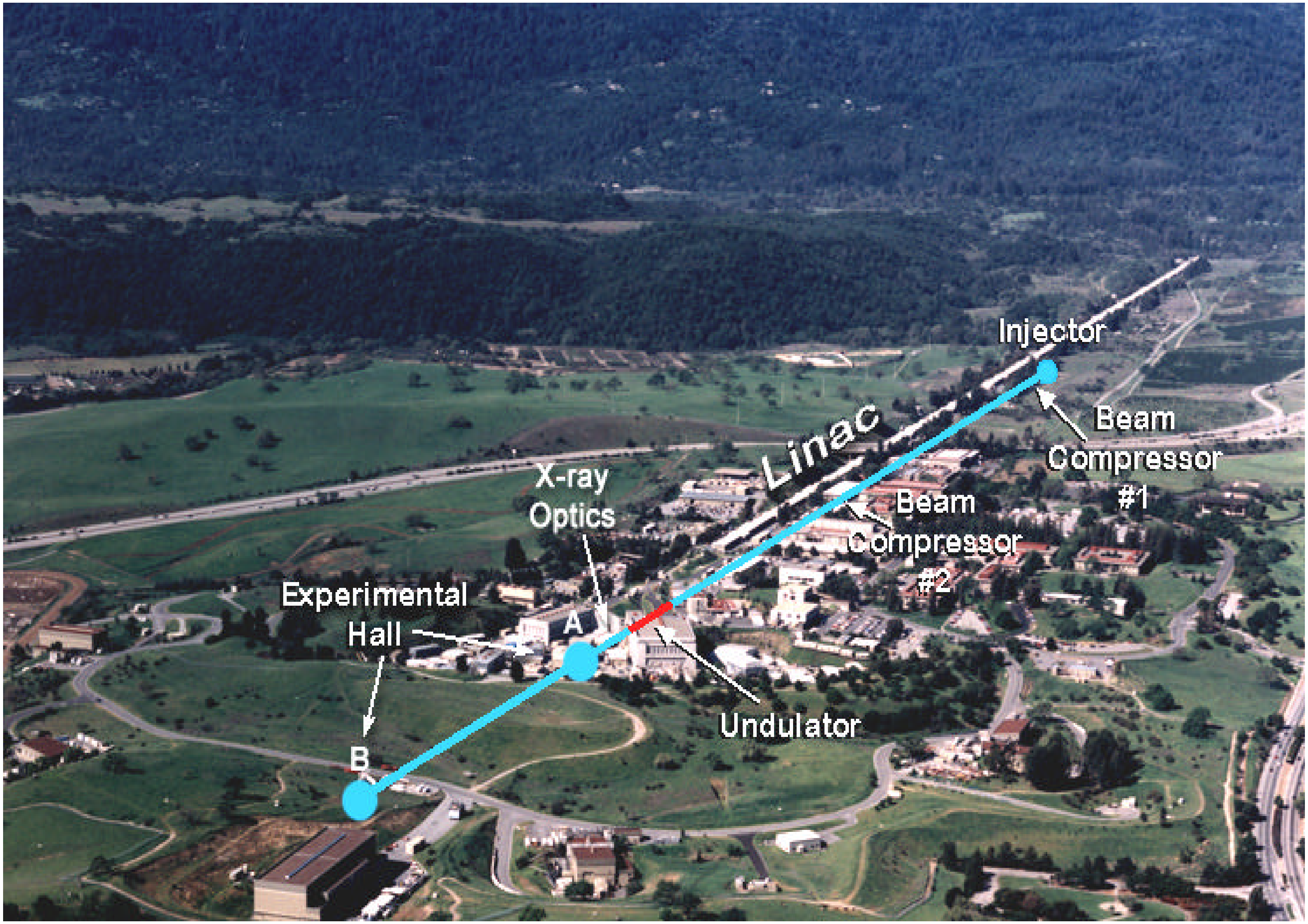
APS-FEL: extension to 50 nm

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/mm^2/mrad^2/ 0.1%-BW

LCLS

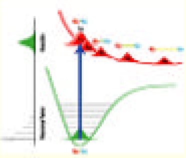
Total Estimated Cost ($FY2002)	$ 196.5 M
• Project Engineering and Design (direct)	$ 29.7 M
• Construction(direct)	$ 106.2 M
• Overhead	$ 23.1 M
• Contingency	$ 37.5 M

Timescales

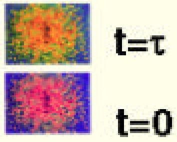
May 2002	Projected DoE approval of preliminary project baseline (CD-1)
Jan. 2003	Projected DoE approval of performance project baseline (CD-2)
Mar. 2004	Projected DoE approval for start of construction (CD-3)
Oct. 2004	Start of Construction
Oct. 2007	Projected DoE approval for start of operation (CD-4)

LCLS Science Program

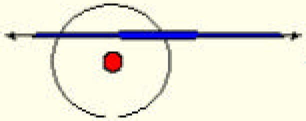
Program developed by international team of ~45 scientists working with accelerator and laser physics communities



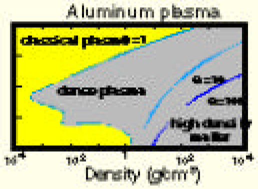
Femtochemistry



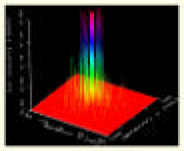
Nanoscale Dynamics in Condensed matter



Atomic Physics



Plasma and Warm Dense Matter



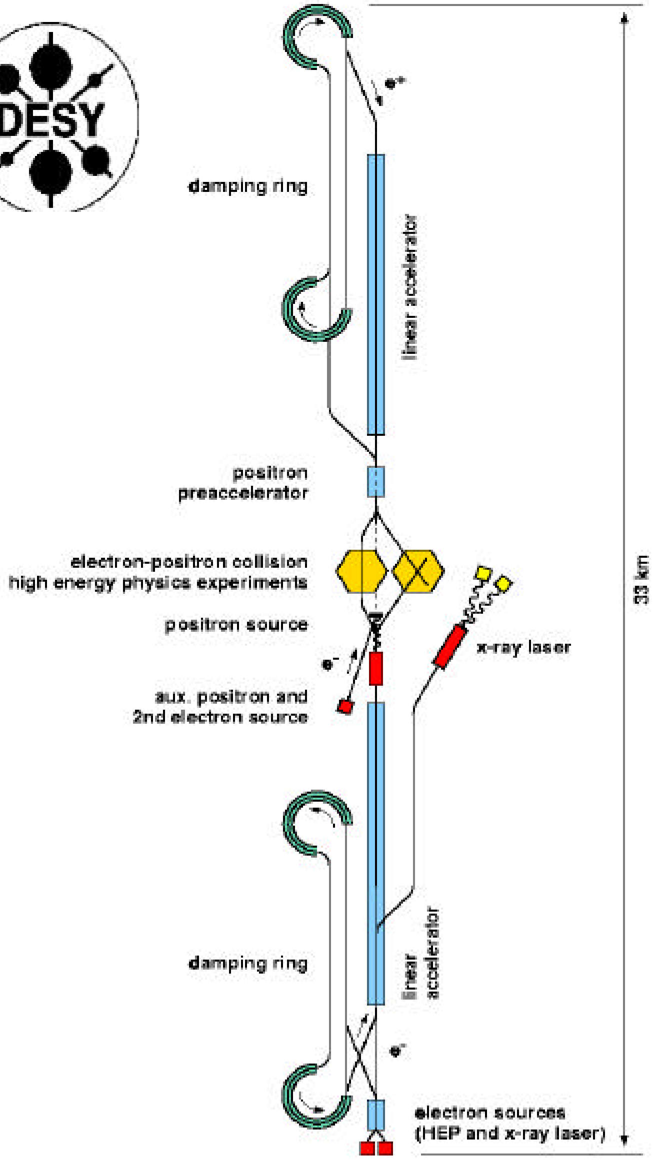
Structural Studies on Single Particles and Biomolecules

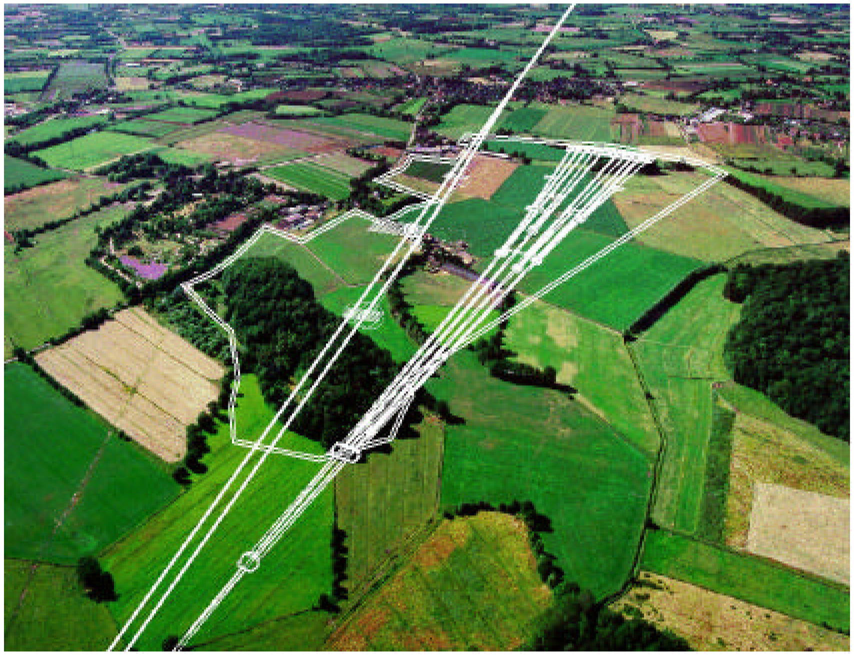
X-ray Laser Physics

Stanford
Linear
Accelerator
Center

SSRL

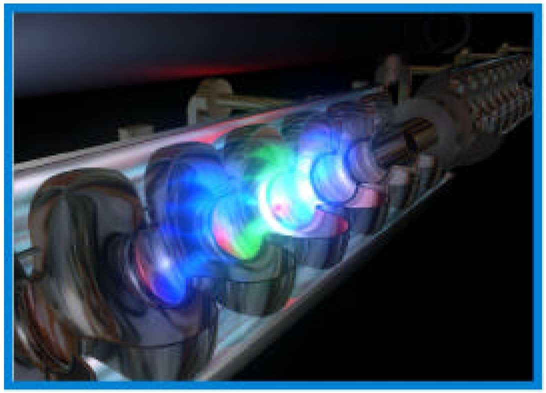
TESLA: The Superconducting Electron-Positron Linear Collider with an Integrated X-ray Laser Laboratory

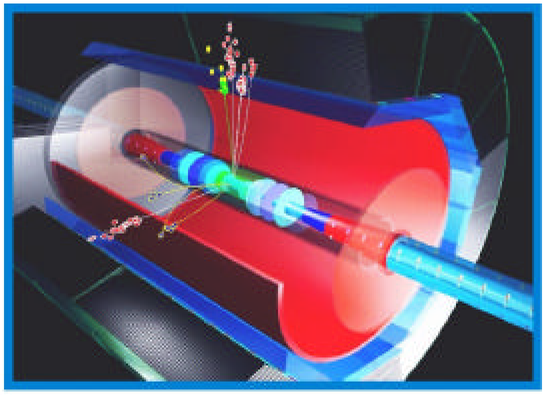


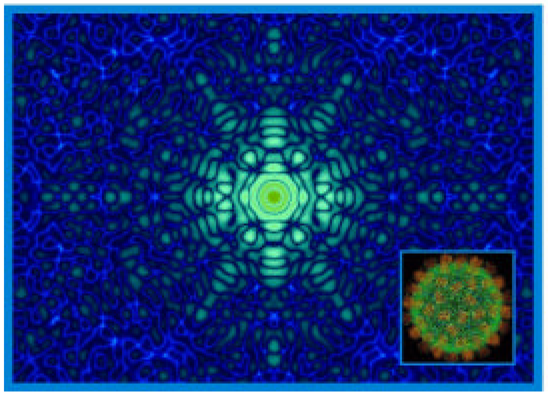


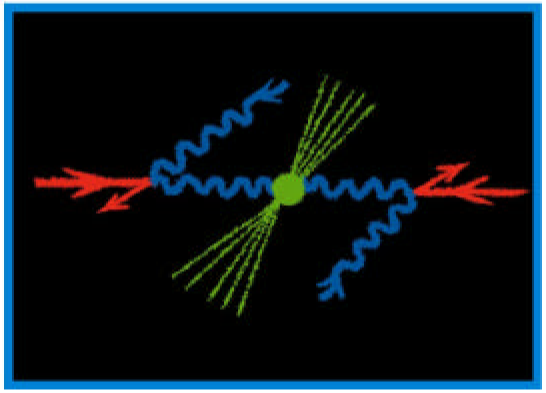
500 GeV linear collider	*3136 M EUR*
Detector for Particle Physics	*210 M EUR*
Additional cost for X-FEL	*531 M EUR*
TOTAL	*3877 M EUR*
Construction time	*8 years*

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



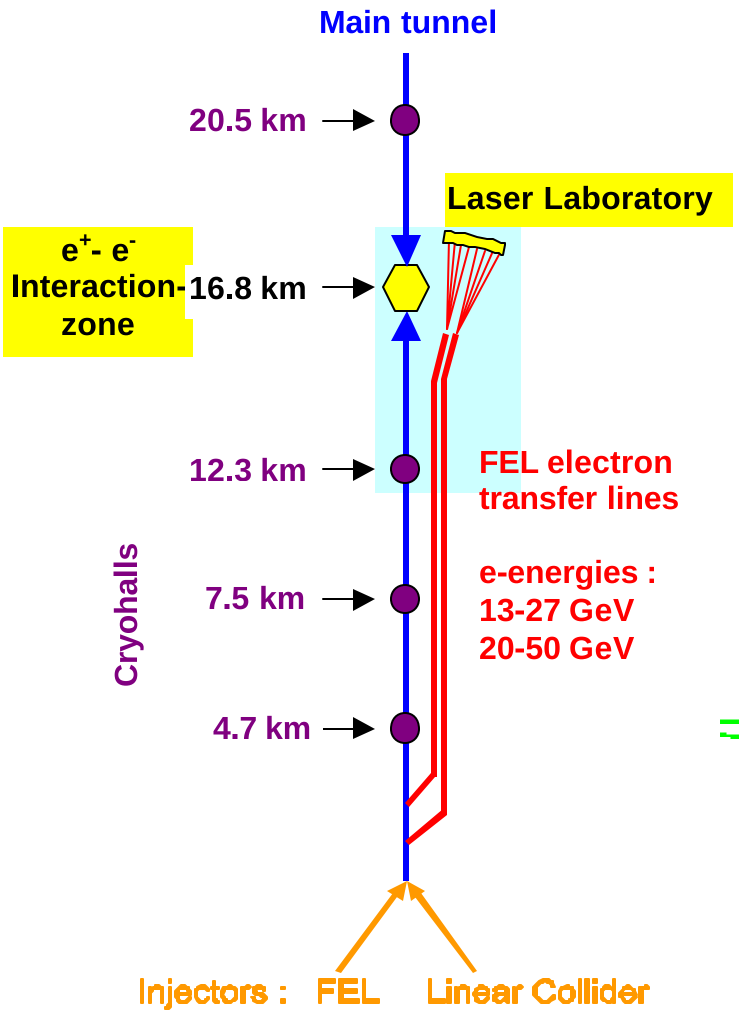


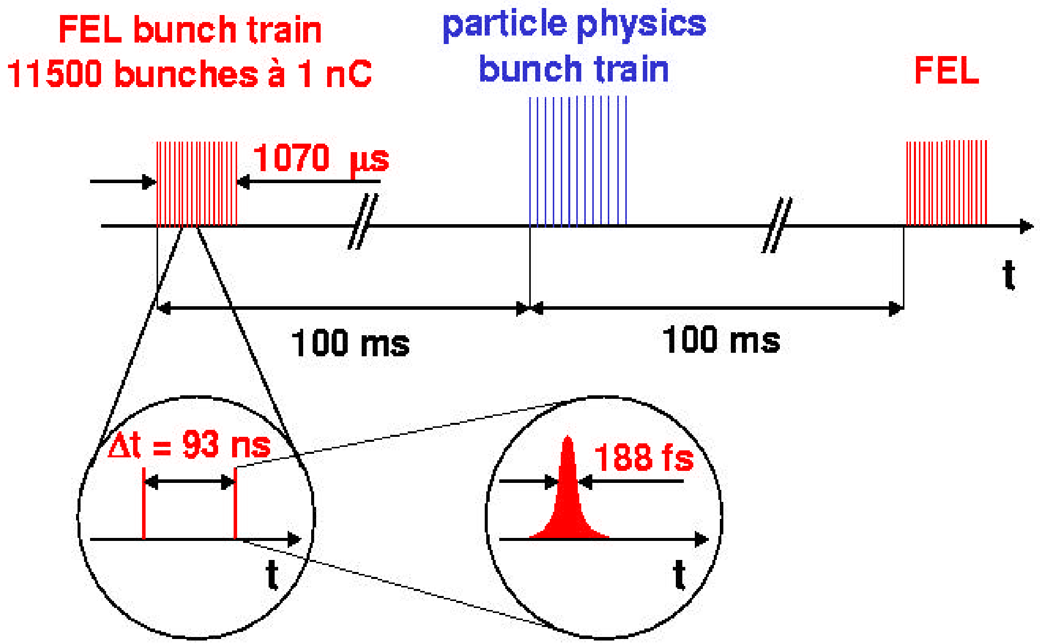


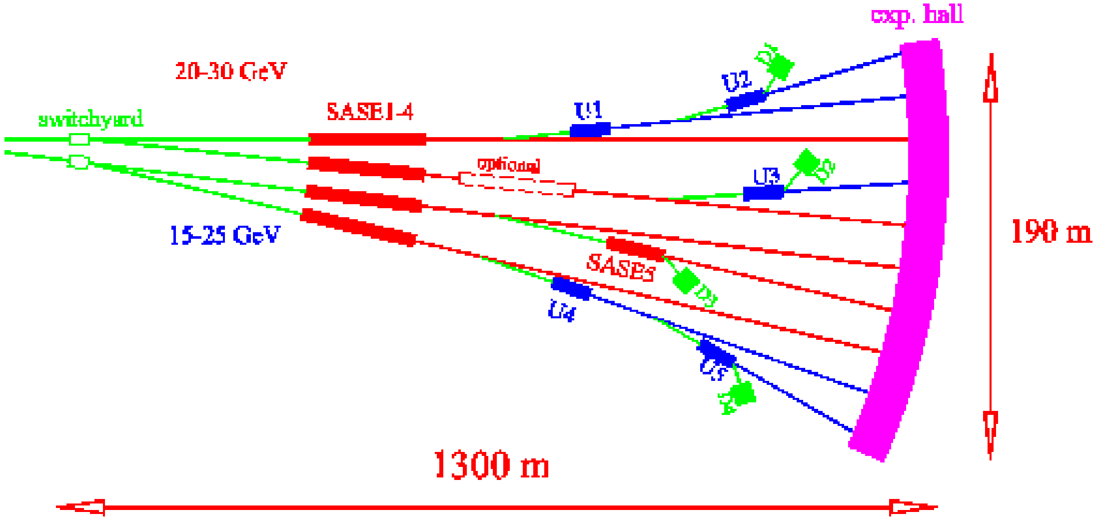


Technical Design Report March 2001

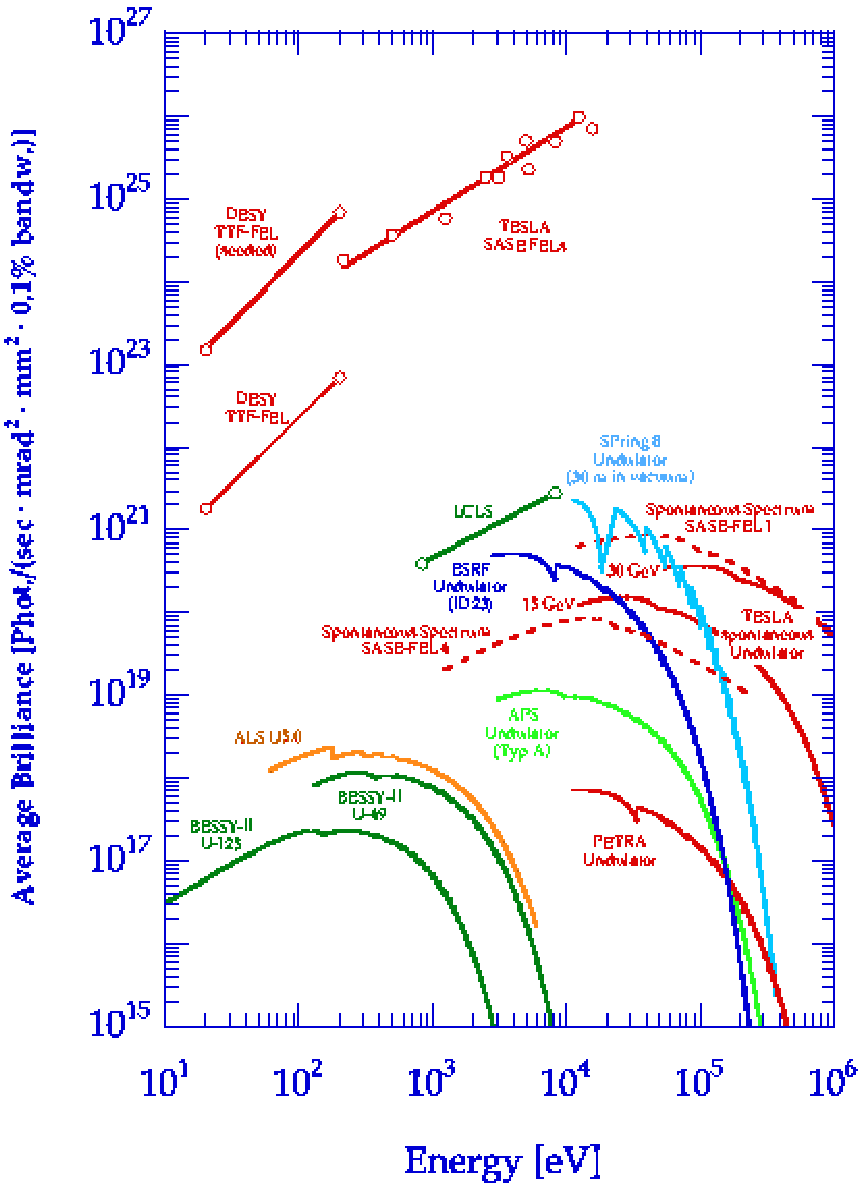
TESLA XFEL: Integration with the Linear Collider

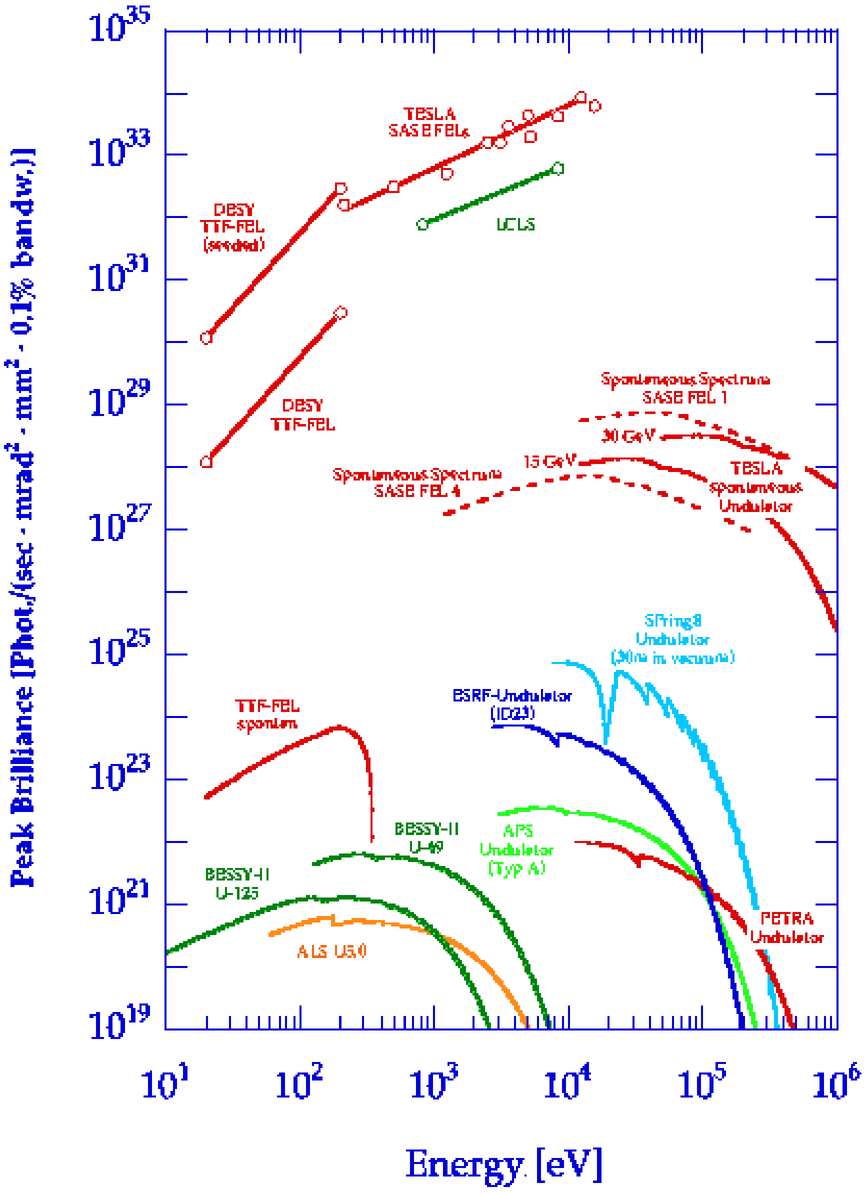




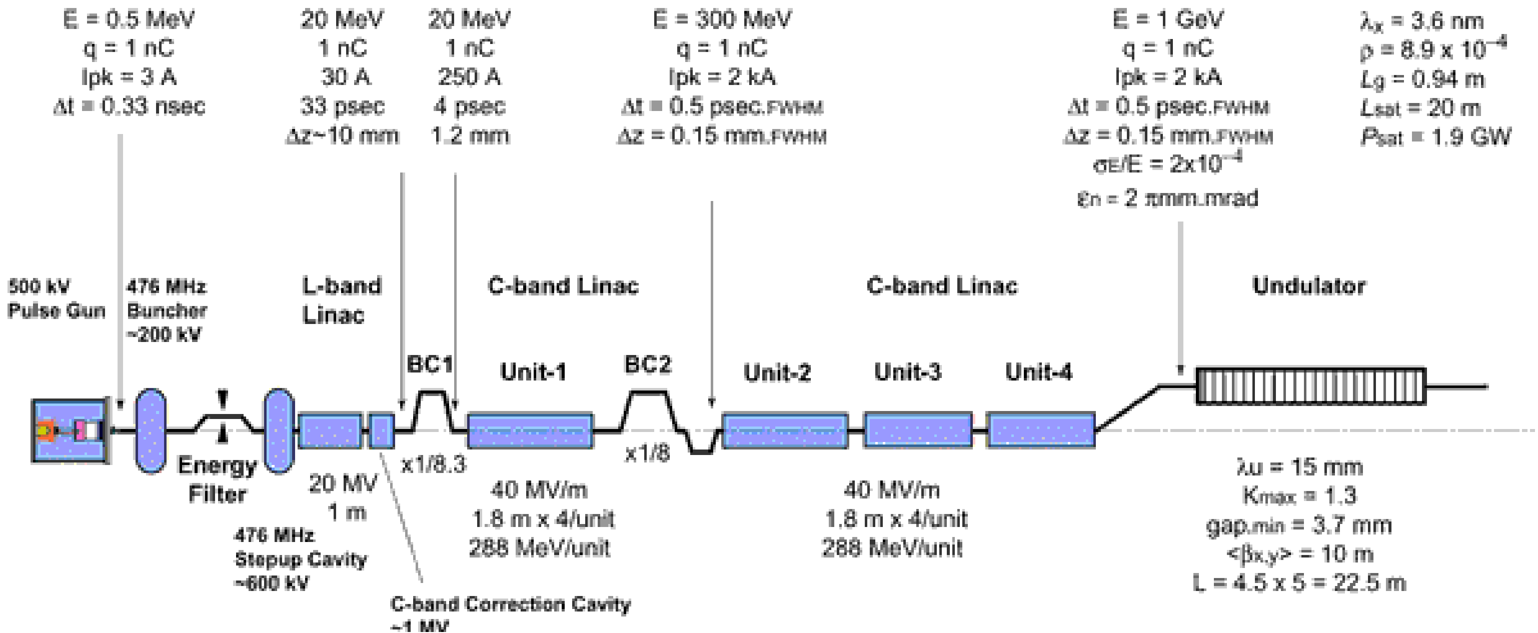


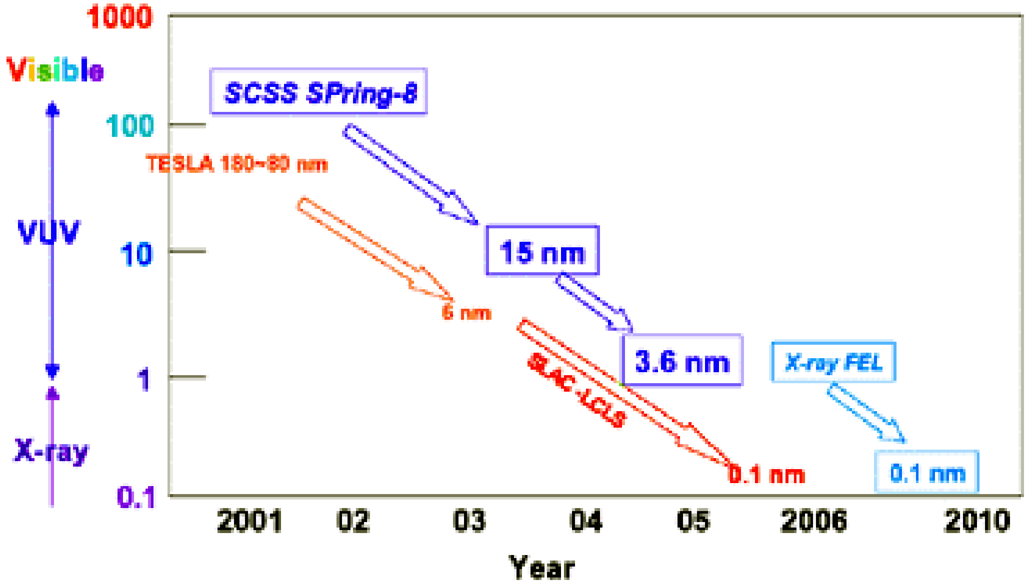
LCLS and TESLA XFEL Performance





Spring-8 Compact SASE Source

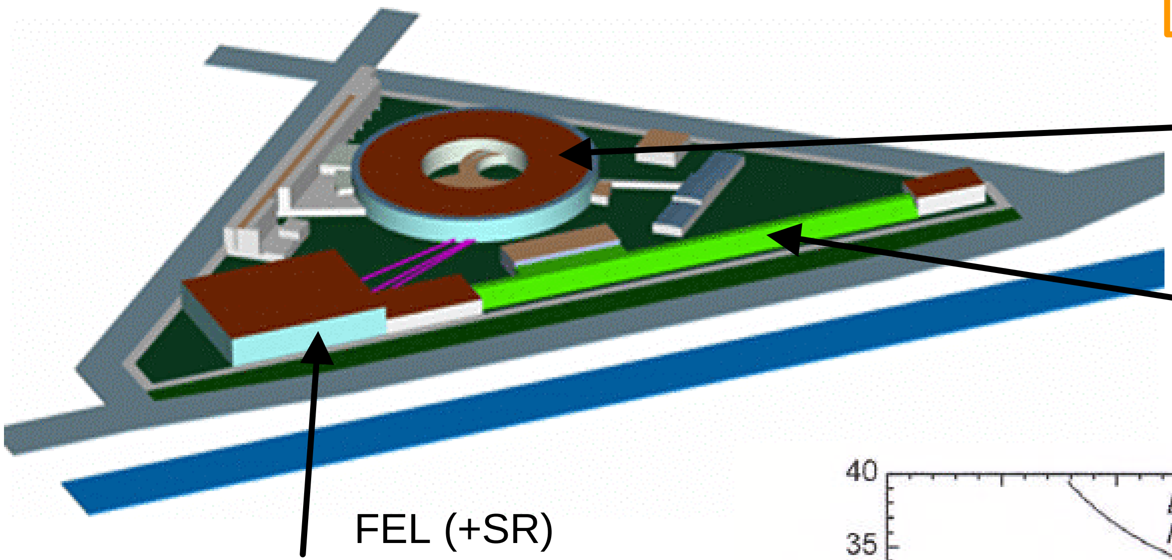




The BESSY FEL

Wavelength: 60 - 1.2 nm

Photon energy: 20 eV - 1 keV

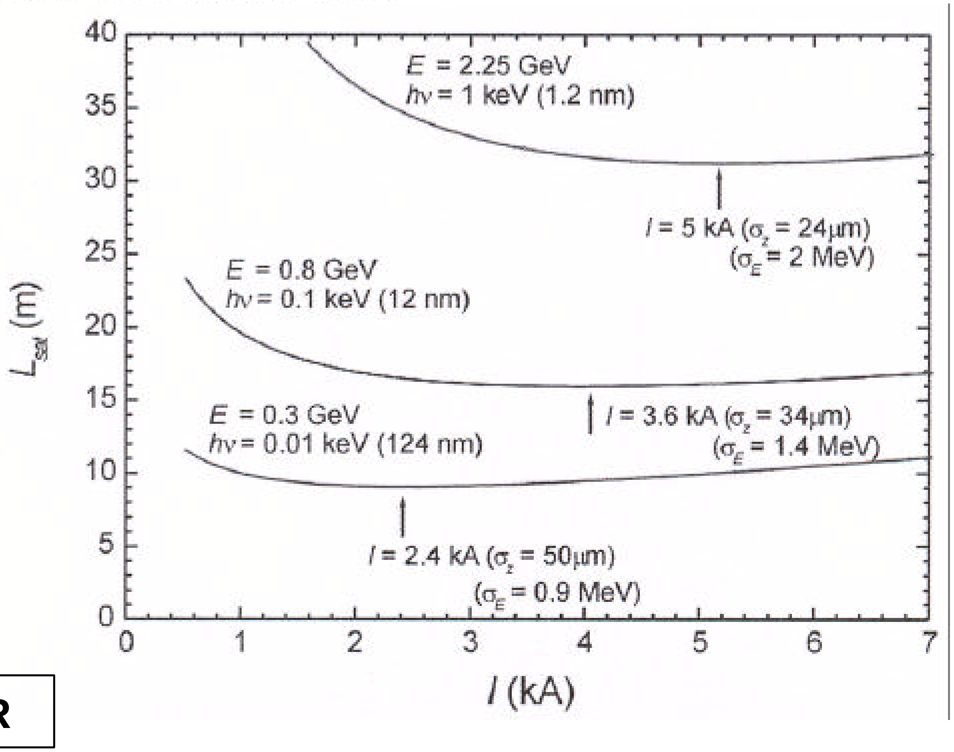


BESSY II 1.7/1.9 GeV storage ring

proposed 2.25 GeV superconducting linac

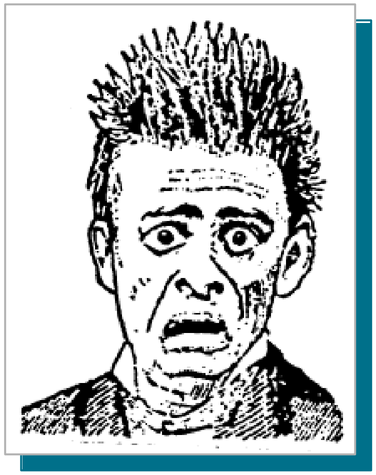
FEL (+SR) experimental hall

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



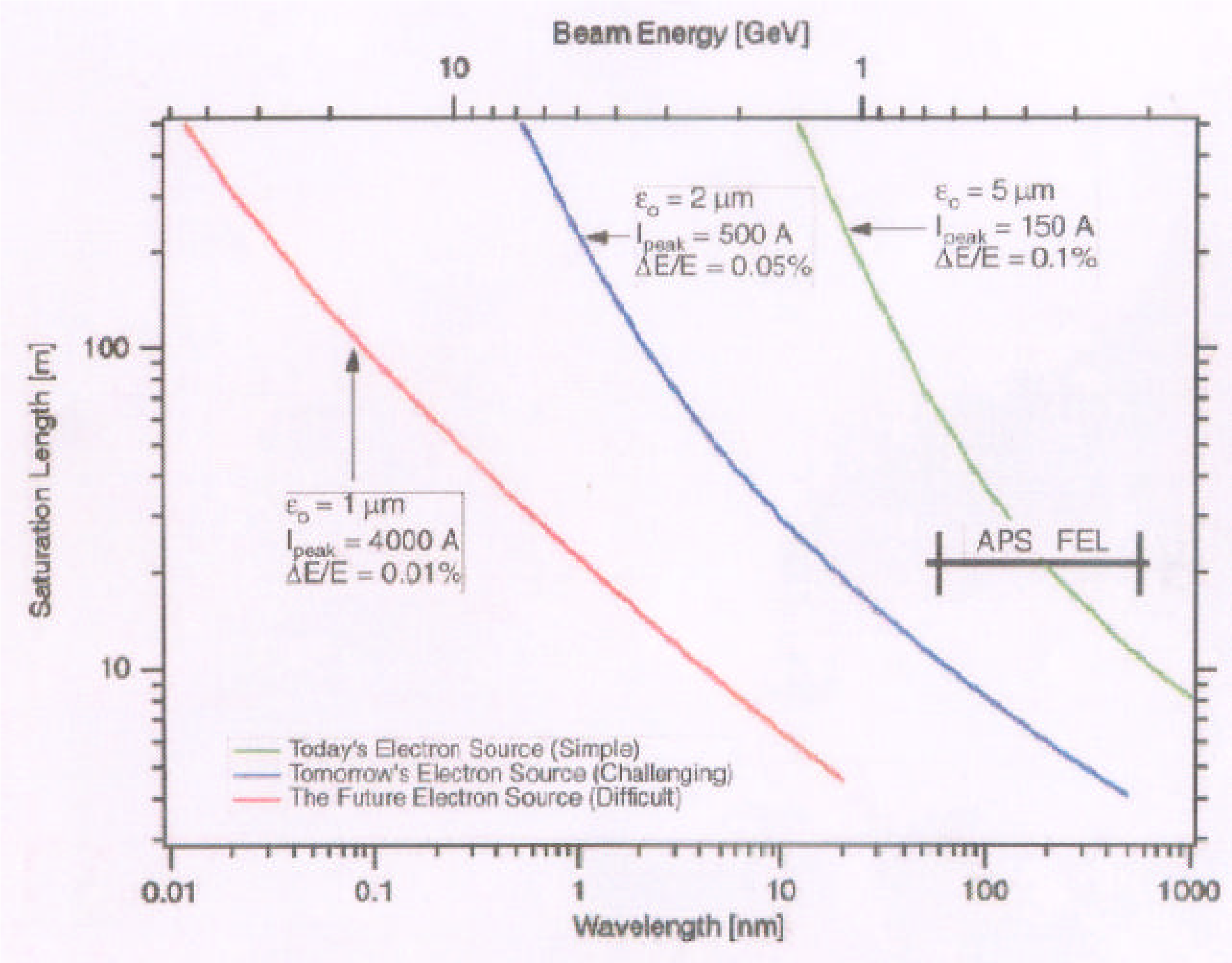
initial cost estimate: 148 M EUR

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

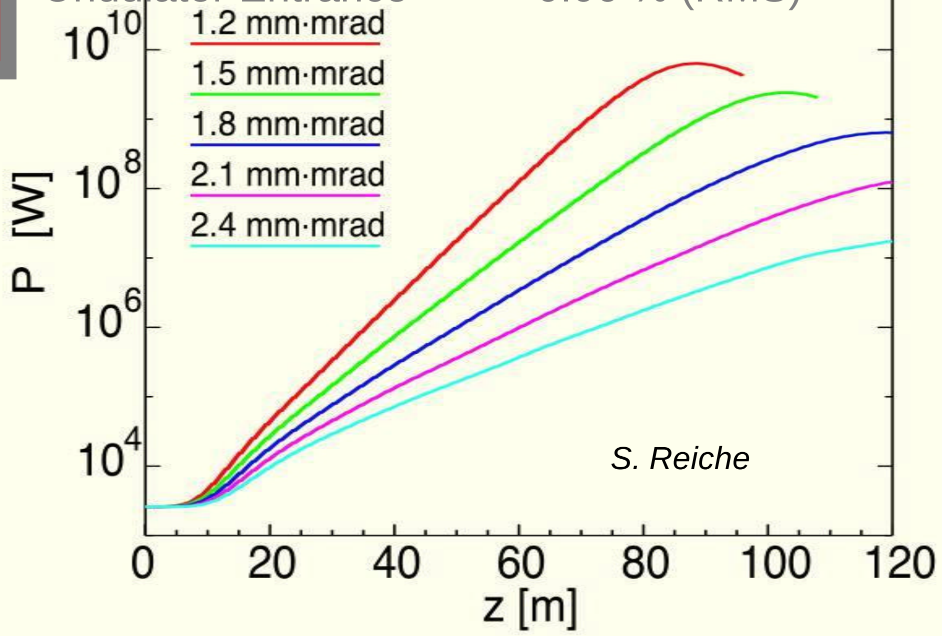
Parameter	**Location**	**LCLS Goal Values***
Normalized Slice Emittance	Injector (@150 MeV)	1.0 mm mrad (RMS)
	Undulator Entrance	1.2 mm mrad (RMS)
Normalized Projected Emittance	Injector (@150 MeV)	1.2 mm mrad (RMS)
	Undulator Entrance	1.5 mm mrad (RMS)
Slice Energy Spread	Injector (@150 MeV)	<0.01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

% (RMS) Undulator Entrance 0.06 % (RMS)

At a peak current of 3400 A at the undulator

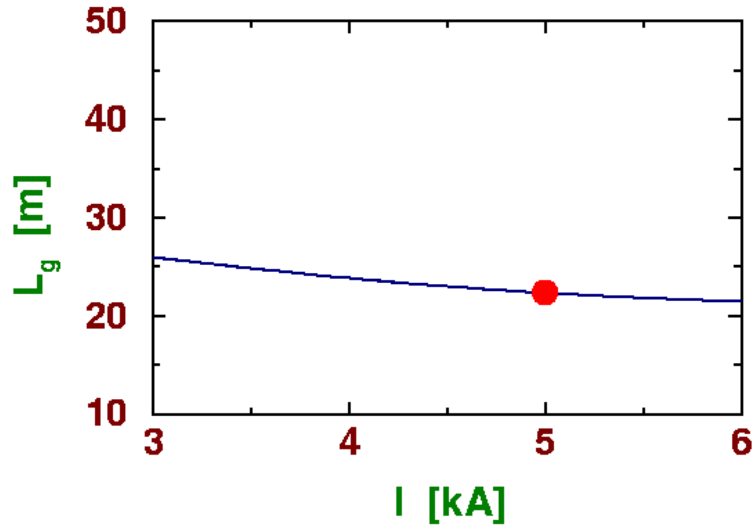
1.7 mm·mrad is the largest <u>slice emittance</u>, which allows saturation within the LCLS Undulator (120 m, including gaps between modules), assuming a local current of 3.4 kA.

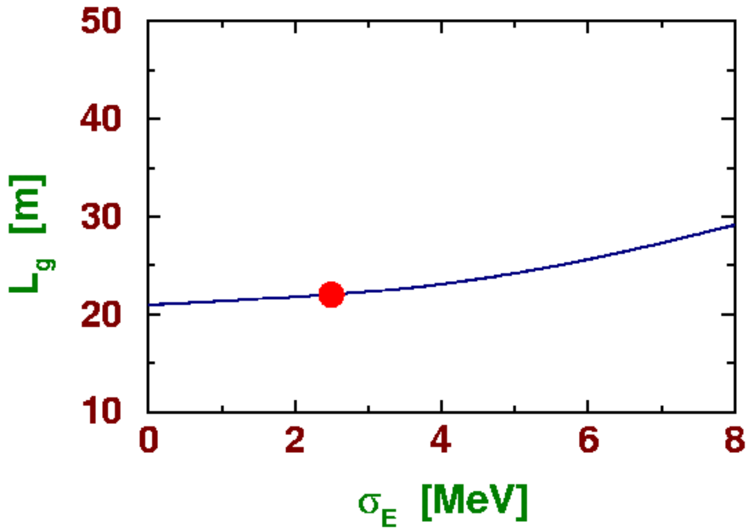
"slice emittance" is the local emittance over a cooperation length.

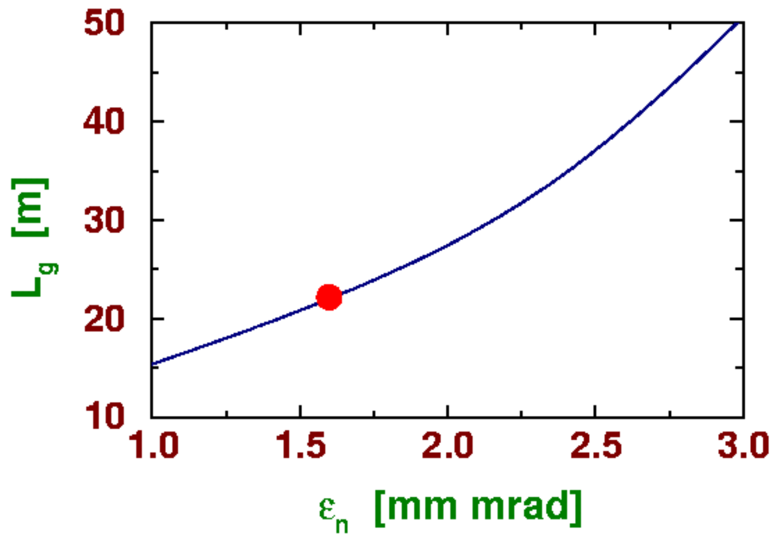


S. Reiche

TESLA XFEL: Parameter sensitivity



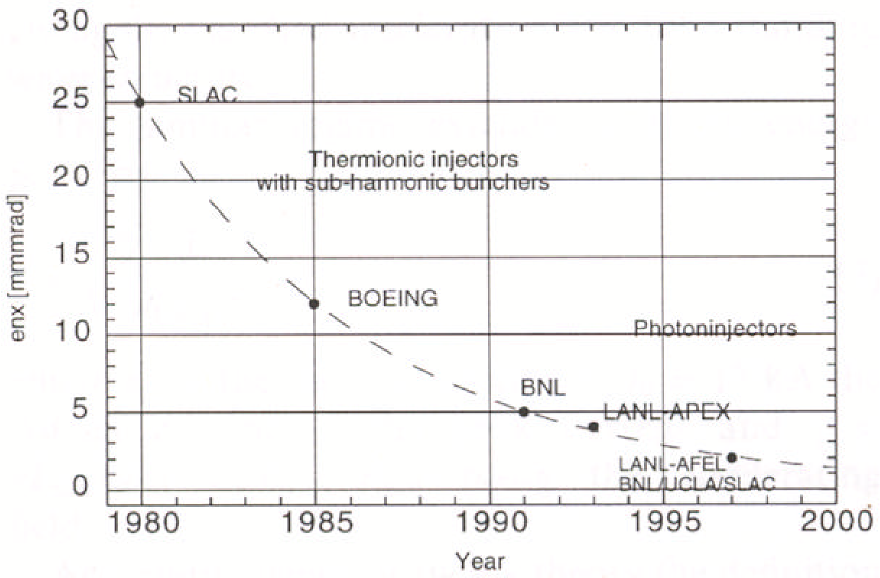


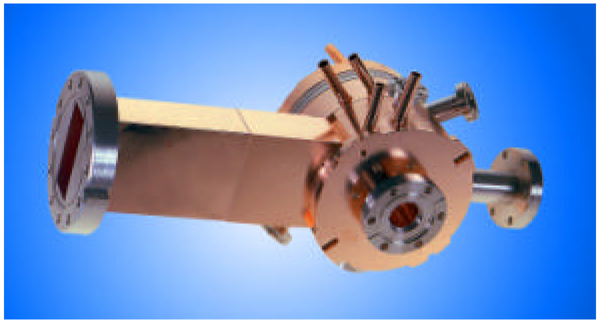


Nominal values are 5 kA peak current with 1.6 μm slice emittance

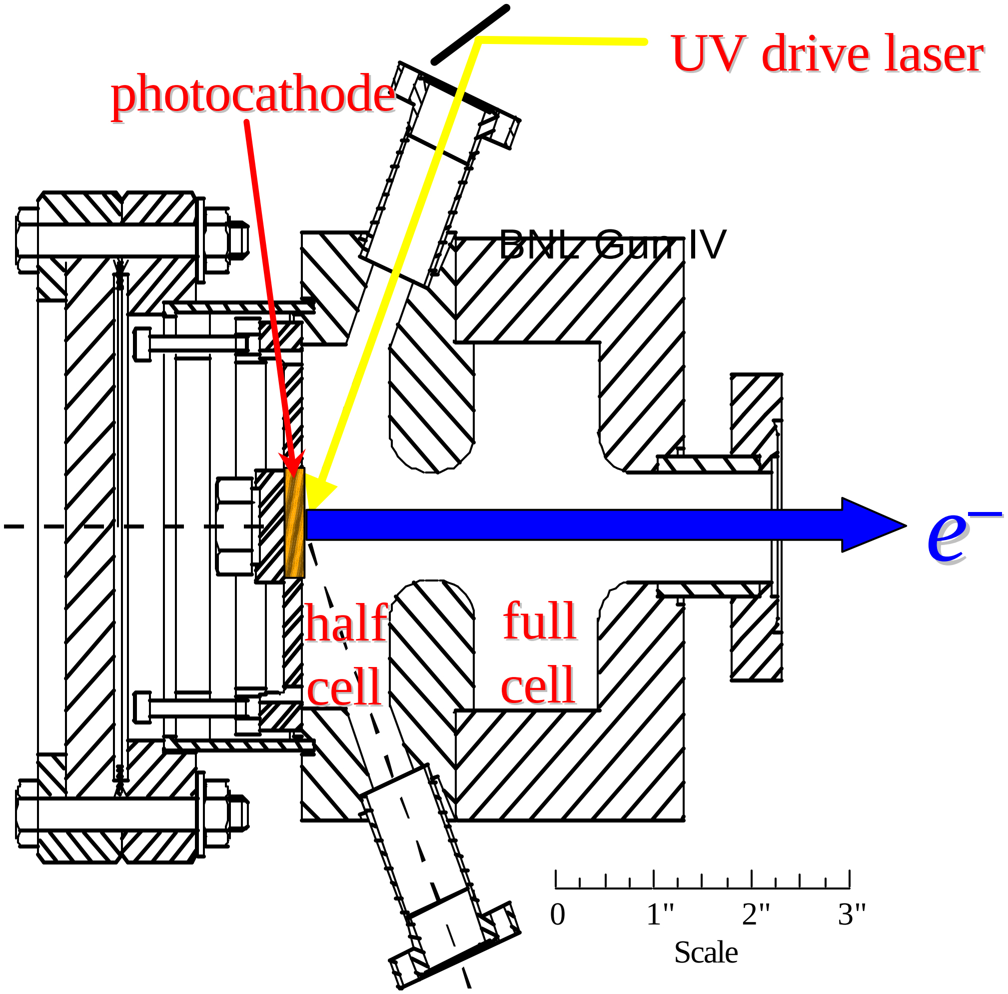
Photo-injectors

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

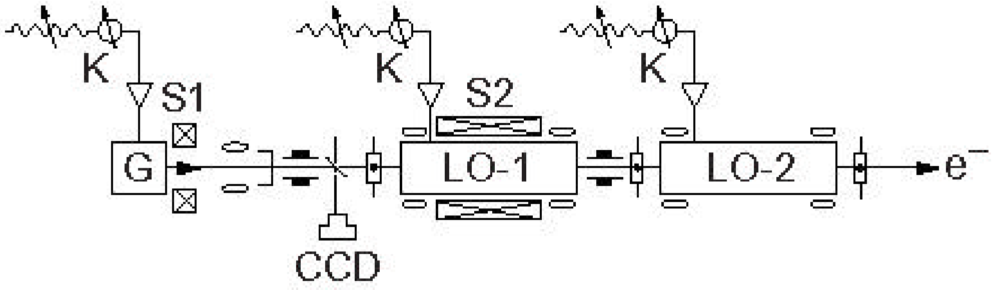




"Standard" 1.6 cell design:



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

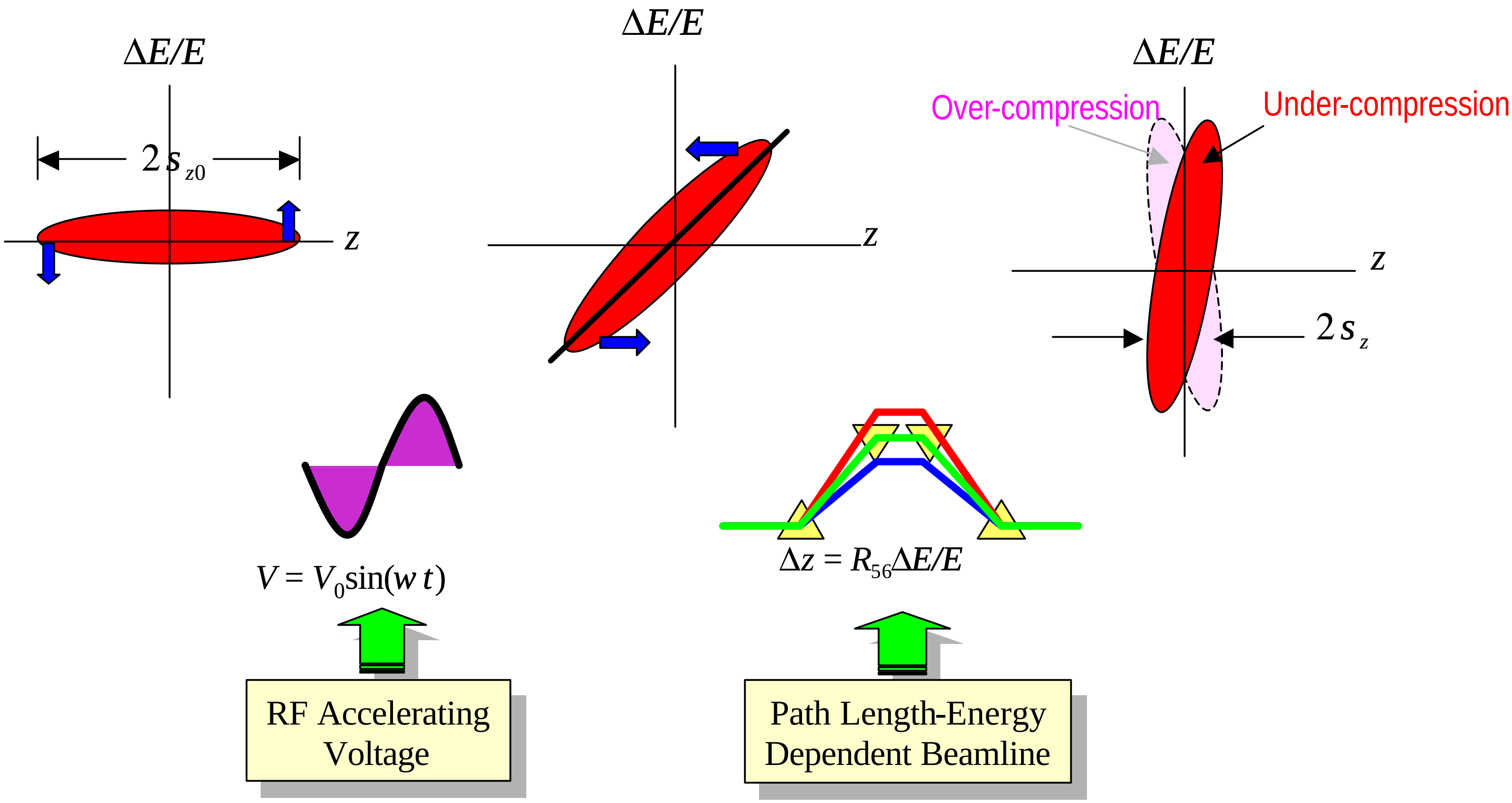
"Recent" results (PAC '01)

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



$V = V_0 \sin(\omega t)$

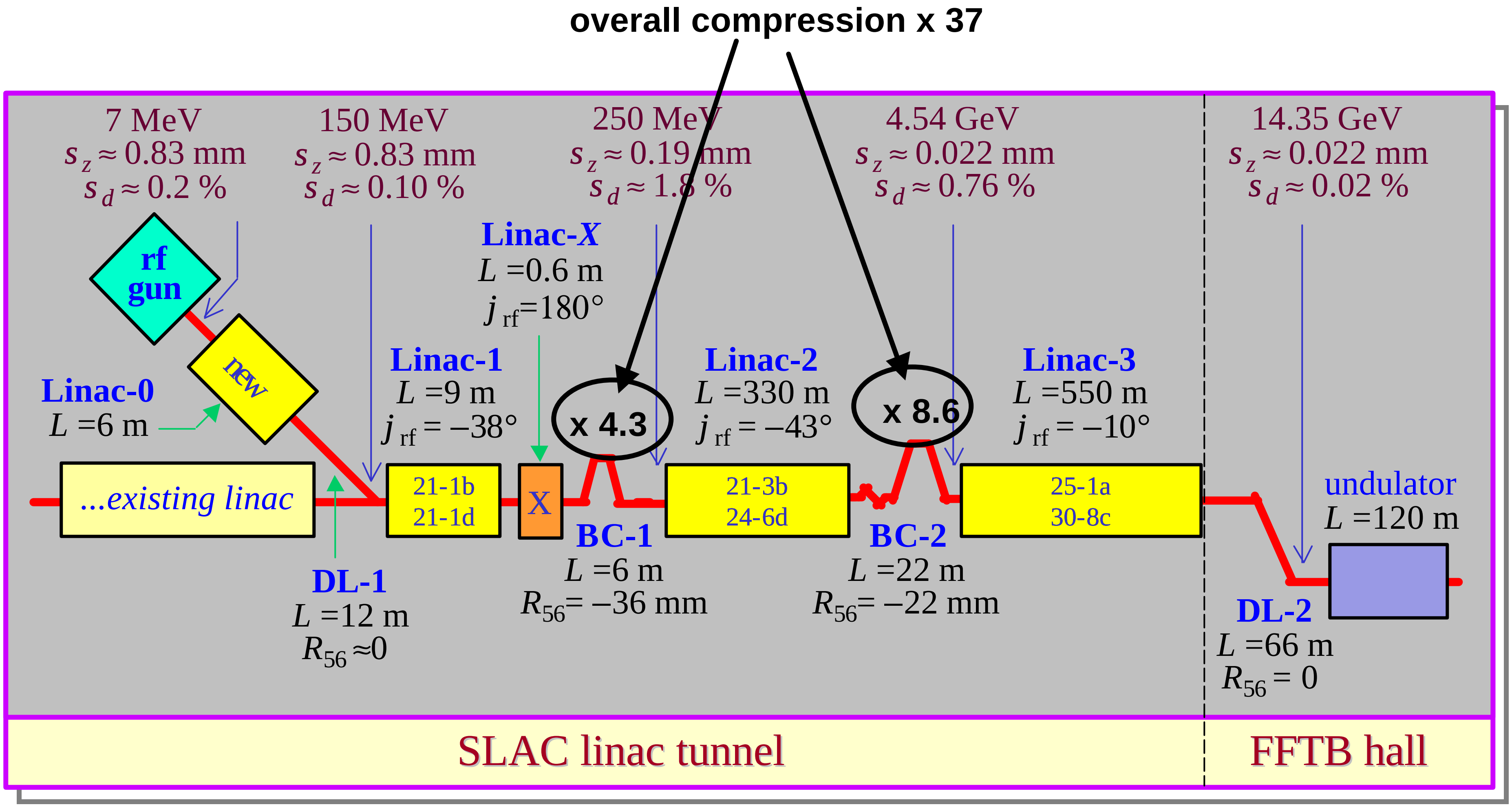
$\Delta z = R_{56} \Delta E/E$

RF Accelerating Voltage

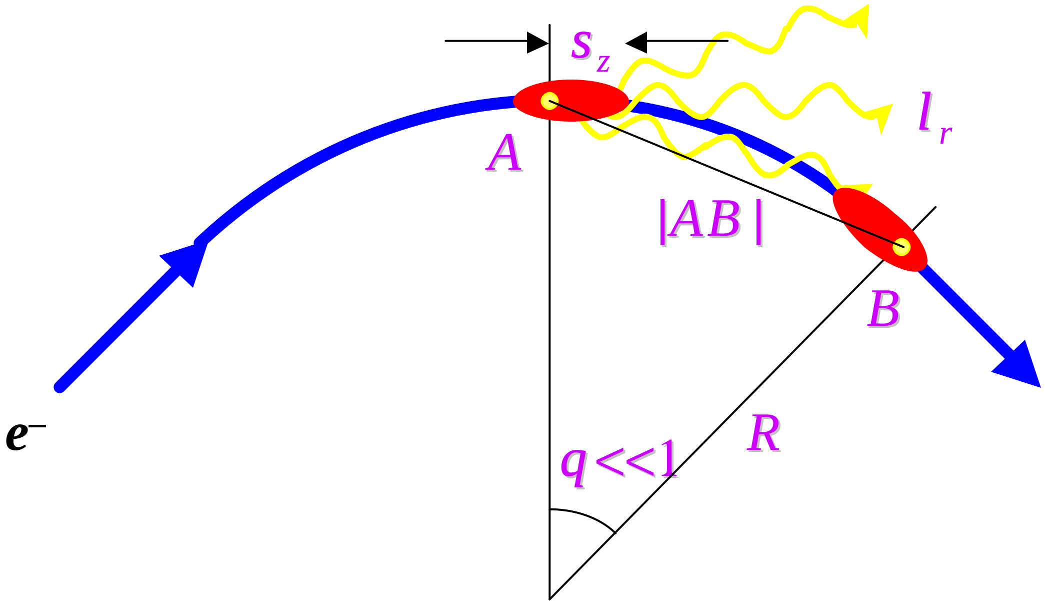
Path Length-Energy Dependent Beamline

Magnetic Bunch Compression

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



Coherent Synchrotron Radiation (CSR)



Coherent radiation for:
$l_r >> s_z$

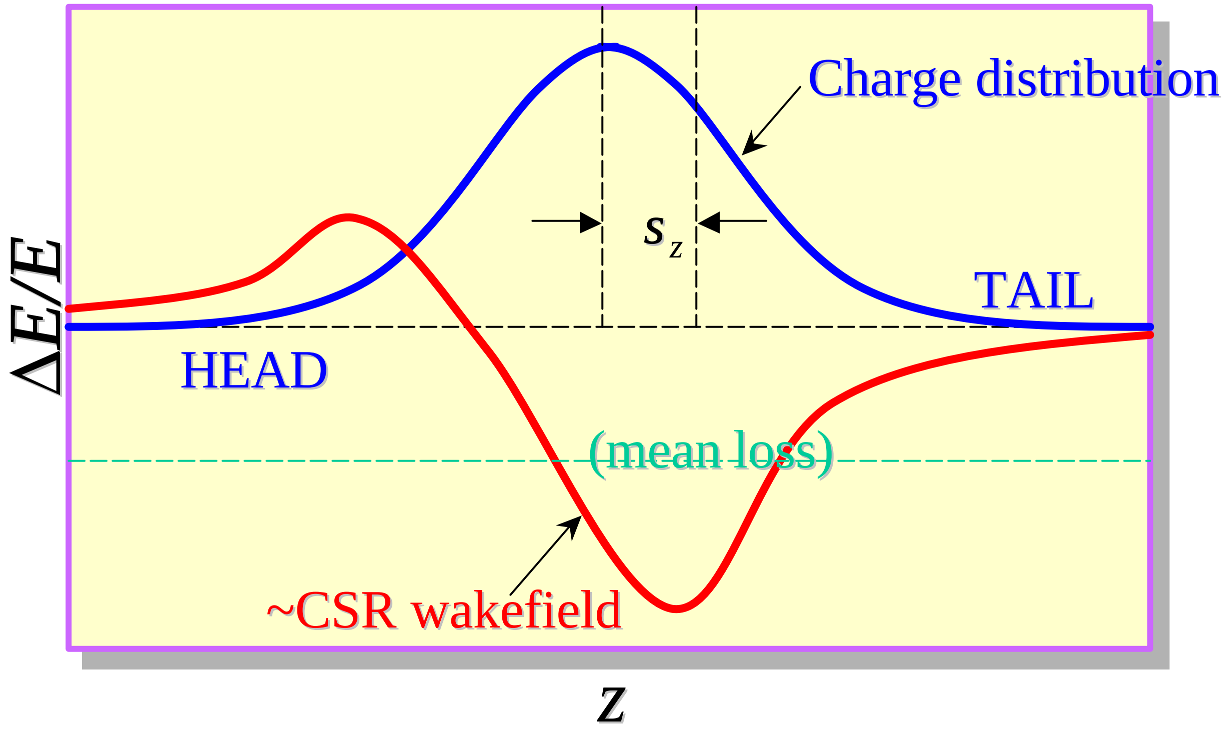
Free space radiation from bunch tail at point ***A*** overtakes bunch head, a distance ***s*** ahead of the source, at the point ***B*** which satisfies...

$$s = \text{arc}(\boldsymbol{AB}) - |\boldsymbol{AB}| = Rq - 2R\sin(q/2) \approx Rq^3/24 = s_z$$

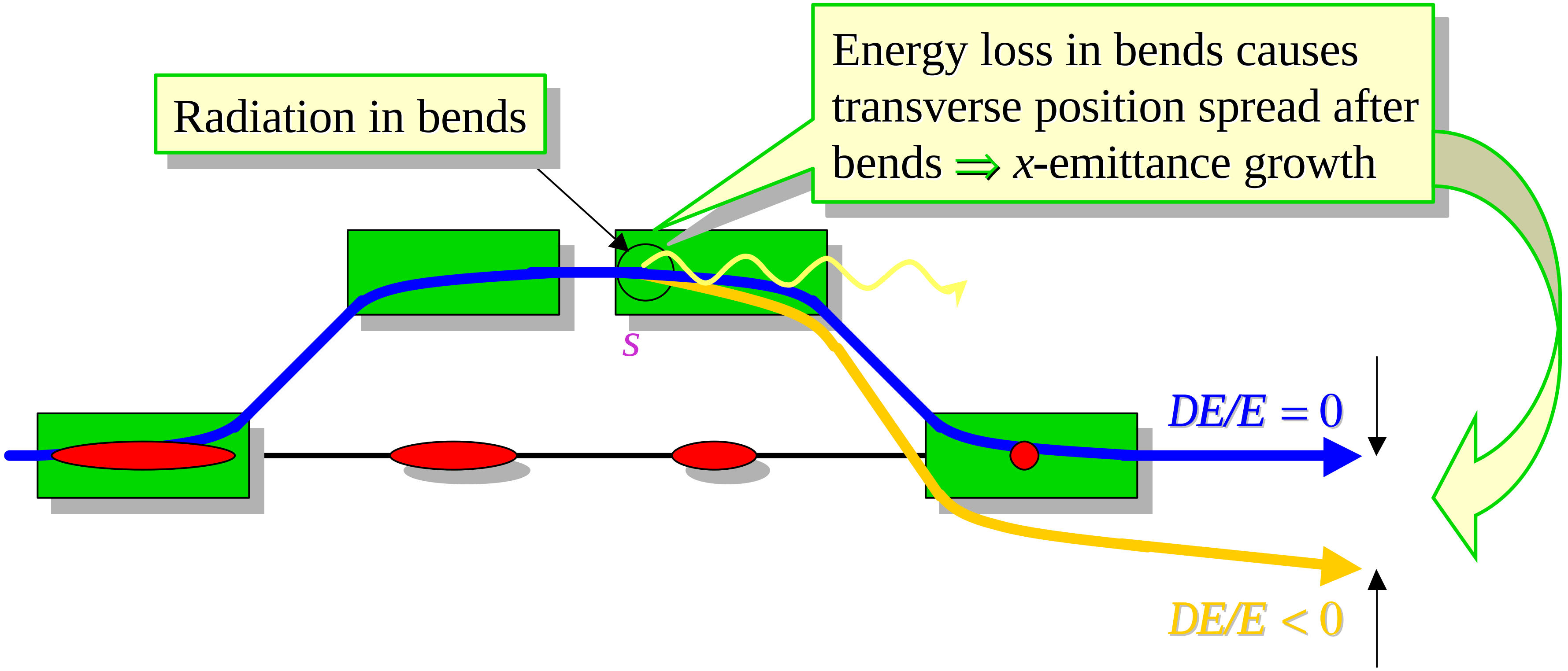
i.e. when $Lq^2 = 24 s_z$

for LCLS: $s_z = 22\ mm$, $Lq^2 \sim 5\ 10^{-4}$
= 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 ...

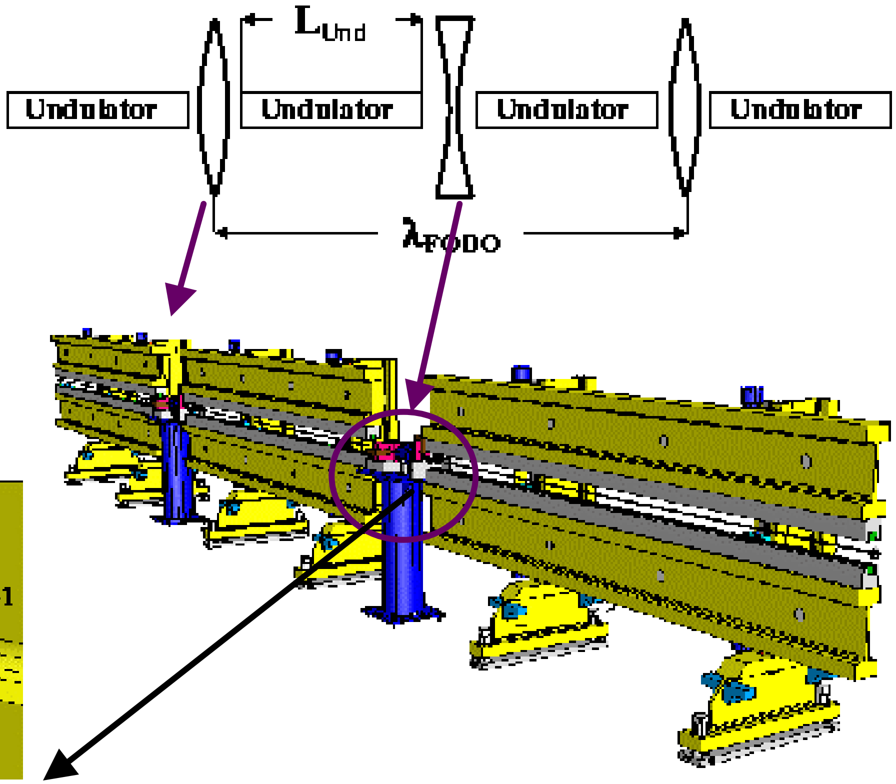
All four cases reach saturation

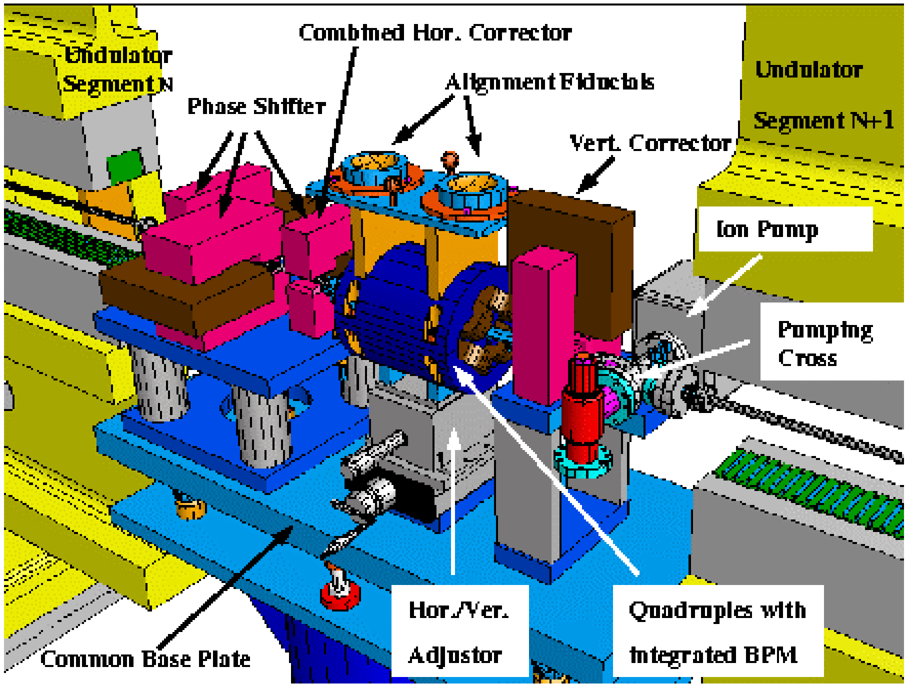
S. Reiche

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

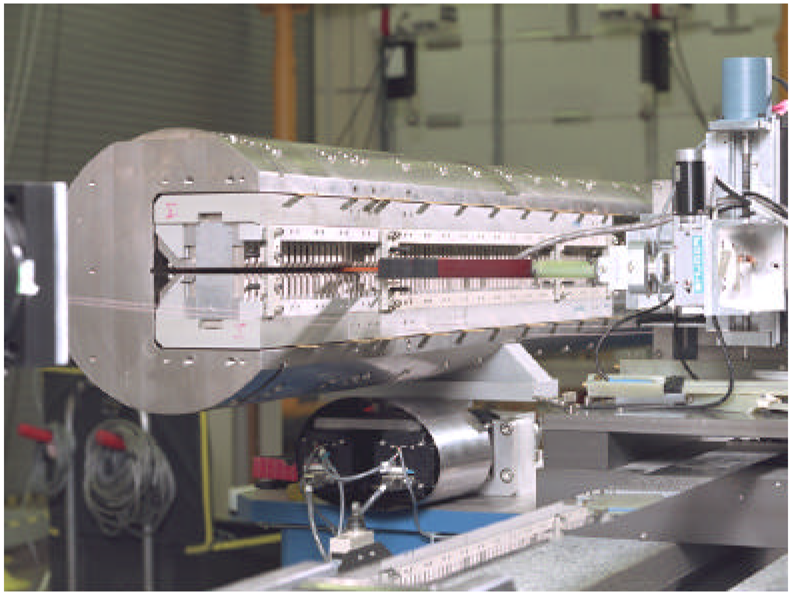
Total No. Segments	*231*	
Total Undulator Length	*1.1*	*km*

TESLA TDR, March 2001

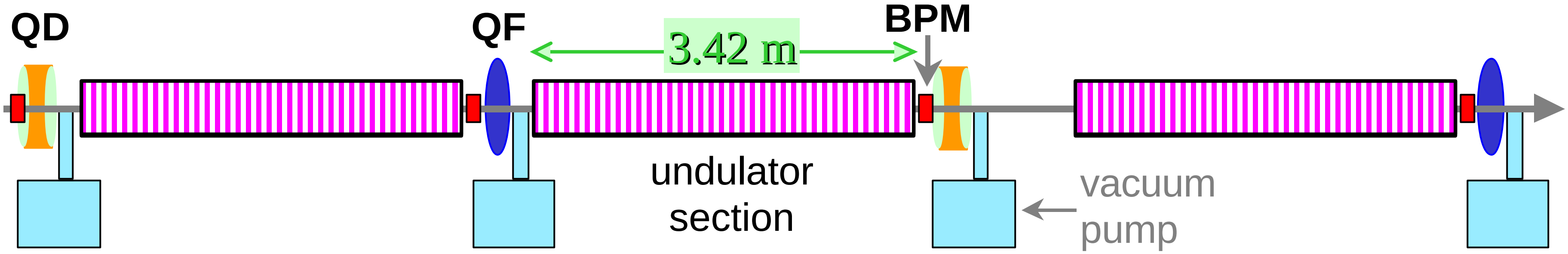
LCLS Undulator

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*



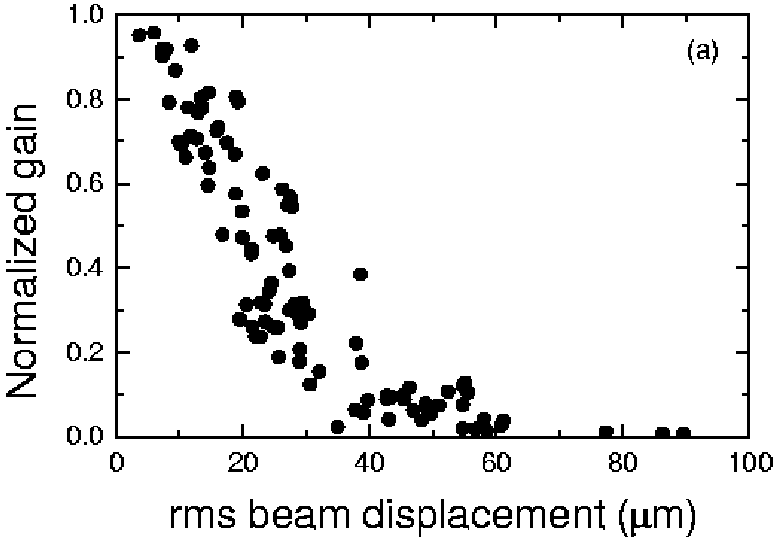
Prototype LCLS undulator under test



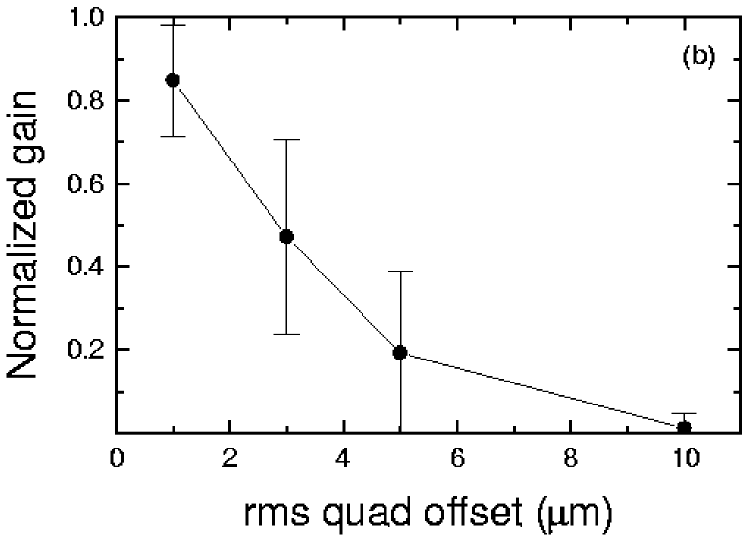
Vacuum Chamber
5 mm ID / 5.6 mm OD

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



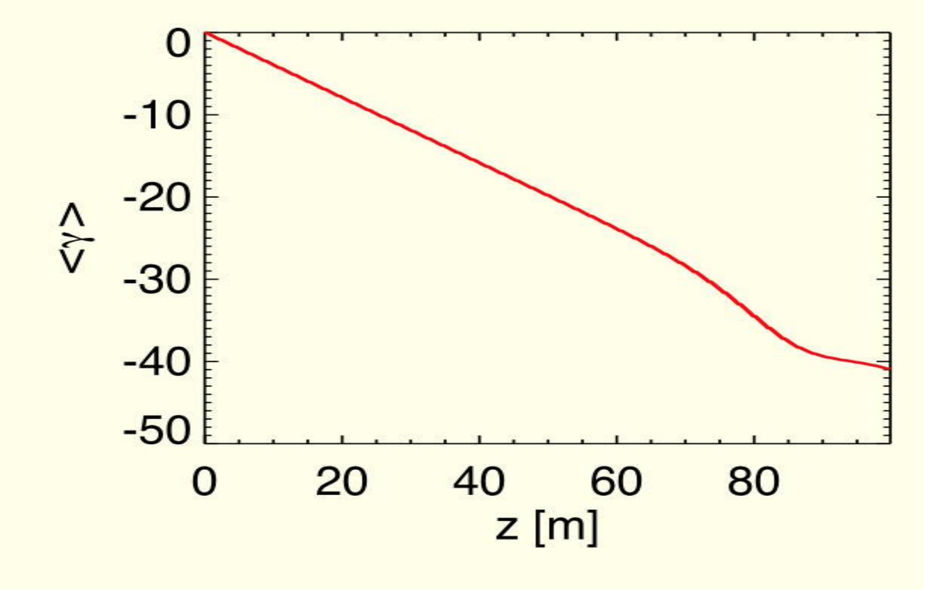
reduction in gain due to trajectory errors caused by random undulator field errors



reduction in gain due to random quadrupole misalignments, before correction

Effect of Spontaneous Radiation

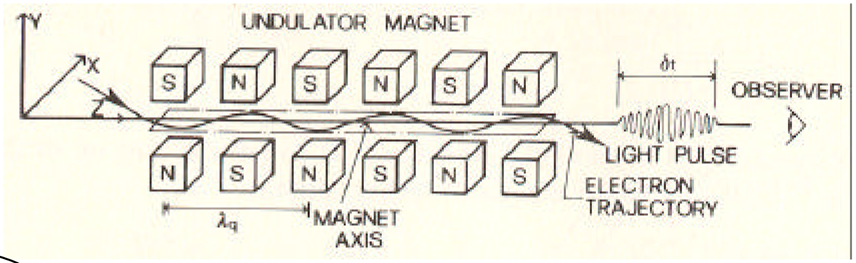
Weak taper of undulator field needed to compensate change in resonance condition due to energy loss caused by spontaneous emission :



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

Harmonics

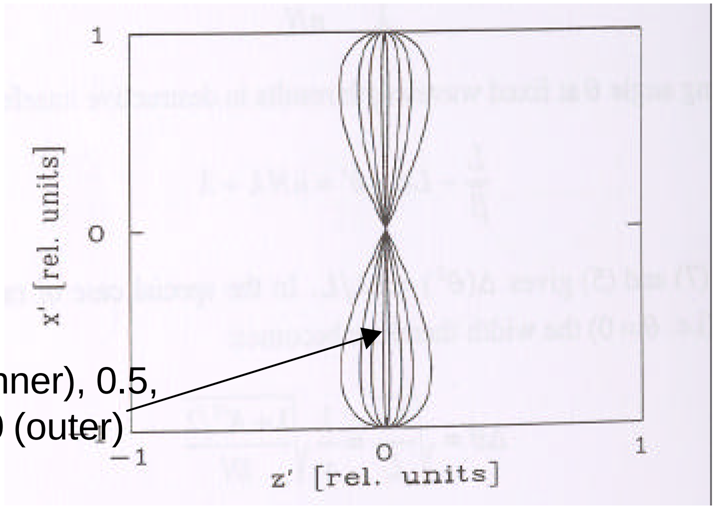
where do the harmonics come from in a planar undulator ?



$$b_x = \frac{K}{g}\cos(kz) \qquad b_x^2 + b_z^2 = b^2 \quad (= \text{constant})$$

$$b_z \cong b\left(1 - \frac{K^2}{4g^2} - \frac{K^2}{4g^2}\cos(2kz)\right)$$

the velocity along the z-axis is <u>modulated</u> due to undulating motion



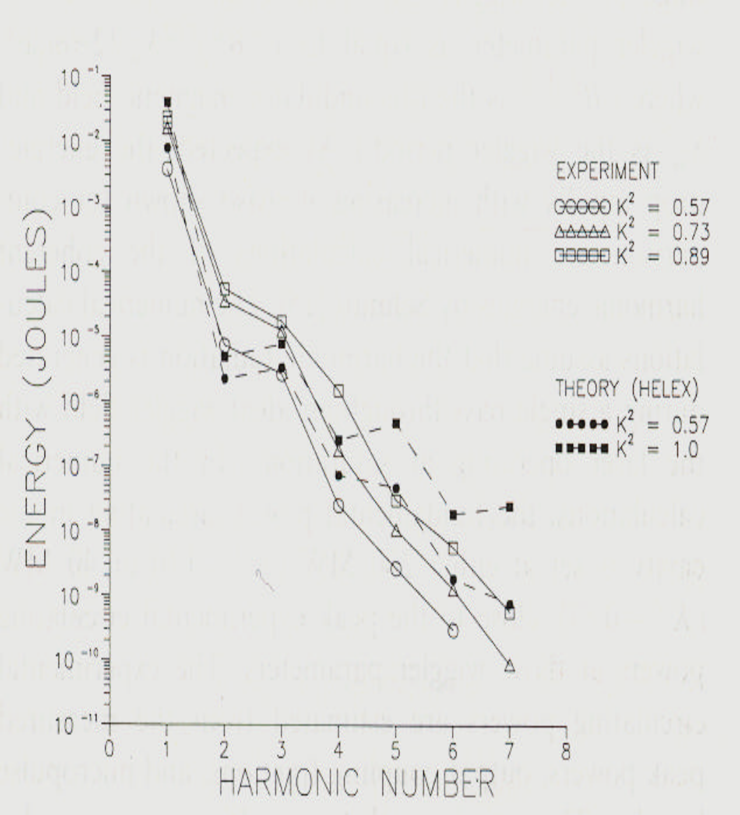
K=0.1 (inner), 0.5, 1.0, 10.0 (outer)

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.

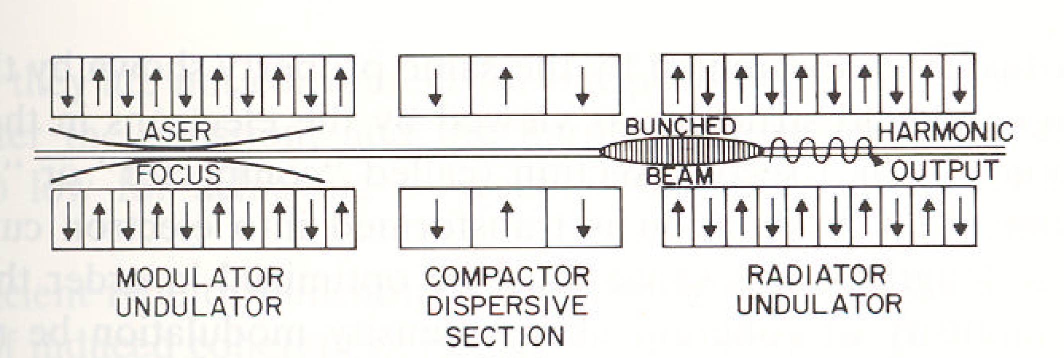
Harmonics in the low-Gain FEL

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).

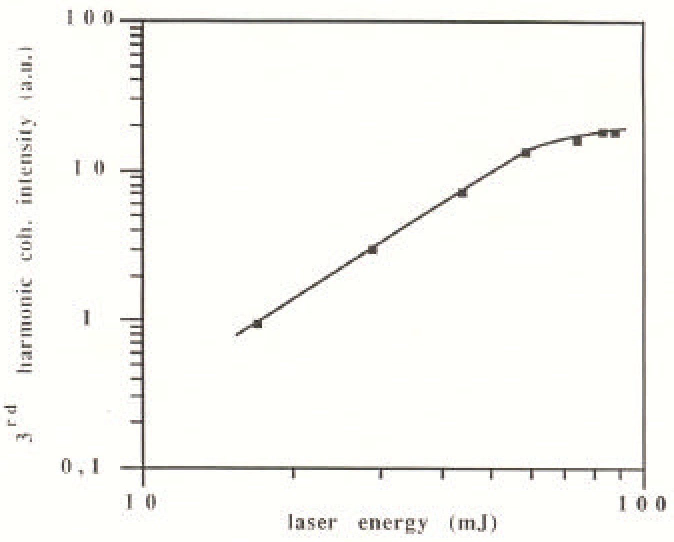


Coherent Harmonic Generation



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.

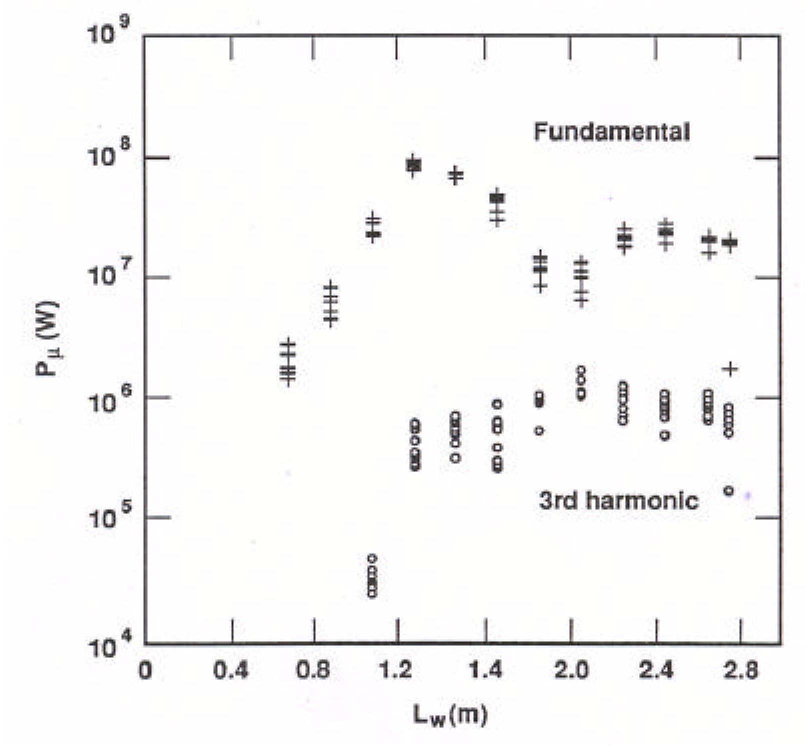


- requires very precise alignment of laser and electron beams

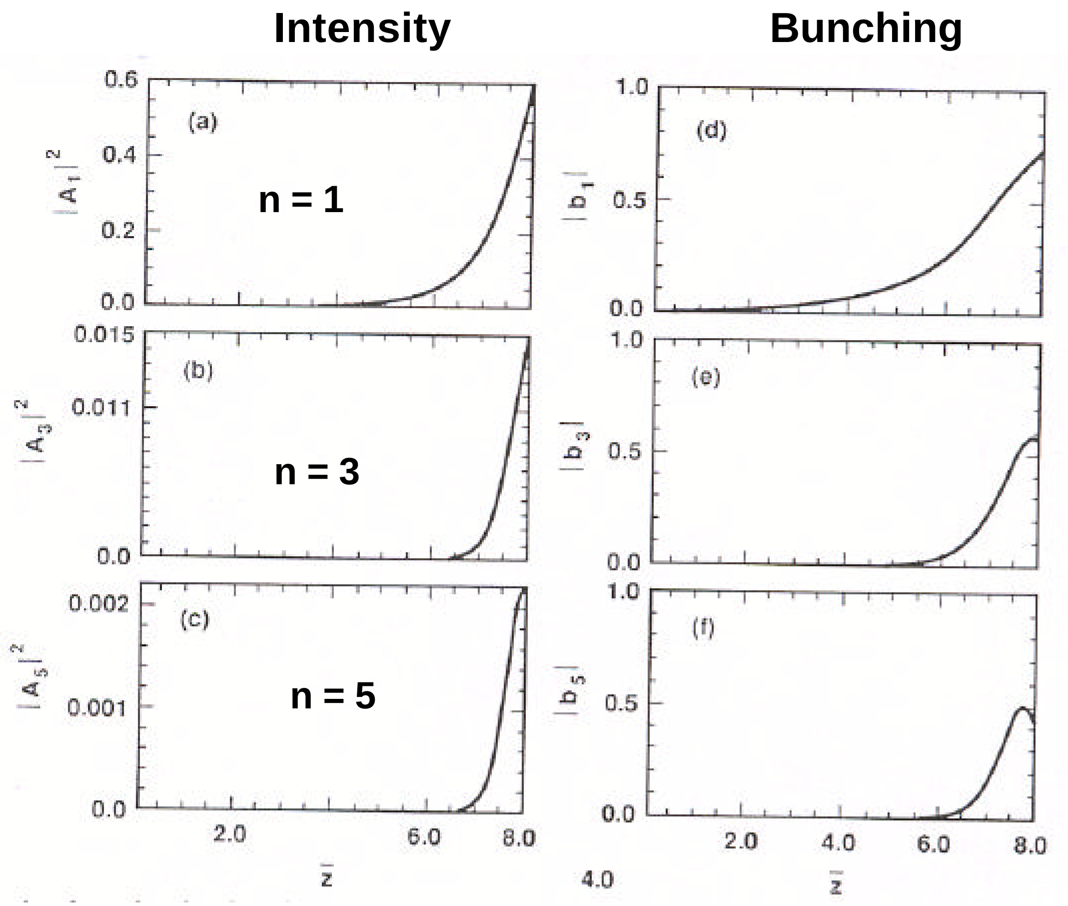
- average CHG output is limited by the laser repetition frequency (10-20 Hz in these experiments).

"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

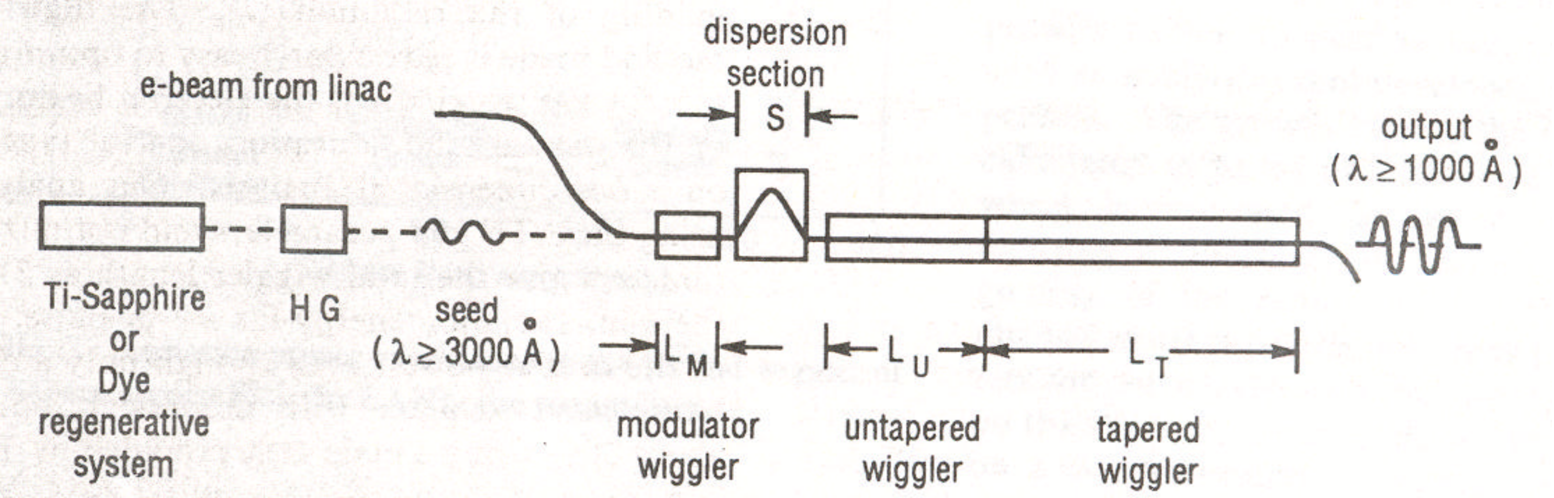
- advantages of an amplifier configuration (narrow linewidth)

- 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:

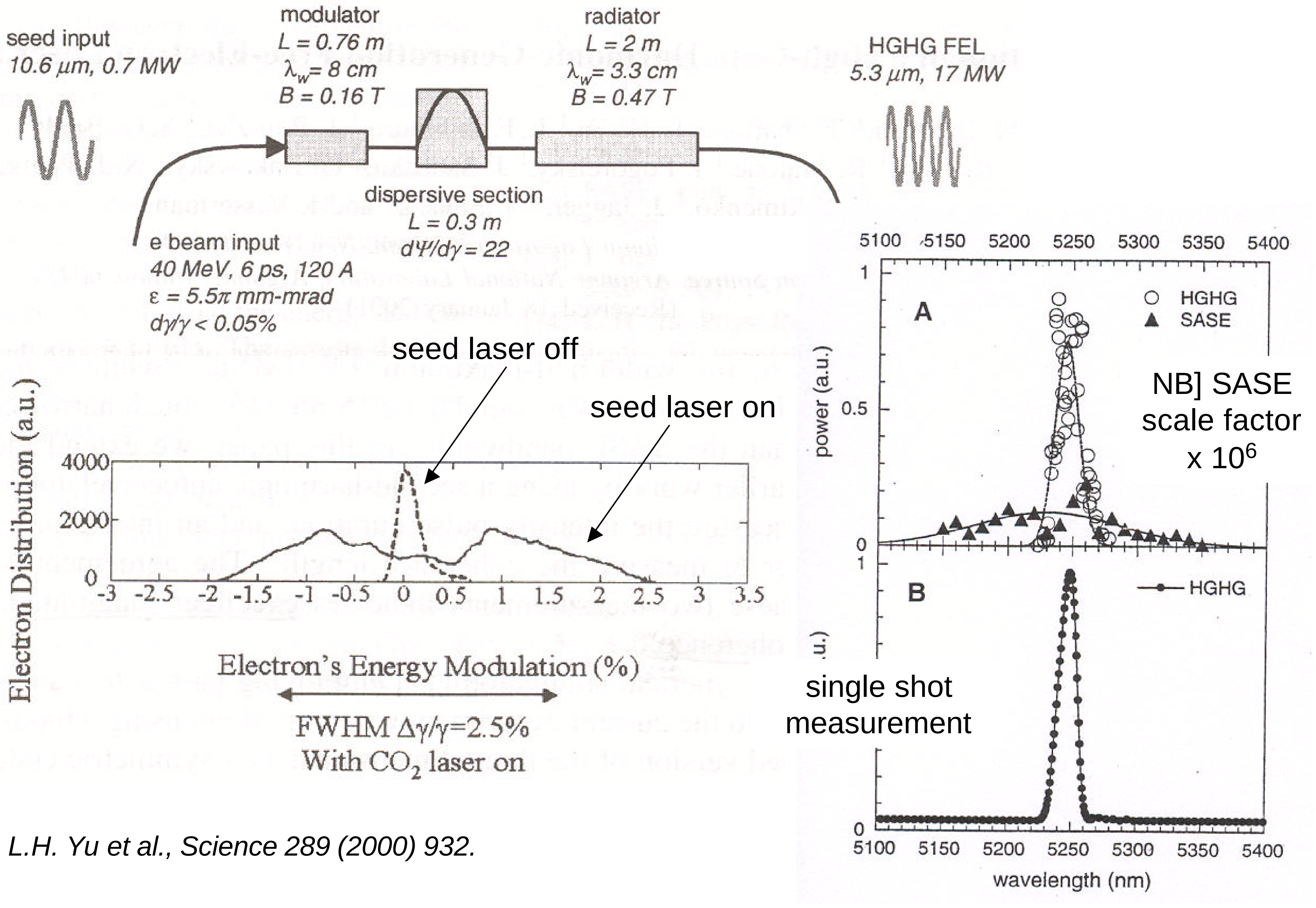


Advantages of HGHG, compared to SASE:

- 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

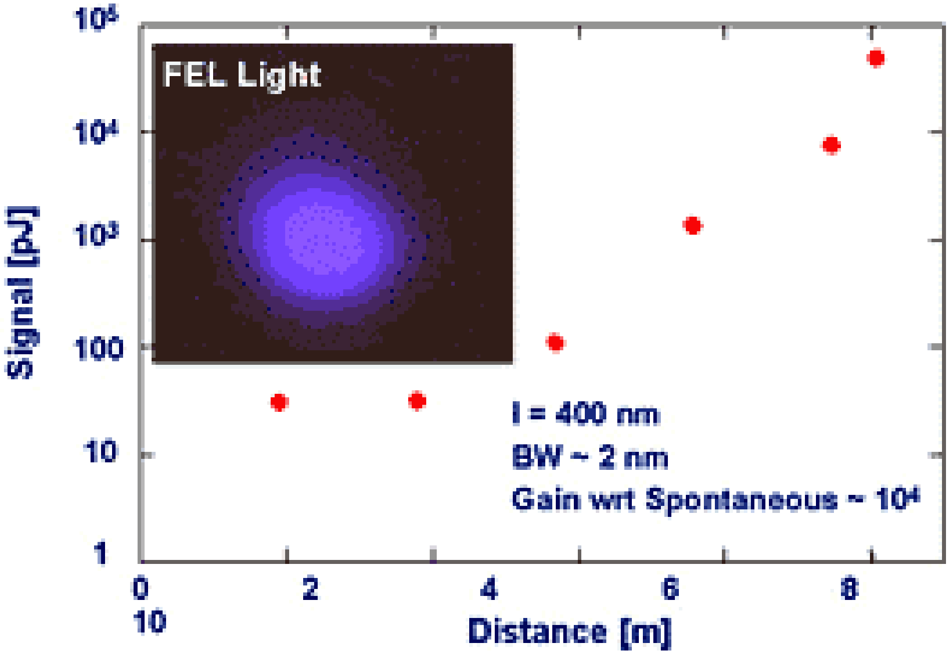
NB] SASE scale factor x 10^6

single shot measurement

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

Deep-Ultraviolet FEL (DUV-FEL), BNL

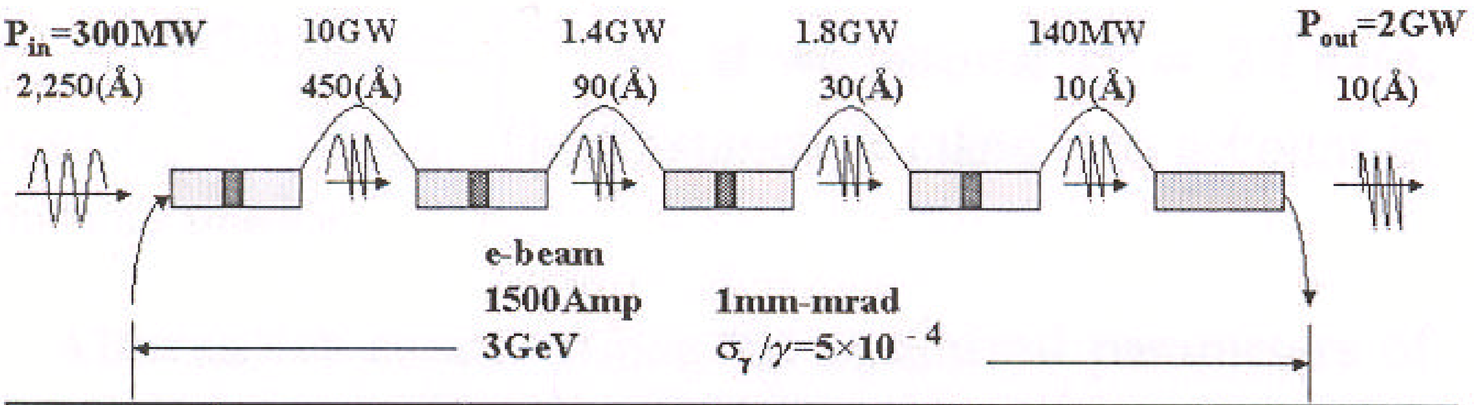
First lasing at 400 nm
Feb. 2002



	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 (ge, mm-mrad)	7	4	3
Peak current (A)	300	500	1000

HGHG X-ray FEL

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

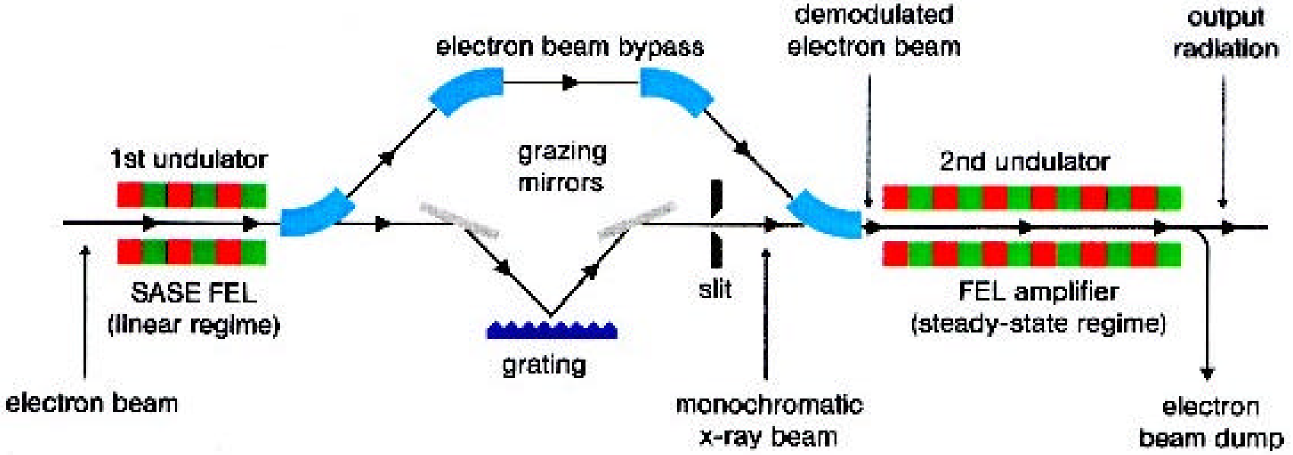


	1st Stage		2nd Stage		3rd Stage		4th Stage		Amplifier
λ(Å)	2250	450	450	90	90	30	30	10	10
λ_w(cm)	8.5	5.6	5.6	3.8	3.8	2.9	2.9	2.3	2.3
$d\psi/d\gamma$	0.4		0.1		0.1		0.1		
L_w(m)	4	9.5	1	4	2	8.5	1.5	5.5	10
L_G(m)	0.74	0.87	0.87	0.93	0.93	1.12	1.12	1.86	1.86

L_{total}=46m to reach 2 GW

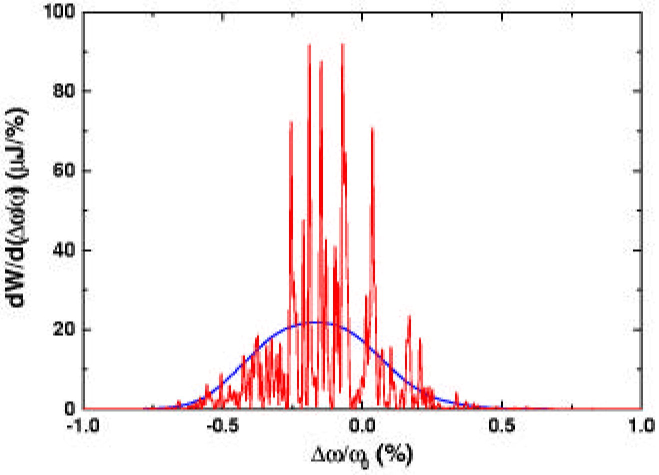
J. Wu and L.H. Yu, Proc. PAC 2001

Two-stage SASE FEL

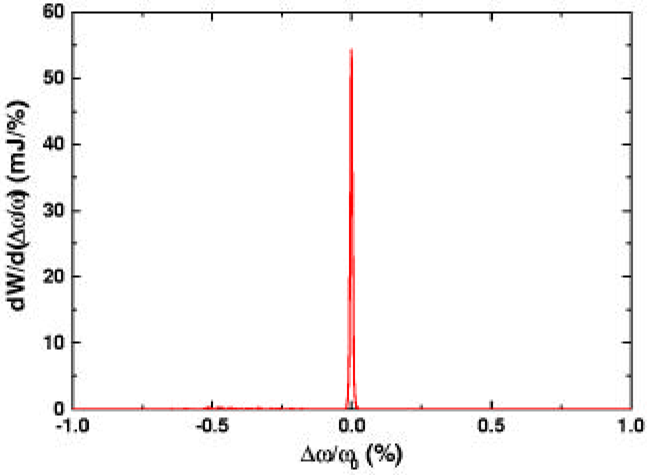


being implemented as part of TTF Phase II

without seeding



with seeding



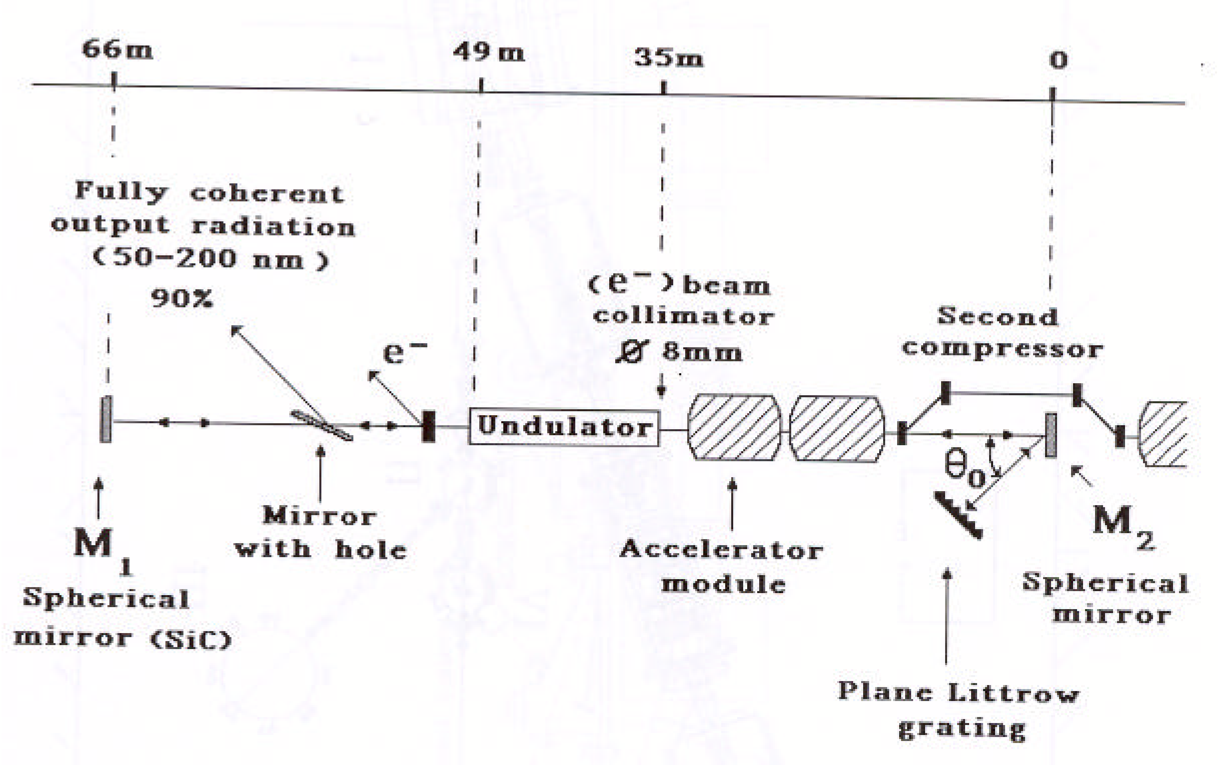
J. Feldhaus et al., Optics Comm. 140 (1997) 341.

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*).

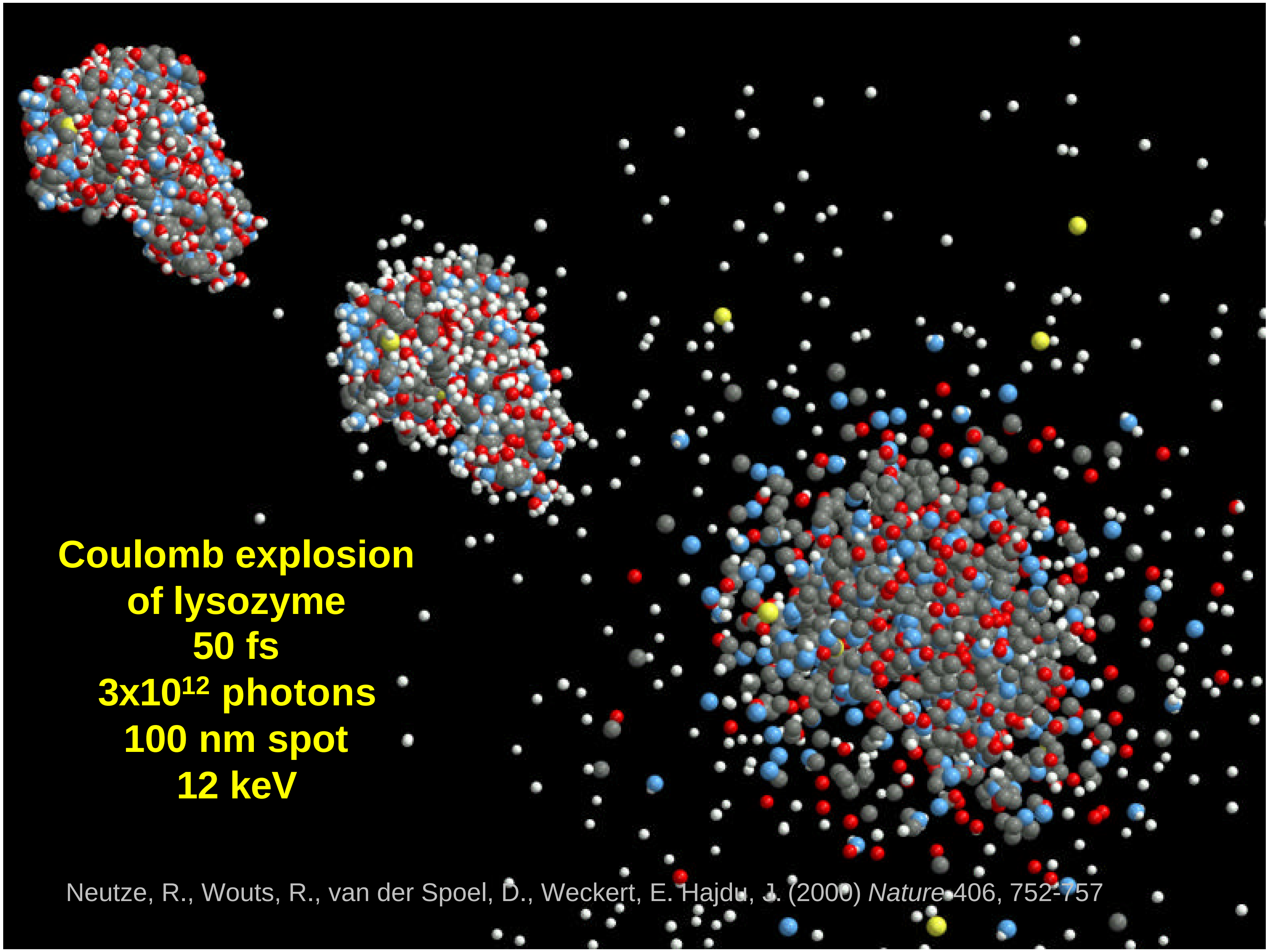
The concept was then modified to include monochromatization so that the seed radiation is longitudinally coherent.*(Faatz et al., 1999)*

Experiment is currently being carried out at TTF-1:



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

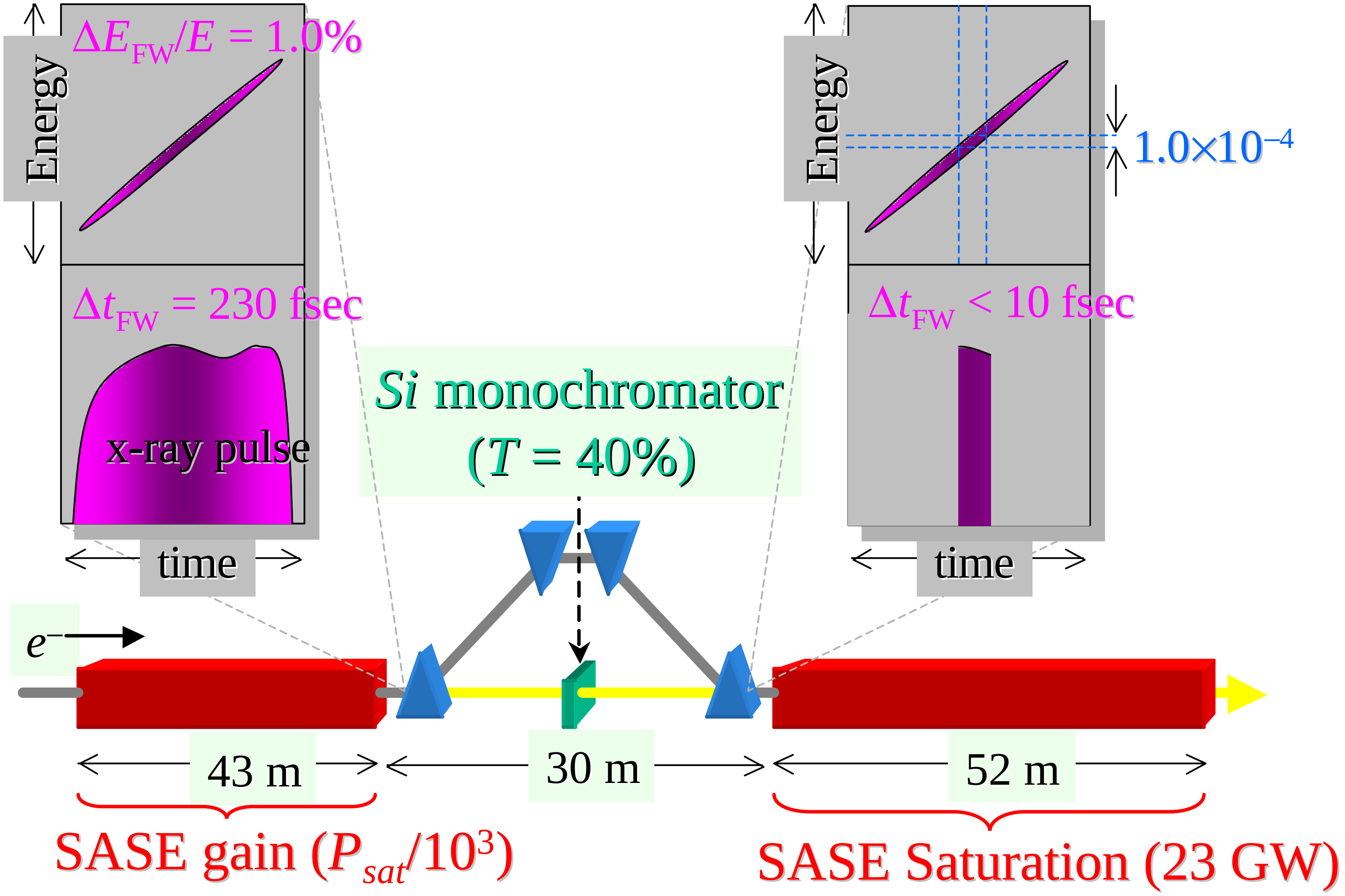
Motivation for Shorter Pulses: Radiation Damage



Coulomb explosion
of lysozyme
50 fs
$3x10^{12}$ photons
100 nm spot
12 keV

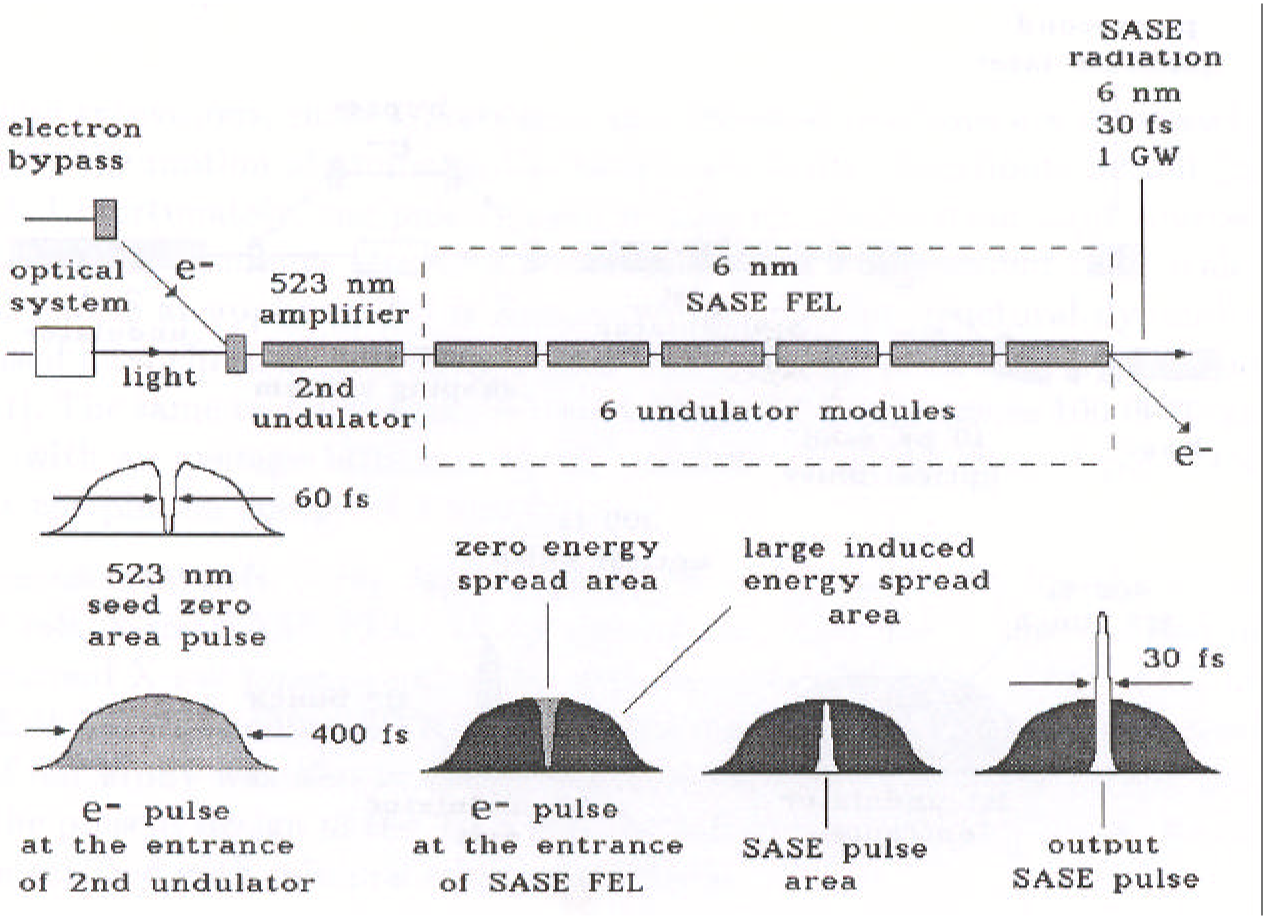
Neutze, R., Wouts, R., van der Spoel, D., Weckert, E. Hajdu, J. (2000) *Nature* 406, 752-757

Chirped-beam Two-stage SASE FEL



C.B. Schroeder et al., PAC 2001

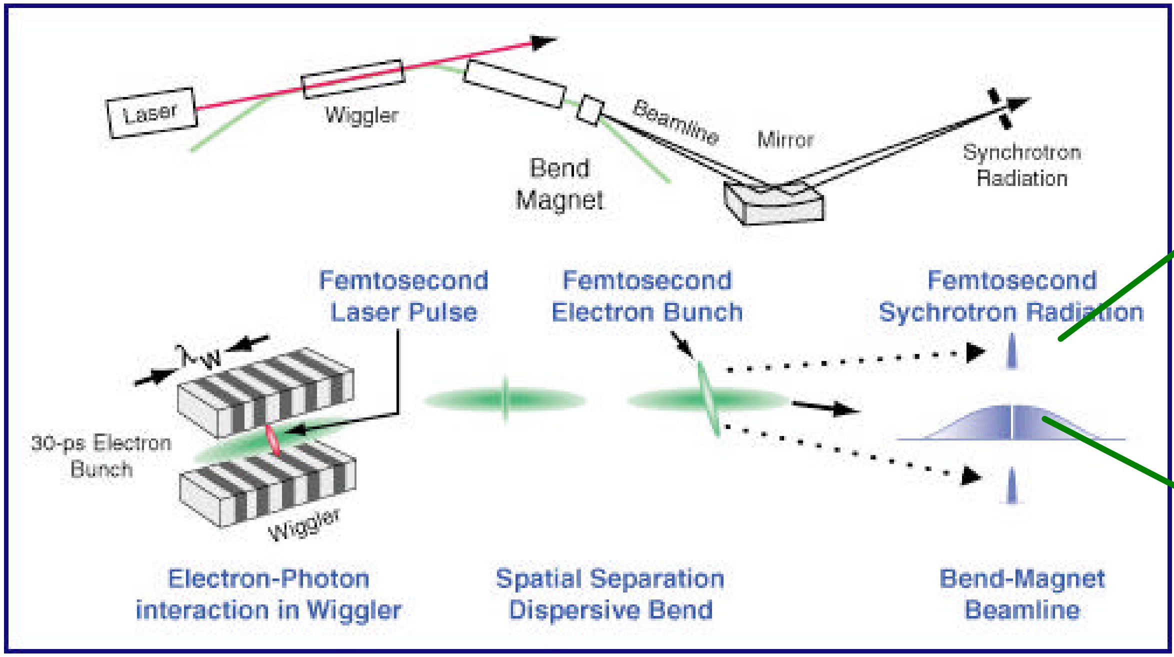
Reduction of pulse length by seeding

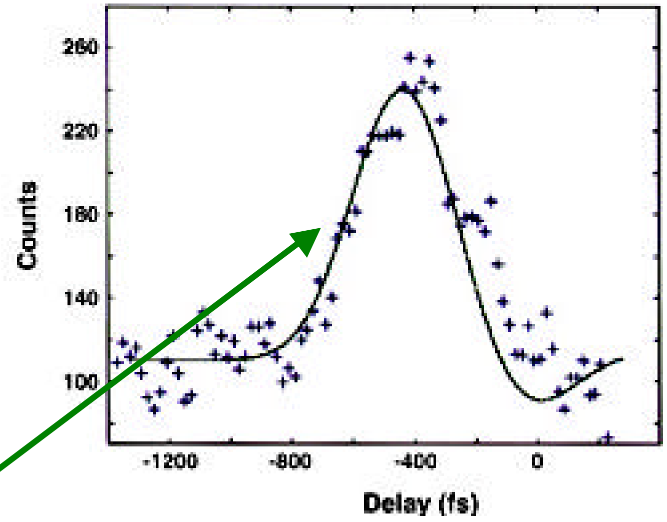


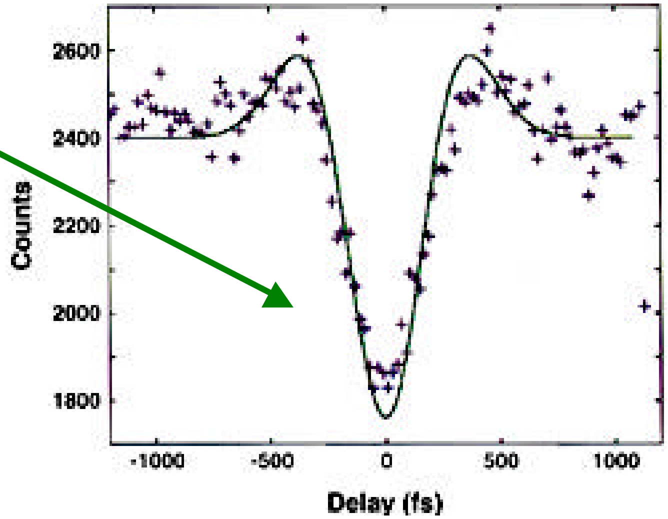
W. Brefeld et al., TESLA-FEL2001-02

“Pulse Slicing” using the FEL interaction

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







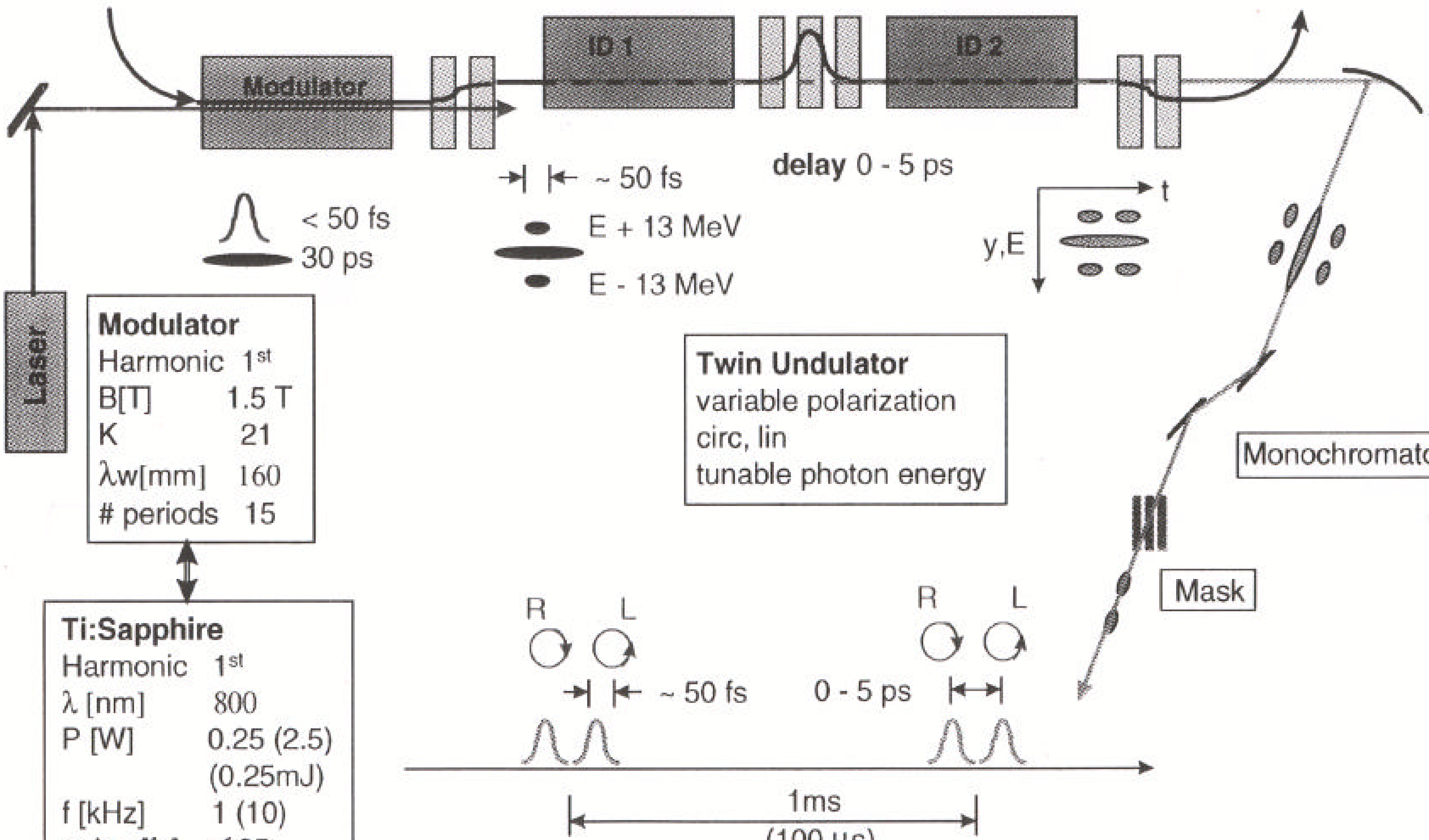
A.A. Zholents and M.S. Zolotorev, Phys. Rev. Lett. 76 (1996) 912.

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

Femtosecond bunch slicing* in one straight: ~ 50 fs

e^- - beam
E = 2.4 GeV

11m long straight 5L, vertical dispersion D ≈ 5 cm



Modulator

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

Twin Undulator
variable polarization
circ, lin
tunable photon energy

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.