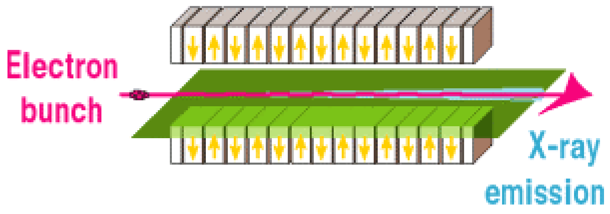
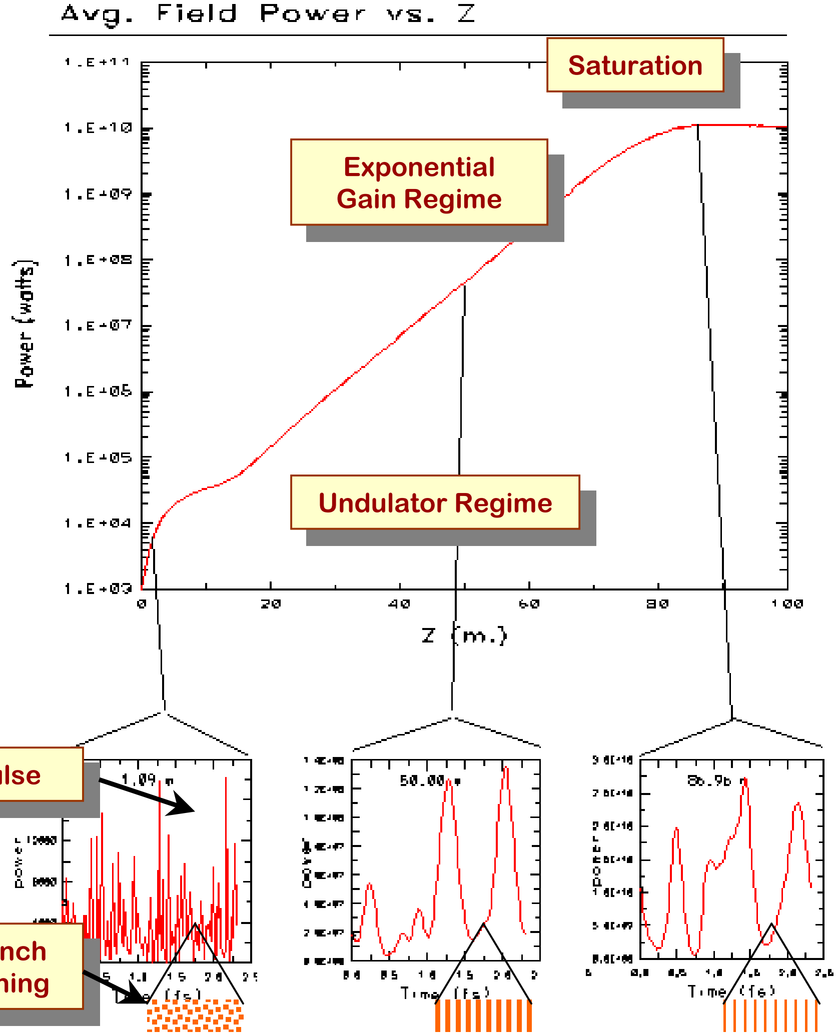
Excitements and Challenges for Future Light Sources Based on X-Ray FELs

26th ADVANCED ICFA BEAM DYNAMICS WORKSHOP ON NANOMETRE-SIZE COLLIDING BEAMS

Kwang-Je Kim
Argonne National Laboratory
and
The University of Chicago
Lausanne, Switzerland
September 2-6, 2002

SASE FELs





Saturation

Exponential Gain Regime

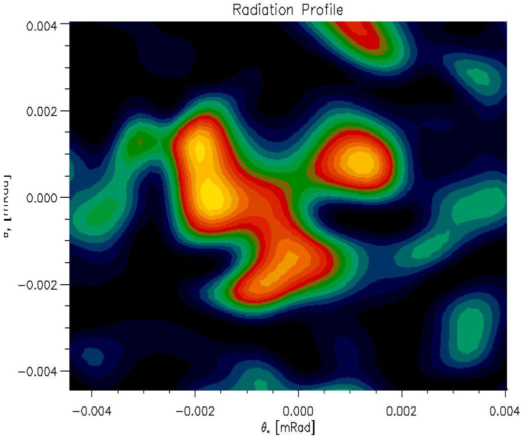
Undulator Regime

1 % of X-Ray Pulse

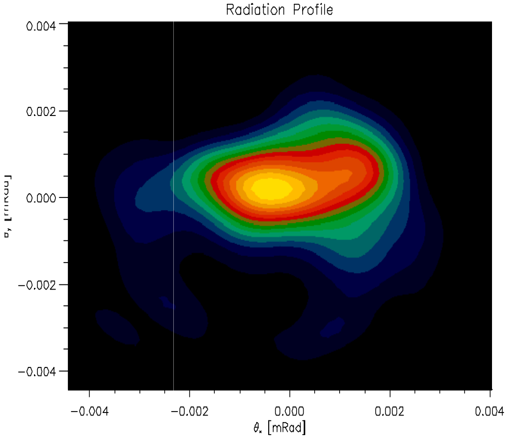
Electron Bunch Micro-Bunching

Transverse Coherence

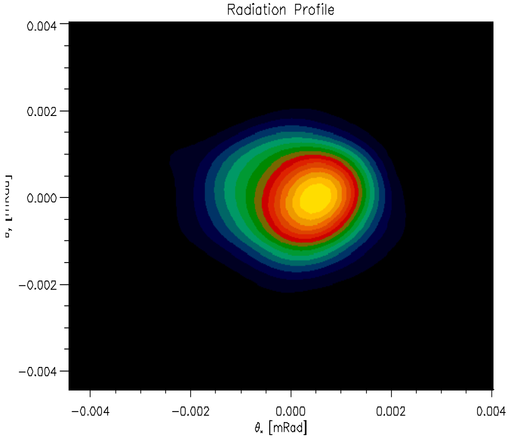
Z=25 m



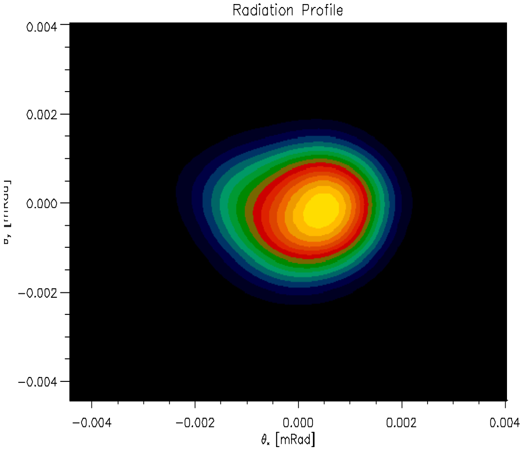
Z=37.5 m



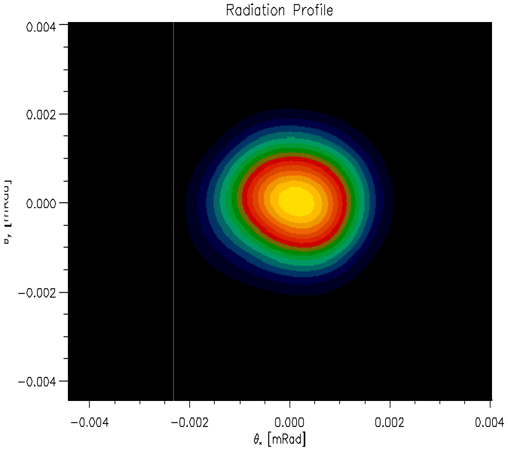
Z=50 m



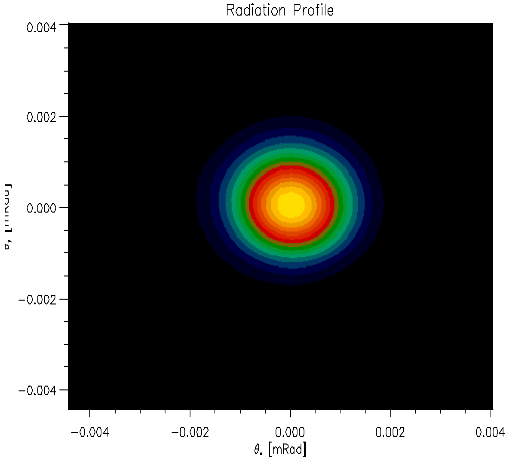
Z=62.5 m



Z=75 m



Z=87.5



Courtesy of Sven Reiche, UCLA

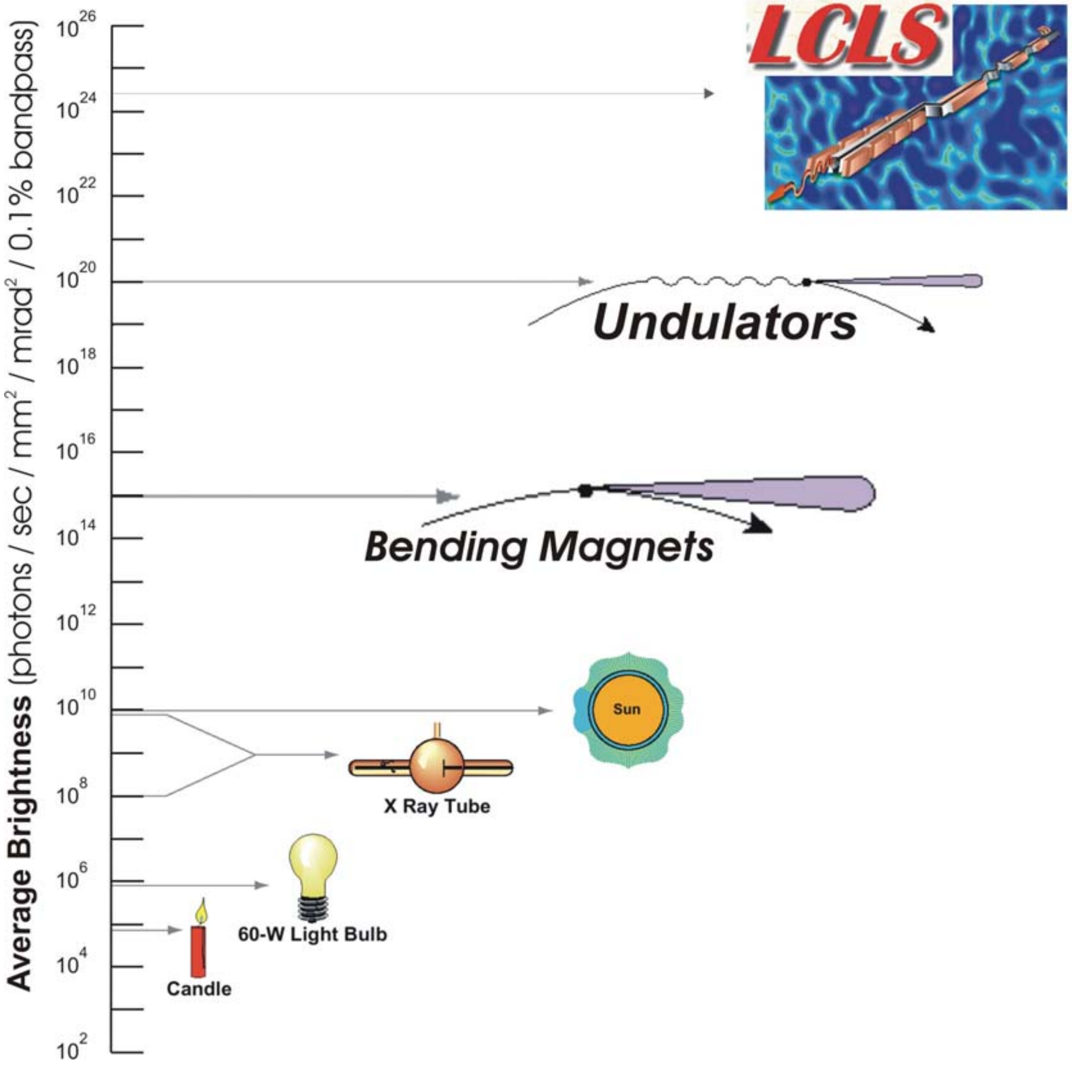
Peak Brightness Enhancement From Undulator To SASE

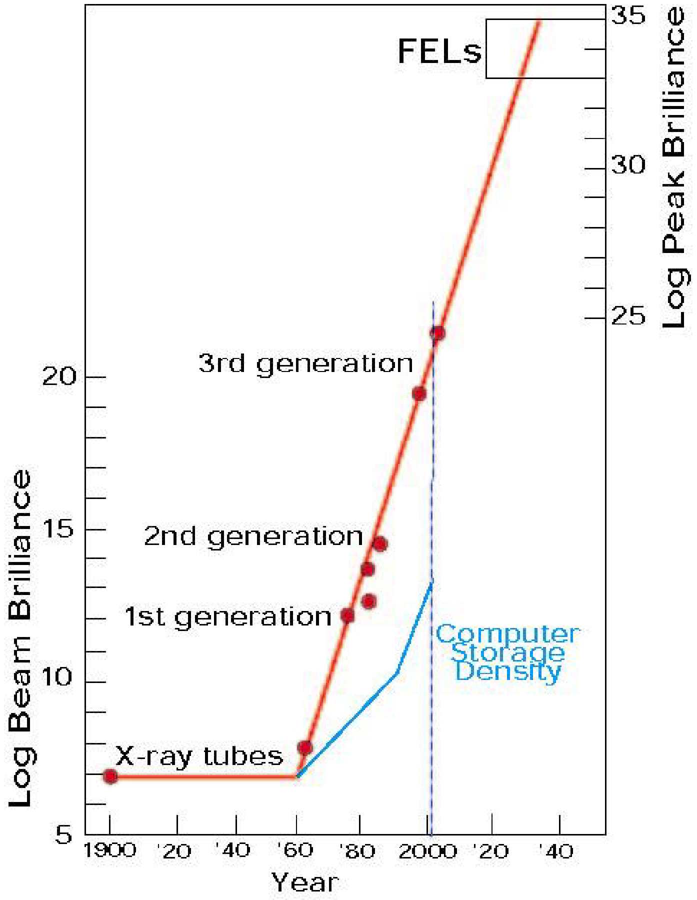
$$B = \frac{\#\text{of photons}}{\Omega_x\,\Omega_y\,\Omega_z} \qquad (\Omega_i\text{- phase space area})$$

	Undulator	SASE	Enhancement Factor
# of photons	αN_e	$\alpha N_e N_{l_c}$	$N_{l_c} \sim 10^6$
$\Omega_x \Omega_y$	$(2\pi\varepsilon_x)\,(2\pi\varepsilon_y)$	$(\lambda/2)^2$	10^2
Ω_Z	$\frac{\Delta\omega}{\omega}\cdot\left(\frac{\sigma_Z}{c}\right) = 10^{-3} \times 10\,ps$	$\frac{\Delta\omega}{\omega}\cdot\left(\frac{\sigma_Z}{c}\right)_{\text{compressed}} = 10^{-3} \times 100\,fs$	10^2

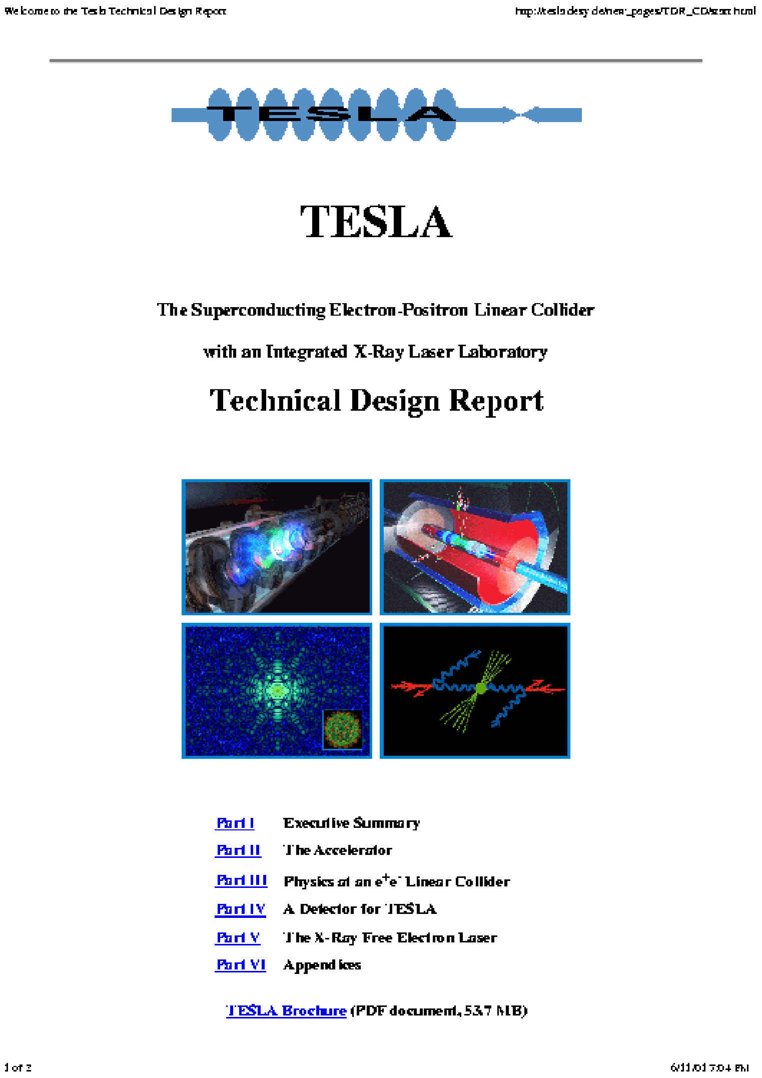
l_c -coherence length

How bright are different light sources ?





Projects: TESLA



Welcome to the Tesla Technical Design Report http://tesla.desy.de/new_pages/TDR_CD/start.html

TESLA

The Superconducting Electron-Positron Linear Collider

with an Integrated X-Ray Laser Laboratory

Technical Design Report

Part I	Executive Summary
Part II	The Accelerator
Part III	Physics at an e^+e^- Linear Collider
Part IV	A Detector for TESLA
Part V	The X-Ray Free Electron Laser
Part VI	Appendices

TESLA Brochure (PDF document, 53.7 MB)

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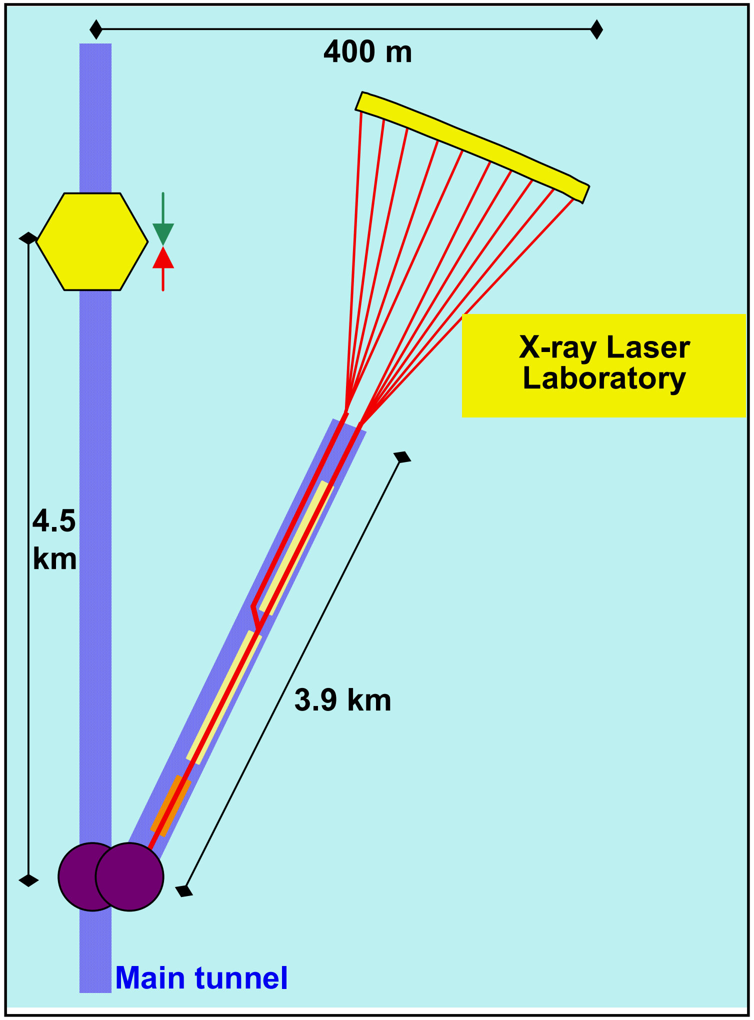
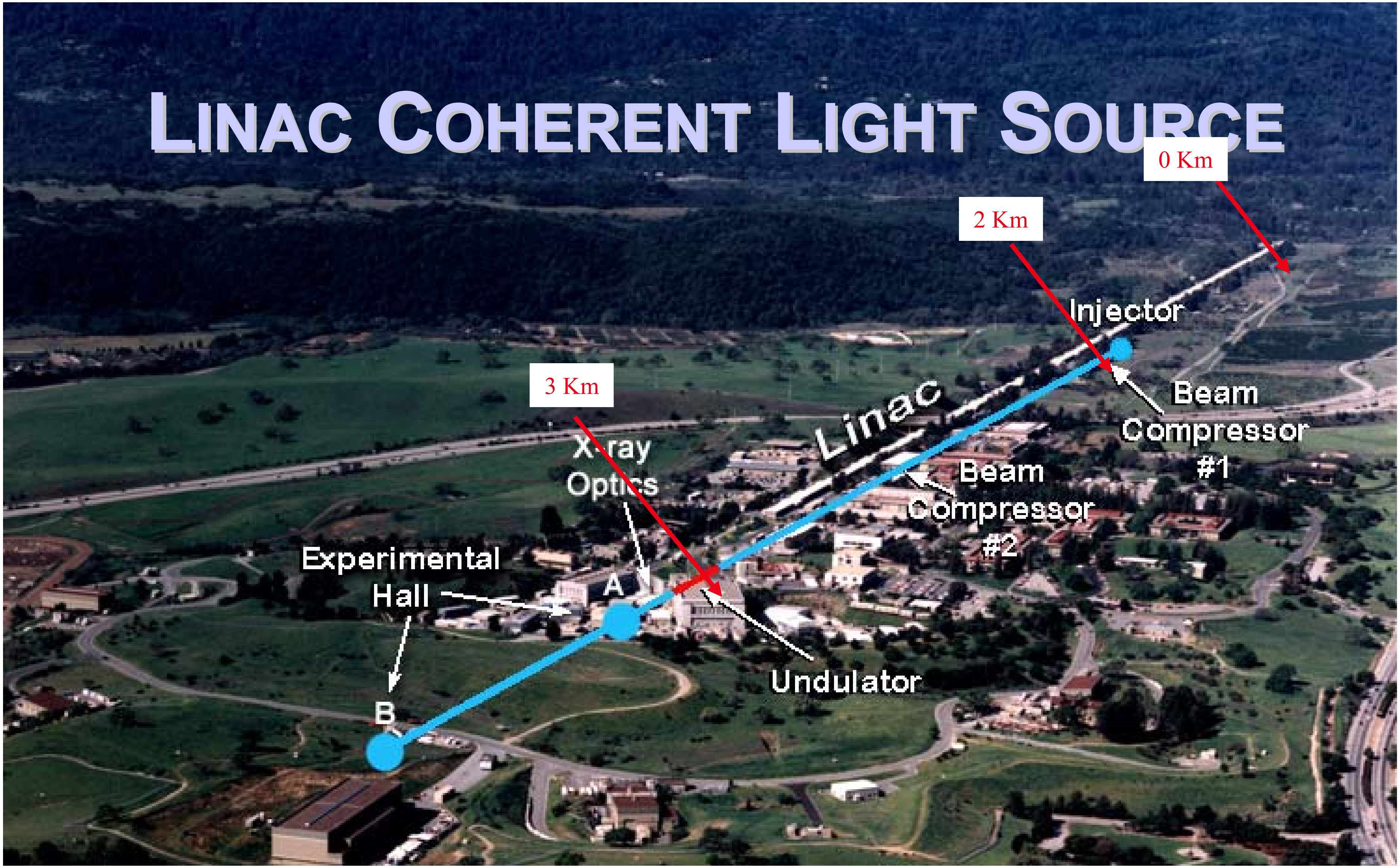


LINAC COHERENT LIGHT SOURCE



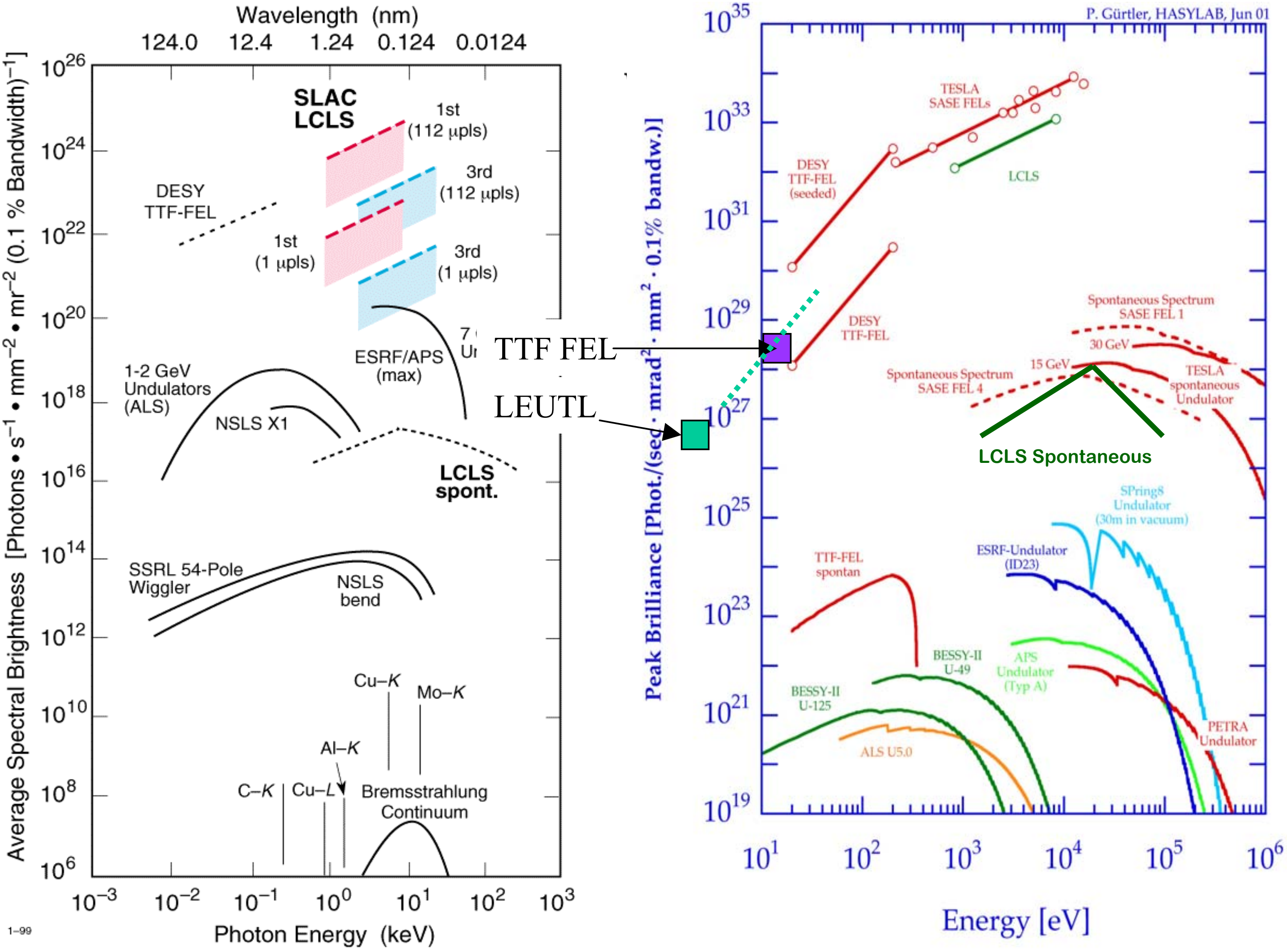
LCLS: Parameters & Performance

FEL Radiation Wavelength	**15.0**	**1.5**	Å
Electron Beam Energy	4.54	14.35	GeV
Repetition Rate (1-bunch)	120	120	Hz
Single Bunch Charge	1	1	nC
Normalized rms Emittance	**2.0**	**1.5**	mm-mrad
Peak Current	**3.4**	**3.4**	kA
Coherent rms Energy Spread	<2	<1	10^{-3}
Incoherent rms Energy Spread	<0.6	<0.2	10^{-3}
Undulator Length	100	100	m
Peak Coherent Power	11	9.3	GW
Peak Spontaneous Power	8.1	81	GW
Peak Brightness *	1.2	12	10^{32}

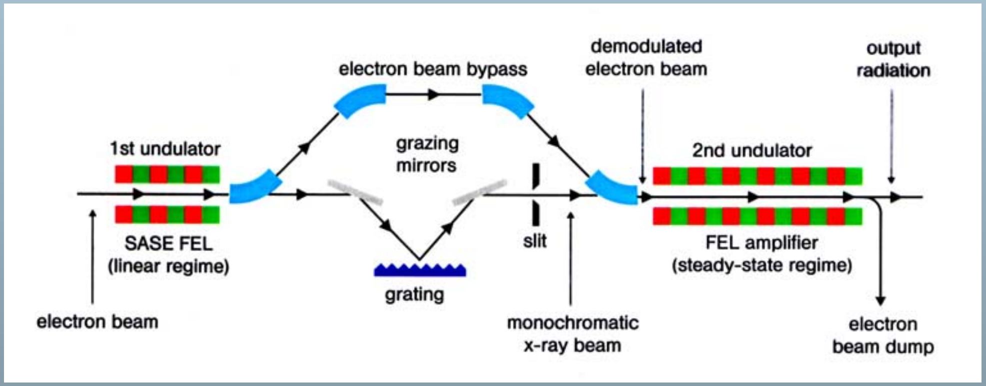
* photons/sec/mm^2/mrad^2/0.1%-BW

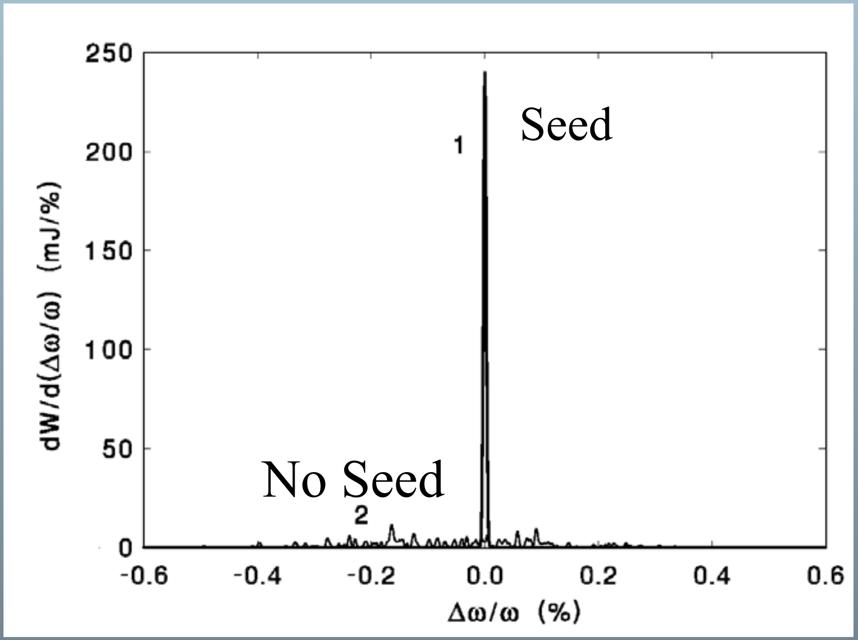
Performance Characteristics

Peak and time averaged brightness of the LCLS and other facilities operating or under construction



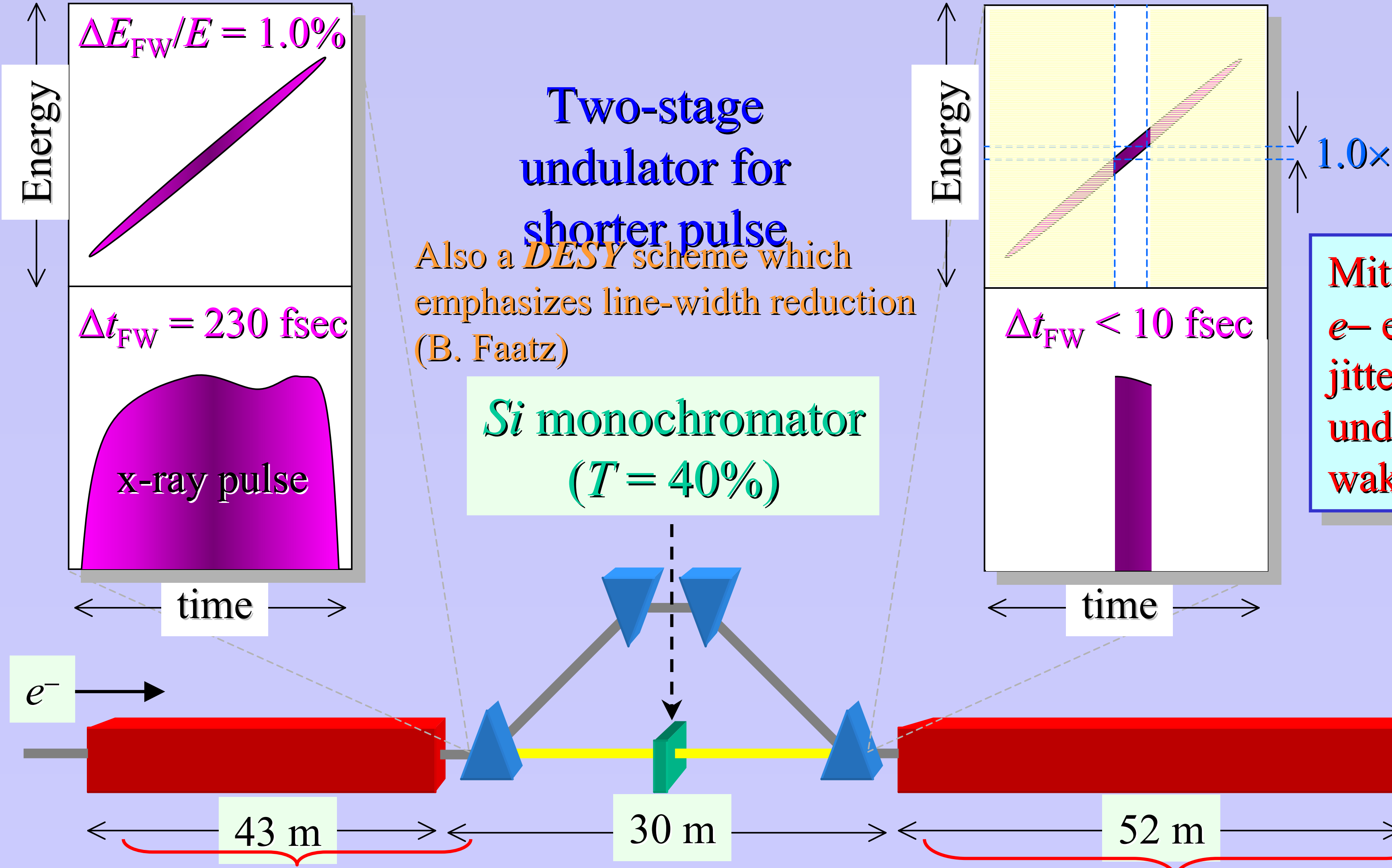
Self Seeding Scheme for Full Longitudinal Coherence





Two-stage undulator for shorter pulse

Also a ***DESY*** scheme which emphasizes line-width reduction (B. Faatz)



$\Delta E_{FW}/E = 1.0\%$

$\Delta t_{FW} = 230$ fsec

$\Delta t_{FW} < 10$ fsec

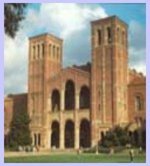
1.0×10^{-4}

Si monochromator ($T = 40\%$)

SASE gain ($P_{sat}/10^3$)

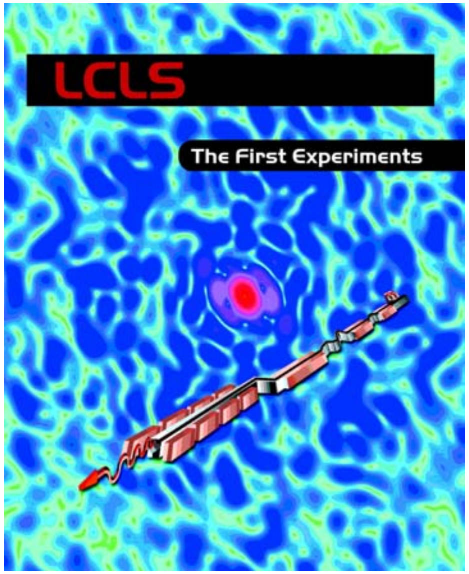
SASE Saturation (23 GW)

Mitigates *e*– energy jitter and undulator wakes



UCLA

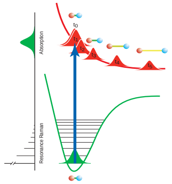
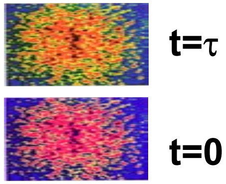
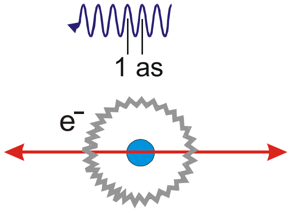
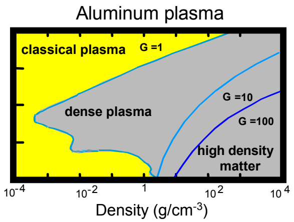
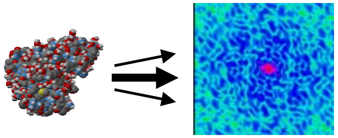
LCLS - The First Experiments



LCLS

The First Experiments

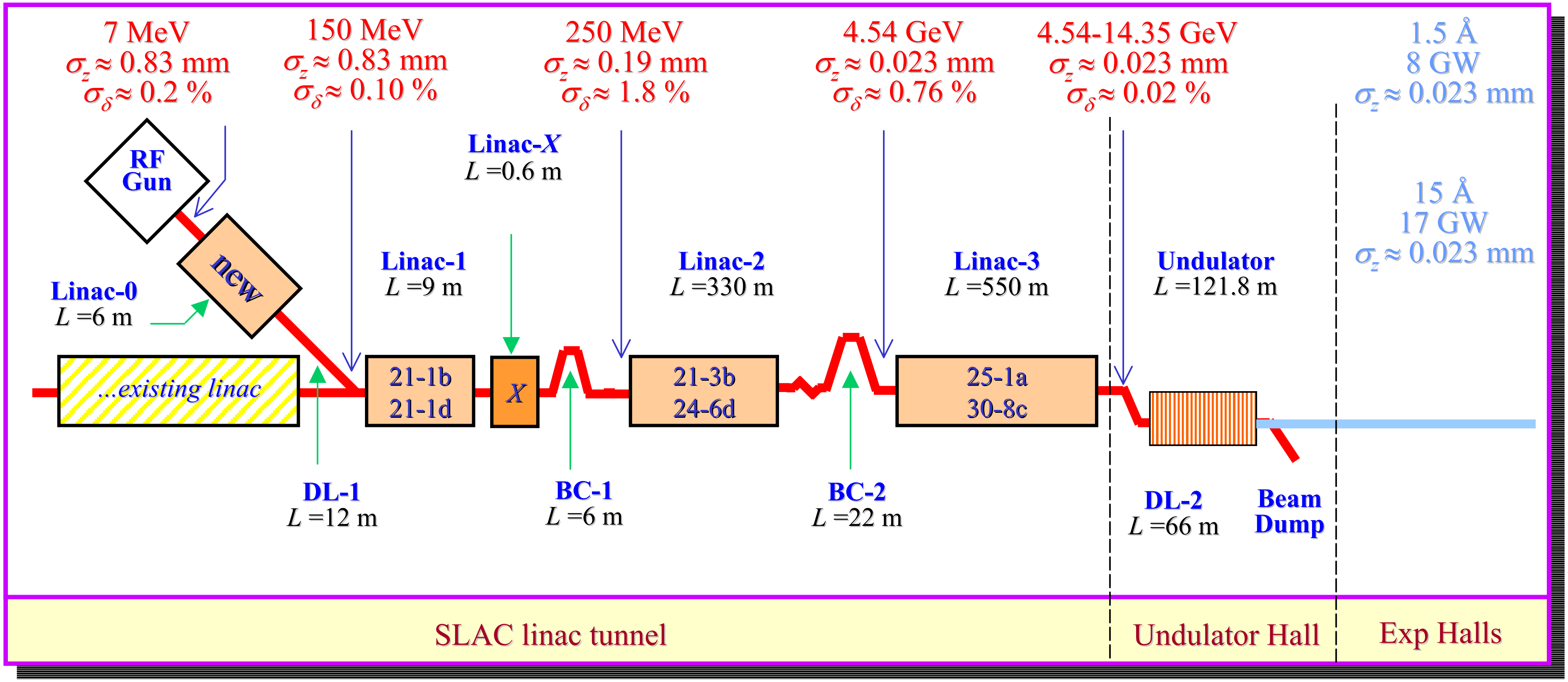
Report developed by international team of ~45 scientists working with accelerator and laser physics communities

		Team Leaders:
	***Femtochemistry***	Dan Imre, BNL
	***Nanoscale Dynamics in Condensed Matter***	Brian Stephenson, APS
	***Atomic Physics***	Phil Bucksbaum, Univ. of Michigan
	***Plasma and Warm Dense Matter***	Richard Lee, LLNL
	***Structural Studies on Single Particles and Biomolecules***	Janos Hajdu, Uppsala Univ.

Accelerator System

- *RF Photo-cathode gun*
- *Emittance Preservation in Linacs*
  - *transverse wakefields*
  - *CSR microbunching instability*
  - *misalignments & chromaticity*
- *Machine Stability*
  - *jitter tolerance budget*
  - *simulation of budget*

LCLS: System Components



7 MeV
$\sigma_z \approx 0.83$ mm
$\sigma_\delta \approx 0.2$ %

150 MeV
$\sigma_z \approx 0.83$ mm
$\sigma_\delta \approx 0.10$ %

250 MeV
$\sigma_z \approx 0.19$ mm
$\sigma_\delta \approx 1.8$ %

4.54 GeV
$\sigma_z \approx 0.023$ mm
$\sigma_\delta \approx 0.76$ %

4.54-14.35 GeV
$\sigma_z \approx 0.023$ mm
$\sigma_\delta \approx 0.02$ %

1.5 Å
8 GW
$\sigma_z \approx 0.023$ mm

15 Å
17 GW
$\sigma_z \approx 0.023$ mm

RF Gun

new

Linac-0
L =6 m

...existing linac

DL-1
L =12 m

Linac-1
L =9 m

21-1b
21-1d

Linac-*X*
L =0.6 m

X

BC-1
L =6 m

Linac-2
L =330 m

21-3b
24-6d

BC-2
L =22 m

Linac-3
L =550 m

25-1a
30-8c

Undulator
L =121.8 m

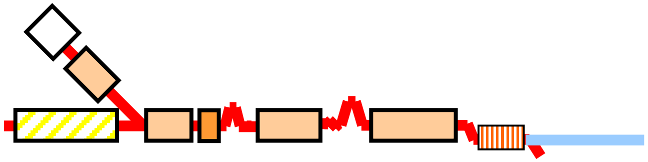
DL-2
L =66 m

Beam Dump

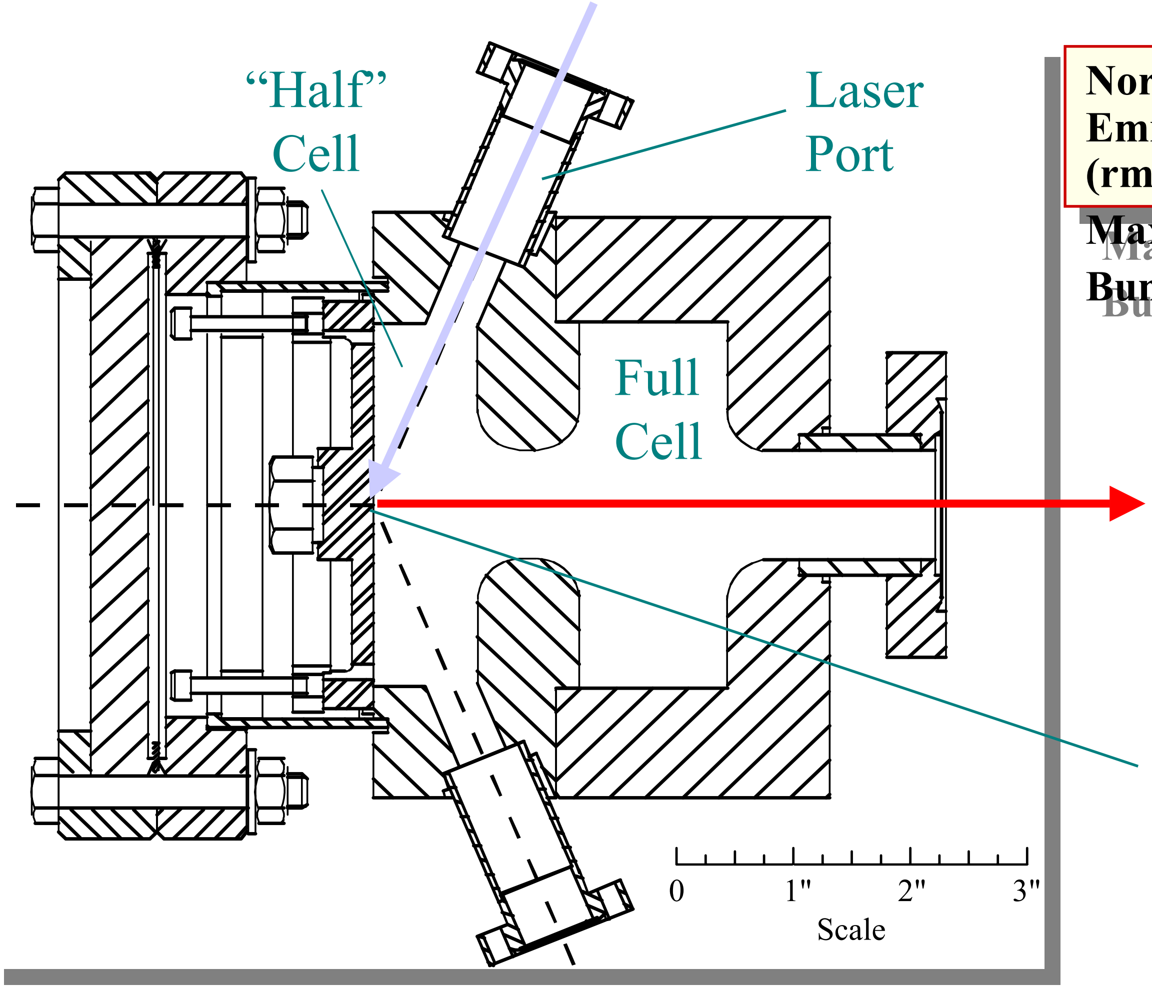
SLAC linac tunnel

Undulator Hall

Exp Halls

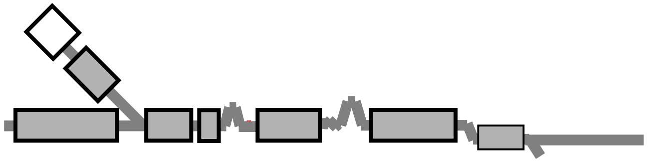


RF Photo-Cathode Gun



Normalized Slice Emittance: (rms)	**1 μm rad**
Max Bunch Charge:	**1 nC**
Bunch Length:	**0.8 mm**

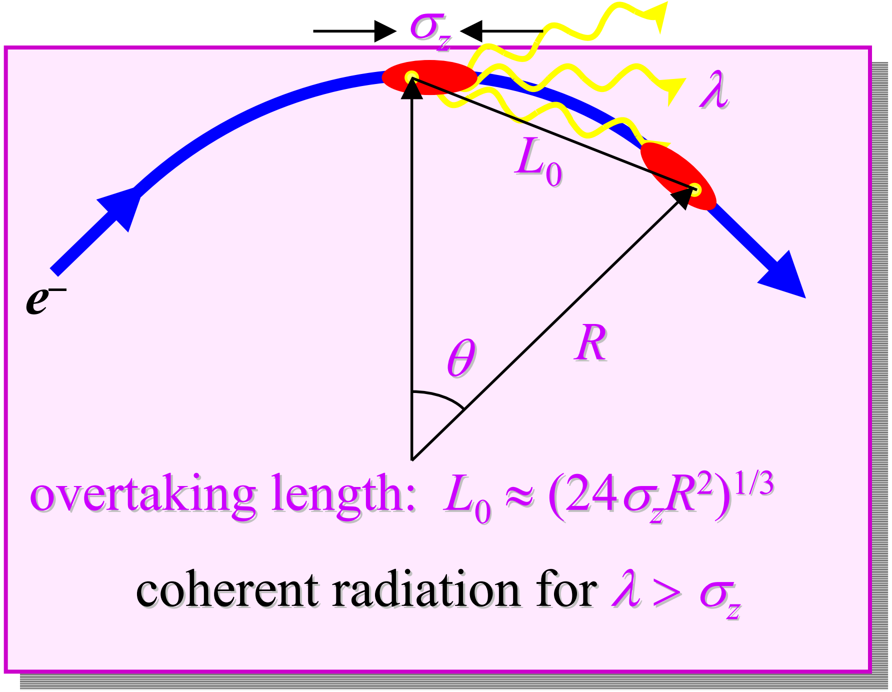
Max Bunch Charge: 1 nC
Bunch Length: 0.8 mm
Photocathode



Coherent Synchrotron Radiation (CSR)

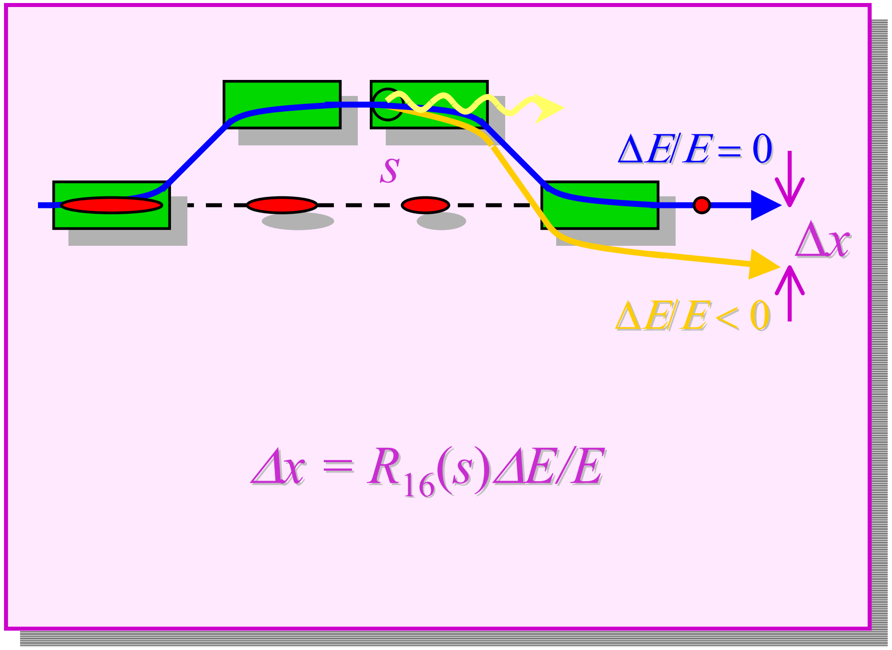
- Induced energy spread breaks achromatic system
- Causes bend-plane emittance growth (short bunch is worse)
- Powerful radiation generates energy spread in bends

bend-plane emittance growth



overtaking length: $L_0 \approx (24\sigma_z R^2)^{1/3}$

coherent radiation for $\lambda > \sigma_z$

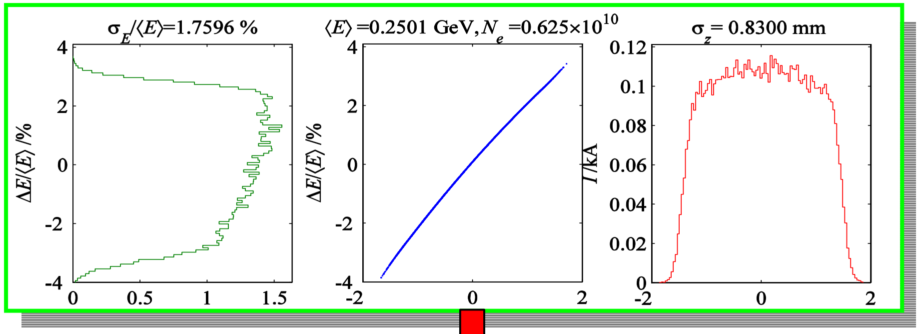


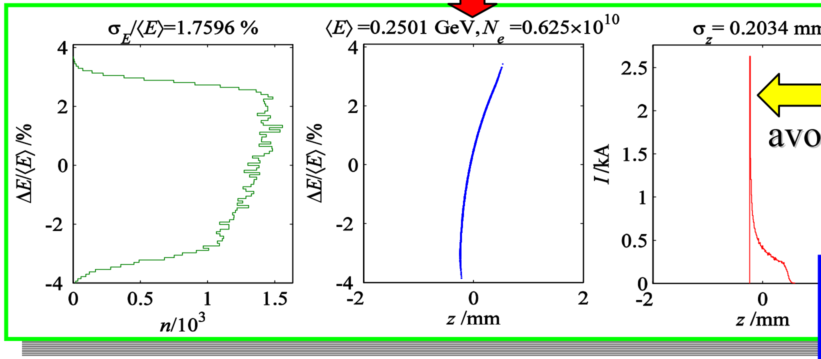
$\Delta x = R_{16}(s)\Delta E/E$

X-band RF used to Linearize Compression

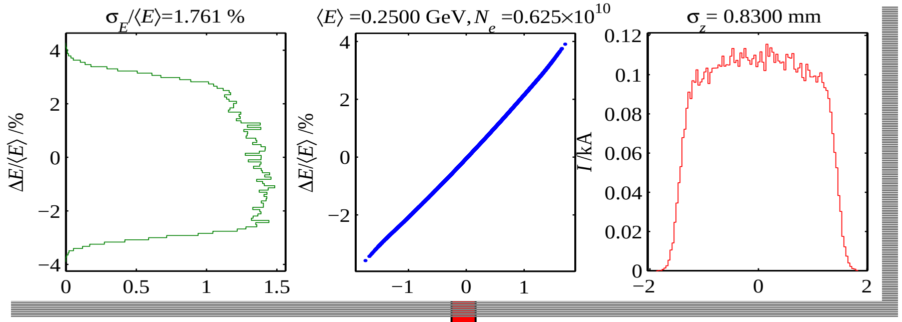
(f = 11.424 GHz)

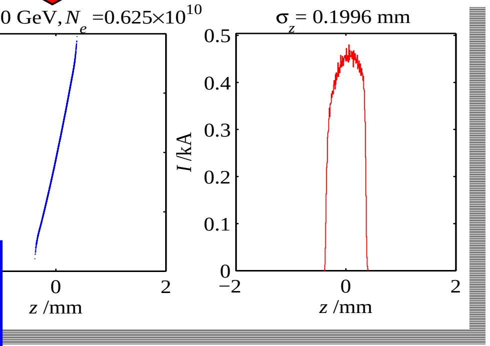
S-band RF curvature and 2nd-order momentum compaction cause sharp peak current spike



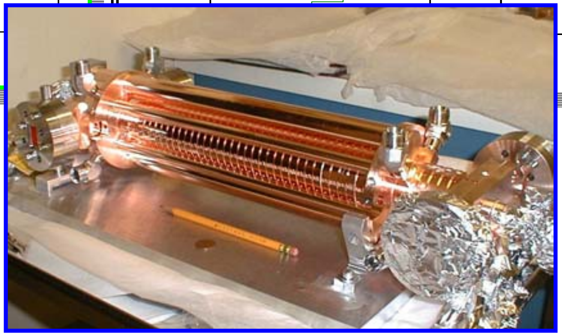


X-band RF at decelerating phase corrects 2nd-order and allows unchanged z-distribution



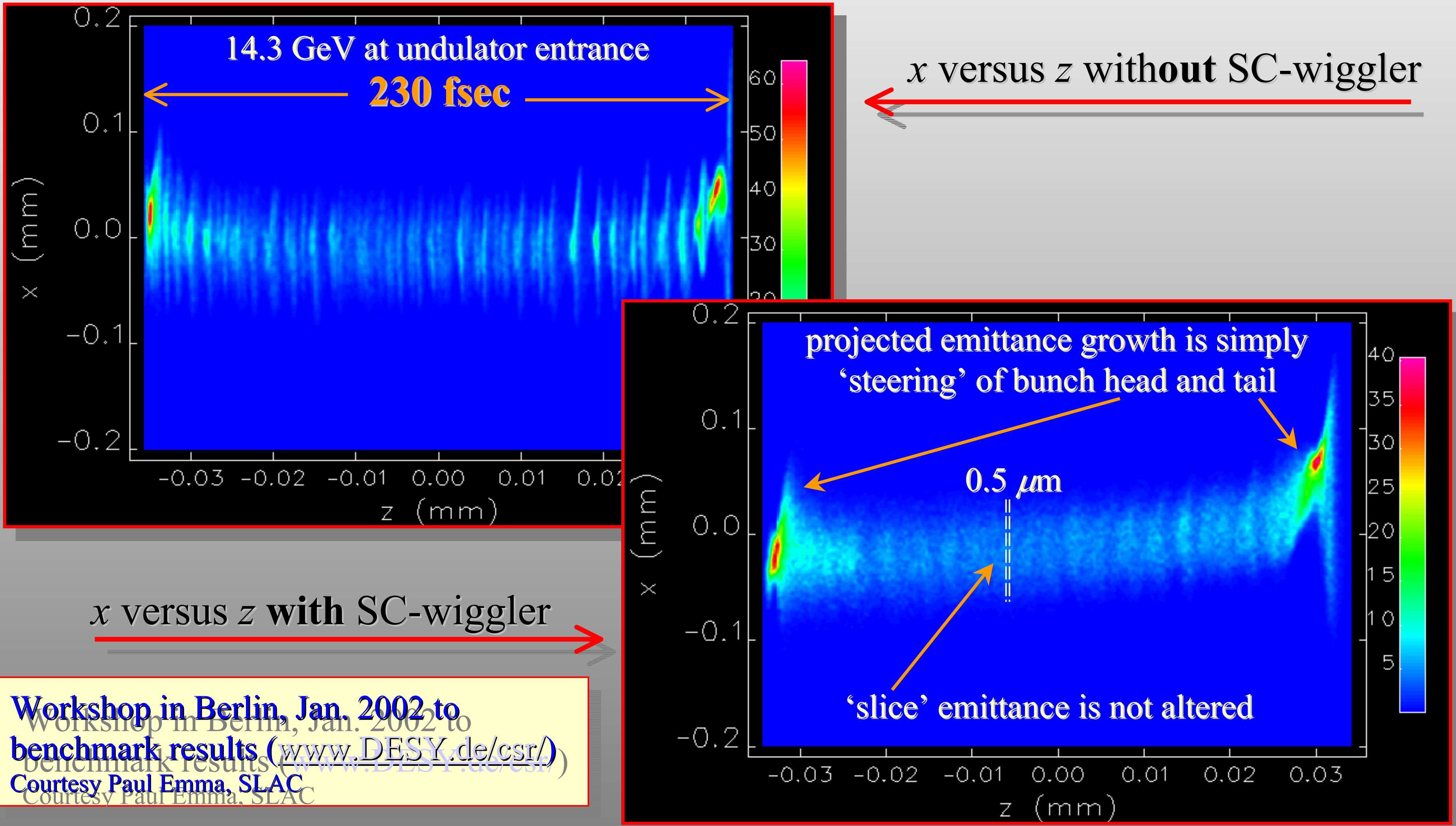


$$eV_x = \frac{E_0\left[1-\frac{1}{2\pi^2}\frac{\lambda_s^2 T_{566}}{R_{56}^3}\left(1-\sigma_z/\sigma_{z_0}\right)^2\right]-E_i}{\left(\lambda_s/\lambda_x\right)^2-1}$$



0.6-m section, 22 MV available at SLAC (200-μm alignment)

CSR Micro-bunching and Projected Emittance Growth



14.3 GeV at undulator entrance

230 fsec

projected emittance growth is simply 'steering' of bunch head and tail

0.5 μm

'slice' emittance is not altered

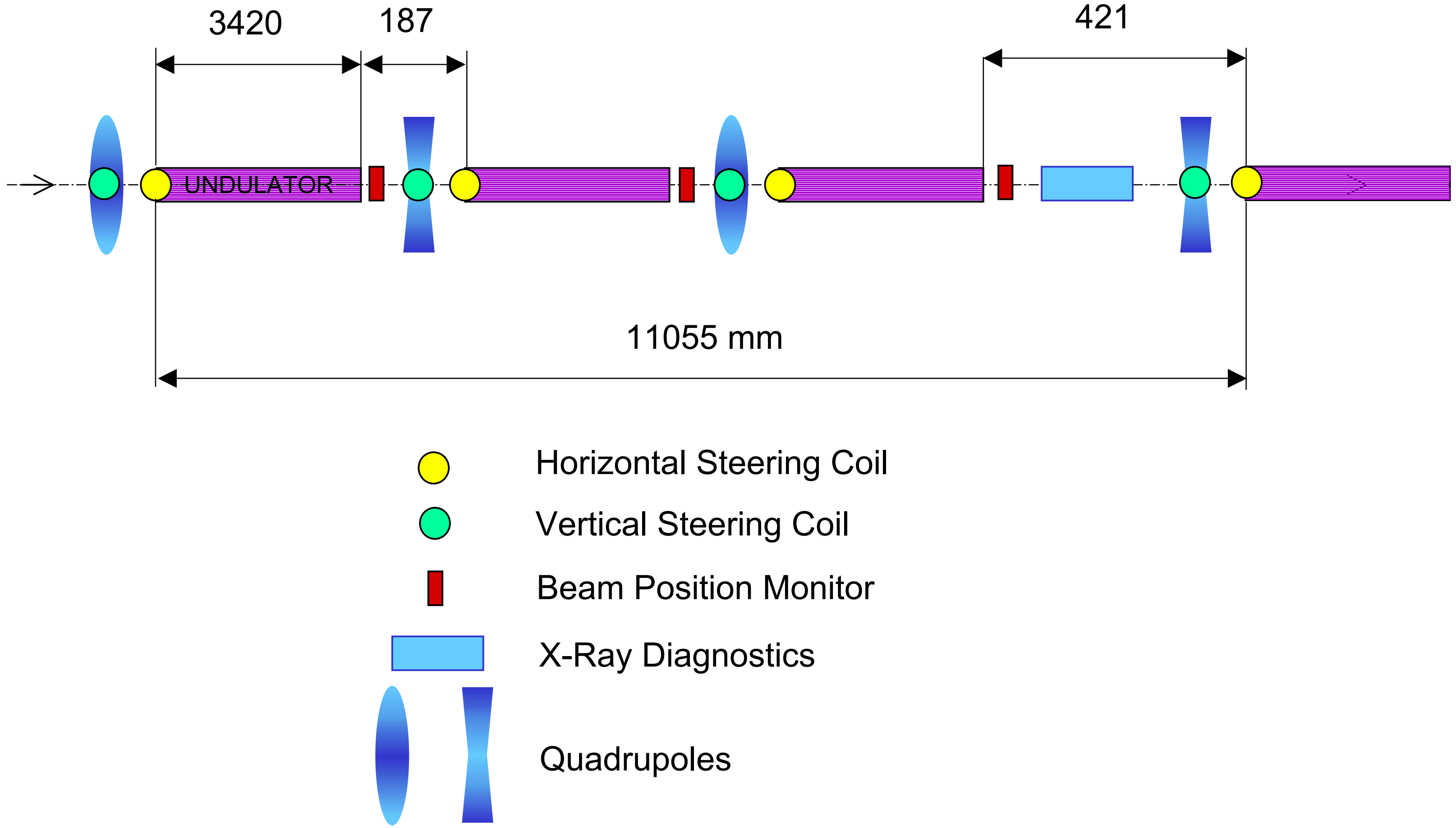
x versus *z* with**out** SC-wiggler

x versus *z* **with** SC-wiggler

Workshop in Berlin, Jan. 2002 to benchmark results (www.DESY.de/csr/)

Courtesy Paul Emma, SLAC

Cell structure of the LCLS undulator line



Start-to-End Tracking Simulations

- Track entire machine to evaluate beam brightness & FEL

space-charge

compression, wakes, CSR, …

SASE FEL with wakes

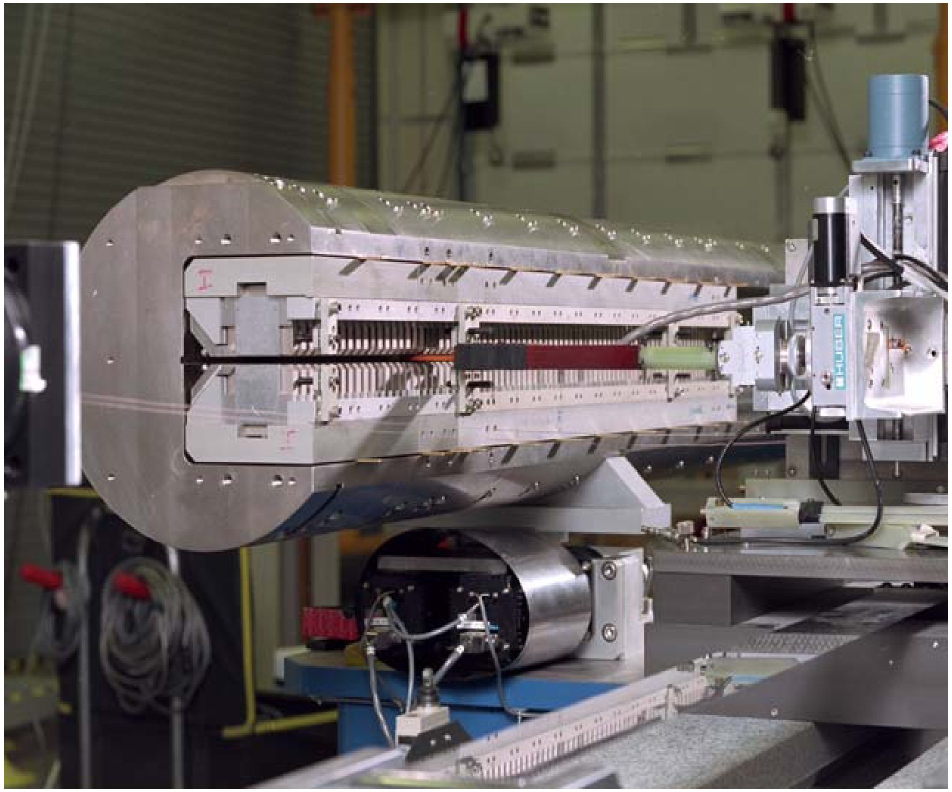
Parmela

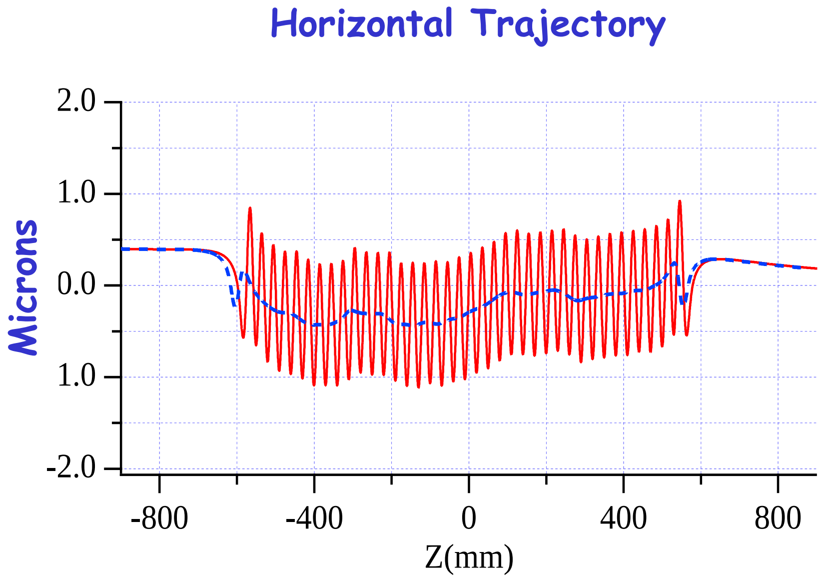
Elegant

Genesis

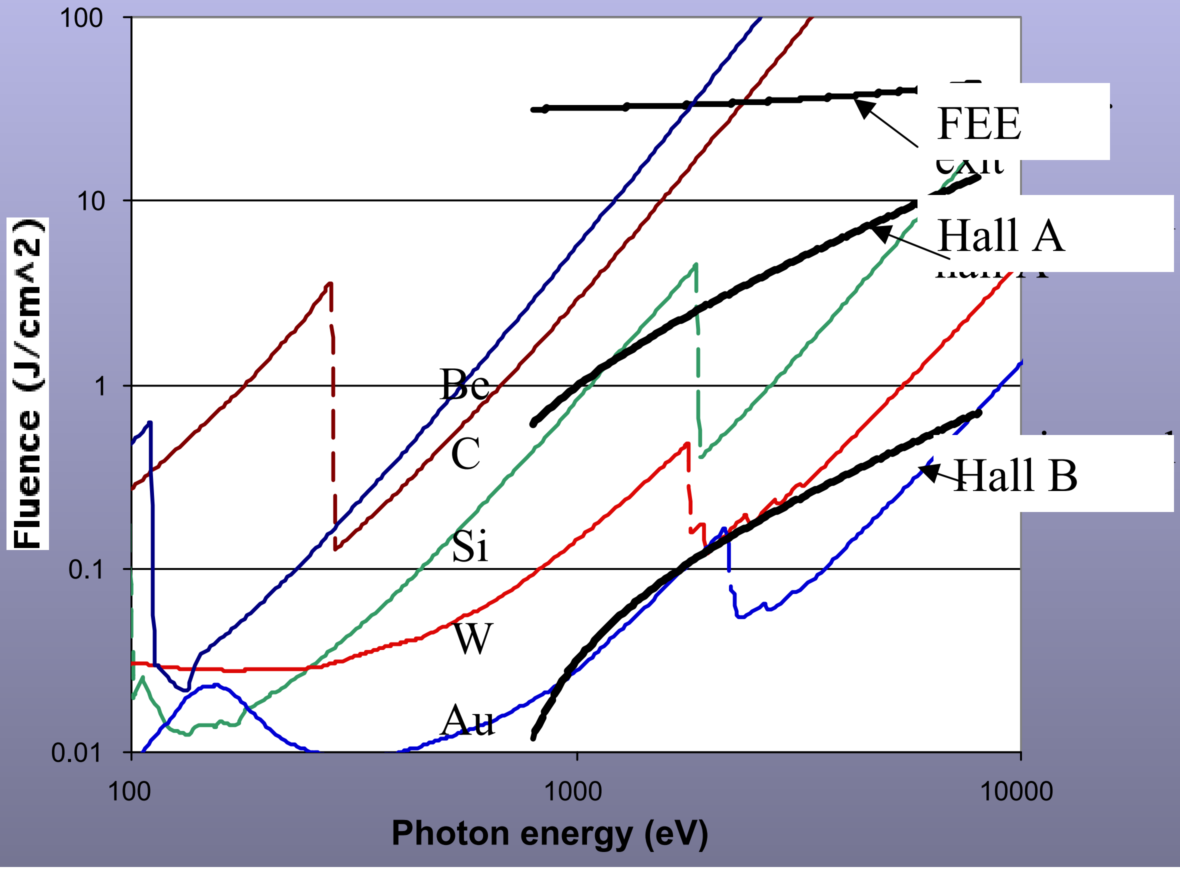
- Track machine many times with jitter to test stability budget (M. Borland, ANL)

Magnetic Measurement of the Prototype





Potential for Damage to X-Ray Optics



- In Hall A, low-Z materials will accept even normal incidence. The fluences in Hall B are sufficiently low for standard optical solutions. Even in the Front End Enclosure (FEE), low Z materials may be possible at normal incidence above ~4 keV, and at all energies with grazing incidence. In the FEE, gas is required for attenuation at < 4 keV

SASE Demonstration Experiments at Longer Wavelengths

- **IR wavelengths:**

  UCLA/LANL ($\lambda = 12\mu$, G = 10^5)
  LANL ($\lambda = 16\mu$, G = 10^3)
  BNL ATF/APS ($\lambda = 5.3\mu$, G = 10, HGHG = 10^7 times S.E.)

- **Visible and UV:**

  TESLA Test Facility (DESY): E_e = 390 MeV, L_u = 15 m, λ = 42 nm

  VISA (BNL-LANL-LLNL-SLAC-UCLA): E_e = 70 MeV, L_u = 4m, λ = 0.8 μ

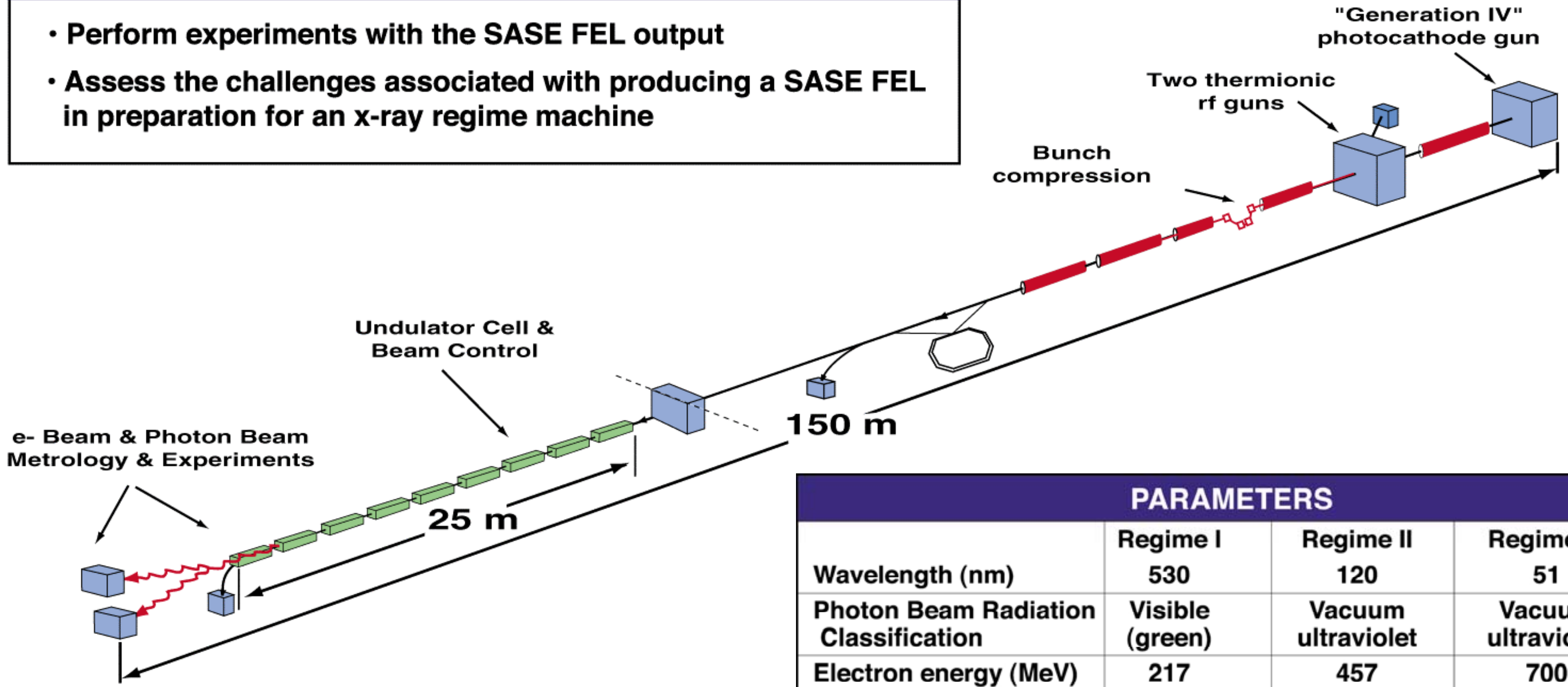
  APS LEUTL: $E_e \leq$ 700 MeV, L_u = 25 m, 120 nm $\leq \lambda \leq$ 530nm

All successful!

LOW-ENERGY UNDULATOR TEST LINE PARAMETERS

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

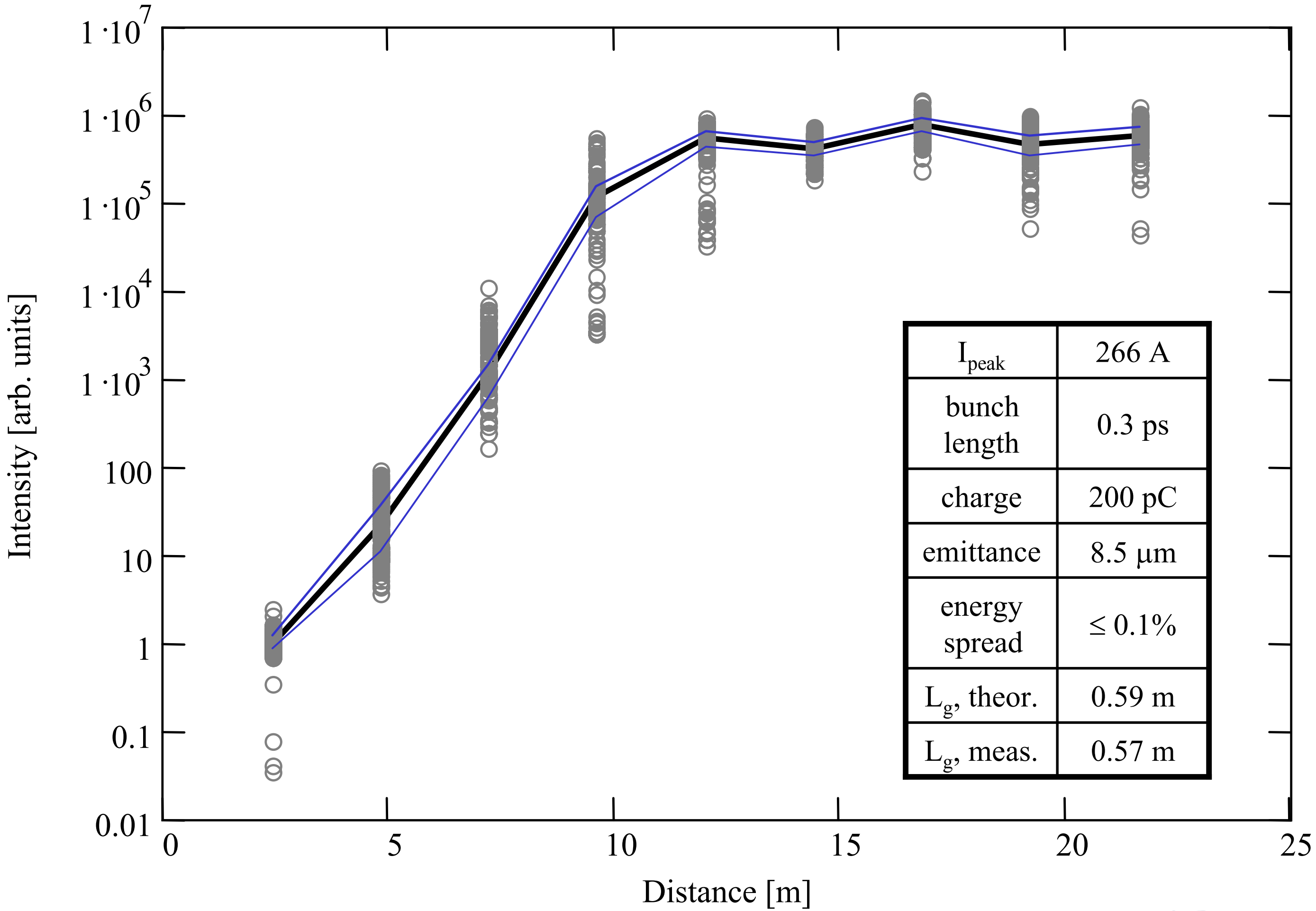


PARAMETERS

	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

Optical Intensity Gain

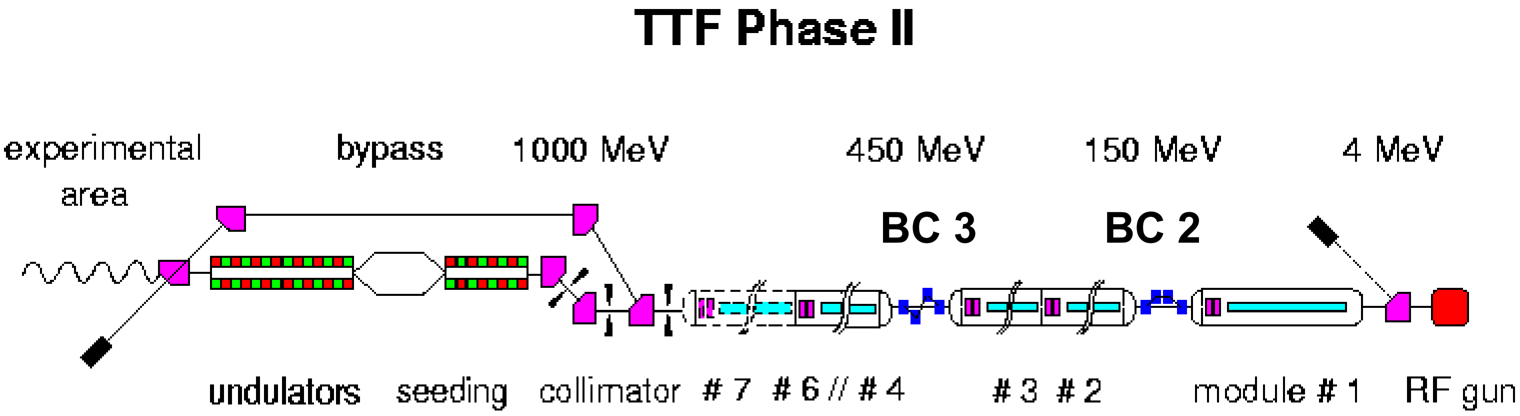


I_{peak}	266 A
bunch length	0.3 ps
charge	200 pC
emittance	8.5 μm
energy spread	≤ 0.1%
L_g, theor.	0.59 m
L_g, meas.	0.57 m

Science, v. 292, pp 2037-2041 (2001)

Advanced
Photon
Source
Argonne National Laboratory

TTF2: Soft-X ray User Facility / Overview

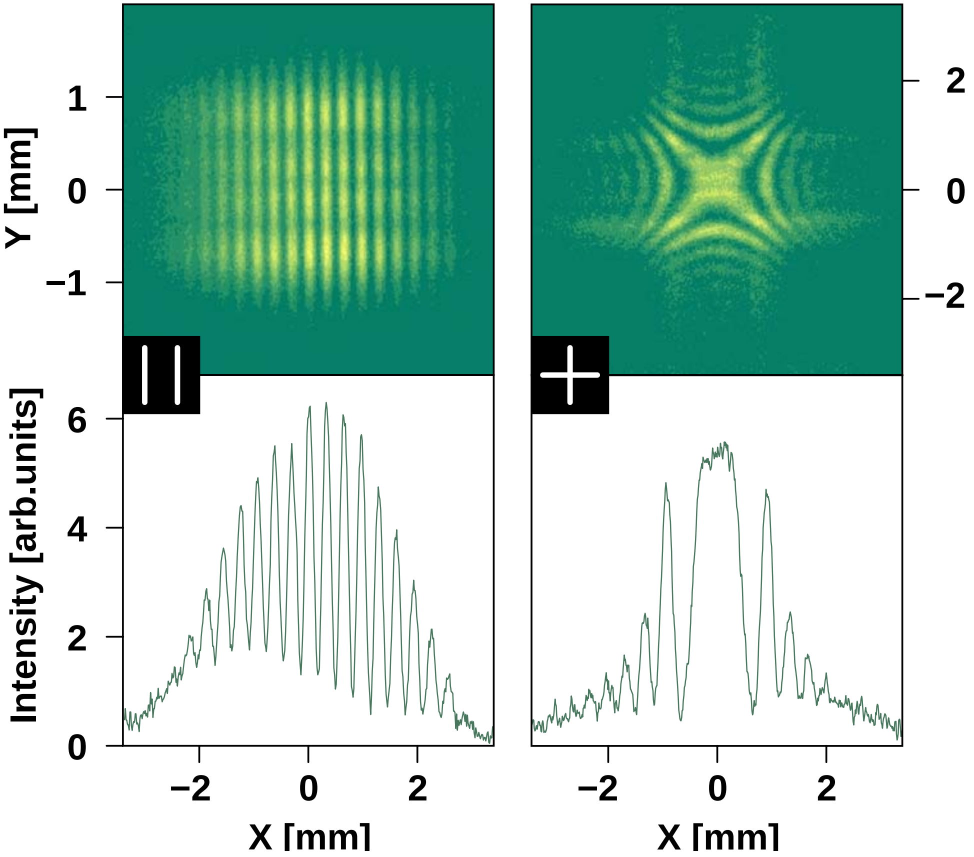


Properties of SASE FEL radiation:

1) transv. coherence
2) long. coherence
3) fluctuations

1) Transverse coherence should be almost 100 % at saturation

Observation of diffraction pattern at TTF FEL:



after double slit

after cross

Future Light Sources based on X-ray FELs

- A leap in electron beam and photon beam technology
- A leap in x-ray science
- Proposals around the world for UV and x-ray facilities
- LCLS turns on in 98

Acknowledgement

- I thank my colleagues at SLAC, DESY, and ANL for making these excellent VGs available to me !