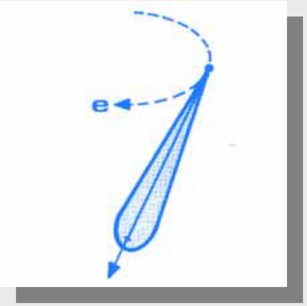
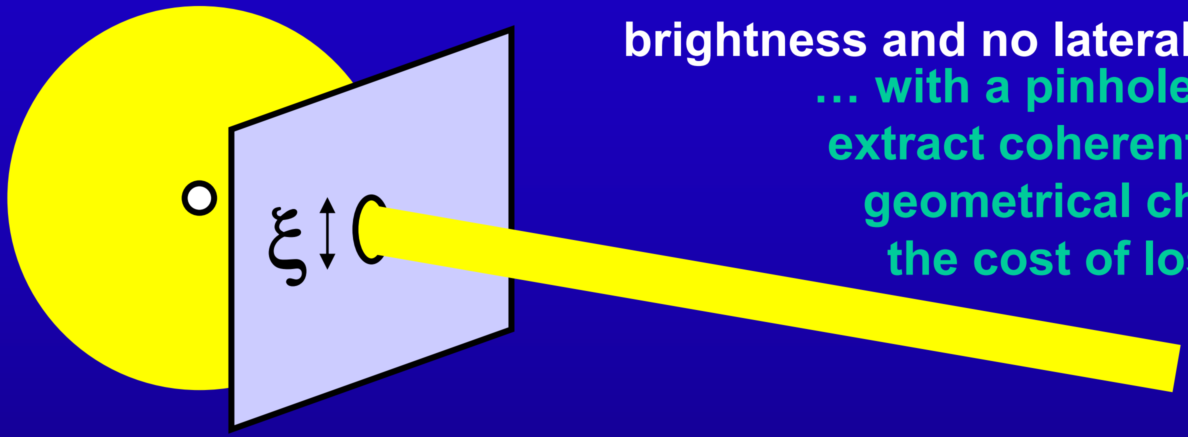


SYNCHROTRON RADIATION
FREE ELECTRON LASERS

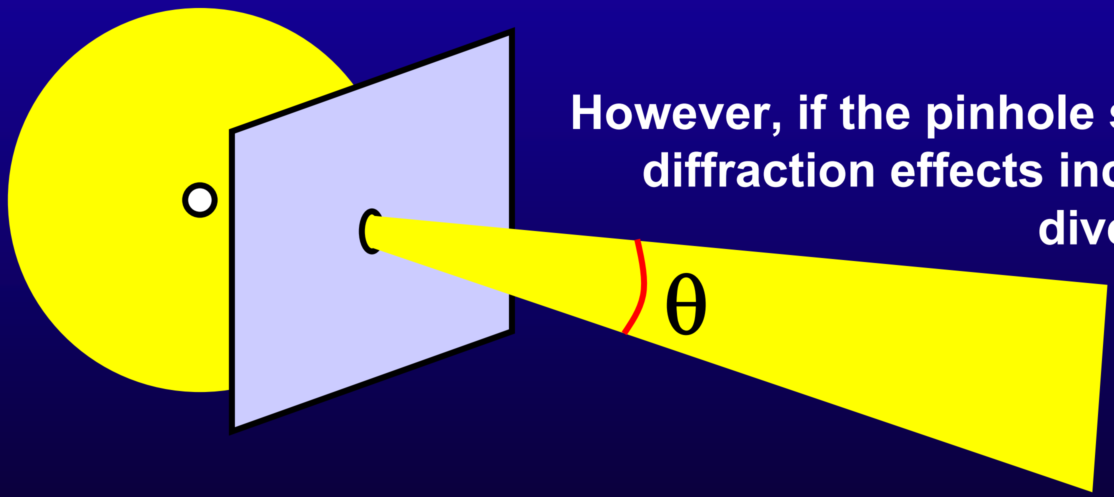
Lenny Rivkin
Paul Scherrer Institute, Switzerland

ICTP SCHOOL ON SYNCHROTRON RADIATION AND APPLICATIONS
Trieste, Italy, May 2006



Take a standard photon source with limited brightness and no lateral coherence …

… with a pinhole (size ξ), we can extract coherent light with good geometrical characteristics (at the cost of losing most of the emission)



However, if the pinhole size is too small diffraction effects increase the beam divergence so that:

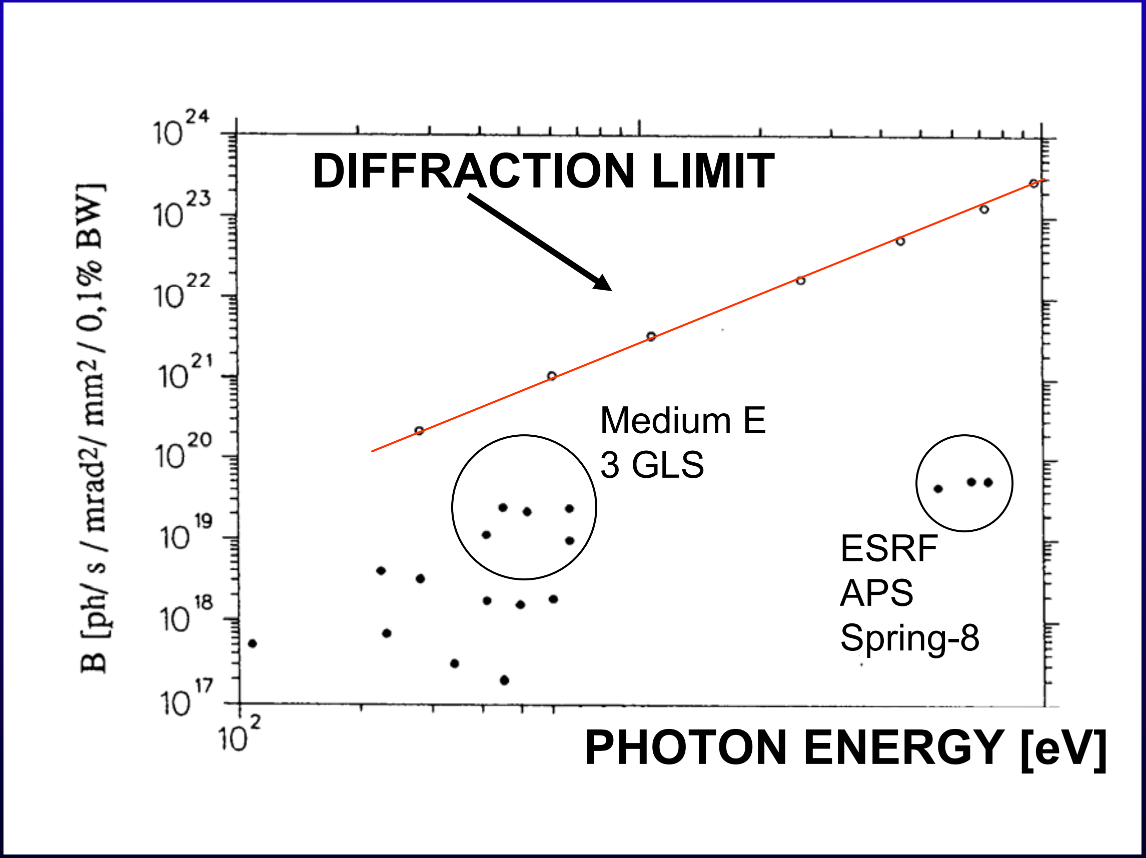
$$\xi\theta \geq \lambda$$

<u>No</u> source geometry beats this <u>diffraction limit</u>

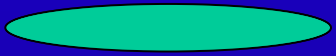
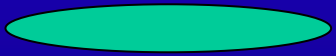
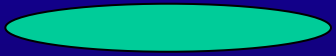
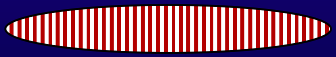
G. Margaritondo

PERFORMANCE OF 3th GENERATION LIGHT SOURCES

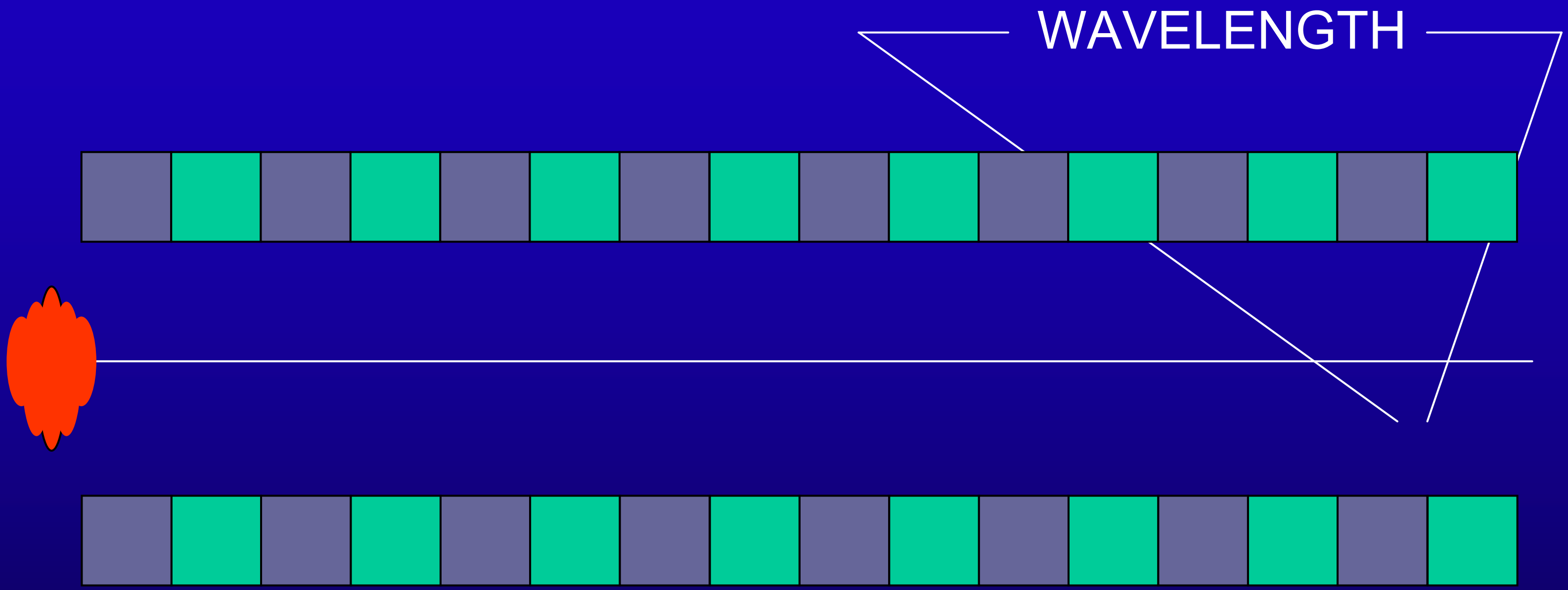
BRIGHTNESS:

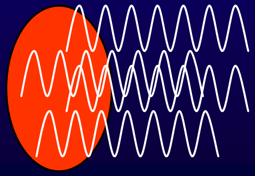


BRIGHTNESS OF SYNCHROTRON RADIATION

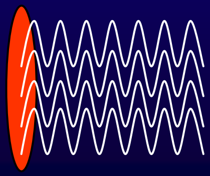
	electrons	*periods*		
Bending magnet	$\sim N_e$			
Wiggler	$\sim N_e$	$\sim N$		10
Undulator	$\sim N_e$	$\sim N^2$		10^4
FEL	$\sim N^2_{\mu\text{-b}}$	$\sim N^2$		10^{10}
Superradiance	$\sim N_e^2$	$\sim N^2$		10^{12}

MUCH HIGHER BRIGHTNESS CAN BE REACHED BY COHERENT EMISSION OF THE ELECTRONS





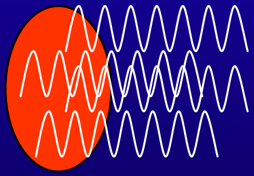
INCOHERENT EMISSION



COHERENT EMISSION

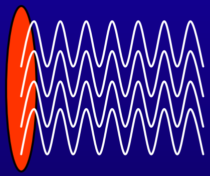
COHERENT EMISSION BY THE ELECTRONS

Intensity $\propto N$



INCOHERENT EMISSION

Intensity $\propto N^{2}$



COHERENT EMISSION

FIRST DEMONSTRATIONS OF COHERENT EMISSION (1989-1990)

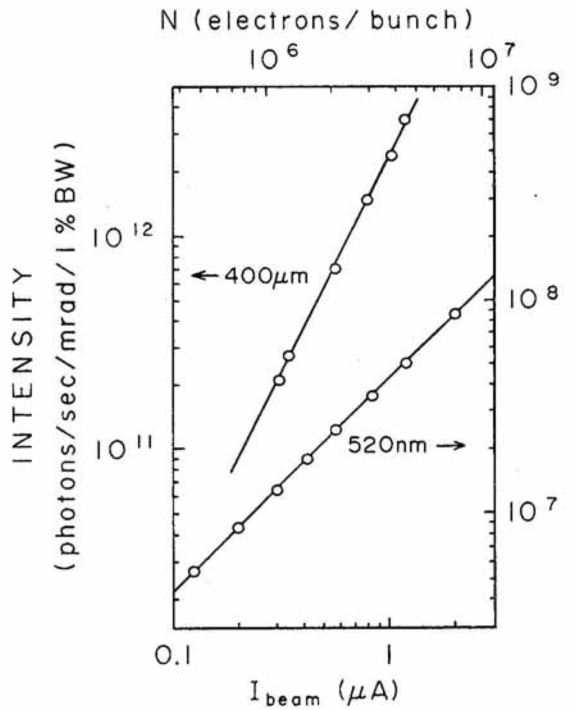


Fig. 4. Dependence of SR intensity on the beam current at $\lambda = 400$ μm and $\lambda = 520$ nm for the long pulse/short bunch beam. The ordinate is given on the left-hand side for $\lambda = 400$ μm and on the right for $\lambda = 520$ nm. The two lines show the linear and quadratic relations to the beam current. The beam current is converted to the average number of electrons in a bunch on the upper side.

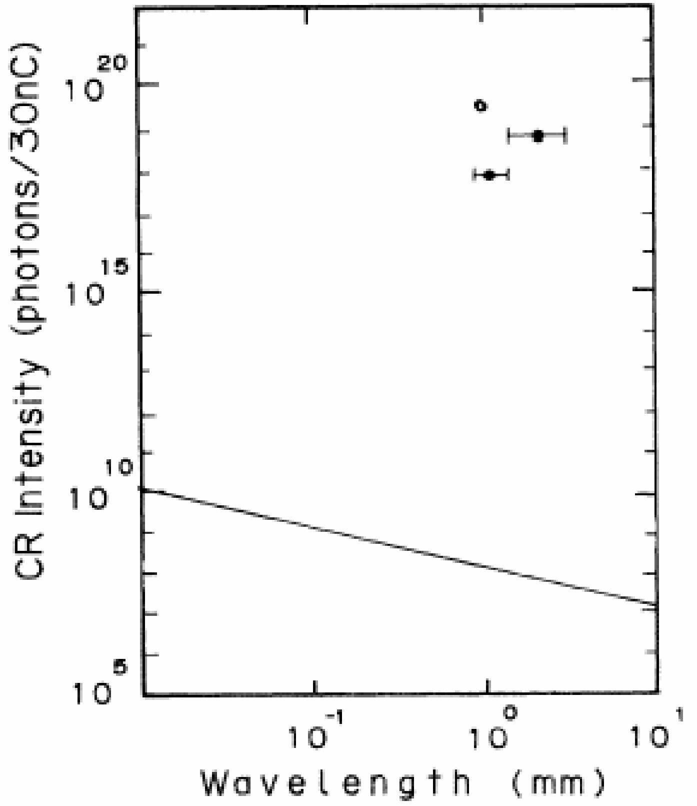


FIG. 3. The intensity of the CR measured for the bandwidths indicated with horizontal bars, the spectrum calculated according to Eq. (1) for 10% bandwidth (solid line), and the intensity expected for the complete coherence over the bunch for 10% bandwidth (open circle).

180 MeV electrons

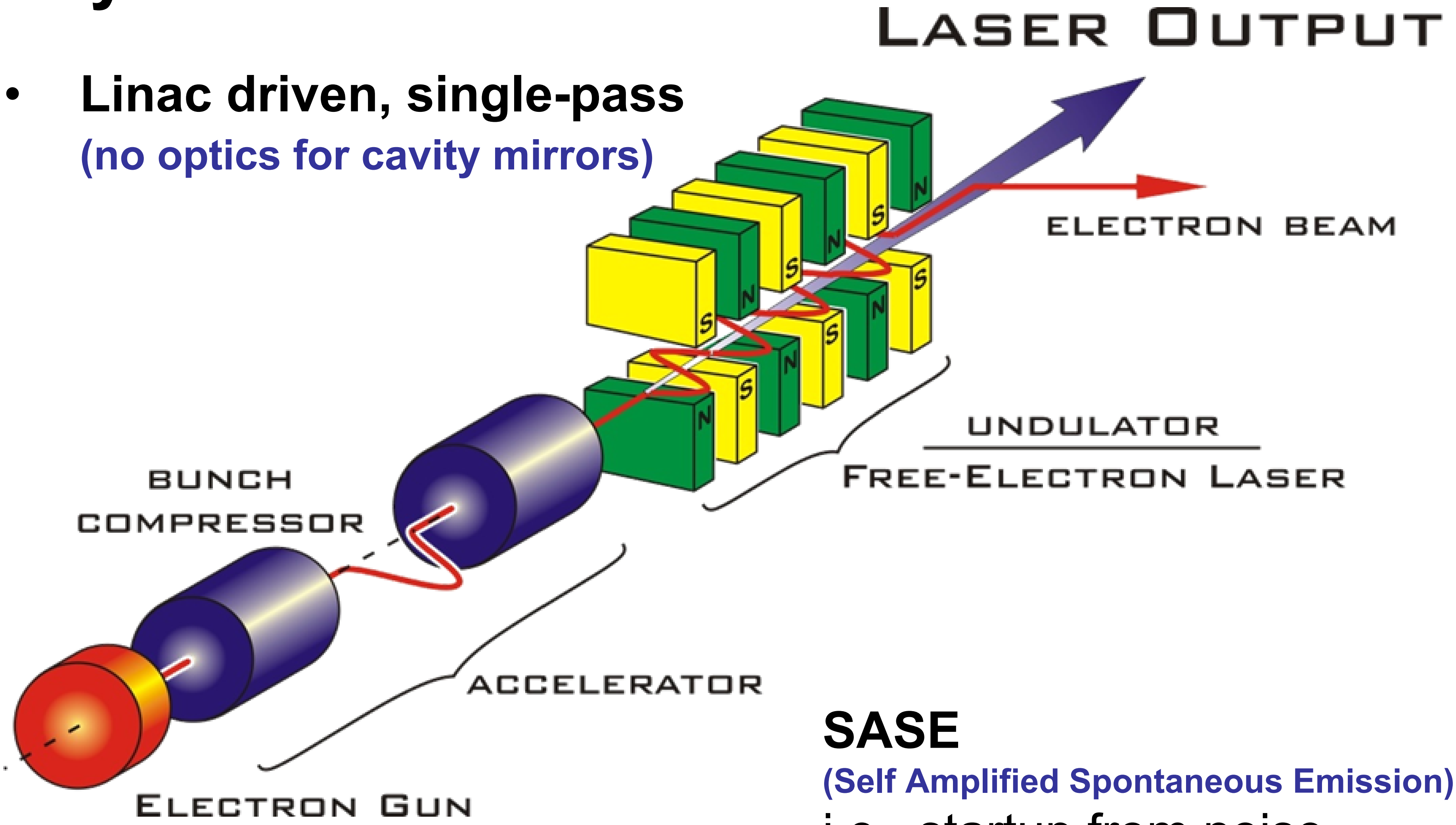
T. Nakazato et al., Tohoku University, Japan

30 MeV electrons

J. Ohkuma et al., Osaka University, Japan

Keywords:

- **Linac driven, single-pass**
  (no optics for cavity mirrors)



SASE
(Self Amplified Spontaneous Emission)
i.e., startup from noise

SASE FEL

- **UNBEATABLE BRILLIANCE**

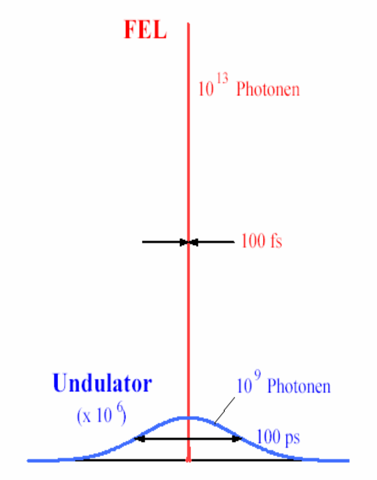
  (10^{30} - 10^{33})

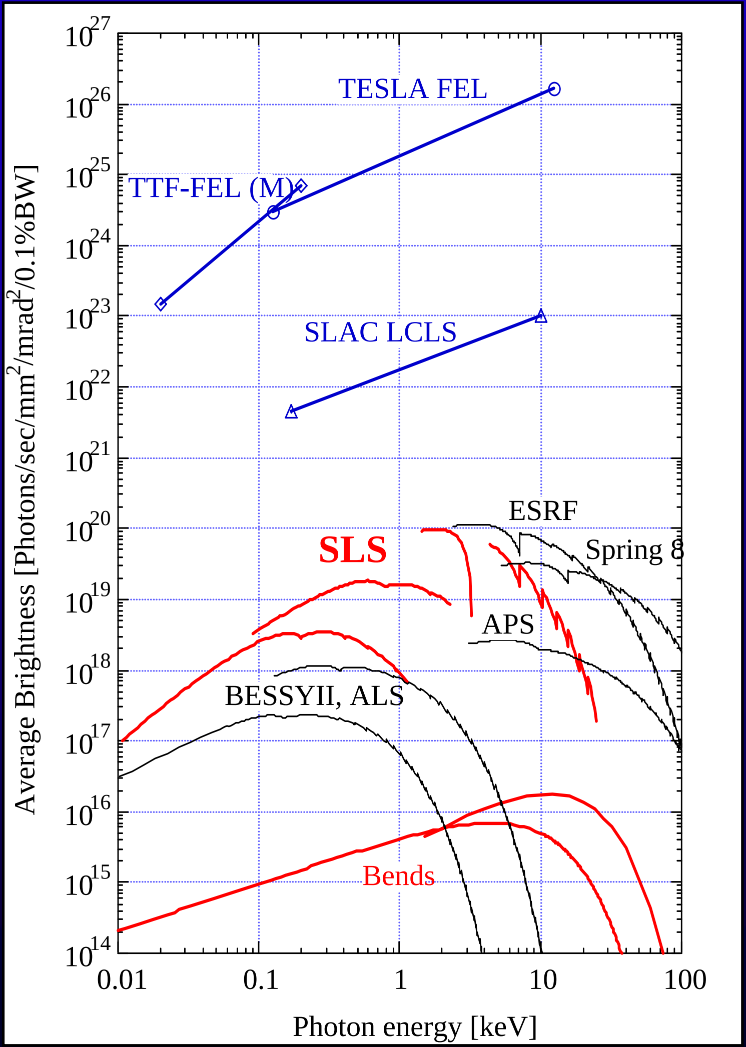
- **HIGH AVERAGE BRILLIANCE**

  (10^{22} - 10^{25})

- **SHORT PULSES**

  (1 ps – 50 fs)



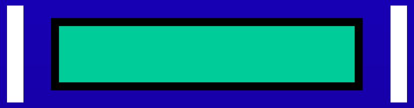


Self-amplified spontaneous emission x-ray free-electron lasers (SASE X-FEL's)

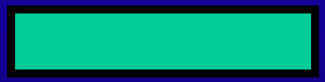
Normal (visible, IR, UV) lasers:

optical amplification in amplifying medium

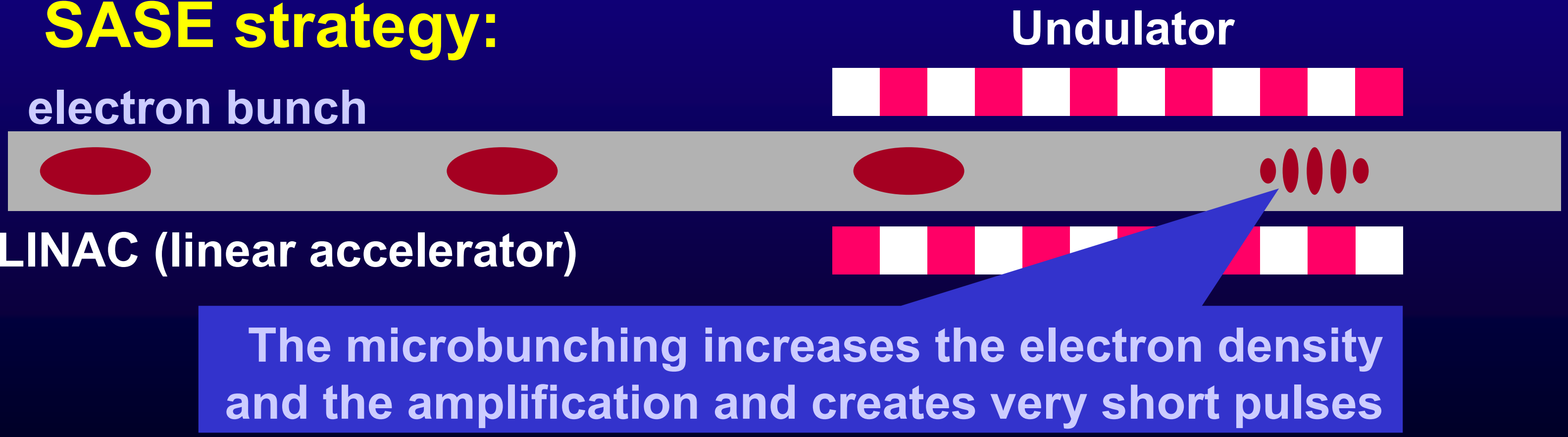
plus optical cavity (two mirrors)



X-ray lasers: no mirrors → no optical cavity → need for one-pass high optical amplification



SASE strategy:



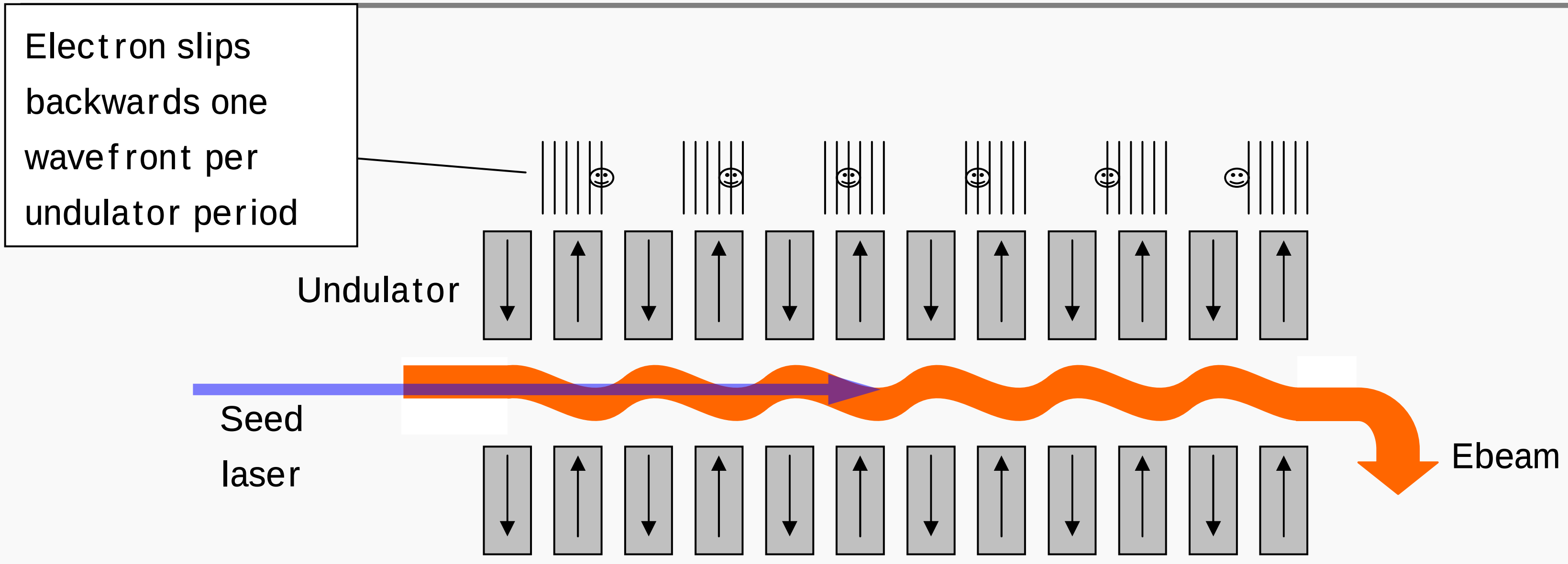
Undulator

electron bunch

LINAC (linear accelerator)

The microbunching increases the electron density and the amplification and creates very short pulses

FEL Interaction

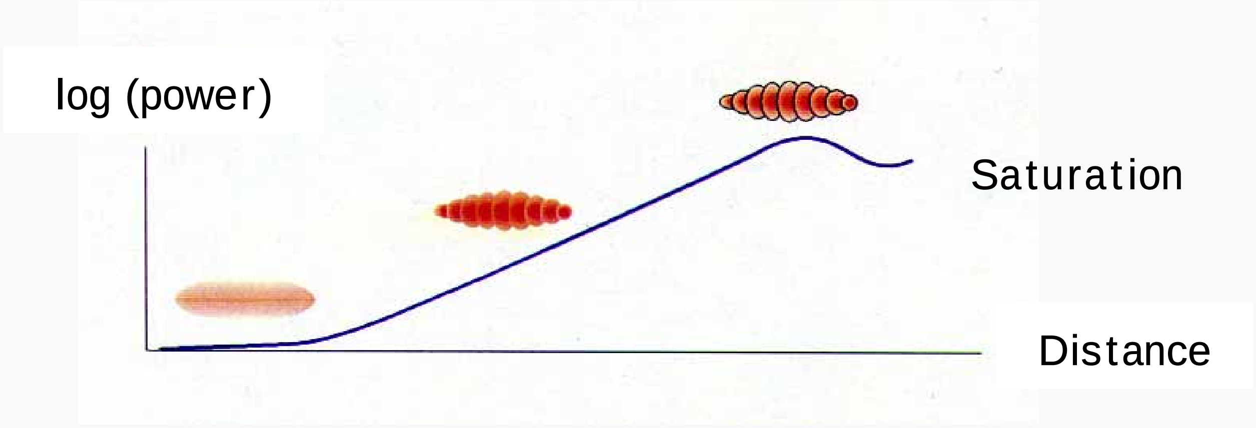


Electron slips backwards one wavefront per undulator period

Undulator

Seed laser

Ebeam



log (power)

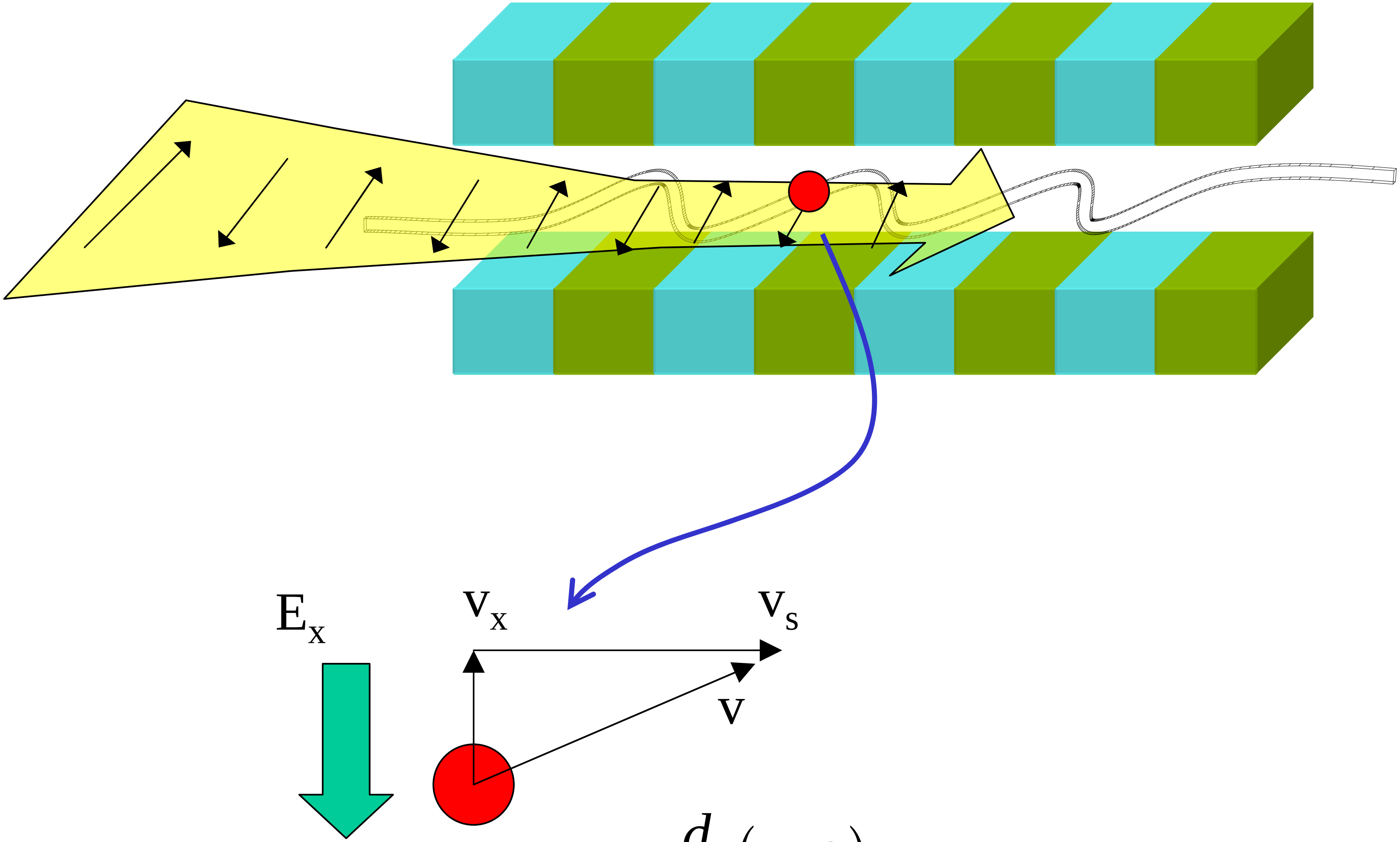
Saturation

Distance

Electrons are bunched under the influence of the light that they radiate.

The bunch dimensions are characteristic of the wavelength of the light.

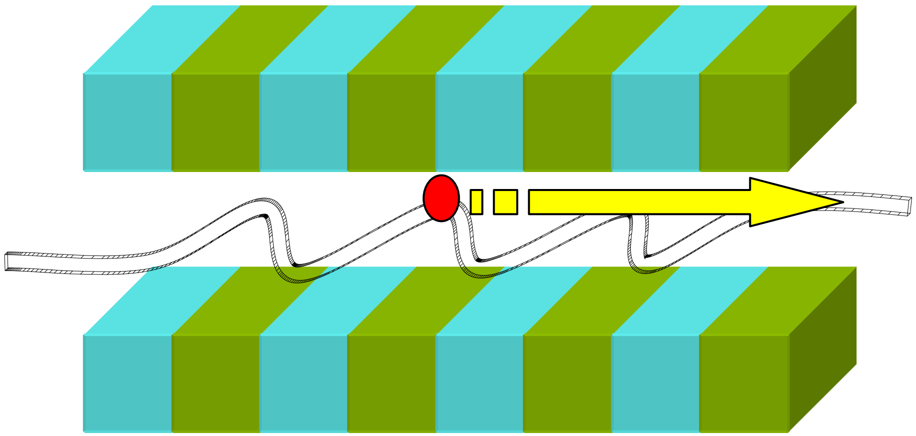
Mixing light, e- and undulator

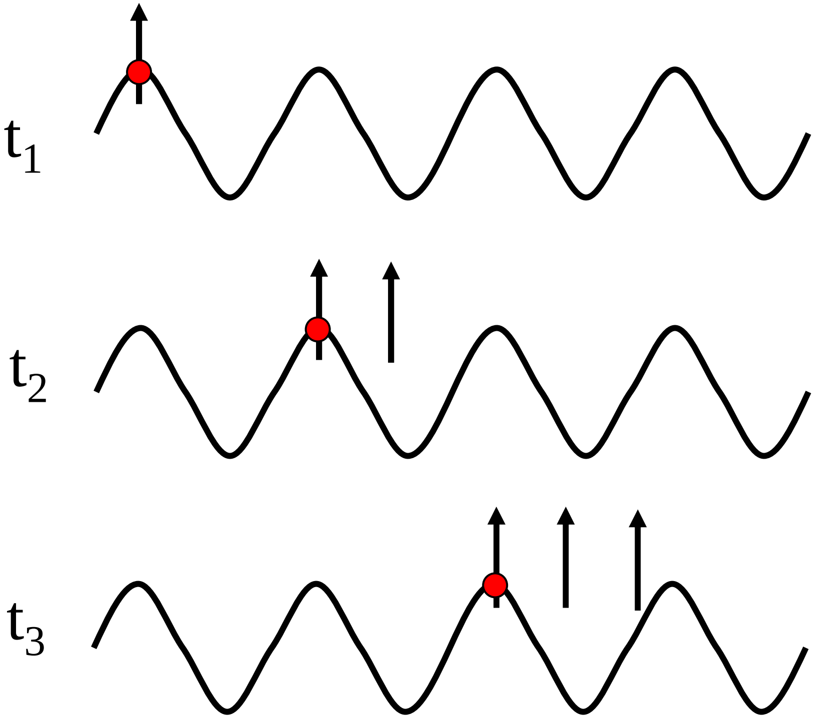


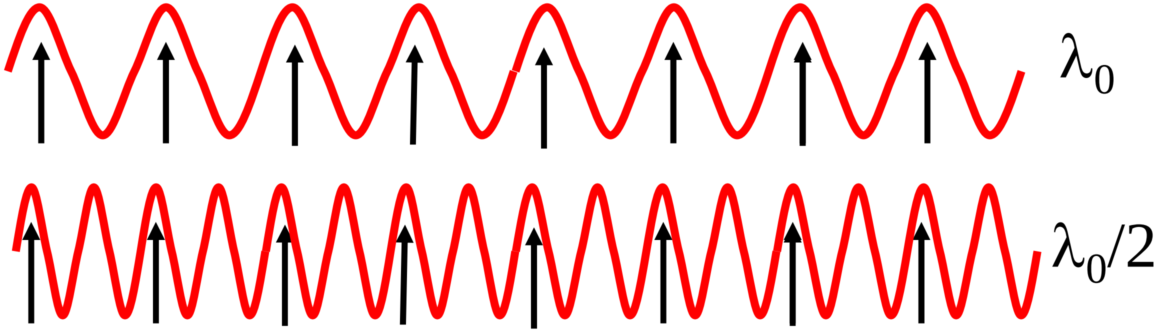
$$\frac{d}{dt}\left(mc^2\right) = -ev_x E_x \neq 0$$

S. Werin

Undulator radiation

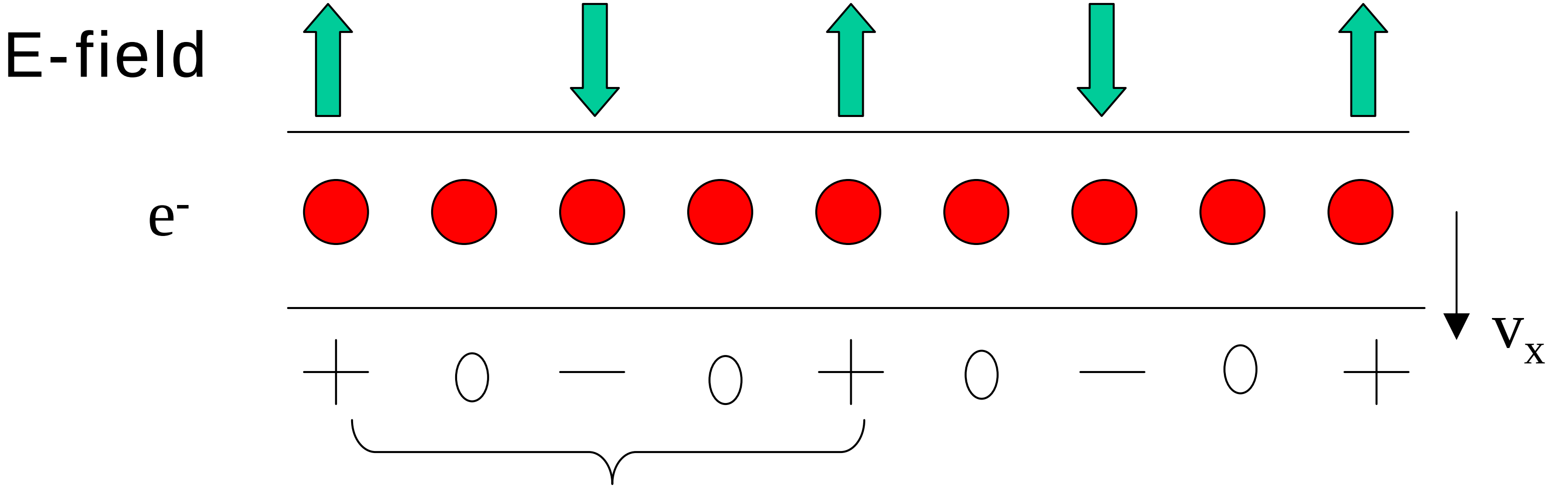






S. Werin

Energy exchange



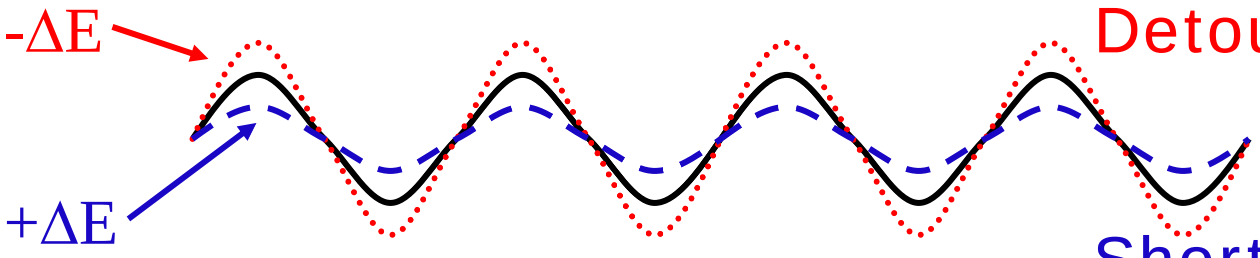
Some e^- gain energy

Some e^- lose energy

$\Sigma = 0$

S. Werin

Bunching

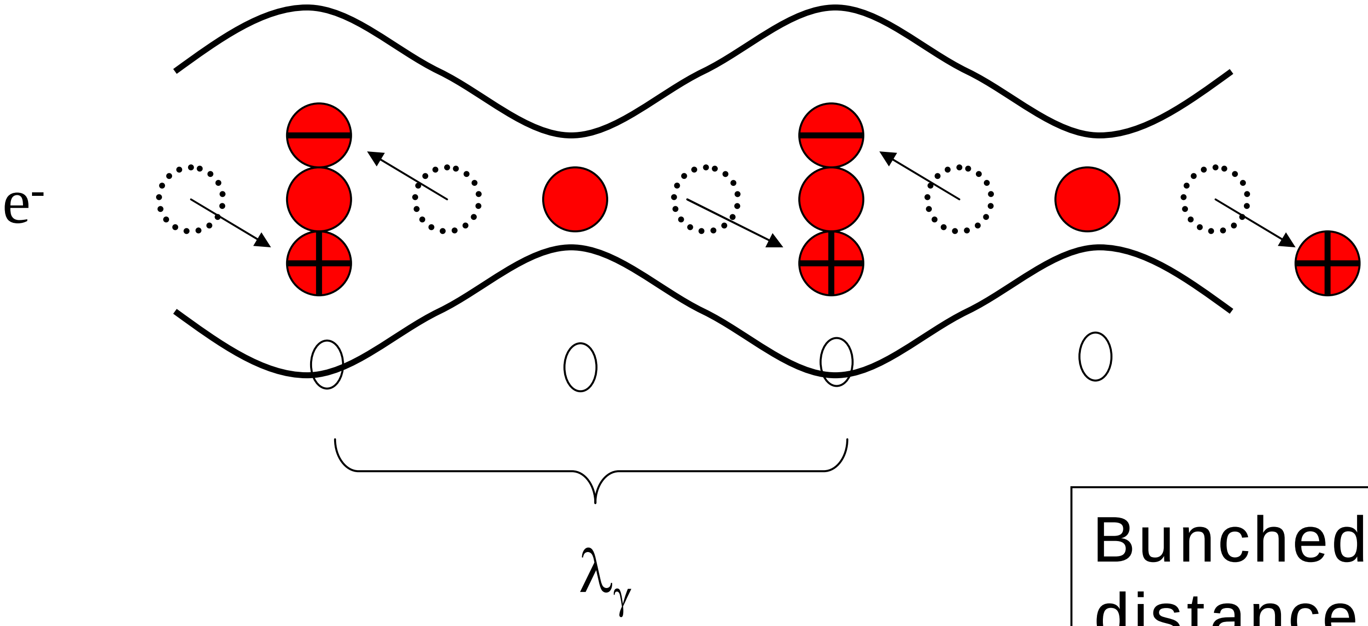


$-\Delta E$

$+\Delta E$

Detour & lower v

Shortcut & higher v



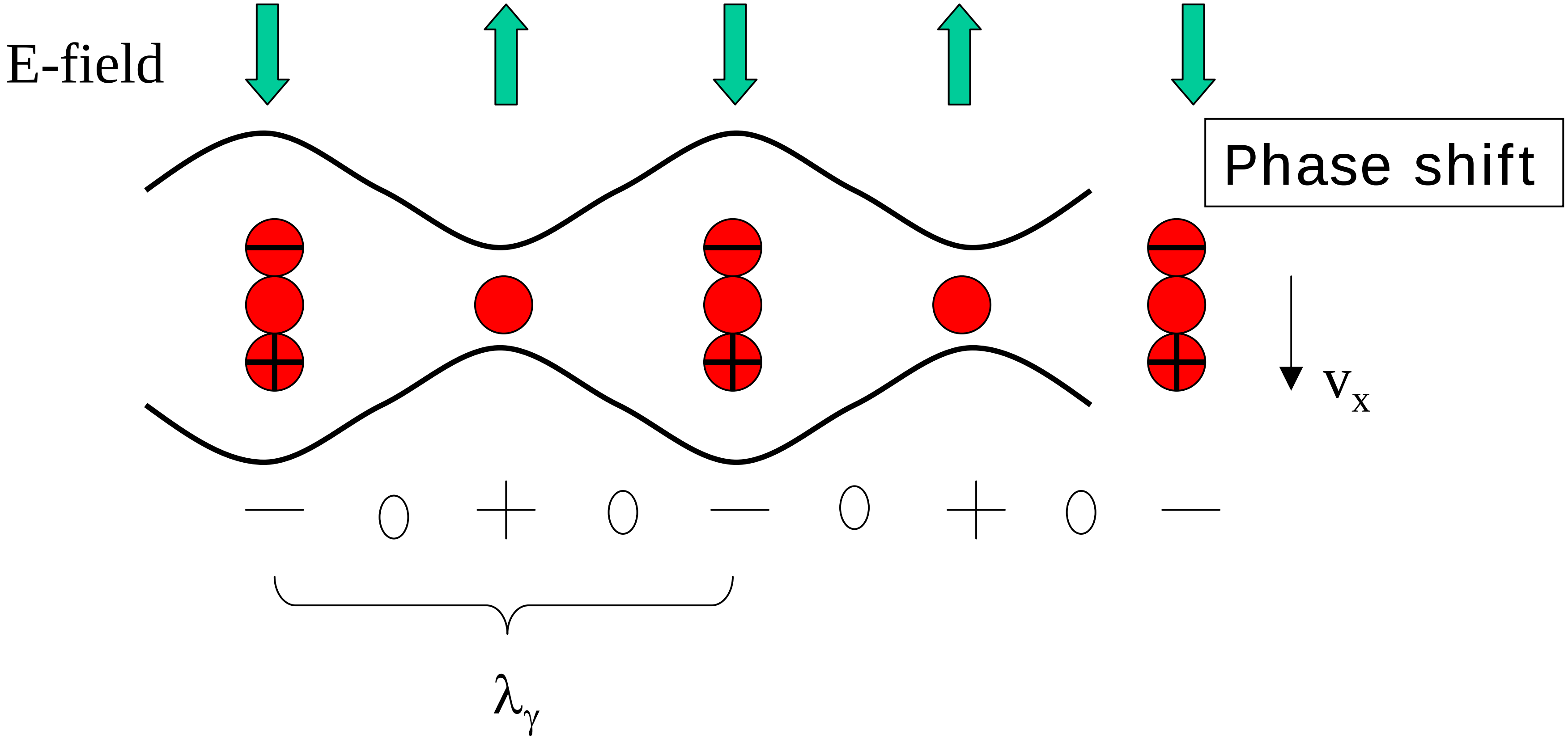
e^-

λ_γ

Bunched e^- with distance of light wavelength

S. Werin

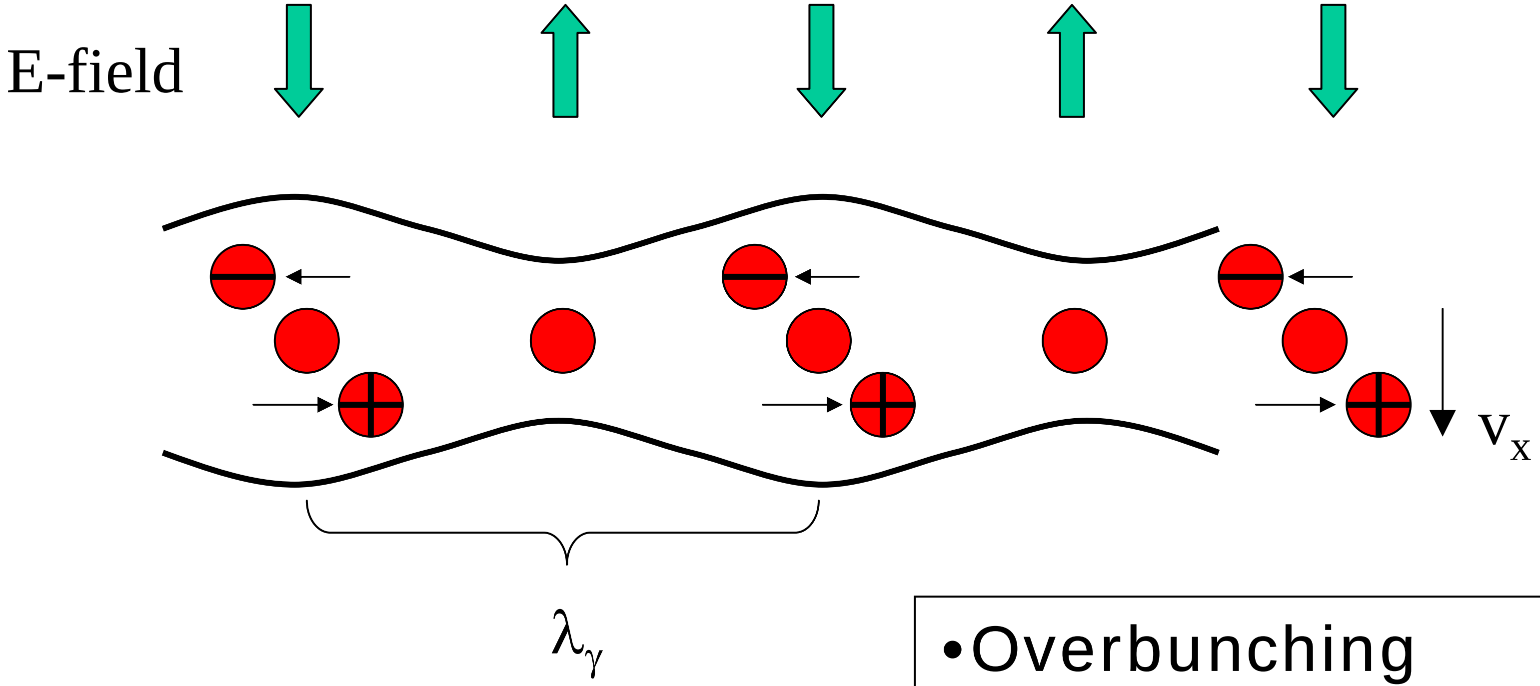
Amplification



- All e^- loose energy
- E-field gains energy
- Σ 🕒 0

S. Werin

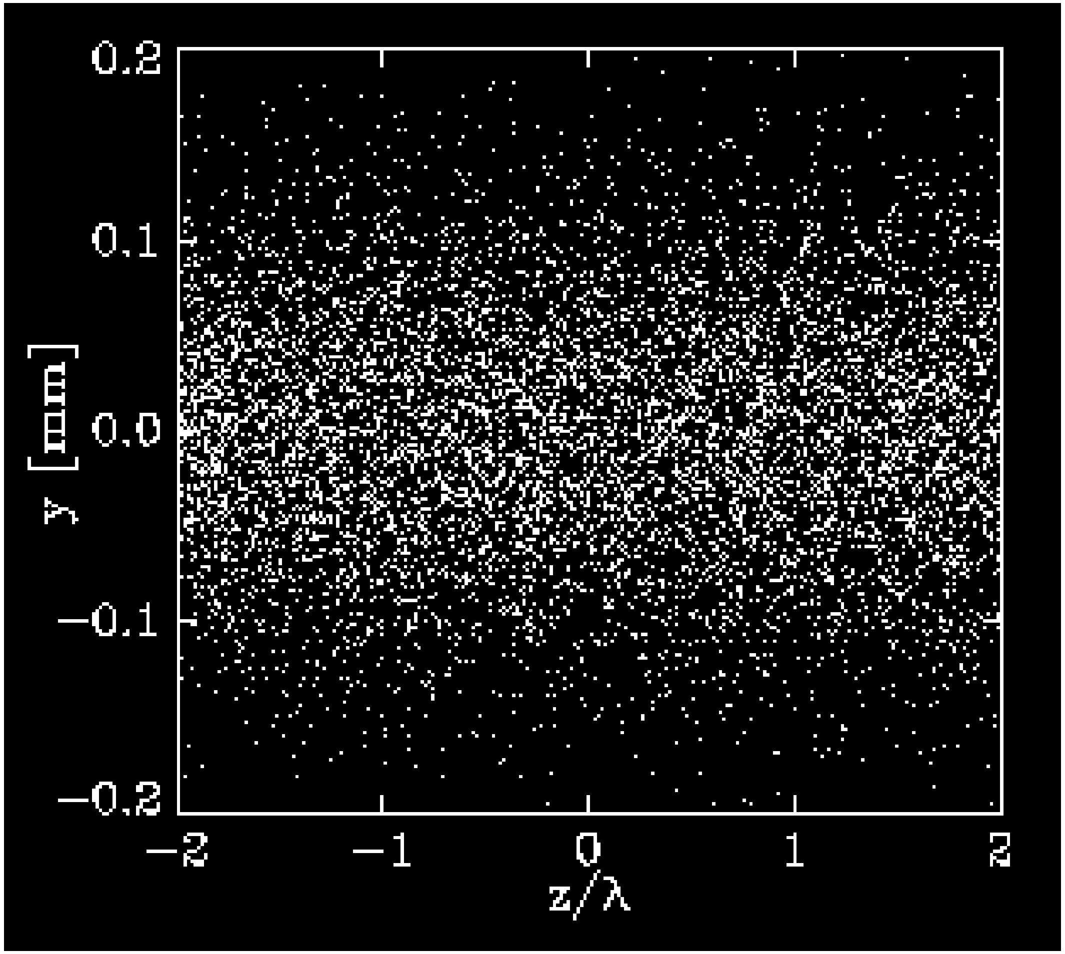
Saturation



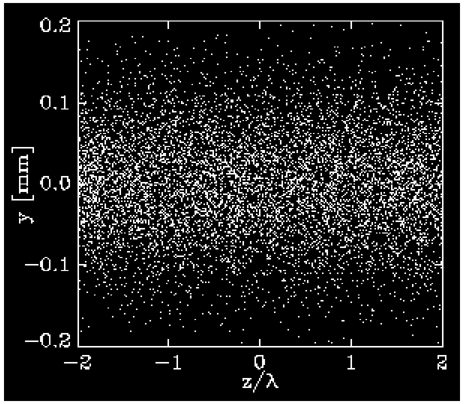
- Overbunching
- Amplification dies off

S. Werin

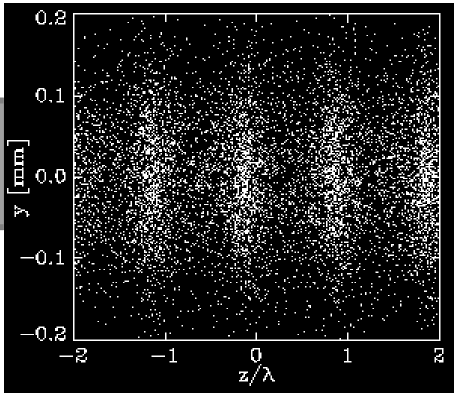
Microbunching through SASE Process



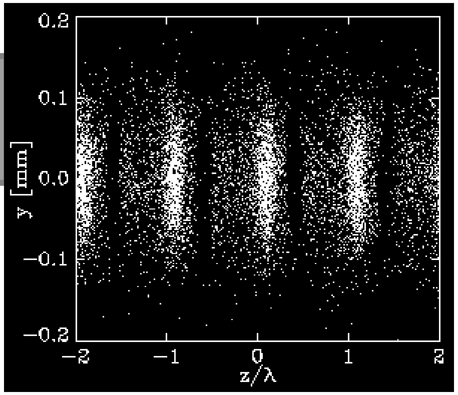
undulator entrance



half-way saturation



full saturation



GENESIS **- simulation for TTF parameters**

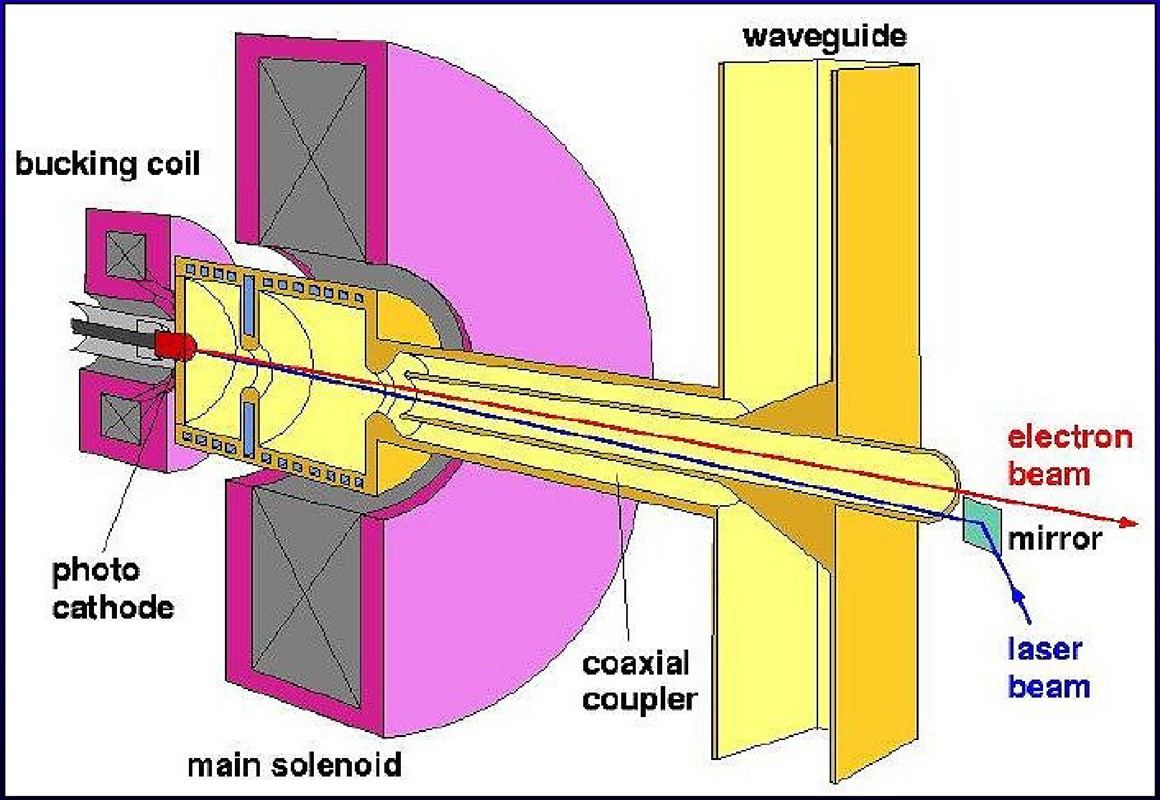
Courtesy - Sven Reiche (UCLA)

Stringent requirements on electron beam

- Emittance (slice) on the order of radiation wavelength
- High peak current ~ kA
- Low energy spread ~ 10^{-3}

CRITICAL ELEMENT OF A FEL = ELECTRON GUN

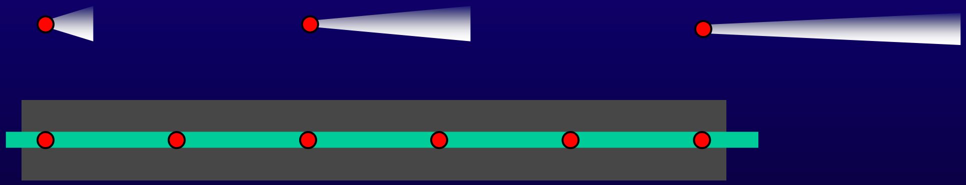
FOR SMALL INITIAL BEAM SIZES THE DIMENSIONS OF A FEL ARE CORRESPONDINGLY REDUCED



Emittance damping in linacs:

ε $\frac{\varepsilon}{2}$ $\frac{\varepsilon}{4}$

Ω $\frac{\Omega}{2}$ $\frac{\Omega}{4}$



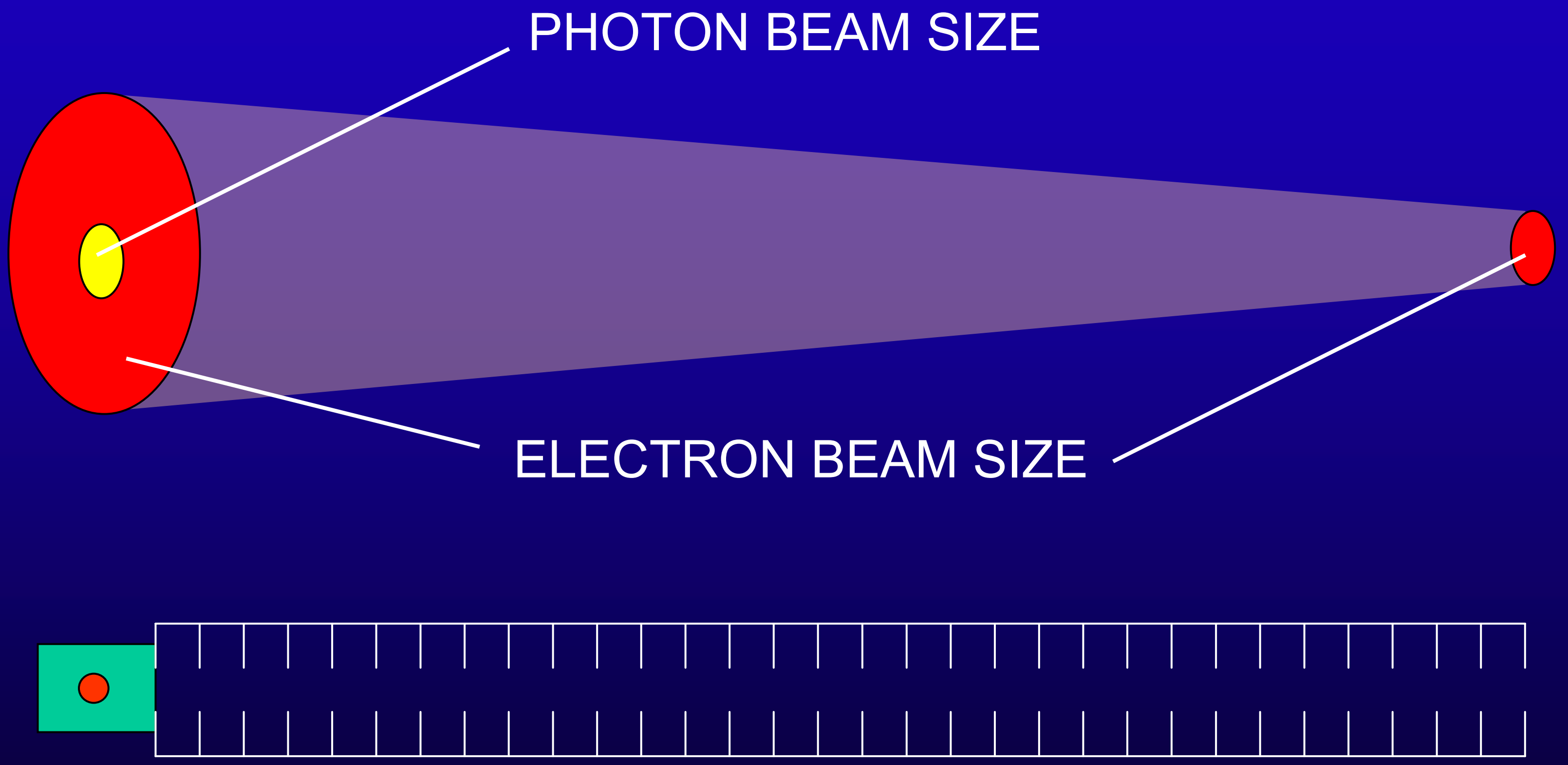
γ 2γ 4γ

$$\varepsilon \propto \frac{1}{\gamma}$$

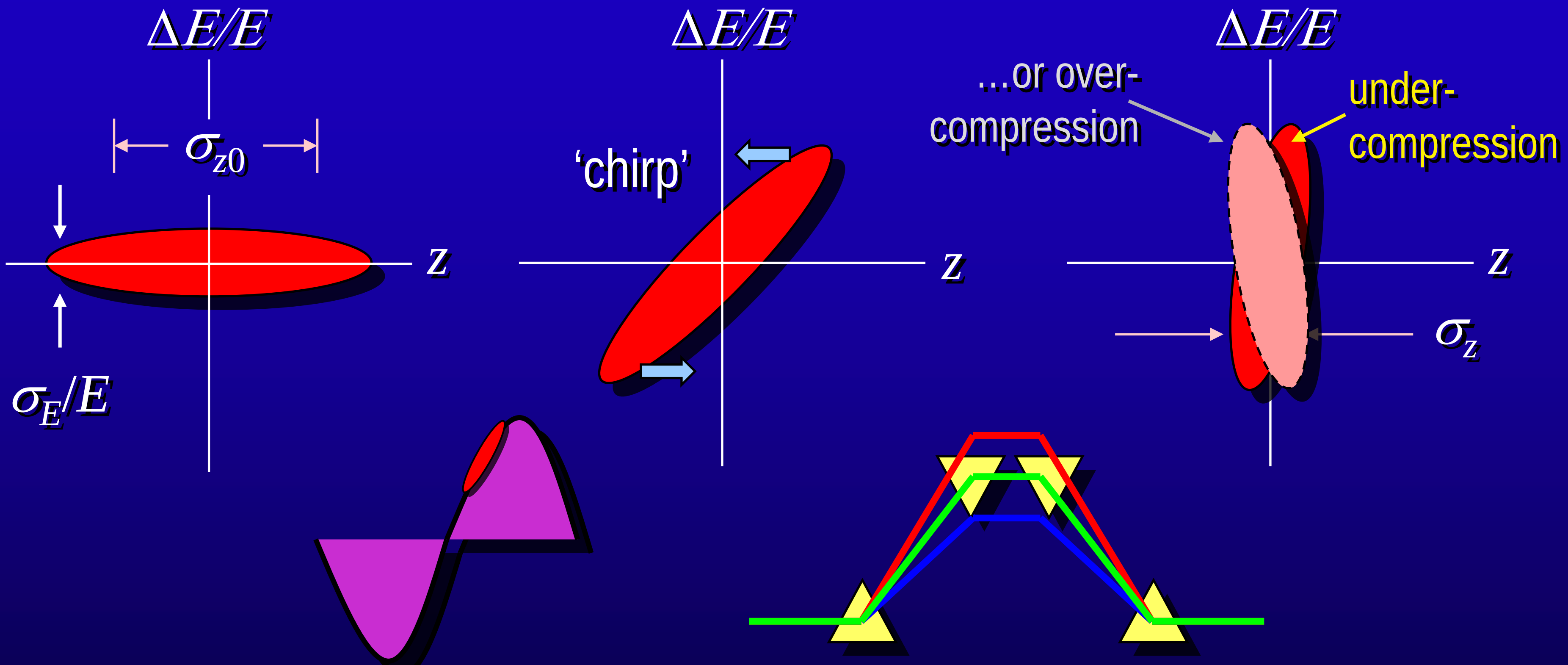
or

$$\gamma\varepsilon = \text{const.}$$

THE ELECTRON BEAM SHOULD BE ~ 1 Å
AS SMALL AS THE X-RAY WAVELENGTH!



Magnetic Bunch Compression



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

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

RF Accelerating Voltage

Path Length-Energy Dependent Beamline

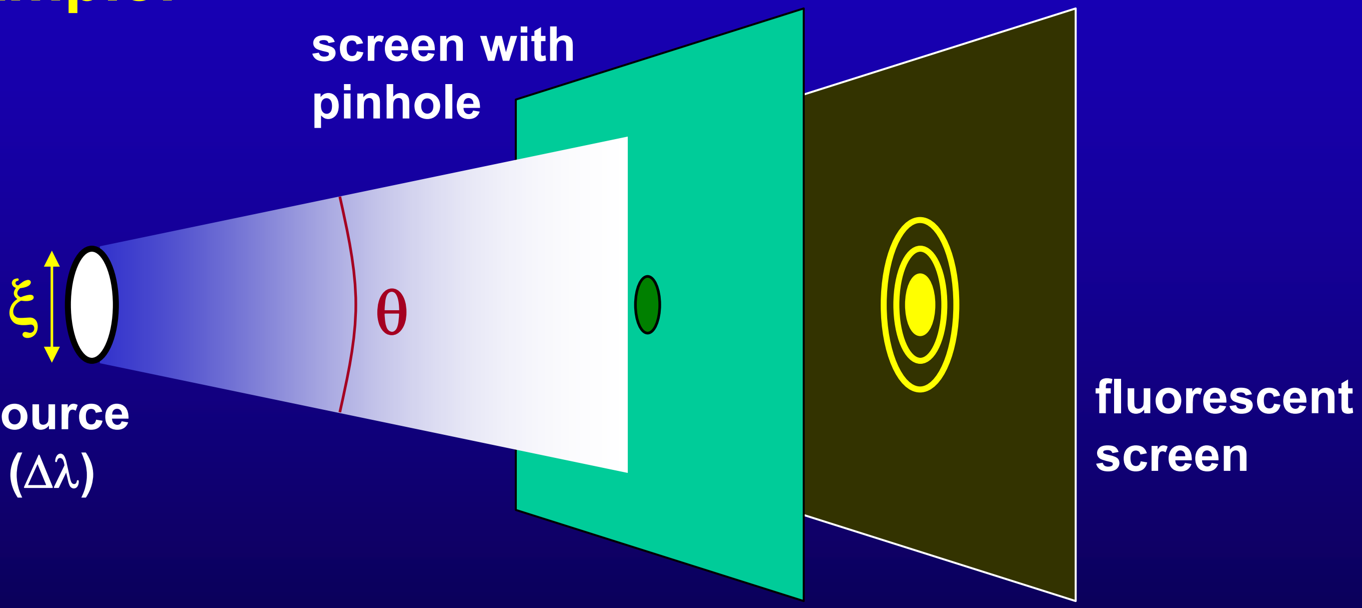
P. Emma

Coherence

- High brightness gives coherence
- Wave optics methods for X-rays
- Holography

Coherence: “the property that enables a wave to produce **visible** diffraction and interference effects”

Example:

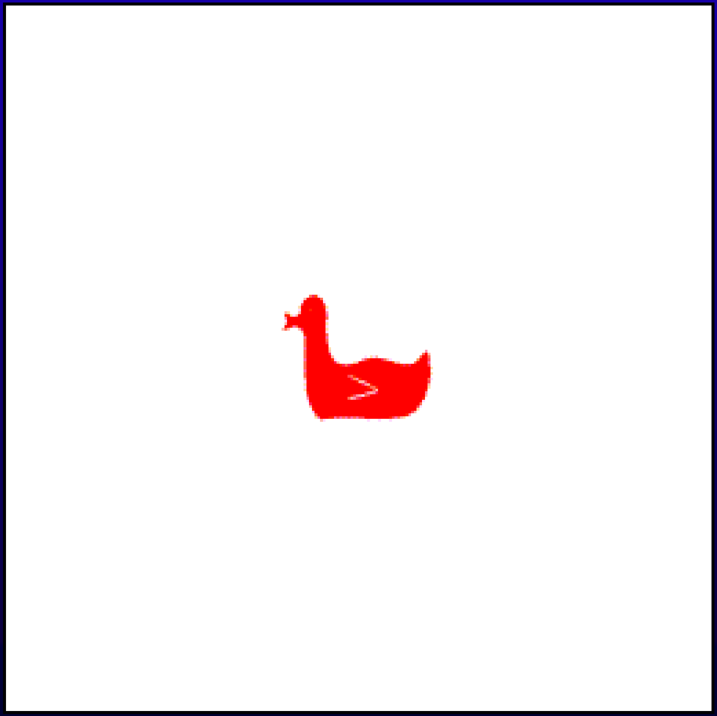


The diffraction pattern may or may not be visible on the fluorescent screen depending on the source size ξ, on its angular divergence θ and on its wavelength bandwidth Δλ

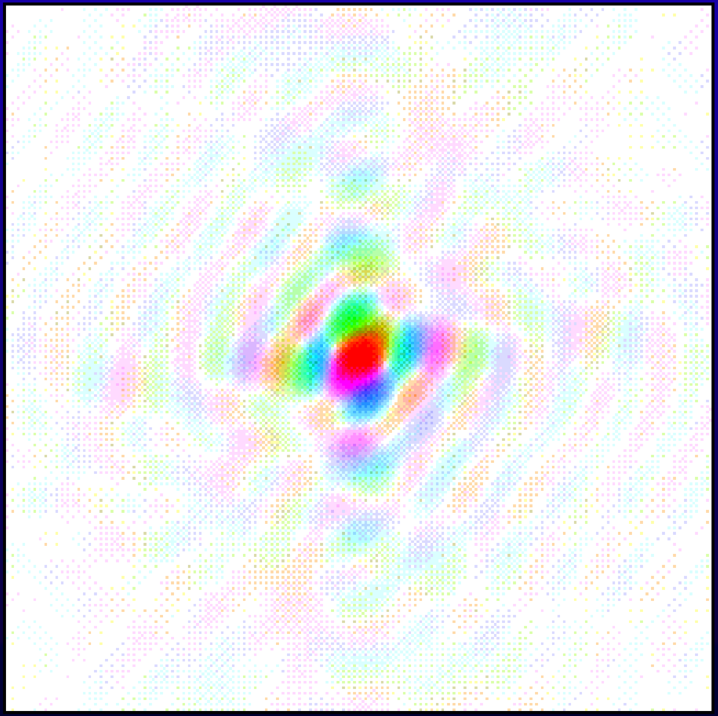
Relevance of Coherence

Diffraction Pattern of a Duck

A (two-dimensional) duck



…creates this diffraction pattern (the colors encode the phase)

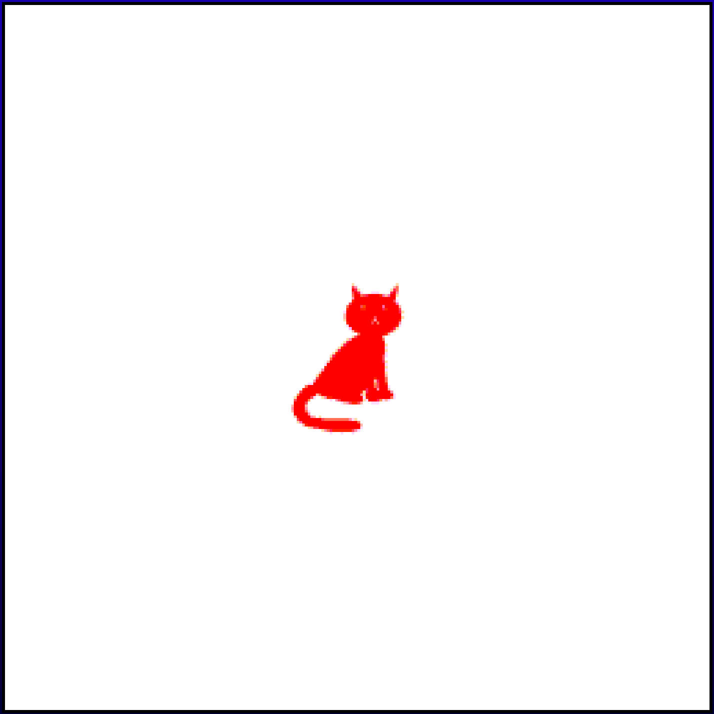


Images by Kevin Cowtan, Structural Biology Laboratory, University of York

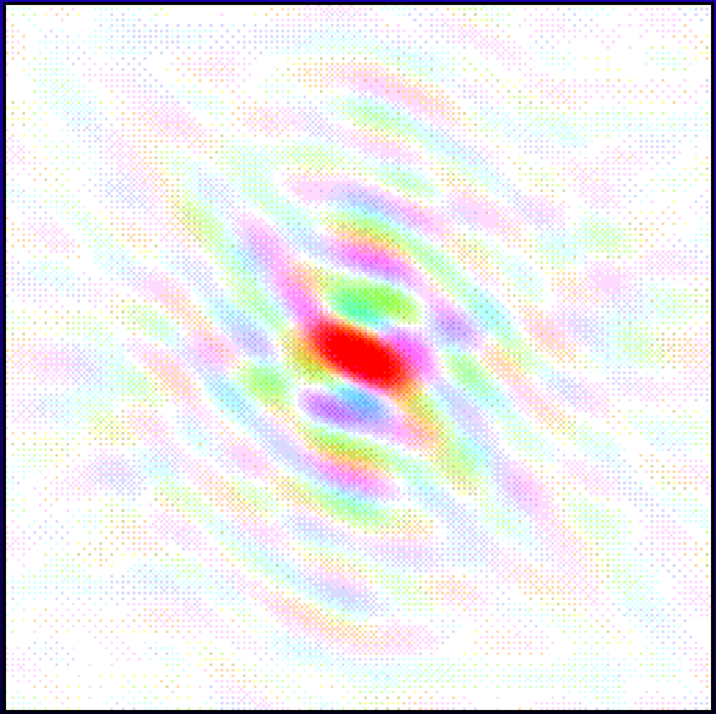
Relevance of Coherence

Diffraction Pattern of a Cat

A Cat



…and its Diffraction Pattern

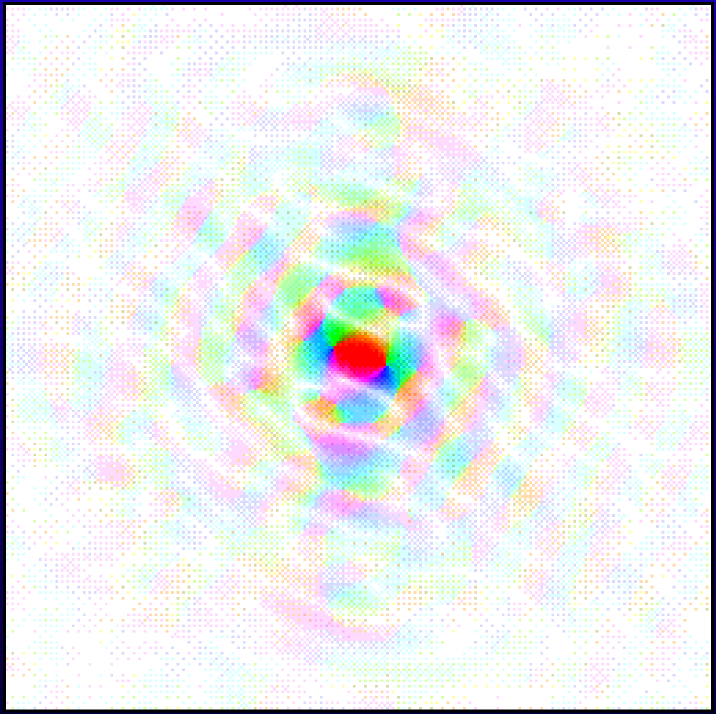


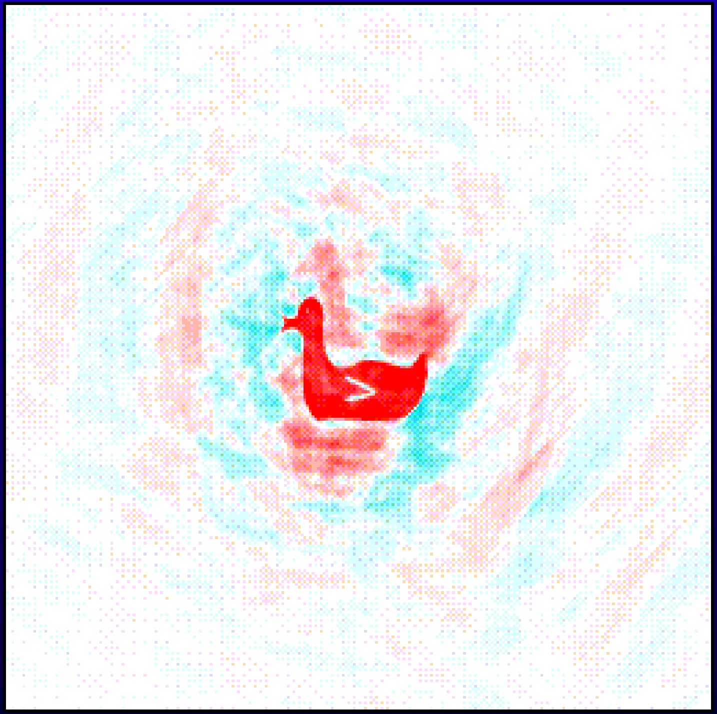
Images by Kevin Cowtan, Structural Biology Laboratory, University of York

Relevance of Coherence

Reconstruction

Combine the amplitude of the diffraction pattern of the cat and the phase of the diffraction pattern of the duck





The result: a duck!

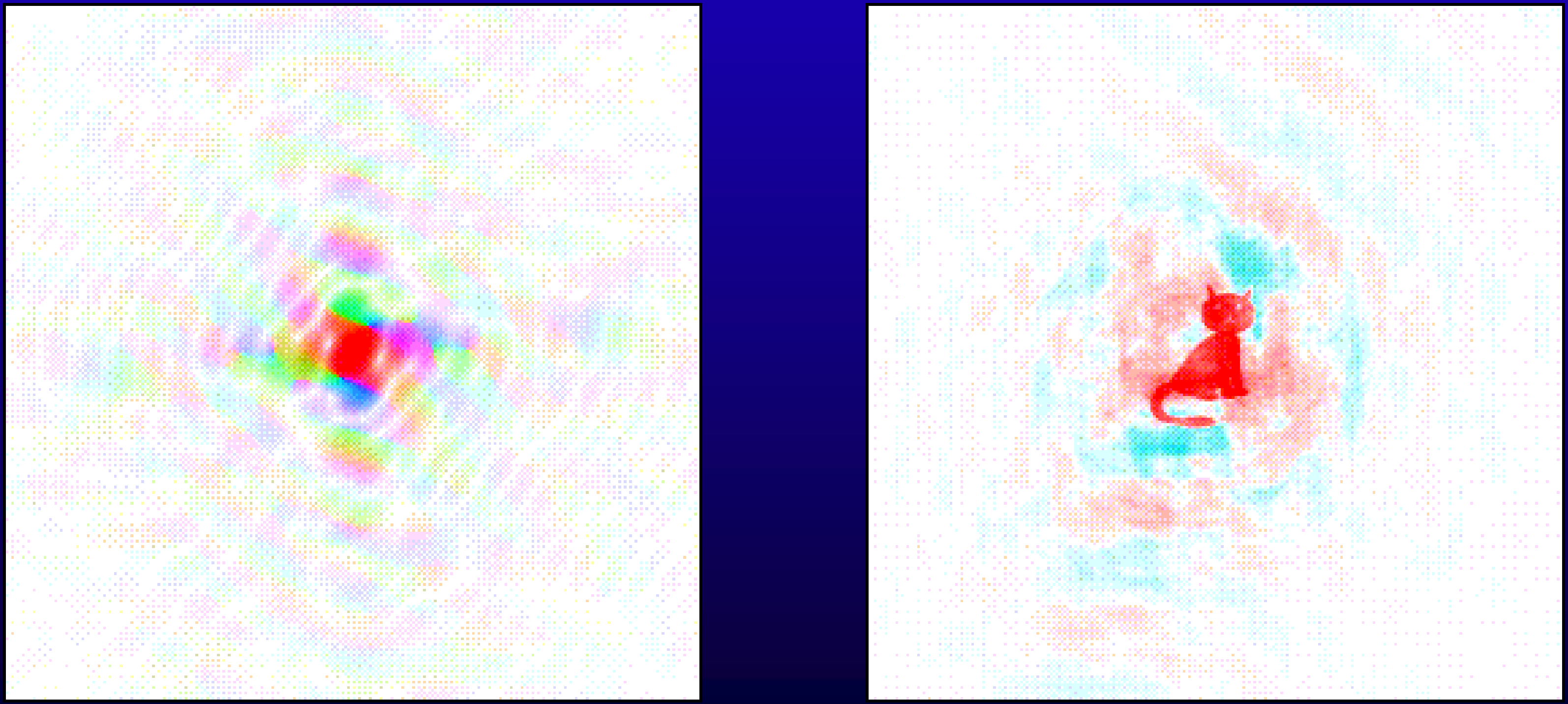
Images by Kevin Cowtan, Structural Biology Laboratory, University of York

Relevance of Coherence

Reconstruction

Of course, one can also do the opposite trick:

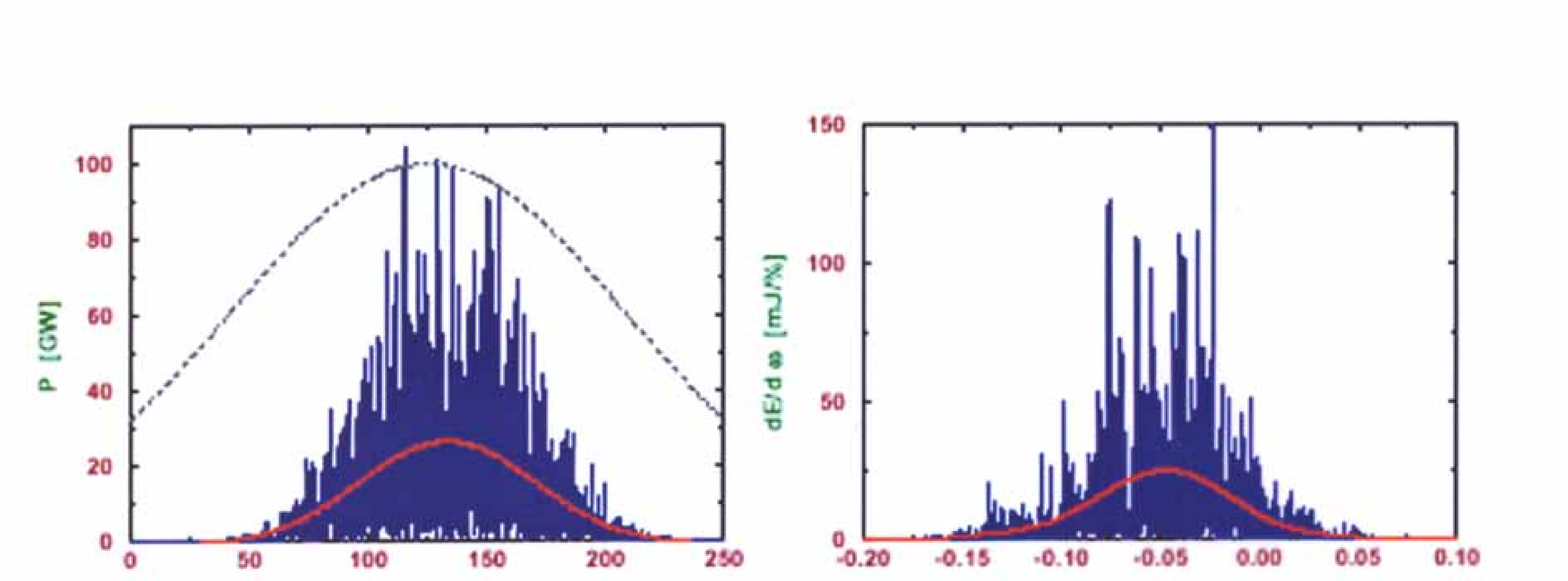
combine the amplitude of the duck and the phase of the cat



This is the famous **Phase Problem**

Images by Kevin Cowtan, Structural Biology Laboratory, University of York

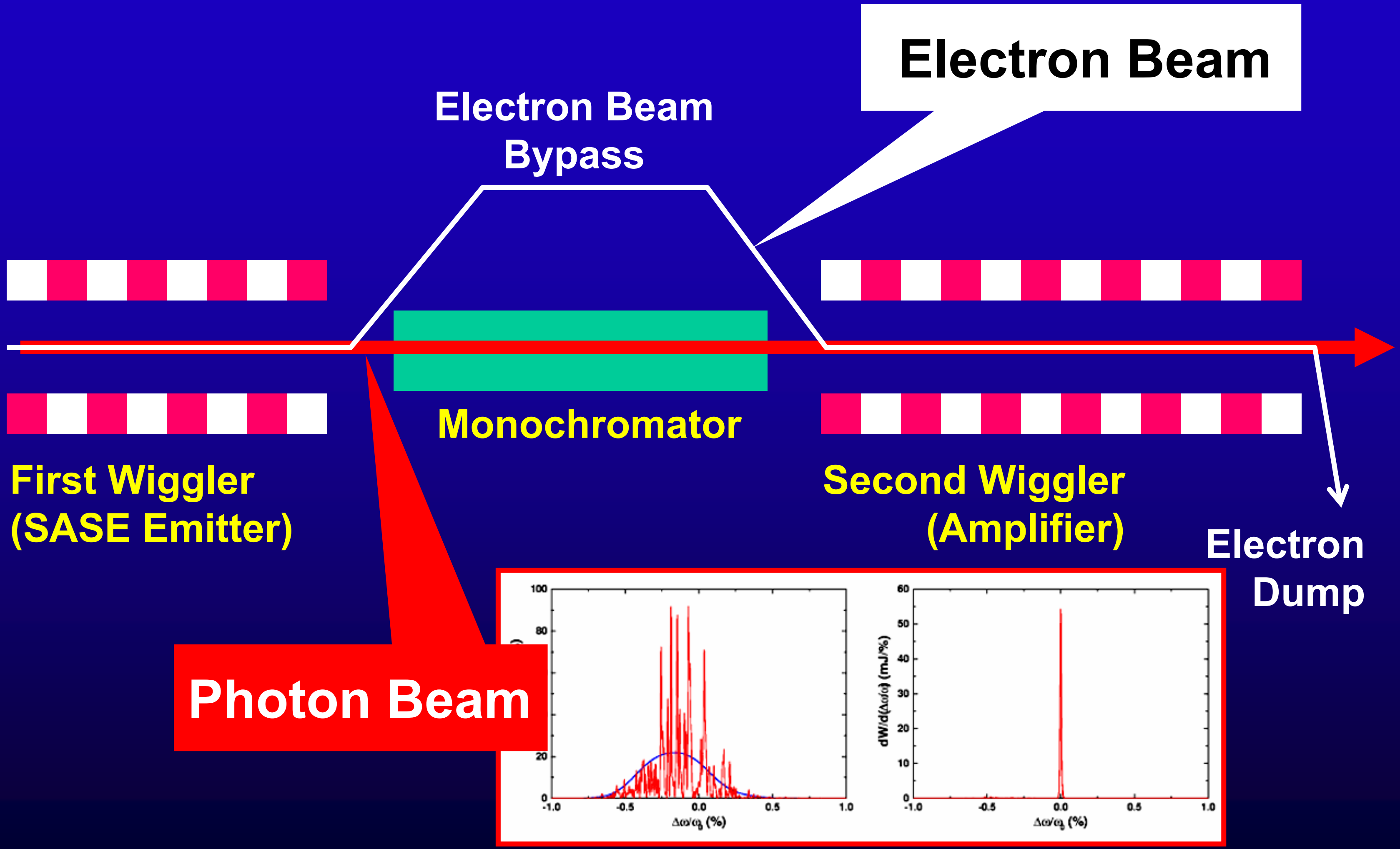
SASE Radiation is Powerful, But Noisy



τ (fs)

Δω/ω (%)

Seeded-Amplifier X-FELs



Electron Beam

Electron Beam
Bypass

Monochromator

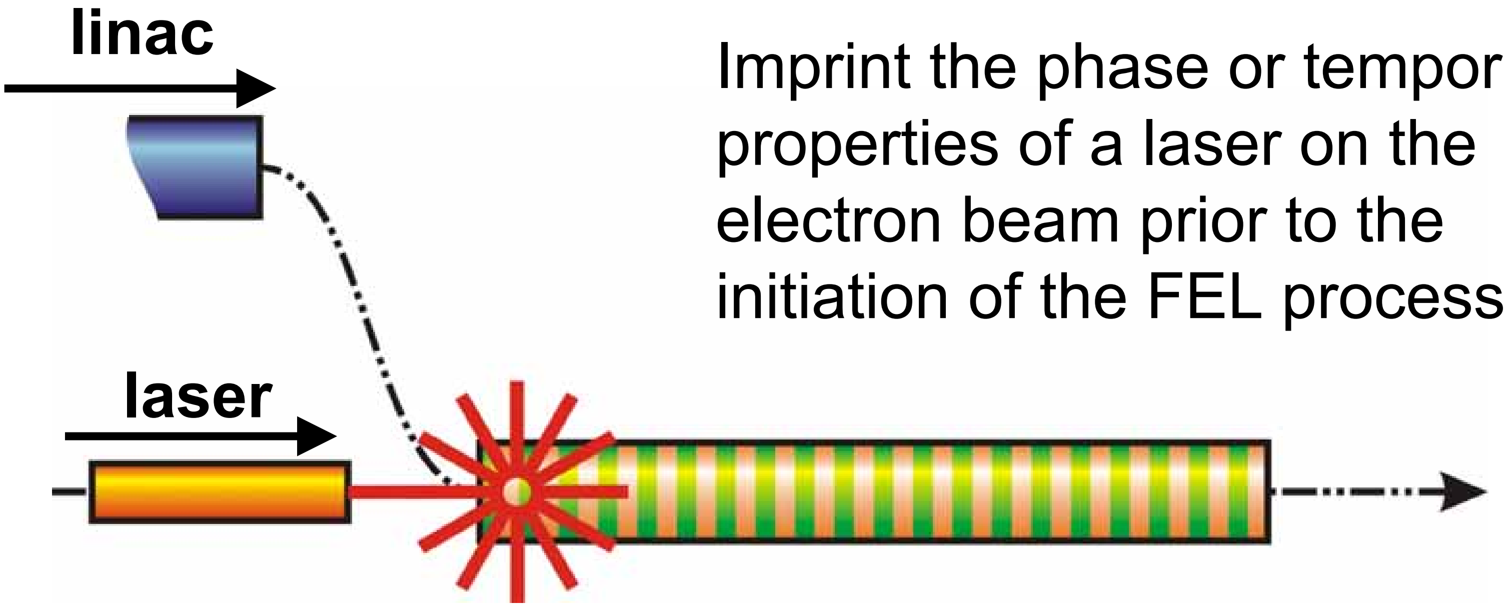
First Wiggler
(SASE Emitter)

Second Wiggler
(Amplifier)

Electron
Dump

Photon Beam

Seeded FEL



Imprint the phase or temporal properties of a laser on the electron beam prior to the initiation of the FEL process

laser →
- classical laser system (e.g., T:Sa)
- laser + harmonics generation
- other free-electron laser

User Facilities

- **X-FELs**
  Emphasis on resolving structure on the atomic scale with femto-second temporal resolution.

- VUV and soft X-ray FELs
  Emphasis on resolving material properties (e.g., chemical reactions) with femto-second resolution.

  Better control and more flexible timing structure.

X-FEL facilities

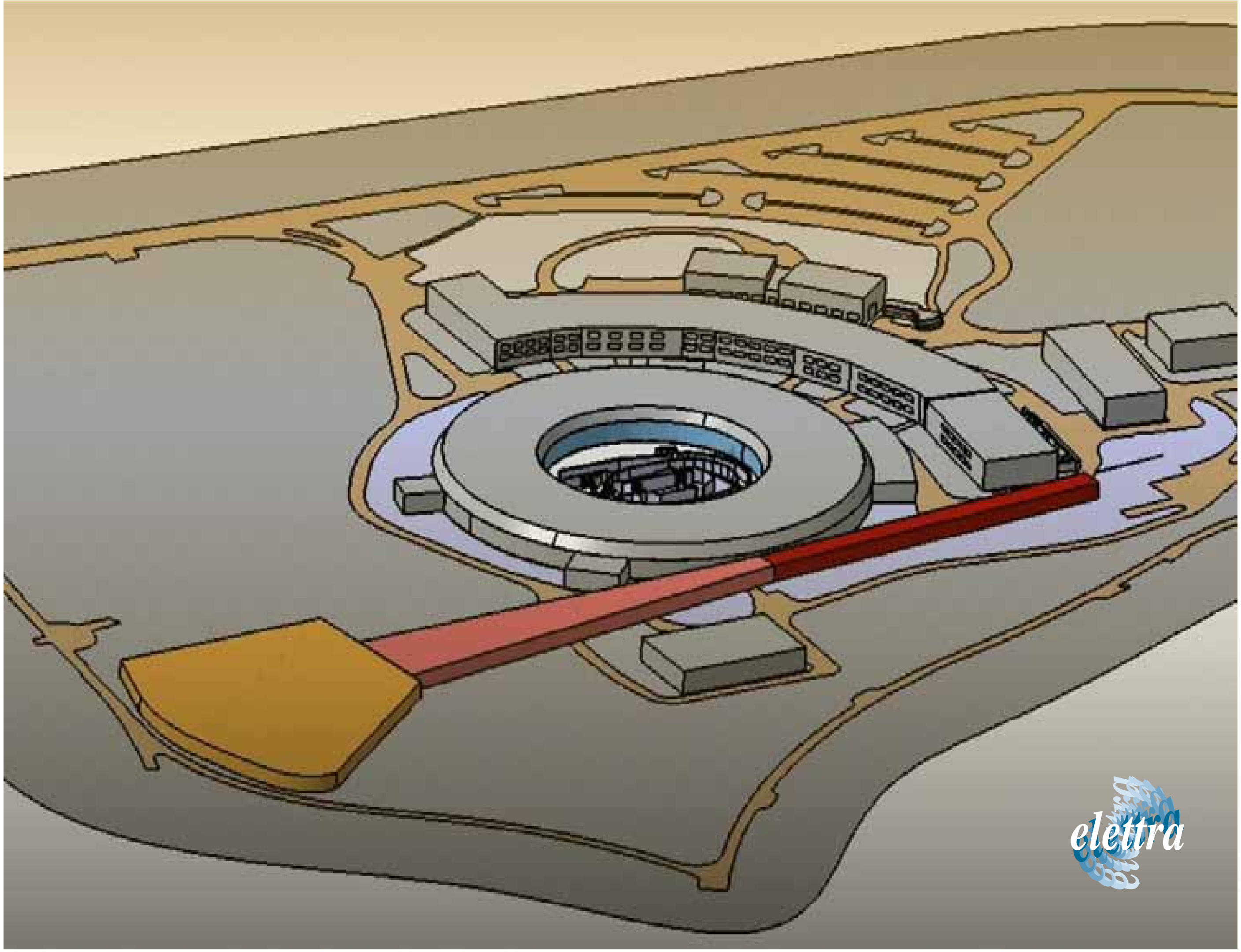
Europe
X-FEL – DESY 2012

Japan
SCSS – SPring8 **2010**

USA
LCLS - SLAC **2009**

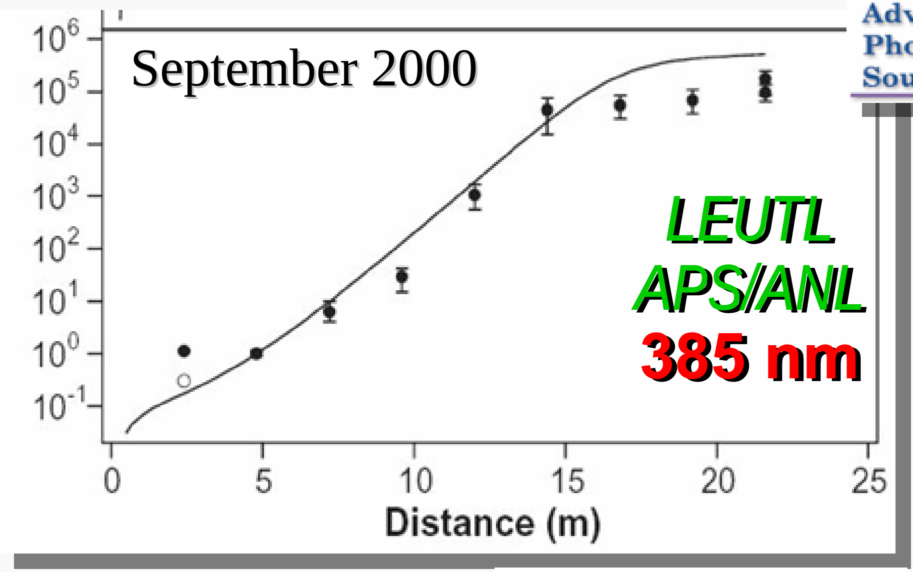
FERMI@ELETTRA (Trieste, Italy)

- User Facility
- λ ≥ 10 nm
- Seeding



SASE Saturation Results

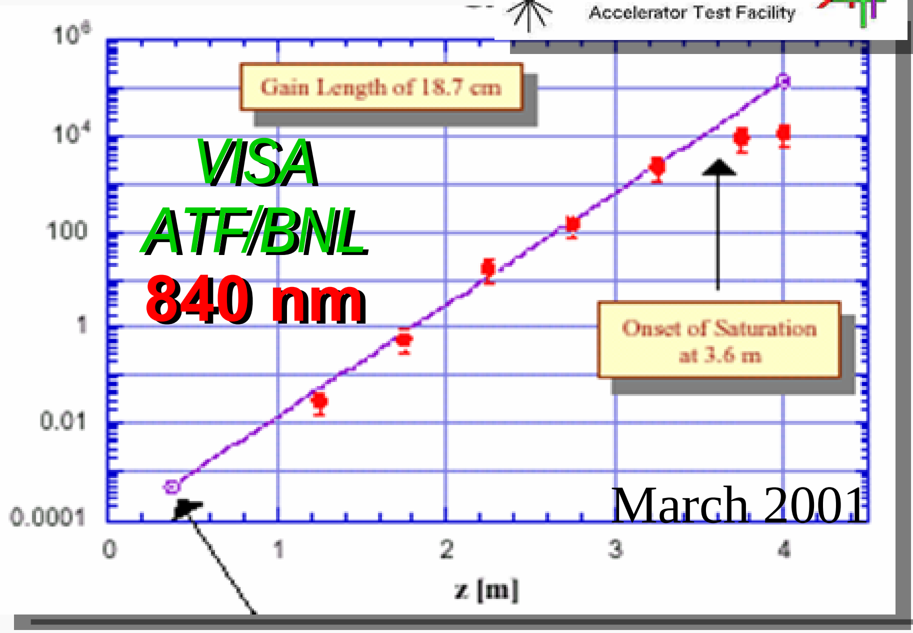
Advanced Photon Source



September 2000

LEUTL
APS/ANL
385 nm

Brookhaven National Laboratory
Accelerator Test Facility



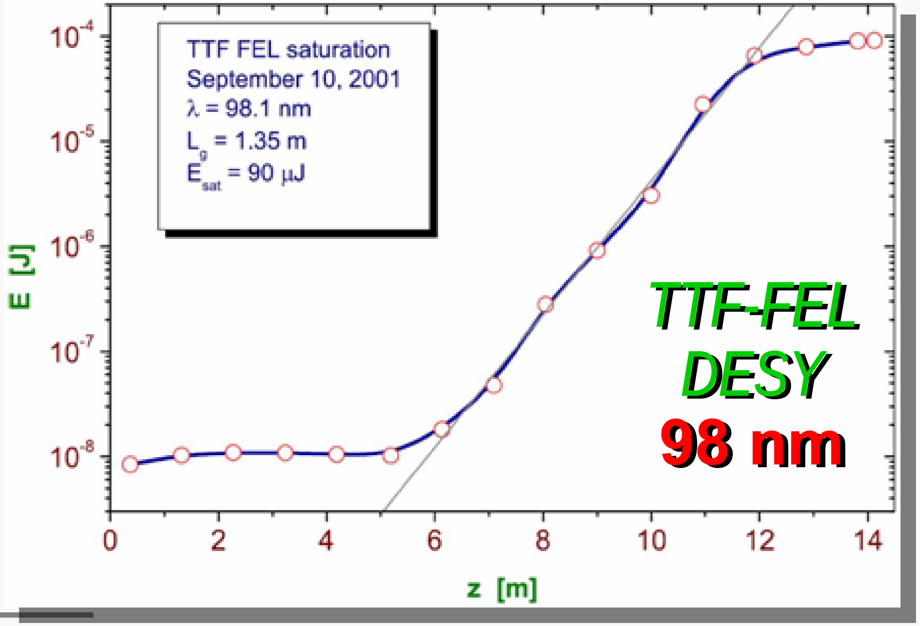
Gain Length of 18.7 cm

Onset of Saturation at 3.6 m

VISA
ATF/BNL
840 nm

March 2001

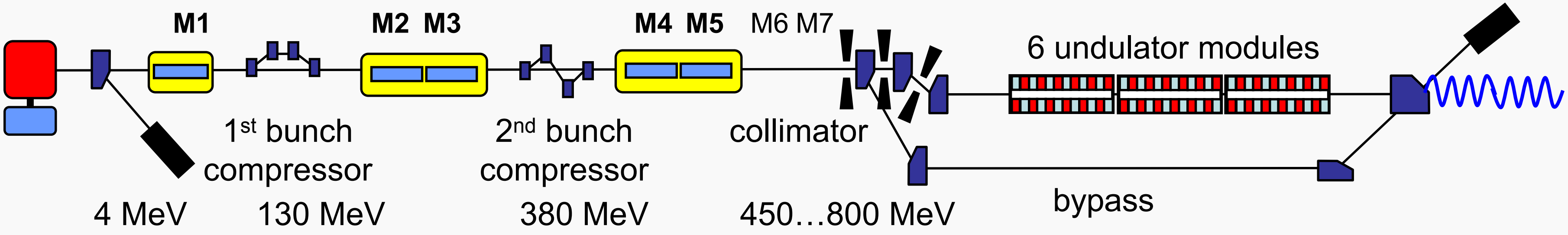
TESLA FEL



TTF FEL saturation
September 10, 2001
λ = 98.1 nm
L_g = 1.35 m
E_{sat} = 90 µJ

TTF-FEL
DESY
98 nm

FLASH: Free Electron LASer in Hamburg

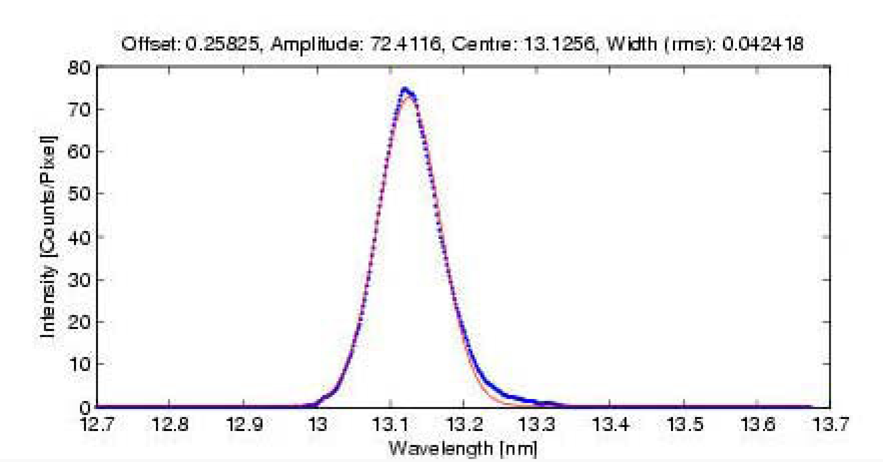


250 m

April 24, 2006: FLASH achieves SASE at 13 nm!

Electron beam energy 700 MeV

Average energy ~ 6 mJ per pulse, still in the exponential growth



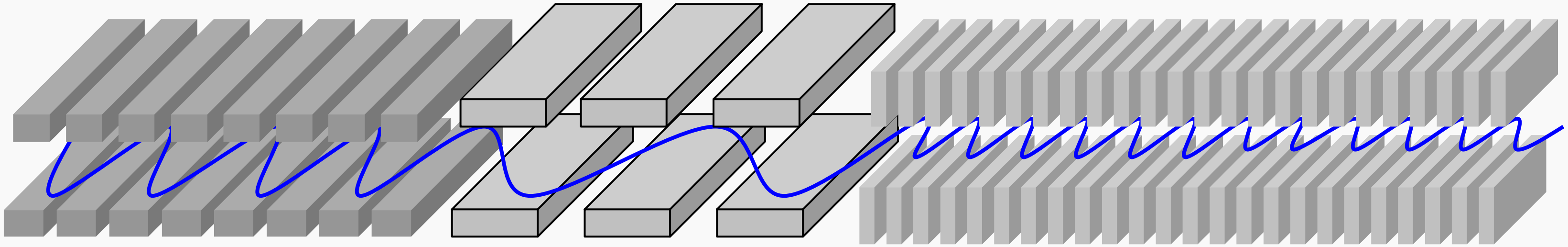
High Gain Harmonic Generation

Method to reach short wavelength FEL output from longer wavelength input seed laser.

Input seed at ω_0 overlaps electron beam in energy modulator undulator.

Energy modulation is converted to spatial bunching in chicane magnets.

Electron beam radiates coherently at ω_3 in long radiator undulator.



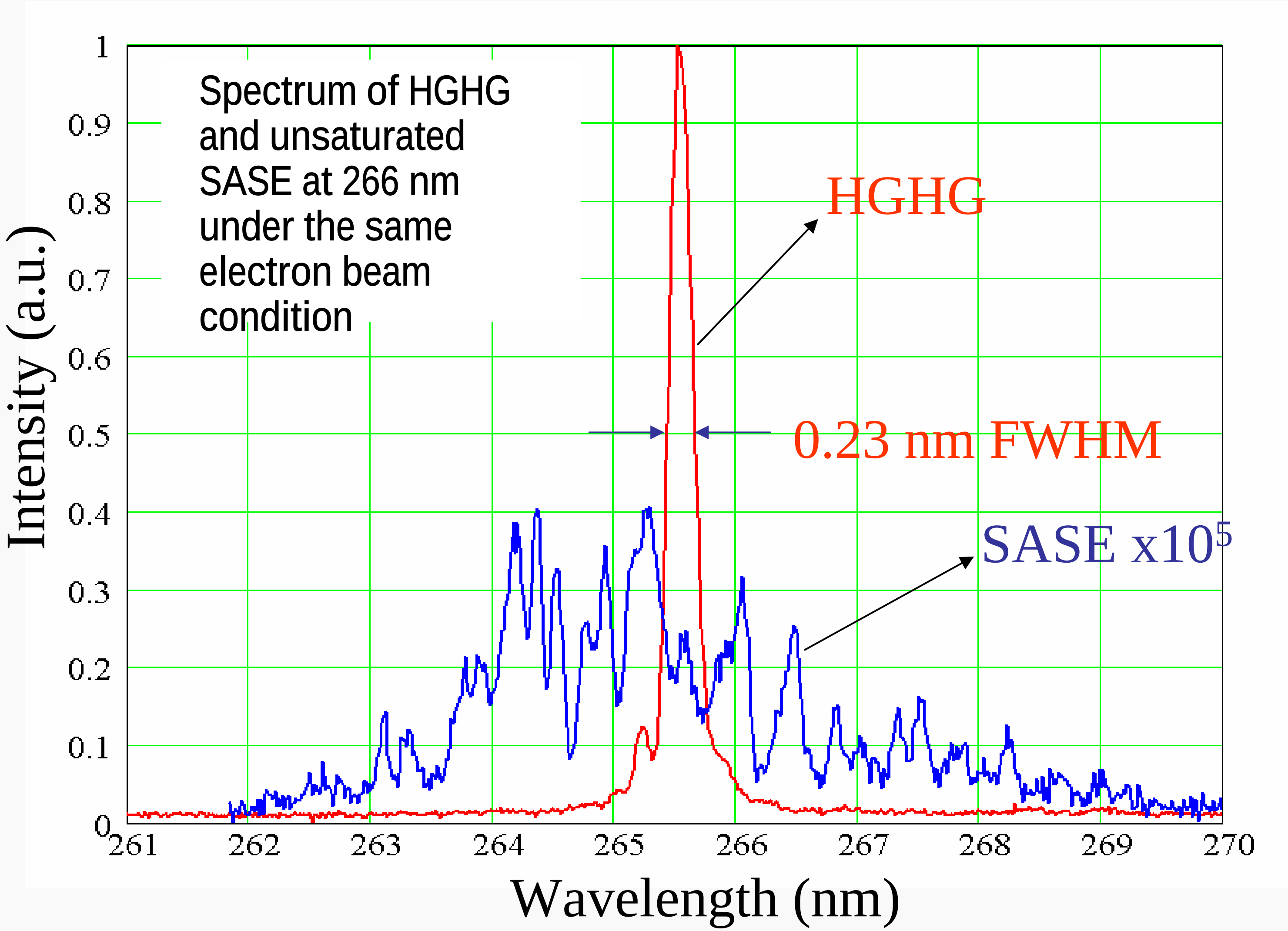
Modulator is tuned to ω_0.

Electron beam develops energy modulation at ω_0.

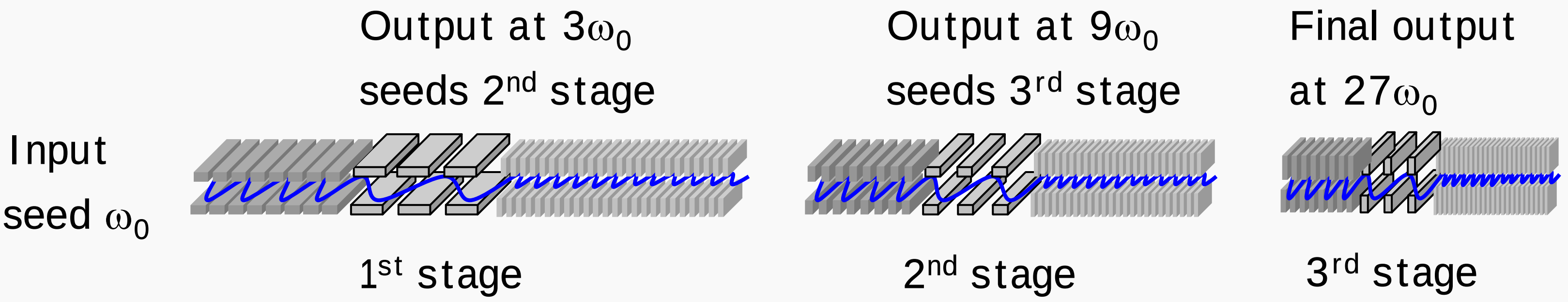
3rd harmonic bunching is optimized in chicane.

Radiator is tuned to ω_3.

Measured HGHG & SASE Spectra (BNL DUV-FEL)

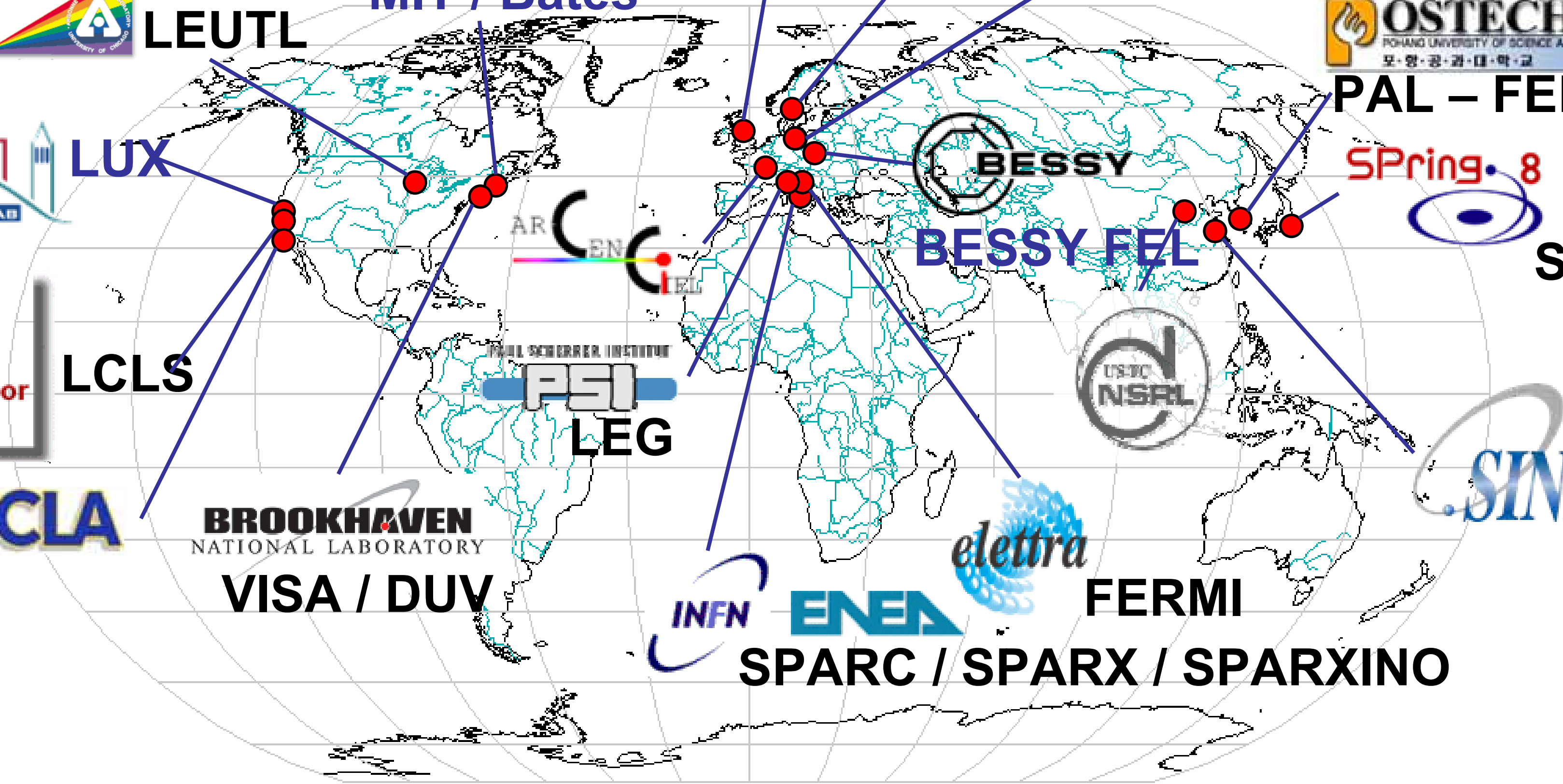


Cascaded HGHG



- Number of stages and harmonic of each to be optimized during study.
- Factor of 10 – 30 in wavelength is reasonable without additional acceleration between stages.
- Seed longer wavelength (100 – 10 nm) beamlines with ~200 nm harmonic from synchronized Ti:Sapp laser.
- Seed shorter wavelength (10 – 0.3 nm) beamlines with HHG pulses.

Single Pass FEL Activity



MAX-lab

CCLRC
4GLS

DESY
TTF / XFEL

Massachusetts Institute of Technology
Bates Linear Accelerator Center
MIT / Bates

Advanced Photon Source
LEUTL

POSTECH
POHANG UNIVERSITY OF SCIENCE AND TECHNOLOGY
포·항·공·과·대·학·교
PAL – FEL

BERKELEY LAB
LUX

BESSY

SPring-8
SCSS

ARC-EN-CIEL

BESSY FEL

Stanford Linear Accelerator Center
LCLS

PAUL SCHERRER INSTITUT
PSI
LEG

USTC NSRL

SINR

UCLA

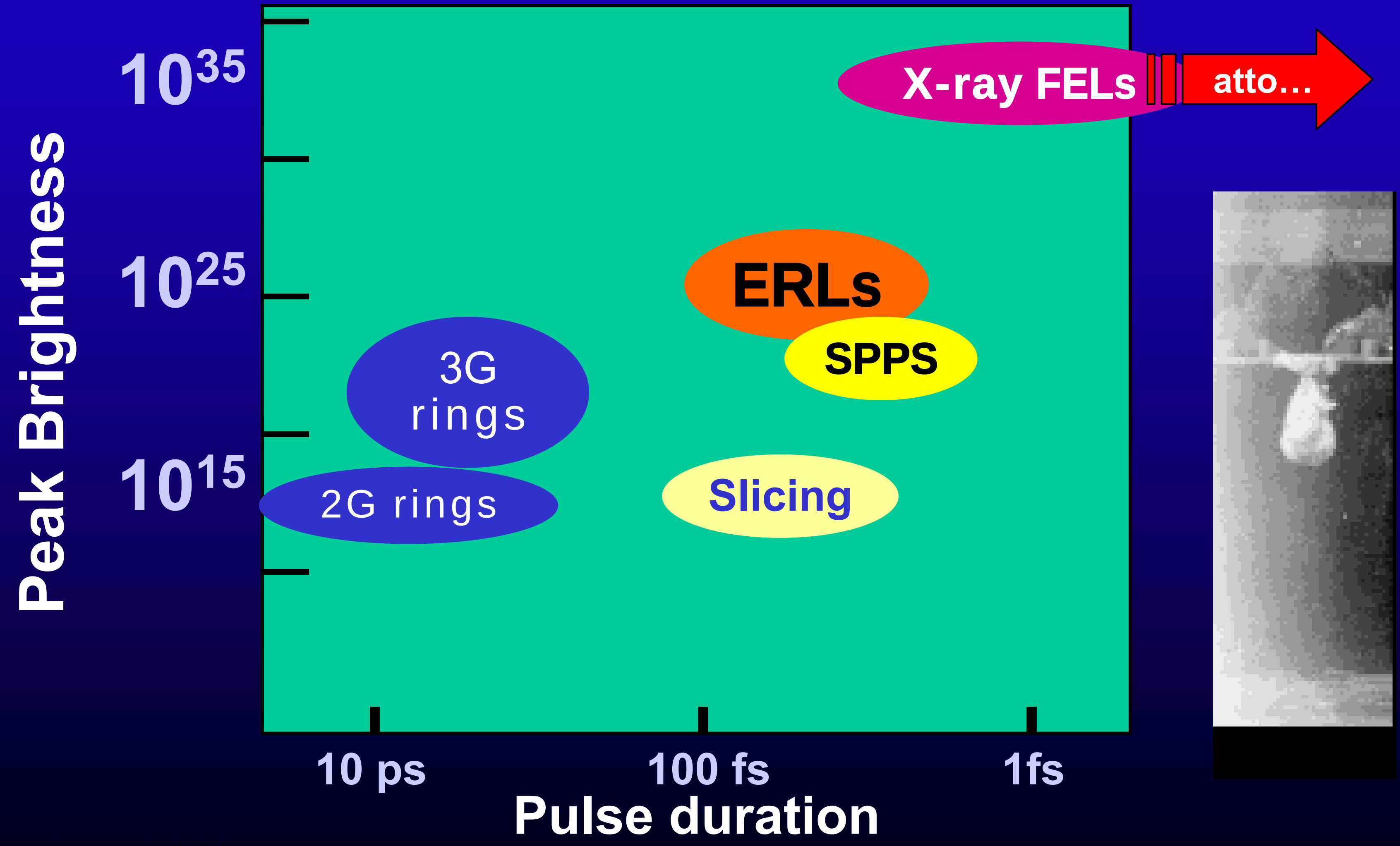
BROOKHAVEN NATIONAL LABORATORY
VISA / DUV

elettra
FERMI

INFN
ENEA
SPARC / SPARX / SPARXINO

SC technology / NC technology

ONLY FELs CAN PROVIDE THIS EXTRAORDINARY LIGHT



H.-D. Nuhn, H. Winick

END