***CAS** / INTRODUCTION TO ACCELERATOR PHYSICS*
Zakopane, Poland, 1-13 October 2006

FREE ELECTRON LASERS (FEL)

AN INTRODUCTION

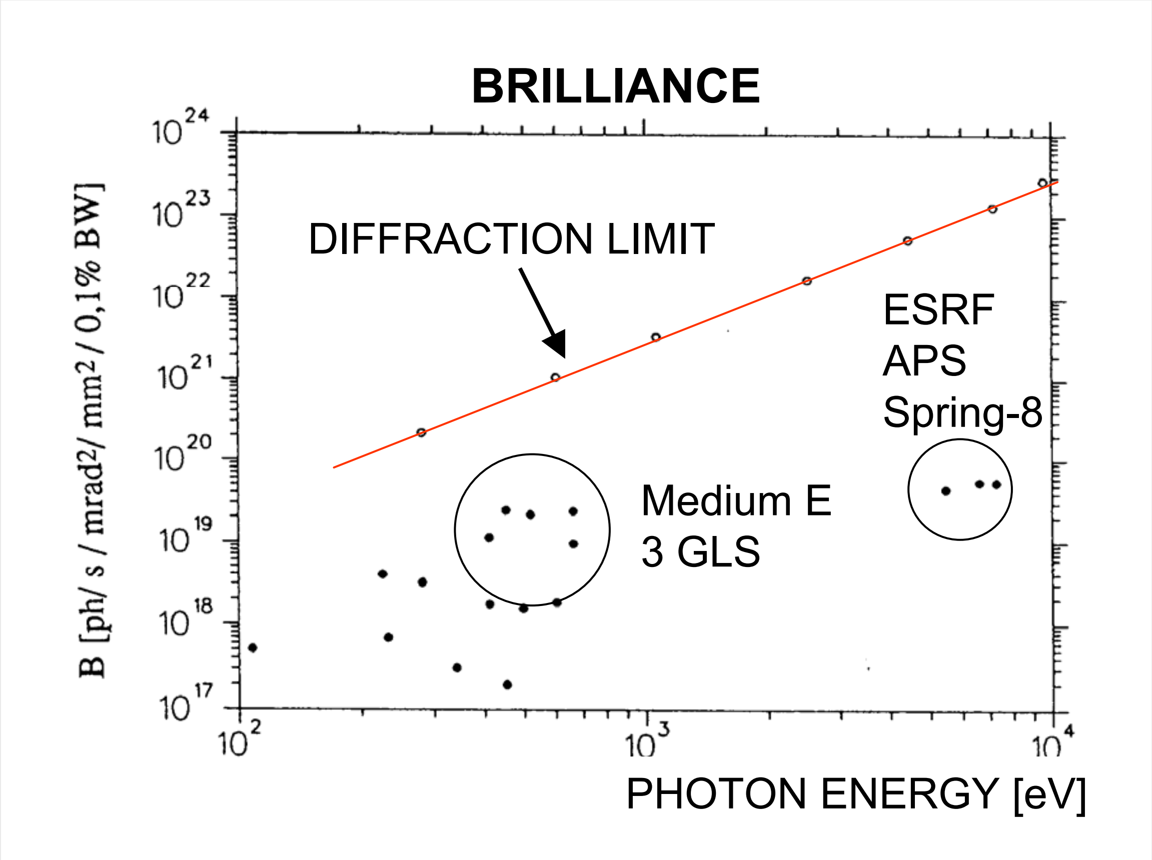
Albin F. Wrulich

- FEL = 4th Generation Light Source
- FEL Basics
  - Lasing conditions →
  - Electron beam characteristics →
  - Accelerator and experimental systems
- FEL – Concepts
- FEL – Extending the scietific endeavor
- FEL Projects in the world

LIMITS OF 3rd GENERATION LIGHT SOURCES

Performance Limits of 3rd Generation Light Sources:

Storage ring based light sources are for short wavelengths (high photon energies) far away from the theoretical limits →

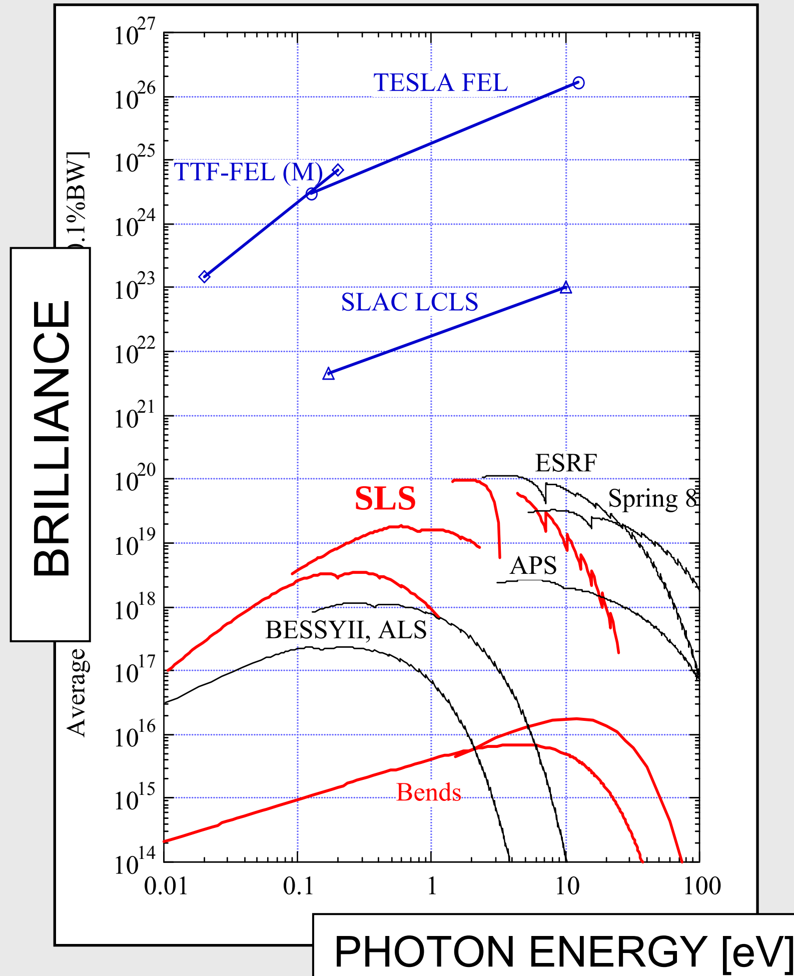


A new Concept is needed to overcome this limit

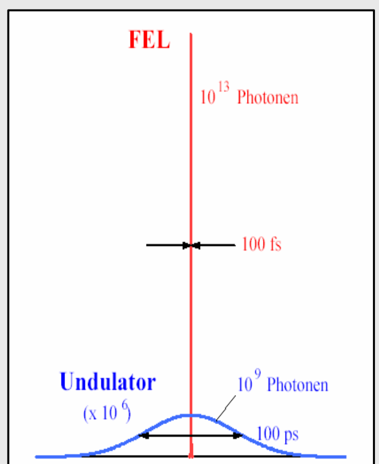
↓

FREE ELECTRON LASERS

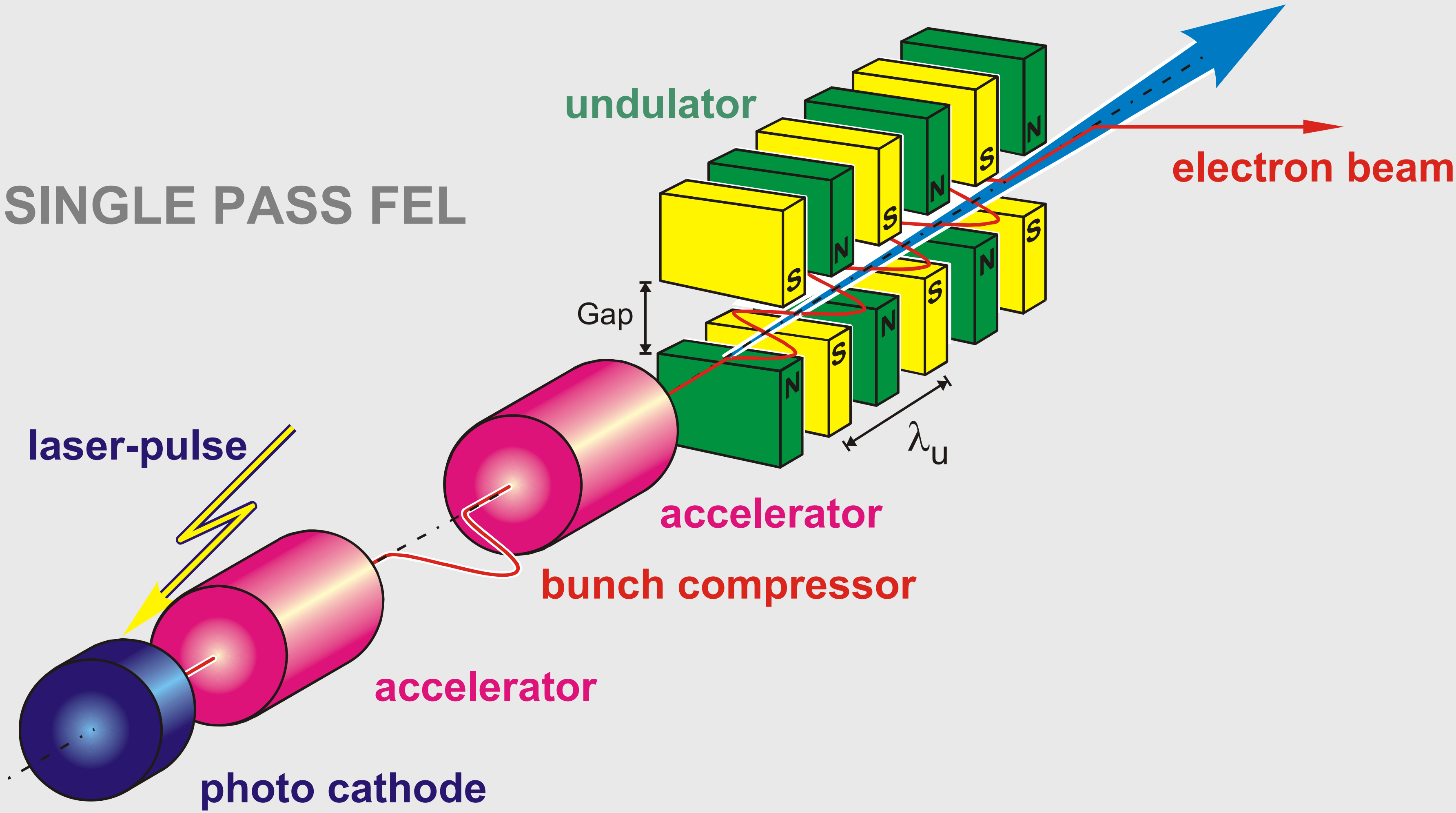
- HIGH PEAK BRILLIANCE (10^{30}-10^{33})
- HIGH AVERAGE BRILLIANCE (10^{22} - 10^{25})
- SHORT PULSES (1 ps – 50 fs)
- SMALL BANDWIDTH



BANDWIDTH →

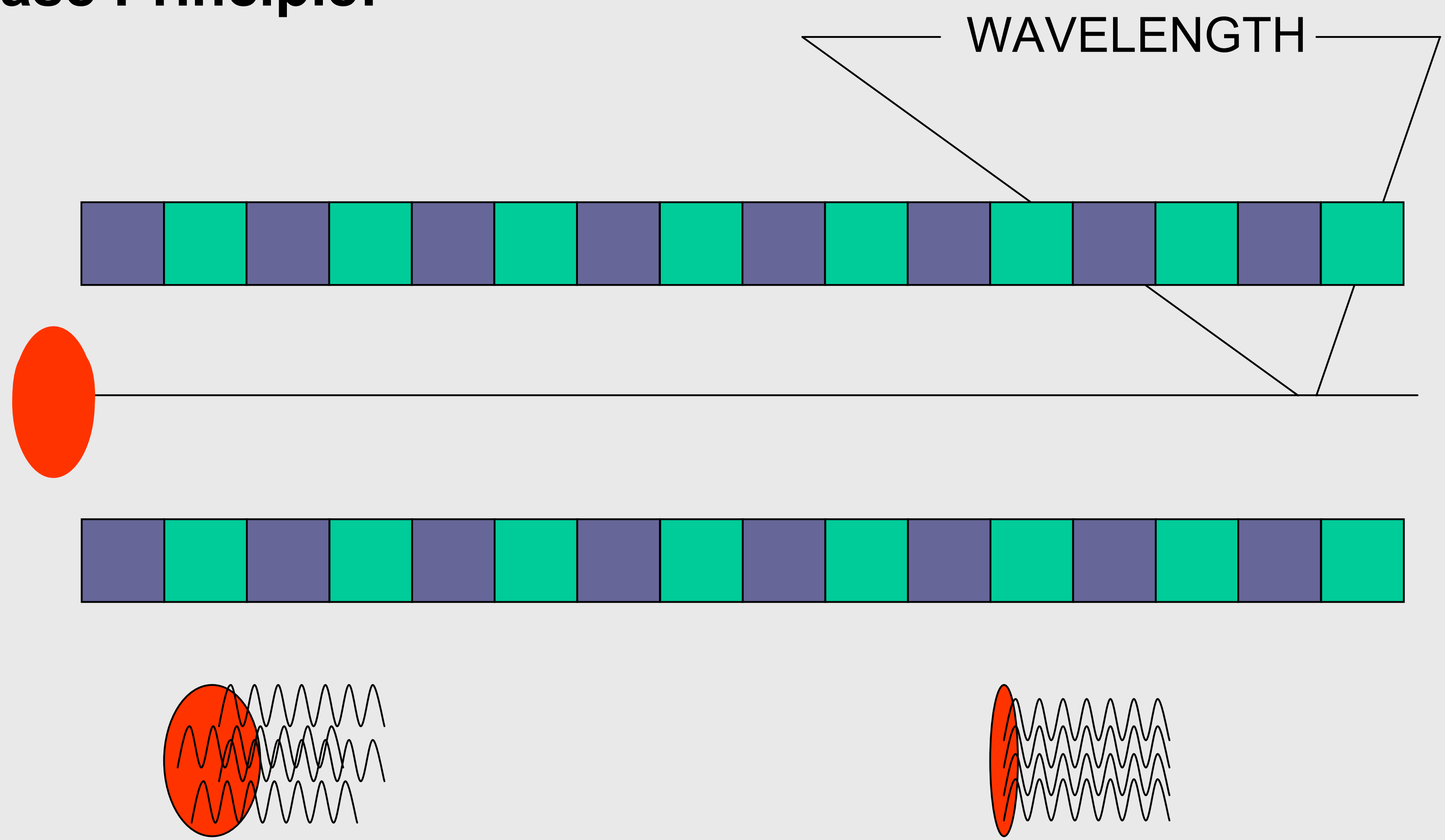


Free Electron Laser



FEL BASICS

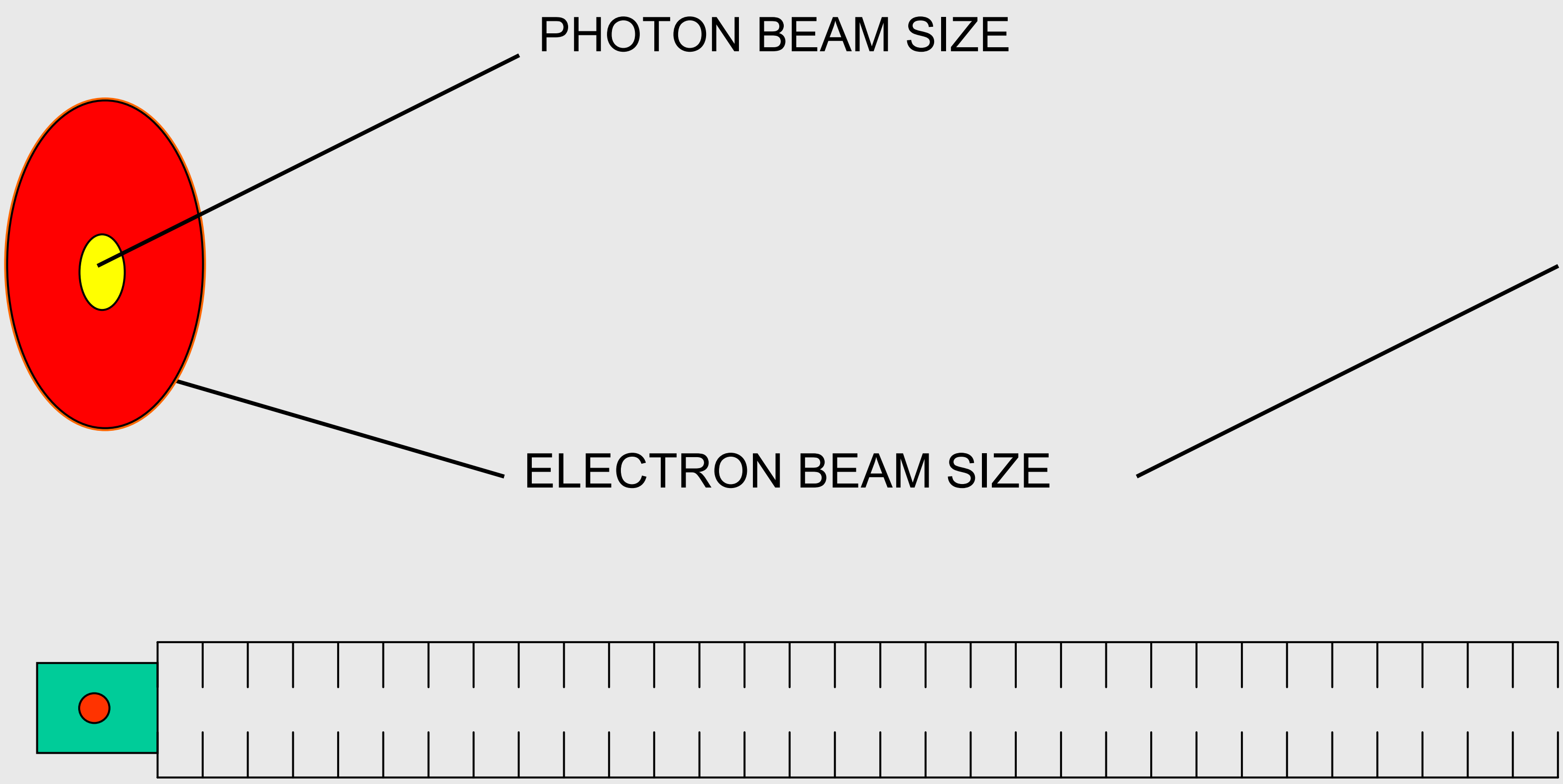
Sase Principle:



INCOHERENT EMISSION

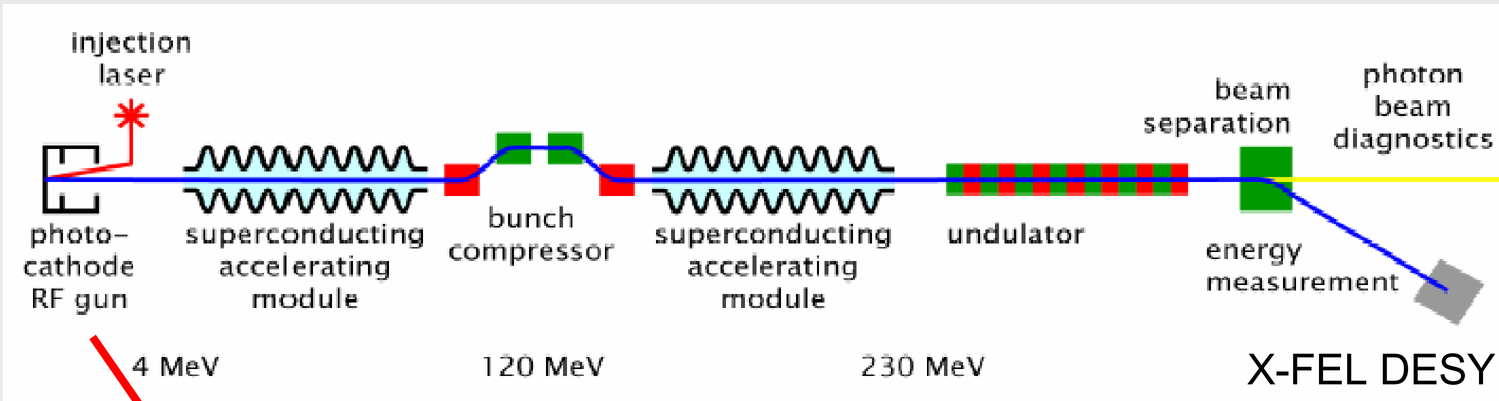
COHERENT EMISSION

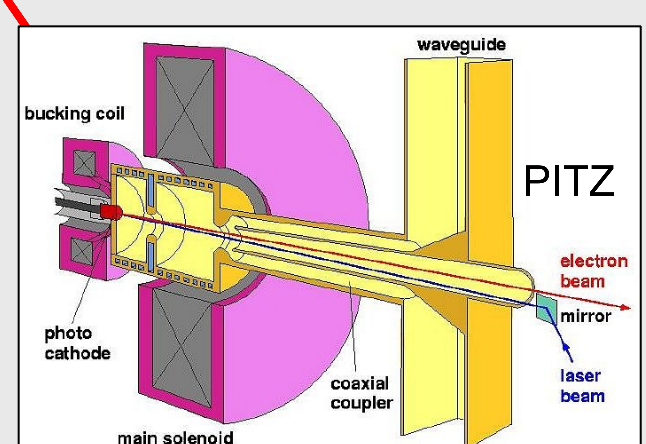
Requires a small electron beam !



FEL MAIN COMPONENTS

FEL Main Components (1)

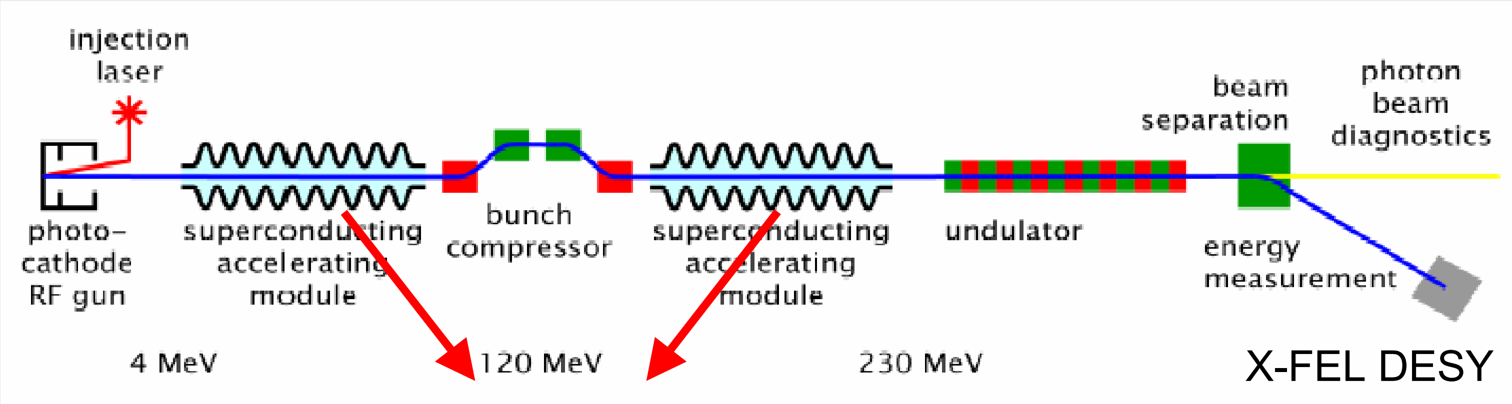




ELECTRON GUN

→crucial element of a
Free Electron Laser !

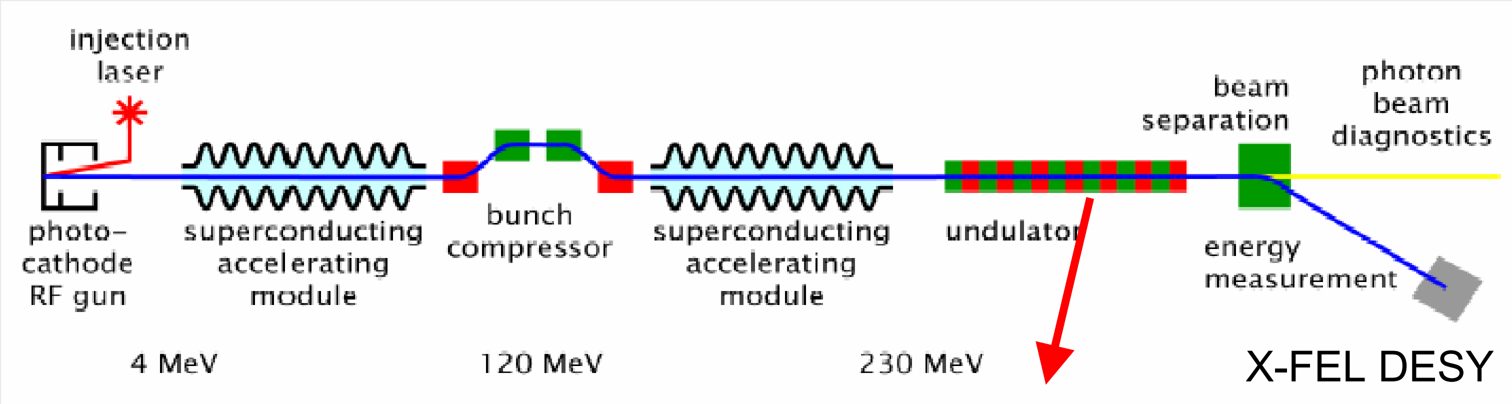
FEL Main Components (2)



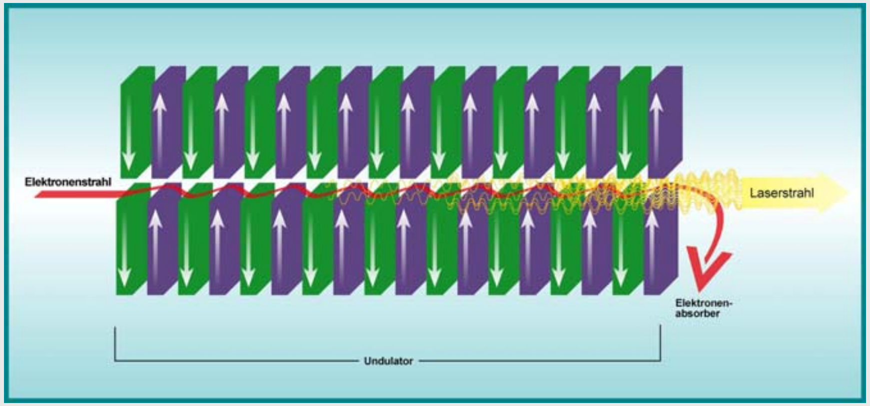
LINEAR ACCELERATOR

→acceleration
to reduce beam size by adiabatic damping

FEL Main Components (3)



UNDUALTOR
→micro-bunching
→coherent emission

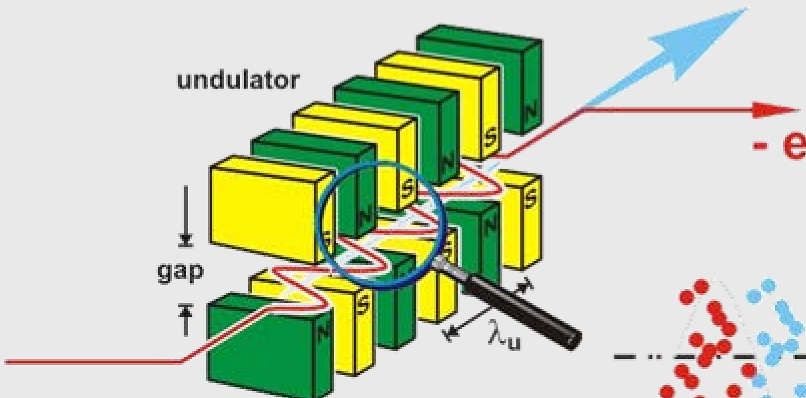


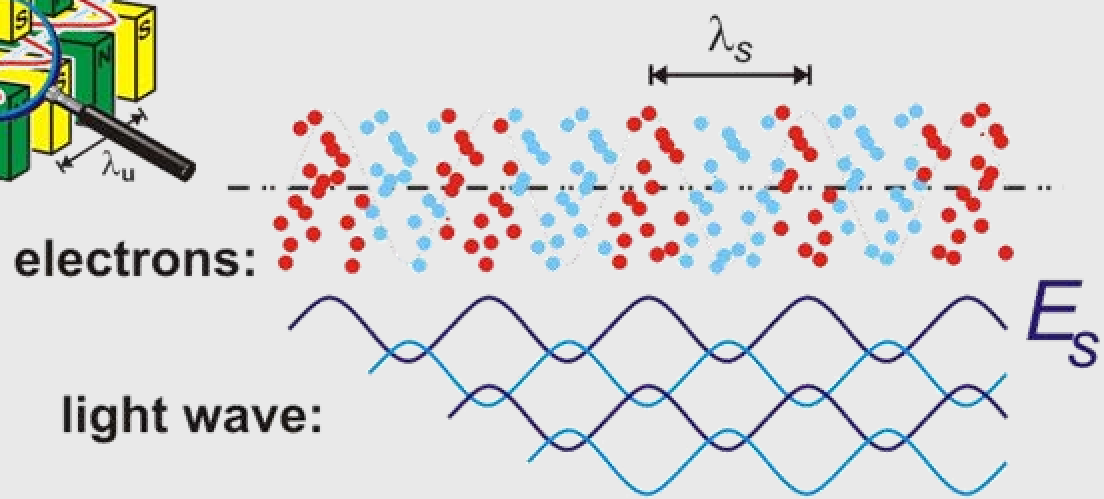
LASING PROCESS

Synchrotron Radiation

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

$$K \approx 0.93\ \lambda_u\ [\mathrm{cm}]\ B_u\ [\mathrm{T}]$$





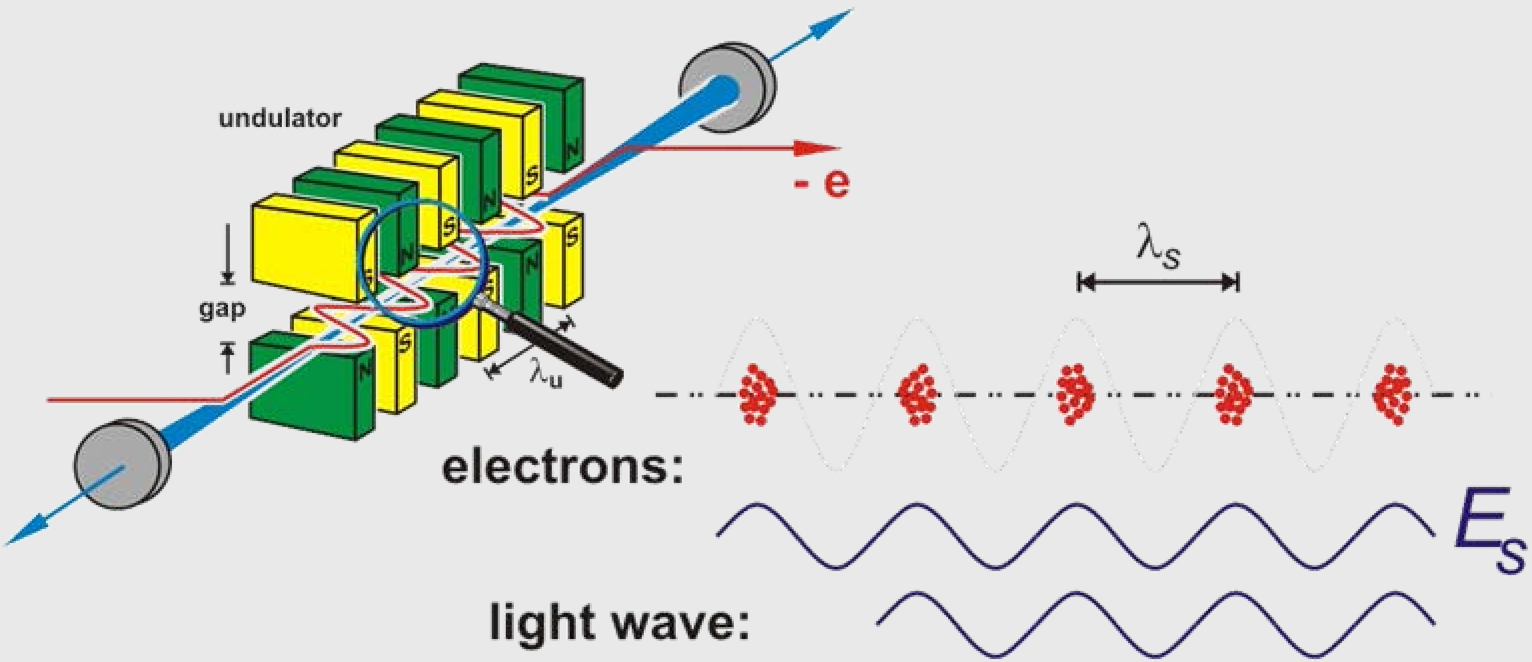
Radiated Power:

$P \propto n_e$ (number of electrons)

destructive interference

⟶ **shotnoise radiation**

FEL interaction



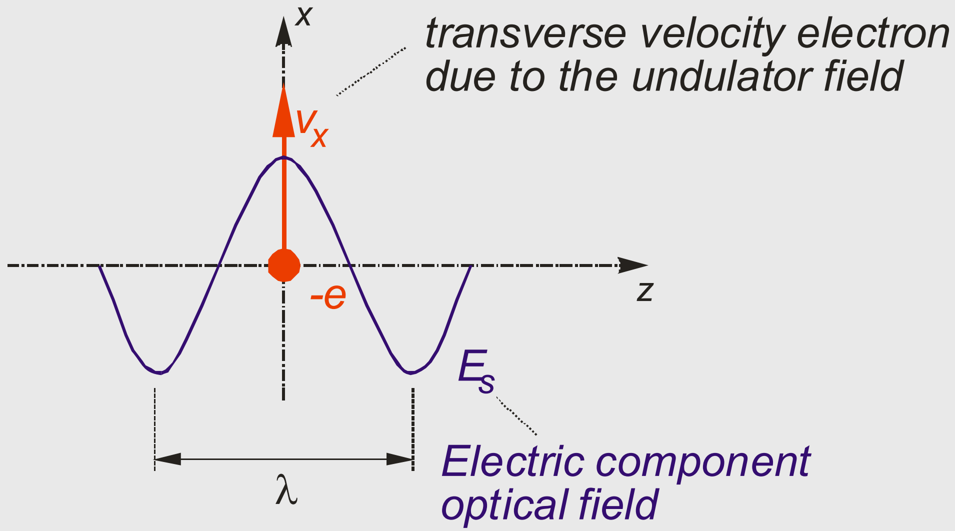
Radiated Power :

$$P \propto n_e^2 \begin{pmatrix} \text{number of electrons} \\ n_e \sim 10^6 - 10^9 \end{pmatrix}$$

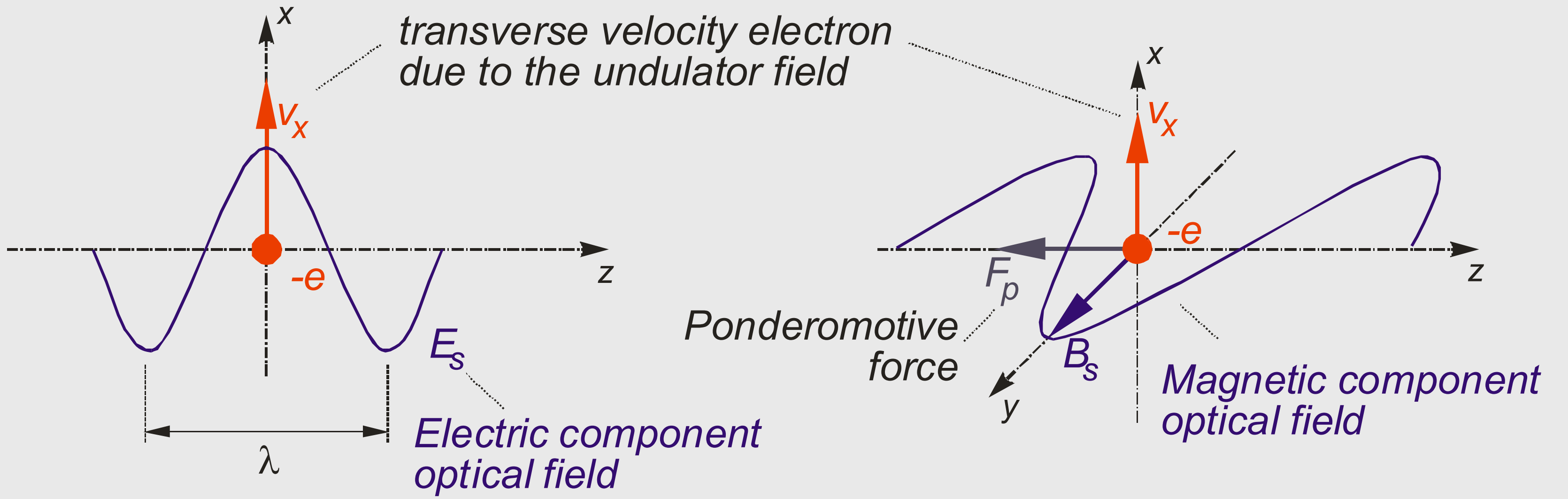
constructive interference

⟶ <u>**enhanced emission**</u>

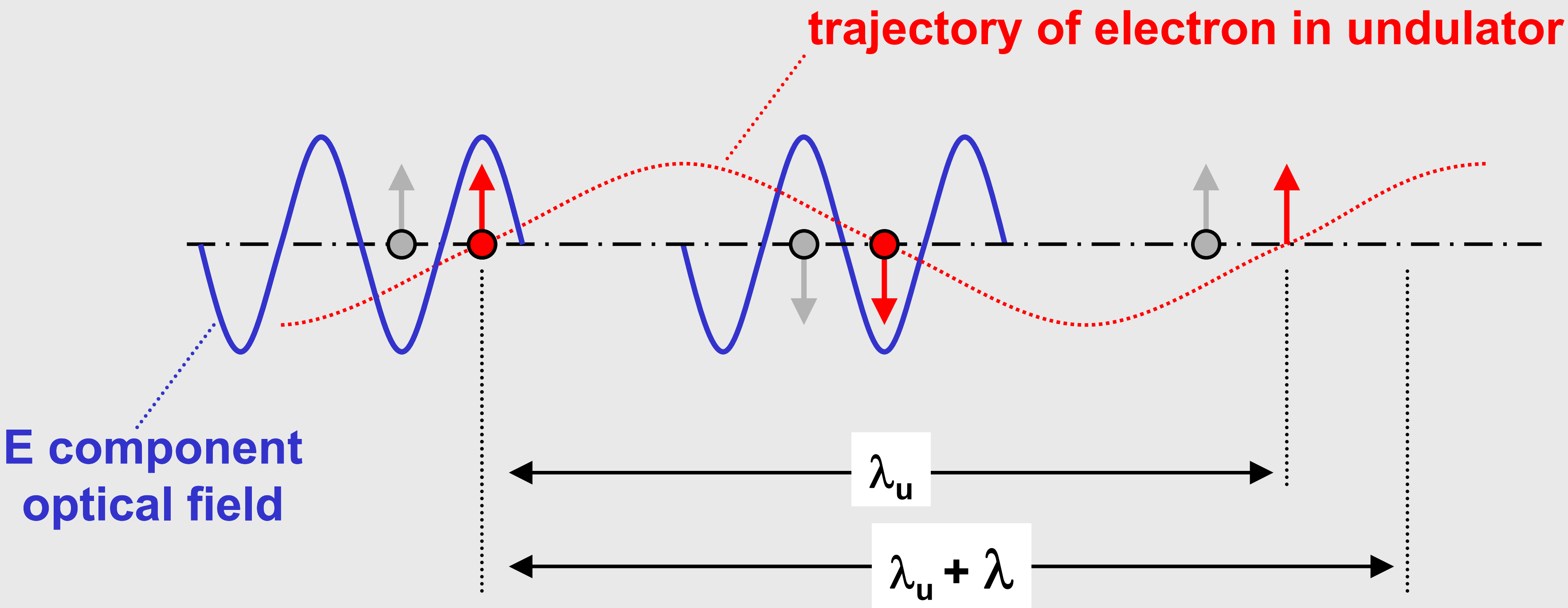
Interaction between an electron and the optical field



Interaction between an electron and the optical field

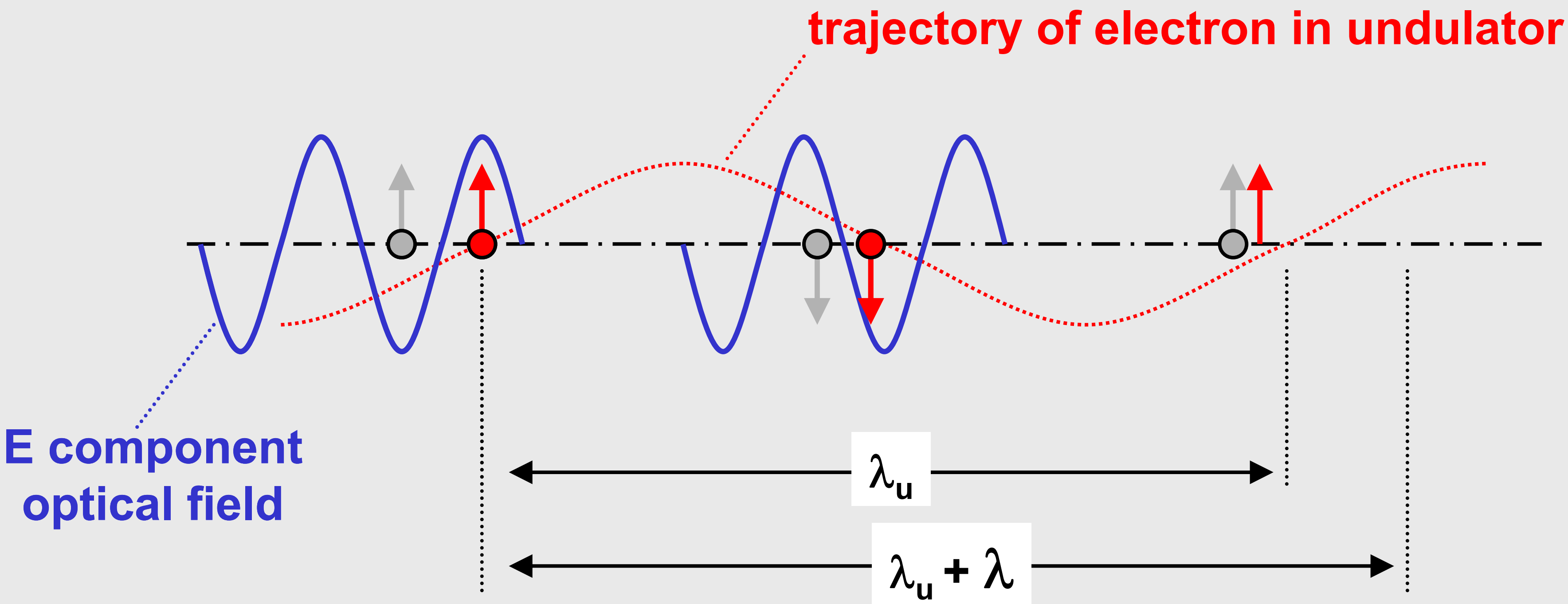


Resonance Condition



$$\frac{\lambda_u + \lambda}{c} = \frac{\lambda_u}{v_z} \quad \Longleftrightarrow \quad \lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

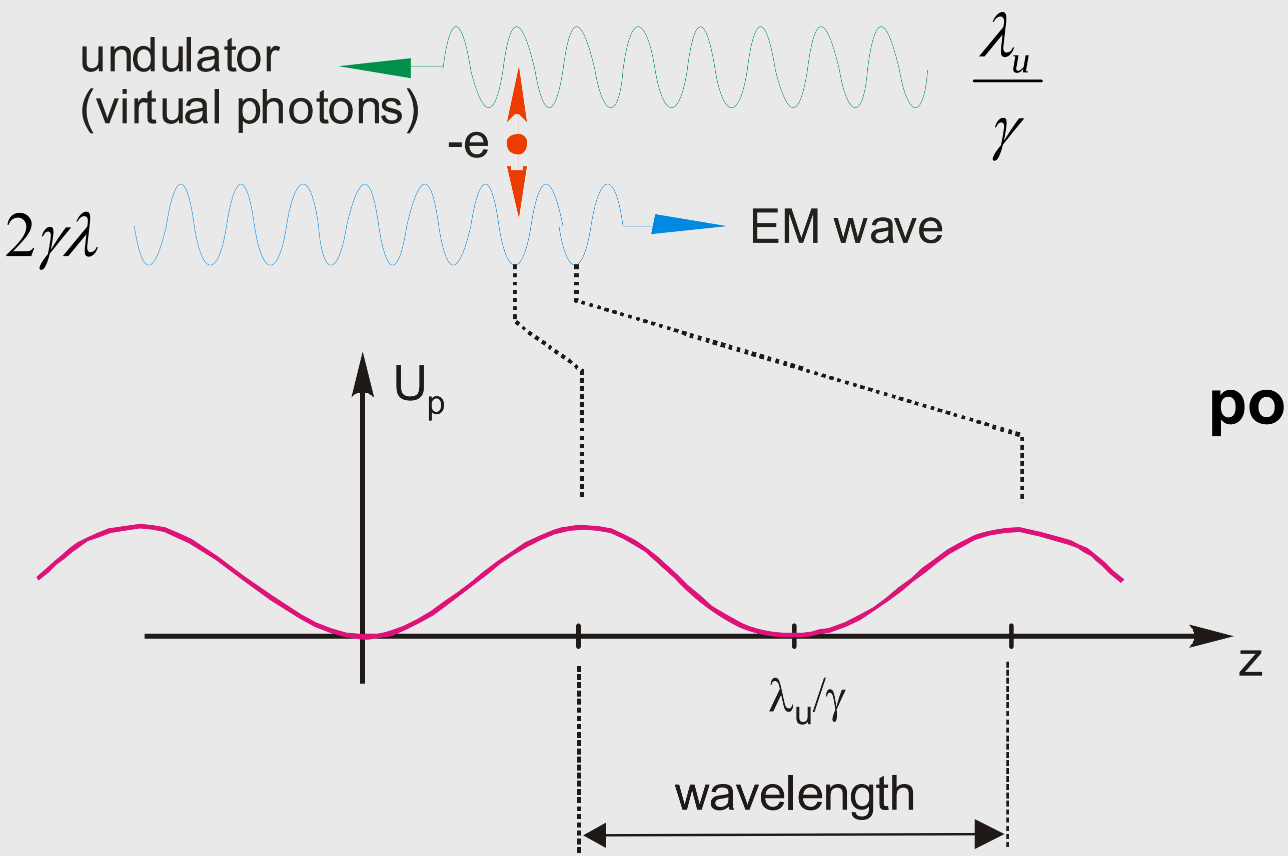
Resonance Condition



$$\frac{\lambda_u + \lambda}{c} = \frac{\lambda_u}{v_z} \quad \Longleftrightarrow \quad \lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

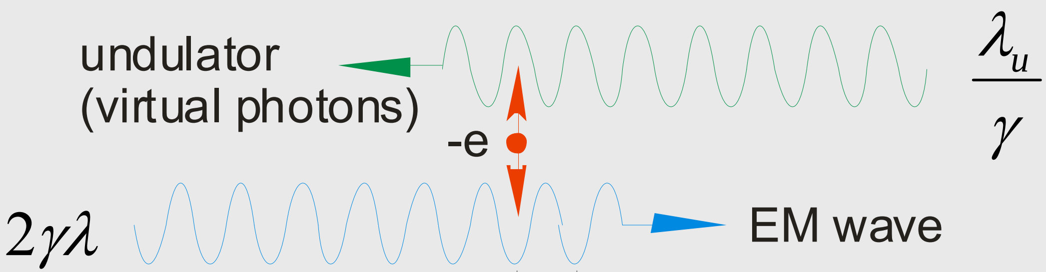
Electron Dynamics

electron rest-frame: $\langle v_z \rangle = 0$

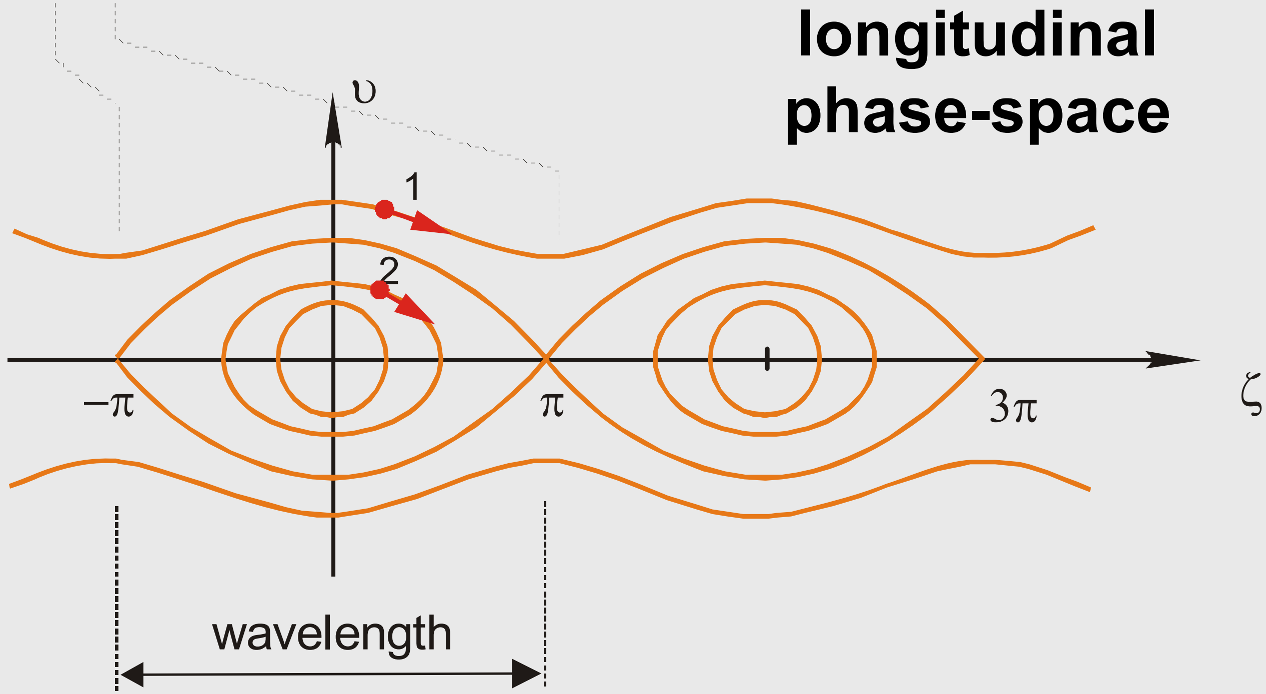


ponderomotive potential

Electron Dynamics



longitudinal phase-space



pendulum equation

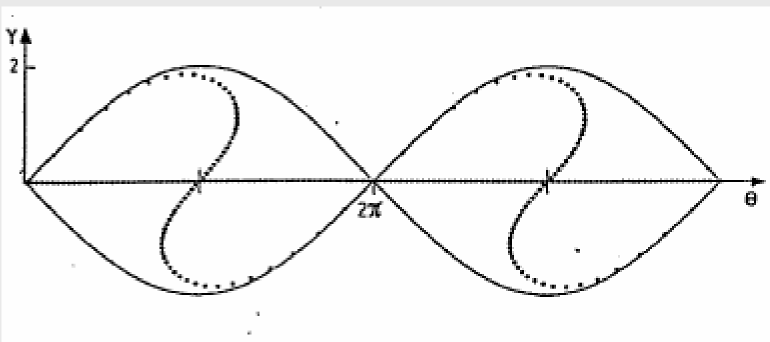
$$\frac{\partial^2 \zeta_i}{\partial \tau^2} = |a_z| \cos(\zeta_i + \phi_i)$$

$$\frac{\partial a_z}{\partial \tau} = -j \left\langle e^{-i\zeta_i} \right\rangle_i$$

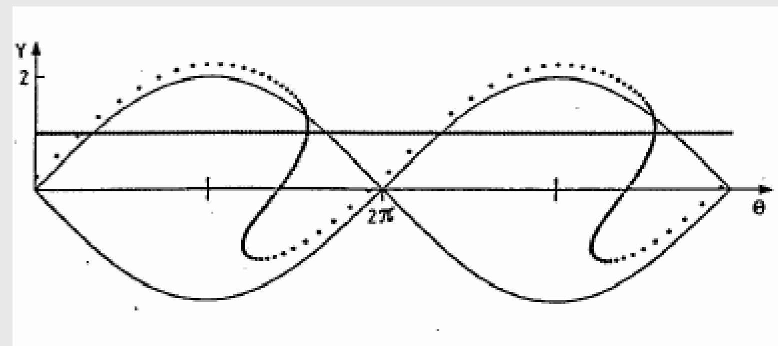
Bunching

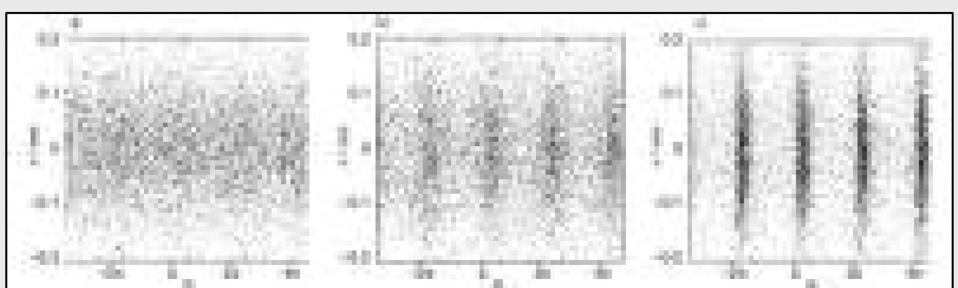
→ Inject electrons with energy slightly above the resonance energy

at resonance



above resonance





Bunching

ELECTRON BEAM REQUIREMENTS FOR LASING

1 SMALL BEAM SIZE (EMITTANCE)

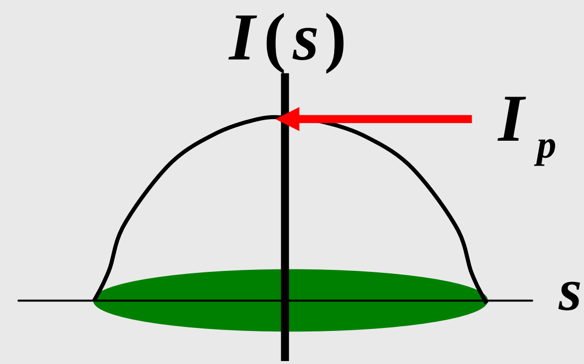
→ to have a good overlap of the electron beam with the photon beam

$$\sigma_{h\nu} = \frac{\sqrt{\lambda L_u}}{4\pi}$$

$$\sigma'_{h\nu} = \sqrt{\frac{\lambda}{L_u}}$$

$$\varepsilon < \frac{\lambda}{4\pi}$$

2 MANY PARTICLES IN THE ELECTRON BEAM → high peak current I_p



3 SMALL ENERGY SPREAD

→ to have many particles within

→ the lasing bandwidth

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

Gain (RHO) Parameter:

$$P_{h\nu} = \rho \, P_{beam}$$

→ Defines the fraction of beam power extracted from the electron beam

$$\rho \sim \left(\frac{I_p}{\gamma^2 \, \varepsilon_n} \right)^{1/3}$$

$\varepsilon_n = \beta\gamma\varepsilon$ Normalized emittance

Resonance condition $\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$

Electron Beam Requirements

- Sufficient Beam Energy:

λ	E
100 μm	15 MeV
10 nm	~1 GeV
1 nm	~3 GeV

IR: 50 A
X-ray: 5 kA

- Sufficient Current:

$$N_{e,\lambda} = \frac{I\lambda}{ec}$$

$$N_{e,\lambda} = 1 \rightarrow \begin{cases} 0.5\ \mu\text{A}\ \ (\lambda = 100\,\mu\text{m}) \\ 0.5\ \text{A}\ \ (\lambda = 0.1\,\text{nm}) \end{cases}$$

- Good Electron Beam Quality:

Transverse Emittance :

$$\varepsilon \leq \frac{\lambda}{4\pi}, \quad \varepsilon = \varepsilon_n / \gamma$$

Energy spread :

$$\frac{\sigma_E}{E} \leq 10^{-3} \quad (\leq \frac{1}{4N}, \leq \rho)$$

Difficult for short wavelengths

Difficult for long wavelengths

LOW EMITTANCE BEAM GENERATION

Difficulties

1 / To get a small emittance from the electron source

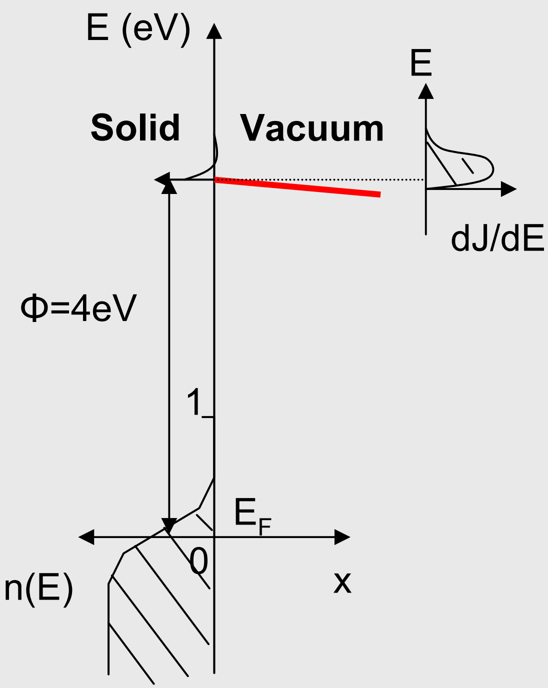
2 / To maintain the small emittance during the acceleration process → Emittance blow up due to:

- space charge effects
- nonlinearities of the acceleration field
- wake fields
- coherent synchrotron radiation

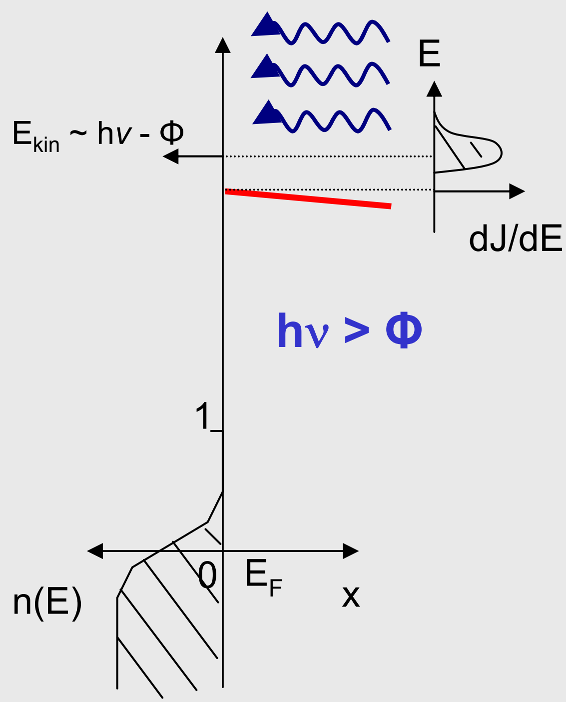
ELECTRON SOURCES

There are 3 methods to extract electrons from a material

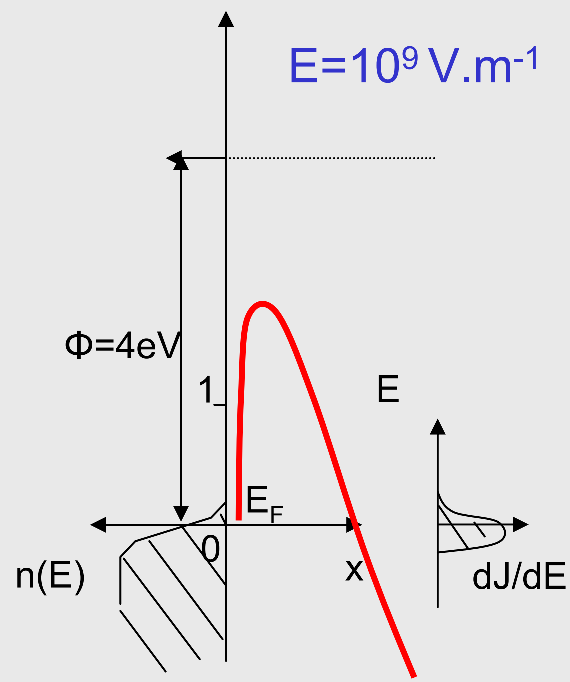
Themal Emission



Photoemission



Field Emission



T=1500K

Thermionic Emission

$$E_{kin} \sim \frac{3}{2} kT$$

Emission Characteristics:

$$J(T) = a T^2 \exp\left[-\frac{b \cdot \phi}{T}\right]$$

RICHARDSON/DUSHMANN EQUATION

a, b	constants
T	temperature
ϕ	work function
r	spot radius

$a = 120\ A/cm^2$

$b = 11'600$

Emittance Limitation:

$$\varepsilon_{thermal} = \frac{r}{2}\sqrt{\frac{2E_{kin}}{3m_o c^2}}$$

THERMAL EMITTANCE

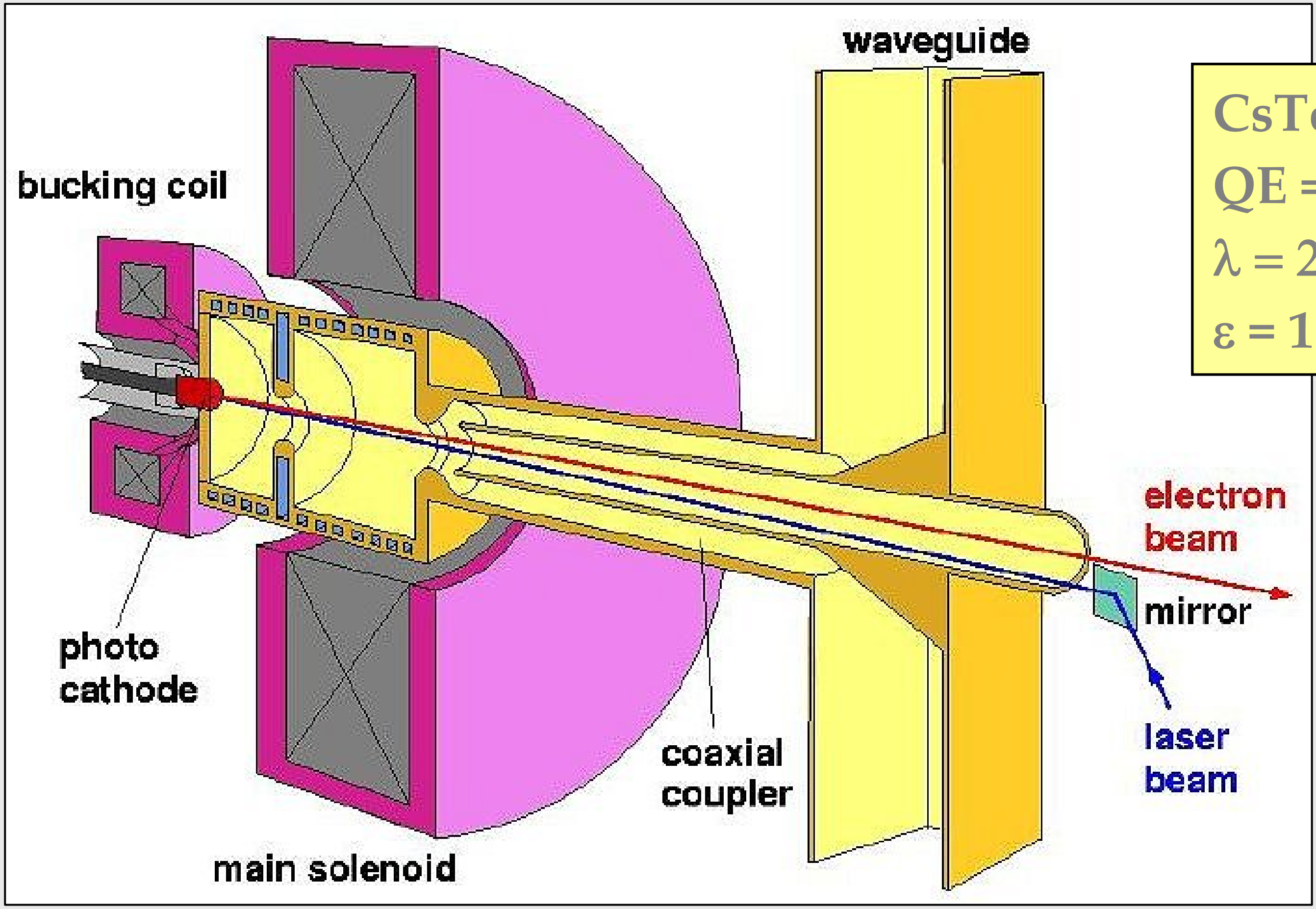
Photoemission

Emission Characteristics:

$$E_{kin} = h\nu - \phi + \underbrace{e\sqrt{\frac{eE}{4\pi\varepsilon_o}}}_{\text{SCHOTTKY EFFECT}}$$

SCHOTTKY EFFECT

STATE OF THE ART → Laser driven cavity gun:



CsTe
QE = 10^{-4}
λ = 262 nm
ε = 1 μm

PITZ/DESY

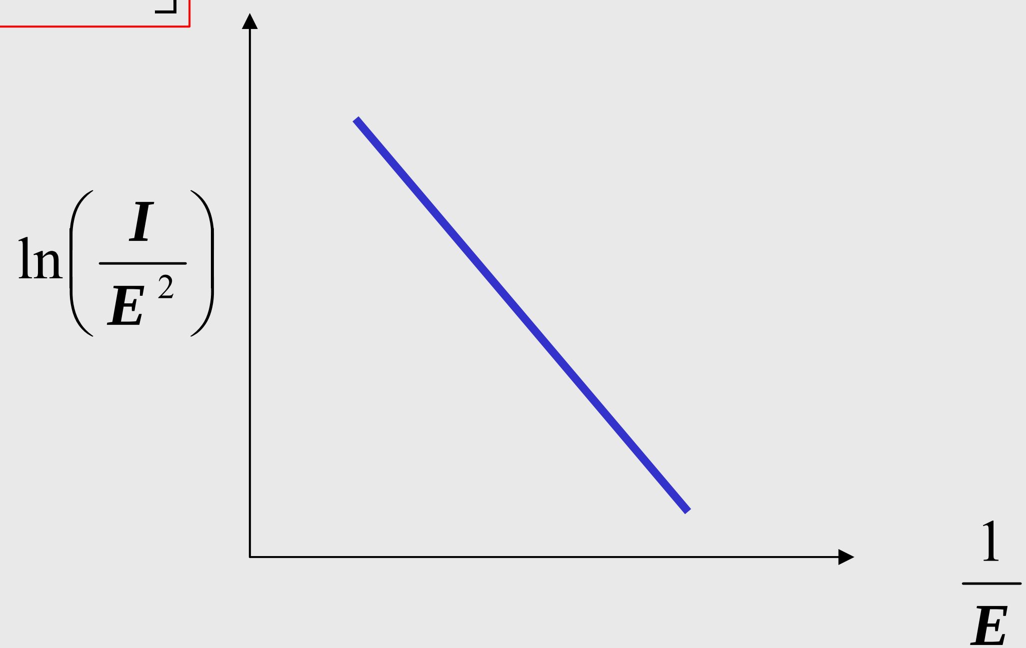
Field Emission

Emission Characteristics:

$$I(E) = a\,A\,\frac{E^2}{\phi}\exp\left[\frac{b}{\sqrt{\phi}} - \frac{c\cdot\phi^{3/2}}{E}\right]$$

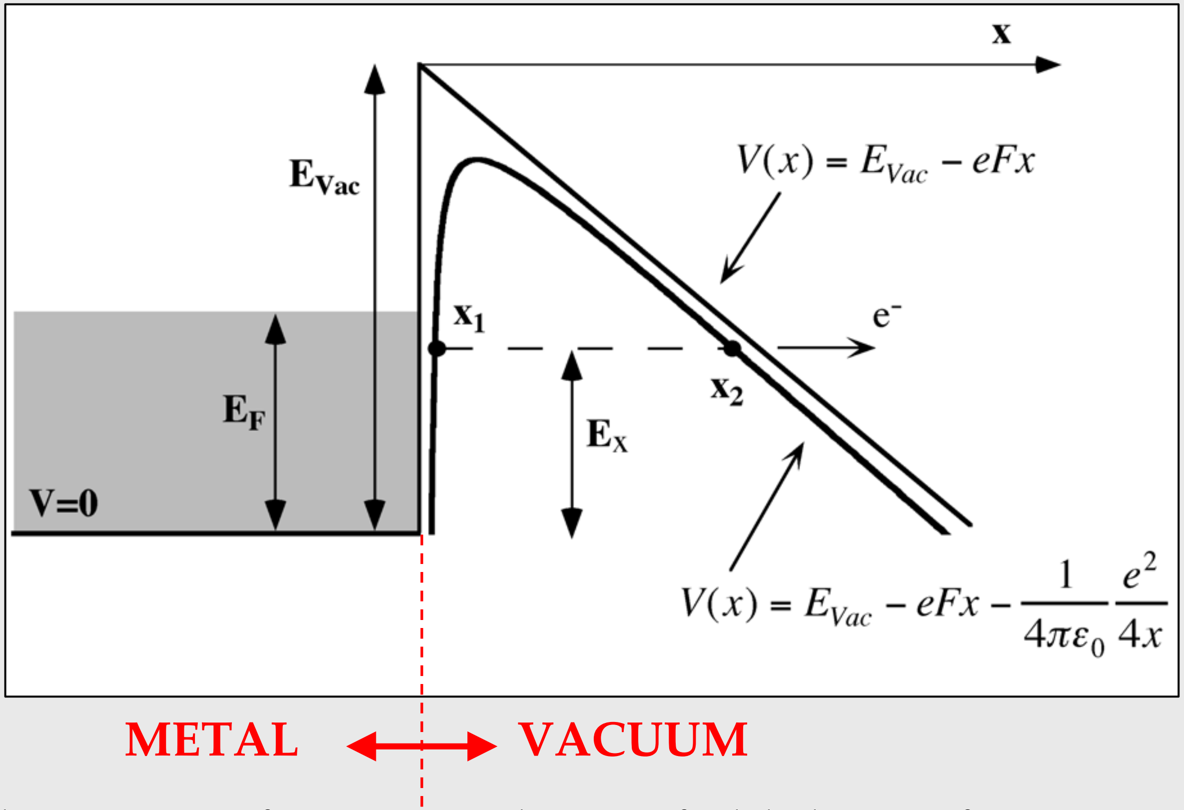
FOWLER NORDHEIM LAW

a, b, c	constants
A	area
E	electric field
ϕ	work function



In principle much smaller emittances can be reached

PRINCIPLE OF FIELD EMISSION



Under the action of a strong electric field the surface potential barrier can become narrow enough (< 2nm) so that electron near the Fermi-Energy can tunnel trough.

$\Phi = 4.5$ eV ; w = 2 nm
(TUNGSTEN)

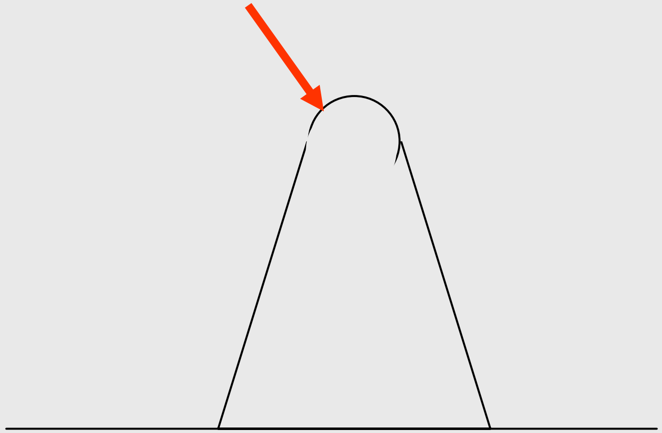
$$\Rightarrow \quad F = \frac{\phi}{e \cdot w} = 2.25 \left[GVm^{-1}\right]$$

Difficulty: Very high fields are needed → few GV/m

➔

To overcome this problem use nanostructured tips with large field enhancement factor →

Apex radius ***r***



Field amplification

$$E = \beta E_o \qquad \beta \sim \frac{1}{r}$$

Difficulty: One tip does not provide enough current

→ *USE SEVERAL THOUSENDS OF TIPS*

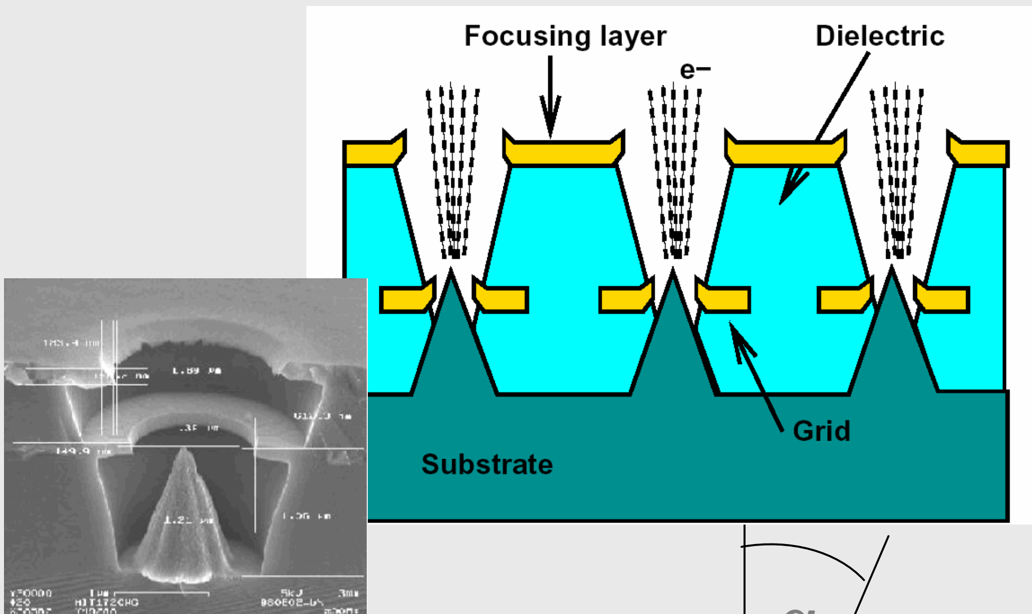
Problem: The emission area is increased, the divergence is as large as for the single tip, i.e. the emittance is increased !!

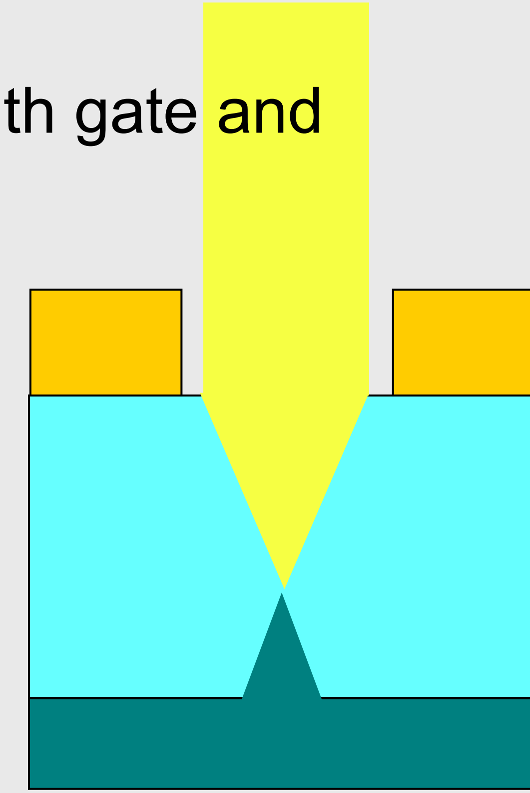
➔

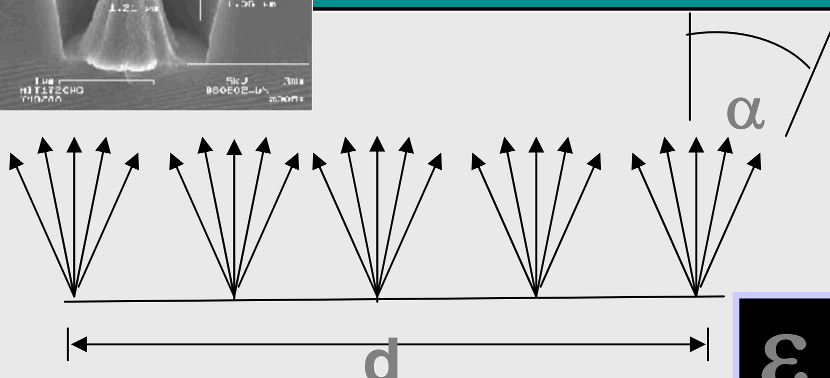
Introduce focusing for the electron beams emitted from a single tip.

NEW APPROACH:

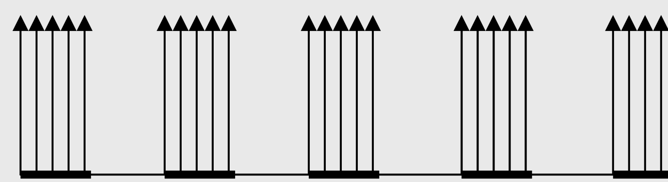
- Field emitter array (cold emission) with gate and focusing layer →





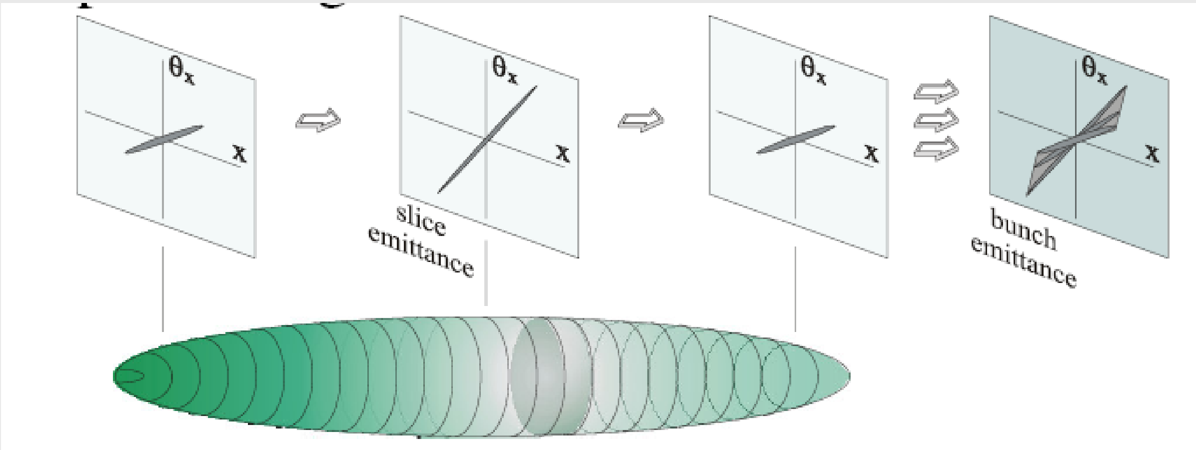


$$\varepsilon = d \times \alpha$$

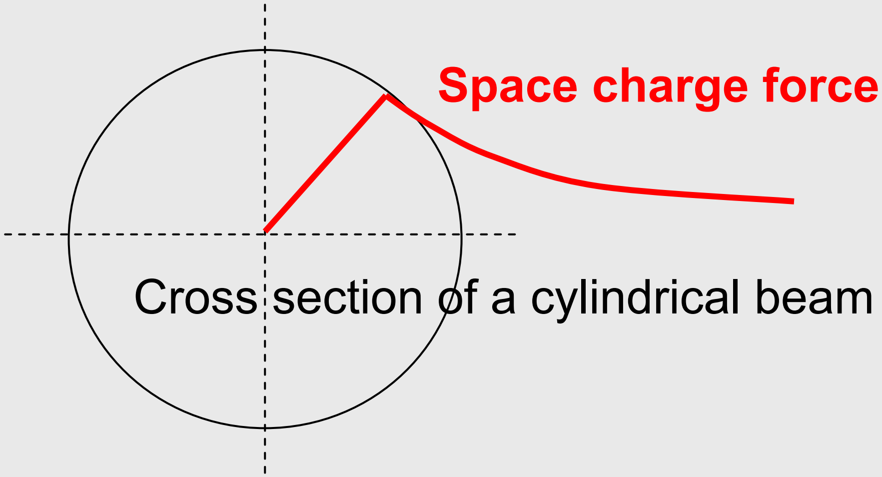


EMITTANCE DEGRADATION

Emittance Blow Up due to Space Charge Effects

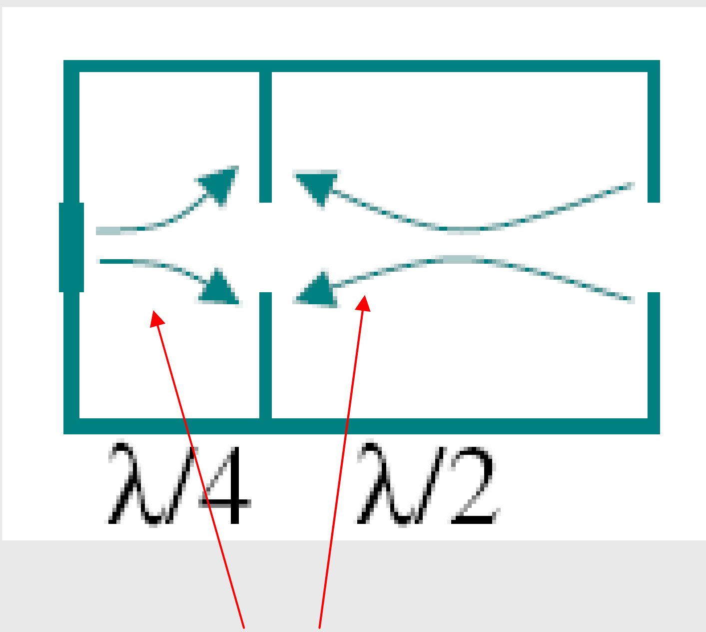


due to the intensity variation over the bunch length, the defocusing transverse space charge forces are changing → **blow up of the projected emittance!**



For a homogeneous charge distribution of an infinite cylindrical beam the space charge force inside the beam is purely linear and defocusing

Emittance Blow Up due to RF-Nonlinearities



Nonlinear RF-field

KIM – NIM A 275

$$\varepsilon_x^{RF} = \frac{eE_o}{2mc^2} \frac{k_{RF}^2 \sigma_x^2 \sigma_y^2}{\sqrt{2}}$$

PEAK CURRENT GENERATION

Maximum Current from a Photocathode:

EXAMPLE BNL/PITZ:

1 nC in pulse with 10 ps length → 100 A

BUT

Several 1000s Amperes are needed for the lasing process

WAY OUT

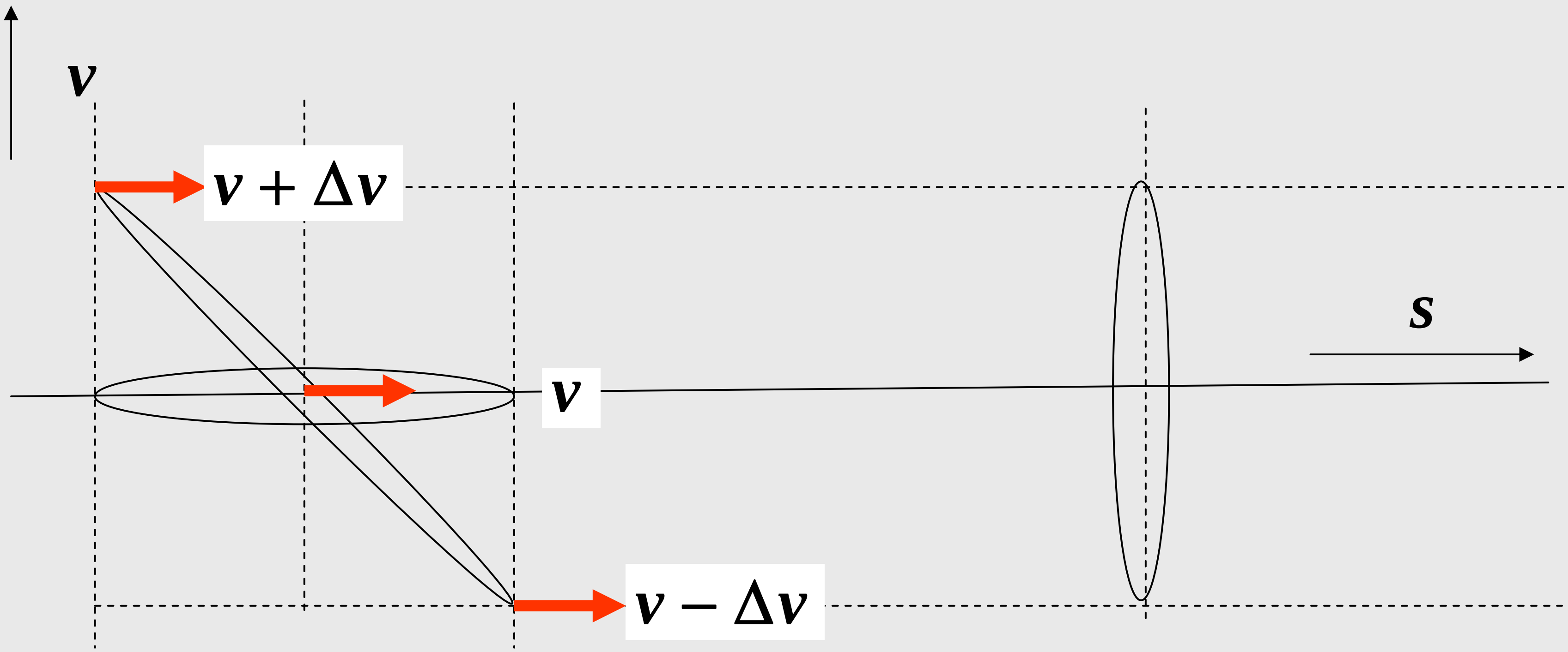
Take longer pulses and compress them

/1/ Velocity (Ballistic) Compression

Works good at low energies when the electrons are not yet relativistic!

Principle:

Create a velocity chirp in the beam and add a drift length →



/2/ Magnetic Compression

At high energies the difference in velocity difference between particles with different energies is strongly reduced

$$\gamma = \frac{1}{\sqrt{1-\beta^2}} \rightarrow d\beta = \frac{d\gamma}{\beta\gamma^3}$$

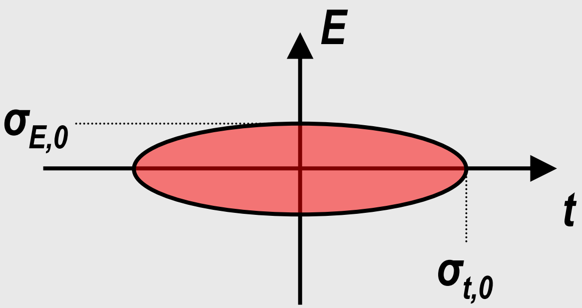
THE BEAM IS FROZEN !

Way out:

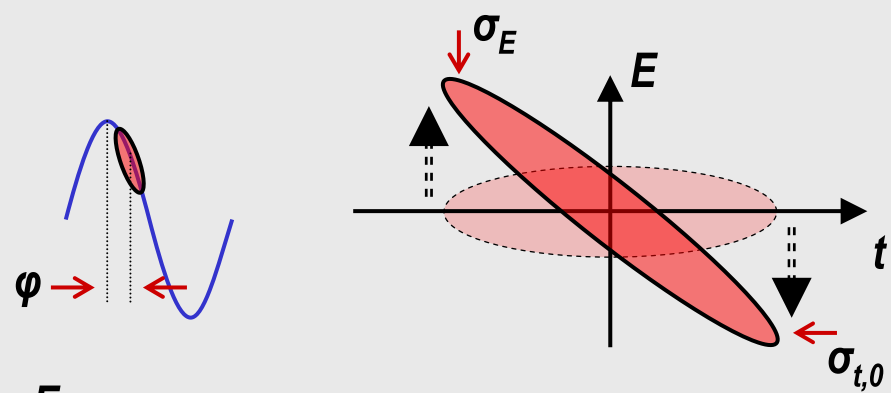
Use path length changes in a dispersive magnet system

Magnetic Bunch Compression

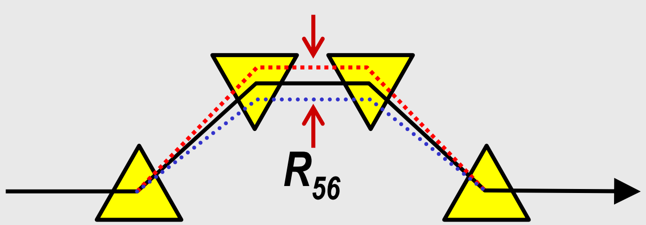
1. Initial condition

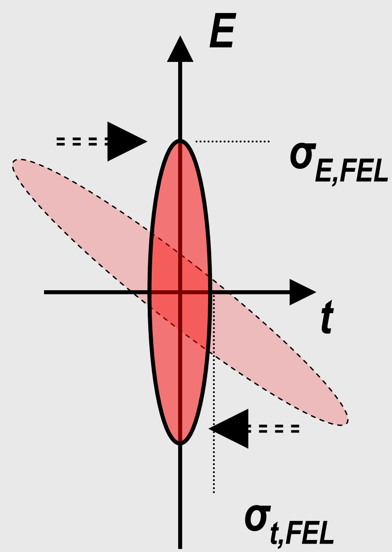


2. Offcrest RF acceleration



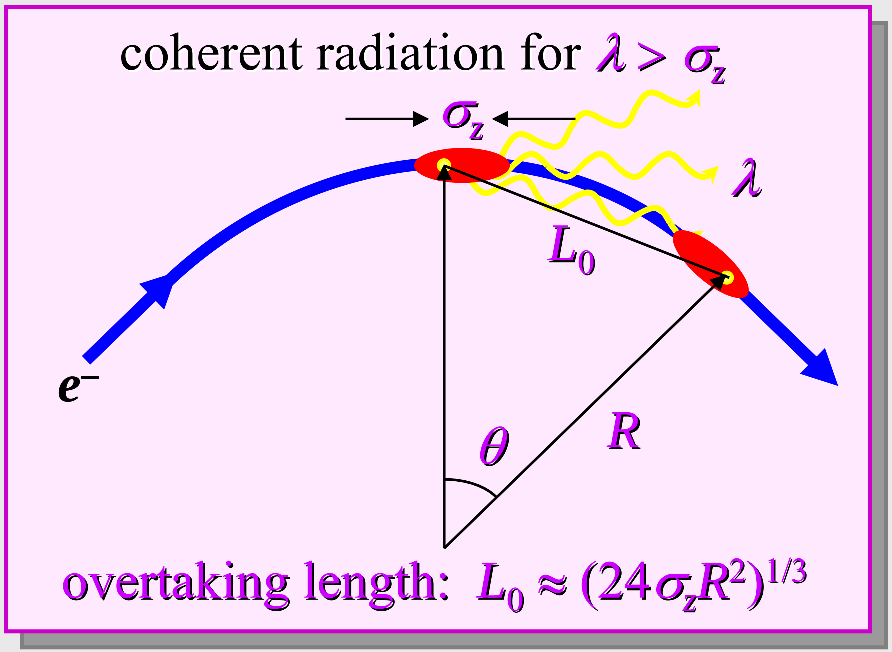
3. Compressor (dipoles): E_c

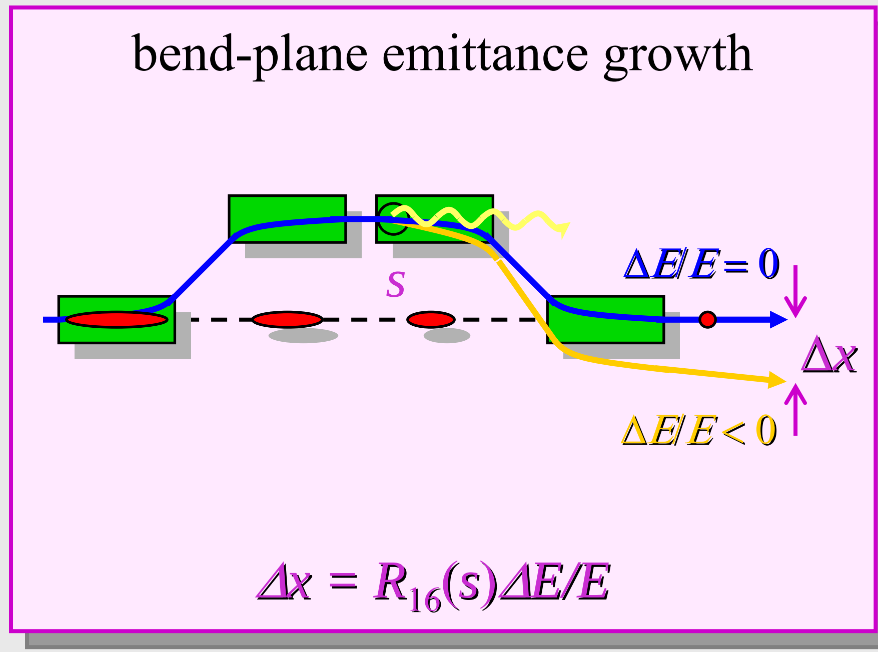




Magnet bunch compressors create a sever problem → COHERENT SYNCHROTRON RADIATION

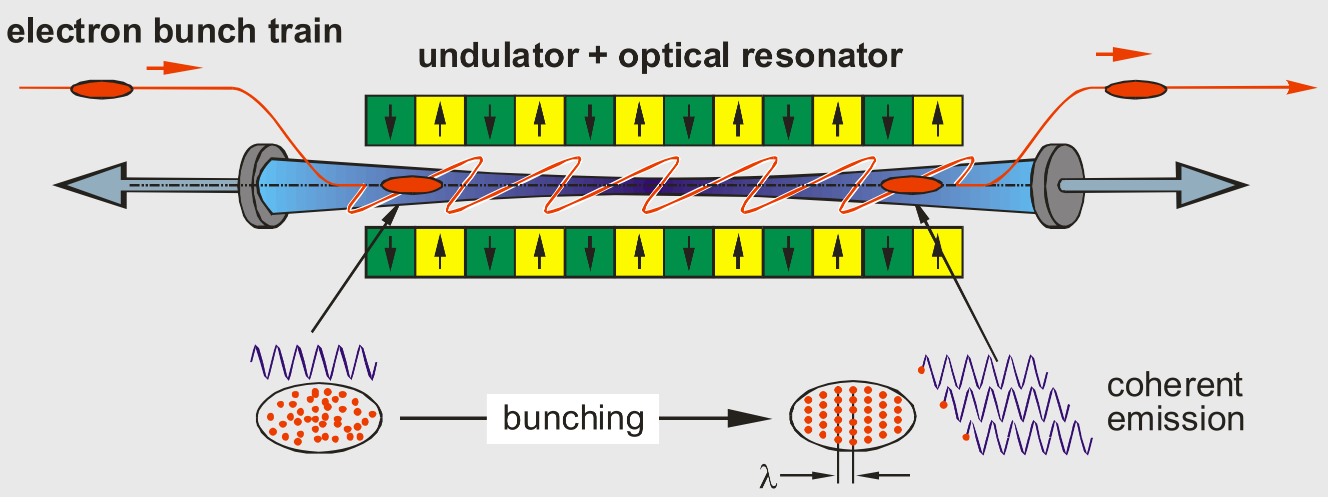
Powerful radiation generates energy spread in bends
Induced energy spread breaks achromatic system
Causes bend-plane emittance growth (short bunch is worse)





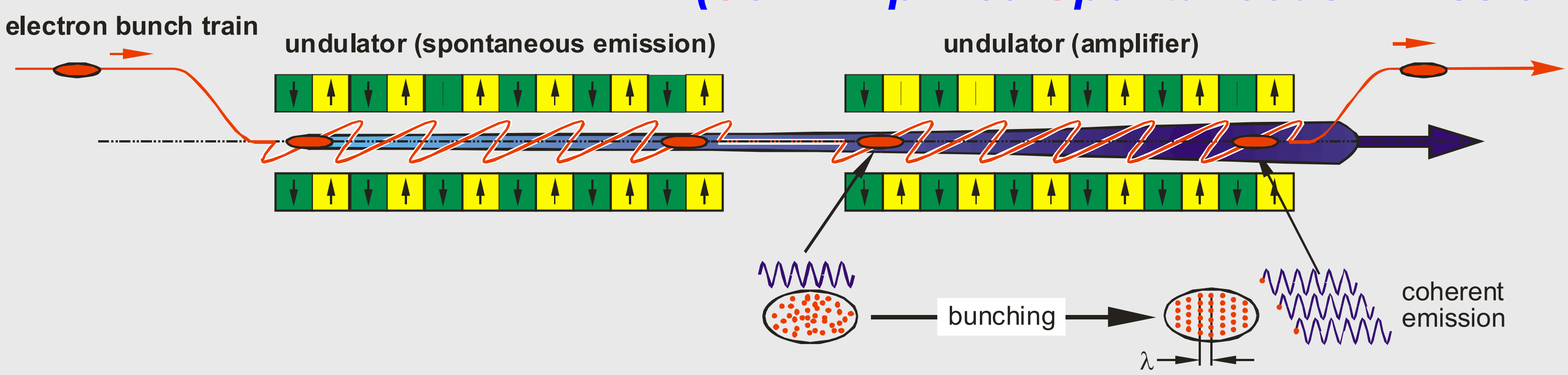
FEL CONCEPTS

Classical FEL Scheme



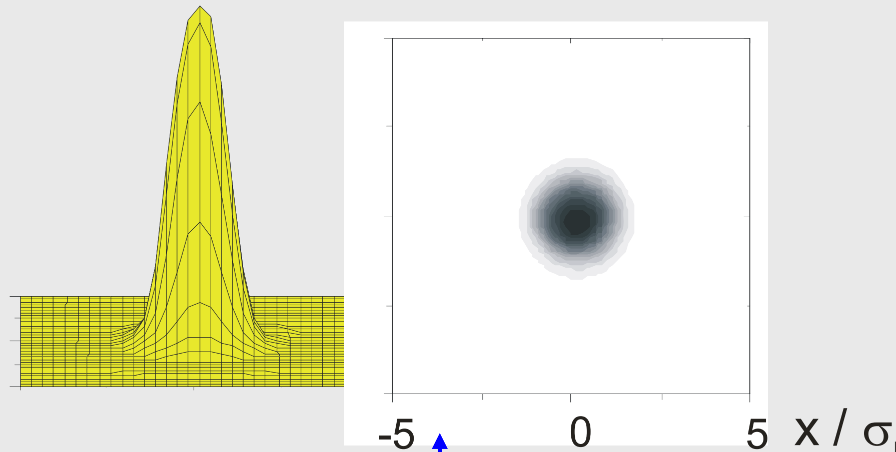
SASE FEL Scheme

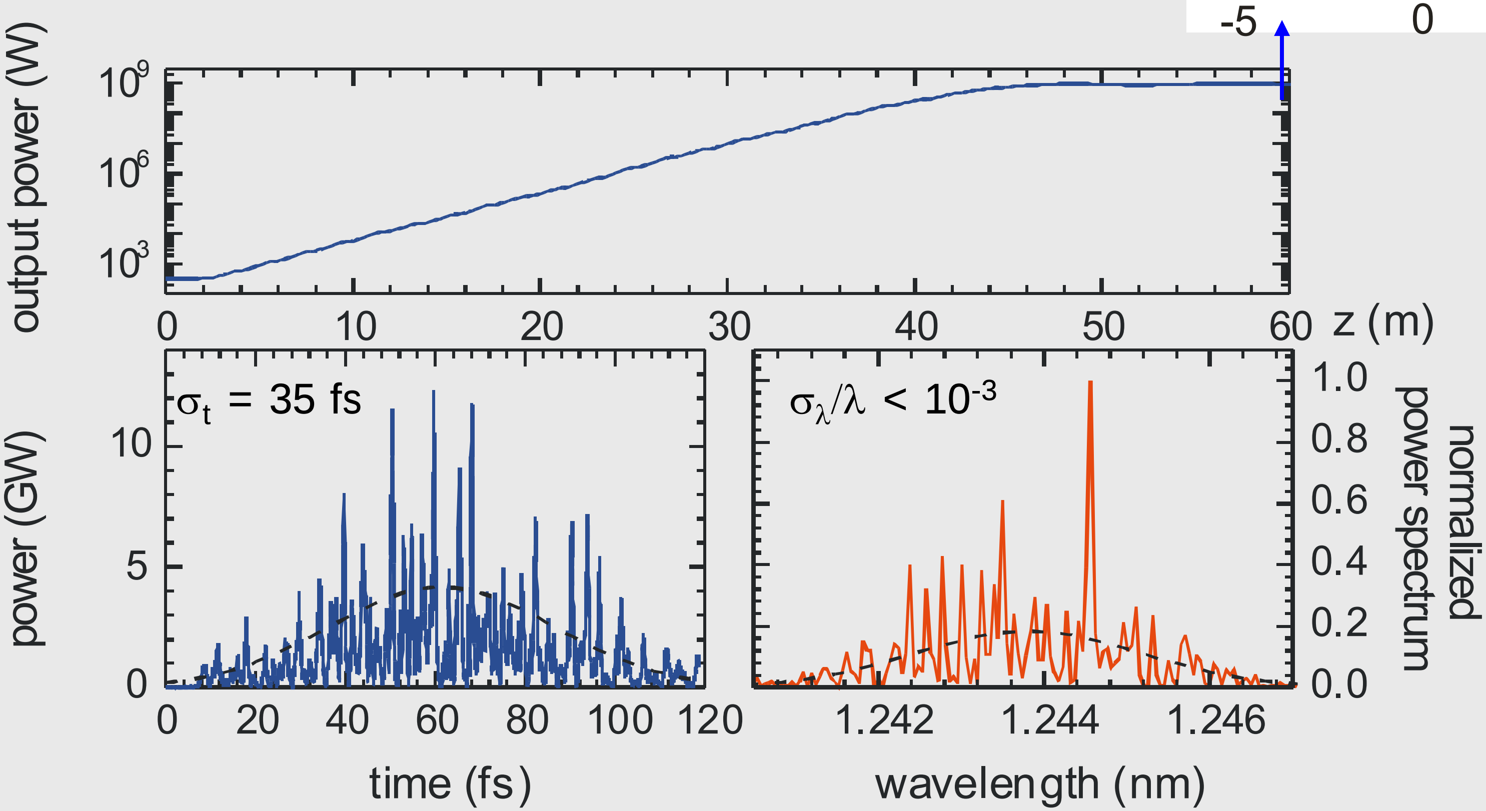
(Self Amplified Spontaneous Emission)



Output properties

transverse:
diffraction limited TEM_{00} mode



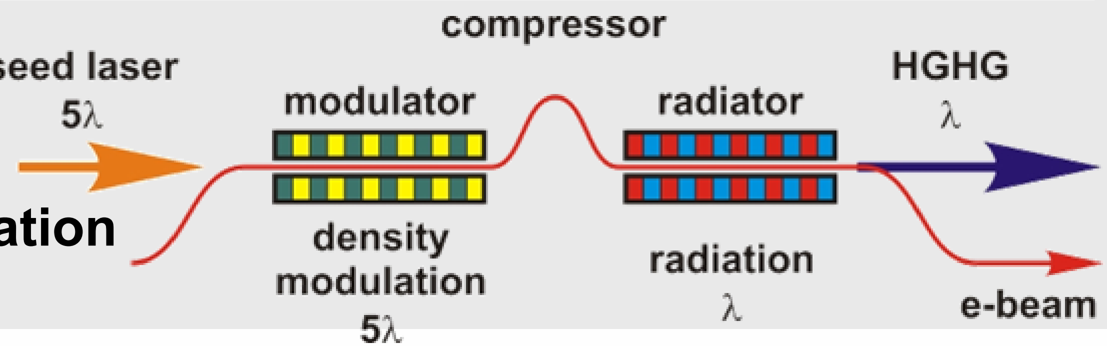


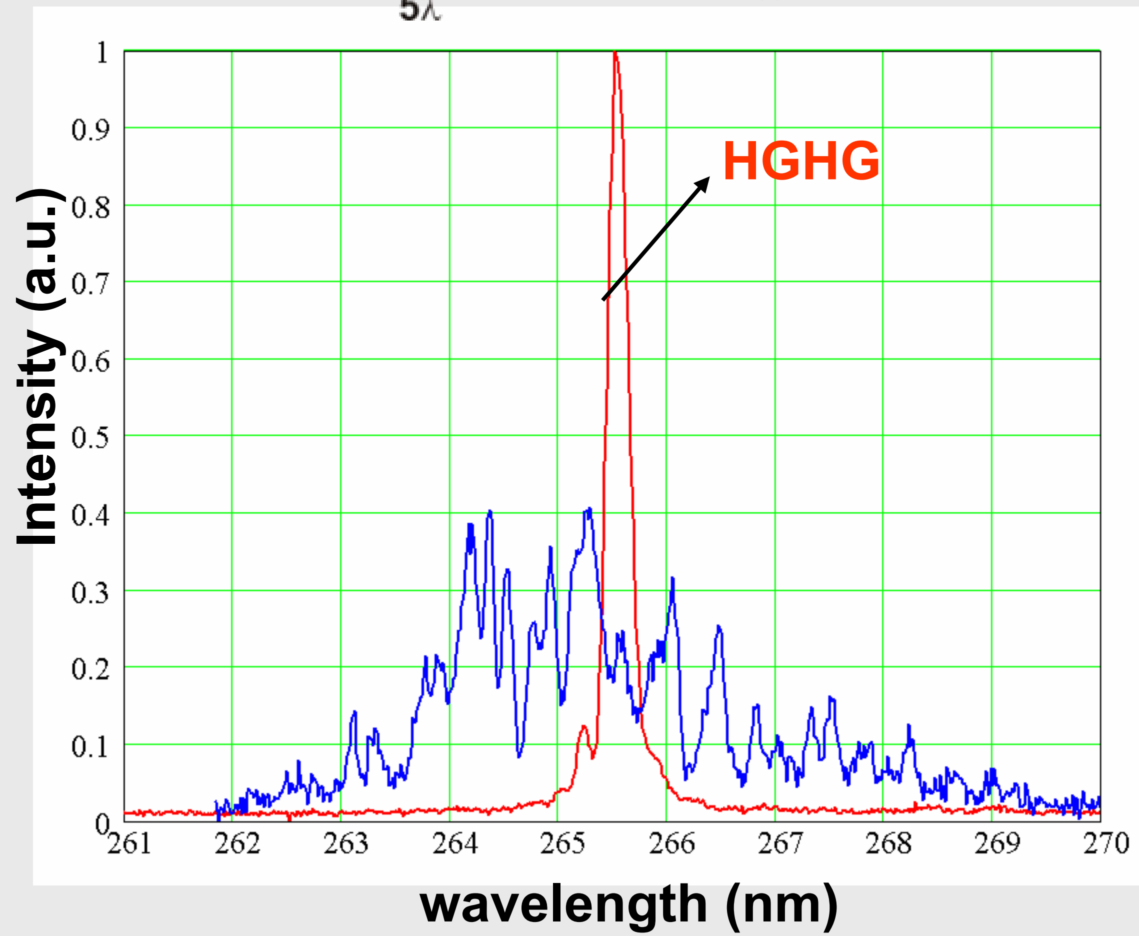
SEEDING

Courtesy Li Hua Yu (BNL)

Seeding: HGHG

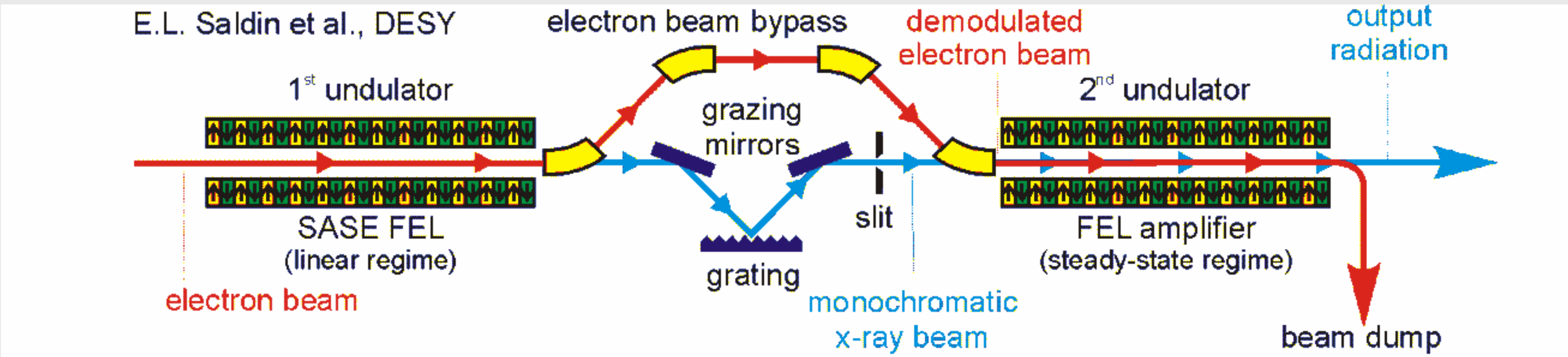
High Gain Harmonics Generation

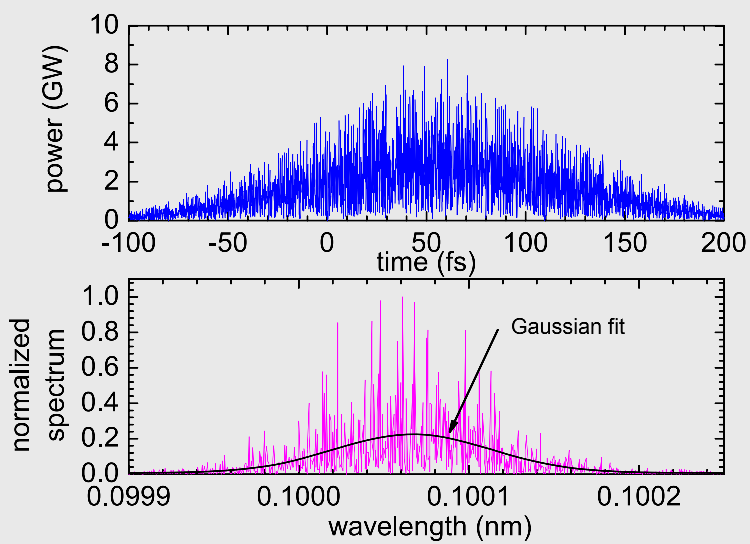


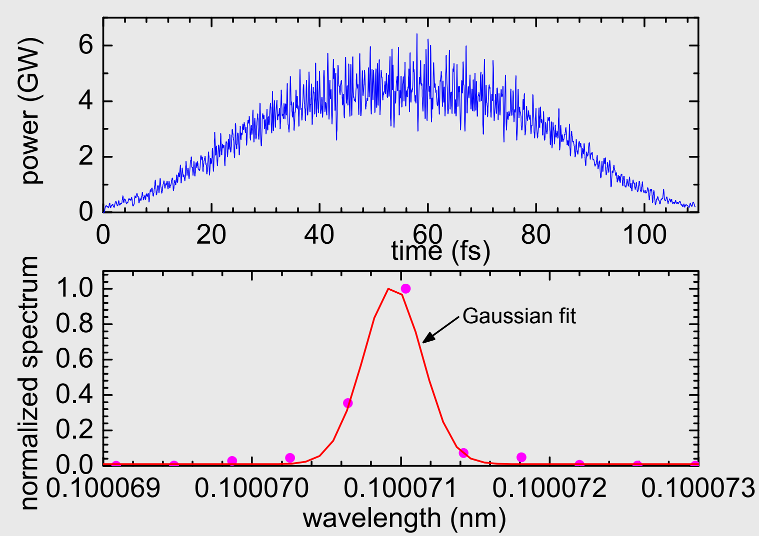


Seeding: SELF SEEDING

(demo for X-FEL)





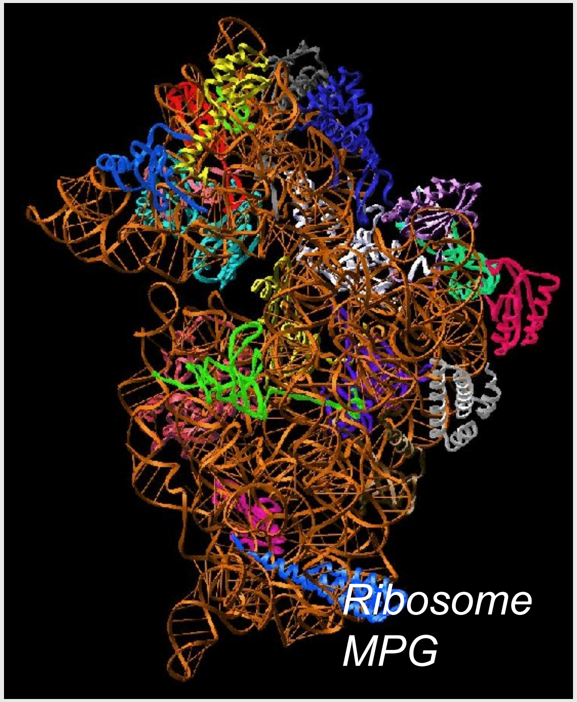


FEL EXPERIMENTS

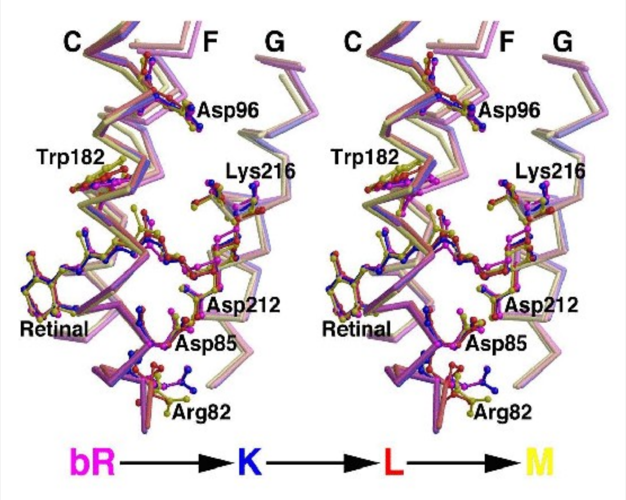
Users Dream will become Reality →

- SINGLE SHOT imaging of single biomolecular complexes

NEEDS MANY PHOTONS ON THE SAMPLE !



***LYSOZYME** MOLEKUEL*



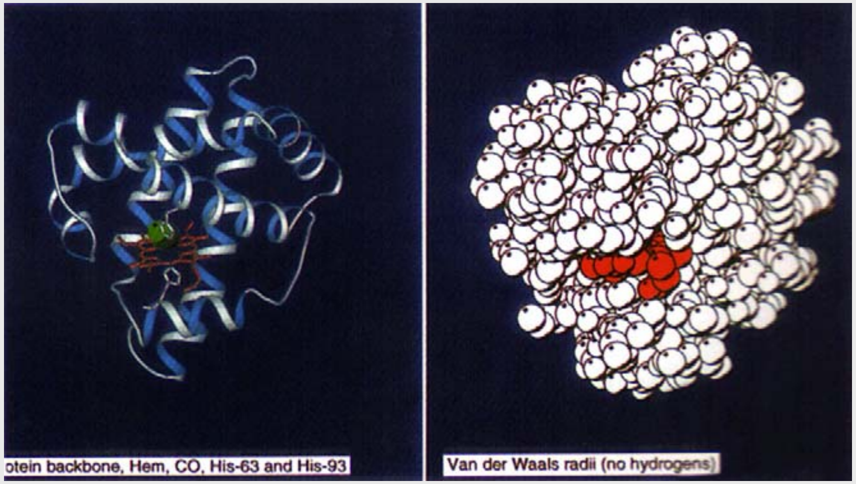
Light induced structural changes during photocycle

- TIME RESOLVED studies of structural processes during chemical and biological reactions

NEEDS VERY SHORT PULSES !

→ permits time resolved studies at the atomic level

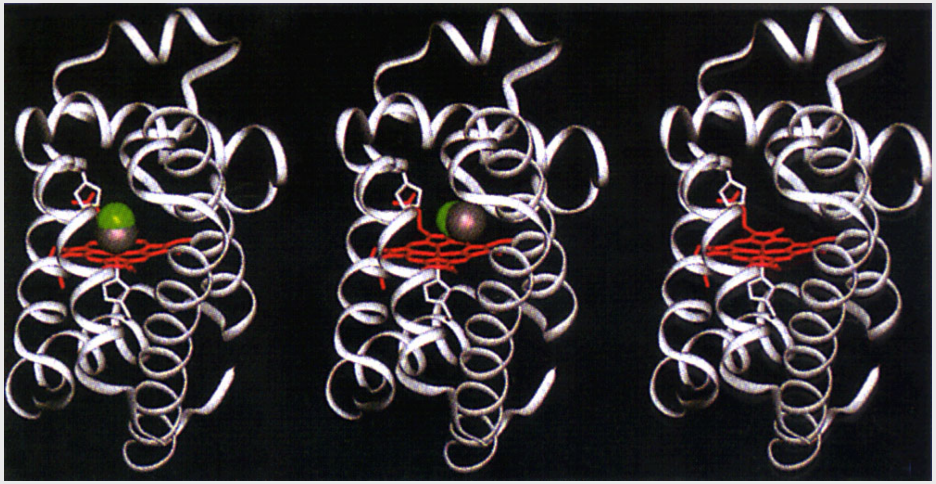
SHORT PULSES in the range of fs are needed in order to study the dynamics on the atomic and molecular level



Myoglobin:

How does the oxygen get in and out of the haeme unit?

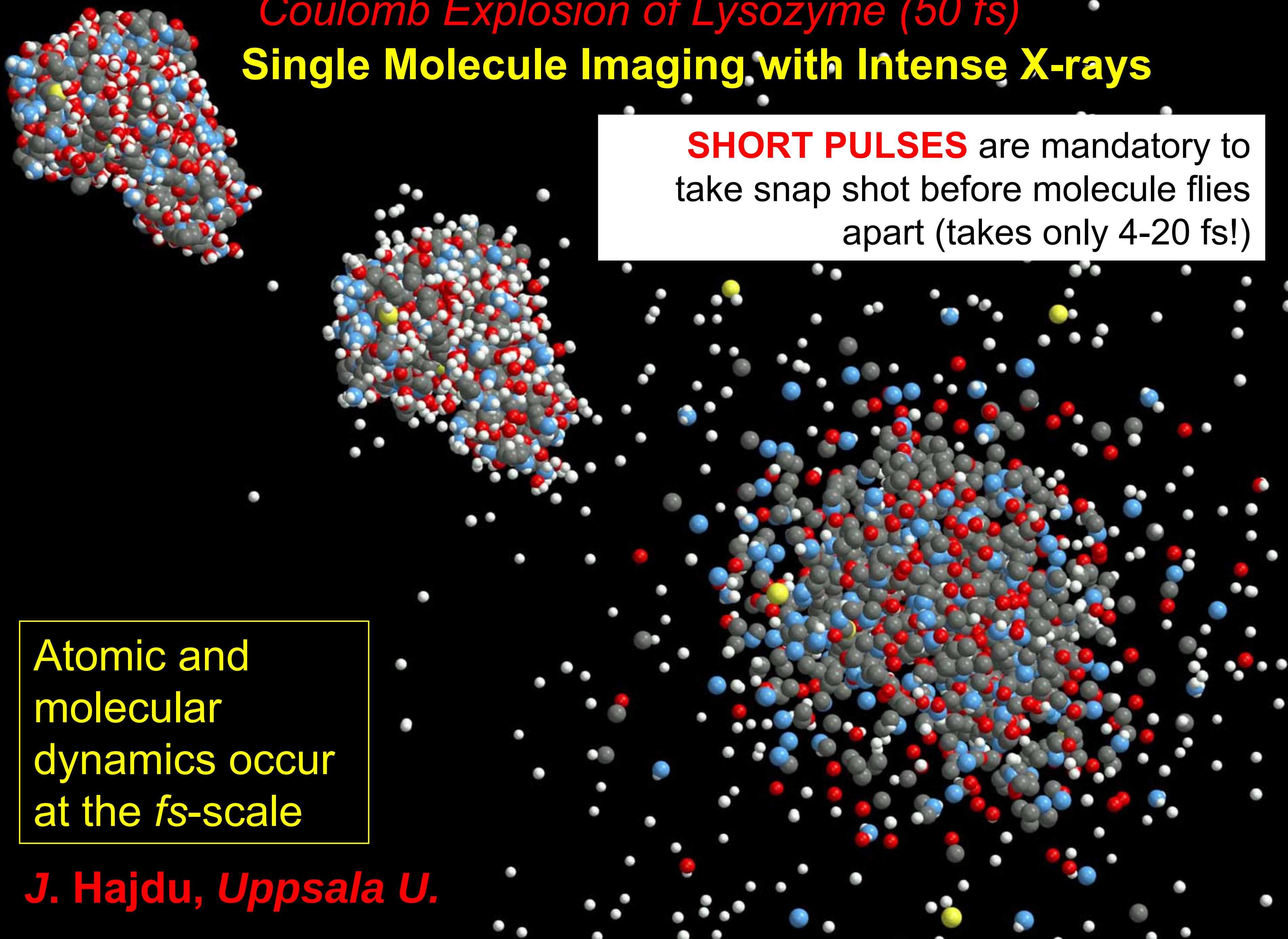
- **t=0: Photodissociation**
- **4 ns: CO rotates 90°, moves 4Å from Fe and stays in site for 350 ns**
- **1 ms: CO located in outer protein coat**



Schotte et al Science ***300*** *1944 (2003)*

Coulomb Explosion of Lysozyme (50 fs)

Single Molecule Imaging with Intense X-rays



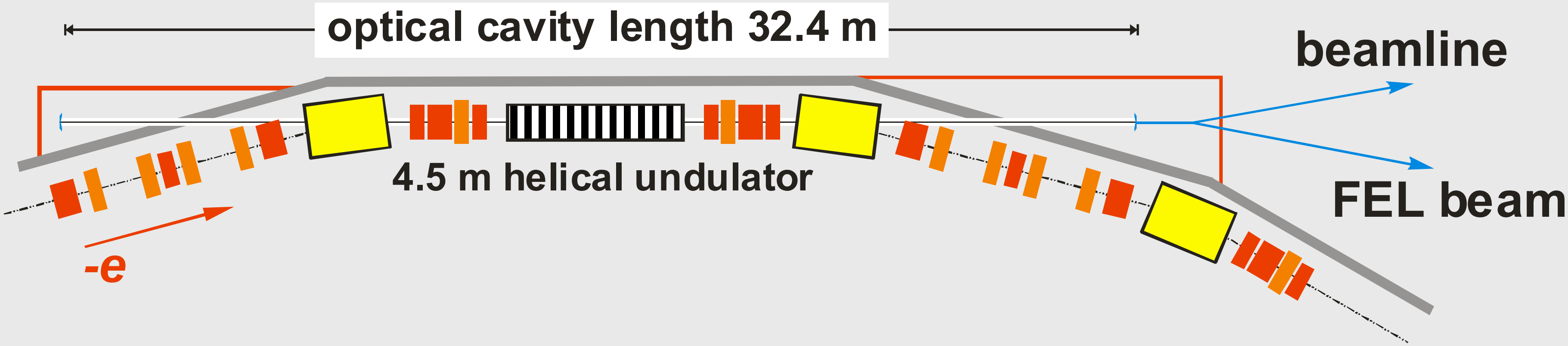
SHORT PULSES are mandatory to take snap shot before molecule flies apart (takes only 4-20 fs!)

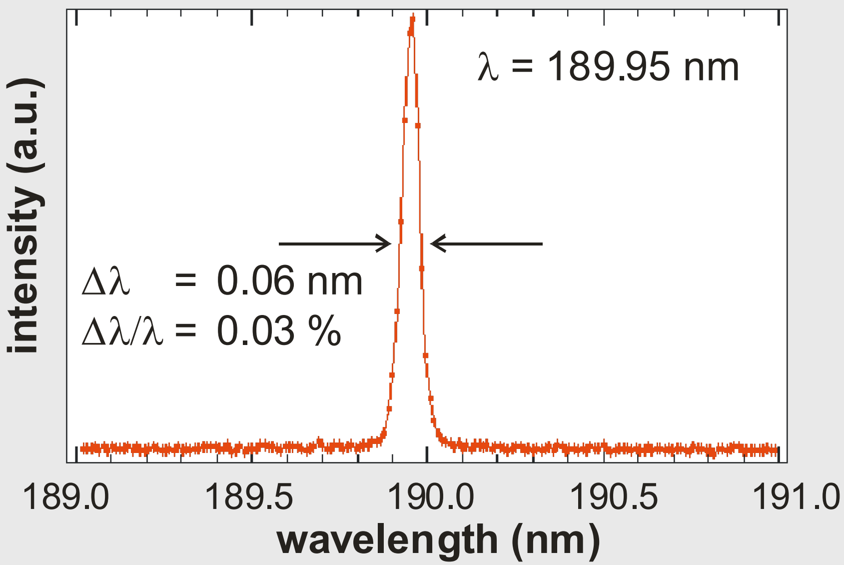
Atomic and molecular dynamics occur at the *fs*-scale

J. Hajdu, Uppsala U.

FEL PROJECTS
(a selection)

The Elettra Storage Ring FEL





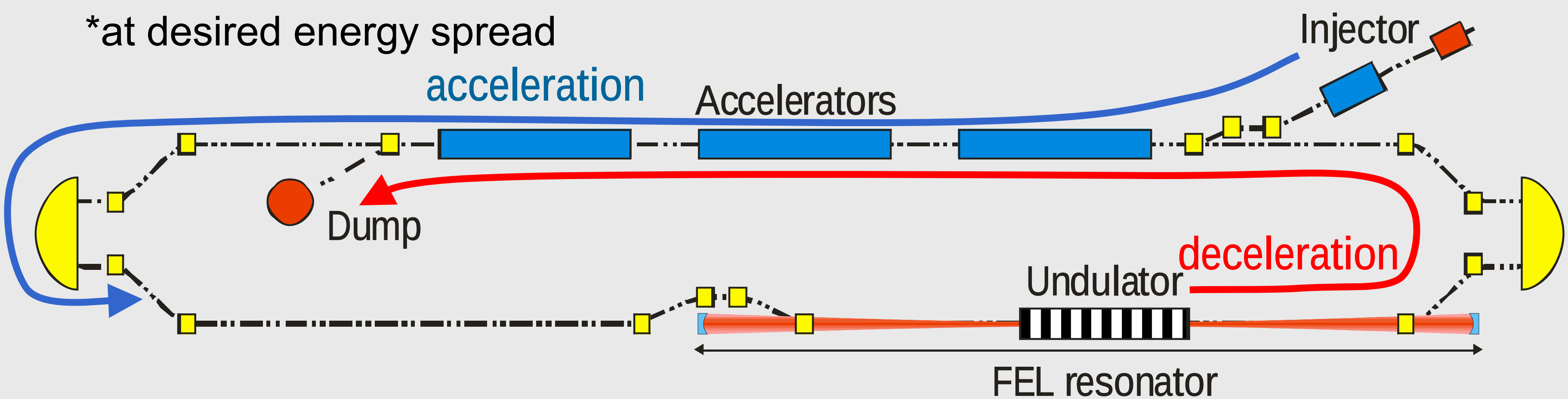
Storage ring operation*	1.0	GeV
Tunability range	350 – 190	nm
	3.5 – 6.5	eV
Average power	≥ 1	W
Pulse length (FWHM)	~ 5	ps
Peak power	≥ 40	kW
Pulse energy	≥ 0.2	mJ
Photon flux**	$\geq 10^{18}$	photons/s
Polarization	circular (linear may also be possible)	
Repetition rate	4.6	MHz
Synchronization with synchrotron radiation	1:1	

*4-bunch operation, **within the laser bandwidth

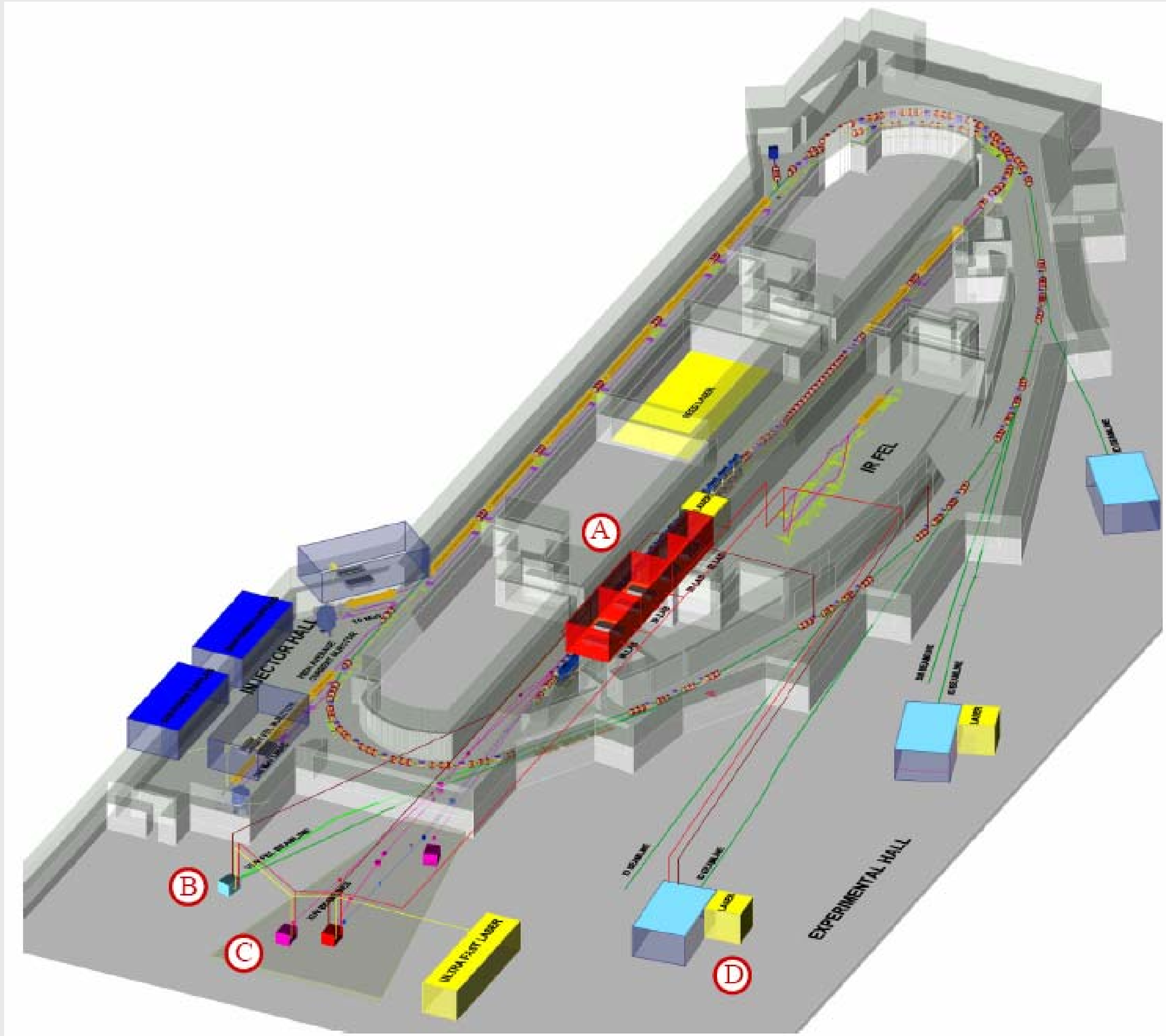
JLAB recirculating FEL

Driver Accelerator	Design Spec.	Achieved (as of Jul. 21 2004)
Linac Energy	145 MeV	160
Linac Ave. Current	10 mA	9.1
Charge	135 pC	150
Transverse Emittance	30 mm-mrad	<15
Energy Spread	0.3%	0.3
Bunch length *	0.5ps	0.35
FEL System		
Ave. Power (cw)	10 kW	8.5
Lasing efficiency	1 kW/mA	2.6
Stored Optical Power (@6μm)		132 kW

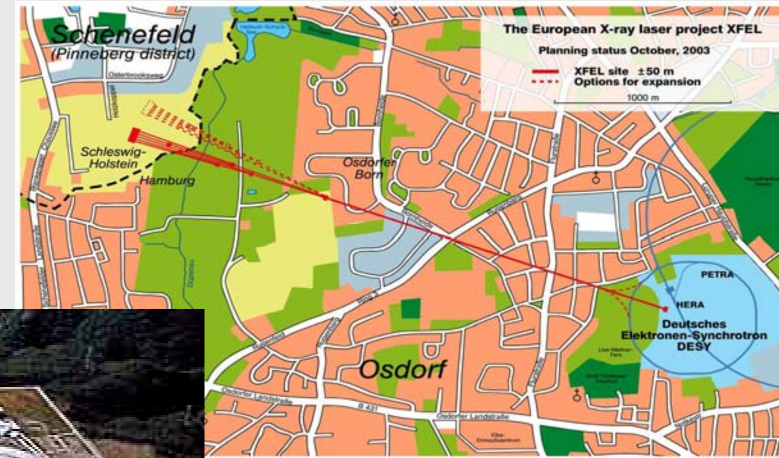
*at desired energy spread



4GLS Daresbury

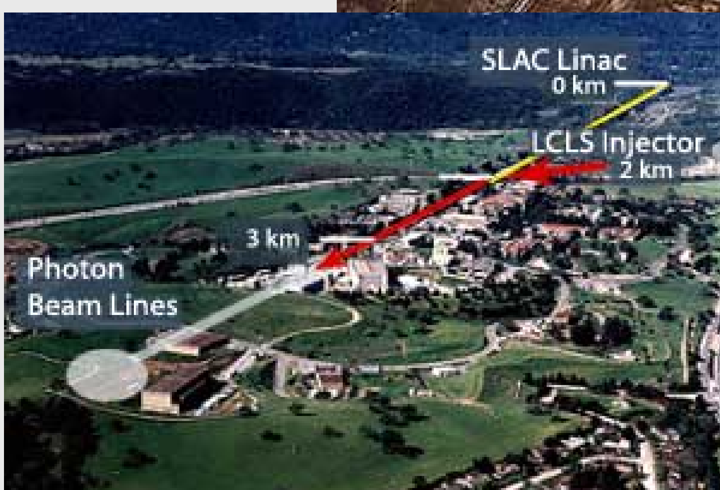


X-FEL facilities



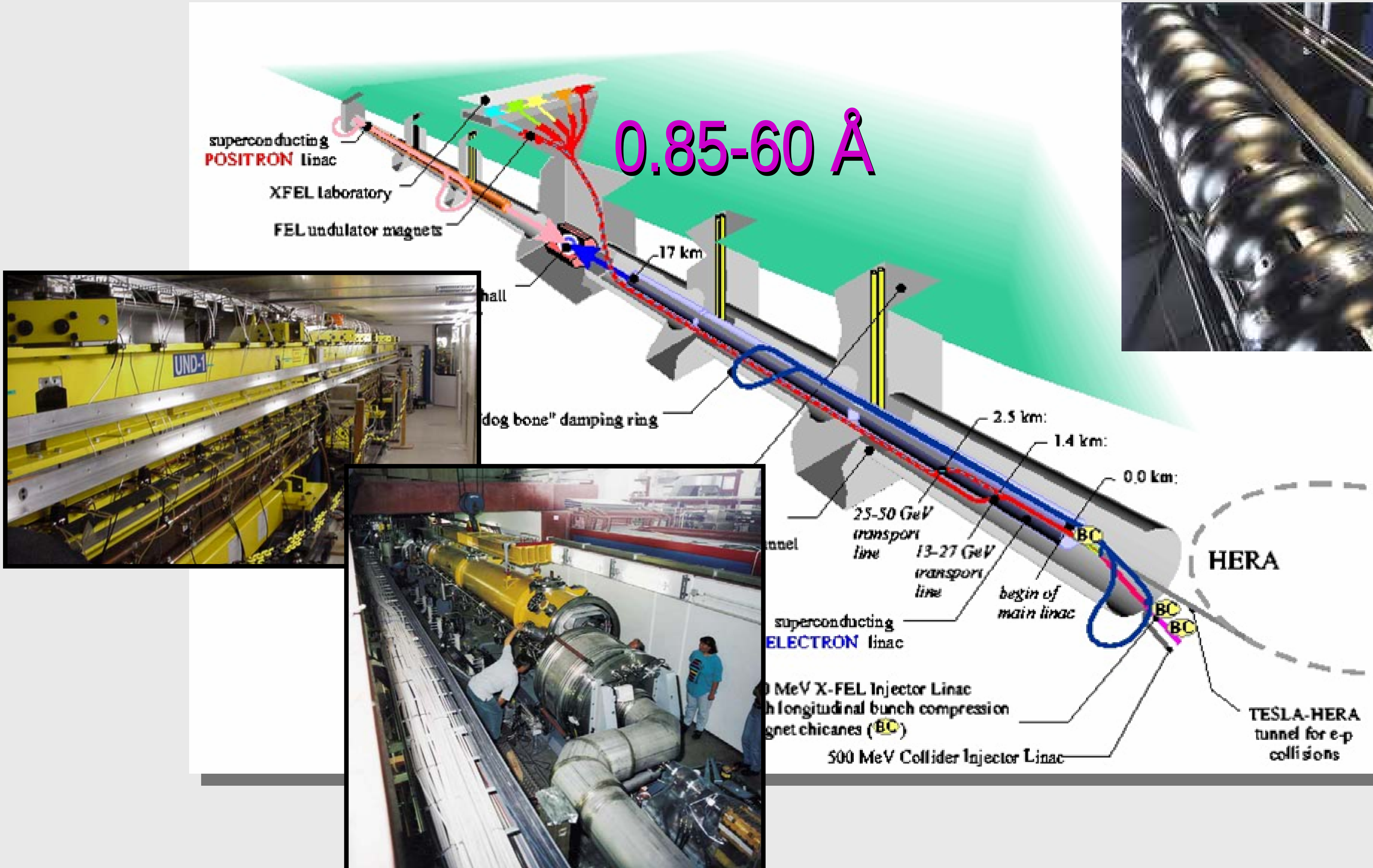
Europe
X-FEL – DESY 2012

Japan
SCSS – SPring8 2010



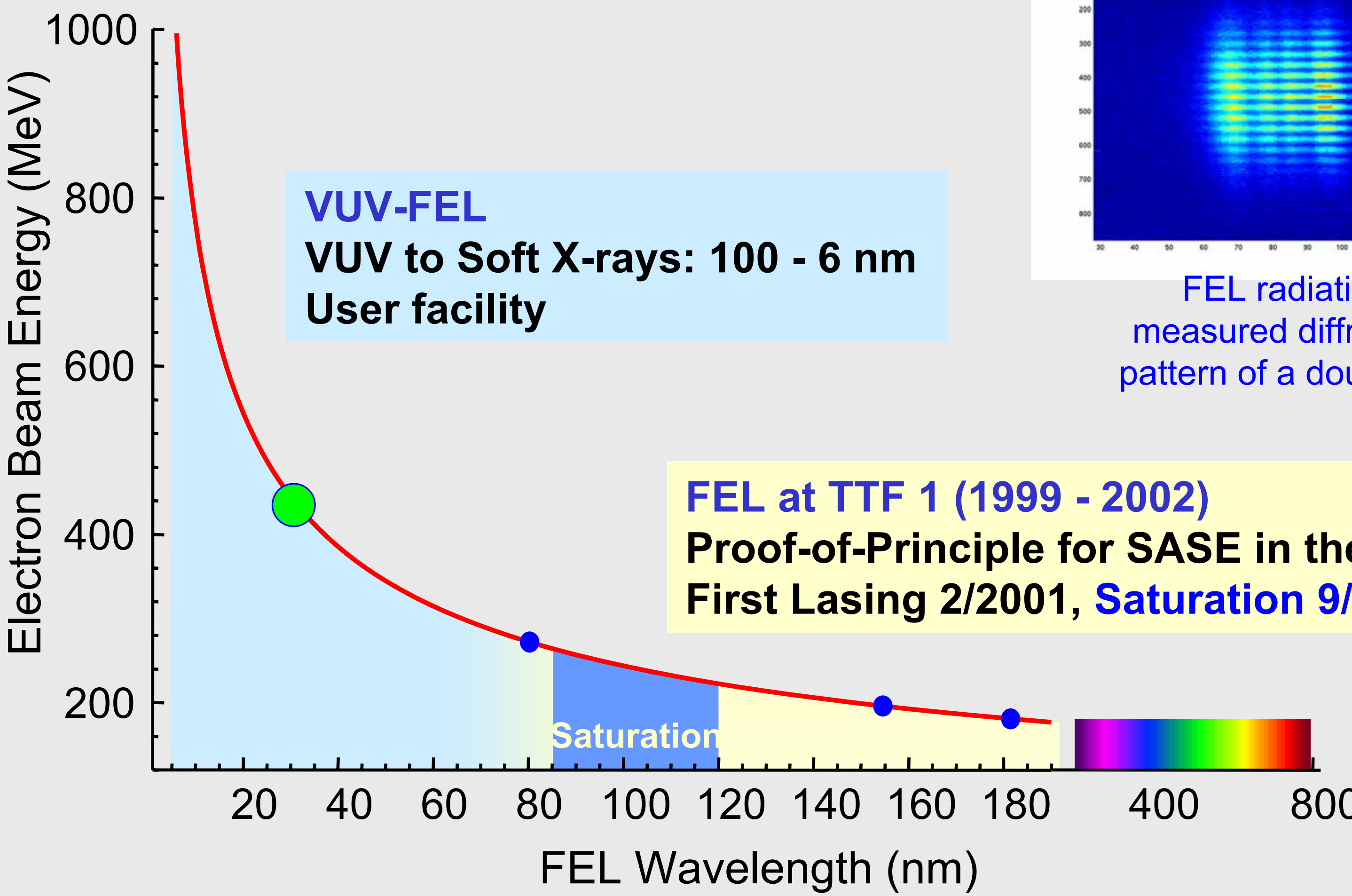
USA
LCLS - SLAC 2009

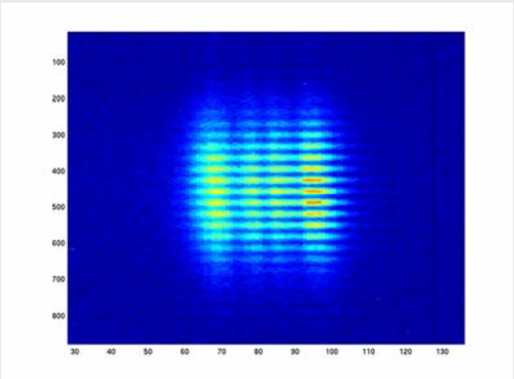
TESLA X - FEL at DESY



Courtesy Bart Faatz (DESY)

Beam Energy and Wavelength



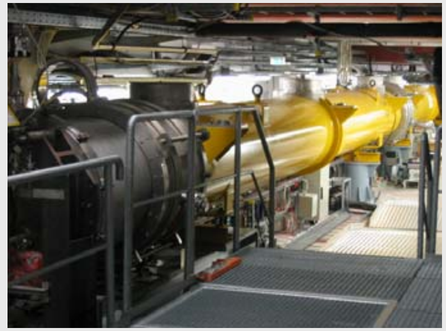


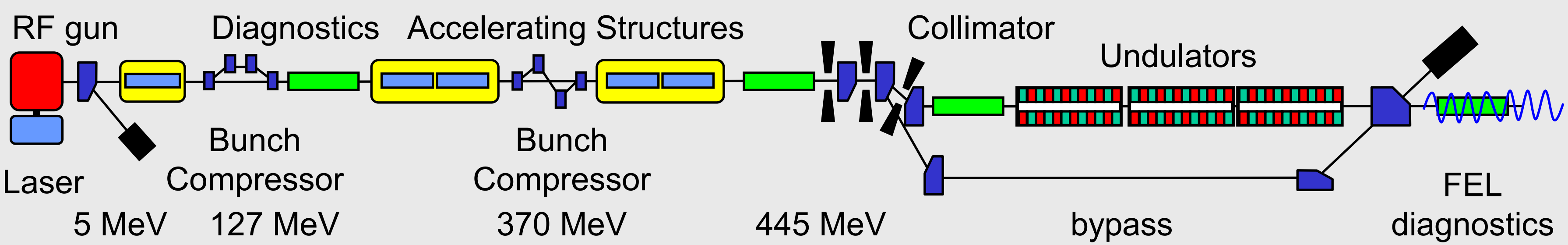
FEL radiation:
measured diffraction
pattern of a double slit

TESLA

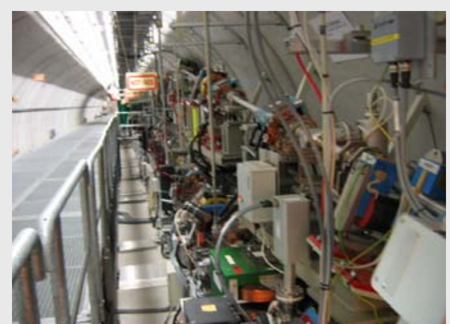
Courtesy Bart Faatz (DESY)

FLASH (DESY)

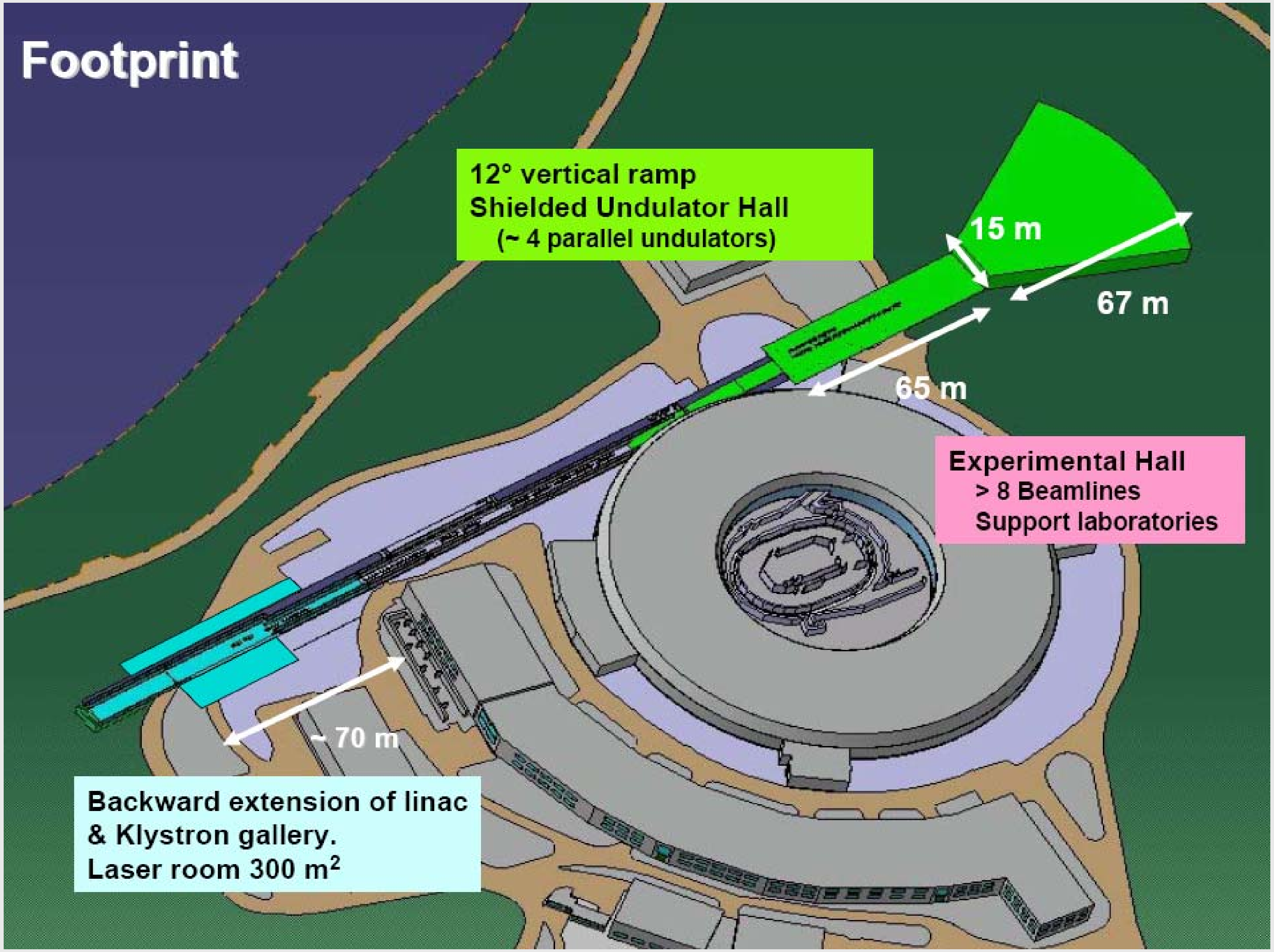




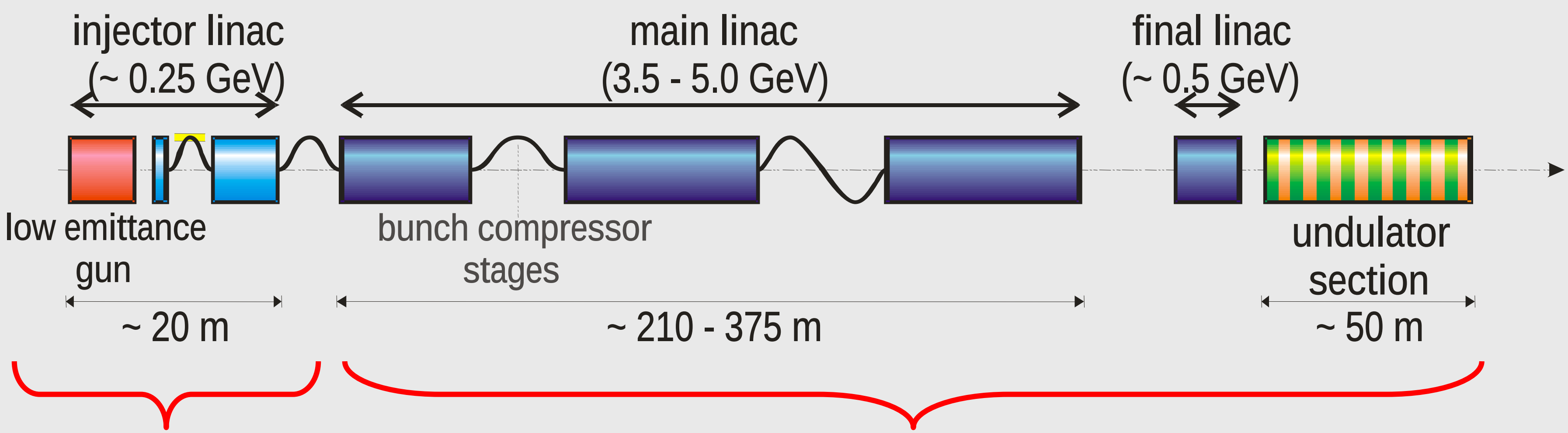



250 m

FERMI (Sincrotrone Trieste)



PSI-FEL (Switzerland)



Critical part of the machine

Similar problems as other projects

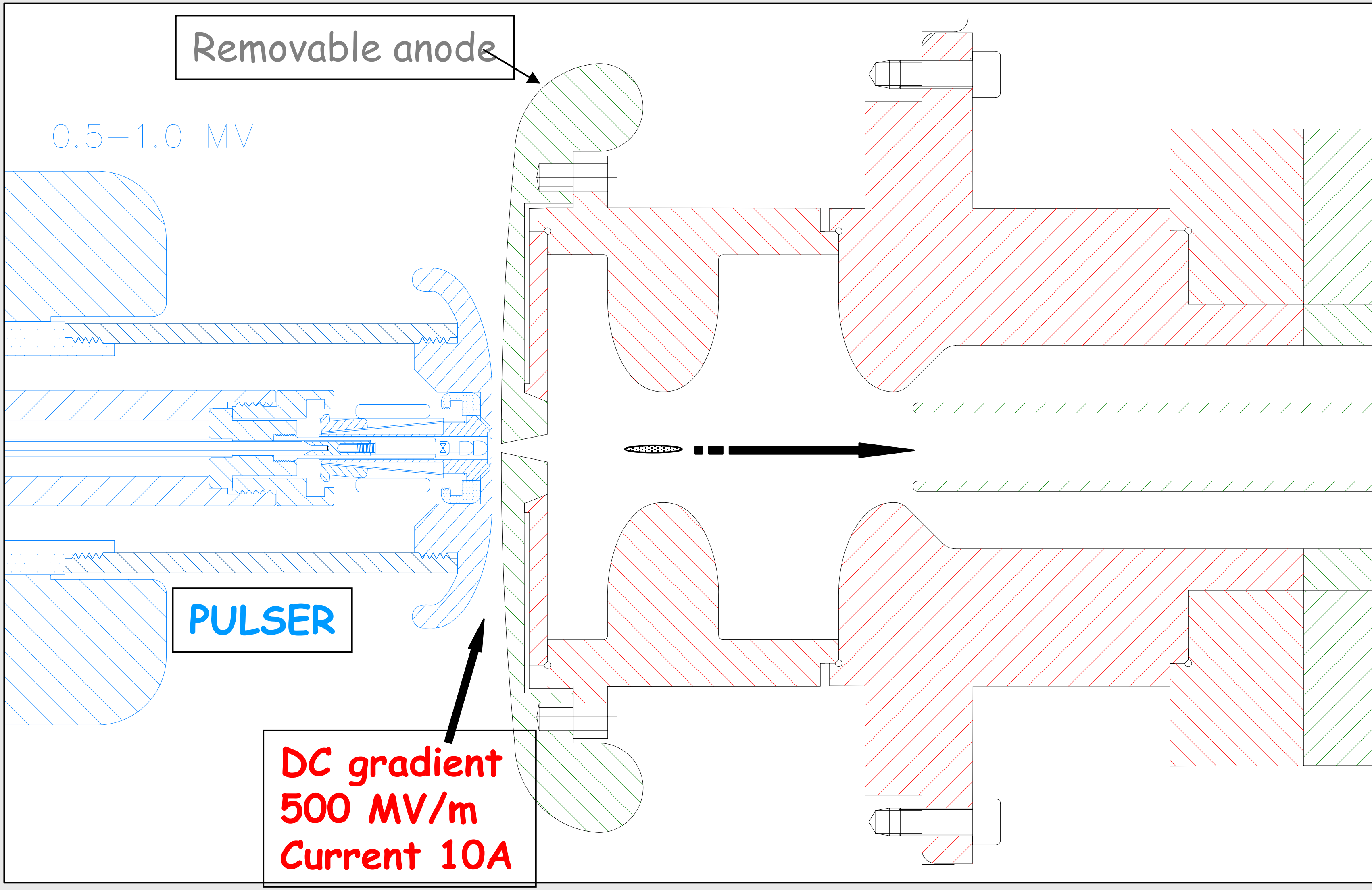
R. Bakker

PSI-XFEL Project

NEW APPROACH – has 4 characteristic elements:

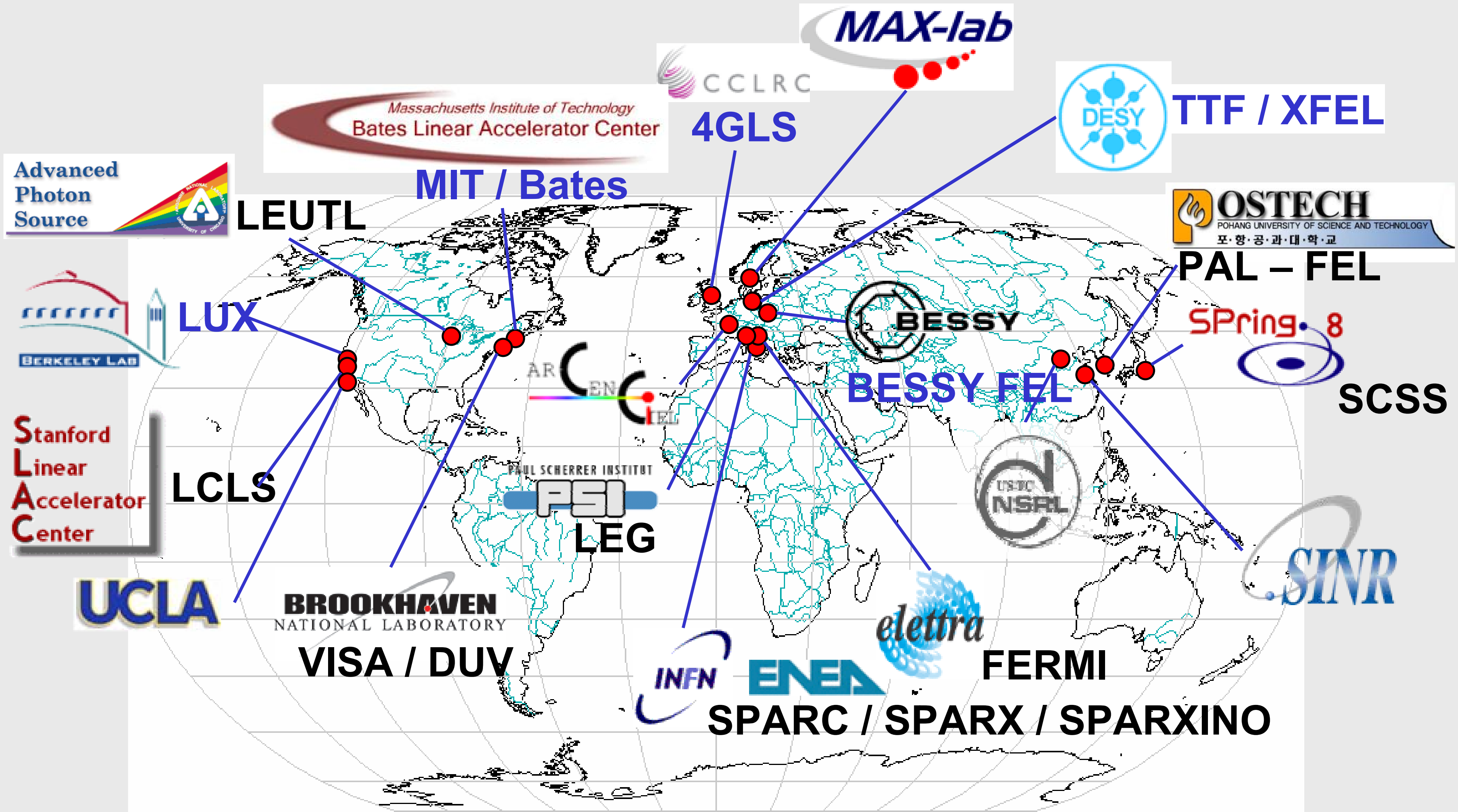
1. **Field emission from a nano-structured tip array**
   → homogeneous beam distribution
2. **Focusing of the individual beamlets**
   → reduction in emittance
3. **High gradient acceleration in diode configuration**
   → reduction of beam blow up due to space charge forces
4. **Two frequency cavity for linear gradient**
   → allows longer pulses and higher compression

CATHODE AND DIODE ASSEMBLY WITH 2 FREQUENCY RF-CAVITY



… and many more !

Single Pass FEL Activity



SC technology / NC technology

THE END