ACCELERATOR GROUP
European Physical Society

IPAC23

14th International Particle Accelerator Conference

IPAC '23

7 - 12 May 2023

VENICE, ITALY

Student Tutorials 6,7 May

Giovanni De Ninno

Free-electron lasers: How do they work

Student Tutorials 5,6 May


wehi.tv
DrewBerry
DNA replication
2003

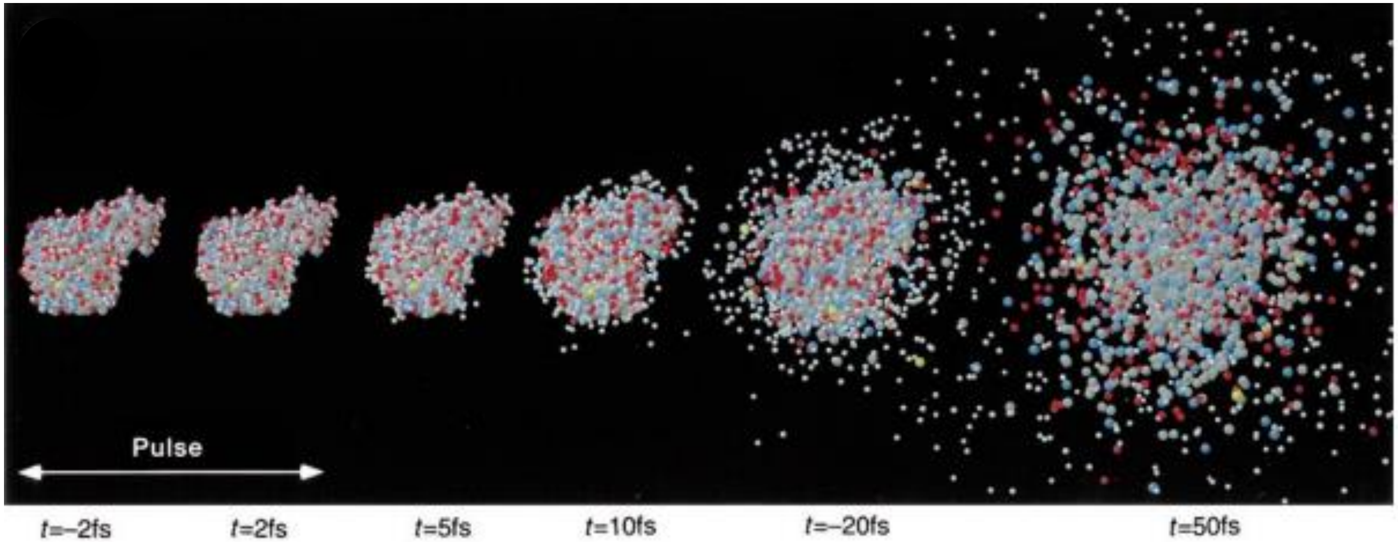
Static properties of matter

Static picture of a macro-molecule

Need light !

Required properties

- Short wavelength (X-ray)
- High energy per pulse
- Ultra-short pulse (few femtoseconds)
- Coherence



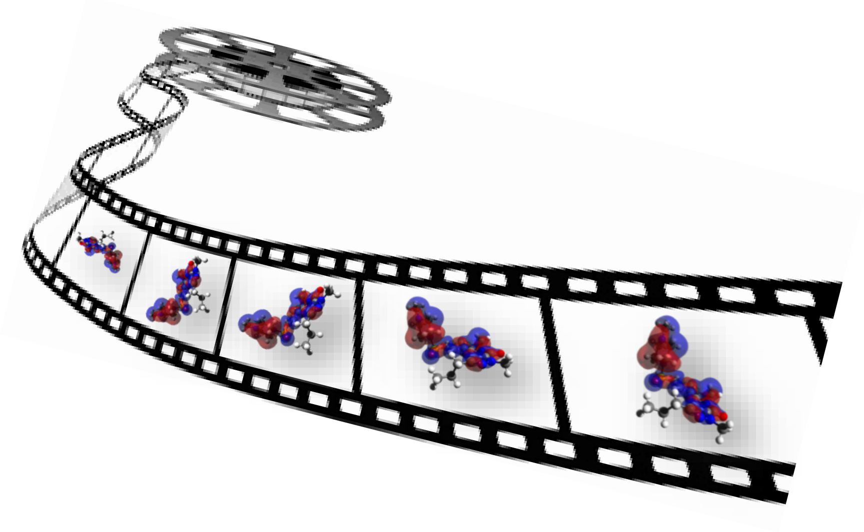
Pump-probe technique

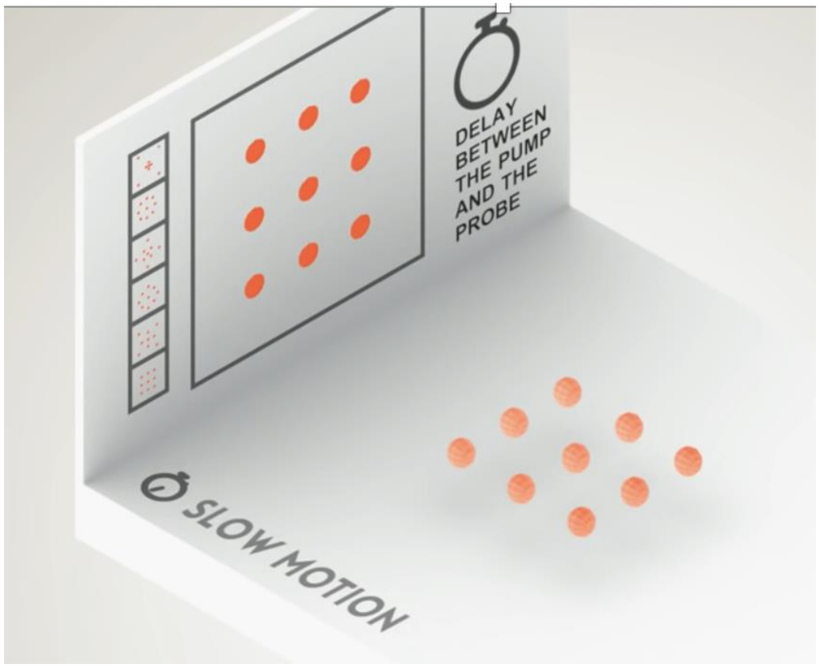
https://www.youtube.com/watch?v=YTj4Hi1HdJQ

Dynamical properties of matter

Dynamics of a molecular, atomic or electronic process

Courtesy of C. Vozzi





Required properties

- Ultra-short pulses (few femtoseconds)
- Monochromaticity
- Defined polarization
- Stability and reproducibility

Want list

In order to be suited for the study of both static and dynamical matter properties, a light source should produce pulses with the following properties:

- Short-wavelength (X-rays)
- High-energy
- Ultra-short (few femtoseconds, or less)
- Coherence
- Monochromaticity
- Tunabilty in wavelength
- Defined polarization
- Stability and reproducibility

Motivation

In the the **IR/UV spectral region**, the large majority of previously mentioned properties can be obtained by means of conventional table-top lasers

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However, in the **VUV/X-ray spectral domain** only light sources based on "free" accelerated electrons are able to meet all requirement

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In the the **IR/UV spectral region**, the large majority of previously mentioned properties can be obtained by means of conventional table-top lasers

However, in the **VUV/X-ray spectral domain** only light sources based on "free" accelerated electrons are able to meet all requirement

During this lecture, we will review the principle, the challenges and the perspectives of the light sources built with the aim of generating radiation with laser-like properties in the VUV/X-ray spectral domain, i.e.

free-electron lasers

Outline

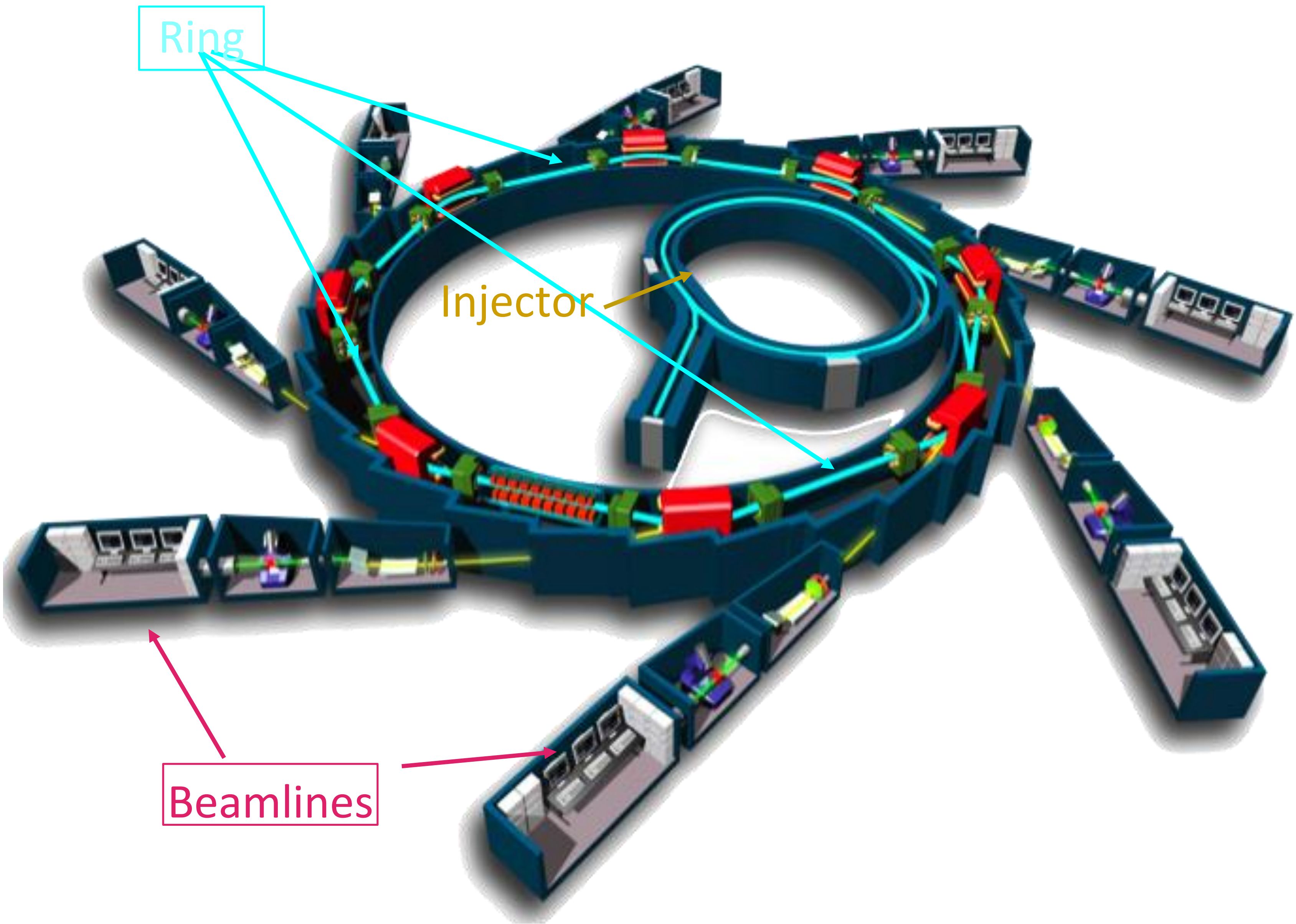
- From synchrotron radiation to free-electron lasers (**FEL's**)

- Basic principles of FELs

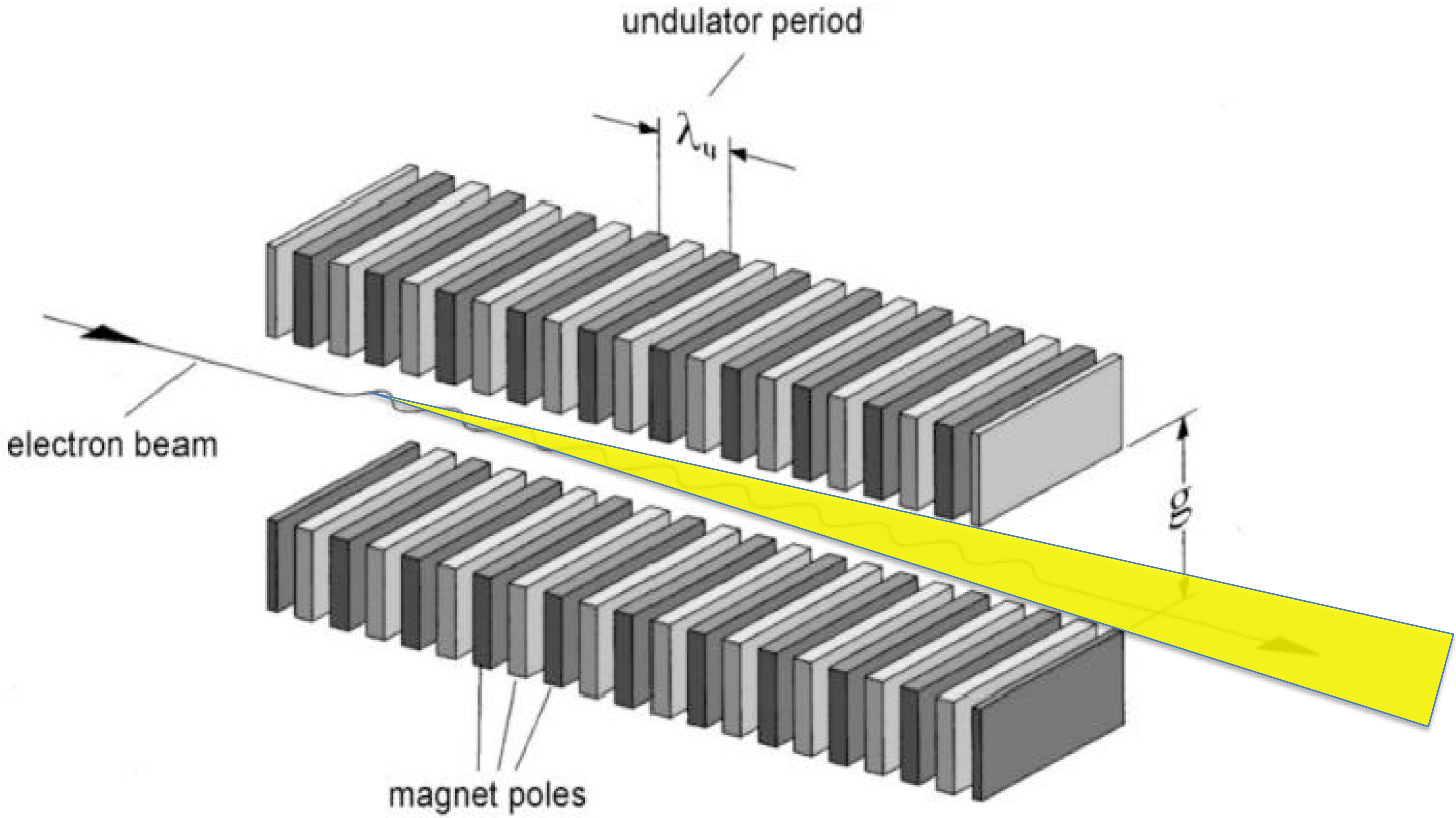
- Different schemes for producing FEL light

- Properties of FEL radiation

Synchrotron



Undulator



Undulator's spectral properties

Emitted wavelength

$$\lambda_n = \frac{\lambda_u}{2n\gamma^2}(1 + K^2)$$

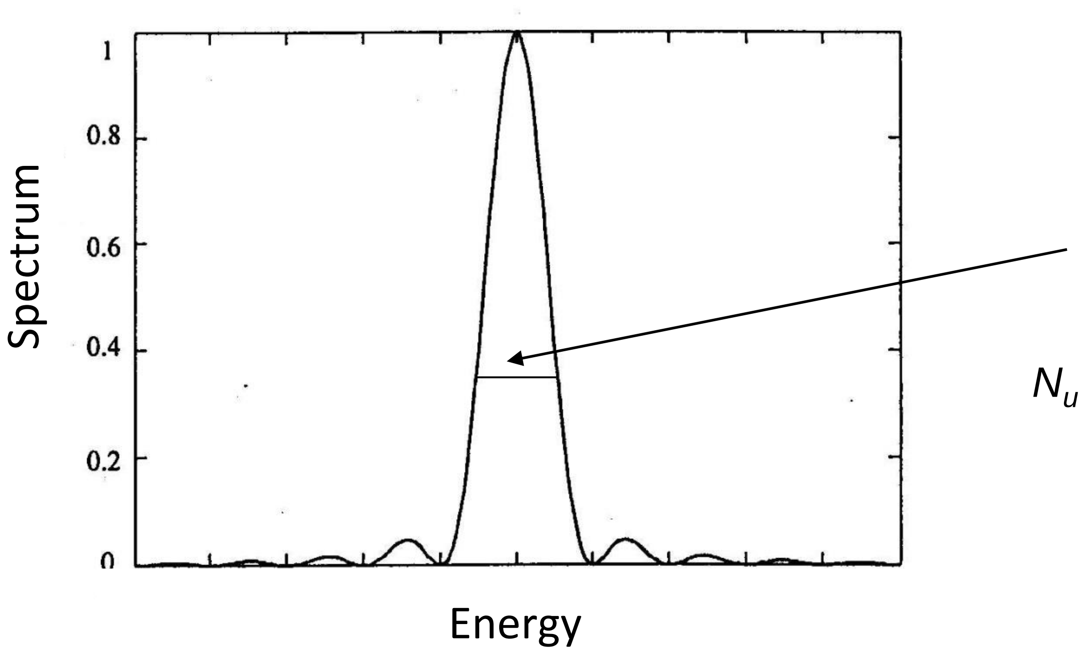
λ_u undulator's period

γ electrons' energy

$K \propto \lambda_u B_0$ undulator's strength

B_0 peak undulator's field

n is an integer



Relative bandwidth

$$\frac{\Delta E}{E} = \frac{1}{nN_u}$$

N_u : number of undulator's periods

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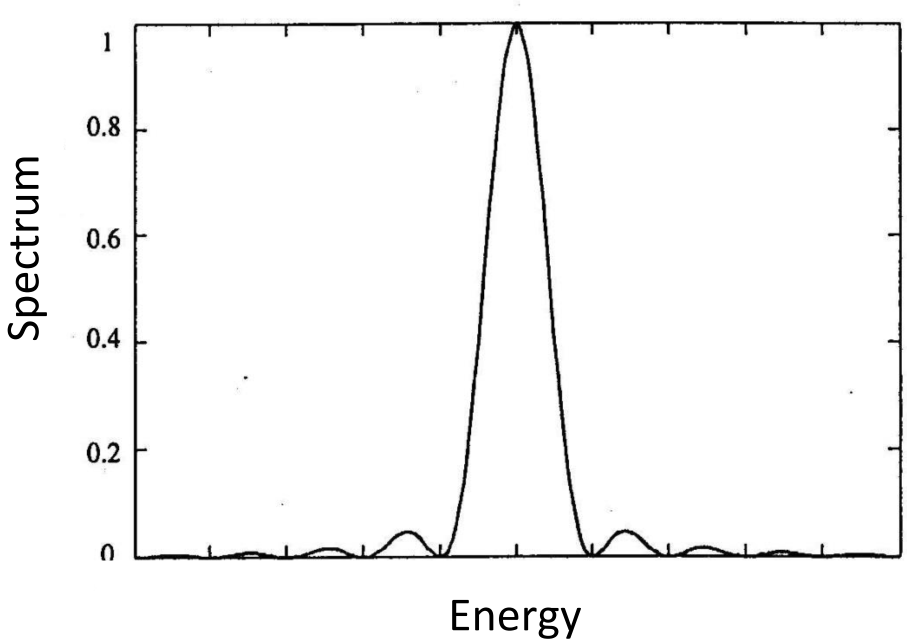
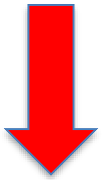


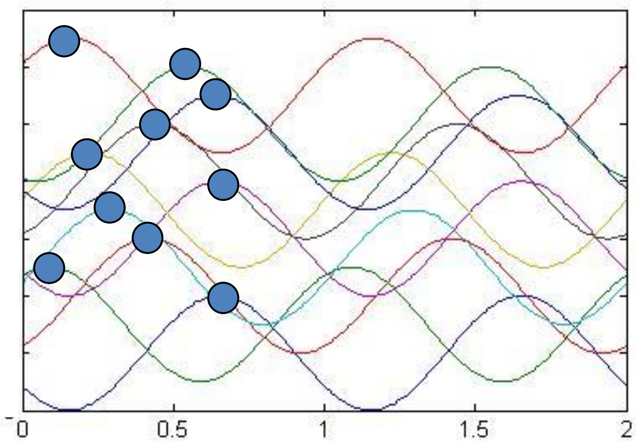
Radiated power proportional to the number of electrons



Incoherence!

A question of coherence…

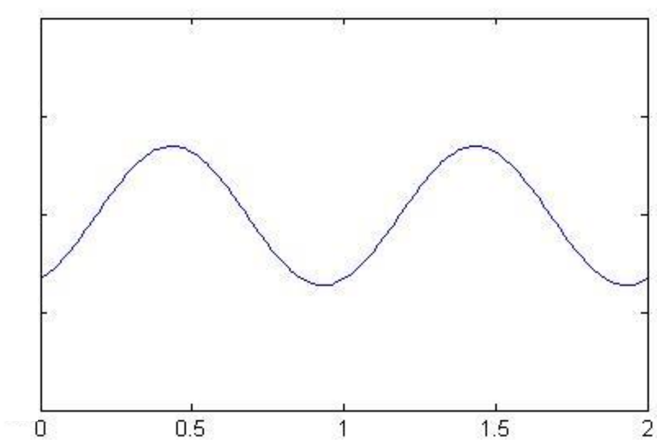
Incoherent emission
(Synchrotron radiation)



Radiated power

Radiation cycles

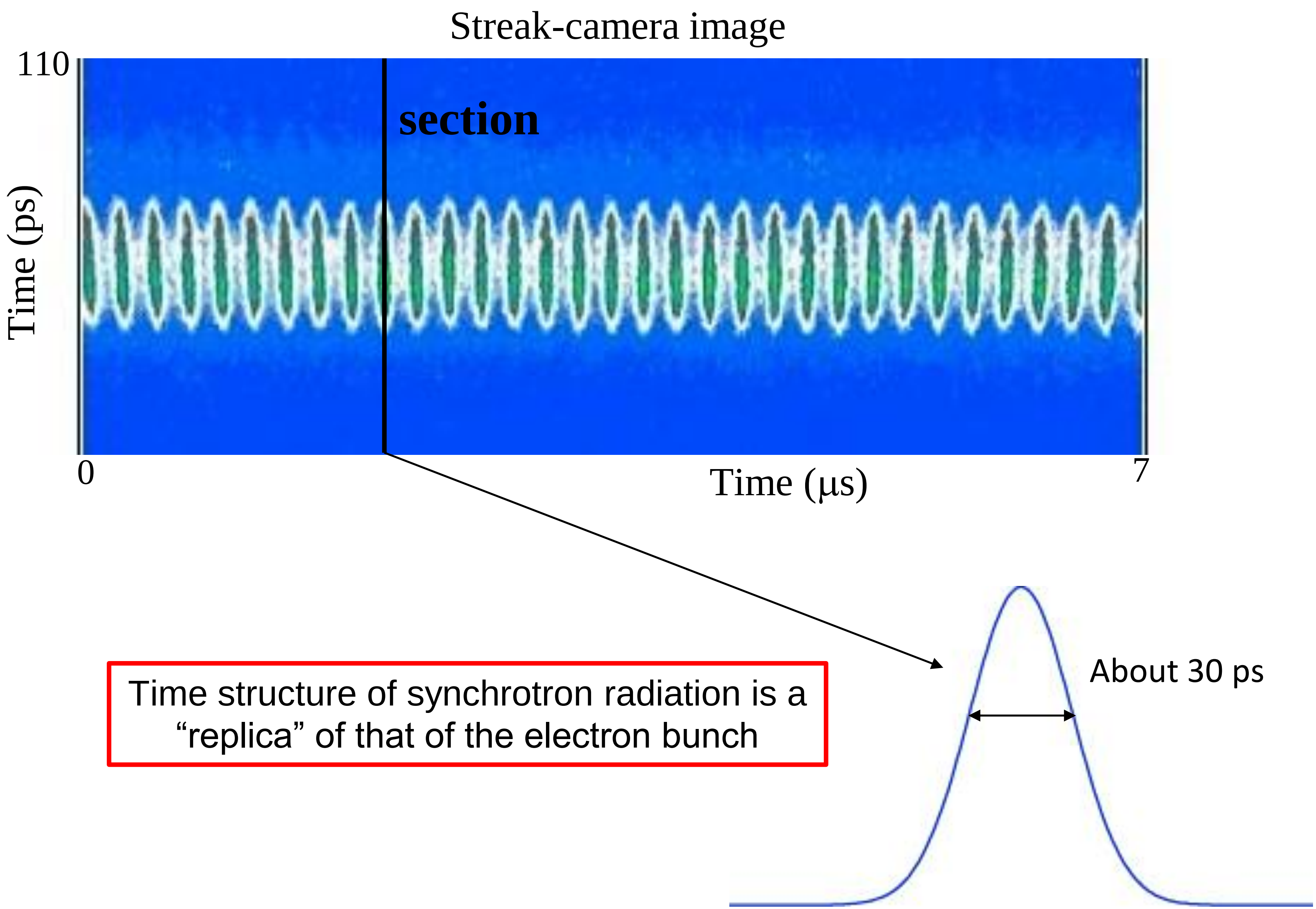
Radiated power
<u>linear</u> with electron current



Radiated power

Radiation cycles

Temporal structure



Time structure of synchrotron radiation is a "replica" of that of the electron bunch

Synchrotron radiation

Tunability: Broad (between IR and X-rays)

Shot-to-shot reproducibility: Very good →

- power stability
- spectral stability
- pointing stability
- low temporal jitter

Polarization: Fully adjustable

Repetition rate: hundreds of MHz

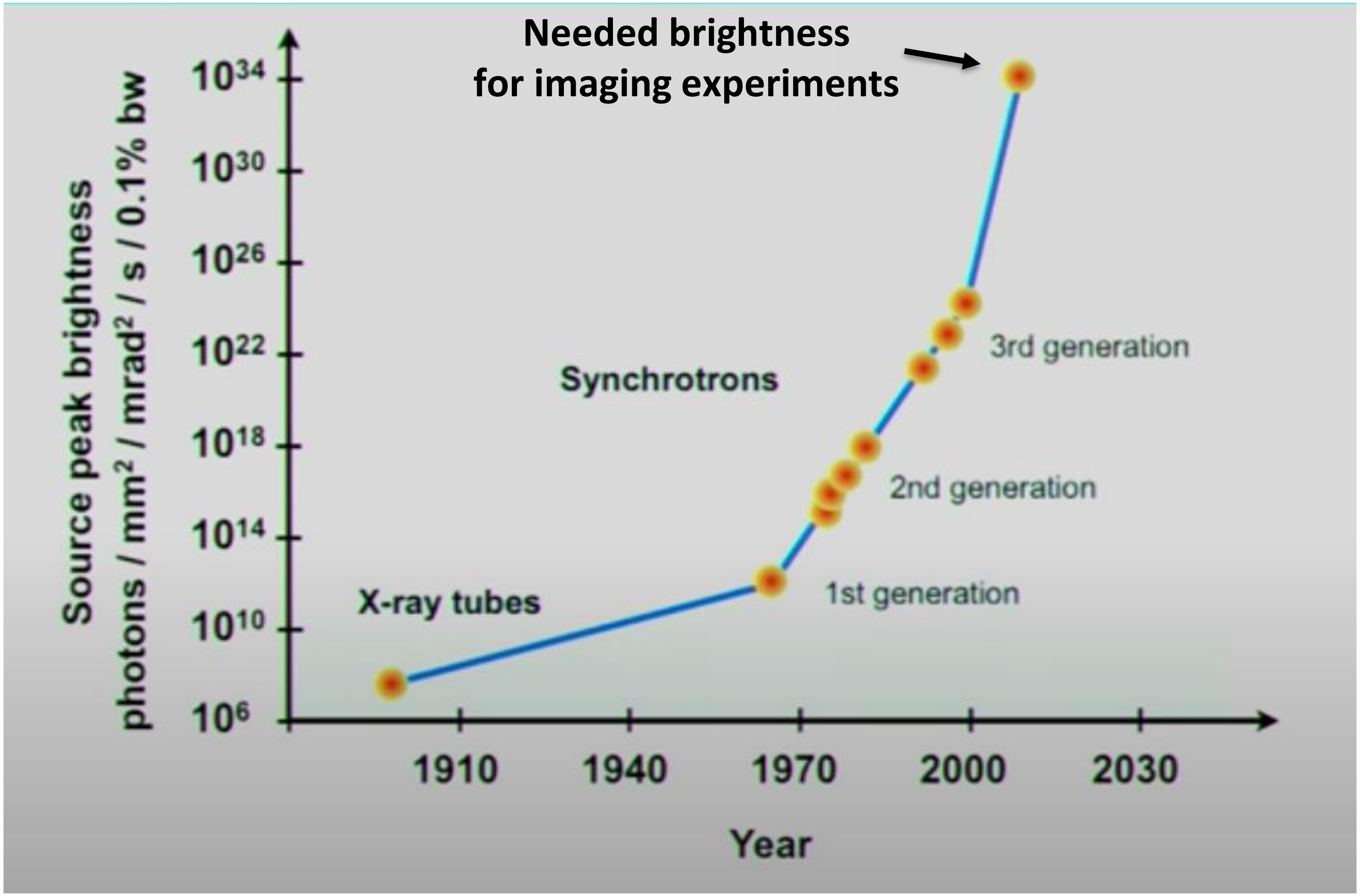
Peak brightness: ≈ 10^{25} ph/s/0.1%BW/mm^2/mrad^2 (at 10 keV)

Pulse duration: tens of picoseconds

Natural spectral resolution: ≈ few percent

Coherence: good transverse, poor longitudinal

Peak brightness



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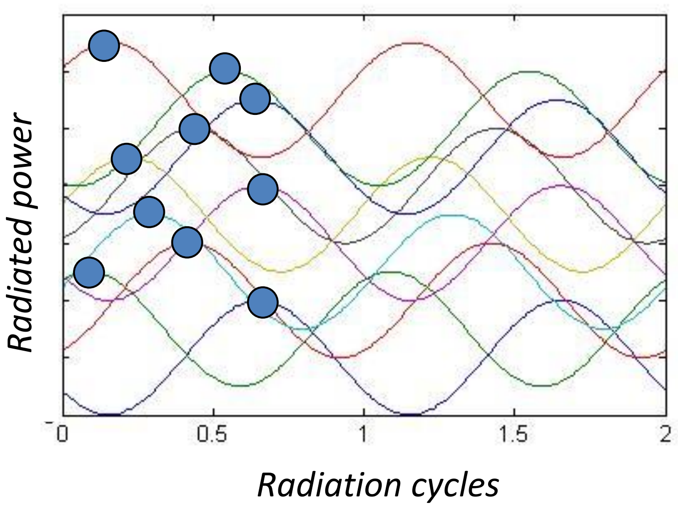
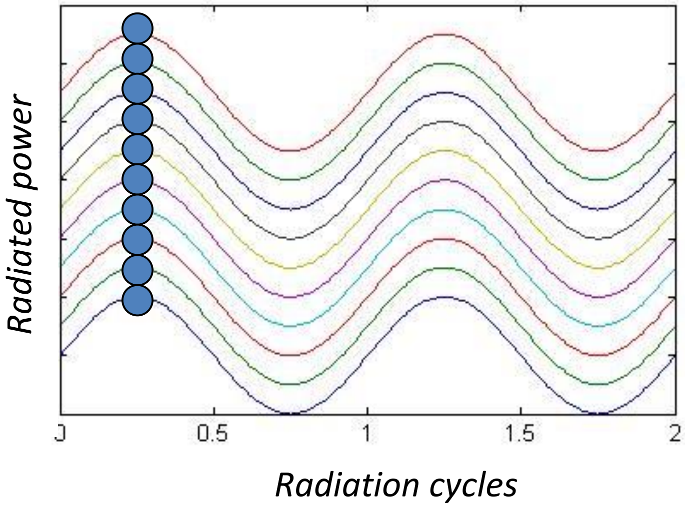


Coherent emission



A question of coherence…

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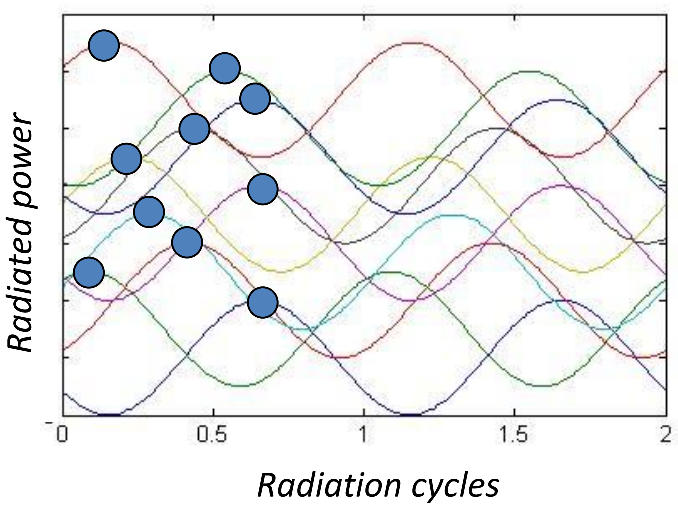
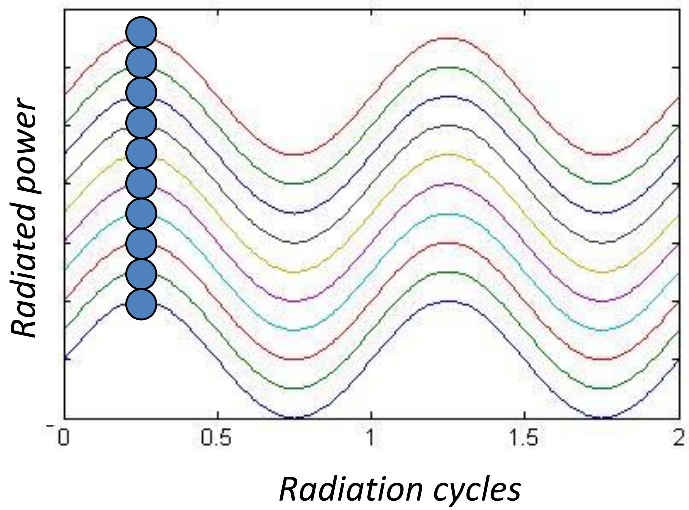
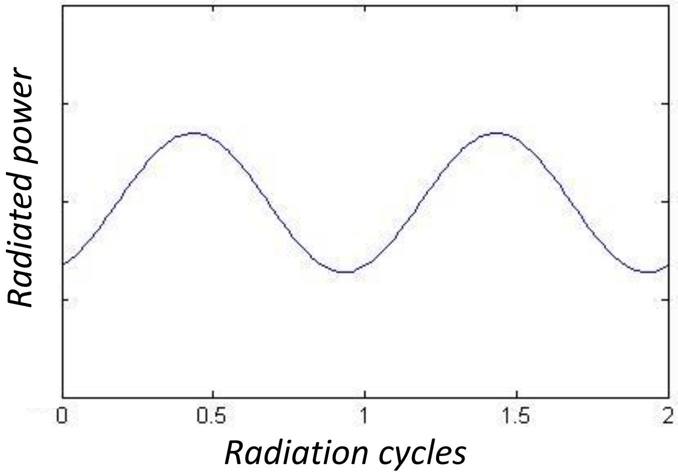


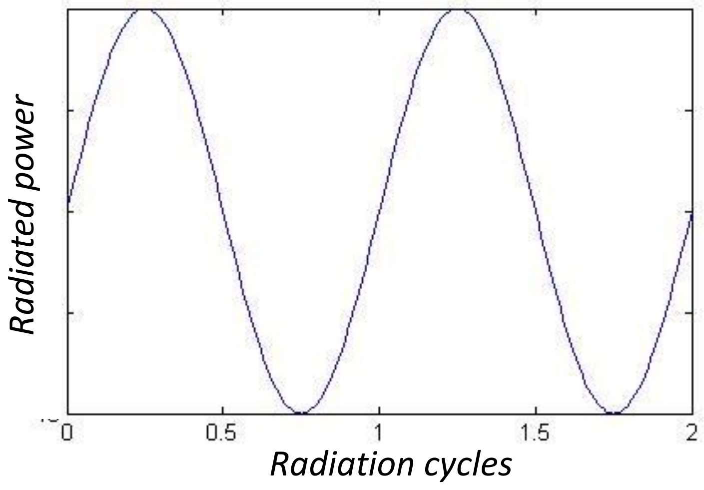
Coherent emission



Radiated power
linear with electron current

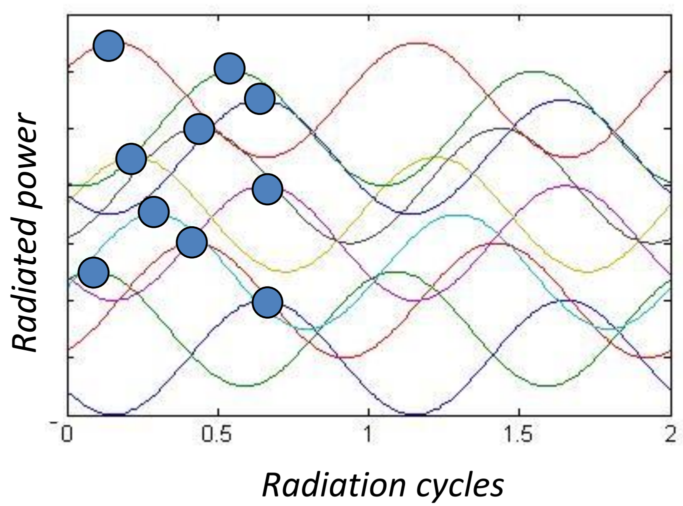


Radiated power
quadratic with electron current

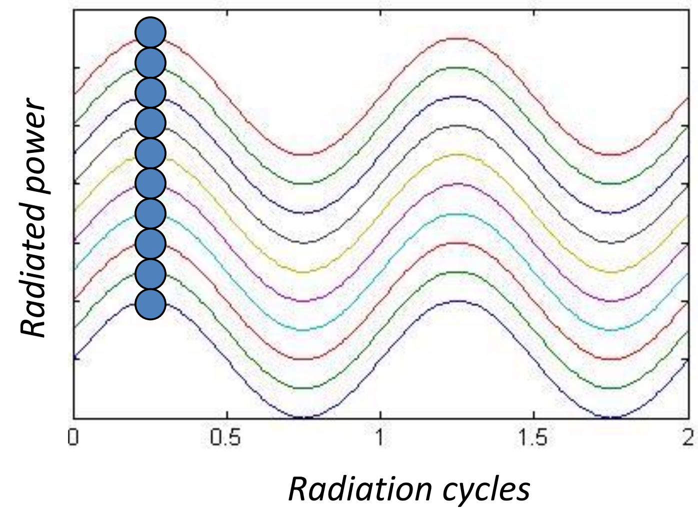


A question of coherence…

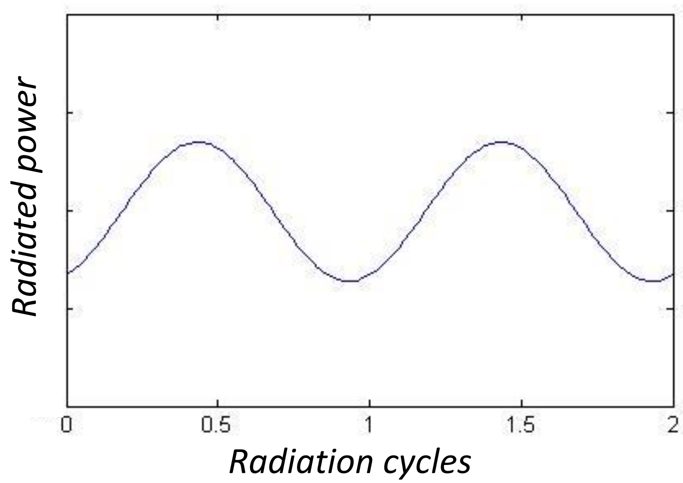
Incoherent emission
(Synchrotron radiation)



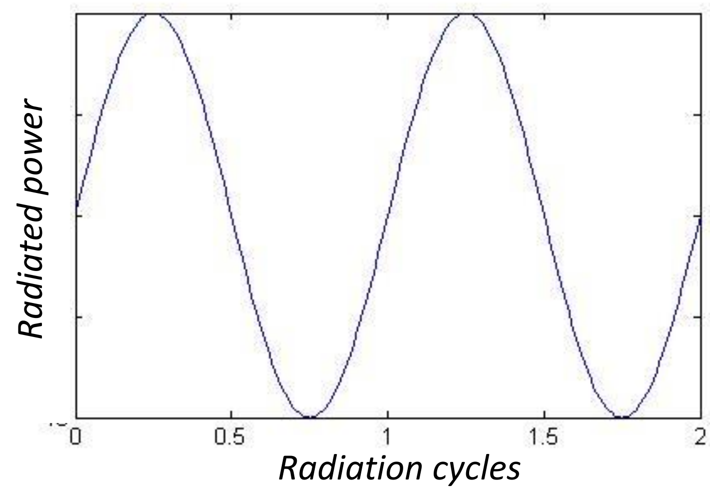
Coherent emission
(Free electron laser)



Radiated power
<u>linear</u> with electron current



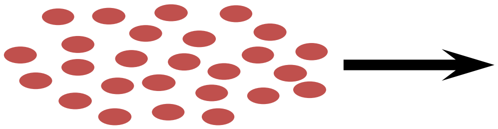
Radiated power
<u>quadratic</u> with electron current



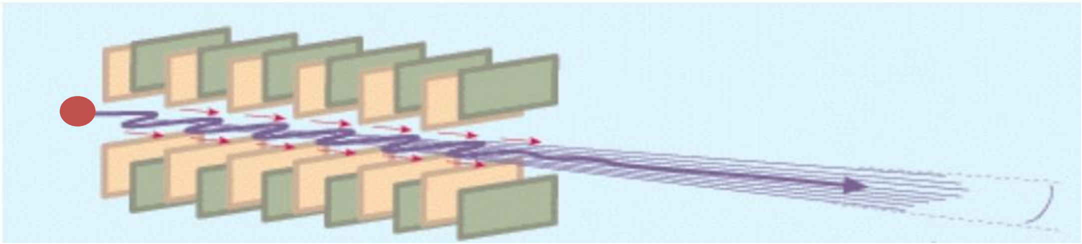
Fundamentals of FEL’s

FEL basic ingredients

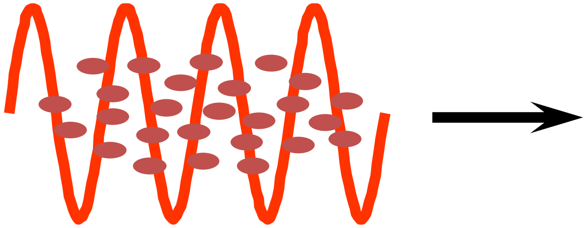
Relativistic **electron beam**



Undulator



Electromagnetic field co-propagating with the electron beam and **getting amplified** to the detriment of electrons' kinetic energy

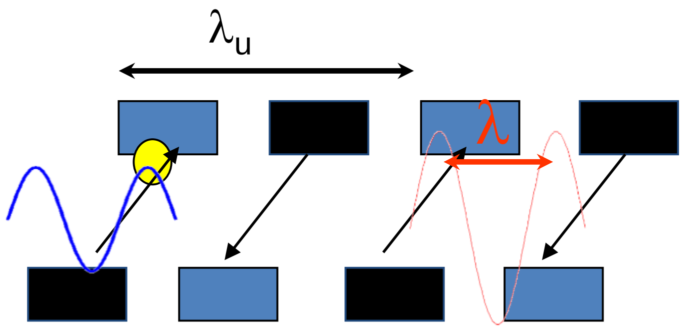


Light amplification: resonance condition

Electrons move slower than the co-propagating electromagnetic wave (**slippage**)

Resonance condition:

The slippage between the electromagnetic wave and a given electron, while the electron moves forward by one undulator period (λ_u), must be equal to the field wavelength λ.



When this happens, the relative phase between the radiation emitted by the electron and the co-propagating field remains constant (constructive interference)

Resonance condition

$$\lambda_n = \frac{\lambda_u}{2n\gamma^2}(1 + K^2)$$

Theoretical framework

Evolution of electron's momentum and energy:

$$\frac{d\left(\gamma m\vec{v}\right)}{dt} = e\left[\vec{E} + \frac{v}{c}\times\left(\vec{B}_{und} + \vec{B}\right)\right]$$

$\vec{E},\vec{B}$

electric and magnetic fields
of the co-propagating wave

$$\frac{d\left(\gamma mc^2\right)}{dt} = e\vec{E}\cdot\vec{v}_\perp$$

Evolution of the co-propagating wave (1D)

$$\left(\frac{\partial^2}{\partial z^2} - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)\vec{A}(z,t) = -\frac{4\pi}{c}\vec{J}_\perp(z,t)$$

$\vec{A}$ vector potential

$\vec{J}_\perp$ electrons' transverse current

Theoretical framework

$$\vartheta_j = \left(\frac{2\pi}{\lambda} + \frac{2\pi}{\lambda_w}\right) z - \omega t$$

phase of the *j*-th electron in the combined "ponderomotive" (radiation + undulator) field

$$p_j = \frac{\gamma_j - \gamma_r}{\gamma_r}$$

γ_j energy of the j-*th* electron

γ_r resonance energy

Under some approximations the previous equations can be reduced to

$$\begin{cases} \dfrac{d\theta_j}{dz} = p_j \\ \dfrac{dp_j}{dz} = -\left(A \exp\left[i\theta_j\right] + c.c\right) \\ \dfrac{dA}{dz} = \langle \exp[-i\theta] \rangle \equiv b \end{cases}$$

Bunching

$$b = \frac{1}{N} \sum_{j=1}^{N} \exp(-i\theta_j)$$

N: electrons' number

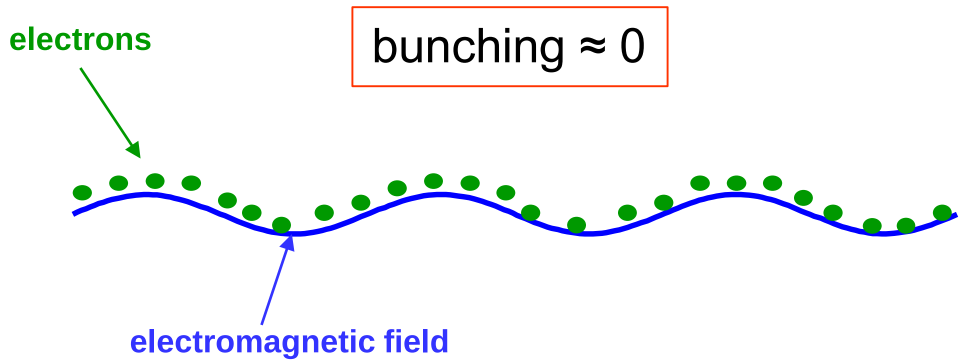
R. Bonifacio et al. Nuovo Cimento, 13 (1990)

Bunching as source term

Initial condition:

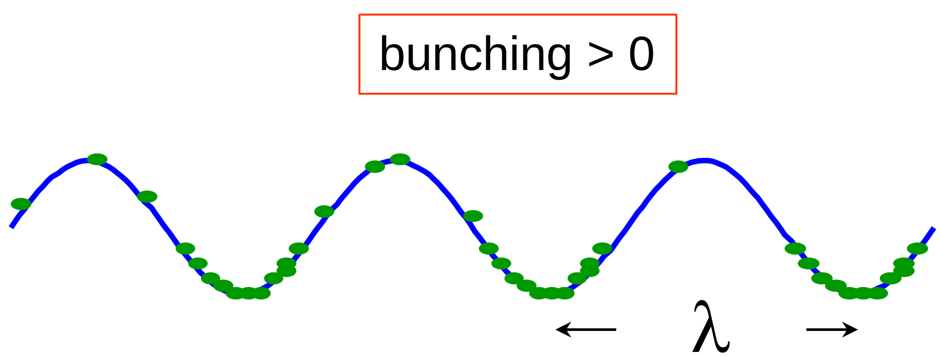
- weak electromagnetic field

- electrons randomly distributed in phase

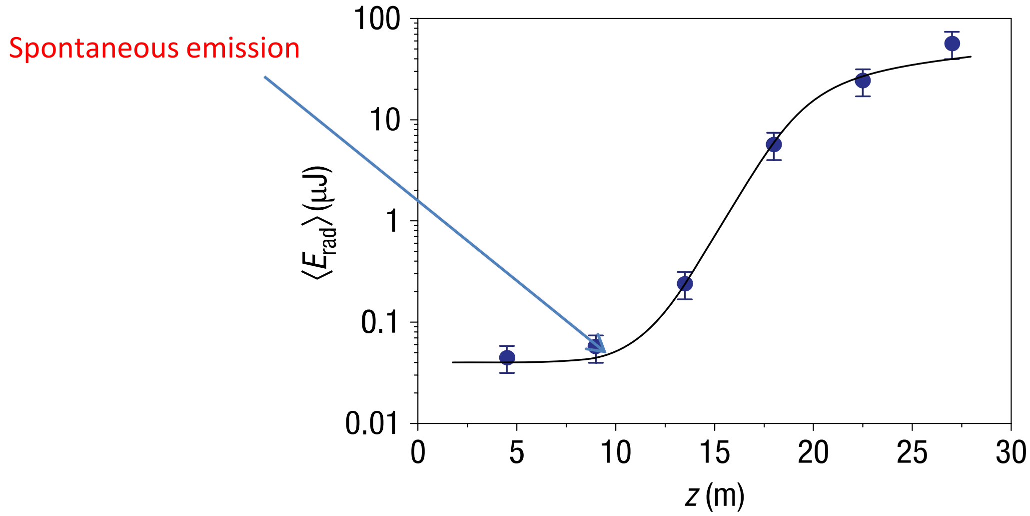


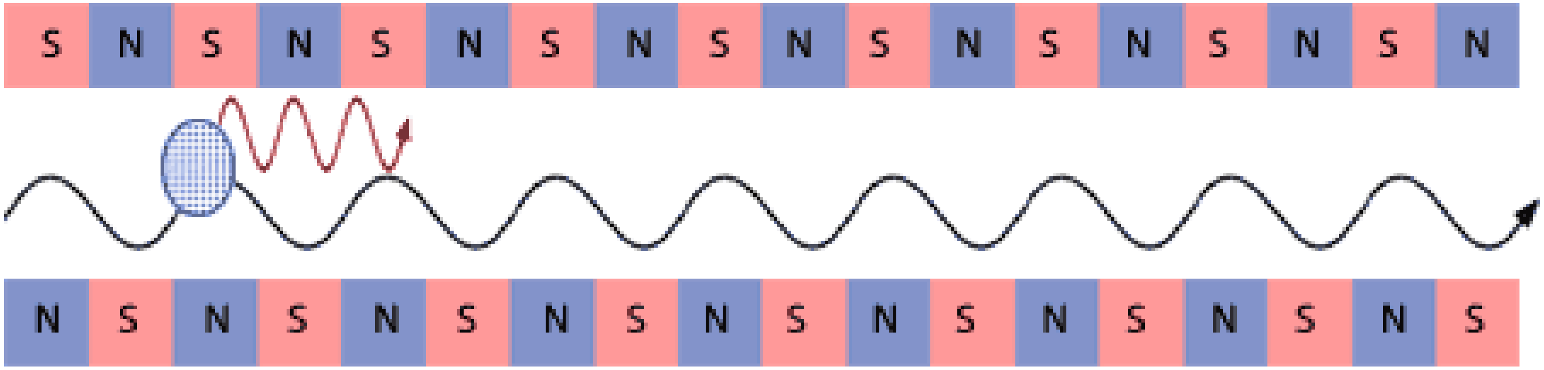
Electrons start bunching on a λ scale

and the wave is amplified



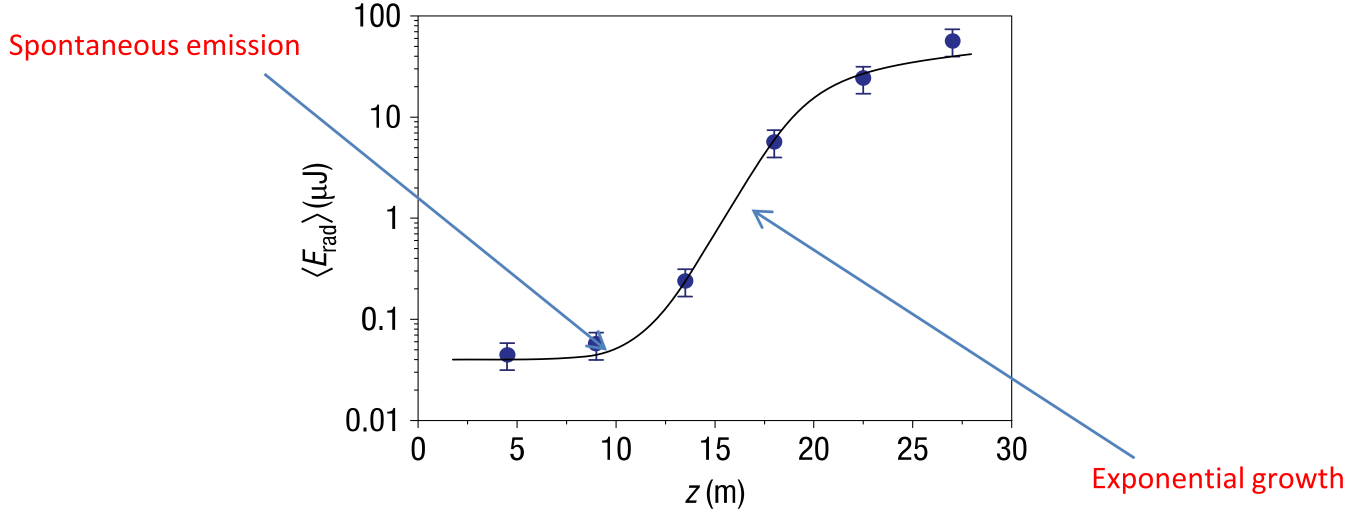
Self-amplified spontaneous emission

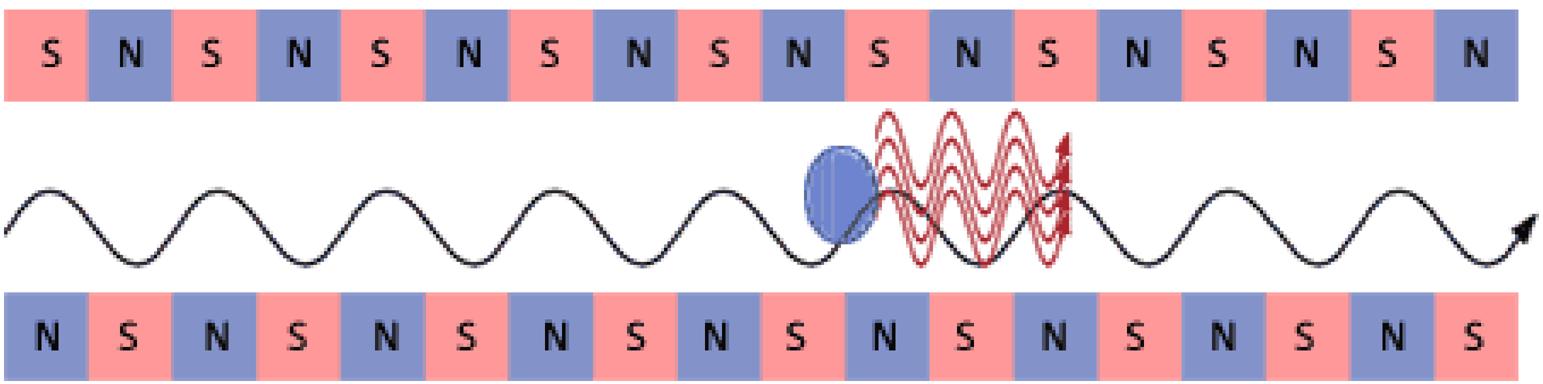




Pictures from: www-ssrl.slac.stanford.edu/lcls/glossary.html

Self-amplified spontaneous emission





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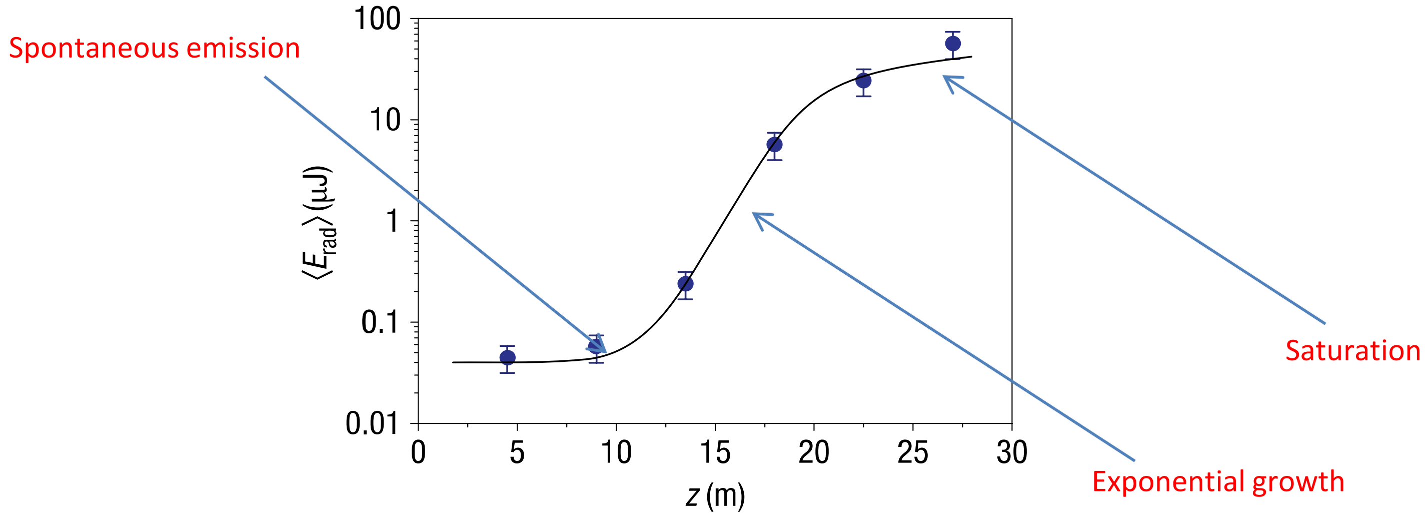
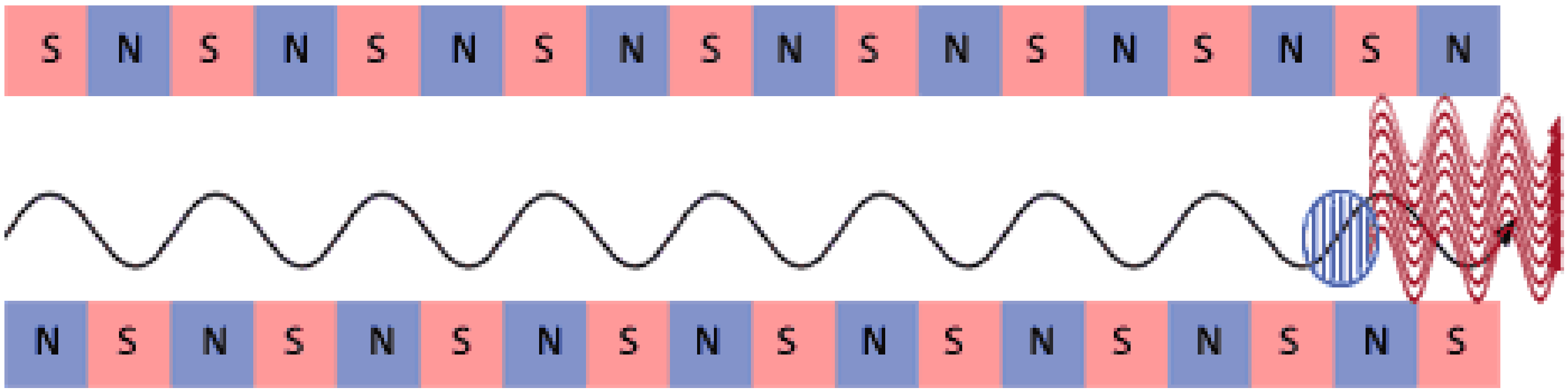
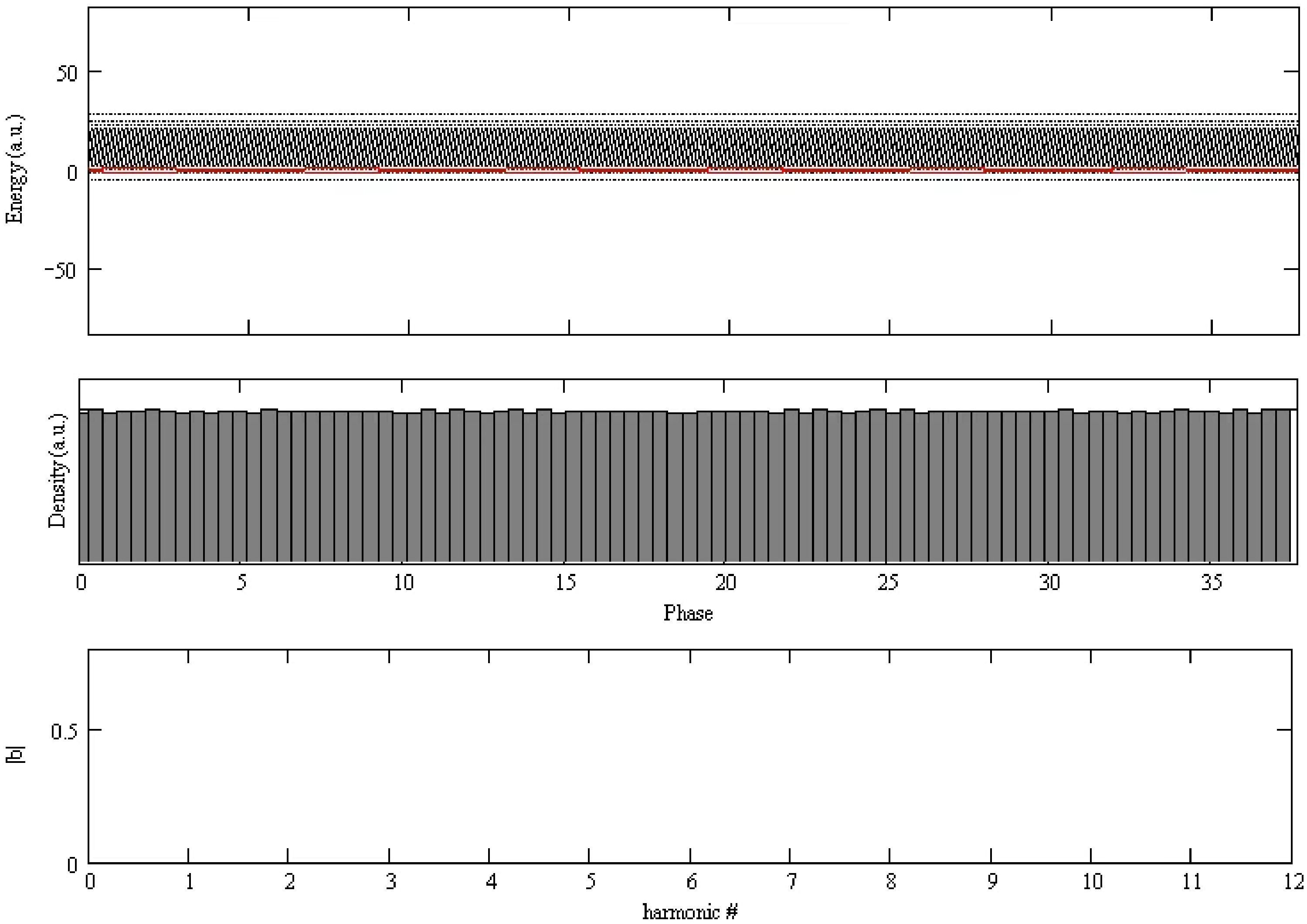
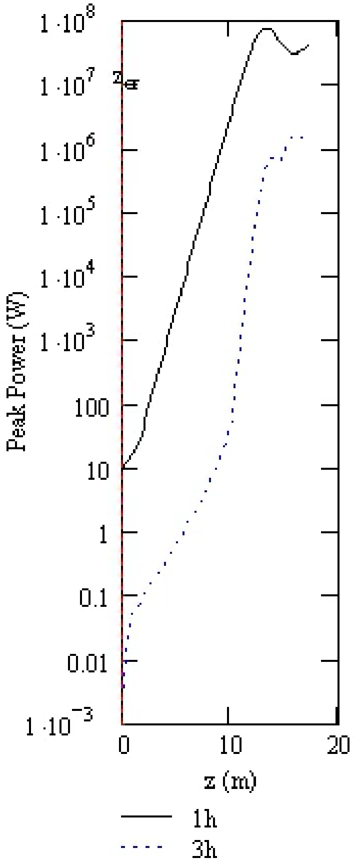


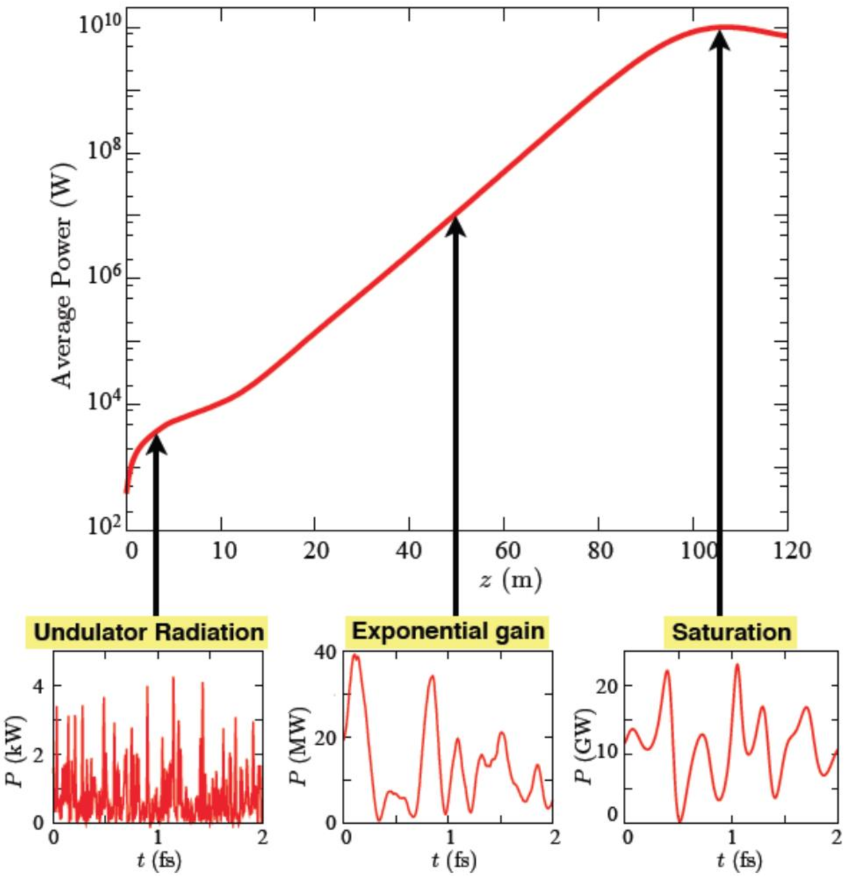


Bunching evolution





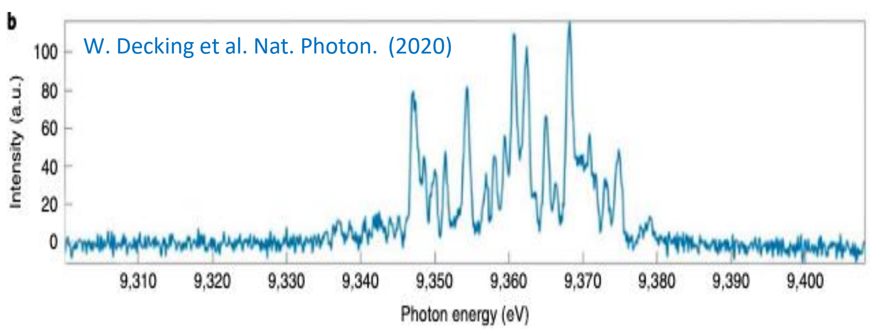
Self-amplified spontaneous emission (SASE)



- X-ray emission
- Output power: several of GW
- Pulse duration: tens of fs
- Spectral bandwidth: 10^{-3}
- High degree of transverse coherence

- Limited longitudinal coherence
- Strong shot-to-shot fluctuations

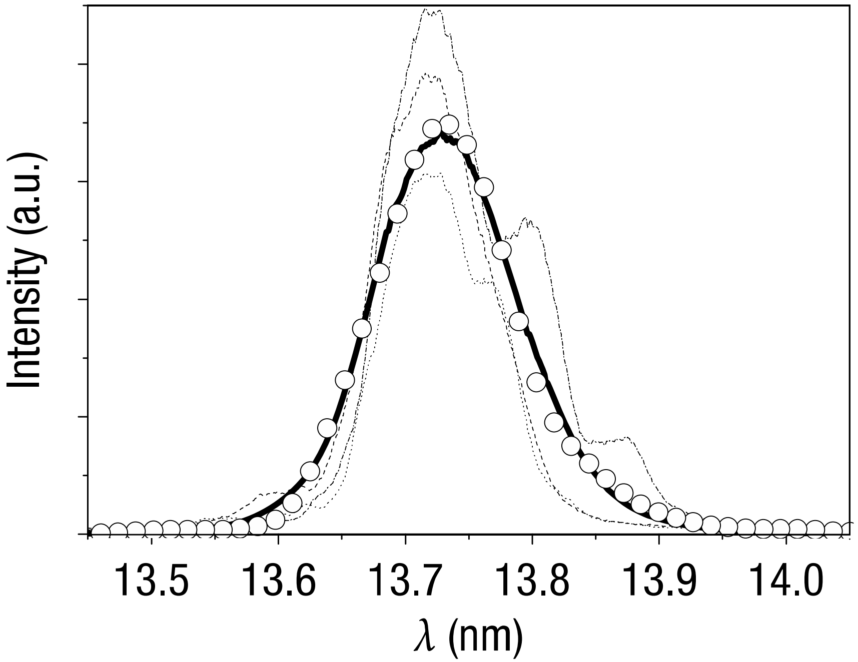
XFEL,Hamburg (Germany)



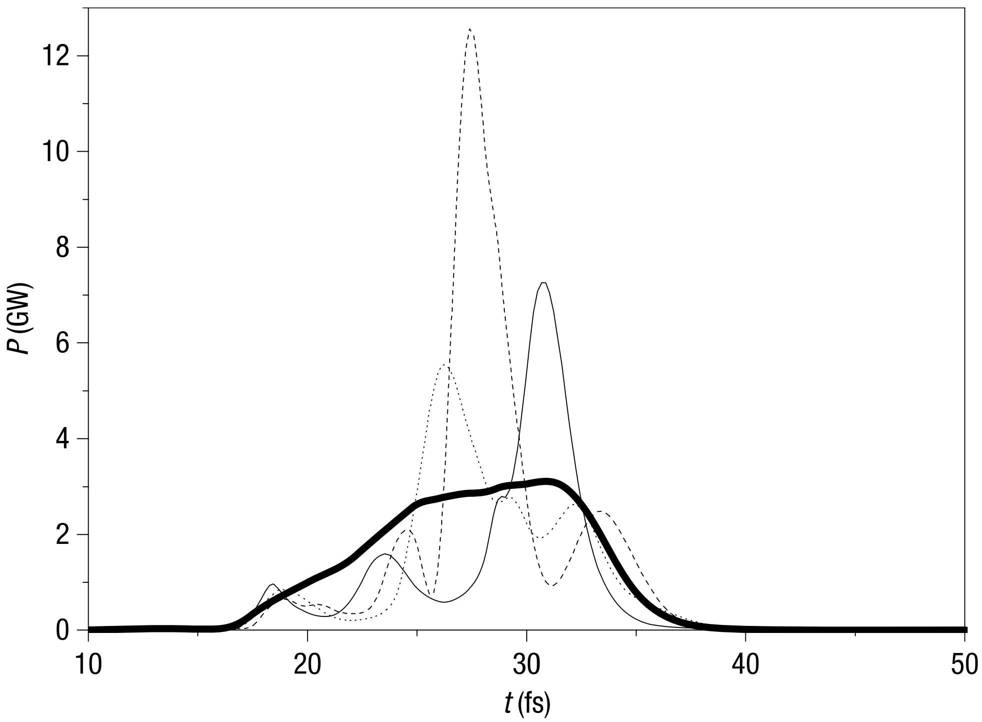
SASE spectral and temporal performance

(FLASH FEL, Hamburg, Germany)

Spectral profile



Temporal profile



W. Ackermann et al., Nature, 2007

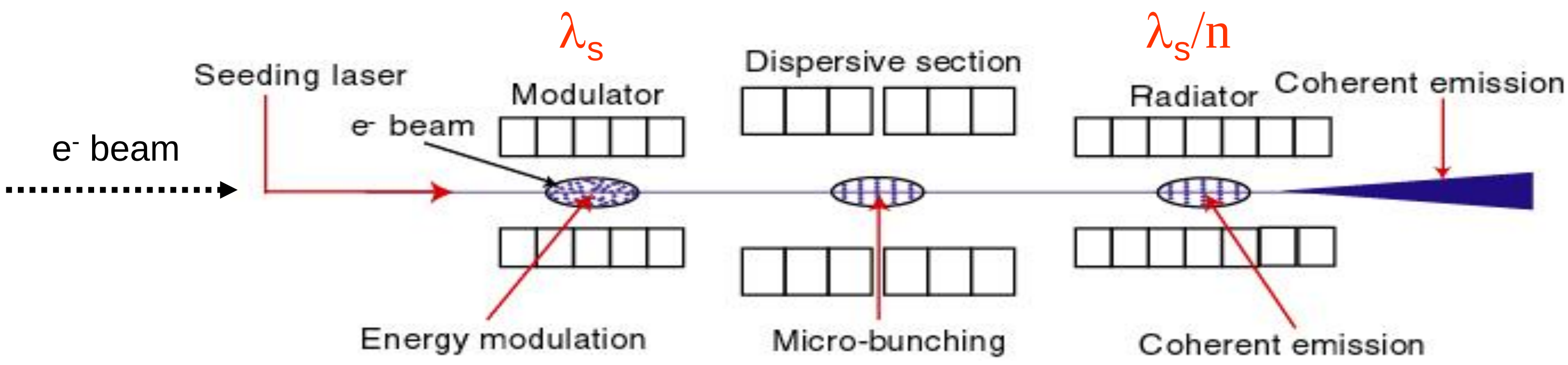
How to overcome SASE limits?

Use an **external coherent seeding** signal
(instead of spontaneous emission)
to generate electron bunching

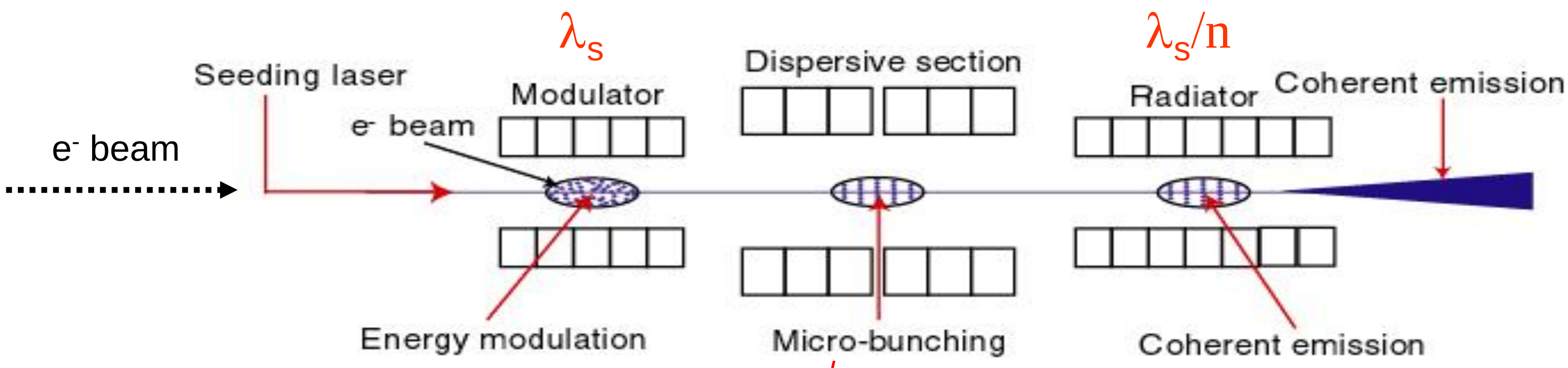
↓

Seeded High-Gain Harmonic Generation (**HGHG**)

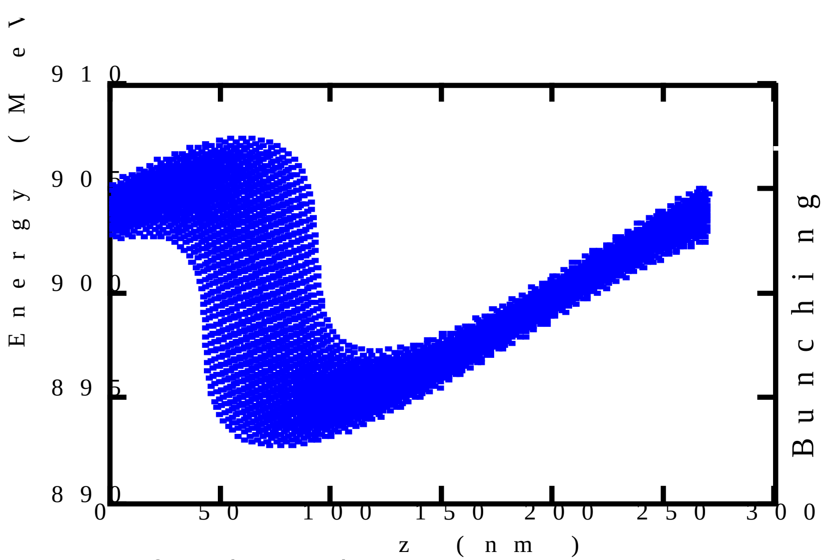
Seeded harmonic generation: the principle

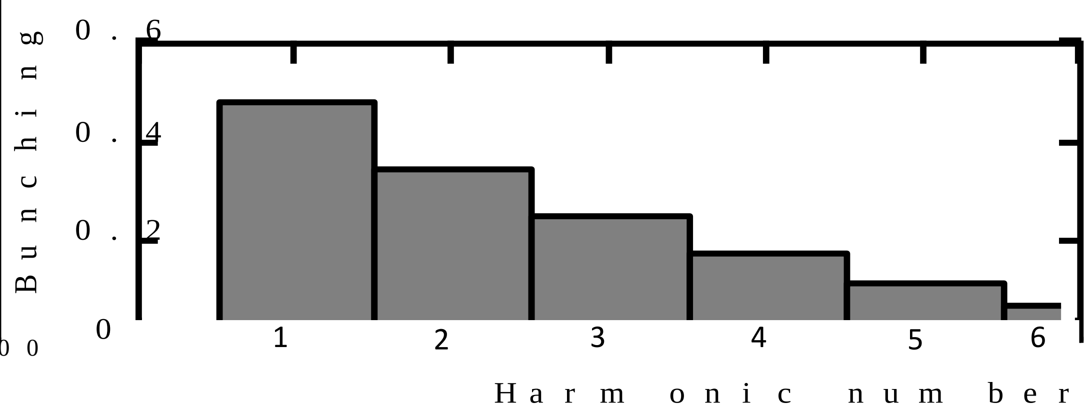


Seeded harmonic generation: the principle



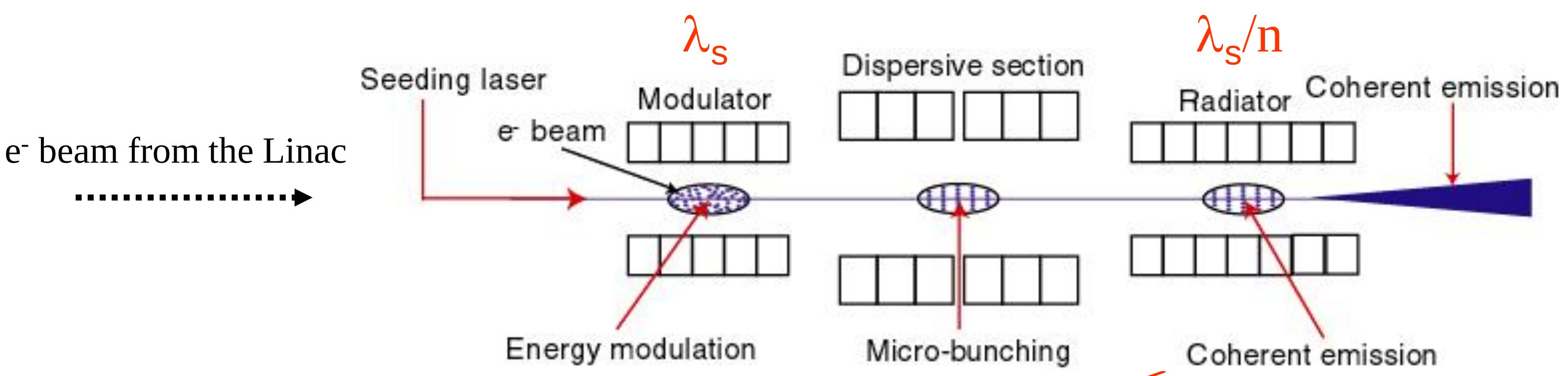
Dispersive section





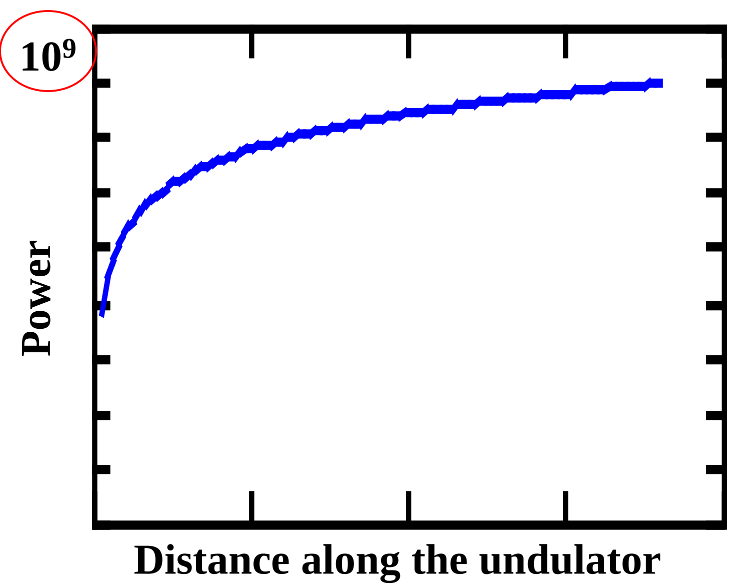
Courtesy of L. Giannessi

Seeded harmonic generation: the principle



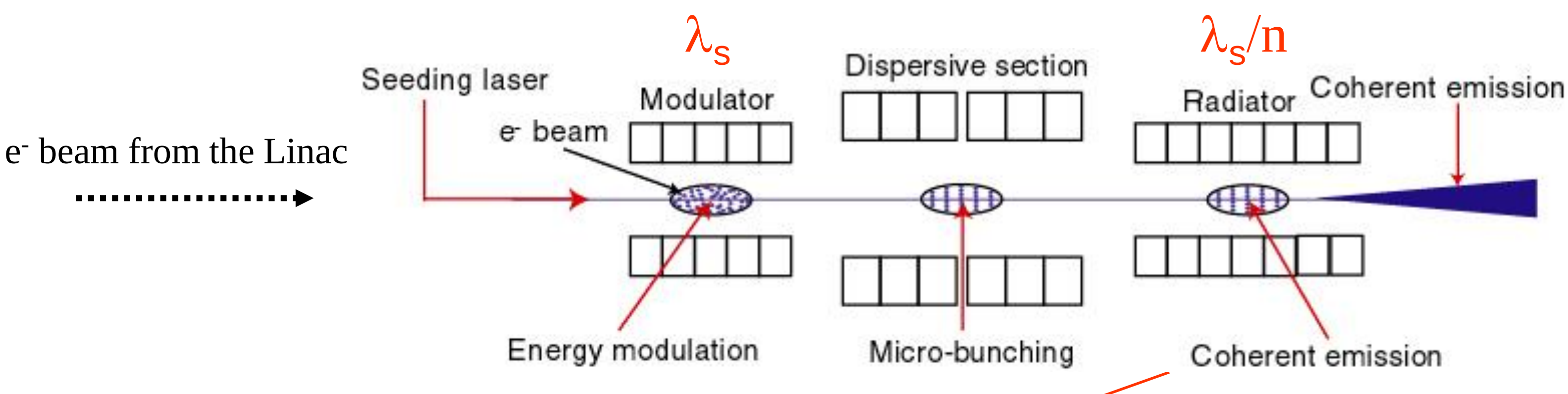
Radiator

Evolution of the harmonic signal



~ GW output signal

Seeded harmonic generation: the principle



Radiator

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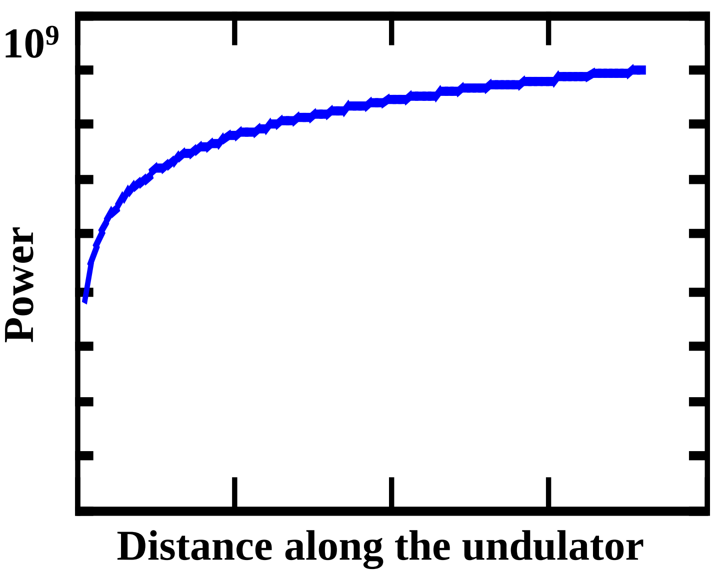
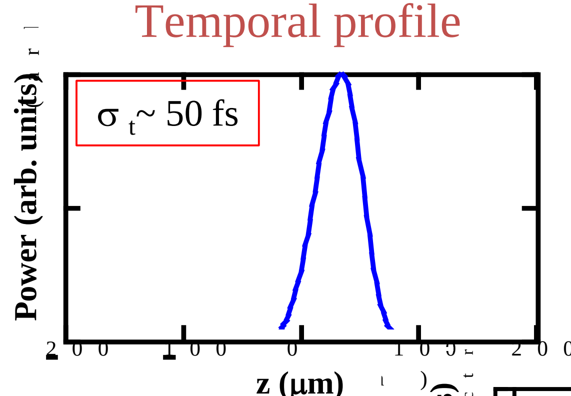
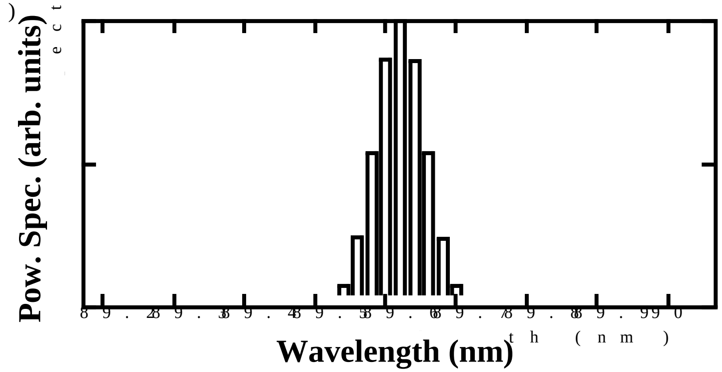


Temporal profile



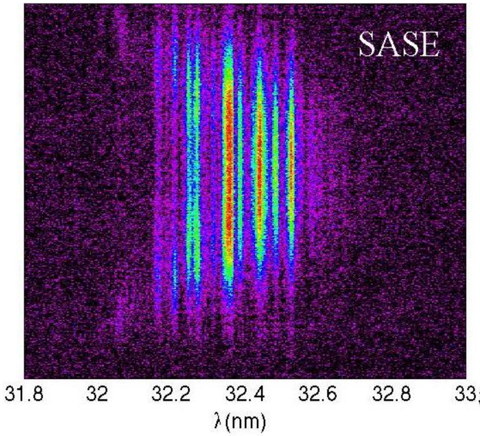
Transform limit

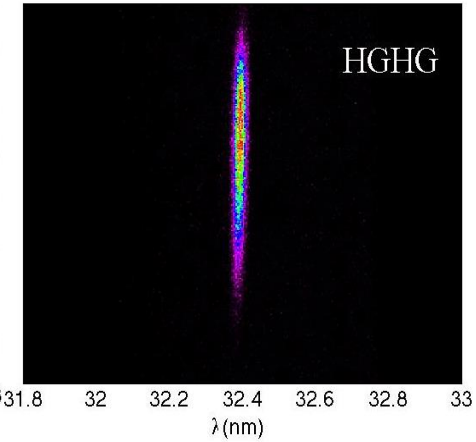
Spectrum profile

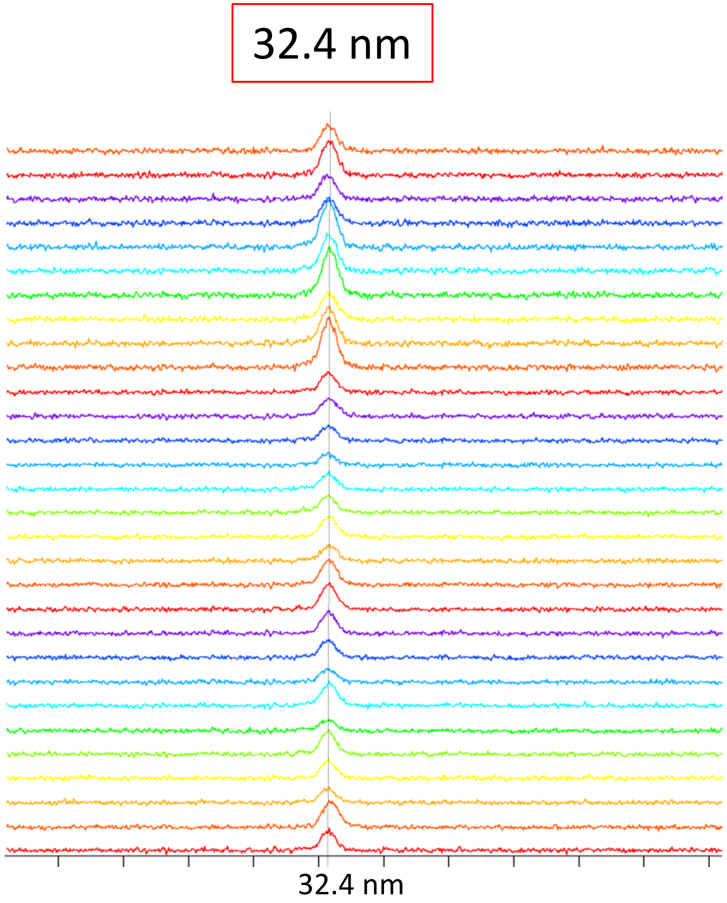


Spectral bandwidth

FERMI FEL operated in SASE and HGHG mode







Spectral peak jitter: < 1 part in 10^4

Spectral width: 0.1%

Electron beam quality

Electron beam parameters
(FERMI FEL, Trieste, Italy)

Charge	800	pC
Peak current	1	kA
Energy	1.5	GeV
Energy spread	150	keV
Emittance	1	mm mrad

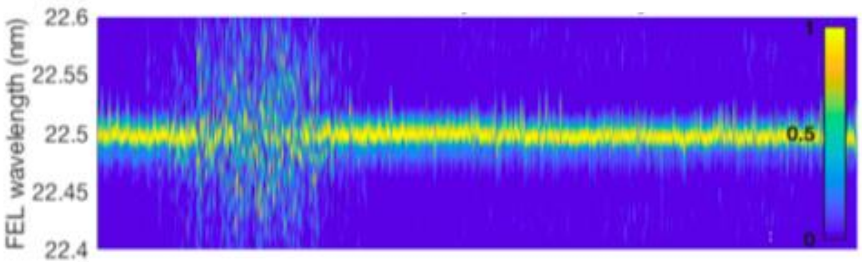
Need to monitor and control the growth of micro-bunching instability!

Micro-bunching instability

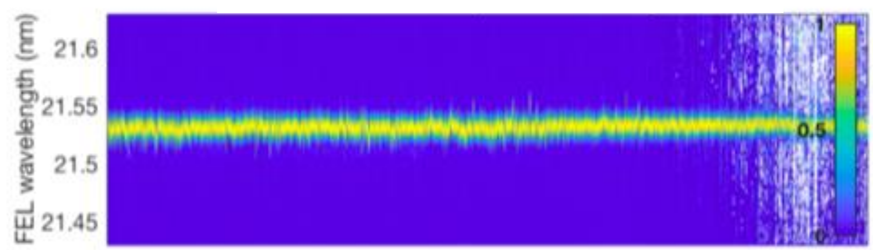
(FERMI FEL, Trieste, Italy)

Strong micro-bunching perturbation

Smooth beam

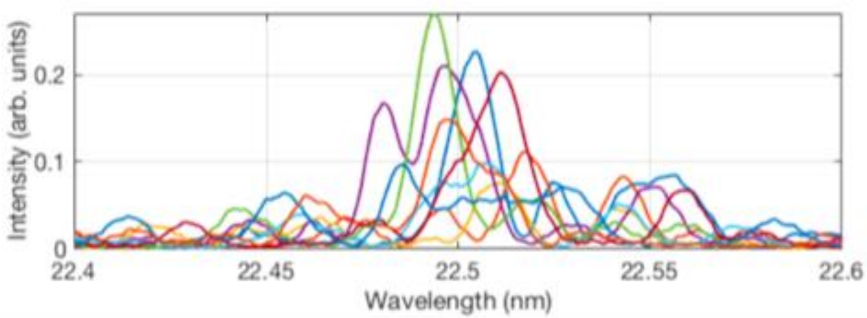


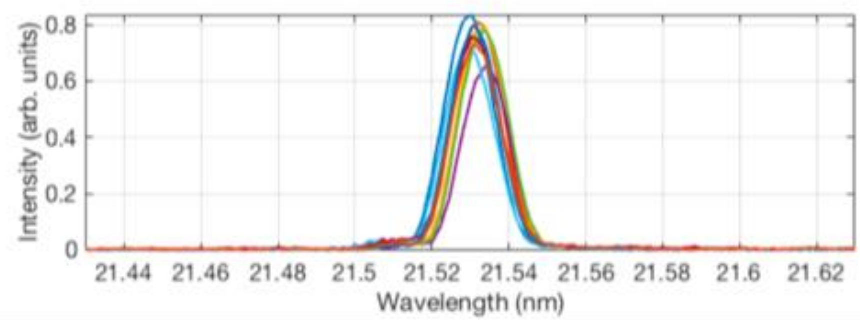
FEL shots



FEL shots

Spectra



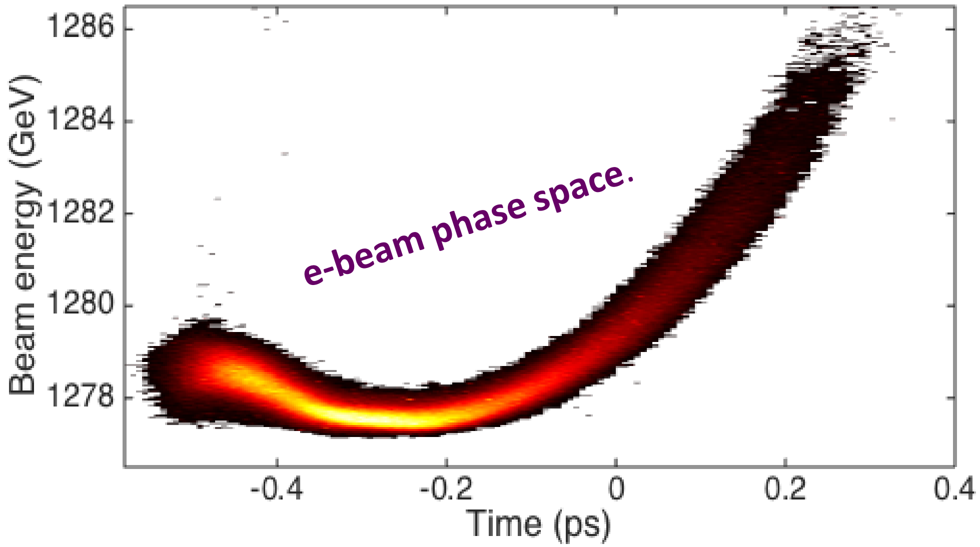


Electron beam quality

Electron beam parameters
(FERMI FEL, Trieste, Italy)

Charge	800	pC
Peak current	1	kA
Energy	1.5	GeV
Energy spread	150	keV
Emittance	1	mm mrad

Electron-beam phase space



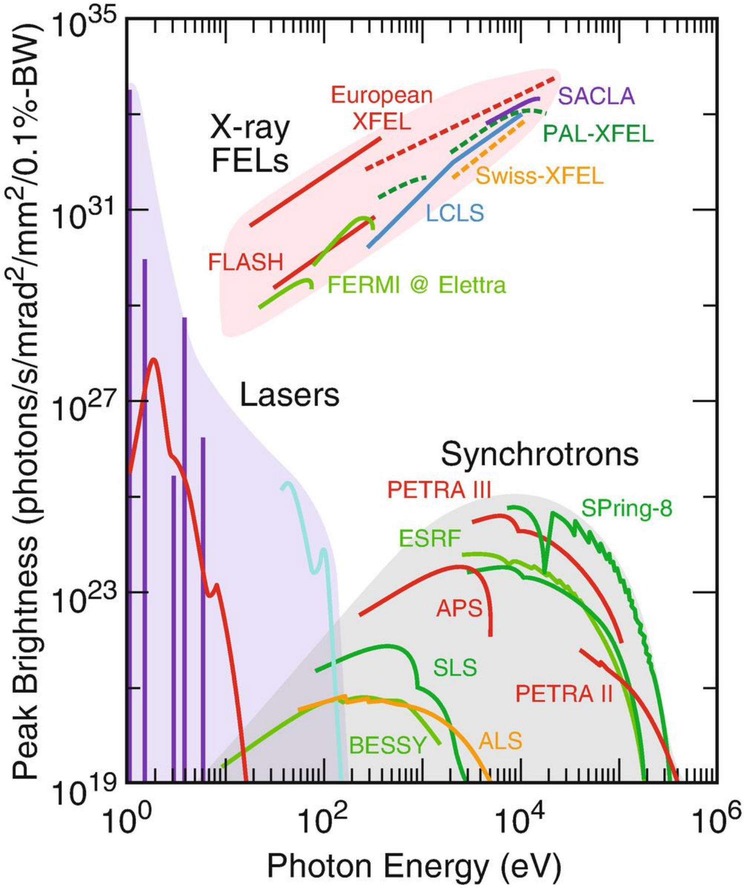
Conclusions

The use of a high-quality relativistic electron beam of free electrons allows the generation of laser-like radiation in the X-ray spectral range.

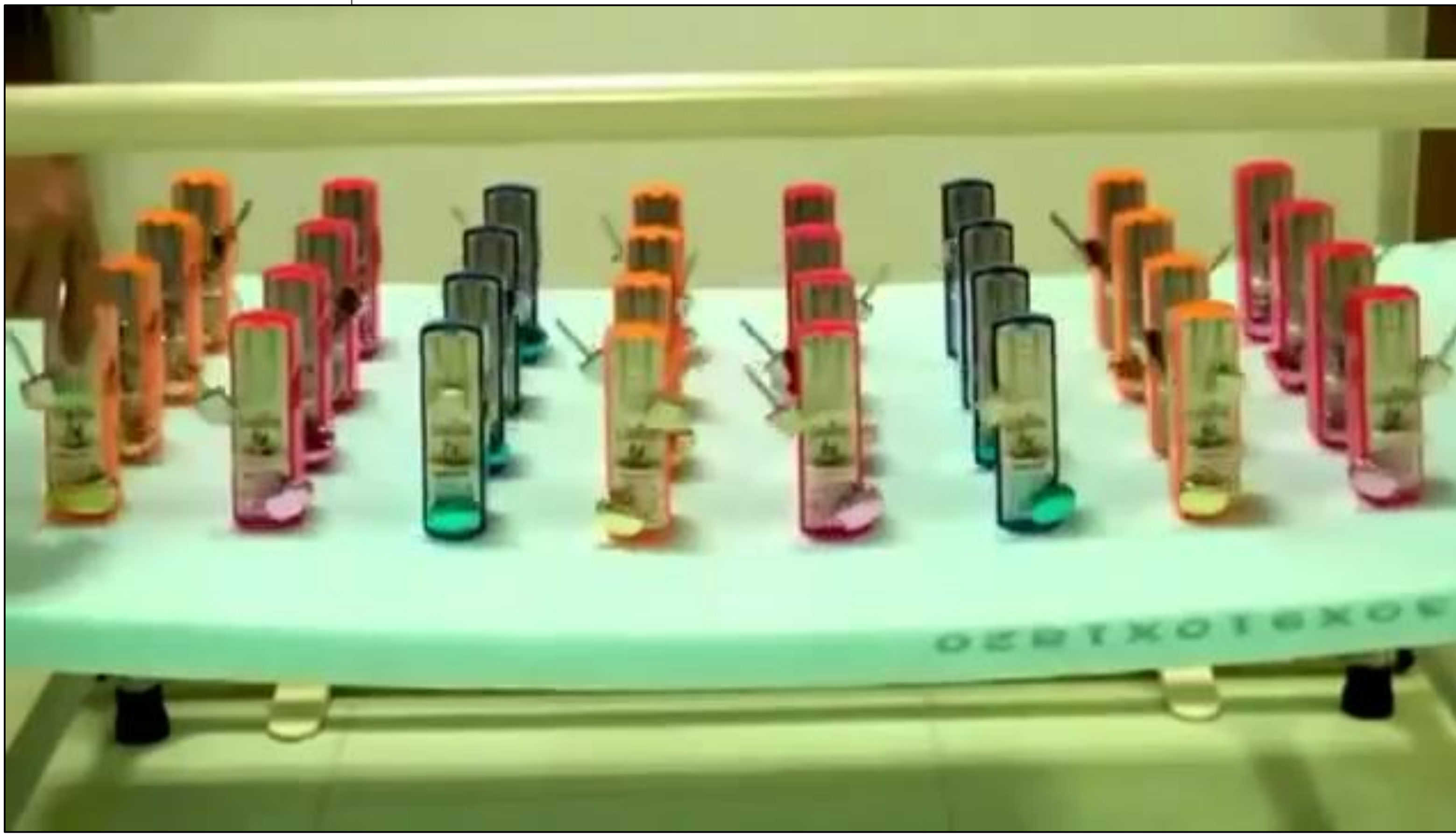
The two main schemes that can be used to generate FEL radiation, that is self-amplified spontaneous emission (SASE) and high-gain harmonic generation (HGHG), are based on quite different philosophies: SASE is generally simpler to implement and allows to produce FEL light in the hard X-ray spectral region; HGHG relies on a more involved architecture, works well in soft X-ray region (no hard X-rays), but allows to generate fully coherent pulses.

Conclusions

Performance of present FELs around the world (several in Europe, one in USA, one in Japan, one in Cina), in terms of peak brightness vs photo energy.



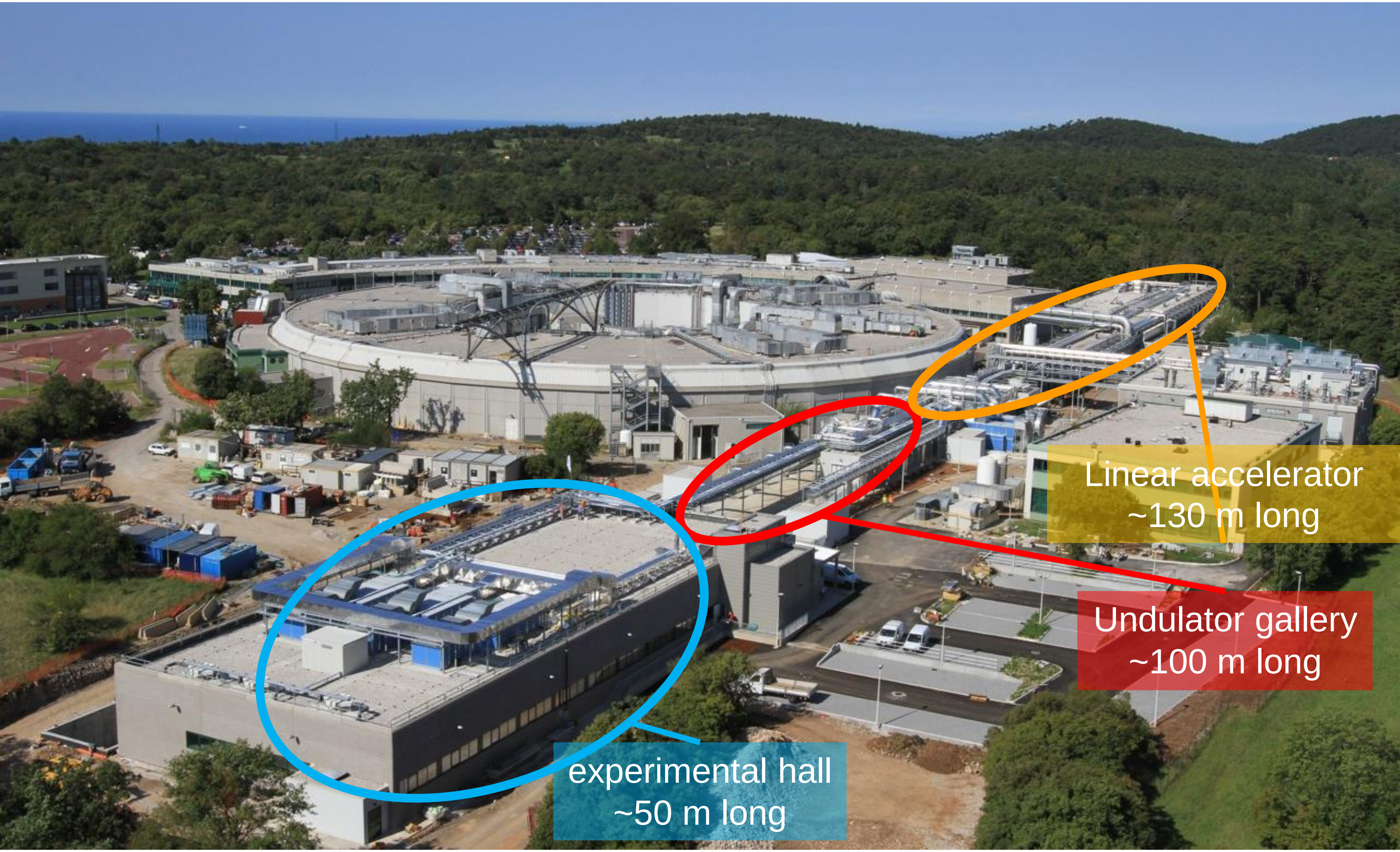
BACK



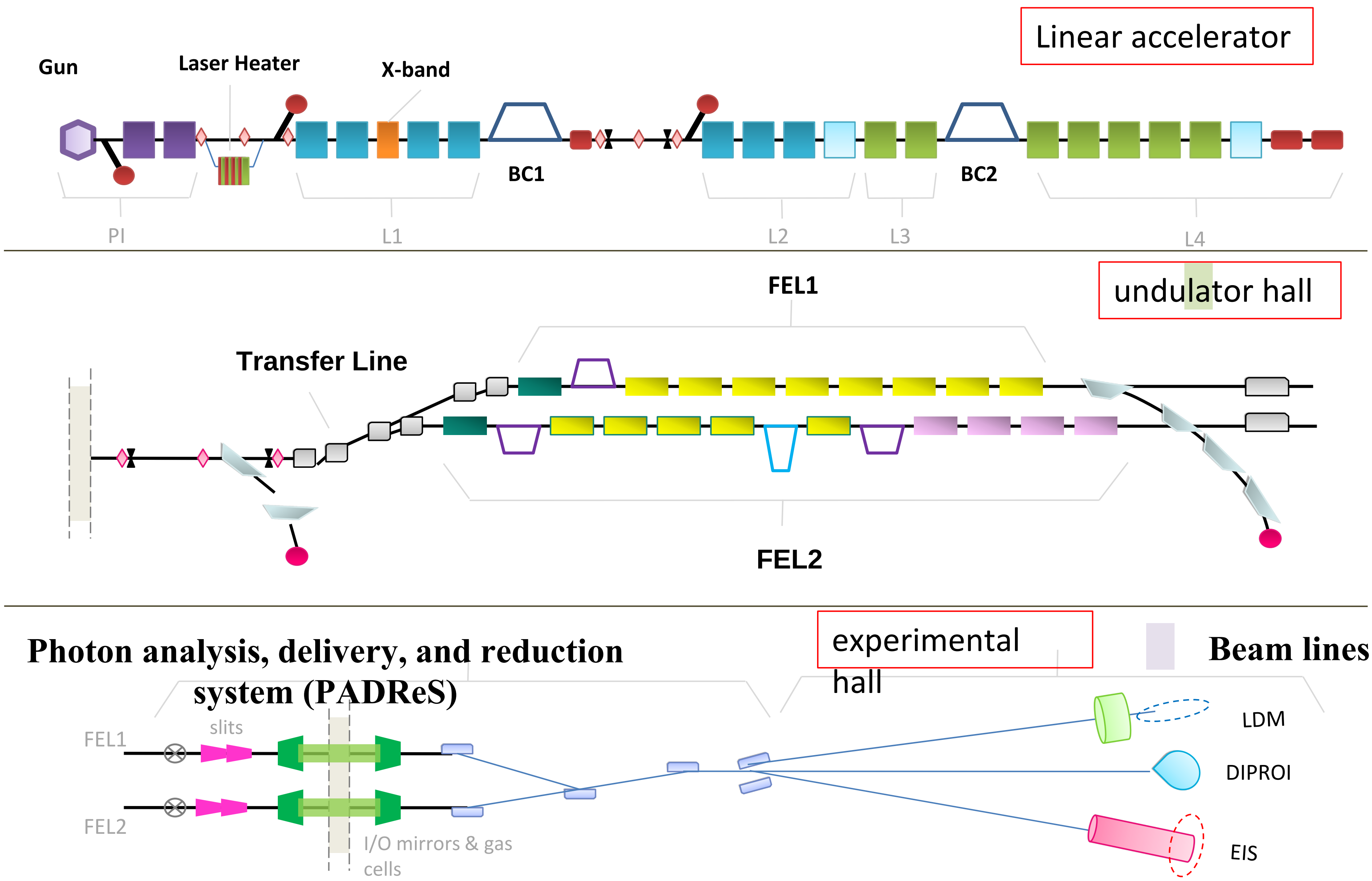
SASE facilities open to users

	FLASH	LCLS
Wavelength range (fundamental) [nm]	4.1 – 47	0.12 – 1.2
Photons per pulse	$10^{12} – 10^{13}$	$10^{12} – 10^{13}$
Pulse duration (FWHM) [fs]	10 – 70	70 – 500
Spectral width (FWHM)	1%	0.1%
Polarization	Fixed linear	Fixed linear
Spatial coherence	High	High
Temporal coherence	Limited	Limited
Shot-to-shot reproducibility	Poor	Poor

The FERMI@Elettra project



FERMI Layout

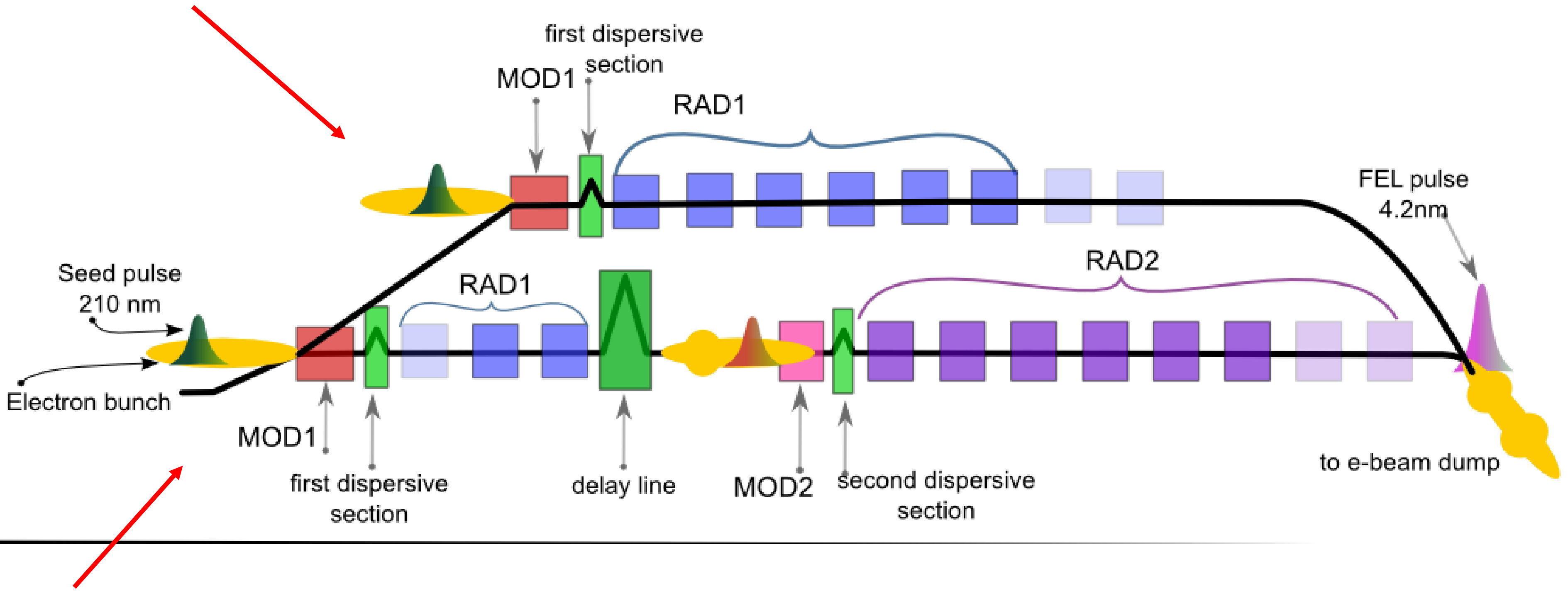


LDM: Low-Density Matter ; DIPROI: Diffraction and PROjection Imaging; EIS: Elastic and Inelastic Scattering

The two FERMI’s amplifiers: FEL-1 and FEL-2

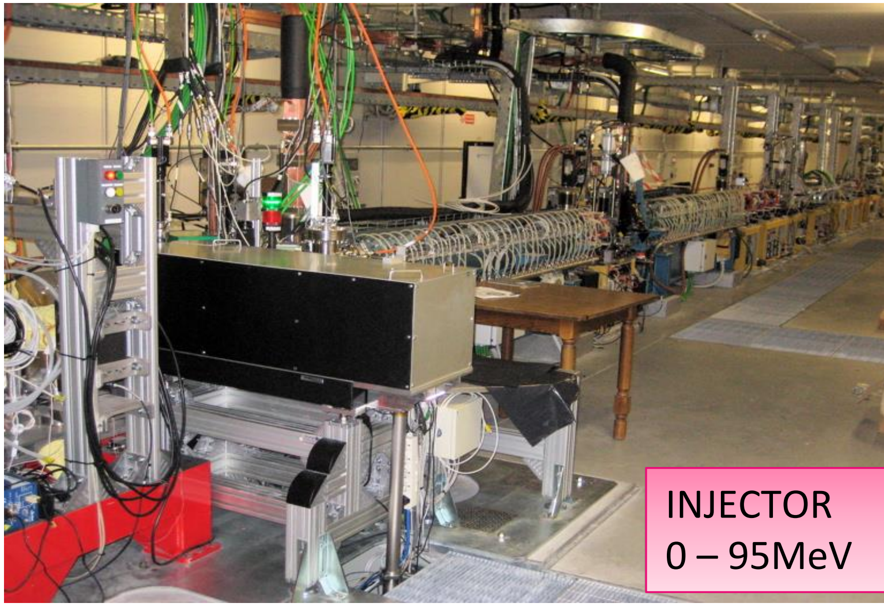
FEL-1 is based on a single-stage high-gain harmonic generation scheme.

It will cover the spectral range from ~100 nm to 20nm.

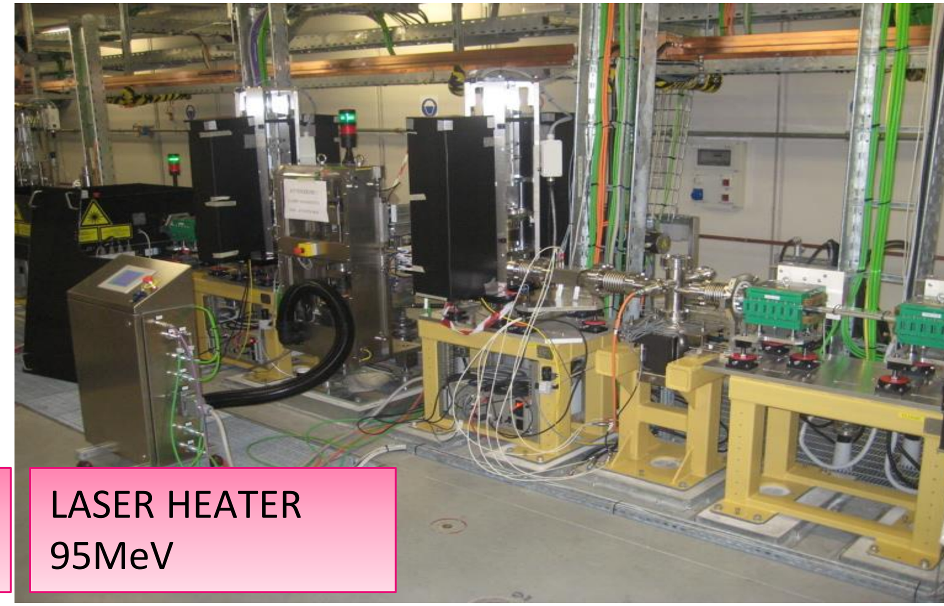


FEL-2, will allow to cover the wavelength range from 20 nm to ~4 nm. It will be based on a double-cascade of high-gain harmonic generation. A magnetic delay line, placed between the two stages, will allow to implement a “fresh bunch” technique. Both schemes are flexible enough to allow other FEL configurations.

accelerator

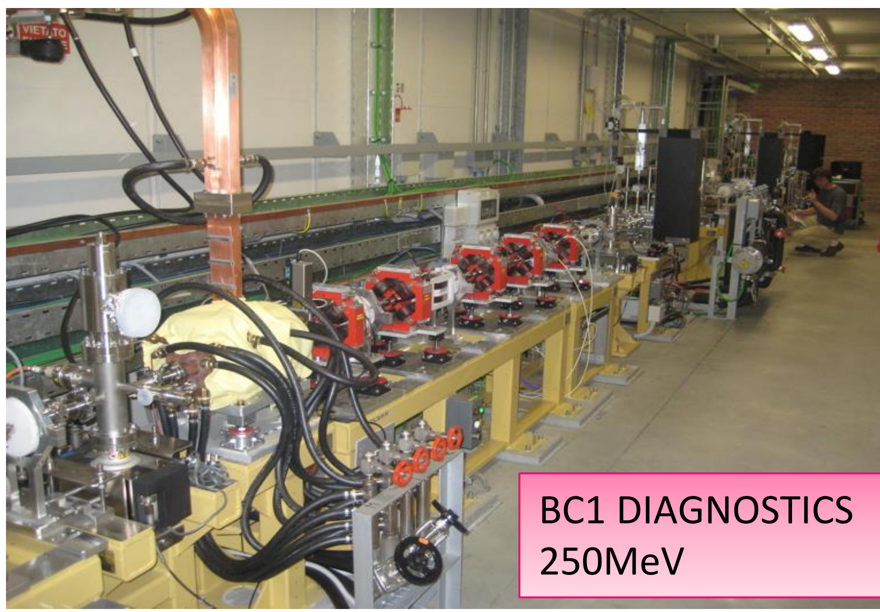


INJECTOR
0 – 95MeV

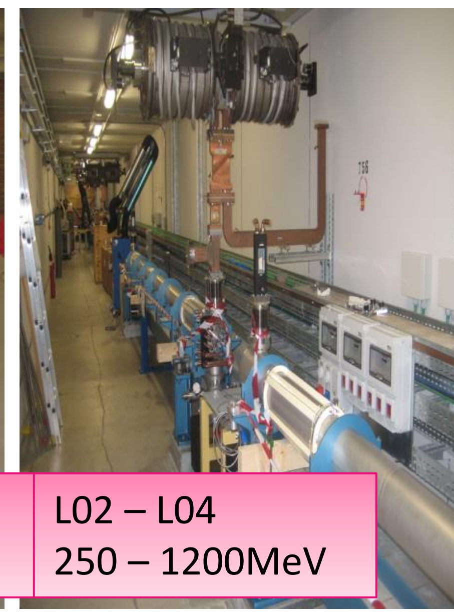


LASER HEATER
95MeV

L01
95 – 250MeV



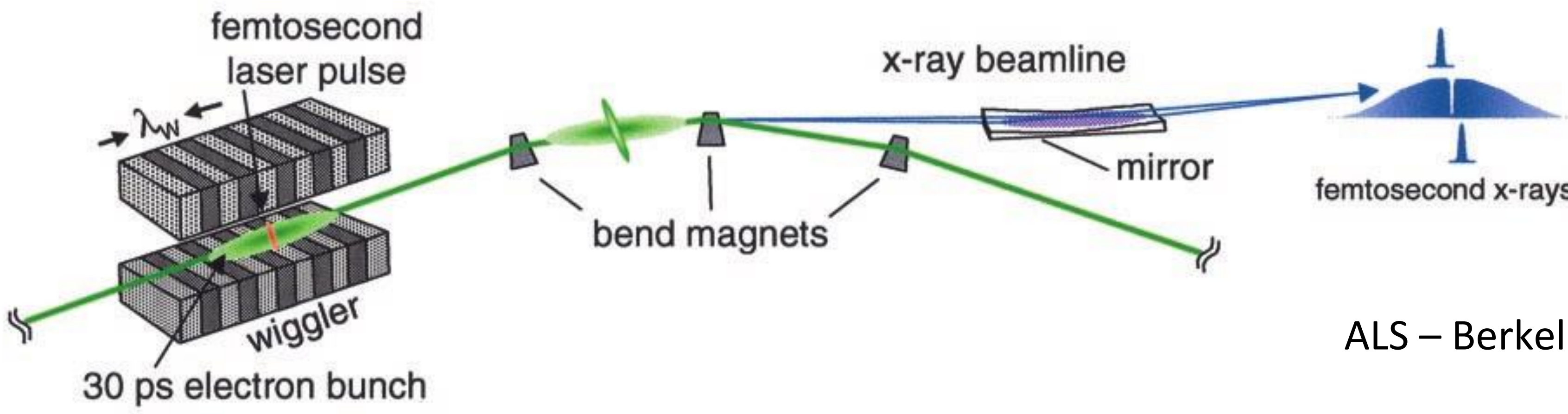
BC1 DIAGNOSTICS
250MeV



L02 – L04
250 – 1200MeV

Decreasing pulse duration
femto-slicing

A femtosecond laser can be used to create femto-second time structure on a long electron bunch through energy modulation of an ultra-short slice of the bunch.



ALS – Berkeley

$\approx 10^7$ ph/pulse

Brilliance: 10^{11} ph/s/0.1%BW/mm^2/mrad^2

R. W. Schoenlien et al., Science, 2000