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Theory and general properties of X-Ray FEL'S

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Theory and general properties of X-ray free-electron lasers

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Motivation

Light is one of the most effective tools to explore the inner properties of matter. This includes, e.g., the possibility of studying how atoms or a molecules aggregate, break up or change their characteristics under the effect of their environment.

However, to be suited for this purpose, a light source must own well defined features. Ideally, it has to be:

- powerful [in order to produce many events, i.e. a good statistics, when interacting with the sample under study];

- short-wavelength (high-energy) [wavelength corresponds to resolution, i.e. to the minimum spatial scale of the sample one can explore];

-monochromatic [in order to excite in the sample only the event one is interested in, something like a “bistoury”];

-tuneable [in order to allow a continuous “scan” of the of events one wants to explore, e.g. the excitation of an atom at different energy levels];

-“fast”, e.g., subdivided in short independent pulses [in order to be able to explore fast dynamic processes, such as, e.g., the electronic relaxation of an excited atom];

-stable and reproducible.

Nowadays, only light sources based on accelerated electrons are able to satisfy

all these requirements at the same time.

This seminar is about the basic principles of this kind of sources, and, in particular,

about **free-electron lasers**

Outline

- From synchrotron radiation to free-electron lasers

- Basic concepts of light-electron interaction in a Free-Electron Laser

- Different schemes for producing Free-Electron Laser light

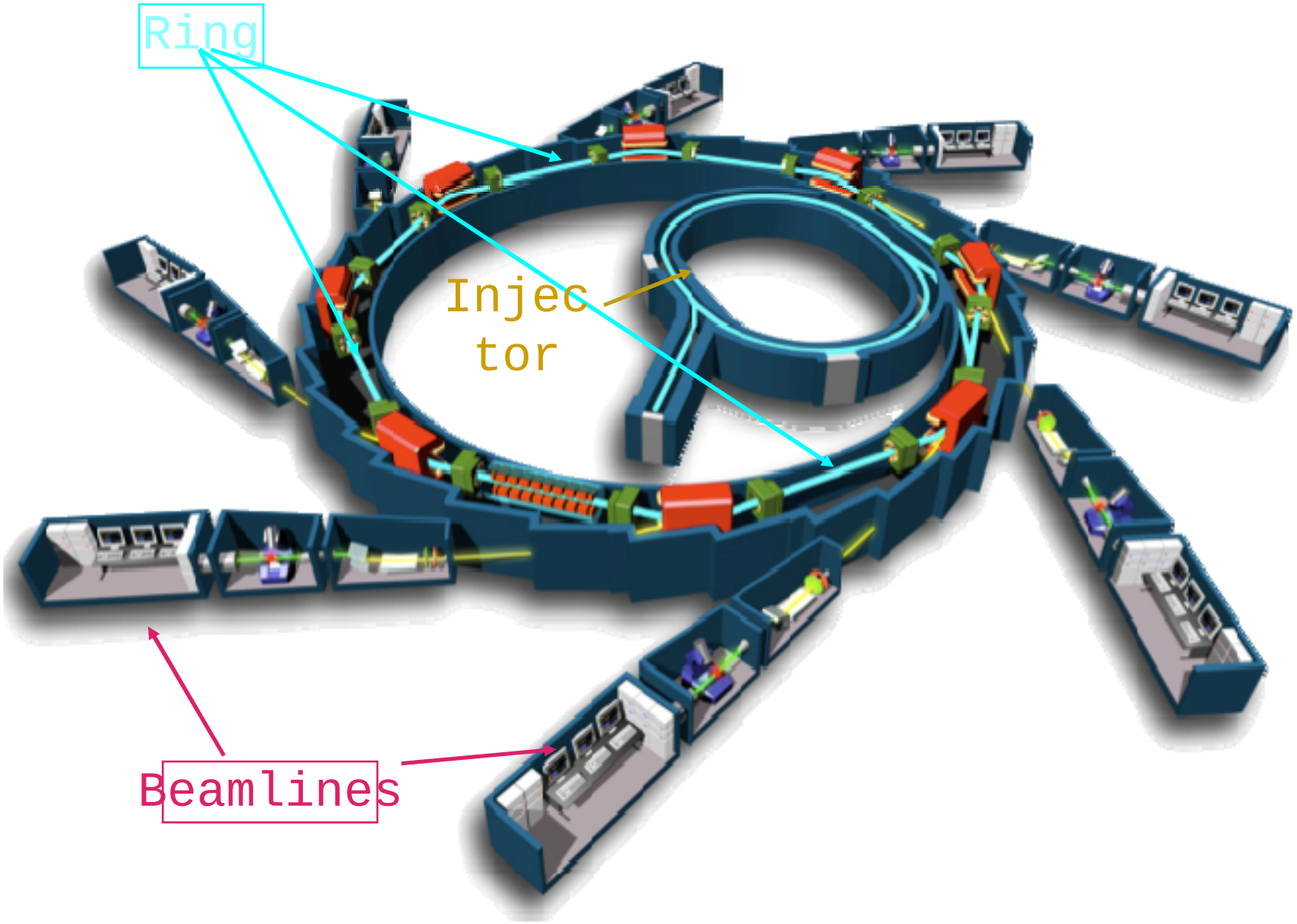
- Properties of Free-Electron Laser radiation

- Free-Electron Lasers at work:

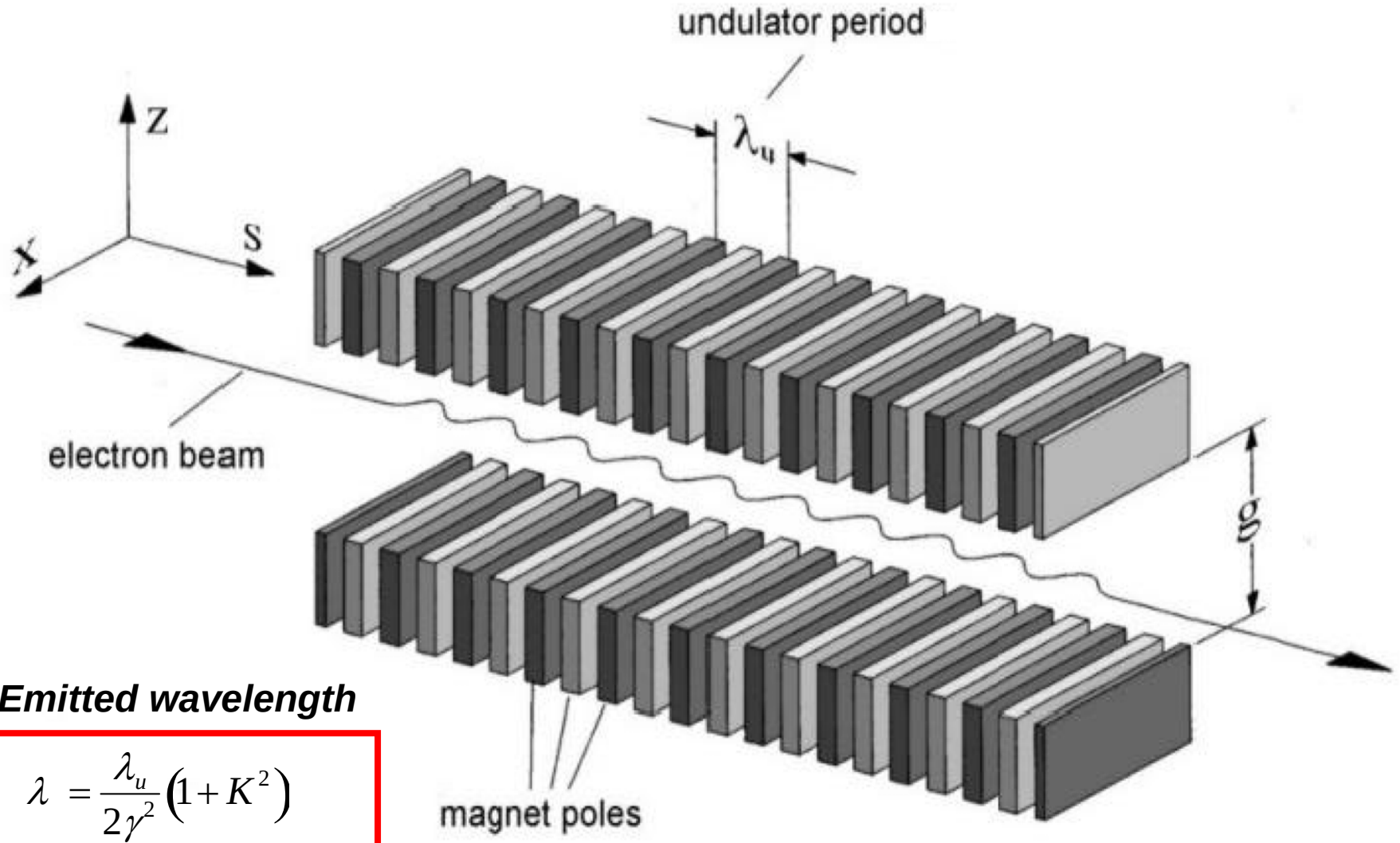
    - The Elettra storage-ring Free-Electron laser

    - The FERMI project

A synchrotron



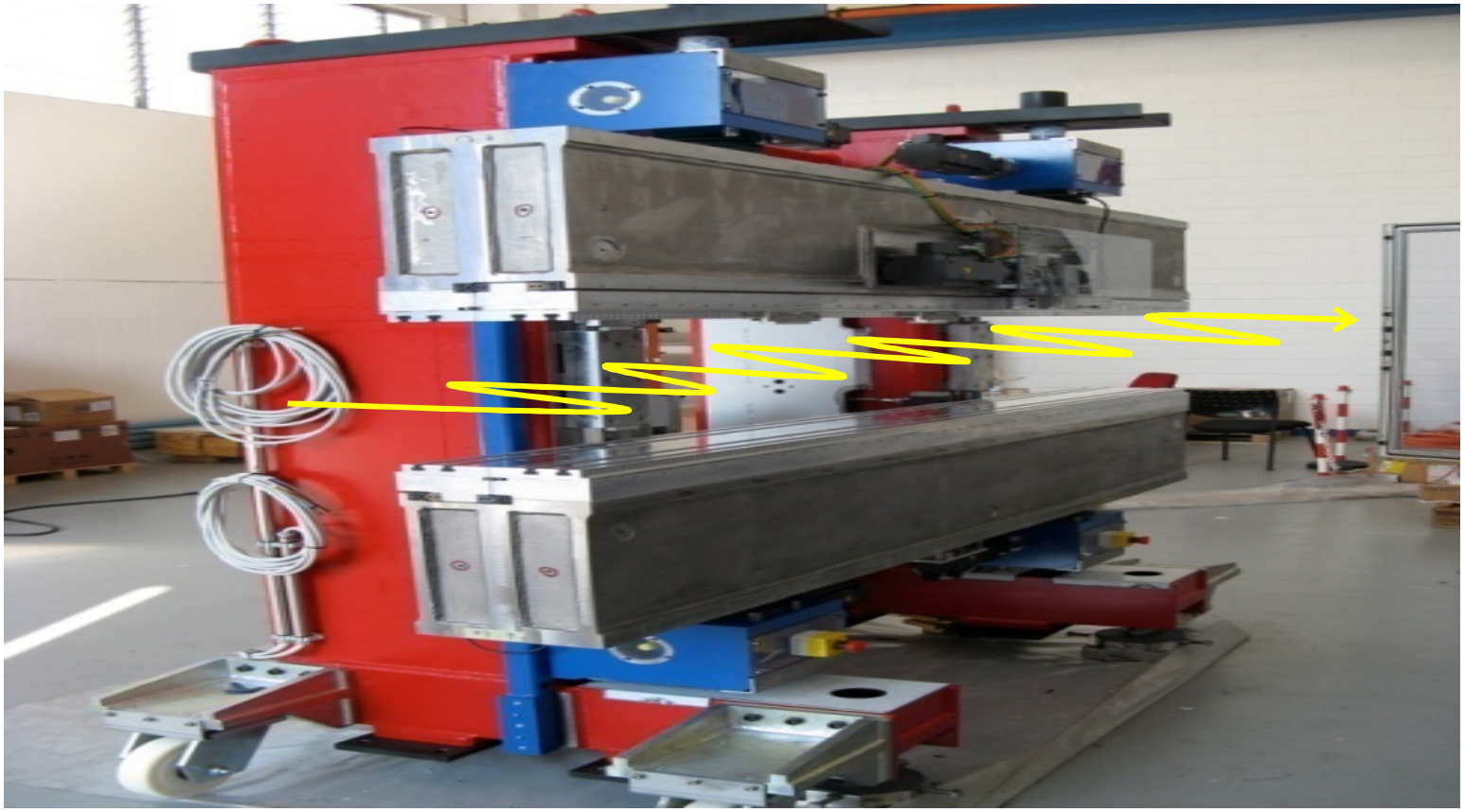
Undulators

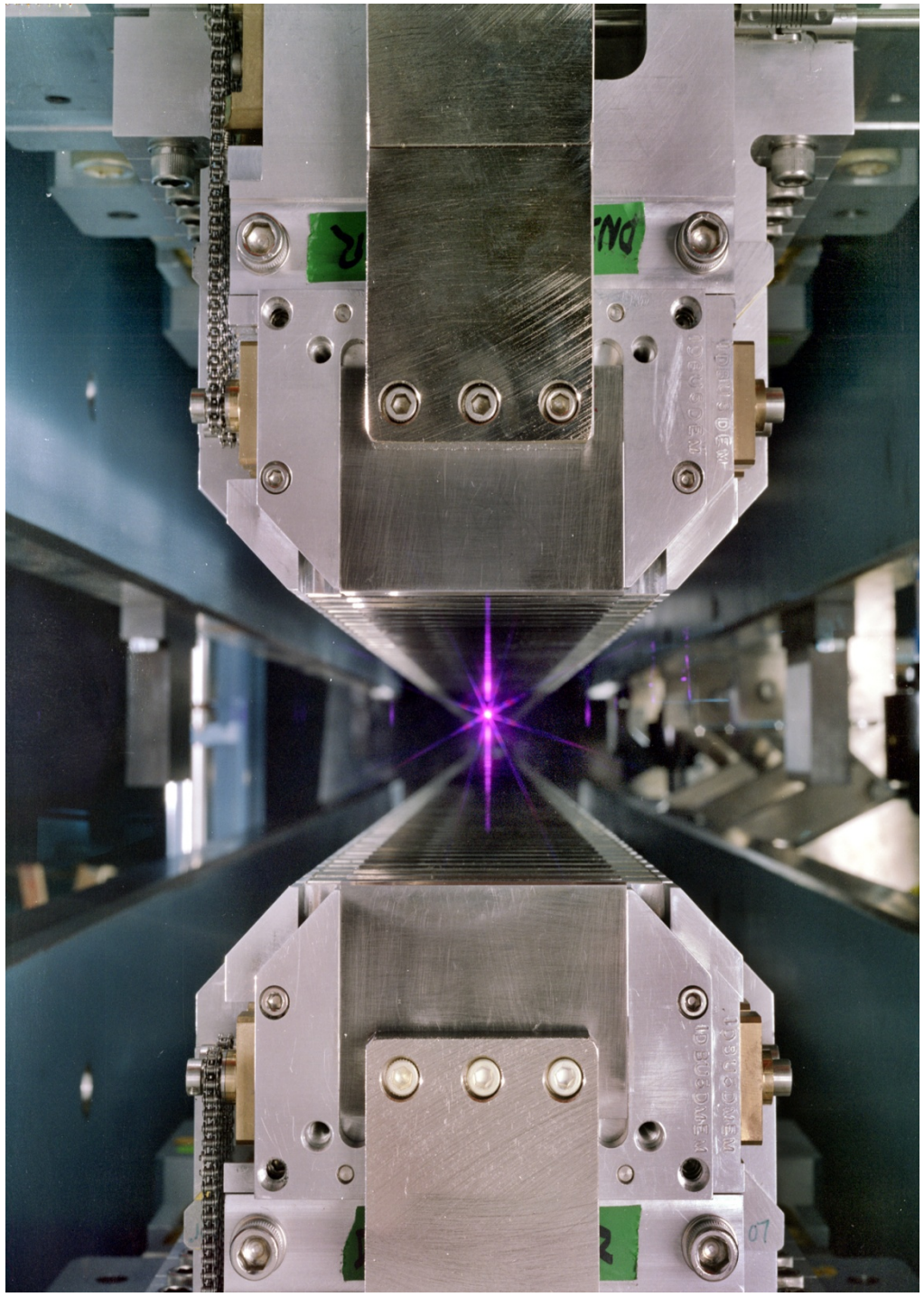


Emitted wavelength

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

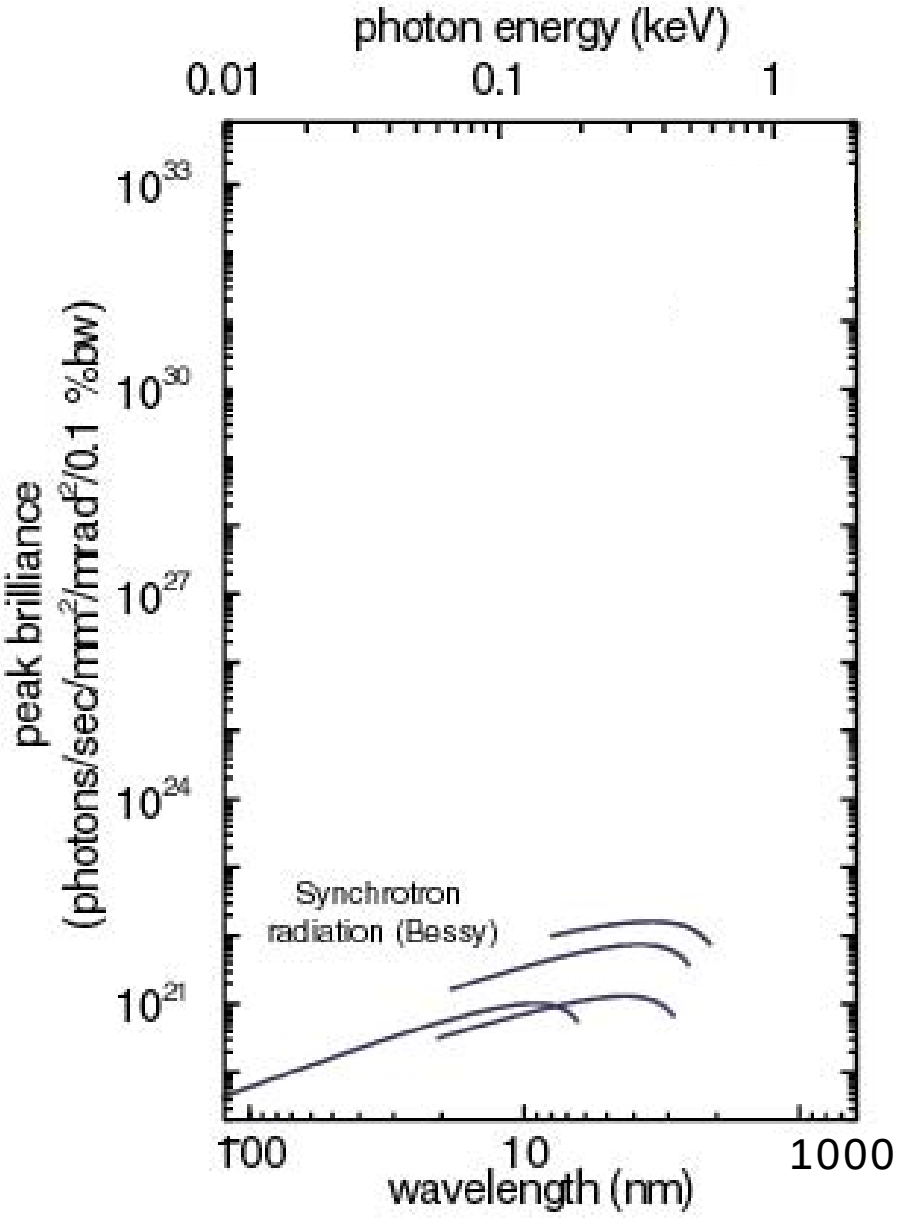
Undulators





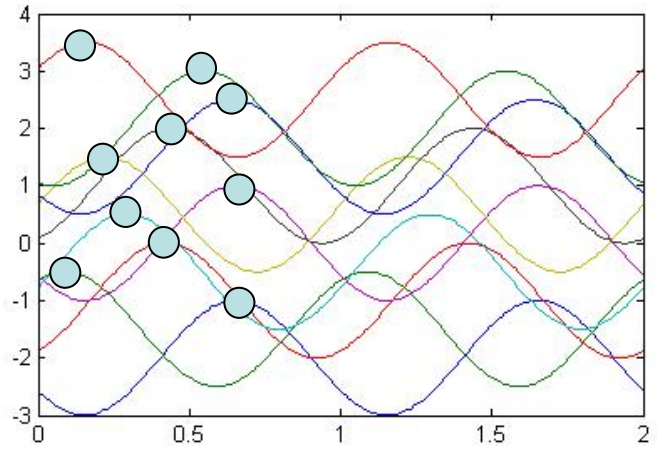
An undulator

Peak brilliance: synchrotron radiation



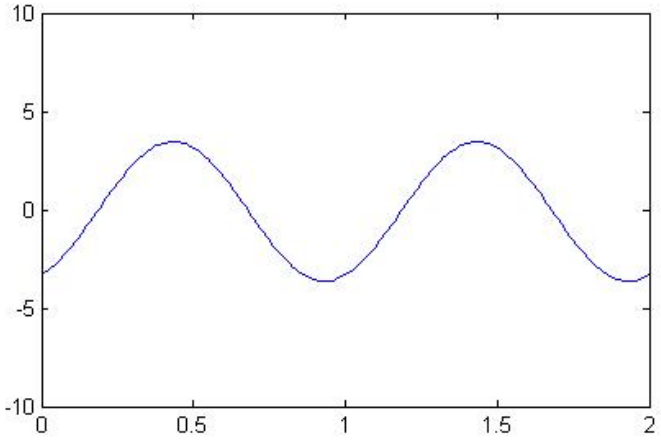
A question of coherence…

Incoherent emission
(Synchrotron radiation)



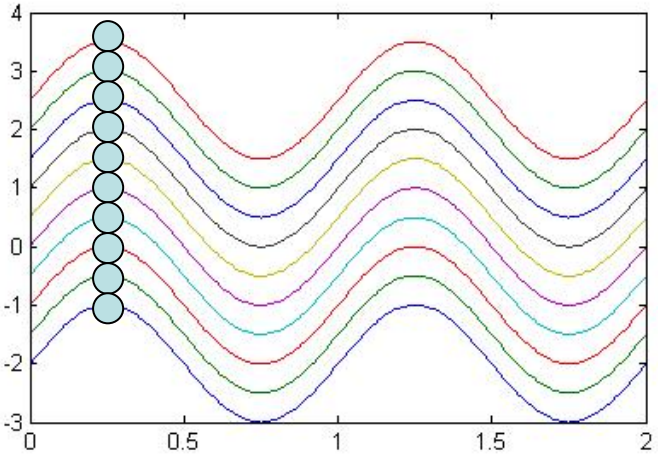
λ

Output power proportional to N



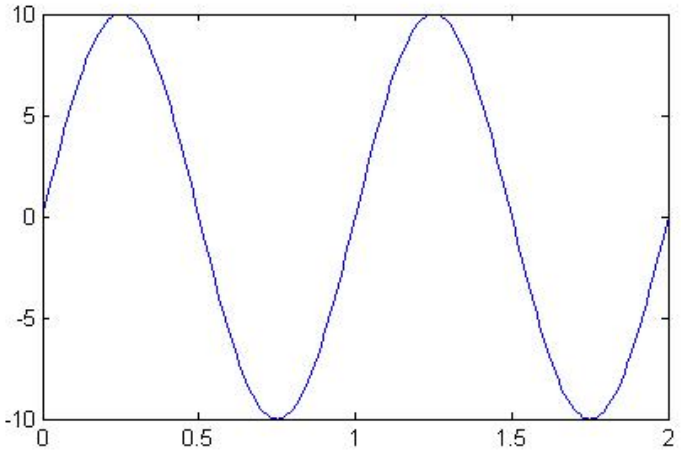
λ

Coherent emission
Free-electron laser



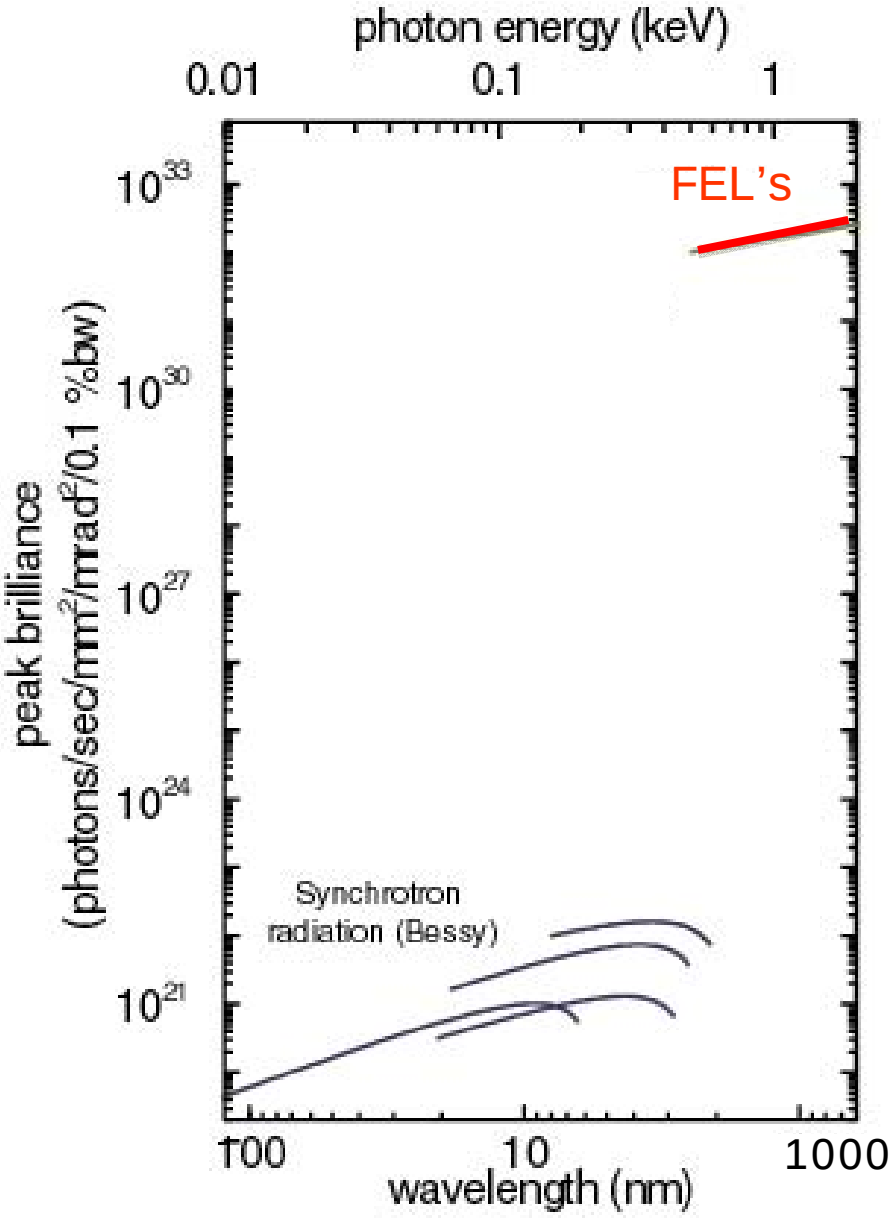
λ

Output power proportional to N2



λ

Peak brilliance: synchrotron vs. FEL radiation

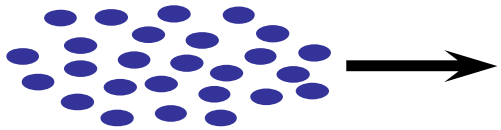


Fundamentals of FEL's

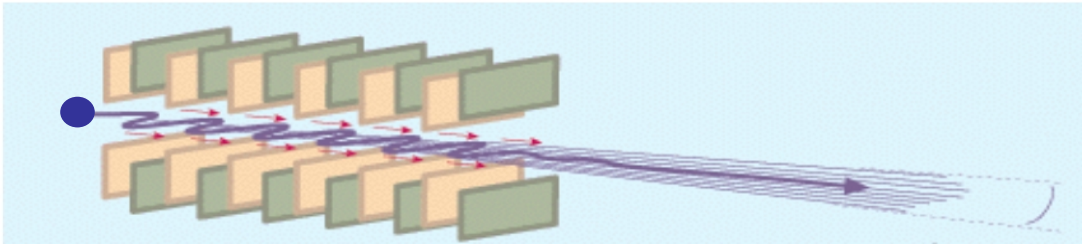
A **Free-Electron Laser** is a light source exploiting the spontaneous and/or induced emission of a relativistic electron beam "guided" by the periodic and static magnetic field generated by an undulator

Basic ingredients

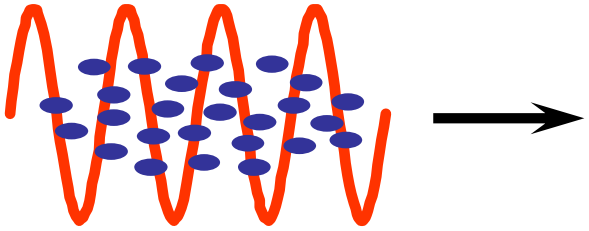
1) Relativistic **electron beam**



2) Undulator



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



Light amplification: resonance condition

When transversally accelerated by the undulator field, electrons emit **synchrotron radiation**

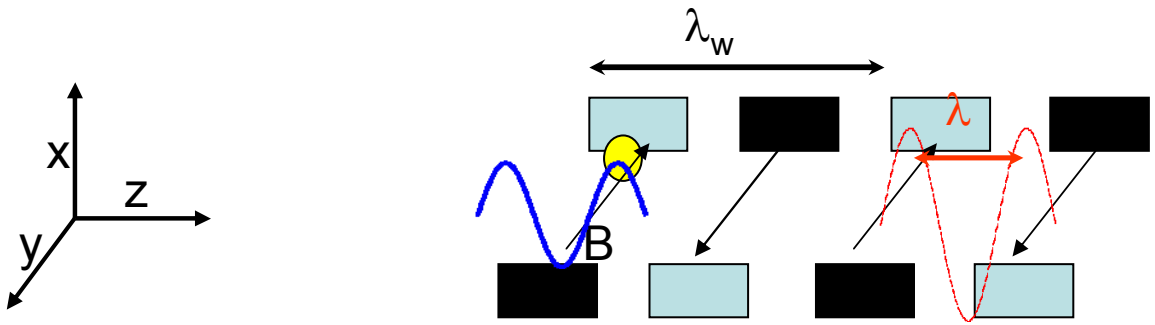
Electrons move slower than the co-propagating electromagnetic wave (**slippage**)

Resonant condition:

The slippage between the electromagnetic wave and a given electron,

while the electron advances by one undulator period (λ_w),

must be equal to the field wavelength λ.



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

Light amplification: resonance condition

Analytically:

$$\frac{\lambda_w}{\beta_{\|}}\left(1-\beta_{\|}\right)=\lambda$$

($\beta_{\|}$: electron's velocity along the undulator axis normalized to c)

$$\frac{1}{\gamma^2}=1-\beta_{\|}^2-\beta_{\perp}^2$$

(γ : electron's energy)

($\beta_{\perp}$: electron's transverse velocity normalized to c)

$$|\beta_{\perp}|\approx\frac{K}{\gamma}$$

(K : undulator parameter, $K\sim\lambda_w B_{und}$)

Resonance condition

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

Theoretical framework

Evolution of the momentum and of the energy of each electron:

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

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

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

electric and magnetic field
of the co-propagating wave

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

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

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

ω wave (single) frequency

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

γ_j : energy of the j-*th* electron

γ_r : resonance energy

Under some approximations the previous equations can be reduced to

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

"bunching"

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

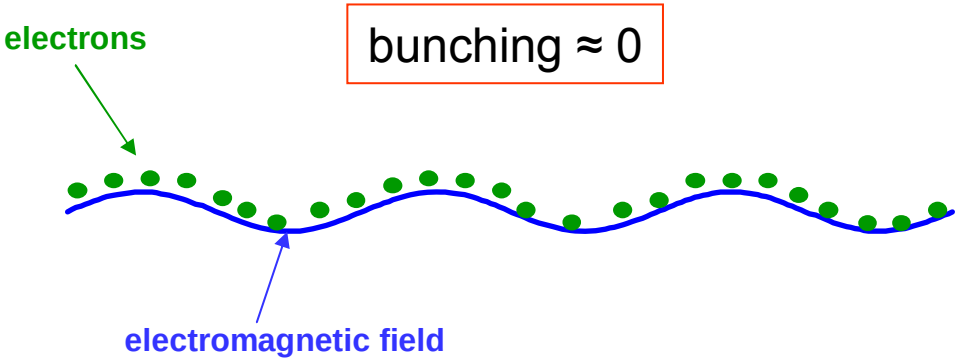
N: electrons' number

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

Bunching as source term

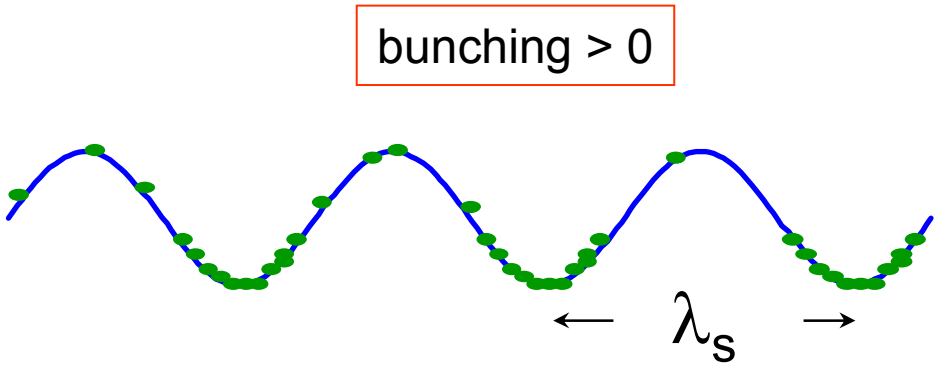
Initial condition:

- weak electromagnetic field
- electrons randomly distributed in phase

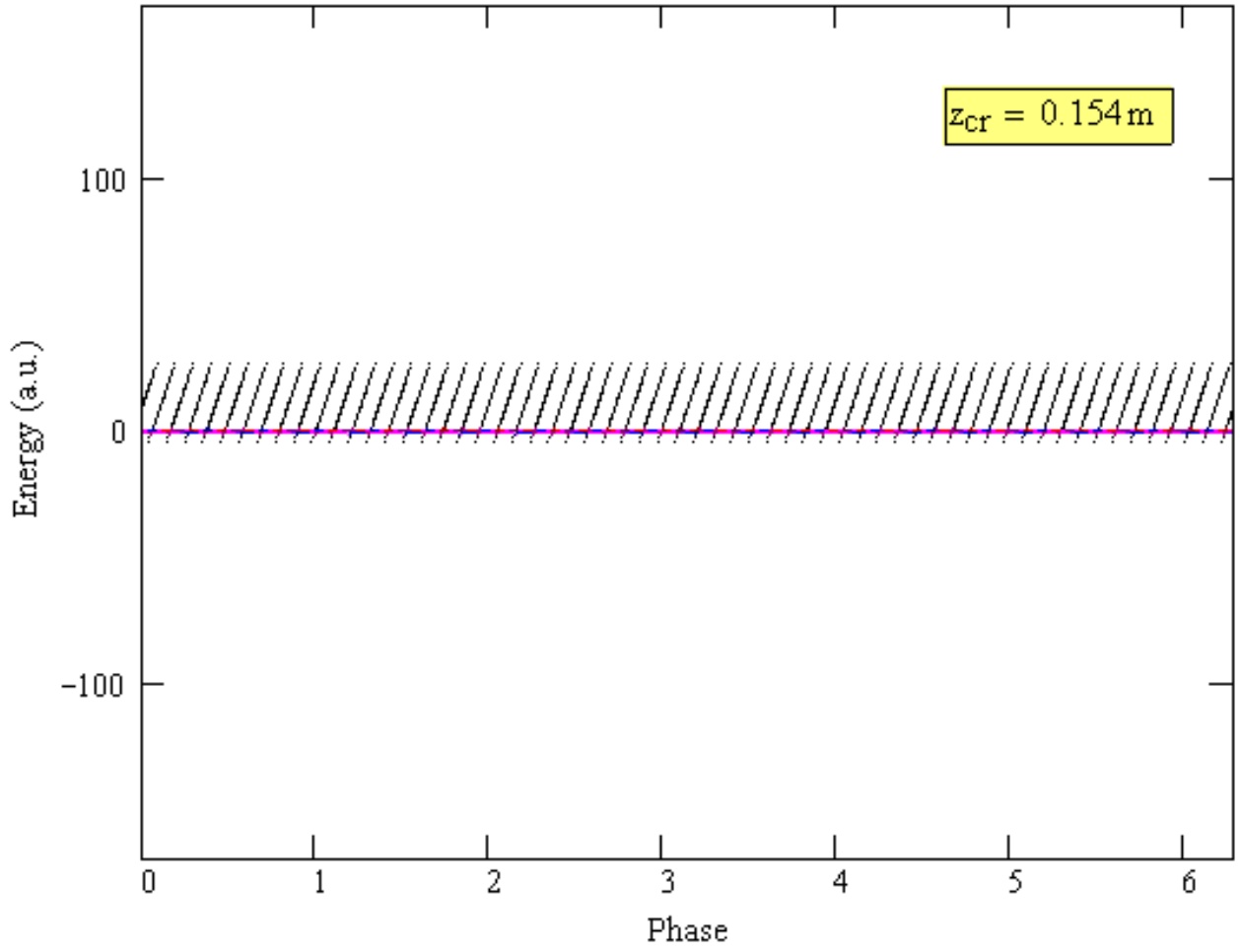


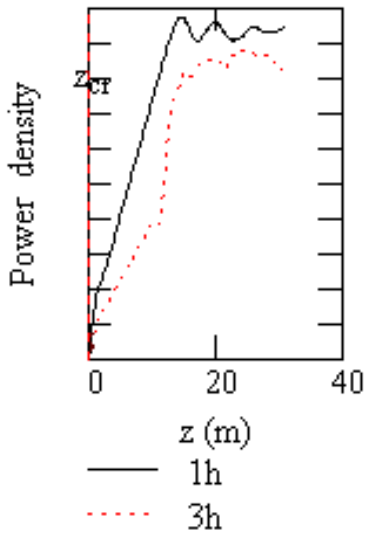
electrons start bunching on a λ_s scale

and the wave is amplified



FEL process in electrons' phase space





FELs are being considered as the next generation light sources

This because:

- They allow to generate high intensity, short pulse radiation in the spectral region from deep ultraviolet down to hard x-ray wavelengths.

- They are tuneable: the radiation wavelength can be continuously varied by changing the electron-beam energy and/or the undulator parameter K in the resonant condition $\lambda_s = \frac{\lambda_u}{2\gamma^2}\left(1+K^2\right)$.

The properties of the FEL radiation strongly depend on the origin of the electromagnetic wave co-propagating with the electron beam along the undulator.

Schemes

and

radiation properties

The origin of the co-propagating wave

An initial “seed” is necessary for initiating the amplification process.

This can be provided by:

- the initial spontaneous emission of the electron beam

⇒ The spontaneous emission can be stored in an optical cavity and amplified by means of several consecutive interactions with a “fresh” or re-circulated electron beam (oscillator configuration)

⇒ The spontaneous emission is amplified during a single interaction with the electron beam (Self Amplified Spontaneous Emission (SASE) configuration)

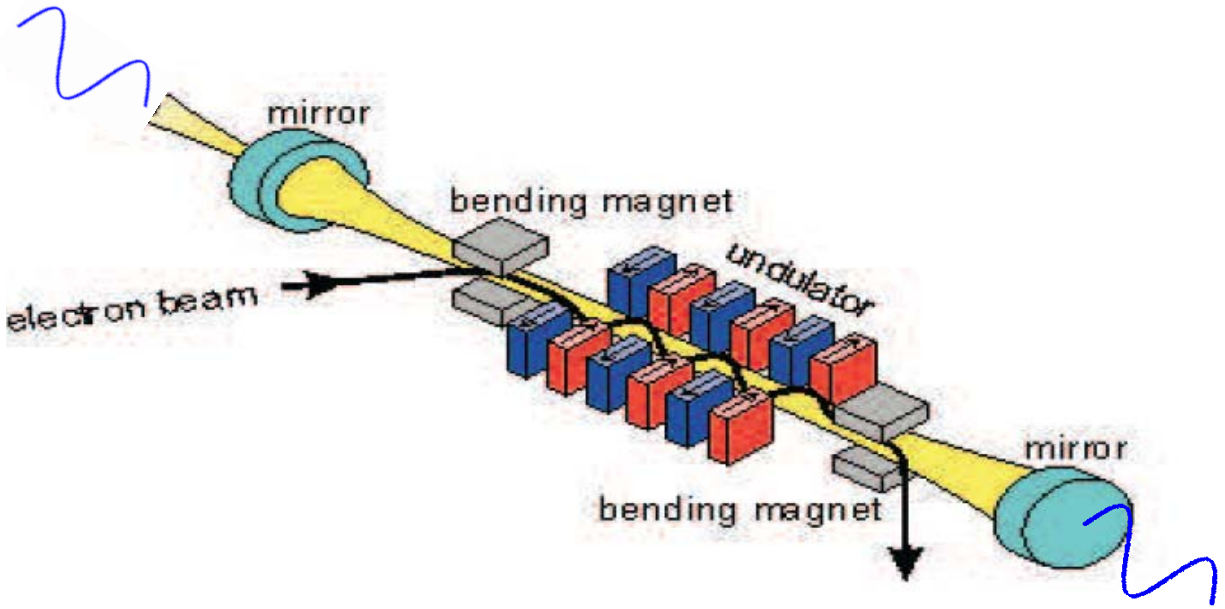
- a signal produced (e.g.) by an external laser

⇒ The external signal is amplified by the FEL (direct-seeding configuration)

⇒ The external signal is used to create harmonic bunching and thus generate coherent radiation to a harmonic of the original seeding wavelength (Coherent Harmonic Generation (CHG) configuration)

Oscillator FEL

The use of an optical cavity allows to trap the radiation which is amplified as a consequence of multiple interaction with the electron bunches



•The system is tunable with good spectral properties

•The repetition rate can be very high, allowing to generate high average power

•The system requires mirrors of very good quality. This currently prevents the possibility of working at wavelength shorter than ≈170nm

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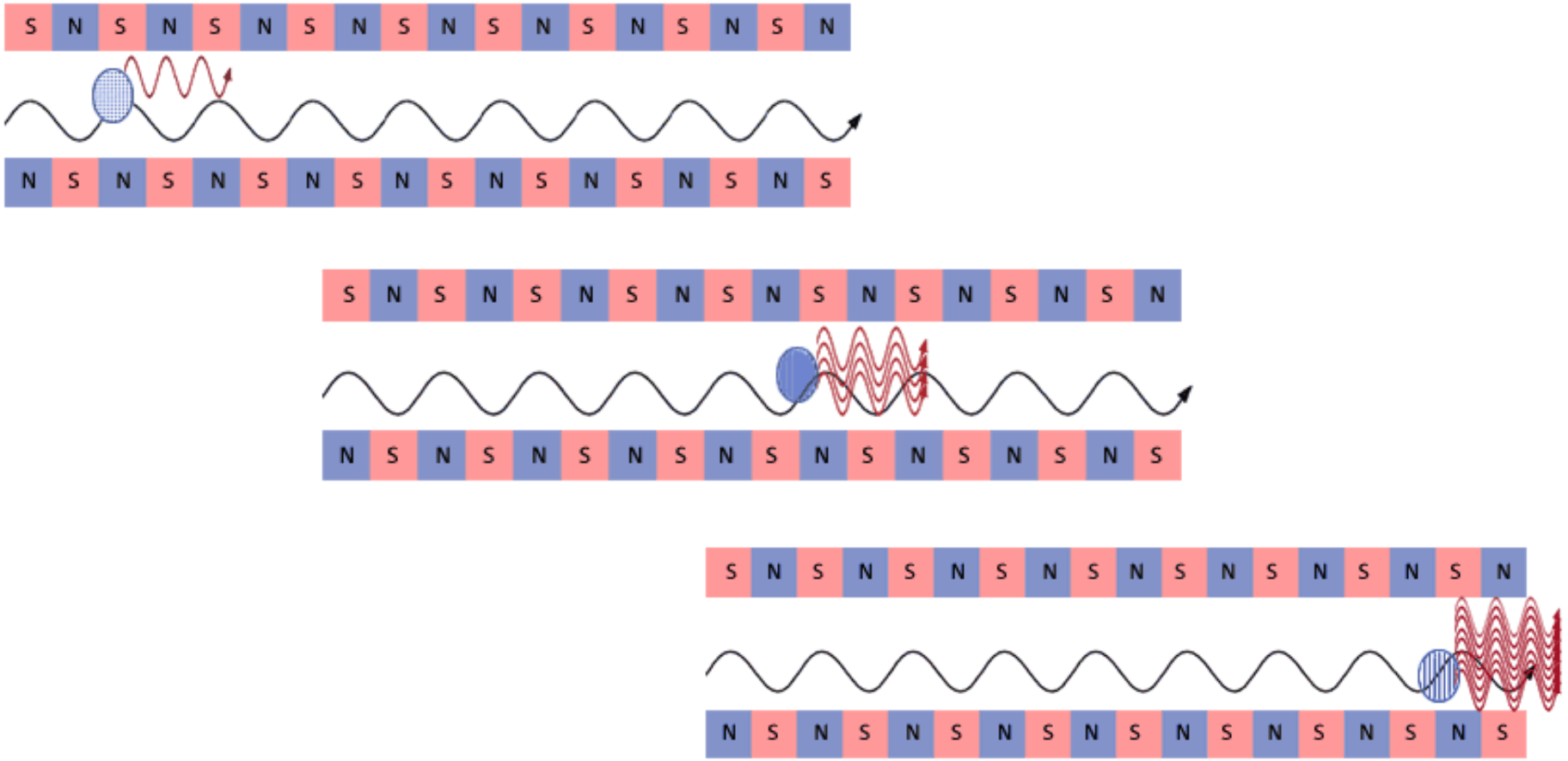
SASE FEL

The electron beam and the electromagnetic field co-propagate in a long undulator.



Due to the strong interaction, the electron beam shows bunching at the resonant wavelength: emission becomes strong and coherent

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

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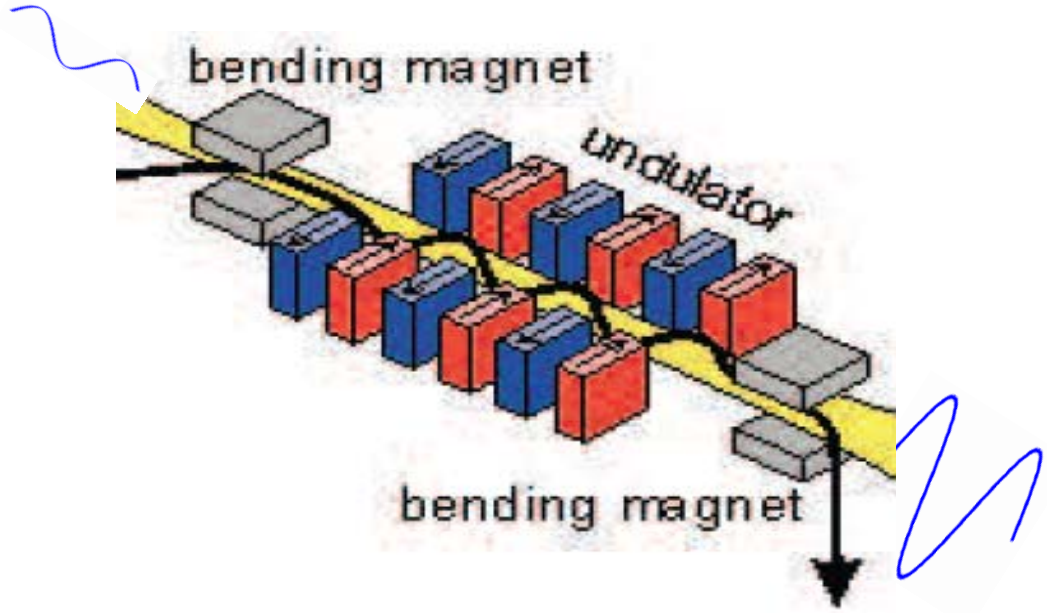
Direct seeding FEL

The FEL process is initiated by an external weak coherent signal



- **The output radiation reproduces the properties of the input seed (coherence, wavelength, …)**
- **The tunability range is limited by the availability of coherent sources.**

The use of this technique in combination with high harmonics generated in gas jet can extend the FEL tunability toward x-rays.

The origin of the co-propagating wave

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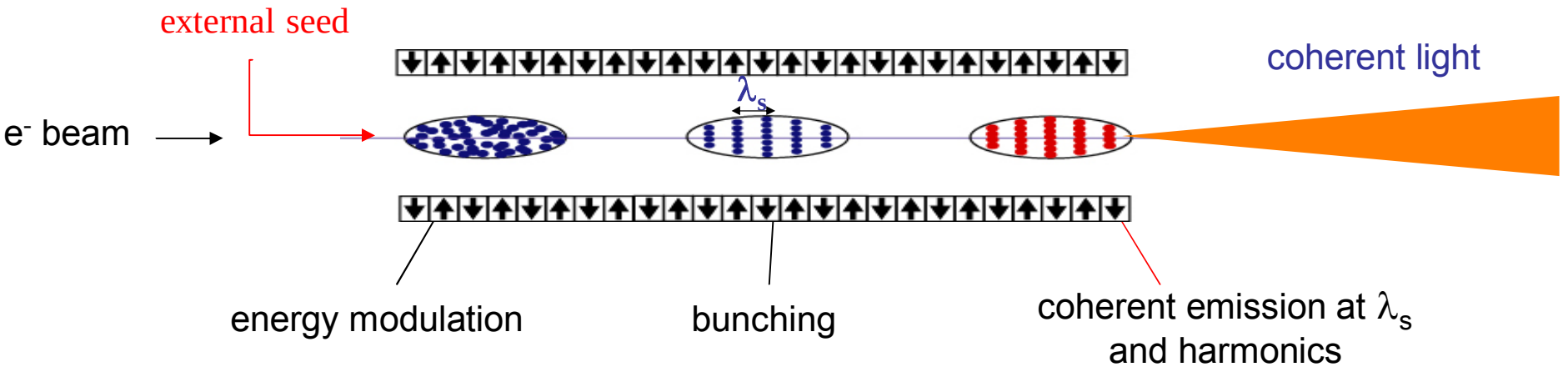
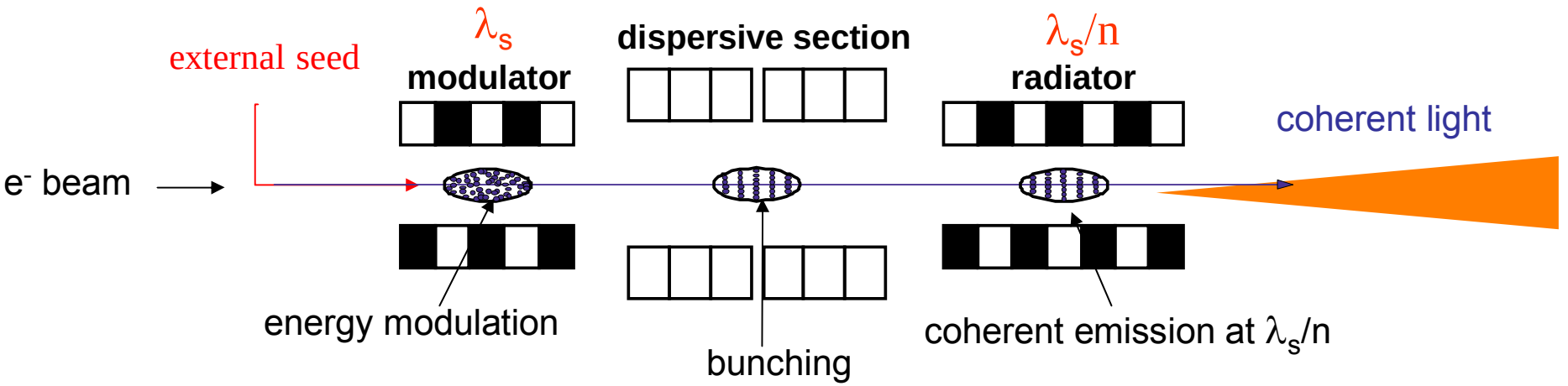
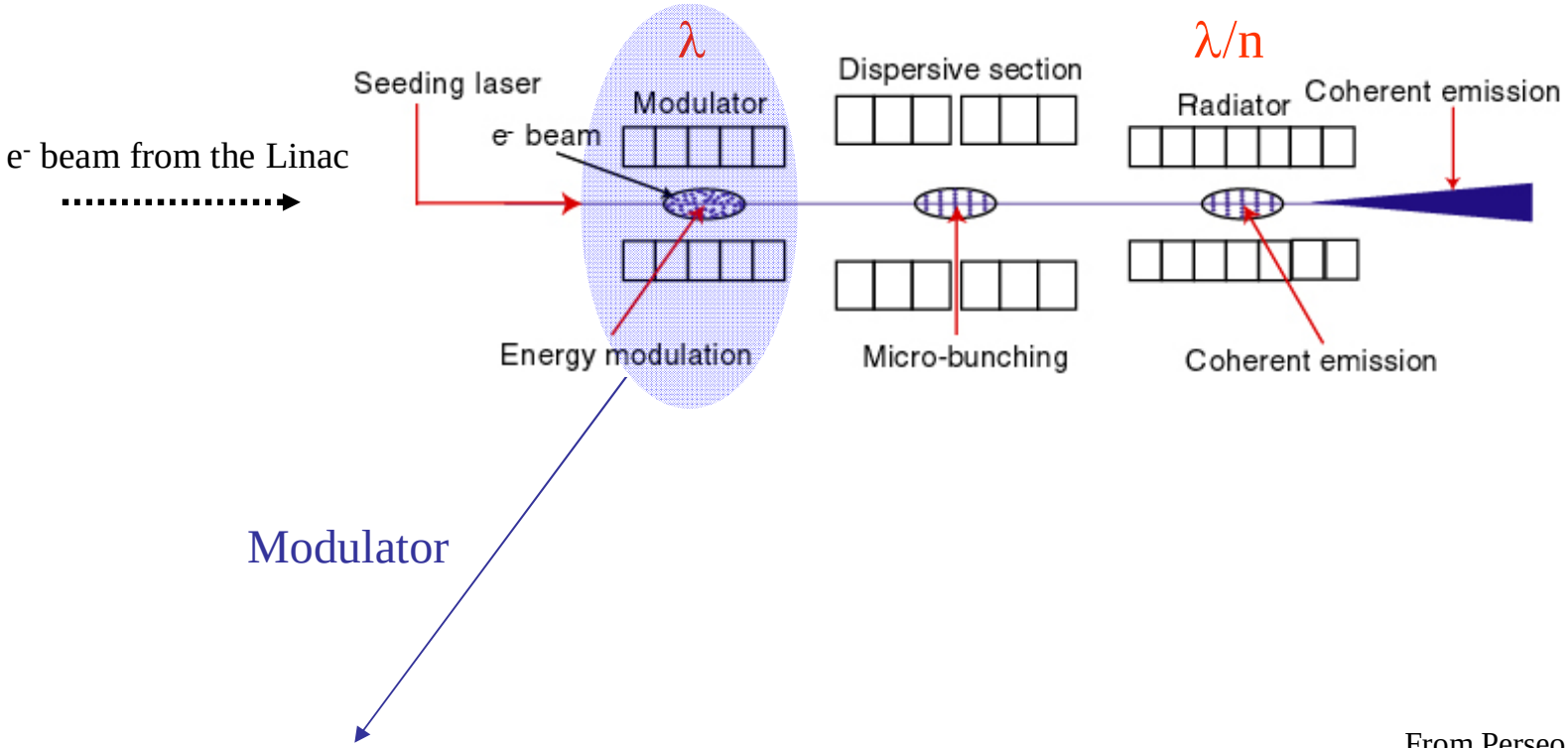
Single-stage harmonic generation



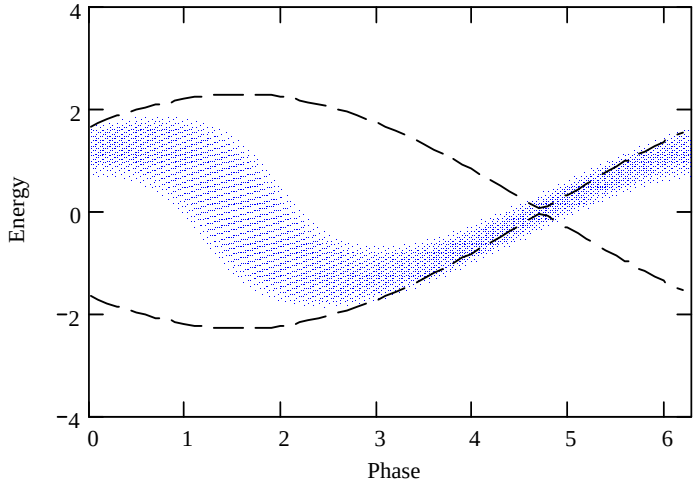
Multi-stage harmonic generation



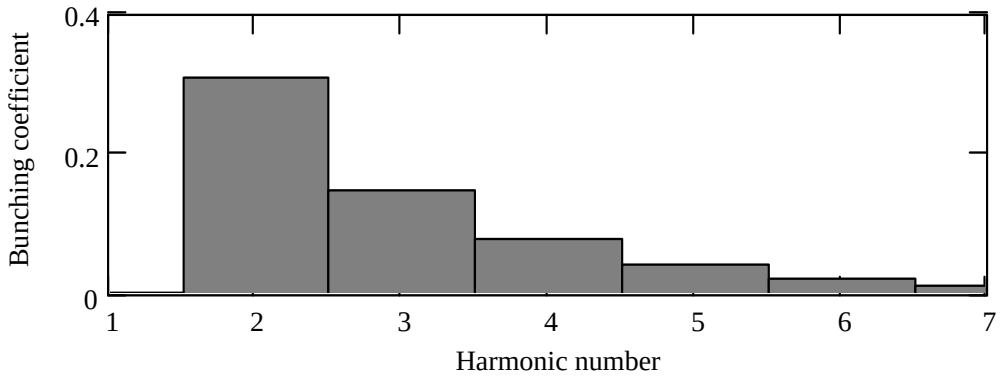
Multi-stage harmonic generation: the principle (1/2)



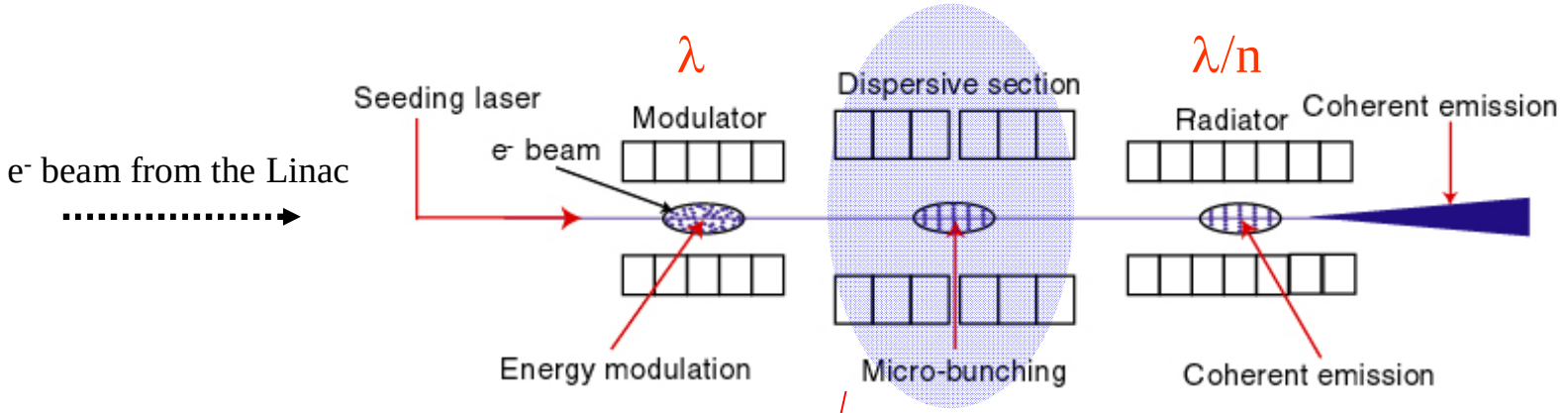
Modulator



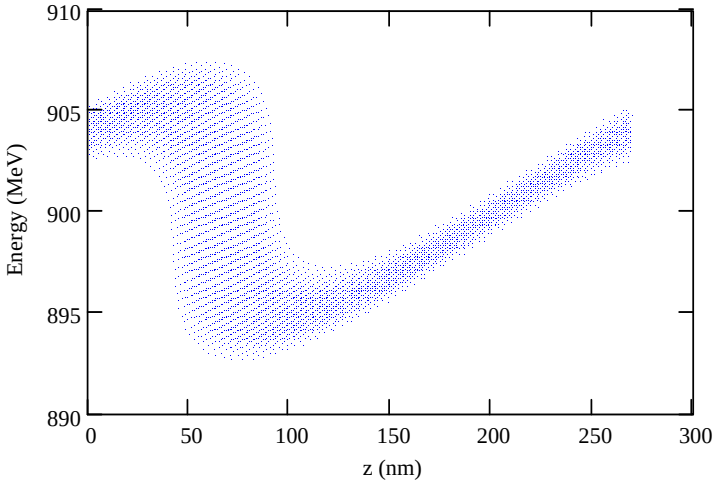
From Perseo,
a numerical code by L. Giannessi



Multi-stage harmonic generation: the principle (1/2)



Dispersive section



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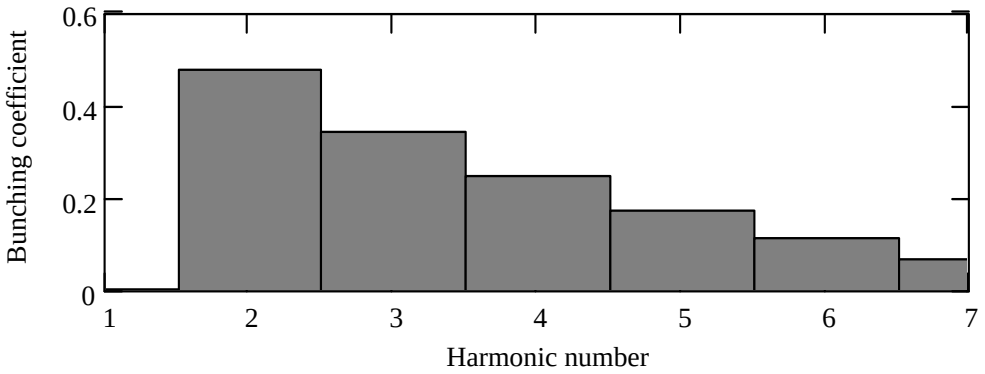
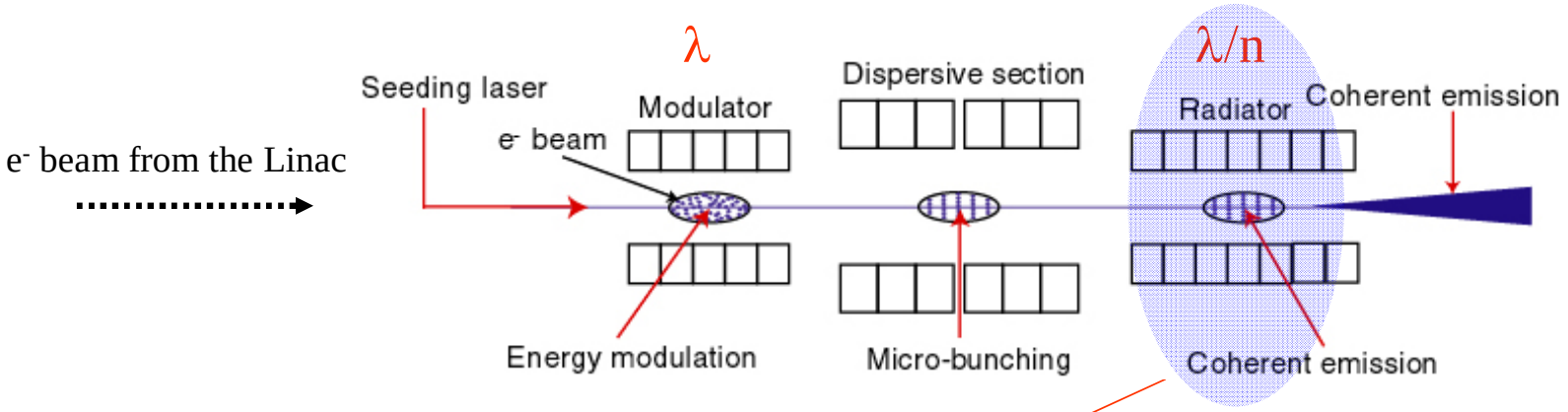
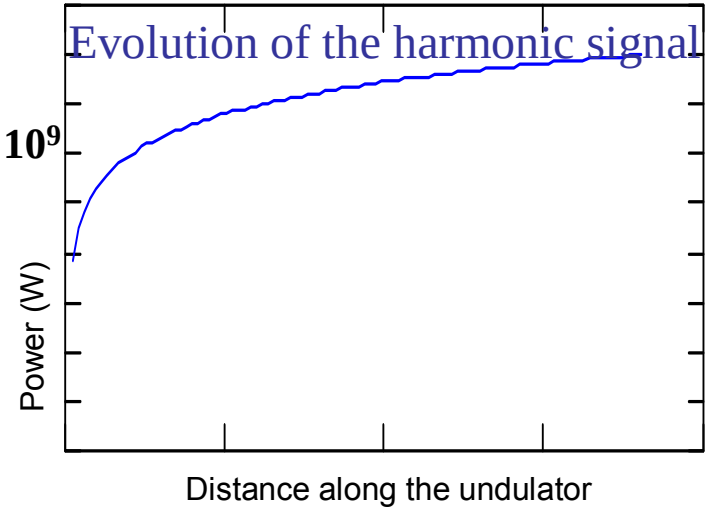


Multi-stage harmonic generation: the principle (2/2)

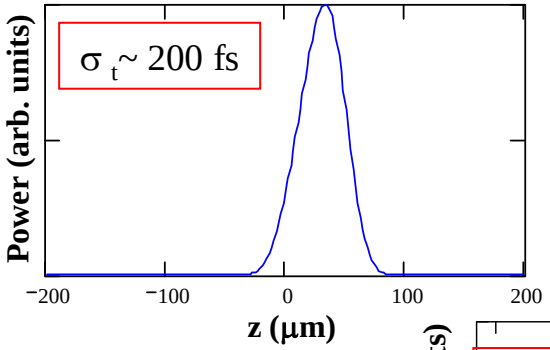


Radiator

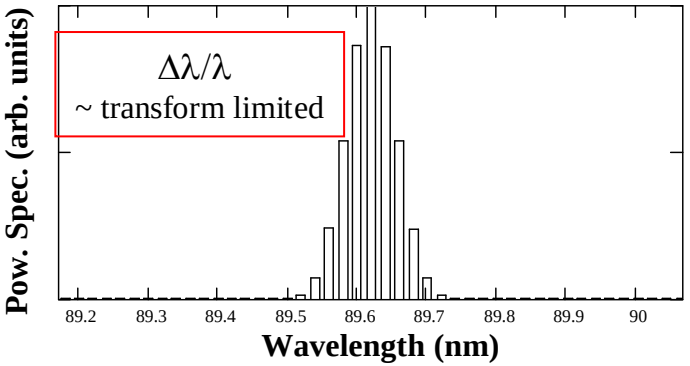
Evolution of the harmonic signal



Pulse profile

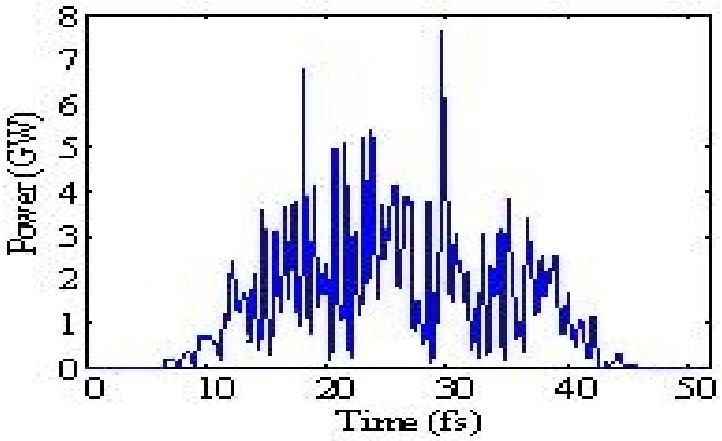


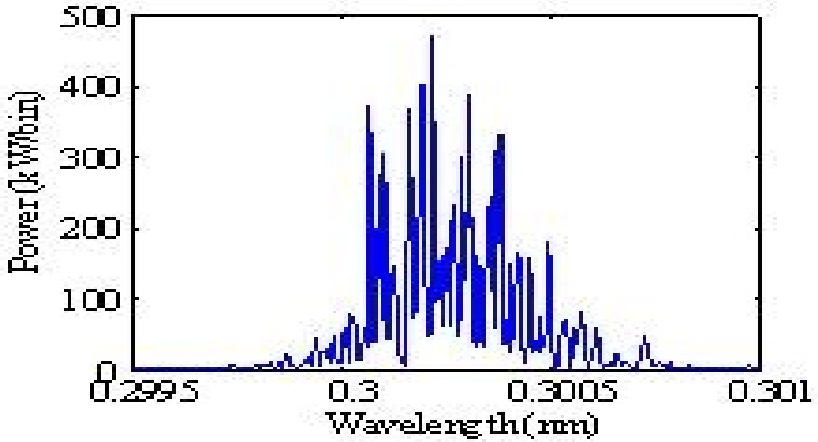
Spectrum profile



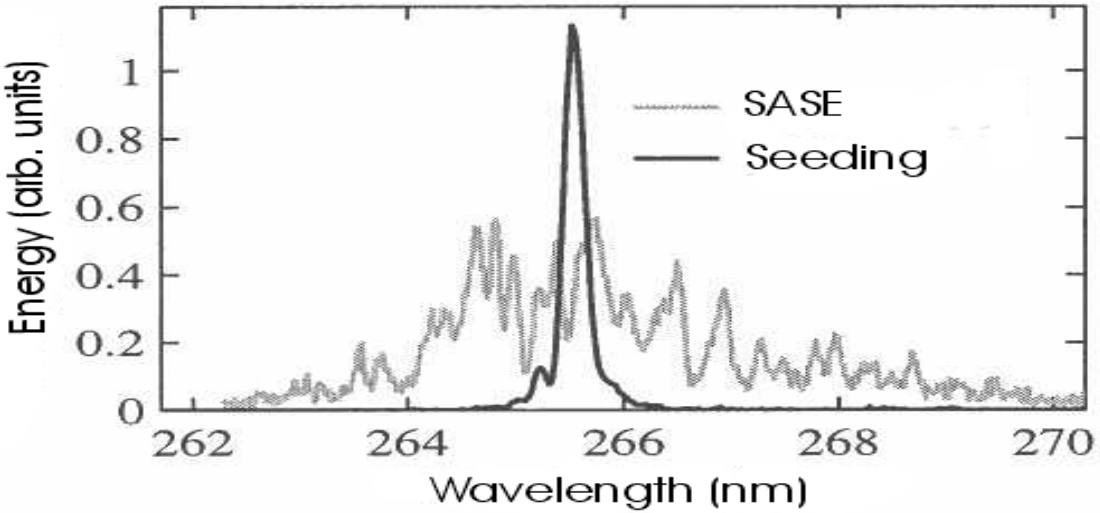
SASE versus Seeding

SASE





Seeding



Critical parameters and “real word” effects

Previous analysis concentrated on the longitudinal electron-wave interaction and assumed a perfect transverse overlap between the light spot and the electron beam. In reality, also the transverse dynamics plays a very important role.

In order to insure a good transverse overlap, the electron beam emittance must satisfy the following relation: $\varepsilon < \lambda$. Such a condition becomes critical at short wavelengths.

Another critical parameter is the electron beam energy spread: only electrons having an energy within a given bandwidth (~$1/N_u$) with respect to the resonant energy contribute to the FEL process.

A **low emittance** and a **small energy spread** constitute essential characteristics of a high-quality electron beam.

The electron beam quality may be degraded by several detrimental phenomena occurring immediately after the beam generation and/or during the transport thorough the Linac. For example: space charge, wakefields, coherent synchrotron radiation, …

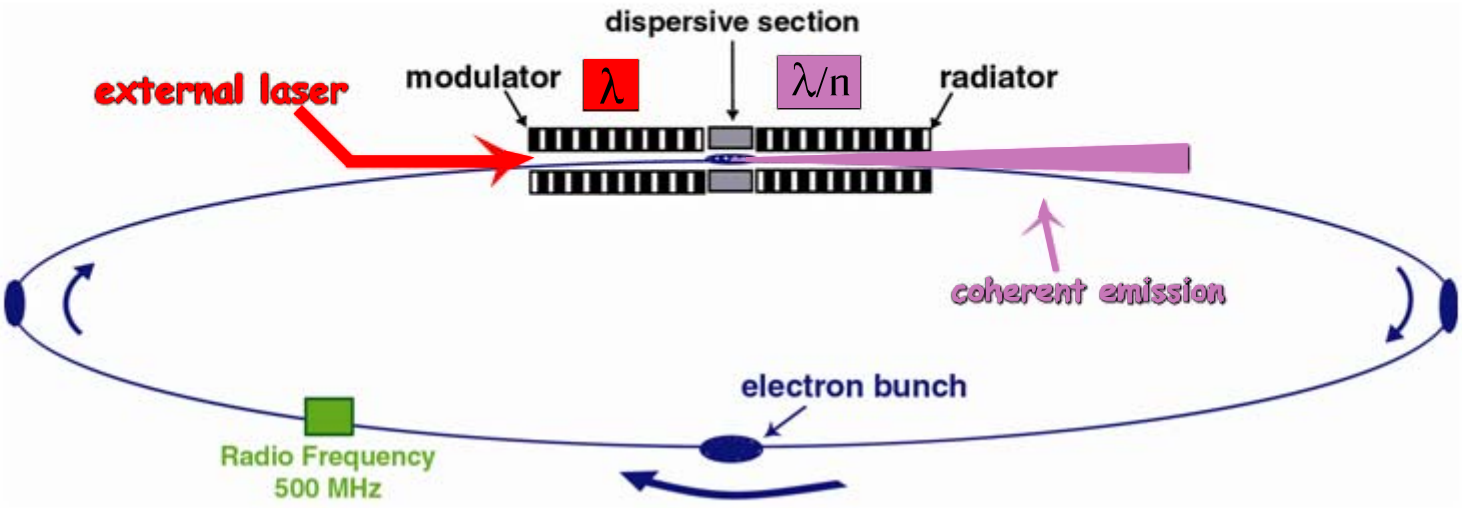
Free Electron Lasers at work

- The Elettra Storage-Ring Free-Electron Laser

- The FERMI project

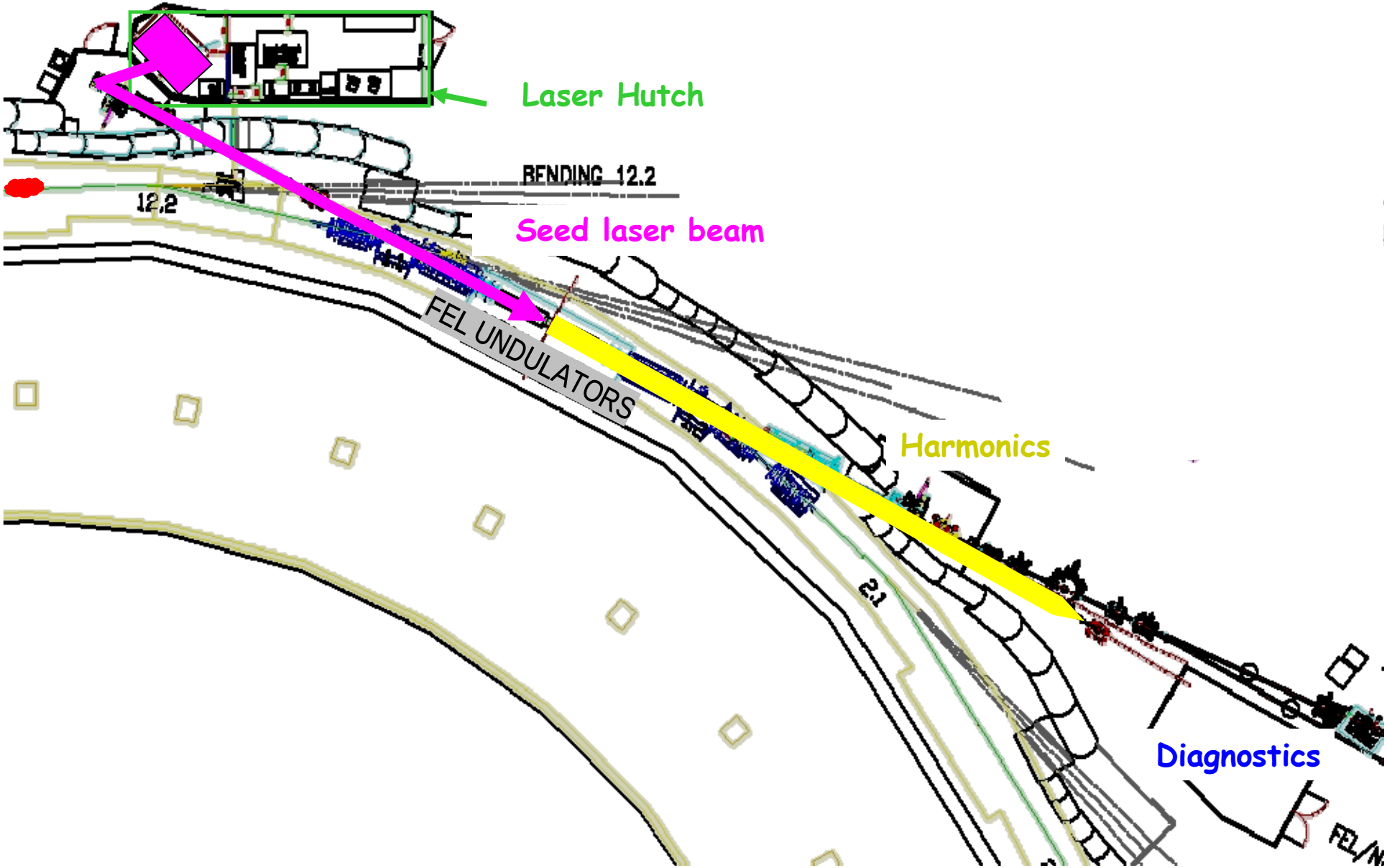
Overview of the ELETTRA laboratory

Sorage-Ring FEL: experiment layout

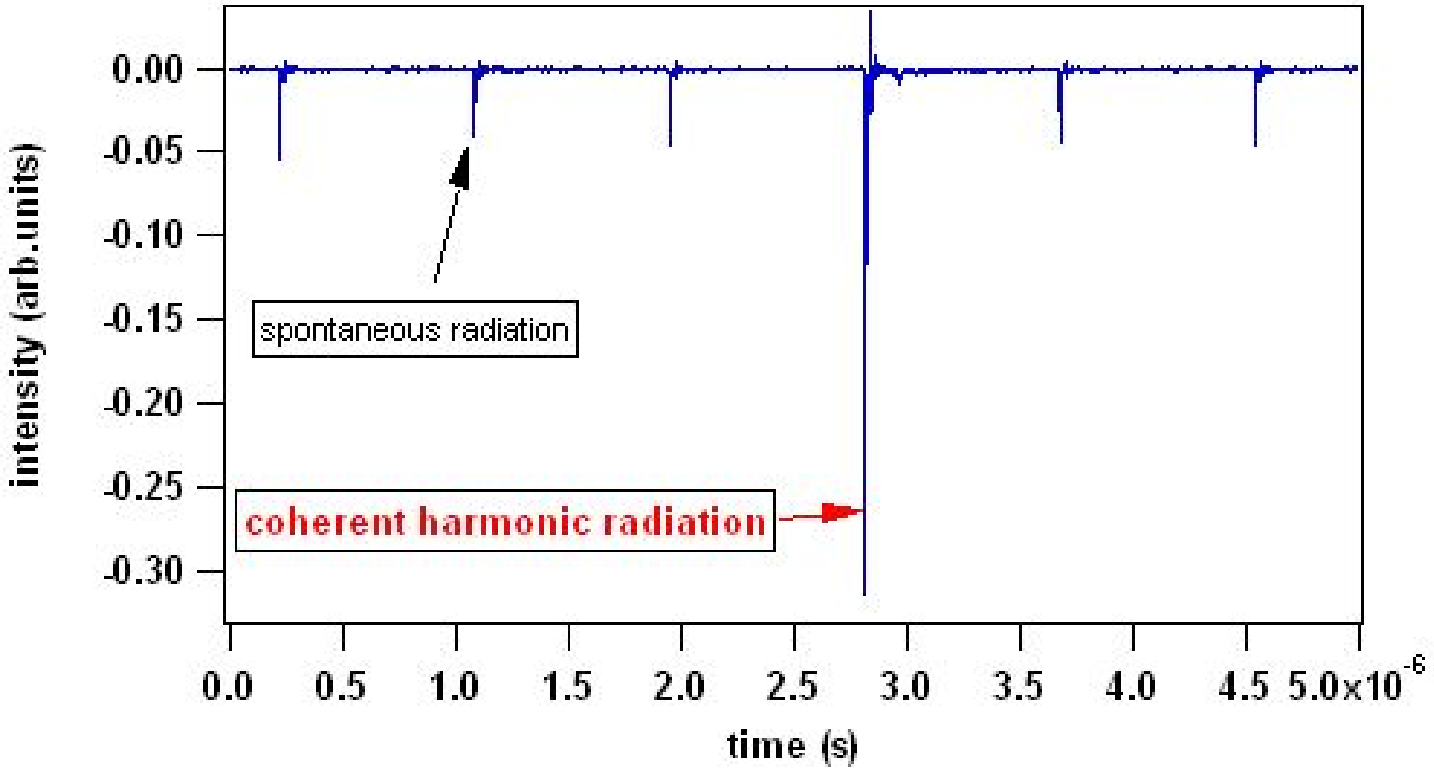


Elettra working conditions	
Beam energy	0.75 GeV Š 1 GeV
Current per (single) bunch (max)	~ 1 mA
Normalized H/V emittance (1GeV)	3.2/0.32 mm mrad
Bunch duration	~ 30 ps (rms)
Bunch relative energy spread	~ 10^{-3}

FEL working principle



Harmonic generation: temporal analysis

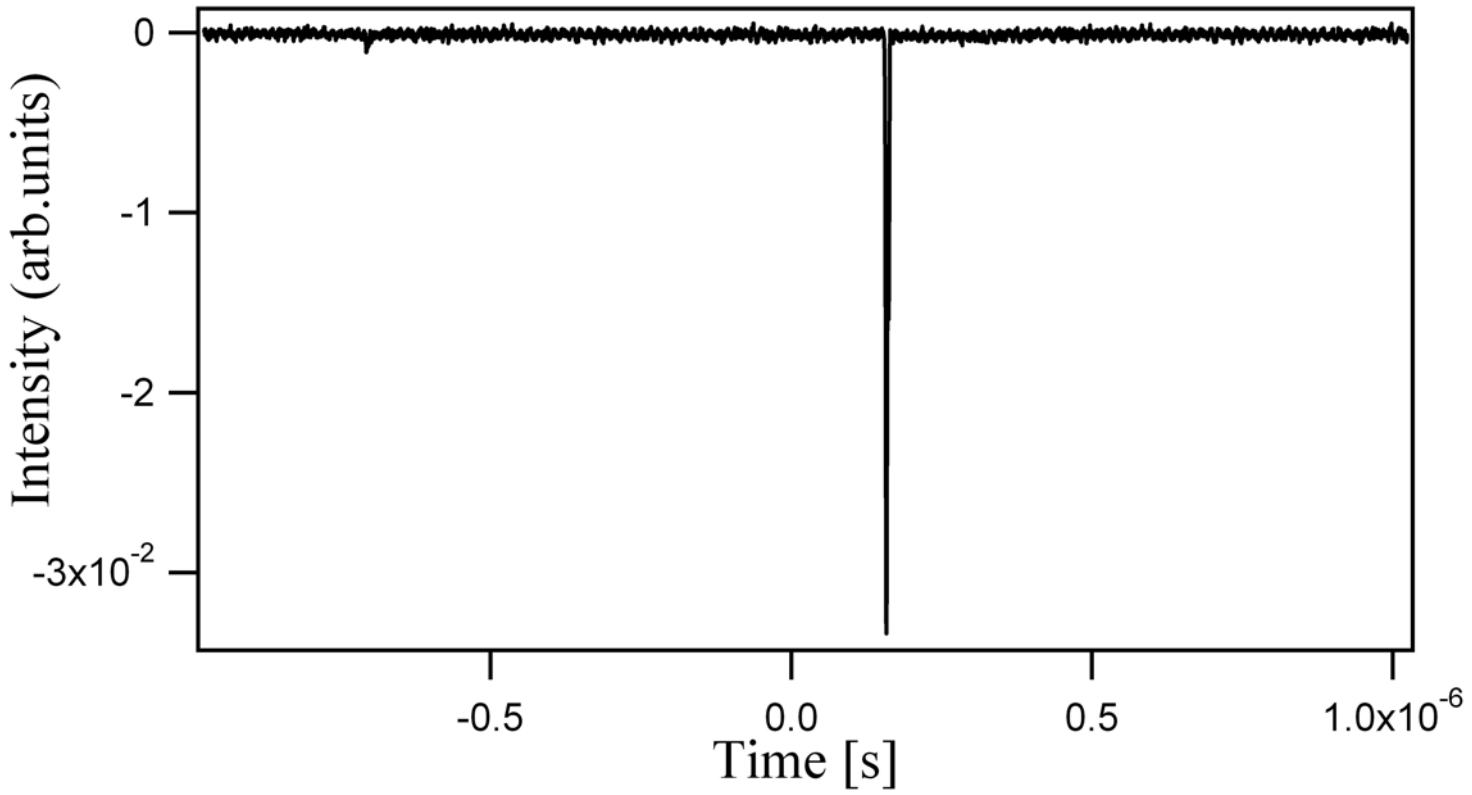


Vertical axis: integrated signal of the monochromatized radiation at 260 nm acquired with a photo-multiplier tube. Horizontal axis: acquisition time. The enhanced peak is the coherent signal generated by the seeded electron bunch, small peaks represent the spontaneous (i.e., un-seeded) radiation.

Pulse repetition rate: 1 KHz; pulse length: 100 fs (FWHM)

After some tuning…

synchrotron radiation falls into noise!

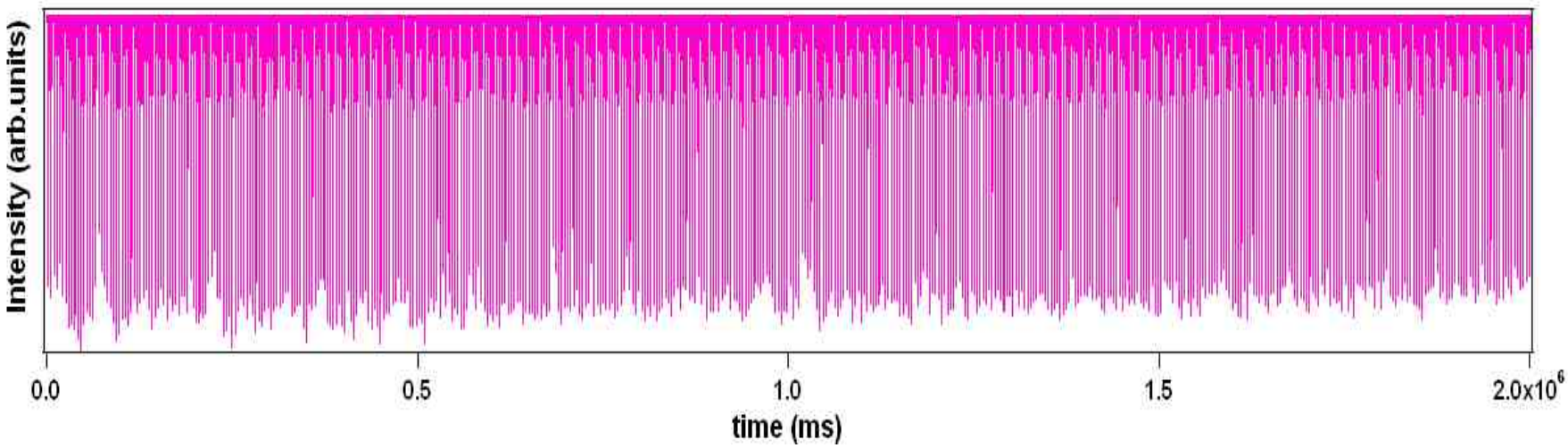


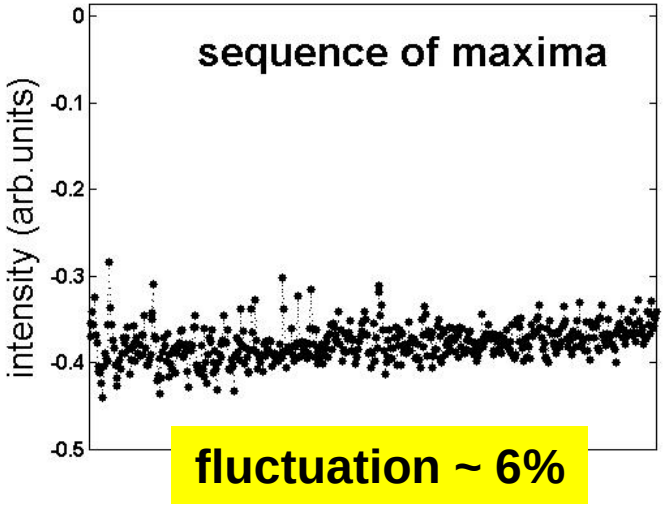
Seeded signal is a factor about **50** above spontaneous emission.

The factor becomes about $\mathbf{10^4}$ taking into account the difference between spontaneous (30 ps) and seed (100 fs) pulse durations.

Shot-to-shot stability

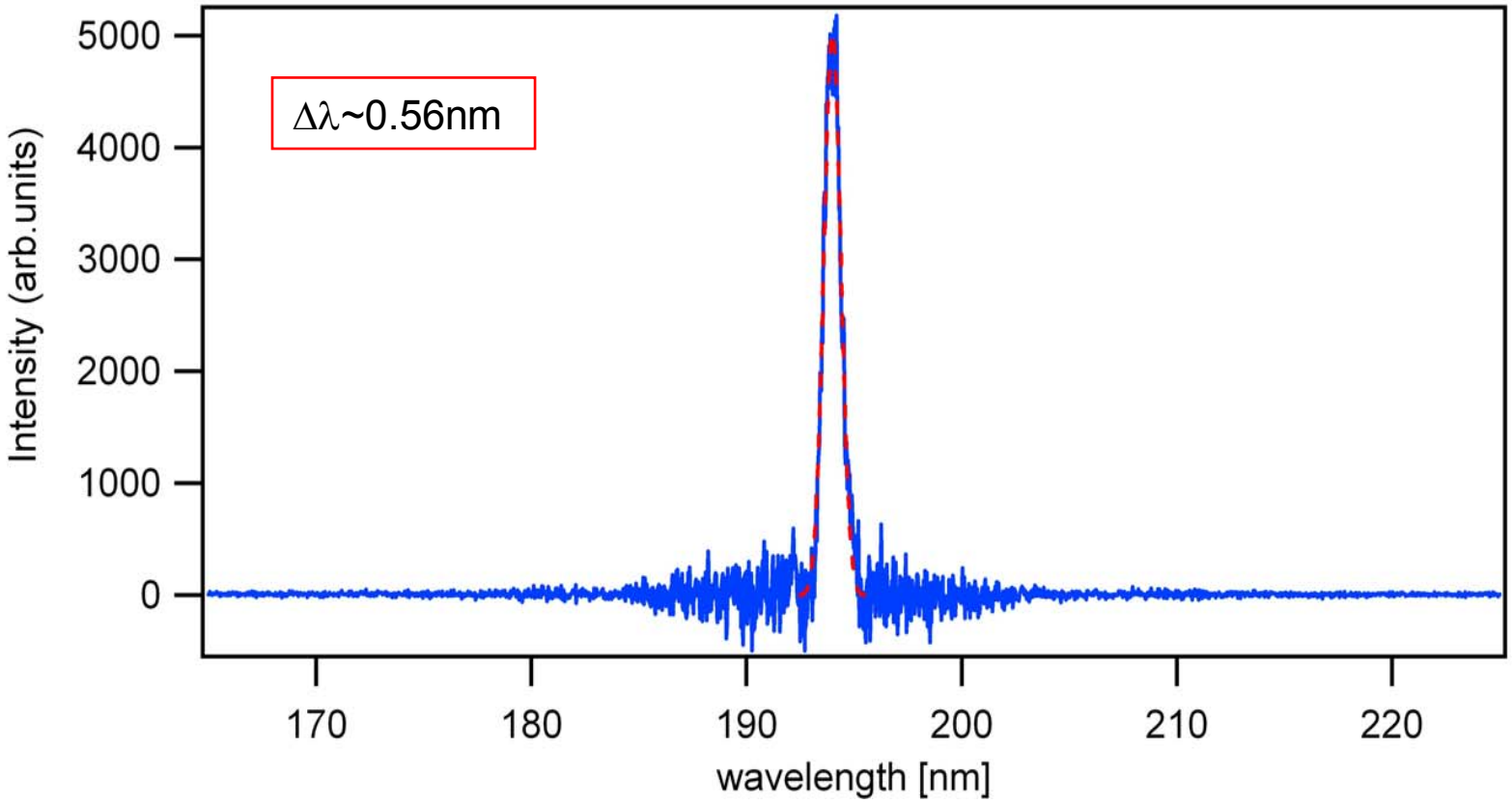
Sequence of 500 coherent pulses





fluctuation ~ 6%

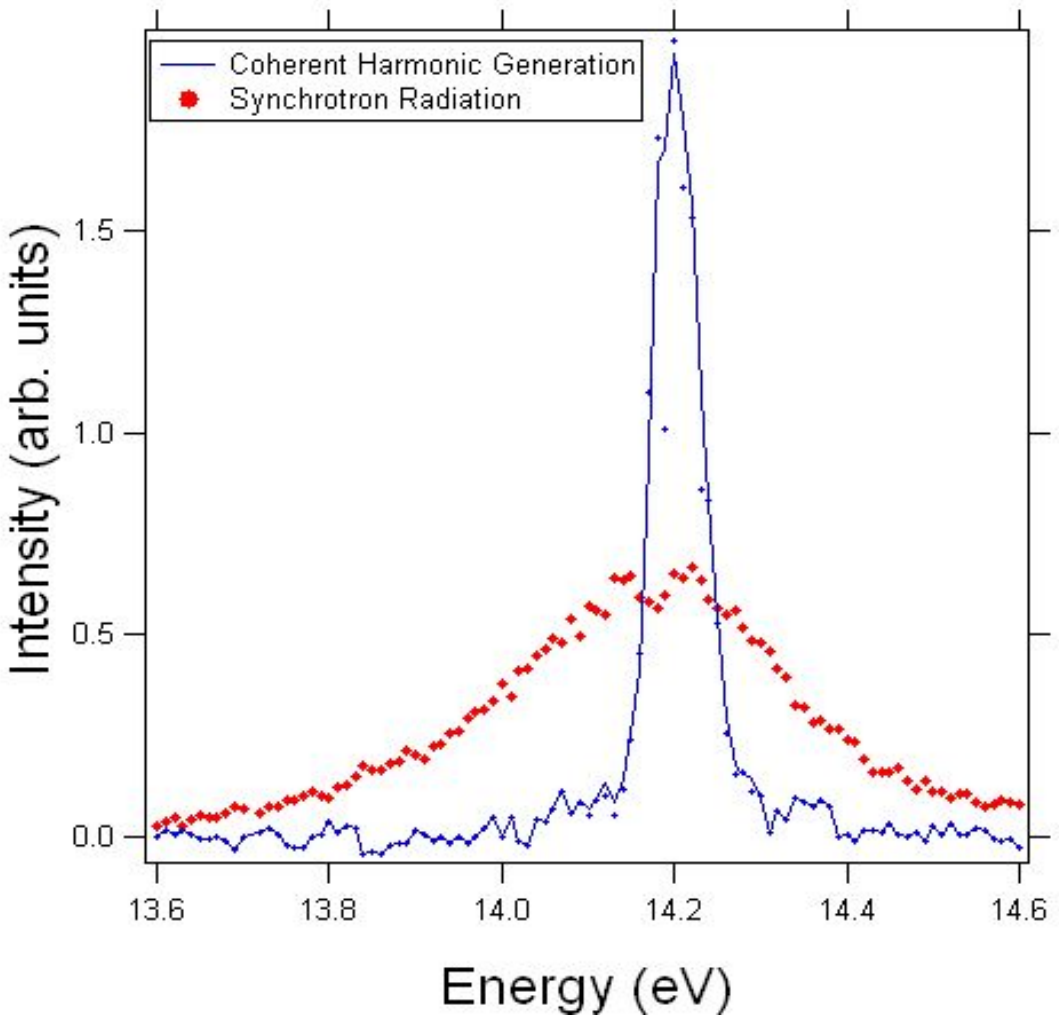
Harmonic generation: spectrum



Optical pulse is close to Fourier limit

Coherent harmonic generation at 87 nm

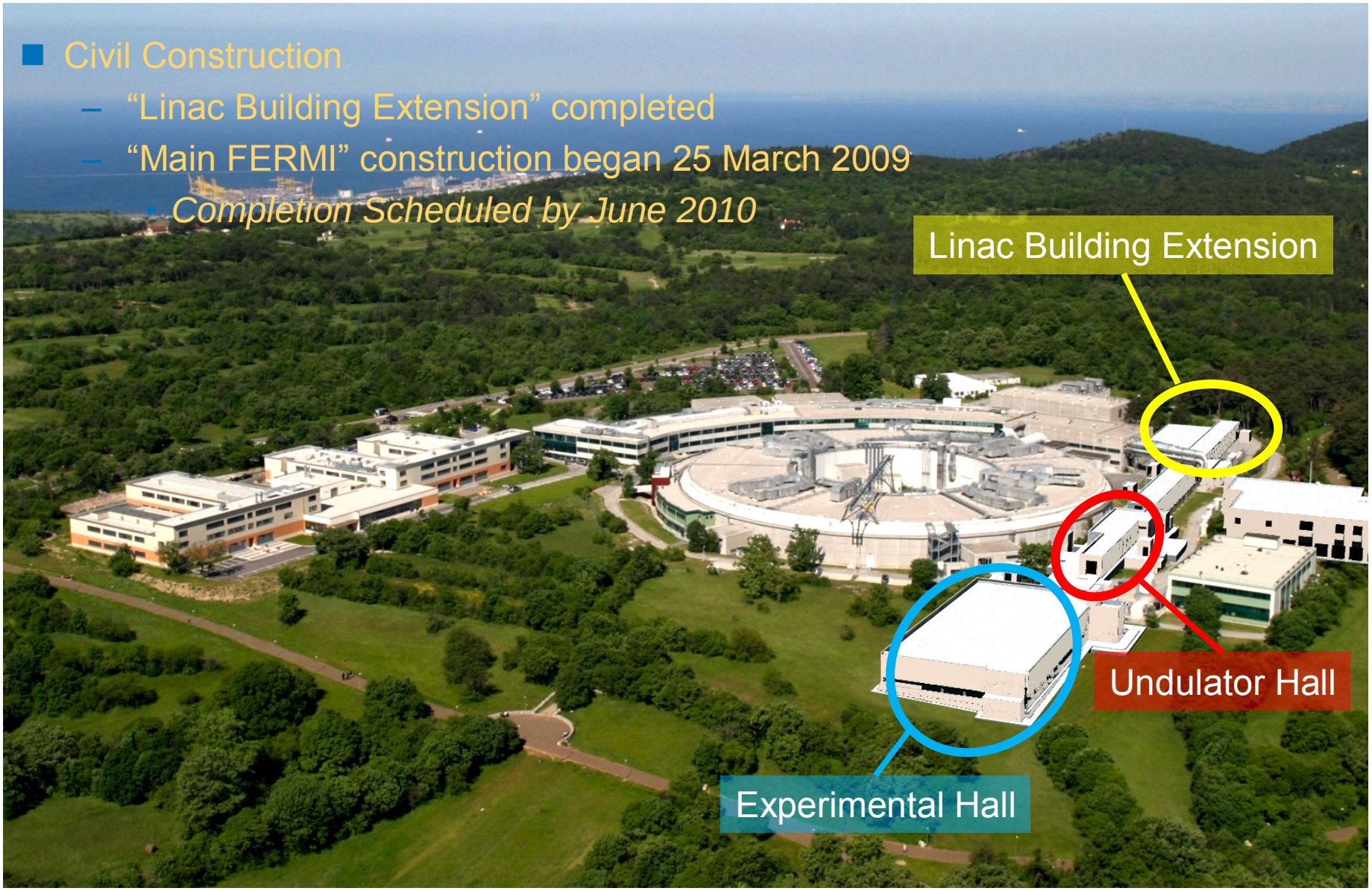
The SPELEEM microscope installed at the Elettra Nanospectroscopy beamline was used to observe the photo-electron yield from a **Au** thin film, as function of the photon energy



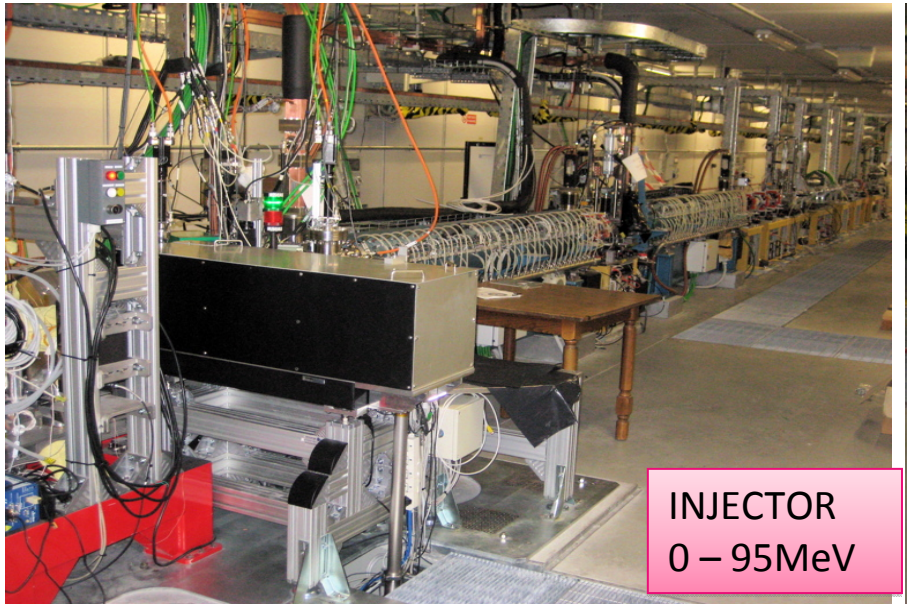
11/05/2009

The FERMI project

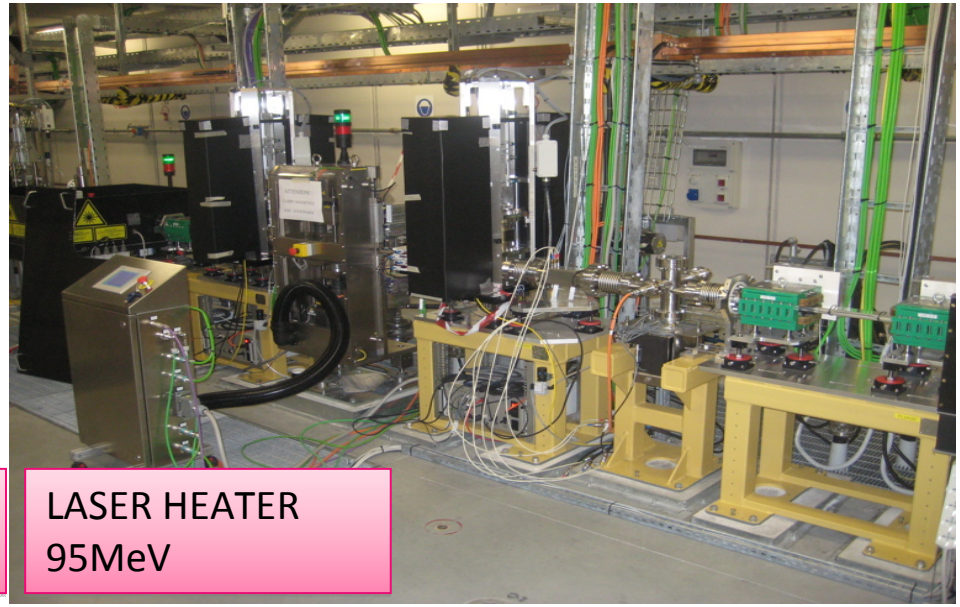
civil engineering



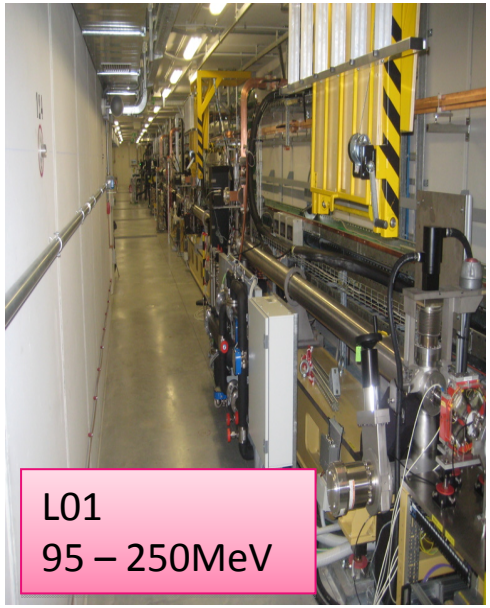
accelerator



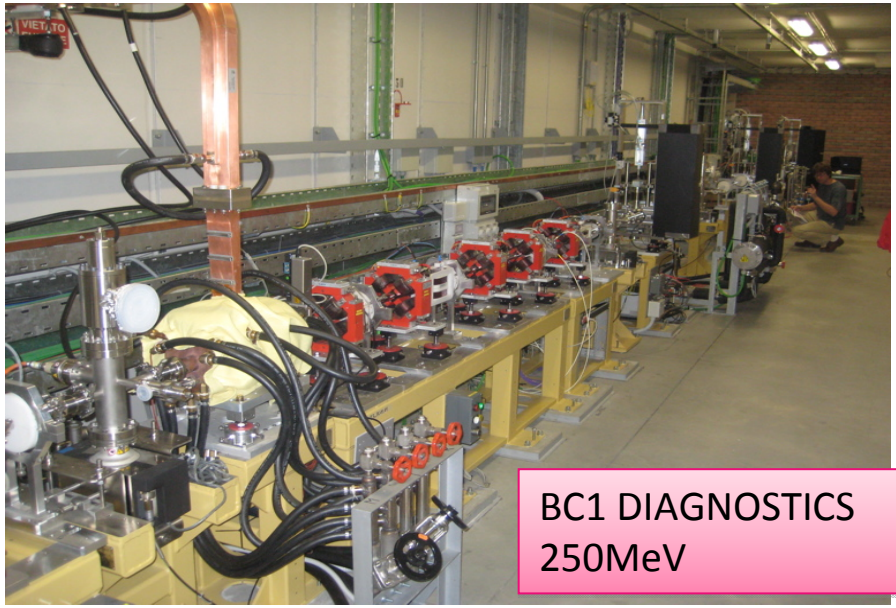
INJECTOR
0 – 95MeV



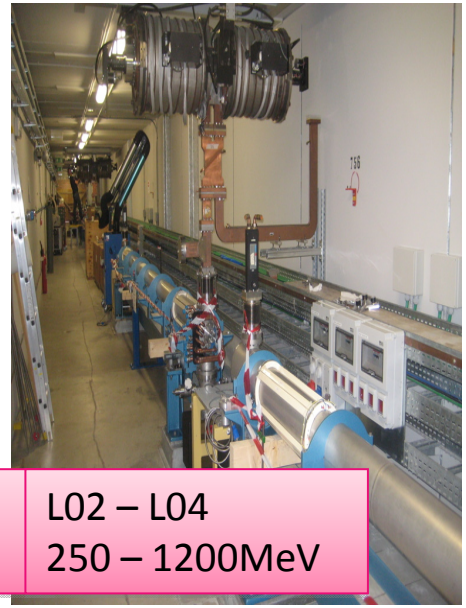
LASER HEATER
95MeV



L01
95 – 250MeV

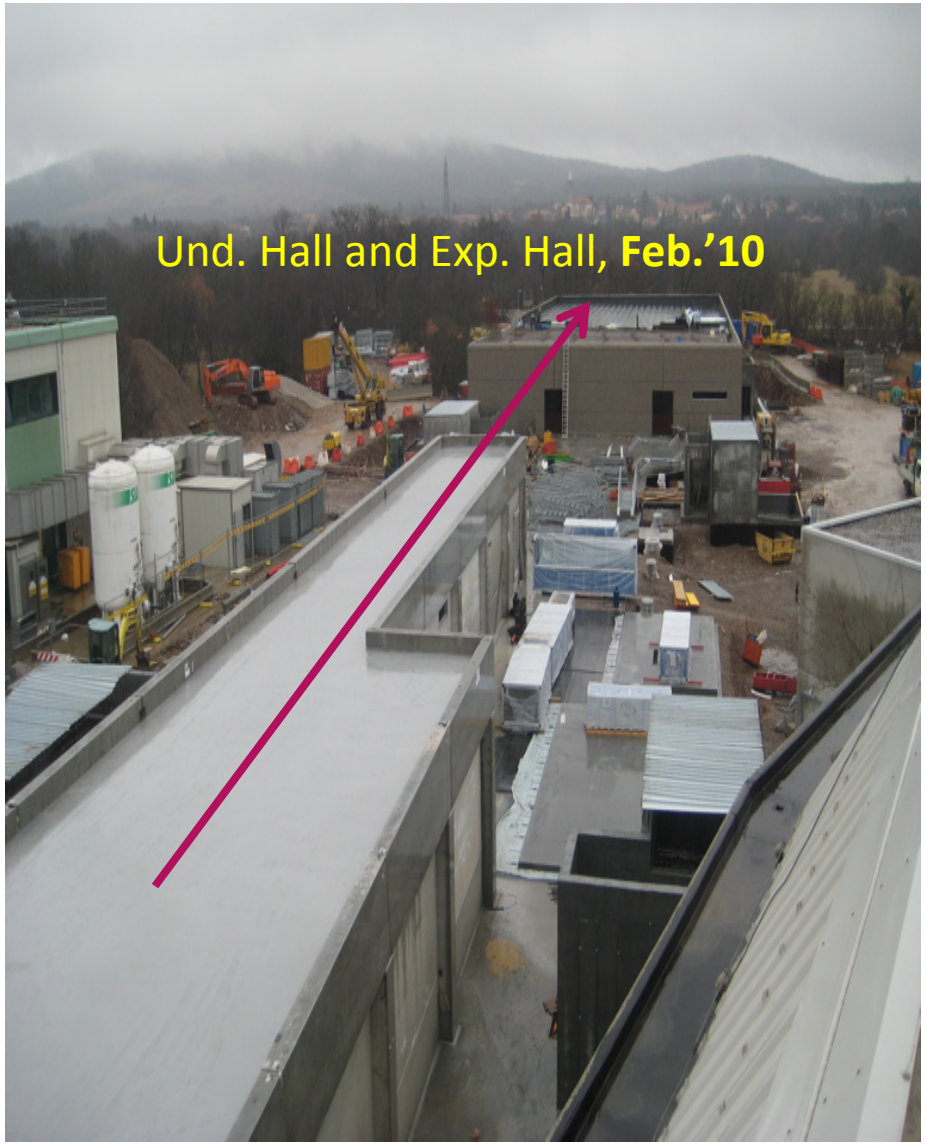


BC1 DIAGNOSTICS
250MeV

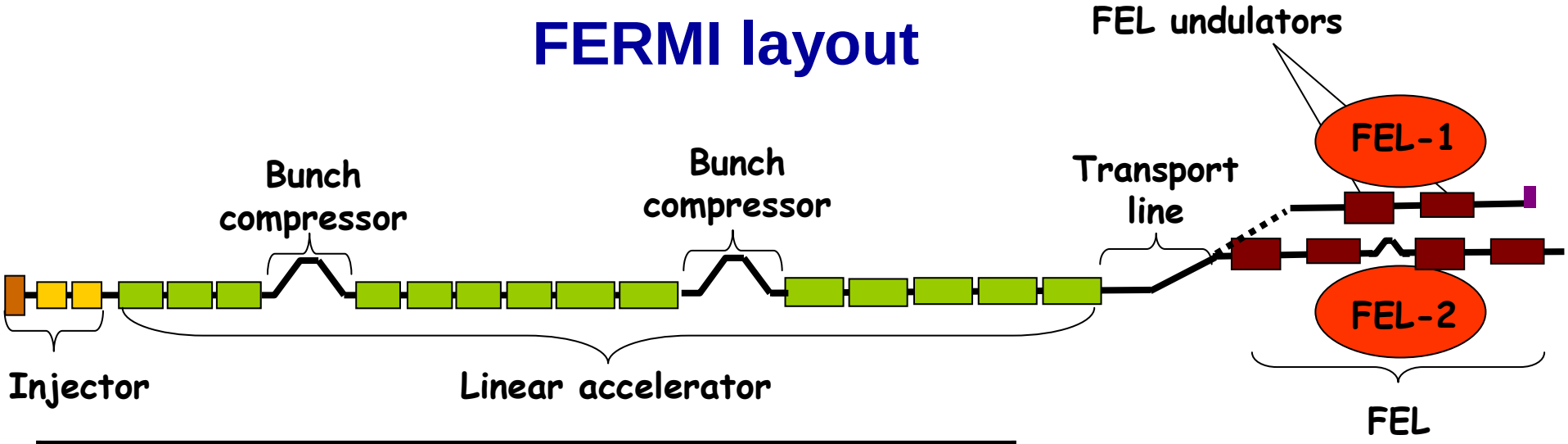


L02 – L04
250 – 1200MeV

undulator and experimental hall



FERMI layout



Parameter	*Medium bunch*	*Long Bunch*
Beam energy	1.2 GeV	1.2 GeV
Peak current	0.8 KA	0.5 KA
Uncorrelated energy spread	200 KeV	150 KeV
Normalized Emittance	1.5 mm·mrad	1.5 mm·mrad
Bunch length	~ 0.6 ps	~ 1.4 ps

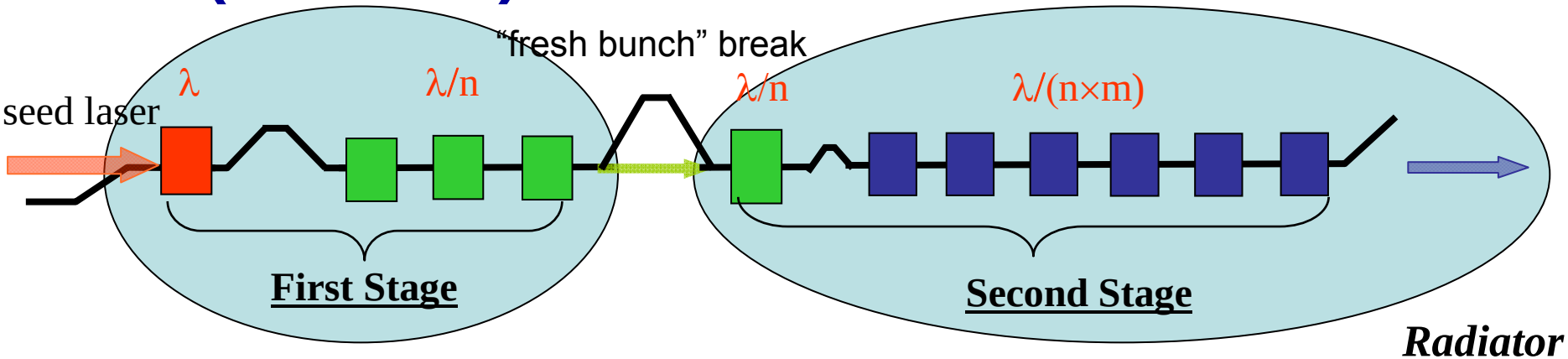
Two different ondulator lines for two different spectral regions:

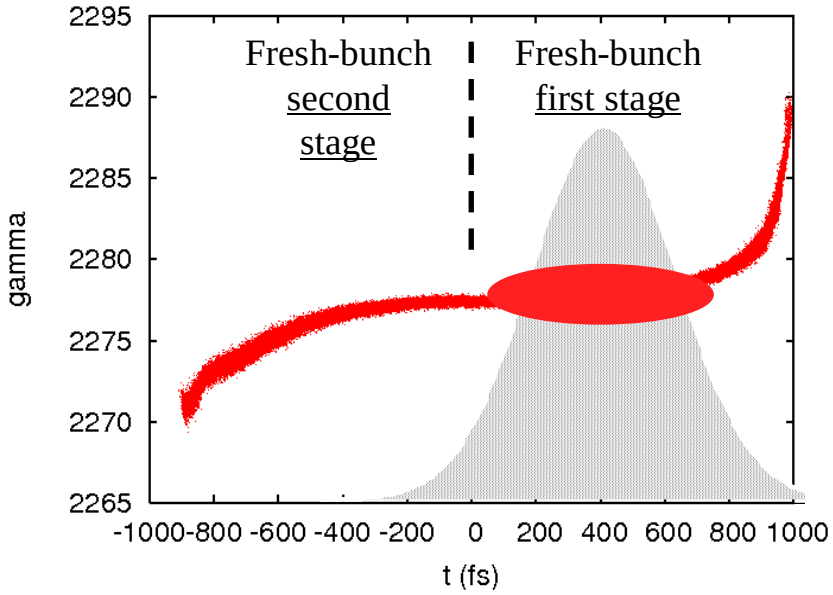
- **FEL-1** covers the spectral region between 100 and 40 nm
- **FEL-2** the region between 40 and 4 nm

Both FEL's are based on the Harmonic Generation scheme and make use of APPLE II type ondulator for producing light with variable polarization

FEL-2 (40 - 4 nm)

Total length FEL-2 ~ 37.5 m



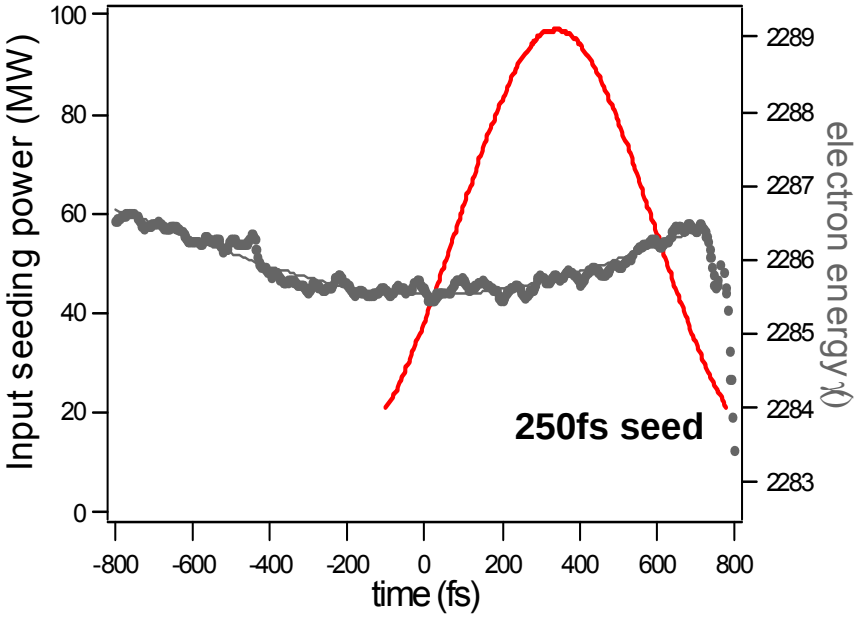


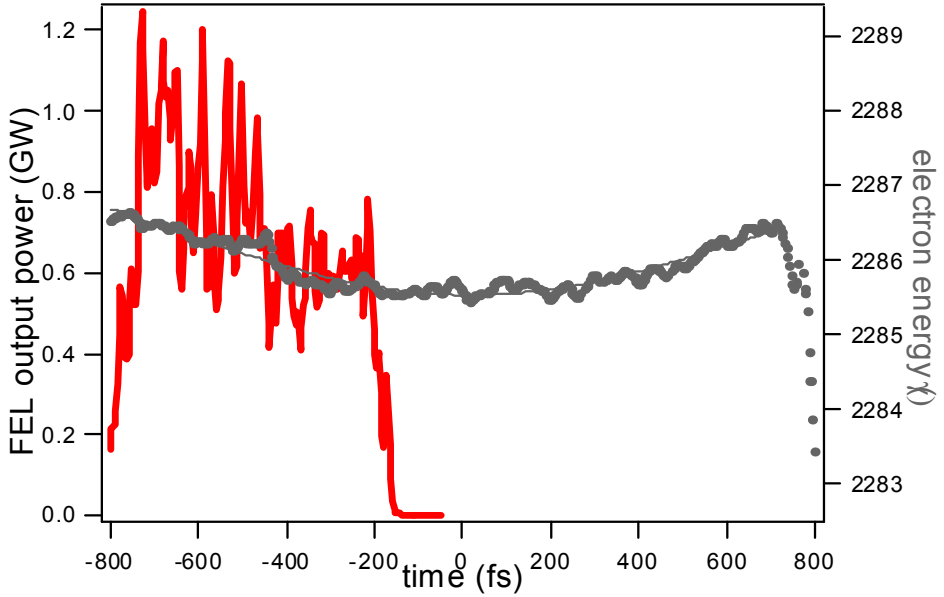
Radiator

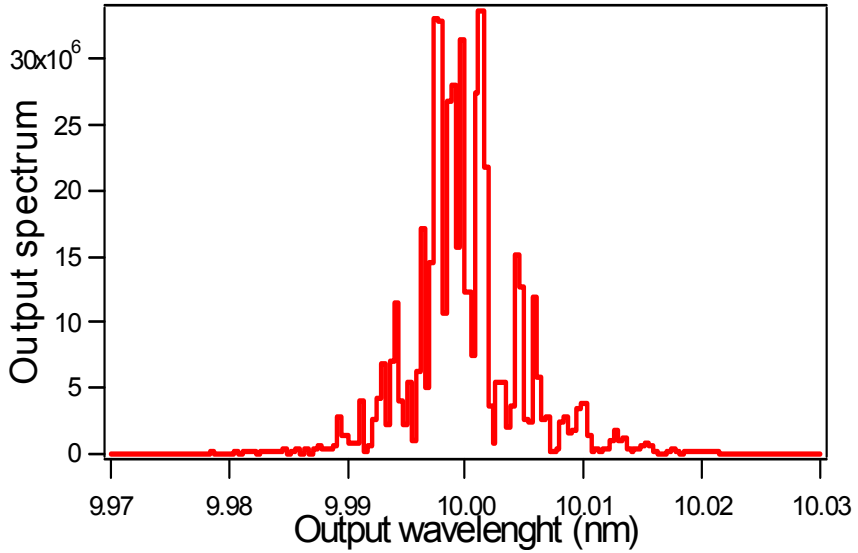
Parameter	*Value*
Type	Apple
Structure	Segmented
Period	5 cm
Segment length	2.4 m
K	1.1 - 2.8
Break length	1.06 m
Total length	19.7 m

The radiation produced at the end of the first stage is used as a seed for the second stage. The space between the two stages hosts a delay section to allow the electron-beam modulation in the second stage to be performed on a fresh part of the bunch, whose energy spread has not been increased by previous interactions in the upstream undulators.

FEL2 simulation at 10nm







- The length of the electron bunch allows the use of a seed pulse of 250 fs rms placed on the tail of the bunch.
- After the cascade the 10nm coherent emission is produced from the head of the bunch.
- Energy chirp and microbunching lead to a broadening of the bandwidth.

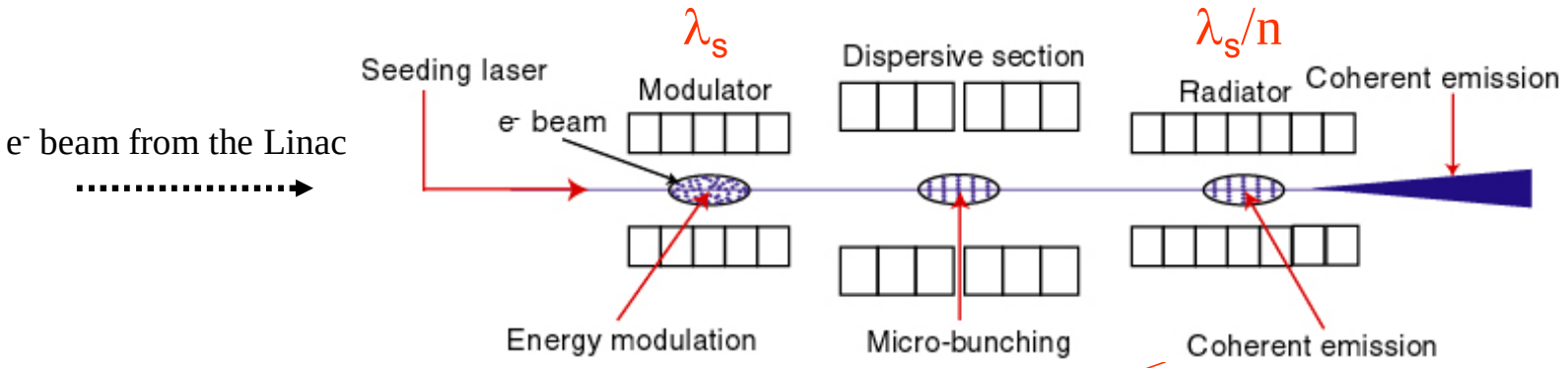
Pulse width (rms) = 170 fs
Photon number = 2.2e+13
Bandwidth (%) = 0.04

FERMI will It will be one of the first FEL user facilities in the world operating at wavelengths in the VUV to soft X-ray range.

This design and realization of a facility like FERMI relies on many different expertises: Accelerator and laser physics, electron and light diagnostics, high-level engineering.

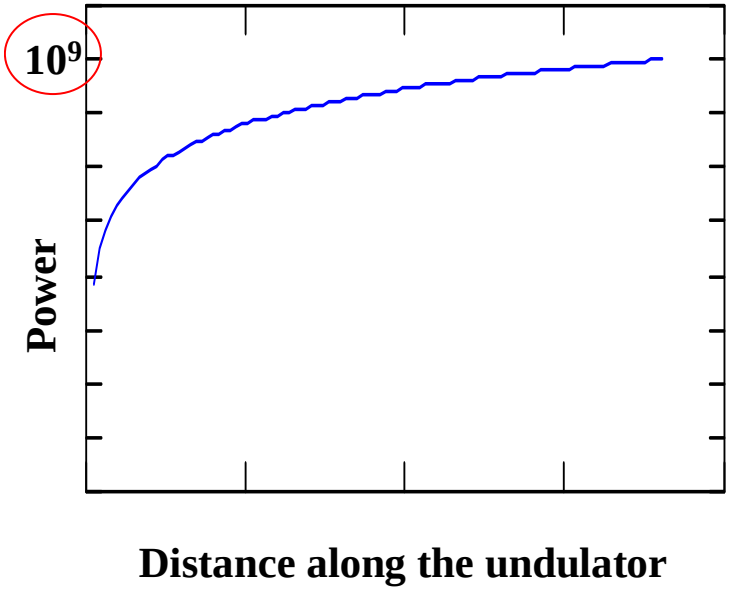
IDEAL ENVIRONMENT FOR BRILLIANT STUDENTS and POST DOCS INTERESTED IN APPLIED SCIENCES…

Multi-stage harmonic generation: the principle

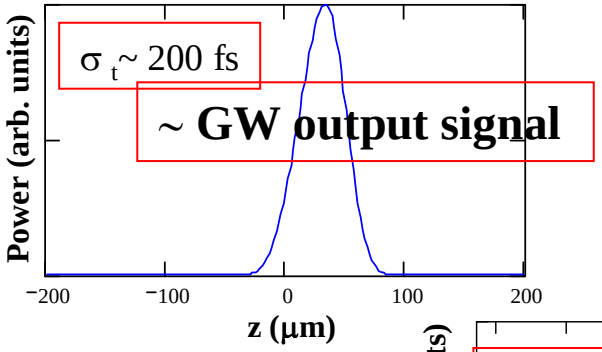


Radiator

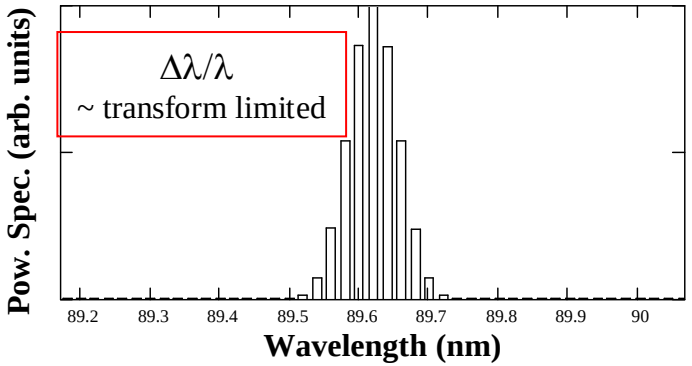
Evolution of the harmonic signal



Temporal profile



Spectrum profile



SASE FEL

$$\rho = \left[\left(\frac{I}{I_A} \right) \left(\frac{\lambda_w A_w}{2\pi\sigma_x} \right)^2 \left(\frac{1}{2\gamma_0} \right)^3 \right]^{1/3}$$

$I_A = 17.045$ kA is the Alfven current

$A_\omega = f(K)$

$$L_g = \lambda_w / 4\pi\sqrt{3}\rho$$

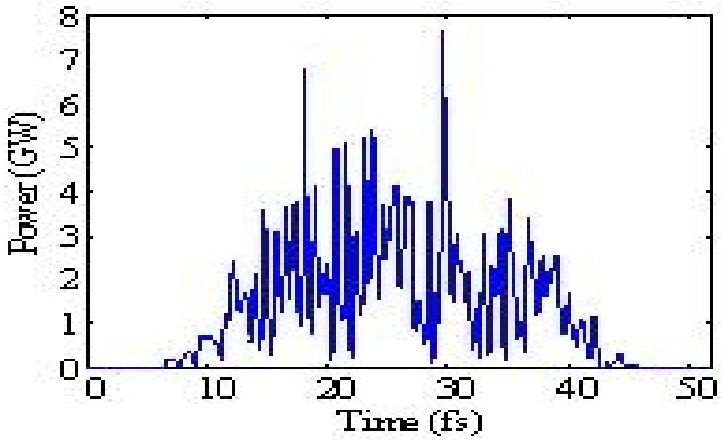
$$P_{sat} \approx \rho P_{beam}$$

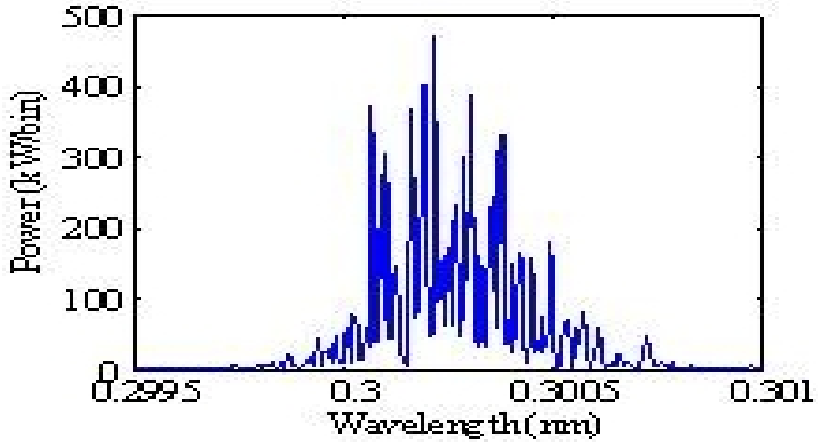
P_{beam}[TW] = E_0[GeV]I[kA]

$$P = \alpha P_n e^{z/L_g} < P_{sat}$$

$\alpha = 1/9$

SASE FEL



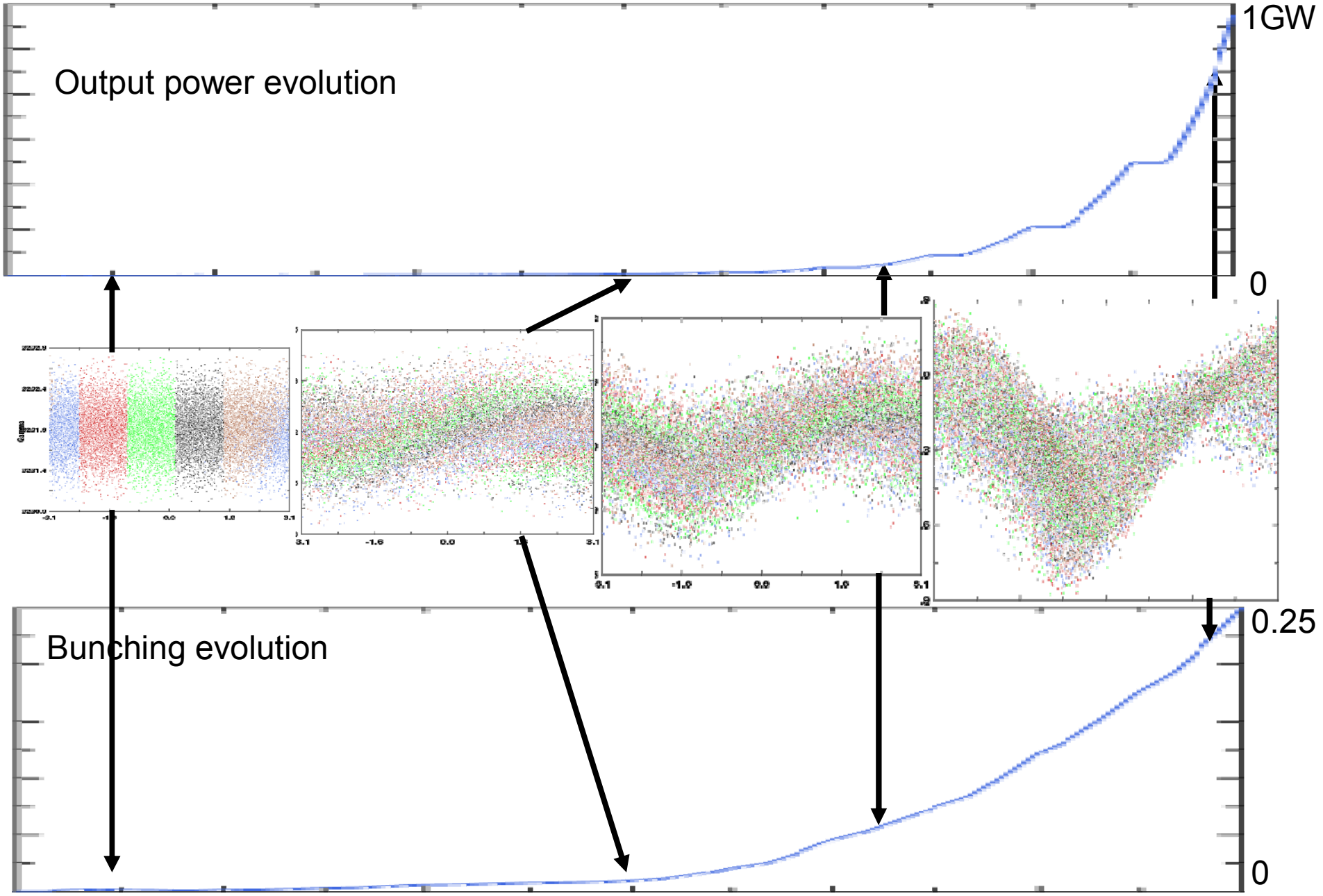


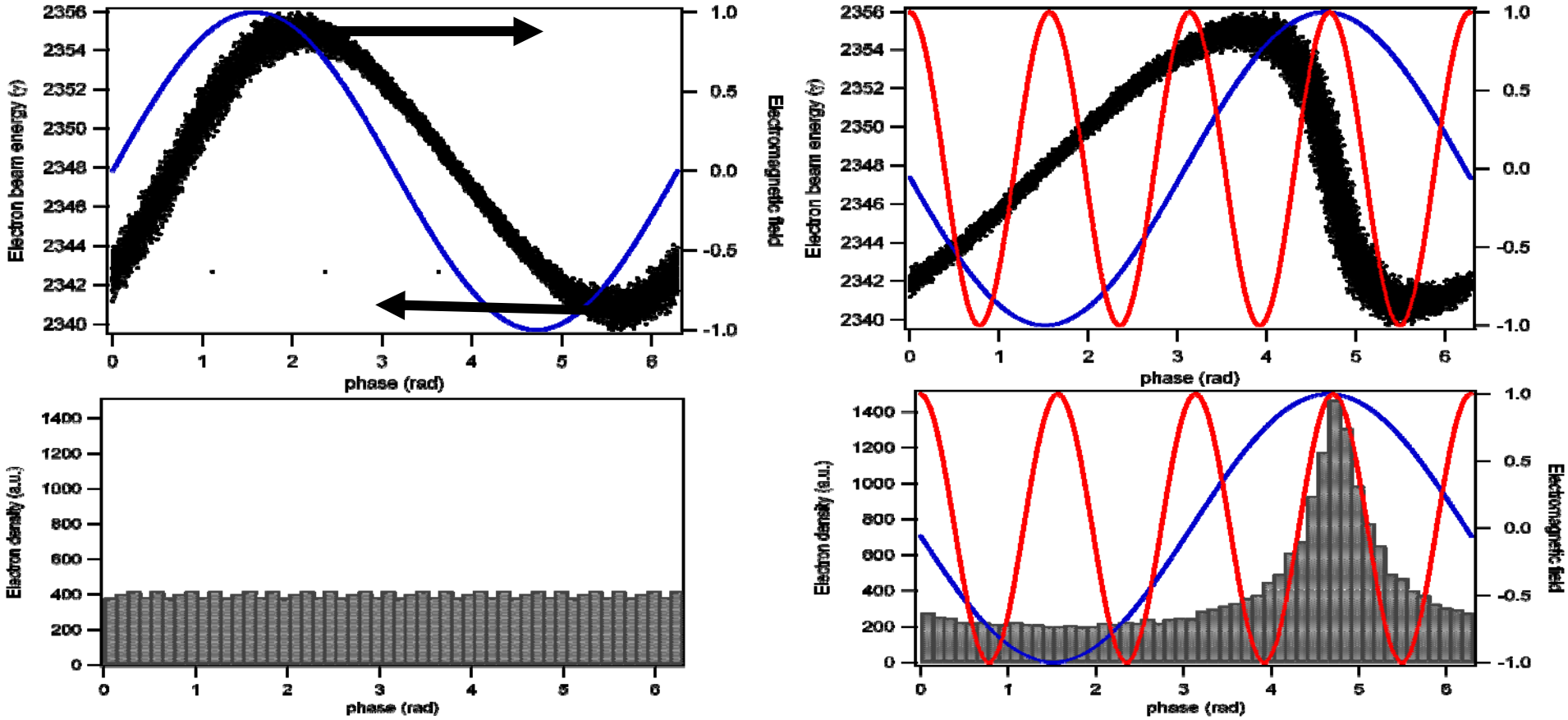
L. H. Yu et al.

- **The system is completely tunable**
- **It is possible to reach very high peak power**

- **The process is initiated by shot noise and both temporal and spectral properties are affected by that**

SASE FEL



Multi-stage CHG

In the modulator the interaction with a strong coherent signal produces bunching also at the harmonics of the seed wavelength