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Advanced School on Synchrotron and Free Electron Laser Sources and their Multidisciplinary Applications

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Free Electron Lasers (I)

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Outline

-Basic concepts of light-electron interaction in a Free-Electron Laser
  -Why a free electron laser
  -How it works

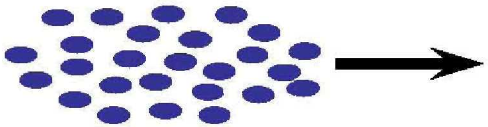
- Different schemes for FEL
  -FEL aplifier
  -FEL oscillator
  -Self Amplified Spontaneous Emission FEL (SASE)
  -Coherent Harmonic Generation FEL (CHG)

- Application to the FERMI project at Elettra
- Recent experimental results on the Elettra storage ring FEL

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

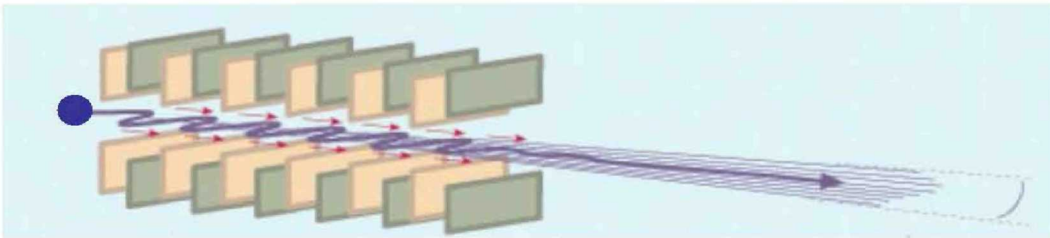
Basic ingredients

1) Relativistic **electron beam**



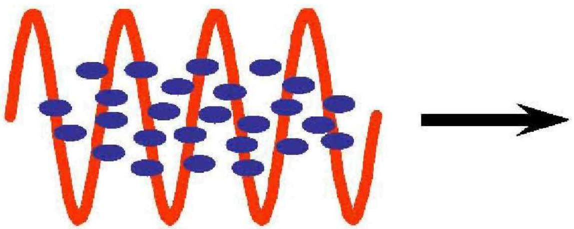
Energy (γ)
Current (I)
Emittance (ε)
Energy spread ($\delta\gamma$)
Dimensions (σ)

2) Undulator



Magnetic period (λ_w)
Magnetic strength (K)
Undulator length (L)

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



Wavelength (λ)
Power (P)

Light amplification: resonance condition

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

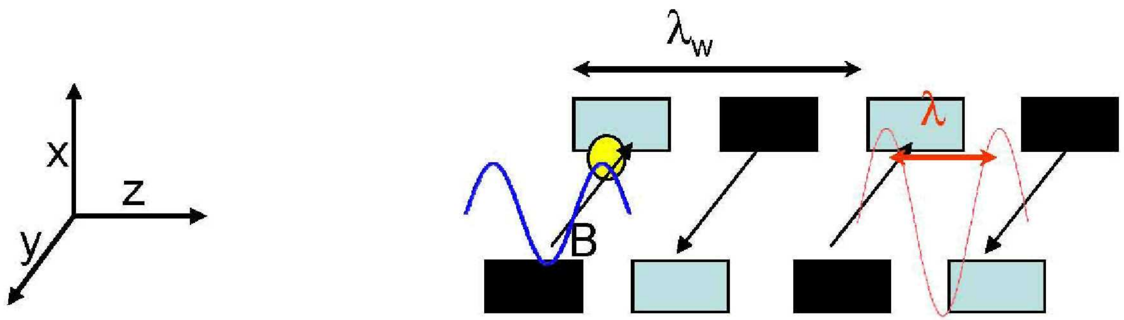
Electrons move slower than the co-propagating electromagnetic wave (**slippage**)

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 wavelenght 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)

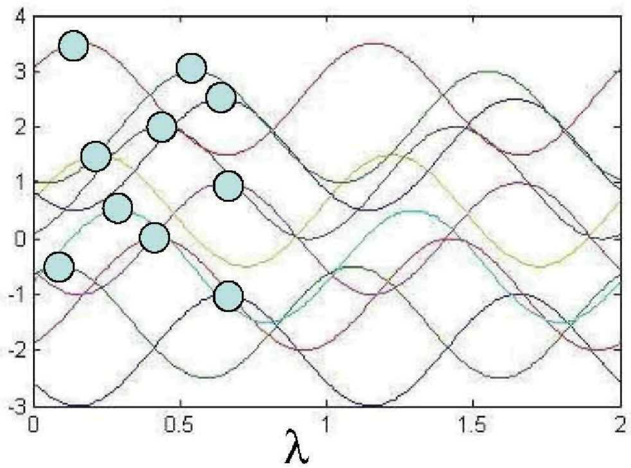
$$|\beta_{\perp}|\approx\frac{K}{\gamma}$$

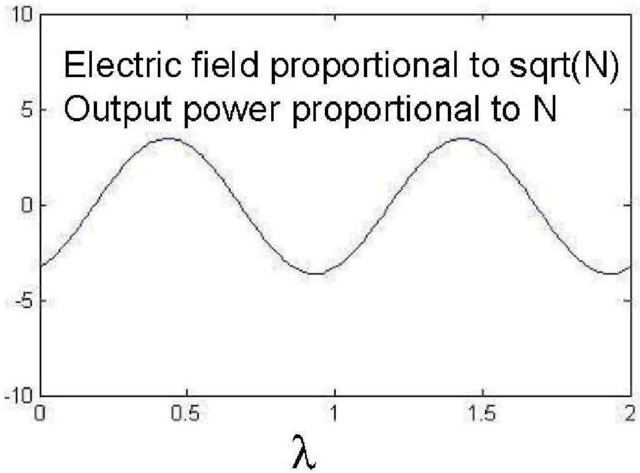
(K : undulator parameter, $K \sim \lambda_w B_{und}$)

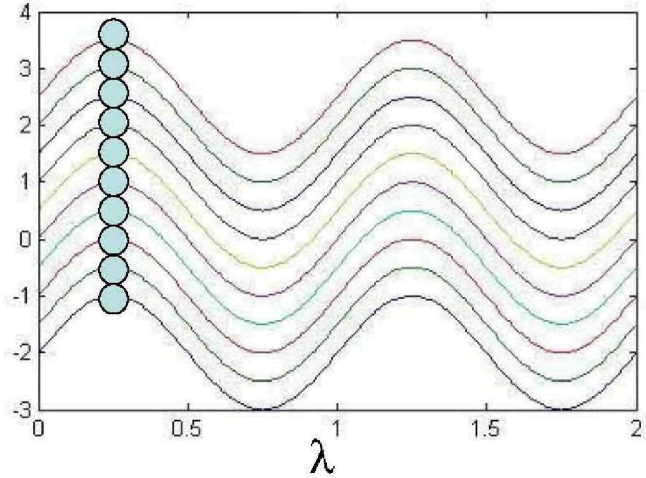
Resonance condition

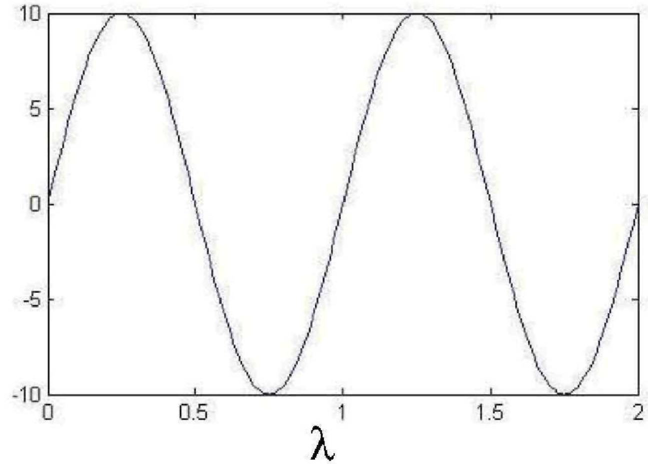
$$\lambda=\frac{\lambda_w}{2\gamma^2}\left(1+K^2\right)$$

Advantages of FEL with respect to synchrotron radiation









Electric field proportional to (N)
Output power proportional to N^2

Theoretical framework

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

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

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

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

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 (<u>single</u>) frequency, i.e. **<u>no harmonics</u>**

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

γ_j : energy of the j-*th* electron

γ_r : resonance energy

Under some approximations the previous equations can be reduced to

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

"bunching"

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

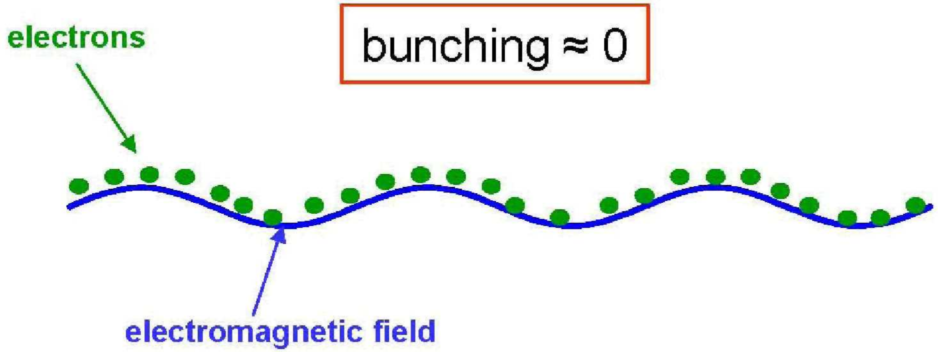
N: electrons' number

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

Bunching as source term

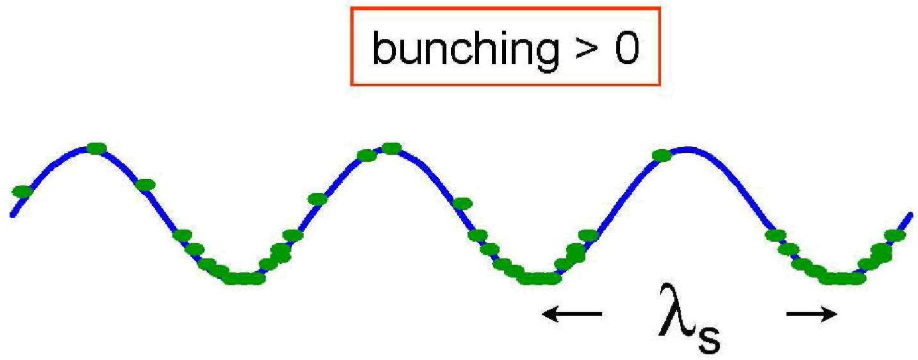
Initial condition:

- weak electromagnetic field
- electrons randomly distributed in phase



electrons start bunching on a λ_s scale

and the wave is amplified



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))

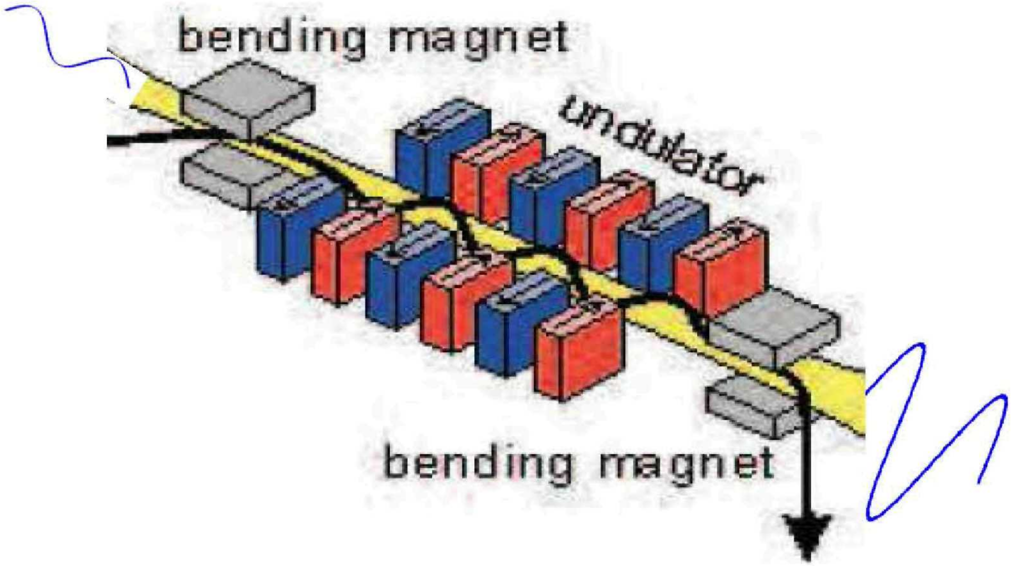
- a signal produced (e.g.) by an external laser

⇨ The external coherent signal is amplified by the FEL (direct seeding)

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

Direct seeding on a FEL

The FEL process is initiated by an external coherent signal



•**The output power preserve the properties of the input signal (coherence, wavelength)**

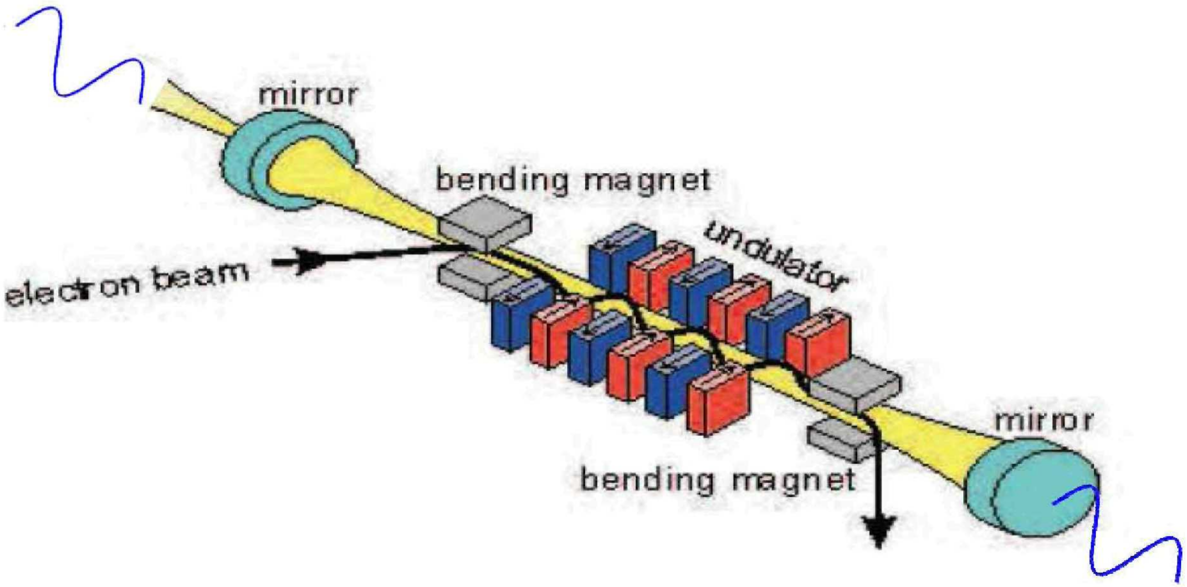
•**The tunability range is limited by the availability of coherent sources.**

The use of this technique in combination with high harmonics generated in gas jet can extend the tunability toward x-rays([1,2]).

1. G. Lambert et al. Nature Physics (09 Mar 2008), doi: 10.1038/nphys889
2. http://www.sparx.it/

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

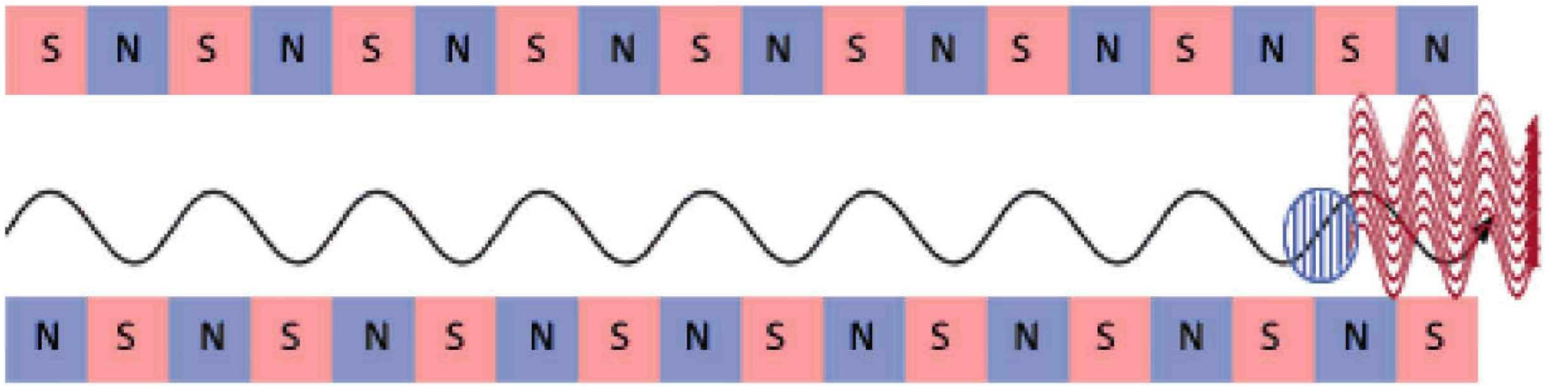


- The system is tunable with good spectral properties
- The repetition rate can be very high allowing high average power

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

SASE FEL

The electron beam and the electromagnetic field co-propagate in a long undulator.
As a consequence of the strong interaction, the electron beam show bunching at the resonant wavelength.
As a consequence of the bunching the emission becomes strong.



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

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

$A_\omega = f(K)$

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

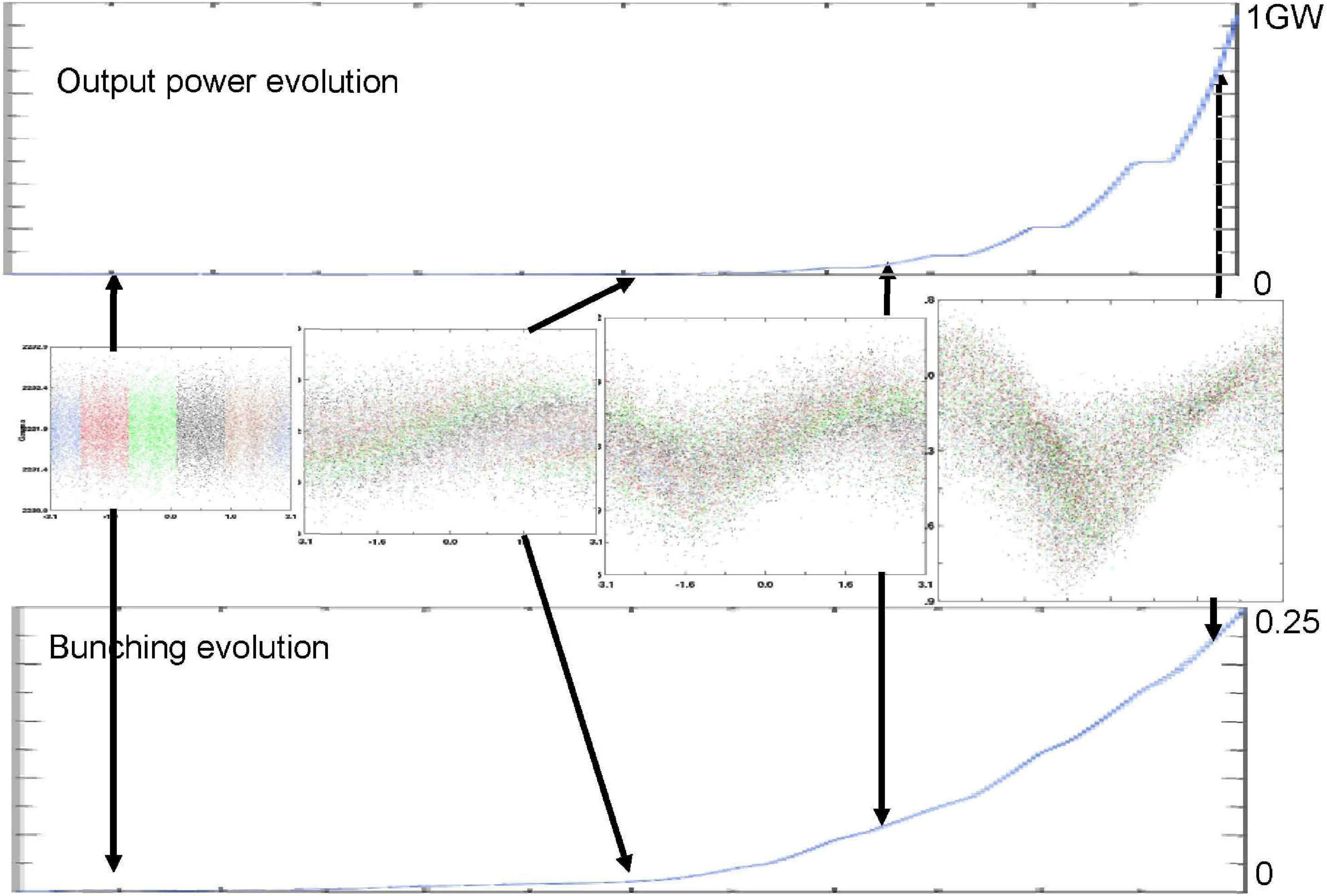
$$P_{sat} \approx \rho P_{beam}$$

$P_{beam}[\text{TW}] = E_0[\text{GeV}]\, I[\text{kA}]$

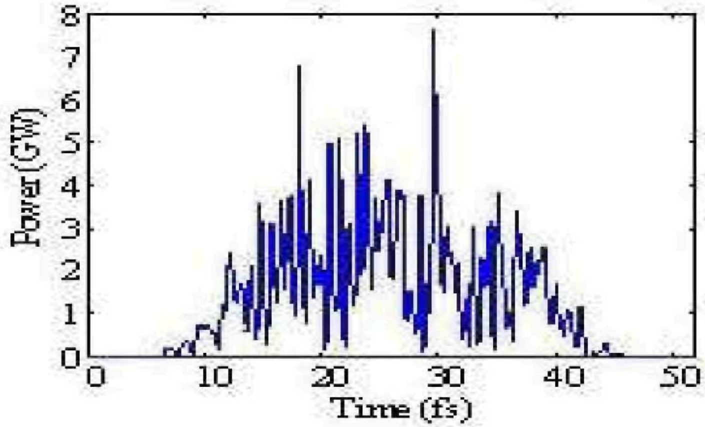
$$P = \alpha P_n e^{z/L_g} < P_{sat}$$

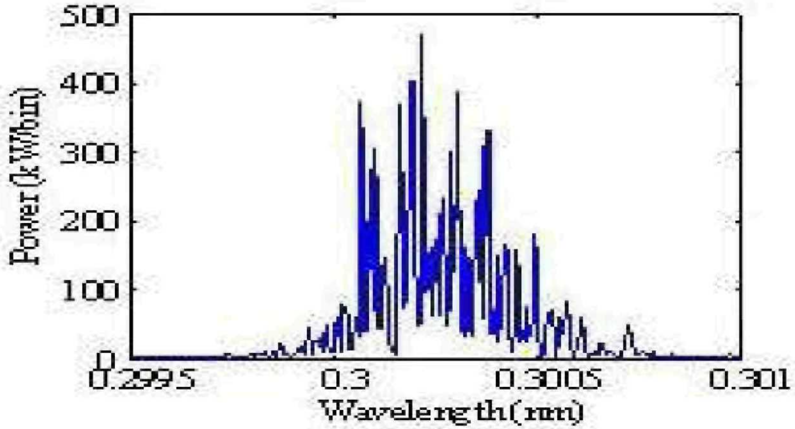
$\alpha = 1/9$

SASE FEL



SASE FEL





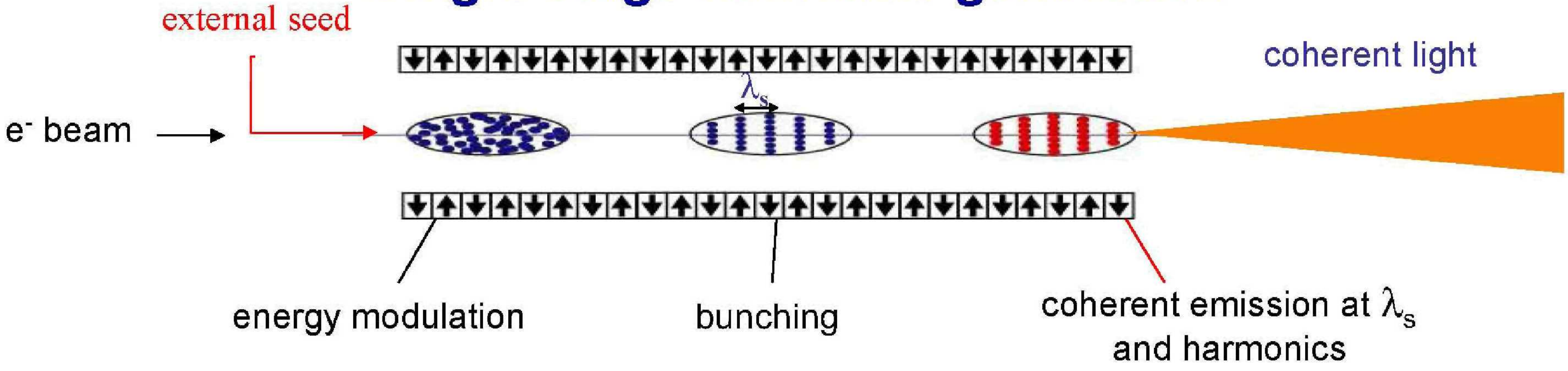
L. H. Yu et al.

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

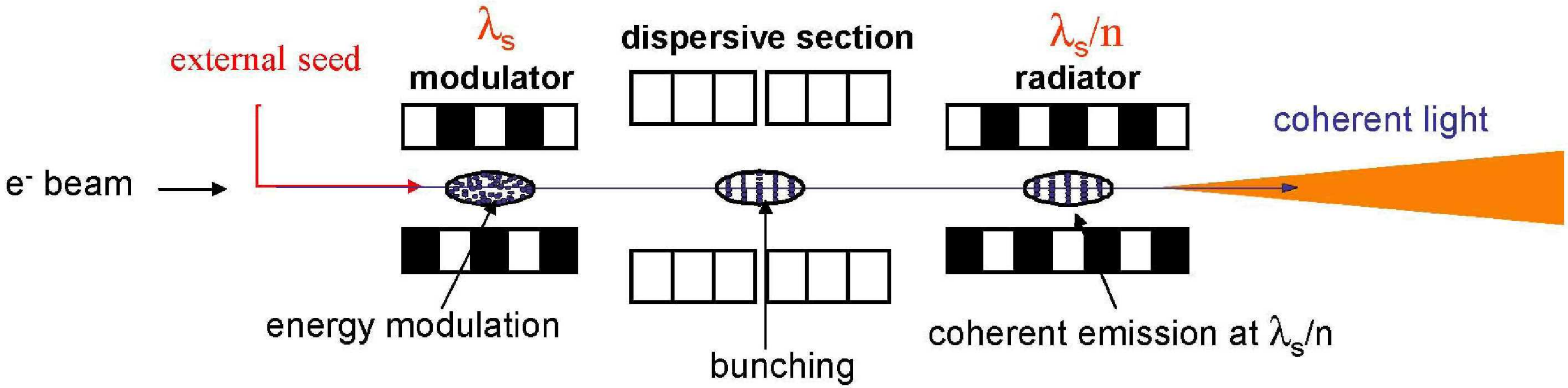
- The process is initiated by shot noise and both temporal and spectral properties are affected by that

CHG FEL

Single-stage harmonic generation

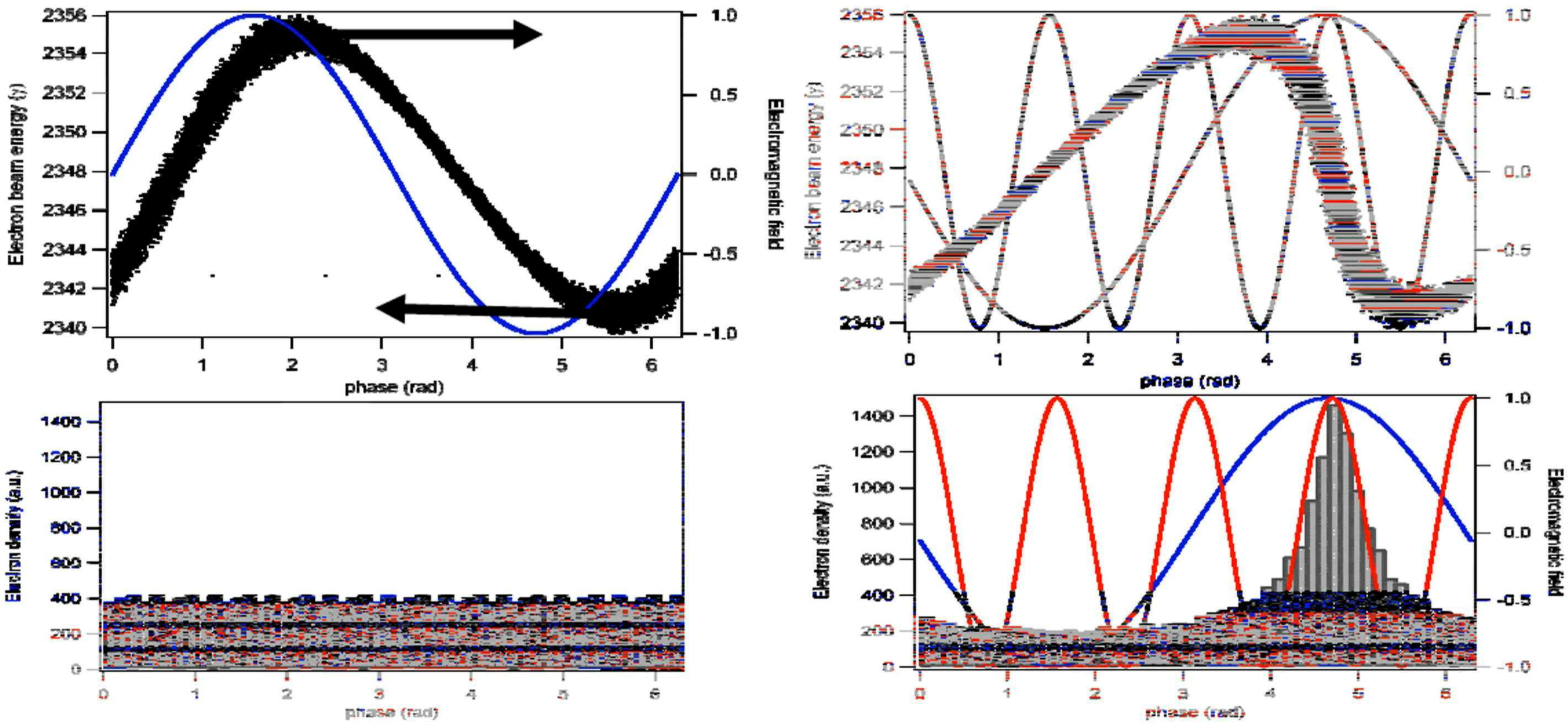


Multi-stage harmonic generation

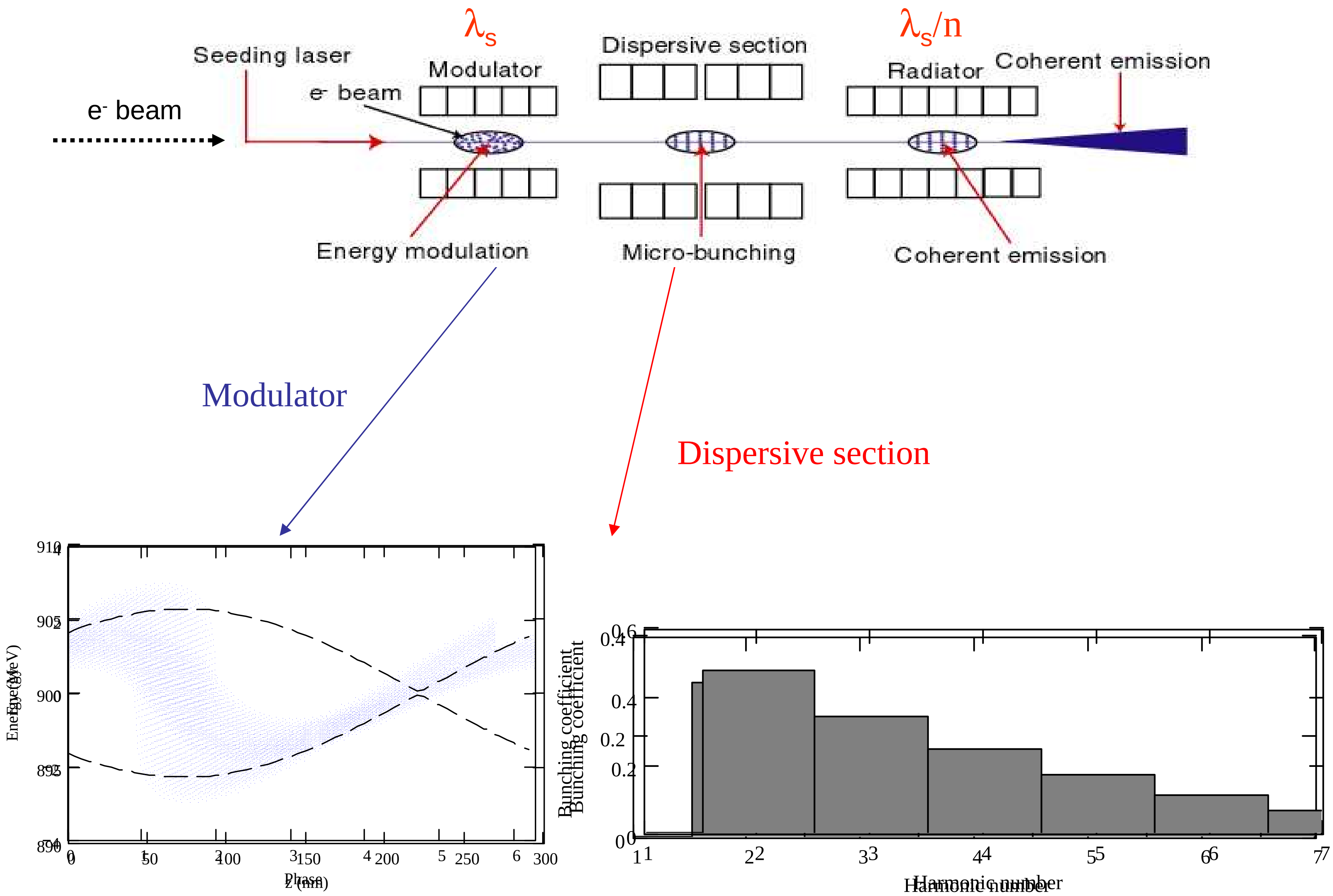


Multi-stage CHG

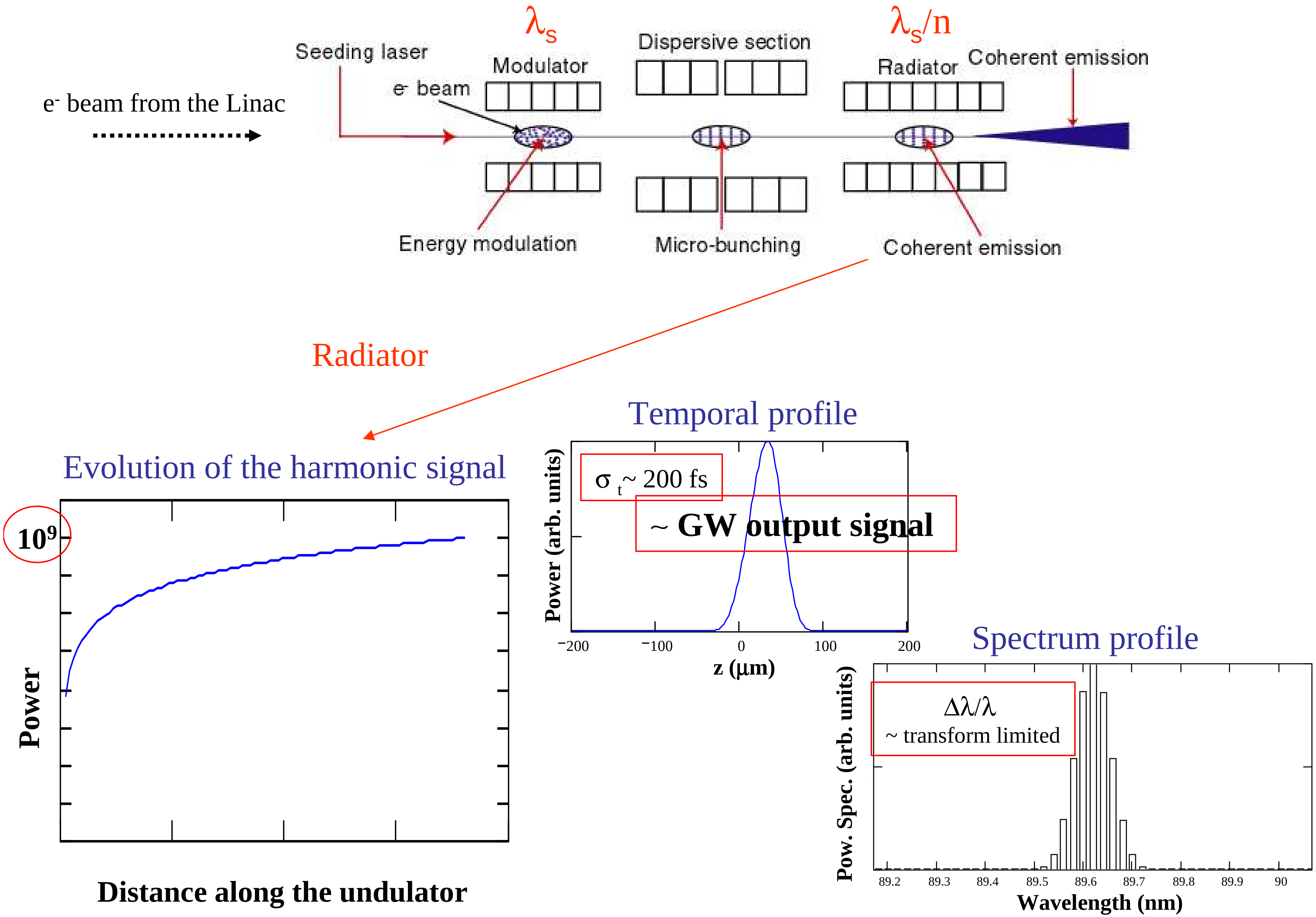
In the modulator the interaction with a strong coherent signal produces bunching also at the harmonics of the seed wavelength



Multi-stage harmonic generation: the principle

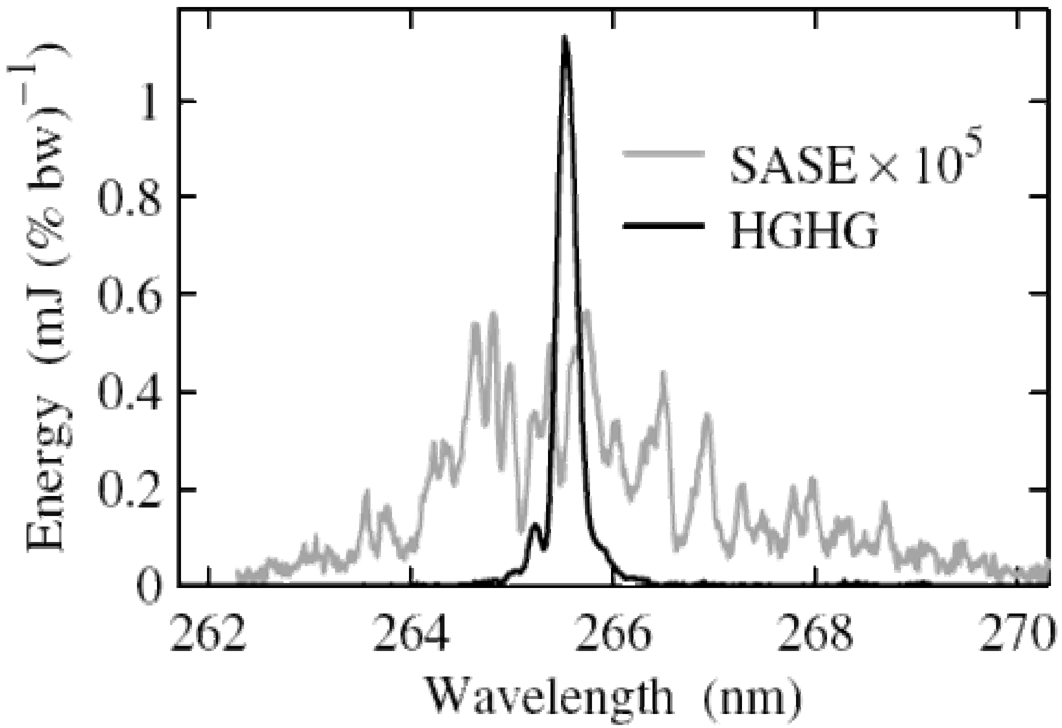


Multi-stage harmonic generation: the principle



SASE versus Seeding

- The system is tunable
- It is possible to reach very high peak power
- Temporal and spectral profiles are well defined and close to Fourier limit



- It has to be initiated by and powerful coherent
- The harmonic at which is possible to produce bunching is limited

L. H. Yu et al. Phys. Rev. Lett. 91, 074801 (2003)

Single pass 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 tunable: 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.

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 ($\sim 1/N_u$) 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, …