Free Electron Laser

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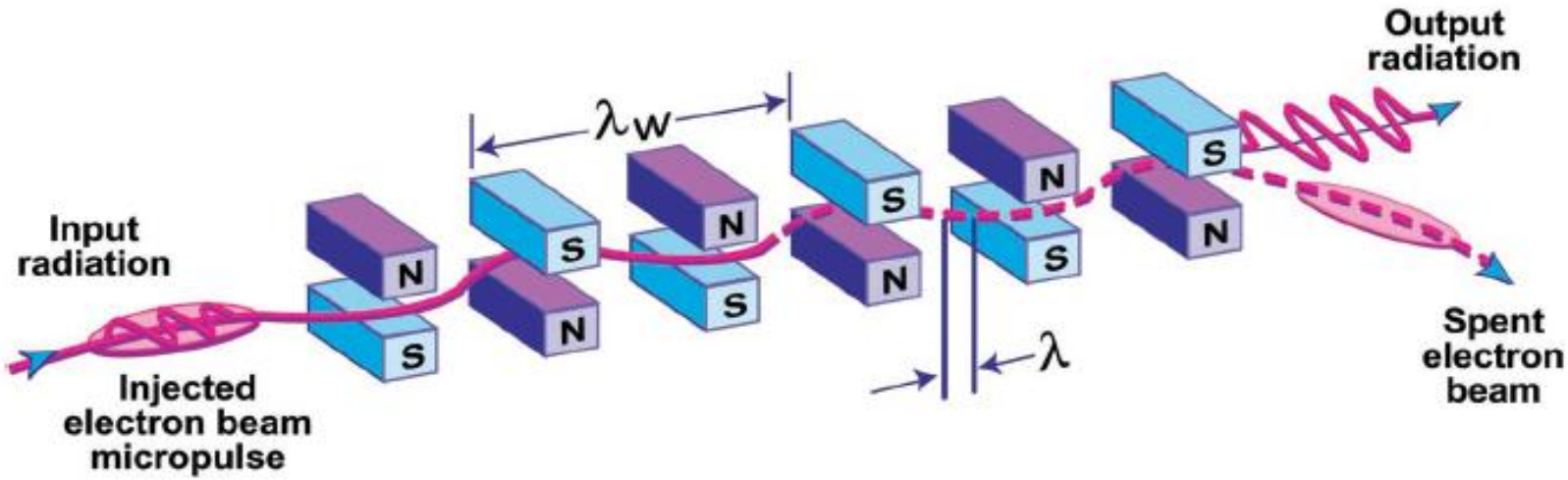
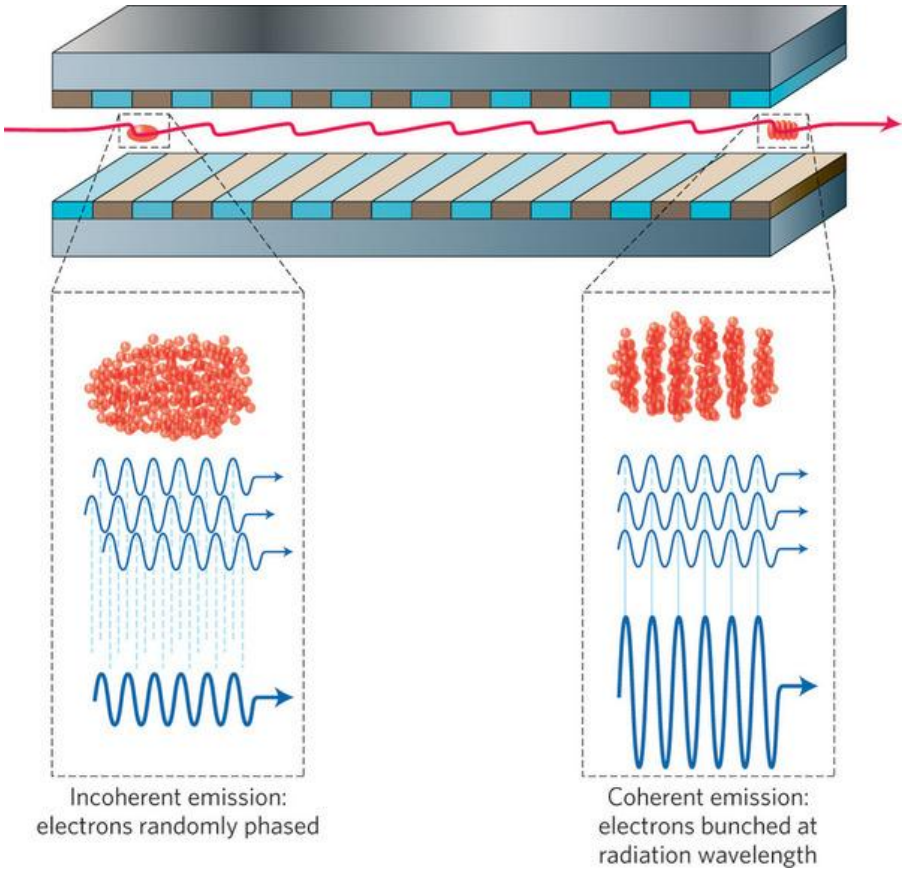
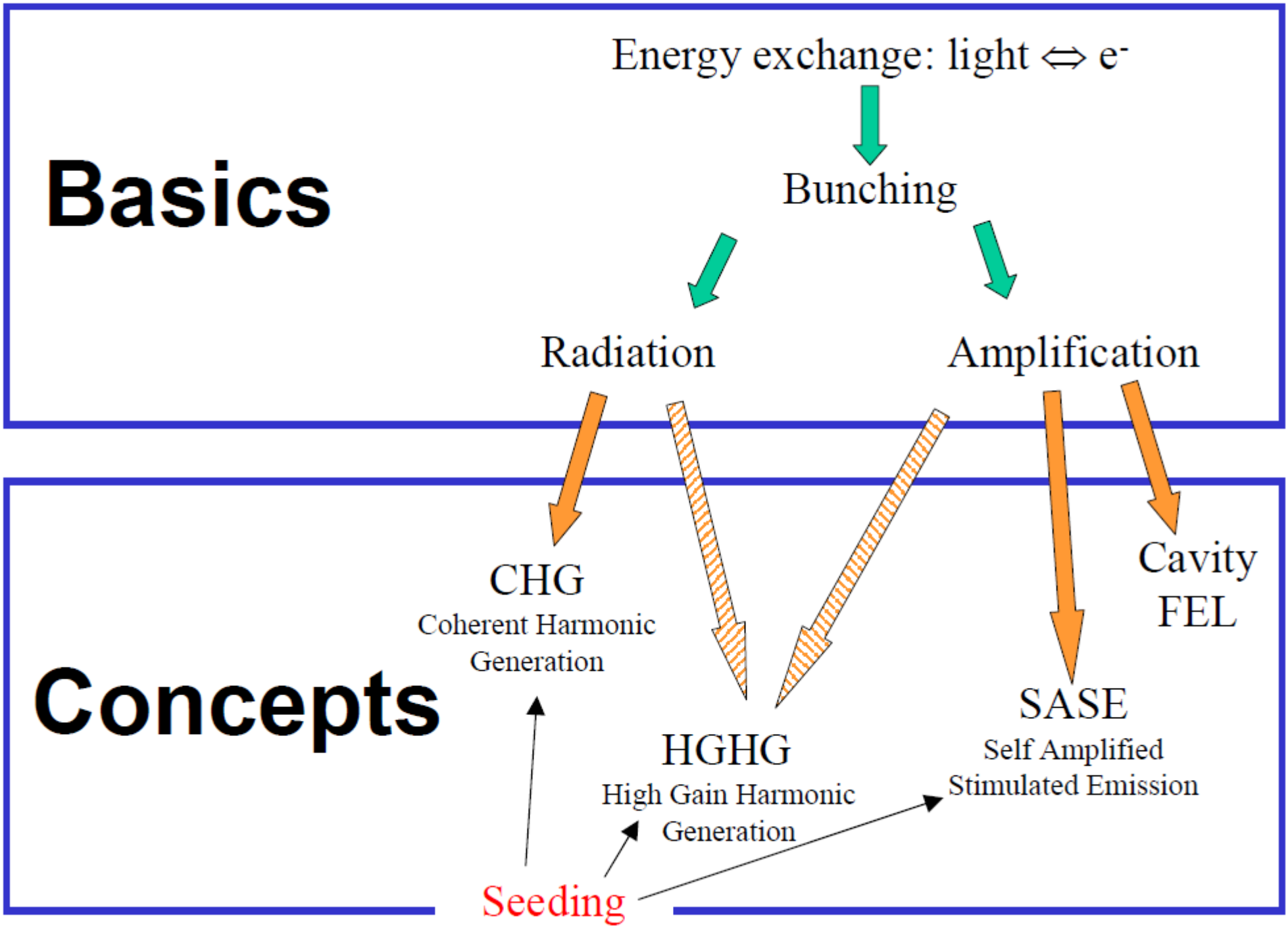
School of Particle and Accelerator

IPM



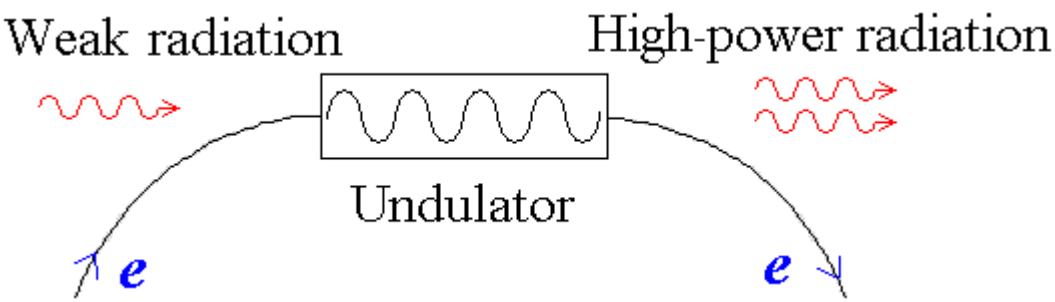
$$v_{ph} = \frac{\omega}{k + k_w}$$



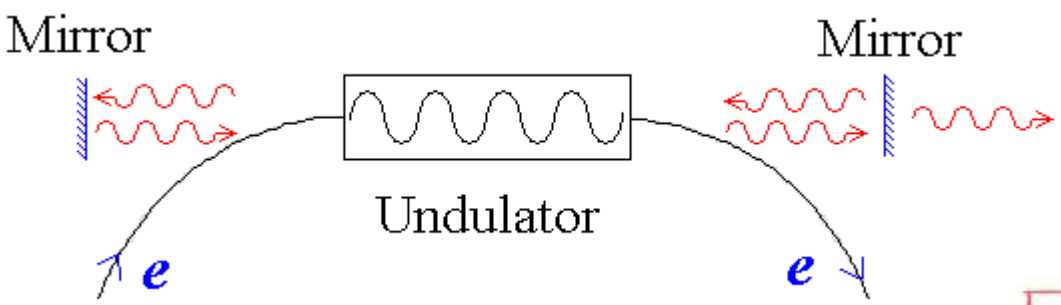

Basics
Energy exchange: light ⇔ e-
Bunching
Radiation
Amplification
Concepts
CHG
Coherent Harmonic Generation
HGHG
High Gain Harmonic Generation
SASE
Self Amplified Stimulated Emission
Cavity FEL
Seeding

•The basic principle of FEL operation

The single-flight regime



The cavity FEL

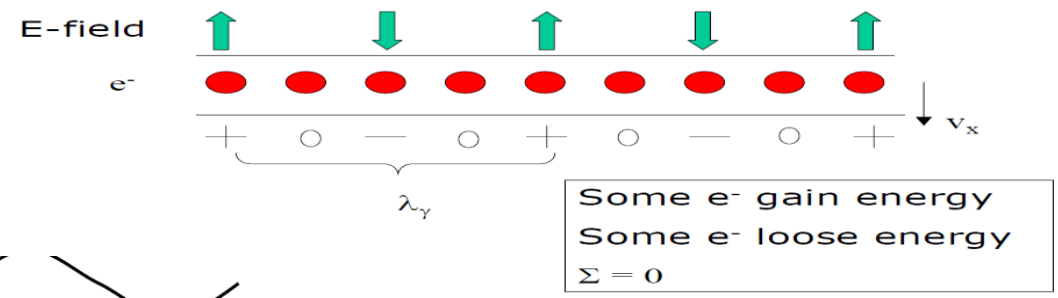


$$\boxed{\lambda_e = \frac{\lambda_u}{2\gamma^2}\left(1+\frac{K^2}{2}\right)}$$

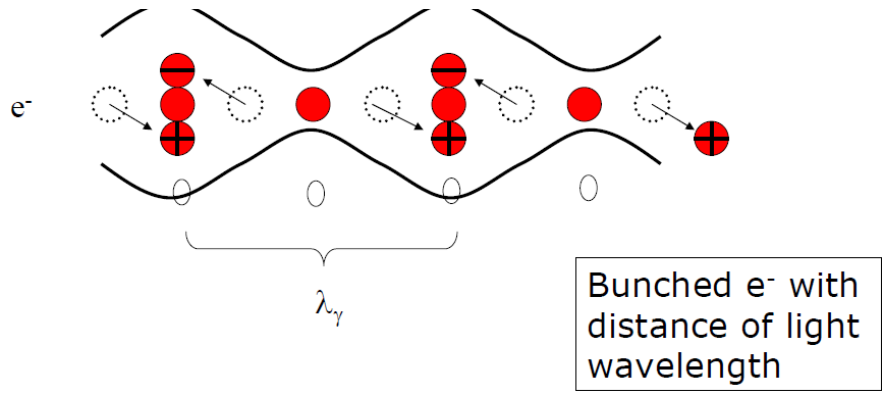
monochromatic radiation

1- Making E and v parallell

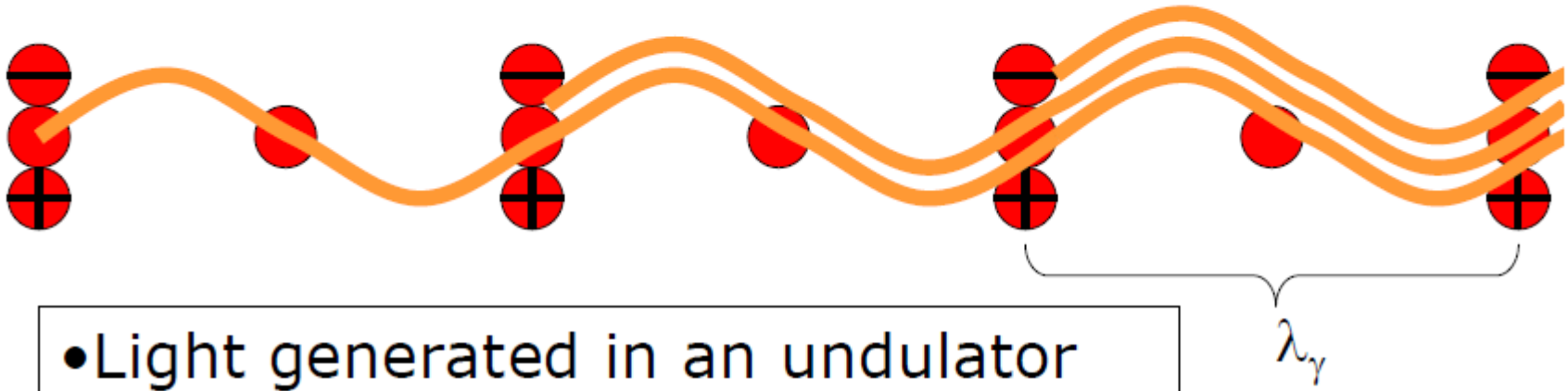
2- Energy exchange



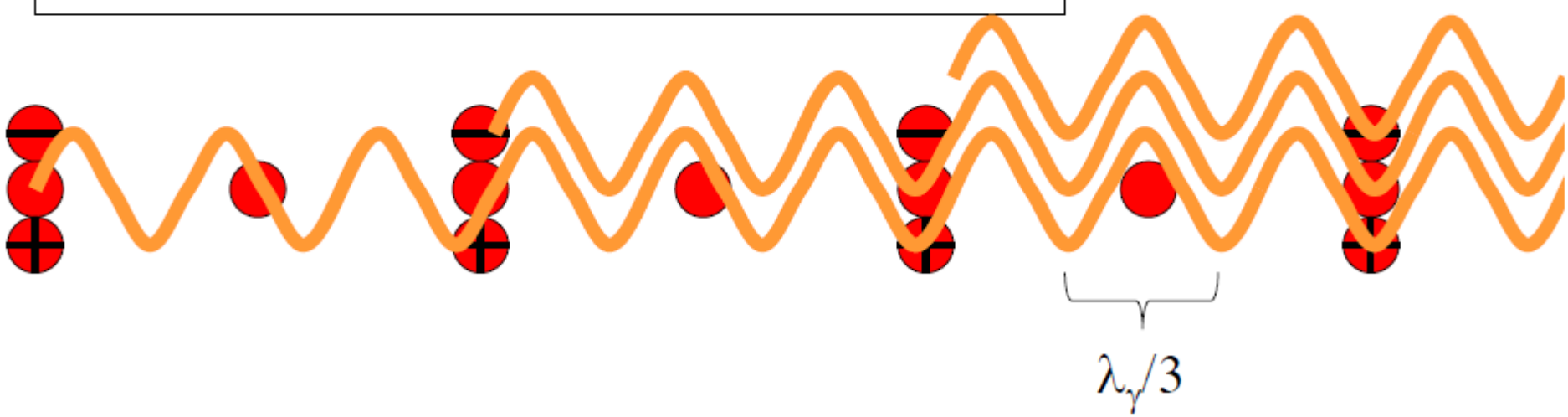
3- Bunching

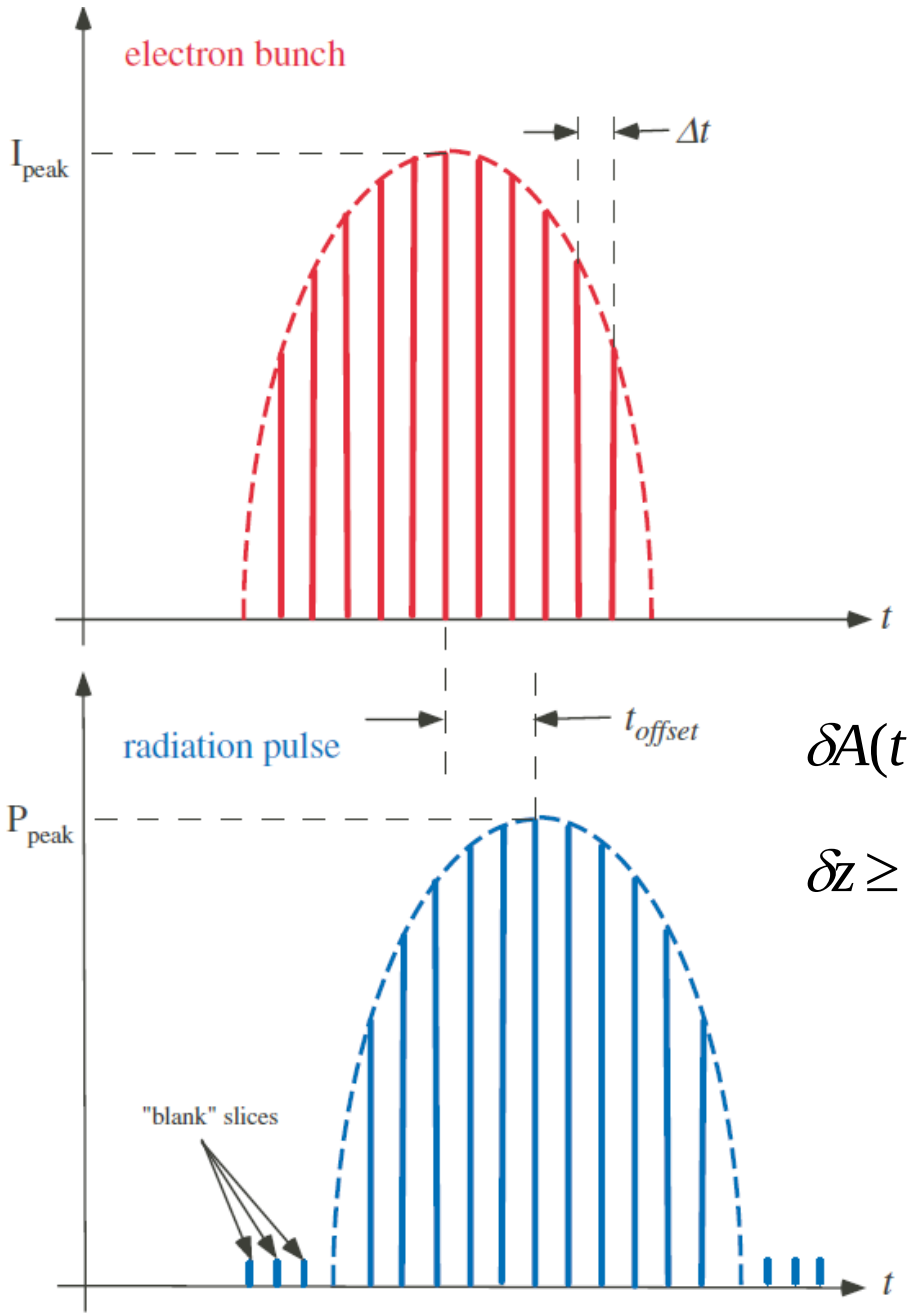


4- Radiator



- Light generated in an undulator
- Coherent
- With harmonics

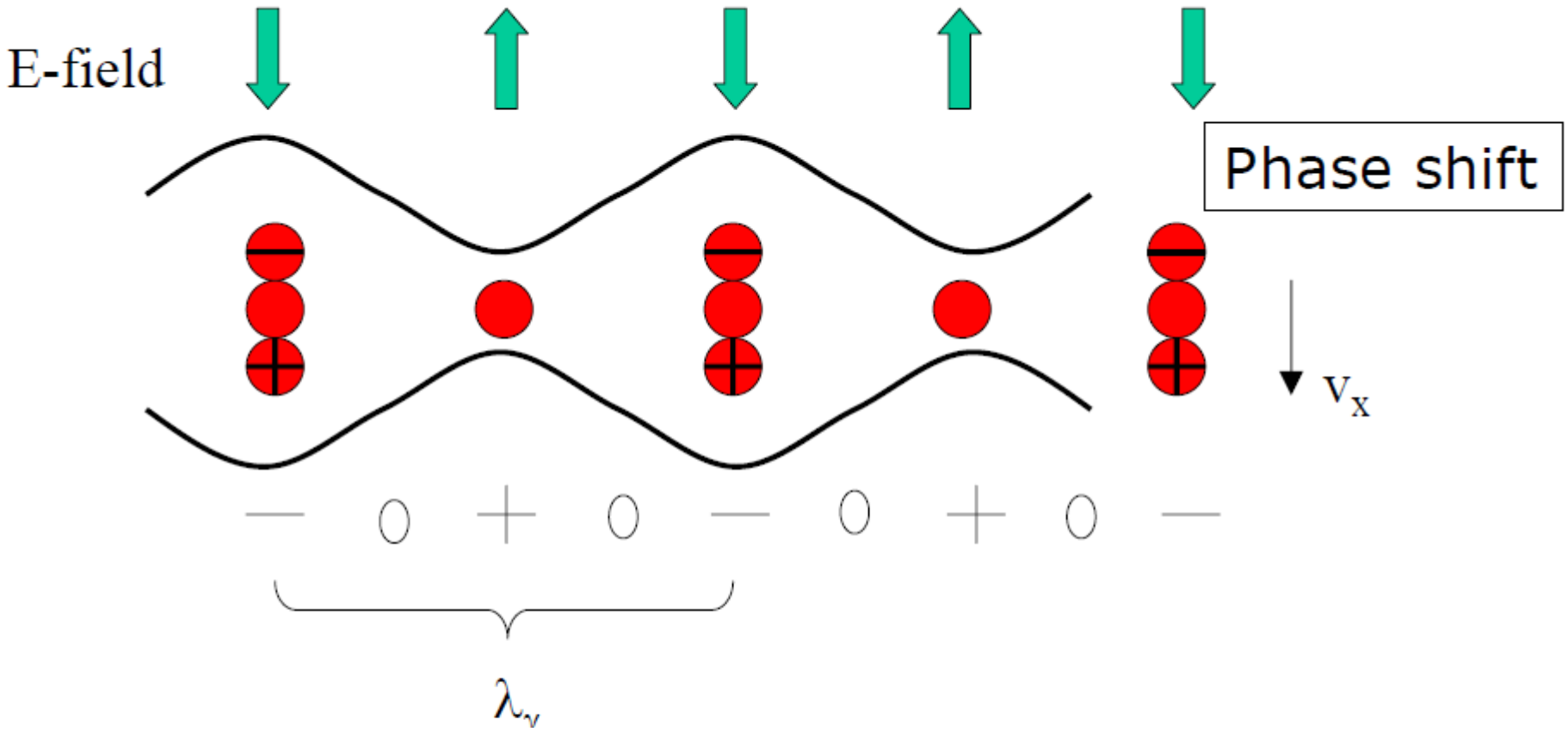




$$\delta A(t) = \delta A(t) - \left(\frac{\lambda_w}{\delta z}\right)\left(\frac{\lambda}{c\Delta t}\right) \times [\delta A(t) - \delta A(t - \Delta t)]$$

$$\delta z \geq \Delta z$$

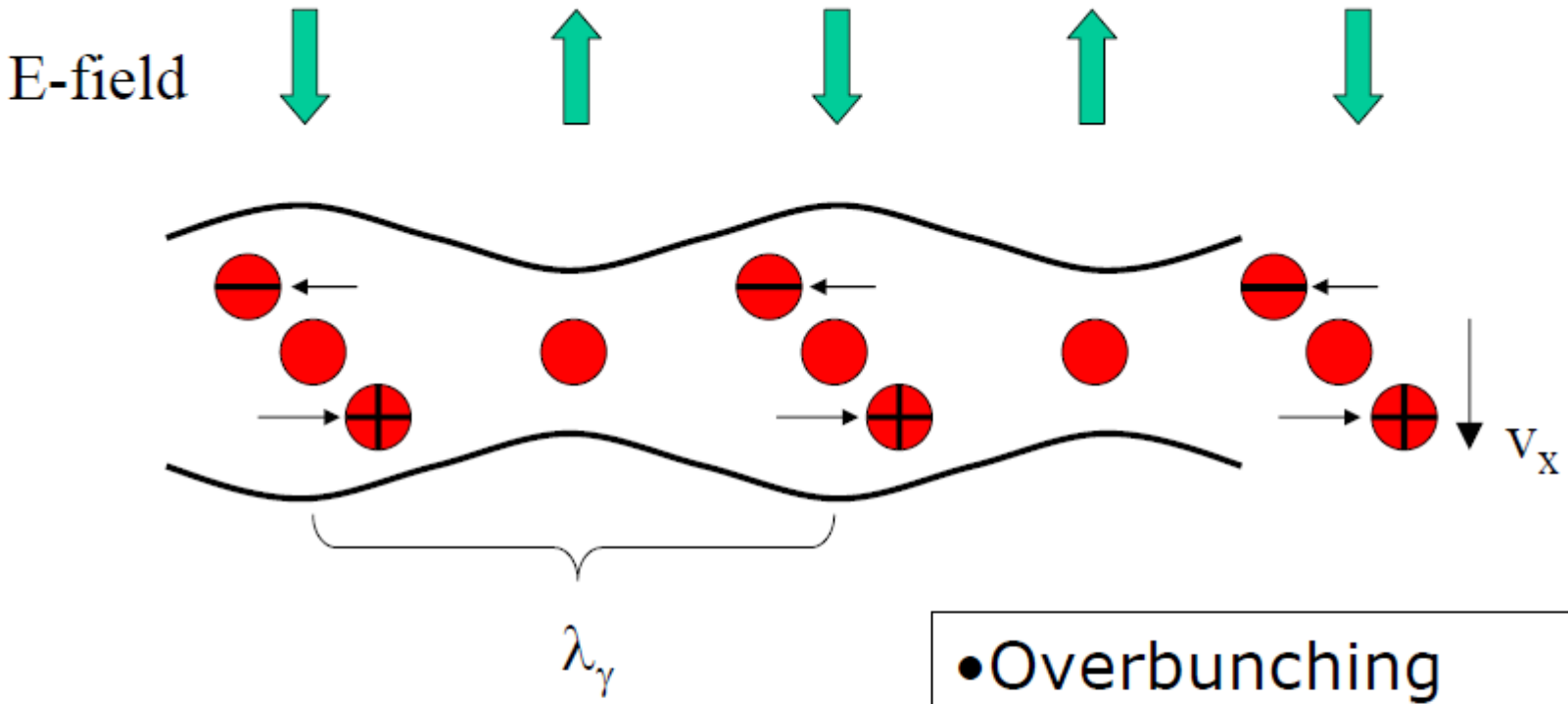
5- Amplification



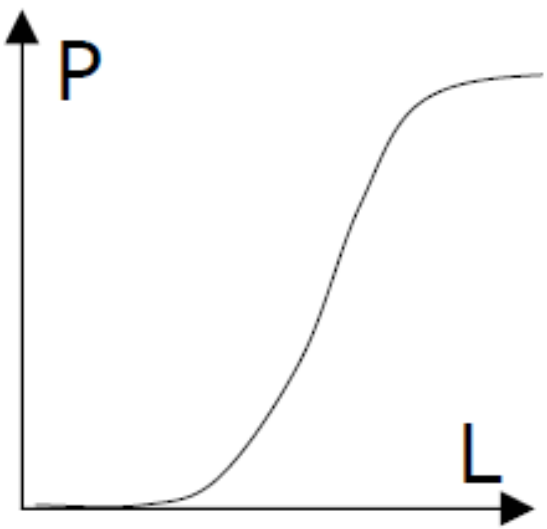
$$\left(\frac{\partial^2}{\partial z^2} - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right) a(z,t)\exp[i(kz-\omega t)] =$$

$$= i\frac{4\pi e^2}{mc^2} n_\perp \sum_{j=1}^{N} \frac{a_w \exp[-ik_w z] - ia\exp[i(kz-\omega t)]}{\gamma_j} \delta(z - z_j(t))$$

6- Saturation



- Overbunching
- Amplification dies off



FEL radiation parameters

$$\rho_{1D} = \frac{\lambda_u}{4\pi}\left[\frac{4\pi^2 j_o K_{rms}^2 A_{jj}^2}{I_A \lambda_u \gamma^3}\right]^{1/3}.$$

Field gain length: $L_g \approx \lambda_u/(4\pi\rho_{1D})$,

Saturation length: $L_{sat} \approx 10 \times L_g$,

Effective power of shot noise: $\frac{W_{sh}}{\rho_{1D} W_b} = \frac{3}{N_c\sqrt{\pi \ln N_c}}$,

Saturation efficiency: ρ_{1D},

Power gain at saturation: $G = \frac{N_c}{3}\sqrt{\pi \ln N_c}$,

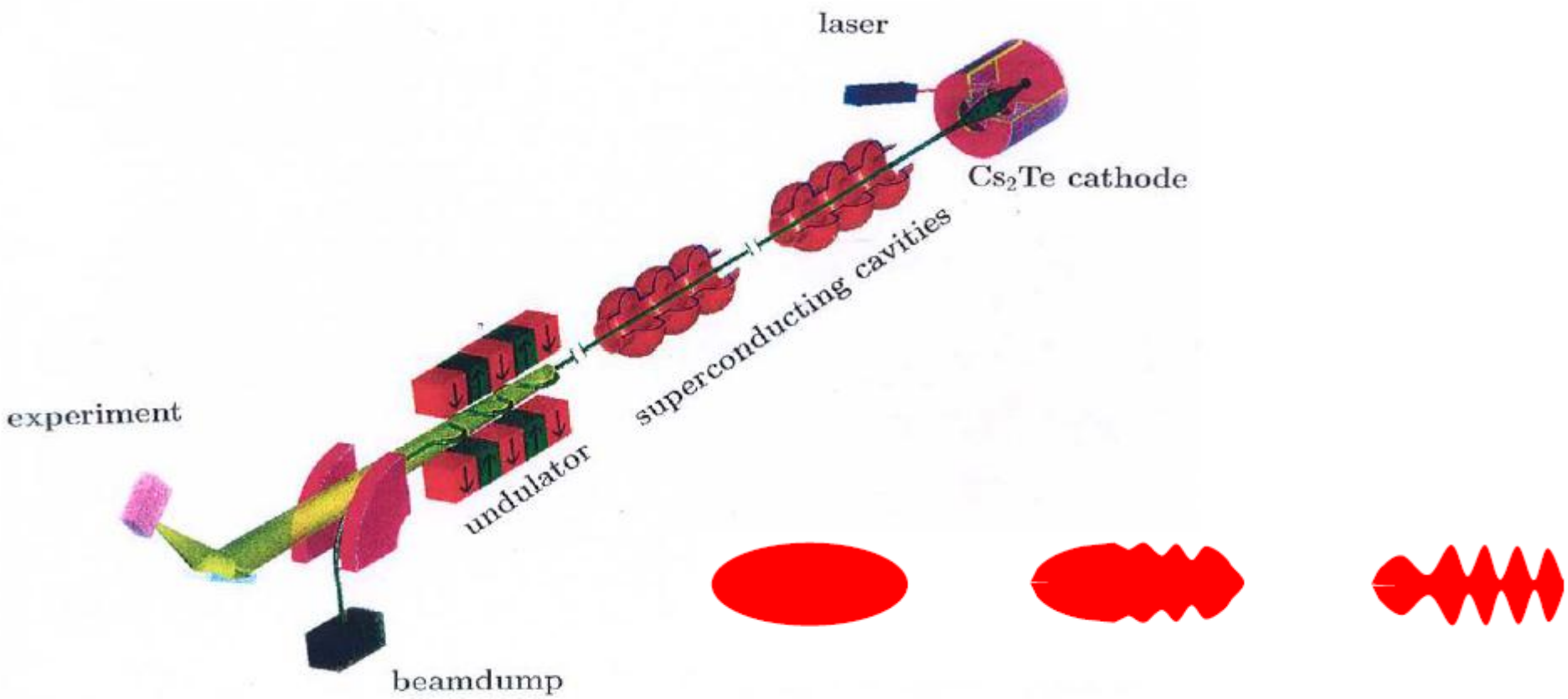
Spectrum bandwidth: $2\rho_{1D}$,

Coherence time at saturation: $\tau_c = \frac{1}{\rho_{1D}\omega}\sqrt{\frac{\pi \ln N_c}{18}}$,

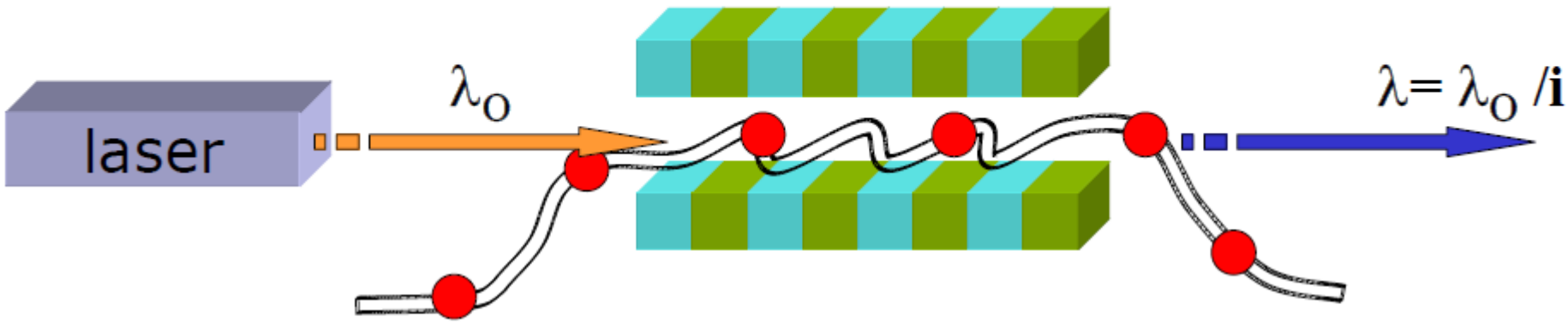
Main problem

- Seed
- Prebunched beam
- Shot noise
- Two-beam FEL

Self Amplified Spontaneous Emission (SASE) Free Electron Laser

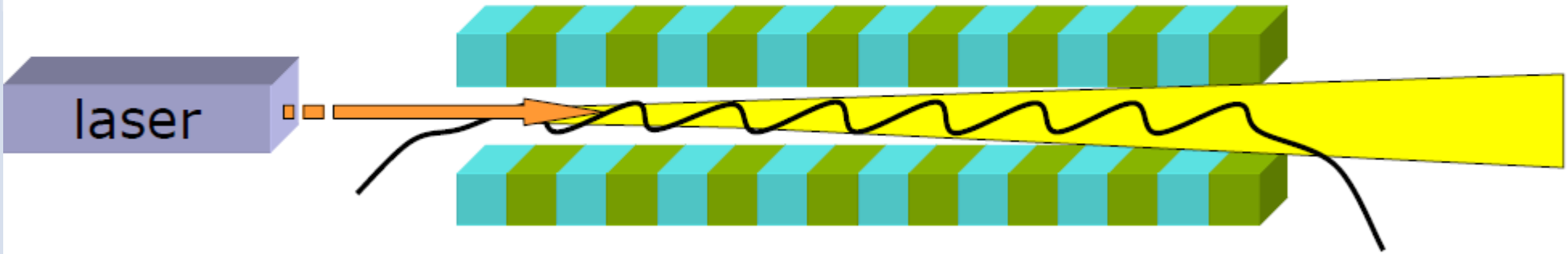


CHG - Coherent Harmonic Generation

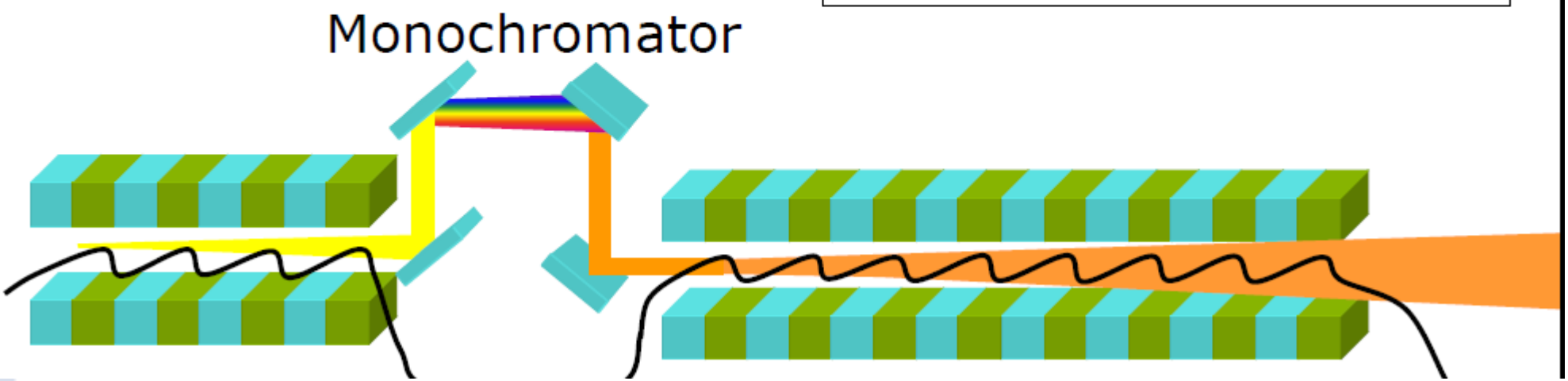


- i = 1, 3, 5, ?
- λ ¤ 100 nm
- coherent

SEEDING



- Remove instabilities
- CHG with gain HGHG



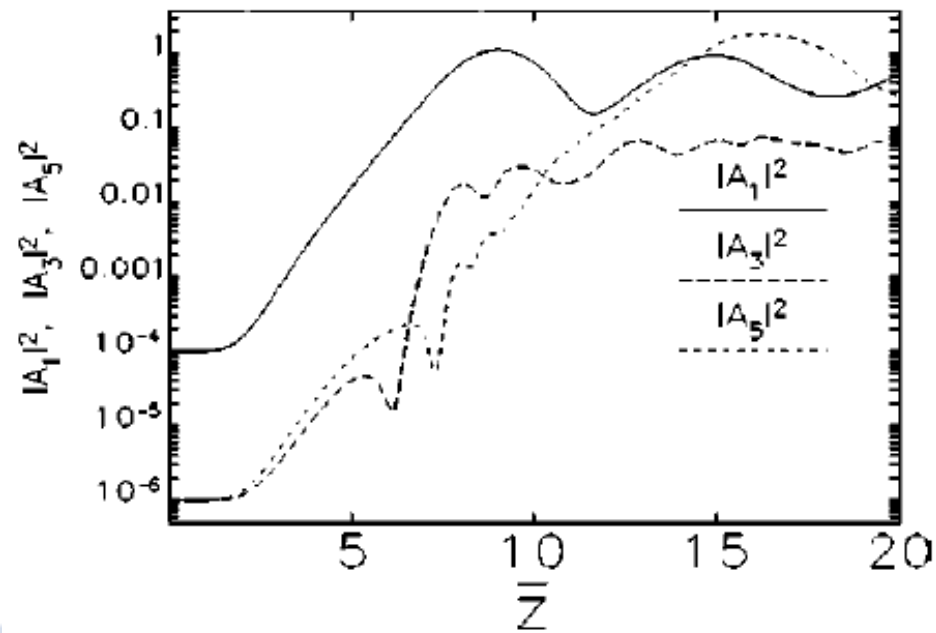
TWO-Beam FEL

It was proposed by McNeil et al, two relativistic electron beams with different energy were exploited.

Nth harmonic of low energy beam is seed for fundamental resonance of high energy beam.

$$\gamma_h = \sqrt{n}\gamma_l$$

$$\frac{I_h}{I_l} = R$$



- One beam

KMR R. Bonifacio

WKB H. P. Freund

1 D

3 D

- Two beams

B. W. McNeil

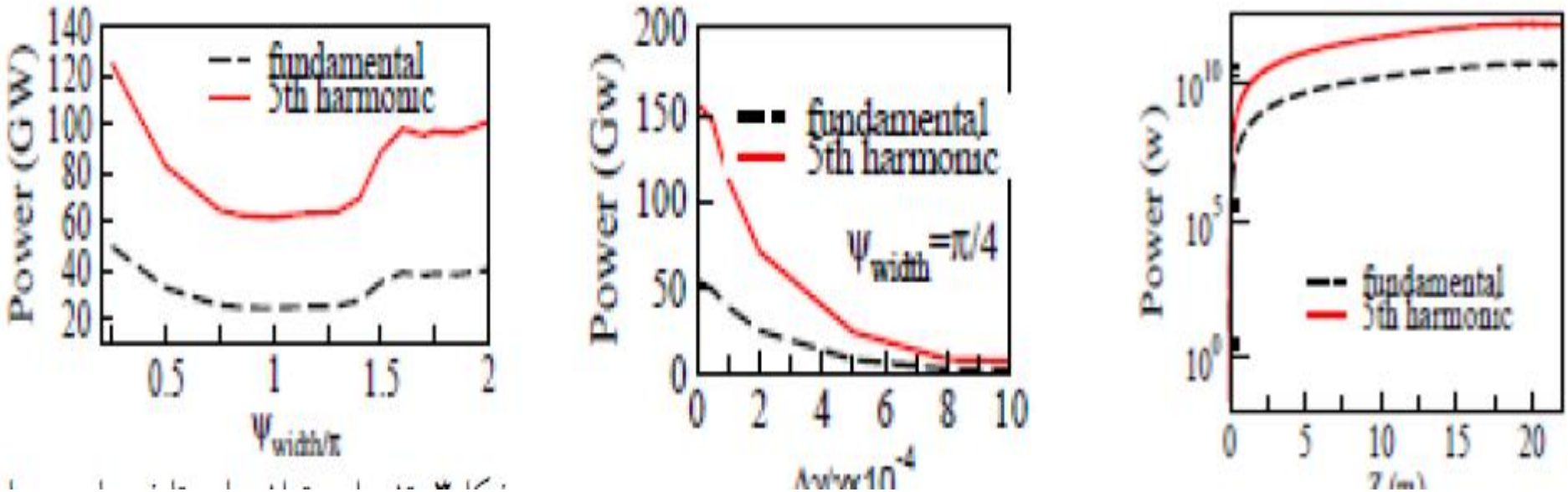
B. Maraghechi

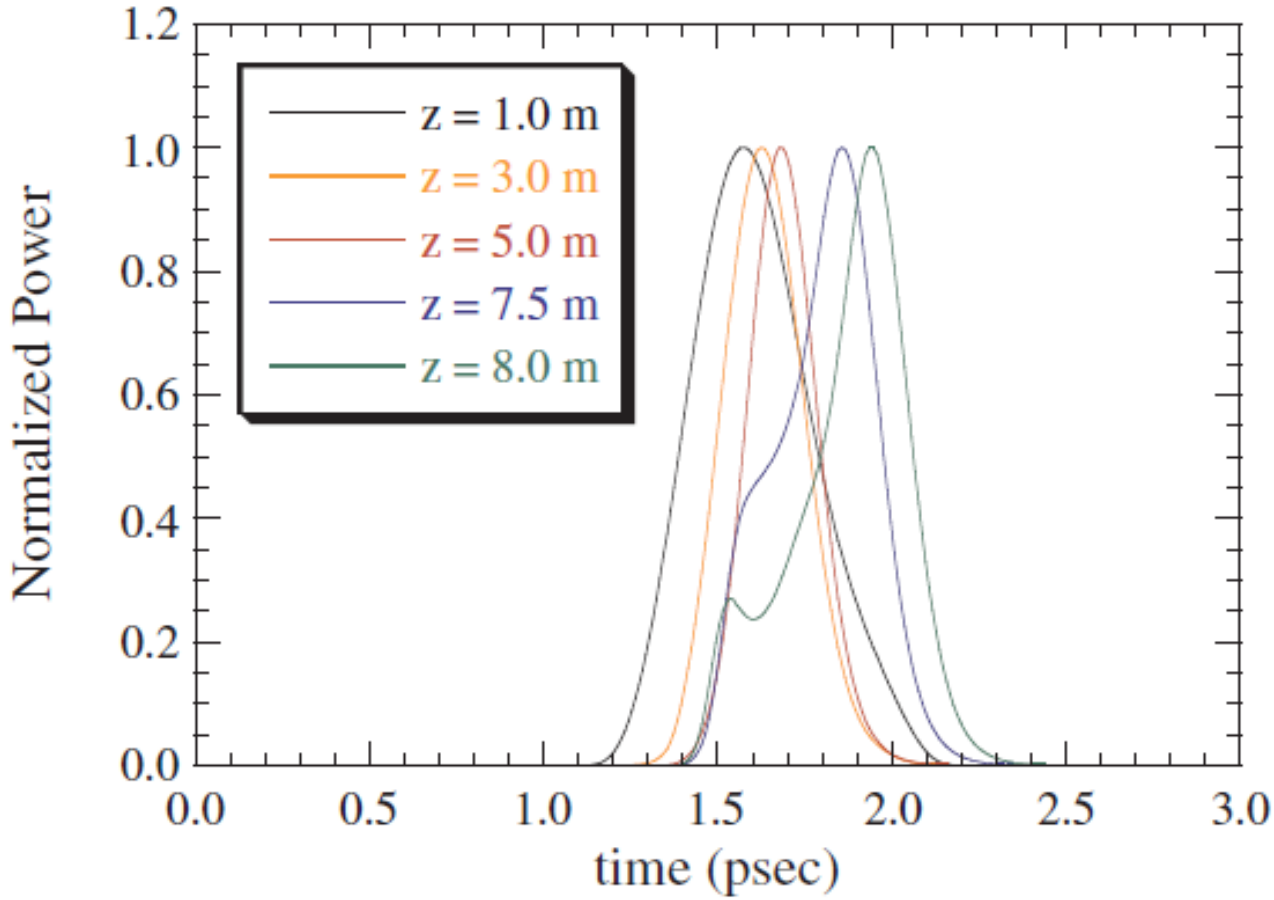
$$\left(\frac{\partial}{\partial z}\right)\begin{pmatrix}\delta a_h^{(1)}\\ \delta a_h^{(2)}\end{pmatrix}=\frac{\omega_b^2}{h\omega c}\beta_{z0(low)}\begin{pmatrix}\left\langle\frac{u_{x(low)}}{|u_{z(low)}|}\cos\alpha_h\right\rangle\\ \left\langle\frac{u_{x(low)}}{|u_{z(low)}|}\sin\alpha_h\right\rangle\end{pmatrix},$$

$$\left(\frac{\partial}{\partial z}\right)\begin{pmatrix}\delta a_n^{(1)}\\ \delta a_n^{(2)}\end{pmatrix}=\frac{\omega_b^2}{n\omega c}\beta_{z0(low)}\begin{pmatrix}\left\langle\frac{u_{x(low)}}{|u_{z(low)}|}\cos\alpha_n\right\rangle\\ \left\langle\frac{u_{x(low)}}{|u_{z(low)}|}\sin\alpha_n\right\rangle\end{pmatrix}$$

$$+\frac{\omega'^2_b}{n\omega c}\beta_{z0(high)}\begin{pmatrix}\left\langle\frac{u_{x(high)}}{|u_{z(high)}|}\cos\alpha_n\right\rangle\\ \left\langle\frac{u_{x(high)}}{|u_{z(high)}|}\sin\alpha_n\right\rangle\end{pmatrix}.$$

$$\langle(\ldots)\rangle=\int_0^{2\pi}\frac{\delta(\psi_0)}{2\pi}d\psi_0\int_0^{\infty}dp_zG_0(p_z)(\ldots),$$


Power (GW)
fundamental
5th harmonic
ψ_{width}/π
Power (Gw)
fundamental
5th harmonic
$\psi_{width}=\pi/4$
Power (w)
fundamental
5th harmonic


z = 1.0 m
z = 3.0 m
z = 5.0 m
z = 7.5 m
z = 8.0 m
Normalized Power
time (psec)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
0.0
0.5
1.0
1.5
2.0
2.5
3.0

END