Phase Shifters for Free Electron Lasers

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Synchrotron Light Sources

1st Generation Light Sources

Parasitic experimets on benging magnets

2nd Generation Light Sources

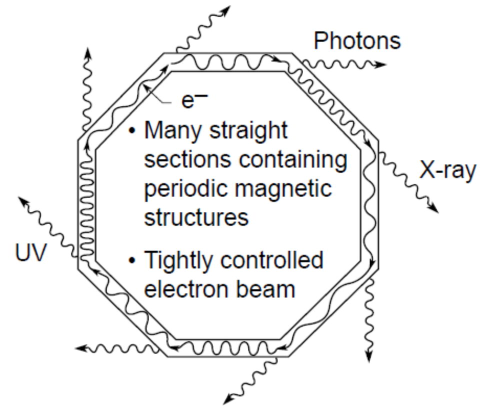
Dedicated Rings with bending magnets

3rd Generation Light Sources

Dedicated rings with multiple insertion devices

4th Generation Light Sources or Free Electron Lasers

Linear Accelerators with very long undulators



Schematic 3rd generation light source

Synchrotron Light Sources

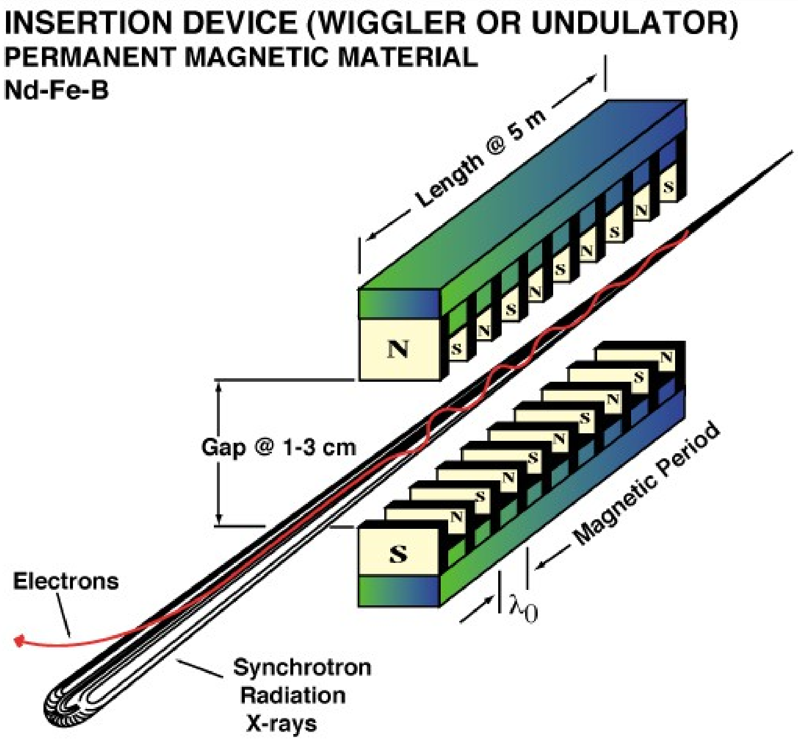
Elettra and FERMI@Elettra

3rd and 4th generation light source

NSLS-2 at Brookheaven National Laboaratory

Undulator

Magnetic structure
Periodically oscillating magnetic field



Lorentz force on the charge

$$\frac{d\vec{p}}{dt} = e(\vec{E} + \vec{v} \times \vec{B}) \qquad \vec{p} = \gamma m \vec{v}$$

↓

Periodic magnetic field

↓

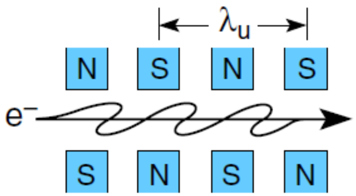
Periodic oscillation of a charge

↓

Radiation

Undulator Radiation

Laboratory Frame of Reference

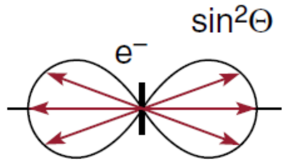


$E = \gamma mc^2$

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$$

N = # periods

Frame of Moving e^-



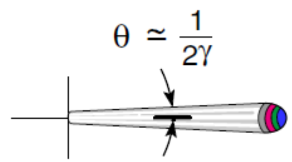
e^- radiates at the Lorentz contracted wavelength:

$$\lambda' = \frac{\lambda_u}{\gamma}$$

Bandwidth:

$$\frac{\lambda'}{\Delta\lambda'} \simeq N$$

Frame of Observer



Doppler shortened wavelength on axis:

$$\lambda = \lambda'\gamma(1 - \beta\cos\theta)$$

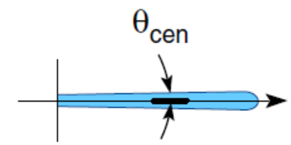
$$\lambda = \frac{\lambda_u}{2\gamma^2}(1 + \gamma^2\theta^2)$$

Accounting for transverse motion due to the periodic magnetic field:

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

where $K = eB_0\lambda_u/2\pi mc$

Following Monochromator



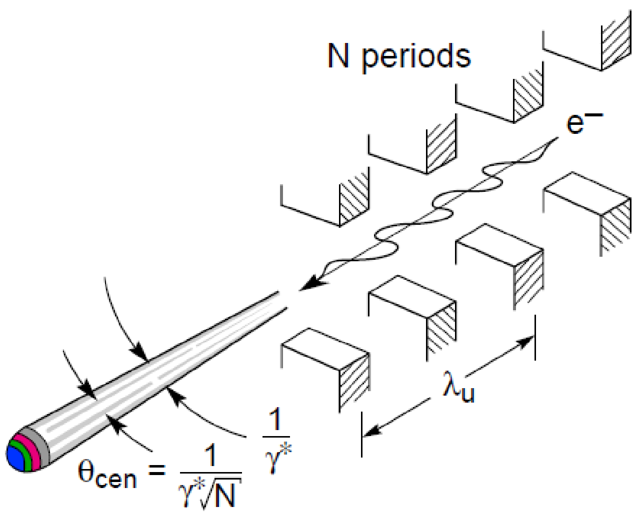
For $\frac{\Delta\lambda}{\lambda} \simeq \frac{1}{N}$

$$\theta_{cen} \simeq \frac{1}{\gamma\sqrt{N}}$$

typically

$$\theta_{cen} \simeq 40 \text{ rad}$$

Undulator Radiation Properties



Undulator equation

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

Magnetic deflection paramter

$$K = \frac{e}{2\pi m_0 c}\lambda_u B_0$$

Effective Lorentz factor

$$\gamma^* = \frac{\gamma}{\sqrt{1 + \frac{K^2}{2}}}$$

Central Radiation Cone

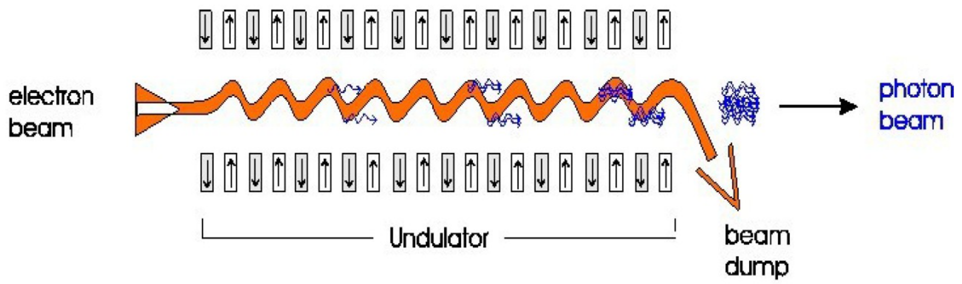
$$\Theta_{cen} = \frac{1}{\gamma^*\sqrt{N}} \qquad \left(\frac{\Delta\lambda}{\lambda}\right)_{cen} = \frac{1}{N}$$

Average power in the central cone

$$P_{cen} \simeq \frac{\pi e \gamma^2 I}{\epsilon_0 \lambda_u} \frac{K^2}{(1 + K^2/2)^2}$$

Free Electron Laser

Reality: Electron bunches with 10^9 electrons. Bunch Length >> radiation wavelength



Uncoordinated emisson from electrons:

Spontaneous undulator radiation: $P \propto N_e P_1$ Intensities add

Coordinated emission from electrons:

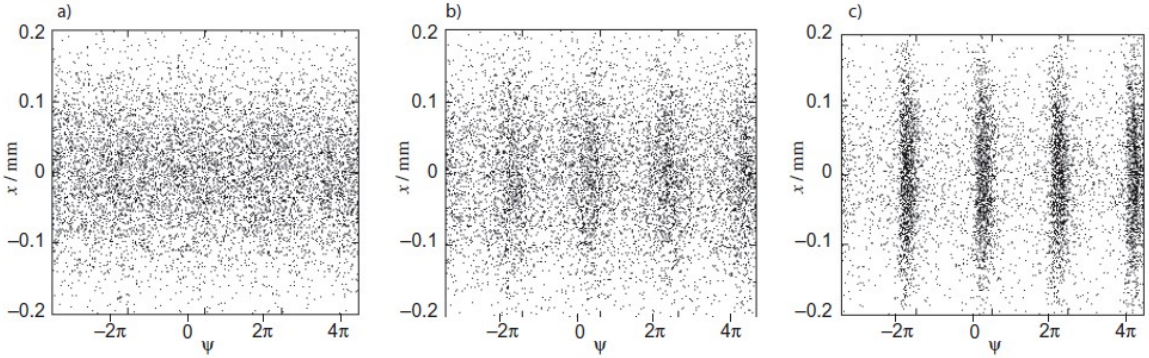
FEL radiation: $P \propto N_e^2 P_1$ Electric fields add

Prequisites for FEL process:

Electrons must slip back one radiation period in one undulator period.

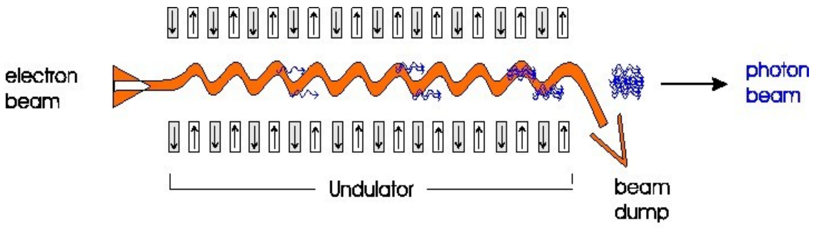
Micro-bunching. Created with radiation.

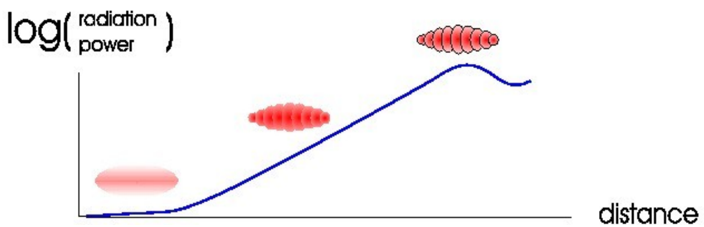
Long Magnetic Structure



Ponderomotive phase

$$\psi = (k_u + k_r)z - \omega_r t$$





To reach saturation very long magnetic structure is needed

Can only be acheived by segmentation

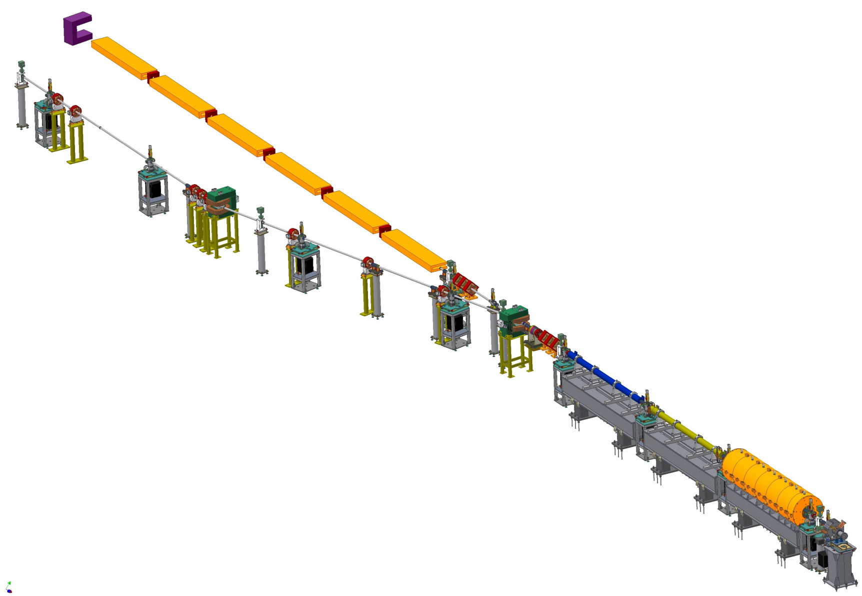
Control of electron bunch slippage is needed

Example FEL with segmented Undulator

Segmentation of the undulator is needed:

Mechanical structure can not be longer than ~ 5 m

Beam adjustments are necessary in a very long vacuum chamber



SPARC at ENEA

Phase slippage between segments must be adjusted to match resonant condition

Slippage can be controlled with adjustment of empty space distance.

Works only for one radiation wavelength.

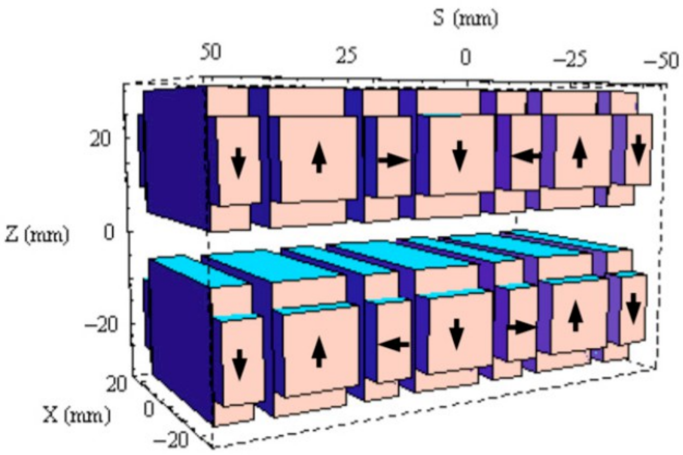
In a tunable FEL a variable phase shift is necessary in the free space between undulator segments.

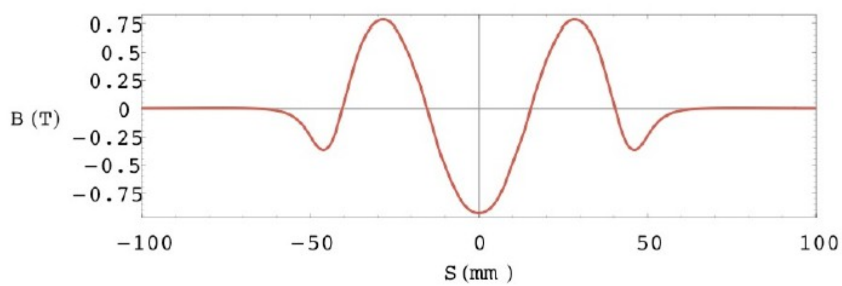
Phase Shifter

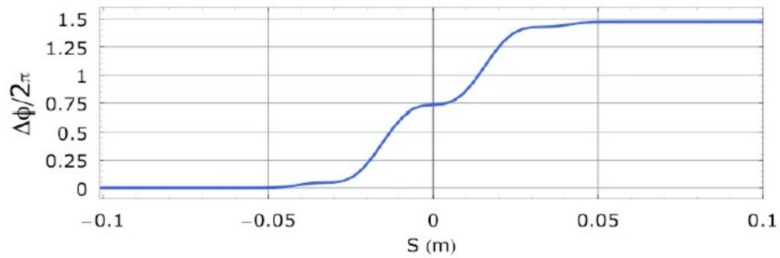
In a periodic magnetic structure a delay between electron and light wave can be adjusted by adjusting the K value.

$$\psi(z) = \frac{2\pi}{\lambda_r}\left\{\frac{z}{2\gamma^2} + \frac{1}{2}\int_{-\infty}^{z} x'^2(z')dz'\right\} \qquad x'(z) = -\frac{e}{\gamma m_0 c}\int_{-\infty}^{z} B(z')dz'$$

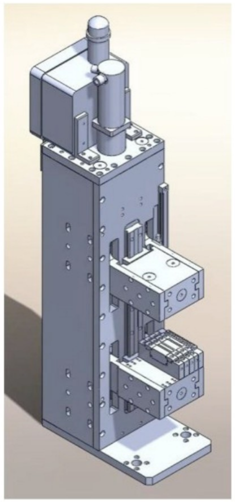
$$\Delta\psi(z) = \frac{2\pi}{\lambda_u(1+1/2(K_u^2))}\left(\frac{e}{mc}\right)^2 \int_{-\infty}^{z}\left(\int_{-\infty}^{z''} B(z')dz'\right)^2 dz''$$

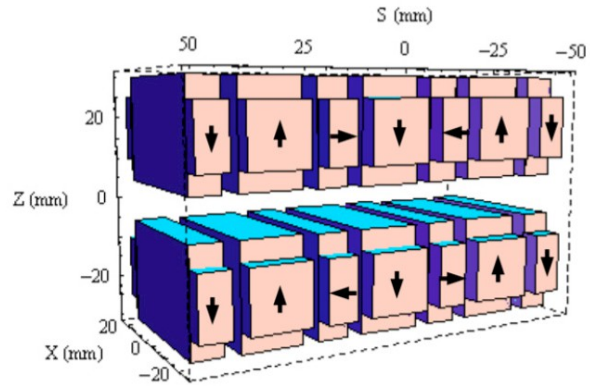


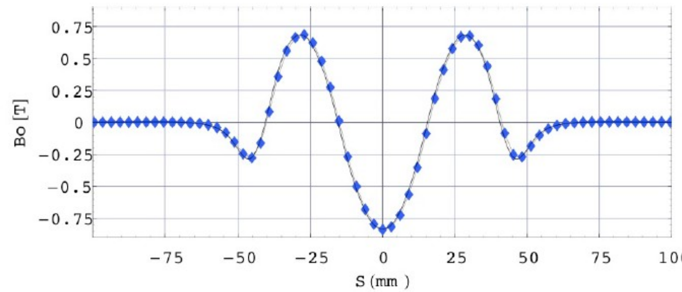


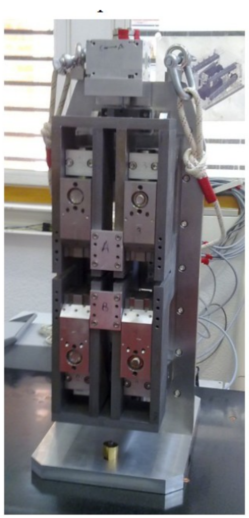


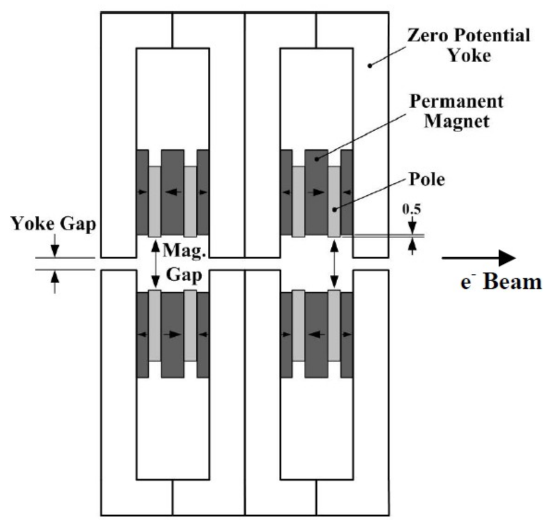
Examples of Phase Shifters

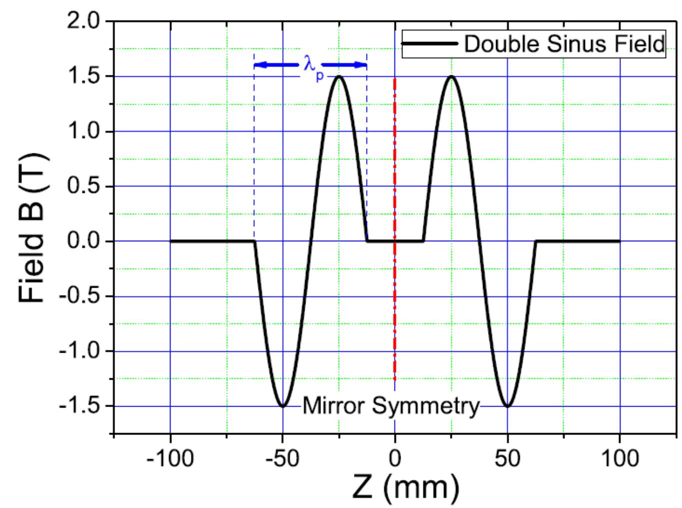








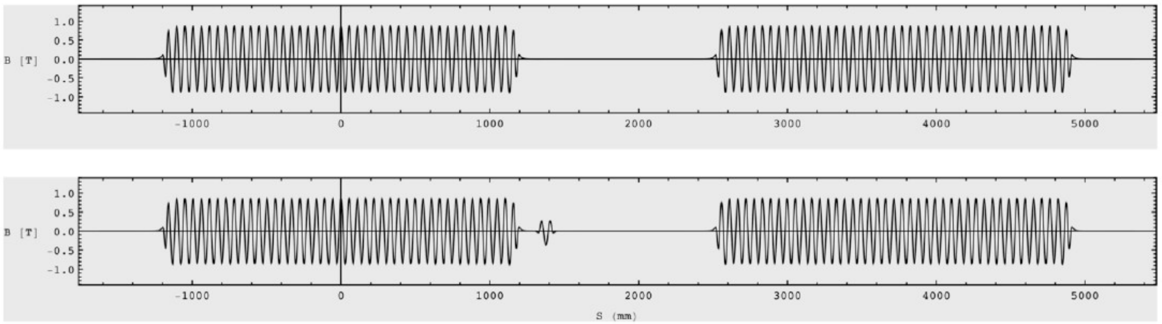


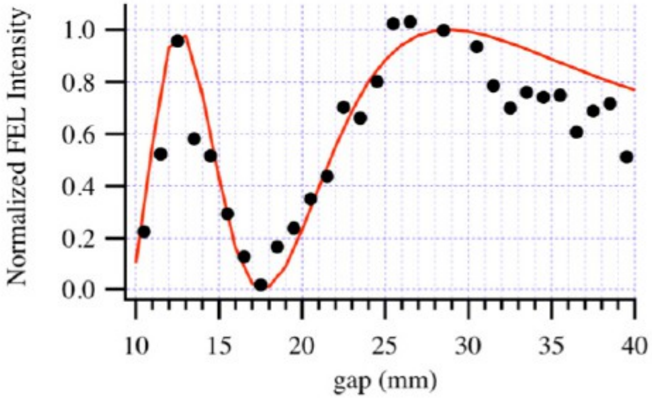


Measurements of the FERMI Phase Shifters

Phase Shifters were measured with a hall probe and flip coil.

- Phase shifters should not interfere with the quality of the electron beam.
- Should not effect the undulator field when mounted in close proximity





Check of phase shifter performance in the FEL-1 of FERMI@Elettra

Phase Shifters for fine tuning of an FEL

In an FEL electrons loose energy to radiation

↓

Resonant condition changes trough the undulator

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

↓

Adjusted by tapering the undulator (changing K)

↓

In a segmented undulator this can also be adjusted with a phase shift between undulator segments

Effective only if there are enough segments.

Conclusions

- FELs can create very intense, coherent and tunable light (also in X- ray region)
- Undulators for FELs are very long and need to be segmented
- Phase shifters are needed to control slippage of electrons in a free space between segments.
- Phase shifters can also be used for fine tuning of and FEL.