Interference-Based Ultrafast Polarization Control at Free Electron Lasers

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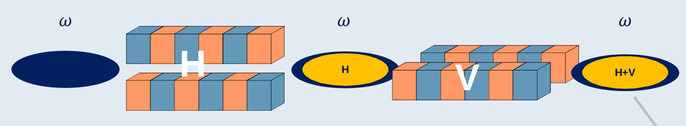
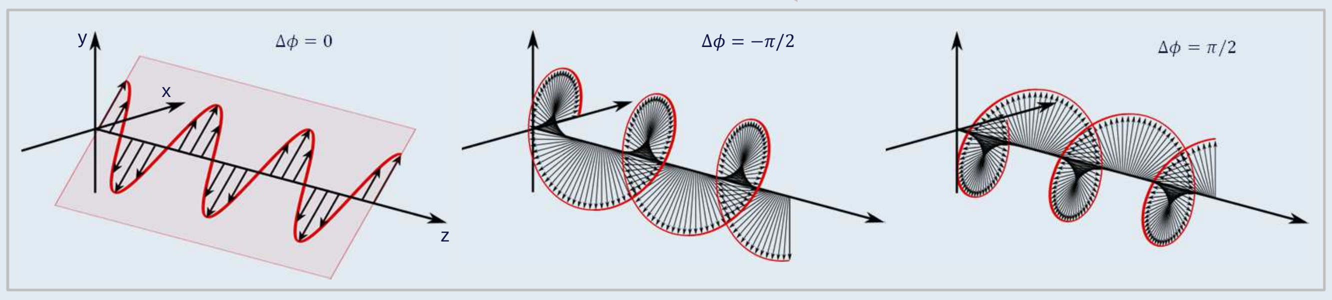
Abstract

X-Ray Free Electron Lasers (XFELs) provide short high power pulses of X-rays with a high degree of polarization, where polarization properties are determined by undulator magnetic field. Fast control of these properties would allow for unique experiments. Here we propose a scheme to modulate the polarization of FEL radiation (polarization shaping) or generate on average non-polarized radiation with FELs. This scheme is based on “crossing” APPLE-X helical undulators.

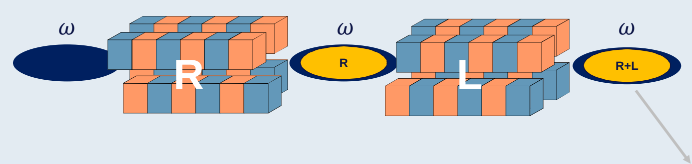
Crossed planar undulators



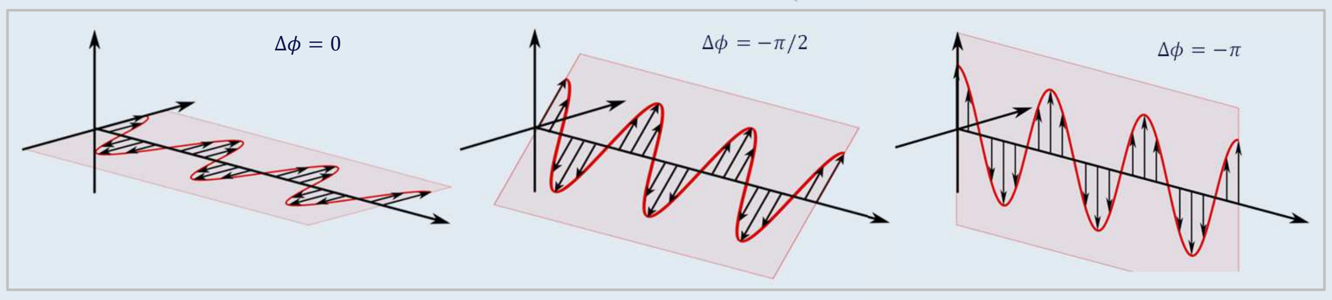
- Crossing two planar undulators allows one to obtain circular polarization if phase shift $\Delta\phi = \pm\pi/2$



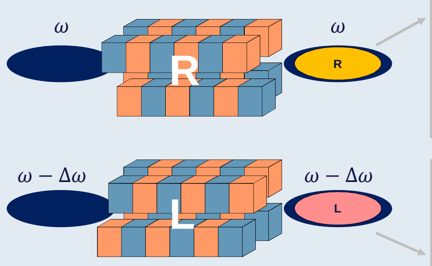
Crossed helical undulators

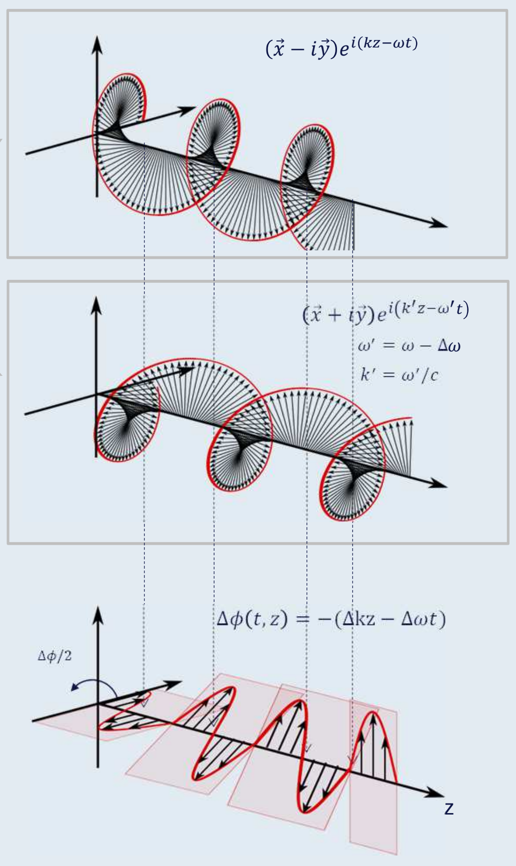


- Crossing two helical undulators will yield linearly polarized radiation (with plane orientation that depends on phase shift)



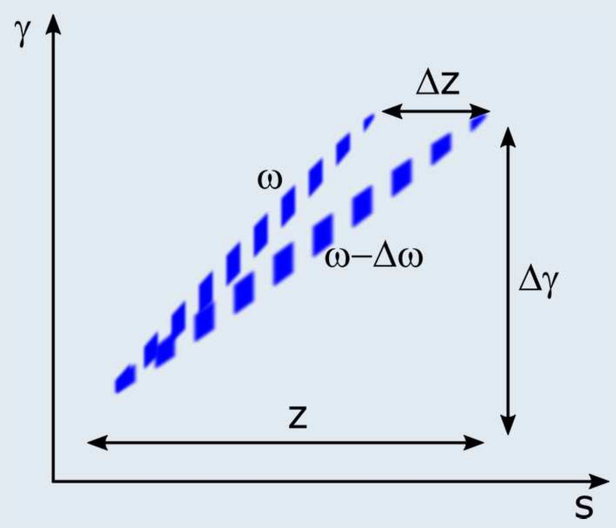
Crossed helical undulators with a linear phase chirp between the pulses





- Shifting frequency in one of the undulators would create phase chirp between the two radiation pulses.
- Polarization plane of radiation depends on longitudinal position along the beam
- Frequency of the bunching should be changed between the undulators

Modifying bunching frequency between the undulators



- Chirped electron beam undergoes (de-)compression in the dispersive environment.

$$\frac{\Delta s}{s} = \frac{R_{56}\Delta\gamma}{\gamma s}$$

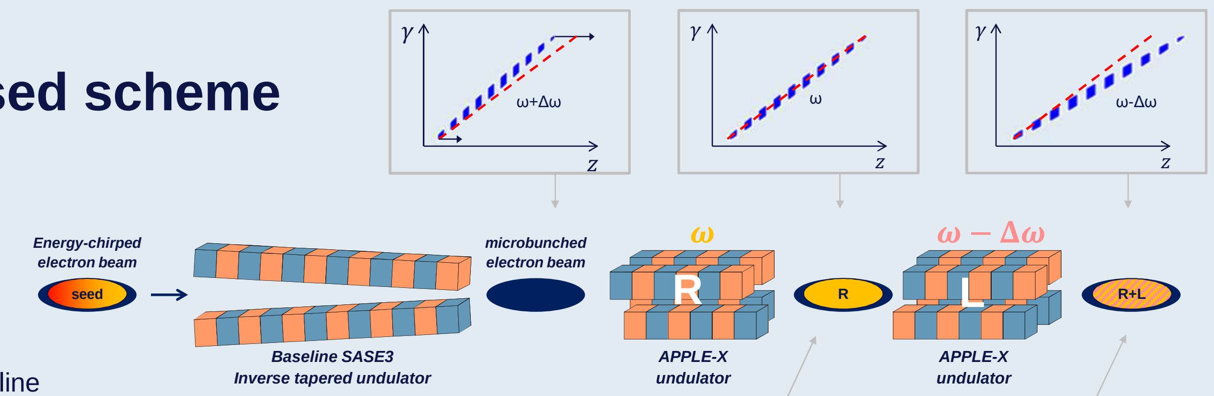
- Frequency of density modulation (if present), is modified proportionally to the beam compression:

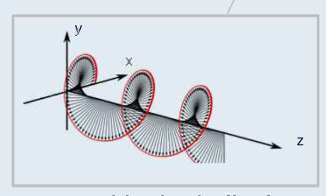
$$\frac{\Delta\omega}{\omega} = \frac{\Delta s}{s}$$

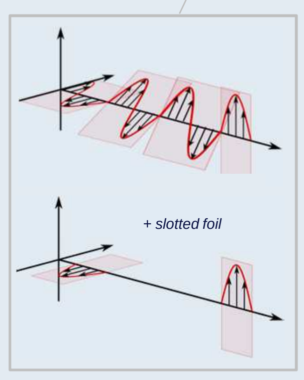
- Undulator with N periods tune to wavelength λ has dispersion $R_{56} = -2N\lambda$
- Therefore the bunching frequency will be shifted by

$$\Delta\omega = -4\pi cN\frac{\Delta\gamma}{\gamma s}$$

Proposed scheme

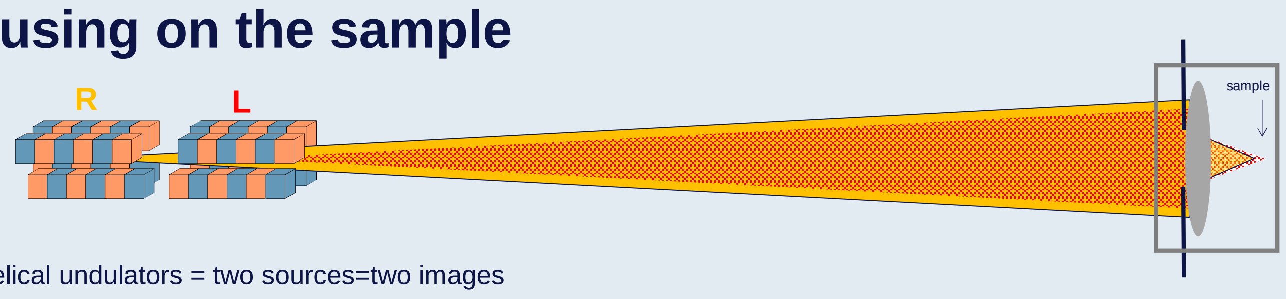




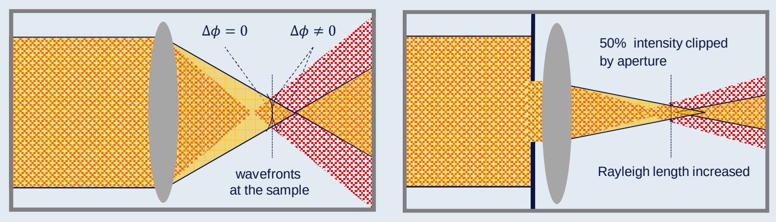


- SASE3 beamline of the European XFEL
- Consider seeded electron beam (seed may be chirped to satisfy resonance condition along the beam) - optional
- Bunching is developed downstream the inverse tapered undulator
- Two overlapping radiation pulses with linear phase chirp are generated in the helical APPLE-X undulators, the resulting radiation pulse will have modulated polarization.
- Polarization scrambling at Tera-radian/second rate
- Two pulses of polarization-of interest if combined with slotted foil with two slots
- Can operate in SASE mode
- - Frequency chirp in radiation will be present
- Twin-bunch technique may be beneficial

Focusing on the sample



- Two helical undulators = two sources=two images
- Convenient to locate sample between two images (maximizing energy density)
- Both radiation wavefronts are curved
- $\Delta\phi$ varies with the distance from the optical axis
- Introducing aperture in focusing system increases Rayleigh length, decreases transverse phase chirp



- Degree of polarization:

96% - on axis 70% - transversely integrated 95% - transversely integrated with aperture

Stokes parameters

- Polarization stated can be expressed with Stokes parameters

$$S_0 = \langle E_x E_x^* \rangle + \langle E_y E_y^* \rangle$$
$$S_1 = \langle E_x E_x^* \rangle - \langle E_y E_y^* \rangle$$
$$S_2 = \langle E_y E_x^* \rangle + \langle E_x E_y^* \rangle$$
$$S_3 = i(\langle E_y E_x^* \rangle - \langle E_x E_y^* \rangle)$$

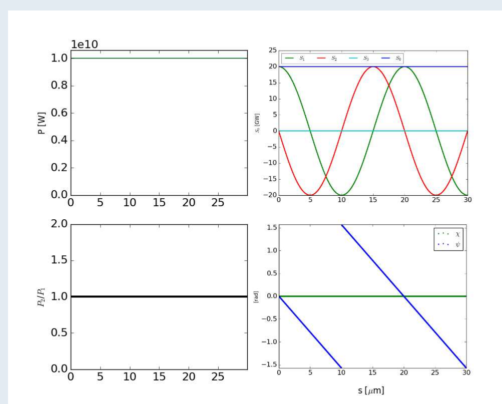
- Brackets $\langle\ldots\rangle$ denote an average over observation time

- Total degree of polarization

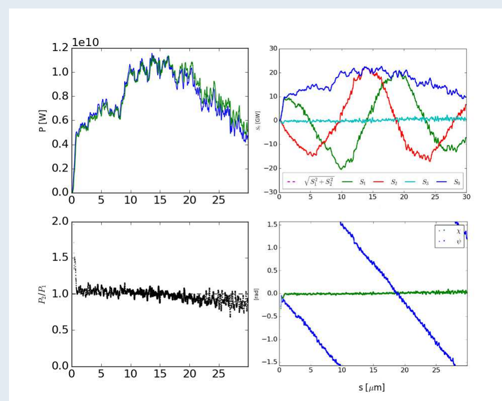
$$D = \frac{\sqrt{S_1^2 + S_2^2 + S_3^2}}{S_0}$$

- Degree of linear polarization

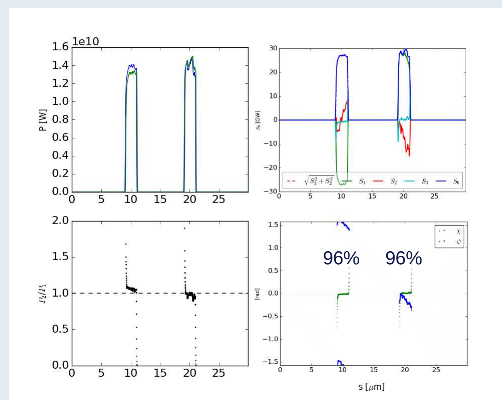
$$D_{lin} = \frac{\sqrt{S_1^2 + S_2^2}}{S_0}$$



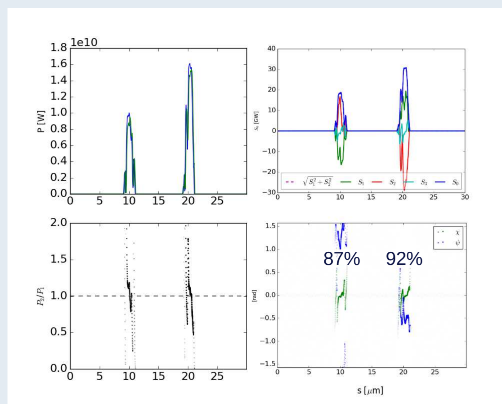
Model beams 10GW each



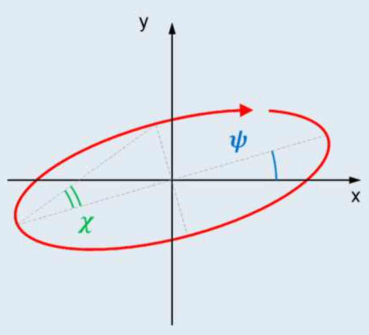
Seeded FEL



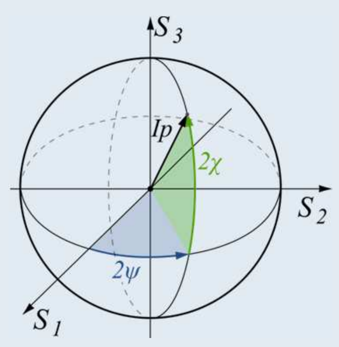
Seeded FEL + slotted foil



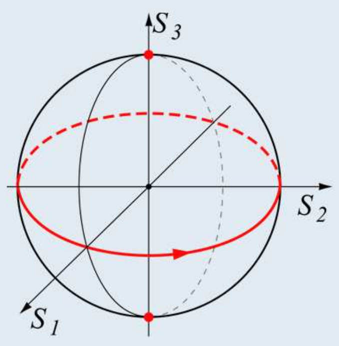
SASE FEL + slotted foil



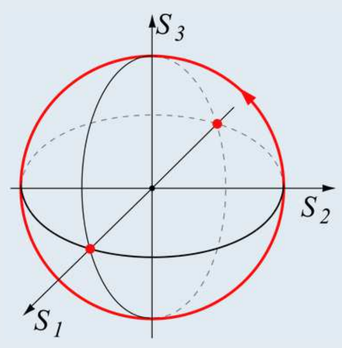
Polarization ellipse



Poincare sphere



Stokes vector rotation for crossed helical undulators



...for crossed planar undulators

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