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 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.

Modifying bunching frequency between the undulators
Chirped electron beam undergoes (de-)compression in the dispersive environment.

\[ \Delta Z = \frac{R_w \Delta \gamma}{F} \]

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

Undulator with \( N \) periods tune to wavelength \( \lambda \) has dispersion:

\[ R_w = \frac{N \lambda}{2} \]

Therefore the bunching frequency will be shifted by

\[ \Delta \omega = -4\pi c N \frac{\Delta \gamma}{F} \]

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 ladder 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 1.6 radian/second rate
- Two pulses of polarization-of interest # 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:
  - 95% - on axis
  - 70% - transversely integrated
  - 95% - transversely integrated with aperture

Stokes parameters

- Polarization stated can be expressed with Stokes parameters
  \[ S_0 = (E_0 F_0) \]
  \[ S_1 = (E_0 F_1 - E_1 F_0) \]
  \[ S_2 = (E_0 F_2 - E_2 F_0) \]
  \[ S_3 = (E_0 F_3 - E_3 F_0) \]

- Brackets \( \langle . \rangle \) denote an average over observation time

- Total degree of polarization
  \[ D = \frac{S_0^2 + S_1^2 + S_2^2 + S_3^2}{S_0^2} \]

- Degree of linear polarization
  \[ D_{LP} = \frac{S_1^2 + S_2^2}{S_0} \]

References
E. Berge, arXiv:1704.07105