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 the 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.

INTRODUCTION

X-ray Free Electron Lasers (XFELs) opened up the possibility of obtaining polarized X-ray pulses with unprecedented power and femtosecond-order duration. In recent years there has been a growth of demand for pump-probe schemes that deliver FEL radiation for both pump and probe with variable wavelength and delay.

At the LCLS the generation of two pulses with variable polarization and delay was demonstrated after installation of a helical undulator, following the main planar undulators [1]. In the current paper we propose another, alternative scheme to shape the polarization of FEL radiation on 100-femtosecond timescale and exemplify it for the SASE3 beamline of the European XFEL. This scheme does not require any special hardware, but only the components already being proposed for installation at this facility, namely:

- Emittance spoiler (slotted foil).
- Soft X-ray Self-Seeding monochromator (optional).
- Corrugated structure located upstream the SASE3 undulator.
- Two APPLE-X helical undulators located downstream the baseline SASE3 undulator, separated by a phase shifter.

The main elements of the proposed setup are the two helical APPLE-X undulators [2], tuned to the same resonant frequency ω, but with opposite polarization direction (as a basis for reasoning, the first undulator is tuned to produce radiation with right-handed circular polarization as defined from the point of view of the source (negative helicity), while the second one - left-handed (positive helicity).

PROPOSED METHOD

Two radiation beams with mutually orthogonal polarizations can be generated and naturally overlapped by propagating an electron beam through two planar undulators with the orthogonal polarization planes located one after the other. If the electron beam is delayed by $\lambda/4$ between these undulators, the combined radiation would be circularly polarized, as illustrated on Fig. 1, first column. This was studied in [3] for synchrotron facilities. Later this approach was extended for FELs [4], experimentally demonstrated [5] and is currently referred to as the "crossed undulator technique".

We consider the case, when, instead of linearly polarized radiation, two circularly polarized pulses with equal intensities, opposite helicity and a phase shift $\Delta\phi$ with respect to each other are generated. Then the resulting radiation will be always linearly polarized, with a polarization plane depending on the phase shift value $\Delta\phi$ (see Fig. 1, second column).

When the carrier frequency of the second pulse is shifted by $\Delta\omega$, then the phase difference $\Delta\phi$ varies linearly along the radiation pulses. In other words, one pulse has linear phase chirp with respect to the other. Then the polarization plane of the resulting linearly polarized radiation would gradually and periodically change its orientation (i.e. rotate) with frequency $\Delta\omega/2$, as schematically shown on Fig. 1, third column.

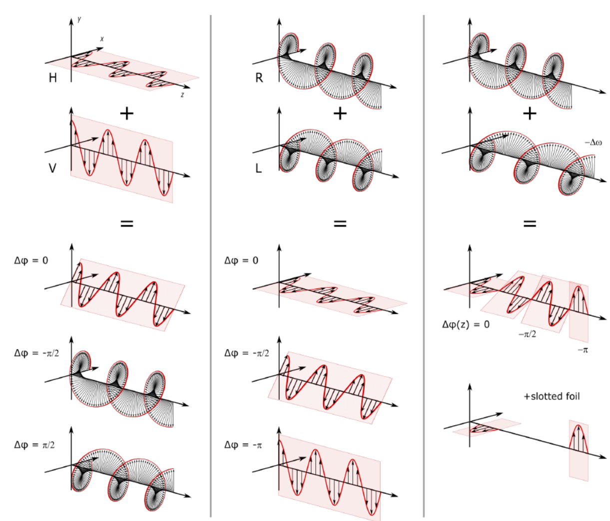

Figure 1: Combination of radiation pulses with different polarization: two linearly polalrized (left column), two circularly polarized (central column), and two circularly polarized with linear phase chirp (right column). Note that for illustration purposes the depicted radiation carrier frequency is small, while the actual frequency would be much higher compared to rate of the polarization plane rotation. The same remark applies to radiation after slotted foil introduction.

On the large timescales this radiation is not polarized, since due to rotation of the Stokes vector its averaged length

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approaches zero, i.e. the polarization is "scrambled". Let us consider a nominal electron beam microbunched at frequency ω entering two consecutive helical undulators. The microbunching can be obtained in an upstream FEL section by applying for example, inverse tapering [6, 7].

In order to obtain radiation with shaped polarization, the bunching frequency of the electron beam should be shifted by a finite $\Delta\omega$ upstream the second helical undulator. This frequency shift would take place naturally if the modulated electron beam has an energy chirp and passes through a dispersive environment (as illustrated on Fig. 2).

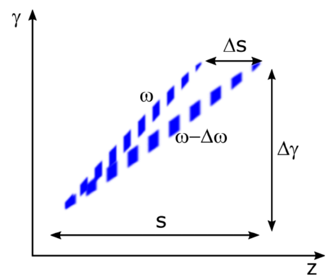

Figure 2: Longitudinal phase space of a linearly chirped electron beam with coherent density modulation at frequency ω. This frequency is shifted by $\Delta\omega$ upon propagation through dispersive environment.

Undulators have dispersive properties, given by $R_{56} = -2N\lambda$, where R_{56} is momentum compaction factor, N denotes a number of undulator periods, and $\lambda = 2\pi c/\omega$ is a resonant undulator wavelength. This means, that while propagating through an undulator, the total length of a linearly chirped electron beam is modified.

Dispersion in the undulator is too small to significantly affect the amplitude of the electron density modulation, but is sufficient to change its frequency proportionally to the final electron beam elongation $\Delta s = -R_{56}\Delta\gamma/\gamma$:

$$\frac{\Delta\omega}{\omega} = -\frac{\Delta s}{s} = \frac{R_{56}\Delta\gamma}{\gamma s}.$$

One may see that the resulting bunching frequency shift $\Delta\omega$ does not depend on the resonance frequency ω:

$$\Delta\omega = -4\pi c N \frac{\Delta\gamma}{\gamma s}.$$

The crossed undulator scheme implies that the radiation from the first undulator does not interact with the electron beam in the second, i.e. the radiation from the first undulator does not "seed" the second one.

In the case of crossed planar undulators this is always true, since the projection of the electric field of the "seed" onto the transverse electron velocity in the second undulator is always zero. In case of helical undulators this projection is not zero, but it is not constant along the undulator length. Therefore, no synchronism takes place and *on average* the "seed" does not interact with the electron beam.

Let us now consider an electron beam with positive energy chirp that enters an inverse tapered undulator, as illustrated in Fig. 3. This energy chirp in the electron beam can be achieved by installing the corrugated structure upstream the main undulator [8].

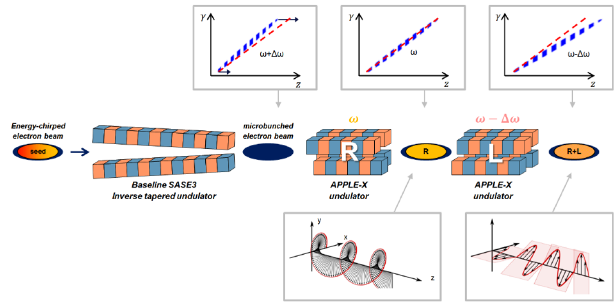

Figure 3: Illustration of the proposed scheme.

For the sake of argument, we define the bunching frequency at the center of the beam immediately after the first helical undulator as ω. The radiation emitted by this part of the beam has therefore carrier frequency ω. After propagation of the electron beam through the second undulator, the frequency of the bunching will be shifted by $\Delta\omega$. Therefore the same frequency shift $\Delta\omega$ should be expected in the carrier frequency of the radiation emitted in the second undulator. As long as the chirp in the electron beam is linear, the same frequency shift applies along the entire radiation pulse independently of the longitudinal position.

We performed numerical simulations with GENESIS code. To model the helical undulators we assume APPLE-X segments with 9 cm periods and 22 periods per segment. For simulations we used a model 30 um-long electron beam. Its energy in terms of Lorenz factor was varying from 16500 at the tail to 16700 at the head, while the other values remained constant: current (4 kA), normalized emittances (1 mrad) and beta functions (20 m). Results of the numerical simulations are presented in Fig. 4-(b).

For pump-probe experiments it may be necessary to select only two regions of the resulting pulse with desired polarization plane. Lasing in the electron beam can be selectively inhibited by introducing slotted foil into the last bunch compressor in LINAC. Using aluminum foil with two slots, the transverse emittance of the electron beam may be spoiled except for two short 2 μm lasing windows, separated by 10 μm along the bunch. In the scheme considered above it corresponds to nearly quarter of the polarization plane rotation or half the rotation of the Stokes vector. The two resulting pulses would have high degree of linear polarization (96 %) with planes orthogonal with respect to each other, see Fig. 4-(c).

There are 3 degrees of freedom to independently control state of polarization of the two resulting pump and probe pulses: the gap of the corrugated structure, distance between slots in the slotted foil and delay of the electron beam introduced in phase shifter between the two helical undulators.

Polarization plane of the both pulses can be simultaneously changed by varying the delay in the phase shifter. The

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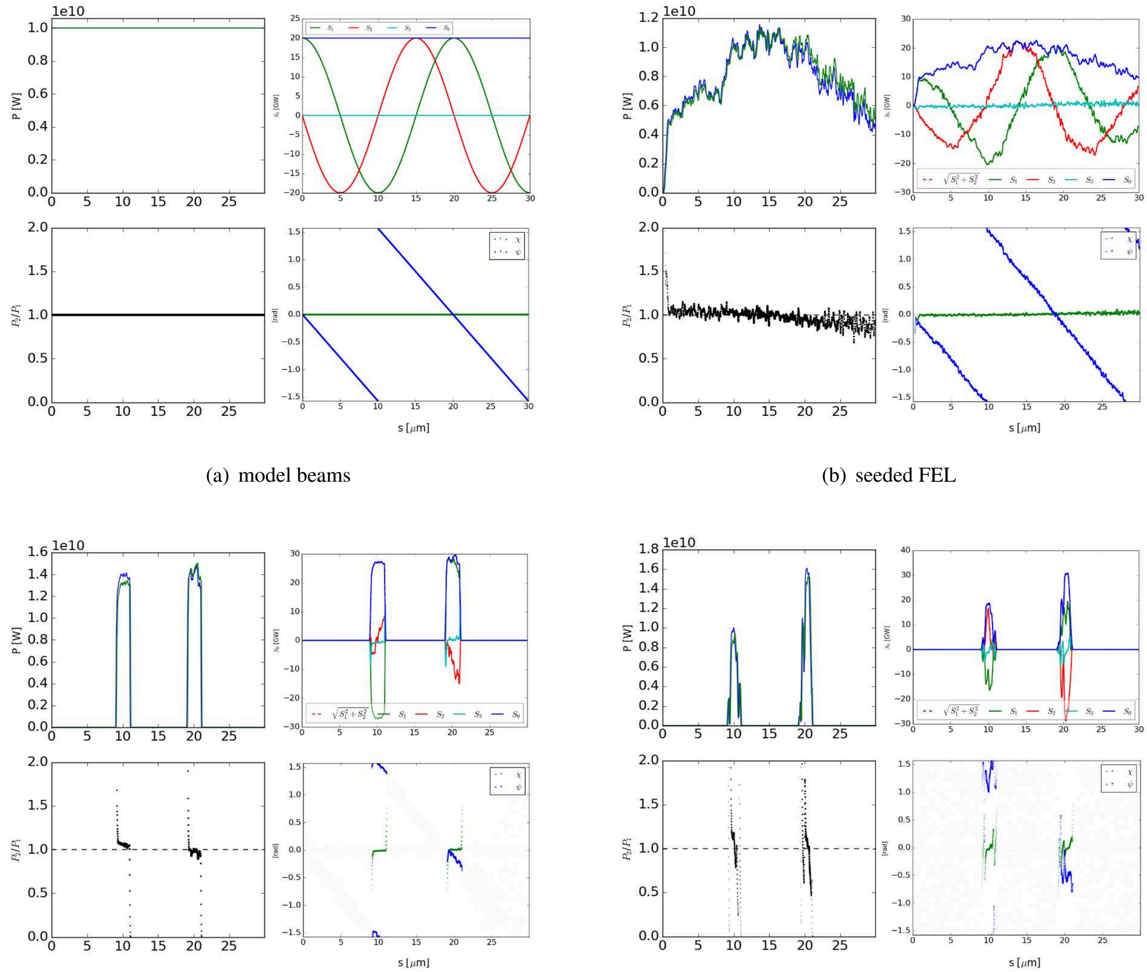

(a) model beams

(b) seeded FEL

(c) seeded FEL with slotted foil

(d) SASE FEL with slotted foil

Figure 4: Result of polarization modulation in case of combining two model pulses is illustrated on subfig. (a). Genesis simulation results for the seeded FEL without, and with slotted foil are presented on subfigs. (b) and (c) correspondingly. Both pulses in subfig. (c) yield 96% of linear polarization. Simulation results without seed (subfig. (d)) show 87% and 92% degree of polarization. The top left plots show the power of combined pulses, bottom left plots show the ratios of the pulse power, top right plots show Stokes parameters of the resulting radiation and bottom right plots - spherical coordinates of the Stokes vector.

delay between these pulses can be changed by varying both the separation between the slots of the slotted foil and gap in the corrugates structure.

It is worth noting that the scheme proposed above also works if the crossed undulators are planar. In that case the polarization of the resulting radiation will be alternating between right- a left-handed circular polarizations with an intermediate state of linear polarization with 45° tilt, as in Fig. 1 (first column).

Measurement the polarization properties at the sample location (between two waists of right-handed and left-handed polarized radiation), would show that they depend on the transverse offset from the optical axis. In our case the sample is located, where the radiation with the left-handed circular polarization has passed the waist and is diverging, while the radiation with the right-handed polarization is still converging for the waist located downstream the sample. The phase difference between the two beams grows nearly quadratically as a function of the distance from optical axis, hence the resulting state of polarization varies. This effect is interesting by itself and may possibly yield to some applications. A the same time it causes degradation of the degree of polarization at the sample from 96% down to 70%. In order to account for this effect one may increase Rayleigh length of the image waists. The easiest way to accomplish it is to introduce an aperture at the location of the focusing element (lens or mirror). We have numerically propagated the radiation wavefronts with OCELOT code [9] and have found that by blocking half of the radiation intensity with the square aperture upstream the mirror it is possible to improve the transversely integrated degree of polarization up to 95%, almost reaching the on-axis value of 96%.

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In Fig. 4-(d) we present Stokes parameters for the case when no temporal coherence is introduced to the density modulation of the electron beam. Both radiation pulses exhibit temporal structure of SASE radiation and, when combined, show degree of linear polarization around 90%. This value may potentially be improved by either decreasing the total radiation slippage (installing shorter helical undulators) or by increasing the coherence time with, for example, pSASE technique [10]

It may be beneficial to utilize twin bunch technique [11] instead of combination of corrugated structure and slotted foil to obtain comparable results.

The extensive study of the proposed method will be published elsewhere.

CONCLUSION

In this paper we presented a method to modulate the polarization state of the FEL radiation pulse along its position. It can be achieved by introducing the microbunched electron beam with a linear energy chirp into two helical undulators located one after another. If magnetic field of the undulators is tuned to emit right- and left-handed circular polarization, then the resulting radiation would be linearly polarized with polarization plane changing along the pulse, i.e. polarization-shaped. If magnetic field in the undulators is tuned to generate the linearly polarized radiation with orthogonal polarization planes, the resulting radiation will be alternating between right and left circular polarization. This method allows to scramble the polarization of FEL radiation with rate of several Tera-radians per second.

Two short pulses with polarization-of-interest may be selected by introducing a slotted foil in the accelerator. Both pulses will be naturally overlapped and synchronized. One can independently control their polarization state and temporal separation by varying: magnetic field of the phase-shifter between the helical undulators, distance between the slots in the slotted foil and the corrugated structure gap.

Degradation of polarization degree due to transverse effects can be accounted for by introducing apertures at focusing mirror locations.

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