DESIGN STUDY OF AN ISOCHRONOUS BEND FOR A HELICAL RADIATOR AT THE EUROPEAN XFEL

Y. Li, W. Decking, B. Faatz, J. Pflueger
Deutsches Elektronen-Synchrotron (DESY), Notkestrasse 85, 22607 Hamburg, Germany

Abstract

The planar SASE3 undulator system of the European XFEL will produce linearly polarized radiation in the wavelength range 0.4 to 1.6 nm. There is, however, a strong demand for circular polarized radiation in this wavelength range. After the planar undulator the electron beam is completely bunched. Sending it through a suitable radiator is an economically and technically convenient method to generate radiation with polarization properties fully determined by the radiator. If a bend is used to separate the light created by the linear SASE3 from that of the radiator there are two independent light sources. In this case the light of the radiator is not contaminated by the light of the upstream linear FEL. The micro bunching of the planar undulator must be preserved through the bend. In this paper, a first order isochronous bend is presented, which uses beta function matching to minimize nonlinear aberrations. This solution is capable to preserve micro bunching at wave lengths larger than 1.6nm.

INTRODUCTION

The European XFEL [1] will generate of X-rays using the principle of Self-Amplified Spontaneous Emission (SASE) [2, 3]. Currently there are three beam lines under construction: SASE1, SASE2 and SASE3. SASE1 and SASE2 are hard X-ray beam lines in the wavelength range of 0.1 nm to 0.4 nm. SASE3 is a soft x-ray beam line which can generate light from 0.4 nm to 1.6 nm. The SASE2 and SASE3 undulators make use of adjustable gaps. Their wavelength can be tuned without change of the electron energy. All undulators will be built as planar undulators, which therefore supply linear polarized light. There is, however, a strong demand in the user community that there is circular polarized radiation at wavelengths of 1nm and above. A solution must be compatible with the existing SASE3.

Several possible helical schemes have been discussed in the context of SASE3. The first is replacing some of the planar undulator segments by helical ones. The planar undulator pre-bunches electrons. The last 3-4 gain lengths are filled with a relatively short helical undulator tuned to the same wavelength in order to generate powerful circular polarized light. The drawback of this scheme is that a back ground of linear polarized light can not be avoided, which reduces degree circular polarization. A second proposal was made by K.J. Kim [4, 5]. In this scheme, a short orthogonal planar undulator is placed after the long planar undulator. If the crossed undulator length is 1.3 times the FEL gain length, the two orthogonal linear lights components have equal intensities [6]. Therefore their combination results in circular polarized light if both intensities are equal. FEL 3D gain length, however, depends on a number parameters such as wavelength, peak current, emittance, energy spread, β function etc. Some of them might fluctuate leading to fluctuations of the polarization.

There is another option: Like in the first proposal above the planar undulator is used as a buncher. After the buncher, the electron beam is separated from the linear radiation by a bend. Successively the beam is passed through the helical radiator. Because the micro bunch structure has been formed in the buncher, intense coherent radiation is emitted in the helical radiator. A quite short helical radiator can generate powerful circular radiation. In this case linear and circular polarized radiation are well separated by the bend. This option has two advantages: First, two independent beam lines can be served, one with linear and the other with circular radiation. Moreover the time structure in both beams is naturally synchronized. Second, the polarization properties of the radiator are completely independent from the light of the buncher. So polarization should be high and its fluctuation should be very small.

Using this scheme micro bunching on the scale of several angstroms as formed in the planar buncher, must be maintained throughout the bending system. There are two difficulties to overcome:

1. The micro bunch length is 0.4-1.6 nm.
2. In the planar SASE3 a large uncorrelated energy spread ($> 20\ MeV$) is induced to electron beam by the FEL process.

To illustrate the problem Fig. 1 illustrates the first order geometric aberration on an uniform circularly symmetric bunch. It is a bend by a single dipole. From this plot it is seen, that after passing through the dipole, the micro bunching is still preserved along its original direction. But it is rotated relative to its new direction by the bending angle α.

Thus the micro bunching expands with respect to the new orbit. The expanded micro bunch length is given by the transverse beam size and the bending angle α. As an example, suppose the transverse size $\sigma_e = 20\ \mu m$, the bending angle α is as small as only $100 \mu rad$, then the length expansion is given by $\Delta L = \sigma_e \sin\alpha = 2\ nm$. This is already more than the longest 1.6 nm wavelength in SASE3 with 17.5 GeV beam. So along the new orbit, the micro bunching is destroyed. In order to solve this problem the beam must be rotated as shown in Fig. 1. This can be done using an achromatic bend, which is described in this paper.

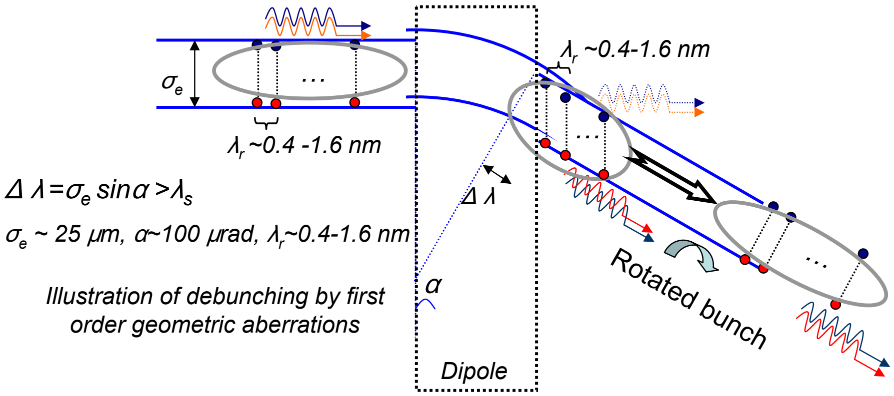

Figure 1: Illustration of the first order geometric aberration. An electron bunch is deflected by a single dipole. The slices of the micro bunches are indicated. It is only preserved along the original direction

BASIC PARAMETERS AND MINIMUM BENDING ANGLE

The parameters of the European XFEL and SASE3 are listed in Table. 1.

Table 1: Parameters of the European XFEL and SASE3 Used for the Simulations

Parameter	Value	Unit
Undulator period, λ_u	68	mm
rms Undulator parameter, K	3.58-7.36	
Segment length	5	m
Electron beam energy	17.5	GeV
Radiation wavelength, λ_r	0.4-1.6	nm
Energy spread	30.0	MeV
Bunch peak current	5	kA
Normalized emittance, ϵ_n	1.4	mm mrad
Average $\beta_{x,y}$ in undulator	15	m
$\beta_{x,y}$ at undulator exit	19 & 8	m
$\alpha_{x,y}$ at undulator exit	0.0 & 0.0	

The purpose of bending system is to separate the linear polarized radiation from the SASE3 undulator from circular polarized one generated by the radiator. The beam divergence in both cases is assumed gaussian and can be calculated using 3D FEL codes. For 1.6 nm it is 11 μrad. A minimum bending angle of $\alpha = 100\ \mu rad$ provides 9 σ separation of both beams, which is considered large enough.

FIRST ORDER ISOCHRONOUS BEND

In Fig. 1 it was illustrated that in order to preserve the micro bunching, the macro bunch must be rotated with respect to the new orbit. This rotation requires that the elements of the transport matrix $R_{51} = R_{52} = 0$. Because these two matrix elements are correlated to the dispersion of the bending system it means that the system must be achromatic to first order. Moreover, additional debunching occurs due to the large energy spread induced by SASE3.

The bunch factor b_n used to describe the micro bunch quality is defined as:

$$b_n = \left| < e^{-i\phi} > \right| \tag{1}$$

where ϕ is the electron’s pondermotive phase.

Assuming $b_{n,i}$ and $b_{n,f}$ are bunch factor before and after bending system, their ratio is:

$$\frac{b_{n,f}}{b_{n,i}} = e^{-2(\frac{R_{56}\pi}{\lambda_r})^2\sigma^2_{\Delta E/E}} \approx 1 - 2(\frac{R_{56}\pi}{\lambda_r})^2\sigma^2_{\Delta E/E}. \tag{2}$$

Where $\sigma_{\Delta E/E}$ is the relative energy spread and R_{56} is the compression parameter. The condition of $R_{56} = 0$ means that in first order electrons with different energies have the same path lengths through the bending system. R_{56} can be expressed by the integration:

$$R_{56} = \int_0^L \frac{D(s)}{\rho(s)} ds, \tag{3}$$

where $D(s)$ denotes to the dispersion, $\rho(s)$ denotes to the local bending radius. Eq. (2) requires $R_{56} = 0$ to achieve the largest bunch factor at the entrance of helical radiator. Together with $R_{51} = R_{52} = 0$ this means that the bending system is isochronous to first order.

On the other hand the micro bunch is quite short and second order aberrations can make a significant contribution. By some analysis [7] it was shown that if the initial Twiss parameters satisfy the relationship:

$$\begin{aligned} \beta_{x0} &= \frac{2T_{522}}{\sqrt{4T_{511}T_{522}-T^2_{521}}} & \alpha_{x0} &= \frac{T_{521}}{\sqrt{4T_{511}T_{522}-T^2_{521}}} \\ \beta_{y0} &= \frac{2T_{544}}{\sqrt{4T_{533}T_{544}-T^2_{543}}} & \alpha_{y0} &= \frac{T_{543}}{\sqrt{4T_{533}T_{544}-T^2_{543}}}, \end{aligned} \tag{4}$$

the contribution of second order aberrations is minimized. In these equations T_{5ij} are the second order aberration elements. They can be analytically expressed by integrations over all magnet elements [8, 9]. Beam dynamics transport codes such as ELEGANT can give the specific values for a specific system. As a consequence of Eq. (4) the β functions over the bending system are mirror symmetric.

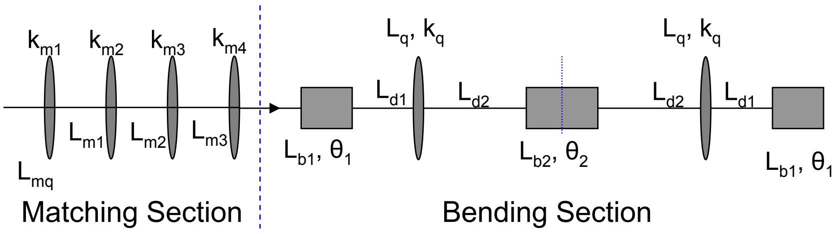

Figure 2: Illustration of the magnet system. It is subdivided into the Twiss parameters matching section and the isochronous bending section. The matching section, consisting of four quadrupoles, is used to match the β functions as required by Eq. (4) in order to minimize second order aberrations. The bending section is isochronous in first order.

Fig. 2 shows the Twiss parameter matching section consisting of four quadrupoles and the first order isochronous bend. In the matching section the initial Twiss parameters according to Eq. (4) are tuned. The bending section is a first order isochronous system. It consists of three dipoles and two quadrupoles and is mirror symmetric. The two quadrupoles are used to tune the derivative of the dispersion, D', to zero at the middle plane making the system achromatic.

The two outer dipoles have the same bending angles (536 μrad). The inner dipole has a reverse but much smaller bending angle of ($-4.57\ \mu rad$). The dispersion in the inner dipole is much larger than in the two outer ones, see Fig. 3. Therefore, due to the opposite sign of the inner dipole the integration in Eq. (3) over the bending section can be made zero.

While Fig. 2 gives an overview over the required elements numerical values are listed Table. 2. Since this is a numeric study only magnet lengths etc. not match standard dimensions. The total deflecting angle is 1067 μrad, which is much larger than the minimum required bending angle of 100 μrad.

The six dimensional phase space evolution over the matching and bending section, see Fig. 2, was calculated using the code ELEGANT and tracking 20000 particles. Gaussian phase space distributions were assumed. Initial values for the transverse dimensions as well as the initial energy spread were taken from Table. 1. For the longitudinal position one representative micro bunch was modelled using a gaussian with σ values of .067nm and .267nm, which correspond to 3 σ full widths containing of 99 % percent of the particles of 0.4 and 1.6nm, respectively. Results are shown in Fig. 4. The top row shows the evolution of the 0.4nm case. Starting with an initial bunching factor, b_n, of 0.573 at the entry it completely degradates to b_n=0.0635 at the exit. Correspondingly σ increases from 0.067 to 0.285nm. The distribution at the exit is clearly non-gaussian. For the 1.6nm case, however, the bunching decreases much less. From b_n=0.573 at the entry to b_n=0.355 at the exit. The final distribution looks more gaussian. Its rms increases from σ= 0.267 at the entrance to b_n=0.384 at the exit. It is evident that at these wavelengths bunching is much better preserved.

Since the system is isochronous to first order and only linear magnetic elements are used the debunching observed in Fig. 4 is due to higher order aberrations, which are evaluated by ELEGANT. The results of Fig. 4 demonstrate that the short bunch length limit of this system is at about 1.6nm. Shorter bunch lengths require more effort to correct for higher order effects.

Fig. 3 shows the β functions and the horizontal dispersion of this scheme. It is seen that the matching section focuses β_x from about 20 m down to 4 m and defocuses β_y from about 8 m up to about 31 m.

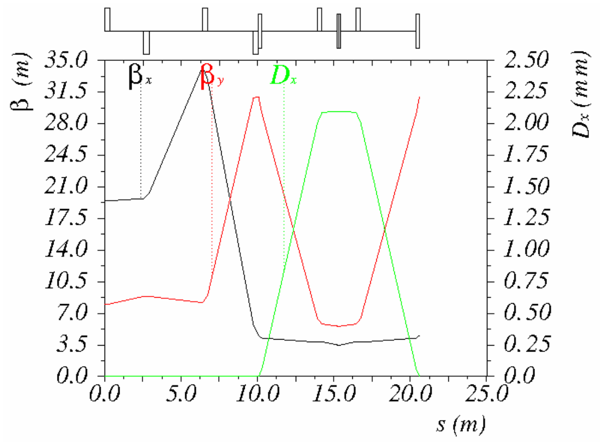

Figure 3: β functions and dispersion of the matching section and the first order isochronous bending system.

SUMMARY

This paper focuses on a beam dynamic study for an ischronous bend, which preserves microbunching and can be used as a part of a scheme to create circular polarized radiation using the microbunched beam of the SASE3 undulator system and a helical radiator. Only linear optical elements were used for this study. By using a matching section and optimizing the initial Twiss parameters second order aberrations are minimized. A comparative study at micro bunch lengths of 0.4 and 1.6nm showed that the short wavelength limit, which can be achieved with this scheme is about 1.6nm. For shorter wavelengths the microbunching cannot be maintained. In order to preserve microbunching

Table 2: Numerical Values of the Elements Shown in Fig. 2

L_{b1}	θ_1	L_{b2}	θ_2	L_{d1}	L_{d2}	k_q	L_q
0.2 m	536 μrad	0.2 m	-4.57 μrad	3.65 m	1.01 m	0.86 m^{-2}	0.30 m

L_{m1}	L_{m2}	L_{m3}	k_{m1}	k_{m2}	k_{m3}	k_{m4}	L_{mq}
2.2 m	3.5 m	3.0 m	0.002 m^{-2}	-0.225 m^{-2}	0.775 m^{-2}	-0.883 m^{-2}	0.34 m

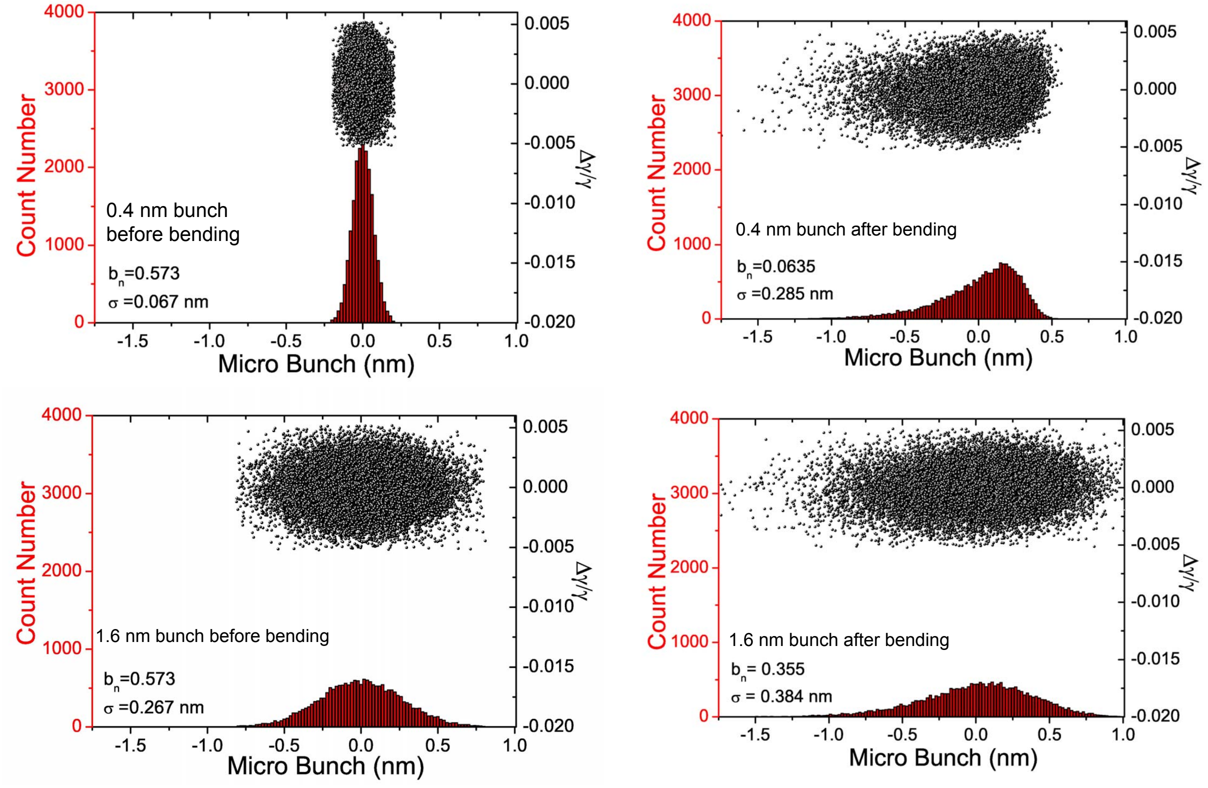

Figure 4: Debunching starting from beginning (left column) to the end (right column) of the matching section and the first order isochronous bend. The top row shows the case for a 0.4 nm micro-bunch, the bottom row shows the 1.6 nm case. The initial longitudinal distributions are assumed to be gaussians with 3σ of 0.4 and 1.6nm.

down to 0.4 nm more sophistcated schemes have to be involved [10, 11]. This will be subject to future studies.

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