STUDY OF A DEFLECTING DISPERSIVE CHICANE FOR THE BESSY SOFT X-RAY FEL*

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Abstract

High power, short pulse length and full coherence are the main parameters of the second generation free electron lasers like the BESSY Soft X-ray FEL. To provide radiation with these properties, BESSY proposed a seeded FEL facility based on high-gain harmonic-generation (HGHG) scheme [1]. This scheme uses cascaded stages each consisting of undulator/dispersive chicane/undulator section to up-convert the seeding frequency.

The transverse separation of the seeding radiation and electron beam after the first undulator is desirable, as not only the output of the following undulators improves but also the seeding radiation itself can be used for diagnostics.

Based on an exact linear model, a dispersive chicane is designed for the BESSY FEL, which deflects the electron beam providing the separation without coupling and spoiling effects [2]. The linear model and the deflecting chicane will be presented and the properties of the chicane will be discussed by means of simulation results.

INTRODUCTION

The BESSY Soft X-Ray FEL is designed as a multi-user facility consisting of three independent FEL lines. Each line is seeded by a tunable laser covering the spectral range of 230 nm to 460 nm. The target wavelength ranges from 51 nm to 1.24 nm with peak powers up to a few GWs and pulse lengths less than 20 fs (rms). The polarization of the fully coherent radiation will be variable.

Cascades of two to four HGHG stages are planned to reduce the existing laser wavelength to the target range of the BESSY-FEL. In the first undulator of such an HGHG stage, the modulator, an energy modulation is imprinted on the electron beam by the seeding radiation. The following dispersive chicane converts this energy modulation to a spatial modulation which is optimized for a particular harmonic. The second undulator, the radiator, is resonant to this harmonic and generates radiation at the higher harmonic, which serves as seed for the next stage. The last HGHG-stage is followed by the so-called final amplifier. It is seeded at the desired wavelength and the amplification process is brought to saturation.

The quality of the FEL output radiation depends strongly on the quality of the frequency up-conversion procedure, which again depends on the quality of the spatial modulation (bunching) and on the quality of the seeding radiation. Although in an HGHG stage, the radiator is resonant to a harmonic of the seeding radiation, short interactions between the seeding radiation and the electron beam are still possible. During such an interaction the phase correlation between the seeding radiation and the electron beam is good enough to permit an energy exchange. These interactions are short as the resonance condition is not fulfilled for the seeding radiation, but due to the high intensity of the radiation, the electron beam quality degrades, and thus the radiator output quality suffers. Separating the seeding radiation and the electron beam after the energy modulation would avoid these undesired interactions. In addition, the separation offers the possibility to use the radiation - seeding radiation as well as the spontaneous undulator radiation- for diagnostics.

In principle, the separation can take place before, inside or after the dispersive chicane, but it has not to affect the spatial modulation. Also other effects like residual dispersion, coupling or increased beam size have to be avoided. Each of the dispersive chicanes planned for the BESSY FEL consist of four dipoles providing a closed bump. Generally, the dispersion strength, which is necessary to convert the energy modulation to the spatial modulation, is not high. Hence the bump amplitudes are not large enough to install mirrors or other optical elements to deflect the radiation. A separation of the radiation and electrons can only take place by an additional bending of the electron beam. A simple bending, with an additional dipole or due to a mismatch of the four bump dipoles, causes residual dispersion, coupling between transverse and longitudinal motion and spoils the bunching. Thus it deteriorates the radiator output strongly.

However, an exact linear model offers the possibility to design an optimal dispersive section, which allows the separation of the electron beam and seeding radiation without any coupling and spoiling effect. In this paper we present the dispersive section which is designed based on this model. Comparisons of simulation results of an HGHG stage using the four dipole chicane and the deflecting dispersive section respectively, demonstrate that the new dispersive section meets all demands.

THE DEFLECTING DISPERSIVE CHICANE

The dispersive chicane, which converts the energy modulation of the bunch to a spatial density modulation is optimized for a particular harmonic of the seed. This spatial modulation results when the energy modulated beam passes through a dispersive chicane, which is described by

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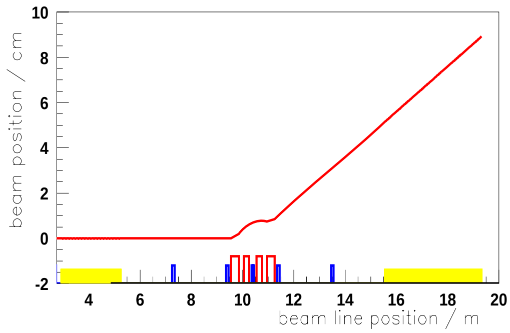

Figure 1: Horizontal trajectory of the electron beam as a function of beam line position. The red line shows the trajectory for the deflecting chicane (dipoles in red, quadrupoles in blue and undulators in yellow colours).

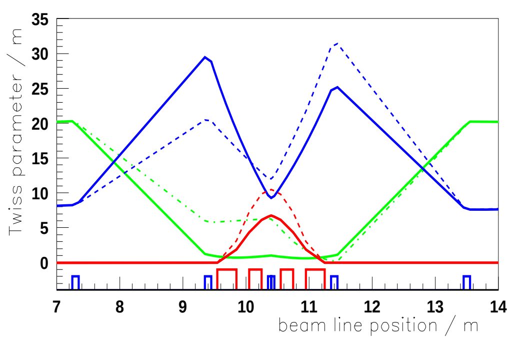

Figure 2: Horizontal (blue) and vertical (green) beta functions and dispersion (1000 times enhanced, red) of the deflecting chicane. The value of m_{56} is tuned to $6.5 \cdot 10^{-5}$ (solid line) and $26 \cdot 10^{-5}$ (dots), colours of magnets as described in fig. 1.

a properly chosen matrix element m_{56}. The energy modulated electrons must be shifted by $\lambda/4$ in the longitudinal position within the dispersion section for the optimal radiator output. For BESSY FEL seeding wavelength, this translates to a distance of 60 nm to 120 nm. Note, the factor two in the distance tuning-range is given by the spectral range of the seeding radiation.

The necessary density modulation is commonly achieved by a simple four dipole bump of zero integrated dipole field strength. By a scaled field strength change of the four dipoles, m_{56} can be varied.

Instead of the simple 2 m long bump, we propose a more elaborate optics, which deflects the beam by a fixed angle of 10 mrad, see Fig. 1 and 2. In addition, the value of m_{56} can be varied by a factor of four, twice as much as required.

This deflecting chicane consists of two dipole families and one quadrupole, tuned as an achromatic bend with variable m_{56} value. The integrated dipole fields are kept constant to define the deflection angle. One family is excited opposite to the other one, the difference between the integrated fields of both family yields the value of m_{56}. The quadrupole tunes the dispersion outside of the chicane to zero. At the entrance and exit side of the chicane an optical matching section is required, consisting of one quadrupole doublet on each side. For the full optical line m_{56}=$6.5 \cdot 10^{-5}$, the same tuning as for the simple bump. Different settings of the dipoles leads to different orbits inside the quadrupole, this steering has to be taken into account.

This optics is 10 m long and has the advantage of separating the electron and photon beams, and delivering the necessary m_{56}. In addition it avoids the coupling between different planes of the electron motion as described below. The separation can be used for easier diagnostics purposes and eliminates further unwanted interaction of the photon beam with the electrons.

The linear matrix theory can be used, to discuss the coupling of the horizontal (x, x') and longitudinal (z, z') particle oscillations [2]. Effects of the vertical plane have to be treated similarly, but are presently not discussed. A general transfer matrix m_{ij} describes the chicane plus matching sections. The longitudinal elements m_{51} and m_{52} are not independent. They are coupled to the horizontal plane, described by

$$m_{51} = m_{16}m_{21} - m_{11}m_{26}$$

and

$$m_{52} = m_{16}m_{22} - m_{12}m_{26}.$$

The coupling depends on the dispersive terms m_{16} and m_{26}. If dispersion is produced and m_{16} and m_{26} are nonzero, for example by a single dipole kick, one gets a dependency of the longitudinal position z on the horizontal plan (x, x'). Even a single dipole kick of 5 mrad generates dispersion and in turn coupling. Using the BESSY FEL parameters of a horizontal beam emittance of $0.9 \cdot 10^{-9}$ m rad one obtains a longitudinal spread of 280 nm as a result of the final beam diameter. This can not be tolerated for a proper seeding process. With the presented chicane, this coupling is cancelled, i.e. the matrix elements m_{51} and m_{52} are zero.

As the transverse beam amplitudes and the accumulated spread in chromatic phase errors stay sufficiently small, the layout of this section is done without any higher order correcting multi poles. The comparison between the simple dipole bump and this deflecting chicane shows very good agreement, as shown in the next section. For the comparison, the deflecting chicane has the same Twiss parameters β and α as the four bump chicane at the start and end points. Both sections have a m_{56} value of $6.5 \cdot 10^{-5}$. In this case the rms-beam dimensions are equal (within the numerical uncertainties due to limited number of macroparticle in the

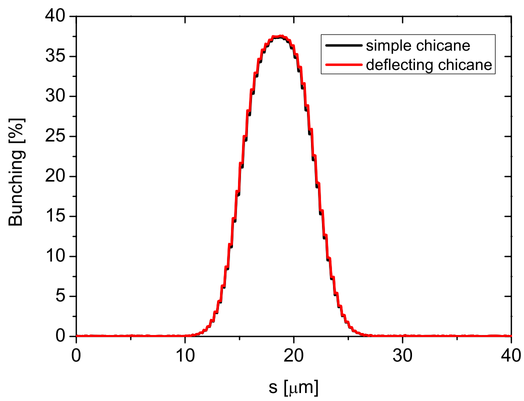

Figure 3: The bunching at the entrance of the first radiator of medium-energy FEL along the bunch for both dispersive sections. Both dispersive sections produces the optimal density modulation for the given energy modulation.

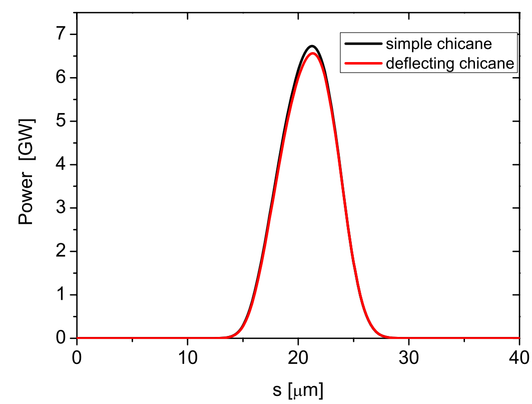

Figure 4: The radiator output power of the first stage of the medium-energy FEL for both dispersive sections. There exists a small difference between both cases, which is negligible concerning the seeding of the next section.

simulations) for both solutions, independent of the different phase advances obtained from the different approaches.

This chicane is similar to the optics of the NewSUBARU storage ring [3, 4]. It was recognized in this ring, that even a very small power supply ripple of the dipole families could limit the isochronous tuning of the optics [5]. However, this seems not to be a problem for our parameters. A deflection error of 10^{-3} in one of the dipole families leads to a two times larger error of m_{56}, which is negligible.

PERFORMANCE SIMULATION OF BOTH DISPERSIVE SECTIONS

In order to compare the performance of the new deflecting dispersive chicane with the simple four dipole chicane, the first stage of the medium-energy FEL-line of the BESSY FEL [1] was simulated for both cases. The simulations were carried out using a modified version of the simulation code GENESIS 1.3 [6] which includes a transfer matrix routine. This routine was used to model both dispersive sections at the entrance of the radiator.

The bunching at the entrance of the radiator is shown in Fig. 3 for both cases. For the given energy modulation, both dispersive sections produce the optimal spatial modulation. Fig. 4 displays the temporal power distribution at the exit of the first radiator. This radiation will be used as a seed for the next section. The difference in maximum power between both cases is negligible concerning the seeding.

The development of the horizontal and vertical electron beam size (rms) along the first radiator is shown in Fig. 5 and 6 for both dispersive sections. Because of the limited number of macroparticles that can be simulated, numerical deviations of the rms beam size of order 0.5% are expected. Therefore any deviation in beam sizes less than 0.5 % can be neglected. Obviously, there exist a small difference in

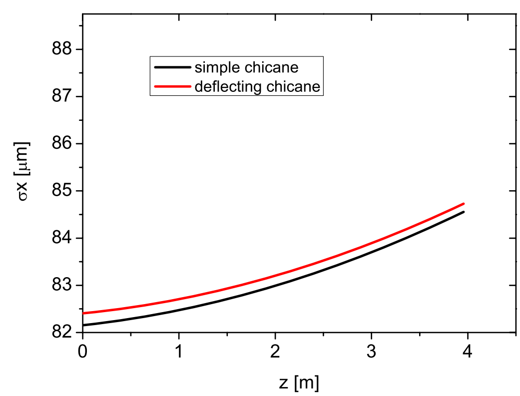

Figure 5: The development of the horizontal electron beam size (rms) along the first radiator for both dispersive sections. The difference between the beam sizes is less than 0.5 % and can be neglected.

vertical divergence for both cases of about 0.4 μ rad. This difference might also indicate small tuning differences of the two chicanes.

The above simulations were done for constant average energy along the bunch. In order to exclude undesired effects due to the energy chirp of the electron beam needed for the bunch compression [7], the simulations of both dispersive sections were repeated with an energy chirped beam. The bunching and radiator output are almost the same for both dispersive sections. The spectral purity is conserved for both dispersive sections, see Fig. 7. Due to the energy chirp, there is a shift in the wavelength [7], which is independent of the choice of the dispersive section.

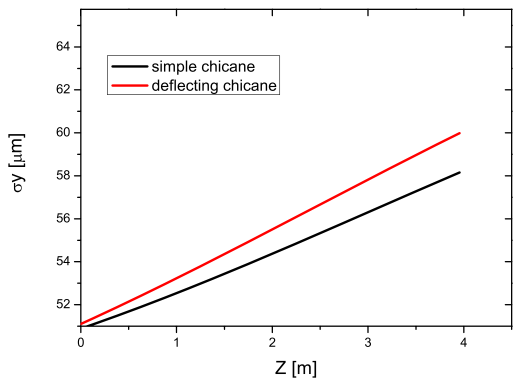

Figure 6: The development of the vertical electron beam size(rms) along the first radiator for both dispersive sections.

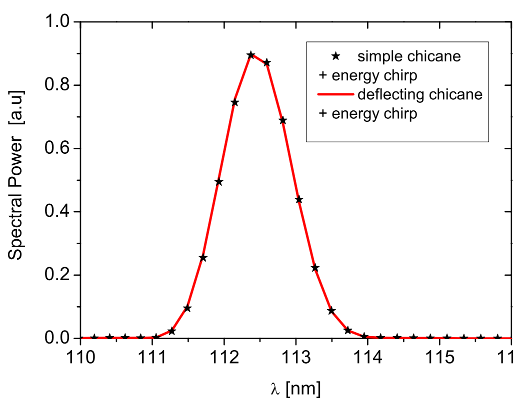

Figure 7: Spectrum of the output radiation for both dispersive sections. There is a shift in the wavelength due to the energy chirp. This is independent of the dispersive section.

CONCLUSION

Using an exact linear model an optimized dispersive section is designed for the medium-energy FEL-line, which allows the separation of the electron beam and seeding radiation without any coupling and spoiling effect. Based on the linear coupling matrix, a deflecting dispersive chicane is introduced. The comparison of the simulation results of an HGHG stage shows that the new dispersive section meets all demands.

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