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CROSSED-UNDULATOR CONFIGURATION FOR VARIABLE POLARIZED THz SOURCE

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Abstract

A variable polarized THz source employing a crossed-undulator configuration has been developed at Research Center for Electron Photon Science (ELPH), Tohoku University. An initial experiment will be demonstrated shortly using newly constructed compact planar undulators at a femtosecond short-bunch facility, t-ACTS, in ELPH. The undulators have equivalent parameters such as the period length of 8 cm and the number of periods is 7, but the field directions are crossed each other perpendicularly. The resonant frequency of 1.94 THz for the beam energy of 22 MeV. Magnetic field measurements have been already performed. The measured field strength distributions of the two undulators were mostly identical to each other. A beam transport line of variable R56 triple bend lattice intersecting the crossed-undulator configuration has been studied for phase control of interference between two radiations (namely the phase shifter). According to a tentative design of the phase shifter beam line, the degree of circular polarization may exceed 0.9 for the fundamental frequency of 1.94 THz in a narrow cone of angular spread of 2 mrad.

INTRODUCTION

Polarization control using the crossed-undulator configuration proposed by M. B. Moiseev et al. and K-J. Kim [1, 2] was firstly demonstrated by J. Bahrdt et al. on a synchrotron radiation source BESSY-1 in 1990 [3]. The crossed-undulator configuration consists with two planar undulators with magnetic fields perpendicular to each other separated by an electromagnetic modulator (we call "the phase shifter line"). The phase shifter had brought variable delay time and then the phase difference between two radiation waves was able to vary from 0 to 2π. Since a monochromator was used the two waves is coherently superposed and then any states of polarization from linear to circular in both helicities can be produced. A great advantage in this method is that first helicity switching is enable owing to small change of beam pass length in the phase shifter line, meanwhile changing magnetic field helicity in the identical helical undulator takes some considerable time even using electromagnetic undulator. In studies for handedness (chirality) in materials, the first helicity switching is pretty important because signal-to-noise ratio of circular dichroism experiment is usually very poor.

Circular dichroism spectroscopy using longer wavelength electromagnetic radiations is valuable for the studies of structural analysis of biomolecules such as proteins, nucleic acids. Since polarization control using optical elements for the solid-state/laser based THz sources is well established yet, it would be worth to consider the first helicity switching of circular polarization for accelerator-based THz source. In this sense, without monochromators, direct superposition of coherent THz radiations from the crossed-undulator configuration is a state-of-the-art solution for the biomolecular circular dichroism.

In this article, a current status of development of the variable polarized THz source at ELPH, Tohoku University.

THz CROSSED-UNDULATOR CONFIGURATION

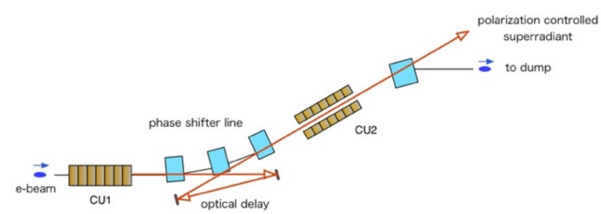

Figure 1: Crossed-undulator configuration. Path length difference between the beam and THz superradiance has to be varied in the phase shifter line. Since the e-beam transport matrix element of R_{56} should be variable for compensation of bunch lengthening due to momentum dispersion, the optical delay is controlled so as to satisfy the radiation phase difference from 0 to 2π.

Conceptual layout of the crossed-undulator configuration is shown in Fig. 1. The lower energy beam causes bunch lengthening in itself because of finite energy spread. In addition, R_{56} inside of the undulator has to be taken into account as well. So careful consideration of the phase shifter line is indispensable. At present, we have a tentative design of triple-bend beam achromat transport with small bending angle, which is better than a chicane type line. The study regarding the phase shifter beam line will be reported elsewhere [4].

Femtosecond Short-Bunch Facility, t-ACTS

At the t-ACTS (test Accelerator as Coherent THz Source) facility [5], Tohoku University, the short-pulse electron beam is stably produced via velocity bunching scheme in a traveling wave accelerating structure [6]. A specially designed independently tunable cells thermionic RF gun (ITC-RF gun) is employed to manipulate the longitudinal phase space of the beam extracted from LaB_6 cathode. The beam filtered in an alpha magnet accelerated in a 3 m S-band linac. The usual bunch length of a micro-pulse deduced from CTR spectrum measured by a Mi-

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chelson interferometer is 80 ~ 100 fs [7]. Macropulse duration is able to vary from 1 to 2 μs, so that it contains 3000 ~ 5000 micropulses (typical charge is ~ 2 pC/bunch). We have already observed 3 THz undulator super-radiance successfully. Although the maximum beam energy is 50 MeV, velocity bunching mode provides an energy of 22 MeV due to off-crest acceleration.

Crossed-Undulator

Table 1: Undulator Parameters

Magnet array	Halbach type
Block dimension	70 mm x 23 mm x 20 mm
Period length	80 mm
Number of periods	7
Magnet material	NdFeB
Residual magnetic field	1.22 T
Gap	33 mm
Peak magnetic field	0.471 T
K value	3.52

In order to demonstrate a proof-of-principle experiment, fixed-gap planar undulators for the crossed-undulator configuration were designed, in which one is for horizontal deflection (CU1) and the other is vertical one (CU2). The undulator parameters are given in Table 1. The fundamental frequency has been chosen to be ~ 2 THz because taking the bunch length and beam energy of the t-ACTS linac into account the coherent radiation around such frequencies is easily generated with no troublesome machine tuning. The number of periods is only 7 for both undulators because available space in the t-ACTS facility is limited and the first step of this study would be a proof-of-principle experiment.

For the low energy electron beam, undulator focusing powers in perpendicular direction to the deflecting plane is often disturb the quality of the radiation and the expected optics of beam transport for the experiment. The focusing power per unit length is calculated as $k = \frac{1}{2}\left(\frac{B_0}{B\rho}\right)^2$, where B_0 and $B\rho$ are the undulator peak magnetic field and the beam rigidity and obtained to be 20.6 m^{-2} for the beam energy of 22 MeV that is considerably large and then not able to ignored. Phase advance of the betatron motion along the whole undulator length is approximately π. In addition, the oscillating amplitude in the particle trajectory is not so small that another focusing power in the deflecting plane arises as well. Particle tracking simulation with a 3 D magnetic field calculation [8] was performed to evaluate the focusing powers and find matching conditions so as to make a beam waist at the centre of undulator for both planes. Deduced focusing powers in the plane perpendicular to the deflecting plane and the deflecting plane are 22.2 m^{-2} (this is consistent with the theoretical value) and -1.2m^{-2}, respectively. The matching conditions of Twiss parameter (β, α) for the non-deflecting plane and the deflecting plane were obtained to be (2.4 m, 2.6) and (2.8 m, 1.8), respectively for an entrance position of 1 m upstream of the undulator centre. Simulated trajectory of particles in the non-deflecting plane is shown in Fig. 2 for instance.

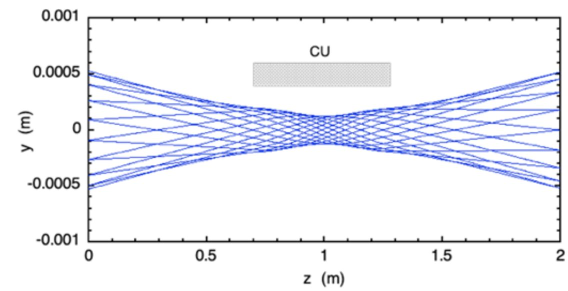

Figure 2: Symmetric beam trajectory satisfying a matched condition in the non-deflecting plane.

The undulators were manufactured and fabricated already at a Japanese industry, NEOMAX engineering Co., Ltd. Measured magnetic fields of CU1 and CU2 are denoted in Fig. 3 together with calculated one using RADIA [9] with the residual field of 1.221 T. Those field distributions are well agreed. Since the target wavelength is longer, accuracy of the field characteristics such as phase error is not critical.

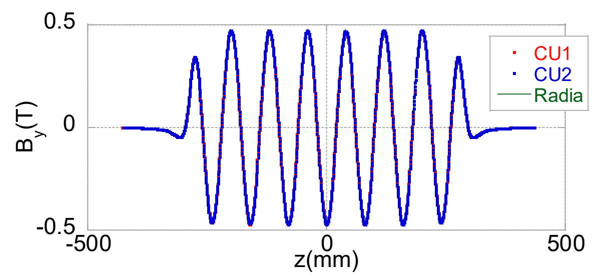

Figure 3: Measured magnetic fields in the direction perpendicular to deflecting planes of both CU1 and CU2. RADIA calculation is also plotted.

R_{56} IN THE UNDULATOR

Quality of coherent radiation from CU2 is really important for complete control of the polarization. As one notices, there seems to be some obstacles should be considered. If the 6-dimensional phase space of the beam is preserved, two radiations would be successfully composed. Coherent synchrotron radiation (CSR) would affect the transverse phase space in bending transport lines. The CSR effect is, however, able to reduce by choosing small bending angle. In this crossed-undulator configuration, a serious issue is bunch lengthening caused during passing through undulator because of lower beam energy. In order to design the phase shifter line introducing proper R_{56} that compensates that in the undulator, accurate estimation of path length difference in the undulator is required.

Using the first order approximation, the path length difference ΔL of a particle having a relative energy deviation δ is calculated as

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$$\Delta L = R_{56}\delta = = c\beta_0 t_0\left(\frac{1}{\gamma_0} - \alpha_c\right)\delta, \quad (1)$$

where the subscript 0 denotes the reference particle. The momentum compaction factor α_c is calculated as

$$\alpha_c = \frac{1}{L_0}\int_0^{L_0}\frac{\eta}{\rho}ds \quad (2)$$

It should be noted that even in a drift space R_{56} is not vanished and negligible. Figure 4 shows the path length dependence of R_{56} calculated by a tracking simulation using the realistic magnetic field. As one can see R56 is rapidly increasing than the drift space because of the dispersion function in the undulator, and bunch lengthening in the undulator is approximately 20 µm for the 1 % energy spread that is comparable to the initial bunch length. In addition, bunch lengthening in the drift space is significant as well. Consequently, the beam optics for the phase shifter line has to be carefully designed.

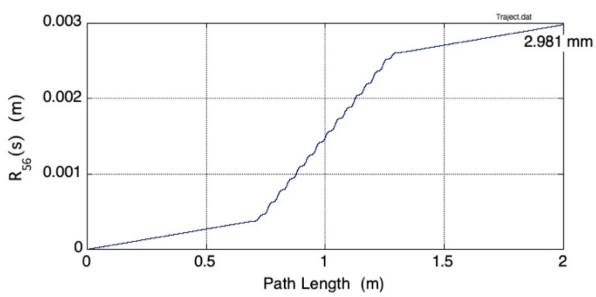

Figure 4: R_{56} variation along the beam line include the undulator. Straight lines at both sides are in drift spaces.

DEGREE OF CIRCULAR POLARIZATION

Polarization properties of the radiation is well-expressed by using Stokes parameters $S_{1\text{-}3}$ [10]. Degree of Circular polarization (*DoCP*) is expressed as $DoCP = S_3/S_0$ (= +1: right hand, = -1 left hand). Assuming complete sinusoidal electric field of the undulator radiation with angular dependence of the resonant wavelength as

$$\lambda(\theta) = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right), \quad (3)$$

After some maths angular dependence of *DoCP* is deduced to be

$$DoCP(\theta) = sin\left[\pi\frac{4k(cos\theta - 1) \pm \zeta}{2\zeta + \theta^2}\right] \times\left[1 - \frac{4k(cos\theta - 1) \pm \zeta}{N_u(2\zeta + \theta^2)}\right], \quad (4)$$

where $\zeta = \frac{1}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$ and N_u is the number of periods of the undulator. A symbol $k = \ell/\lambda_u$ and ℓ is the distance between centres of two undulators. Equation (4) is expressed for which the on-axis phase difference between two undulator radiations is tuned to a complete circular polarization. Figure 5 shows expected angular dependence of DoCP for the case of the undulator parameters in Table 1 with a beam energy of = 22 MeV and the distance is 2.6 m. Higher DoCP might be obtained at solid angle within ~ 2 mrad It should be noted that the calculation is for single-particle case. Although effects of transverse beam emittance is not estimated yet, the normalized beam emittance of the t-ACTS linac (~5 mm.mrad) is so smaller than diffraction limit of THz radiation that the effects would be limited.

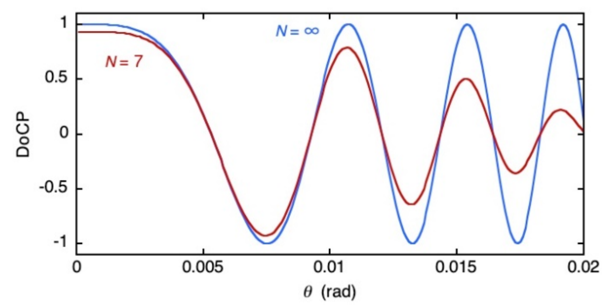

Figure 5: Calculated DoCP according to Eq. (4).

CONCLUSION

A variable polarized THz light source using a crossed-undulator configuration has been developed at Tohoku University. Currently preparation including hardware for a proof-of-principle experiment at t-ACTS facility is underway. The measured magnetic fields of undulators are in good agreement with each other. Fundamental frequency and angular spread of the radiation are estimated to be 1.9 THz and 17 mrad (HWHM), respectively. A phase shifter has been under designing work by considering bunch lengthening in whole system geometry and the undulator. Assuming the sinusoidal radiation fields, degree of circular polarization larger than 0.9 would be obtained in the solid angle of 2 mrad. Detailed study is still under way.

ACKNOWLEDGEMENT

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