A VARIABLE ELLIPTICALLY POLARIZED UNDULATOR AND ITS COHERENT THZ RADIATION

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Abstract

A new type of coherent THz light source is being built in Shanghai Institute of Applied Physics, Chinese Academy of Science. It will use the femto-second electron beam with energy of 20-30 MeV and bunch length of 200-300 fs passing through a variable elliptically polarized undulator to produce the high bright THz radiation with various linear, elliptical or circular polarizations. The undulator was designed with the Apple-II structure and has 5 periods with the period length of 100 mm and the fixed gap of 36 mm. The paper describes the design of the undulator and the simulation results for the flux density, spectrum, polarization and coherence of its THz radiation.

INTRODUCTION

Intense, coherent, polarized far-infrared (FIR) radiation can be derived from relativistic f-sec electron bunches passing through an undulator or a bending magnet. The radiance of this radiation greatly exceeds that available from conventional black body radiation or synchrotron radiation thus providing an effective new tool for FIR research [1]. In SINAP, CAS, such a new type of coherent THz light source is being built. The f-sec electron beam facility can provide the electron bunches with energy of 20-30 MeV and bunch length of 200-300 fs. A variable elliptically polarized undulator with the Apple-II structure has been manufactured and the magnetic measurement is being done. The undulator has 5 periods with the period length of 100 mm and the fixed gap of 36 mm.

The simulation calculation of the flux density, spectrum, polarization and coherence of the THz radiation has been done. The conventional method to calculate the flux density of the radiation is to use the far field approximation. But in the IR range, the observer is close to the source and the typical distances lie at about 1 m. Therefore this approximation is not valid [2]. This paper uses the general formula to calculate accurately the flux density at any collection window by an observer positioned at the limited distance from the source. The magnetic field of the undulator will use the 3D expression calculated by the analysis formulae rather than the sinusoidal function.

THE MAGNETIC FIELD OF THE UNDULATOR

Table 1 lists the main parameters of the undulator. The magnetic structure of the undulator consists of four permanent magnet arrays as shown in Fig. 1. The upper-front and lower-back magnet arrays can be moved independently along the longitudinal direction within a range of ±60 mm. Each magnet array consists of 25 blocks of NdFeB including six end blocks. The thicknesses of the end blocks are designed so as not only to make the first and the second integrals of fields (horizontal and vertical) along the axis of the undulator be zero but also to give no offset of the oscillation axis from the axis of the undulator. The total length of each array is 0.566 m. The same dimensions of the width and the height of all blocks will give more freedom in the magnet sorting procedure. The gap is fixed but the magnet holder can be adjusted within ±0.25 mm in horizontal and vertical positions by using different thickness shims for the magnetic field tuning [3]. The clearance of 1 mm between two magnet arrays, which provides the space for the magnet holder adjustment in horizontal direction, makes the field profile at the central region drop slightly.

Table1: The Main Parameters of the Undulator

Period	100 mm
Number of periods	5
Gap (fixed)	36 mm
Vertical peak field	0.59 T
Horizontal peak field	0.35 T
Peak field at circular polarization	0.30 T
Phase shift range of two magnet rows	±60 mm
Phase of horizontal linear polarization	0 mm
Phase of vertical linear polarization	±50 mm
Phase of circular polarization	±33.3 mm
Magnet block size (width × height)	40×40 mm
Wave length of horizontal linear polarized radiation	0.501 mm
Wave length of circular polarized radiation	0.269 mm

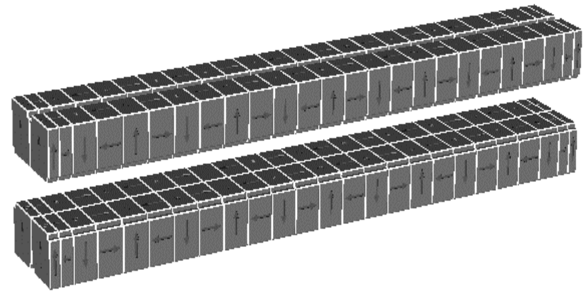
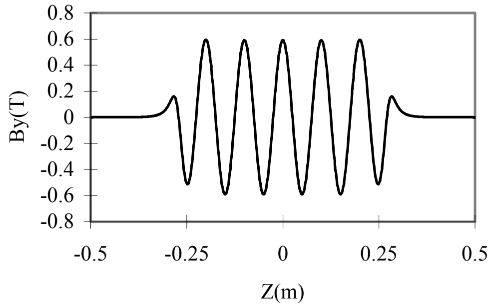
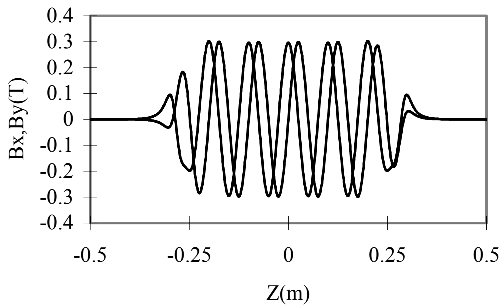


Figure 1: Four magnet arrays of the undulator.

The magnetic fields were calculated using the analysis formulae for each magnet and then linearly superposed for all the magnets. Fig. 2 shows the magnet fields on the axis of the undulator for the horizontal linear polarization mode and the circular polarization mode with the permanent field of the magnet being 1.2 Tesla.

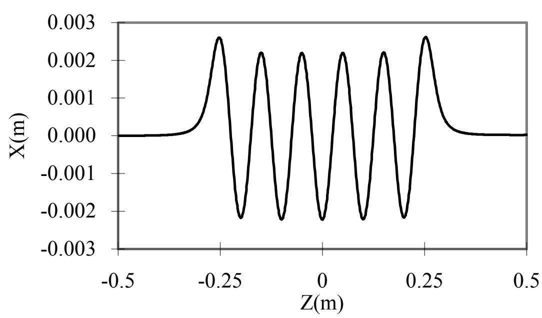


(1) Horizontal linear polarization mode

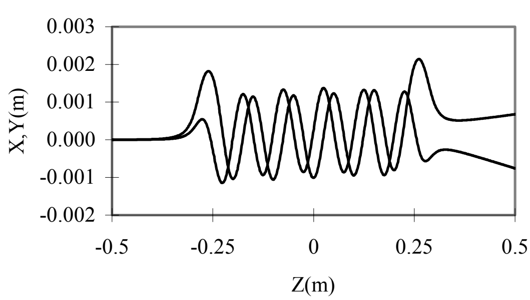


(2) Circular polarization mode

Figure 2: The magnetic fields on axis in two polarization modes.



(1) Horizontal linear polarization mode



(2) Circular polarization mode

Figure 3: The trajectories of the central electron in two polarization modes.

Fig. 3 shows the trajectories of an electron which enters the undulator along the axis with an energy of 20 MeV in corresponding modes. In the circular polarization mode, the electron moves helically with a radius of about 1.2 mm where the multiple components of the vertical and horizontal fields as well as the longitudinal field are so large that after the electron passes through the undulator it obtains an obvious transverse displacement. The trajectory simulation has been done for an electron bunch with the emmitance of about 1.5π mm.mrad and the energy of 20 MeV. It is indicated that this transverse displacement does not influence the beam transport.

CALCULATION FOR THE COHERENT RADIATION

To calculate the coherent radiation intensity of a relativistic electron bunch, the radiation from each electron of the bunch will be calculated. The total radiation from an electron bunch is the summation of the electric fields emitted by each individual electron and the total radiated energy is then equal to the square of the total electric field. The coherent radiation energy is proportional to the square rather than linear proportional to the number of radiating electron. Since there are 10^8 to 10^9 electrons in each bunch, the radiation intensity is enhanced by that same large factor over incoherent radiation. We divided a bunch of N electrons with M sub-bunches, the electrons in each sub-bunch have the same phase and are coherent completely. Then we can obtain the total energy emitted by a bunch per frequency unit per collection area positioned at distance R from the source:

$$\frac{d^2 I}{d\omega\, dA} = \frac{\varepsilon_0 c}{\pi}\left|\int_{-\infty}^{\infty}\Big[\sum_{i=}^{M}\vec{E}_i(\vec{x},t)\Big]e^{i\omega t}\,dt\right|^2 \left(\frac{N}{M}\right)^2. \quad (1)$$

Where $\vec{E}_i(\vec{x},t)$ is the electric field at point and time emitted by the i-th electron. If this electron is delayed by the distance l_i to the central electron, the field emitted by this electron will be delayed by a phase $\Delta\phi_i = -2\pi(l_i/\lambda)$, λ is the wave length of the radiation.

The electric field emitted by a relativistic charged particle submitted to any acceleration is given by [4]

$$\begin{aligned}\vec{E}(\vec{x},t) &= \frac{e}{4\pi\varepsilon_0}\left\{\frac{\vec{n}}{R^2}+\frac{R}{c}\frac{d}{dt}\frac{\vec{n}}{R^2}+\frac{1}{c^2}\frac{d^2\vec{n}}{dt^2}\right\}_{t'} \\ &= \frac{e}{4\pi\varepsilon_0}\left\{\frac{\vec{n}\times[(\vec{n}-\vec{\beta})\times\dot{\vec{\beta}}]}{(1-\vec{n}\cdot\vec{\beta})^3 Rc}+\frac{\vec{n}-\vec{\beta}}{\gamma^2(1-\vec{n}\cdot\vec{\beta})^3 R^2}\right\}_{t'}.\end{aligned} \quad (2)$$

Where $\vec{x}$ is the coordinate of the observer, t is the observer time, t' is the retarded time, $t=\int(1-\vec{n}\cdot\vec{\beta})dt'$, $\vec{R}(t')$ is the distance vector from the electron to the observer, $\vec{n}$ is its unit vector, $\vec{\beta}$ is the velocity of the electron in unit of the light speed c,

$\dot{\vec{\beta}} = (-e/m)\vec{\beta} \times \vec{B}$ is the acceleration of the electron forced by the Lorentz force, $\vec{B}$ is the magnetic field. This formula is the general expression and is accurate for photons in any energy range. When the far field approximation is included, the formula (2) can be simplified to the expression which is used for the majority of calculation for both dipole magnets and insertion devices. In our case, the general expression (2) is used.

THE SIMULATION RESULTS

Using formulae (1) and (2), we can calculate the flux density, spectrum, polarization and coherence for the radiation emitted by the electron bunch passing through the undulator. Fig. 4 and Fig. 5 are the flux density distributions of the horizontal linear polarized radiation with the wave length 501 μm and the circular polarized radiation with the wave length 269 μm. The energy of the electron bunch is 20 MeV, the charge is 50pC (the electron number is 3×10^8), the emittance is 1.5πmm·mrad, the bunch length is 200 fs. The collection distance is 1 m from the center of undulator and the collection window is 80×80mm.

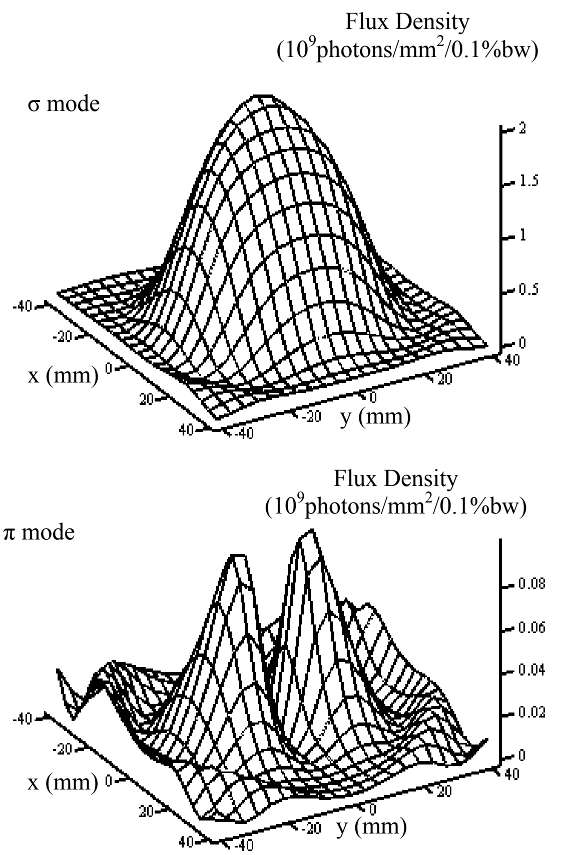


Figure 4: Flux density of the horizontal linear polarized radiation with the wave length 501μm.

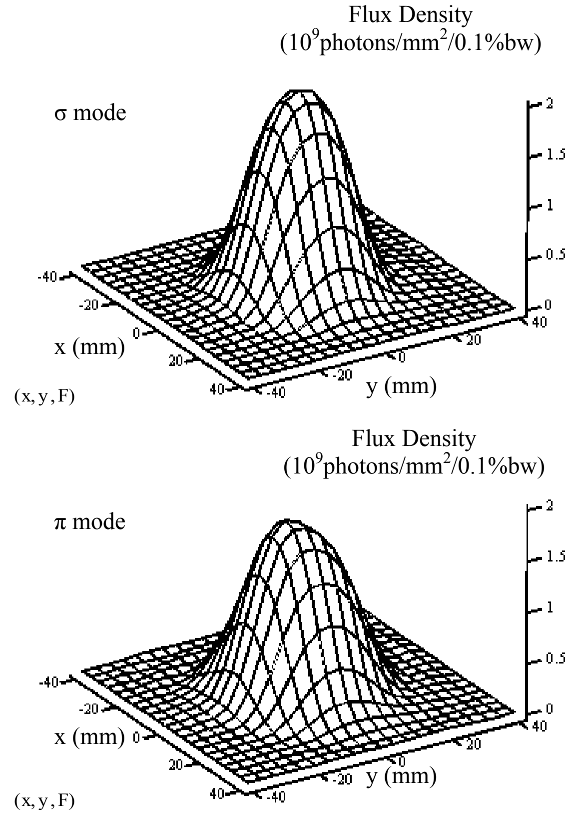


Figure 5: Flux density of the circular polarized radiation with the wave length 269μm.

SUMMARY

The undulator has been manufactured and the magnetic measurement is being done. The magnetic fields will be optimized for the horizontal linear polarization mode and the circular polarization mode by shimming within ±0.25 mm in horizontal and vertical positions. With the femto-second electron bunch of low energy it can produce the high bright THz radiation with various linear, elliptical or circular polarization. The simulation results show that for the electron bunch with the energy 20MeV, the emittance 1.5πmm·mrad, the bunch length 200fs and the electric charge 50pC, the THz radiation with the horizontal linear polarization or the circular polarization of the maximum flux density of 2×10^9 photons/mm^2/0.1%bw can be obtained at the distance 1m from the center of the undulator with 0.6m long.

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