DESIGN CALCULATION ON BEAM DYNAMICS AND THz RADIATION OF DELHI LIGHT SOURCE*

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Abstract

The development of a compact light source facility, Delhi Light Source (DLS), based on pre-bunched Free Electron Laser has been initiated at Inter University Accelerator Centre (IUAC) [1-3]. A photocathode based normal conducting RF gun will generate a low emittance 'comb' electron beam with a maximum energy of ~8 MeV, which when injected into a 1.5 metre compact undulator magnet (~0.4 < K_{rms} < ~2) will produce intense THz radiation in the frequency range of 0.15 to 3.0 THz. There will be provision to vary the spatial separation between the successive microbunches of the electron beam so that by varying the Undulator magnetic field and/or electron energy, the THz frequency can be tuned. The detailed information of the radiation to be generated from the facility along with the optimized beam optics results will be presented in the paper.

INTRODUCTION

Delhi Light Source (DLS) is a project initiated by Inter University Accelerator Centre to develop a compact THz radiation facility based on the principle of prebunched Free Electron Laser [1-3]. The facility will consist of a fibre laser system to generate 'comb' laser pulses with variable separation in frequency range of 0.15 to 3 THz which will be incident on the photocathode (Cu or Cs_2Te) to generate the electron micro-bunches. The electron beam generated from the photocathode will be accelerated by the normal conducting 2.6-cell copper cavity to produce an electron energy of ~8 MeV.

In this paper, we discuss the simulation results of generation of e-beam microbunches from the photocathode and its evolution through the beam line. General Particle Tracer [4] was used to track the electron beam from the photocathode to the exit of the undulator. The characteristics of the THz radiation to be produced from the wiggling electrons through the undulator was studied numerically by solving the Lienard-Wiechert fields for ensemble of charged particles, moving relativistically under the combined influence of the interaction fields and the undulator fields.

PRINCIPLE OF OPERATION OF DLS

The first phase of DLS is intended to produce THz radiation in the wavelength range of 0.15 to 3 THz. To reduce the cost and complication of the project, it was decided to design a compact facility with maximizing the peak electron current and peak intensity of radiation within a time width of a few hundreds of femtoseconds. This challenging goal can be achieved by producing thin slices of electrons called microbunches and then producing a train of those microbunches with a variable separation equal to the wavelength of the frequency range by varying the separation of the laser pulses. If the bunch length of the individual microbunches in the electron beam is extremely small with respect to the radiation wavelength, then the emitted radiation from individual electrons is added up in phases resulting in maximum radiation intensity and the bunches are called "super-radiant" [5]. Further, if each microbunch is super-radiant and inter microbunch separation is maintained at one radiation wavelength, then the radiation from each microbunch will be coherently added and the intensity will be proportional to the square of the total number of electron in e- beam. The total electric field [6] from the train of microbunches will be given by the following summation where k is the microbunch number, N_m is the total number of the microbunches, t_0 is the observation time for the radiation pulse from first microbunch and t_k is the temporal separation of the kth microbunch from the first microbunch. Since $\exp\left(-i\omega(t_0+t_k)\right)$ is a periodic function and $\exp\left(-i\omega(t_0+t_k)\right) = \exp(-i\omega t_0)$ if $t_k = T_{\mathrm{radiation}}$; therefore; the equation for total electric field will be reduced to $E_{\mathrm{total}} = E_0 N_m N_e B_w$ where B_w is called bunching factor and the intensity will scale as $I \sim E_0^2 N_m^2 N_e^2 B_w^2$. Thus, pre-bunching should result in enhancement of the emission spectral energy for the frequency to be generated [5].

BEAM OPTICS SIMULATIONS

The beam optics simulations have been performed by using the GPT code and it includes the generation of the electron beam at the photocathode, its acceleration through the 2.6 cell RF cavity, transportation of the beam from the exit of the RF cavity up to the undulator exit with help of a solenoid magnet and a quadrupole magnet. To improve the quality of the e-beam, the simulation calculations have been performed a) to reduce the size, energy spread and emittance of the beam b) to maximize the bunching factor of the beam and c) to avoid the overlapping of the microbunch structure of the beam bunches starting from undulator entrance to exit. The beam optics calculations have been done with radial beam and important simulation parameters are given in Table 1.

The e- beam profile in x and y direction for the two extreme frequencies of 0.15 and 3THz from the photocathode

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up to the exit of undulator is shown in Figure 1. The microbunch structures at the entrance of the undulator for 16 and 2 microbunches (corresponding to 3 and 0.15 THz respectively) are shown in Figure 2. The bunching factor for 16 microbunches (3 THz) is shown in Figure 3. During simulation calculations, the parameters of the electron beam, the solenoid and quadrupole field are adjusted to maximize the bunching factor and to reduce the merging effect of the electron microbunches at the undulator's entrance.

Table 1: Parameters for DLS at Undulator's Entrance

Radiation Frequency (THz)	0.15	3
No. of microbunches	2	16
Charge per microbunch (pC)	15	15
Accelerating field (MV/m)	58.5	110
Energy (MeV)	4	8
Energy spread (%)	1.1	0.43
FWHM (fs)	~750	~ 200
$\sigma_{y,x}$ (mm)	0.19, 0.25	0.175, 0.275
Emittance, $\varepsilon_{x,y}$ (π mm-mrad)	3.7, 0.04	0.2, 0.01
Avg. separation	6.6 ps	345 fs
Peak current (A)	20	75

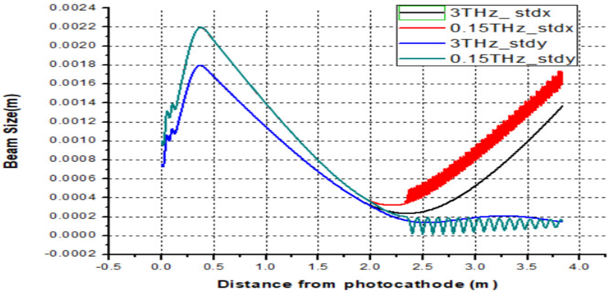

Figure 1: Electron-beam size from photocathode to undulator's exit.

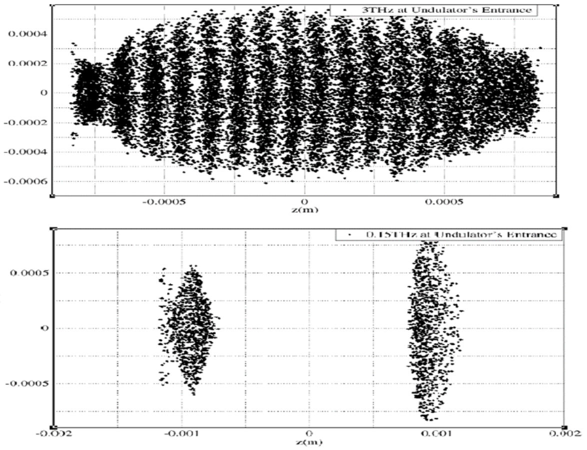

Figure 2: Beam profile for 3 THz (top) & 0.15 THz (bottom) at undulator's entrance.

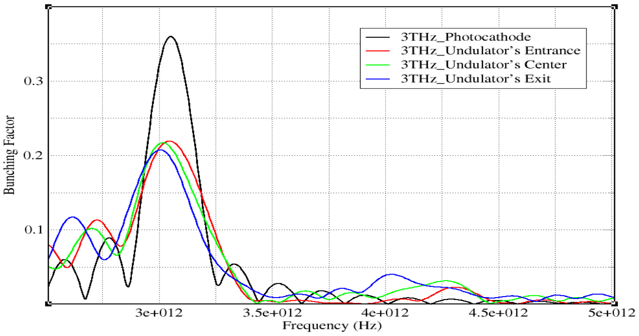

Figure 3: Bunching factor at different beamline positions.

SIMULATION CALCULATIONS OF TERAHERTZ RADIATION

The simulated electron bunch structure at the undulator entrance obtained from GPT code was used to simulate the radiation fields. An in-house code based on C++ was developed to perform the radiation simulation. In this code, the radiation fields are simulated by solving the Lienard-Wiechert fields for a point particle, given by the following equations [7]:

$$\boldsymbol{E}(r,t) = \frac{q}{(4\pi\epsilon_0)}\left(\frac{\boldsymbol{n}-\boldsymbol{\beta}}{\gamma^2(1-\boldsymbol{n}.\boldsymbol{\beta})^3|\boldsymbol{r}-\boldsymbol{r}_s|^2} + \frac{\boldsymbol{n}\times((\boldsymbol{n}-\boldsymbol{\beta})\times\dot{\boldsymbol{\beta}})}{c(1-\boldsymbol{n}.\boldsymbol{\beta})^3|\boldsymbol{r}-\boldsymbol{r}_s|}\right)_{t_r}$$

$$B(r,t) = \frac{\boldsymbol{n}(\boldsymbol{t_r})}{c}\times\boldsymbol{E}(r,t)\ ,$$

where $\boldsymbol{n}$, $\boldsymbol{\beta}$, $\dot{\boldsymbol{\beta}}$, $\boldsymbol{r}-\boldsymbol{r}_s$, are the unit vector pointing from source of radiation to the observation point, velocity of the particle, acceleration of the particle and the distance of the observation point from the source of radiation respectively. In the code, the particles are loaded and tracked through the undulator's field using Vay Algorithm [8]. The entire history of the trajectory and information like velocity, momentum, acceleration and position of the particles are recorded. In order to calculate the fields, firstly the retarded time at which the radiation was emitted is calculated and then the relative distance (between source of radiation and observation point), velocity and acceleration of the particle are evaluated at that retarded time. In present simulations, the interaction between the electrons and the electron-radiation have been ignored.

Table 2: Undulator Parameters Used for THz Calculations

undulator		freq. (THz)	e-energy (MeV)	K	Bu (T)
length (m)	period (mm)	0.15	4	2.802	0.69
1.5	50	3	8	0.467	0.1

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The radiation wave train was calculated for on-axis distance of 3.5 m from the exit of the undulator (Table 2) and the growth of the radiation emitted from the 16 microbunches is shown in Figure 4. The scope of the paper limits the discussion to 3 THz only. As explained earlier, the linear growth in the field amplitude is because of the in-phase addition of the radiation wave packets from different microbunches. The growth in the first few period is slow because the first few microbunches in the microbunch structure (see Figure 2) is "washed out"; resulting in incoherent emission from these bunches. Figure 5 shows the spectrum obtained after doing a Fast Fourier Transform of the field obtained in Figure 4 with a sharp peak at 3 THz.

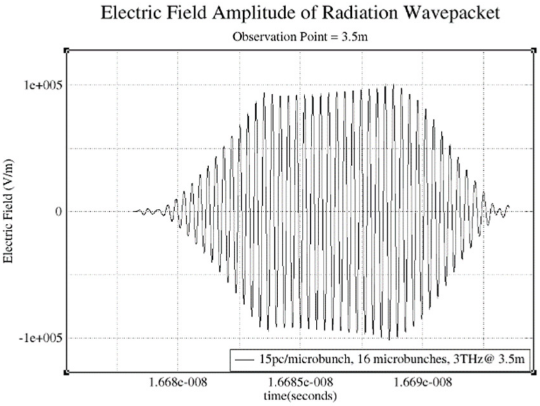

Figure 4: Electric field variation in a radiation wave packet observed on axis at 3.5 m from undulator's exit.

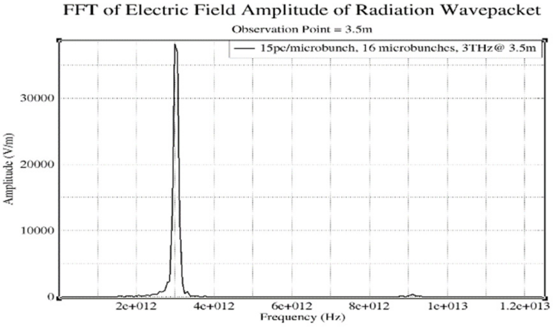

Figure 5: Spectrum of the radiation wave train emitted by 16 microbunches.

An important point to consider for DLS system is the transverse radiation beam profile. The radiation beam profile for 3 THz was evaluated at 0.5 m away from the undulator's exit, a transition point between the smaller size of beam pipe to a larger size where the radiation propagation can be treated as a free space propagation. The beam pipe to be installed inside the undulator will be 40 mm(x) × 20 mm(y). In order to cover the entire frequency range, the minimum gap required between the two jaws of undulator is 20 mm; which limits the maximum size of rectangular beam pipe in y-dimension. However, Figure 6 (left) suggests that the beam size will be comparable to the beam-pipe dimensions. Therefore, it is expected that the radiation envelope will undergo multiple reflections on the walls of the beam pipe. This effect was simulated and it was observed that due to the reflections from the wall, the radiation envelope at the exit of undulator's beam pipe will be somewhat "squeezed" in the y-dimension (see Figure 6-right). Radiation beam profile obtained on the 30 mm × 30 mm grid was used to first find the Poynting vector and then integrated with respect to time and area to find the total pulse energy. The calculation shows that the total energy contributed from 16 microbunch train at 0.5 m from the undulator's exit is 12 micro-joules for 3 THz.

CONCLUSION

In the paper, the feasibility study of generating prebunched e-beam by manipulating the laser pulses incident on the photocathode is reported. For the case of 3THz, the simulation calculation shows that a bunching factor of the 16 microbunch train can be maintained to a value of ~ 0.2 from the entrance to the exit of the undulator. The output radiation waveform for 3THz shows that the radiation wave packet emitted from trailing microbunches interfere constructively with the radiation wave packets emitted by leading microbunches and the radiation field grows linearly (Figure 4). The study of the transverse beam profile and the effect of beam-pipe inside the undulator on the beam profile suggests that there will be some distortion due to the beam pipe. It is expected that this effect will be dominant for longer wavelength.

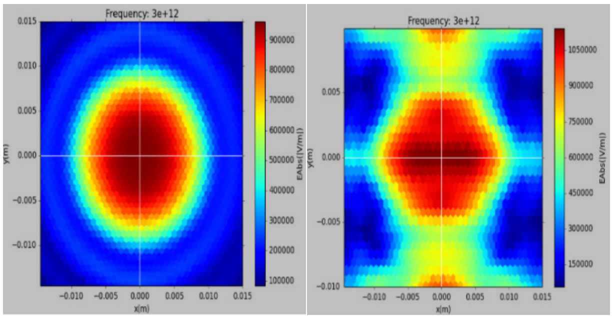

Figure 6: 3 THz: Transverse beam profile (left) and effect of beam pipe on the beam profile (right).

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