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SIMULATION CALCULATIONS OF COMPACT THz FACILITY AT IUAC, NEW DELHI

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Abstract

A compact THz radiation source based on the principle of pre-bunched Free Electron Laser is at the commissioning stage at Inter University Accelerator Centre (IUAC), New Delhi. The facility will generate low emittance train of electron micro-bunches (2, 4, 8 or 16 numbers) from a RF photocathode gun in the energy range of 4 to 8 MeV and inject into a compact undulator to generate coherent THz radiation in the frequency range of ~ 0.18 to 3.0 THz. To optimise the intensity at a given frequency, the beam bunching factor and the betatron oscillation amplitude in the non-wiggling plane of the electron micro bunches inside the undulator has been maximized and minimized respectively. The paper presents the optimized beam optics simulation results for two frequencies viz 0.5 and 2 THz. The on-axis radiation spectral intensity computed by in-house developed code using the trajectory data of the beam optics simulation is also presented for the two frequencies.

INTRODUCTION

To cater to the growing research interest using THz radiation, a compact and intense THz facility is being commissioned at IUAC, New Delhi. The facility named as Delhi Light Source (DLS) will generate coherent radiation in the frequency range ~ 0.18 to 3.0 THz by injecting electron micro-bunches (2, 4, 8 or 16 in number) in the energy range of 4 to 8 MeV into a compact undulator [1,2]. The beamline consisting of a 2.6 cell 2860 MHz RF photocathode (PC) gun, an emittance compensating solenoid, a quadrupole singlet and an undulator at a distance of ~ 2.3 m from the PC is shown in Fig. 1. Presently the RF gun conditioning is going on and the first signature of electron beam in the form of dark current has been recorded [3].

To achieve coherence and tunability, micro bunches (with FWHM ≤ 200 fs at photocathode) with separation adjusted to match the wavelength corresponding to a given beam energy and undulator field setting, will be injected into a planar undulator having specifications given in Table 1 [4]. The corresponding wavelength is given below by the undulator equation

$$\lambda_{rad} = \frac{\lambda_{un}}{2\gamma^2}\left(1 + K_{rms}^2\right) \qquad (1)$$

where, $K_{rms} = 0.66 B_{un}[\mathrm{T}]\lambda_{un}[\mathrm{cm}]$ is the rms undulator parameter, λ_{un} the undulator period, γ the dimentionless energy and B_{un} the undulator magnetic field.

The paper presents the optimizations in the beam optics simulation performed using GPT [5] at two frequencies viz. ~ 0.5 THz and ~ 2.0 THz using 4 and 8 micro-bunches respectively. The computation and the results of the on-axis

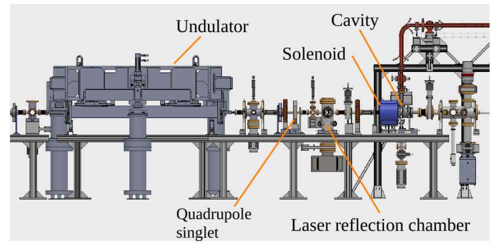

Figure 1: The beamline design of DLS upto undulator.

Table 1: Undulator Specifications

Parameter	Description
Technology	PPM
Periods	33
Period length	48 mm
Magnetic length	1 584 mm
Gap range	16 mm - 45 mm
Peak field	0.61 T - 0.12 T
K parameter (rms)	1.932 - 0.38

spectral intensity of the two frequencies using the particle trajectory data from the beam optics simulations is also presented.

BEAM OPTICS SIMULATIONS

The beam optics optimizations has been aimed to minimize line width and maximize the spectral intensity of the THz radiation.

Line width can be minimized primarily by proper beam matching at the undulator entrance in the non-wiggling plane along with keeping the energy spread to as minimum possible. A matched beam at the undulator entrance minimises the betatron oscillation amplitude, thus minimizing the undulator main field variation seen by the beam in the non-wiggling plane. The beam matching is achieved by tuning the solenoid in combination with a quadrupole singlet.

The spectral intensity is expressed by the following relation given below [6]

$$I \propto N_m N_b^2 B_0^2(\omega) \qquad (2)$$

where, N_m is the number of micro-bunches, N_b is the number of electrons per microbunch and $B_0(\omega)$ is the bunching factor (BF) of the macro bunch at angular frequency ω. The BF is defined as the Fourier transform of the bunch longitudinal distribution and expressed as [7]

$$B_0 = \frac{1}{N}\sum_{j=1}^{N} e^{i\omega t_j} \qquad (3)$$

where, N is the total no of particles in the distribution, ω

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is the frequency of interest and t_j is the position of the j^{th} electron in time scale.

Since spectral intensity is proportional to the square of BF, maximising the BF becomes important in achieving good coherence. The BF can be maximized by optimizing the micro-bunch separation, beam transverse size at photo-cathode and focussing field of the solenoid and quadrupole singlet for a given charge and temporal width. The quadrupole singlet serves to reduce the space charge force acting within a micro-bunch and also between them by transverse redistribution of the particles (defocussing in the wiggling plane).

Table 2 lists some important simulation parameters for 0.5 THz and 2 THz respectively. The plots of transverse rms

Table 2: Simulation Parameters

Parameter	~ 0.5 THz	~ 2.0 THz
Charge/micb	15 pC	15 pC
No. of micb	4	8
rms transverse size @PC	9 mm	11 mm
rms temporal size @PC	85 fs	85 fs
micb separation @PC	2350 fs	626 fs
particles/micro-bunch	10000	10000
Beam energy	6.44 MeV	8 MeV
rms energy spread @ und.	36.5 keV	30 keV
Cavity field	88 MV/m	110 MV/m
Injection phase	30°	30°
undulator field	0.6 T	0.273 T

beam size variation from the PC up to the undulator exit (~ 3.88 m) is shown in Fig. 2(a) and 2(b) for the case 0.5THz and 2 THz respectively. The beam rms size is optimized to ≤ 0.2 mm in the non-wiggling plane for both the cases. Figure 2(c) and 2(d) shows the bunching factor spectrum at the undulator and also its variation through the undulator at the respective frequencies.

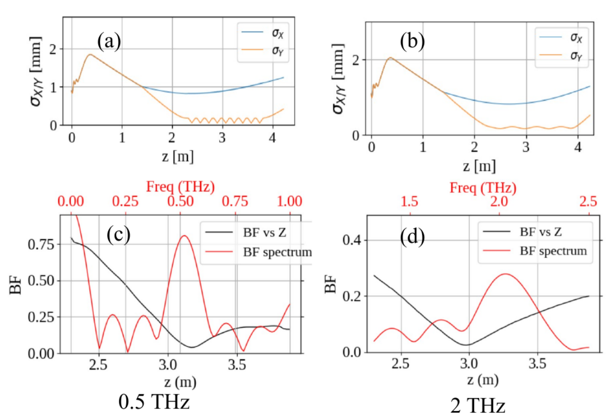

Figure 2: Simulation result for 0.5 and 2 THz showing the (a, b) transverse rms beam size variation and (c, d) the BF spectrum (in red) at undulator and the BF variation through the undulator at said frequency.

The optimization of BF is gauged from the area under BF vs Z curve at the frequency of interest computed as

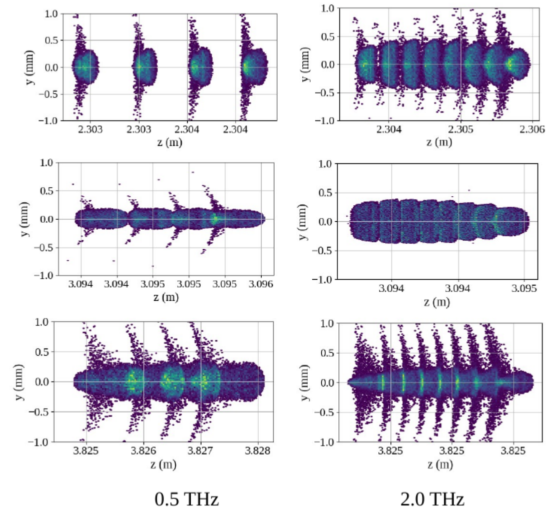

Figure 3: For the two frequencies the longitudinal profile at (TOP) undulator start, (MID) undiulator middle and (BOTTOM) at undulator exit.

$Ar\_BF(\omega) = \sum_z B_0(z, \omega)\Delta z$. The optimization is achieved by adjusting the micro-bunch separation. In both the cases of BF vs Z plot, a dip in the BF is present inside the undulator, which can be realized from the longitudinal particle distribution through the undulator. Figure 3 shows the distribution at undulator start (~ 2.3 m), middle (~ 3.09 m) and exit (~ 3.8 m), where it is seen that the distribution appears highly diffused at the undulator middle which explains for the dip in the BF variation with Z.

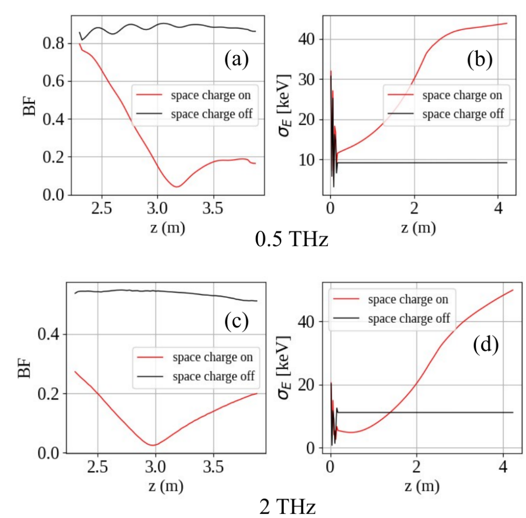

Figure 4: For the two frequencies, the variation of BF through undulator (a,c) and the energy spread variation (b,d) simulated with and without space charge.

To further infer the observation, the simulation was repeated with space charge put off and the results of BF vs Z and the energy spread variation is compared for the two cases at the two frequencies in Fig. 4. It is seen that the with space charge off the dip is absent and the energy spread is also less by a factor of ~ 4. It can thus be inferred that space charge

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introduces a dynamic energy spread in the micro bunches as well as in the macro bunch structure, due to which the micro bunches undergoes a dispersive motion in the undulator field which is strong enough to longitudinally expand the micro bunches. The outward moving particles of adjacent micro bunches on approaching close for overlap, tends to repel which slows down their relative opposite motion to form a cluster giving rise to an ordered distribution again.

RADIATION CALCULATION

To compute the radiation field and intensity, the position $\vec{r}_e(x, y, z, t)$ and velocity $\vec{\beta}(\beta_x, \beta_y, \beta_z, t)$ data of the particles at the simulation time steps was used. First the radiation electric field pulse was computed at an observer point $\vec{r}_{ob}$ in advanced time t_{ad} using the field equation [8]

$$\vec{E}(\vec{r}_{ob}, t_{ad}) = \frac{q}{4\pi\varepsilon_0}\left[\frac{(\vec{n}-\vec{\beta})}{R^2\gamma^2(1-\vec{\beta}.\vec{n})^3} + \frac{\vec{n}\times\left[(\vec{n}-\vec{\beta})\times\dot{\vec{\beta}}\right]}{cR(1-\vec{\beta}.\vec{n})}\right] \quad (4)$$

where, $t_{ad} = t + \frac{|\vec{r}_{ob}-\vec{r}_e(t)|}{c}$, $\vec{R}(t) = \vec{r}_{ob} - \vec{r}_e(t)$ and $\vec{n} = \frac{\vec{R}}{|\vec{R}|}$. The fields were then interpolated at equidistant advanced time grids to have the radiation field pulse. The field in frequency domain $\vec{\varepsilon}(\omega)$ was then obtained by Fourier Transform of the time domain field [9]. With the computed field $\vec{\varepsilon}(\omega)$ the radiation spectral intensity was computed using the relation [8]

$$\frac{d^2 I}{d\Omega d\omega} = 2.|\vec{\varepsilon}(\omega)|^2 \quad (5)$$

Codes written in FORTRAN were used to compute the on-axis field pulse and the spectral intensity which is shown in Fig. 5 for the two frequencies.

The dip in the envelope of the field pulse of the two frequencies is a consequence of the diffusion and re-formation of the micro-bunch structure discussed in the last section. The two close-by peaks in the spectrums shows that the micro bunch structure before and after diffusion have slightly different micro bunch separation.

The frequency positions of the peaks can be fine tuned by adjusting the initial micro bunch separation at the photo cathode. The energy content/FWHM of the taller peak for the two cases are obtained as 3.88 μJ with FWHM 0.0122 THz (at 0.476 THz) and 22.44 μJ with FWHM 0.043 THz (at 1.953 THz) respectively. The corresponding values of the peak power are 50.4 kW and 1.12 MW respectively.

CONCLUSION

The beam optics optimization simulation done using GPT code for 0.5 THz and 2 THz using 4 and 8 micro bunches respectively, for optimizing the radiation output has been discussed. The betatron oscillation amplitude in the undulator, minimized by tuning the solenoid and quadrupole singlet, and the bunching factor maximised by adjusting the micro bunch separation to improve the radiation quality has been presented along with the results. The appearance of a dip in the BF plot is also analysed and explained.

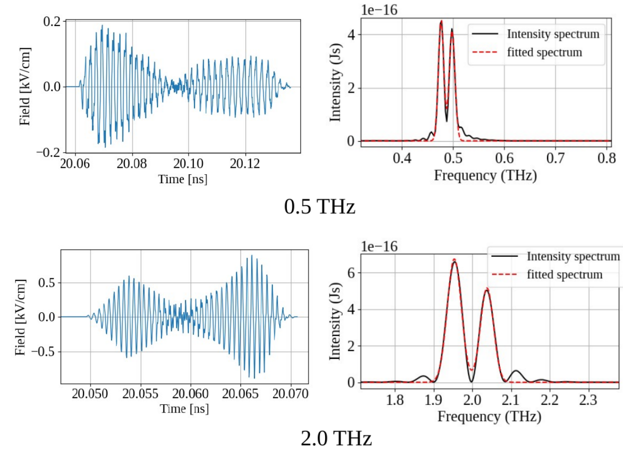

Figure 5: For the two frequencies the on-axis (LEFT) THz radiation field pulse and (RIGHT) on-axis spectral field and intensity plot.

The computation of the THz field pulse and the spectral intensity done by in-house written codes using the particle trajectory data is shown along with the peak powers calculated from the results.

The results will be useful to gain insight and estimate the power of THz radiation when the facility gets operational.

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