PRELIMINARY DESIGN OF THE PROPOSED IR-FEL IN INDIA

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Abstract

We discuss preliminary design studies of an infrared (IR) free-electron laser (FEL) proposed to be built at the Raja Ramanna Centre for Advanced Technology (RRCAT). The design calculations and optimisations have been performed using the three-dimensional time-dependent oscillator code GINGER [1].

INTRODUCTION

A terahertz free electron laser, the CUTE-FEL, designed to lase around a wavelength of 80 μm using a 10 MeV linac is in an advanced stage of construction at RRCAT [2]. In the next step in our FEL activities, we have proposed to build an IR-FEL. In this context, we have performed design studies of an IR FEL to lase between 12-50 μm, which will use a 15-25 MeV linac. In this paper, we focus mainly on 30 μm simulations and briefly discuss the results at 12.5 μm and 50 μm also. The high power, short pulse and widely tunable coherent radiation from this IR-FEL can be used for performing a wide range of interesting research applications that include experiments on direct as well as indirect band-gap semiconductors, IR microscopy of biological samples, multi-photon dissociation experiments, isotope separation, reaction dynamics studies, etc.

In the next section, we discuss the basic design considerations and then in the following section, we discuss design simulation results. We finally conclude in the last section.

DESIGN CONSIDERATIONS

After preliminary consultaions with users, we found that a wavelength range of 12-50 μm is interesting for a wide range of many interesting experiments. Using a 15-25 MeV electron beam from an electron linac, and an undulator having period (λ_u) of 40 mm and undulator parameter K in the range 1-2, it should be possible to cover this wavelength range, as can be seen from the following formula:

$$\lambda_R = \frac{\lambda_u}{2\gamma^2}(1 + \frac{K^2}{2}), \quad (1)$$

where λ_R is the radiation wavelength, γ is the electron energy in units of its rest mass energy and $K = eB_u\lambda_u/2\pi mc$, B_u is the peak undulator field, m is the rest mass of electron and c is the speed of light. Note that we have chosen maximum value of $K = 2$ such that we get a wavelength tunability up to a factor of two by varying K in the range 1-2. We will use a Halbach configuration of pure permanent magnets for the undulator, where the dependence of peak magnetic field on the gap g between the jaws of the undulator is given by[3]

$$B_u = 1.43 B_r \exp(-\pi g/\lambda_u). \quad (2)$$

Here B_r is the remanent field of the permanent magnet used in the undulator. Using B_r = 1.2 T for NdFeB magnets, we obtain the gap to be 15 mm for $K = 2$. We therefore will need to use an undulator vacuum pipe having inner diameter (ID) of 11 mm.

The number of undulator periods N_u is chosen to be 60 on the basis of gain considerations. The 2.4 m long undulator will be immersed in a 4.1 m long optical cavity. The undulator will be asymmetrically placed in the optical cavity such that we have 1.05 m of space available for beam transport and diagnostic on the upsteam side and 0.65 m of space available on the downstream side. Assuming a Rayleigh range of 0.8 m, which is one third of the undulator length, the rms optical beam size at the waist is 1.4 mm. We therefore chose the rms electron beam horizontal size σ_x at the waist to be around 1 mm for good overlap with the optical beam. The rms electron beam size σ_y in the vertical direction is taken to be the matched beam size in the undulator given by [3]

$$\sigma_y = \sqrt{\frac{\epsilon_n \lambda_u}{\sqrt{2}\pi K}}, \quad (3)$$

where ϵ_n is the normalized rms electron beam emittance. We choose ϵ_n = 30 mm-mrad for our design calculation.

For the electron beam, we will use a micropulse charge in the range 0.2-0.5 nC. The electron beam rms pulse width is taken to be 4 ps and the relative rms energy spread is taken to be 0.5%. These parameters are easily acheivable. In the next section, we present the results of design simulations.

DESIGN CALCULATIONS

For performing the design simulations, we have used the FEL code GINGER [1], a multidimensional [full 3D for macroparticles and 2D ($r - z$) for radiation], time-dependent code to simulate the FEL interaction in single-pass amplifier as well as oscillator configurations. GINGER utilizes the KMR [4] wiggle-period-averaged electron-radiation interaction equations and the slowly-varying envelope approximation (SVEA) in both time and space for radiation propagation. For propagation outside the undulator for oscillator problems, the code uses a Huygens integral method. Shot noise is modeled by giving a controlled amount of randomness to the initial longitudinal

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phases of macroparticles; the algorithm [5] generates the statistically-correct shot noise at the fundamental as well as at harmonics.

The design parameters of the IR-FEL are given in Table 1. For the 30 μm simulations reported here, we have used γ = 45.25. We first performed the time-independent simulation using the code TDAOSC [6] which is an oscillator version of the code TDA [7]. For the parameters mentioned in Table 1, we obtained the single pass, small-signal gain of 135%, saturated cavity power of 9.8 MW and hole out-coupled power of 2.0 MW. The resonator parameters were optimized using TDAOSC and we obtained optimum performance for the Rayleigh range of 0.8 m and the location of the waist in the middle of the optical cavity. The optical mode profile at both the mirrors and the entrance of the undulator is shown in Fig. 1. We find the modes are nearly Gaussian.

Table 1: Design parameters used in the simulation

Electron beam energy (E)	22.6 MeV
Peak beam current (I)	20 A
RMS energy spread (σ_γ/γ)	0.5%
RMS normalised emittance	30 mm-mrad
RMS pulse width (σ_z)	1.2 mm
Micropulse rep. rate	36.62 MHz.
RMS e-beam size (σ_x, σ_y)	0.37 mm, 1.00 mm
Electron macropulse width	8 μs
Undulator period (λ_u)	40 mm
Peak und. parameter (K)	2.0
Undulator length ($N_u\lambda_u$)	2.4 m
Undulator gap	15 mm
Beam pipe diameter	11 mm (ID)
Radiation wavelength (λ_R)	30 μm
Optical cavity length	4.1 m
Location of down mirror	65 cm from und. exit
Location of up mirror	105 cm from und. entr.
Mirror radii of curvature	2.36 m (d), 2.36 m (u)
Mirror reflectivity (power)	99%
Hole radius in down. mirror	2 mm

Next, we performed time-dependent simulations using GINGER. We simulated the time-structure of the electron bunch as Gaussian with rms width of 4 ps. A time window of six times the rms width has been used for simulating the electron bunch, which is discretized into 60 electron slices, the separation between slices being 4 radiation wavelengths. A total number of 96 such radiation slices were used in the simulation. We studied the effect of cavity length detuning on the performance of the FEL. Fig. 2 shows the dependence of out-coupled power on cavity length detuning ΔL_c. Here, ΔL_c is defined as the reduction in the cavity length compared to the synchronized length. We find that the optimum performance is obtained at ΔL_c = 27 μm. We used this value for further simulations

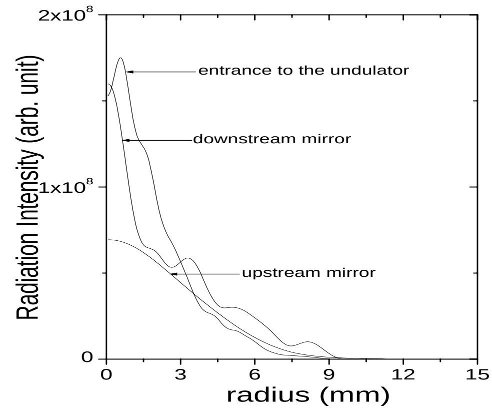

Figure 1: Mode profile of the radiation beam at different locations as indicated in the figure.

done at this wavelength.

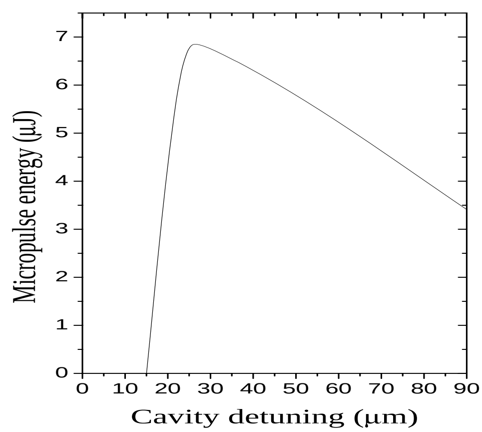

Figure 2: Energy in the out-coupled micropulse as a function of cavity detuning.

Next, we studied the growth of power starting from shot noise, which is shown in Fig. 3. The saturated intracavity average power is 5 MW, where averaging is done over effective electron pulse width, which is approximately 2.5 times the rms width for a Gaussian bunch. As seen in Fig. 3, it takes around 150 round trips for the power to saturate. This means that the start-up time is around 4 μs since cavity length is 4.1 m.

The time structure of the out-coupled power is shown in Fig. 4. We find that the peak out-coupled power is 1.35 MW and the total energy in the micropulse is 6.9 μJ.

We thus find that assuming a modest set of design parameters mentioned in Table 1, it should be possible to lase and generate around 1 MW of peak out-coupled power at 30 μm. We have also performed preliminary simulations at 12.5 μm and 50 μm and found that the lasing is possi-

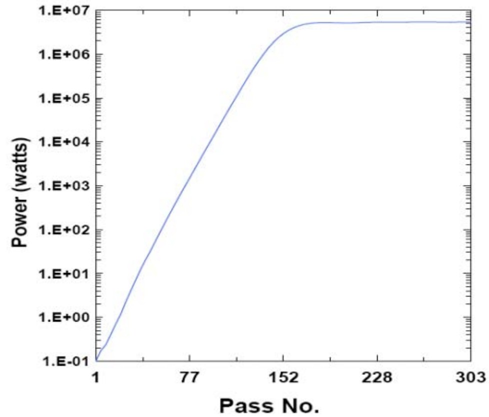

Figure 3: Growth of average intracavity power from noise. Parameters used in the simulation are given in Table 1.

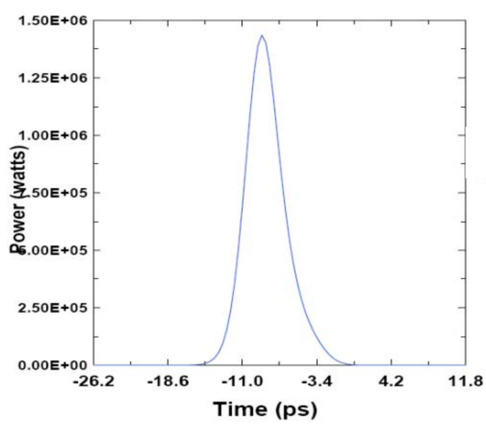

Figure 4: Time structure of the out-coupled power. A hole of radius 2 mm in the downstream mirror is used for this calculation.

ble even at these wavelengths with these parameters. Fig. 5 shows the growth of power from shot noise for these two cases. Note that we have assumed an electron energy of 25.32 MeV ($\gamma = 50.55$) and $K = 1.0$ for the 12.5 μm simulation. For the 50 μm simulation, the electron beam energy is assumed to be 17.4 MeV ($\gamma = 35.07$) and $K = 2.0$. We have used a peak electron beam current of 50 A for the 12.5 μm simulation. Since the gain is less at shorter wavelengths, we have used a larger current for this case. Also, we have taken the radius of the out-coupling hole in the downstream mirror to be 1 mm since the radiation beam size is smaller for this case. The peak out-coupled power for the 12.5 μm case is around 3.2 MW and for the 50 μm case, it is 1.1 MW.

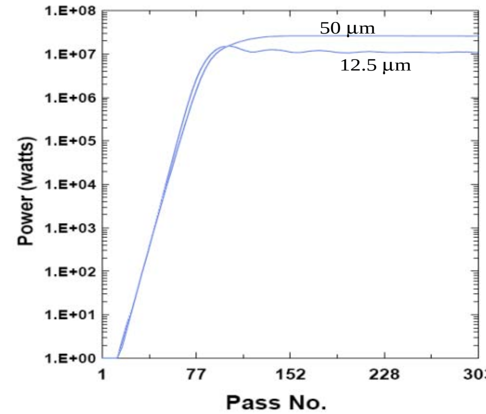

Figure 5: Growth of average intracvity power from shot noise for the 12.5 μm and 50 μm cases. Parameters used in the simulation are discussed in the text.

DISCUSSIONS AND CONCLUSIONS

We have not included the effect of wave-guiding in our calculation. Since we are planning to use a rather smaller beam pipe ID, the effect of wave-guiding may become important. We plan to focus on this issue in the future.

To summarize, we have presented the results of preliminary design calculations for an IR FEL proposed to be built at RRCAT. We find that with modest design parameters, it should be possible to lase in the range 12.5 - 50 μm and obtain peak out-coupled power more than 1 MW. Detailed design simulations and optimization are still underway.

ACKNOWLEDGEMENT

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