DESIGN OF AN INFRA-RED FREE-ELECTRON LASER AT RRCAT

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Abstract

An infrared free-electron laser (IR-FEL) that will be tunable at around 30 μm wavelength is currently being developed at the Raja Ramanna Centre for Advanced Technology (RRCAT), Indore. The FEL will use a 15-25 MeV normal conducting linear accelerator and a 50 mm period, 2.5 m long undulator housed in a 4.1 m long optical cavity. In this paper, we discuss the physics design of the IR-FEL and the design/development of various sub-systems.

INTRODUCTION

An infrared (IR) free-electron laser (FEL) is currently being developed at RRCAT, Indore, which will generate high peak power, short pulse and widely tunable coherent radiation having a wide range of research applications in condensed matter physics and chemistry. In an FEL, a high quality relativistic electron beam consisting of a train of bunches from an accelerator is injected along the axis of an undulator. The electron beam from the accelerator has macropulses, typically few μs long, repeating at a rep. rate of few Hz Inside the macropulse, there are micropulses, typically few tens of ps long for S-band linacs, repeating at few tens or hundreds of MHz. The electrons oscillate in the horizontal plane due to the interaction with the static, vertical sinusoidal on-axis magnetic field of the undulator and therefore radiate at a wavelength $\lambda_R = (\lambda_u/2\gamma^2)(1+K^2)$, where γ is the electron energy in units of its rest mass energy, $K = eB_u\lambda_u/2\pi mc$, B_u is the rms undulator field, λ_u is the undulator period, m is the rest mass of electron and c is the speed of light. In an FEL oscillator, the undulator is placed in an open resonating cavity consisting of mirrors at the two ends. The radiation is partially out-coupled through a hole at the centre of one of the mirrors. If the cavity round trip length is suitably matched to an integral multiple of spacing between electron micropulses, the radiation pulse will keep interacting with co-propagating fresh electron micropulses coming from the accelerator. As a result of this interaction, oscillating electrons will experience a longitudinal ponderomotive force, which after several round trips of the radiation pulse in the resonator cavity produces microbunching inside each micropulse at radiation wavelength that results in coherent emission.

DESIGN CONSIDERATIONS

The wavelength range of 12.5 - 50 microns is considered to be useful from the user application considerations. We have chosen the electron energy in the range 15-25 MeV. Higher energy is useful since that gives us the scope for increasing the undulator parameter K for a given λ_u and λ_R. The increased undulator parameter gives us higher gain and more tunablity. Variable electron energy allows for wavelength tuning by varying the energy.

We have explored various values of undulator period in our design simulations - 40 mm, 50 mm, 60 mm and 70 mm. We found the performance to be optimum at undulator period of 50 mm. The design with a period of 40 mm requires a gap of 15 mm between the undulator jaws and vacuum pipe inner diameter (ID) of 11 mm, assuming NdFeB magnets based pure permanent magnet undulator. This design option requires wave-guiding at wavelengths longer than 30 μm, and was therefore not chosen. The better design option was found by taking the undulator period as 50 mm, in which case, we get K=1.2 with an undulator gap of 25 mm and vacuum pipe ID of 20 mm, and wave-guiding is not needed for operation up to 50 μm since the vacuum pipe ID is large enough. The longer undulator periods, e.g., 60 mm and 70 mm were also considered. But, these designs required longer undulator. For example, 70 mm period design required 3.5 m long undulator instead of 2.5 m long undulator for 50 mm period design. Since we are initially planning to use the triode electron gun with grid pulsing at 36.62 MHz, procured for our earlier CUTE FEL project [1], we have a constraint that the optical cavity length should be 4.1 m, which is matched to the micropulse rep. rate of 36.62 MHz. We therefore did not go for the longer period option since it would be difficult to fit the 3.5 m long undulator in 4.1 m optical cavity with proper beam transport and beam diagnostics. The rms undulator parameter at minimum gap is 1.2. If the gap is increased up to 39 mm, the undulator parameter will reduce to 0.5. By varying the undulator gap, one can thus tune the wavelength by a factor of 2. Further tuning can be achieved by varying the electron beam energy.

Next, we discuss the scheme for the injector system. We are planning to use a thermionic triode electron gun that delivers 1 nC charge in 1 ns FWHM pulses with a rep rate of 36.62 MHz for 10 μs. This electron bunch train will then go through a pre-buncher followed by a buncher and a linac. We will be using a 2856 MHz linac and our pre-buncher will be operating at the sixth subharmonic of this frequency. Prebuncher structure and its rf source will be similar to that used for the CUTE FEL project [1]. We are planning to procure a travelling wave linac structure that will be powered by a 25 MW Thales make TH2171 klystron. The klystron has already been procured. A 65 MW peak power line type pulsed modulator that is currently

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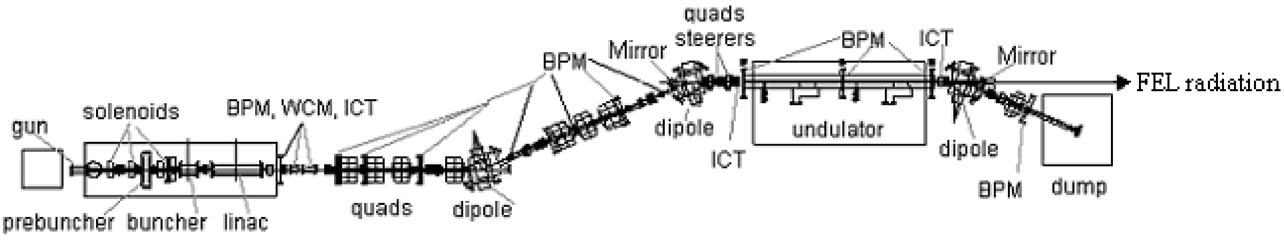

Figure 1: Schematic layout of IR FEL

under development will apply 250 kV, 10 μs flat top pulses at a rep rate of 10 Hz to the klystron. Assuming a transmission of 50% through these structures, we can expect to get around 0.5 nC charge accelerated by the linac. Note that the grid pulse frequency of 36.62 MHz is the thirteenth subharmonic of the prebuncher frequency. The optical cavity length is 4.1 m such that the round trip time is same as the separation between the subsequent electron bunches from the injector. Note that in this scheme, we are filling one out of every seventy-eight rf buckets to avoid the problems due to beam loading in the linac structure and also to reduce the average rf power requirements. Since our macropulse width is around 8 μs, we will have around 293 micropulses in one macropulse. The rms bunch length of the electron beam is chosen to be 4 ps. Shorter pulse length helps in increasing the peak beam current by compressing the bunch, but at the same time, it reduces the gain by making the detrimental effect arising due to slippage between radiation and electron pulses more prominent. At longer bunch length, energy spread in the accelerator becomes higher unless one goes for lower rf frequency accelerating structure. The rms bunch length of 4 ps is an optimum choice. The peak beam current will then be in the range 30 - 50 A. For a good transverse overlap of the electron beam with the radiation beam in the cavity, the normalised rms emittance is chosen to be better than 30 mm-mrad. The rms energy spread is chosen to be 0.5%.

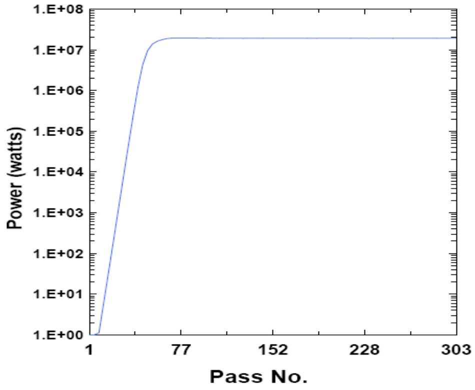

Figure 2: Growth of intracavity power (averaged over 10 ps) as a function of pass number.

The dependence of FEL gain on the number of undulator periods N_u is non-monotonic. Initially, the gain increases as N_u^3, but as N_u is further increased, the gain starts decreasing since the deterioration in FEL gain due to energy spread and slippage becomes more important for longer undulators. For the rms energy spread and pulse length mentioned earlier, we find that the optimum performance is obtained in terms of single pass gain and growth rate for N_u = 50. We therefore choose the undulator length to be 2.5 m. The undulator for this FEL is currently being procured.

The schematic layout of IR FEL showing the beam transport line elements and diagnostic elements are shown in Fig. 1. The transport line has a dogleg bend and is achromatic and isochronous [2]. Development of transport line magnets is currently under progress.

PHYSICS DESIGN SIMULATIONS

We have performed design calculations in the range 12.5 – 50 μm using a computer code `GINGER` [3]. Here, we present the results for λ_R = 30 μm case only. We have taken the beam energy as 22.6 MeV, micropulse peak current as 30 A, and the rms undulator parameter as 1.2. The vertical rms beam size is taken as 0.45 mm, which is the matched beam size in the undulator. The horizontal beam size is taken as 1.0 mm at the middle of the undulator. The radii of curvature of the upstream and downstream mirrors are taken as 2.5 m and 2.25 m respectively, which are optimised for maximum small signal gain. The radius of the out-coupling hole in the downstream mirror is taken as 1.5 mm, which gives optimum performance in terms of small signal gain as well as saturated out-coupled power. With these parameters, the growth of the intracavity power from shot noise is shown in Fig. 2, which shows that the net small signal gain is 49% and the start-up time is 1.6 μs. These calculations are done for optimum cavity detuning (defined as reduction in cavity length from synchronised length) of 60 μm. The peak out-coupled power is 2.2 MW and the average CW power is calculated as 40 mW for 10 Hz rep rate.

REFERENCES

[1] A. Kumar et al., *in these proceddings*.
[2] R. S. Saini et al., *in these proceeding.*
[3] W. Fawley, A user manual for GINGER and its post-procesor XPLOTGIN, LBNL-49625-Rev. I ed., LBNL(2004).