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Status of the development of Delhi Light Source (DLS) at IUAC

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ABSTRACT

A project to construct a compact pre-bunched Free Electron Laser by using a normal conducting photocathode electron gun has been undertaken at Inter University Accelerator Centre (IUAC), New Delhi, India. In this facility, the short laser pulses from a high power laser system will be split into many pulses (2–16) commonly known as 'Comb beam' and will strike the photocathode material (metal and semiconductor) to produce electron beam bunches. The electrons will be accelerated up to an energy of ~8 MeV by a copper cavity operated at a frequency of 2860 MHz and the beam will be injected into a compact, planar permanent undulator magnet to produce THz radiation. The radiation frequency designed to be tuned in the range of 0.15–3 THz by varying the magnetic field of the undulator and/or changing the energy of the electron. The separation of the laser micro-pulses will be varied by adjusting the path length difference to alter the separation of the electron micro-bunches and to maximise the radiation intensity.

1. Introduction

The demand for intense terahertz radiation to perform studies in various fundamental and applied research fields is increasing steadily. To address the requirement, a compact Free Electron Laser (FEL) named as Delhi Light Source (DLS) is under construction at IUAC, New Delhi. The complete project will be developed in three phases [1,2]. In Phase-I, a normal conducting (NC) photocathode electron gun will be operated to generate the pre-bunched electron beam of energy ~8 MeV which will be injected into a short undulator magnet to produce THz radiation. In Phase-II, a superconducting (SC) photocathode RF gun will be developed to produce the electron beam of similar energy but with higher average beam power. The beam will then be injected into long undulator magnets to produce THz radiation with more average power. In Phase-III, electron beam bunches from NC RF gun or from SC RF gun will be injected into a series of SC accelerating structures to increase the beam energy up to 40 MeV which will be injected into long undulator magnets to produce infrared radiation. In addition, the electron beam will be also used to produce X-rays by Inverse Compton Scattering (ICS) with the help of a laser beam colliding with the electron beam. In all the three phases, both the photon beam and the electron beam will be used to perform experiments. Presently, effort is being dedicated to make the Phase-I (Fig. 1) operational. The details of Phase-I are described in the following subsection.

2. Principle of operation of Phase-I of DLS

In the conventional FEL based on the principle of Self Amplified Stimulated Emission (SASE), the length of the initial electron beam bunch is approximately of the order of a few pico-seconds to a few tens of pico-second (electron bunch length $\gg$ radiation wavelength). The electron beam wiggling inside the long undulator magnet, interacts with the photon beams coming from the preceding electrons and the exchange of energy between electrons and photons takes place. Thus the energy of the individual electrons in the bunch is modulated and the electron macro-bunch will be divided into many micro-bunches after a sufficient travel length. The micro-bunched electrons while wiggling through the undulator magnet will produce the electromagnetic radiation by satisfying the equation given below (Eq. (1)). The radiation from the train of micro-bunches will be added up in phases if the separation

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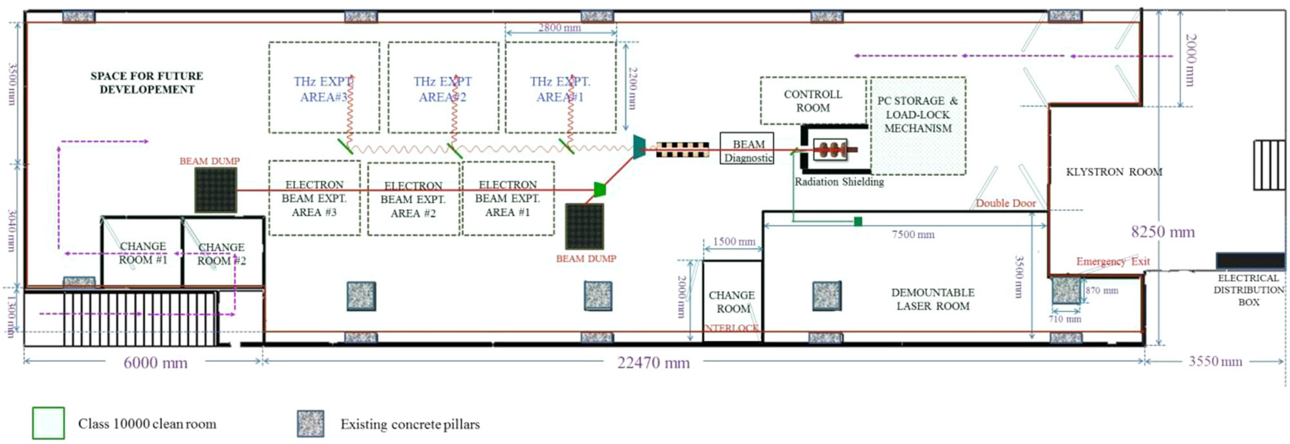

Fig. 1. Schematic of the DLS project, Phase-I including the experimental stations for electrons and THz radiation.

of the micro-bunches matches with the radiation wavelength and then the coherent radiation will be produced resulting to its maximum intensity.

$$\lambda_R = \frac{\lambda_u}{2\gamma^2}\left[1 + \frac{K^2}{2}\right] \tag{1}$$

where,the undulator parameter, $K = 0.934 \times B_u(T) \times \lambda_u$ (cm)

B_u = magnetic field of the undulator (T)

λ_u = undulator wavelength

λ_R = radiation wavelength

$\gamma = E/E_0$, ratio of electron energy to its rest mass energy

In DLS, the electromagnetic radiation with high peak intensity will be generated by micro-bunched electron beams. The concept of DLS stems from the fact that the coherent emission from the pre-bunched electron beams [3,4] can be achieved immediately from the injection point of the compact undulator magnet. This is only possible if the bunch length of the electron microbunches is much shorter than one radiation wavelength (λ_R) with all the microbunches separated successively by one λ_R (this also helps to improve the bunching factor). If this condition is satisfied then inside the undulator, the radiation emitted from a given micro-bunch meet the electrons in the advanced micro-bunches as explained in Fig. 2. Thus the photons are added up in phases and the intensity of radiation is proportional to $(N_e \times N_m)^2$, where N_e is the no. of electrons in each micro-bunch and N_m is the number of micro-bunches varying from 1 to 16. This is commonly referred to as super-radiant undulator radiation and was discussed in many Refs. [5–10]. The pre-bunched electron beam will be produced by the laser micro-pulses striking the photocathode. There will be provision to vary the separation of the laser micro-pulses and thus, the separation between the electron bunches can be also varied. If the separation of the electron micro-bunches is made to be equal to the required wavelength of the radiation emitted by the electron beam through the undulator magnet with its adjusted magnetic field (Eq. (1)), then the photons emitted from the microbunch trains will be added up in phase and the intensity of the radiation will be maximised.

3. Development in major areas of Phase-I of DLS

3.1. Beam transport simulation of Phase-I of DLS

The beam transport simulation has been done by using the ASTRA [11] and General Particle Tracker (GPT) [12] code. The simulation aims at the generation of the frequency ranging between 0.15 and 3.0 THz. The calculation include the electron microbunch generation at the RF photocathode and then transporting the beam through the RF gun, emittance compensation solenoid, drift space and finally through a planar permanent magnet undulator of tentative length of 1.5 m positioned at 2.3 m from the photocathode. A quadrupole singlet has been used. It is positioned at 1.385 m from the photocathode (between the solenoid and the undulator) to control the vertical size of the electron beam structure inside the undulator. Focusing the electron beam only in the vertical direction is important since the magnetic field of the undulator is not homogeneous along the Y-axis. The beam profile in X and Y direction is simulated for both the frequencies of 0.15 and 3.0 THz and the results are shown in Fig. 3(a) and (b) respectively. The undulator magnet starts at 2.3 m and ends at 3.8 m.

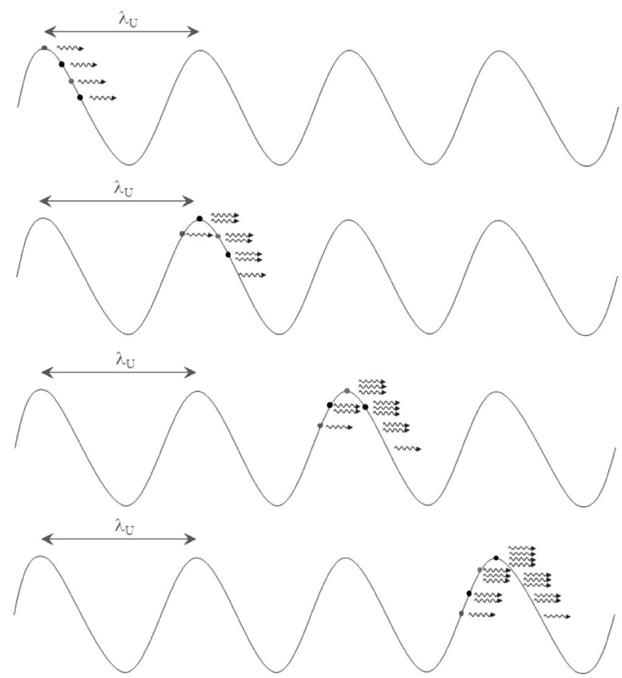

Fig. 2. Enhancement of photon intensity by the wiggling micro-bunches inside the undulator periods.

The output data from GPT has been used to calculate the bunching factor (BF) at the entrance of the undulator magnet shown in Fig. 3(c) and it is observed that the BF peaks at ~0.15 and 3.0 THz as expected. The calculated power generated from 2 and

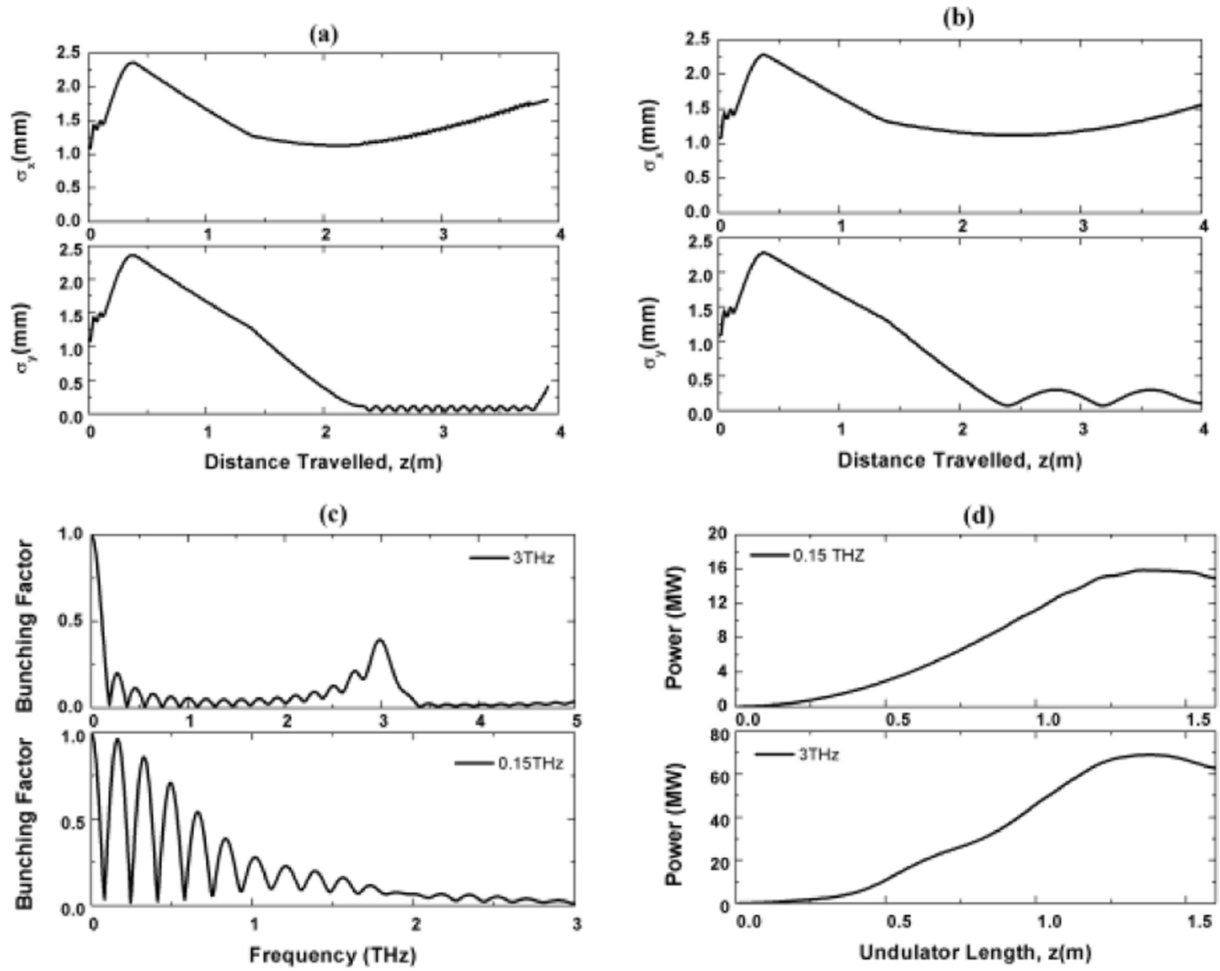

Fig. 3. (a) Beam profile, σ_x, σ_y for 0.15 THz, (b) Beam profile, σ_x, σ_y for 3.0 THz, (c) Bunching factor at the entrance of undulator and (d) Power generated at the end of the undulator.

Table 1
Estimated and calculated [13] parameters for DLS for two extreme radiation frequencies.

Two extreme radiation frequency (THz)	**0.15**	**3**
Accelerating field – e-gun (MV/m)	55	110
Launching phase (deg)	30	30
Electron energy (MeV)	4.11	8.06
Energy spread (keV)	70	34.5
e-beam FWHM @ Cathode (fs)	100	100
Total charge (pC)/microbunch	15	15
Number of microbunches	2	16
Separation in ps between microbunches @ Cathode	8.7	0.424
B-solenoid (T)	0.120	0.231
Quad field (T/m)	0.071	0.120
e-beam FWHM @ undulator entrance (fs)	350	117.5
Peak Current (A) at PC	150	150
Beam Area (mm^2)	3.2	4
Normalised beam emitt. in x (mm-mrad)	1.05	1.16
Normalised beam emitt. in y (mm-mrad)	12.89	1.40
Period of the undulator(m)	0.045	
K-Parameter of the undulator	2.98	0.42
Mag. Field of the undulator (T)	0.71	0.1
Gap of the undulator (mm)	15	42
FEL gain parameter (Γ) $\left[\frac{\mu_0 \hat{K}^2 e^2 k_u n_e}{4\gamma_r^3 m_e}\right]^{1/3}$	5.72	7.06
Gain Length in 1D (Lg), $\frac{1}{\sqrt{3}\Gamma}$	0.1	0.08
Pierce Parameter (ρ) $\left[\frac{\Gamma}{2k_u}\right]$.	0.020	0.025
Estd. power from undulator (1.485 m. long) (MW)	16	70

16 microbunches for 0.15 and 3.0 THz respectively is shown in Fig. 3(d) which shows that the length of the undulator need not to be more than 1.5 m to extract maximum radiation power out of the electron micro-bunches. An in-house code has been developed to calculate the bunching factor and the power generated from the wiggling electrons inside the undulator magnet. The simulated FEL parameters from ASTRA and GPT to generate two extreme radiation frequencies (0.15 and 3 THz) are given in Table 1.

3.2. The copper cavity as the electron gun

The electron beam is generated from a photocathode placed inside an RF electron gun. As soon the electron beams are produced, they will be accelerated to a maximum energy of 8 MeV by an accelerating field of 110 MV/m in RF gun. The resonance frequency of the electron gun is 2860 MHz which is chosen to synchronise with the frequencies of the superconducting cavities (1.3 GHz) to be developed in future for Phase-II/III of DLS project by using the clock frequency of 130 MHz. The design of the copper cavity is similar to those at BNL and KEK [14,15] and was developed in collaboration with KEK, Japan.

The mechanical fabrication of the copper cavity, vacuum brazing of its different parts and tuning at different stages were executed at KEK, Japan. After fabrication of the cavity, the cavity was tested jointly by IUAC and KEK personnel. The cavity is now under evacuation at IUAC and will be installed shortly in the beam line of

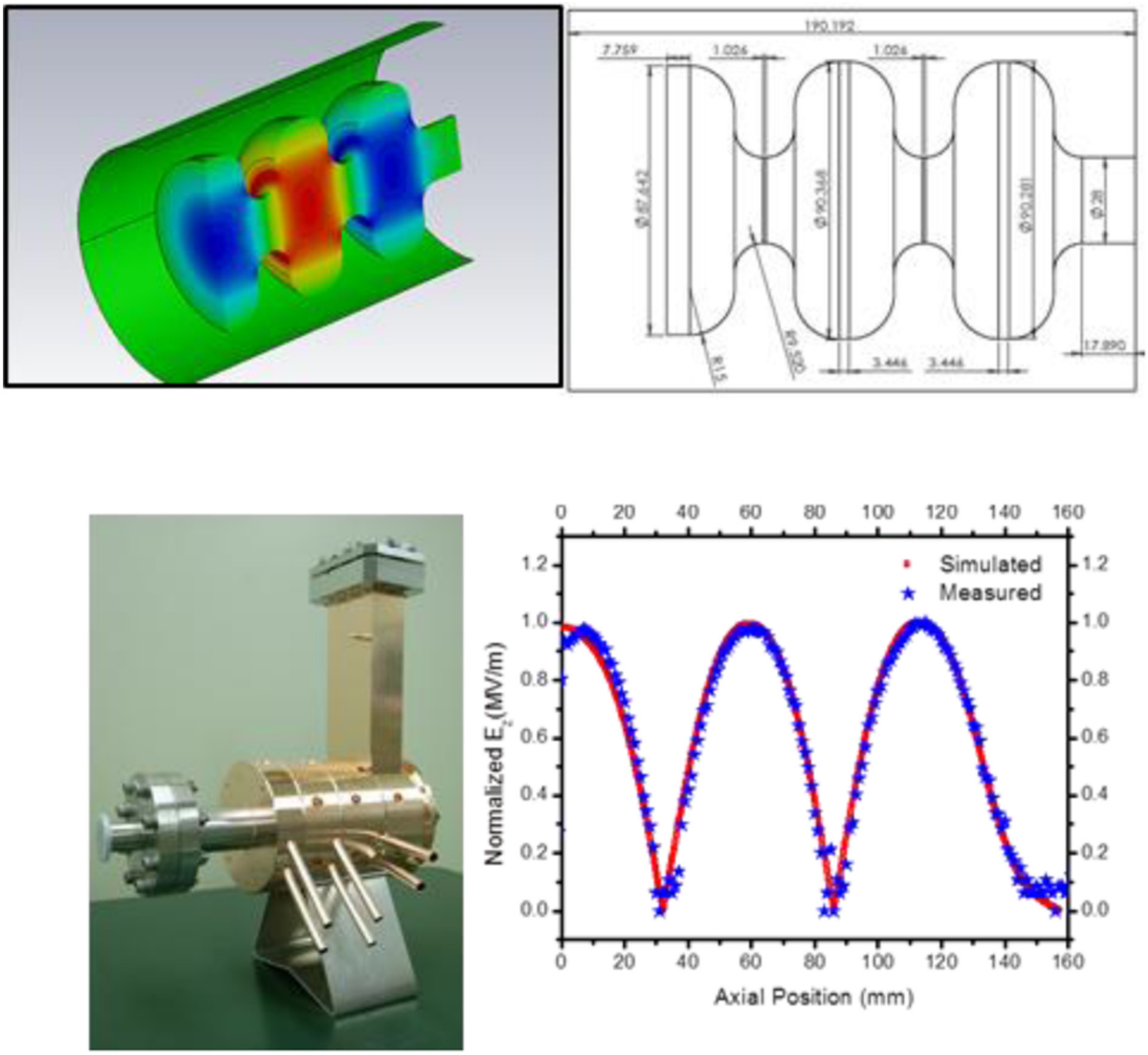

Fig. 4. Details of the copper cavity: Field simulation by CST microwave studio (top left), Mechanical drawing (top right), Fabricated complete cavity (bottom left) and Matching of Superfish [16] field profile with the bead pull data (bottom right)

DLS. The details of the cavity and its bead pull data are shown in Fig. 4. The quality factor and the frequency of the copper cavity had been measured to be 15,000 and 2859.795 MHz @ 24.5 °C respectively. The operating temperature of the copper cavity will be kept at 30 °C during operation, so the resonance frequency of the cavity should be easily brought to 2860 MHz.

3.3. The photocathode preparation and insertion mechanism

The electron beam in the photocathode (PC) RF gun will be produced initially from the copper photocathode. However, to increase the electron current and hence the power of radiation, the deposition system to deposit caesium telluride on molybdenum substrate is planned to be developed. The assembly drawing of the complete deposition system is shown in Fig. 5.

The copper photocathode prior to its loading inside the electron gun, will be irradiated inside the insertion chamber (Chamber#4 in Fig. 5) by high power laser pulses and subsequently, the Quantum Efficiency (QE) of the photocathode will be measured by using a low power laser. If the QE of the photocathode is measured to be satisfactory (about 1×10^{-5} or more) then the photocathode will be inserted into the copper cavity for the routine production of electron beams.

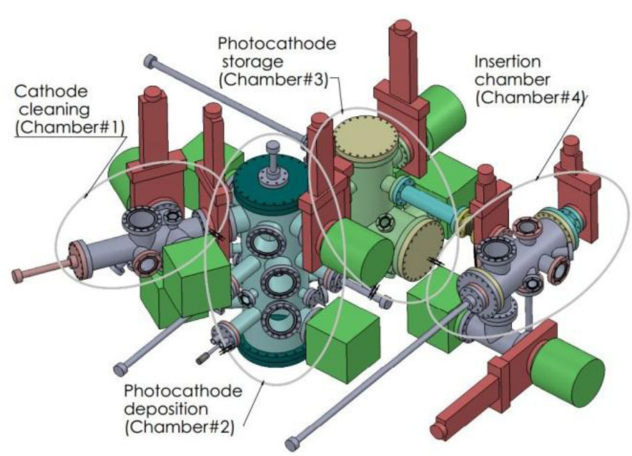

Fig. 5. The schematic of the Photocathode deposition chamber

Table 2
Parameters the proposed fiber laser.

Pulse rep. rate (MHz)	Energy per pulse @ 266 nm (μJ)	Pulse width	Photo-cathode	No. of micro bunches	Charge/pulse
130	25	100–200 fs	Cu	2, 4, 8 & 16	23, 10, 4, 2 pC
			Cs_2Te	2, 4, 8 & 16	11, 5, 2.5, 1.2 nC

In the case of deposition of semiconductor (e.g. Cs_2Te) thin film on a metal substrate (e.g. Mo), first the photocathode plug will be loaded in chamber#1 and the active surface of the plug will be thoroughly cleaned with a high power laser. Then it will be transported to chamber#2 for deposition of Te (~10 nm) followed by Cs (~90 nm) subjected to the maximisation of the measured QE.

Then the deposited photocathode will be shifted to the storage chamber (chamber#3) which can store up to six photocathode. Finally the individual photocathode will be brought into the insertion chamber#4 and prior to its insertion into the RF cavity, its surface is to be evaluated by another measurement of QE in the chamber#4.

3.4. RF gun laser system

High power pulse laser beam is necessary to illuminate the photocathode to generate the electrons. The specification of an appropriate laser system suitable for our application is currently being finalized. With the recent progress in fiber laser system, it is decided to develop a fiber laser system for DLS. The same system can be used for the laser cleaning of the photocathode material.

As per the design criteria, each laser pulse will be split into 2, 4, 8, 16 micro-pulses to generate 'comb beam' with the separation of a few hundreds of femtosecond. There will be a provision to precisely vary the separation between successive microbunches to enhance the intensity of the THz radiation.

The design and development of the high power fiber laser system will be executed in collaboration with KEK, Japan. The tentative parameters of the laser system are given in Table 2.

Table 3
Main Parameters for klystron & modulator.

	Parameter – RF system	Value
1	Peak output power	≥25 MW
2	Average output power	≥5 kW
3	Operating frequency	2860 MHz
4	Bandwidth (−1 dB)	±1 MHz
5	RF pulse duration	0.2 μs–4 μs
6	Pulse repetition rate	1–50 Hz
7	Pulse top flatness	±0.3%
8	Rate of rise and fall of modulator output voltage	200–250 kV/μs
9	Long term stability	±0.05 %

3.5. RF system of DLS

The RF system of DLS is governed by the beam stability requirement of the system that includes mainly the RF phase stability of 0.1 degree and amplitude stability better than 0.01%.

The RF system consists of a Low Level RF (LLRF) section and high power RF system containing klystron and modulator to power the RF cavity. The high power RF pulse should have the pulse flatness to match the beam stability requirement. Specifications of the high power system are mentioned in Table 3. There will be additional control to make the clock of the laser oscillator synchronized with the LLRF system.

3.6. The undulator magnet

The preliminary calculation related to undulator/wiggler magnet has been initiated and the actual design of the magnet with the code Radia has been started. As per the design goal, the frequency range of the THz radiation to be produced from Phase-I of DLS is to be confined between 0.15 and 3 THz. If the energy of the electron beam is varied between 4–8 MeV, then for the expected frequency range mentioned above, the tentative parameters for the undulator has been calculated and is given in Table 1. Detailed design calculation of the undulator will be taken up shortly.

3.7. Design of the beam line for Phase-I of DLS

The initial design of the beam line is shown in Fig. 6. The beam optics calculation shows that a solenoid magnet placed after the electron gun will focus the electron beam uniformly at the undulator magnet. In addition, a singlet quadrupole magnet is necessary to focus the beam in the vertical direction as the height of the beam pipe inside the undulator is limited to ~15 mm (including the wall thickness). Beam optics and beam diagnostic devices are being finalized and they will be installed at the appropriate places of the beam line of DLS as shown in Fig. 6.

4. Present status of the Phase-I of Delhi Light Source

The main effort to commission the Phase-I of DLS is dedicated to design and develop the subsystems and procure the required devices. To accommodate the entire accelerator and experimental

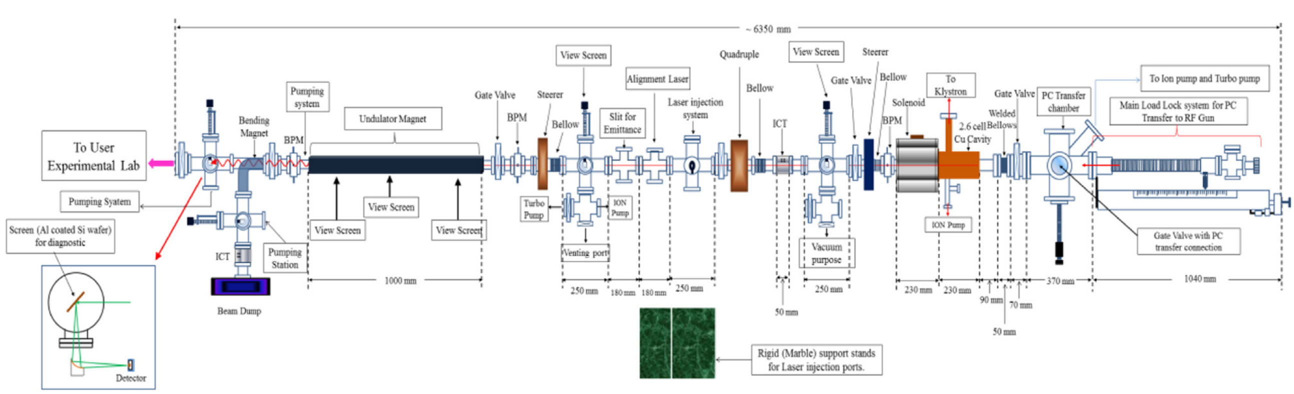

Fig. 6. The initial design of the beam line for phase-I of Delhi Light Source.

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facility, a class 10,000 clean room has been developed. The copper cavity has been fabricated and tested and is ready to be installed in the beam line. The design of the photocathode deposition chamber and the photocathode in-vacuum transfer mechanism inside the cavity has been finalized and the fabrication drawings are being prepared for procuring the items.

The specifications for klystron and modulator to power the copper cavity have been finalized and the purchase order has been placed. The design of the RF and control system at the block diagram level is going on. The high power fiber laser system is planned to be developed in collaboration with KEK, Japan. The design and procurement of undulator and other electromagnets has been started. The beam transport calculation has been done with ASTRA and currently being fine-tuned with GPT code to configure the beam line components. The complete facility to provide electron beam ($\sim$ 8 MeV) and THz radiation is expected to be operational by end of 2018.

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