COMMISSIONING AND INITIAL OPERATION OF A COMPACT FEL-THz FACILITY AT IUAC, NEW DELHI[*]

B. K. Sahu [†][1], P. Patra[1], J. Karmakar[1], B. Karmakar[1], Madhuri[1], A. Sharma[1], A. Aryshev[2],
P. K.Mukhopadhyay[3], Markus Tischer[4], T. Rao[5], S. Ghosh[1], A. C. Pandey[1]
[1]Inter University Accelerator Centre, New Delhi, India
[2]High Energy Accelerator Research Organization, KEK, Tsukuba, Japan
[3]Raja Ramanna Centre of Advanced Technology, Indore, India
[4]Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany
[5]Brookhaven National Laboratory, Upton, NY, USA

Abstract

A compact THz facility, based on Free Electron Laser (FEL) system has been commissioned at Inter University Accelerator Centre (IUAC), New Delhi. The design of the facility is based on pre-bunched FEL where a train of electron micro-bunches having maximum energy of 8 MeV are intended to be injected into a short undulator to produce the THz radiation in the range of 0.18 THz–3.0 THz. The electron micro bunches are produced from the photocathode by striking with the ultra-short laser pulses generated from an advanced Fibre laser system. These electron micro-bunches are being injected in to the undulator to produce the THz radiation and the electron beam along with the THz radiation are co-propagating through the undulator. At the exit of the undulator, a thin Titanium foil is kept through which the electron beam passes through and the THz radiation gets reflected, subsequently detected by the Schottky Barrier Diode detector. The commissioning details and the initial operation of the of the various sub-systems of the compact FEL-THz facility e.g. high-power RF systems, electron gun, fibre laser system, state of the art photocathode deposition system, undulator, various beam transport and beam diagnostic systems, etc. are being presented in this paper.

INTRODUCTION

Accelerator-based THz radiation sources are the most intense, narrow band and tunable among all known THz sources. These sources offer high peak power, tunability, and narrow radiation bandwidth [1, 2]. Undulator radiation is a well-established mechanism for generating narrowband electromagnetic radiation from relativistic electron beams, and it can be extended into the THz regime using low-energy electron beams and long-period undulators. A key challenge in undulator-based THz generation is to achieve a sufficiently high radiation intensity at longer wavelengths. One effective strategy is to exploit coherent radiation, in which the longitudinal structure of the electron beam leads to constructive interference of the emitted radiation. When electron beams exhibit a periodic longitudinal density modulation, radiation emitted by successive microbunches can interfere constructively, leading to coherent enhancement at frequencies corresponding to the microbunch repetition rate [3]. Although most FEL based THz sources are oscillator type, several pre-bunched FEL facilities either operational or under construction are increasingly gaining prominence. The Compact Free Electron Laser facility known as Delhi Light Source (DLS) [4, 5] at IUAC, New Delhi is a pre-bunched undulator based THz facility for the generation of THz radiation from an undulator driven by multi-microbunch electron beams produced using a normal conducting RF photocathode gun. RF photocathode guns provide a direct and flexible means of generating such structured beams by imprinting the temporal structure of a drive laser pulse train onto the emitted electrons that has recently generated first signature of THz radiation.

DLS Pre-Bunched FEL Facility

The main concept of pre-bunched FEL facilities, as shown in Fig. 1, is the enhancement of the radiation intensity due to super-radiance which is achieved when the bunch length of electron beam is small compared to radiation wavelength so that the contribution from the individual electrons from the same micrbunch adds up in phase and enhance the coherence. Additionally, if there are multiple bunches separated by the radiation wavelength the intensity gets further enhanced by the superposition of the photons in phases from the trailing micobunches of the electrons. The intensity is given as

$$I(\omega) = I_1(\omega)\left[N + N(N-1)|b(\omega)|^2\right], \qquad (1)$$

where,

$$b(\omega) = \frac{1}{N}\sum_{j=1}^{N} e^{i\omega t_j} \qquad (2)$$

is the bunching factor at frequency ω, N is the number of electrons and $I_1(\omega)$ is the spectral intensity of a single electron.

The DLS user facility is designed for THz frequencies in the range 0.18 –3.0 THz using the range of beam energies 4 –8 MeV and the magnetic field of the undulator 0.61 –0.12 T respectively. Electrons are generated from a 2.6 cell copper RF photocathode gun operating at 2860 MHz, by injecting pulsed UV lasers at the proper RF phase. An emittance compensation solenoid is used to focus the beam

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[†] bhuban@iuac.res.in

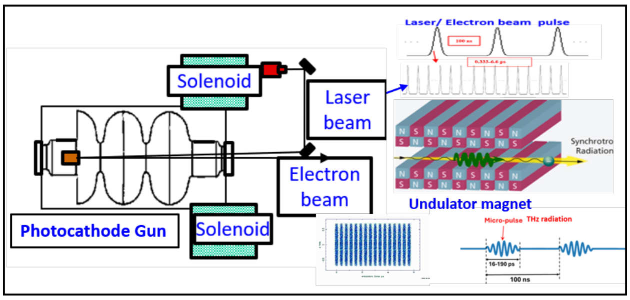

Figure 1: Pre-bunched FEL facility for THz production

at the undulator entrance to obtain beam matching to minimize the betatron oscillations inside the undulator. At undulator exit a THz reflector(Titanium foil) is used to extract the THz and the electron beam passes through the thin foil. The pulsed UV laser for electron generation is produced from a laser system capable of producing femto second laser pulses having energy up to few micro joule at 5 to 10 MHz repetition rate. The system is also capable of generating micro-bunched pulses of numbers 2, 4, 8 & 16 with micro-bunch separation that can be varied to match the aimed THz wavelength to enhance coherence.

Simulations of Beam Optics and THz Radiation

The simulations for the beam optics optimizations has been done using GPT [6] code. To optimize the THz radiation output, beam optics simulations has been done to match the beam at the undulator entrance so as to have minimum betatron oscillations in the non-wiggling plane. The matched rms envelope for 4 MeV and 8 MeV beams with single bunch of 10 pC for frequencies of 0.3 THz and 2.5 THz respectively, are shown in Fig. 2 (a) and (b). Since the electron beam energy is within 8 MeV the space charge effects are non-negligible, which can increase the energy spread and can enhance the bunch length thus degrading the bunching factor. Both effects can limit the ideal THz radiation intensity given by Eq. (1). The simulation parameters used for 0.3 and 2.5 THz are shown in Table 1.

Table 1: Simulation Parameters for Two THz Frequencies

Parameter	**0.3 THz**	**2.5 THz**
Beam energy (MeV)	4	8
Peak RF field (MV/m)	57	110
RF phase (°)	31	32
RMS spot size at PC (mm)	1.2	1.2
RMS micro-bunch length (fs)	130	130
Undulator field (T)	0.4735	0.196
Macro/single bunch Charge(pC)	10	10
No of micb	1, 4	1, 8
micb sep (fs)	2860	545
Macro/single bunch NOP	40000	40000

The GPT generated position $\vec{r}_e(x, y, z, t)$ and velocity $\vec{\beta}(\beta_x, \beta_y, \beta_z, t)$ data of all particles at all time-steps inside the undulator are used to compute the spectral radiation intensity [7, 8] as shown in Eq. (3) using an indigenous code written in house.

$$\frac{d^2W}{d\omega\, d\Omega} = \frac{e^2}{16\pi^3\varepsilon_0 c}\left|\int_{-\infty}^{\infty}\frac{\mathbf{n}\times\left[(\mathbf{n}-\beta)\times\dot{\beta}\right]}{(1-\mathbf{n}\cdot\beta)^2}\, e^{i\omega\left(t-\frac{\mathbf{n}\cdot\mathbf{r}(t)}{c}\right)}\, dt\right|^2, \tag{3}$$

where W is the total radiated energy, ω is the THz frequency, Ω is the solid angle in the observation direction, $\mathbf{n}$ is the dynamic unit vector pointing from a particle to the observer, β is the normalized velocity of the particle, $\dot{\beta}$ is the normalized acceleration, $\mathbf{r}(t)$ is the position vector of the electron as a function of time, t is the retarded time. The simulated THz radiation spectrum for 0.3 THz and 2.5 THz using 4 and 8 micro-bunches respectively, is compared against single bunch case for both frequencies and shown in Fig. 2 (c) and (d). For both cases, the peak intensity from a train of micro-bunches is higher than the single bunch case, although the total macro-bunch charge is same. This is because the space charge force will be higher for a single bunch than if the same charge is split into multiple micro-bunches. For the single bunch, this leads to more bunch length elongation compared to the micro-bunch case, degrading the bunching factor form factor and the degree of coherence. The small shift in central frequency for the two cases at 2.5 THz can mainly be attributed as the bunching factor through the undulator changes during the transit. For 0.3 THz the difference appears in the form of double peak for the single bunch case. The simulated on-axis radiation energy per FWHM per solid angle is also shown in Table 2.

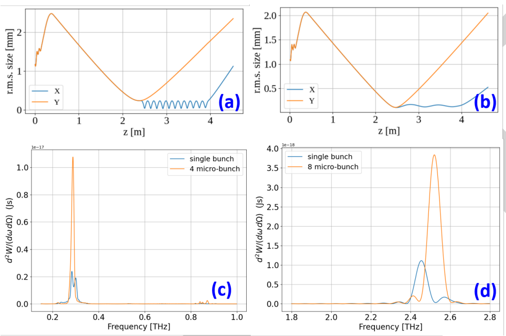

Figure 2: (a)simulation for matched beam (rms) envelope for minimum betatron oscillation amplitude for 10 pC single bunch at (a)4 MeV(a) and (b)8 MeV (b) and simulated spectral intensity for 0.3 THz (c) and 2.5 THz (d) using 4 and 8 micro-bunches respectively, compared against single bunch.

Table 2: Simulated THz Radiation Output

Parameter	**0.3 THz**	**2.5 THz**
single bunch intensity (nJ/Ω)	41.6	59.8
single bunch FWHM (%)	8.6	2.7
micro-bunch intensity (nJ/Ω)	93.1	215
micro-bunch FWHM (%)	3.8	2.7

VARIOUS SUBSECTIONS OF THE COMPACT FEL FACILITY

DLS, the compact, pre-bunched Free Electron Laser based THz facility is commis-sioned at IUAC in a class 10000 clean room. The operational facility is capable of producing electron beam having energy maximum up to 8 MeV for the production of THz radiation in the range of 0.18 THz to 3 THz. A fiber laser system capable of producing ultra-short UV laser pulses with a maximum energy of ~1.5 µJ with a pulse width of ~500 fs is being used to produce these high energy pulsed electron beams from the RF photocathode gun. In order to increase the intensity of THz radiation by increasing the charge produced in the photocathode, an advanced photo cathode deposition setup is installed for the development of semiconductor photo cathode material. Specification and commissioning details of all these subsystems are presented in detail.

RF Photocathode Gun

Photocathode gun, also known as photoinjector, is one of the critical components of the free-electron laser system. This is meant to generate high-brightness electron beams by using a laser to illuminate a photocathode (e.g., copper or semiconductor like Cs_2Te) inside an RF cavity. These electrons are immediately accelerated in the RF field to relativistic energies, forming ultra-short bunches with low emittance and high peak current. The Photo-cathode RF gun of IUAC compact FEL consists of a 2.6 cell Normal-conducting (copper) gun operating at S-band at central frequency 2.86 GHz with maximum gradients of 120 MV/m. The cavity, operating in π-mode, is developed and fabricated in collaboration with KEK Japan using oxygen-free high-conductivity copper to achieve high quality factor and stable RF performance [9]. Careful cavity shaping and symmetric RF coupling are employed to suppress dipole fields and have higher mode separation to avoid degradation of the beam quality. The cavity is used to generate a peak Electric field 110 MV/m when powered by a Klystron- modulator system at a peak power of ~12 MW to ensure the production of 8 MeV beam energies maximum at the injector exit.

RF System for the Photocathode Gun

The high-power RF system for DLS as shown in Fig. 3 is meant to power the 2.6 Cell normal conducting photo cathode RF gun operating at 2860 MHz. The system consists of a Thoshiba make klystron operating in pulsed mode using a solid-state modulator of Scandinova [10] make with a maximum power rating of 25 MW for a duration of 4 µs with repetition frequency up to 50 Hz. The RF distribution system used to transport RF power consists of vacuum based WR284 waveguide system to avoid any contamination of semiconductor photo cathodes to be used during operation. RF conditioning is required to reach the target accelerating gradient while minimizing breakdown and dark current. Stable ultra-high vacuum conditions ($<10^{-9}$ mbar) are essential for reliable operation. As per the initial design a special RF isolator consisting of Vacuum based Circulator could not be installed due to technical problems associated with fabrication of such a circulator. So a SF_6 based isolator was installed to withstand higher values of reflected power during conditioning.The distribution section includes straight sections, E and H-bends, directional couplers, RF windows and pumping sections having Merdinian/SLAC type flange connector along with high power isolator consisting of SF_6 circulator and load [11] The installation of SF_6 based Isolator has enabled us to condition the RF Gun to the desired forward RF power up to 12 MW to increase the field gradient greater than 100 MV/m for the pulse length of 4 µs with 10 Hz repetition rate [12]. Low level RF control is integrated to keep the phase and amplitude constant at given RF power.

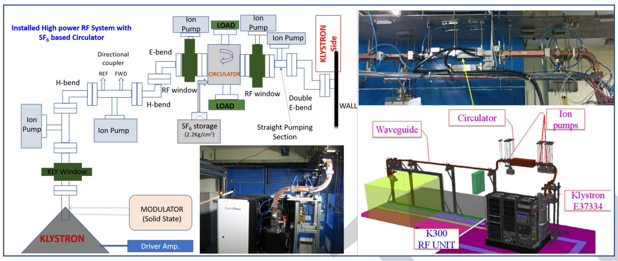

Figure 3: High power RF system for FEL facility

Laser System

The laser system is one of the most crucial subsystems of the compact FEL facility of IUAC. The pulse width and stability of the laser pulses are responsible for the quality of the electron beam produced from the photocathode, while the synchronization of laser injection with the RF phase of the photocathode gun determines the energy gain of the electron beam. A state-of-the-art Fiber Laser system was being developed as a collaborative project between IUAC and High Energy Accelerator Research Organization (KEK), Japan. The laser system was installed in a laser hut inside the class 10000 clean room close to the RF Gun and being used to produce ultra-short laser pulses with energy ~1.5 µJ with a pulse width of ~500 fs [13, 14]. The frequency of the Oscillator of the fiber laser system is 130 MHz which, after down-conversion, produce laser pulse at a repetition rate of 5 –10 MHz. A provision to split a single laser pulse into 2,4,8 and 16 pulses has been incorporated. The block diagram of the installed laser system is shown in Fig. 4. The pulsed fiber laser system operating with 130 MHz laser oscillator is used as master reference and made to synchronize with the 2860 MHz RF gun signal by indigenously built RF up-conversion module using commercially available RF components such as frequency mixers, multipliers, attenuators, amplifiers and band pass filters. Voltage controlled phase shifter has been used to control the relative phase between the RF signal and laser pulses along with variable attenuator to control the signal amplitude. A very narrow

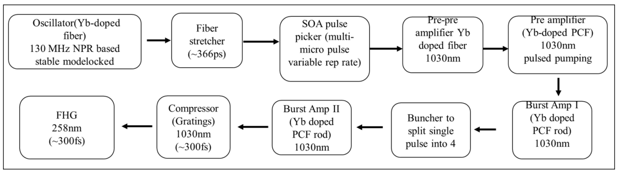

Figure 4: Block Diagram of Laser System

band (+/- 25 MHz) filter at 2860 MHz has been used at the final stage to get a spectrally pure 2860 MHz signal. This upconverted frequency is being used for powering the RF gun and synchronized with laser oscillator with a relative timing jitter of less than 5 ps to produce stable electron beam.

Undulator

As the compact FEL facility is designed to produce the radiation wavelength in the range of 0.18 THz to 3 THz using the available electron beam having maximum energy up to 8 MeV, the period and on the axis peak magnetic field of the undulator has to be compatible for the same.The required undulator parameters are mentioned in Table 3 [15, 16]. This configuration has vertical Y-Z plane as the wiggle plane, since the fields are horizontal. The undulator for the FEL facility was received as a donation from Helmholtz Zentrum Berlin (HZB), Ger-many, whose specification closely matches with its design parameters to produce THz radiation. Few refurbishments were done at DESY, Germany along with the control mechanism to make it suitable for the operation at IUAC. The Undulator is installed in the beamline along with its vacuum chamber after proper alignment with the beam axis along with the control electronics to vary the undulator gap from remote.

Table 3: Undulator Parameters

Parameter	**Value**
Technology	PPM
Periods	33
Period length	48 mm
Magnetic length	1584 mm
Gap range	16 mm - 45 mm
Peak field	0.61 T - 0.12 T
K parameter (rms)	1.932 - 0.38

Beam Transport and Diagnostic System

The complete beam line design and the 3-D drawing were made for an efficient transmission of the electron beam without any beam loss as shown in Fig. 5. Various beam transport and diagnostic systems such as Solenoid magnet, Quadrupole, steering magnets, Beam Position Monitor, Integrated Current Transformer, beam viewer with digital camera etc. were commissioned up to the user experimental chamber. The stripline BPMs along with Integrated current transformers and YAG screen based beam viewers were used in the beamline for optimization of beam transmission. The in house developed faraday cup has been used to distinguish the multi micro pulse structure. The laser insertion chamber having a donut-shaped mirror at the center was installed before the undulator for the injection of the laser pulse being reflected on the photocathode. The electron beam passes through the aperture of the mirror to enter in to the undulator. A THz extraction chamber at the exit of the undulator was installed and it contains a Titanium foil to reflect the produced THz signal allowing the electron beam to pass through the foil. Two Dipole magnets serving as achromatic bends were installed at the downstream of the undu-lator after the Terahertz extraction chamber. As the facility also plans to deliver the electron beam for experiments, the beam is brought up to a dedicated electron experimental line through the achromatic bend [17]. A mixture of Indigenous control scheme along with EPICS based control has been implemented for the control and monitoring of beam parameters.

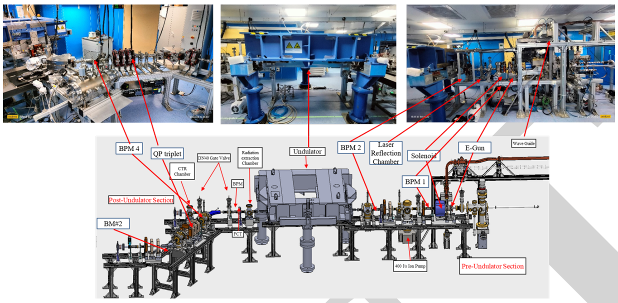

Figure 5: Schematic of DLS beam line

Photocathode Deposition System

Presently the production of THz radiation is demonstrated using the electron beam produced from the Cu photocathode. In order to enhance the electron beam production using semiconductor photocathode, a dedicated photocathode deposition system was developed in collaboration with Brookhaven National Laboratory (BNL), USA and installed at IUAC. The system consists of UHV chambers having a base vacuum of ~1×10^{-10} mbar, precision manipulators, and controlled evaporation sources, enabling the preparation and storage of new photocathodes along with insertion mechanism to insert it into the photocathode gun [18]. Besides the development of Cs_2Te photocathode, fabrication of some advanced alternative photocathode materials such as multi-alkali antimonides are undertaken.

OPERATION FOR THE PRODUCTION OF THZ RADIATION

After commissioning the compact FEL facility, multi micro bunch electron beam having energy up to 6.5 MeV and pulse width of ~500 fs has been produced with hundreds of femto Coulomb (fC) charge. This is produced from the copper photocathode placed inside inside the RF Photocathode Gun by striking the pulsed UV laser beam from the fiber laser system and shown in Fig. 6. The electron beam is being focused using a solenoid and transported through the Undulator for the production of THz radiation.

Production of Broadband and Narrow Band THz Radiation

The femto second electron beam just after the RF Gun and solenoid is made to incident on a Aluminum mirror to produce Coherent Transition Radiation (CTR). CTR is produced when the electron beam is incident on the vacuum-dielectric surface, resulting in emission of electromagnetic radiation in the THz range. The produced THz signal is broadband in nature [19]. When CTR is not produced, the same multi micro bunch electron beam is injected into the compact Undulator for the production of narrowband tuneable Coherent Undulator Radia-tion (CUR). The produced THz radiation gets reflected by the Titanium reflecting surface installed in the THz extraction chamber to guide the THZ beam to the THz detector. The intensity of the THz radiation is much low due to low charge from Cu photo-cathode. As discussed in the initial design section, splitting of laser pulse is also explored for coherent THz production from each bunch. Already the first detection of the laser pulse splitting into 2 and 4 micro pulses are observed along with the observation of the generated 2 and 4 electron micro-bunches in the YAG screen at 1.4 m downstream of the RF gun. The same is planned to be injected into the undulator after optimization of beam tuning parameters. In future this will further be splitted into 8 and 16 micro bunches to produce intense coherent THz radiation.

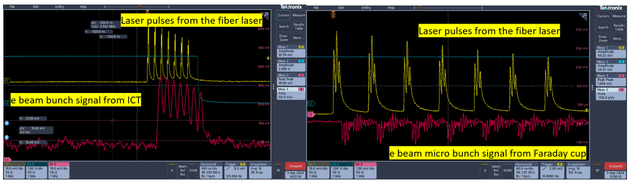

Figure 6: Production of multi micro bunch electron beam for THz production

Detection of THz Radiation

As the expected intensity of THz radiation is much less, Schottky Barrier Diode based detectors are chosen for the measurement of THz radiation [20]. The testing of the detectors (including the calibration of transport components) has been performed with known THz source prior to its characterization of the produced THz radiation. The responsivity of detectors along with their polarization sensitivity by following the transmission curves of the view port and lens have been obtained in the desired frequency range. Based on these calibrations, electron beam is tuned with undulator gap suitable for the production of 0.3 THz. Appropriate focusing mirrors and lenses are used for the transport of the THz beam to the detector. The measured THz radiation using CTR method and CUR method is shown in Fig. 7. The measured Burst Energy for the generated THz is measured to be ~0.63 pJ at 0.3 THz frequency (using the calibration of SBD detector). The detailed characterization of THz radiation is being worked out using Michelson interferometer technique.

SUMMARY AND CONCLUSION

The commissioning of the compact Free Electron Laser along with all the subsystems for the production of electron beam is successfully accomplished at IUAC. The multi micro bunch electron beam having energy up to 6.5 MeV has been produced regularly for scheduled user experiments. Initial production and detection of THz radiation has been accomplished and characterization of THz radiation is also performed. The intensity of the produced THz radiation is going to be measured by increasing the charge produced from the photo cathode. With the installation of the laser beam splitting mechanism in the installed fibre laser system, the intensity of THz will further be increased. Along with the two experimental stations for electron beam experiments, two stations for THz radiation based experiments are being planned. Transport of THz radiation to the user experimental stations are being designed and soon to be implemented.

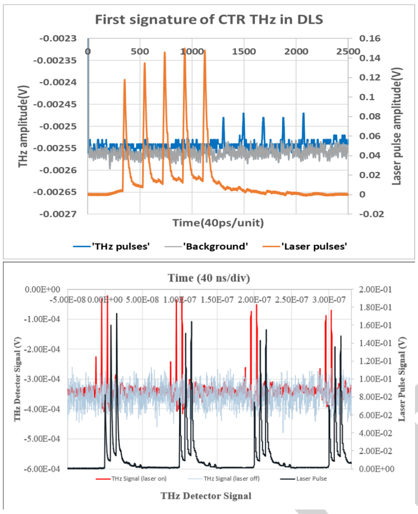

Figure 7: Measurement of THz radiation from 3 MeV Electron beam using CTR (top) and Coherent Undulator radiation CUR (bottom).

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