Signature of build-up of coherence in an indigenously built Compact Ultrafast Terahertz Free Electron Laser set-up

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A Compact Ultrafast Terahertz Free Electron Laser based on a novel plane wave transformer (PWT) linear accelerator (linac) structure has been built at the Raja Ramanna Centre for Advanced Technology, Indore, and is presently undergoing commissioning. We report here a measured out-coupled terahertz (THz) radiation power more than 100 times higher than the expected spontaneous emission power for the beam parameters measured in the experiment. This is the first observed signature of build-up of coherence in the system, which has been made possible with the introduction of a fundamental frequency pre-buncher to increase peak accelerated electron beam current through the PWT linac. This note discusses these recent results and the ongoing efforts to increase the radiation frequency to >1 THz with a further significant increase in THz power by increasing energy and peak current of the electron beam from the injector linac.

Free electron lasers (FELs) are proven sources of intense, tunable radiation over a large wavelength range spanning from millimetre waves to hard X-rays[1]. They have demonstrated the ability to operate efficiently in wavelength regions where conventional sources either do not exist or are not efficient. With the recent worldwide growth of interest in sources of terahertz (THz) radiation for wide-ranging applications from condensed matter physics to biology[2–4], various FELs have been designed and built at these wavelengths with operational parameters depending upon the intended application.

The compact ultrafast terahertz free electron laser (CUTE-FEL) being built at the Raja Ramanna Centre for Advanced Technology (RRCAT), Indore is designed to lase at 80–150 μm wavelength with an electron beam of energy 7–10 MeV. Figure 1 shows a schematic of the CUTE-FEL sub-systems and Table 1 gives the important design specifications of CUTE-FEL, its undulator and injector linear accelerator (linac). An important feature of CUTE-FEL is that all its important sub-systems like the injector linac, the undulator and the beam transport line have been developed in-house. A novel S-band (2856 MHz) accelerating structure called a plane wave transformer (PWT) linac structure serves as the injector linac, which, to the best of our knowledge, is the second operational PWT linac structure in the world, the first one being at the University of California, Los Angeles (UCLA)[5]. The geometry of a PWT linac structure is different from that of conventional disk-loaded linac structures with the central array of disks, which support the transverse magnetic (TM) mode-like field pattern with longitudinal electric field required for acceleration, being separated from the outside tank envelope. Consequently, the structure is electrically

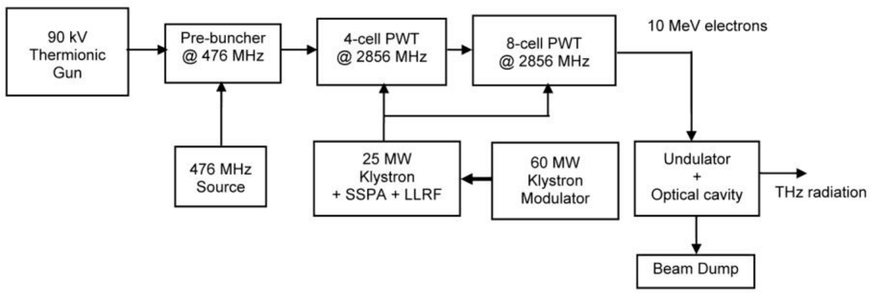

Figure 1. Schematic of the CUTE-FEL set-up.

Table 1. Design parameters of CUTE-FEL and its sub-systems

Parameter	Value
Design parameters	
Operating wavelength	80–150 μm
Configuration	Oscillator
Out-coupled power	0.4 MW (peak)/6 mW (CW average @ 10 Hz)
Optical radiation pulse width	10 ps (FWHM)
Undulator parameters	
Type	Planar, NdFeB pure permanent magnet-based
Period length (λ_u)	50 mm
K parameter (peak)	0.8 at 35 mm gap
Magnet size	$12.5 \times 12.5 \times 50$ mm^3
Remnant field	1.1 T
No. of periods (N_u)	50
Mechanical gap	Variable, 16–100 mm
CUTE-FEL design gap	35 mm
Linac parameters	
Type	S-band, plane wave transformer, standing wave
No. of cells	7 full + 2 half cells
Length	420 mm
Operating mode	π-mode
Resonant frequency	2856 MHz
Energy gain	5–10 MeV
RF power	3–7 MW

equivalent to a co-axial transmission line supporting a transverse electromagnetic (TEM) mode, which couples power to neighbouring cells. This open geometry results in good inter-cell coupling of the electromagnetic fields making the structure more tolerant to machining errors. Figure 2 shows a photograph of the disk-array of an eight-cell PWT linac structure during brazing, and its outer tank envelope, which also serves as the vacuum envelope. Multiple variants of this novel linac structure have been successfully built and tested at RRCAT, and a 42 cm long, eight-cell PWT linac presently employed in the CUTE-FEL set-up has successfully accelerated the electron beam to 6.5 MeV consuming ~3 MW RF power. Though this structure is designed to accelerate electrons to 10 MeV consuming 7 MW RF power, reaching this stage is time-intensive since the structure has to undergo RF conditioning with gradually increasing RF power level and pulse width before its operation becomes stable at the rated power levels.

This note discusses the stages of commissioning experiments performed on the CUTE-FEL set-up for generation of THz radiation.

Stage 1: Experiments with an unbunched, low-energy electron beam from the electron gun injected directly into the PWT linac structure

In the design injector for CUTE-FEL, a schematic of which is shown in Figure 1, a 1ns FWHM bunch of electrons from a custom-built thermionic electron gun of 90 keV (Calabazas Creek Research, Inc., USA) is pre-bunched to ~30–50 ps in a sub-harmonic pre-buncher operating at 476 MHz, before injection into the PWT linac structure for further bunching to ~10 ps and acceleration to rated energy of 7–10 MeV. While the CUTE-FEL injector system has been built according to design, it could not be operated as designed since the RF power source for the 476 MHz sub-harmonic pre-buncher, which was to be custom-designed and built to our specifications by an outside company, is not yet available. In the absence of this RF power source, the sub-harmonic pre-buncher acts as a drift space and the 1 ns bunches from the electron gun are injected directly into the $\beta = 1$ PWT linac structure where they undergo acceleration and drastic bunching resulting in significant loss of charge. Here, β is the ratio of electron velocity to the phase velocity of light. Beam dynamics simulations for this configuration using the code PARMELA[6] estimate the peak accelerated current from the PWT linac with a root mean square (rms) relative energy spread of 0.5% necessary for lasing to be ~3 A.

Since a 1 ns long unbunched beam is injected directly into a 2856 MHz linac structure, the electron beam spans ~ three RF cycles in the linac. Consequently, the first few cells effectively select electrons out of the injected bunch that fall in a phase extent suitable for capture and acceleration, and this bunch is subsequently accelerated in the remaining cells of the linac. As the phase extent of bunches in this scheme is expectedly large, the accelerated bunches emerging from the linac have a large rms relative energy spread $\Delta E/E$ in the order of 22%. However, since the FEL interaction gains only from charge with an rms relative energy spread of 0.5%, the 'chopper' option in a post-processor of PARMELA is employed to eliminate charge having a larger relative energy spread. Figure 3 *a* shows the simulated energy spectrum of the total accelerated charge in the central bunch in stage 1, while Figure 3 *b* shows the zoomed version of Figure 3 *a* after selecting charge with an rms relative energy spread of 0.5%. Only 336 out of the total 1671 macroparticles in the accelerated bunch have an rms relative energy spread of 0.5%.

The first measurement of THz radiation from the CUTE-FEL set-up in this configuration was made in February 2011 using a liquid helium cooled bolometer [QMC, QGeB/2]. Due to the low available peak current (~3A) in the absence of a pre-buncher cavity, no further increase in THz radiation output was possible without increasing the peak current.

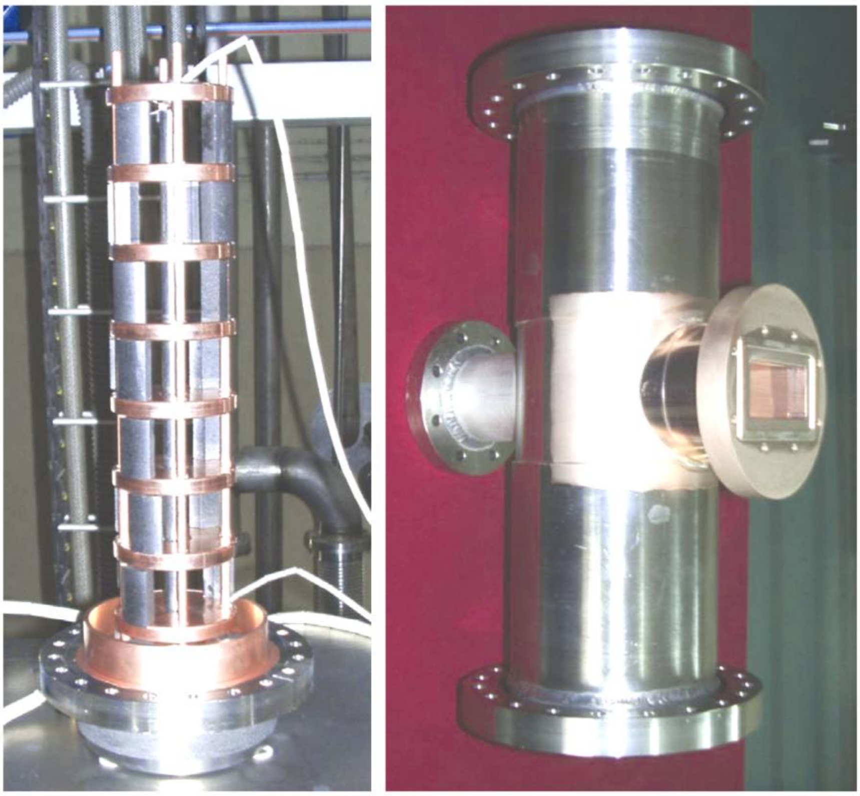

Figure 2. Disk array and tank envelope of 8-cell PWT linac just after brazing.

FEL and beam dynamics simulations

Simulations of CUTE-FEL with a 7 MeV electron beam impose a requirement of >30 A for the peak electron beam current with a relative energy spread < 0.5% for the FEL power output to saturate. At lower currents, build-up of coherence, which is a signature of lasing, may be initiated but the FEL power does not saturate. CUTE-FEL operates in an oscillator configuration

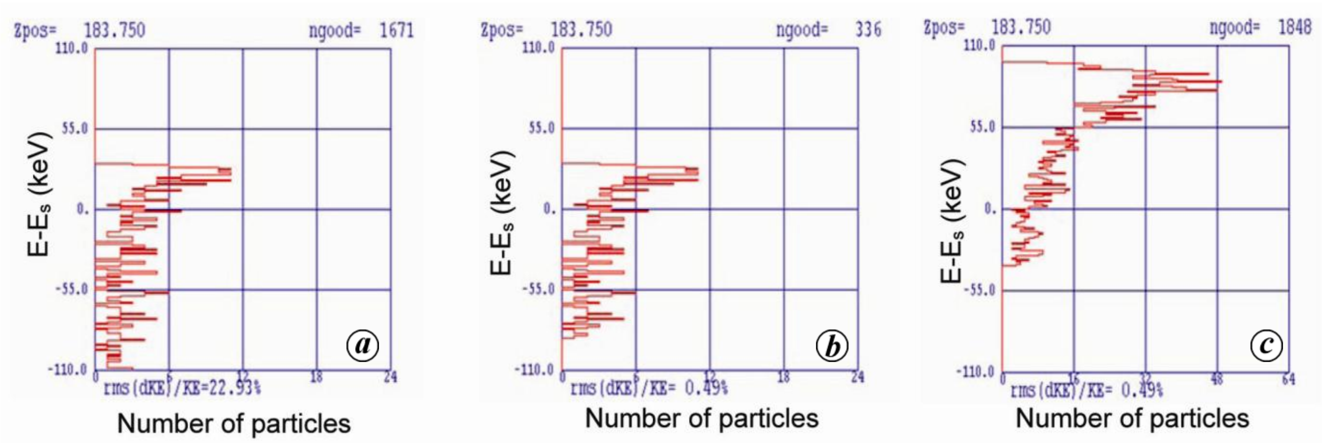

Figure 3. Electron beam energy spectrum at exit of eight cell PWT linac: (***a***) Total accelerated charge for stage-1 experiments without pre-buncher. (***b***) Fraction of accelerated charge within $\delta E/E \leq 0.5\%$ for stage-1 experiments without pre-buncher and (***c***) Fraction of accelerated charge within $\delta E/E \leq 0.5\%$ for stage-2 experiments.

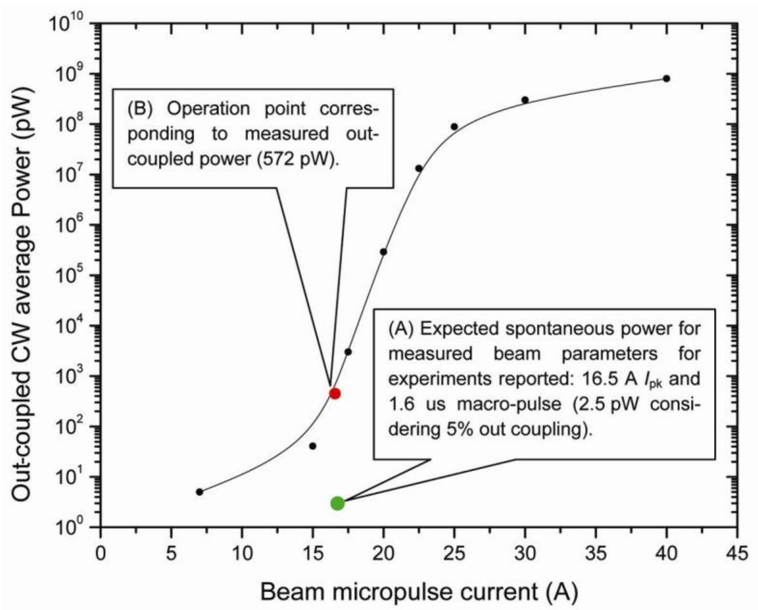

Figure 4. Expected variation of out-coupled THz power with beam current for a 7 MeV electron beam.

with a 4.1 m long optical cavity in which the round trip time of the optical radiation (27.3 ns) matches the spacing between micro-bunches from the electron gun operating at 36.615 MHz. FEL simulations show that it needs >180 round-trips of the optical radiation in the optical cavity of CUTE-FEL for coherence build-up, or lasing action, to start and for it to ultimately saturate with a peak electron beam current >30 A. Consequently, CUTE-FEL requires a macro-pulse width greater than 5 μs for the out-coupled power to saturate. Alignment of the axis of the optical cavity with the electron beam axis inside the optical cavity and tuning of the optical cavity length to precisely match the electron micro-bunch spacing are critical issues for lasing to initiate.

The continuous curve in Figure 4 shows a plot of the expected variation of out-coupled THz power from CUTE-FEL with the peak micro-pulse current in the electron beam at the design energy of 7 MeV and after 183 round-trips of the optical beam inside the optical cavity. This plot has been generated from computer simulations of CUTE-FEL using GINGER[7], a multidimensional [full 3D for macro-particle and 2D (r–z) for radiation], time-dependent code to simulate FEL interaction in single-pass amplifier as well as oscillator configurations. As seen in the plot, the power output varies relatively slowly with the peak current till ~15 A after which the slope changes significantly indicating build-up of coherence or initiation of lasing action. While initial expected average out-coupled power at a peak current of ~3 A is a few pW, the corresponding expected average out-coupled power at the point with a significant change of slope (> 15 A) is close to 500 pW, with a very fast increase of out-coupled power and small increase in peak current beyond this point.

In the absence of the RF power source for the originally planned 476 MHz sub-harmonic pre-buncher, the feasibility of incorporating a fundamental frequency pre-buncher at the S-band was studied through beam dynamics and RF simulations to increase peak current in the CUTE-FEL set-up from the initial estimate of ~3 A. A new pre-buncher design based on modified photocathode RF gun geometry was studied and a single-cell fundamental frequency pre-buncher was fabricated by modifying a 1.5 cell, S-band photocathode RF gun built earlier for another application. Beam dynamics simulations confirmed that this fundamental frequency pre-buncher could be mounted at the same location as that of the sub-harmonic pre-buncher causing minimum disturbance in the CUTE-FEL beam transport line. With ~250 W RF power fed to the fundamental frequency pre-buncher, the 1 ns FWHM bunches at 90 keV from the thermionic electron gun can be bunched to ~30 ps at the entry to the linac, which further bunches and accelerates the beam to rated energies with a significantly higher total charge transmission through the injector linac system. PARMELA simulations indicate that with the fundamental frequency pre-buncher powered on, charge with the required 0.5% rms energy spread in each micro-bunch is close to five times that without the fundamental frequency pre-buncher, which leads to an estimate of >15 A for the peak micro-pulse current for the present set of experiments. Since 1 ns electron pulses from the gun are injected into the fundamental frequency pre-buncher in these experiments, each electron pulse is distributed over three RF cycles in the fundamental frequency pre-buncher. Consequently, each electron pulse from the gun is broken into three bunches with a major fraction of charge contained in the centre bunch. Ignoring the side bunches, the phase extent of the charge in the central bunch is further reduced in the drift space between the pre-buncher and linac. Consequently, the accelerated bunch from the linac now has a significantly higher charge or peak current (>15 A) with the 0.5% rms relative energy spread required for FEL operation compared to stage-1 experiments. Figure 3 *c* shows the energy spectrum for this fraction of charge in an accelerated bunch with ~1848 particles and an rms relative energy spread of 0.5%. This is approximately five times the number of particles with the same rms relative energy spread for stage-1 of experiments without the pre-buncher, as shown in Figure 3 *b*. In addition to this charge that contributes mainly to FEL action, there is a significant amount of additional charge at other energies too which contributes to a larger relative energy spread in the total accelerated electron beam emerging out of the PWT linac. PARMELA simulations estimate that if the rms relative energy spread window is increased from 0.5% to 1% and if charge distributed over all the three micro-bunches corresponding to each electron gun pulse is considered, the total accelerated charge transmitted through the PWT linac with the fundamental frequency pre-buncher powered on is a little more than twice the total charge without powering the pre-buncher. This is the charge per pulse that is measured in the experiments using an Integrating Current Transformer (ICT; Bergoz), since it cannot discriminate between micro-bunches spaced 350 ps apart. Therefore, the measured doubling of charge in these experiments agrees well with predictions of PARMELA simulations for the total charge transmission.

Stage 2: Experiments with low energy electron beam from gun bunched in fundamental frequency pre-buncher before injection into PWT linac structure

Experiments for measurement of THz radiation generated in the CUTE-FEL set-up with the fundamental frequency pre-buncher were performed after modification of the low-level RF line (LLRF) to simultaneously power two S-band structures from a single LLRF system. The phase difference between RF fed to the linac and the pre-buncher structures is now crucial since in a wrong phase, the transmitted accelerated charge can be much lower than that in the absence of the fundamental frequency pre-buncher. After optimization of phase, experiments incorporating the newly built fundamental frequency pre-buncher show a doubling of the total accelerated charge transmitted through the PWT linac. These experiments used an ICT (Bergoz, ICT-122-020-5:1) with an output pulse duration of 20 ns to measure the charge in each micro-bunch. Figure 5 shows ICT traces of the pulse train before and after the linac with the fine pulse structure of the electron beam clearly resolved by the ICT. Since there is good agreement between measured and simulated values of enhancement of charge transmission for the 1% rms relative energy spread window measured in these experiments, it is expected that charge in the 0.5% rms relative energy spread window required for FEL operation should be close to five times that without the fundamental frequency pre-buncher, as predicted by simulations.

Experiments for the measurement of out-coupled THz power from the CUTE-FEL set-up were repeated with the fundamental frequency pre-buncher powered on. Figure 6 shows a typical trace of the measured bolometer signal corresponding to the out-coupled THz power in the modified configuration. The beam energy used in these experiments was ~5.5 MeV with an expected photon wavelength of ~250 μm. The measured average out-coupled THz power of 570 pW at 2 Hz operation of CUTE-FEL translates to a photon flux of $\sim 6.6 \times 10^{11}$ photons/s, which is more than 100 times larger than the expected spontaneous emission power for the measured beam parameters used in the experiment.

Discussion of results and plans for the future

For spontaneous emission from a bunch of accelerated electrons, the radiated power varies linearly with the number of electrons n_e in the bunch, since each electron in the bunch radiates independently. As coherence builds up gradually due to initiation of lasing, the power output has stronger dependence on beam current, as is visible in a change in slope in Figure 5 beyond 15 A peak current. For full coherence, the power output varies as n_e^2. For FELs, saturation usually sets in much before the n_e^2 dependence is achieved. For CUTE-FEL, simulations with a 7 MeV electron beam indicate that saturation of output power is expected beyond 30 A peak current. For the electron beam energy of 5.5 MeV used in the experiments, the expected spontaneous emission power for the measured electron beam parameters used in the experiments, which is proportional to n_e as discussed above, is a few picowatt (pW). The measured power of 571 pW therefore indicates a nonlinear dependence on n_e, which can only be due to some build-up of coherence. Point A in Figure 4 shows the expected spontaneous emission power for the electron beam parameters employed in the experiment. Point B in the same figure shows the measured power of 571 pW, which corresponds to a peak electron beam current of 15 A.

At a lower beam energy, the curve shown in Figure 4 is expected to be modified with lasing action expected to initiate and saturate at higher peak currents due to higher losses on account of the larger optical beam size in the optical cavity at longer wavelength. However, the vacuum beam-pipe could act as a waveguide for the optical beam compensating the losses to some extent, which is not considered by the simulation code used to generate Figure 4. Further, this code studies the growth of radiation inside the optical cavity starting from shot-noise, and it is known that simulations in this initial stage of amplification of radiation may not be accurate. Due to

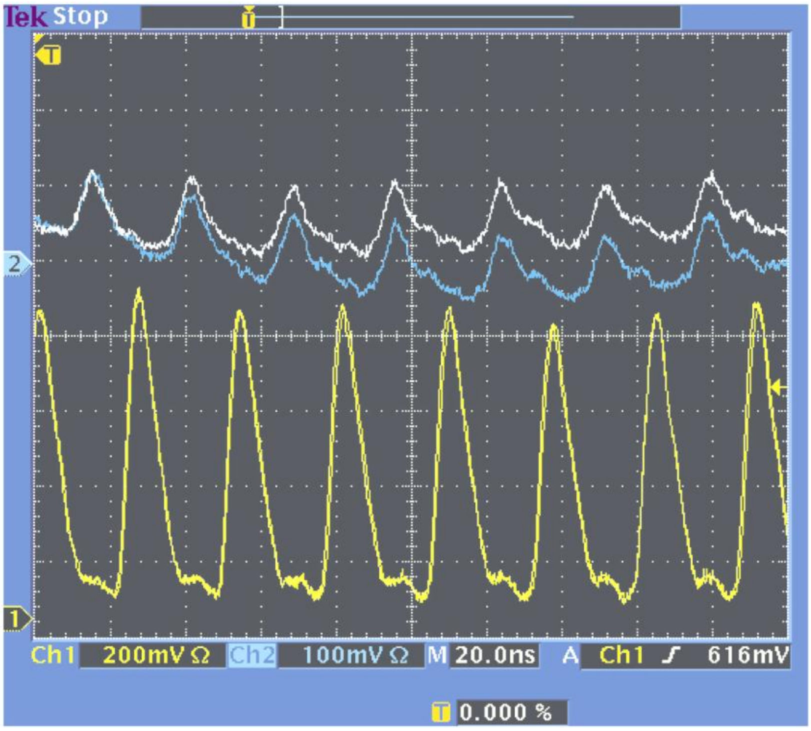

Figure 5. ICT traces of the electron beam: yellow, before and blue, after the linac.

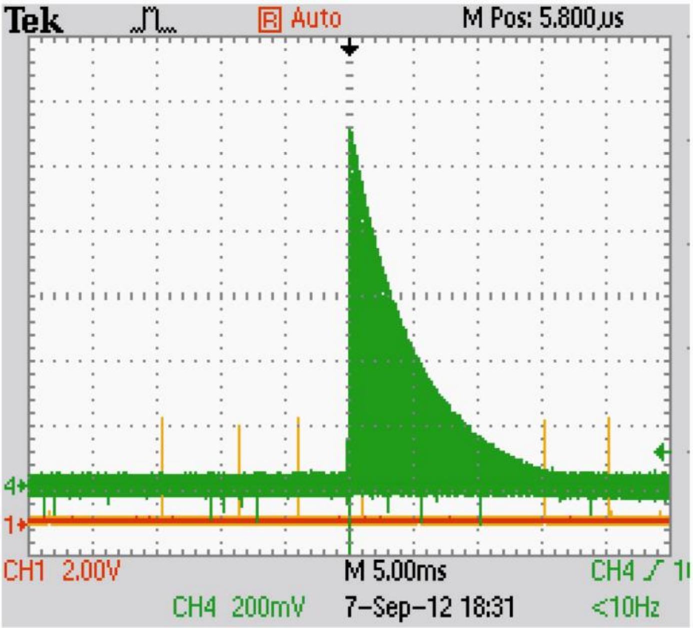

Figure 6. Bolometer trace of the measured out-coupled THz power.

some bunching of electrons coming from the linac, the initial radiation emitted may not be purely spontaneous emission, but somewhat enhanced spontaneous emission, as a result of which the FEL instability does not really start from shot-noise. These could be possible reasons for the 570 pW power measured at an estimated peak current ~15 A for a 5.5 MeV electron beam, while this power level is actually expected at similar current levels for a 7 MeV electron beam after initiation of lasing action, as shown in Figure 5. These aspects are presently being examined in greater detail. However, the fact that the measured out-coupled power is more than 100 times higher than the expected spontaneous emission power for the beam parameters used in the experiments indicates the initiation of build-up of coherence in the radiation from the CUTE-FEL set-up.

Before operation at design accelerating gradients, RF linac structures need to be 'conditioned', which involves operation of the structure for long durations with gradually increasing RF pulse width and power. A high repetition rate RF system is usually employed for the purpose in order to minimize the time required to reach the desired field gradient levels. Our RF system is custom-built for the design repetition rate of <10 Hz for CUTE-FEL, which by design is a low average power machine with low duty cycle. This resulted in the long time (>1 year) it took to achieve the required levels of conditioning in the CUTE-FEL injector linac system. An alternate option is to employ longer accelerating structures at lower average field gradients, which eliminates conditioning at high RF power levels. Towards this, a prototype 12-cell PWT linac structure has been successfully built and tested and the final 12-cell and 20-cell variants of a PWT linac structure are presently awaiting final assembly by brazing. The 20-cell structure will be capable of accelerating the beam up to 15 MeV consuming close to 10 MW RF power.

In order to further increase THz power output from CUTE-FEL, operation of the injector linac in the design configuration with the powering of the sub-harmonic pre-buncher is essential. Towards this, alternate routes of development of a 476 MHz RF source to power the sub-harmonic pre-buncher have been explored and it is expected that initial experiments will be possible in the near future with a low-power prototype 476 MHz RF source developed in-house. A 12-cell PWT linac structure that will be brazed in the near future is also proposed to be employed to increase the energy of the electron beam to design value of 7–10 MeV. Both these developments are expected to result in a further significant enhancement of THz power output from the CUTE-FEL set-up with operation at a shorter wavelength between 80 and 150 μm.

In conclusion, a signature of build-up of coherence has been observed in the CUTE-FEL set-up, which has resulted in more than 100 times higher out-coupled

THz power from the device compared to the expected spontaneous emission power for the beam parameters used in the experiment. Further enhancement of THz power is possible with the powering of the sub-harmonic pre-buncher cavity to increase peak electron beam current to the design value, towards which efforts are presently underway.

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Science Writing in India

Current Science introduces a special feature on 'Science Writing in India' as a web special. The collection of articles written by well-known science writers and editors reflects how science writing is practiced in India. There are several challenges and issues that a science journalist faces. This special feature is an attempt to learn and understand from some of the leading science writers in the country on the state of science journalism. T. V. Padma pens down the challenges faced by a science scribe and feels that courses on journalism and mass communication in the national universities of many countries, do not have, an optional course or paper in science journalism and how blogging, podcasts and multimedia offer newer ways to disseminate information (*See*: Science journalism in South Asia – untapped potential). But Subhra Priyadarshini views that for full-time reporters and editors, who chase news as a day job, retaining the quality and freshness of blogs is a challenge (*See*: Is blogging journalism and other questions). With many media outlets being closed for science journalists, freelancing is slowly emerging in India. Nidhi Jamwal in her article 'Science for all' offers a few tips on how to take on freelancing in India, especially if a freelance science writer for whom the payment can never match up to the salary of a full-time journalist. But, like an employed science journalist, even a freelance science writer acts as a broker between scientists and the general public, she notes. Seema Singh shares the elements of being a science writer (*See*: The (science) writing life). Sopan Joshi who writes in Hindi says if one manages to put together good material into a good narrative, the readers respond with the kind of love one never gets from the English readership (*See*: Science reporting in Hindi). Science reporting is event oriented. Archita Bhatta who reports primarily on climate change writes that media coverage peaks correspond with extreme weather. (See: Lessons for a climate change scribe!). Unlike their peers, Shubashree Desikan and A. S. Ganesh in a conversational style put together their views on writing science for children (*See*: Writing science for school children).