T.2 : The CUTE-FEL Project

S. Krishnagopal (skrishna@cat.ernet.in), B. Biswas, S. K. Gupta, U. Kale, A. Kumar, V. Kumar, S. Lal, P. Nerpagar, K. K. Pant and A. Patel

1. Introduction

The Beam Physics and FEL Laboratory of RRCAT is building a Compact Ultrafast TErahertz Free-Electron Laser (CUTE-FEL), both as a technology demonstrator, as well as for applications in the relatively unexplored terahertz region of the electromagnetic spectrum. As part of this effort, we have also developed expertise and technology in associated areas such as accelerating cavities, insertion devices and pulsed power-supplies.

In this article we discuss, very briefly, free-electron lasers and their relevance to future light sources, and focus on the tasks we have undertaken, the challenges we have faced, our efforts to overcome them, and the milestones we have achieved.

2. Free-electron lasers

Free-electron lasers (FELs) are a new kind of classical laser in which the electrons are not bound in atomic or molecular systems. The source of these 'free' electrons is an electron accelerator, such as a linac or a synchrotron. In essence, the FEL converts the kinetic energy of the electrons into coherent electromagnetic radiation. This conversion takes place in the catalytic presence of a static magnetic field that is produced by a device called an undulator.

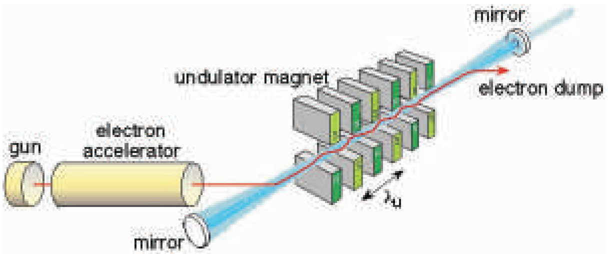

Fig.T.2.1. Schematic of a typical free-electron laser.

Fig.T.2.1 shows a schematic of an FEL. The three major components of the device are: (i) the electron accelerator, (ii) the undulator, and (iii) the resonator cavity. An electron accelerator can produce a beam of relativistic electrons with energy ranging from MeVs to GeVs, and peak currents ranging from hundreds of milli-amperes to tens of kilo-amperes. This electron beam passes through the undulator, which produces a transverse magnetic field (*i.e.* perpendicular to the direction along which electron beam is travelling) that is static in time but varying sinusoidally in space. The amplitude of this magnetic field is typically a few kilo-gauss, and the period is typically a few centimetres. This kind of magnetic field can be produced either with permanent magnets or with electromagnets. Permanent magnets are preferred when one wants to produce magnetic fields with shorter periods.

If the FEL has to run as an oscillator, there has to be a resonator cavity as shown in Fig.T.2.1 (in blue), which provides the positive feedback. One usually uses a Fabry–Perot resonator with mirrors at both ends. Radiation is typically coupled out through a hole in one of the mirrors or sometimes by putting a partially reflecting mirror in the cavity. When the FEL is to be operated as an amplifier, the resonator cavity is absent, but then a coherent seed has to be provided.

In a world awash with photons from 'conventional' lasers and synchrotron radiation sources, FELs are exciting sources of electromagnetic radiation because of the following characteristics of the radiation:

(a) the wavelength is very broadly tuneable, from the terahertz to x-rays;

(b) in principle, very high power operation is possible, because the medium, electrons, cannot be broken down;

(c) very short, femtosecond, pulses can be obtained at any wavelength.

One of the most exciting things about an FEL is the capability of operating it with neither a resonator cavity nor any seed radiation—the Self-Amplified Spontaneous Emission (SASE) principle. SASE FELs are now seen as the most promising candidates for an x-ray laser, and as fourth-generation light sources, and a number of hard and soft x-ray FELs are presently being built around the world. More details on FELs and their applications can be found in review articles [1-2] and text-books [3-4], and the references therein.

3. The CUTE-FEL project

3.1 Overview

Figure T.2.2 shows a schematic of the CUTE-FEL [5]. Major parameters of the CUTE-FEL are given in Table 1. The injector will be a 90 kV pulsed thermoionic gun which is under procurement – presently we are using a 40 kV gun that was built by another group at RRCAT. The beam from the gun will be focussed through two solenoids into a 476 MHz pre-buncher that will bunch the 1 ns beam into 20 ps long bunches, simultaneously increasing the peak beam current. The beam from the pre-buncher will then pass through a 2856 MHz buncher, which will accelerate the beam to around 3-4 MeV, and compress it to around 10 ps. The beam will then go through the main accelerating structure, also operating at 2856 MHz, where it will be accelerated to around 10 MeV. The 2856 MHz RF cavities are powered by a 10 MW klystron, which is driven by a 25 MW, 10 μs, pulsed modulator. This beam will finally be transported in an achromatic transport line, through a 2.5 m long undulator, which will cause the beam to emit coherent terahertz radiation. An important part of our efforts has been focussed on technology development – of linear accelerators, insertion devices, and high-power microwaves.

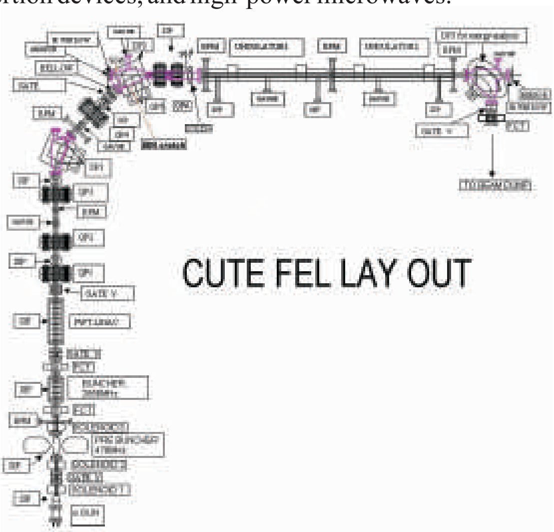

Fig.T.2. 2. Beamline layout for the CUTE-FEL.

Parameter	Value
Electron beam energy	10-12 MeV
Peak beam current	20 A
Beam micro-pulse	10 ps @ 36.62 MHz
Beam macro-pulse	10 μs @ 10 Hz
Undulator period	5 cm
Undulator length	2.5 m
Undulator parameter	0.8
Radiation wavelength	50-100 μm

Table 1. Main parameters of the CUTE-FEL.

3.2 Accelerating structures – pre-buncher, buncher and linac

A major challenge has been the indigenous development of the linear accelerator technology. We have built two types of accelerating structures – a 476 MHz pre-buncher cavity, and 2856 MHz buncher and linac cavities.

The purpose of the pre-buncher is only to bunch and not to accelerate. It therefore has smaller field-gradients (around 1-2 MV/m). Also, requirements on the geometrical tolerances and surface finish are somewhat relaxed. We designed and tested a cavity with nose-cones and first fabricated an aluminium prototype for RF qualification. Based on the feedback, we redesigned the final structure and had it fabricated with SS 304L. This structure, shown in Fig.T.2.3, has been leak-checked and RF qualified, and we are in the process of establishing vacuum. We measured a Q of 858, and a resonant frequency of 474.3 MHz in air. Once in vacuum the frequency will increase by around 800 kHz, and final tuning to 476 MHz will be done using the tuners. Fig.T.2.4 shows the electric field profile for this cavity.

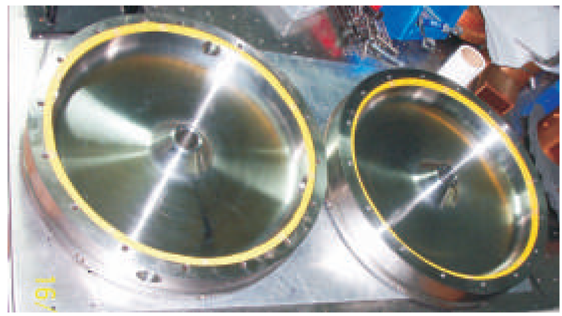

Fig.T.2. 3. Photograph of the two halves of the fabricated 476 MHz pre-buncher cavity.

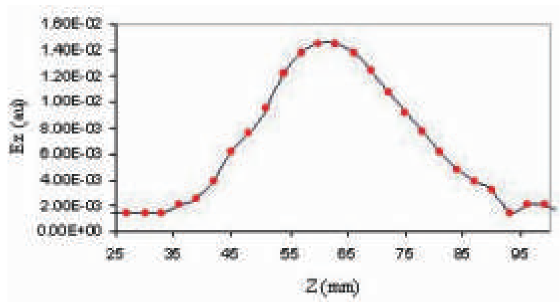

Fig.T.2. 4. Bead-pull results on the 476 MHz pre-buncher cavity, showing the on-axis electric field.

The 2856 MHz buncher and linac structures presented a much greater challenge [6, 7]. They involved precision machining and controlled atmosphere brazing of Oxygen Free Electronic (OFE) grade copper components. OFE copper is a soft material, and it is therefore difficult to machine it to the required geometrical tolerances (around 30 μm) and surface finish (0.2 μm R_a). The situation is complicated by the fact that the material will see an ultra-high vacuum (UHV) and high electromagnetic field environment, which places constraints on the engineering techniques that can be employed.

We chose to build a rather unconventional structure – the

Plane-Wave Transformer (PWT) linac, which is a standing-wave structure operating in the π mode. It is a very open structure, with strong coupling between the cells, and consequently with relaxed fabrication tolerances. When we started out on this enterprise, there was little experience in these areas in the country. After building a number of prototypes and ascending a steep learning curve, we successfully built a four-cell, 21 cm long structure, PWT3, that was fabricated to the required tolerances and surface finish, which can hold UHV ($1x10^{-8}$ torr), resonates at the desired frequency of 2856 MHz, has a loaded Q of 8000, and which has accelerated an electron beam to 4.5 MeV, corresponding to an accelerating gradient of around 28 MV/m. We have also built and qualified a prototype of an eight-cell structure, and components of the final 8-cell structure have been machined and are ready for brazing. In addition we have also built and cold-tested a second four-cell structure, PWT4, which has better RF properties than PWT3. Both PWT4 and the prototype 8-cell structure are shown in Fig.T.2.5. The four-cell structure will serve as the buncher, and the eight-cell one as the accelerator, in future experiments. Results of the bead-pull test on PWT4 are shown in Fig.T.2.6.

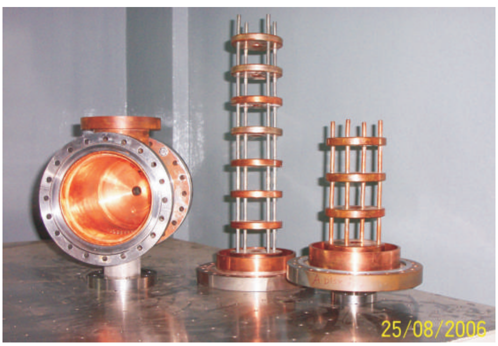

Fig.T.2.5. Photograph of the central part of the 4-cell PWT4 structure, the disk-array, which will serve as the buncher for the CUTE-FEL, and of the prototype 8-cell accelerator structure. The vacuum envelope for PWT4 is also seen at the left.

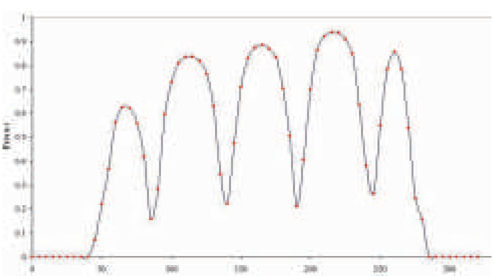

Fig.T.2.6. Bead-pull test for PWT4. The two narrower peaks on either side correspond to the two end half-cells, and the other peaks correspond to the three central full-cells of PWT4.

3.3 Insertion devices - undulator

The undulator we have built is a planar, Halbach configuration, pure permanent magnet undulator, 2.5 m long, built in two section of 1.25 m each [8]. A total of 400 magnets were used, each of size 12.5 x 12.5 x 50 mm^3, giving an undulator period of 50 mm and a total of 50 periods. The magnets are powerful NdFeB magnets, with a remnant field of 1.2 T. The undulator was designed for a nominal undulator parameter of 0.8, which corresponds to a magnetic field of 0.17 T and requires an undulator gap of 35 mm.

Fig.T.2.7. Both 1.25 m sections of the undulator. The corrector coil can be seen on the far end.

The undulators presented a completely different technological challenge compared to the accelerating structures. The magnetic field has to be uniform to better than 1% over the entire length of 2.5 m. To achieve this, one requires strict quality control over the variation in magnetization strength from magnet to magnet and in the geometrical tolerances of the support structure. The former was achieved by measuring the magnetization of 575 magnets, choosing the best 400, and then deriving the optimal arrangement of the magnets using a *simulated annealing* algorithm. In addition, the material close to the magnets should be strictly non-magnetic. In our case, though we chose a nominally non-magnetic material like SS316 for the magnet holders, it had to be annealed in order to reduce the permeability to below 1.01. In addition, since this is the first variable-gap undulator in the country, a gap-variation mechanism had to be designed to ensure that the variation in the undulator gap was less than 35 μm over the entire length of 2.5 m. Finally, since the forces between the magnets are very large, the support and clamping structures had to be designed to accommodate forces of around 1 tonne, and still maintain the strict geometrical tolerances.

The undulator has been fabricated (see Fig.T.2.7) and field-mapped using a three-axis teslameter with a high spatial resolution (0.25 mm^3) probe [9]. The quality of the undulator is within specifications. For example, we had calculated a requirement of a field quality of better than 1%

in $\Delta B/B$ – we obtained 0.9% in one segment and 0.7% in the other. We have also measured the optical phase error (less than 2 degrees with steering compensation and gap tuning), and the beam wander (less than 1.5 wiggle amplitudes). The rms error in the undulator period was measured to be less than 100 μm. The field quality and the straightness of the trajectory have been improved by the use of corrector coils and by shimming the magnets, as shown in Fig.T.2.8.

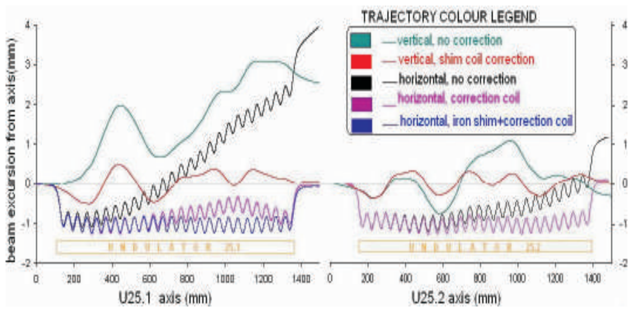

Fig.T.2.8. Results of the field-mapping on both sections of the undulator, presented in terms of the electron trajectory through the undulator. It can be seen that by using corrector coils and shims, the trajectory can be straightened out to better than 1 mm.

3.4 Pulsed power-supply – klystron modulator

We have also developed a 25 MW, 10 μs, pulse modulator for powering a 10 MW, S-band klystron [10]. This klystron has a rated impedance of 194 ohms, and at full rating draws a current of 355 A, for a voltage of 69 kV.

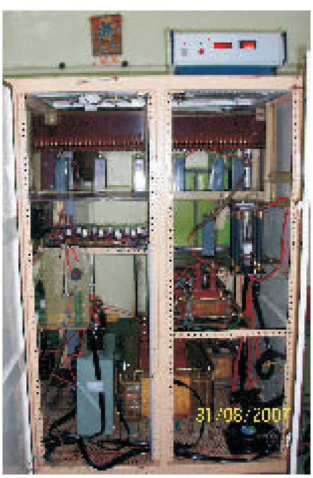

Fig.T.2.9. A view of the klystron modulator cabinet, showing the DC power supply at the bottom, and the PFN at the top.

The modulator we have developed is a standard long-pulse, line-type modulator. The DC power supply produces 12 kV DC from the 3-phase line voltage, with a ripple less than 1%. It consists of a 3-phase motorized variac with an EHT transformer, and two six-pulse rectifiers in series, followed by an LC-filter. A charging choke is used to double this voltage to charge the Pulse Forming Network (PFN) to a maximum of 24 kV. This is a Gullimen-E type PFN with 15 sections of mutually-coupled cascaded low-pass filters. This reduces the non-linearity of the network leading to pulses with better trailing edge response, thus enhancing the energy efficiency of the modulator. The PFN is discharged by a thyratron switch into the primary of a pulse-transformer, which has a nominal turns ratio of 1:6. The pulse transformer has 4 stacks of closed type 50 μm Cold Rolled Grain Oriented (CRGO) laminations, consisting of two primary and two secondary windings on a tapered bobbin. Two primaries with suitable capacitors on the high voltage and low voltage side also provide isolation for the klystron filament power supply, forming a low-pass filter. The pulse transformer has been also provided with ten biasing turns to compensate for droop for its operation at the rated voltage. The modulator cabinet, one view of which is shown in Fig.T.2.9, is provided with proper grounding, RF shielding and other safety features. Fig.T.2.10 shows the output pulse at the secondary of the pulse transformer. With this modulator we have extracted up to 7 MW of RF power from the klystron.

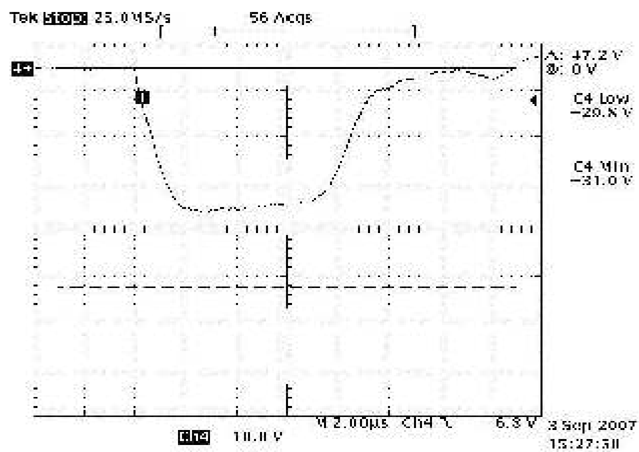

Fig.T.2.10. A clean rectangular pulse from secondary of the pulse transformer.

4. Beam acceleration and production of terahertz radiation

Once the individual sub-systems had been designed, developed and tested, the first step was to actually accelerate beam through the PWT linac structure. To this end, a test beamline was built, and a 40 keV, 2 μs electron beam was accelerated through the 4-cell PWT3 linac. Since at this stage, the pre-buncher was not used, simulations predicted acceleration of around 25% of the charge in the un-bunched input beam, to an energy of 3.7 MeV [11]. Our measurements of 30 mA current in 1.7 μs pulses at 3.7 MeV correspond to a transmission of around 18%. With subsequent conditioning of the linac, the highest accelerated beam energy obtained in this experiment was 4.5 MeV with around 4 MW RF power being fed into the linac. Details of the acceleration results obtained are shown in Fig.T.2. 11.

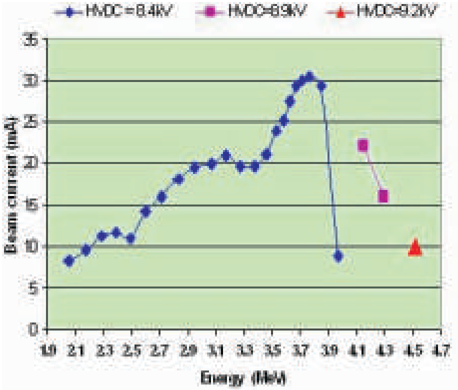

Fig.T.2. 11. Results of the acceleration experiments. The highest energy achieved is 4.5 MeV, corresponding to an accelerating gradient of around 28 MV/m. The highest accelerated current is 30 mA, at a lower energy. Note that there was no pre-buncher in these experiments.

The next step was to put beam through the undulator. After energy analysis, the accelerated electron beam was transported through one 1.25 m undulator segment, and dumped into a Faraday cup. About 64% transmission was obtained with an undulator gap of 40 mm. With this transmission, calculations show that we must be producing terahertz radiation at around 500 μm, with around 10 μW power in 2 μs pulses. Unfortunately, due to lack of the requisite equipment, we are at present not in a position to actually measure this radiation.

Fig.T.2.12. Final beamline of the CUTE-FEL, under assembly.

We are now gearing up for experiments with the optical cavity so that we can look for spontaneous emission, and subsequently for stimulated emission as well. The final vacuum beam-line for the CUTE-FEL has been designed, fabricated, and is in an advanced stage of assembly, (see Fig.T.2.12) and we will commence experiments soon.

5. Conclusions

We are in an advanced stage in the construction of the CUTE-FEL. In the process, we have mastered the technology of accelerating structures, insertion devices, and klystron modulators. We have built only the second PWT linac in the world, and achieved a significant accelerating gradient of around 28 MV/m. We have built the first variable-gap undulator in the country. We have built the highest (peak) pulsed-power klystron modulator in the country.

All this has been possible only because these activities were pursued in a collaborative framework. We have received support and assistance from colleagues at RRCAT, too numerous to list. However, we must make special mention of Sanjay Chouksey and Vijendra Prasad, who provided mechanical engineering support for the linac as well as the undulator. Our collaborative network extended beyond RRCAT. Our brazing efforts started at the Defence Metallurgical Research Laboratory (DMRL), Hyderabad, and presently continue at the Liquid Propulsion Systems Centre (LPSC), Bangalore. Our precision machining efforts commenced at United Engineering, Mumbai, and presently continue at the Indo-German Tool Room, Aurangabad. We thank all those who have supported and contributed to the CUTE-FEL project. Finally we thank the leadership at RRCAT, at all levels, for their support and encouragement to our activities – especially when times have been tough, and the going slow.

References

1. K.-J. Kim, A. M. Sessler, Science 250, 88 (1990).
2. S. Krishnagopal, V. Kumar, S. Maiti, S. S. Prabhu, S. K. Sarkar, Current Science 87, 1066 (2004).
3. *Free-Electron Lasers*, C. A. Brau, Academic Press, San Diego, 1990.
4. *Free-Electron Lasers*, T.C. Marshall, Macmillan, New York (1985).
5. S. Krishnagopal *et al.*, *Proceedings of the 2006 International Free-Electron Laser Conference*, 27 August – 1 September 2006, Berlin, Germany, p. 496.
6. K.K.Pant *et al.*, CAT Internal Report, CAT/2002-08 (2002).
7. A. Kumar, K. K. Pant, S. Krishnagopal, Phys. Rev. ST Accel. Beams **5**, 00033501 (2002).
8. V. Kumar, S. Chouksey, S. Krishnagopal, *Proceedings of the DAE-BRNS Indian Particle Accelerator Conference-2003*, Indore, Editors: S. C. Bapna, S. C. Joshi, P. R. Hannurkar, (Allied Publishers Pvt. Ltd., New Delhi, 2003), p. 359.
9. B. Biswas, V. Kumar, S. Chouksey, *Proceedings of the DAE-BRNS Indian Particle Accelerator Conference-2005*, Kolkata, Ed: V. S. Pandit, p. 89.
10. U. Kale, R.K. Gupta, P. Nerpagar, K.K. Pant, S. Krishnagopal, Proc. International Linac Conference, Gyeongju, Korea, August 2002.
11. K. K. Pant *et al.*, *Proceedings of the DAE-BRNS Indian Particle Accelerator Conference-2006*, 1-4 November 2006, Bhabha Atomic Research Centre, Mumbai, (InPAC 2006 Organizing Committee, Mumbai, 2006), p. 44.