FEL ACTIVITIES IN INDIA

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Abstract

We are building a Compact Ultrafast TErahertz Free-Electron Laser (CUTE-FEL), designed to lase from 50 – 100 μm. The FEL will be driven by a 10-15 MeV electron beam from a Plane-Wave Transformer (PWT) linac. The undulator is a 5 cm period, 2.5 m long PPM planar undulator. We present details of the FEL design and the present status of activities. We also present very preliminary plans for a short-wavelength SASE FEL in India.

INTRODUCTION

FEL activity in India is presently restricted to the Raja Ramanna Centre for Advanced Technology, Indore, where a terahertz FEL is under construction. Earlier, however, there was some activity at Pune University, where a 26 mm period, 39 cm long pure permanent magnet undulator was built and characterized [1]. At the Institute for Plasma Research, Ahmedabad, there was interest in FELs for plasma heating and diagnostics. A 50 period electromagnet undulator was developed, a 300 keV sheet electron beam from a Tesla transformer was transmitted through this undulator, and spontaneous emission was observed [2].

In this paper we focus on ongoing activities at RRCAT, and present briefly our plans for the future.

THE CUTE-FEL PROJECT

The terahertz is a relatively unexplored part of the electromagnetic spectrum, and there is presently substantial interest in terahertz sources. For an FEL the terahertz is attractive because the long wavelength allows for higher gain, and reduces the requirements on the beam current and quality. A THz FEL is therefore a good green-field FEL project.

The Compact Ultrafast TErahertz FEL (CUTE-FEL) project aims to lase between 50-100 μm. The layout of the beamline is shown in Figure 1. The main parameters of the FEL are given in Table 1.

The electron source is a thermionic electron gun, that will provide 90 kV, 1 nC, 1 ns (FWHM) electron pulses at 36.62 MHz. The design normalized rms beam emittance is 5π mm-mrad, and the rms energy spread will be better than 1%. This gun is under procurement. In the meantime we continue experiments with a 40 kV, 2 μs, triode gun that was built by another group in RRCAT [3].

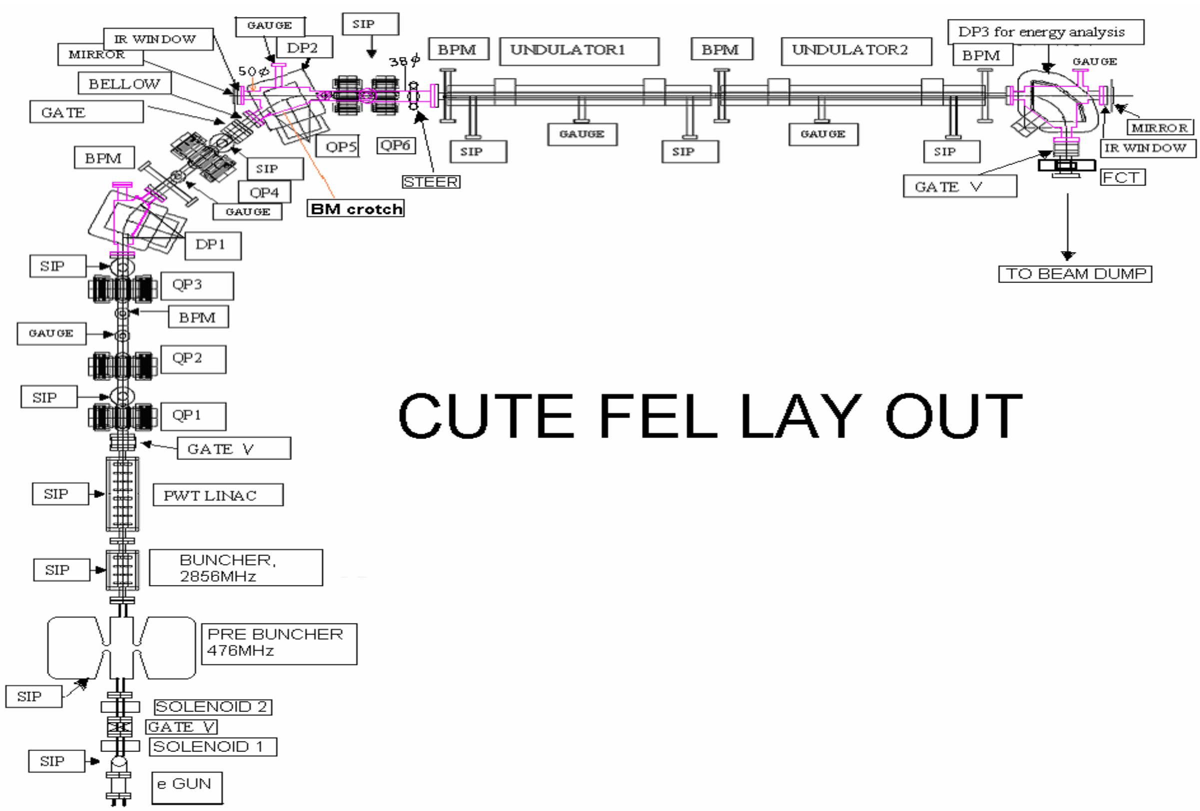

Figure 1: Beam-transport line for the CUTE-FEL.

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The electrons from the gun will be bunched in a 476 MHz pre-buncher, which has been designed by us and is presently being fabricated. The design is a standard re-entrant pillbox cavity, and will compress the beam by a factor of around 18.

The buncher at 2856 MHz will be a 4-cell Plane Wave Transformer (PWT) structure, and the linac itself will comprise up to two 8-cell structures to go to a maximum energy of 15 MeV. More details on the PWT structure, which we have developed ourselves, are given in a later section.

Table 1: Main parameters of the CUTE-FEL

Parameter	**Value**	**Unit**
Energy	10-15	MeV
Peak current	20	A
Micro-pulse	20 @ 36.62	ps @ MHz
Macro-pulse	8 @ 10	µs @ Hz
Und. period	5	cm
Und. length	2.5	m
Und. param.	0.8	
Wavelength	50-100	µm

The undulator is a standard Halbach configuration, planar PPM undulator, using NdFeB magnets. It has a period of 5 cm and a total length of 2.5 m. We have performed detailed design simulations using the code TDAOSC [4] AND GENESIS 1.3 [5]. In order to make the FEL compact, we have tried to keep the optical cavity as short as possible – it is only 4.1 m long. The resonator is near-concentric, to provide good mode stability.

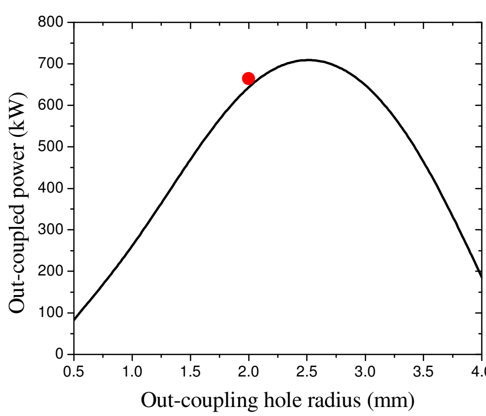

Figure 2: Optimisation curve for the size of the out-coupling hole.

Radiation is out-coupled through a hole at the centre of one of the gold-plated copper mirrors. The optimal hole radius, to maximize the out-coupled power while maintaining a good mode profile, was determined to be 2 mm (see Fig. 2). For our design we get a peak out-coupled power of around 0.5 MW. The small-signal gain is 88%, while the round-trip loss is 15%.

Figure 3 shows the variation of the FEL beam size down the undulator. At the entrance and exit of the undulator the maximum 1/e beam radius is around 5 mm. Note that the matched rms vertical beam size of the electron beam within the undulator is 0.8 mm.

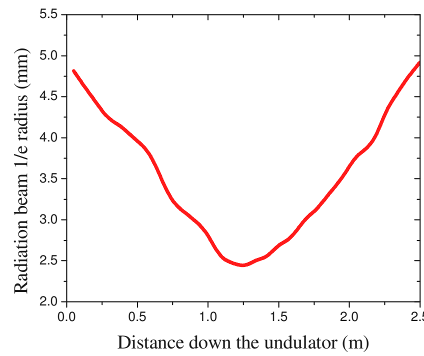

Figure 3: Size of the radiation beam as a function of distance down the undulator.

UNDULATOR

The 5 cm period, 2.5 m long PPM undulator has been constructed [6] in two equal segments of 25 periods each (Fig. 4). The undulator gap can be varied from 20-100 mm. The magnets are made of NdFeB, each 12.5 x 12.5 x 50 mm^3 in size. Individual magnets were characterized, and their arrangement in the undulator determined using a global optimisation (simulated annealing) algorithm. Field measurement of the assembled undulator segments was done using a three-axis Hall probe (Senis GmbH), with a spatial resolution of 0.1 mm.

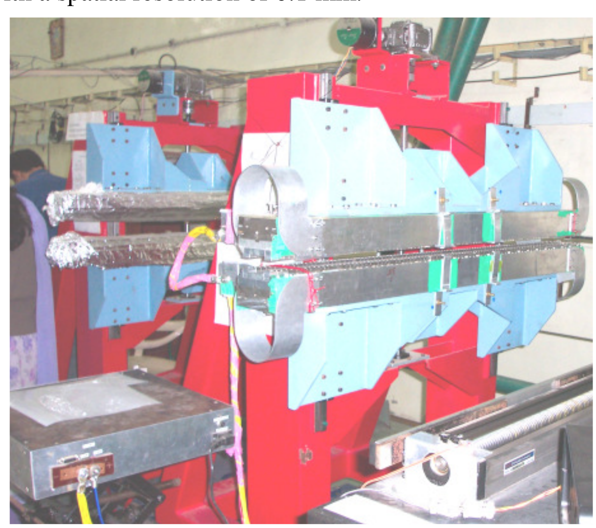

Figure 4: A view of the two undulator segments, each of length 1.25 m.

A summary of the measurements is given in Table 2. It can be seen that almost all the parameters are within the design specification. Our initial measurements showed that the beam trajectory through U25.2 had a degree of drift. To correct this we built a corrector coil that gives a small, 0.77 G, vertical field. With this correction the trajectory straightens out to within acceptable limits (Fig. 5). Further improvements can be done by shimming the magnets.

Table 2: Design and measured parameters of the two undulator segments

Parameter	**Design value**	**U25.1 measured**	**U25.2 measured**
Error in peak field	< 1%	0.9%	0.7%
Error in period	< 100 μm	82 μm	85 μm
rms phase-shake	< 5°	2°	2°
Beam wander	< 1	1.14	0.33

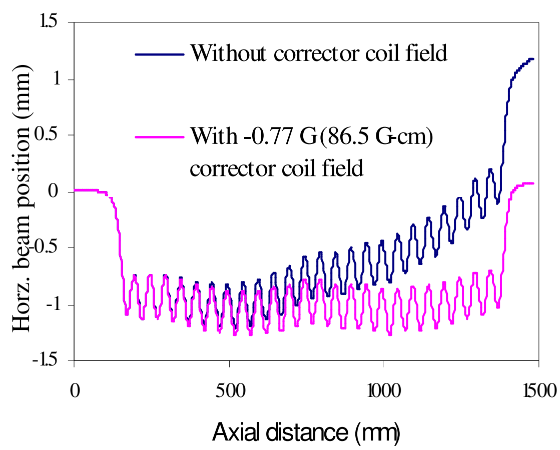

Figure 5: Electron beam trajectory through the undulator, with and without the corrector coil.

PWT LINAC

A major challenge has been the indigenous development of the linear accelerator technology. We also chose to build a rather unconventional structure – the plane wave transformer (PWT) linac [6]. This is a much more open structure, with strong coupling between the cells – and consequently with reduced fabrication tolerances. The only PWT linac working in the world is at UCLA [7], where it is routinely used, mainly for FEL applications.

After building a number of prototypes and ascending a steep learning curve, we now have a four-cell, 21 cm long structure, PWT3 (Fig. 6) that has been fabricated to the required tolerances (30 μm) and surface finish (0.2 μm CLA), which can hold UHV (1x10^{-8} torr), resonates at the desired frequency of 2856 MHz, and has a loaded Q of 8,000.

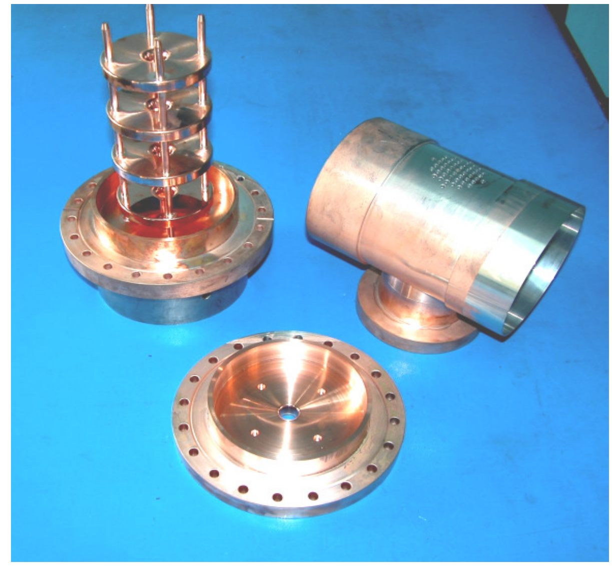

Figure 6: Components of the 4-cell PWT linac structure.

We have injected beam from a 40 kV thermionic electron gun into this structure, and have accelerated it to an energy of 3.5 MeV, corresponding to an accelerating gradient of around 25 MV/m. We also have ready a second 4-cell structure, PWT4, and are presently in the midst of fabricating an 8-cell PWT structure.

S-BAND PHOTOINJECTOR

Independent of the CUTE-FEL project, we have also been developing an S-band photoinjector, keeping in mind the requirements of short-wavelength FELs [8]. Our gun is based on the standard BNL/SLAC/UCLA Gun 4 design. We have performed extensive electromagnetic and beam dynamics design simulations using SUPERFISH, GDFIDL and PARMELA. We have also studied the injection of beam from the gun into a PWT linac structure.

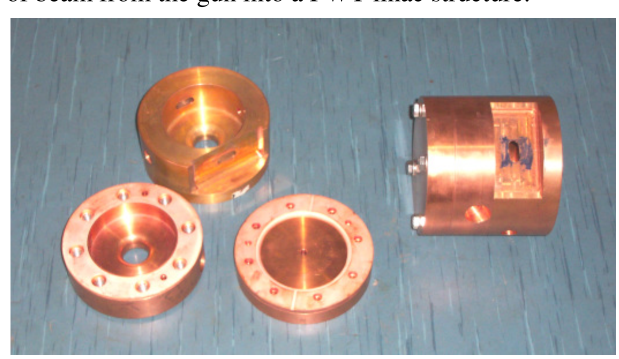

Figure 7: Components of the ETP Cu prototypes of the photocathode RF gun.

We have built a number of prototypes, of ETP and OFE copper, to qualify machining and brazing issues (Fig. 7). We have also built a number of aluminium prototypes for cold tests and for tuning the gun. We have developed a two-step tuning procedure to get the desired gun parameters – resonant frequency of the π-mode at 2856

MHz, β = 1 and field balance of unity, directly, without empirical tuning of the gun during cold-tests (Fig. 8). We have now given an order to an Indian vendor for fabricating four photocathode guns.

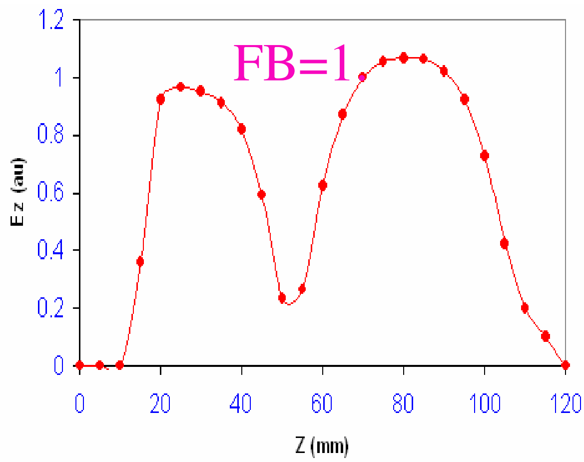

Figure 8: Bead-pull of a tuned Al prototype photocathode gun.

FUTURE PLANS

While we are presently focused on getting the CUTE-FEL lasing, some thought is also being given to future FEL activities in the country.

Table 3: Preliminary proposal of a 3-stage roadmap for the FEL programme in India

	Stage I	Stage II	Stage III
Wavelength (nm)	1,000	10	0.1
Energy (GeV)	0.1	1	10
Norm. emitt. (mm-mrad)	5	3	1
Undulator period (mm)	50	30	30
Undulator length (m)	5	30	100
Undulator param. 'K'	1	1.5	3
Peak current (A)	0.1	2	4
Pulse structure (fs @ Hz)	1,500 @ 50	150 @ 50	75 @ ??
Accel. Tech.	Norm. cond.	Norm. cond.	???

A joint Indo-French Workshop on FELs, was held in Goa, India, in March 2006. The consensus that emerged from this Workshop, especially from the Indian users who participated, was that a phased approach towards short-wavelength FELs, perhaps ultimately culminating in an XFEL, was highly desirable. To this end a preliminary three-stage roadmap has been proposed, summarized in Table 3.

There is already substantial interest amongst the user community in the country, particularly in materials science, for an IR-FEL facility (Stage I of the proposed roadmap). Another user workshop is planned to be held later this year.

CONCLUSIONS

A terahertz FEL, the CUTE-FEL, is in an advanced stage of construction at RRCAT. We have developed a PWT linac injector for the FEL, and have accelerated beam to 3.5 MeV in a 4-cell structure. We have built a 5 cm period, 2.5 m long PPM undulator. We are also in the final stages of development of an S-band photoinjector. Based on this foundation, and on interest shown by the user community, we expect a rapid expansion in the FEL activities in India in the coming years, starting with an IR-FEL facility, and perhaps continuing towards an XFEL in the future.

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