# STATUS OF THE CUTE-FEL PROJECT

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*Abstract*

We are building a Compact Ultrafast Terahertz Free-Electron Laser (CUTE-FEL) designed to lase at around 80 μm. Here we report on the present status. A 2 μs, 40 keV beam from a DC thermionic electron gun has been accelerated up to 4.5 MeV using a 21 cm long, 4-cell, Plane Wave Transformer (PWT) linac. Current measurements using a Fast Current Transformer (FCT) after a bending magnet energy spectrometer show a peak current of about 10 mA at 4.5 MeV. This beam was transported through a 1.25 m long undulator section. We have also built and tested the 476 MHz pre-buncher for the linac, and are in the midst of assembling the final FEL beamline.

## INTRODUCTION

The Beam Physics and Free Electron Laser (BP&FEL) laboratory at the Raja Ramanna Centre for Advanced Technology (RRCAT), Indore, is building a Compact Ultrafast TErahertz Free Electron Laser (CUTE-FEL) designed to lase at 80 μm. Figure 1 shows a schematic of the CUTE-FEL The injector will be a 90 kV pulsed thermionic gun which is soon to be installed – 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 and then through a 2856 MHz buncher, which will accelerate the beam to around 3-4 MeV. The beam will subsequently pass through the main accelerating structure where it will be accelerated to around 10 MeV. The RF structures 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 2.5m long undulator, which will cause the beam to emit coherent terahertz radiation.

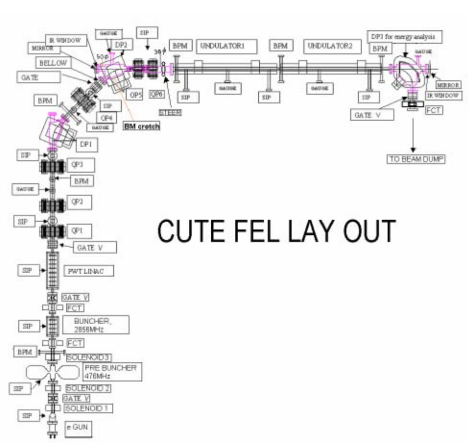


Figure 1: Beam line layout for the CUTE-FEL.

## PRE-BUNCHER

We have designed and tested a 476 MHz pre-buncher cavity with nose-cones. We 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. 2, has been leak-checked, RF qualified, and vacuum tested, and has been tuned to a frequency of 476 MHz. It is presently being integrated into the beamline.

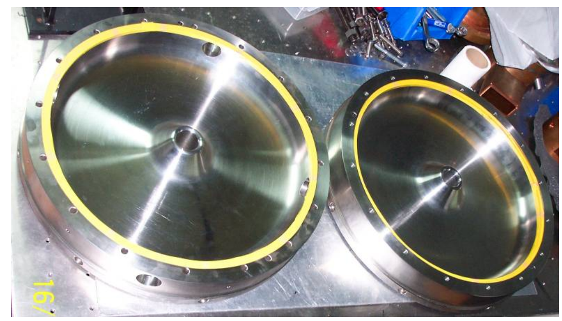

Figure 2: Photograph of 476 MHz pre-buncher cavity.

## PWT LINAC STRUCTURE

The buncher and accelerator are Plane Wave Transformer (PWT) structures, operating in the π mode. We have successfully built the four-cell, 21 cm long buncher, 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, and has a loaded Q ~ 8000 [1]. We have also built and qualified an eight-cell prototype structure, and components of the final 8-cell structure have been machined and are ready for brazing. Both structures are shown in Fig. 3.


Figure 3: Photograph of different components of 4 and 8 cell PWT structures.

## KLYSTRON MODULATOR

We have also developed a 25 MW, 10 μs, pulse modulator for powering a 10 MW, S-band klystron [2]. 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. The modulator we have developed is a standard long-pulse, line-type modulator. The DC power supply produces 12 kV DC with a ripple less than 1%. A charging choke is used 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. The PFN is discharged by a thyratron switch into the primary of a pulse-transformer, which has a nominal turn ratio of 1:6. Fig. 4 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.

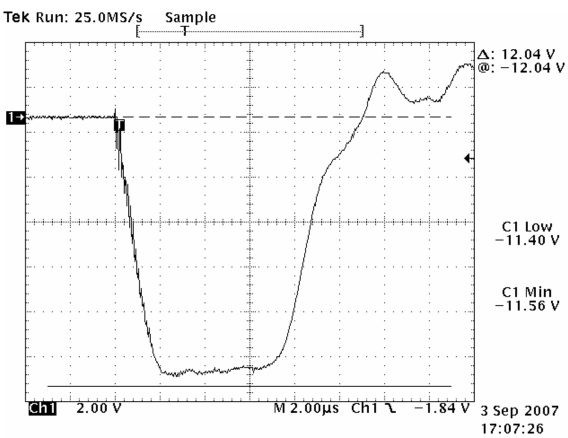


Figure 4: Typical high voltage pulse applied to klystron.

## 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 [3]. 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 at an undulator gap of 35 mm.

The undulator has been fabricated and field-mapped using a high spatial resolution (0.25 mm$^3$) three-axis Hall probe. The quality of the undulator meets our specifications with a field quality of better than the specified 1%, optical phase error less than 2$^o$, and 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. 5. Figure 6 shows the two sections of the fabricated undulators.


Figure 6: The two sections of the undulator. The corrector coil can be seen on the far end.

## ACCELERATION AND TRANSMISSION EXPERIMENTS

Figure 7 shows the beam transport line employed in the acceleration experiments using the 4-cell structure. The accelerated electron beam was energy analyzed using a bending magnet energy spectrometer with beam profile monitors (BPMs) and FCTs employed at different locations for electron beam position/profile and current diagnostics.

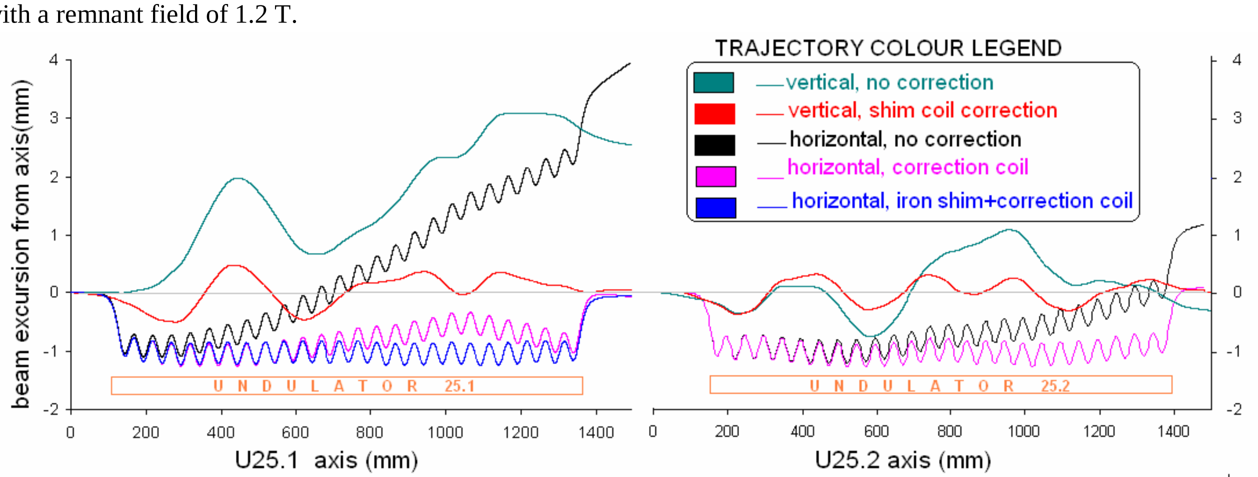


Figure 5: Results of field-mapping on the two undulator sections, shown in terms of the electron trajectory through them.


Figure 7: Beam transport line for acceleration trials.

Initial optimization of electron beam transport through the 4-cell PWT linac was done by tuning the solenoids to maximize beam transmission through the linac with a fine spot observed on a BPM just before it. The beam current through the un-energized PWT linac in these experiments was close to 100 mA. Downstream of the linac, the transport line consisted of a drift of 1.5 m to the bending magnet energy spectrometer and a further 0.7 m to the beginning of the undulator. In later experiments, quadrupoles and steering magnets were added to the transport line after the energy analysis section.

Since we injected 2 μs long pulses of 40 keV directly into the $\beta = 1$ linac, we expect a continuous spectrum of accelerated particles. Fig. 8 shows the typical pulse shape of the energy-analyzed beam at 3.5 MeV after conditioning of the linac structure. Figure 9 shows the energy spectrum of the accelerated beam at an input power level of 3.5 MW (blue trace). A maximum stable current of ~ 30 mA was obtained at 3.8 MeV. The maximum energy of the accelerated beam observed with the PWT linac is 4.5 MeV with an energy analyzed current of ~ 10 mA at this energy, as shown by the red point in Fig. 3. The input RF power at this energy is around 4 MW.

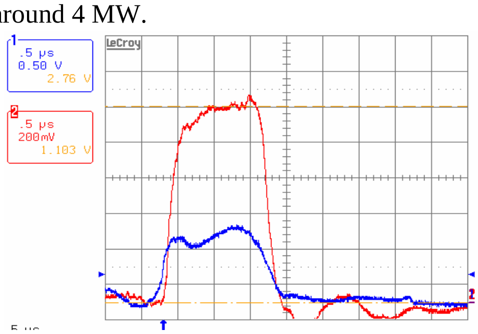


Figure 8: Accelerated/input (red/blue) beam pulse shapes at input power level of 3.5 MW.

Beam dynamics simulations of the above experiment predict a transmission of ~ 40% of the charge at an accelerating gradient of 18 MV/m [4]. In the result shown in Fig. 9, the energy gain of 3.5 MeV over a 21 cm long PWT linac-structure corresponds to a gradient of ~22 MV/m, considering a transit time factor T = 0.75. Comparison of area under both the traces of Fig. 8 shows a transmission of 30% at 3.5 MeV.

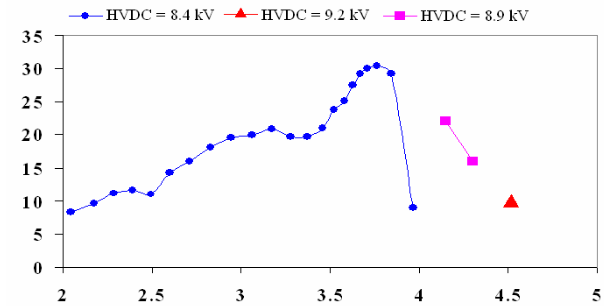


Figure 9: Energy spectrum of the accelerated beam.

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 at an undulator gap of 45 mm. Simulations show that transmission of a 3.5 MeV beam through the undulator at a gap of 45 mm is equivalent (in wiggle amplitude) to transmission of a 10 MeV beam through an undulator at a gap of 35 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 could not actually measure this radiation. We are now procuring a liquid helium cooled bolometer to measure this radiation.

## CONCLUSION

Most sub-systems of the CUTE-FEL have been developed or are in an advanced stage of development/procurement. An un-bunched, non-relativistic electron beam from a thermionic electron gun has been accelerated using a 4-cell PWT linac structure. Measurement of energy gain in the structure indicates that the structure supports field gradients of the order of 22 MV/m. The accelerated beam has successfully been transmitted through a 1.25 m long undulator section and we plan to measure the radiation in near future. Most of the FEL beam-line has been assembled, aligned, and is under vacuum. A new, high-current thermionic gun has recently been procured, and will soon be integrated into the beam-line. The 8-cell accelerating structure is ready for brazing. Our main delay is presently in the procurement of the RF source for the pre-buncher. Once that arrives, we should be able to commence lasing trials.

## REFERENCES

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