MECHANICAL ENGINEERING CHALLENGES IN THE DEVELOPMENT OF THE FEL AT RRCAT

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Abstract

The Compact Ultrafast TErahertz Free-Electron Laser (CUTE-FEL) is being developed by BP&FEL Laboratory, RRCAT, which is designed to lase around 80 µm. Sub-systems like S-band high gradient accelerating structures, pre-buncher, buncher, pure permanent undulator etc. have already been developed and others are in advanced stage of fabrication/commissioning. In this paper we present the design, fabrication, measurements and status of various prototype developments of structures.

INTRODUCTION

The Compact Ultrafast TErahertz Free-Electron Laser (CUTE-FEL) is being developed by BP&FEL Laboratory, RRCAT for condensed matter research and chemistry applications. The FEL is designed to lase around 80 µm and will be driven by a 10 MeV Plane Wave Transformer (PWT) linac and will use planar, pure-permanent magnet (PPM) undulator with 5 cm period and 2.5 m length, developed in-house [1]. The major components needed

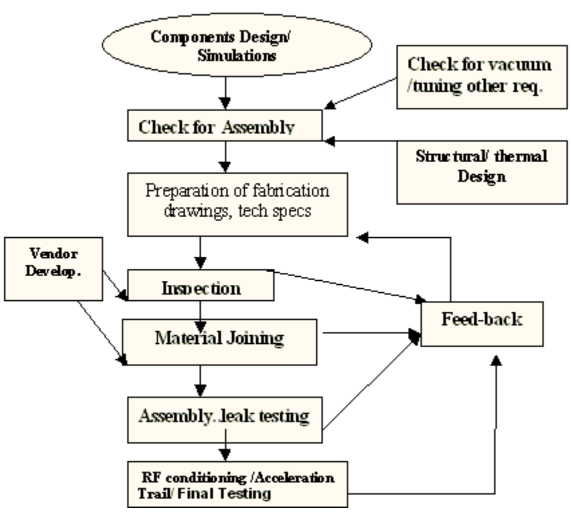

Fig.1 Process plan components development

for the development of the FEL are pre-buncher cavity, buncher, PWT linac and PPM Undulator. PWT linac and high brightness photo cathode guns are high gradient accelerating structures requiring an operational vacuum of better than $1x10^{-8}$ mbar. These devices require precise machining of components for accurate geometry on internal details with desired surface finish, and UHV quality leak tight joining. Development of these structures from simulation to final testing commissioning/ RF trials involves various levels of prototyping. In this paper we present the design, fabrication, measurements and status of various prototype developments of structures. Fig.1 shows our process plan for component development.

In the next section, we will review their engineering considerations, various prototype developments, results achieved and future plan.

COMPONENT DEVELOPMENTS

Pre-buncher cavity

In order to bunch low energy electron beam coming from thermionic electron gun, a sub-harmonic buncher cavity (476 MHz) was designed. Mechanical design considerations are:

- Fabrication of nose cone geometry cavity cell in two asymmetric halves with surface profile tolerance better than 0.05 mm for 350mm inner diameter.
- Accurate assembly of cavity cell in two asymmetric halves with various orthogonal ports.
- Requirements of vacuum sealing & tuning
- Structural and thermal requirements

Fig 2 Aluminium prototype of pre-buncher cavity

Current Status & future plans:

First, a true-to-scale prototype was made out of aluminium alloy T6061 to perform the low power RF test as shown in Fig 2. Inspection results done on CMM showed a tolerance of better than 0.04mm on inner profile. Final structure design was suitably modified based on the feedback received from cold test results. Critical design feature includes water-cooling channels on both sides for heat removal, tuner plungers for RF tuning, spring metal Helicoflex seal of dia 400 mm for UHV

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sealing. Final cavity structure made of AISI 304L is currently under fabrication at local vendor.

PWT linac structure

The PWT linac structure is a disk-washer loaded accelerating structure in which an array of disks (Ø90mm, 12mm, OFE copper), which is the periodic loading element that supports the slow-wave TM mode-like fields in the axial region used for particle acceleration. This is mounted inside a tank structure (AISI 304L) that serves as the outer boundary of the RF cavity and also as the vacuum envelope. The ports required for microwave power input, vacuum pumping, and diagnostics are also fitted onto the tank structure, while the array of disks is mounted on stainless steel (SS 304L) flanges using support tubes (Ø6mm, 1mm thick, SS 304L) that also carry cooling/heating water to the disks from a reservoir brazed to the flange. The beam entry/exit ports are mounted on the other side of these flanges (Fig. 3).

Mechanical design considerations are:

- Machining of components within surface profile tolerance of 0.03 mm Tool finish of better than 0.2 µm CLA on surfaces subjected to high field gradients
- Repeatable hole pattern on disk and supporting reservoir. This is to ensure assembly and required gap for vacuum brazing between disks to tube.
- Concentricity of the beam and disk axis better than 100 µm for complete length of 420mm
- Brazing of complete structure
- Vacuum requirement ~10^{-9} mbar (UHV)
- Structural and thermal requirements

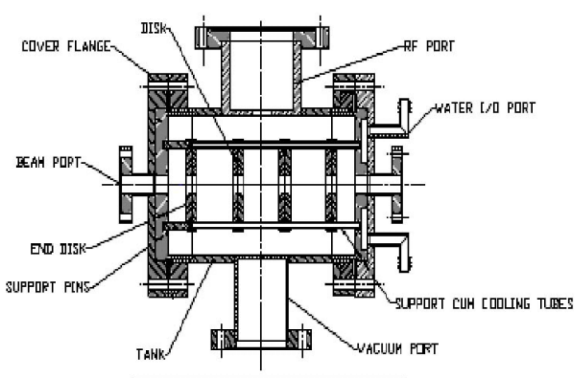

Fig. 3: PWT structure

Developments & present status:

We have built four prototype structures of the PWT linac. First & second prototypes (PWT1 & PWT2) have helped in fixing the parameters for brazing, machining, coating, chemical cleaning and handling of the components.

Machining: After initial trails, machining of the disk and other critical components was done at IGTR, Aurangabad on CNC machine (DECKEL-MAHO) using carbide tooling. Inspection done on CMM in scan mode showed better than 0.02mm profile tolerance and surface finish better than 0.2µm. Fabrication process using drilling jig on PCD ensured required positional accuracy and repeatable hole pattern. Initial prototypes with commercially available SS 304L tubes resulted improper assembly and failures of brazed joints. For 8-cell structure, cold drawn tubes were used.

Material joining: In the initial brazing trials, two-step brazing with 72 Ag - 28Cu (Cusil) & Incusil15 (Ag-Cu-In) was employed. Visual observations of the leak joints showed a poor fillet formation, and improper melting of filler wire at disk-tube junction [2]. Third prototype structure, after assembly was successfully leak-tested to a leak-rate of better than 1×10^{-9} Torr l/s, evacuated to a vacuum of 1×10^{-8} mbar, and acceleration of 3.5 MeV was observed. Another 4-cell structure PWT4 (that will actually used as the buncher) was made and tested. A brazing prototype of 8-cell structure was developed recently. Efforts are underway to build a. 8-cell structure for 10 MeV energy gain

Undulator:

A pure permanent magnet (NdFeB), variable-gap undulator period of 50mm period was designed and developed in two section of 2.5 m-long [3]. Mechanical design considerations are:

- Accurate positioning of mechanical structure jaws at different pole gaps.
- Errors in the physical dimensions of magnet block- < 20µm
- Parallelism of the surface formed by the array of the magnet blocks < 80 µm
- Vertical pole motion (gap) < 10µm.
- Pole gap variation mechanism to take variable magnetic force
- Magnet and frame structure should be rigid to keep minimum deflection within 0.01mm.
- Low magnetic permeability of the material during fabrication near magnet blocks.
- Ease in assembly.
- Provision for Alignment of the Undulator

Undulator was designed for above considerations. Magnets were assembled (Fig. 5) as per the arrangement calculated by the simulation.

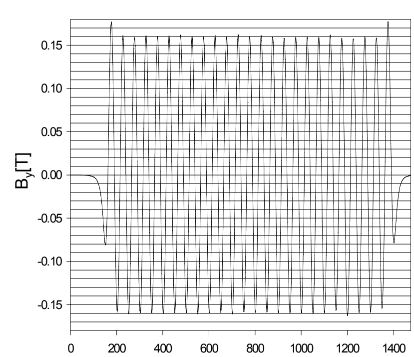

Fig 4: Plot of B_y along the undulator axis

A three-axis magnet field mapping system was developed and used to plot B_y along the undulator axis (Fig. 4). The mean of all the peak magnetic fields is 1.624 kG and the rms error is 0.9%, which is within the rather conservative 1% tolerance limit.

Fig. 5 Photograph of two Undulator segments with the field mapping system and corrector coil mounted

Photocathode gun:

We are developing a S-band, 1.6 cell, BNL/SLAC/UCLA type photoinjector. Electrons are extracted by shining a high power, high-stability Nd:VAN laser onto copper photocathode surface. Since the structure is used to accelerate electron beams to reasonably high energies over short distances, it is fed with high power microwaves to set up the high accelerating electric field gradients (~100MV/m) inside it. This imposes the requirement of precision machining with strict geometrical and dimensional tolerances. A complete gun structure has two accelerating cells (Body full cell & body half cell) and various ports for feeding the microwave power, vacuum pumping, laser entrance/exit and RF diagnostics.

Mechanical engineering considerations:

- Fabrication of accelerating cells with surface profile tolerance better than 0.02mm on internal cavity cell.
- Tool finish on surfaces subjected to high field gradients better than 0.1 micron CLA.
- Orientation between the various orthogonal and angular ports at component and assembly level.
- Concentricity of the oblong slot better than 0.02 mm
- Vacuum requirement $\sim 10^{-9}$ mbar (UHV)
- Material Joining
- Support and assembly

Developments & present status:

We have successfully fabricated OFE Cu prototypes of the main accelerating cells to design specifications on high precision Schaublin lathe with polycrystalline diamond and cemented carbide tool.Inspection Results on ‘Carl Zeiss’ make CMM showed surface profile tolerance better than 0.02mm and surface finish of the order of 0.08 µm. We have also built two ETP Cu brazing prototypes using the eutectic filler alloy Cusil. With these technologies successfully demonstrated, we will now start fabricating four nos. of complete structure at Indo German Tool Room, Aurangabad.

CONCLUSIONS

While the initial trials of component development for the CUTE-FEL project were based on first principles, the actual realisation evolved after a large number of mock trials (Fig. 6). The real situation in fabrication & material joining is always more complex bringing into play a large number of variables. We have successfully built and tested two prototypes of PWT linac structure. We have also successfully built brazing & cold test prototypes and one full prototype of the laser photocathode gun.

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Fig 6: Evolution of prototype developments