DESIGN AND FABRICATION OF A 476 MHZ SUB-HARMONIC BUNCHER CAVITY

Sanjay Chouksey, Shankar Lal, Saket Kumar Gupta, Arvind Kumar, Bhaskar Biswas, S.S. Parihar, K. K. Pant, S. Krishnagopal[1]
Materials & Advanced Accelerator Sciences Division
Raja Ramanna Centre for Advanced Technology, Indore - 452013, India
[1]Bhabha Atomic Research Centre, Mumbai, India

Abstract

A 476 MHz sub-harmonic pre-buncher cavity has been designed, fabricated, tested and installed in the Compact Ultrafast TErahertz Free-Electron Laser (CUTE-FEL) beam line at RRCAT. This paper presents the design, fabrication, assembly and inspection aspects of the pre-buncher cavity.

INTRODUCTION

The Compact Ultrafast TErahertz Free-Electron Laser (CUTE-FEL) is being developed by RRCAT, which is designed to lase around 80 μm[1]. The injector system of CUTE-FEL consists of a 1ns, 90 kV pulsed thermionic electron gun, a 476 MHz sub-harmonic pre-buncher, and a Plane Wave Transformer (PWT) linac capable of accelerating beam up to 10 MeV. The pre-buncher is a re-entrant, standing wave cavity designed to bunch the 1 ns electron bunch from the electron gun (90 keV) into 50 –80 ps consuming around 20 kW peak RF power.

RF SIMULATIONS

The design studies of the pre-buncher cavity were done by employing electromagnetic eigen mode solver codes- 2D code SUPERFISH and 3D codes CST Microwave studio and GDFIDL. These were used to predict the geometry and permissible tolerance on dimensions of the structure for a resonant frequency of 476 MHz in the TM_{010} like mode. The field distribution in cavity obtained from SUPERFISH simulations is shown in Fig1. Based on these studies, dimensional and geometrical tolerances were fixed for the mechanical design.

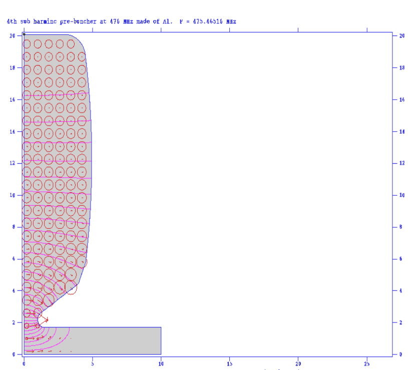

Figure 1: Field distribution in SUPERFISH.

THERMO-STRUCTURAL ANALYSIS

The cavity was analyzed for structural (atmospheric pressure) and thermal loading associated with RF losses during operation using finite element software ANSYS. Thermal analysis was performed for an RF pulse of 2ms repeating at 10Hz.The cooling scheme has radial water-cooling channels of 5mm×8mm on both sidewalls of the cavity. The water inlet is at ID through the radial port and exits at OD in a collection header. Convective heat transfer (h) = 9000W/m^2 for water and 2W/m^2 for ambient natural convection was considered for the analysis. Maximum temperature rise of 2.8 degree at nose cone (Fig. 2) showed effective cooling of the structure. Structural analysis showed an axially inward deflection of 40micron which was later experimentally verified using dial gauge, when the cavity was evacuated. The deflection induced dip in resonant frequency f_o was balanced by the increase in f_o due to change in air to vacuum dielectric constant.

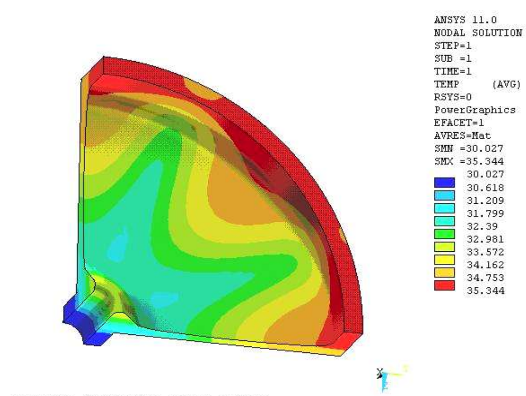

Figure 2: ANSYS thermal results (temperature)

MECHANICAL DESIGN

The mechanical geometry of the cavity was finalized after RF, structural and thermal simulations. An aluminium alloy T6061 true-to-scale prototype was developed to perform low power RF tests before fabrication of the final structure of stainless steel incorporating modifications based on the feedback from the prototype. The final geometry of the pre-buncher cavity has following features:

- Fabrication of nose cone geometry cavity cell in two asymmetric halves with surface profile tolerance better than 0.05 mm for 350 mm inner diameter. Inner geometry of the cavity cell is formed by three straight and five curved profiles (R5 to R465 mm radius).

- Various orthogonal ports for feeding the microwave power, vacuum pumping and beam input and exit ports. Two tuning ports have also been provided for mounting of slug tuners to tune the cavity to its design frequency of 476 MHz.
- Accurate assembly of cavity cells in two asymmetric halves. Structures have provision to ensure the concentricity better than 0.1 mm between cavity cells after assembly.
- A groove has been machined on cavity cell for employing Helicoflex seal for vacuum sealing.
- With stainless steel as the structural material (low thermal conductivity), it was also important to have adequate cooling over a large fraction of the surface of the nose. This was ensured by providing water cooling distributions in multiple machined channels over the surface of the cavity.
- Two lifting lugs are provided on the cavity cells for ease in handling of the structure. Rigid supports with levelling jacks are provided for the precise positioning of the structure during final assembly with beam line.

FABRICATION

Each cavity cell is machined out of single plate of Austenitic Stainless Steel (AISI 304L). Machining was done on CNC machine to ensure surface profile tolerance on inner profile with nose cones. Inspection results done on Coordinate Measurement Machine (CMM) showed a tolerance of better than 0.04 mm on inner profile of the cavity cells and surface finish of the order of 1.2-1.6 μm. Various ports and flanges were TIG welded on the cavity. The joints have been leak tested to better than $1X10^{-9}$ mbar l/s. A custom made spring metal Helicoflex seal of dia 400 mm (copper liner) was used for UHV sealing between the two halves of the cavity.

The structure, after tuning, shows a leak rate better than $1x10^{-9}$ mbarl/s. This pre-buncher cavity has already been integrated with the CUTE-FEL injector beam line and evacuated to a vacuum of $1x10^{-7}$ mbar.

COLD TESTS

The SS pre-buncher structure has been developed and characterized at low RF powers (cold test). The resonant frequency and quality factor were measured using a Vector Network Analyzer (VNA) in transmission mode. Bead-pull measurements were done to find the profile of on-axis accelerating field and shunt impedance of the cavity. Structure has been tuned to 476 MHz using two tuners, and the cavity has a tunability of 2 MHz with variation in tuner position. The quality factor of the cavity is 1893 and shunt impedance is 175 MΩ/m. The on axis accelerating field profile is shown in Figure.3. After RF characterization, the pre-buncher cavity has been integrated in the CUTE-FEL injector beam line[2]. Figure 4 shows the pre-buncher cavity during assembly of CUTE-FEL injector beam line.

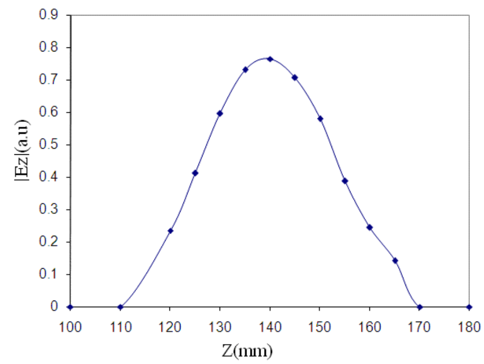

Figure 3. On-axis field profile in pre-buncher cavity.

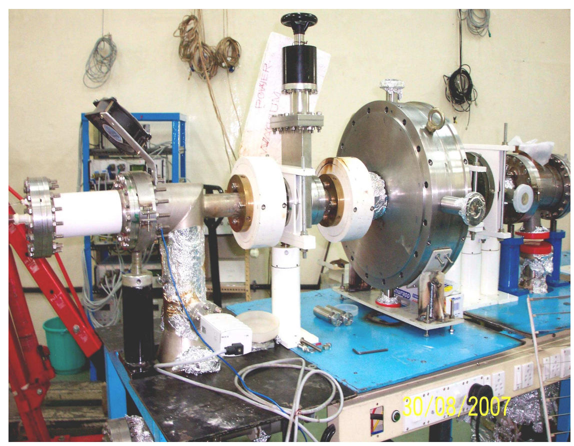

Figure 4: Assembly of CUTE-FEL injector beam line with pre-buncher cavity.

CONCLUSION

A pre-buncher RF cavity has been designed, developed and tuned to resonate at 476 MHz with a leak rate better than $1x10^{-9}$ mbar l/s. After RF characterization, it has been integrated with the CUTE-FEL injector beam line and evacuated to a vacuum of $1x10^{-7}$ mbar. Procurement of a 50 kW peak RF power source to power the pre-buncher is in an advanced stage.

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