FABRICATION AND RF STUDIES ON A PROTOTYPE PWT LINAC STRUCTURE

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Abstract

We have built and cold-tested a four-cell prototype Plane Wave Transformer (PWT) linac structure, resonating at the designed frequency of 2856 MHz in the π mode. Frequency tuning of the structure has been achieved by varying the length of one end-cell, without compromising the vacuum inside the structure. Thermal analysis of a modified structure with copper rods at accelerating gradients of 20 MV/m shows a maximum steady-state temperature rise of about 3.6˚C in 40 minutes.

1 INTRODUCTION

The far-infrared free electron laser at 80 μm being built at CAT requires an electron beam of 10 MeV energy and 5 A peak current, with a normalized emittance of better than 10π mm mrad. For operation at such moderate energies, the Plane Wave Transformer (PWT) linac structure has demonstrated its ability to deliver a high brightness beam, and is planned to be used for various applications, including FELs, at UCLA [1]. An advantage of using a PWT structure is its relatively greater tolerance to machining errors on account of the high inter-cell coupling of electromagnetic fields [2], which has been among the main reasons we chose to build it as the injector for our FEL experiment.

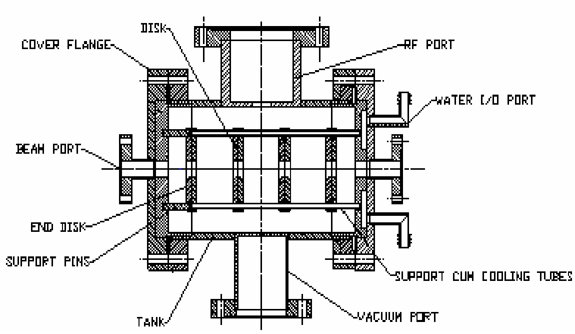

Figure 1: Schematic of the prototype, 4-cell, PWT linac structure.

We have recently built and cold-tested a 21cm long, 4-cell (three full + 2 half cells) prototype PWT structure resonating at 2856 MHz in the π mode. A schematic of the structure is shown in Fig. 1. This has given us the necessary feedback about the accuracy of simulations and feasibility of mechanical fabrication of the structure to prescribed tolerances. The prototype is a complete vacuum-tight structure, which can, in principle, also be used for hot-tests. Based on this experience, the actual accelerating structure is currently being built. In the next Section, we briefly discuss salient features of simulations using SUPERFISH and GDFIDL codes, based on which the prototype was designed. In Section 3, we discuss some aspects of the mechanical design, followed by a discussion of cold-test results in Section 4. We conclude with a discussion of the results in Section 5.

2 SIMULATIONS

Although SUPERFISH is a two-dimensional code that cannot, in principle, be used to study non-axisymmetric structures like the PWT linac, we began with this code to fix the basic dimensions of the structure to resonate at 2856 MHz in the π mode. The advantage of using SUPERFISH for the PWT structure is that it gives the electric field distribution at all points inside the structure, and the power dissipation on all segments on the inside surfaces of the structure. This is useful in fixing the position of support tubes to cause minimum perturbation of the electric fields, and in choosing the location of the cooling channel inside the disks. However, since the support tubes themselves perturb the electric fields, and consequently the resonant frequency, quite significantly, a complete study requires a three-dimensional analysis of the structure, for which we used the code GDFIDL.

Before using GDFIDL to simulate the non-axisymmetric features of the PWT structure, the code was benchmarked by comparing results obtained from simulations of an axisymmetric PWT structure without tubes, with those obtained from SUPERFISH simulations. To fine-tune the simulations with the tubes, a cold-test set-up was made in which disks of different diameters could be supported by four rods going through holes 90˚ apart at a fixed pitch circle diameter (PCD) on all the disks. Based on cold-test results from these dummies, simulation parameters were fine-tuned to obtain the best possible agreement between the two results, which in some cases agreed to better than a few MHz.

To fix the location and size of the support tubes, GDFIDL simulations were performed for different tube PCDs, and also for different tube diameters, for a given PCD and disk size. Figure 2 shows the variation of the resonant frequency of the structure with the radial position of tubes of 6.5 mm diameter. An error in the location of these holes can cause a change in the resonant frequency of the structure. From Fig. 2, it is clear that to minimize the effect of errors in locating the tubes, they should be inserted in the flattest portion of the curve. Figure 3 shows the variation in resonant frequency with the diameter of the tubes for a fixed PCD. To minimize errors due to variations in the tube diameter (ovality of tubes), the diameter of the tubes should be chosen to lie in the flat portion of the curve. A tube diameter of 5.5 mm – 6.5 mm falls within this region. These two effects are coupled to the variation in the resonant frequency due to the diameter of the disks (~10 MHz/mm) [3]. Based on these studies, a disk diameter of 90 mm, with tubes of diameter 6.5 mm going through the disks at a PCD of 74.5 mm, was chosen for the prototype PWT linac structure. GDFIDL simulations predicted a resonant frequency of 2858 MHz for this structure.

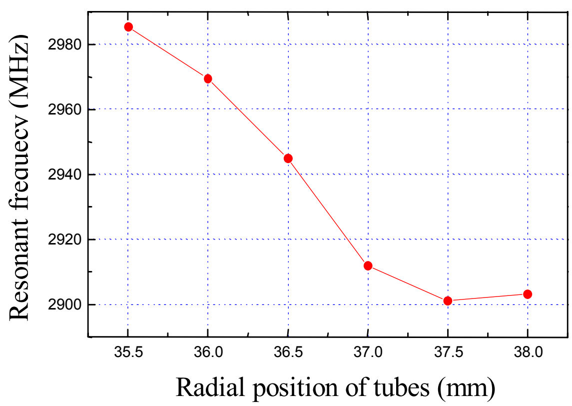

Figure 2: Variation of the resonant frequency as a function of location of the support tubes.

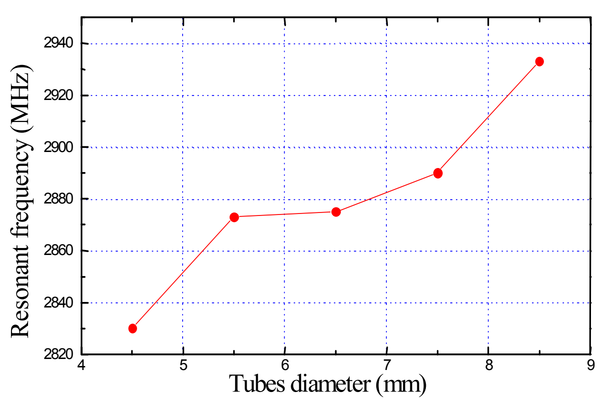

Figure 3: Variation of the resonant frequency with tube diameter, for a fixed PCD of the tubes.

3 MECHANICAL DESIGN

In order to fix the engineering design of the structure, GDFIDL simulations were performed to obtain a tolerance map for the structure, which is the sensitivity of the resonant frequency to perturbations in various dimensions of the structure. Based on these, form tolerances of 30 μm were prescribed for the machining of all components, and a tolerance of 200 μm was prescribed for the assembly of the structure. From simulations, it was observed that the resonant frequency changes more severely for a change in the total length of the assembly (~ 4 MHz/mm), as compared to a change in the length of any one cell compensated by a corresponding change in the neighbouring cell, keeping the total length of the assembly constant (~ 0.4 MHz/mm). Hence, the overall assembly tolerance translates to a frequency tolerance of a few 100 kHz for the prototype structure.

On account of the good inter-cell coupling in the PWT structure, it cannot be tuned using conventional tuning methods. It was decided to use the dependence of resonant frequency on the overall length of the structure to fine-tune the structure to the desired operating frequency of 2856 MHz. To achieve this, negative tolerances were prescribed on the tank length to obtain a resonant frequency higher than the design frequency of 2856 MHz. Since the vacuum sealing was designed with metal gaskets with conflat flanges, gaskets of different thickness were made, which could be used to vary the length of the structure to a few hundred micrometers.

Two configurations of the PWT structure were studied for mechanical stability of the assembly, and for the maximum temperature rise during operation at average electric field gradients of 20 MV/m. The input for these was taken from the post-processor SFO of SUPERFISH, which gives the power dissipated on the surface of all the disks. The first configuration was with cooling/support tubes (SS304L, two inlet & two outlet) carrying water from a reservoir at one end to the cooling channels machined inside all the disks. On account of the poor thermal conductivity of the SS304L tubes and fast heat removal by water (flow rate of 4 litres per minute per tube), the temperature profile of all the disks is nearly the same, with a maximum temperature difference of 0.16˚ between the disks. However, all the disks attain a steady state temperature about 1.9˚ C higher than that of the water at the reservoir. In the second structure, the tubes were replaced by copper rods of the same size, and with the disks without any cooling channel. Removal of heat from the disks is by conduction through the four rods to the cooled reservoirs at both ends. For operation with a 10 μs RF pulse at a repetition rate of 1 Hz, the average power dissipated inside the structure is quite small. It was, therefore, felt that for applications requiring short 'on time' of the linac, heating of the structure might not affect the resonant frequency significantly. A structure with rods would also be relatively easier to fabricate since the critical disk-tube joints only impart mechanical strength and the requirement of leak-tightness is eliminated. Figure 4 shows the steady state temperature profile of the disk-array, attained in 45 minutes. The boundary condition imposed here is that the temperature of the reservoirs at both the ends is kept constant by the cooling water that flows through it. This translates to a heat transfer coefficient of about 8,000 W/m^2 on the reservoir. A maximum temperature rise of about 3.6˚C is observed on the two disks farthest from the reservoirs, while the two disks close to the reservoirs show a temperature rise of about 2˚C. For operation times smaller than 45 minutes, or for average electric field gradients smaller than 20 MV/m, this temperature rise would be smaller.

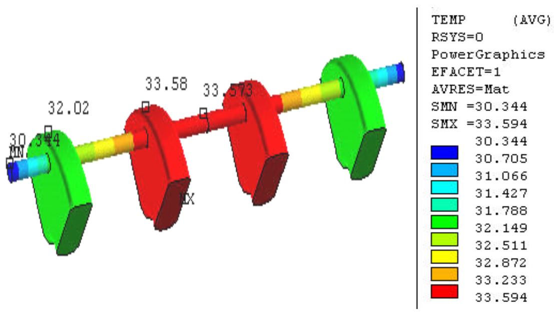

Figure 4: Steady-state temperature profile of the disk-array with copper rods.

The radial expansion for a 3.6˚ temperature rise is 2.64 µm. Using the length of the end cell to tune the structure, it should be possible to account for any change in the resonant frequency caused by this heating.

4 COLD-TESTS

Cold-tests were performed on the prototype PWT structure using a spectrum analyser [Rhode & Schwarz, Mod. FSP7] and a signal generator [Rhode & Schwarz, Mod. SMT03]. A coaxial-waveguide adaptor was mounted on the RF port of the structure to launch 1 mW microwave power into the structure through the coupling slot on the tank wall, and a loop antenna was used to inductively sample the fields set up inside the structure.

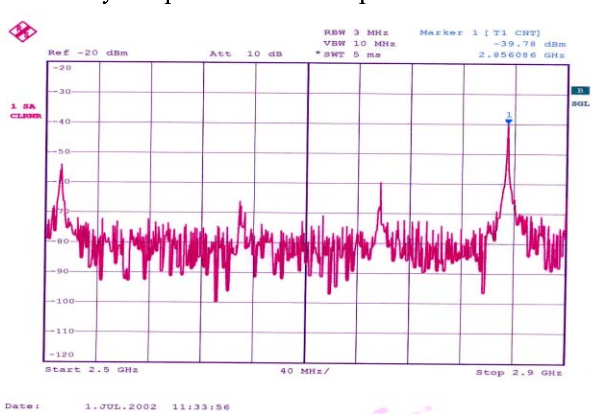

Figure 5: Frequency spectrum of the modes

Figure 5 shows the frequency spectrum of the modes supported by the structure. The structure has been tuned to resonate at 2856 MHz by changing its length using a thicker metal gasket at one end. A bead-pull using a teflon bead was performed on the structure to confirm that the mode supported at 2856 MHz is a π mode, as is shown in Fig. 6, which shows the simulated and measured dispersion curves for the four cell prototype PWT structure. The bandwidth of the structure was measured to be about 400 MHz. The measured value of Q_L was around 8,000, while the r/Q was measured to be 486 Ω.

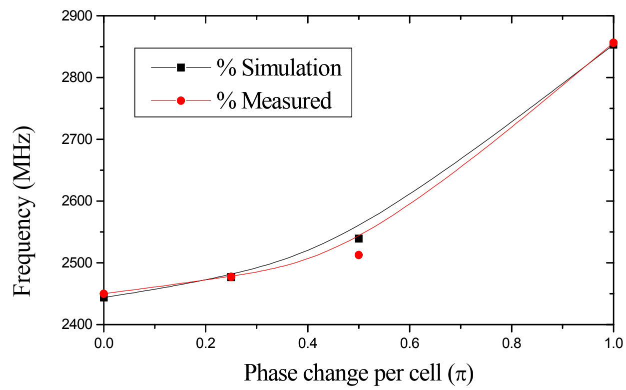

Figure 6: Dispersion curves for the PWT structure.

5 CONCLUSIONS

The four-cell prototype PWT structure fabricated at CAT has been tuned to resonate at 2856 MHz by adjusting the length of one end-cell. The structure can be tuned to a few MHz by this method, and leak testing of the structure after tuning shows a leak rate better than 1x10^{-9} Torr l/s. Thermal analysis of a modified structure without cooling shows that it could be used for small ‘on time’ operations without any serious frequency drifting problems. We are currently building two more four-cell prototypes, one each with SS tubes and with copper rods, which we propose to use for hot tests, and for actual acceleration experiments.

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