TUNING AND RF CHARACTERIZATION OF PLANE WAVE TRANSFORMER (PWT) LINAC STRUCTURES

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Abstract

Four- and eight-cell Plane Wave Transformer (PWT) linac structures have been developed, tuned and characterized for RF properties as part of the injector development for the Compact Ultrafast Terahertz Free-Electron Laser (CUTE-FEL) at the Raja Ramanna Centre for Advanced Technology (RRCAT). In this paper, we discuss tuning of resonant frequency and waveguide-to-cavity coupling coefficient for these structures, and compare results obtained from cold tests with those predicted by RF simulations. We also compare energy gain and RF properties of these structures, determined from transient and steady state behaviour of the structures during recent high power tests, with those predicted by cold tests.

INTRODUCTION

A PWT linac structure is a disk-washer loaded standing wave structure operating in the π mode [1]. By virtue of its design, the structure has high shunt impedance, relaxed fabrication tolerance, and good vacuum conductance. It is a good structure for applications requiring electron beam energies of the order of 10 - 15 MeV.

We have developed two S-band PWT linac structures - one 4 cells (21 cm) and the other 8 cells (42 cm) long. The 4-cell PWT structure is proposed to be used as a buncher and pre-accelerator, while the 8-cell PWT structure will serve as the accelerator for the CUTE-FEL. The waveguide-to-cavity coupling coefficient for the π mode (β_π) for both these structures has been tuned close to critical coupling and RF characterization of both these structures has been done at low powers (cold-tests) and at high RF powers (from the transient and steady-state behaviour of forward and reflected RF power). The structures have been qualified for operation at high gradients by demonstration of acceleration of a 90 kV electron beam from a pulsed electron gun to an energy of 4.7 MeV in the 4-cell structure and to an energy of 6.2 MeV in the 8-cell structure[2].

In the next section, we discuss the tuning of π mode frequency (f_π) and β_π, followed by a discussion of the RF characterization at low and high RF powers in the subsequent sections. We conclude with a comparison of cold test results with those obtained from high power test.

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TUNING OF f_π AND β_π

Generally, the resonant frequency of an accelerating structure is tuned by taking machining cuts on independent cells before brazing, followed by fine tuning after brazing using tuners and water temperature. On account of its open geometry, tuning of independent cells of a PWT structure is not possible and major tuning of frequency can be done only by varying its length after brazing and final assembly. Fine tuning, however, can be done by varying water temperature. RF simulations using 2-D and 3-D codes like SUPERFISH and CST Microwave Studio respectively, predict a variation of ~ 6 MHz/mm in f_π with structure length, while the actual measured value for our structures is ~ 1.5 MHz/mm. In actual experiments structure length is varied by employing gaskets of different thickness. Since the disk-array is brazed to a flange at one end, increase in structure length with thicker gaskets results in an increase in the cell length at the other end. This variation in length of the end cell causes a variation in the ratio of accelerating field in that cell to that in the middle cell, and the effect of this asymmetry on beam dynamics in the structure needs to be understood. To efficiently couple RF power into the accelerating structure, its impedance is matched to that of the high power microwave line for critical coupling (β =1) by optimising the dimensions of the coupling slot on its outer wall. Though dimensions of the slot can be predicted by 3-D electromagnetic codes such as CST Microwave Studio, the actual measured value of β deviates from that predicted by the code as codes consider ideal structures while actual structures have imperfections due to impurities in copper, brazing joints, machining errors, etc which can cause extra power loss. Experimentally, impedance matching is achieved by increasing the slot size iteratively in small steps and measuring β for each step using a Vector Network Analyser (VNA).

Gao [3] has given a scaling law to predict dimensions of the coupling slot for any desired coupling between the microwave line and a single cavity. Since linac structures normally comprise many coupled cells, this scaling law cannot generally be used except in exceptional cases like the PWT linac where the open geometry of the structure results in high inter-cell coupling coefficient due to which the complete structure can be treated as a single cavity to a very good approximation. For a single cavity coupled to a waveguide, the dependence of β on dimensions of the slot is given by

$$\beta = \frac{16 Z_0 \kappa_0 \Gamma_{10} e_0^4 l_1^6 \exp(-2\alpha_0 d)}{9ab[1+\frac{3}{8}e_0^2+\frac{15}{64}e_0^4+\frac{315}{3072}e_0^6+...)^2} \frac{H_1^2}{P_c}, \quad (1)$$

where l_1 is equivalent length of the RF coupling slot, 'd' is the thickness of the slot, and all other parameters are defined in ref [3]. The value of H_1^2/P_c can be determined either from simulations using electromagnetic field solver codes or by measuring the value of β for a very small slot and extracting the value of H_1^2/P_c from it using Gao's formula. Since simulations consider ideal conditions, which may be different from actual experimental conditions, we followed the latter method.

We have employed Gao's scaling law to successfully tune the β_π of a 4-cell and an 8-cell PWT linac with very good agreement between values predicted by Gao's formula and actual measured values. The dimension of the slot machined initially was very small giving β_π ~0.05. Assuming this to be like a structure without any slot, Eq. 1 was used with the measured β_π to obtain a value of H_1^2/P_c, which was subsequently employed again in Eq. 1 to predict values of β_π for different slot sizes. Gao's scaling law was earlier used successfully to tune 4-cell PWT linac structures [4] with very good agreement between measured and predicted values of β_π for different slot sizes. The formula was again used recently with the 8-cell PWT linac structure where it is observed that agreement between predicted and measured values of β_π is better for lower values , while there is some deviation at higher values. Figure 1 shows the variation of β_π with length of the coupling slot for the 8-cell PWT linac structure. The difference between predicted and measured values may be due to the fact that the structure now behaves less like a single cavity due to its larger length.

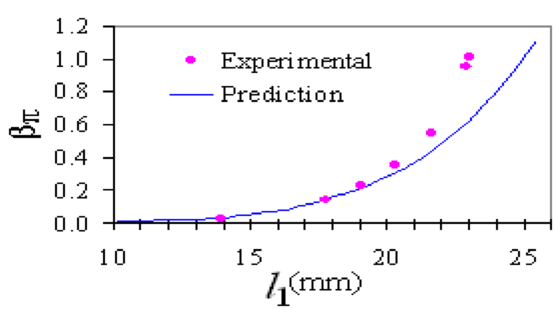

Figure 1: Variation in β_π with RF coupling slot length for 8 cell PWT linac.

RF CHARCTRIZATION

RF parameters of the linac structures such as π mode frequency, quality factor, waveguide to cavity coupling coefficient are measured using a VNA in reflection mode [5-6]. The variation of on-axis accelerating field is measured by conducting a bead–pull on the structure using a small dielectric bead (5.4 mm long and 5 diameter) made of green putty. The variation of on-axis accelerating field can be predicted from the variation in resonant frequency by using the formula [5-8]

$$E_z(z) = \sqrt{\frac{\Delta f_\pi(z)}{f_\pi}} \sqrt{\frac{4\beta}{(1+\beta)^2} \frac{Q_0}{2\pi f_\pi \xi} P_{in}}, \quad (2)$$

where $\Delta f_\pi(z) = f_\pi(z=0) - f_\pi(z)$ is the variation in resonant frequency, ξ is the form factor of bead and P_{in} is the input RF power. To predict the shunt impedance, R/Q is calculated first using the formula and the measured value of Q.

$$\frac{R}{Q} = \frac{1}{2\pi f_\pi^2 \xi} [\int \Delta f dz]^2 . \quad (3)$$

The variation of on-axis accelerating field (E_z) along the structure length for 4-cell PWT linac structures is shown in Fig 2. Other important parameters like filling time and energy gain can be determined from measured values of E(z), Q, beta and R. Table 1 gives a comparison of cold test measurements with predictions of simulations.

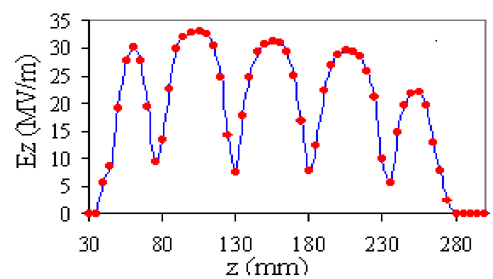

Figure 2: On axis field variation in 4 cell PWT linac.

HIGH POWER RF TEST

To qualify the PWT linac structures at designed operating gradients of 20 – 25 MV/m, high power RF was fed in to the linac structures in the CUTE-FEL beam line. More details of the experimental setup are given in reference [2]. The RF parameters of structures during high power RF test, such as β_π, fill time (t_f) were calculated from transient response of reflected RF power which is given by [7]

$$\frac{P_r(t)}{P_i} = \left[\frac{2\beta_\pi}{1+\beta_\pi}(1-e^{-t/t_f}) - 1 \right]^2 , \quad (4)$$

The transient response of reflected RF power with time for the 8-cell PWT linac at an input power of 1.5 MW is shown in Fig. 3. The resonant frequency was obtained by tuning the input RF frequency for minimum reflected power. The quality factor was calculated from β_π and fill- time measurements by using the definition of fill-time $t_f = 2Q_0 / 2\pi f_\pi (1+\beta_\pi)$.

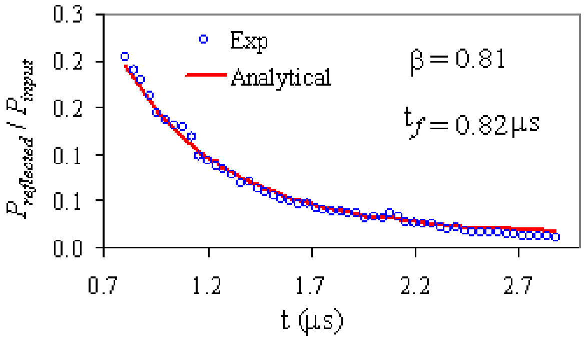

Figure 3: Reflected RF power variation with time for 8 – cell PWT linac for input power of 1.5 MW.

With the 4-cell PWT linac, a maximum energy gain of 4.2 MeV was obtained with ~ 2.4 MW of RF power, while an energy gain of 5.7 MeV was obtained in the 8-cell PWT linac structure with ~2.8 MW of RF power. A comparison of RF parameters obtained from high power tests with those obtained from RF simulations and cold test results is given in table 3. High power RF tests are currently underway with conditioning of the structure to reach the designed operating gradient of 25 MV/m.

CONCLUSION

Two PWT linac structures of 4 and 8 cells have been developed and tuned, and their RF characterization has been done at low as well as high powers to study their RF properties. For critical coupling, good agreement has been obtained between the length of the coupling slot predicted by Gao's formula with that actually made by employing the iterative cut-and-measure technique. Information of RF properties obtained from steady state and transient behaviour at high powers agrees well with those predicted by cold-tests on the structures.

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Table 1: Comparison of RF simulation predictions with cold test measurements for PWT linac structures.

Parameters	4 cell PWT linac			8 cell PWT linac		
	RF Simulation	Cold test	High power test	RF Simulation	Cold test	High power test
f_π (MHz)	2863.51	2856.68	2858.31	2862.24	2859.74	2859.5
Q_0	18112	15652	15861	19840	14632	13330
R (MΩ)	18	13.9	13.06	39	25.93	25
β	1.03	1.04	0.92	1.03	1.02	0.81
RF slot length (mm)	33.2	36.4	36.4	35.8	38	
Fill time (μs)	0.99	0.86	0.92	1.09	0.87	0.82
P(MW) for Ez =25 MV/m	1.5	2	2.15	3	4.3	4.2
Energy gain (MeV)	4.2 @1.8 MW		4.2 @ 2.4 MW	5.7 @ 1.5 MW		5.7 @ 2.8 MW