Study of a novel compact standing wave RF linac

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Abstract

A novel, compact RF linac structure, the plane wave transformer (PWT), is studied. The PWT provides high accelerating field and high efficiency, and can be used to accelerate high-brightness beams. PWT linac prototypes with eight cells at S-band have been developed at UCLA and successfully used to accelerate an electron beam by more than 10 MeV in 40 cm. In this paper, we describe the principal properties of this structure, the electric parameters obtained from numerical simulation, and measurement results from microwave cold tests. The mechanical design for prototype linacs is also reported.

1. Introduction

A compact, efficient, high brightness producing, radio frequency electron linac is desirable for many scientific and industrial applications. Electron accelerators with energies up to a few MeV are used in radiation chemistry studies, for instance the radiation-enhanced chemical reactions of the highly active intermediate chemical states produced by the electron beam. Compact RF linacs, combined with compact, multi-terawatt, sub-picosecond laser systems can be used in the generation of X-rays [1], which could have a significant impact on a number of applications in the areas of X-ray radiology, microscopy and spectroscopy. A compact RF linac that provides a high brightness beam and fits in a small room will also be a powerful facility for scientific research in university laboratories.

There has been tremendous progress in the development of RF accelerator structures in the past half century. Among the widely used RF structures, such as the Alvarez structure [2], the coupled-cavity structure (CCS) [3], and the side-coupled structures (SCS) [4], the SCS linacs are considered as the most successful ones. However, the non-cylindrical symmetry in the SCS linac makes it both inconvenient and expensive to fabricate and difficult to assemble and tune. On the other hand, the plane wave transformer (PWT) [5] linac, which promises high gradient and high electric efficiency, is simpler and less expensive to fabricate. These properties make the PWT linac a very promising candidate for use in research laboratories and the industrial community.

The PWT linac could be dated back to late seventies [6]. Fig. 1 shows its 3-D schematic view. The structure consists of a cylindrical tank and an array of disks. These disks are connected together by several metal bars parallel to the axis. Because it is separated from the cylindrical tank, the array acts as a center conductor to support a TEM-like plane wave between the tank and the array. This TEM wave provides the coupling between the individual cells in the array. Meanwhile, each individual cell supports a longitudinal electrical field on the structure axis. In other words, this structure makes use of a plane wave to transform the external RF power into a longitudinal electric field for acceleration of particles. Thus, it is named a plane wave transformer [5]. This feature causes the PWT structure to have the advantages of high shunt impedance and strong coupling between individual cells. Furthermore, the PWT configuration provides good vacuum conductance and ease of fabrication. However, the operation mode in a PWT structure is a high-order hybrid one instead of the fundamental TM<sub>01</sub> mode operated in most RF accelerating structures. This operation with a high-order mode raises concerns about: the possible excitation of other, undesired, modes either by the external source or by the electron beam; the stability of the acceleration field; and the wake field effect on beam dynamics. These issues have to be studied in order for the PWT to be operated successfully.

In this paper, we describe the principal properties of the PWT structures. Then we present the results from
both the numerical simulation and the microwave cold tests, with a comparison between the two different configurations developed at UCLA. We also discuss the short range wake-field and its effect on beam quality. The mechanical design of the UCLA PWT prototypes is also presented in detail. In a companion paper we give the numerical simulation, including the space charge effect, of the beam dynamics in the linac, and the experimental results obtained in accelerating a beam.

2. Electrical properties

The PWT structure is simulated by using both the SUPERFISH and MAFIA [7] codes. The SUPERFISH code is very helpful in finding the dimensions of the PWT for a given operation frequency. However, the connecting metal bars cannot be included in the simulation due to their lack of cylindrical symmetry in the structure. Therefore, the 3-D code MAFIA has been used to obtain a more complete picture of the electromagnetic field distribution in the structure and information about other, possibly interfering, modes.

Fig. 2 shows arrow plots from MAFIA of the electric field distribution for two cells (one full cell plus two half cells) of a PWT structure at different cross sections. The electric field distribution of the longitudinal cross section along the axis is shown in Fig. 2(a). A plane wave (TEM-like) pattern is clearly seen in the space between the outer tank and the loaded-disk array. The acceleration electric field distribution in the region close to the axis is a π-mode. Fig. 2(b) shows the electric field distribution at the transverse cross section at the center of the full cell. Due to the transition from a TM-mode field pattern to a TEM field distribution, the longitudinal electric field varies from maximum on the axis to almost zero in the middle of the radial direction. This field pattern does not exist in a pure TM01 mode. However, the magnetic field distribution in the transverse cross section, as shown in Fig. 2(c), is very similar to that of a TM01 mode. It should be noted that connecting metal bars produce only a minor perturbation on the field distribution for this operation mode, which explains why the SUPERFISH code could give very good results. In fact, the displacement current on axis does not return in the region between the disks. Instead, it circulates via the wall of the tank. Therefore we name the operation mode as a TM01-wall mode.

The shape of the disks near to the axis can be used to control the electric field profile on the axis. We have considered two cases: disks loaded with nose cones and flat disks. The disks loaded with nose cones are used in a PWT to increase the shunt impedance of the structure by concentrating the electric field near the axis. This configuration is just suitable for moderate acceleration gradient, due to a high peak surface electric field on the tips of the nose cones. The linac using disks with nose cones at UCLA is called PWT2. The electric
The resonance frequency at a mode in a PWT structure is exclusively determined by the dimensions of the disks and the cell length, and is independent of the diameter of the cylindrical tank. This behavior can be understood by examining the field pattern as shown in Fig. 2(a). Due to the TEM plane-wave field distribution in the region near the inner wall of the tank, the increase of the diameter of the tank does not perturb the field lines. Therefore, the resonance frequency remains unaffected. This property might make the PWT more attractive to operate at higher frequency, say X-band, where it is usually difficult to fabricate structures because of the small physical dimensions and stringent tolerances. However, an increase of the tank diameter will store more energy in the structure while the RF power dissipation in the outside tank stays almost unchanged, except a slight increase in the end-flanges of the tank. Therefore the unloaded-\( Q \) increases with the diameter of the tank. In addition, the TEM field dissipates less RF power on the wall of the tank than does a structure employing

field amplitude on the disk surface in a PWT is shown in Fig. 3(a). It is seen that the maximum ratio of the peak surface field on the tip of a nose cone to the on-axis field is about 2.5. This ratio has to be reduced to close to unity in order to achieve a high-gradient operation. This low peak surface field can be obtained using flat disks. The linac using flat disks at UCLA is called PWT3. Fig. 3(b) shows the relative peak field amplitude along a flat disk surface in the PWT3. The maximum ratio is reduced to about 1.2 for a disk thickness of 1.2 cm. Thicker disks are favorable for a low field ratio but unfavorable for good shunt impedance. The dependence of the field ratio and the shunt impedance upon the disk thickness is shown in Fig. 4. The UCLA PWT3 prototype chose a disk thickness of 1.2 cm as a trade-off with an effective shunt impedance of about 57 M\( \Omega/m \), calculated from MAFIA. The electrical parameters of the PWT prototypes with different types of disks calculated from MAFIA are listed in Table 1. As a comparison, the measured results from cold tests are also listed.
Fig. 4. Shunt impedance and field ratio versus thickness of the flat disks in an eight-cell PWT.

Table 1
The electrical parameters of two PWT prototypes calculated from MAFIA and measured in cold tests

<table>
<thead>
<tr>
<th>Parameters</th>
<th>PWT2 Simulation</th>
<th>PWT2 Cold test</th>
<th>PWT3 Simulation</th>
<th>PWT3 Cold test</th>
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<tbody>
<tr>
<td>Frequency (MHz)</td>
<td>2800</td>
<td>2856.3</td>
<td>2828</td>
<td>2856.3</td>
</tr>
<tr>
<td>Unloaded Q</td>
<td>28500</td>
<td>14800</td>
<td>26900</td>
<td>16100</td>
</tr>
<tr>
<td>Effective shunt impedance (M Ω/m)</td>
<td>62.8</td>
<td>33.2</td>
<td>57.2</td>
<td>34.6</td>
</tr>
<tr>
<td>R/Q (Ω)</td>
<td>1550</td>
<td>1592</td>
<td>1586</td>
<td>1604</td>
</tr>
<tr>
<td>Transit time factor</td>
<td>0.775</td>
<td>0.771</td>
<td>0.75</td>
<td>0.75</td>
</tr>
</tbody>
</table>

Table 2
The numerical comparison in half cell electrical parameters and some of their dimensions for a PWT with nose cones and an SCS

<table>
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<tr>
<th>Parameters</th>
<th>PWT</th>
<th>SCS</th>
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<td>Frequency (MHz)</td>
<td>2856</td>
<td>2856</td>
</tr>
<tr>
<td>Unloaded Q</td>
<td>41800</td>
<td>16800</td>
</tr>
<tr>
<td>Effective shunt impedance (M Ω/m)</td>
<td>104.8</td>
<td>86.9</td>
</tr>
<tr>
<td>R/Q (Ω)</td>
<td>105</td>
<td>217</td>
</tr>
<tr>
<td>Transit time factor</td>
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<td>0.79</td>
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<tr>
<td>Cavity radius (cm)</td>
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<td>3.9</td>
</tr>
<tr>
<td>Cavity length (cm)</td>
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<td>2.625</td>
</tr>
</tbody>
</table>

3. Dispersion curves and other modes

The behavior of the PWT linac can be studied using a coupled resonator model. For a single cavity mode, there are N structure modes for a chain of N cells. The dispersion curves of a structure are completely determined when the frequencies of these modes are known in the interval 0 – π of phase shifts per cell. This dispersion relation will become a continuous curve if the number of cells in the chain is infinite. The dispersion relation can be also used to determine the coupling coefficients of the structure if the mode frequencies are found through experimental measurements or numerical simulation.

To find these modes and their phase advances per cell, we use MAFIA to simulate this structure with different cell numbers and different boundary conditions. In this way, we can make sure that all different modes with different phase advance per cell can be correctly identified. The arrow plots of the MAFIA graphics outputs are used to distinguish the phase advance for different modes by comparing the field patterns with one another. The dispersion curves of some passbands for a PWT prototype with loaded disks are shown in Fig. 5. The straight line shown in the figure is for the case of phase velocity equal to the velocity of the light.

The dashed line in Fig. 5 is the dispersion curve for the passband associated with the operation mode. The frequency difference between the zero-mode and the π-mode is about 700 MHz. It should be noted that this dispersion curve does not have symmetry about the π/2 mode as does that of a conventionally coupled RF linac structure with identical cells. This feature is unique to a PWT structure and can be interpreted as arising from multi-coupling among the different cells. Since the coupling is provided by a plane wave running back and forth, all cells in the structure are coupled to each other. If we treat the PWT structure as a chain of identical cells, its dispersion relation can, using coupled-mode theory [8],
be written as follows:

\[
\frac{\omega_0^2}{\omega_q^2} = 1 - \sum_{n=1}^{N} k_n \cos(n \phi_q). \tag{1}
\]

where \( q \) is the mode number, \( \phi_q \), the phase advance per cell of the mode \( q \), and \( N \), the total number of cells. Using Eq. (1) to fit the data with \( N = 9 \), we find that the nearest-neighbor cell coupling, \( k_1 \), is dominant with a coupling coefficient of about 0.16. The next-neighbor cell coupling coefficient is about 0.05. Due to the strong coupling between cells, the PWT is insensitive to mechanical errors. Fig. 6 shows the peak field flatness, and the frequency shift versus the variation in central cell length for a nine-cell PWT linac. We see that for a one millimeter change of the cell length, the field amplitude balance from cell to cell is still higher than 0.95 with a shift in resonance frequency just about 0.3 MHz. Therefore the PWT linac can be built without fine tuning each individual cell.

Like any other standing wave accelerator structure, there exist many other cavity modes and their corresponding structure modes in a PWT. The existence of the undesired modes will not be harmful to the performance of the PWT if they are not excited. However, if the resonance frequency of an undesired mode is close enough to the operation frequency, this mode can be excited by the input RF power. If undesired modes are excited in the PWT, not only the electrical efficiency becomes lower due to the power dissipation of those modes, but also the beam quality is degraded and the beam break up (BBU) current threshold is reduced for multi-bunch operation. In the worst case, the structure cannot even be operated at all. In a PWT structure, the operation mode is not in the lowest passband. Furthermore, several other bands also cross over the operation band. This feature raises the possibility of driving some undesired modes by the RF power supply.

The two cavity modes whose dispersion curves cross over the operation passband are the TE\(_{21}\) and the TM\(_{21}\) modes. From MAFIA simulation, the frequencies of the \( \frac{1}{2} \pi \) mode in the TE\(_{21}\) band and the \( \frac{3}{2} \pi \) mode in the TM\(_{21}\) band are close to that of the operation mode. It is evident such a possibility will become much greater for a long structure, due to its smaller frequency separation among different structure modes. For the UCLA prototype with eight full cells, the frequency separation between the nearest mode and the operating mode is found to be greater than 10 MHz, which is outside the bandwidth of the klystron. The field distribution of these modes also shows that they are dipole modes. One way to prevent them from being excited is, even their frequencies are close to the driving source, to choose the orientation of the RF power coupling slot so that it is at 45° relative to the connecting metal bars. In this way, the energy from external power supply cannot be transferred to these modes due to their different parity. This observation is confirmed by cold tests.

Another type of mode that requires attention are the HEM modes, which have large transverse magnetic field components. The existence of these modes can be responsible for serious instabilities in the operation of linear accelerators, even though the RF sources driving them do not in principle supply power at these frequencies. Among these modes, the one with phase velocity close to the velocity of the electron beam, which is almost the
velocity of light, could be excited by an off-axis electron beam. Off-axis electrons will be kicked further from the axis by the magnetic field of these modes. If the electrons happen to be trapped in the deceleration phase, then these modes will have positive feedback and will grow in magnitude. For multiple-bunch acceleration, the excitation of these HEM modes will increase the energy spread, cause emittance growth and even induce the beam break-up (BBU) instability. The effects of these HEM modes on the accelerated beam remains to be studied.

It should be pointed out that the cavity mode associated with the lowest passband is also a hybrid TM_{01} mode. The field distributions of the n-mode at different cross sections are shown in Fig. 7. As is seen in Fig. 7(c), the connecting metal bars greatly perturb its field distribution. Some return current in fact flows along the bars. As a result, this mode has a much lower unloaded Q-value. Not only are their frequencies much lower than that of the operation mode, their phase velocities are also much different from the speed of light. These modes should have little effect on the performance of the structure. Fig. 8 shows the field distribution of the HEM mode at different cross sections.

4. The cold test results

To test what was found in the numerical simulation, a cold test bench stand with a HP network analyzer was set up to measure the parameters of the PWT prototypes. Both the PWT2 and PWT3 prototypes used in the cold tests are built using copper plated external cylinders and aluminum disks.

The on-axis electric field distribution is measured by a bead-pull perturbation technique. The diameter of the copper bead we used is 1.5 mm, which induces a maximum frequency shift of about 1 MHz by on-axis perturbation. To reduce the system error in the
measurements, the room temperature has to be regulated with very small fluctuation. The relative electric field profile on the axis of the two PWT prototypes from microwave measurements and simulations are shown in Fig. 9. It is seen that the measurement field profiles of both PWT2 and PWT3 agree well with those of the simulation.

For the measurement of the unloaded Q-value, the disks are made from oxygen-free high conductivity copper (OFHC). The measured unloaded Q-value is about 14000 for PWT2, compared with the computation value of about 28000. The measured Q-value for PWT3 is 16000, which is greater than that of the PWT2, because all the joints in PWT3 were brazed. The discrepancy between the measured values and the computed ones can be attributed to many factors, such as disk-surface polishing, the copper plating of the external cylinder, which has a lower conductivity, the slots for RF coupling and vacuum conductance, both contributing to additional power losses. The characteristic impedance \( R/Q \), calculated from the measured field distribution, agrees well with that computed from numerical simulation. The measured \( R/Q \) is about 1590 \( \Omega \) in the PWT2 and 1600 \( \Omega \) in the PWT3 (SUPERFISH convention).

To obtain the dispersion curves from measurement, one must identify different modes and their phase advance per cell. One method to make this identification is to measure the phase variation by pulling a metal bead along the axis. From the cycles in phase variation, we can find the phase advance of that mode. This technique is effective in finding modes which have both high \( Q_0 \) values and strong electric field distribution on the axis but fails to identify the majority of higher-order modes. In general, higher-order modes either have low \( Q_0 \) values or have little electric field on the axis. The conventional way to measure the phase advance is not applicable to the measurement of the PWT due to the lack of a metal boundary between cells. What makes the measurement more difficult is that the resonance frequencies of some modes are very close to each other and their frequency spectra become overlapped due to their low \( Q_0 \) values. As a result, it is extremely difficult to find the phase advance of these modes in a PWT structure. The solution to this problem is to start from a test module with just a few cells so that few modes will exist. Then we gradually increase the cell numbers to find more modes. Additionally, we put the coupling probes at locations where the electromagnetic field amplitude is relatively high to enhance the sensitivity and to keep the perturbation to a minimum. These results of the measurements are shown in Fig. 5 by crosses.

5. Wakefields

As is well known, when a bunched electron beam with high peak current traverses an RF accelerating structure, strong wakefields will be excited in the structure [9]. The longitudinal wake will induce an energy spread in the bunch, while the transverse wake leads to kicking the beam further away from the axis and induces emittance growth. However, the longitudinal wake field effects may be compensated, at least partially, by the RF field when the appropriate linac injection phase of the beam is chosen.

The wakefields of the PWT were calculated by using the 2-D numerical code ABC1 [10], which treats cylindrically symmetric structures, in order to save computing time and to reduce memory requirements. Although the support rods are not included in the simulation, there is little error induced by this approximation as far as the short range wake field is concerned, because these support rods are far from the beam axis [9]. We compared the results from ABC1 with that from the 3-D code T3 [7]. The discrepancy between the two codes is less than 1.2%. Fig. 10 shows the wake potentials in an eight-cell PWT2 for a beam bunch length (1σ) of 1 mm. Fig. 10(a) shows the monopole (longitudinal) wake potential \( W_1(s) \), and Fig. 10(b) shows the dipole wakes \( W_2(s) \) (both transverse and longitudinal). The maximum energy loss (monopole wake) is about 48 keV/nC. The maximum transverse kick is about 3.5 kV/(mm nC).

The total energy loss per cell, \( k_{tot} \), and integrated transverse kick per cell, \( \Delta_{kick} \), for different bunch length is shown in Fig. 11. The definition of \( k_{tot} \) and \( \Delta_{kick} \)
are given by

\[ k_{\text{tot}} = \frac{1}{Q} \int_{-\infty}^{\infty} \rho(s) W_x(s) \, ds, \]

\[ \Delta_{\text{kick}} = \frac{1}{Q} \int_{-\infty}^{\infty} \rho(s) W_y(s) \, ds, \]

where \( Q \) is the total charge of the bunch, \( \rho(s) \) the charge density. Compared with the SLAC disk-loaded S-band structure, the PWT2 has slight higher wakefield potentials. It should be noted that the cell length and the iris diameter in the SLAC structure are 3.5 and 2.3 cm, respectively, compared to 5.2 and 1.6 cm in a PWT structure. Since the longitudinal wake field scales down as 1.5 power of the iris radius, the wakefield in the PWT2 is essentially of the same order as that in the SLAC structure. The wakefields in the PWT3 are basically the same as that in the PWT2.

6. Mechanical design of the PWT

The UCLA RF linac system, consisting of an RF photoinjector and a compact linac, is dedicated to studying the production of high quality electron beams, developing novel RF structures, providing a high brightness beam for other particle beam physics experiments, such as free electron lasers (FELs), plasma-based focusing lens and plasma-based accelerators [11]. These experiments requires a nominal beam energy of about 15 MeV with a normalized emittance of less than \( 5 \times 10^{-6} \) m rad. The beam energy exiting from the RF gun is about 4 MeV.
Therefore the PWT linac should provide an energy gain of more than 11 MeV. Additionally, the RF photoinjector and the compact linac share an XK-5 SLAC-type klystron. The RF pulse duration from the klystron is about 3 μs. Therefore, a moderate unloaded merit factor, $Q_0$, for the linac, matching with that of the RF gun cavity ($Q_0 = 10 k$), is desirable for the RF system.

The UCLA PWT linac prototypes has seven full cells with half-cell termination at both ends. The total length of the linac is about 42 cm [12]. The linac length is a compromise between the acceleration gradient and the frequency separation, which is discussed in Section 4. The linac structures are assembled using flanges for the convenience of study. The inside joining-slit between an end-flange and the cylinder tank is one quarter of wavelength away from the inner surface of the end-flange, where the current is at the minimum. The cylindrical tanks are manufactured from stainless steel with OFHC copper plated on the inner wall.

The schematic drawing of the PWT2 is shown in Fig. 12. These loaded disks are soldered to four water tubes which provide temperature control to the linac to stabilize the resonance frequency. Both the disks and water tubes are made from OFHC copper. There is no water flow inside the disks. There is a water reservoir in each of the end-flanges. The four water tubes are connected at one end to a water reservoir but at the other end pass through the end flange, with the joints being vacuum sealed by viton gaskets, and return the water to the temperature-controlled bath. The four small ports at each end of the PWT2 tank, as shown in Fig. 12, are inherited from an earlier design [13]. In the current

Fig. 12. The cross section schematic drawing of the PWT2 linac mechanical design.

Fig. 13. The cross section schematic drawing of the PWT3 mechanical design.
design, two ports are used: one is for housing an RF monitor; another for an ion gage as a vacuum pressure monitor. The remaining ports are idle.

Since the flat disks used in PWT3 are much thicker, they have internal water channels to provide better temperature control. The disk array is separated into two halves. Each half consists of four disks and one end-flange. The two halves join tightly together in a slip fit at the middle of the linac structure. Water does not flow through this joint, but flows through the inner channels in the disks of each half and forms a close loop with the outside water bath. All other joints in the structure are brazed. The viton gaskets present in PWT2 are eliminated. Therefore, the PWT3 could be operated at a much lower vacuum pressure, as is necessary for operating at high acceleration gradient.

The RF power coupling in both linacs is achieved by cutting a slot in the tank. To minimize the effect of this coupling slot on the beam dynamics, the vacuum slots are cut just opposite against the coupling slot. The water tubes, which also serve to connect the disks, are located at places where the RF field is at a minimum. The fine tuning of PWT2 was accomplished by slightly changing the dimensions of the end cells. This tuning for PWT3 is achieved by slightly changing the length of the middle cell. Tuning from cell to cell is not necessary in a PWT structure because of the strong coupling between cells. The fine tuning of the linac resonance frequency is achieved by adjusting the temperature of the cooling water, which is stabilized by a constant-temperature water bath. No water cooling is provided to the outside tank because its low RF power dissipation and the insensitivity of the resonance frequency to the tank diameter. Both PWT2 and PWT3 are successfully operated under high RF power to accelerate beams.

7. Summary

The PWT linac has many advantages over other known structure, such as high gradient, high efficiency, and low cost. Because the separation of the cylindrical tube and the central disk array, this structure is easy to manufacture. These advantages make it attractive for use in medical and industrial application. However, the operation with a higher-order mode (TM_{01-wall}) might make it difficult to build a long structure with much more than eight cells because of the proximity of undesired modes. For acceleration of a multi-bunch electron beam, higher-order mode damping becomes important to preserve a high quality beam and increase the BBU instability threshold. These issues remain to be studied.

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