# THE PLANE WAVE TRANSFORMER LINAC STRUCTURE

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A high-beta, standing-wave linac structure with an effective shunt impedance ($ZT^2$) of 150 MΩ/m at 3 GHz is described. The structure consists of a cylindrical tank with an array of washers along the axis. The outer part of the structure is excited with a TEM-like mode which propagates power back and forth along the structure, at the speed of light, to provide coupling between the individual cells. This standing wave drives a $TM_{02}$-like mode in the space between the washers. Thus the washers serve to transform the transverse electric field of the TEM-mode (a plane wave) in the outer part of the structure to a bidirectional longitudinal electric field along the axis for acceleration of particles - hence the name - "plane wave transformer".

## Introduction

There are more commercial applications for electron linacs than for all other types of particle accelerators put together. There are more than 1000 electron linacs, of the side-coupled linac (SCL) design, installed in U.S. hospitals for X-ray and electron-beam medical therapy and diagnostics purposes. There are thousands of electron linacs used for a variety of applications in industry. There are lots of applications for high performance electron linacs in the scientific community, such as injector linacs for synchrotron light sources, free electron lasers, and accelerating structures for microtrons.

The principle linac structure, used for most of these applications is the SCL structure, invented in Los Alamos in the mid-60s.[1] Technically, it is a superb structure, but practically, it is expensive, heavy, fragile, difficult to fabricate, and difficult to tune. An electron linac structure that would alleviate any or all of these deficiencies would be a welcome addition to the linac family. The plane wave transformer (PWT) linac structure appears to be a good candidate.

The PWT linac structure offers advantages over other known linac structures in the areas of power efficiency, field stability, weight, fabrication simplicity and costs. The exceptional efficiency and stability of this structure should translate into significant commercial advantages in most of the medical, industrial and scientific applications. The structure offers higher output energies and/or higher beam currents for the same input power, or requires less input power for the same energies and currents than other linac structures. Relatively large temperature differences are allowed within the structure, thereby simplifying the cooling system. The structure is relatively light weight, simple to fabricate, simple to evacuate, easy to tune, and easy to excite.

Specific areas where this new linac structure might find application include medical therapy and diagnostics, including the relatively new application of intraoperative radiation therapy (IRT), industrial radiography for non-destructive testing of thick metal parts, munitions, and rocket motors, materials modification as in crosslinking of polymers, sterilization of waste products, radiation processing of food and medical products, and pest control in grain, fruit, etc. As the applications mature, the demand for higher energy (more penetrating) radiation will increase, underscoring the advantages of the electron linac as the source of the radiation.

## The PWT Linac Structure

The PWT linac structure represents a novel resonant cavity configuration supporting an electromagnetic field mode having high rf power efficiency for acceleration of highly relativistic particles and good field stability. The acceleration results from a standing-wave pattern of electromagnetic fields having strong electric components along the axis where the particles travel.

Along the axis, this structure is similar to other coupled-cavity linac (CCL) structures used to accelerate "high-β" particles. The electric fields alternate in direction in successive gaps. The particles are concentrated in the gaps with the accelerating fields. The washer-like electrodes are spaced at $\beta\lambda/2$ apart so that when the particles have moved into the next cell, the fields have reversed to represent an accelerating field in that cell. In this way, the particles receive an accelerating impulse in each cell of the structure.

The unique feature of this structure is the use of the transverse electric and magnetic field mode (TEM-mode) to propagate power along the structure to provide coupling between the individual cells. Power propagates in this mode at the speed of light, back and forth between the end plates, setting up the standing wave patterns shown in Fig. 1. This standing wave pattern drives a $TM_{02}$-like mode in the space between the washers. Thus the washers serve to transform the transverse electric field of the TEM mode (a plane wave) in the outer part of the structure to a bidirectional longitudinal electric field along the axis for acceleration of particles.

Half cell geometries and electric field patterns for the PWT and SCL linac structures are shown in Fig. 2. The geometrical dimensions and electrical properties are compared in Table I. Both structures resonate at 3000 MHz.

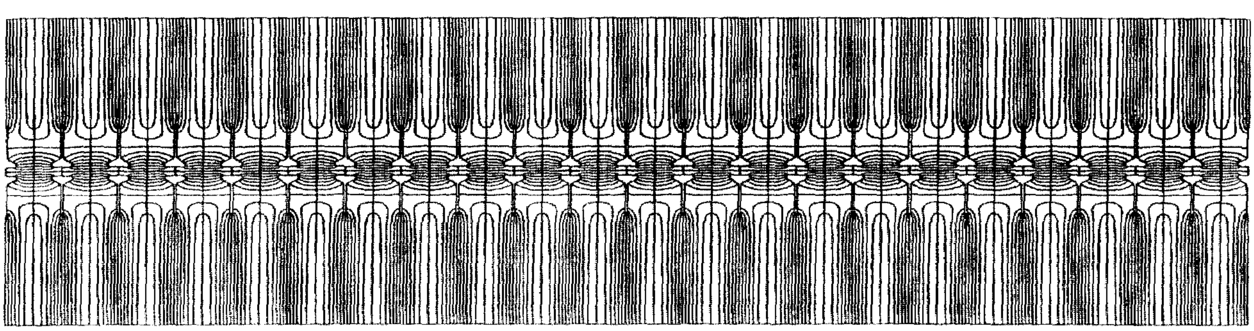

Fig. 1. Plane Wave Transformer Linac Structure Field Pattern.

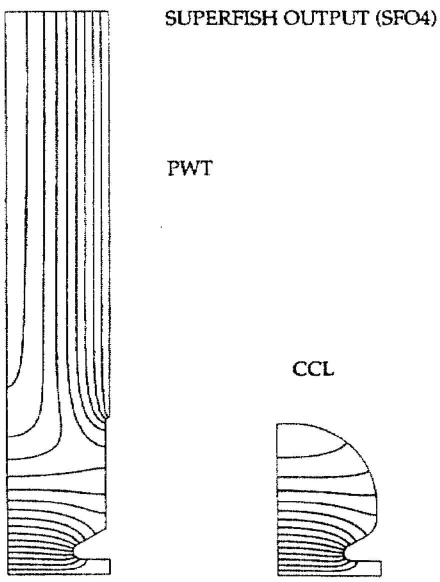


Fig. 2. PWT and CCL Half-Cell Field Patterns.

Both have the same gap length, bore radius, nose cone radius, and nose cone angle. Both are near their optimum effective shunt inpedance ($ZT^2$) for the specified nose cone geometry. The field patterns in the vicinity of the beam axis are nearly identical.

Here the similarity ends. The PWT linac structure is significantly larger in diameter, but lighter in weight. The most important electrical quantity is the effective shunt impedance ($ZT^2$), which is 45% higher for the PWT than for the basic, uncoupled SCL cell. The stored energy in the PWT is higher and the power losses are lower, resulting in a Q for the PWT that is substantially higher than for the SCL.

The rf efficiency of the structure is high because of the interplay between the TEM and $TM_{02}$-like modes. Some of the real currents (ohmic heating) required to support these modes independently are replaced by displacement currents (no losses) in this unique field pattern.

The outer wall losses decrease with cavity radius while the end wall losses increase with radius. The optimum cavity radius depends on the length of the structure.

## Mechanical

The PWT linac structure is lightweight because it is mostly empty, and the outer shell can be made of a copper plated aluminum pipe. The rf power density on the outer wall of the PWT is 8600 times smaller than that of the SCL.

For short, 10-20 MeV, PWT linacs, the washers can be supported on three or more thin rods extending from endplate to endplate through the region on the washers where the electric fields vanish. For longer linacs, intermediate radial supports to the outer wall can be positioned in the electric field null regions of the plane wave, as shown in Fig. 5.

The washer support rods must be in the form of hollow tubes to provide a means for cooling the washers. The washers can be very thin to reduce their mass. The nose cones can be make of invar to reduce their thermal coefficient of expansion. Due to the small amount of material within the structure and the choice of nose cone material, the resonant frequency should be relatively independent of washer temperature, thus suggesting that relatively large (20-40 $^{o}C$) temperature differences on the washers are tolerable.

Table 1 Comparison of PWT and CCL Unit Geometries

| | PWT | CCL | |
|---|---|---|---|
| | Identical Geometry Near Axis | | |
| Cavity Length | 2.500 | 2.500 | cm |
| Gap Length | 1.600 | 1.600 | cm |
| Bore Radius | 0.400 | 0.400 | cm |
| Nose Radius | 0.200 | 0.200 | cm |
| Cone Angle | 30 | 30 | deg |
| Transit Time Factor (T) | 0.793 | 0.793 | - |
| Field Nomaliation ($E_0$) | 1.00 | 1.00 | MV/m |
| Surface Field (max) | 3.29 | 3.29 | MV/m |
| | Different Cavity Volume | | |
| Resonant Frequency | 3000 | 3000 | MHz |
| Cavity Diameter | 14.000 | 3.823 | cm |
| Stored Energy | 480 | 144 | µJ |
| Magnetic Field (outerwall) | 16 | 1488 | A/m |
| Power Dissipation | 104 | 151 | W |
| Cavity Q | 86948 | 17921 | - |
| Shunt Impedance (Z) | 240 | 165 | MΩ/m |
| $ZT^2$ | 151 | 104 | MΩ/m |
| | Power Distribution | | |
| Nose Cone | 18 | 18 | W |
| Rest (R < 4cm) | 66 | 133 | W |
| Rest (R > 4cm) | 20 | - | W |
| Total | 104 | 151 | W |

Hence, the washers may be cooled by thermal conduction to the points of support. The washer spacing, which has a larger effect on resonant frequency, is determined by the support rods, which are well cooled.

The structure is powered by driving the plane wave portion of the mode from either the outer wall or an end plate. Many options for coupling to this extended mode are available.

The structure is evacuated through ports on the outer wall. The vacuum conductance from the high field regions between the washers and the vacuum pumps is excellent.

Although larger than conventional linac structures, this structure should be lightweight and geometrically sound. It should be simple to fabricate, easy to assemble, easy to tune easy to excite, and easy to evacuate.

A mechanical model of this structure, designed to operate at 3 GHz, is shown in Fig. 3. The tank, flanges, and endplates

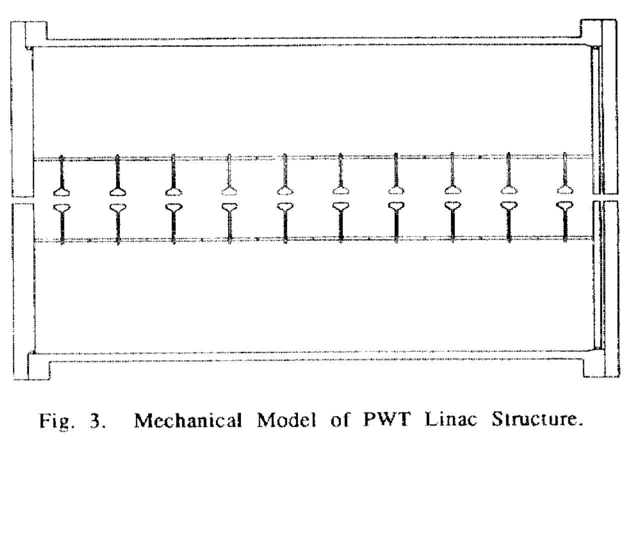

Fig. 3. Mechanical Model of PWT Linac Structure.

will be made of aluminum, the washers will be made of OFHC copper, and the washer supports will be made of stainless steel. The aluminum and stainless steel surface, exposed to rf fields, will be copper plated for conductivity. The model will be economical to fabricate and will serve for cavity mode and structure studies and development of rf power coupler geometries. With the additional of a low-b section, rf power couplers and vacuum ports, this model can graduate to an operating linac.

## Field Stability

The subject of field stability in long PWT structures has been addresseed by both multicell SUPERFISH studies and evaluation of the dispersion curve by a "periodic" SUPERFISH.[2]

Multicell SUPERFISH runs can provide a measure of field stability against end cell frequency perturbations. This is the computational analog of the technique used in the laboratory to evaluate the field stability and power propagation properties of linac structures. Five- and ten-cell geometries, terminated in half cells, were run on SUPERFISH with both normal and perturbed end cells. The perturbed geometries had the nose cone extended by 1 mm on one end and contracted by 1 mm on the other end. In the CCL geometry this corresponds to an end cell frequency perturbation of $\pm$ 56 MHz. In the ten-cell PWT, the field strength increased by 7% in the end with the negative frequency perturbation and decreases by 7% in the end with the positive frequency perturbation.

The dispersion curve for the PWT structure is shown in Fig. 4. The lower passband is very wide implying strong coupling. This passband spans the frequency range from 810 MHz to 3000 MHz yielding a cell-to-cell coupling constant of 86%. The points where the second and the third passbands cross 3000 MHz are of some concern. Operational experience with a model cavity would help these concerns.

## Design Example

The design of a 150-MeV electron linac, shown in Fig. 5, is presented here for comparison with other extended linac designs. At a gradient of 15 MeV/m, it has a length of 10 m and a theoretical peak power of 15 MW. Adding 40% for practical considerations and 1.5 MW for beam loading (10 mA beam current) yields a total peak power requirement of 22.5 MW, which is well within the capacity of a single 50-MW SLAC klystron.

All standing-wave linac structures reflect a majority of the incident power during the cavity filling time. In very high power klystron-driven applications, the klystron must be protected from this reflected power to avoid damage. One

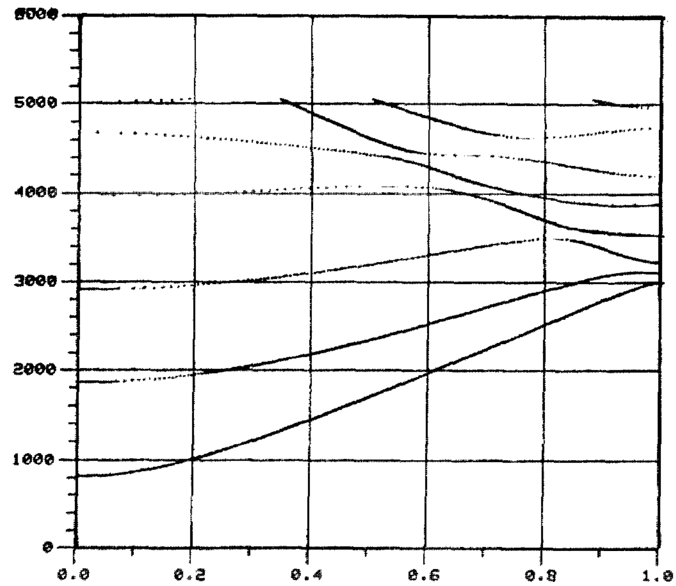


Fig. 4. PWT Dispersion Curve.

simple solution is to organize the linac as two equal-length sections driven from one klystron through a 3-db power splitter with a dummy load on the 4th arm.[3] During the cavity filling time, the reflected power from each linac section is diverted to the dummy load. This technique has been thoroughly tested at SLAC on their standing-wave energy storage cavities (SLED).

## Conclusions

Thw PWT linac structure offers many advantages over other known electron linac structures. The most fundamental advantage is the exceptionally high shunt impedance, which translates into performance advantages and reduced operational costs. Many of the practical advantages relate to the ease of fabrication, assembly, handling, tuning, cooling, evacuation, and excitation, which translate into reduced capital costs. This structure should find its way into many existing electron linac applications, and may, because of its economical format, open the door to new electron linac applications.

## Acknowlegments

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## References

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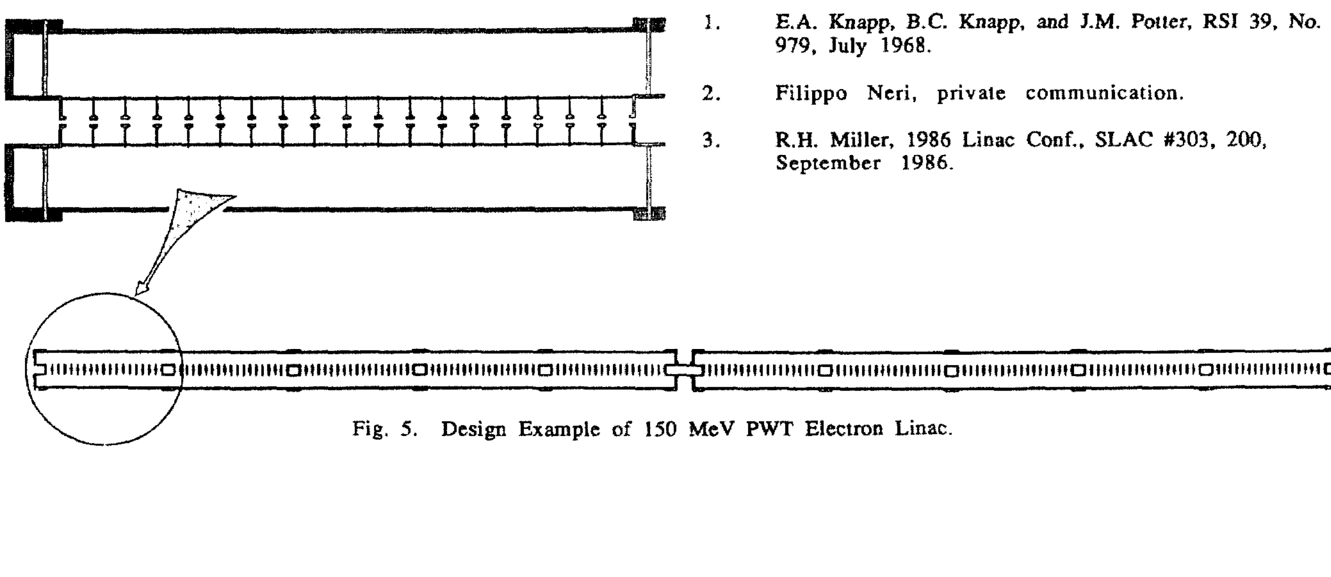

Fig. 5. Design Example of 150 MeV PWT Electron Linac.