A PLANE-WAVE-TRANSFORMER PHOTOELECTRON LINAC

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Abstract

We develop a novel photoelectron linear accelerator using a plane wave transformer (PWT) design [1]. In this design the input RF power is coupled to the accelerating cavities via a large concentric manifold cavity. The scheme makes possible very strong coupling between the accelerating cells, and relaxes manufacturing tolerances. The compact photoelectron linac integrates a photocathode directly into a PWT linac structure, and eliminates the drift space between a photoinjector and the linac which would otherwise lengthen the electron bunches. Using an emittance compensation scheme [2], the PWT photoelectron linac produces a high-brightness beam. We have demonstrated by simulations the feasibility of a 20-MeV PWT photoelectron linac design with a set of eleven iris-loaded disks suspended and cooled by four water tubes inside a large cylindrical tank.

INTRODUCTION

In this Small Business Innovation Research (SBIR) project DULY Research Inc. teams up with University of California at Los Angeles (UCLA) to develop a novel photoelectron linear accelerator using a plane wave transformer (PWT) design [3]. The goal is to accelerate a short pulse (~5 ps), low emittance (~1 mm-mrad), high charge (~1 nC) electron beam in a compact (~30 MV/m), inexpensive linear accelerator. This kind of compact linac will have broad commercial and research applications [4].

The conventional RF electron linac design, typified by that of the Stanford Linear Accelerator Center (SLAC) and by commercial medical linacs, consists of iris-coupled disks separated by metal cup spacers and enclosed in a cylindrical tube to form a set of accelerating cavities. The RF input power is fed into an accelerating section by means of waveguide(s) coupled to a single input cavity. Once inside the slow-wave linac structure, the electron beam is accelerated by RF fields traveling in phase with the bunched beam. In general, the manufacturing tolerances of the accelerator components are extremely tight, and consequently the cost of machining and brazing is high, because the precise dimensions determine the phase and cavity properties essential for proper RF acceleration. It would be desirable to find methods to relax manufacturing tolerances and reduce cost for linac structures, especially for repetitive production of accelerating sections as in a linear collider, or for mass production of commercial linacs.

A novel plane-wave-transformer (PWT) accelerating structure which is recently under development at the University of California at Los Angeles (UCLA) [1] has the potential of making such improvements. The PWT linac structure is a multi-cell, standing-wave system operating in the π-mode. A schematic of our 20 MeV PWT linac is shown in Fig. 1. The structure consists of an assembly of iris-coupled disks suspended along the axis of a large cylindrical tank. In this design of the PWT linac, the disks are connected longitudinally by cooling tubes which are supported at the end plates of the tank. The input RF power is fed into the cylindrical tank outside the disk/iris assembly and propagates predominantly in a TEM-like mode in the coaxial manifold, which resembles a plane wave propagating in free space. This TEM-like accelerating mode transfers external RF power into a TM-like accelerating mode between the irises. As there are no walls separating the disk assembly and the manifold tank, all individual cells are strongly coupled to the manifold and to each other. The unique and simple design of the PWT linac structure allows tolerant dimensions (about 100 μm for an S-band structure), and is easy and inexpensive to build. The PWT is also easy to operate due to its large vacuum conductance.

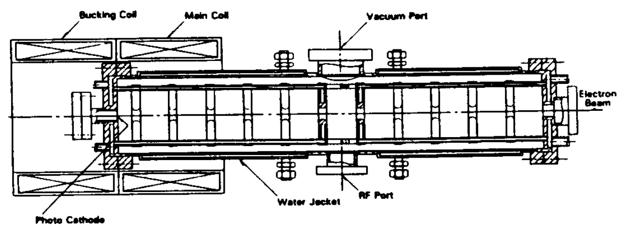

Figure 1. Schematic of a 20-MeV PWT photoinjector linac

TECHNICAL APPROACH

The previous UCLA photoinjector is based on a well-tested Brookhaven National Laboratory design [5] currently adopted by many laboratories over the world. It consists of a 1 + ½ cell RF cavity operating at S-band, with the cathode placed at the center of the end wall of the first half-cell. The photoinjector is currently driven by a mode-locked YAG laser which uses chirped pulse amplification and compression to obtain 7.5-ps (FWHM) pulses containing up to 300 μJ per pulse of UV light (262 nm).

In this DULY/UCLA project, the photoinjector is modified and integrated into a PWT electron accelerator in which the RF cavities are open to a large cylindrical tank, and the fields therein are strongly coupled between cells. This is an integrated structure with a total of eleven (11) full cells and one (1) half cell, including the photoinjector and the linac structure. The accelerating structure consists of a row of equidistant, circular washers which are aligned along the axis of a large cylindrical tank (Fig. 1). These copper disk washers are fixed in position by

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means of four metal tubes parallel to the tank axis. The metal tubes are also water conduits for cooling the disks. Because the disks are separated from the cylindrical tank, they act as a center conductor to support a TEM-like mode in the coaxial manifold, which is excited by high power RF coupled through an input slot on the tank wall. The strong coupling between the TEM wave in the manifold and a TM-like mode along the beam axis provides a π-mode longitudinal accelerating field profile, through the irises, by which electrons are accelerated. These features of the PWT linac provide advantages of high shunt impedance and strong coupling between individual cells, thus relaxing manufacturing tolerances and reducing manufacturing costs.

The design objective is optimization of a photoelectron accelerator design and performance of parametric studies of beam dynamics for a 20-MeV PWT photoinjector linac, to be built and tested in the following experiment. Specific technical objectives include: (1) accelerator design, (2) beam dynamics study; (3) solenoid magnet design, with results presented in the following sections.

CALCULATION OF ELECTROMAGNETIC FIELDS AND RF PROPERTY

The RF structure of the PWT linac has been specified in a two-stage design process: initial optimization of the field profile for acceleration using 2-D electromagnetic field solver, SUPERFISH, followed by a 3-D analysis using the code MAFIA. In the first stage, we make a first specification of a baseline geometry and the nominally axisymmetric fields in the beam channel. This specification is subject to the following constraints:

- maximizing shunt impedance
- minimizing higher spatial harmonic content
- cell number and gradient appropriate to deliver 20 MeV beam
- good coupling and mode separation
- relatively low Q_0 to allow for structure filling in < 6 μs
- minimizing outer diameter to allow compact focusing solenoid

The SUPERFISH results have been used to deduce the spatial harmonic content of the accelerating field. It is important that the higher spatial harmonic content be minimized in an RF photoinjector, so that the beam would not suffer nonlinear RF-derived emittance growth. The amplitudes of the high spatial harmonics have been well minimized given our desire for high shunt impedance.

While the shunt impedance in the PWT is mainly derived from the properties of the iris geometry, the cell-to-cell coupling, and therefore the mode separation is a function of the distance from the inner radius of the outer wall to the outside of the disks. In the SUPERFISH calculations, we have chosen the wall radius to be 5.5 cm, and the disk radius to be 4.07 cm. For these parameters, the coupling is quite large — the width of the lowest passband is over 795 MHz. The mode separation between the π and the 11π/12 is 13 MHz, which is many times the width of the modes due to the finite Q_0. This mode separation compares favorably with the 0-π mode separation in the current UCLA 1.5-cell, 2856 MHz gun (< 2 MHz), and is larger than the mode separation of the next generation 1.625 cell guns being developed by a BNL/SLAC/UCLA collaboration.

We have studied several configurations of the support rod structure using MAFIA: a no-rod, a two-rod, and a four-rod PWT structure, each supporting 11 metal disks (1.2065 cm thick) with 1.5875-cm irises, inside a cylindrical tank with a radius of 5.5 cm. The dimensions of each structure are chosen to allow a TM_{01n} accelerating π-mode at a frequency of 2856 MHz. The structure is tuned by adjusting the position of the support rods and the disk radius. Arrow plots of the electric field for the 4-rod PWT structure accelerating mode as simulated by MAFIA are shown in Fig. 2. The shunt impedances and Q_0-values for these cases are shown in Table 1. The ratio of R/Q_0 is seen to be roughly constant (even increasing slightly with the introduction of rods), while the Q_0 degrades with the introduction of extra rods. The zero-rod structure represents both an ideal baseline, and a representation of a DULY innovation in RF structure design. The two-rod case, while offering a high Q and shunt impedance, is problematic from two points of view: the field perturbation, which is at lowest order quadrupole, and the mechanical integrity of the structure. Because of these considerations, we have decided to pursue our program of building a PWT prototype using the four-rod design, and at the same time continue R&D on a highly promising no-rod design.

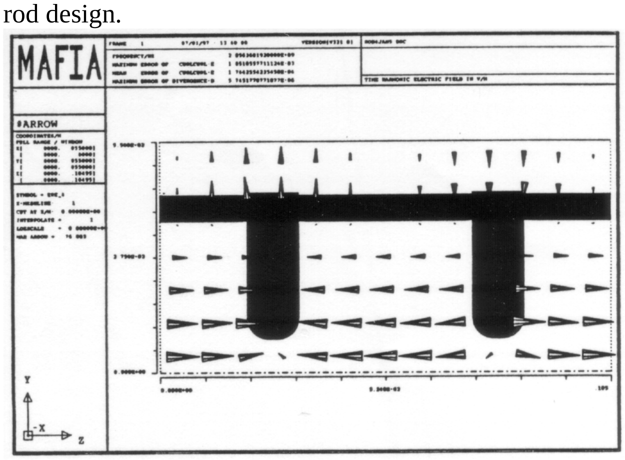

Figure 2. The electric field in the 4-rod PWT structure

Table 1. RF Characteristics of PWT Designs (for 4-rod, 2-rod and no-rode cases, from the MAFIA simulations)

	Q_0	R(MΩ/m)	R/Q_0 (Ω/m)
4-rods	24,560	121.3	4939
2-rods	28,316	128.8	4547
No rods	32,572	141.7	4350

THERMAL AND MECHANICAL ANALYSIS

The high frequency RF power used to accelerate the electron beam also produces heating on the surfaces of the metallic structure. A design of the PWT structure uses four stainless steel tubes to provide mechanical support of eleven suspended disks, and to carry cooling water to the disks for heat removal. To control the temperature, an annular channel carrying flowing water (~10 liters/min at the reservoir) at a constant temperature (~65°F) is cutaway around the interior of each disk to carry heat away from the metal. Water from an external constant-temperature bath flows into one reservoir, passes into the disks via two of the four water tubes, returns to another reservoir through the remaining two tubes, back to the bath to form a closed loop. We have performed a thermal analysis of a typical PWT disk subject to pulsed RF heating and continuous water cooling, using a PC version of a general finite-element thermal/structure code, COSMOS/M. The temperature result is sensitive to the value of the convective film coefficient, which is dependent on the flow, and can vary between 1-10°C because of the uncertainty in the film coefficient. A higher flow rate (> 15 liters/min at the reservoir) and a larger hydraulic diameter will ensure better turbulent flow and heat transfer. The temperature variation between different disks can be tightly controlled by adjusting the size of the flow orifice connecting to the cooling channel. Such cell-to-cell tuning is probably not necessary because of the strong coupling between individual cells in the PWT linac.

BEAM DYNAMICS CALCULATIONS

The design of beam optics in an RF photoinjector linac is intimately related to the RF design of the structure, as well as to the design of the focusing solenoid, in sometimes subtle ways. We made use of an emittance compensation technique to achieve low beam emittance and high beam brightness.

The analytical theory developed by SR [2] also allows the beam parameters which give emittance compensation to be specified. It requires that, in order to prevent the beam from expanding unnecessarily in the initial few cells, the peak in the solenoid focusing field of the solenoid be placed as close to the cathode as possible. This has been done for our preliminary design, as discussed further below. Another condition is that the parameter $a = eE_0/k_{RF}m_ec^2$ be limited to the order of unity, thus setting the peak field (on the order of 60 MV/m), the accelerating gradient (on the order of 30 MV/m), and the nominal launch phase (32 degrees, where 90 is taken by convention to be the RF crest). This condition can be explained as follows: for higher gradients, the invariant envelope is smaller, and thus the launched beam must be radially smaller in order to be matched to the invariant envelope well beyond the solenoid. In that case, the beam is too dense (the beam plasma frequency is high) and expands excessively in the first half-cell, thus denying the possibility of invariant envelope matching. Therefore, in order to minimize the emittance, we have chosen a moderate accelerating gradient of 33 MV/m.

PRELIMINARY DESIGN OF THE SOLENOID MAGNET

To implement emittance compensation, the transverse beam profile should be immediately under control by the external focusing field after the electrons are emitted from the cathode. This can be accomplished by a focusing solenoid with a very fast-rising longitudinal field profile which increases linearly in the first half-cell and is maximum and close to constant in the first full cell. In our preliminary design, the focusing solenoid is integrated in a single yoke assembly with its mirror image bucking solenoid. The mirror symmetric bucking coil is run in series with the focusing coil. Each coil has 144 water-cooled, ¼-inch square, copper windings, and runs at approximately 140 A to obtain the design field values. The inner radius of the coil and the yoke is 6.5 cm, which provides a one-centimeter clearance between the inner radius of the RF tank and the solenoid assembly; the outer radius is 15 cm. This design is similar to that used in several UCLA projects, but here with even more modest field and current values. We are working on a new compact solenoid design in which the large mirror bucking coil is replaced by a very small one located behind the cathode.

COLD TEST OF A PWT LINAC WITH A PHOTOCATHODE

In order to demonstrate the feasibility of integrating a photocathode into a PWT linac structure without significantly perturbing its RF properties, we have outfitted an existing PWT linac structure at UCLA with a cathode plug (and associated spring-contact RF joint), and performed cold microwave measurements on the combined structure. This structure consists of seven (7) full cells and two (2) half cells with eight nearly identical disks, held together by four rods. It has fewer cells and a larger tank than the PWT structure we propose to build in the next step, but otherwise has many similar features.

CONCLUSIONS

Our work has successfully demonstrated the feasibility of an integrated PWT photoelectron linac system design. The system concepts and detailed dimensions of a prototype 20-MeV PWT photoelectron linac using a 4-rod design have been specified. We have used computer simulations and emittance compensation techniques to optimize the system performance. Limited cold tests have been performed to support the viability of integrating a photocathode and a PWT linac into a combined system. Based on these results, we can now move into the next step of the construction and test of a compact, high brightness, PWT photoelectron linac prototype system.

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