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HIGH EFFICIENCY TRAVELING WAVE LINAC WITH TUNABLE ENERGY *

Valery Dolgashev†, Agustin Romero, Anatoly Krasnykh, SLAC, Menlo Park, CA, USA
Sergey Kuzikov, Roman Kostin, Euclid Techlabs LLC, Bolingbrook, IL, USA
Philipp Borchard, Dymenso LLC, San Francisco, CA, USA

Abstract

We will present the physics design of a compact, highly efficient, energy-tunable 9.3 GHz linac to generate up to 500 W of 10 MeV electron beam power for medical and security applications. This linac will employ a patented travelling wave accelerating structure with outside power flow which combines the advantages of high efficiency with energy tunability of traveling wave cavities. Unlike standing wave structures, the proposed structure has little power reflected back to the RF source, eliminating the need for a heavy, lossy waveguide isolator. In contrast to the side-coupled cavity designs, the proposed structure is symmetrical and therefore it does not have deflecting axial fields that impair the beam transport. The high shunt impedance will allow the linac to achieve an output energy of up to 10 MeV when powered by a compact commercial 9.3 GHz 1.7 MW magnetron. For pulse-to-pulse tuning of the beam output energy we will change the beam-loaded gradient by varying the linac's triode gun current.

INTRODUCTION

The goal of this project is to design and high-power test a prototype of a linac which is based on a new highly efficient traveling wave accelerating structure [1, 2]. The structure offers high shunt impedance comparable to side-coupled standing wave structures, but without the disadvantage of RF power reflected back to the RF source. The goal is to meet or exceed most of the performance metrics required by Department of Energy funding opportunity announcement DE-FOA-0002463. The linac's accelerating cavity will be approximately 60 cm in length. The final linac will produce electron pulse bursts with tunable energy up to 10 MeV, an average beam power of at least 500 W and duty factor of about 0.08% driven by a commercial 9.3 GHz 1.7 MW magnetron [3]. These target requirements and the main design features are summarized in Table 1.

The physics design of the linac progressed in following steps: the first we performed an analytical study of the linac parameters in which we understood that the linac has to be of constant gradient type. To build the constant gradient linac, we need to tune group velocity, so we completed a parametric study of a unit cell to understand dependencies of the group velocity *vs.* cell shape. In the next step we performed beam dynamics simulations of a gridded gun to show that it could achieve required currents, then we created a concept of the mechanical design of the cavity.

Table 1: Linac Target Requirements and Design Features.

Metrics	**Requirements**
Energy Tuning Range	<5 MeV...10 MeV
Output average beam power at 10 MeV	>500 W
Maximum cavity size	10x10x60cm
Target capital cost	< $1M
Other Design Features	
Travelling wave structure with outside power flow	
No circulator	
Duty factor	0.08%
Frequency	9.3 GHz

Table 2: Initial acc. structure and linac parameters [2].

Metrics	**Requirements**
Qo	6800
Shunt Impedance	144 MOhm/m
Phase Advance per Cell	120 deg.
Cell length [mm]	10.745 mm ($\beta = 1$)
Number of cavities	56 (approximately)

Table 3: Analytical linac parameters.

Parameter	**Value**
Structure type	Const. Gr.
Linac length [cm]	60
Attenuation parameter, τ	1.0
Group Velocity, %c	2 …0.3
Beam current at 5 MeV	200 mA
Beam current at 10 MeV	70 mA
Average beam power at 5 MeV	800 W
Average beam power at 10 MeV	500 W

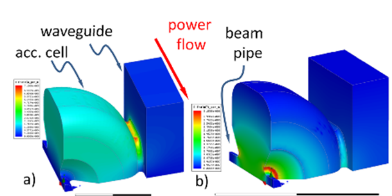

Figure 1: Quarter-cell finite element model of the $\beta = 1$, 9.3 GHz, 120 deg. phase advance per cell traveling wave accelerating

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† dolgash@slac.stanford.edu

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structure. Surface electric fields are normalized to 100 MV/m accelerating gradient: a) magnetic fields with peak magnitude of 0.71 MA/m; b) electric fields with peak of ~325 MV/m [2].

ANALYTICAL STUDY

We have performed an analytical study of a traveling wave structure based on a linac's regular cell parameters published in [2] and shown in Table 2 and Figure 1. For this initial study we considered ultra-relativistic beam and tuning of the output beam energy using beam loading. The results of this study are published in [4] and shown in Table 3 and in Figure 2. We have found that a structure with a constant impedance cannot achieve the target parameters, and the structure must have at least a constant unloaded gradient. We also found that increasing the length of the structure from 60 to 80 cm makes it possible to increase the output energy above 10 MeV while maintaining the average beam power of 500 W. For the next steps in the beam-dynamics study we will use Sergei Kutsaev's code *Hellweg 2d* [5], which includes physics of beam loading and space charge.

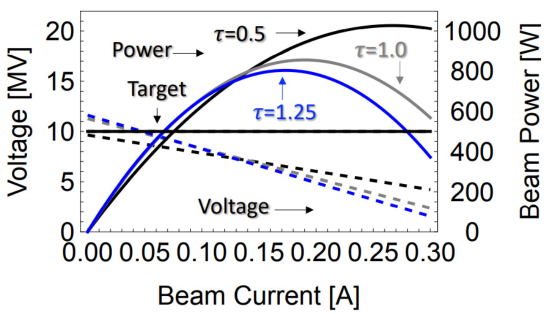

Figure 2: The net voltage gain and average beam power for the constant gradient structure with length of 60 cm. Solid curves show average beam power for magnetron duty factor of 0.08%. Dashed curves show beam loaded output energy. It can be seen from the graph that the linac with attenuation factor $\tau = 1$ is the closest to achieving the target parameters, and the result is not sensitive to the small change of τ. For details, see [4].

TUNING OF THE GROUP VELOCITY

The analytical study showed that to achieve constant unloaded gradient, the group velocity of the structure should vary between 2 and 0.3%*c* from input to output. In traditional, on-axis coupled traveling wave structures, the group velocity is tuned by changing the beam aperture. In the structure shown in Figure 1 there is no coupling through the beam aperture, so we used coupling hole between the cavity and the waveguide to tune the group velocity.

We created the parametrized HFSS [6] model for the structure's cell. Using this model, we investigated the dependencies of the group velocity on the cell shape. For this investigation, we fixed the waveguide position relative to the cell axis and sizes of the waveguide. We could vary two hole dimensions, in the longitudinal direction, along axis, h_z and in the transverse direction, h_y. This allowed us to obtain group velocities in the range 0.4% - 5%*c* which are sufficient for the design of a constant gradient structure with the parameters shown in Table 3. The results of this study, dependence of the group velocity, shunt impedance and Qo are shown in Figure 3. Next, we investigated multimode properties of the structures for these cell shapes. We found the structure is single-moded in the whole range of group velocities.

GRIDDED GUN

We have considered two methods of varying output beam energy well suited for a traveling wave structure: changing phase velocity of the electromagnetic wave and changing the current of a thermionic electron gun. For now, we are focused on changing the current of a gridded electron gun. For the beam dynamics study we investigated two electron guns, one operating at 15 kV, which is available commercially from AcceleRAD Technologies [7], and a custom 30 kV version which may result in better linac performance as compared with the 15 kV gun. Results of our simulations of a 30 kV triode gun are shown in Figure 4. The gun parameters should be sufficient to allow for 70 mA to 200 mA of captured electron current, assuming at least 40% capture, which is conservative. The beam data from simulations of both guns will be used in beam dynamics simulation in both *Hellweg 2d* and a Particle-In-Cell code.

MECHNICAL DESIGN CONCEPT

Accelerator structures are usually manufactured by precision turning of individual cells and combined with precision milling for complex parts such as rf power couplers. These multiple parts are brazed into a complete structure. For our accelerating structure, we propose to use an alternative approach of precision-milling to cut cells into metal blocks that comprise either half of the complete structure.

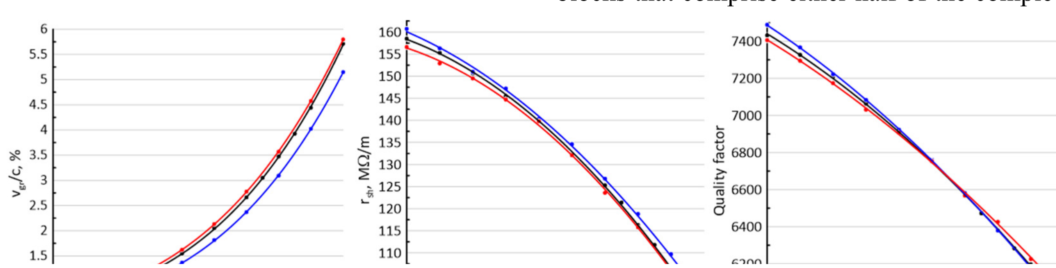

Figure 3: Group velocity (a), shunt impedance (b), and Qo *vs* transverse hole's size, h_y for longitudinal sizes h_z: 5 mm (blue), 6 mm (black), and 7 mm (red). The structure is 9.3 GHz, traveling wave with 120 deg. phase advance per cell.

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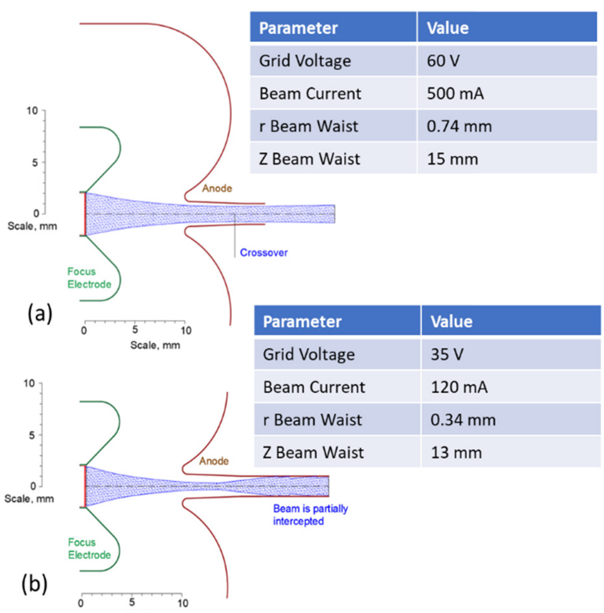
The two metal blocks are then brazed together. We used this approach to build prototypes for the CERN Compact Linear Collider project [8–11]. We had utilized several novel approaches for the structure design and manufacturing which could potentially decrease manufacturing costs and improve operational performance. The dramatic reduction in the number of parts also results in lower production costs. The simplified mechanical design improves the reliability of the manufacturing process.

We show our mechanical design concept of the new linac in Figure 5. The constant gradient traveling wave structure is built out of two brazed halves. To facilitate constant gradient the shape of each cell is different. The input part of the structures is used for both bunching and acceleration and thus has shorter cells than the downstream, $\beta = 1$ section. The structure has two parallel waveguides feeding the cells, so we incorporated a milled-in waveguide power splitter.



Parameter	Value
Grid Voltage	60 V
Beam Current	500 mA
r Beam Waist	0.74 mm
Z Beam Waist	15 mm

Parameter	Value
Grid Voltage	35 V
Beam Current	120 mA
r Beam Waist	0.34 mm
Z Beam Waist	13 mm

Figure 4: Results of beam dynamics simulations of 30 kV triode gun.

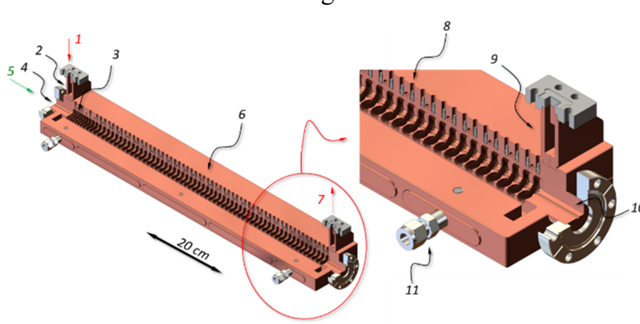


Figure 5: Solid model of a high efficiency traveling wave accelerating structure. Upper left part is cut to show internal geometry. This is a 9.3 GHz, $2\pi/3$ phase advance structure. Notation as follows: 1 – input RF power; 2 – input waveguide; 3 – low β section for beam bunching; 4 – input beam pipe, future location of a triode electron gun; 5 - direction of electron beam; 6 – $\beta = 1$ section of the accelerating structure; 7 – output RF power; 8 - tuning pin; 9 – output waveguide; 10 – output beam pipe, future location of X-ray target; 11– fitting for water cooling.

SUMMARY

We have completed the initial study of a compact and efficient electron linac. It is tunable from 5 MeV beam energy and 800 W of average beam power to 10 MeV and 500 W average beam power. The tuning is performed by changing the injected current from a triode electron gun. The accelerating structure is of constant gradient type, 60 cm long, with beam current ranging from 70 mA to 200 mA, fed by a 9.3 GHz, 1.7 MW commercial magnetron. The beam energy increases beyond 10 MeV with 500 W average beam power if the structure is lengthened from 60 to 80 cm. We determined the dependence of the group velocity to the structure shape to facilitate the constant gradient. For the gun, we are considering two options, a commercial 15 kV version, and our new 30 kV design. We developed a mechanical design concept for the linac fabrication, which will be milled out of two blocks and brazed together. We will follow this study with further beam dynamics simulations and the engineering design. We plan to build and test a 11.424 GHz version of the structure in 2023.

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