# CRYOGENIC ACCELERATOR DESIGN FOR COMPACT VERY HIGH ENERGY ELECTRON THERAPY*

E. C. Snively†, M. Shumail, C. Nantista, Z. Li, M. Oriunno, G. Bowden, V. Borzenets, A. Krasnykh, S.G. Tantawi, SLAC National Accelerator Laboratory, Menlo Park, CA, USA

B.W. Loo, Dept. of Radiation Oncology, Stanford School of Medicine, Stanford, CA, USA

## Abstract

We report on the development of a cryogenic X-band (11.424 GHz) accelerator to provide electron beams for Very High Energy Electron therapy. The distributed coupling linac is designed with a 135° phase advance, optimized to produce a 100 MeV/m accelerating gradient in a one-meter structure using only 19 MW when operating around 77 K. This peak power will be achieved through pulse compression of a 5-8 MW few-μs pulse, ensuring compatibility with a commercial power source. We present designs of the cryogenic linac and power distribution system, as well as a room temperature pulse compressor using the $HE_{11}$ mode in a corrugated cavity. We discuss scaling this compact and economical design into a 16 linac array that can achieve FLASH dose rates (> 40 Gy/s) while eliminating the downtime associated with gantry motion.

## INTRODUCTION

The linear accelerator (linac) design presented here aims to demonstrate a Very High Energy Electron (VHEE) therapy system that is compact enough to fit within a conventional clinical radiation treatment room. Because VHEE therapy eliminates the process of using the electron beam to produce X-rays, relying instead on the therapeutic dose provided by the electrons themselves, this treatment scheme inherently allows for higher dose rates, making it an attractive approach to deliver FLASH treatments exceeding 40 Gy/s.

Electron beam energies on the order of 100 MeV are needed to reach deep-seated tumors throughout the body. Designing a linac capable of accelerating electrons up to 100 MeV within a meter is well within the known state of the art. However, the typical amount of RF power needed to power the linac to achieve this high gradient requires sources that are incompatible with existing medical treatment facility infrastructure. Typically, the required RF-power is on the order of 150 to 200 MW at X-band. The sources that can generate this type of power typically occupy the space of several treatment rooms. Furthermore, the cost of such a source would be highly prohibitive; a VHEE device with these power requirements would not be competitive with other radiotherapy modalities.

## SYSTEM DESIGN

The accelerator design presented here requires only 5-8 MW of RF power at 11.4 GHz to generate a 100 MeV beam, compared with the typical 150-200 MW required for conventional linacs. This breakthrough in power efficiency is accomplished through the development of a novel high efficiency linac operated at cryogenic temperatures and a novel ultra-compact RF pulse compression scheme.

### 135 Degree Phase Advance Linac

The phase advance of this standing wave linac design, 135° per cell, provides the highest possible geometric shunt impedance, reaching 192 MΩ/m at room temperature. A narrow beam pipe radius of 1 mm reduces coupling between cells to the point where the relative phase can be arbitrarily chosen to maximize shunt impedance. The cavity geometry, shown in Fig. 1, features a re-entrant nose cone to maximize the ratio of on-axis accelerating gradient to surface field using a geometric optimization approach [1]. The $Q_0$ of the cavity is 8100 at room temperature. By reducing the operating temperature to 77 K, we expect to gain a factor of 2.7 in $Q_0$, with a corresponding increase in the shunt impedance by the same factor [2].
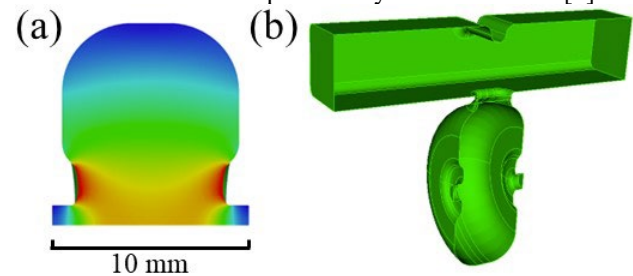


Figure 1: (a) Cross-section of the electric field profile simulated in one half of the 135° phase advance linac cavity. (b) 3D model showing one half of the power distribution waveguide with coupling iris for a single cavity.

Power is coupled to each cell through a distributed power coupling manifold. To accommodate the 135° phase advance, four parallel manifolds are used. The phase advance between the feeding junctions on each waveguide is 180° which allows feeding every fourth cavity as the phase advance to every forth cavity is 135°×4 ≡ 180°. The full one-meter structure is composed of 104 cells. Power couples to the cell through an iris at the cell equator, as shown in Fig. 1 b. The parameters of the iris, along with the inverted feature opposite the cell in the waveguide, have been optimized using the parallel ACE3P solvers developed at SLAC to produce the correct transfer S-matrix and coupling for a beam-loaded cavity.

### RF Pulse Compressor

The VHEE system presented here is intended to be compatible with a commercial 11.424 GHz RF power source, taking a 6 MW peak power input in a ~4 μs pulse length

† esnively@slac.stanford.edu

and producing a 19 MW peak power in a ~200 ns flattop. While the average power is consistent with the system requirements, this peak power is insufficient to drive the 100 MeV/m gradient needed in the structure. To compensate, a pulse compressor is included within the scope of the VHEE system design. The pulse compressor design operates under the same principle as the original SLED cavity [3]. The energy in the long RF pulse produced by the klystron is stored in a single high-Q cavity, with two polarized modes replacing the original SLED design concept of two energy storage cavities [4]. Before the end of the RF pulse is reached, the phase of the klystron output is flipped by 180 degrees using the low-level RF input. As a result, incoming power from the klystron to the coupler on the high-Q cavity is reflected on towards the accelerator structure while simultaneously summing with the stored power now being discharged from the cavity.

In order to reach the required gain in peak power, the pulse compressor for the VHEE system must meet the simultaneous challenges of a high $Q_0$, roughly 400,000, and a high coupling beta, on the order of 10. Coupling to the desired mode without significant mode coupling distortion is nontrivial. The design presented below uses an $HE_{11}$-mode in a corrugated cylindrical cavity.
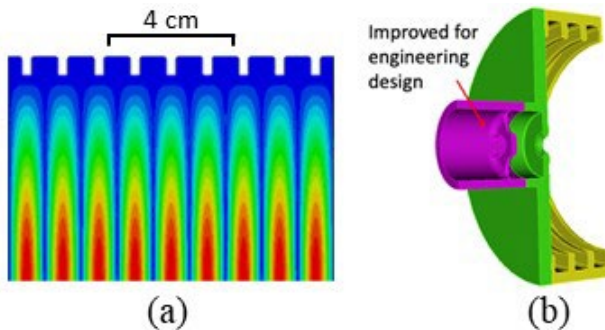


Figure 2: (a) Cross-section of the simulated $HE_{11}$ mode profile shown for 9 periods in one half of the pulse compressor cavity. (b) 3D model showing one half of the coupler with an intermediate low-Q cavity at the end plate of the pulse compressor.

The field profile of the $HE_{11}$-mode in the high-Q compressor cavity is shown in Fig. 2a. This design benefits from low losses because the fields tend to zero at the wall, while still allowing for tuning and coupling at the end faces. To enable a large coupling factor without spoiling the high-Q mode in the compressor cavity, a specialized coupler was designed with a secondary low-Q $TE_{11}$ cavity, as shown in Fig. 2b. The small aperture in the compressor cavity keeps the perturbation to the $HE_{11}$ mode small, while the four irises into the low-Q cavity enhance the coupling factor.

Because the $Q_0$ of the compressor scales with the cavity frequency $f$, radius $a$, and length $L$, as

$$Q_0 = \frac{2391.448\, a^3 f^{5/2} L}{a^3 f^2 + 121.126\, L}, \qquad (1)$$

the necessary quality factor can be achieved with an appropriate length of cavity without needing further enhancement through techniques like cryogenic cooling. The VHEE compressor design achieves a $Q_0$ of 405,000 with a cavity length of 0.87 m.

## Mechanical Design

The increased complexity of the distributed coupling linac fed by four parallel manifolds requires innovation in the mechanical design of the structure. The designs of previous distributed coupling linacs produced at SLAC have used a split-block fabrication technique with two halves either brazed or diffusion bonded. In this case, the minimum number of distinct pieces that can be used when milling out the vacuum space of the distributed coupling linac is four, as shown in Fig. 3. This design includes the RF waveguides routing to each of the four manifolds at the center of the structure. The four copper slabs include holes for alignment pins to assist during assembly. In addition, angled holes running the length of the structure allow access for four tuning pins per cell.

The four slabs are designed for diffusion bonding. An investigation into the predicted stress distribution during the diffusion bonding process is shown in Fig. 4. The primary concern is the variability in the stress distribution as a result of the vacuum spaces of the power distribution waveguides and cavities themselves. Sufficient pressure must be applied for the surfaces to bond, without excessive pressure deforming the cavity geometry. The simulation shown in Fig. 4 takes advantage of symmetry and structure periodicity to reduce computational time, rendering only one half of the structure over four periods. The variation in normal stress at the interface running through the center of the cavities covers a range up to 8 MPa, within the expected tolerance for the diffusion bonding process.
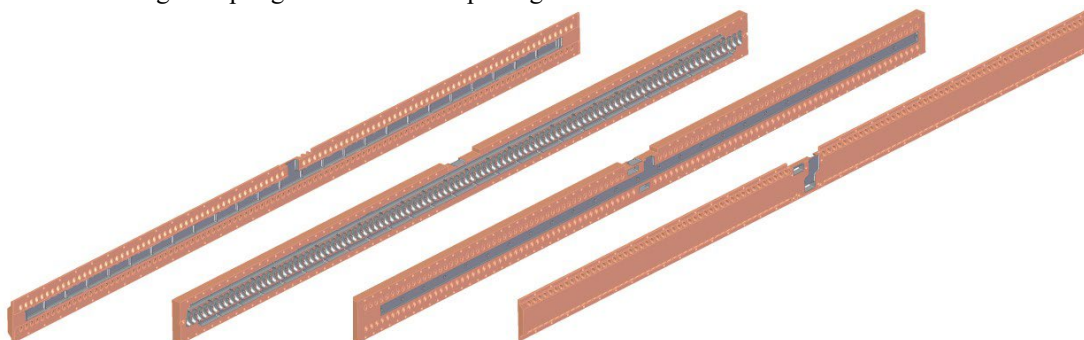


Figure 3: 3D model of the mechanical design for the four copper slabs composing the VHEE distributed coupling linac.

**Electron Accelerators and Applications**

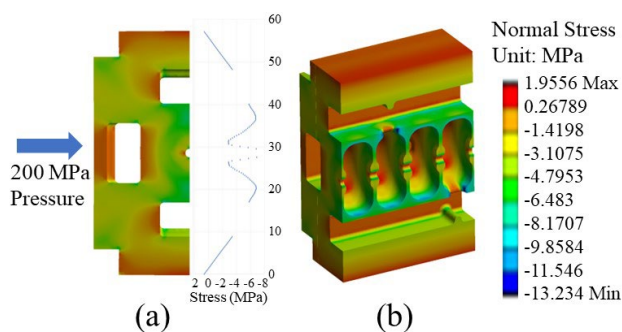**Industrial and medical accelerators**

Figure 4: (a) Cross-section of the simulated stress distribution in one half of the VHEE linac. Pressure would be evenly applied at the flat outer surface on the left during diffusion bonding. A line-out plot indicates the variation in normal stress at the right-most boundary that runs through the center of the cavity irises. (b) 3D view of the stress distribution in one half of four periods of the structure.

The operating temperature of the VHEE linac is controlled with a single stage cold head providing up to 250 W of cooling power at 80 K. The schematic shown in Fig. 5 illustrates the configuration of the thermal strap providing flexible contact between the linac and cold head, along with the RF input consisting of 4 rectangular waveguides bundled together. These waveguides are made of stainless steel plated with copper in order to reduce the thermal conductivity. The assembled linac design includes stainless steel reinforcement bars running the length of each side.
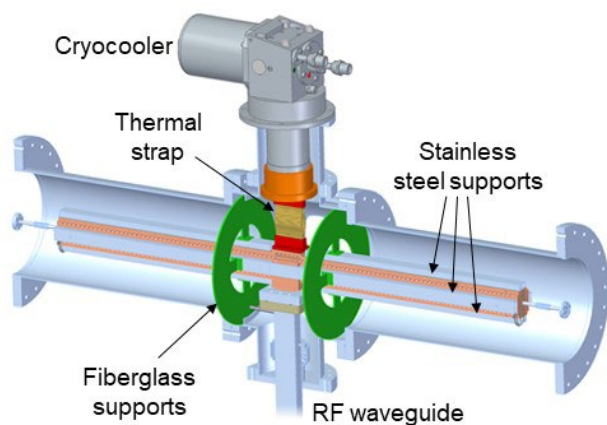


Figure 5: 3D model of the VHEE linac inside of the cryostat. The system is designed for an operating temperature of 77 K.

Upstream of the distributed coupling linac, a thermionic gun provides the electron beam, followed by an injector section to facilitate bunch capture and bring the beam up to a relativistic energy. The pulsed average current at the output of the injector is 20 mA. At a repetition rate of 30 Hz, this single linac system provides an average current of 120 nA. This corresponds to an expected dose rate of around 50 Gy/s in a treatment area of 6 cm$^2$.

This prototype configuration is sufficient for preclinical animal studies of the FLASH treatment regime. Ultimately, this VHEE system could be scaled into a multi-linac array, enabling a larger treatment field as well as dose delivery

from multiple angles of approach without the need for gantry motion. An extension of this single VHEE linac system into a 16-linac architecture will be able to leverage the innovations in the PHASER project, which uses the same approach to eliminate gantry motion and provide high dose rates for conventional X-ray radiation therapy [5].

## CONCLUSION

The designs presented here for a distributed coupling linac with 135° phase advance and compact RF pulse compression system provide a technological solution to the challenge of delivering a VHEE beam (100 MeV) with equipment that can be installed in existing radiation therapy facilities. The necessary acceleration gradient of 100 MeV/m in a one-meter X-band structure is achieved using an RF source with only 5-8 MW peak power. This modest power requirement represents a breakthrough in terms of the viability of a VHEE treatment system which could offer a path to higher dose rates for FLASH therapy as well as greater accessibility for medical care using accelerator technology. The VHEE linac design shown here demonstrates the novel capability of the distributed coupling concept to enable a standing wave linac with fully optimized phase advance, providing the highest possible geometric shunt impedance. The extreme efficiency of this cryogenic X-band linac combined with the innovation in room temperature high-Q pulse compressor design continue to advance the cutting edge in compact accelerator technology.

## REFERENCES

[1] M.H. Nasr and S.G. Tantawi, "New Geometrical-Optimization Approach using Splines for Enhanced Accelerator Cavities' Performance", in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, pp. 4395-4397.
doi:10.18429/JACoW-IPAC2018-THPMK049

[2] M. Nasr, E. Nanni, M. Breidenbach, S. Weathersby, M. Oriunno, and S. Tantawi, "Experimental demonstration of particle acceleration with normal conducting accelerating structure at cryogenic temperature", *Phys. Rev. Accel. Beams,* vol. 24, p. 093201, 2021.
doi:10.1103/PhysRevAccelBeams.24.093201

[3] Z.D. Farkas, H.A. Hogg, G.A. Loew, and P.B. Wilson, "SLED: A method of doubling SLAC's energy", in *Proc. HEACC'74*, SLAC, CA, USA, May 2-7, 1974, p. 576, SLAC-PUB-01453.

[4] J. Wang, S. Tantawi, C. Xu, M. Franzi, P. Krejcik, G. Bowden, S. Condamoor, Y. Ding, V. Dolgashev, J. Eichner, and A. Haase, "Development for a supercompact X-band pulse compression system and its application at SLAC", *Phys. Rev. Accel. Beams*, vol. 20, p. 110401, 2017. 2017.
doi:10.1103/PhysRevAccelBeams.20.110401

[5] Maxim, P. G., Tantawi, S. G., and Loo, B. W., "PHASER: A Platform for clinical translation of FLASH cancer radiotherapy", *Radiotherapy and Oncology*, vol. 139, pp. 28-33, 2019.
doi:10.1016/j.radonc.2019.05.005p