

# EFFICIENT CONTINUOUS-WAVE NORMAL CONDUCTING ACCELERATOR FOR INDUSTRIAL APPLICATIONS\*

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## Abstract

A normal conducting, high power, high efficiency copper linear accelerator prototype is being developed for industrial applications. The system will be powered by low-cost high-efficiency magnetron RF sources and will use a gridded thermionic cathode electron gun. Leveraging the significant accelerator expertise at JLab and industry partners, these technologies will be combined to deliver high-power (>100 kW) electron beams with energies of 1 MeV or higher that are cost-effective to produce and operate. The design is modular such that energy and power can be increased by adding additional sections as required. The status of the design, prototype fabrication and plans for a beam demonstration at JLab are described.

## INTRODUCTION

There is a growing need for compact, reliable, powerful and affordable continuous wave (CW) electron beam sources for various industrial applications including replacements of isotope-based radiation sources. A compact, efficient and powerful CW electron linear accelerator (LINAC) beam source suitable for static or mobile applications is being developed [1]. The proposed design is readily scalable to  $\geq 5$  MeV and  $\geq 100$  kW power.

This project is developing a prototype section of such a LINAC, starting with a 30 kV electron source, operating up to 1 MeV, 20 kW CW, scalable to a 100 kW demonstration and ultimately higher power industrial systems, see Table 1. The LINAC will operate at 915 MHz to take advantage of commercial magnetron sources that are available for  $\leq \$2/W$  [2]. The system will use a gridded thermionic electron gun to pre-bunch the beam and solenoid focusing to guide it through the LINAC. RF to beam efficiency is expected to exceed 75% at high power.

## LINAC DESIGN

Since the electron gun will operate at 30 kV the LINAC must accept particles traveling at less than the speed of light, and accelerate them rapidly. To accommodate the electron's varying velocity the cell lengths are adjusted

according to the beta along the acceleration path, see Fig. 1. The cavity operates in standing wave in the pi mode. The gradients in each cell are made to be equal so the energy gain is roughly linear with distance. Figure 2 shows the field amplitude and Fig. 3 the energy gain along the LINAC. After the first LINAC cavity additional beta one modules may be used for further acceleration.

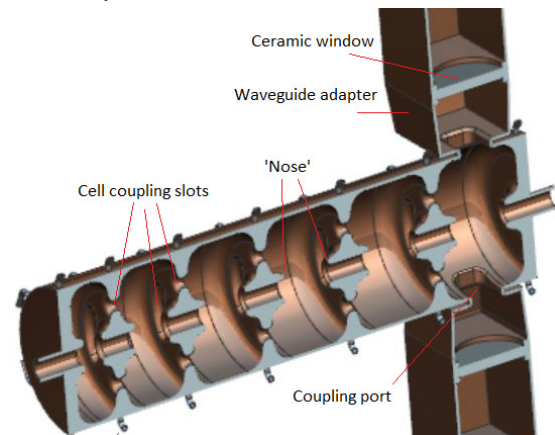


Figure 1: Graded-beta pi mode standing wave LINAC.

Table 1: Key Performance Parameters for the Developmental Stages of the Systems

	Prototype System	Demo System	Industrial System
Energy	1 MeV	1-5 MeV	1-5 MeV
Current	20 mA	1-100 mA	$\leq 500$ mA
Power	20 kW	$\leq 100$ kW	$\leq 500$ kW
Cost	N.A.	$< \$10/W$	$< \$10/W$
Efficiency	$\sim 35\%$	$> 50\%$	$> 75\%$

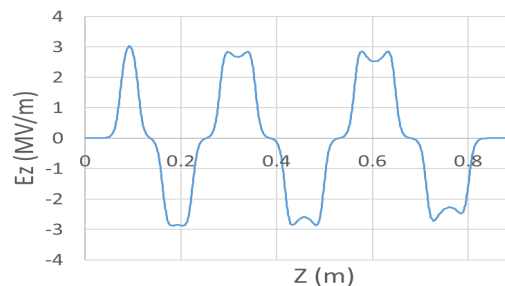


Figure 2: Field profile in the LINAC cavity.

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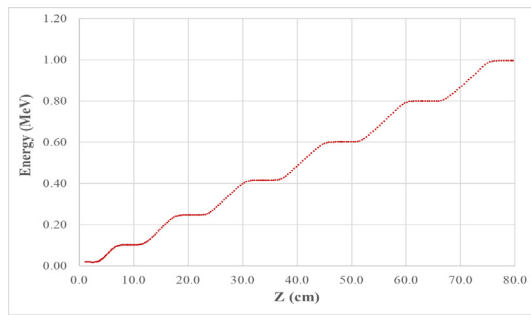


Figure 3: Energy profile along the LINAC.

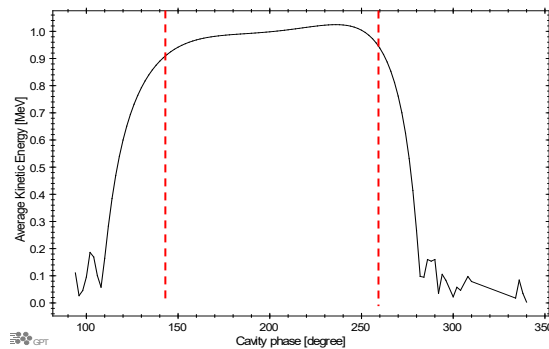


Figure 4: RF acceptance window for 30 kV electrons.

By varying the phase of the incoming particle in simulation the range of acceptance of the cavity can be mapped out, see Fig. 4. The design has a broad acceptance window of about 120 degrees of phase. For efficient transmission the pre-bunched beam should fit within this window.

## THERMAL DESIGN

Operating CW the maximum usable gradient is limited by wall power dissipation. An efficient, re-entrant cavity shape is used with a small beam iris and nose cones to give a high shunt impedance [3]. Figure 5 shows the RF heat flux imported into ANSYS<sup>TM</sup> for thermal and mechanical simulations. The peak flux is less than 100 W/cm<sup>2</sup> and the total power is approximately 38 kW. The peak temperature rise over the inlet water is less than 70°C and the maximum temperature rise in any cooling circuit is 13°C. The calculated maximum stress in the copper is 4.8 ksi, less than half of the allowable limit for annealed copper of 10 ksi.

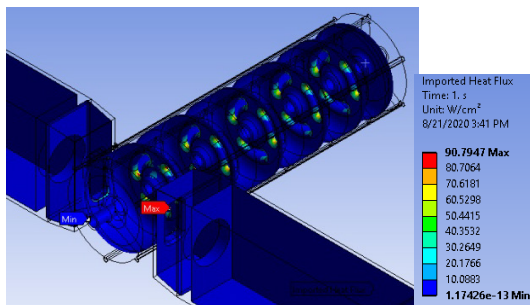


Figure 5: Heat map applied to the interior surfaces.

## ELECTRON BEAM DYNAMICS

The General Particle Tracer (GPT) particle tracking software [4] has been used to study the preliminary beamline

layout. A bunched beam is simulated from the cathode, assuming both DC and RF bias on the grid. On entering the LINAC the bunches are accelerated by the RF field using a 2D field map. To optimize capture the cavity is operated slightly off crest, providing longitudinal bunching at the beginning of the LINAC. The trade-off is a diverging beam, see Fig. 6, which requires a downstream solenoid.

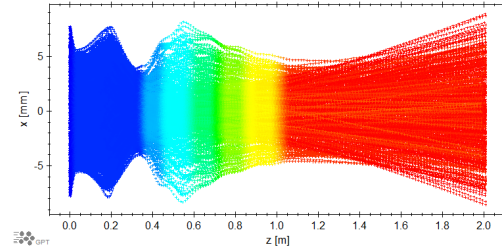


Figure 6: Transverse beam profile from the cathode to the exit of the LINAC.

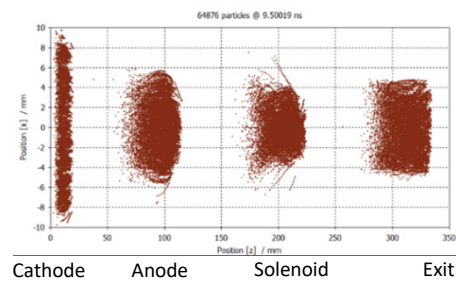


Figure 7: Evolution of the bunch from cathode to gun exit.

The real electron gun is being manufactured by InnoSys Inc [5]. Simulations show that an 138 pC electron bunch, emitted from the cathode using a 3D model of the grid fields, with 0.3 mm spacing, is transmitted through the LINAC with minimal losses. The peak current is ~0.7 A and the average current is 126 mA, exceeding the specification for the prototype and demonstration systems. Figure 7 shows the evolution of the bunches in the gun and Fig. 8 shows the longitudinal distribution at the exit. There is a small tail that falls outside the acceptance of the LINAC causing a few percent particle losses.

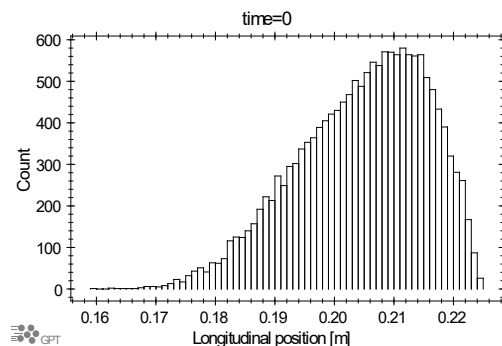


Figure 8: Longitudinal profile of the bunch at the gun exit.

## LINAC FABRICATION

The LINAC cavity is being fabricated by Euclid Tech-labs Inc. [6]. The cavity will be assembled from machined cups, assembled on the bench for frequency and field flatness tuning, Fig. 9, and brazed in a vertical stack. After

brazing fine adjustments can be achieved by “dimple” tuning, in which a small section of the wall is plastically distorted by an external tool. In operation the overall frequency will be controlled by adjusting the water temperature. The waveguide assemblies will be joined to the body by e-beam welding. The final assembly will be supported in a frame, as in Fig. 10, for handling and shipping.

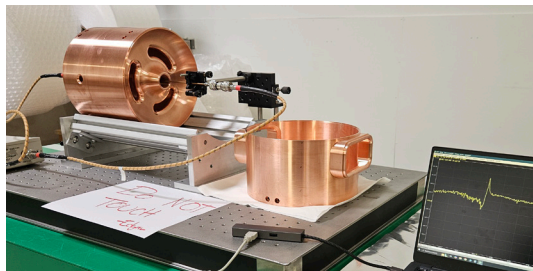


Figure 9: Bench check for frequency and field flatness.

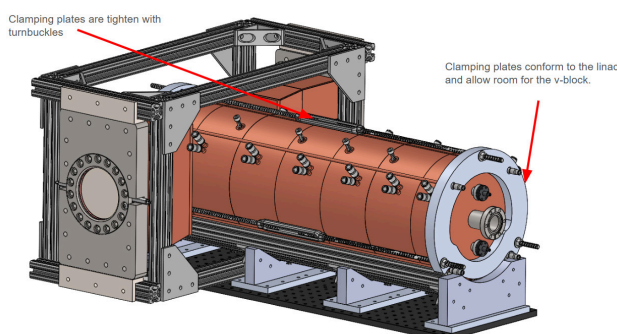


Figure 10: LINAC cavity in tuning/shipping fixture.

### RF WINDOW

The WR975 RF windows of the cavity are in the detuned short position to avoid excessive electric field levels in the case of sudden beam loss. The RF window is a scaled version of the high-power PEP-II window [7,8]. For the RF test without beam an additional resonant iris may be used to match the cavity to the waveguide. The RF windows are also being fabricated by Euclid using high purity aluminum oxide ceramics. Figure 11 shows the measurement of the window match frequency on the bench to verify the ceramic properties.

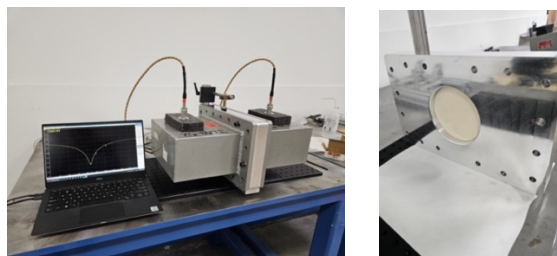


Figure 11: RF window ceramic cold test.

### RF POWER SOURCE

Commercial 75 kW 915 MHz CW magnetron systems will be used. Wall plug to RF efficiency over 80% has been demonstrated. Dual magnetron feeds can be combined in the LINAC to achieve beam power of 100 kW or higher.

## COMMISSIONING

The e-gun, cavity, beam line and RF power systems will be assembled and verified at Jefferson Lab as shown schematically in Fig. 12. The cavity and gun will be conditioned separately before final assembly. The RF windows will be pre-conditioned by running with the cavity detuned. The beam will be sent to a diagnostic beamline and shielded beam dump. Set up, optimization and beam properties will be measured and compared to simulation and overall system efficiency will be validated.

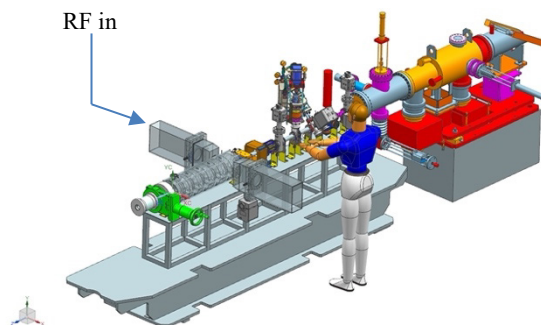


Figure 12: Prototype beamline to be built at JLab.

### POTENTIAL FUTURE WORK

The initial prototype with one magnetron RF source is expected to produce a 20 mA CW beam at 1 MeV. By adding an additional magnetron station power can be increased to 100 kW. To reach higher energies additional copper LINAC sections can be added, possibly including recirculation. Alternatively a compact superconducting booster module could be added [9] to reach the final energy of at least 5 MeV in one stage with even better electrical efficiency. A beam delivery system and optional x-ray converter would allow testing of various applications, either at JLab or possibly at a user location. A transportable or containerized system could be useful in testing operating scenarios, remote applications, or field campaigns.

## CONCLUSION

A compact, powerful, and efficient LINAC is being developed for industrial applications. The system uses low-cost high-efficiency magnetron RF sources and a reliable thermionic electron gun and leverages the accelerator expertise at JLab and in industry. Applications include the replacement of radioisotope-based sterilization sources, high throughput bulk treatment of medical devices, food, liquids and products and materials. This technology can eliminate biological hazards in the water supply including persistent “forever chemicals”, viruses, bacteria, pharmaceuticals, etc.; an important emerging application space.

### ACKNOWLEDGEMENTS

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## REFERENCES

- [1] Jefferson Lab, “Slot-coupled CW standing wave accelerating cavity”, US Patent 9,655,227, May 16, 2017.
- [2] H. Wang *et al.*, “Magnetron R&D progress for high efficiency CW RF sources of industrial accelerators”, in *Proc. NAPAC'22*, Albuquerque, NM, USA, Aug. 2022, pp. 597–600. doi:10.18429/JACoW-NAPAC2022-WEZD3
- [3] S. Wang, J. Guo, R. A. Rimmer, and H. Wang, “The new design for capture cavity of CEBAF”, in *Proc. IPAC'14*, Dresden, Germany, Jun. 2014, pp. 3955-3957. doi:10.18429/JACoW-IPAC2014-THPRI080
- [4] M. J. de Loos and S. B. van der Geer, “General Particle Tracer: A 3D code for accelerator and beam line design”, in *Proc. EPAC'98*, Stockholm, Sweden, Jun. 1998, paper THP18F, pp. 1245-1247.
- [5] InnoSys Inc. 2900 S Main St, Salt Lake City, UT 84115. www.innosystech.com
- [6] Euclid Techlabs LLC. 367 Remington Blvd, Bolingbrook, IL 60440, www.euclidtechlabs.com
- [7] M. Neubauer, K. Fant, J. Hodgson, J. Judkins, H. Schwarz, and R. A. Rimmer, “High-power RF window and coupler development for the PEP-II B factory”, in *Proc. PAC'95*, Dallas, TX, USA, May 1995, paper WPR08, pp. 1803-1805.
- [8] R. A. Rimmer *et al.*, “A High-Power L-Band RF Window”, in *Proc. PAC'01*, Chicago, IL, USA, Jun. 2001, paper MPPH063, pp. 921-923.
- [9] G. Ciovati *et al.*, “Development of a prototype superconducting radio-frequency cavity for conduction-cooled accelerators,” *Phys. Rev. Accel. Beams*, vol. 26, no. 4, pp. 044701, 2023. doi:10.1103/PhysRevAccelBeams.26.044701