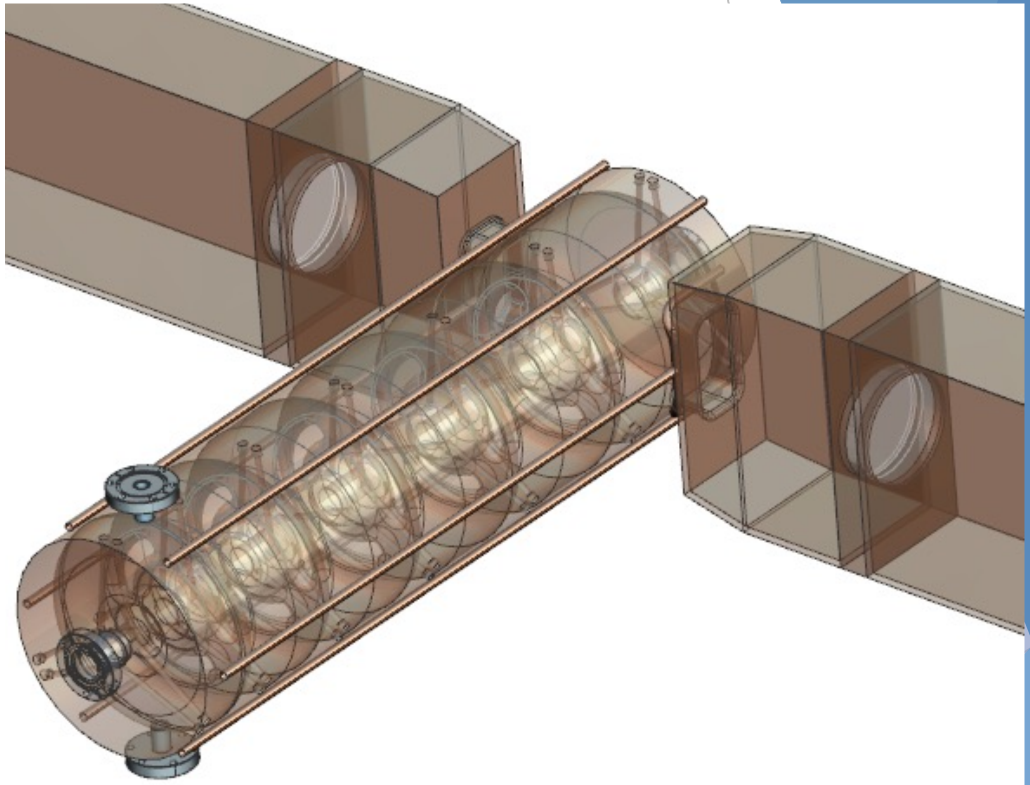
A compact normal-conducting CW accelerator for industrial applications

Abstract:

We will present a concept for a compact and efficient room temperature CW accelerator for industrial applications using a copper linac, magnetron RF and a thermionic electron source. These technologies have been proven reliable in field applications and major components can be sourced commercially. Thermionic cathodes have been shown to have very long operational lifetimes and can be replaced in-situ. Magnetrons are the lowest cost, highest efficiency RF sources available in this frequency range. Leveraging the significant accelerator expertise at JLab, these technologies will be combined to deliver high-power electron beams (up to 100 kW), with energies of 1-5 MeV that are cost-effective to produce and operate.



R. Rimmer, M. Dion, J. Henry, M. Marchlik, S. Overstreet, S. Wang, Jlab,

F. Hannon, Phasespacetech Inc.

Tuesday March 19, 2024

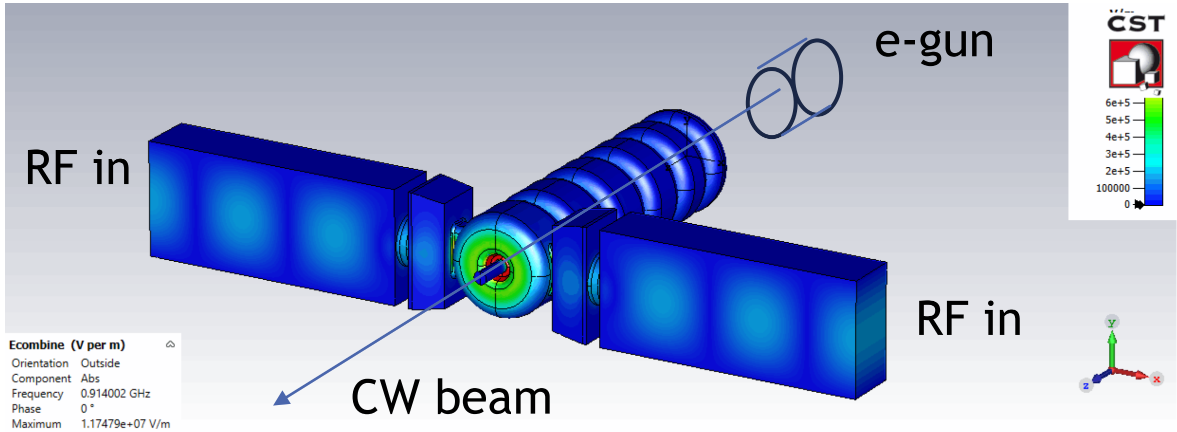
This research was supported by the U.S. Department of Energy, National Nuclear Security Administration, Office of Defense Nuclear Nonproliferation Research and Development (DNN R&D). This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics under contract DE-AC05-06OR23177.

Norfolk, Virginia

AccelApp'24

Goal and Objective of the project

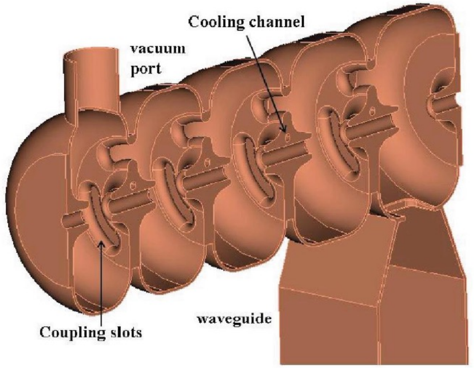
- This research will develop and test a prototype normal conducting, **CW copper linear accelerator** with **magnetron RF** and **thermionic gun** for industrial sterilization applications*. The technologies being used to support this research have been proven rugged and easy to maintain even in field applications and supporting components will be sourced commercially. Leveraging the significant accelerator expertise at JLab and partnering with industry, these technologies will be capable of delivering high-power (>100 kW) electron beams with energies >5 MeV that are cost-effective to produce and operate .
- The proposed research will deliver a working prototype in 3 yrs of effort of the first **1 MeV** of a modular system, industry partners will supply the electron gun, build the LINAC section and supply the magnetron RF source.



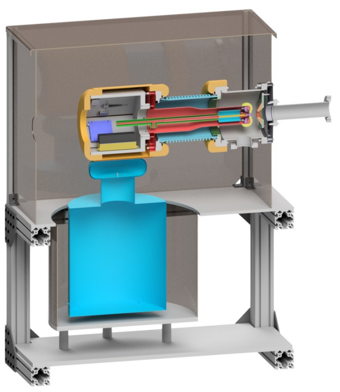
* Does not include X-ray converter target

Previous effort that links to the project

- As part of an injector upgrade study for CEBAF, a new compact copper graded-beta capture cavity was developed. A simple slot-coupled pi-mode structure was adopted with optimized shape. For CW operation active cooling passages close to the coupling slots are used and an average gradient of ~1 MV/m (3 MV/m peak on axis) can be achieved.
- Scaling this concept to 915 MHz (ARDAP project) total wall power dissipation for 1 MV output energy is only about 36 kW.
- Jlab previously investigated gridded thermionic guns capable of high power CW operation (Xelera SBIR, CPI, Heatwave).
- JLab has also developed a high-power CW magnetron RF source using commercially available 915 MHz magnetrons, efficient programmable switching power supplies and employed phase locking techniques to provide stable amplitude- and phase-control. Wall plug to RF efficiency above 80% has been achieved.



New CEBAF capture cavity


Prototype Xelera RF/thermionic gun


Modified Industrial 915 MHz magnetron RF source

Shaoheng Wang, Jiquan Guo, Robert Rimmer, Haipeng Wang, THE NEW DESIGN FOR CAPTURE CAVITY OF CEBAF, Proceedings of IPAC’2014, edited by JACoW (www.jacow.org), p. 3955.
H. Wang et. al., MAGNETRON R&D PROGRESS FOR HIGH EFFICIENCY CW RF SOURCES OF INDUSTRIAL ACCELERATORS, WEZD3, proc. NAPAC22, Albuquerque, NM, USA.

Copper LINAC Design and Fabrication

Task 1 is to design and build the first graded-beta LINAC section optimized for this application

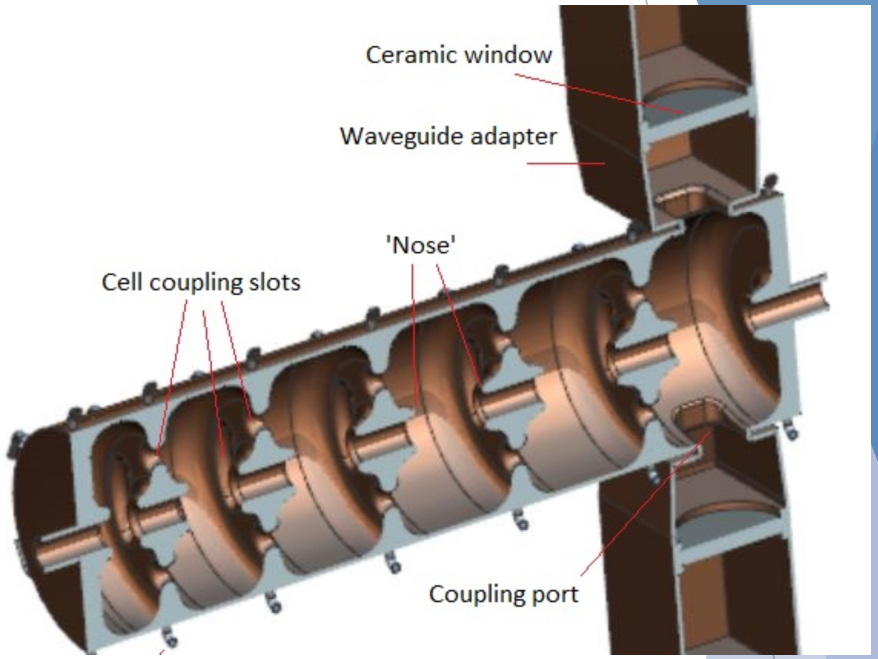
Status:

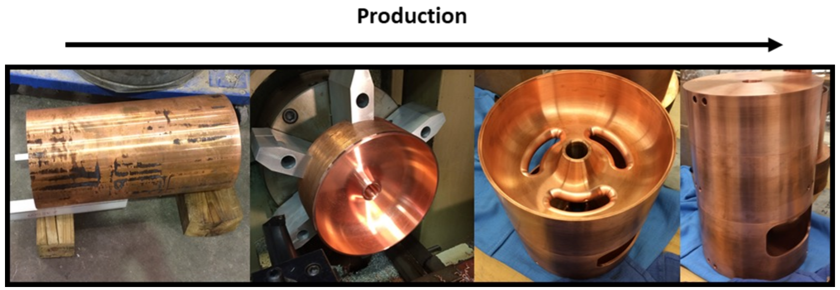
LINAC cavity design has been fine-tuned to accept lower energy beam from e-gun (20 kV vs 35 kV).

Procurement process started, getting questions from vendors now.

Parts for two cells were already fabricated at JLab to test this process. Machining these parts from solid copper means that cooling channels can be drilled between each cell.

The cavity will be built preferably using industrial partners in order to facilitate development of potential vendors for future turn-key units.



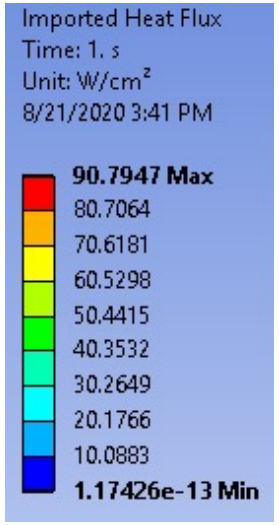


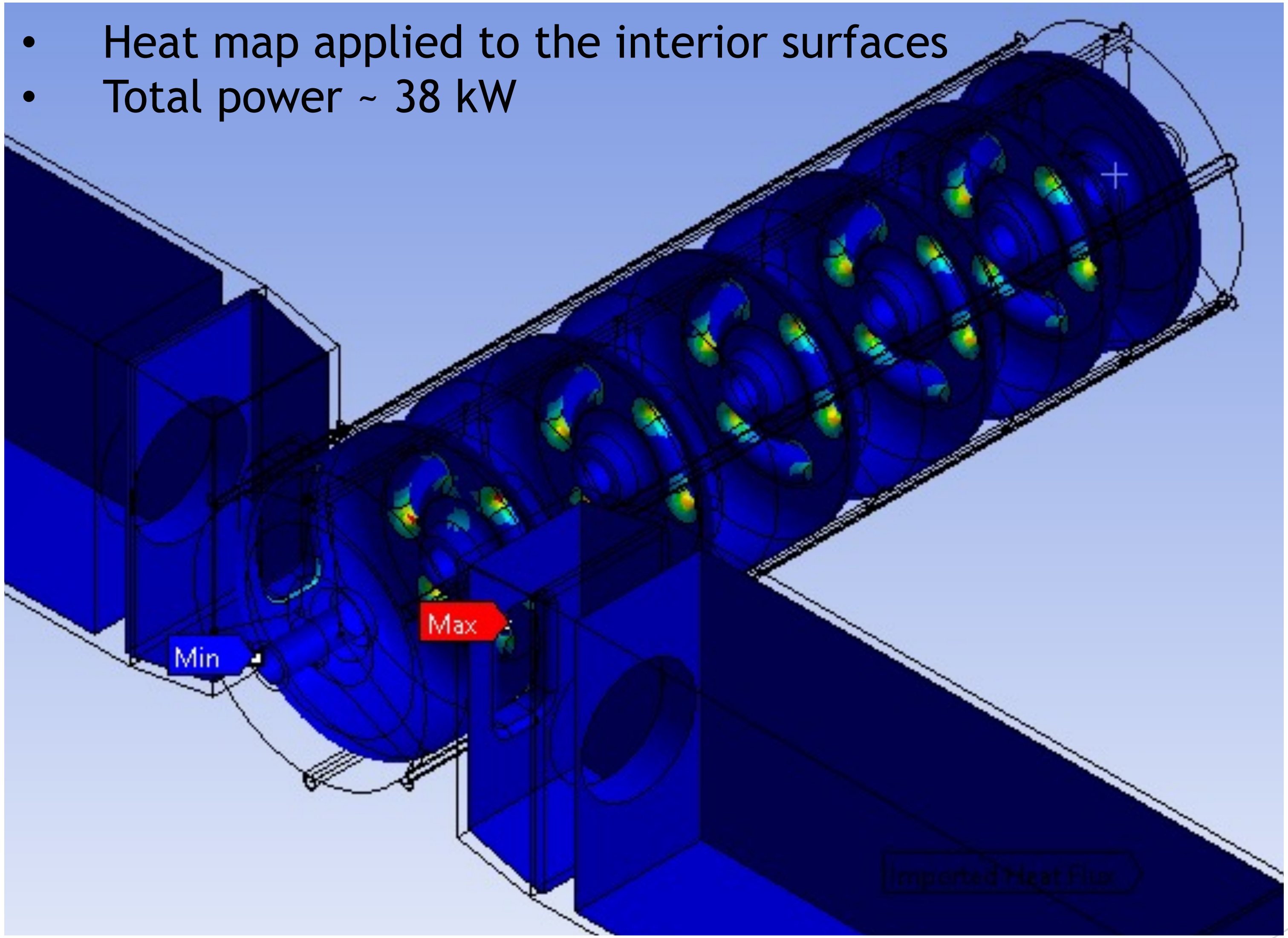
915 MHz parts: a) 9” diameter copper billet, b) half-cell on a lathe, c) center cell showing slot coupling geometry, d) 2-cell dry fit up.

Norfolk, Virginia
AccelApp'24

RF heat load

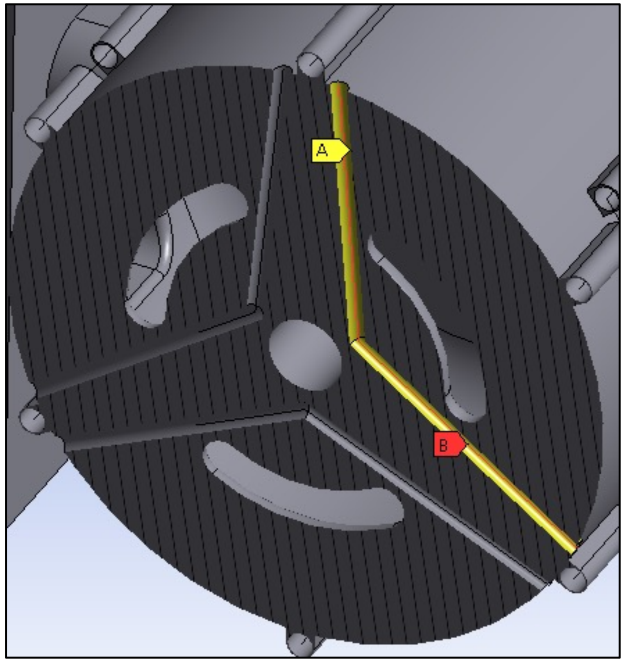
- Heat map applied to the interior surfaces
- Total power ~ 38 kW





Norfolk, Virginia
AccelApp'24

Cooling system

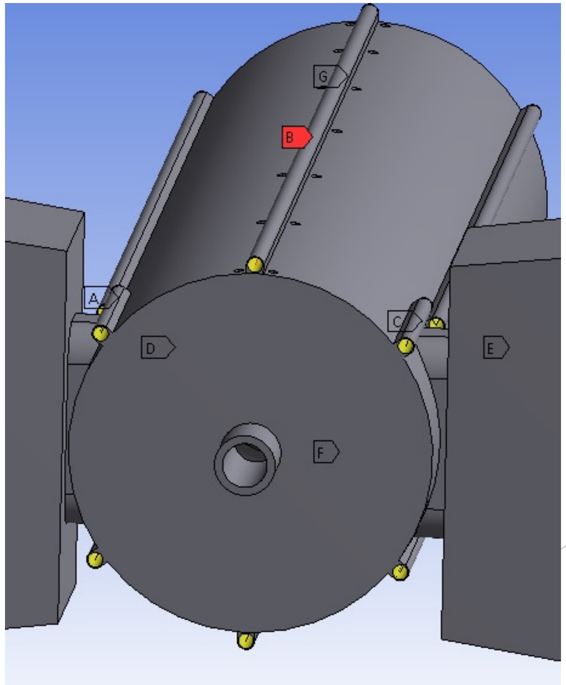


Spoke Cooling

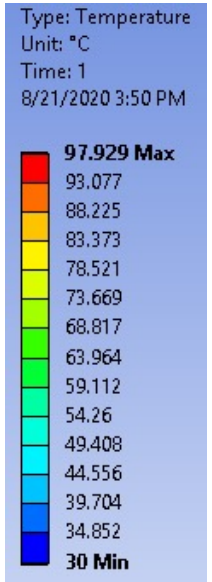
- Each spoke contains three individual water cooling circuits
- ¼” diameter
- 30 C inlet Water temperature
- Mass flow rate of 78 g/s
- Velocity of 2.5 m/s
- Reynolds number of 21,871, turbulent flow
- Convection coefficient of 1.11 W/cm^2-K

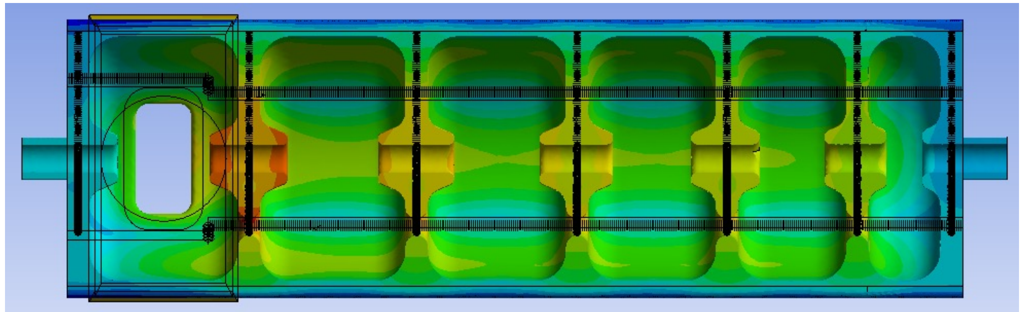
Outer Cavity Body Cooling

- 6 individual cooling circuits on the exterior of the cavity body
- 3/8” diameter
- 30 C inlet Water temperature
- Mass flow rate of 188 g/s
- Velocity of 2.7 m/s
- Reynolds number of 34,994 m/s, turbulent flow
- Convection coefficient of 1.07 W/cm^2-K

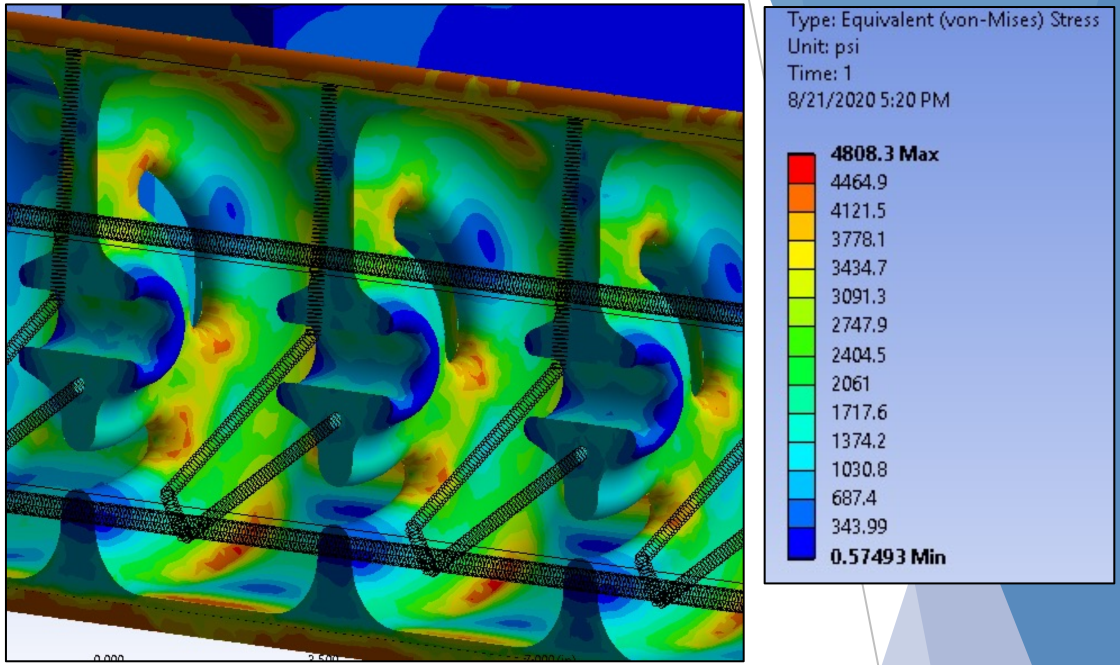


Thermal stress analysis





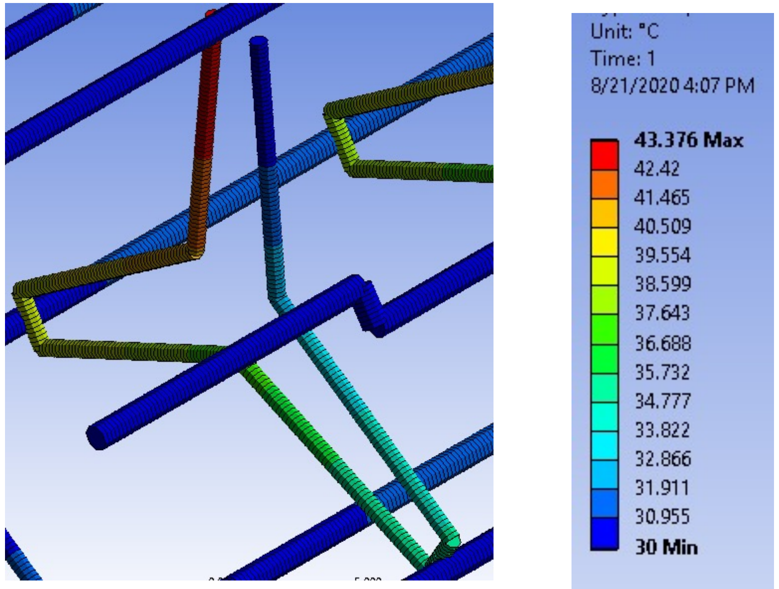
Body temperature Results



Stress Results

The maximum stress found in the entire model is 4.8 ksi. Annealed OFHC Cu has a minimum yield strength of 10 ksi, therefore, the results are acceptable.

Water Temperature Results



Electron Source and Optics Design

Task 2 is to select the e-gun source, design the transport optics and procure needed hardware.

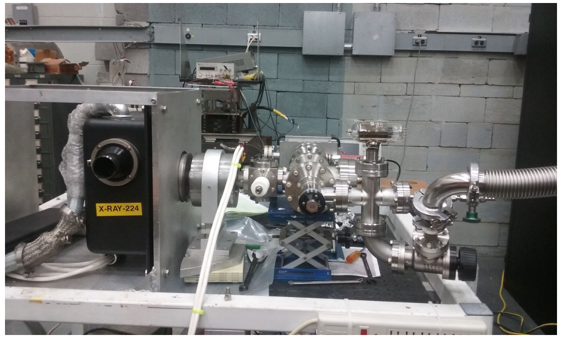
Status:

The General Particle Tracer (GPT) particle tracking software has been used to verify the preliminary beamline layout with 20 kV input energy.

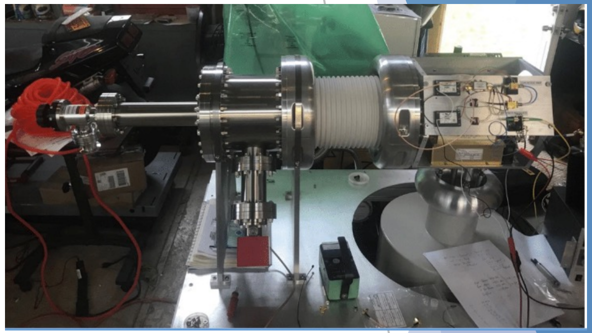
Evaluating commercial e-gun options

Started discussions with Innosys Inc. about their 20 kV e-gun.

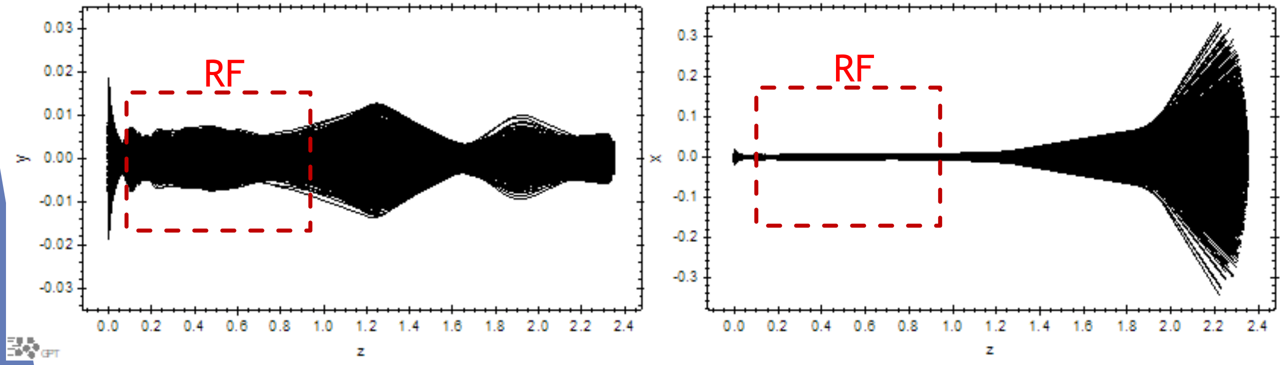
Preparing specification for procurement.



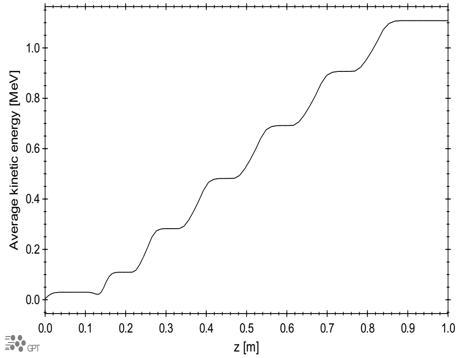
CPI gun

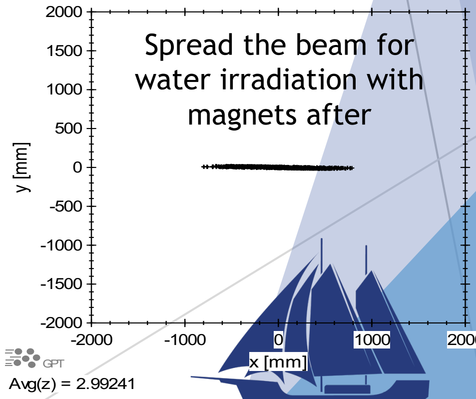


Xelera gun



Transverse particle trajectories. Cavity between 0.1 m and 0.9 m from the cathode.





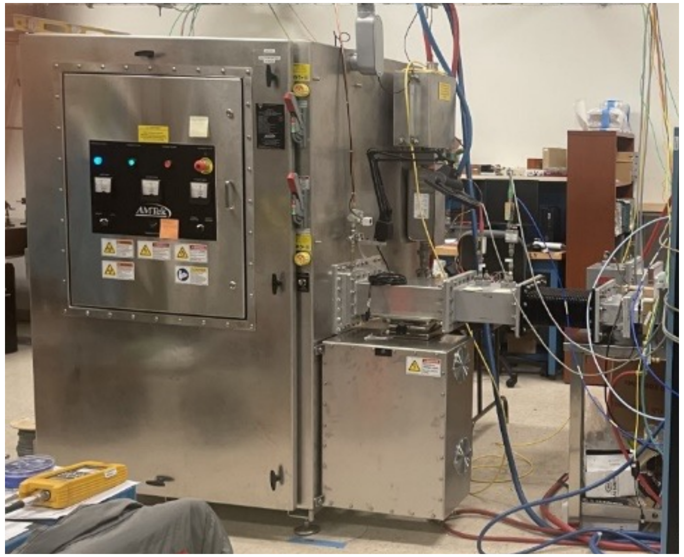
RF Source Specifications

Task 3 is to specify the RF parameters and upgrade an existing magnetron RF source to power the system

Confirmed RF requirements for demo machine.

JLab has existing magnetron power sources capable of delivering 75kW CW at 915 MHz from ARDAP project (H. Wang).

RF lab at LERF has penetration to the vault that can accommodate coaxial hard line to the cavity.



AMTek Commercial 75 kW CW magnetron supply with JLab modified controls

75 kW, 915 MHz magnetron

Innosys Inc. Prototype magnetron digital switching HV power supply

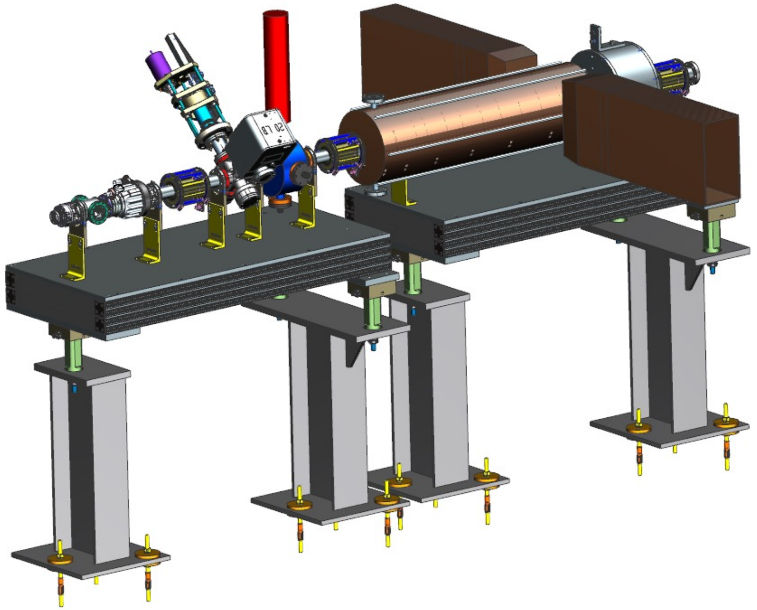
System Integration and Testing

Task 4 will be the integration, commissioning and testing of one full LINAC section with e-gun, magnetron RF, controls and diagnostics.

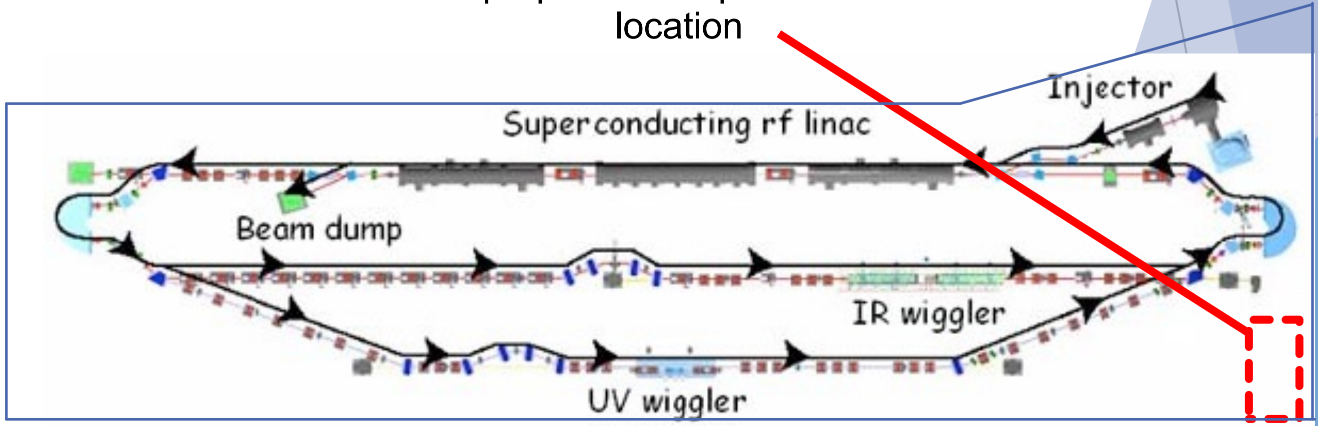
The accelerator layout will consist of a gridded thermionic gun electron source, a normal conducting cavity followed by beam transport magnets. The cavity, cooling, vacuum and RF power systems will be assembled and verified at Jefferson Lab. The beam will be sent to a diagnostic beamline and shielded beam dump.

The magnetron, cavity, window, iris and beam dump will all require cooling.

Status: Possible location for testing at LERF Identified.

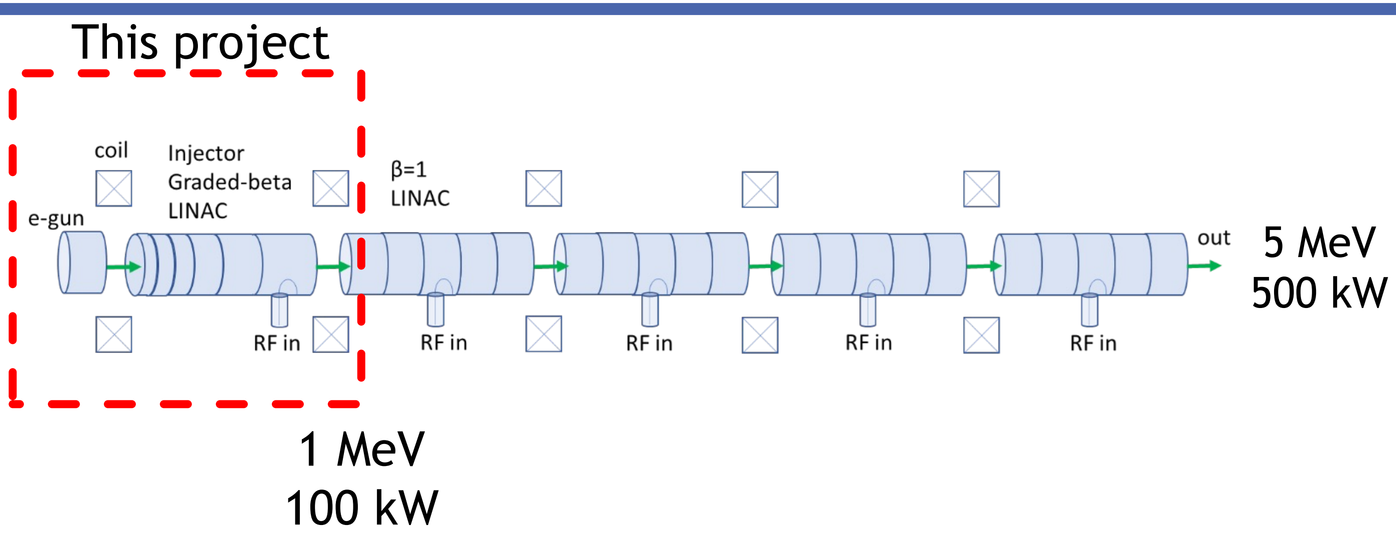


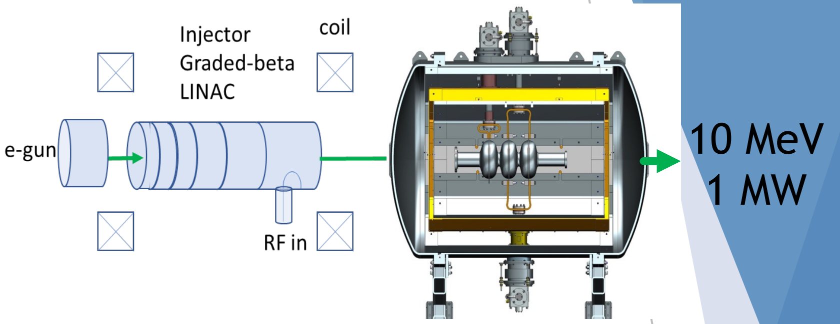
proposed compact linac location



Not to scale

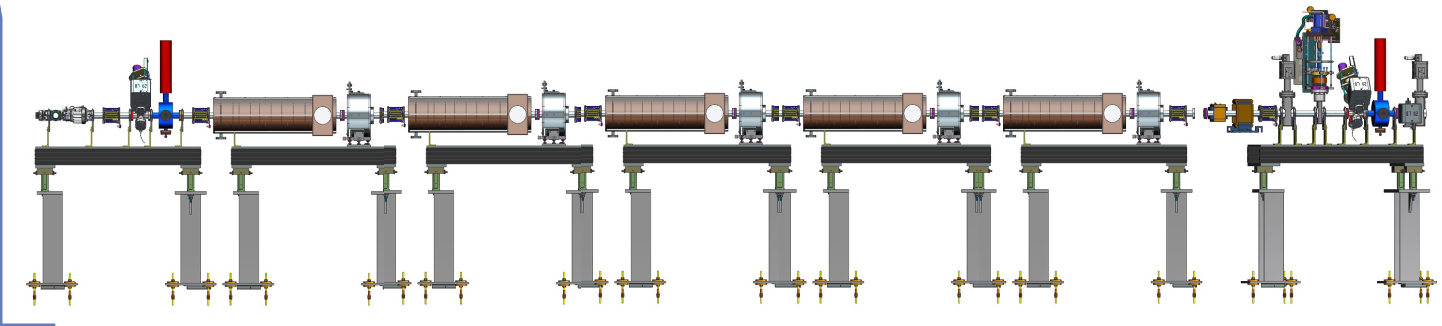
Options for going to higher energy

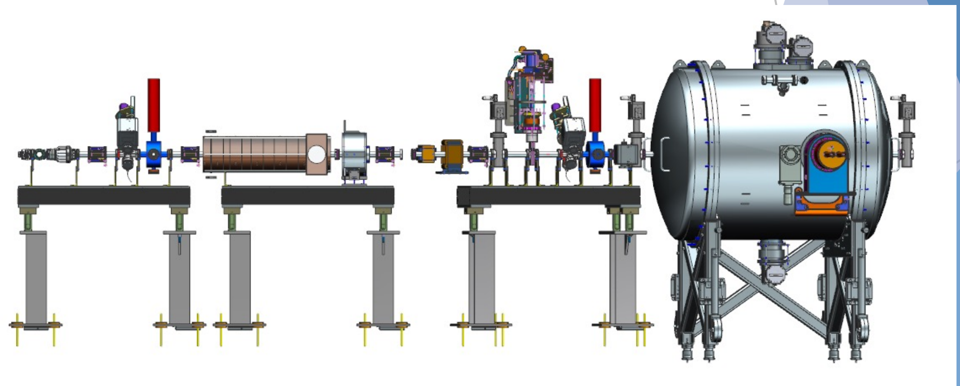




Schematic of a conventional LINAC

Schematic of a SRF booster LINAC





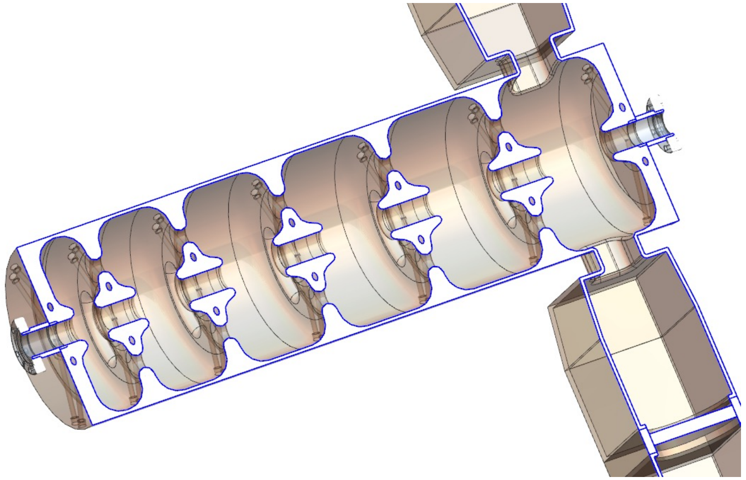
Summary

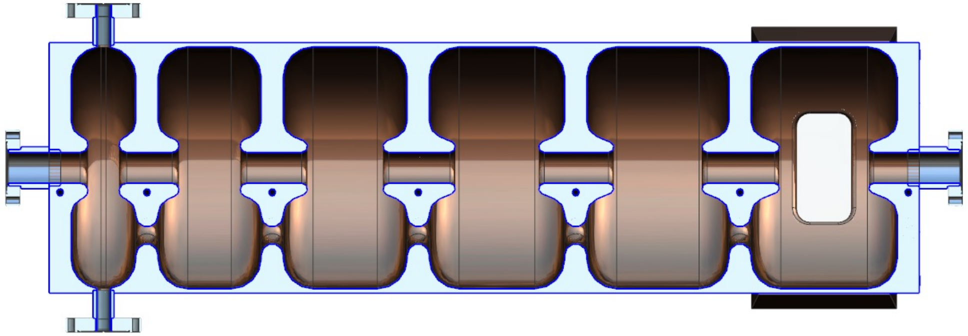
- Goal is to raise system TRL from 3 to 4 or 5 in three years
- Benefit greatly from similar prior and ongoing work at Jlab
- Experienced team and strong technical capabilities at Jlab and partners
- Leverage Industry participation whenever possible
- Prototype system will demonstrate key technologies, fully scalable to final requirements
- Potential partners and users welcome!

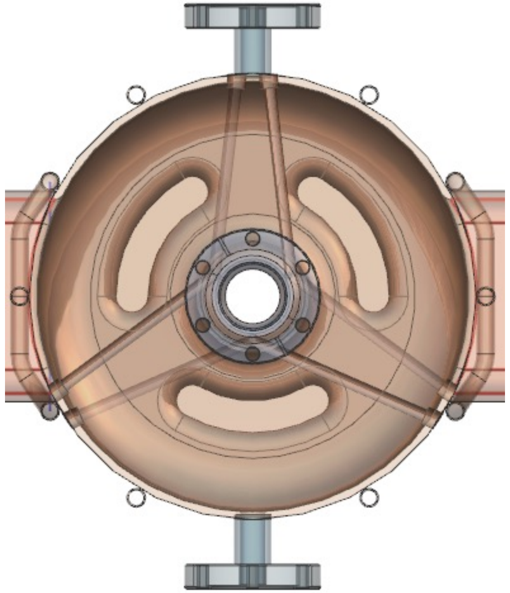
funded

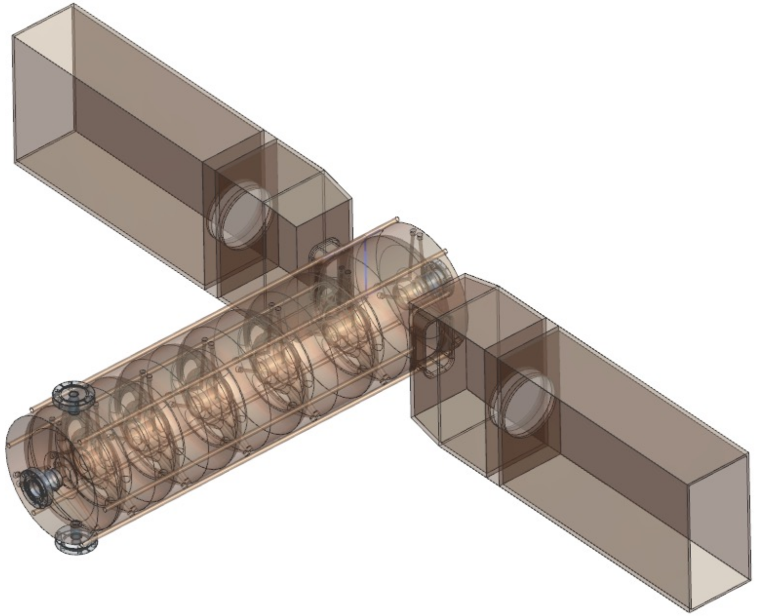
Description	Prototype system	Demo -scale system	Industrial system
Electron Beam Energy	1 MeV	1-5 MeV	1-5 MeV
Electron Beam Power	20 kW	≤100 kW	500 kW
Electron Beam Current	20 mA	1-100 mA	100-500 mA
Target Capital Cost	N.A.	<$10/W	<$10/W
Target Electrical Efficiency	~35%	>50%	>75%

Backup



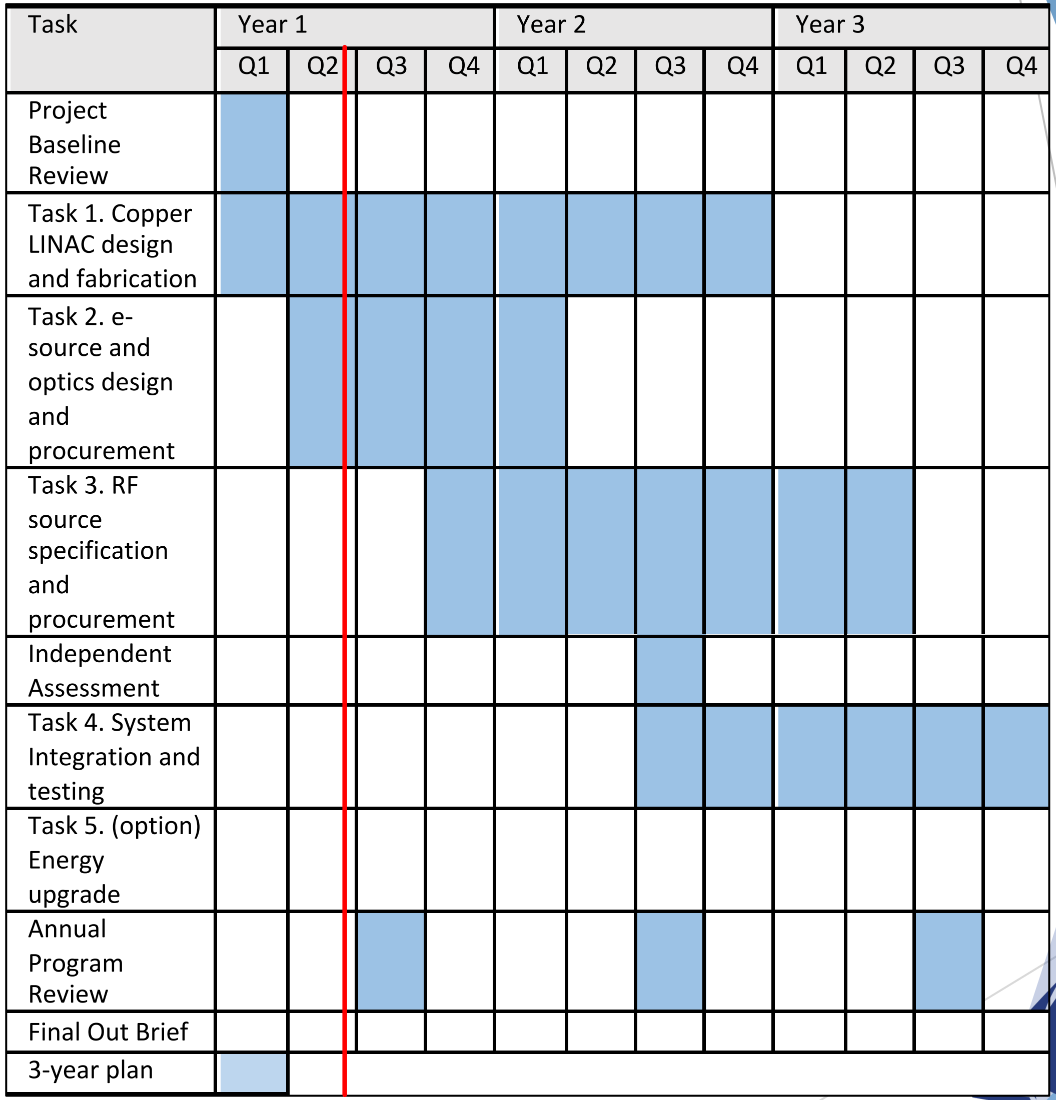






Objectives from the LCP

- Task 1. Copper LINAC Design and Fabrication (FY2024-26)
- Task 2. Electron Source and Optics Design (FY2024-26)
- Task 3. RF Source Specifications (FY2024-26)
- Task 4. System Integration and Testing (FY2024-26)
- Additional/Optional Tasks (beyond this project)
  - Energy or power upgrade?
  - Integration with target?
  - Off-site demonstration?



Technology Readiness Level (TRL)

The critical technology elements (CTE) of the system are the electron gun, the copper LINAC structure, the RF source and its power supply, the solenoid focusing channel and the control system.

The lowest TRL is the copper LINAC structure at TRL=3. Since this is an essential element of the system, the project will commence at TRL=3. Although copper LINACs are common, this new design is new and has not been tested. By the end of year two we will have completed the LINAC fabrication and initial testing so it will reach TRL level 4. By the end of year three we will have completed the integrated system test with beam, RF and controls in the lab so the TRL will be 4-5.

The solenoid focusing channel (3) has been designed using well benchmarked software tools but has not yet been implemented in hardware. It will start at TRL=3 and be refined in year one, and the components procured and tested individually in year two (TRL=4). The final integrated system will be completed in year 3 (TRL=4-5).

All other CTE 's are already at higher starting TRL. The electron gun is a COTS system from CPI or L3 (TRL~7), The RF magnetrons and switching power supplies are also COTS (TRL~7). The control system will follow lab practice used for other existing accelerators with the exception of the low-level RF (LLRF) controls, which are specific to the magnetron supplies. These have been proven individually in the laboratory so will start at TRL=4, rising to TRL=5 when coupled to the copper LINAC at the end of year two and TRL=6 at the completion of year 3 with the full system demo. If the project is successful the overall system TRL will be at 4-5 at the end of year three, see Table.

Fiscal Year	Project TRL	Explanatory Notes
2024	EOY Goal TRL-3	TRL is set by the copper LINAC starting TRL.
2025	EOY Goal TRL-4	By end of year 2 LINAC has been built and tested with RF. LINAC fabrication and system design maturity is TRL=3-4.
2026	EOY Goal TRL-4	Full system laboratory demo with beam reaches TRL=4 by end of year 3.

Norfolk, Virginia
AccelApp'24

Technical team

- <u>Research Team</u>
- Dr. Robert Rimmer (PI), JLab, rarimmer@jlab.org, 757-754-4980
- Dr. Rimmer will be the PI. He is a principal scientist in the accelerator division at JLab and will oversee the design, fabrication, integration, testing and reporting efforts. He has over 35 years of experience designing, building and operating RF cavities and systems for accelerators. (10% time)
- Dr. Shaoheng Wang, JLab, wang@jlab.org
- Dr. Wang has 20 years of experience in design, simulation and operation of accelerators. He will perform the RF cavity design and optimization, lead the manufacture, perform bench measurements, and provide oversight to the RF testing. (30%)
- Dr. Fay Hannon, Phase Space Tech, phasespacetech@gmail.com
- Dr. Hannon has 15 years of experience in design, simulation and operation of accelerators. She will perform the beam dynamics simulations, assist in the manufacture, aid bench measurements and RF testing, and specify the diagnostics needed. (10%)
- James Henry, lead designer, Matt Marchlik, engineering, Sarah Overstreet, coordination and fabrication support.