High-flux Positron Source Based on an SRF Electron Linac and Liquid-metal Target

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Accelerating Your Particles

Outline

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- High-power Superconducting RF Linac Technology
  - Two-pass accelerator layout
  - Accelerator Subsystems
  - Commercial Applications of High-Power Electron Beams
- High-Power Liquid Metal Targets for High-Flux Positron Sources

Niowave's Commercial Markets

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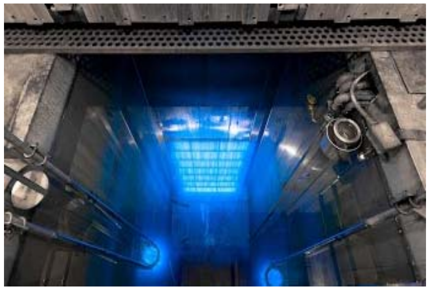
Superconducting Electron Linacs

< 9 MeV →

Sterilization & Advanced Manufacturing
Eliminate dirty bomb material



9 MeV →

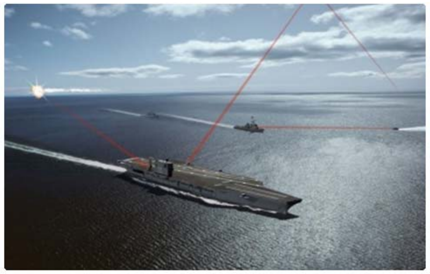
Radiography & Active Interrogation
Cargo inspection for contraband and shielded nuclear bombs

> 9 MeV →

Medical & Industrial Radioisotopes
Domestic supply without nuclear reactor and weapons-grade uranium

→

Free Electron Lasers
High power, tunable at wavelengths not available today



Why Superconducting?

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- 10^6 lower surface resistance than copper
  - Most RF power goes to electron beam
  - CW/continuous operation at relatively high accelerating gradients >10 MV/m

frequency

superconducting transition temperature

$$R_{BCS} \propto f^2 \exp\left(-\frac{T_c}{T}\right)$$

operating temperature

- For commercial electron linacs the minimum costs for a system occur around:
  - 300-350 MHz (multi-spoke structures)
  - 4.5 K (>1 atmosphere liquid helium)

Superconducting Linac Facility

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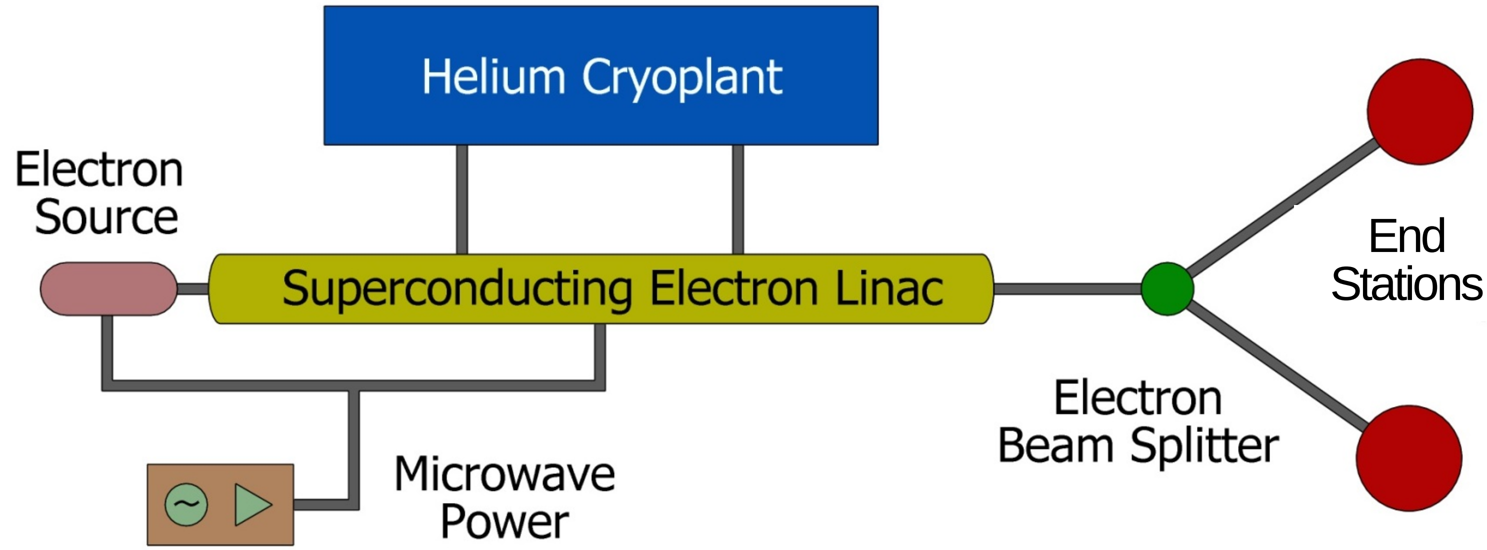

Turn-key Systems

- Superconducting Linac
- Helium Cryoplant
- Microwave Power
- End Station
- Licensing

Beam Energy	~9 MeV
Average Beam Power	10-100 kW
Duty Cycle	10-100%
Closed-loop Cooling Capacity	40-110 W @ 4 K

Superconducting Electron Linac

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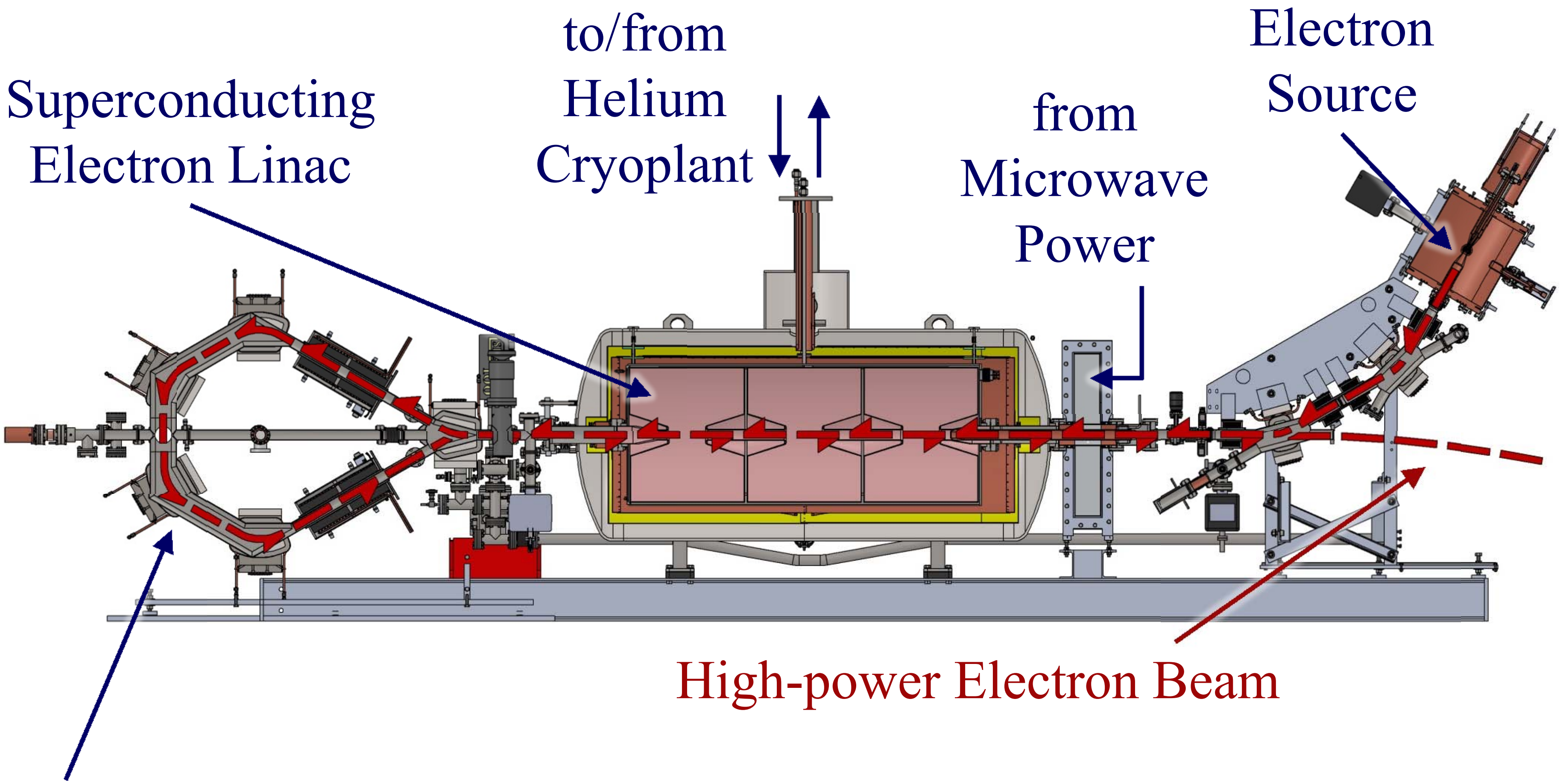

In this design, a magnetic arc (at left) brings the beam through the accelerator a second time, reducing costs for the cryomodule and refrigerator.

Linac Subsystems [1]

Superconducting niobium cavities in specialized geometries

Cryomodules

Linac Subsystems [2]

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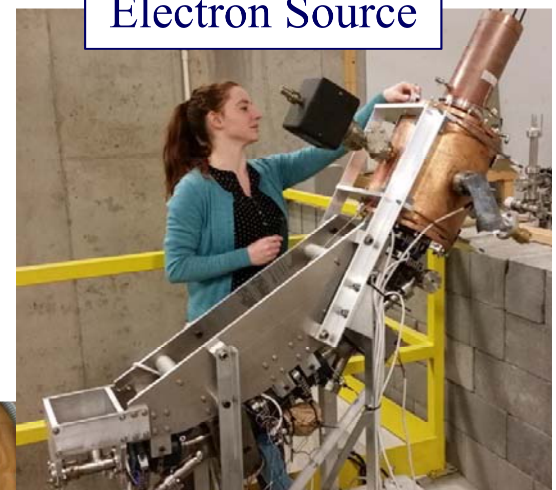
Recirculating Arc

Electron Source



Superconducting Cryomodule

Linac Subsystems [3]

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Solid-state and tetrode RF amplifiers (up to 60 kW)

Commercial 4 K refrigerators (rugged piston-based systems, 110 W cryogenic capacity)

NW-HR110 Refrigeration System

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- 114W helium refrigerator paired with radiation shielded linac
- Collins cycle, with robust reciprocating piston expander
- Vacuum insulated, nitrogen shielded, low-loss cryolines
- Modular cryolines allow quick switch between linac tests
- Long term operation ready:
  - 5000 hr. major maintenance interval
  - No warmup for short term maintenance

Niowave's Commercial Markets

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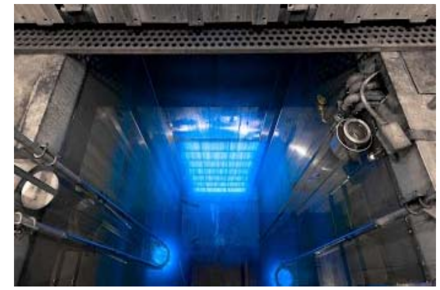

Sterilization & Advanced Manufacturing

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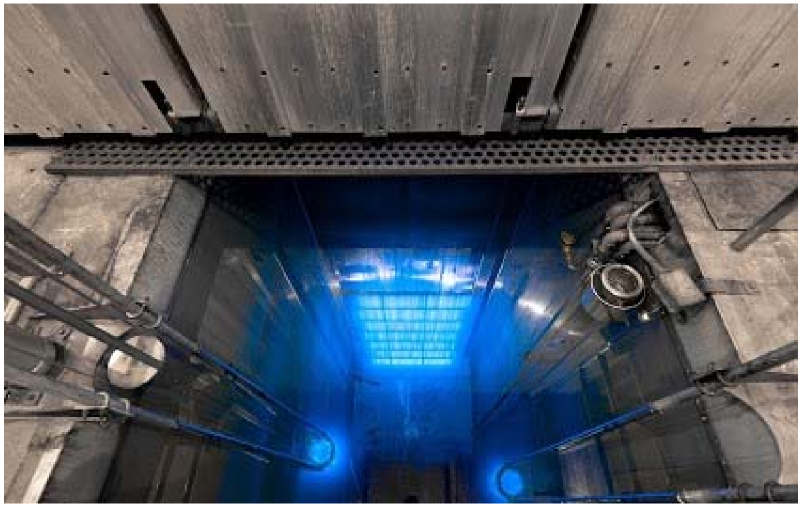
Opportunity

- Superconducting linac facilities for sterilization and advanced manufacturing that are economically competitive with large gamma facilities
- A 9 MeV 140 kW superconducting linac can deliver the same sterilization throughput as a 3.5 MCi Co-60 facility for ~30% less cost
- Eliminates the need and availability of radioactive materials that can be stolen and used in a dirty bomb



Radiography & Active Interrogation

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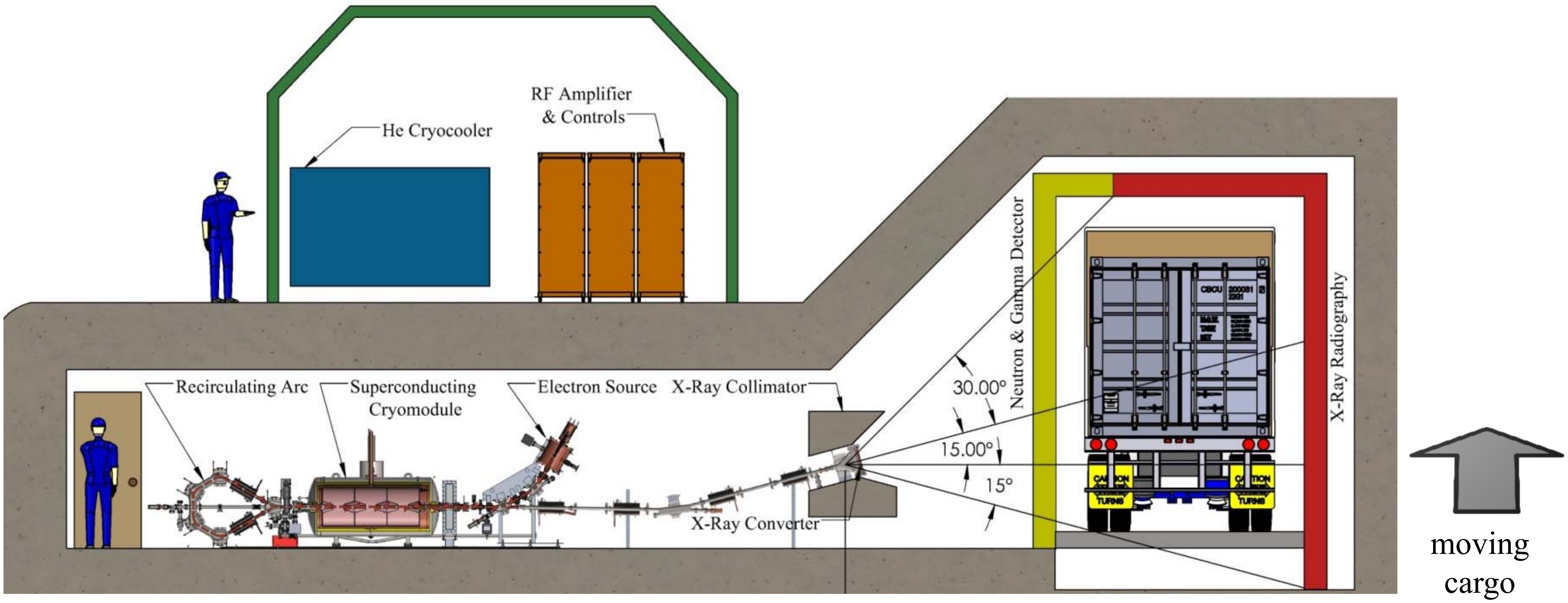
Opportunity

- Superconducting linac and detector array to detect contraband and shielded nuclear materials (nuclear bombs) in truck and train cargo
- Affordable to install and operate, this system will deploy to most points of entry with minimal delays to commerce



Uranium Target Assembly and Detector Suite

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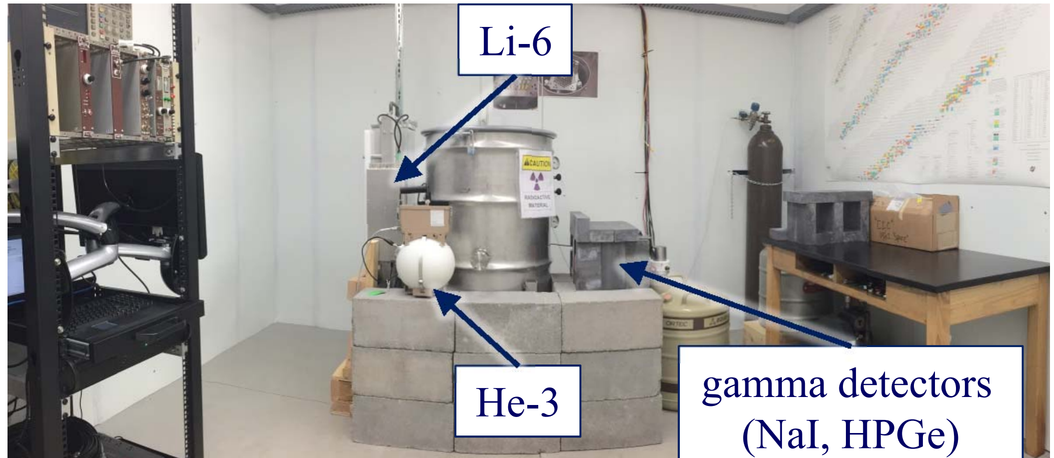
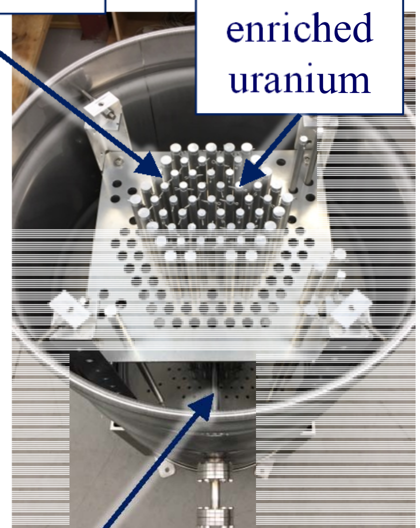
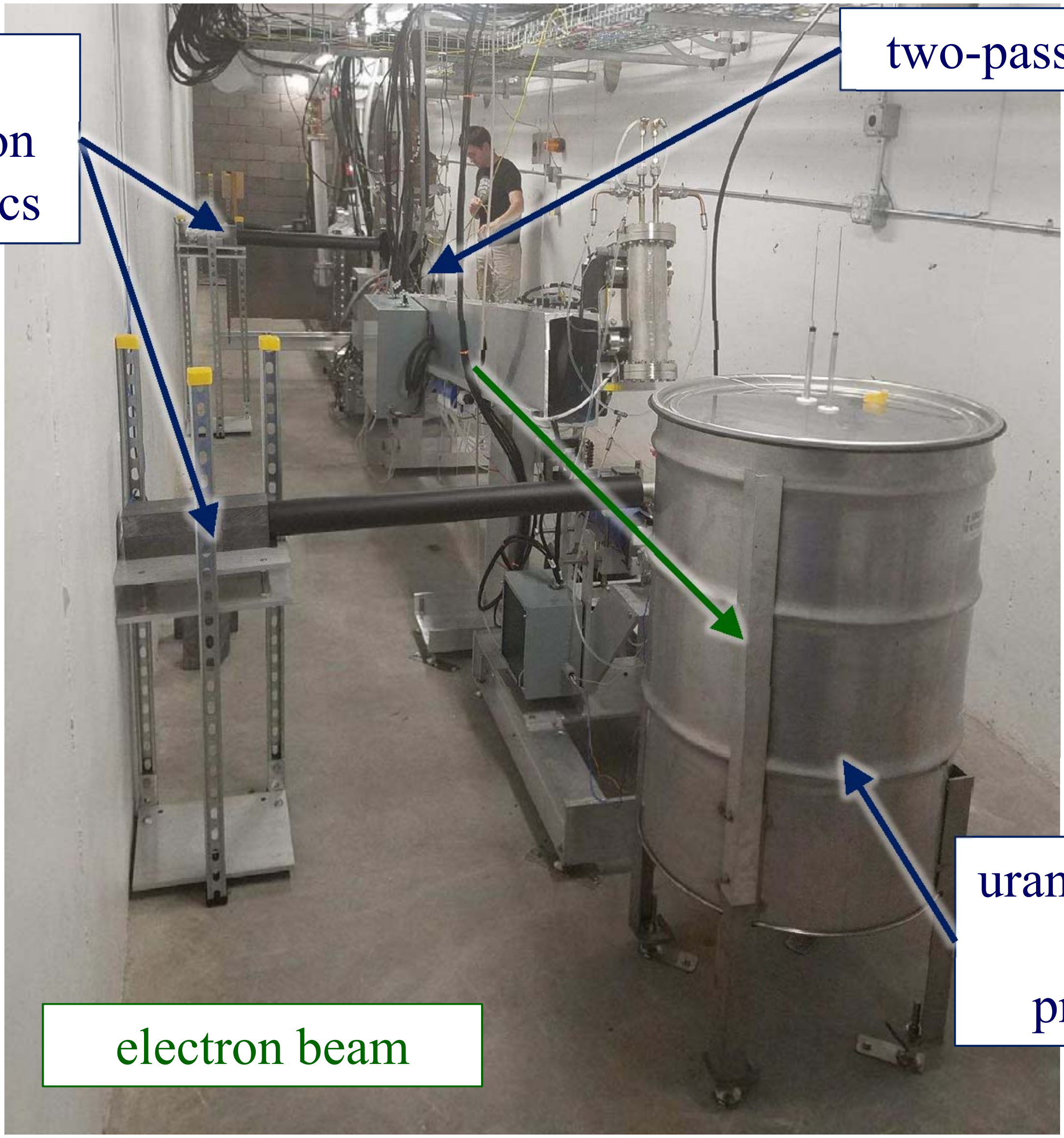




The prototype uranium target mounts to a linac or can be driven with a Cf-252 neutron source (10^4 n/s) or a water-cooled DD neutron source (10^7 n/s).

Uranium Assembly with Accelerator



Medical & Industrial Radioisotopes [1]

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Opportunity

- Domestic source of Mo-99 and other fission fragments from a low enriched uranium target that is driven by a superconducting linac

Advantages

- Facility is simpler and less costly to license and operate compared to a nuclear reactor
- Small batch radiochemistry can be automated, and does not require licensing as a nuclear reprocessing facility
- Uses existing radiopharmaceutical supply chain and FDA approval process
- Eliminates the need for a nuclear reactor and weapons grade (HEU) uranium

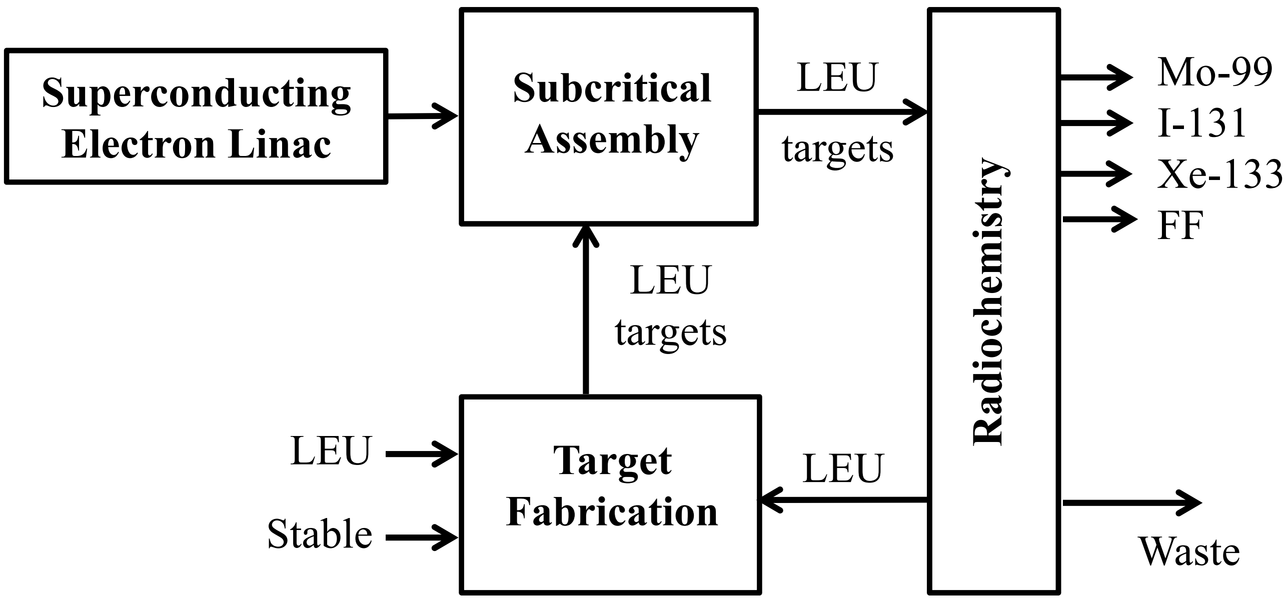
SPECT imaging system

Cut-away of Mo-99/Tc-99m generator

Medical & Industrial Radioisotopes [2]

Status & Plans

- Deliver sodium molybdate ($Na_2{}^{99}MoO_4$) to existing suppliers
- Deliver Xe-133 and other volatile radioisotopes to existing suppliers
- Increase licensed LEU quantities and activity levels to Ci levels
- Deliver other isotopes to partners for industrial and radiopharmaceutical purposes



NRC License

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Licensed to possess, machine, and distribute source material

- Thorium and depleted uranium (license #21-35145-01)

Licensed to produce, possess, and distribute certain radioisotopes, as well as special nuclear material

- Natural and Low Enriched Uranium (license #21-35144-02)
- Radioisotopes
  - Mo-99, Sr-89 and other fission fragments
  - Xe-133, I-131 and other volatiles

NRC FORM 374 PAGE 1 OF 3 PAGES

U.S. NUCLEAR REGULATORY COMMISSION

MATERIALS LICENSE

Pursuant to the Atomic Energy Act of 1954, as amended, the Energy Reorganization Act of 1974 (Public Law 93-438), and Title 10, Code of Federal Regulations, Chapter I, Parts 30, 31, 32, 33, 34, 35, 36, 37, 39, 40, and 70, and in reliance on statements and representations heretofore made by the licensee, a license is hereby issued authorizing the licensee to receive, acquire, possess, and transfer byproduct, source, and special nuclear material designated below; to use such material for the purpose(s) and at the place(s) designated below; to deliver or transfer such material to persons authorized to receive it in accordance with the regulations of the applicable Part(s). This license shall be deemed to contain the conditions specified in Section 183 of the Atomic Energy Act of 1954, as amended, and is subject to all applicable rules, regulations, and orders of the Nuclear Regulatory Commission now or hereafter in effect and to any conditions specified below.

Licensee

1. Niowave, Inc.
2. 1012 North Walnut Street
   Lansing, MI 48906-5061

3. License number 21-35144-02
4. Expiration date March 31, 2025
5. Docket No. 030-38770
   Reference No.

6. Byproduct, source, and/or special nuclear material	7. Chemical and/or physical form	8. Maximum amount that licensee may possess at any one time under this license
A. Scandium-46	A. Solid	A. 1 millicurie
B. Scandium-47	B. Solid	B. 1 millicurie
C. Manganese-56	C. Solid	C. 1 millicurie
D. Zinc-65	D. Solid	D. 1 millicurie
E. Copper-67	E. Solid	E. 1 millicurie
F. Selenium-75	F. Solid	F. 1 millicurie
G. Yttrium-88	G. Solid	G. 1 millicurie
H. Strontium-89	H. Solid	H. 1 millicurie
I. Yttrium-90	I. Solid	I. 1 millicurie
J. Molybdenum-99	J. Solid	J. 1 millicurie
K. Holmium-166	K. Solid	K. 1 millicurie
L. Iridium-192	L. Solid	L. 1 millicurie
M. Gold-198	M. Solid	M. 1 millicurie
N. Uranium-234	N. Solid	N. 0.015 gram (93.7 microcuries)
O. Uranium-235	O. Solid	O. 2.3 grams (5 microcuries)
P. Uranium-238	P. Solid	P. 21 grams (7 microcuries)
Q. Any byproduct material with Atomic Numbers 1-83 with a half-life less than or equal to 120 days	Q. Incidentally activated products in solid form	Q. 15 millicuries total

Free Electron Lasers

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Opportunity

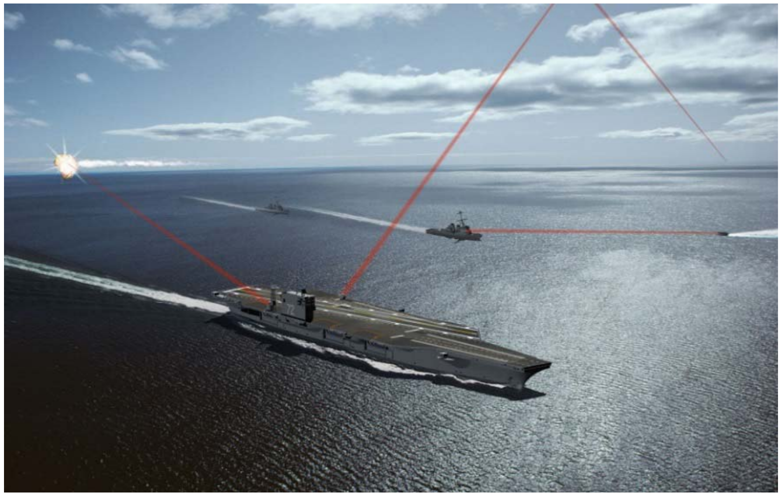
- Superconducting linac based free electron lasers for defense, research and industrial applications

Advantages

- High power tunable lasers at wavelengths not available today
- Extremely low cost development path since the entire facility is built and operated for other commercial applications

Status & Plans

- Update DOD-ONR and DOD-JTO on status of Niowave's superconducting linacs
- Identify customers and applications for tunable high power terahertz and infrared lasers



Niowave Facilities

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75,000 square feet

- Engineering & design
- Machine shop
- Fabrication & welding
- Chemistry facility
- Class 100 Cleanroom

Test Facilities (2)

- Cryogenic test lab
- Two operating 100 W cryoplants
- 3 MW available at each location
- Licensed to operate up to 40 MeV and 100 kW

Lansing, Michigan Headquarters

Headquarters Test Facility

The high-power test facility at Niowave headquarters allows parallel development on multiple superconducting linacs

- 3 MW electrical power available
- three below-grade trenches for source and cavity testing
- two shielded tunnels for beam operation up to 40 MeV, 100 kW

Niowave Airport Facility

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- Production & processing facility
  - Layout similar to HQ
  - 24/7 operation
  - Isotopes, x-rays, etc.
- Lansing International Airport
  - Foreign Trade Zone

Positrons for Nuclear Physics

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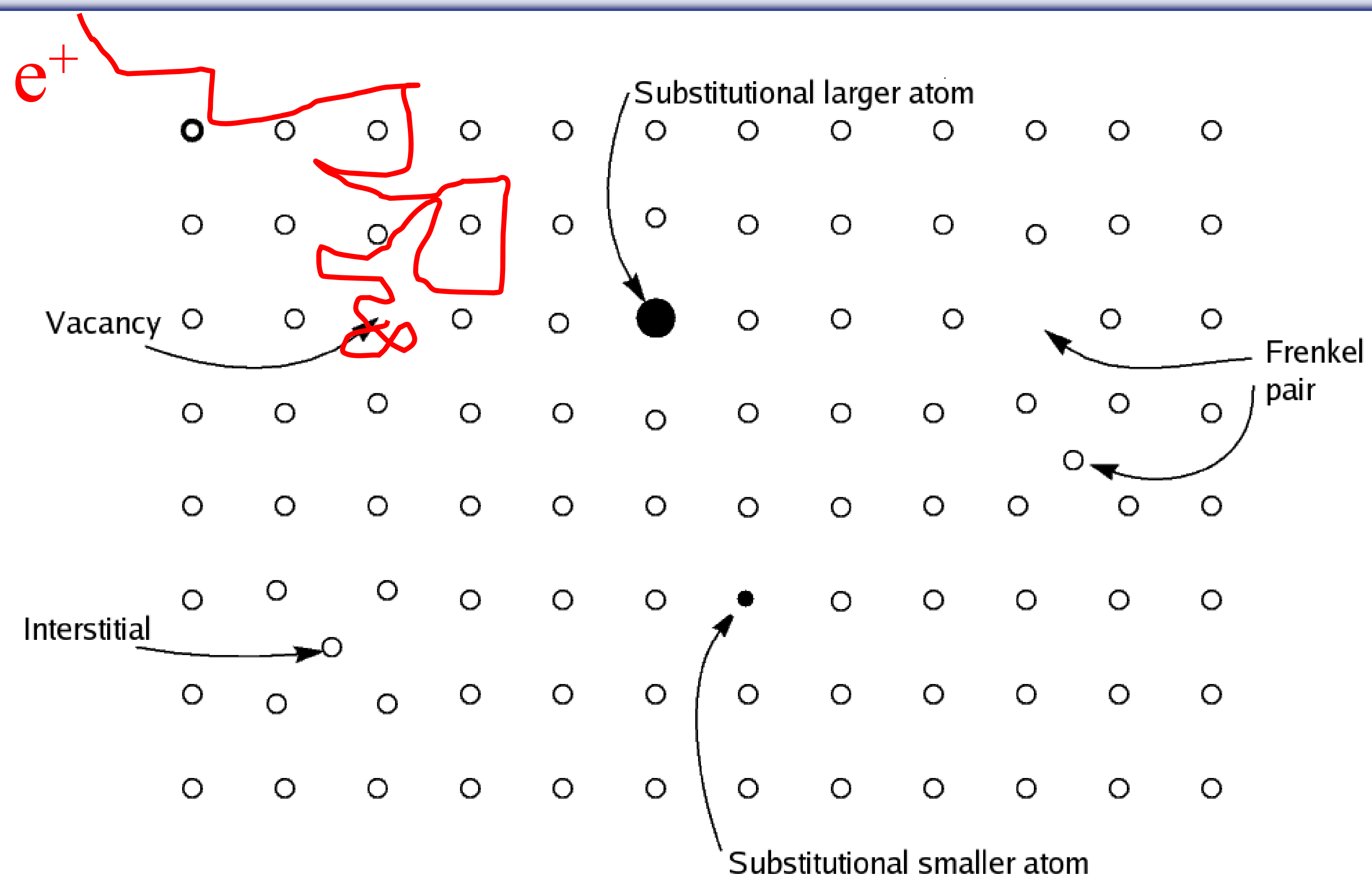
- Polarized positron collisions are an important program component at proposed next-generation lepton-ion colliders (JLEIC at JLab and eRHIC at BNL)
  - lepton polarization asymmetry in neutral current deep inelastic scattering
  - charged current deep inelastic scattering and charm production
  - physics beyond the standard model
- Transfer of polarization from a low-energy highly polarized electron beam has been demonstrated (PEPPo)

Positrons for Non-Destructive Testing of Materials [1]



Positrons thermalize before annihilation with an electron, often becoming stuck in lattice defects.

Positrons for Non-Destructive Testing of Materials [2]

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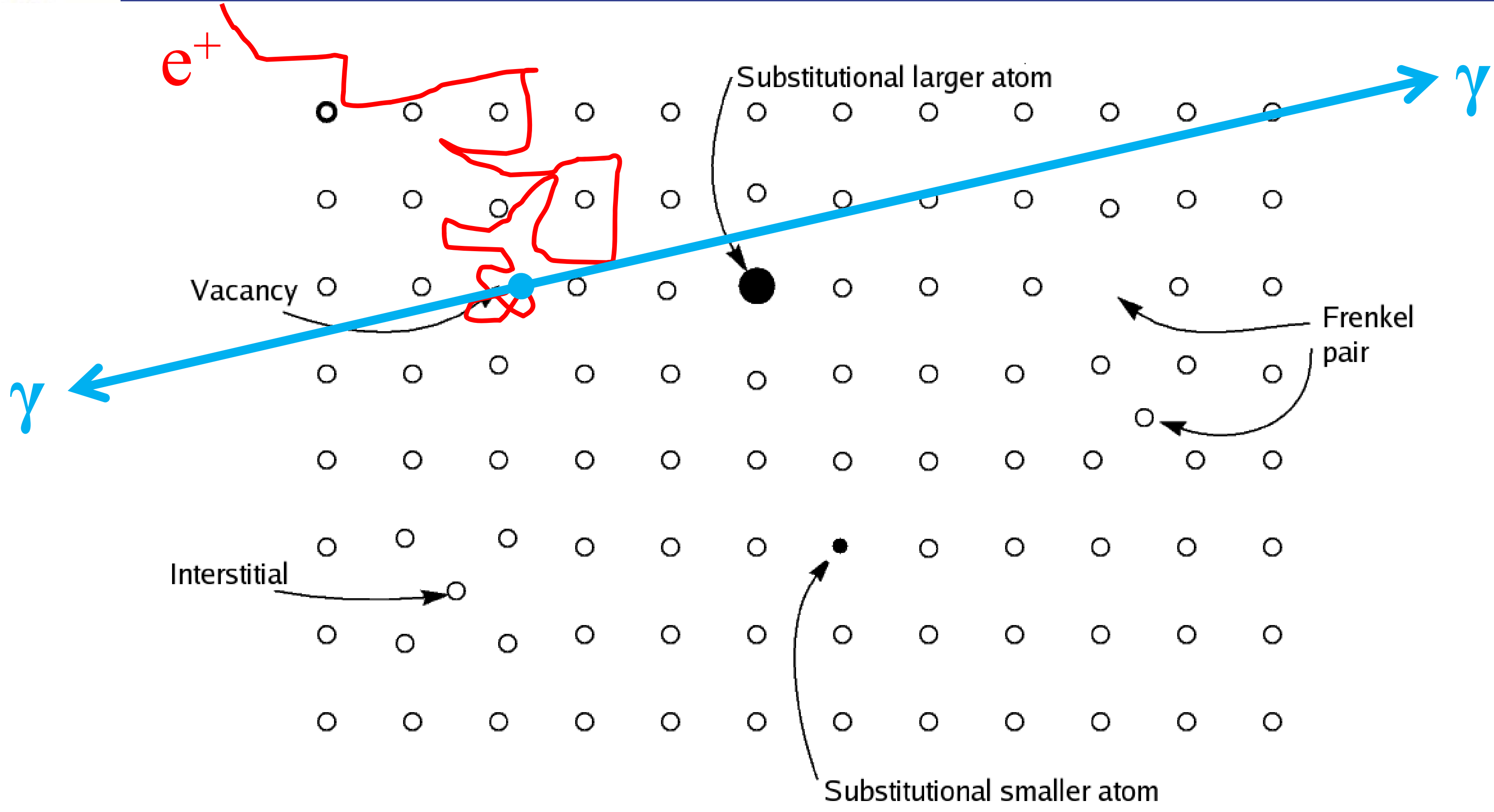

Gamma-ray emission from annihilation will come preferentially from the defect sites, locating them.

Positron Production Conceptual Design

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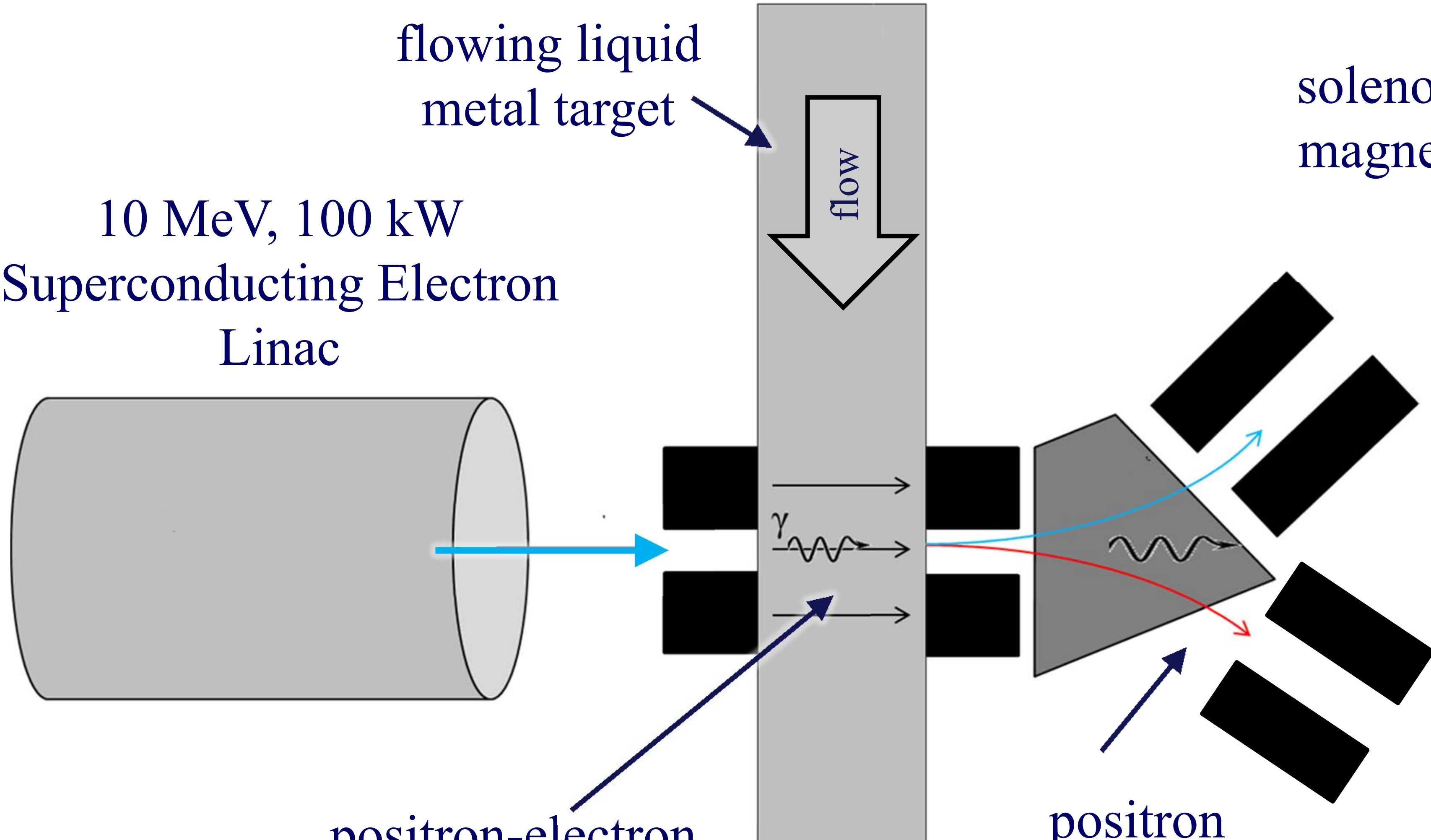

Positron System Schematic

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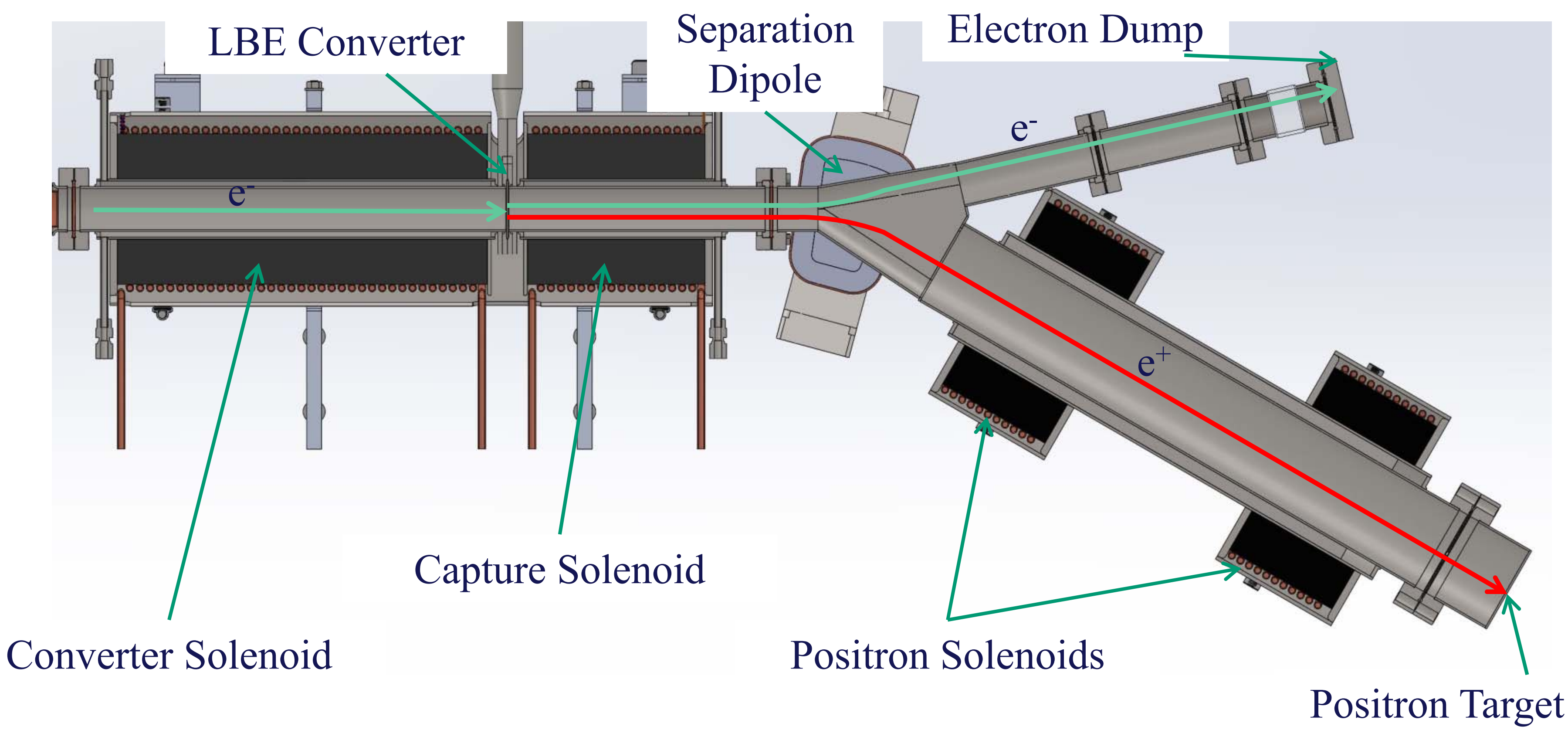

- The e^+ beamline is designed to be dispersion free at positron target location, so that different energy positrons arrive at the same point
  - 0.2 Tesla solenoid collects ~20% of e^+ produced at converter
- ~4×10^{-4} e^+ leave the capture solenoid per incident 10 MeV e^- on the converter

Positron System Hardware

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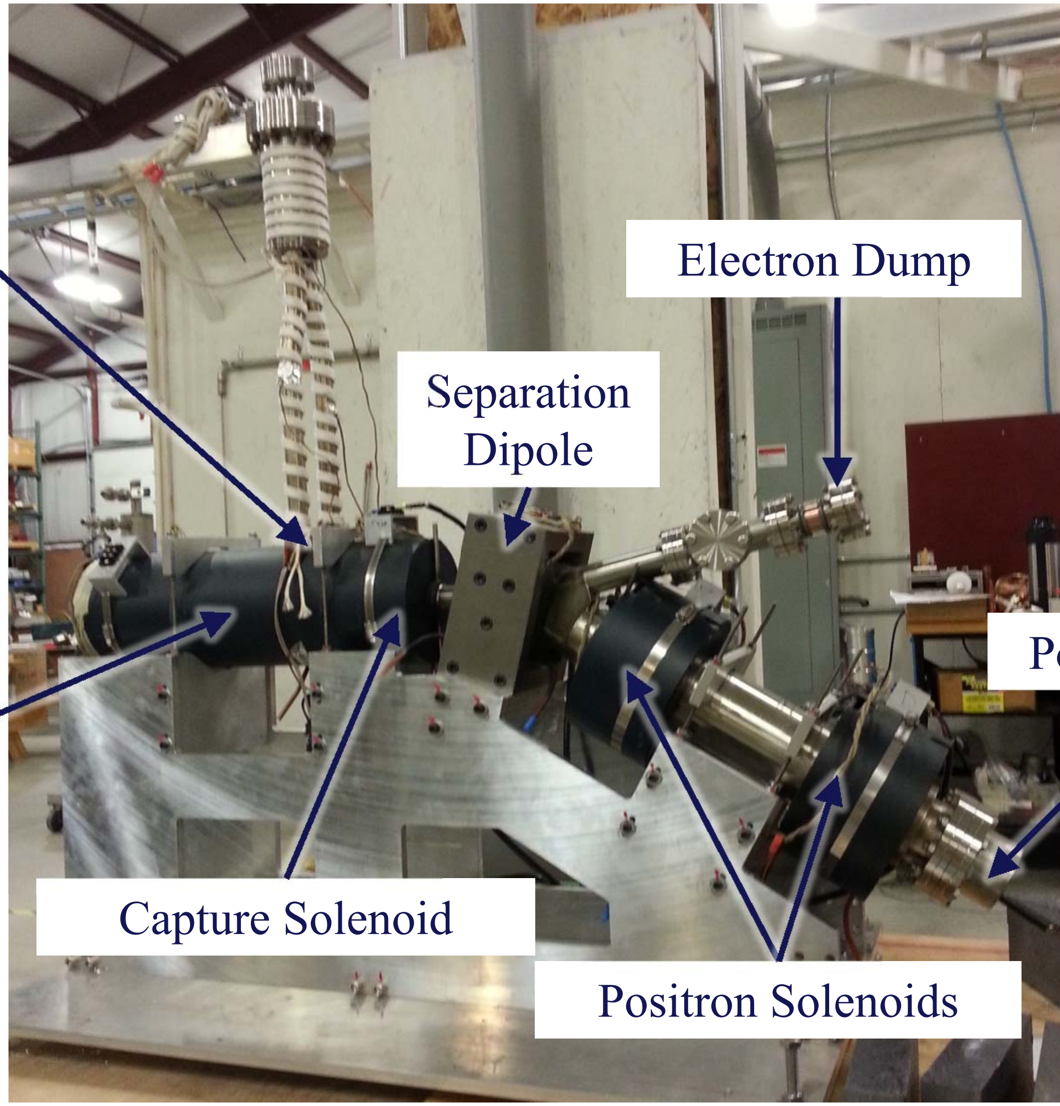
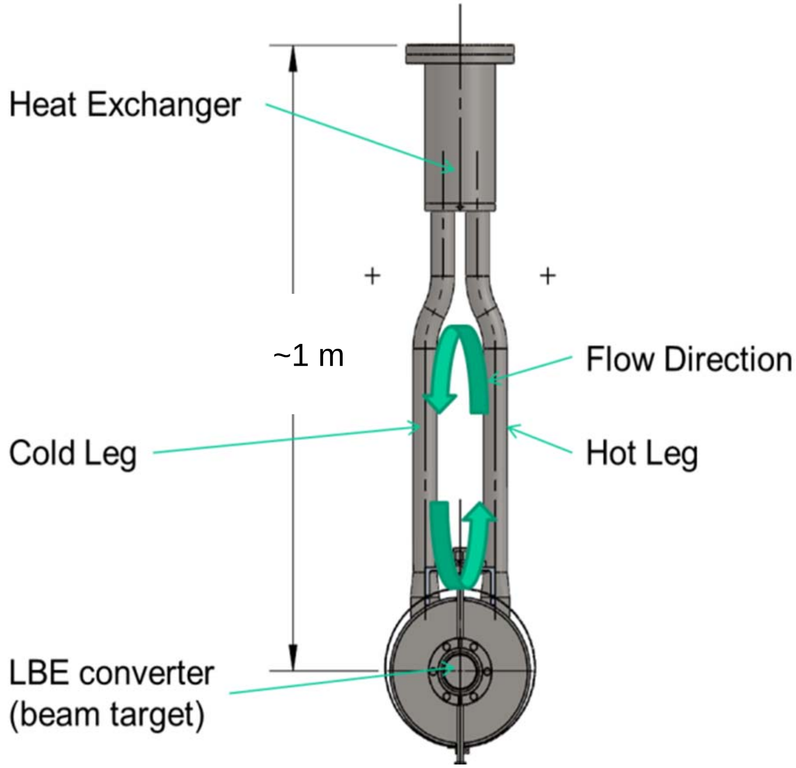
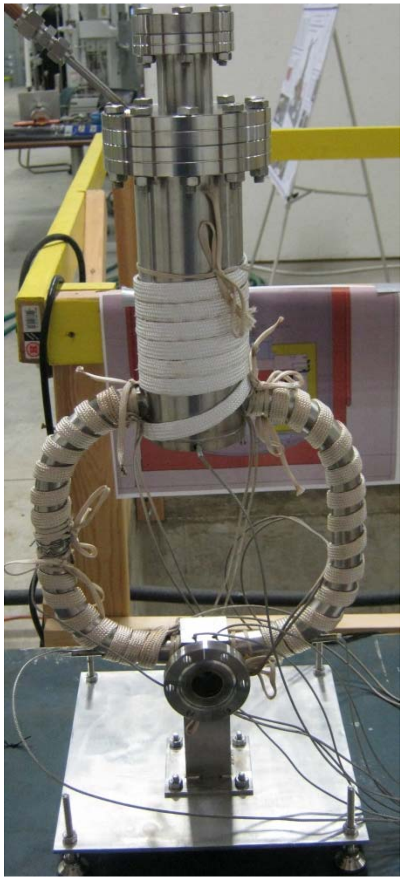


Liquid Metal Target with Natural Circulation



- Lead-bismuth eutectic
  - Low melting point: 124°C
  - High boiling point: 1670 °C
  - Z = 82, 83



Density differential between hot and cold leg drives flow

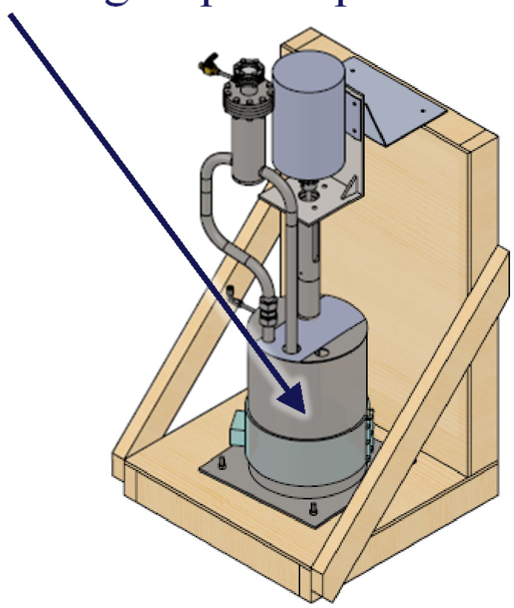
- Heat input from beam goes into hot leg
- Heat exchanger removes heat at reservoir on top

Liquid Metal Target with Mechanical Pumping

Mechanical pumps can also be used with lead-bismuth eutectic to increase and control the flow rate.

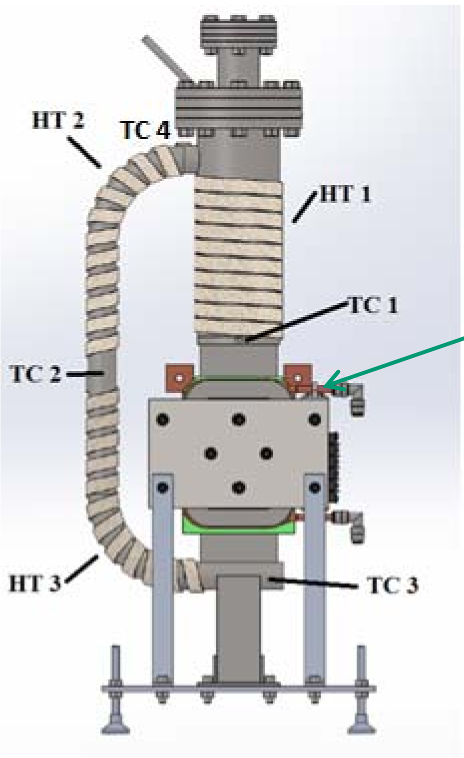
More flow allows for better cooling of the target, and handling of more beam power.

Spinning impeller provides liquid metal flow.



Liquid Metal Target with Electromagnetic Pump

Active pumping of the liquid metal with electromagnetic pump (no moving parts) has also been prototyped and tested.



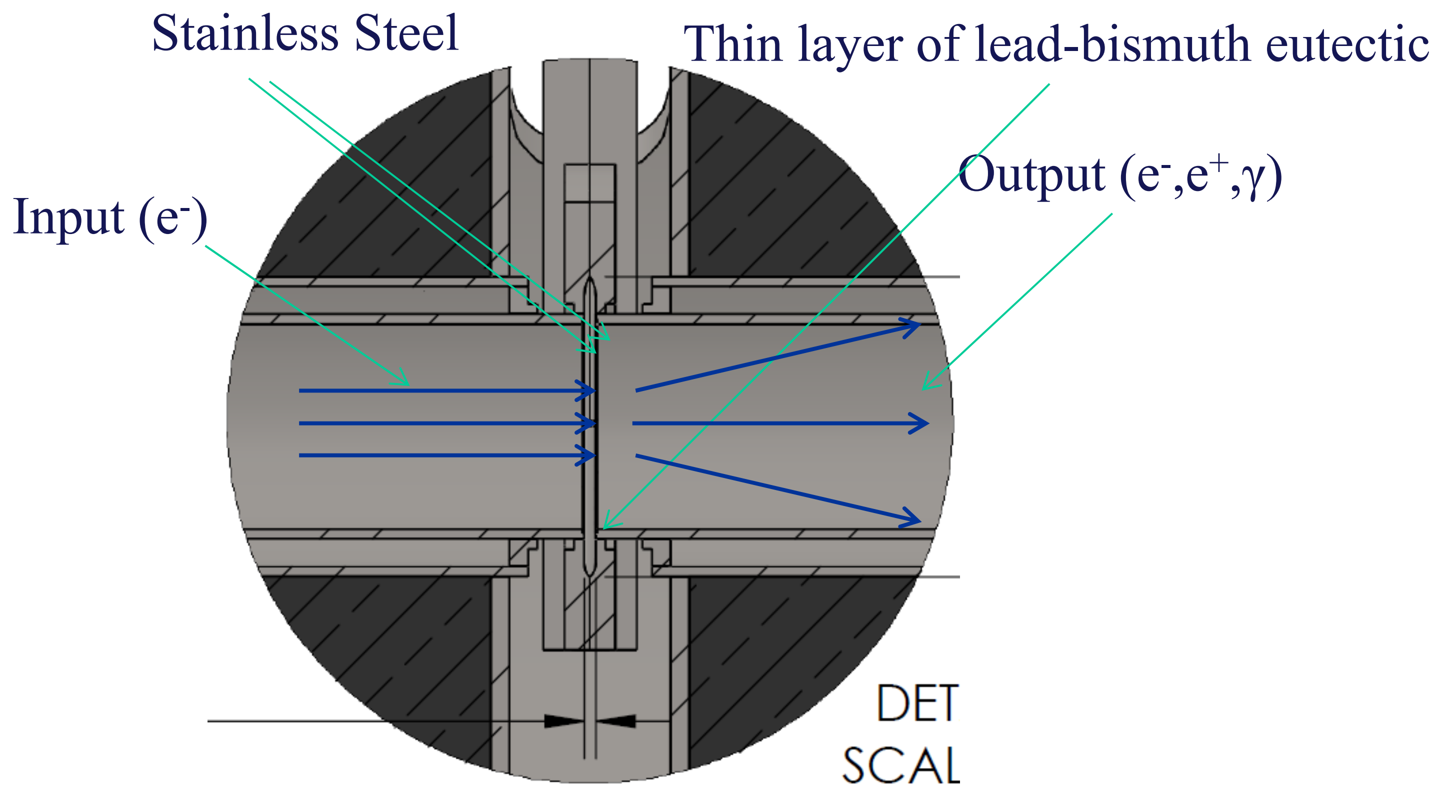
Current through liquid metal in magnetic field drives LBE down towards target, where it heats and then rises to exchanger

Verified flow with 200 A current through lead-bismuth eutectic

Liquid Metal Target Design

Input electron beam passes through:

- 0.25 mm SS
- 2 mm LBE, chosen for highest rate of production of e^+ using 10 MeV e^- (~2×10^{-3} e^+/e^-)
- 0.25 mm SS



Momentum of e^+ and e^- after Converter

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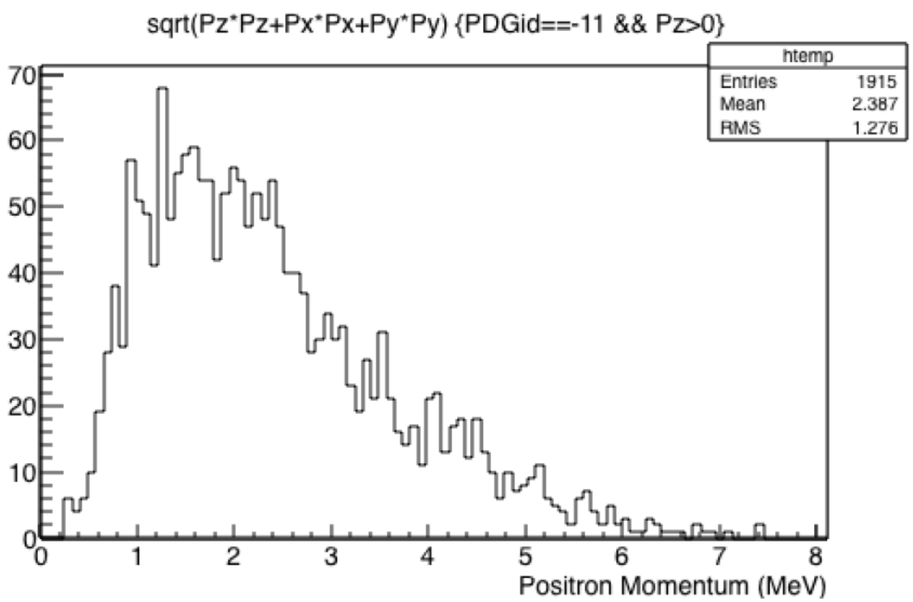
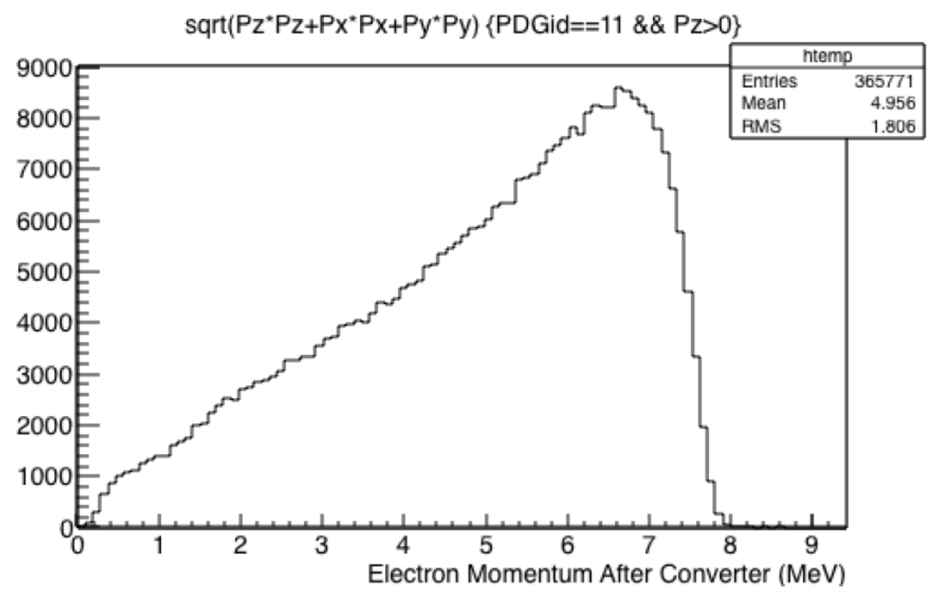
- Positron and electron momenta distributions using 10 MeV beam (simulated by IAC)
  - Peak of e^- at ~7 MeV
  - Peak of e^+ at ~2 MeV





Converter-Only Testing

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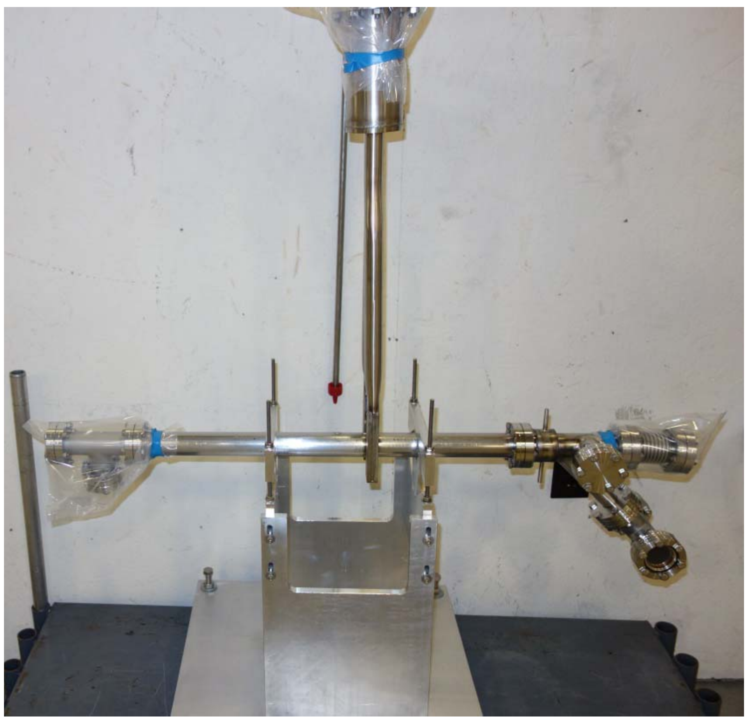
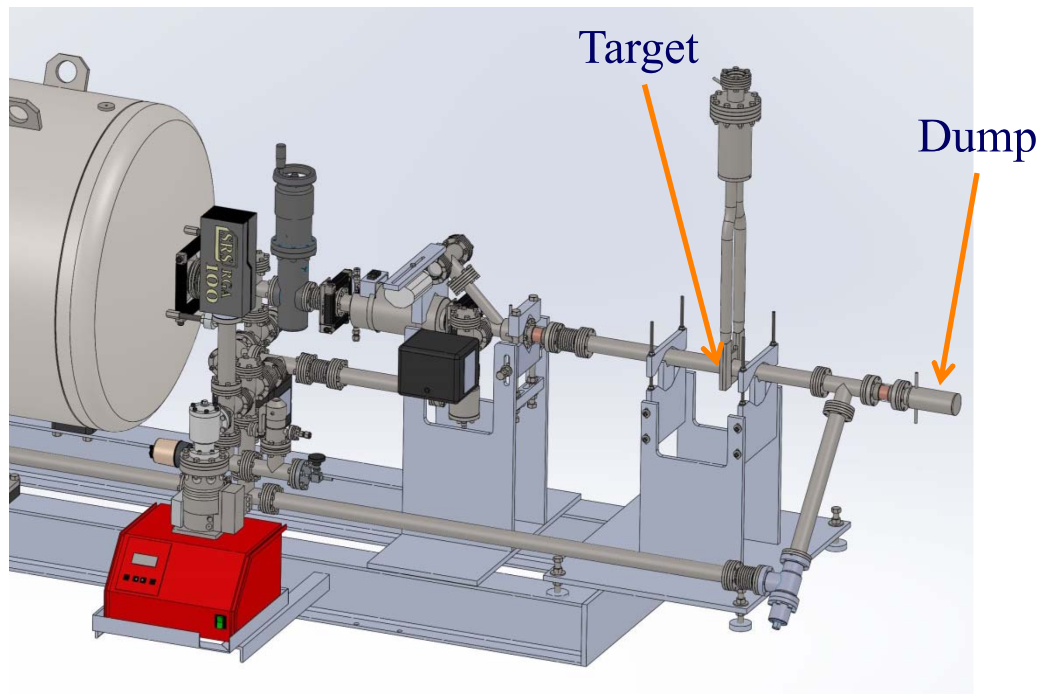
Completed testing a simplified target region, a bare beampipe with the LBE target with beam up to 4.5 MeV

- Temperature along beamline pipe, for power deposition
- Collected current at dump, for e^- transmission through LBE
- X-ray detection, for radiation doses





Test Results – Radiation Spectrum

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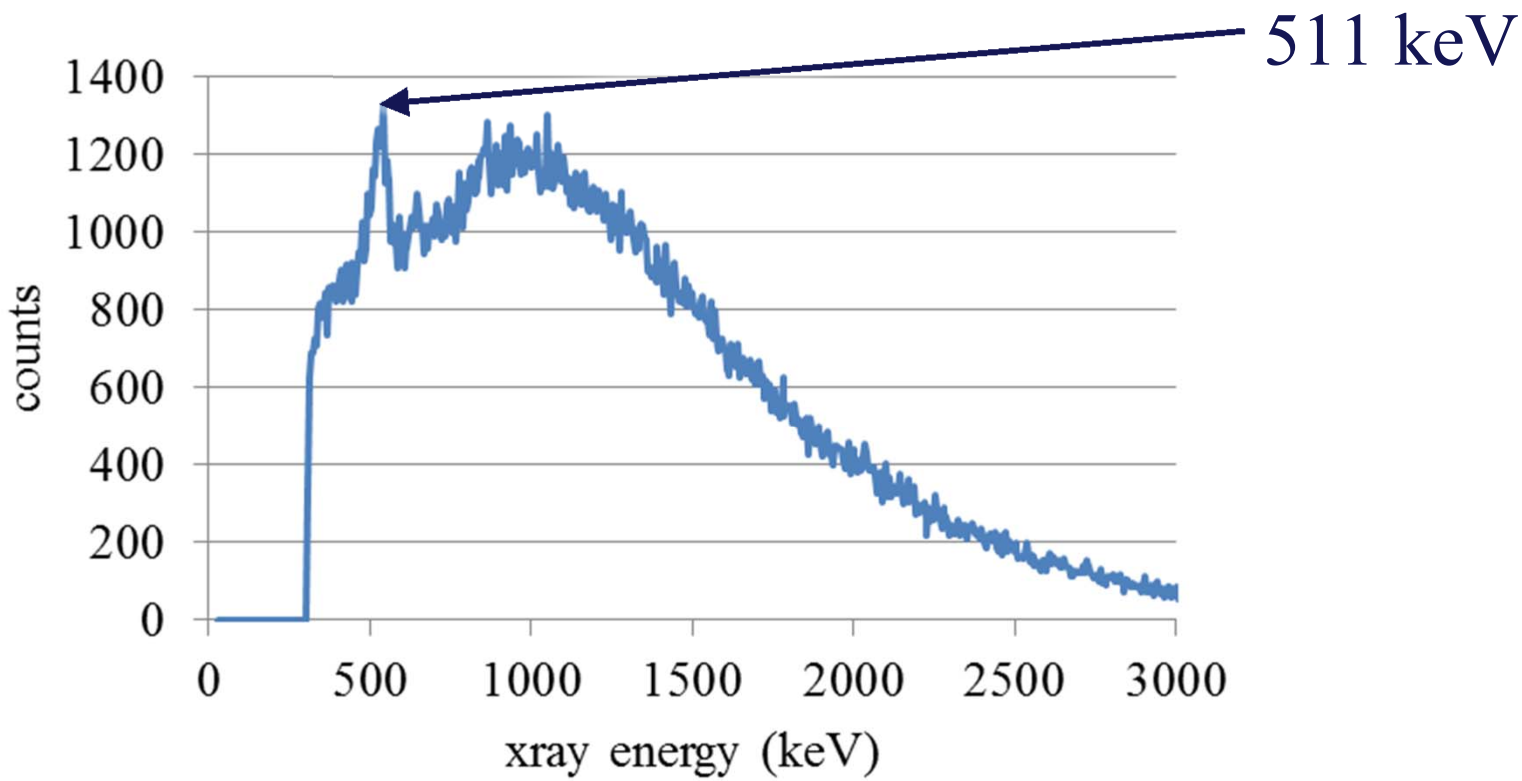
The NaI detector was able to clearly resolve the positron annihilation peak even without magnetic capture (this spectrum includes positrons generated all along the beamline).



Positron System Testing

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Verification of the natural convection flow was performed with converter and capture solenoids at design field levels.

Project Summary

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- A robust, industrial positron source is needed for both nuclear physics and materials science applications
- This SBIR project has developed and built a positron production system
  - 10 MeV superconducting electron accelerator
  - high-power liquid metal target
  - magnetic capture and separation systems
- Further opportunities for funding and for testing of the hardware with partners are being pursued