Mo-99 Production Using a Superconducting Electron Linac

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Lansing MI

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Outline

- Key personnel
- Superconducting electron linacs & their applications
- Photonuclear isotope production
  - Research isotopes (DOE Isotope Program)
  - Mo-99 (commercial market)
- Mo-99 production rates
- Mo-99 recovery
- NRC & state licenses
- Niowave headquarters – prototype & commission
- Niowave airport facility – production & distribution

Key Personnel

Dr. Terry Grimm

President & Senior Scientist

- PhD Nuclear Engineering, MIT
- Founded Niowave in 2005
- Over 25 years experience in superconducting accelerators

Dr. Valeriia Starovoitova

Nuclear Physicist

- PhD Nuclear Physics, Purdue
- Researcher at Idaho Accelerator Center
- Over 10 years experience in nuclear physics

Erik Maddock

Nuclear Engineer

- MS Radiological Physics, Wayne State
- Niowave Radiation Safety Officer
- US Navy Nuclear Power School

Jerry Hollister

Chief Operating Officer

- BS Engineering, Univ of Michigan
- Former Naval Officer & Warranted Contracting Officer

Mark Sinila

Chief Financial Officer

- BS Business Admin, Albion
- Over 20 years experience in business administration

Steve Klass

Director of Manufacturing

- BS Engineering, Saginaw Valley
- Over 20 years experience in manufacturing at General Motors

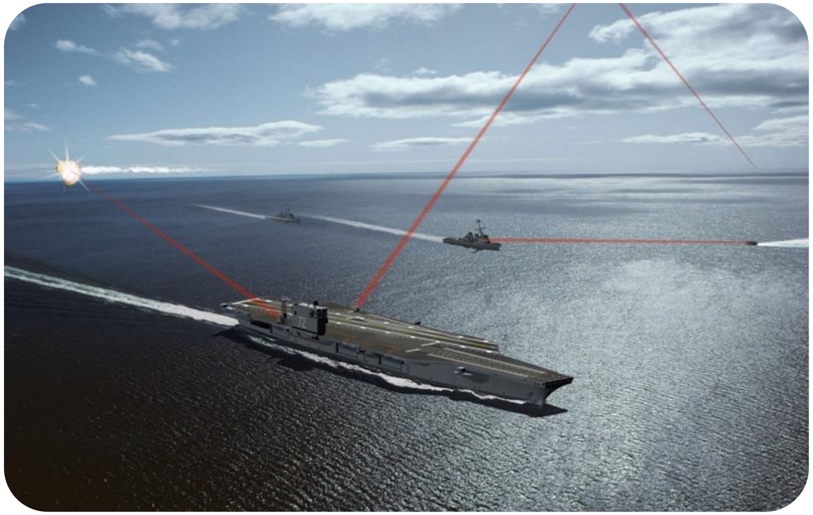
Why Superconducting?

- 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
- Large aperture resonant cavities
  - Improved wake-fields and higher order mode spectrum
  - Preserve high brightness beam at high average current (high power)

Commercial Uses of Superconducting Electron Linacs

High Power X-Ray Sources

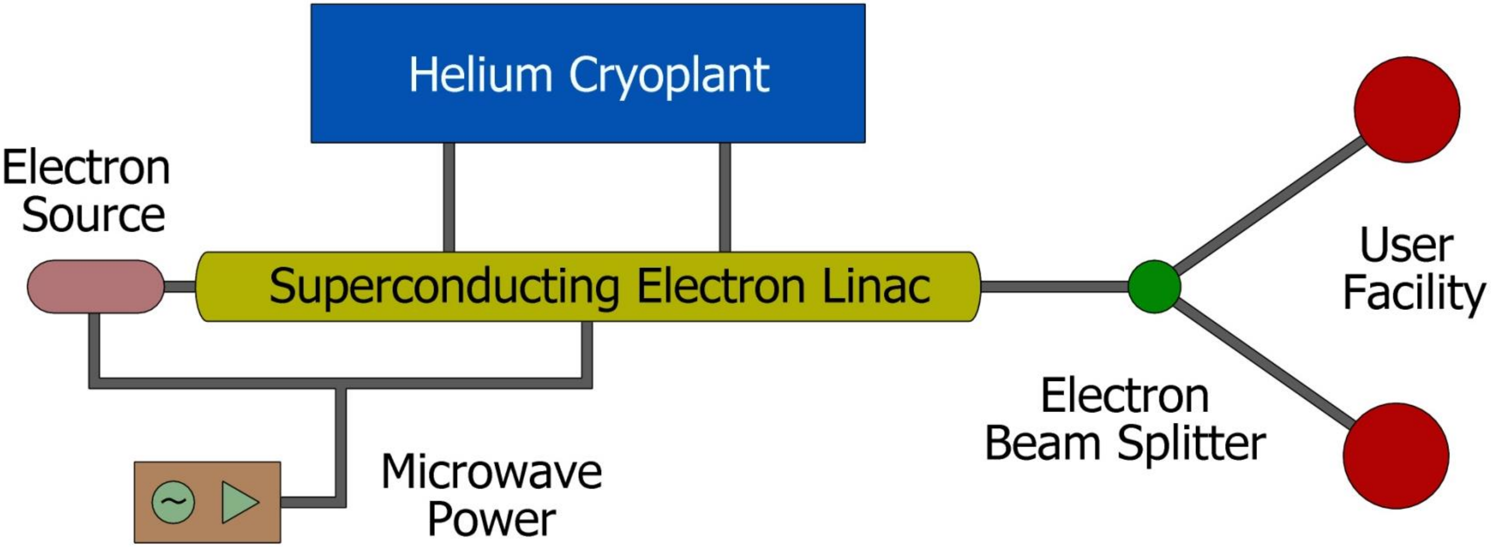
Radioisotope Production



Free Electron Lasers

High Flux Neutron Sources

Superconducting Turnkey Electron Linacs



Turn-key Systems

- Superconducting Linac
- Helium Cryoplant
- Microwave Power
- Licensing

Electron Beam Energy	**0.5 – 40 MeV**
Electron Beam Power	**1 W – 100 kW**
Electron Bunch Length	**~5 ps**

Turnkey Linac Subsystems

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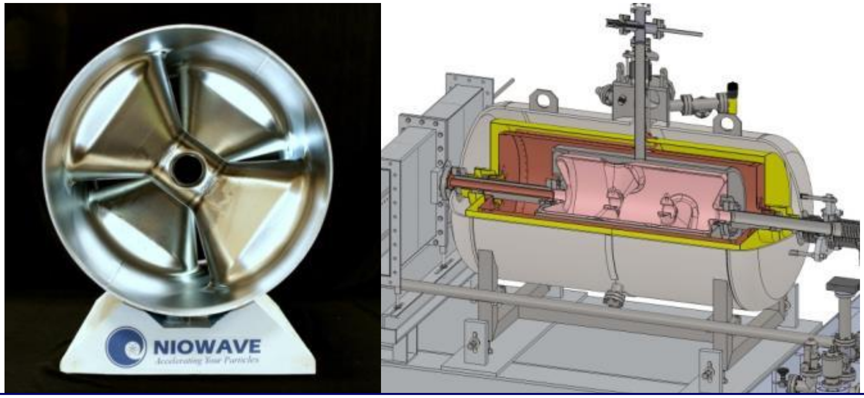
RF electron guns

High-power
couplers

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



Superconducting cavities and cryomodules

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

Superconducting Accelerating Cavities

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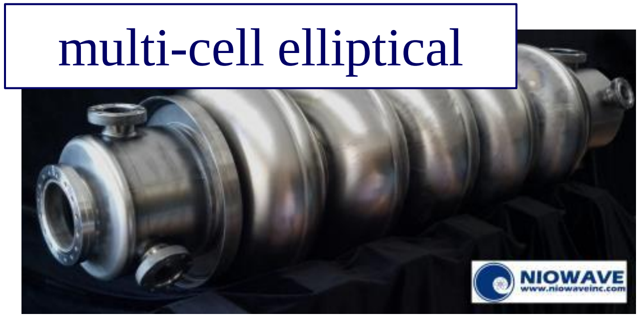
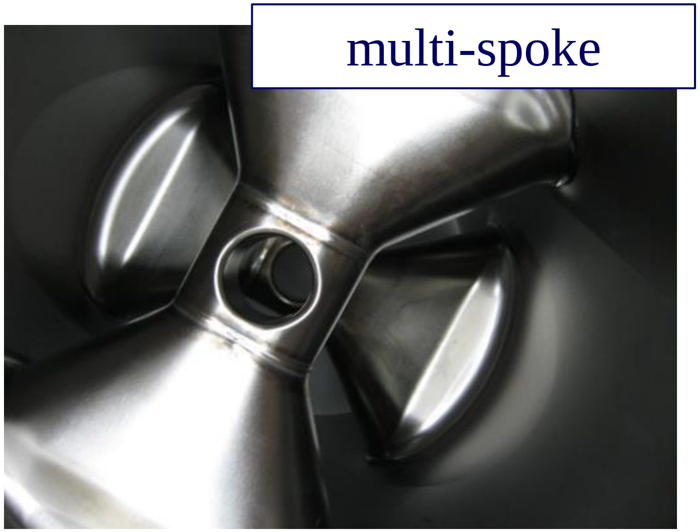
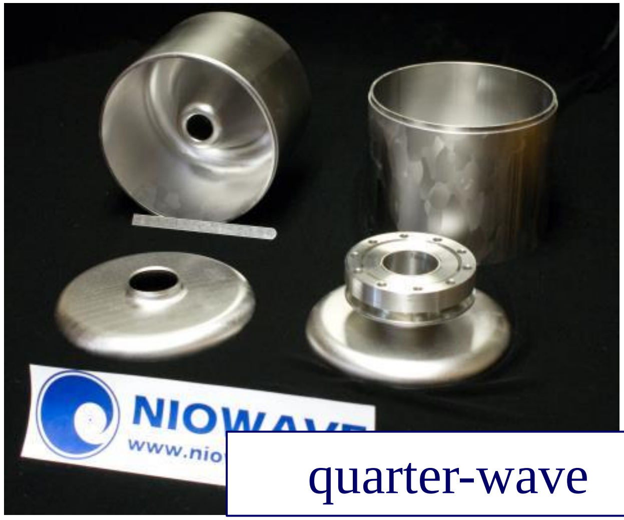


multi-cell elliptical



multi-spoke



quarter-wave

photonic bandgap

Variety of new SRF cavity shapes are allowing compact, low-frequency acceleration with high average beam power.

Frequency & Temperature

- Superconducting linacs have inherent losses due to the time varying fields

superconducting transition temperature

frequency

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

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 Multi-Spoke Cavities

- Advantages for low frequency, high current linacs
  - **Mechanical stability** (stable against microphonics)
  - **Compact geometry** for improved real-estate gradient and low-frequency operation at 4 K
  - **Improved higher-order-mode (HOM) spectrum** and damping

RF Power Sources

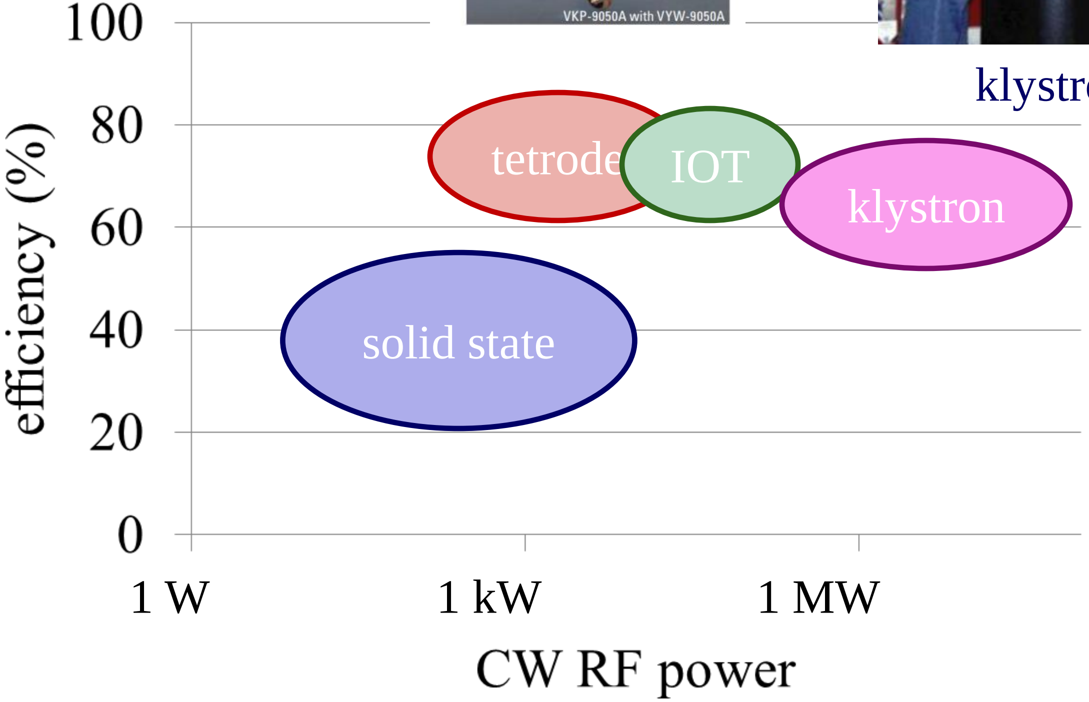
- Solid-state supplies to 5 kW
- Tetrode amplifer to 60 kW
- IOTs to 90 kW
- Klystrons to >1 MW

inductive output tube

klystron

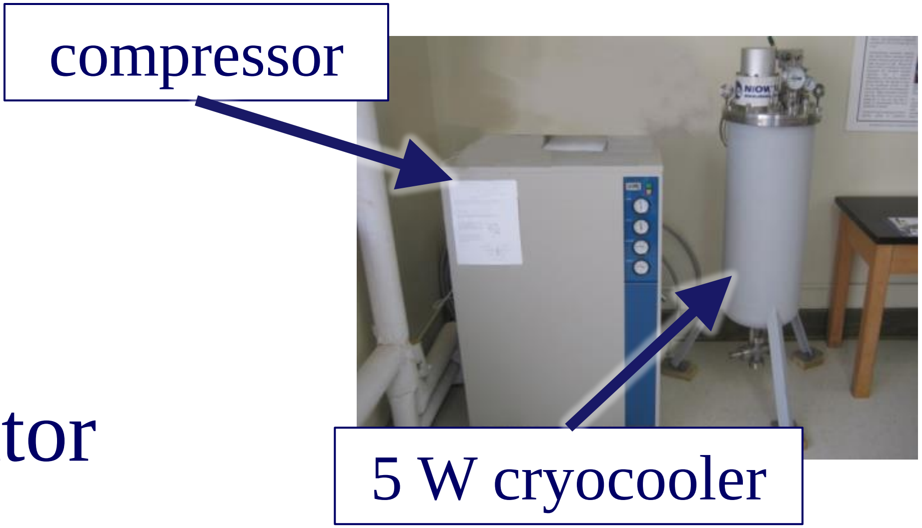
tetrode

solid-state

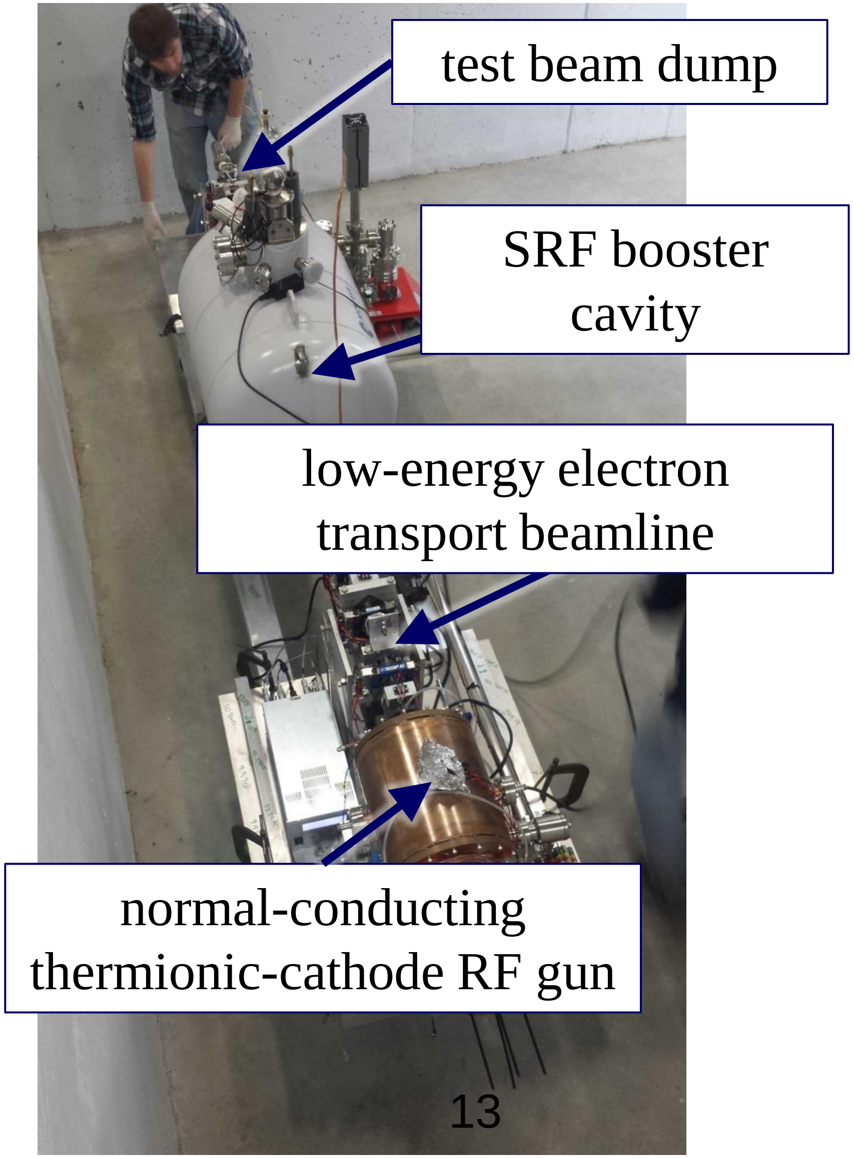


Commercial 4 K Refrigerators

- Cryo-cooler to 5 W
  - 4.5 K operation
  - 5 kW electrical power
- Commercial refrigerator to 110 W
  - 4.5 K operation (slightly above 1 atm)
  - total electrical power 100 kW
  - higher capacity units available



2 & 10 MeV Injectors



test beam dump

SRF booster cavity

low-energy electron transport beamline

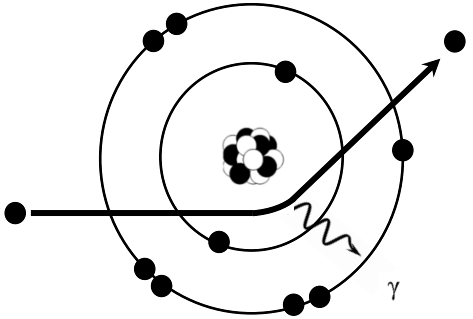
normal-conducting thermionic-cathode RF gun

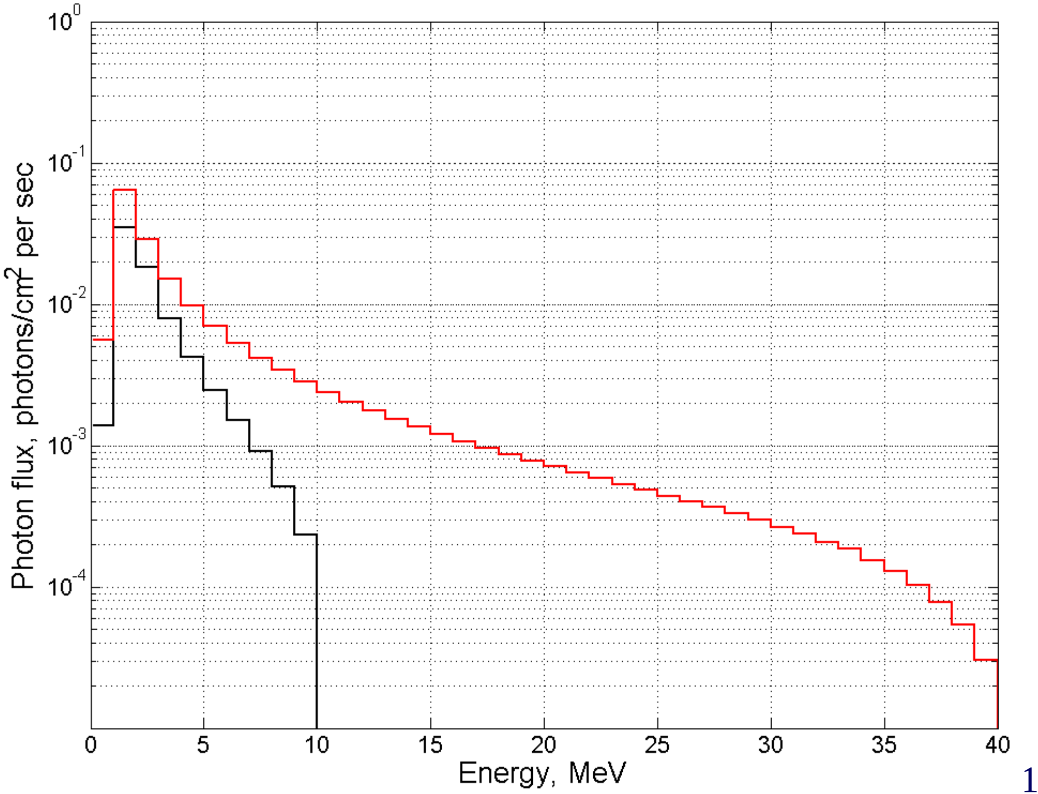
Parameter	2 MeV	10 MeV
cathode type	thermionic	thermionic
NCRF electron gun energy	100 keV	100 keV
SRF booster cavity energy	2 MeV	10 MeV
bunch repetition rate (gun, booster frequency)	350 MHz	350 MHz
transverse normalized rms emittance	3-5 mm mrad	3-5 mm mrad
bunch length @ 2 MeV	2-5 ps	2-5 ps
average beam current	2 mA	1-2 mA

Liquid Metal Converters[1]

Bremsstrahlung Converter:

- High conversion efficiency (high Z)
- High melting point, if the converter is solid
- Low melting point and good thermomechanical properties (e.g., swelling, ductility loss, creep rates, etc.), if the converter is liquid
- Optimum thickness depends on electron energy and material

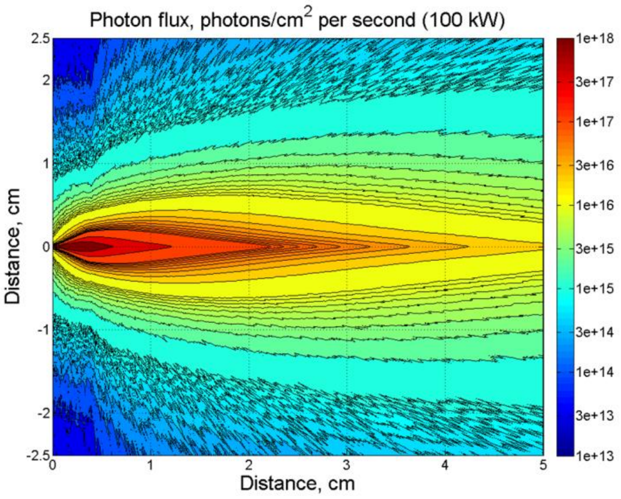


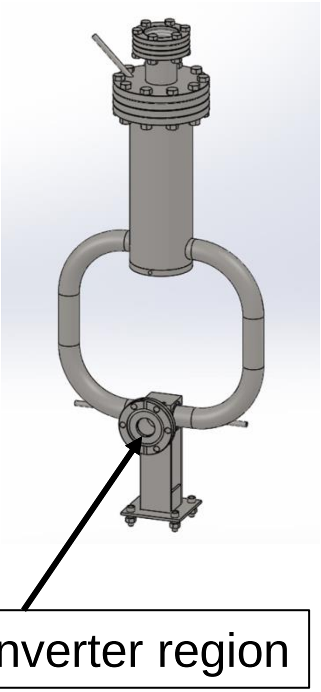


Liquid Metal Converters[2]

Lead-Bismuth Eutectic (LBE)

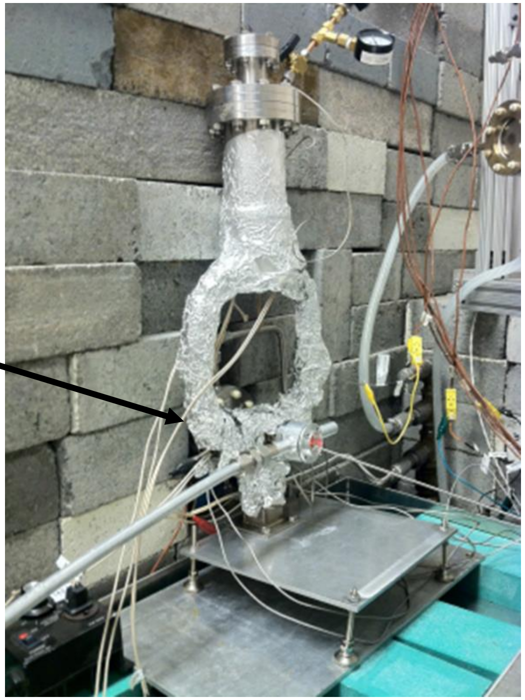
- Low melting point:
  124°C
- High boiling point:
  1670°C
- Z=82,83





Converter region

Electron beam

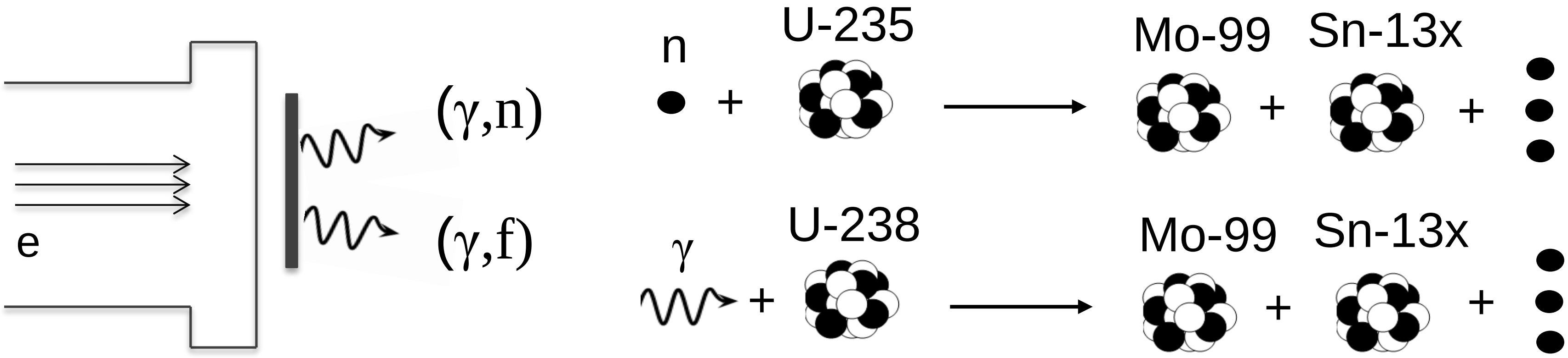


40 MeV, 1 kW test (2013)

Isotope Production

- Photonuclear production of medical, industrial, and research isotopes for DOE Isotope Program
  - (γ, n)
  - (γ, p)
  - (n, γ)
- Mo-99 production from LEU - domestic facilities which do not rely on using highly enriched uranium
  - (γ, fission)
  - (n, fission)

Molybdenum-99



Electrons are accelerated

Electrons brake and produce photons

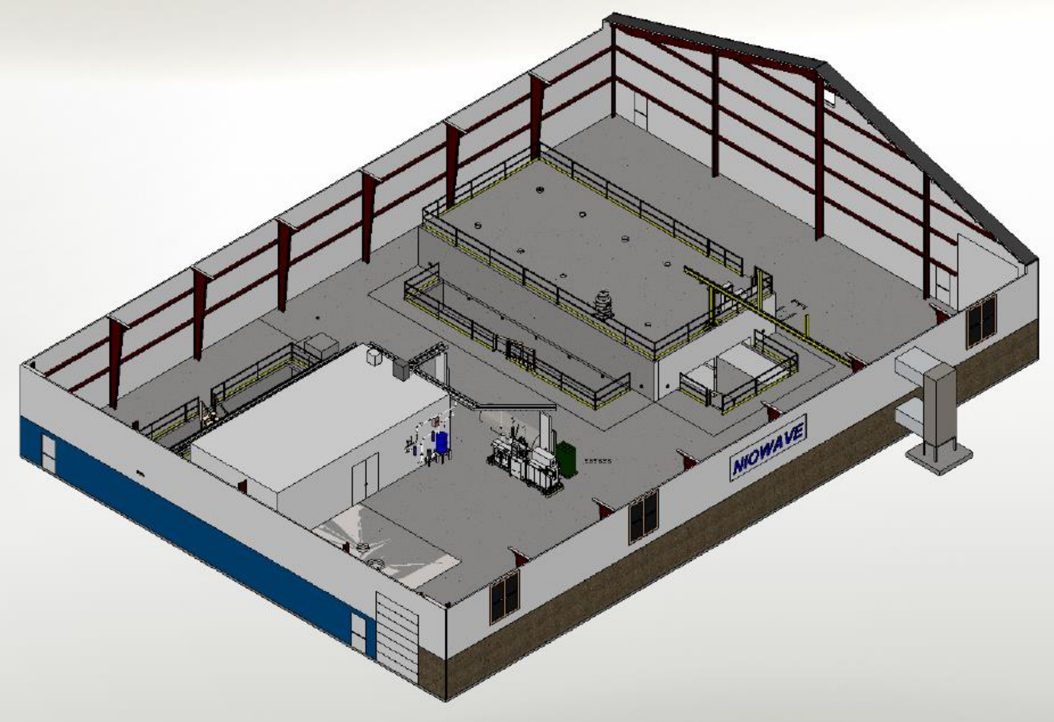
Photons:

a) Induce photon-fission
b) Liberate neutrons via fission and (γ,n) reactions and result in neutron-induced fission

Mo-99 Production Rates

- Using LEU we plan to produce ~9 kCi of Mo-99 (~1,500 six-day curies) weekly at each of the 40 MeV 100 kW facilities

- 4-5 such facilities will satisfy North America's demand of Mo-99



Mo-99 Recovery

- Metal uranium production targets
- Molybdenum recovery
  - Uranium target dissolution with HNO_3
  - Molybdenum adsorption on ion exchange resin
- Standard Tc-99m generators
  - Capable of using the existing supply chain
- Waste consolidated and shipped to LLW/HLW repositories

Licenses

- State of Michigan
  - Licensed to operate 40 MeV, 100 kW linacs
    - License number PR-2013-0346
- Nuclear Regulatory Commission
  - Source Material License
    - Licensed to possess, machine, and distribute DU, ^{nat}U, ^{232}Th
    - License number 21-35145-01
  - Isotope Production Licenses
    - Research isotopes - submitted and under review
    - Mo-99 – submission pending additional assessment and discussion

Mo-99/LEU Licensing Plan [1]

- Plan to scale up production and processing as technical and financial milestones are met
- Phased approach to production and processing

PHASE I
Feasibility Demo
150 6-day Ci/wk
<350 g of U235

PHASE II
Full Scale Demo
1,500 6-day Ci/wk
<10,000 g of U235

PHASE III
Full Production
4-5 facilities in U.S.
6,000 6-day Ci/wk

Mo-99/LEU Licensing Plan [2]

- Phase I – Feasibility Demo
  - – Produce up to 900 Ci/wk (150 6-day Ci/wk)
  - – Inventory of <1,750 g of 20% LEU (<350 g U235)
    - Part 150 Less than critical mass
  - – Batch process <10 g of 20% LEU (<2 g U235)
    - Part 30 Byproduct from accelerators

Mo-99/LEU Licensing Plan [3]

- Phase II – Full Scale Demo
  - Produce up to 9,000 Ci/wk (1,500 6-day Ci/wk)
  - Inventory of <50,000 g of 20% LEU (<10,000 g U235)
    - Part 70 Cat 3 SNM of low strategic significance
  - Batch process <100 g of 20% LEU (<20 g U235)
    - Part 30 Byproduct from accelerators
  - Extract additional isotopes of commercial value
    - I131, Xe133, etc.

Mo-99/LEU Licensing Plan [4]

- Phase III – Full Production
  - Produce up to 36,000 Ci/wk (6,000 6-day Ci/wk)
  - 4 to 5 Production Facilities
    - Distributed around the U.S. to expedite distribution
    - Independently licensed under the same terms as the full scale demo
  - Distribute additional isotopes of commercial value
    - I131, Xe133, etc.

Niowave Headquarters [1]

- Prototype and commission
  - 40 MeV superconducting electron linac
  - Isotope production target
- 2012 Dedication of testing facility
  - Keynote speakers: Senator Carl Levin, Senator Debbie Stabenow, Rear Admiral Matthew Klunder and MSU Provost Kim Wilcox

Niowave Headquarters [2]

- Total 60,000 SF
  - Full in-house design, manufacturing, processing and testing capability
  - 3+ megawatts power
  - 60 kW RF power systems
  - Two 100 W helium refrigerators
  - Licensed to operate up to 40 MeV and 100 kW

A superconducting linac being installed in a Niowave testing tunnel

Interior of Niowave testing facility

Niowave Airport Facility

- New manufacturing facility under construction
  - Beneficial occupancy in Nov 2014
  - Production & distribution of isotopes
    - 24/7 operation
  - Additional expansion space available

Summary

- Niowave’s photonuclear isotope facilities will be capable of supplying the entire Mo-99 requirements of North America
- First Mo-99 production (small scale)
  - Planned for Dec 2014
- Research isotopes supplied to DOE Isotope Program
  - Planned for Dec 2014