Mo-99 Production Using a Superconducting Electron Linac

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Outline

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- 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

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
- 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

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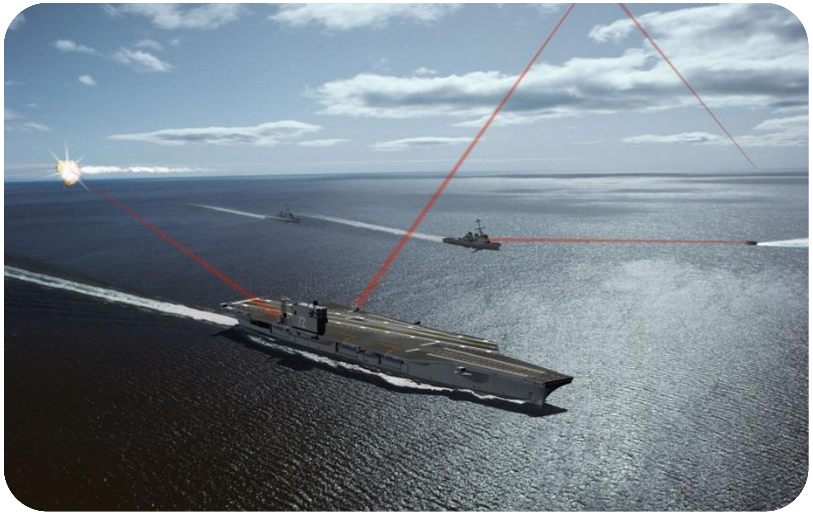
High Power X-Ray Sources

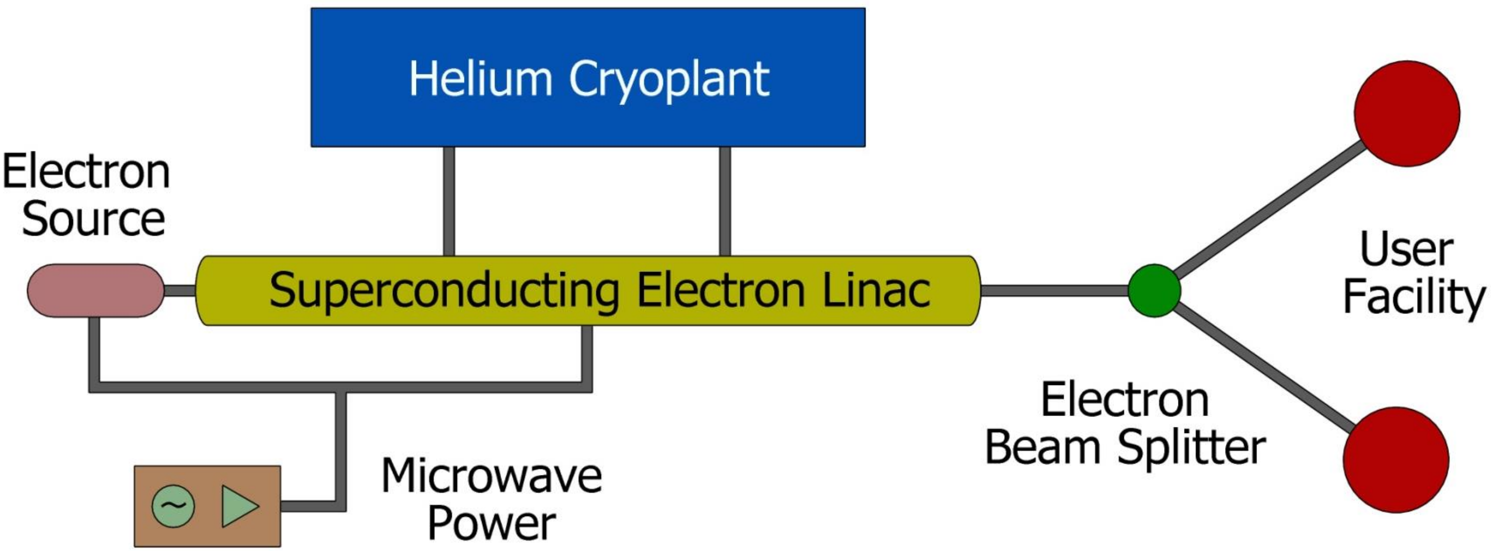
Radioisotope Production



Free Electron Lasers

High Flux Neutron Sources

Superconducting Turnkey Electron Linacs

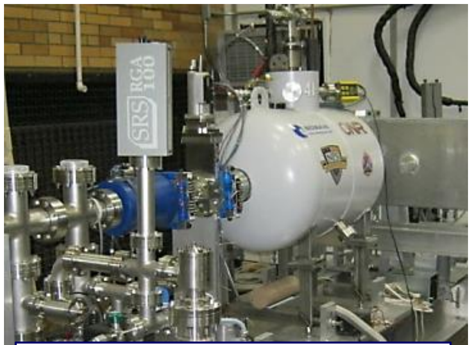


Turn-key Systems

- Superconducting Linac
- Helium Cryoplant
- Microwave Power
- Licensing

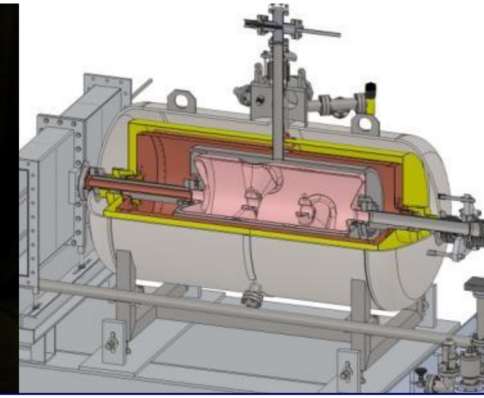
Electron Beam Energy	**0.5 – 40 MeV**
Electron Beam Power	**1 W – 100 kW**
Electron Bunch Length	**~5 ps**

Turnkey Linac Subsystems



RF electron guns

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



Superconducting cavities and cryomodules

High-power couplers

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

Superconducting Accelerating Cavities

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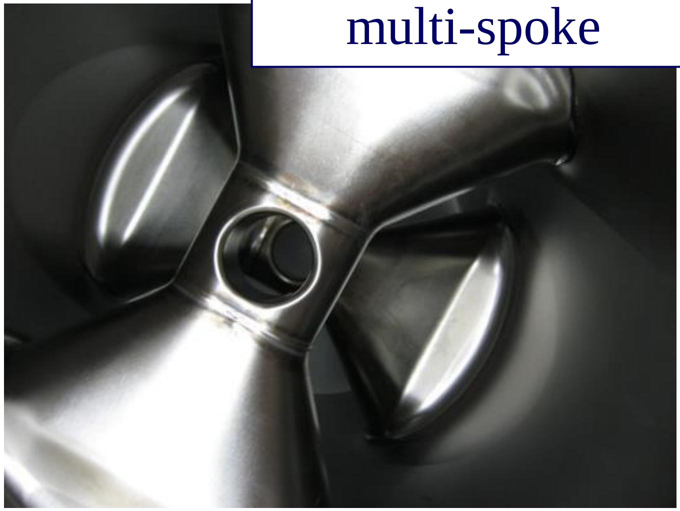
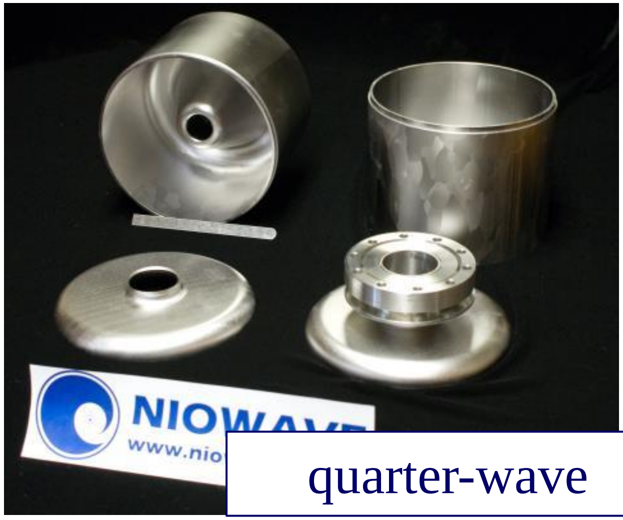
multi-cell elliptical



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

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

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

frequency

superconducting transition temperature

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

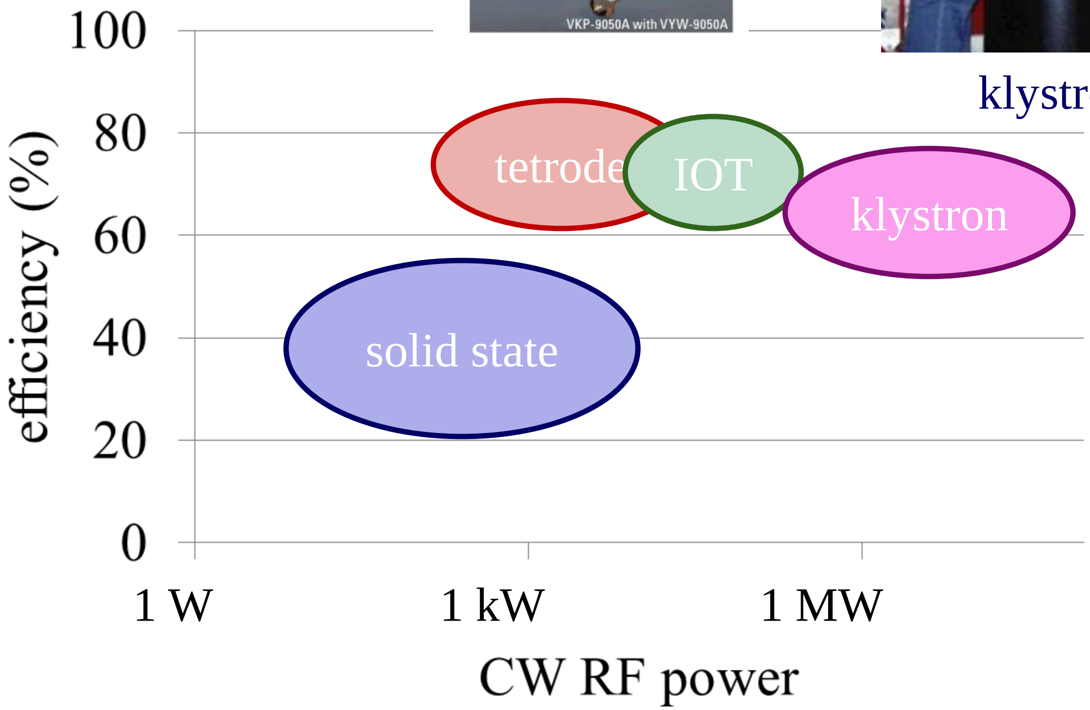
- Advantages for low frequency, high current linacs
  - **Mechanical stability** (stable against microphonics)
  - **Compact geometry** for improved real-estate gradient and low-frequency operation at 4 K
  - **Improved higher-order-mode (HOM) spectrum** and damping

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



Commercial 4 K Refrigerators

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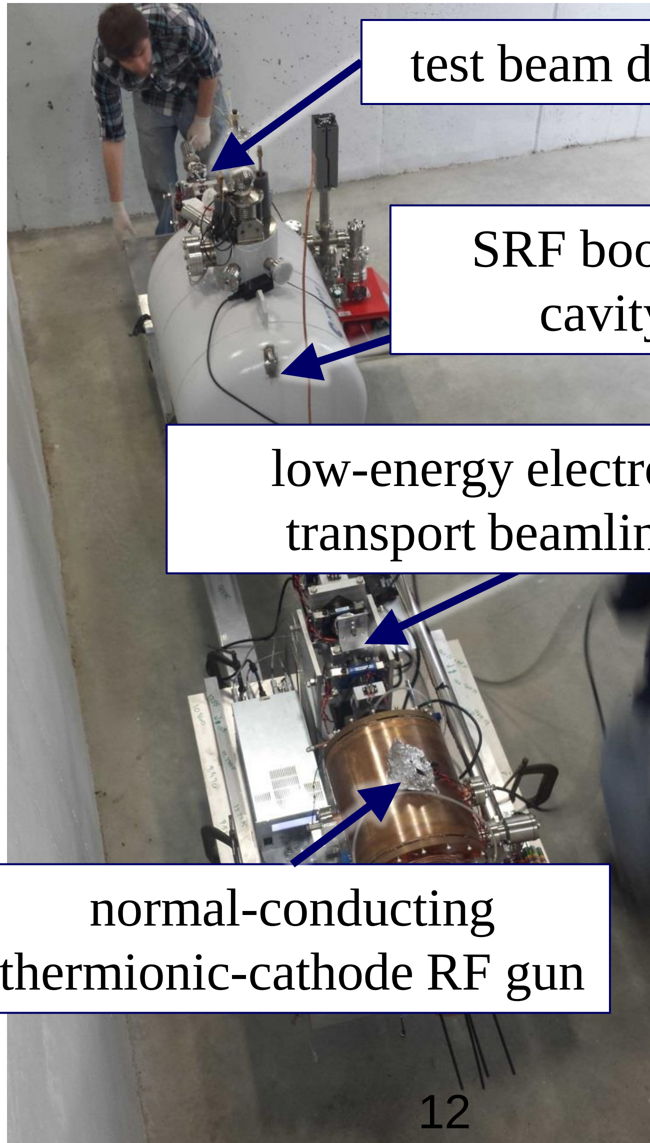
- Cryo-cooler to 5 W
  - 4.5 K operation
  - 5 kW electrical power
- Commercial refrigerator to 110 W
  - 4.5 K operation (slightly above 1 atm)
  - total electrical power 100 kW
  - higher capacity units available

2 & 10 MeV Injectors



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]

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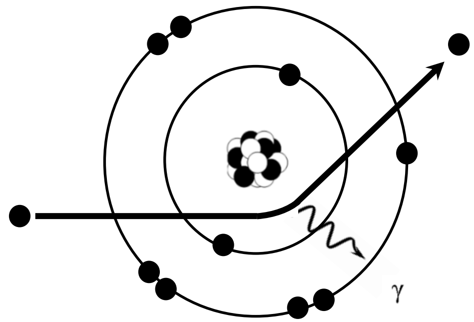
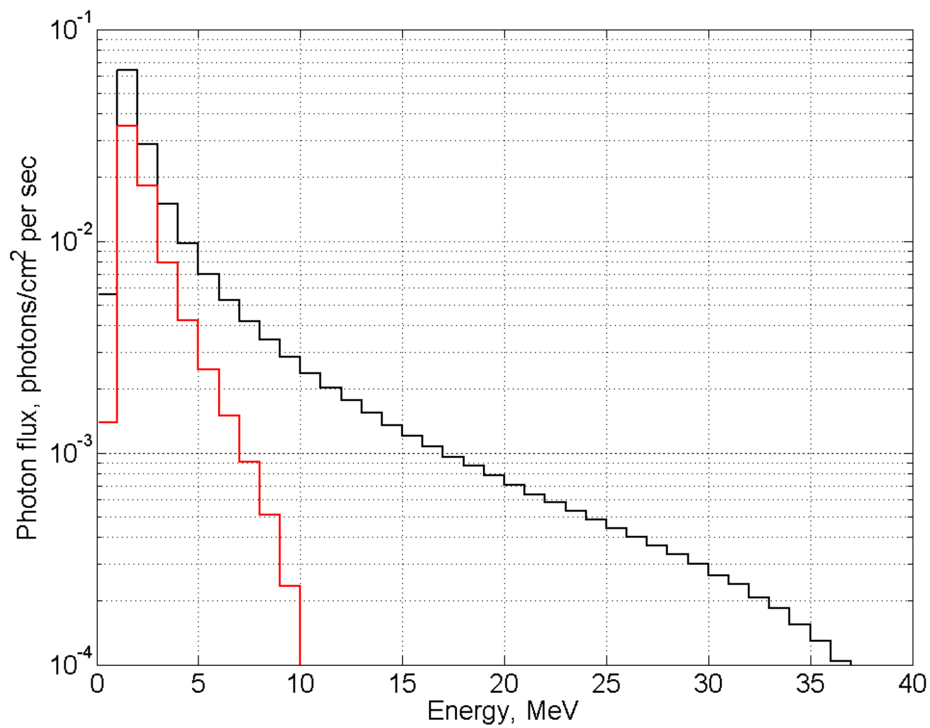
Bremsstrahlung Converter:

- 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]

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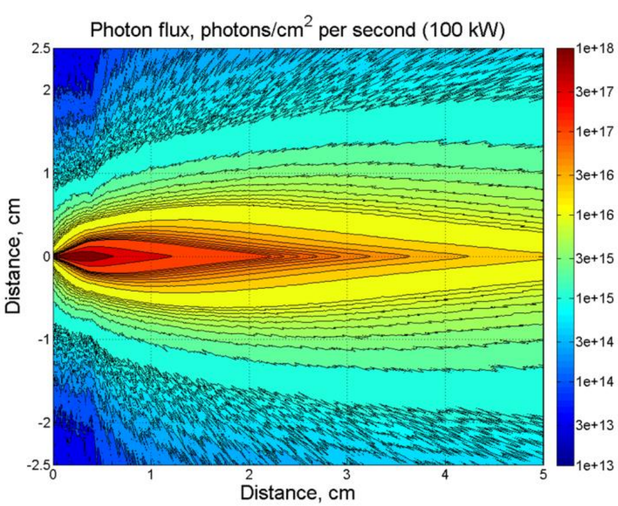
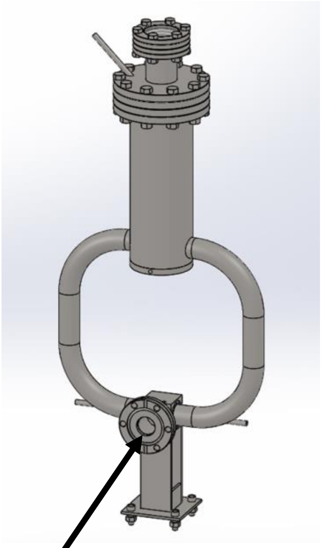
Lead-Bismuth Eutectic (LBE)

- 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

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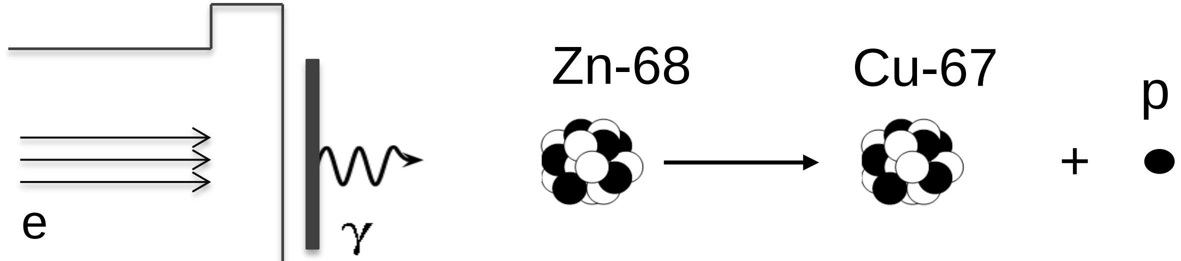
- Photonuclear production of medical, industrial, and research isotopes for DOE program
  - (γ, n)
  - (γ, p)
  - (n, γ)
- Mo-99 production from LEU - domestic facilities which do not rely on using highly enriched uranium
  - (γ, fission)
  - (n, fission)

Photo-production of Isotopes

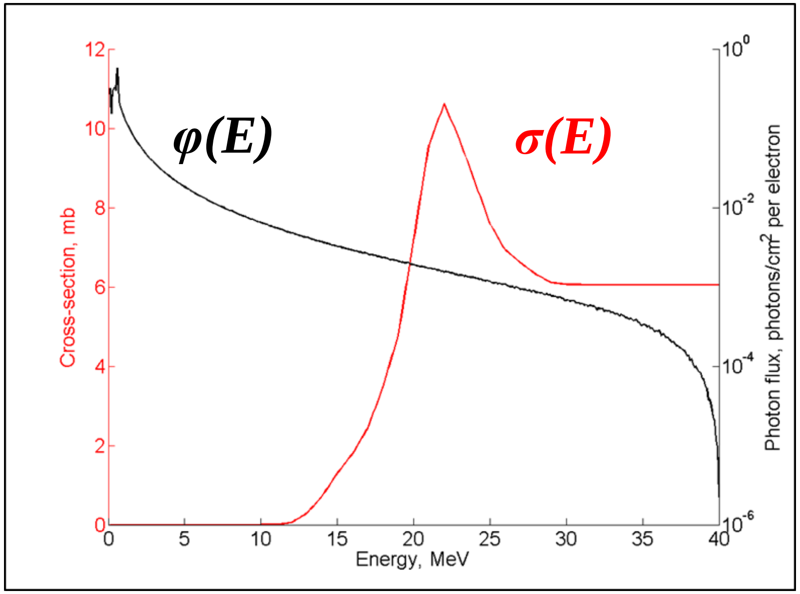


Electrons are accelerated

Electrons brake and produce photons

Photons knock out neutrons (or protons) and new isotopes are formed

$$Y = N\int_{E_{th}}^{E_{max}} \varphi(E)\cdot\sigma(E)dE$$



Copper-67

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$^{68}Zn(\gamma,p)^{67}Cu$

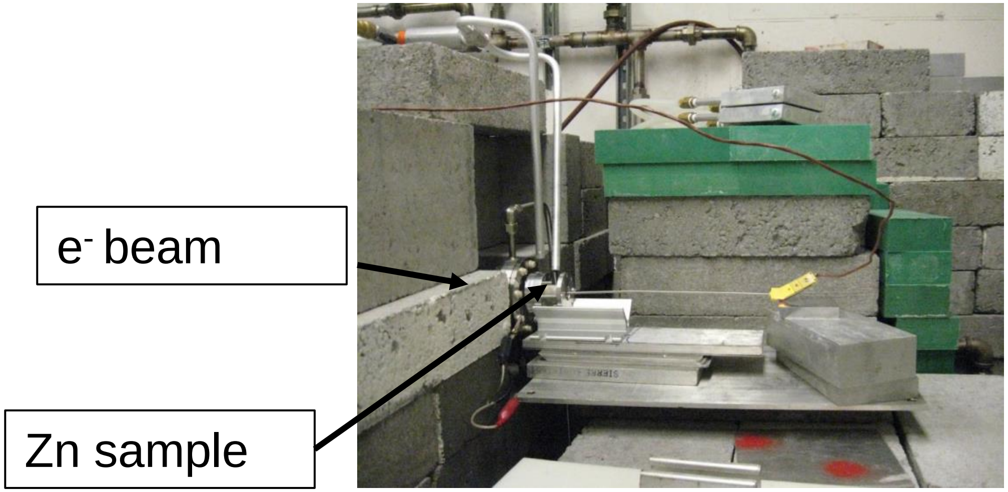
- Cu-67 measured activity:

16.0±0.4 *μCi/(g·kW·h)*

- Predicted activity:

20 *μCi/(g·kW·h)*

Scaled up activity: 0.2 Ci/g (using Zn-68, 100 kW beam and 24 h irradiation)



Actinium-225

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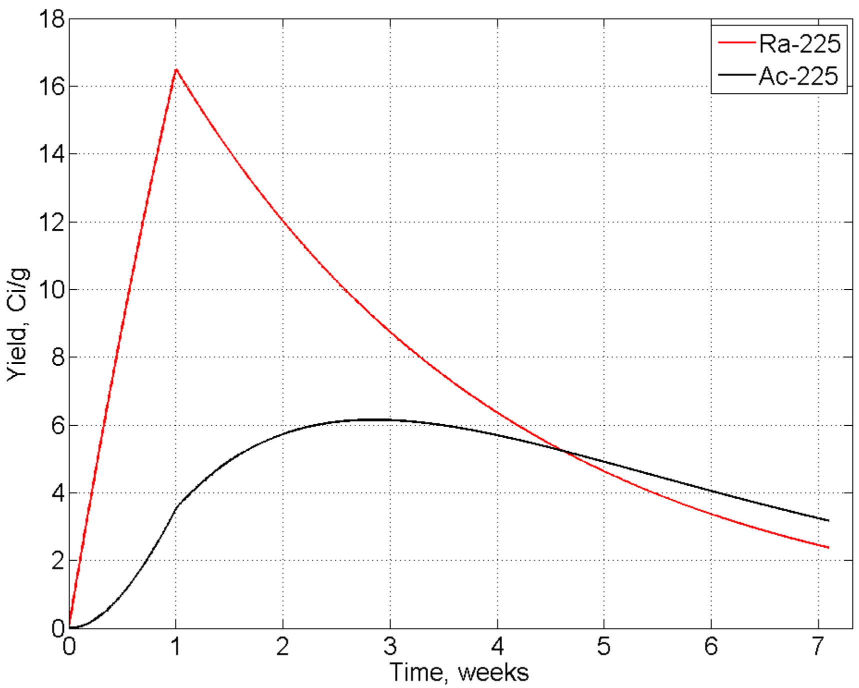
Photoneutron cross-section is typically higher than photoproton cross-section, however the produced isotope is chemically identical to the target material.

$$^{226}Ra(\gamma,n)^{225}Ra \xrightarrow{\beta^-} {}^{225}Ac$$

$T_{1/2}$ = 15 days (^{225}Ra)
$T_{1/2}$ = 10 days (^{225}Ac)



Molybdenum-99

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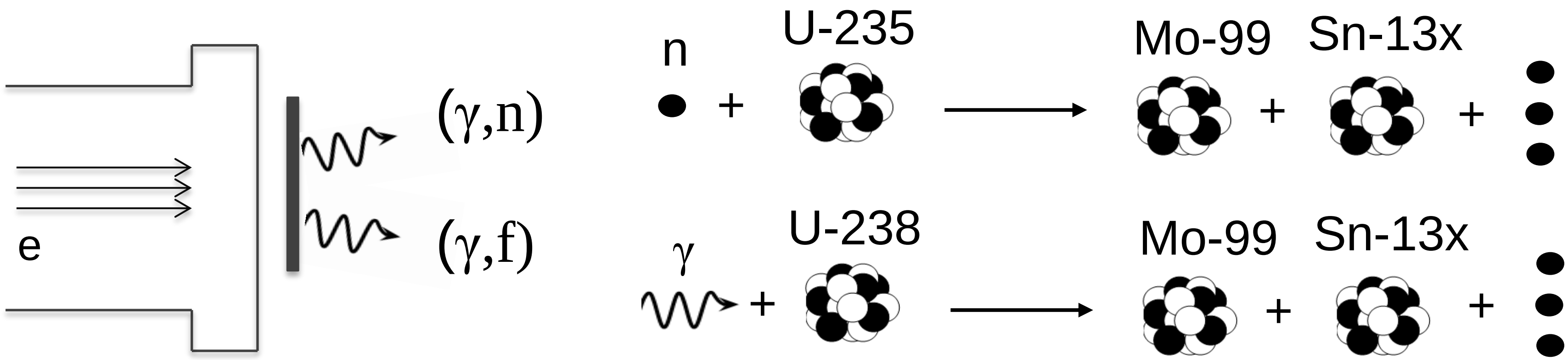

Electrons are accelerated

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

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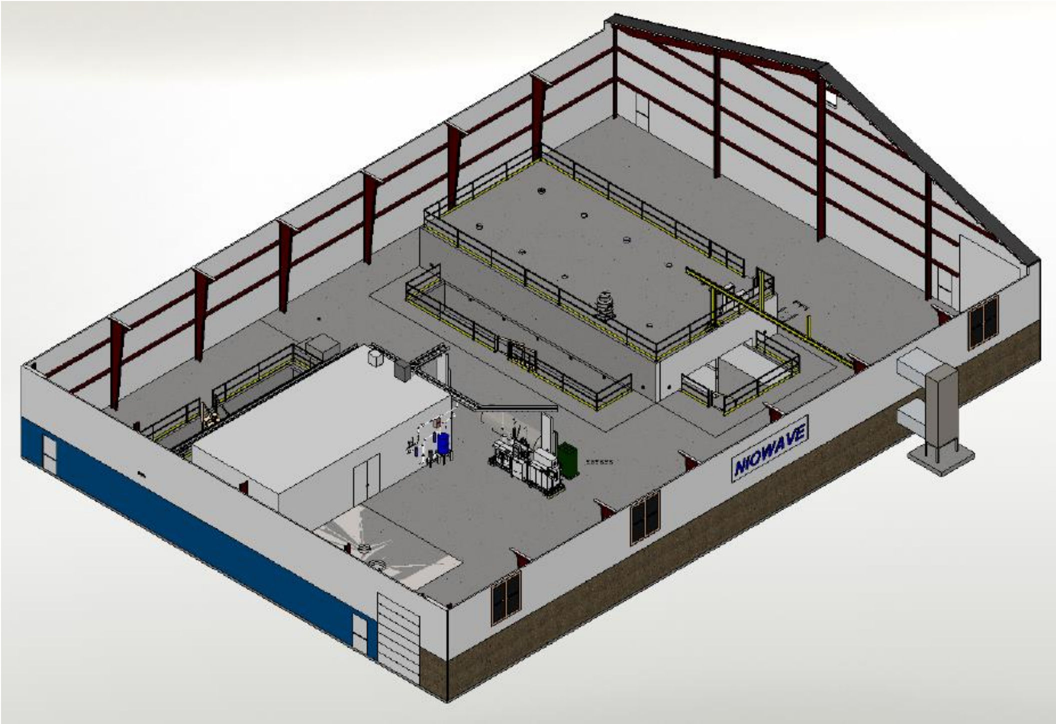
- Using LEU we plan to produce ~9 kCi of Mo-99 (~1,500 six-day curies) weekly at each of the 40 MeV 100 kW facilities

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



Mo-99 Recovery

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- 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

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- State of Michigan
  - Licensed to operate 40 MeV, 100 kW linacs (Agreement State)
- Nuclear Regulatory Commission
  - License to manufacture and distribute isotopes
    - Research isotopes – submitted and under review
    - Mo-99 from LEU – submitted

Niowave Headquarters [1]

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- 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]

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- 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

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

Summary

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- 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