Commercial Applications of Small SRF Accelerators

Dr. Terry L. Grimm

NA-PAC '13
September 2013

NIOWAVE
www.niowaveinc.com

Outline

NIOWAVE
www.niowaveinc.com

- Advantages of superconducting electron linacs
- Superconducting quarter wave electron guns
- Superconducting turnkey electron linacs
- Applications/commercial market

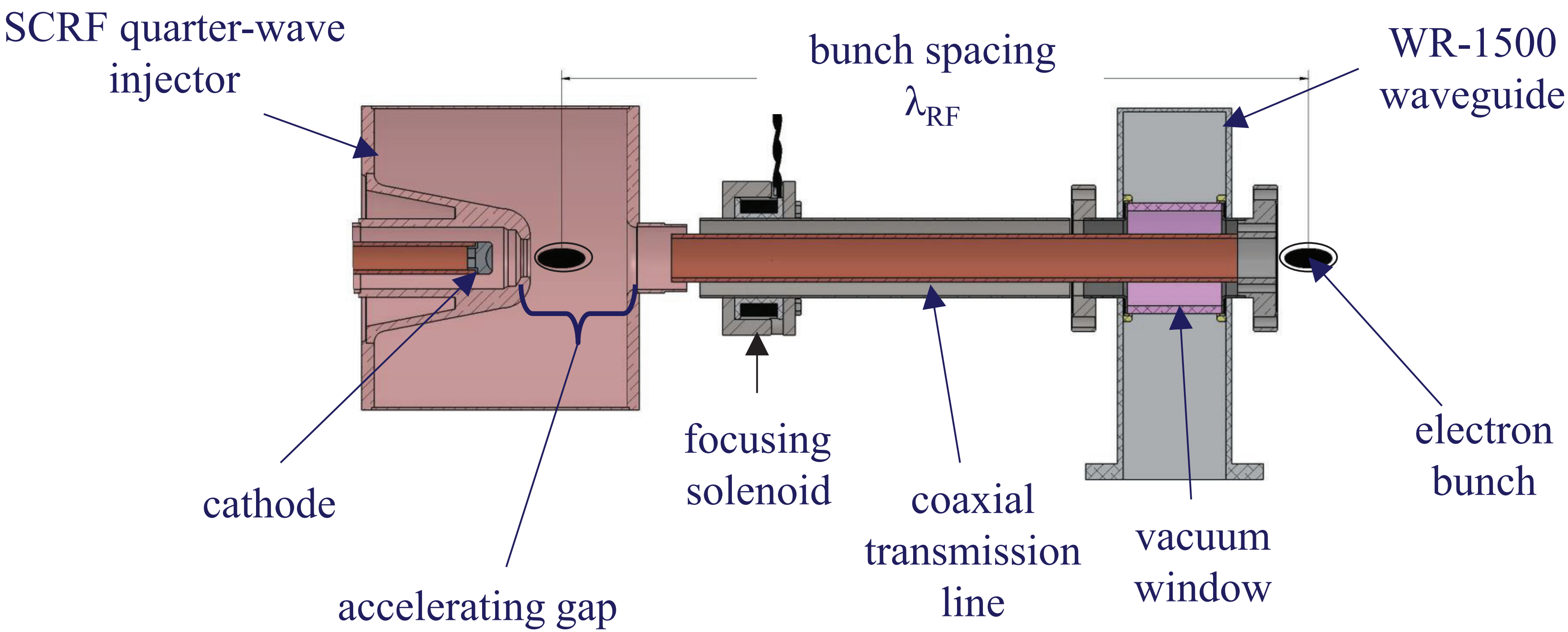
Advantages of Superconducting Linacs

NIOWAVE
www.niowaveinc.com

- Caveat emptor
  - If a copper linac can get the job done, then DO NOT go superconducting
  - Example: MRI machines (medical imaging)
- Advantages of superconducting linacs
  - High average power electron beam
  - High brightness electron beam

Superconducting Quarter Wave Electron Guns [1]

NIOWAVE
www.niowaveinc.com



- Advantages of on-axis coupler: symmetric fields, compact, halo at room temperature, strong HOM coupling on air side
- Additional features (not shown in schematic)
  - liquid nitrogen cooling of cathode & inner conductor
  - DC bias for suppression of multipacting

Superconducting Quarter Wave Electron Guns [2]

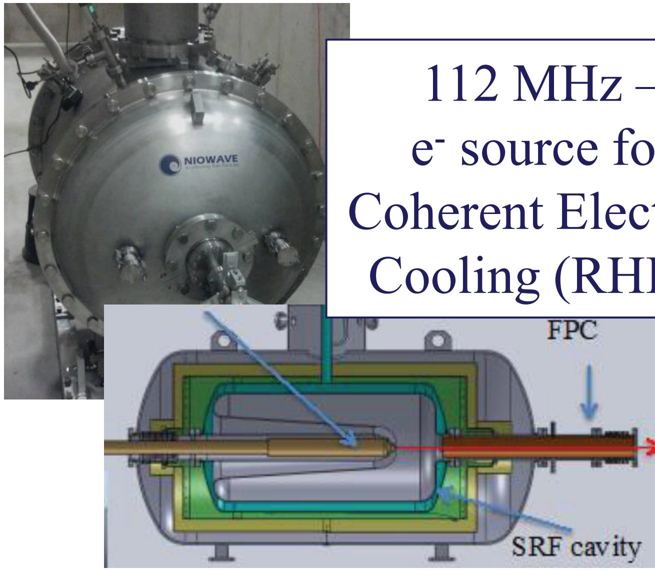
NIOWAVE
www.niowaveinc.com

Niobium cavity body and cap plate – two sets shown before electron beam welding.

resonant frequency	700 MHz
accelerating voltage	1.0 MV
cathode electric field	16 MV/m
peak surface electric field	48 MV/m
peak surface magnetic field	58 mT
ratio B_{peak}/E_{peak}	1.2 mT / (MV/m)
BCS resistance at 700 MHz	190 nΩ
dissipated power	9.4 W
operating temperature	4.2 K
cavity Q	5.3×10^8
geometry factor ($R_s \times Q$)	104 Ω
shunt impedance R/Q (linac definition, $V^2 / \omega U$)	181 Ω
Transit-time factor (β=1)	0.95

Superconducting Quarter Wave Electron Guns [3]

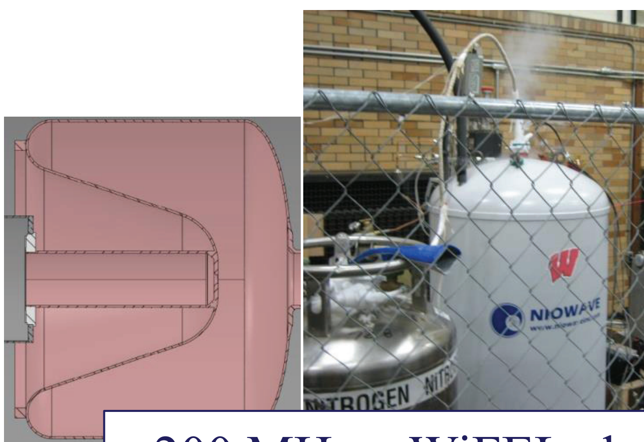
NIOWAVE
www.niowaveinc.com



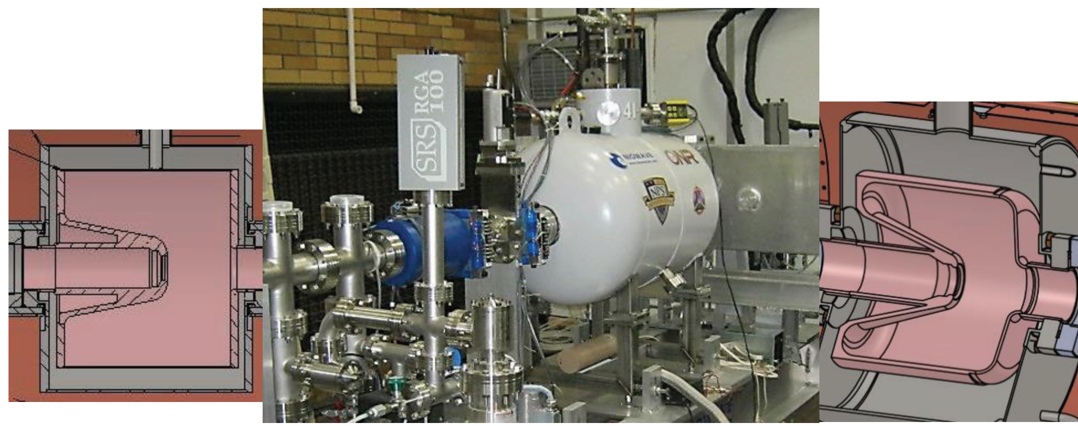
112 MHz –
e^- source for
Coherent Electron
Cooling (RHIC)

Since 2008, Niowave has built, tested and delivered four SRF electron guns

- all have produced electron beams with photocathodes (energy range 0.5 to 2 MeV)
- prototype field-emitter tested at Niowave



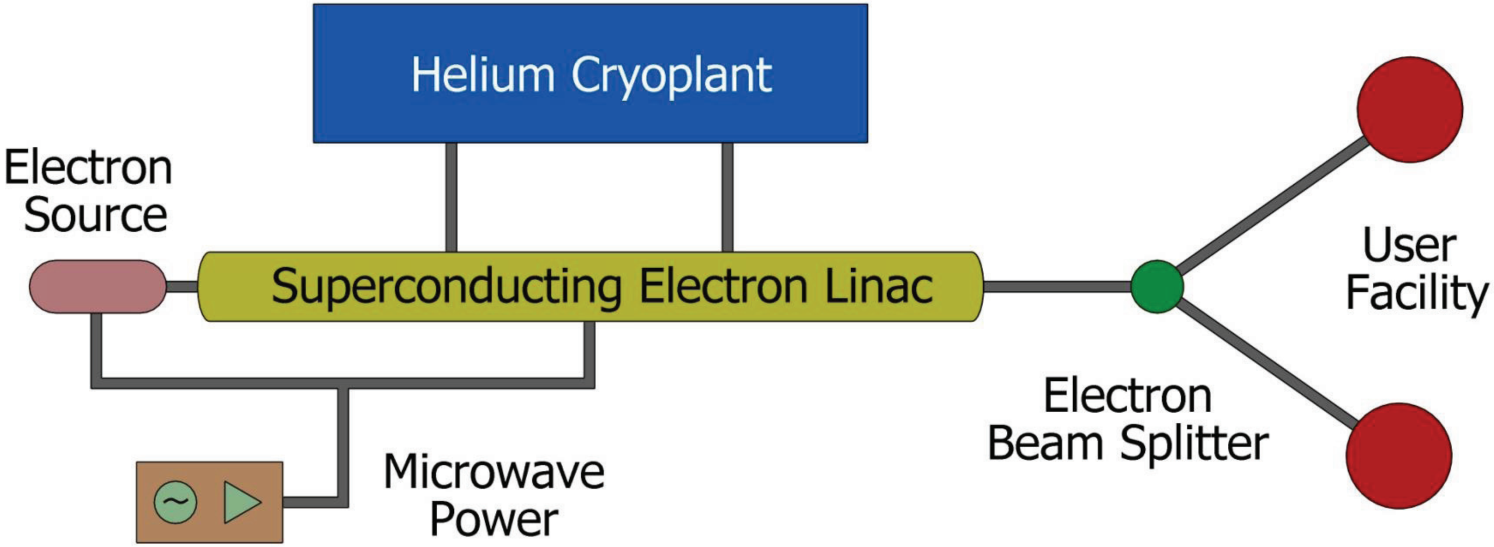
200 MHz – WiFEL electron gun (University of Wisconsin)



500 MHz and 700 MHz – Navy FEL electron guns (Naval Postgraduate School and Los Alamos)

Superconducting Turnkey Electron Linacs

NIOWAVE
www.niowaveinc.com



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**

Frequency & Temperature

NIOWAVE
www.niowaveinc.com

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

frequency

superconducting transition temperature

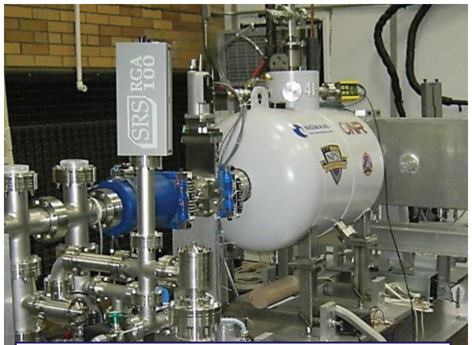
$$R_{BCS} \propto f^2 \exp\left(-\frac{T_c}{T}\right)$$

operating temperature

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

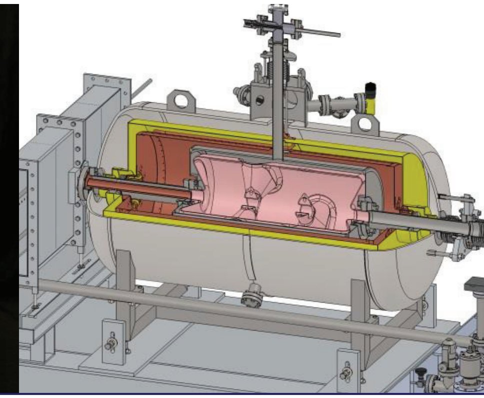
Integrated Systems for 4 K Superconducting Electron Linacs

NIOWAVE
www.niowaveinc.com



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 Multi-Spoke Cavities

NIOWAVE
www.niowaveinc.com

- 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

Revolutionary Research . . . Relevant Results

RF Power Sources

- Solid-state supplies to 5 kW
  – 350 MHz, 700 MHz, etc.
- Tetrode amplifer to 60 kW
  – 300 – 350 MHz
  – CW operation
  – 15 dB gain
  – 70% anode efficiency

Commercial 4 K Refrigerators

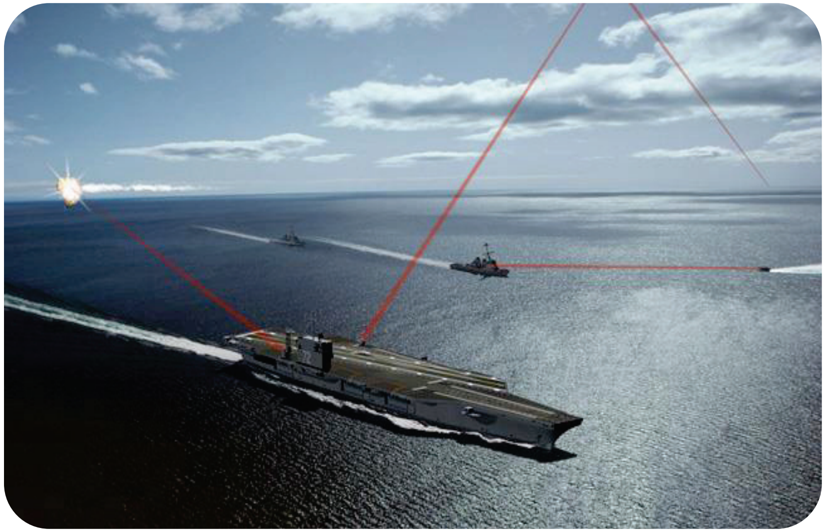
NIOWAVE
www.niowaveinc.com

- 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

Commercial Uses of Superconducting Electron Linacs

NIOWAVE
www.niowaveinc.com



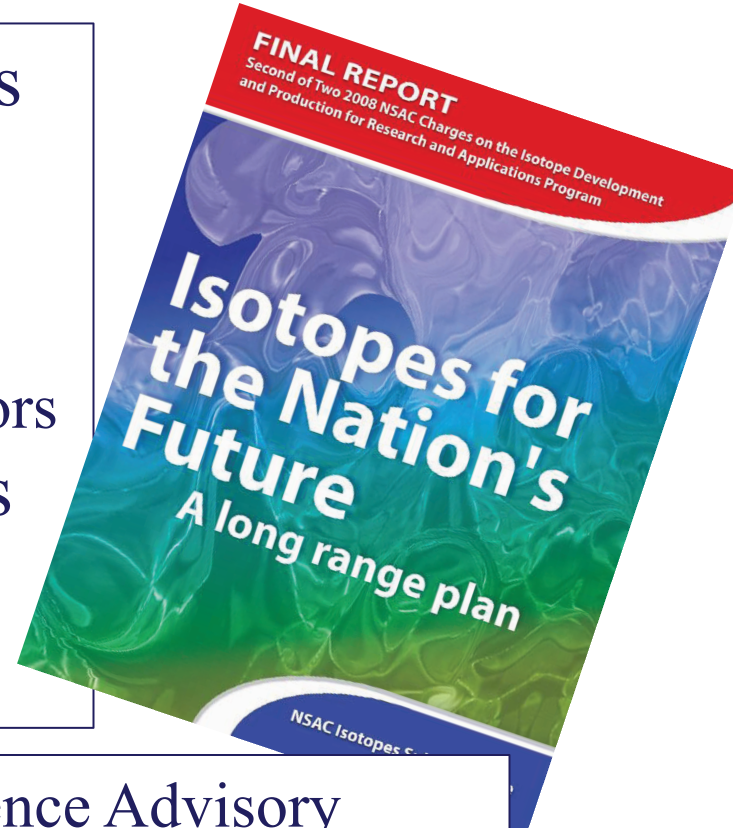
Free Electron Lasers

Radioisotope Production

High Power X-Ray Sources

Background and National Need

- Majority of medical radioisotopes used today come from:
  - foreign suppliers
  - parasitic generation in large government accelerators and reactors
- Nuclear medicine community has recommended dedicated accelerators for over 15 years



DOE Nuclear Science Advisory Committee on Isotopes (2009) list of compelling opportunities includes **"dedicated accelerator facilities for isotope production."**

Superconducting Electron Linac Radioisotope Production

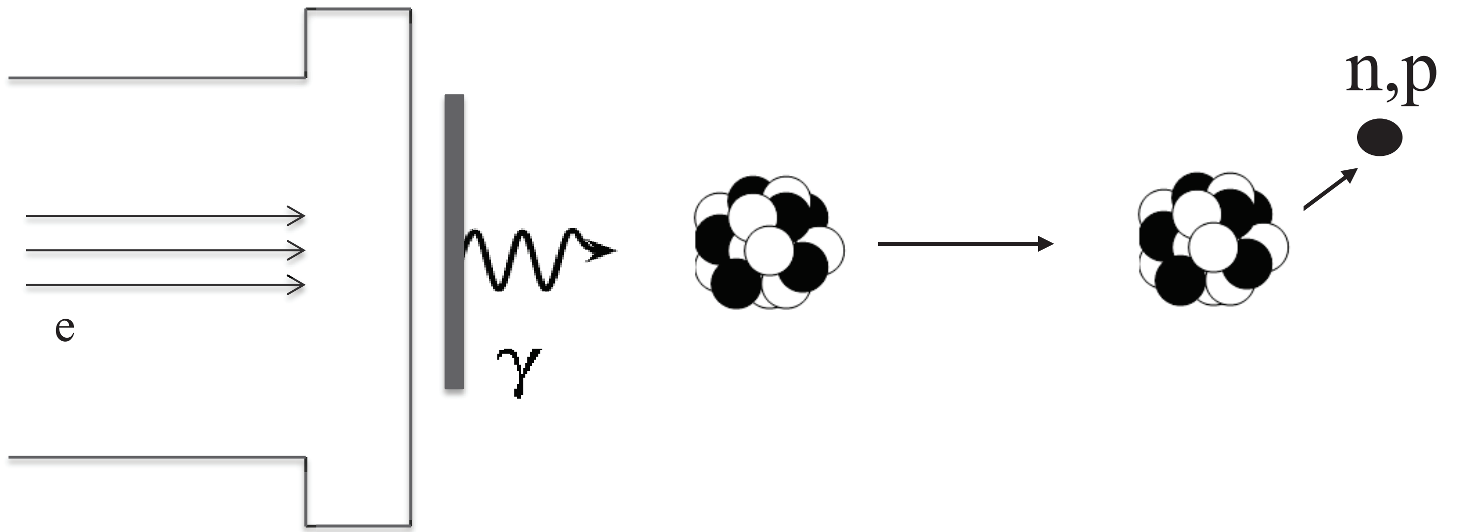
NIOWAVE
www.niowaveinc.com

We are building a **40 MeV, 2.5 mA, 100 kW** superconducting linac for isotope production:

- Photonuclear production
  - (γ,p)
  - (γ,n)
- Photofission
  - (γ,f)

Photonuclear Production

NIOWAVE
www.niowaveinc.com



Electrons are accelerated

Electrons brake and produce bremsstrahlung photons

Photons cause photonuclear reactions

Operating linac at 100 kW requires liquid metal cooling for beam window, which also serves as a converter as well as target cooling.

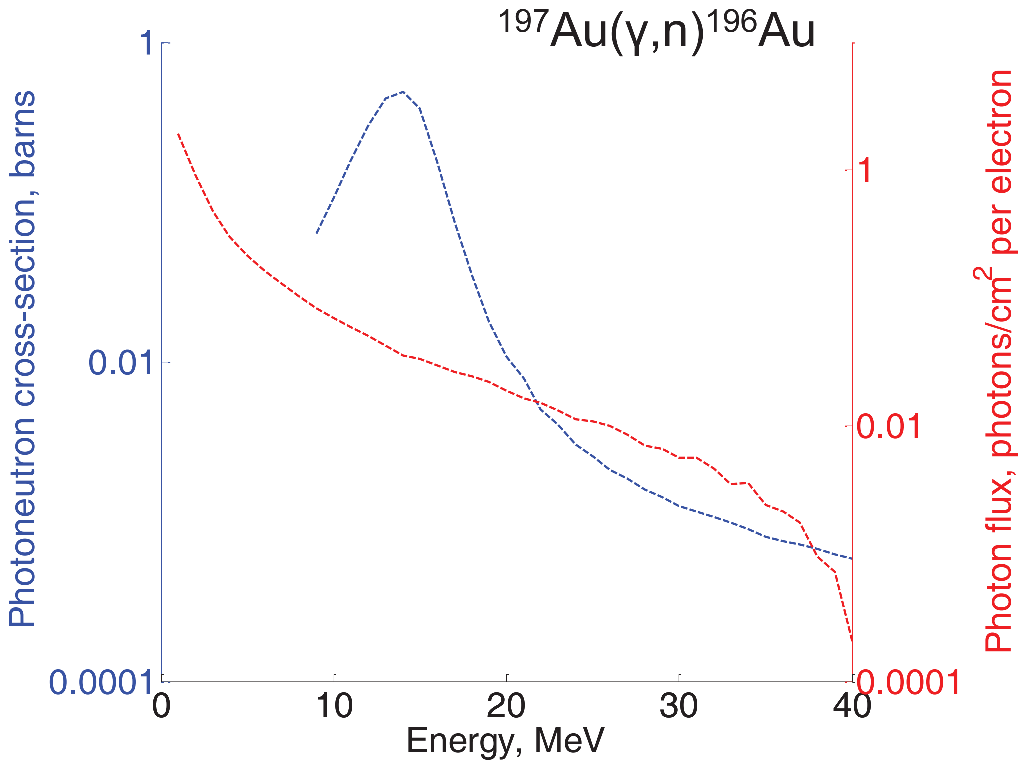
Production Yield

NIOWAVE
www.niowaveinc.com

$$A(t) = N \int_{E_{th}}^{E_{max}} \sigma(E) \cdot \varphi(E, \vec{r}) dE d^3\vec{r} \cdot (1 - e^{-\lambda t})$$

Yield depends on:

- Energy of the electron beam
- Current
- Reaction cross-section
- Mass and geometry of the target
- Efficiency of the converter
- Time of irradiation



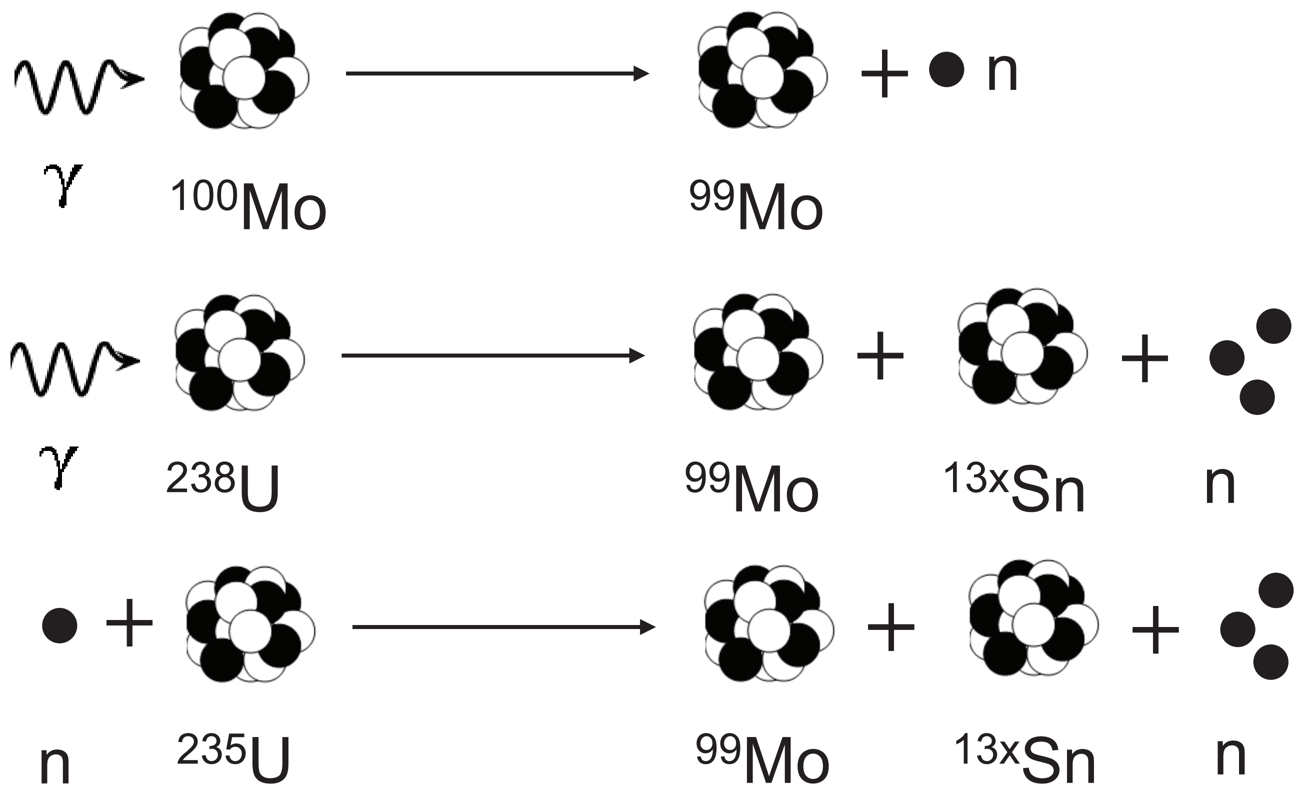
Examples of Linac-Produced Isotopes and Typical Yields

NIOWAVE
www.niowaveinc.com

Reaction	Typical yield (assuming 100 kW and 10 g natural target), Ci/week	Common applications
Medical Isotopes		
$^{68}Zn(\gamma,p)^{67}Cu$	≈ 2	Cancer treatment/diagnostics, monoclonal antibodies, radioimmunotherapy, SPECT or PET.
$^{226}Ra(\gamma,n)^{225}Ra \rightarrow ^{225}Ac$	≈ 15	Monoclonal antibody attachment used for cancer treatment; parent of ^{213}Bi.
Industrial isotopes		
$^{55}Mn(\gamma,n)^{54}Mn$	≈ 5	Is used to predict the behavior of heavy metal components in effluents from mining wastewater.
$^{89}Y(\gamma,n)^{88}Y$	≈ 5	Can be used as a spikant to map out the fractures during directional drilling and hydraulic fracturing in the oil and gas industry.

Linac-Based Production of ^{99}Mo

NIOWAVE
www.niowaveinc.com



- North America demand: 6,000-7,000 six-day Ci/week
- World demand: 10,000-12,000 six-day Ci/week

Free Electron Lasers

NIOWAVE
www.niowaveinc.com

- High power tunable lasers at wavelengths not otherwise available
  - THz to IR
  - Electron energy 2-40 MeV
  - Bunch compression (ballistic and magnetic)
  - Recover unused electron energy improves efficiency

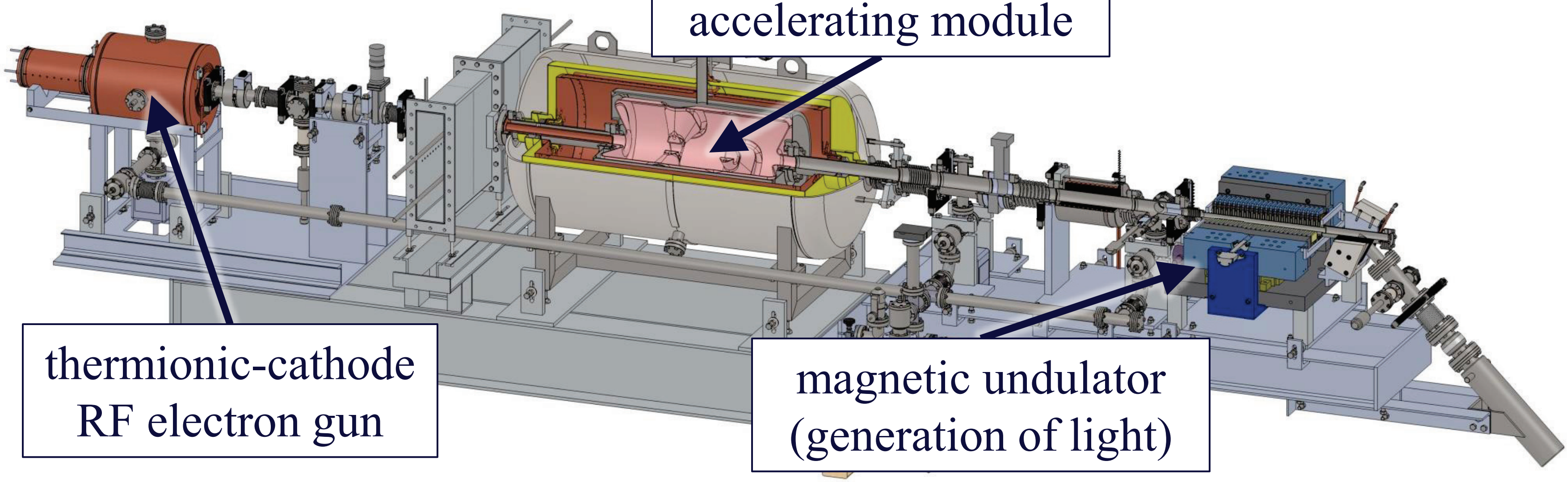
- 2012 National Research Council
  Optics & Photonics, Essential Technologies for Our Nation

Commercial 4 MeV FEL

NIOWAVE
www.niowaveinc.com

Niowave/NPS/STI have built a 4 MeV free electron laser

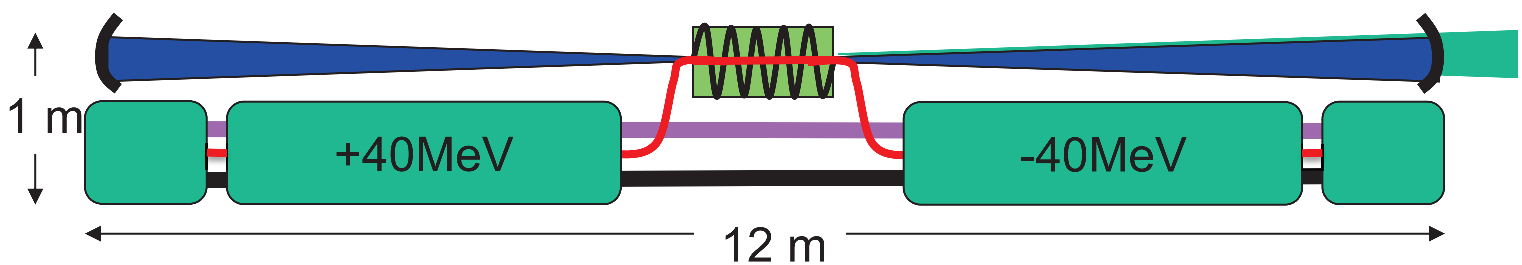
- installed in shielded tunnel at Niowave
- preparing for first tests in a super radiant THz mode
- T. Grimm, et al, “4K Superconducting Linac for Free Electron Lasers,” FEL2013, New York, (2013) TUPSO23



Navy Free Electron Laser

NIOWAVE
www.niowaveinc.com

- Part of long term Directed Energy Program
  - Laser and Rail Gun
  - High power lasers (SSL and FELs)

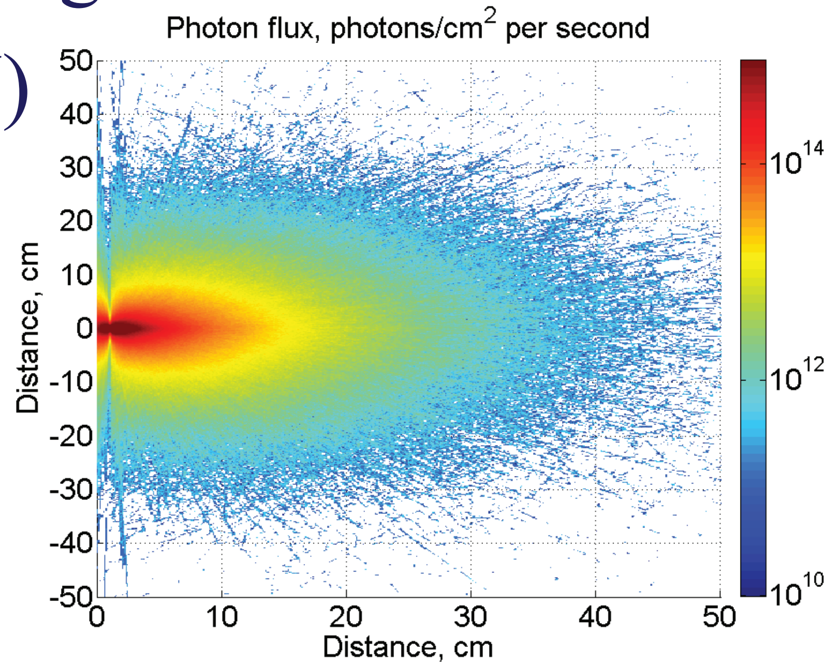


- Megawatt class FEL
  - 350 MHz multi-spoke structures at 4 K

Revolutionary Research . . . Relevant Results

X-Ray Sources

- Superconducting electron linacs compete with:
  - Co-60 (high activity/MCi)
  - Copper electron accelerators (e.g. Rhodatron)
- Liquid metal converter/target
- Applications (2-20 MeV)
  - Materials processing
  - Active interrogation
  - Sterilization



40 MeV, 100 kW electron beam incident on 4 mm of Pb-Bi and graphite slab behind it

Summary

NIOWAVE
www.niowaveinc.com

- Superconducting electron linacs are a prosperous and growing high-tech industry
  - Quarter wave guns
  - Medical radioisotopes
  - Free electron lasers
  - High power x-ray sources
  - Future: fast and thermal neutrons, Compton x-rays, photon activation analysis, wakefield accelerators, ultrafast electron microscopes, etc.
- Similar opportunities for commercial proton and heavy ion linacs are ready to be exploited