4 K Superconducting Linacs for Commercial Applications

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Niowave, Inc.
Lansing MI

North American Particle Accelerator Conference
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Chicago, IL, USA

Talk Outline

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- Advantages of SRF Linacs
- High-power SRF Linac Technology
  - Two-pass accelerator layout
  - Accelerator Subsystems
- Commercial Applications
  - High-power x-ray sources
    - Active Interrogation
    - X-ray Sterilization
    - Positron Sources
  - High-flux neutron sources
  - Medical and Industrial Radioisotopes
  - Free-electron lasers

Why Superconducting?

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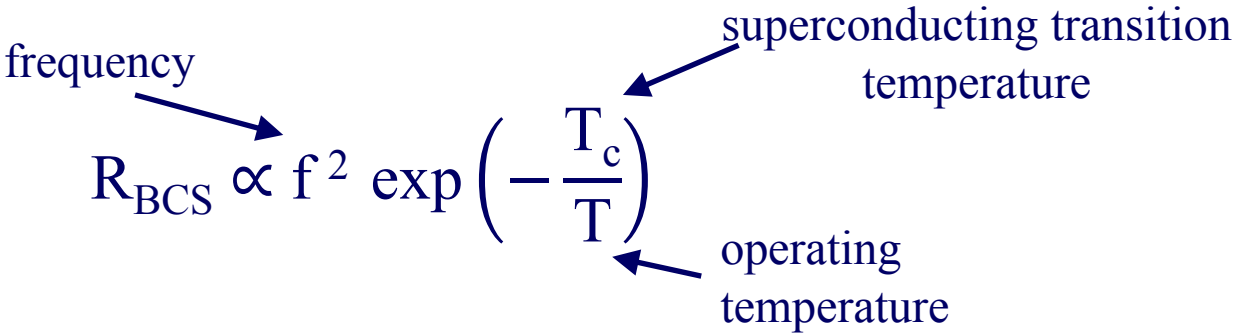
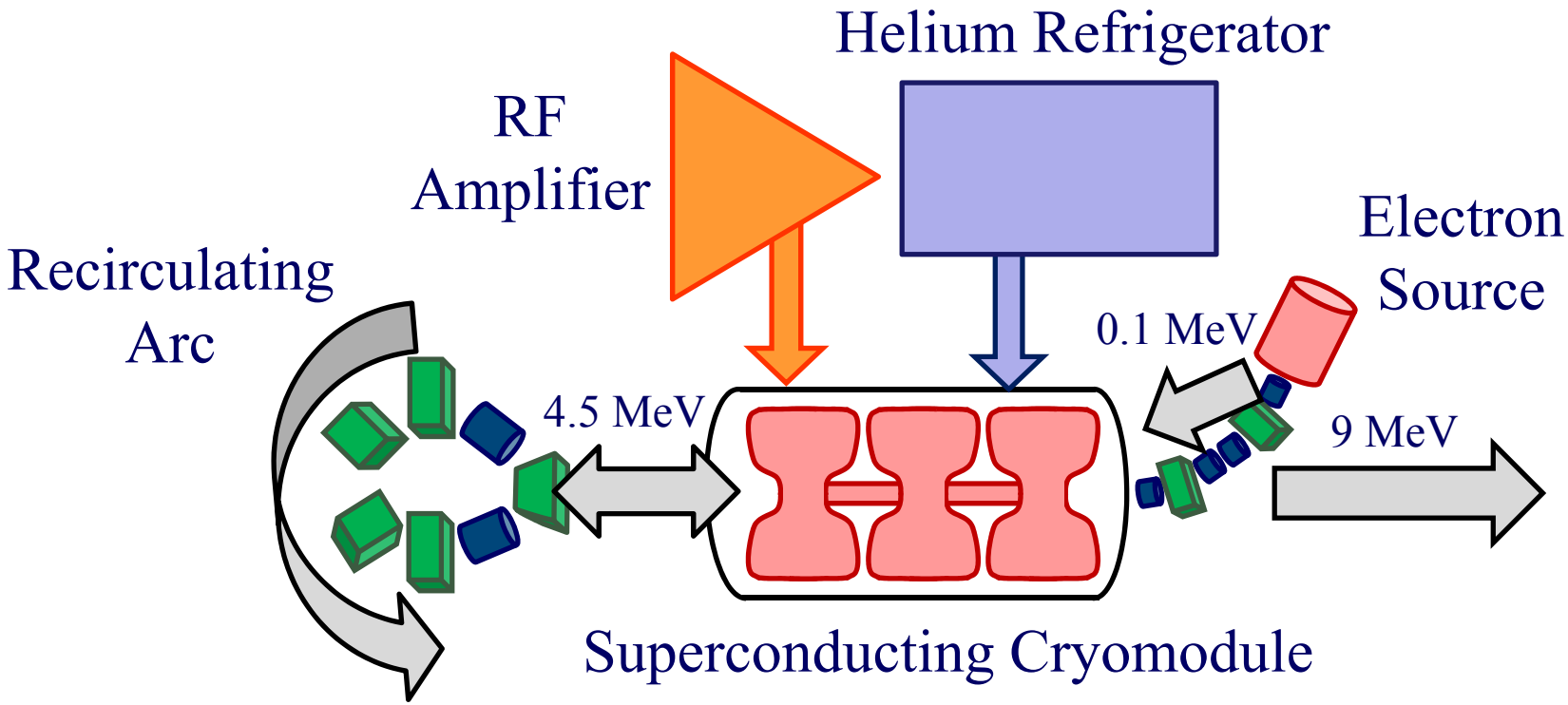
- 10^6 lower surface resistance than copper
  - Most RF power goes to electron beam
  - CW/continuous operation at relatively high accelerating gradients >10 MV/m



- For commercial electron linacs the minimum costs for a system occur around:
  - 300-350 MHz (multi-spokes, re-entrant elliptical cells)
  - 4.5 K (>1 atmosphere liquid helium)

Superconducting Electron Linac [1]



Energy	Application
< 9 MeV	Sterilization & Material Processing
9 MeV	Active Interrogation
> 9 MeV	Radioisotope Production

Superconducting Electron Linac [2]

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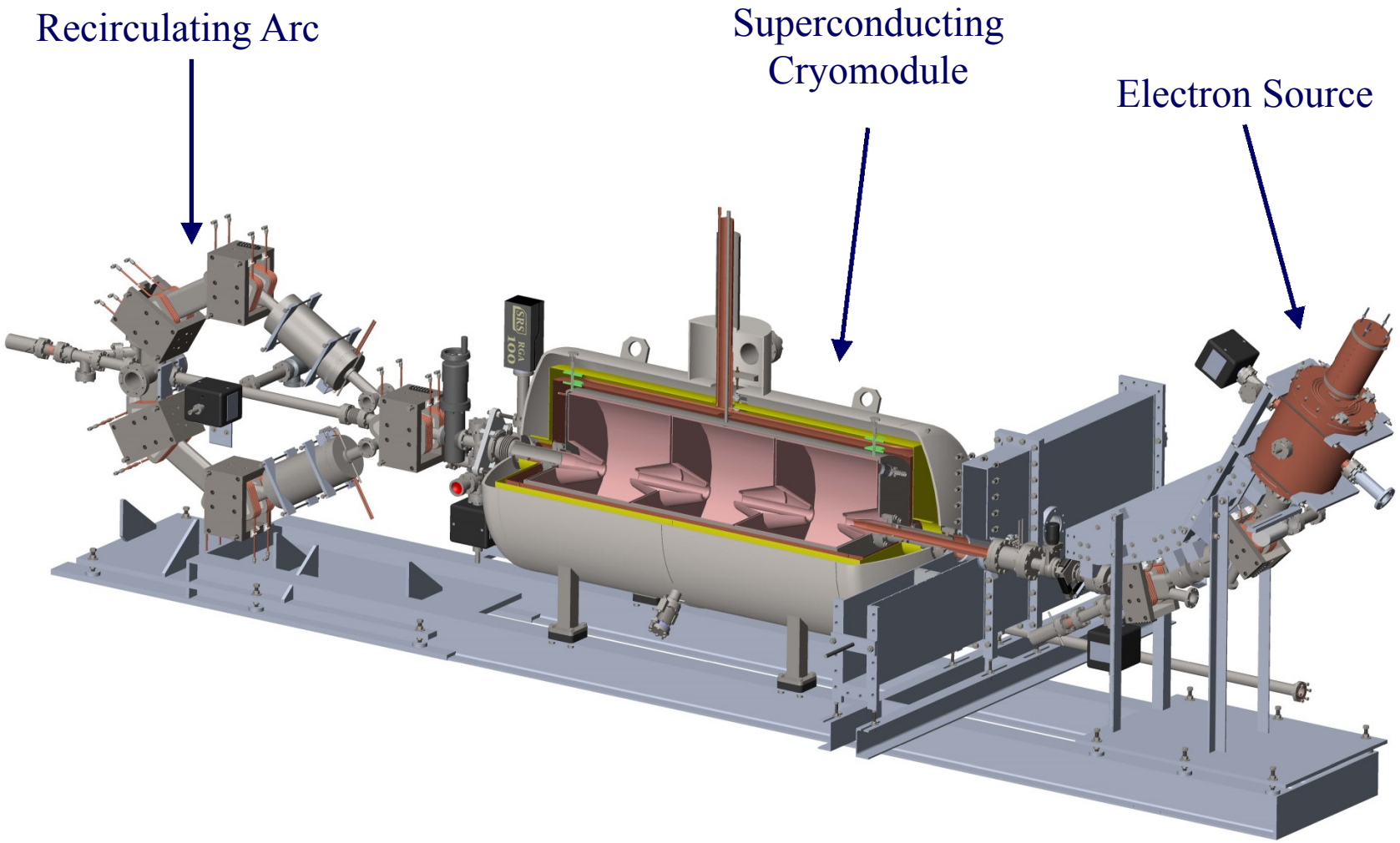

Superconducting Electron Linac [3]

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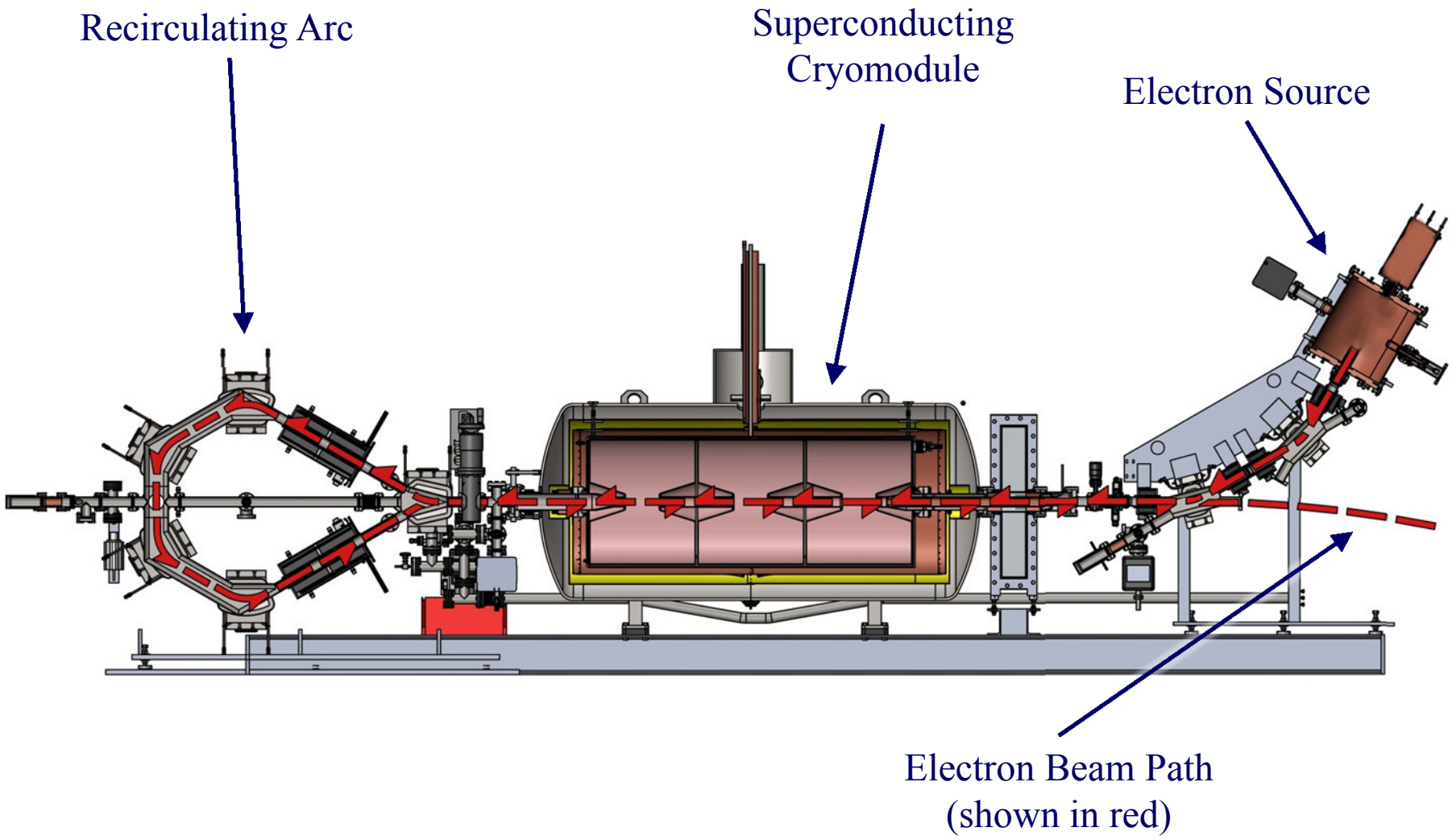

Turnkey Linac Subsystems [1]

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Superconducting cavities
in specialized geometries

Cryomodules

Accelerating Cavity Cryomodules

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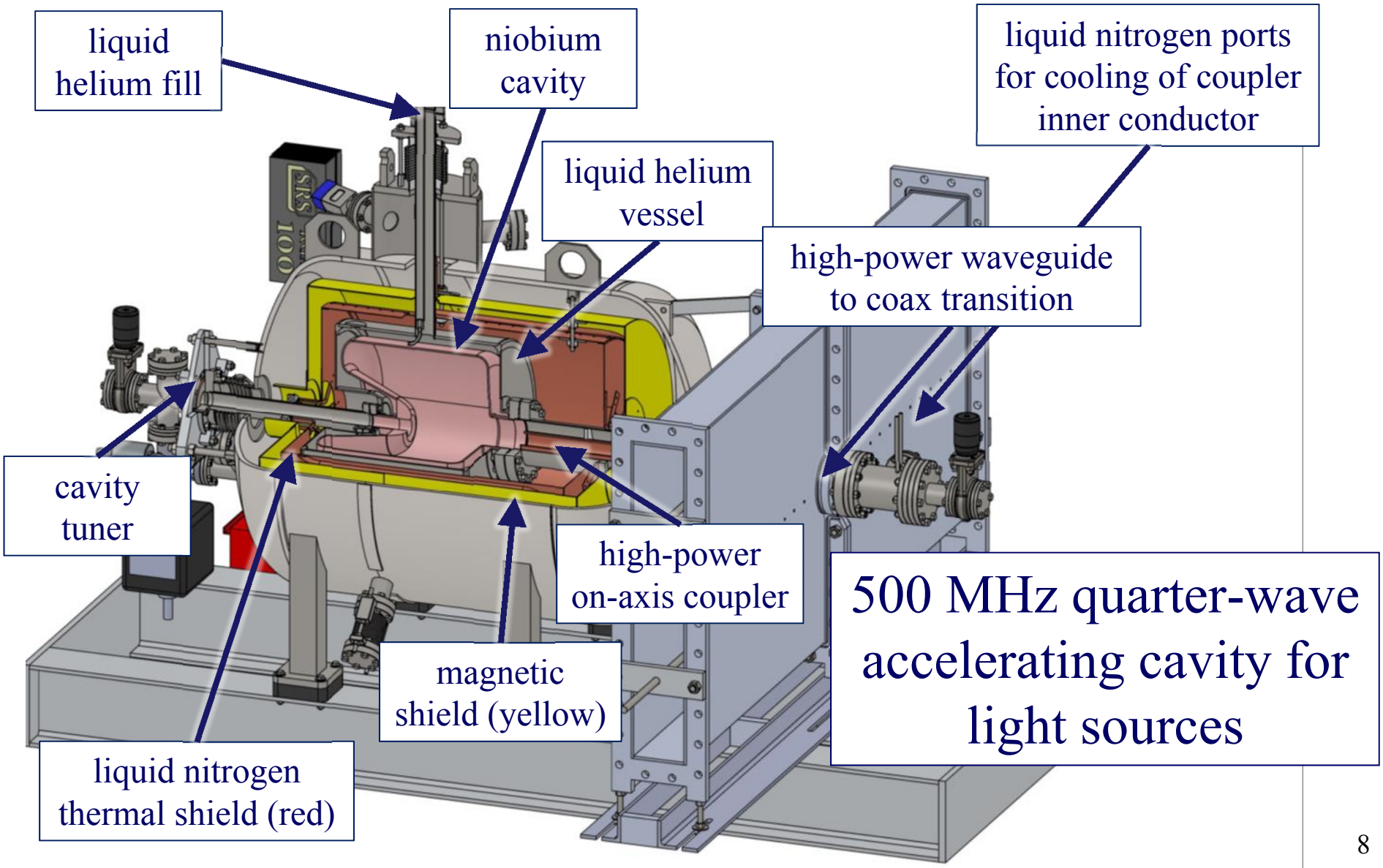

High-power On-axis Couplers for SRF Cavities

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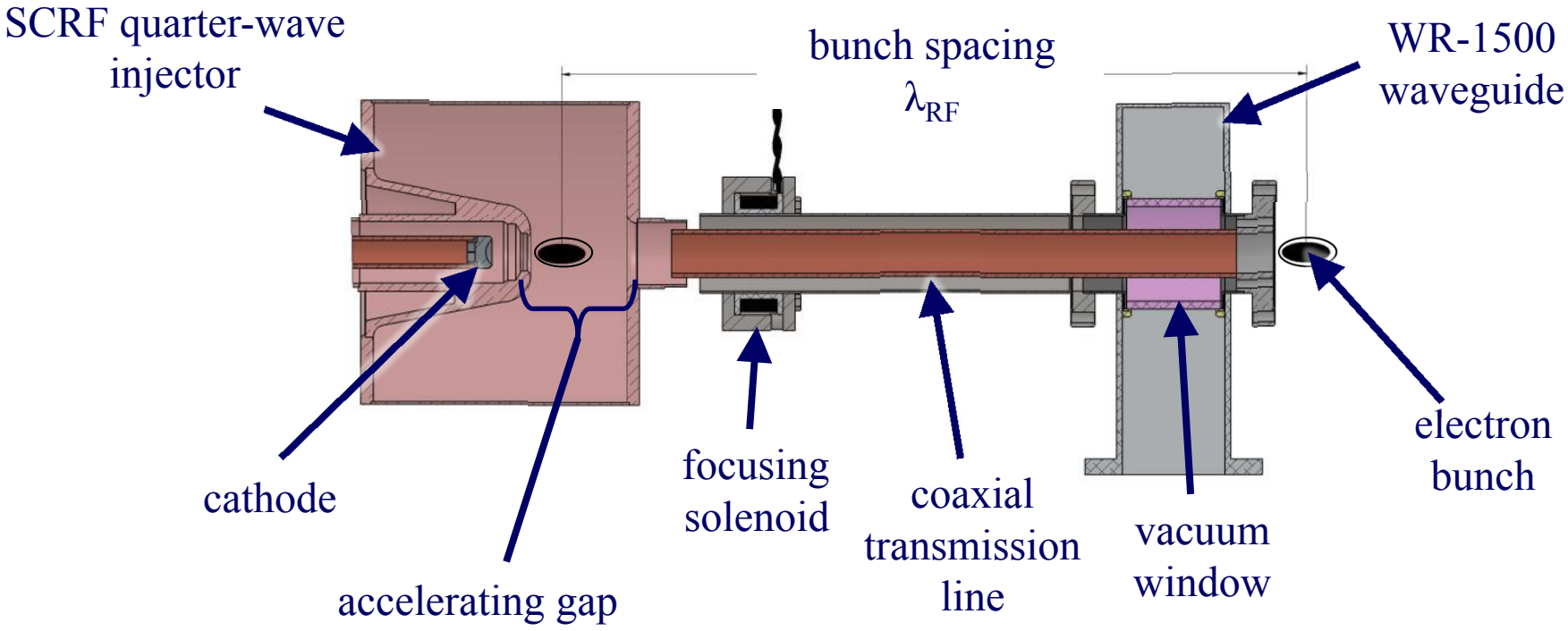

- Advantages of on-axis coupler: symmetric fields, compact, halo at room temperature, strong HOM coupling on air side
- Additional features (not shown in schematic)
  - liquid nitrogen cooling of cathode & inner conductor
  - DC bias for suppression of multipacting

Turnkey Linac Subsystems [2]

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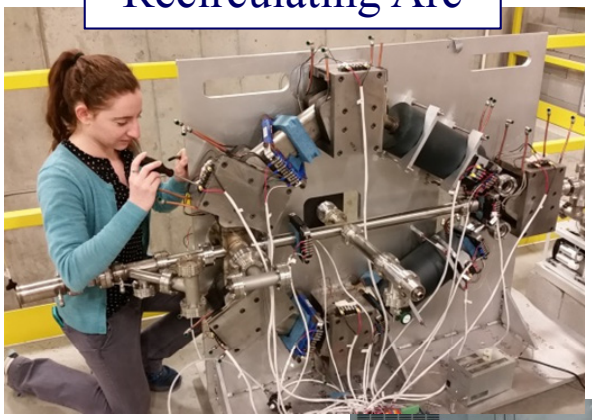
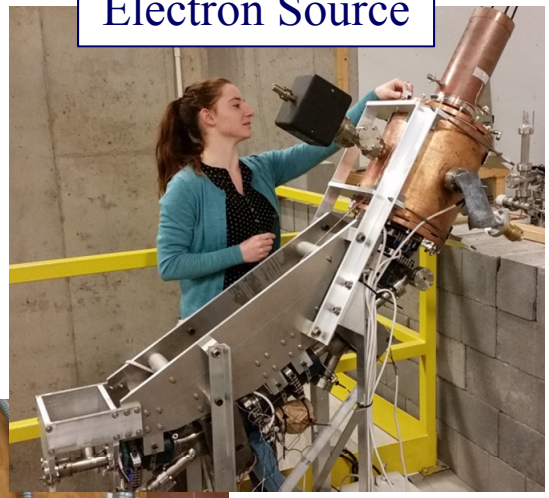
Recirculating Arc



Electron Source



Superconducting Cryomodule

Gated thermionic-cathode RF gun

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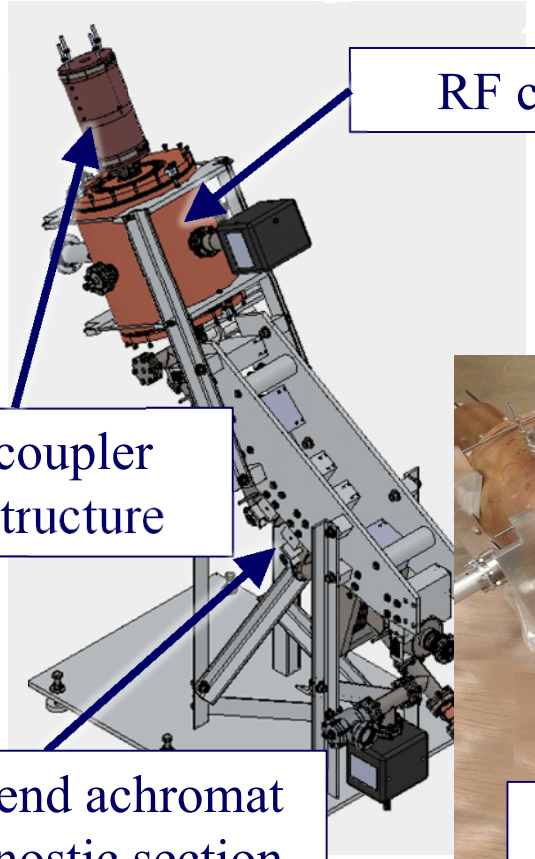
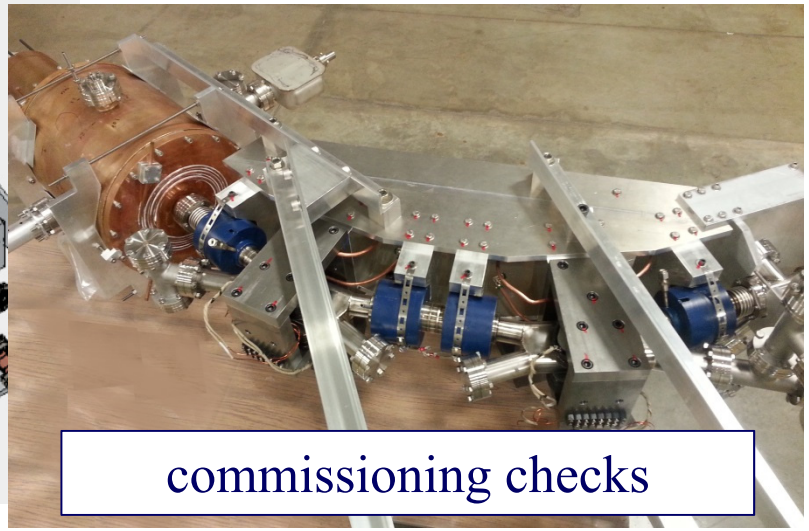
This cavity, now in operation at >10 mA average current, produces ~100 keV beams with ~10 MV/m at the cathode.

resonant frequency	350 MHz
gap voltage	100 kV
power	1 kW
cavity Q	16000
R/Q	560 Ω
geometry factor	79 Ω





Turnkey Linac Subsystems [3]

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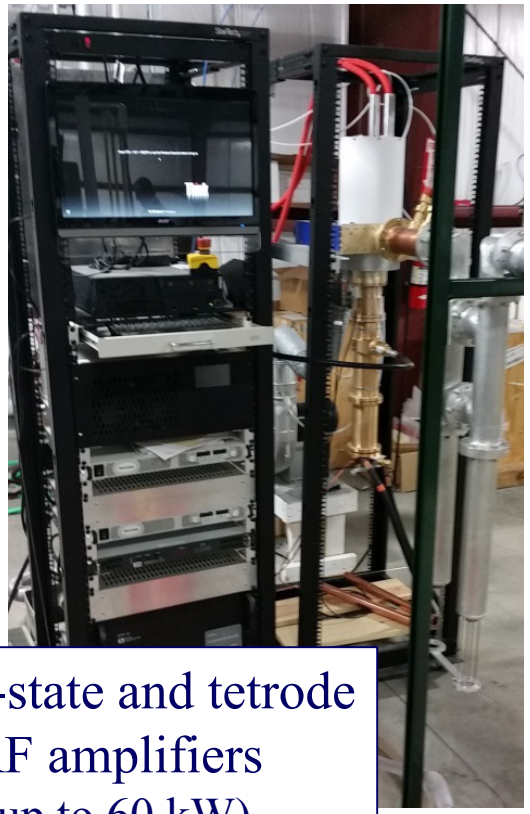
Commercial 4 K refrigerators
(rugged piston-based systems,
100 W cryogenic capacity)

Industrial Accelerator Controls
(Programmable Logic Controllers with
PC interface)



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

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

RF Power Sources

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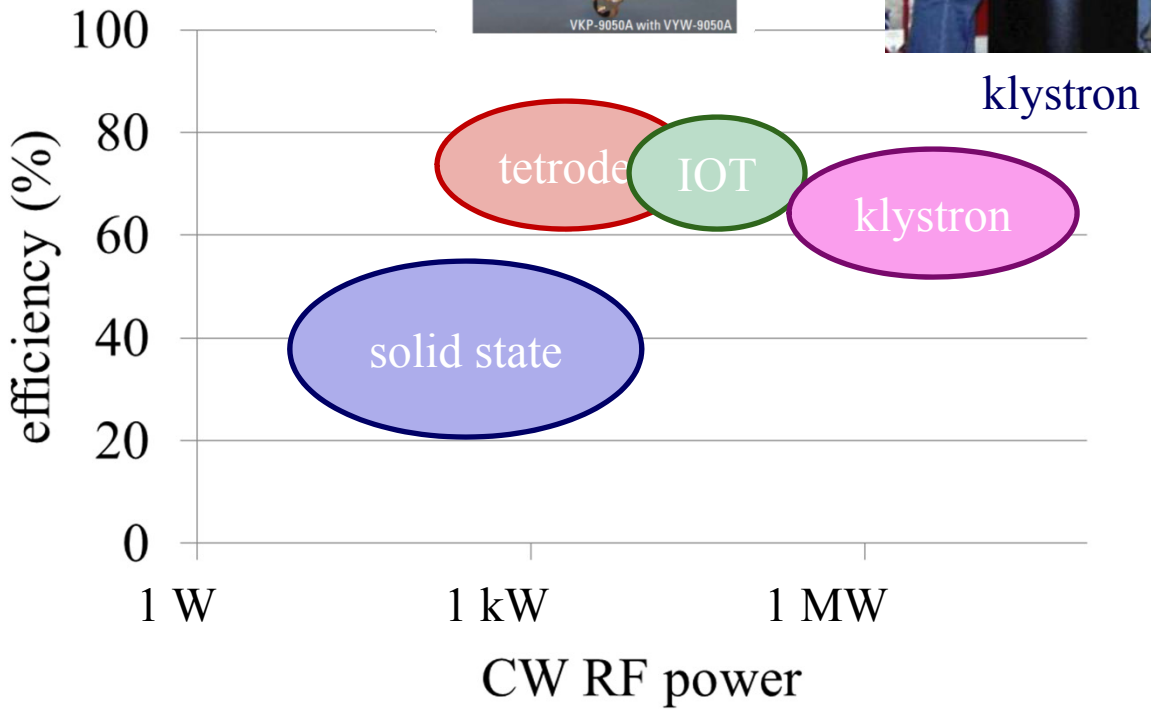
- Solid-state supplies to 5 kW
- Tetrode amplifer to 60 kW
- IOTs to 90 kW
- Klystrons to >1 MW

inductive output tube

klystron

tetrode

solid-state



Commercial Uses of Superconducting Electron Linacs

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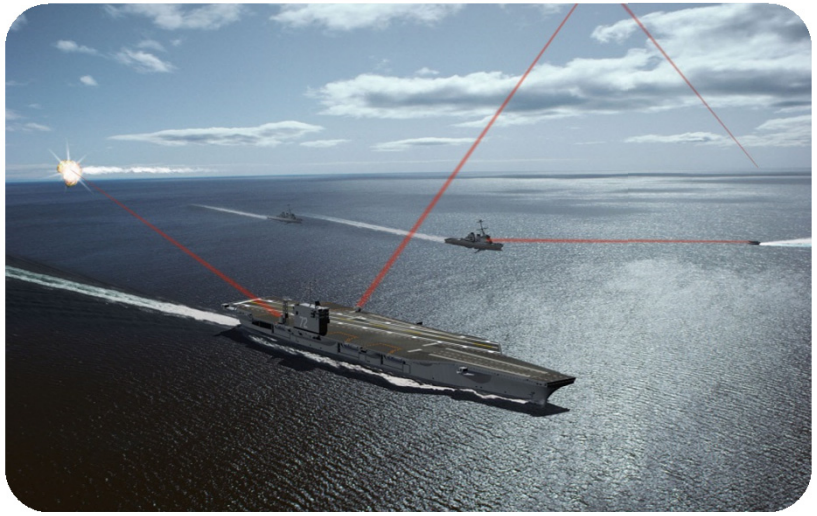
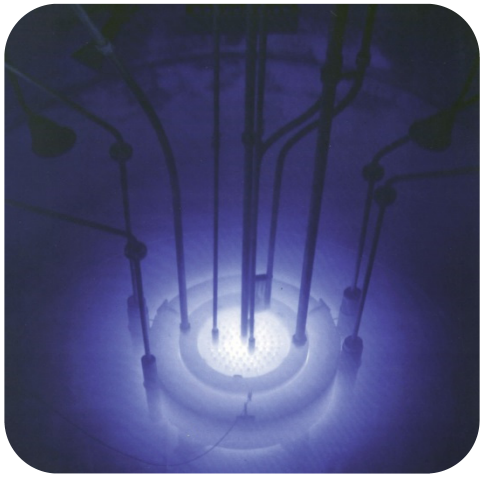
High Power X-Ray Sources

Radioisotope Production



Free Electron Lasers

High Flux Neutron Sources



Commercial Uses of Superconducting Electron Linacs

NIOWAVE
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High Power X-Ray Sources

Superconducting electron beam driving a bremsstrahlung target to make x-rays

- active interrogation (cargo scanning)
- sterilization without radioactive source
- high-flux positron source

Cargo Scanning System

NIOWAVE
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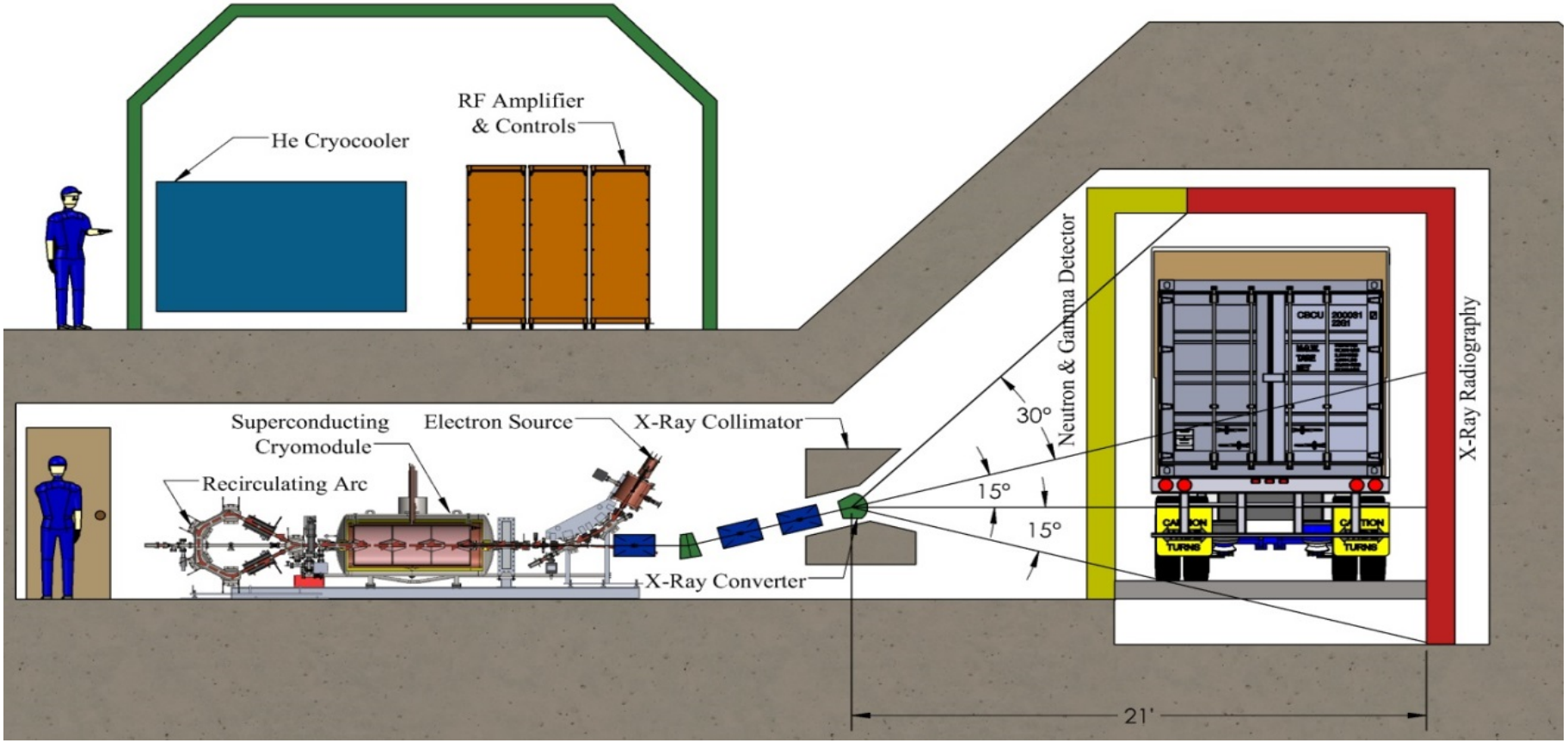
High-energy x-rays photofission nuclear materials

- very specific and low false positive detection
- quick primary scans don't impede flow of commerce



Cargo Scanning Source

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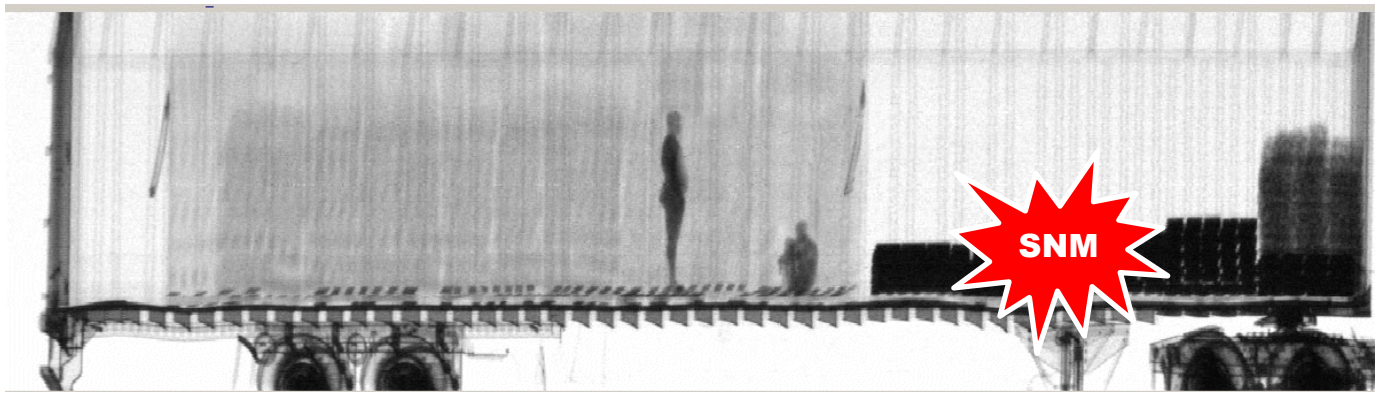
- Superconducting Electron Linac
  - Continuous operation (duty cycles 10-100%)
  - High energy up to activation threshold (9 MeV)
  - High average power (kW and more as shielding allows)
  - Fast power modulation (kHz speed, < 1% - 100%)
  - Small source size for sharp imaging (< 5 mm spot size)
- System cost ~ $1 million per unit



Beam Current Modulation Scheme

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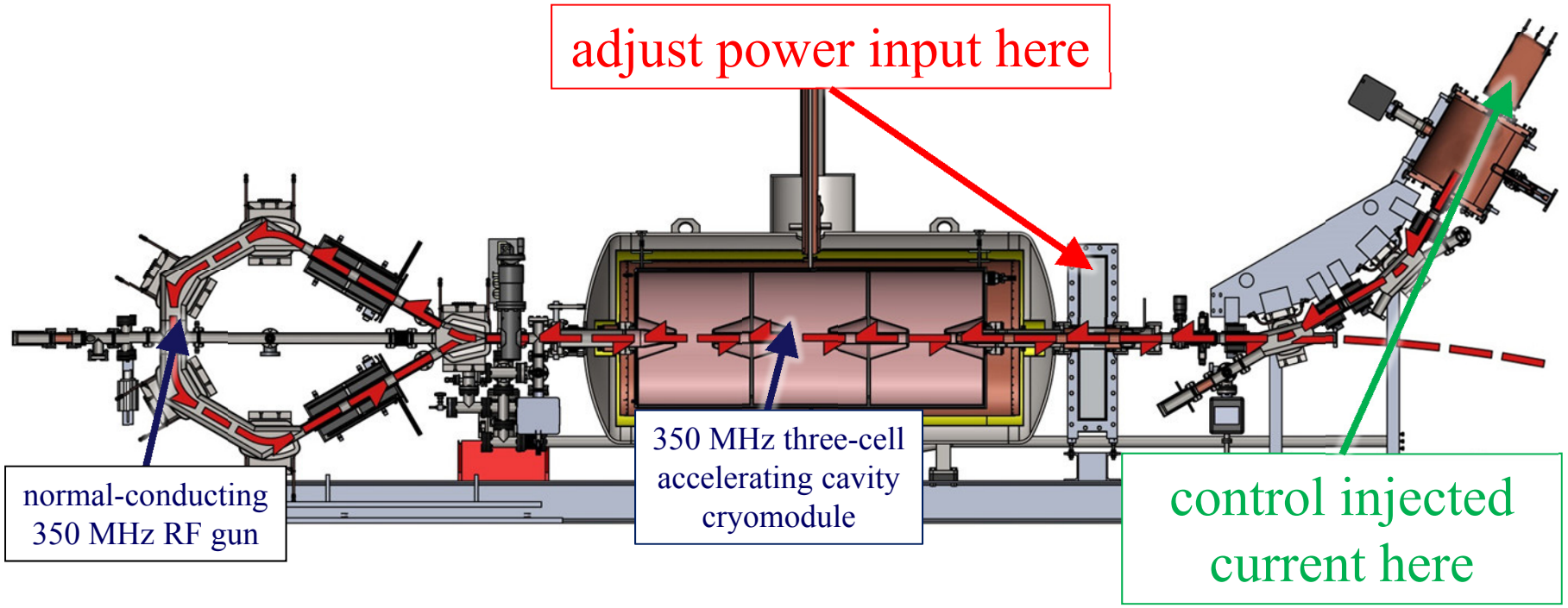

Modulation of the beam involves synchronizing two signals

- Gating signal at the electron source
- Power delivered to the superconducting cavity

High-throughput Sterilization

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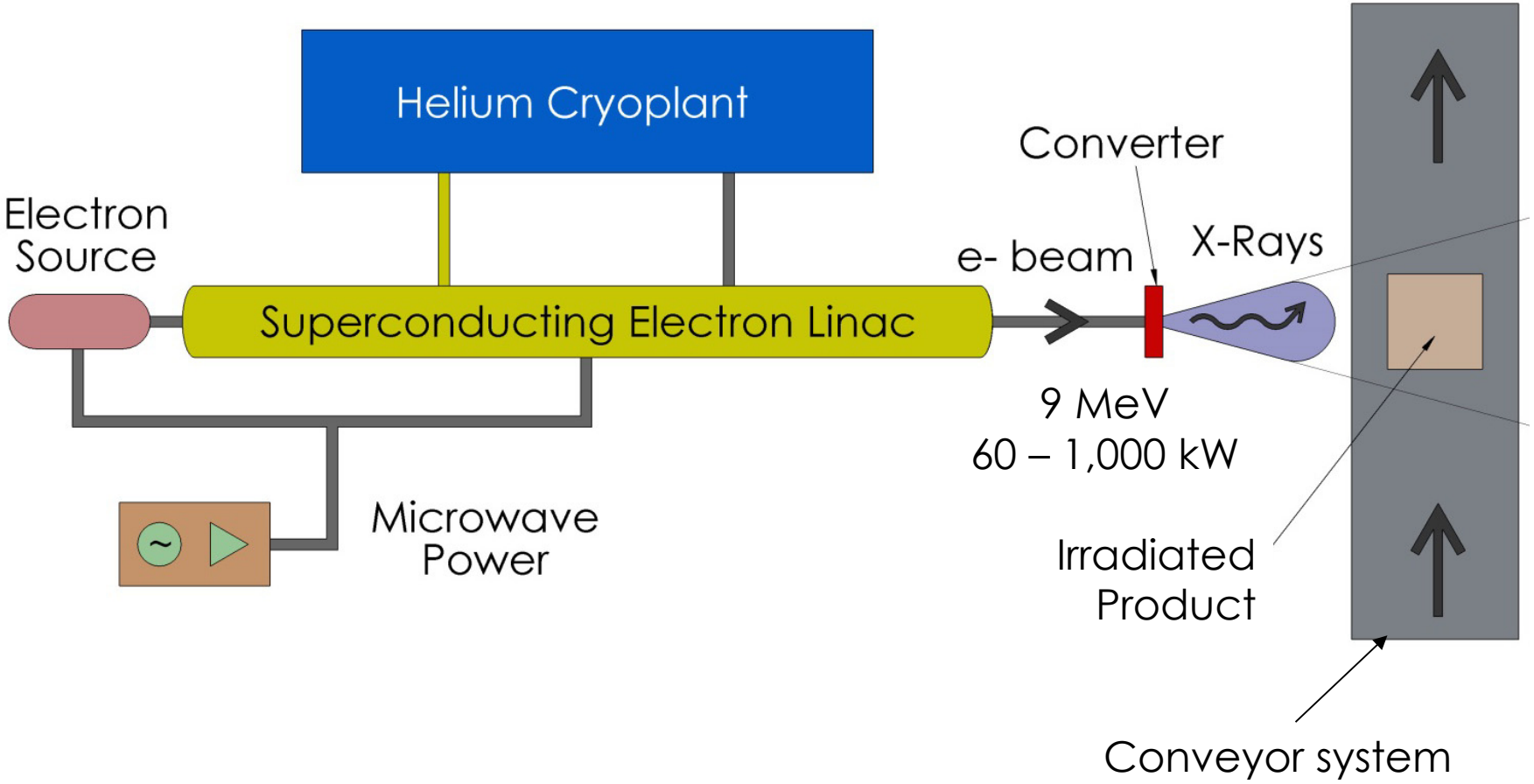
Accelerator-based sterilization eliminates security risk of Co-60 facilities.



Competition

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- Co-60 gamma irradiators 25 kCi to 5 MCi
  - $T_{½}$ = 5.3 years, E_{γ} = 1.1 MeV and 1.3 MeV
  - Increased licensing & safety requirements has led to increased cost of gamma irradiators, especially high activity facilities
  - 1 Ci of Co-60 costs about $2.50

- Electron beams
  - Superconducting linacs 60 kW to 1,000 kW
  - Copper linacs up to 20 kW
  - Rhodotron 100 kW to 700 kW
    - System costs for copper linacs and Rhodotrons ≳ 2x the cost of superconducting electron linacs

Positron Production Conceptual Design

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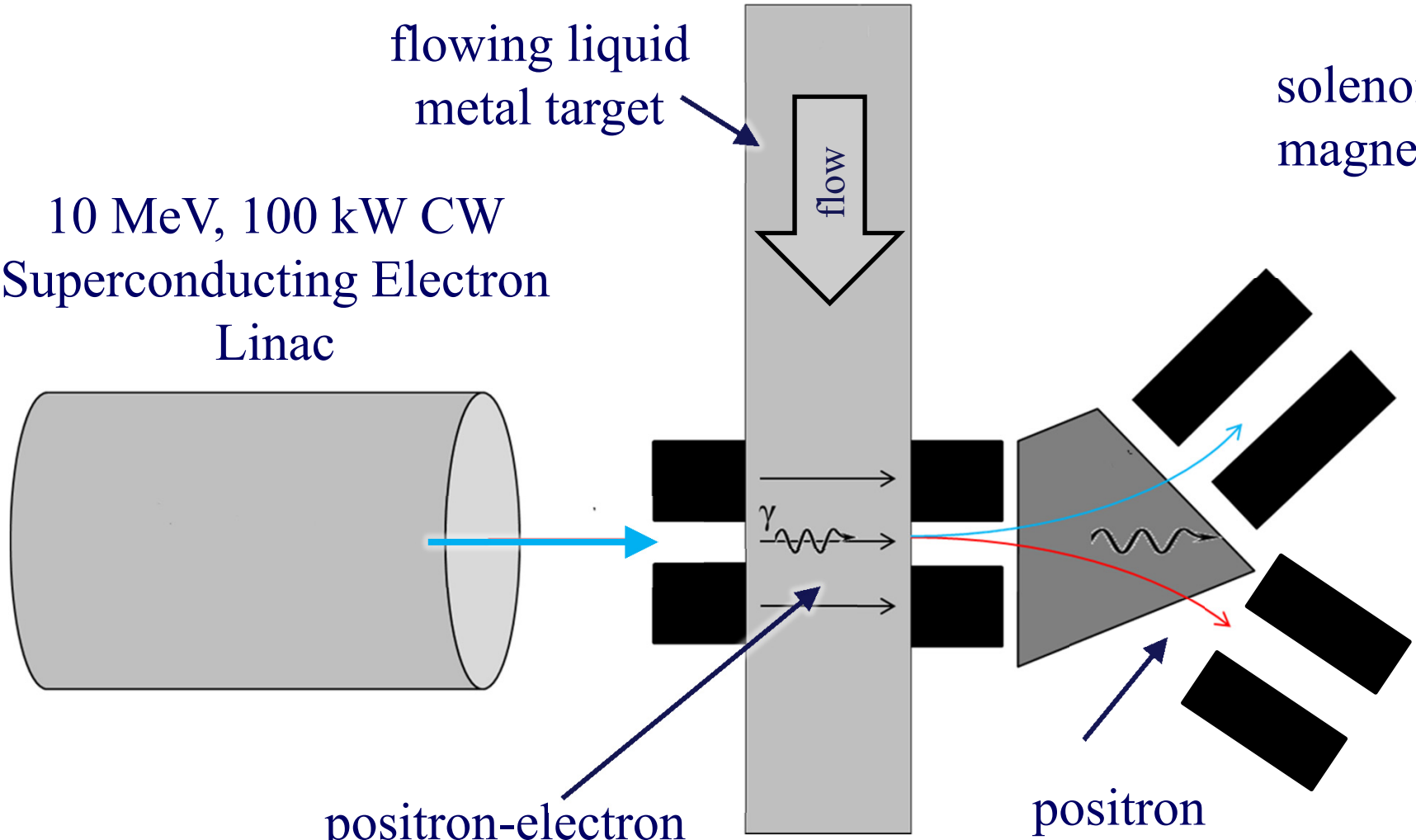

Positron System Hardware

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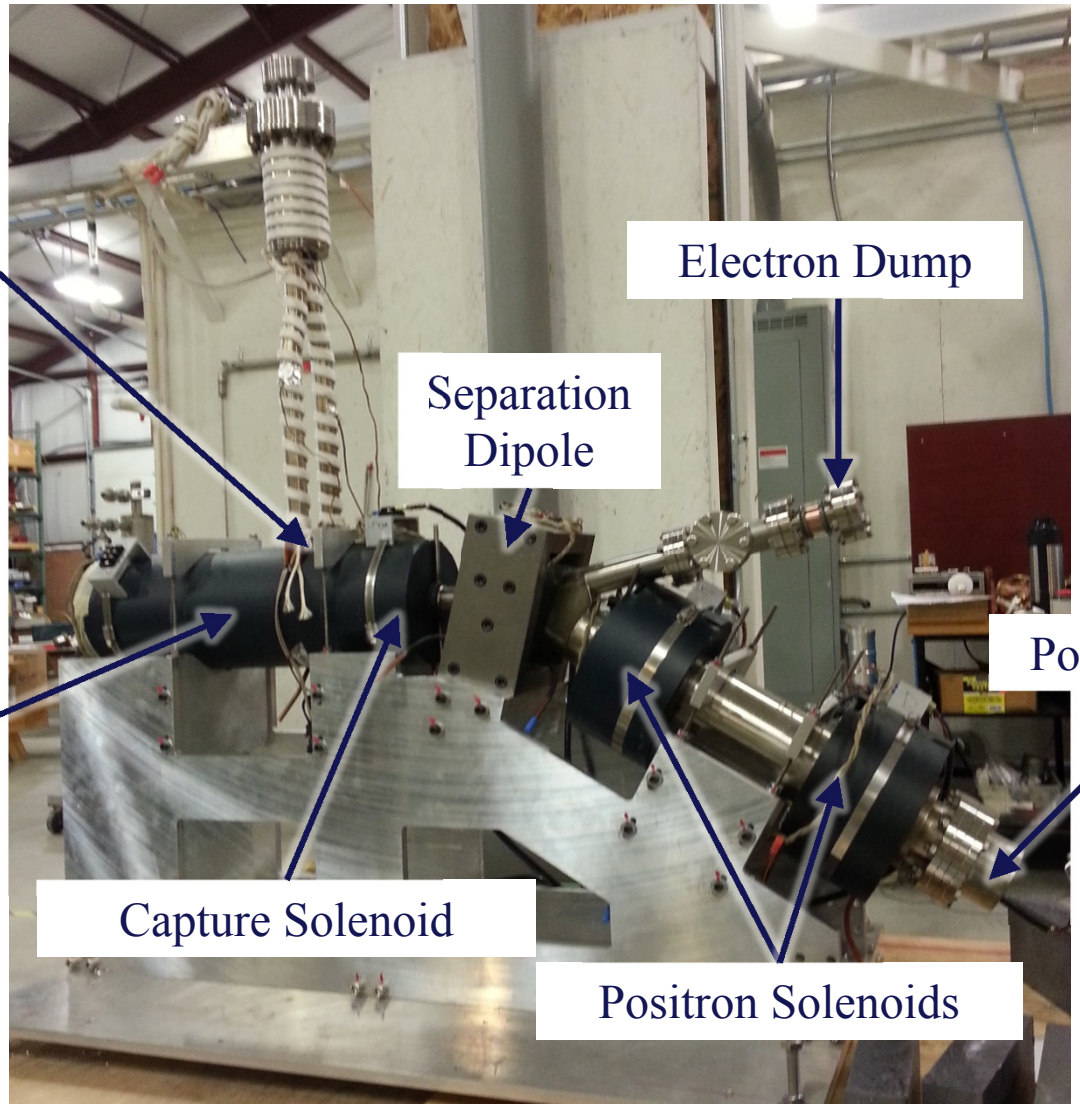

Commercial Uses of Superconducting Electron Linacs

NIOWAVE
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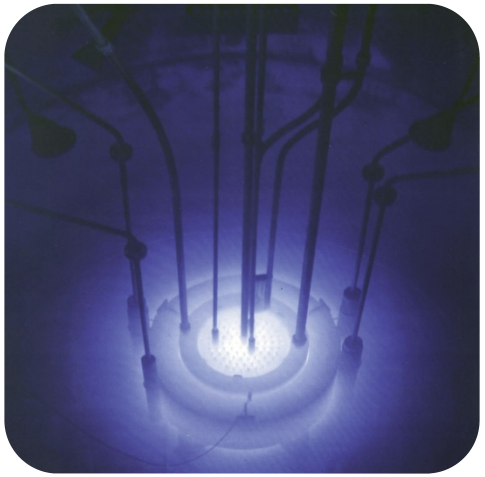
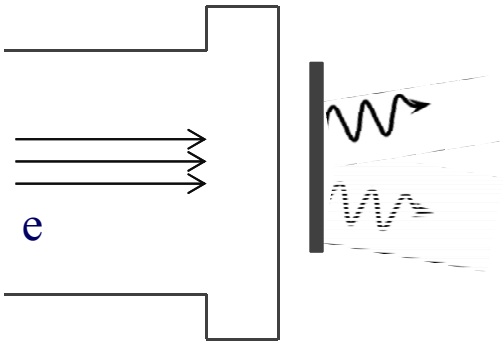
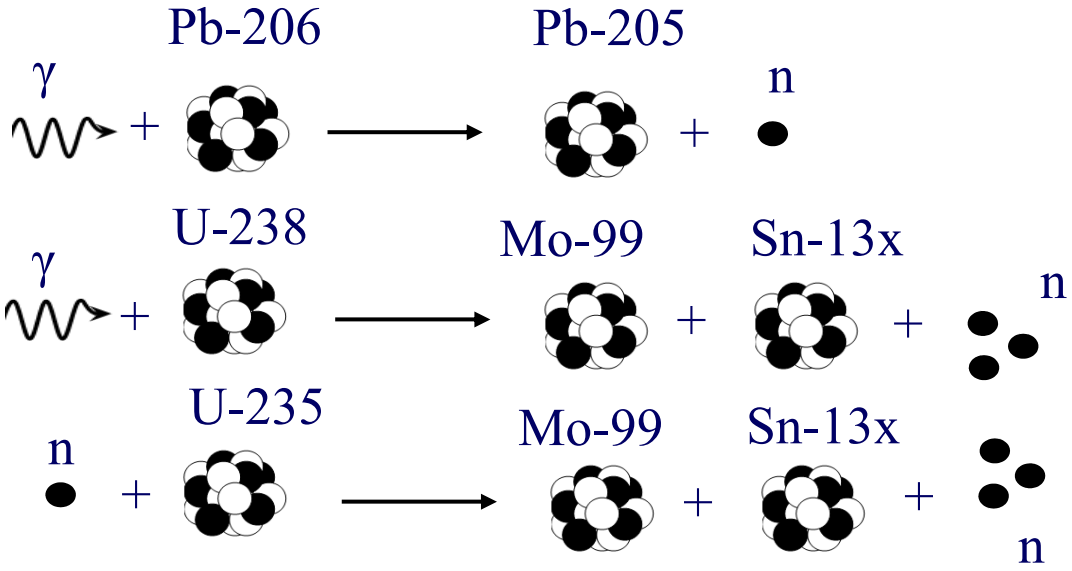
High-flux fast and thermal neutron source without a nuclear reactor

High Flux Neutron Sources



Intense Neutron Source [1]





Electrons are accelerated

Electrons brake and produce photons

Neutrons are generated by:

a) (γ, n) reactions
b) Photo-fissions
c) Neutron-induced fission

Intense Neutron Source [2]

NIOWAVE
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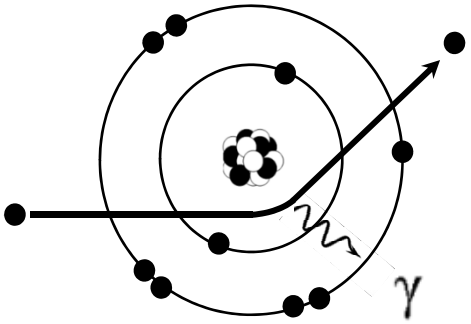
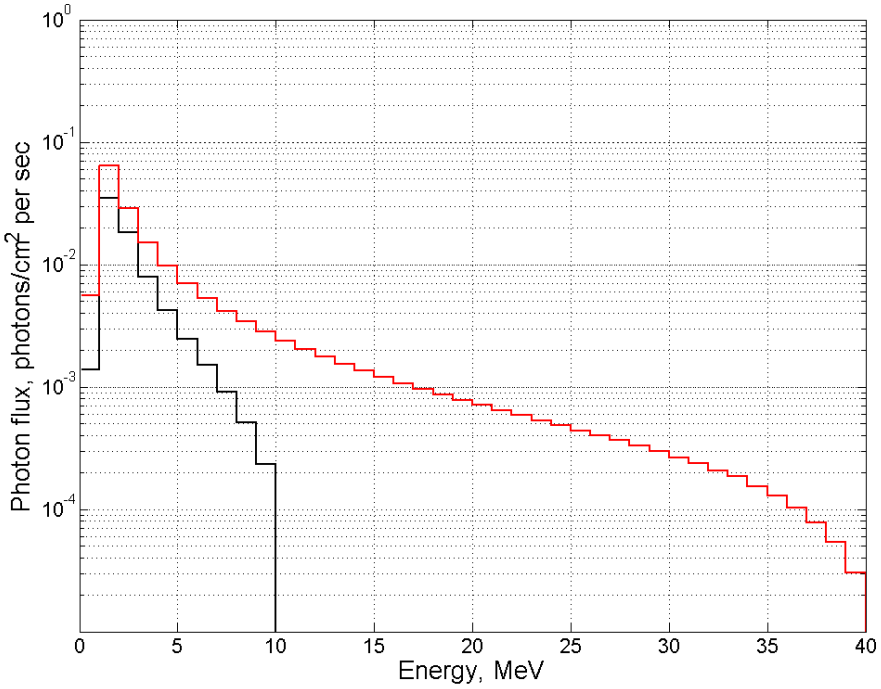
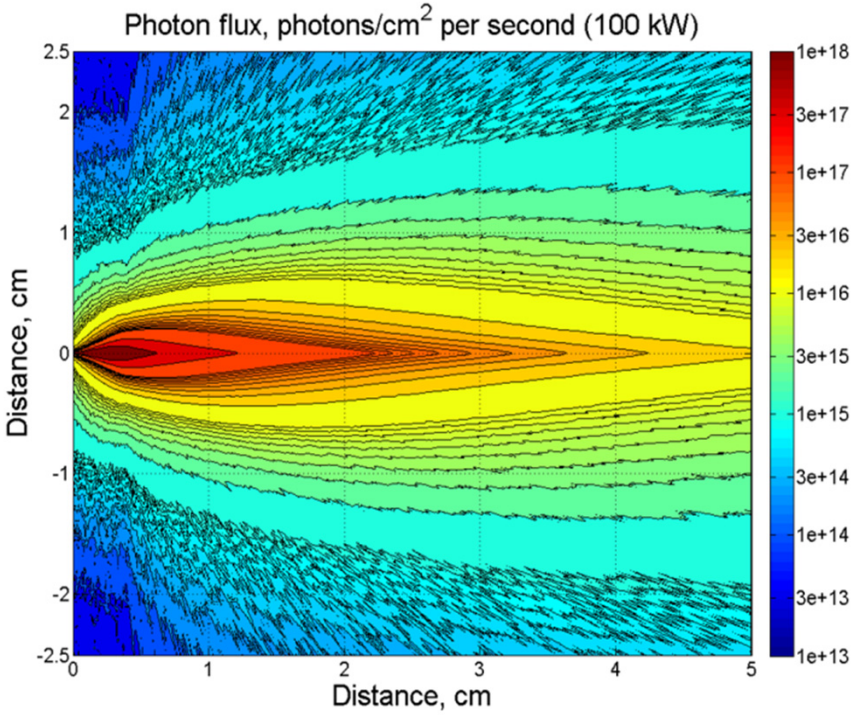
Braking radiation (bremsstrahlung photons):







Intense Neutron Source [3]

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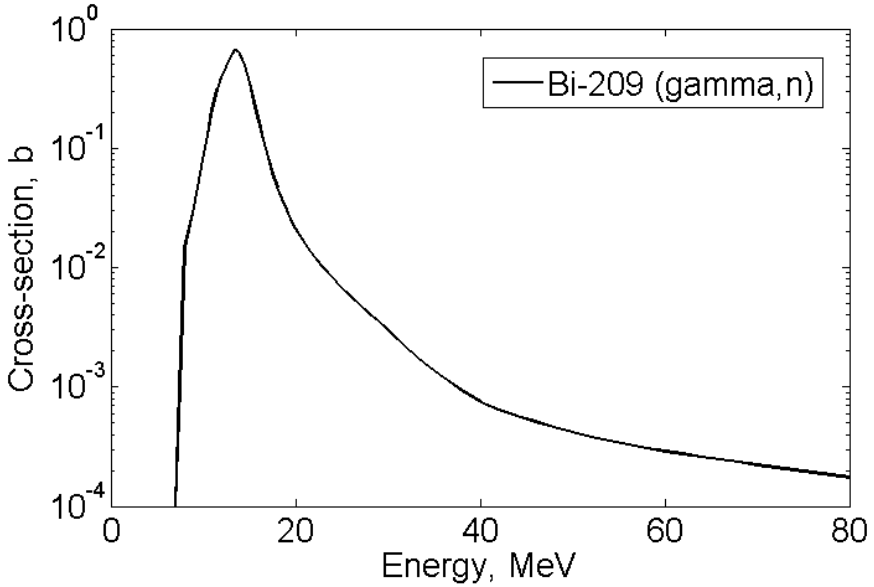
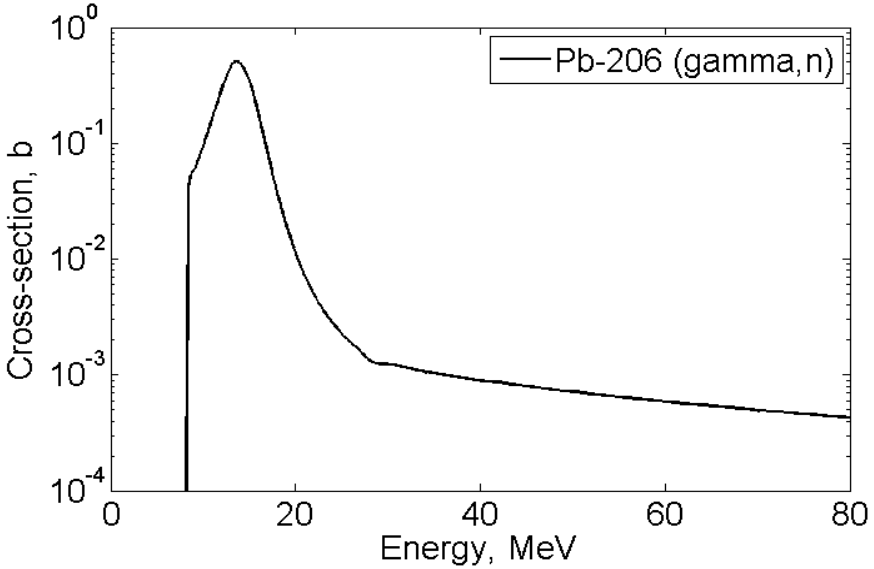
Lead-Bismuth Eutectic has several favorable properties as a liquid metal target material

- High conversion efficiency (Z=82,83)
- Low melting point (124°C)
- High boiling point
- (1670 °C)





Intense Neutron Source [4]

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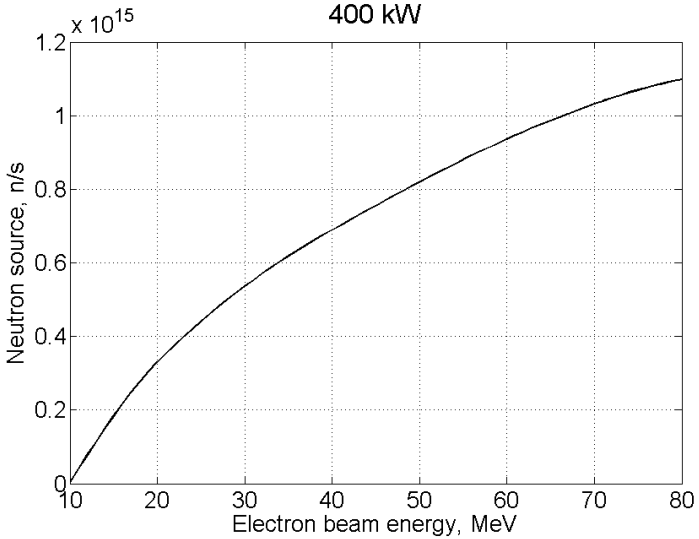
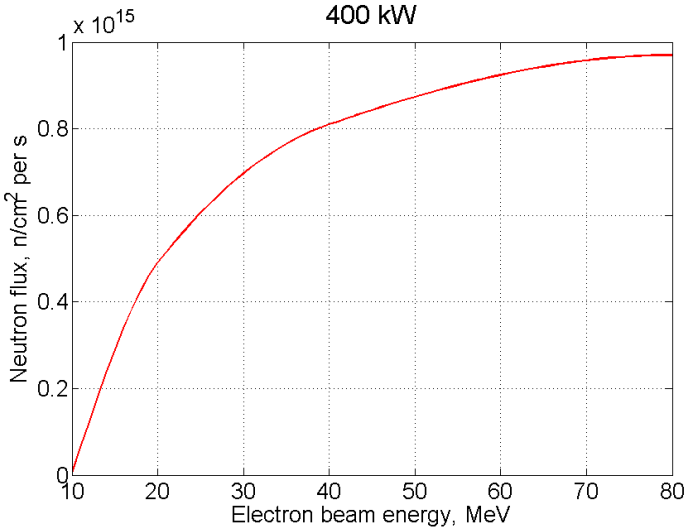
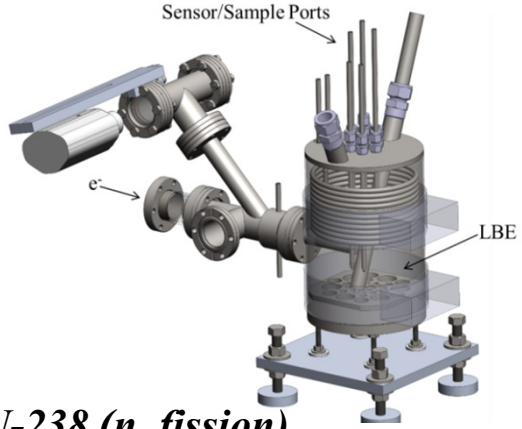
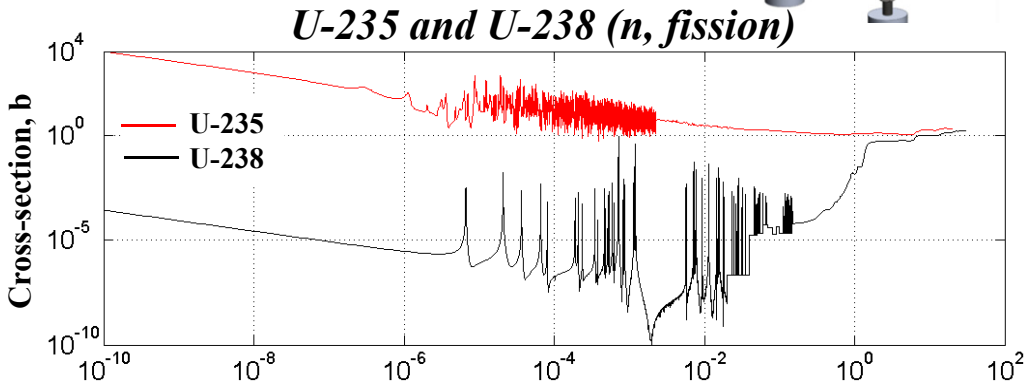
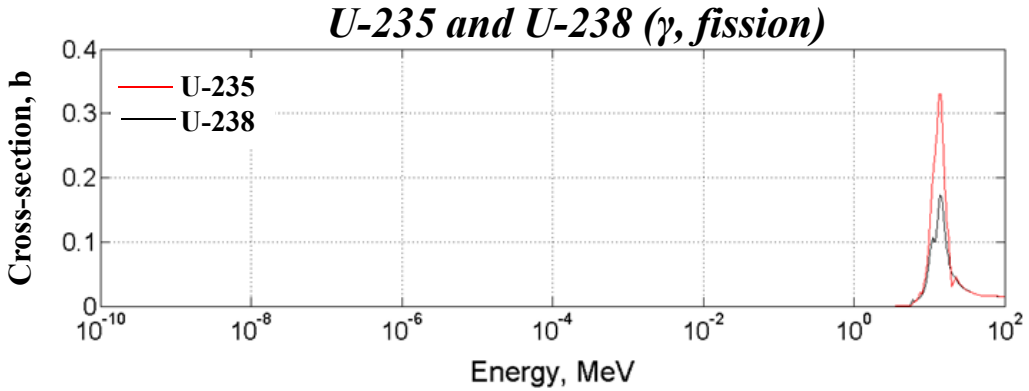
PbBi source intensity & flux:











Commercial Uses of Superconducting Electron Linacs

NIOWAVE
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Radioisotope Production

Medical and industrial isotopes produced domestically, without a nuclear reactor, and without weapons-grade uranium

Conceptual Design

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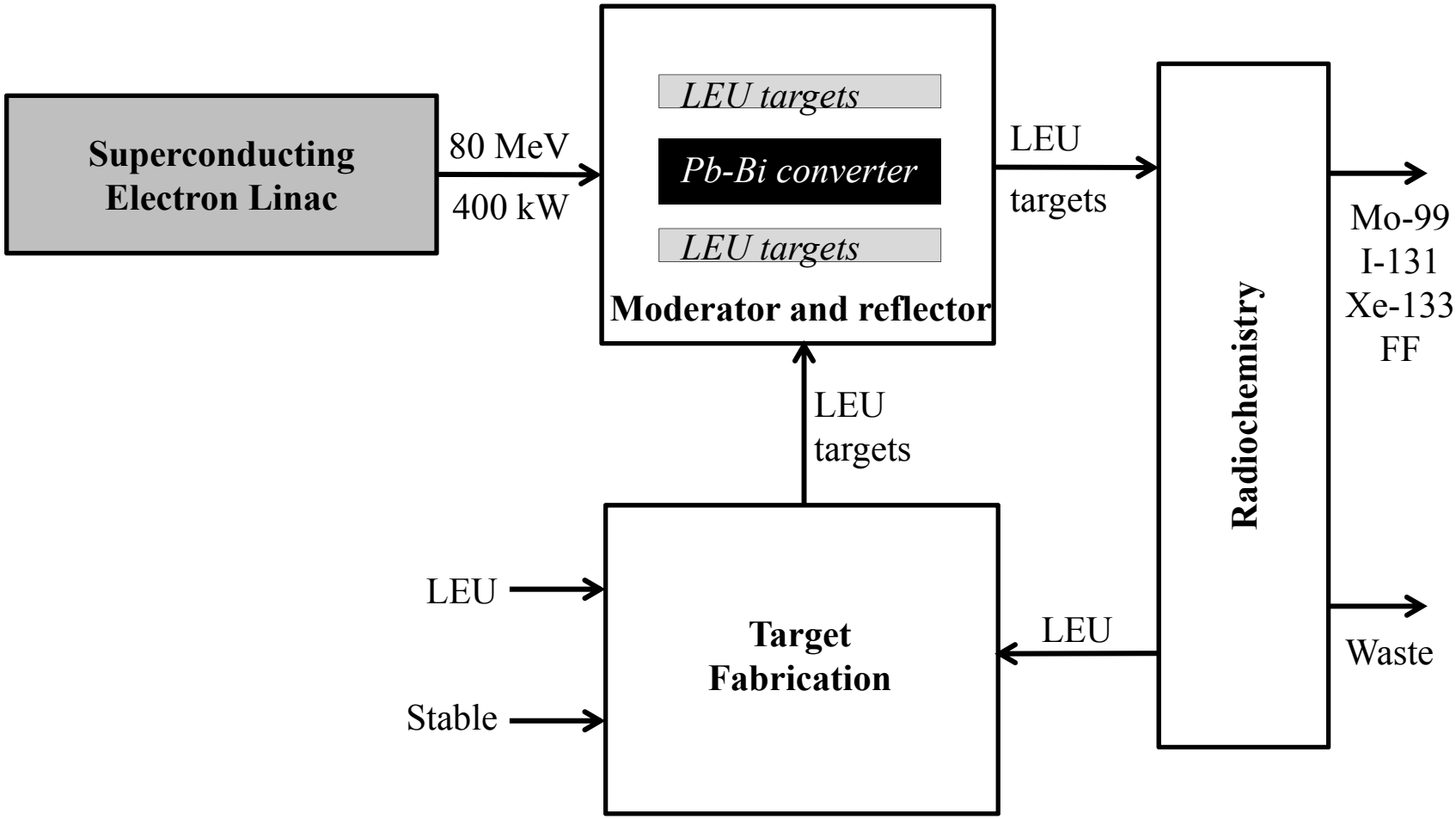
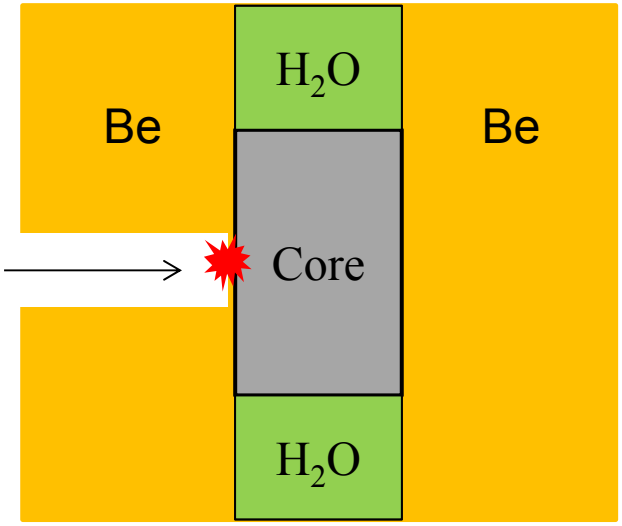
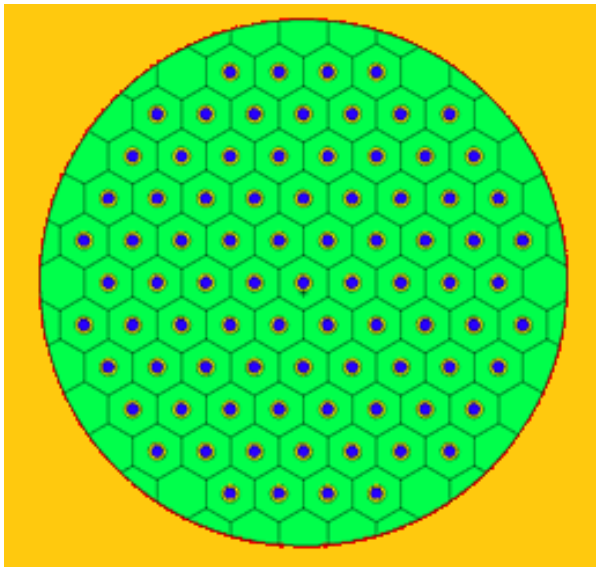


Uranium Targets [1]





LEU mass	< 10 kg
Mass of each rod	< 100 g
Number of rods	~ 90
E-beam power	80 MeV, 400 kW
Neutron source	~ 10^{15} n/s
Peak thermal neutron flux	~ 2x10^{13} n/cm^2*s
Fission power	266 kW
k-value	0.95
Time of irradiation	1 week
U-235 burnup	~ 0.02%
U-235 fissioned	~ 1.7 g/week
Mo-99 activity at the EOB	~ 9 kCi
Total FF activity at the EOB	~ 320 kCi
Total actinide activity at the EOB	~ 43 kCi

Uranium Targets [2]

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- Natural and LEU targets
  - Clad for containment of fission fragments
  - Metal and oxide
- LEU Acquisition
  - Y-12/NNSA
  - Commercial Suppliers

Uranium Targets [3]

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- E-beam: 80 MeV 400 kW
- k=0.95
- LEU core: <20%, <10 kg
- Irradiation: 1 week

Fission fragment	$T_{1/2}$(h)	Activity (kCi/week)	FF Activity Inventory (kCi)		
			EOB	24 hours	3 days
Mo-99	65.9	9.1	~320	~73	~38
I-131	192.5	2.4			
Xe-133	125.8	7.3			
Sr-91	9.6	10.5			
Sr-92	2.7	10.7			

Radiochemistry for Isotope Separation

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- Twelve rods will be processed daily
- Mass of each LEU rod – 99g
  - Regulated as byproduct from accelerators applies
- Produce up to 9,000 Ci/wk (1,500 6-day Ci/wk)
- Extraction of Mo-99 and other isotopes using LEU modified Cintichem process
- Standard Tc-99m generators
  - Capable of using the existing supply chain

Commercial Uses of Superconducting Electron Linacs

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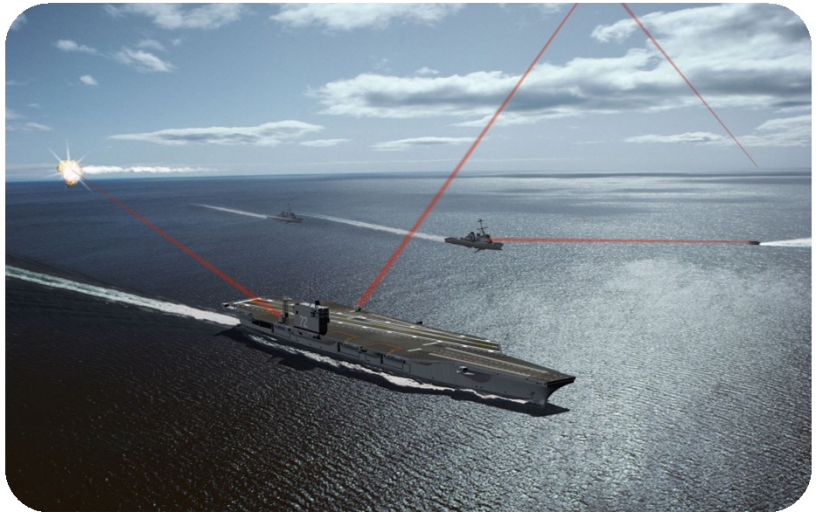
High-power tunable lasers at wavelengths not available from conventional lasers (span the range from THz up to x-rays)



Free Electron Lasers

Navy FEL R&D at Niowave

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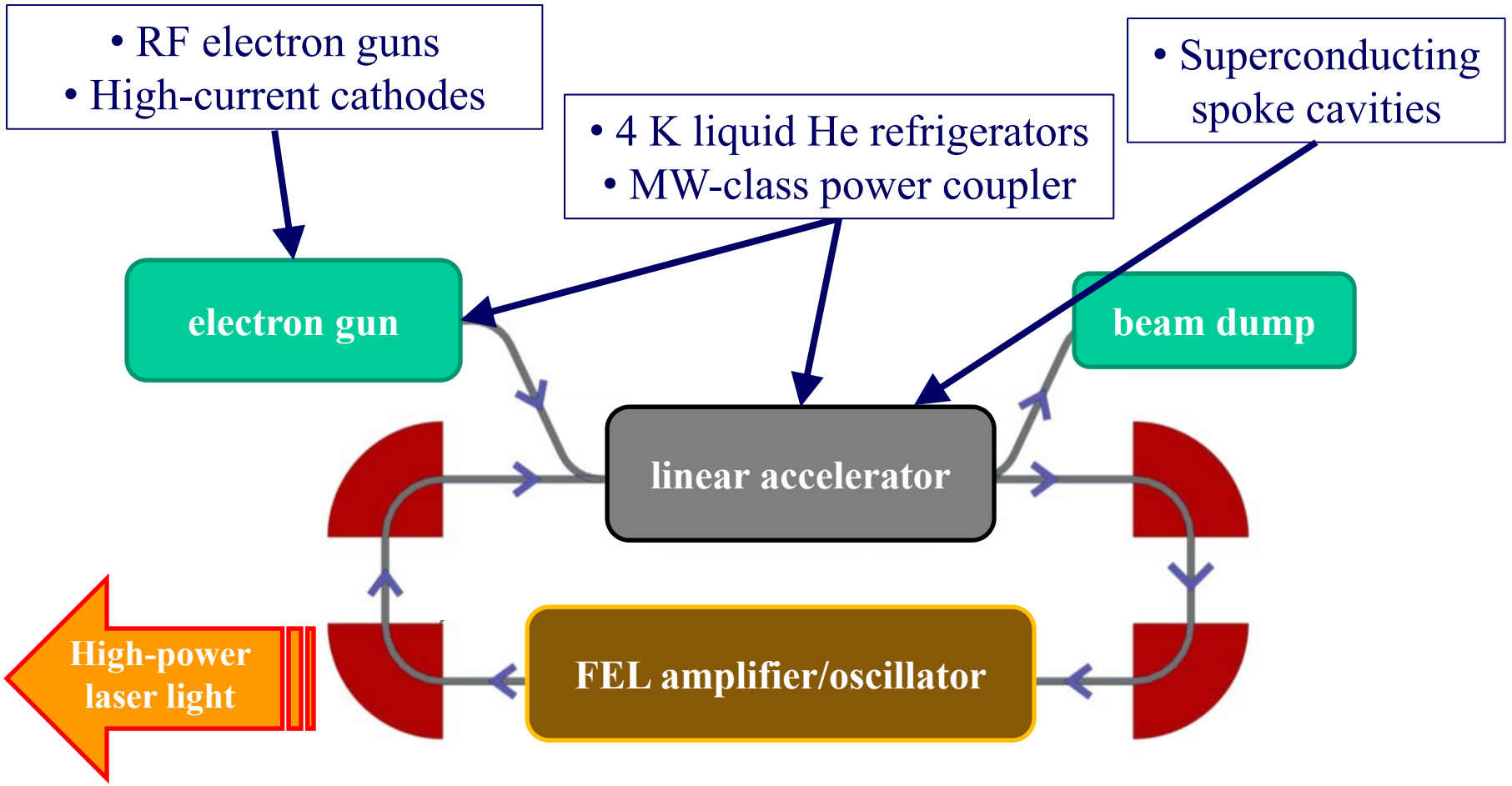

Superconducting Multi-Spoke Cavities

NIOWAVE
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- 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

ONR
Revolutionary Research . . . Relevant Results

Joint Technology Office
High Energy Lasers

NPS
Praestantia per Scientiam

Los Alamos
National Laboratory

Old Dominion University

Niowave Facilities

NIOWAVE
www.niowaveinc.com

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

NIOWAVE
www.niowaveinc.com

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

NIOWAVE
www.niowaveinc.com

- Production & processing facility
  - Occupancy Jan 2015
  - 24/7 operation
  - Isotopes, x-rays, etc.
- Lansing International Airport
  - Foreign Trade Zone

Licenses Possessed [1]

NIOWAVE
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- State of Michigan:
  - Licensed to operate multiple electron linacs
    - Plan approved up to 40 MeV 100 kW
  - License number
    - PR-2013-0346

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Posting of notices to workers
Page 1 of 2

DEPARTMENT OF LICENSING AND REGULATORY AFFAIRS
RADIATION SAFETY SECTION

RADIATION MACHINE REGISTRATION CERTIFICATE

FACILITY REGISTRATION NO. 31020

THIS CERTIFICATE EXPIRES 6/1/2015

CO/FAC 33/20 N

Pursuant to Part 135 of Act 368, P.A. 1978 and the Ionizing Radiation Rules, as amended, and in reliance upon application and fees received from the registrant, this registration certificate is hereby issued authorizing the registrant to own, receive, acquire, possess, use or transfer the radiation machines listed below for the use(s) and at the place(s) designated. This certificate is subject to all applicable rules, regulations and orders of the Department now or hereafter in effect and to any conditions specified below.

REGISTRANT:
NIOWAVE INC
1012 N WALNUT ST
LANSING MI 48906

ATTN: DR TERRY L GRIMM

FACILITY:
NIOWAVE INC
1012 N WALNUT ST
LANSING MI 48906

DESIGNATED RADIATION PROTECTION SUPERVISOR:
ERIK MADDOCK

	MACHINE REGISTRATION NUMBER	LOCATION	MANUFACTURER	MODEL	MAXIMUM RATINGS	MODE OF USE	NO. OF TUBES	AUTHORIZED USES
X	73403	NERD FACILITY	NIOWAVE INC	13-2503	100 kVp	FIXED	4	RES ACCELERATOR
X	73404	NERD FACILITY	NIOWAVE INC	09-4518	12 MeV	FIXED	1	ACCELERATOR CLASS D
X	73662	NERD FACILITY	NIOWAVE INC	13-1002	3 MeV	FIXED	1	ACCELERATOR CLASS D
X	74594	NERD FACILITY	NIOWAVE INC	14-1001	6 MeV	FIXED	1	ACCELERATOR CLASS D
X	74682	NERD FACILITY	NIOWAVE INC	13-0027	2.5 MeV	FIXED	1	ACCELERATOR CLASS D
X	75008	NERD FACILITY	NIOWAVE INC	14-1002	6 MeV	FIXED	1	ACCELERATOR CLASS D

Facility Conditions of Use:

The registrant shall maintain and utilize appropriate calibrated and operable portable radiation monitoring instruments to make physical radiation surveys as deemed appropriate and necessary by the Radiation Protection Supervisor. These intruments shall be capable by design, calibration, and operation of measuring the intensity of the various types and energies of radiation produced by the accelerator. These instruments shall be calibrated at intervals not to exceed one year. Calibration records shall be maintained and made available for examination by the department.

A log of all accelerator operations will be maintained during testing and will be made available for on-site review upon request from the Department. The log shall include the date and location of the test and include the accelerator's on-time and power levels used for the duration of the testing.

The Radiation Protection Supervisor will have the authority to terminate the operation of the accelerator if such action is deemed necessary to minimize danger to public health and safety or property.

The dose to unrestricted areas must be kept below two millirems in any one hour and below 100 millirems in any one year.

A radiation dosimeter shall be permanently assigned to each occupationally exposed individual. This monitoring shall be continuous during employment as a radiation worker.

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Machine Conditions of Use:

Machine number 73404:

INSTRUCTIONS FOR REPORTING CERTIFICATE INFORMATION CHANGES

The registrant shall notify the Department in writing before making any change which would render the information contained in this certificate no longer accurate, pursuant to R325.5188, Rule 188 of the Ionizing Radiation Rules. If there are changes, please note and FAX to (517) 636-0531. If there are questions, call (517) 636-6800 or e-mail RSSINFO@MICHIGAN.GOV.

CERTIFICATE ISSUED ON: 9/29/2014

In accordance with R325.5181, Rule 181, the registrant shall comply with the applicable provisions of the Ionizing Radiation Rules. A renewal notice will be sent to the registrant before the date this certificate expires. If the registrant has filed an application for renewal in proper form not less than 30 days before expiration, this certificate shall not expire until the application has been finally determined by the Department.

BHCS/HFS-500 (Rev 12/12)

415224

Licenses Possessed [2]

NIOWAVE
www.niowaveinc.com

NRC: Source Material

- Licensed to possess, machine, and distribute DU, ^{nat}U, ^{232}Th
- License number 21-35145-01

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U.S. NUCLEAR REGULATORY COMMISSION — Amendment No. 01

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	In accordance with letter dated **August 6, 2014**,
1. Niowave, Inc.	3. License number 21-35145-01 is amended in its entirety to read as follows:
2. 1012 N. Walnut Street Lansing, MI 48906-5061	4. Expiration date July 31, 2024
	5. Docket No. 040-38369 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. Natural Uranium	A. Solid	A. 322 millicuries
B. Thorium-232	B. Solid	B. 50 millicuries
C. Depleted Uranium	C. Solid	C. 1.13 curies

9. Authorized use:

A. through C.
(1) Research and development as defined by 10 CFR 30.4.
(2) Fabrication (to include cutting and machining) of source material for the manufacturer of shielding and accelerator parts.
(3) Distribution of shielding and manufactured accelerator parts to persons authorized by the Nuclear Regulatory Commission or an Agreement State license to receive the material.

CONDITIONS

10. Licensed material shall be used only at the licensee's facilities located at 1012 N. Walnut Street, Lansing, Michigan.
11. The Radiation Safety Officer for this license is Erik Maddock .
12. Licensed material shall be used by, or under the supervision of: Terry Grimm, Ph.D., Valeriia Starovoitova, Ph.D. and Erik Maddock.
13. This license does not authorize distribution, pursuant to 10 CFR 40.13 and/or 40.22, to persons exempt from licensing or to general licensees.

Licenses Possessed [3]

NIOWAVE
www.niowaveinc.com

NRC: LEU & Radioisotopes

- Licensed to produce, possess and transfer certain radioisotopes, as well as special nuclear material
- License number 21-35144-02

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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

Commercial SRF Linacs

NIOWAVE
www.niowaveinc.com

Several technologies coming together to allow SRF linacs to be commercialized

- Rugged, piston-based 4 K helium refrigerators
- Compact low-frequency cavity geometries
- Gated thermionic-cathode RF guns

Applications include isotope production, active cargo scanning, sterilization, positron and neutron sources, free-electron lasers…

Current rapid progress driven by DHS, DOE, and commercial needs for high-power SRF linacs…

leveraging SBIR grants, contract work and Niowave investment towards full system development