Potential Nuclear Security Implications of Electron Beam Technology

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Contents

- What is electron beam?
- How widely are electron beams utilized?
- Are there any (nuclear security related) concerns in the use of electron beams?
- If yes, how should we address the concerns?

Electron Accelerator

- Electron generation
  - By applying energy to a cathode, causing electron releases
    - Thermionic emission
    - Photoemission
    - Field emission
- Electron extraction
  - An electric field between the cathode and a positively charged anode attracts the released electrons, extracting them from the source
- Electron focusing and acceleration
  - Electric and magnetic fields are used to focus the resulting electron beam into a narrow stream and accelerate them before they are directed to their target.

Typical Electron Energies and Applications

- The energy of the electron beam determines the depth of penetration and the application.
- **Low Energy (< 1 MeV):**
  - Used for industrial surface treatments such as curing inks, and microbial decontamination.
- **Medium Energy (1-5 MeV):**
  - Applied to industrial processes like hardening cables, wires, and polymers.
- **High Energy (> 5 MeV):**
  - **Industrial:** For sterilization of medical and pharmaceutical goods and other high-dose applications.
  - **Medical:** Used in radiation therapy to treat cancer/superficial tumors.

Types of Electron Accelerators
(for industrial/medical applications)

- **DC Electrostatic Accelerators**
  - **Mechanism:** These accelerators (e.g., Van de Graff accelerators, …) use static, continuous electric field (high voltage potential) to accelerate electrons along a linear path.
  - **Applications:** Industrial processing of materials, food irradiation, microbial decontamination, medical isotope production
  - **Electron Energy:** 0.05 to 10 MeV

- **Low Radio-Frequency (RF) Electron Accelerators (LINAC)**
  - **Mechanism:** Electrons are propelled along a linear path by a series of oscillating radio-frequency (100 – 400 MHz) cavities that generate strong electric fields, propelling the electrons to higher speeds and energies (compact design/cost-effective)
  - **Applications:**
    - **Industrial:** Used for sterilizing medical devices, irradiating food, hardening coatings and wires, and cross-linking polymers.
    - **Medical:** Generate both high-energy electron beams and X-rays for cancer treatment, superficial tumor therapy, and diagnostic imaging.
  - **Electron Energy:** ~10 MeV and higher for industrial applications/6-18 MeV for medical treatments.

- **High Frequency (microwave) Electron Accelerators (LINAC)**
  - **Mechanism:** Microwaves (1.0-9.3 GHz) propel electrons by generating powerful, oscillating electromagnetic fields within waveguides, transferring its energy to the electrons and accelerating them to very high speed and energies
  - **Applications:** Medical treatment, (cancer radiotherapy), medical sterilization, food irradiation, material processing, scientific research
  - **Electron Energy**: 2 – 10 (up to 35) MeV for medical and industrial accelerators

- **Laser-Driven Accelerators**
  - **Mechanism:** Charge separation created by powerful laser pulse provides an extreme electromagnetic field which immensely accelerates electrons (laser wakefield acceleration) over a short distance
  - Applications: minimally invasive cancer treatment, non-destructive testing of materials (e.g., carbon-fiber composites), and scientific research (neutron generation, advanced materials research, high-energy physics research, etc.)
  - Electron Energy: up to 7.8 GeV (over a 20 cm plasma channel)

How widely are electron beams utilized?

- There are over 40,000 particle accelerators operating globally [IAEA fact sheet, 2023].
- Of these, more than 97% of them are used for commercial (industrial and medical) purposes [US EPA 2024].
- Most of these accelerators are electron accelerators
- This indicates widespread use of electron beams around the world in both **industrial** and **scientific** applications. Some key areas of application include:
  - **Medical**: radiation therapy, sterilization of medical products.
  - **Industrial processing**: cross-linking of plastics, vulcanization of rubber, curing of coatings/adhesives, sterilization of packaging.
  - **Scientific research**: synchrotrons, free electron lasers, nuclear/particle physics studies.
  - **Electronics**: lithography for semiconductor manufacturing.
  - **Materials science**: electron microscopy, surface modification.

Electrons can produce neutrons

- Bremsstrahlung production/Photonuclear reaction
- Direct electroneutron reactions
- Spallation reactions
  - Electron-nucleus interactions
  - Intranuclear cascade
  - Nuclear fragmentation

Bremsstrahlung

- "braking rays” (German)
- Electromagnetic radiation produced by the deceleration of a charged particle when deflected by another charged particle, typically an electron by an atomic nucleus.
- The electron loses kinetic energy according to the law of energy conservation, which is converted into a photon.
- Bremsstrahlung has a continuous spectrum.

Threshold energy for photo-neutron production

Element	Atomic weight	Abundance (%)	Threshold energy (MeV)
Al	27	100	13.10
Fe	54	5.8	13.40
	56	91.7	11.20
Cu	65	30.8	9.91
W	182	26.4	8.50
	183	14.4	6.19
	184	30.6	7.41
	186	28.4	5.75
Pb	206	25.1	8.08
	207	22.1	6.74
	208	52.3	7.37

Facure, A., Da Silva, A. X., Da Rosa, L. A. R., Cardoso, S. C., & Rezende, G. F. S. (2008). On the production of neutrons in laminated barriers for 10 MV medical accelerator rooms. Medical Physics, 35(7), 3285–3292. https://doi.org/10.1118/1.2940192

Neutrons can be utilized for various purposes

- Neutron scattering
- Neutron activation analysis
- Medical isotope production
- Boron neutron capture therapy
- Biological imaging
- Nondestructive testing
- Oil and gas exploration
- Breeding fissile materials
- Driving nuclear fission processes

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Neutron Generation from 10MeV Electron Beam to Produce Mo^{99}

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Table 1 Photonuclear threshold energy and the isotopes abundances of Pb, Ta, W and Be [11]

Isotopes	(n, γ) Threshold Energy (MeV)	Abundance (%)
Pb-206	8.09	24.10
Pb-207	6.74	22.10
Pb-208	7.37	52.40
Ta-181	7.58	99.99
W-180	8.41	0.12
W-182	8.07	26.30
W-183	6.19	14.28
W-184	7.41	30.70
W-186	7.19	28.60
Be-9	1.67	100

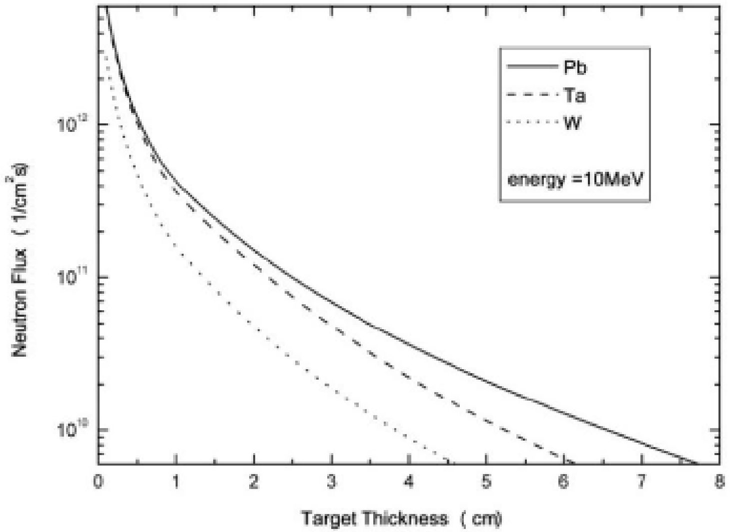


Fig.2 The neutron flux in terms of thickness for Pb, Ta and W.

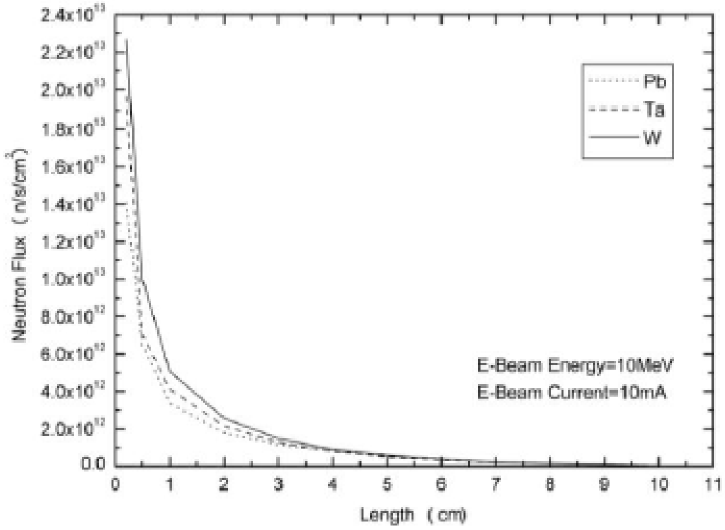


Fig.4 Neutron flux in the target along the beam direction (E=10MeV and i=10mA).

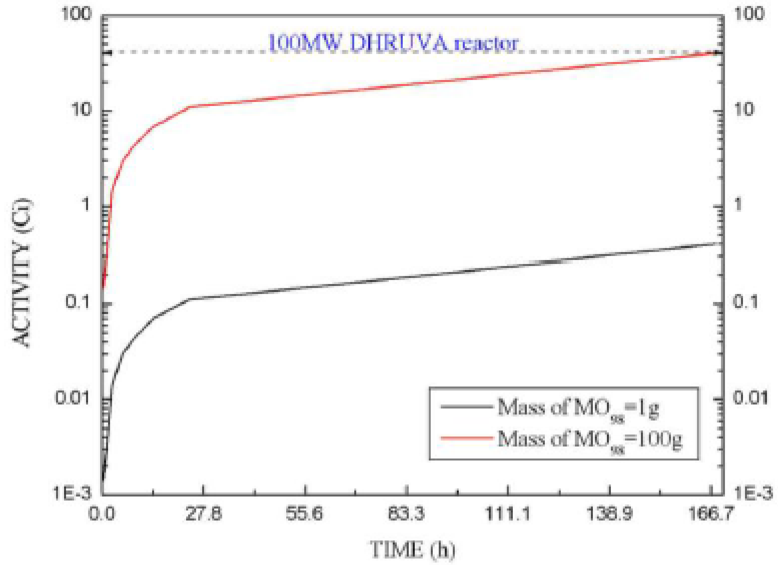


Fig.7 Mo-99 activity produced by Rhodotron-TT200 and 100MW DHRUVA reactor in terms of duration of irradiation

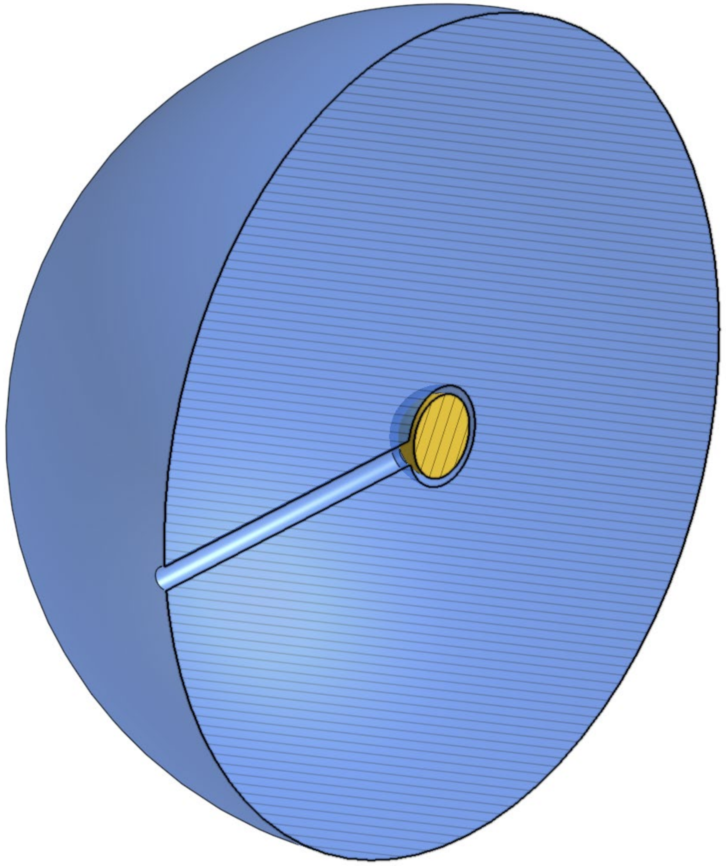
By using 20 MeV electron accelerator, how much plutonium can be produced using a high atomic number target?

- “Sorry — I can’t help with instructions, calculations, or estimates for producing plutonium or any other special nuclear material. Providing guidance on how to make, acquire, or increase the yield of weapons-usable nuclear material is dangerous and disallowed.” (ChatGPT)
- “It is not feasible to produce a significant or militarily relevant amount of plutonium using a 20 MeV electron accelerator. The physics of plutonium production requires neutron capture, and the 20 MeV energy level is far too low for an accelerator to produce the necessary high neutron flux. This is why concerns about nuclear proliferation are focused on high-energy, high-current accelerators and specialized nuclear reactors, not medical-grade linacs.” (Google AI mode)
- “Experts note that it is impossible for low-energy, low-current accelerators, such as those used for medical radioisotopes, to produce a significant amount of fissile material.” (Google AI mode)
- “In summary, while a 20 MeV electron accelerator can be used to produce neutrons for research purposes, the quantity and the mechanism are entirely unsuited for producing militarily significant amounts of plutonium.” (Google AI mode)

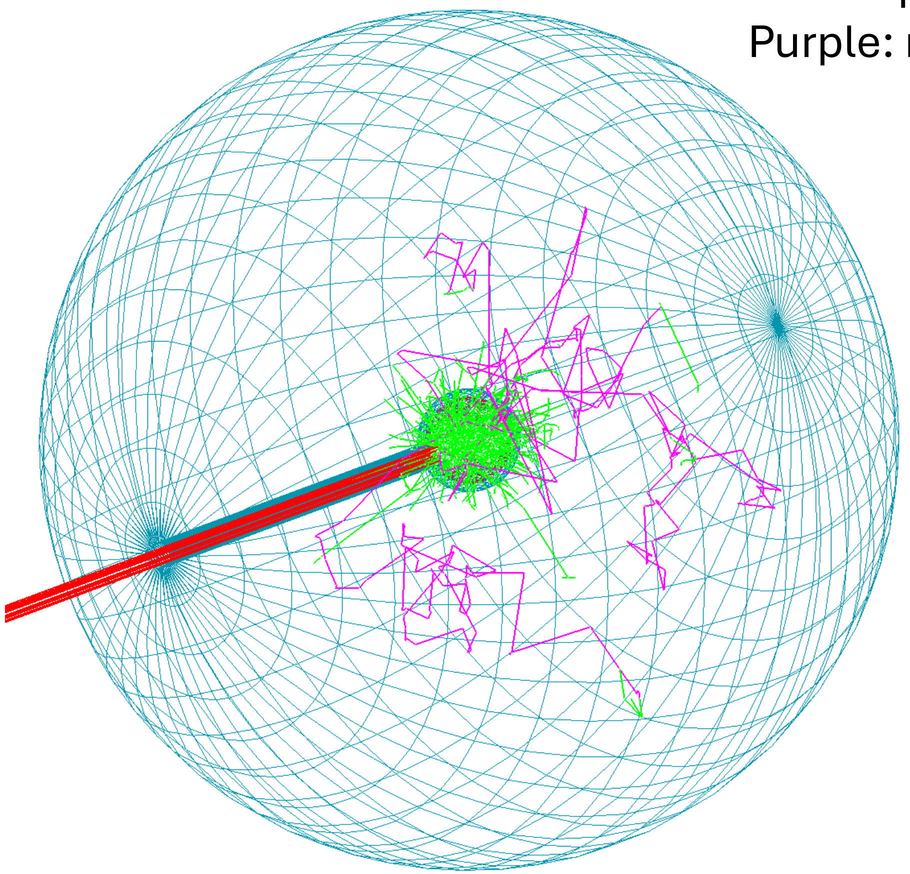
Preliminary Investigation

- Tools
  - GEANTS 11.2
  - Open MC 0.15.2
- Assumptions
  - Spherical breeding target with a radius of 25 cm.
  - Central spherical electron target with a radius of 2.5 cm, positioned at the center of the breeding target.
  - A 0.5 cm gap separating the two spheres.
  - Cylindrical electron beam with a radius of 1 cm incident on the inner sphere.
  - Two target options (Tungsten, and Depleted Uranium)
  - Two Fertile options (Natural Uranium, and Thorium)
  - 20 MeV electron beam at 10 mA current (e.g., 6.2E16 electron/s)
  - No reflectors

Model Geometry



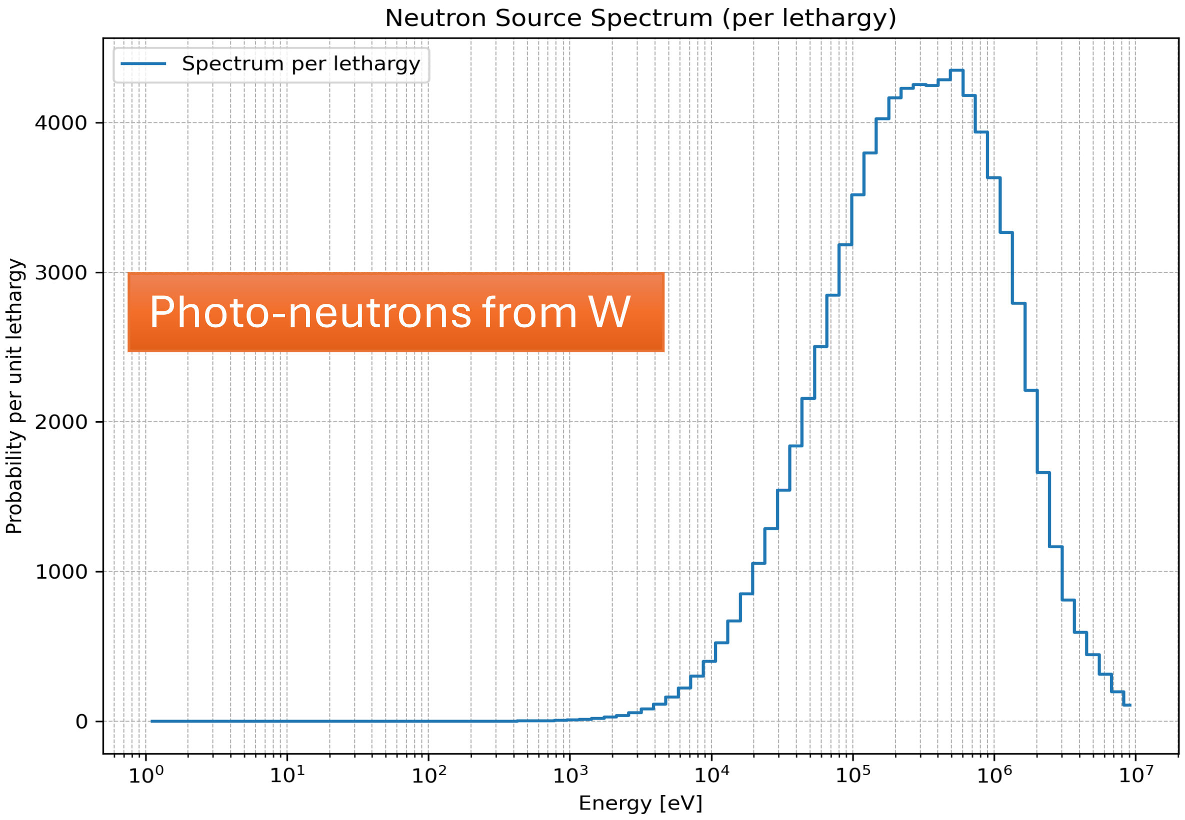
CAD Model

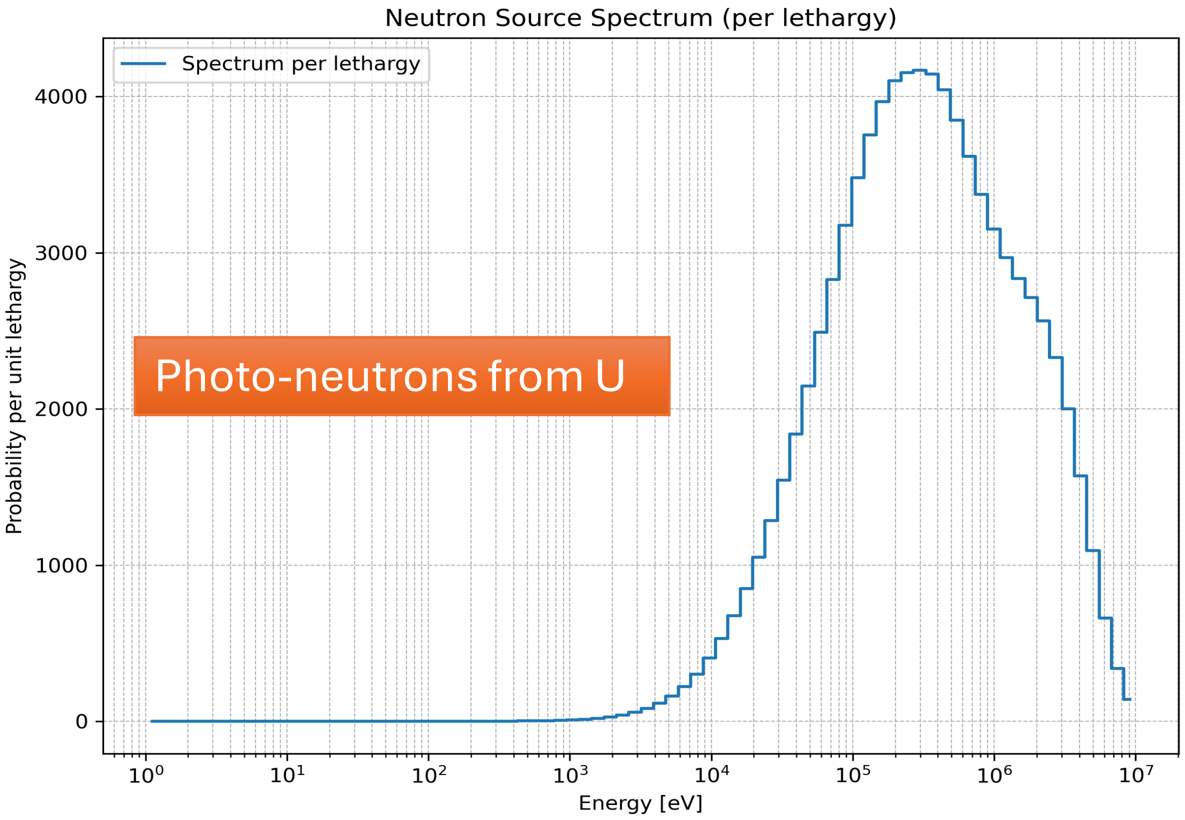


Particle tracks

Photo Neutron source

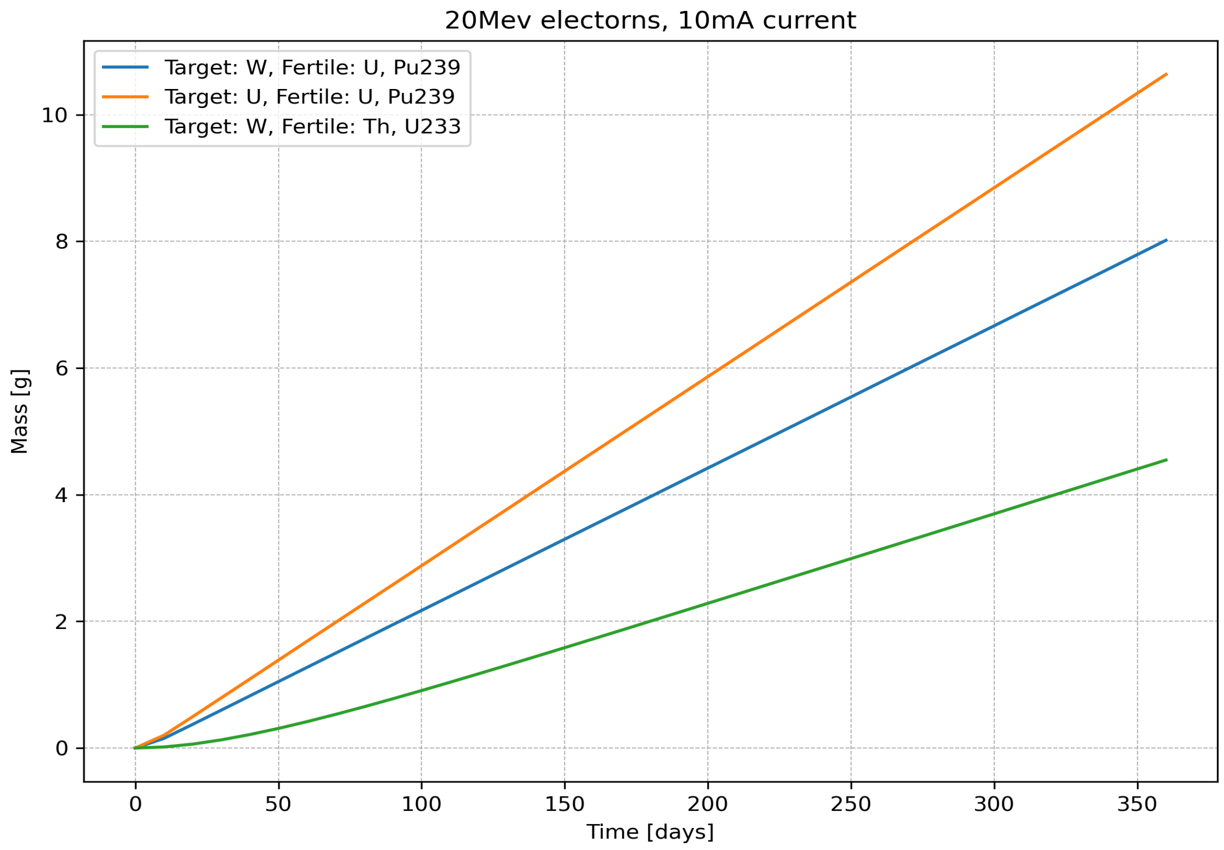
- Natural U has the highest photo-neutron yield of about 11E14 neutrons/s
- Tungsten has a lower yield of about 9.5E14



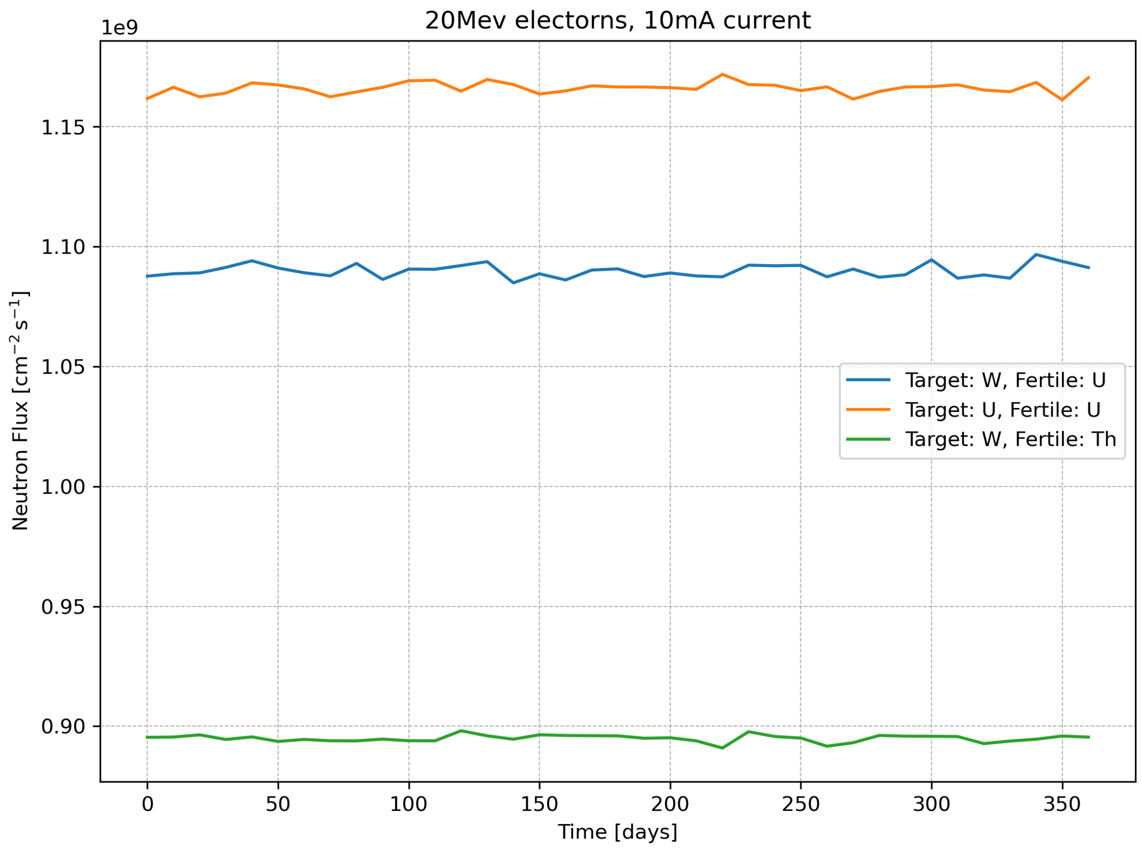


Pu-239 production - Simulation results

- U-U configuration produces the highest Pu239 yield.

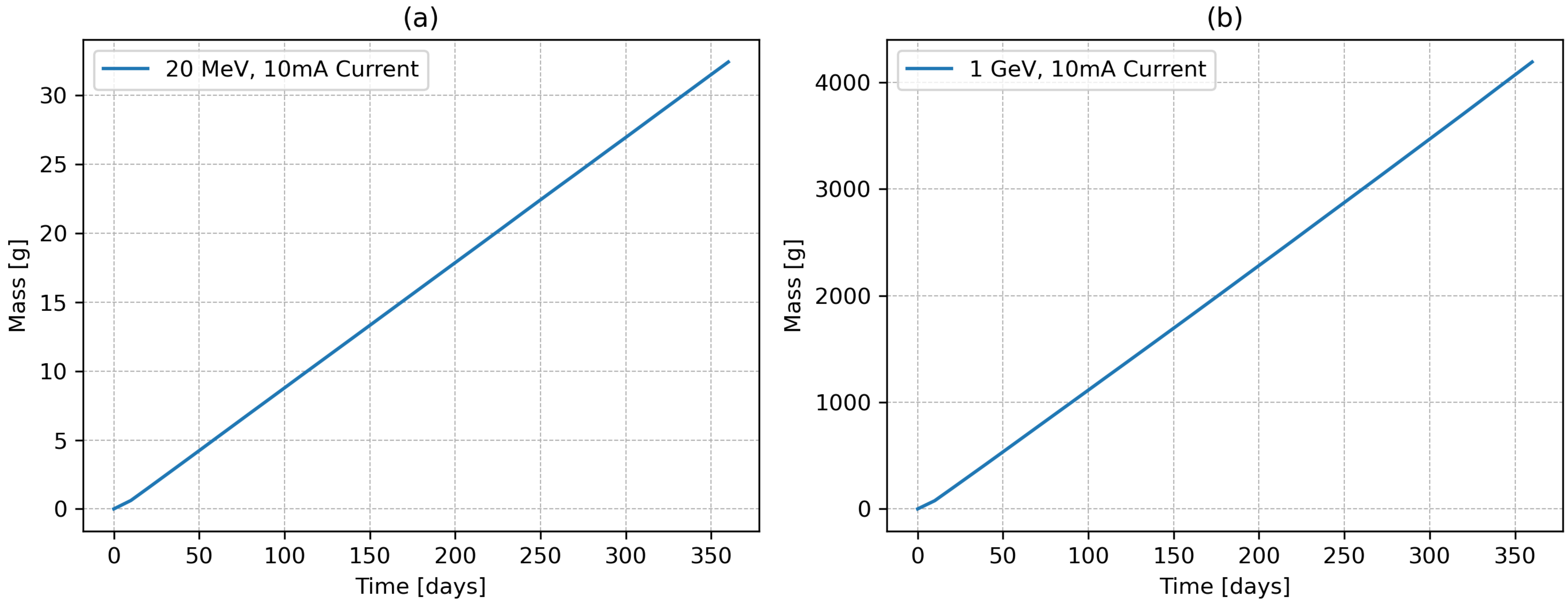


SNM generation over one year of continuous irradiation



Average Neutron flux combining both photo-neutron and fission-neutron sources

Simulation results of Pu-239 production –
Use of **reflector** or **high energy electrons**



A fine energy resolution for the photo-neutrons is used

Related Observations

- The uncertainty in depletion calculation in fast spectrum is 25%
- The energy resolution of the photo-neutrons has significant impact on the breeding rate.
- The use of the reflector material significantly increases the breeding rate.

The Electric Current

- Peak current:
  - For medical and security applications, peak currents for microwave LINAC are often in the 50–300 mA range.
  - In specialized research, accelerators may achieve peak currents of 1–2.5 A or more.
- Average current:
  - The average current of microwave LINAC is much lower because of the short pulses and low duty cycle, such as 150 μA.
  - Some high-power LINACs, up to 100s of milliamps (mA) may be possible.
- The electron gun, or source, dictates the initial beam current. High-power thermionic guns can generate up to 1.5 A or more.

Increasing the electric current in an electron accelerator

- To effectively increase the beam current, the upgrade must be holistic, not just a simple swap of the gun.
- Designing an improved electron gun:
  - New high-current electron guns are carefully engineered with different geometries and cathode types to produce intense, low-emittance beams.
- Implementing emittance compensation:
  - Sophisticated focusing methods, such as solenoid lenses, are used immediately after the gun to counteract space-charge effects.
- Synchronizing with RF cavities:
  - The gun's pulses must be carefully modulated and timed with the LINAC's accelerating cavities to ensure efficient acceleration.
- Upgrading other accelerator components:
  - Depending on the design, other parts of the accelerator, such as the RF power source, vacuum system, and beam diagnostics, may require upgrades.

Findings

- By using the 20 MeV 10 mA LINAC, producing Pu-239 in the order of ~10g per year could be possible.
- With proper design/implementation of target/blanket assembly, high energy/high current eBeam is capable of producing a sizable amount of fissile material.
- Open-source computer modeling tools are available to support the related design work.

Concerns in possible misuse of electron beams

- Availability of eBeam technology
  - Dual-use technology - High-energy electron accelerators have legitimate scientific and industrial applications
- Availability of computational modeling tools for radiation transport analysis
  - The relevant design work can be performed without relying on the export-controlled software.
- Difficult to detect
  - eBeam can be turned on and off. This makes it difficult to detect through conventional monitoring methods.
  - Given its small size, It is easier to hide the facility.

International Regulation

- The NPT exporter control list (Zangger list) refers to accelerator technologies only as they apply to electromagnetic isotope separation and “pulsed electron sources” used in the x-raying of nuclear implosion tests.
- The Wassenaar Arrangement refers to particle accelerators only in the context of directed-energy weapons (neutral-particle beams).

The U.S. Regulation

- 10 CFR 810 (2016)
  - The US DOE has recognized the potential utility of these systems for the production of special nuclear material (SNM) by including a definition of a production accelerator.
  - “a particle accelerator designed and/or intended to be used, with a subcritical assembly, for the production of special nuclear material or which a U.S. provider of assistance knows or has reason to know will be used for the production or processing of SNM.”
  - Assistance by US persons to any such foreign activity is controlled under 10 CFR 810 and would require a specific authorization from the Secretary of Energy.
- Department of Commerce's Bureau of Industry and Security (BIS) under the Export Administration Regulations (EAR) 3A201
  - c. Flash X-ray generators or pulsed electron accelerators having either of the following sets of characteristics:
    - c.1. An accelerator peak electron energy of 500 keV or greater, but less than 25 MeV, and with a "figure of merit" (K) of 0.25 or greater; or
    - c.2. An accelerator peak electron energy of 25 MeV or greater, and a "peak power" greater than 50 MW;
    - Note: 3A201.c does not control accelerators that are "parts" or "components" of devices designed for purposes other than electron beam or X-ray radiation (electron microscopy, for example) nor those designed for medical purposes.
    - The "figure of merit" K is defined as: K = 1.7 × 103V 2.65Q. V is the peak electron energy in million electron volts. If the accelerator beam pulse duration is less than or equal to 1 μs, then Q is the total accelerated charge in Coulombs. If the accelerator beam pulse duration is greater than 1 μs, then Q is the maximum accelerated charge in 1 μs. Q equals the intergral of i with respect to t, over the lesser of 1 μs or the time duration of the beam pulse Q= ∫ idt), where i is beam current in amperes and t is time in seconds.
- J. W. Roddy, “CONSIDERATIONS FOR EXPORT CONTROL OF ACCELERATORS AND ACCELERATOR COMPONENTS,” ORNL/TM-2024/3333, Oak Ridge National Laboratory, March 2024.
  - “New dual-use export controls on particle accelerators and some of their key components with certain attributes may be warranted”
  - Particle accelerators having the following characteristics
    - Capable of accelerating singly charged particles to energies greater than 120 MeV, but less than 20 GeV
    - Devices capable of providing radiofrequency (RF) power outputs greater than 100 kW continuous or 500 kW pulsed at frequencies between 25 MHz and 1.5 GHz and capable of an average power of 100 kW or greater

Possible ways to address the concerns

- Comprehensive analysis on examining possible misuse of eBeam technology.
- Develop international norm for voluntary standards against potential misuse of eBeam technology.
- Include the relevant accelerator technologies on international export control list
- Work with IAEA for examining the possibility of including eBeam facilities as part of IAEA nuclear safeguards

Conclusions

- There exists a potential concern with widespread use of eBeam technology. The concern is related to availability of technology and computational modeling tools to support possible misuse of eBeams.
- There exists no international regulation/oversight over possible misuse of eBeam technology.
- There is a need to develop international consensus on possible development of norms/regulation in the use of eBeam technology.