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# AN ACCELERATOR-BASED NEUTRON SOURCE FOR SUPPORTING SCIENCE AND TECHNOLOGY DEVELOPMENT

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**ABSTRACT –** An electron accelerator driven neutron source (EADNS) is described that can be used for studying the behavior of new reactor materials and fuels, isotope production, neutron radiography, validation or generation of nuclear data for reactor physics codes, semiconductor processing, and for neutron scattering. The source can be augmented by adding other neutron source targets, moderators, and sub-critical reactor blankets. It could also be used to drive a uranium target inside a Super Critical Water (SCW) loop, producing both fission (approximately 3 kW) and extra heat from bremsstrahlung heating (from 10 to 30 kW, depending on amount of uranium present). If a sub-critical assembly were used in conjunction with an SCW coolant loop, it should be possible to reach a neutron flux in excess of $10^{13}$ n/cm$^2$/s. This flux would be high enough to test many of the important corrosion issues that need to be addressed in SCW research programs. The same approach could be used to drive a loop for other technologies, such as molten salt fuel/coolant or liquid metal coolant reactor technologies. This source could address some of the issues arising from the impending and expected closure of the National Research Universal (NRU) multi-purpose research reactor at the Canadian Nuclear Laboratories. Similar sources are now being used in Europe and other nations to complement the use of research reactors, or to fill the gaps left by their closure [1].

## 1. Introduction

Accelerators can produce neutrons via fusion [2], spallation [3], and photonuclear reactions [4]. An EADNS can be a small, simple, and inexpensive tool useful for many applications. Modern electron accelerators are widely used in medicine, industry, isotope production [5], [6], and for research. The widespread adoption of these machines over the last thirty years has occurred partly because they are reliable, inexpensive, work on demand, and are straightforward to maintain. An example is the electron accelerator, presently producing medical isotopes at Canadian Light Source in Saskatchewan, and manufactured by Mevex Corporation, is shown in Fig. 1. Depending on beam energy and average beam power requirements cost could range from $5-$10 million CDN.

An accelerator can deliver its electron beam to materials to examine the effects of heat deposition, to create dislocations in crystal lattices, and to mimic the effect of neutrons on displacements in materials. When coupled to suitable materials (with high Z-numbers such as tungsten or tantalum) the electron beam can be used to generate high-energy photons in the form of bremsstrahlung radiation (X-rays). Bremsstrahlung

radiation can then be used to produce neutrons via the photonuclear (γ,n) process, and also by photo-fission (γ,f) reactions if a fissionable material is used as a primary or a secondary target. By combining the photo-neutron source with a sub-critical reactor blanket, or a number of surrounding fuel assemblies, a large volume of neutron flux can be produced, increasing by a factor of up to 20 relative to one with no fissile fuel assemblies. An accelerator producing a 2.5-mA, 40-MeV electron beam with average beam power of 100 kW will generate a neutron intensity of approximately 2 to $4\times10^{14}$ n/s, depending upon the target material. The neutrons generated have an energy spectrum similar to that of nuclear fission and a nearly isotropic angular distribution. If the primary target is natural uranium (instead of tungsten) there will also be up to $10^{14}$ fissions/s (over 3 kW of fission power).

The neutrons and fission are produced by bremsstrahlung photons of 7 MeV to 30 MeV, which cause (γ,n) and (γ,f) reactions on uranium, not by the direct interaction of the electron beam. Bremsstrahlung can be produced by a high-power converter using water-cooled tantalum or tungsten plates. This technique could enable irradiation of a uranium secondary target inside a boundary such as a test pressure tube that is used as part of a high-pressure SCW loop. The electron beam can be scanned along a converter plate of approximately 10 cm by 2 cm close to the pressure tube. This approach produces only a moderate power density in the pressure tube but still produces both bremsstrahlung heating and fission in a mock-up fuel element.

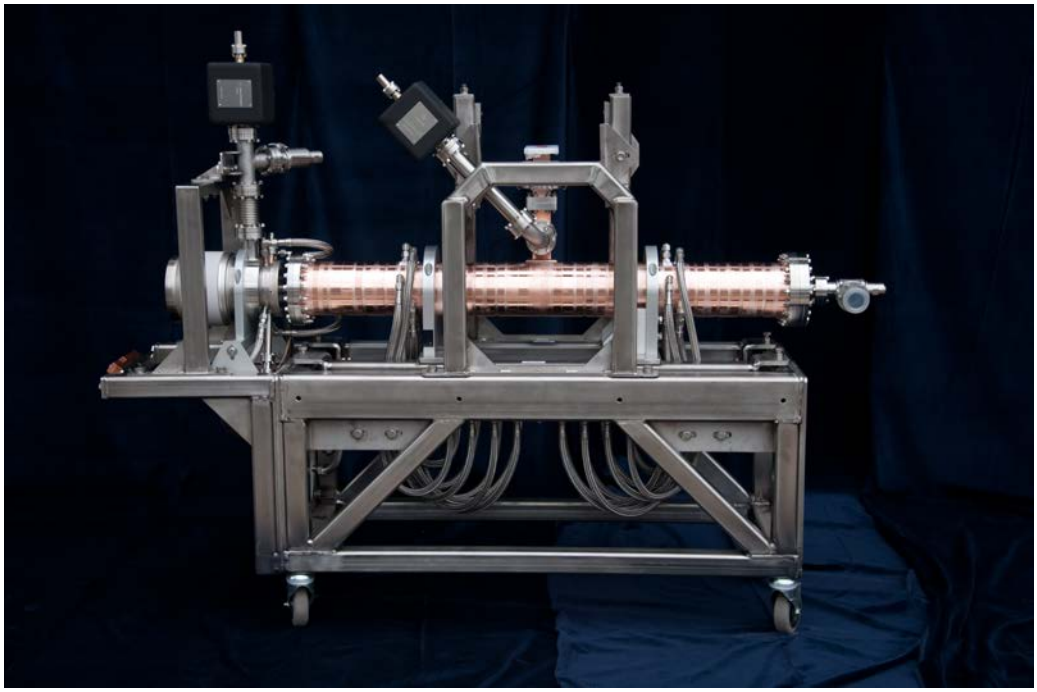

Fig. 1. Mevex Electron Accelerator - 12 MeV, 40 kW, Length: 1.3 m

## 2. Accelerator Neutron Source Facility and Applications

A facility (see Fig. 2) is depicted that consists of one electron accelerator and several rooms each containing a target area. Each room contains a target and experimental equipment including, for example:

- Bremsstrahlung converter and neutron source target (fission spectrum).
- Bremsstrahlung converter and moderated neutron source.
- Combined bremsstrahlung converter/neutron source.
- Electron beam only.
- One or more sub-critical fuel assemblies / reactor blanket.
- Specialized experiments such as a SCW, molten salt, or liquid metal loops.
- Facility to test production of medical or industrial radioisotopes.

The electron beam produced by the accelerator can be easily directed to any of the rooms. Each room can be built of shielding material such as cast-in-place concrete or concrete blocks so that, while one room is being used, the others can be occupied to build, maintain, adjust, or replace experimental equipment. The building housing the facility can be slab-on-grade with a conventional steel frame building. Construction costs would be \$200-\$250/ft$^2$ with cast-in-place concrete (or block) shielding at \$150-\$200/m$^3$. Power to operate the accelerator part of the facility is 400 Volt, 3-phase, approximately 700 kW. Cost of instrumentation and target equipment would depend on applications.

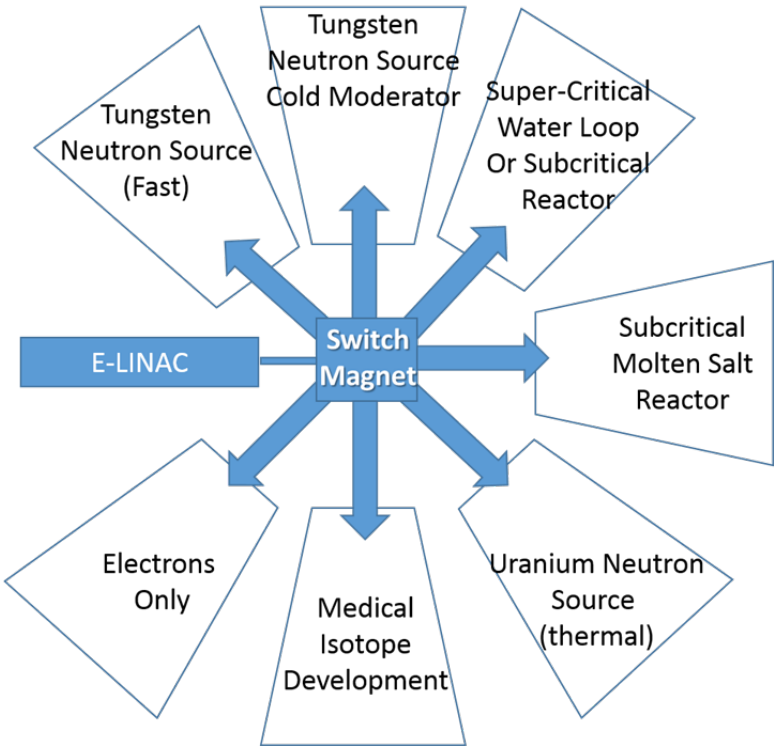


Fig. 2. Block Diagram of User Facility for Electron Accelerator-Based Neutron Source

Fig. 3 shows an example of a bremsstrahlung converter in a water-cooled envelope and a target in its own water-cooled envelope used to produce medical isotopes. The bremsstrahlung is highly forward-peaked in a cone of approximately 20$^o$ and most of it will interact in the metal target with only a small fraction in the walls of the two water envelopes. The separated metal disks in the converter and target with water cooling on each side of the disks allows the use of very high power densities on the assembly (up to 100 kW in a beam diameter of approximately one cm). The bremsstrahlung converter can be optimized using Monte

Carlo analyses of particle transport, but the typical thickness of each plate in the converter target will be approximately one mm. A similar approach can be used for other experimental configurations.

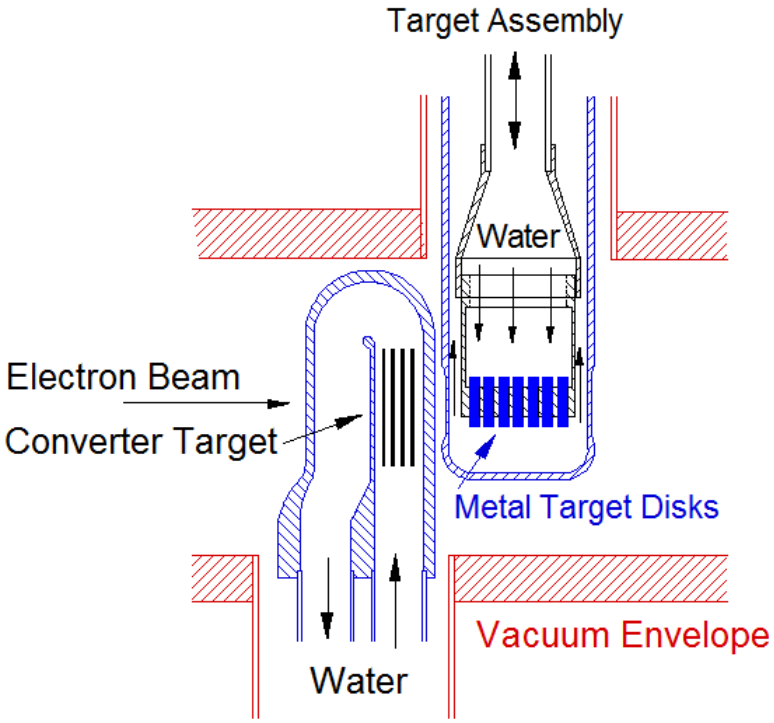


Fig. 3. Basic Electron to Photon to Neutron Target Assembly

The electron beam can also interact directly with a neutron-production target, usually made from tantalum, tungsten, or uranium. A segmented target of three to five cm long would be used with no converter. An electron beam power of 100 kW could be used on a segmented target of 3 to 5 cm diameter and 5 to 7 cm long (to enable water cooling channels), providing a compact bare source of 2 to $4\times10^{14}$ n/s. It would also produce an intense beam of bremsstrahlung photons, strongly peaked in the forward direction. The bare source could be surrounded by a moderator or a sub-critical core to provide a source of thermal neutrons.

For studies of reactor materials and fuels small samples can be irradiated to very high doses in a short time. Combined with small sample Post Irradiation Examination (PIE) techniques, rapid materials evaluation can be done. Another feature of the fast source is the time structure of the electron beam which produces a similar time structure in the resultant fast neutron source. Duration of each beam pulse (100 joule) is 16 microseconds and approximately $1\times10^{12}$ neutrons are produced. This pulse effectively creates an instantaneous neutron dose rate of $6\text{x}10^{16}$ neutrons/s followed by a time that can be varied before the next pulse. Doses of neutrons can be delivered at frequencies up to 1,000 Hz for as long as needed to deliver a total dose to the sample.

The electron beam energy can be applied directly to materials to create displacements similar to those caused by neutrons. The electron beam can also be used to deliver intense and penetrating thermal energy.

Facilities of this type have been built and operated elsewhere. A good compilation is listed in the IAEA TECDOC-1439 [7]. The most recent one under development is the KIPT Facility in the Ukraine [5], [6], which is illustrated in Fig. 4. The KIPT facility is based on an electron accelerator which produces neutrons to drive a surrounding sub-critical reactor.

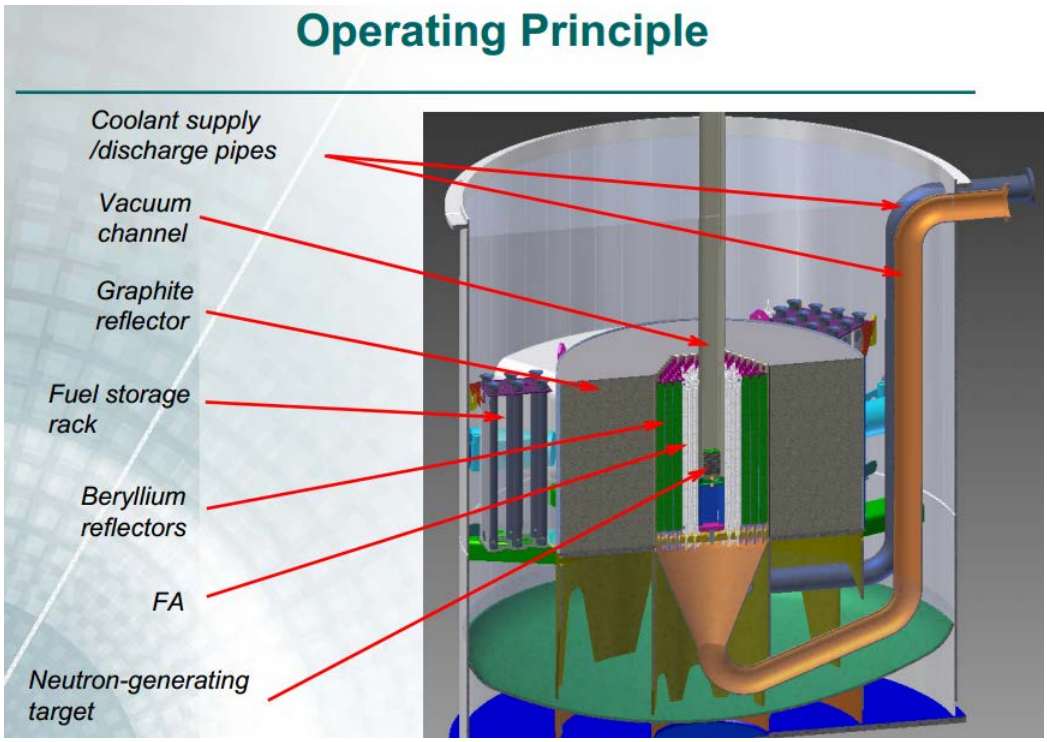


Fig. 4. Layout of KIPT Electron Accelerator-Driven Sub-Critical Facility in Ukraine[1].

## 3. Neutron Fluxes Available

The electron accelerator neutron source, alone, could provide average intensity of approximately $2\times10^{14}$ n/sec with a fission-like neutron energy spectrum. If considered as a point source (actual volume approximately 2.5 cm radius and 6 cm long) and the closest point that can be used to irradiate a sample is approximately 4 to 5 cm, then a fast neutron flux of a 1 to 3 $\times10^{12}$ n/cm$^2$/s could be realized. This primary neutron source could also be moderated (with $H_2O$, $D_2O$, graphite, or BeO) to provide a thermal neutron flux of approximately $2\times10^{11}$ n/cm$^2$/s to a target 20 to 30 cm away, in good agreement with [9]. If the primary neutron source was coupled to a sub-critical fuel assembly, it could provide a larger volume of thermal flux of 1 to $3\times10^{13}$ n/cm$^2$/s for other studies, similar to what is being done with the KIPT facility in Ukraine [5], [6].

## 4. Potential for Development and Deployment in Canada

An electron accelerator-based neutron source could be inexpensive, versatile, and easily sited and licensed. In Canada, all activities with an electron accelerator-driven neutron source can be carried out in compliance with a Class II CNSC (Canadian Nuclear Safety Commission) license, except for the use of sub-critical reactor or fissionable fuel assemblies. The pathway to a complete facility could be staged in evolutionary, affordable steps, as needs develop. This path could start initially with a bare neutron source, moderated or not, and finish with one or more sub-critical fuel assemblies.

The development and implementation of an electron accelerator-based neutron source proposal could be done economically and quickly, making use of existing human resources and facilities available in Canada for example at the National Research Council (NRC) and at the Canadian Nuclear Laboratories (CNL) [8] in Chalk River, Ontario, and elsewhere. Both have resources required for such an implementation and could potentially develop and host an EADNS. Some of the resources and facilities include the following:

**NRC**

- Expert scientific staff in computational physics, radiation transport, instrumentation, materials science, material mechanics, chemistry and corrosion, radiobiology, and other scientific and engineering disciplines.
- Operating electron accelerator with variable beam energy up to 50 MeV.
- Suitable experimental areas.
- CNSC operating license.
- High precision metrology and standards capability.

**CNL**

- A licensed nuclear site.
- Expert scientific staff in neutron scattering, computational physics, neutronics and radiation transport, instrumentation, materials science, material mechanics, thermal-hydraulics, post irradiation examination (PIE) of materials, radiation damage and deformation, chemistry and corrosion, radiobiology, and other scientific disciplines.
- Over thirty supporting experimental facilities, including for example:
    - Analytical Chemistry Laboratories
    - Biological Research Facility
    - Canadian Neutron Beam Centre
    - Digital Radiography and Computer Tomography Facility
    - Fluid Sealing Technology Metrology Facility
    - Fuel Development Laboratories
    - Mechanical Testing Laboratories
    - Metallographic Services Laboratory
    - Model Development Laboratory
    - Nuclear Instrumentation Development Laboratory
    - Surface Science Laboratories
    - Thermalhydraulics Laboratory
    - X-Ray Diffraction Laboratory

- ZED-2 Research Reactor

## 5. Conclusions

An EADNS is described that could be used for studying behavior of new reactor materials and fuels and for neutron scattering. When the need develops, it could be augmented by adding other neutron source targets, moderators, and one or more sub-critical fuel assemblies. The accelerator-based neutron source, by itself, provides an average intensity of approximately $2\times10^{14}$ n/s (useable flux $2x10^{12}$ n/cm$^2$/sec) with a fission-like neutron energy spectrum. That source can be moderated to provide a thermal neutron flux of approximately $2\times10^{11}$ n/cm$^2$/s. If coupled to a sub-critical fuel assembly it could provide large volume moderate flux of approximately $5\times10^{13}$ n/cm$^2$/s for other studies. An EADNS is an option for consideration in Canada, to complement the use of multi-purpose research reactors, and to provide a means to bridge the gap between the closure of older facilities and the construction and opening of new research reactors.

## 6. Acknowledgements

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