

DEVELOPMENT OF MOBILE NEUTRON SOURCES DRIVEN BY X-BAND ELECTRON LINACS FOR INFRASTRUCTURE MAINTENANCE AND NUCLEAR SECURITY

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Abstract

A prototype of compact neutron source has been developed with a combination of a beryllium target and a 3.95 MeV X-band electron linac based X-ray source. Main applications of this neutron source are on-site moisture detection in infrastructures, and nuclear materials measurement in fuel debris for decommissioning Fukushima nuclear power plants. Nondestructive detection of water in concrete have been demonstrated through the fast neutron backscattering method.

INTRODUCTION

We are developing mobile neutron sources driven by electron linear accelerators to solve two problems facing the contemporary Japanese society.

The first problem is aging deterioration of social and industrial infrastructure. Many infrastructures had been built in the high economic growth period of 1960s-70s in Japan. Since these structures will soon exceed their lifetime of about sixty years, there is a strong need for non-destructive inspection of infrastructures which are mainly formed of concrete. In addition to conventional visual and hammering inspections, new methods have been developed to search deep parts of concrete structures which utilize elastic wave, radio waves or high energy X-rays. In a variety of indication of deterioration, the existence of water in concrete implies corrosion of steels, or cracks, void and crumbling of concrete. The detection of water in concrete structures is therefore very important for their maintenance and fixing. High energy neutrons penetrate thick concrete and are thermalized by hydrogen atoms. With this property, we can detect water in concrete nondestructively.

The second problem is decommissioning of Fukushima dai-ichi reactor. The meltdown accident on May 2011 generated nuclear fuel debris, which were mixture of melted core and its surrounding materials, in great quantities. For nuclear safeguards, quantity of nuclear materials, like uranium and plutonium in debris should be measured and controlled when they are removed from around reactor core. The analysis facility for debris in Fukushima starts to be considered with the neutron resonance transmission analysis (NRTA) and the nuclear resonance capture analysis (NRCA) methods. Besides this immobile facility, a mobile/on-site analysis system with a neutron source which can screen melted fuel immediately after taking out it from the reactor is necessary for safety decommissioning.

Moreover, our facility, nuclear professional school of the University of Tokyo, shut down a fast neutron re-

search reactor “Yayoi” in 2011 after forty years operation. We need alternative neutron sources for research and education.

X-BAND LINAC BASED MOBILE X-RAY SOURCES

For the purpose of on-site nondestructive inspections of social/industrial infrastructures, we developed portable X-ray sources based on 950 keV/3.95 MeV X-band (9.3 GHz) electron linac X-ray source several years ago [1]. These accelerating energies are due to Japanese laws and regulations. Electron accelerators with the energy less than 1 MeV are not regarded as radiation generators according to laws concerning the prevention from radiation hazards due to radioisotopes and others. These laws also allow on-site use of electron linacs with the energy up to 4 MeV only for bridge inspection.

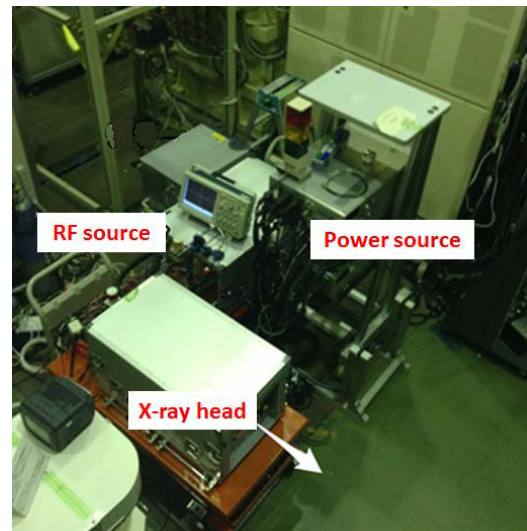


Figure 1: 3.95 MeV X-band electron linac based X-ray source.

This portable system compactly consists of three units: an X-ray head, an RF source (magnetron), and a power system. The X-ray head includes an electron gun, an accelerating tube, a tungsten/copper target for bremsstrahlung and a lead collimator. By adopting X-band (9.3 GHz) for resonance frequency of cavity, short accelerating tube was achieved. The magnetron is connected to X-ray head by a flexible waveguide. X-ray intensity is 50 mGy/min at 1 m away from the source. By using the 950-keV system, we have promoted on-site nondestructive inspections of infrastructures in various environments, for example, a nitrogen acid distillation tower, a reinforced

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concrete pier and a prestressed concrete bridge.

After the success of 950-keV system, a portable 3.95 MeV X-band electron linac driven X-ray source (Fig. 1) have been developed. Its intensity is 40 times higher than the previous system although the basic architecture is almost similar. We demonstrated on-site use of the 3.95 MeV system and obtained X-ray transmission images of a 40-cm thick flange cut from real bridges in only 1 s exposure time.

Table 1: Parameters of 3.95 MeV Linac

RF power output	1.5 MW
Pulse width	4 μ s
Repetition rate	200 pps (max)
Target beam current	100 mA

NEUTRON SOURCE DEVELOPMENT

Our 3.95 MeV system can be applied to a neutron source by utilizing photonuclear reaction. We employ a beryllium target for neutron generation because beryllium has particularly small threshold energy of 1.67 MeV for photo neutron production compared to other conventional heavy metal targets such as lead, tungsten and tantalum. The cross section of beryllium is, however, about two orders of magnitude smaller than those of heavy materials. Figure 2 shows the bremsstrahlung energy spectrum of 3.95 MeV system. 11 % of generated photons have the energy above threshold of photonuclear reaction.

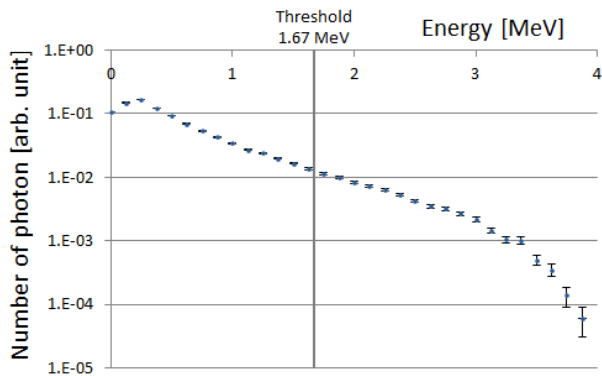


Figure 2: Bremsstrahlung spectrum of 3.95 MeV system.

As a previous study, an Italian group designed a 14-cm-thick beryllium target for a 5 MeV electron linac [2]. Based on this basic idea, we started to design a new target for the 3.95 MeV system with a smaller beryllium block. A mobile X-ray/neutron dual source is so attractive for nondestructive inspections that we adopted an attachment-type target station which should be installed at the downstream of the X-ray head.

Figure 3 shows the developed neutron target station. A beryllium cube 5 cm on a side is surrounded by a graphite reflector layer, a boric acid resin layer for neutron shielding, and a lead layer for γ -ray shielding. Including outer aluminium supports, the total volume of the target station is about 60 cm³. The 5-cm-thick beryllium target can

potentially generate neutrons with the total intensity of $\sim 10^{10}$ n/s when all the photons generated at the 3.95 MeV system are injected into the target. This intensity is one order of magnitude larger than portable D-D/D-T neutron sources [3].

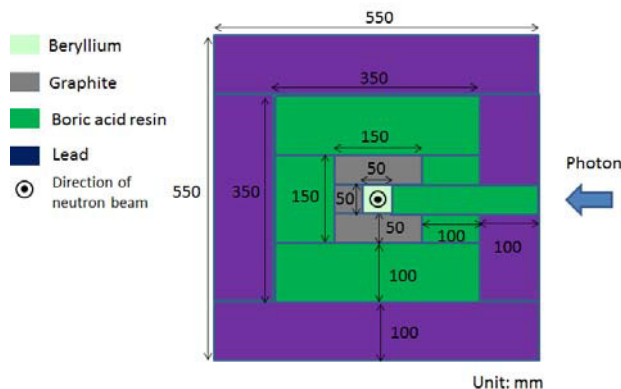
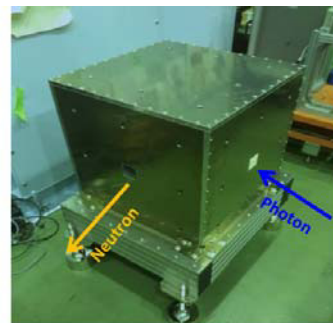


Figure 3: Exterior (top) and cross-sectional (bottom) views of neutron target station.

DETECTION OF WATER IN CONCRETE WITH NEUTRON BACKSCATTERING

RI Neutron Source

Hitachi Power Solutions Co., Ltd. has offered commercially a low-noise type neutron moisture meter “Suikoden” for nondestructive detection of water in lagging material of pipes and tanks at chemical plants [4]. Suikoden includes a radio isotope ²⁵²Cf (0.1 μ g = 2 MBq) as neutron source, a polyethylene moderator, and a ³He neutron detector. ²⁵²Cf source emits fast neutrons with the energy peak between 0.5 and 1.0 MeV. These fast neutrons are backscattered and thermalized by hydrogen atoms in infrastructures. The scattered thermal neutrons are detected efficiently by the ³He detector with multi-slit collimators which reduce background neutrons scattered by some part other than region of interest.

As mentioned in the introduction, nondestructive detection of water in concrete is also a major problem particularly in road maintenance. Figure 4 shows cross-sectional view of the ordinary road, which consists of asphalt pavement and concrete slab. For instance, “gravelization” of concrete slab is a serious deterioration of the road. Gravelization means collapse of concrete slab into sands and gravels by repeated loading. Gravelized slab usually includes rain water.

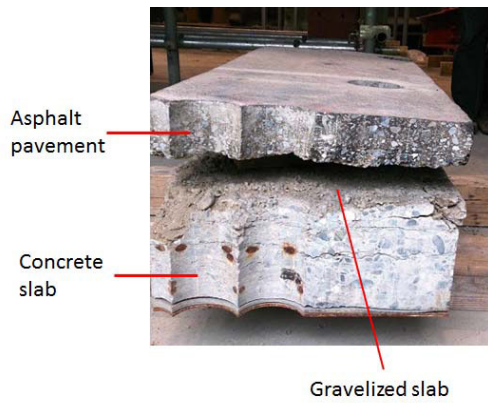


Figure 4: Cross-sectional view of road.

As a pilot study, we tried to detect water in gravelized slab with the Suikoden. The water of 200 mL was infiltrated into the gravelized slab within a radius of about 20 cm, and the 7-cm-thick asphalt pavement was put on the slab. The neutron counts detected by the Suikoden on the pavement were 1148 neutrons/20 s and 1248 neutrons /20s before/after water infiltration, respectively. In consequence, the californium moisture meter could detect water under the asphalt with 3σ confidence level.

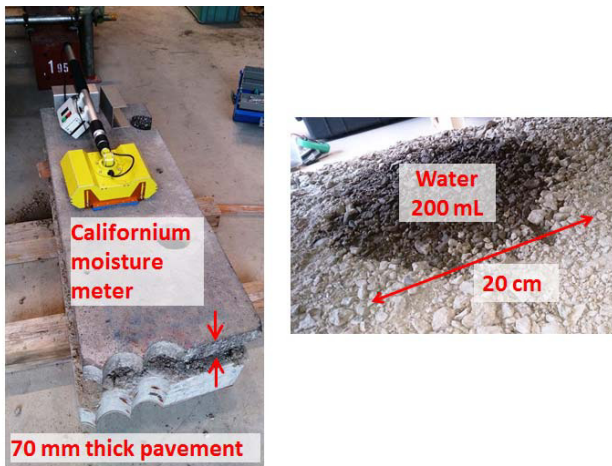


Figure 5: Water detection with californium moisture meter “Suikoden”.

3.95 MeV Electron Linac Based Neutron Source

We carried out a similar experiment with the 3.95 MeV system driven neutron source (Figure 6). Water of 200 mL in a polyethylene bag was placed between 6.5-cm-thick pavement and 14.5-cm-thick slab. The center of the neutron source was located 90 cm apart from the pavement surface. A ³He neutron detector was installed between the neutron source and samples. Because in this setup the beryllium target was 1 m apart from the X-ray source and the average electron current was reduced 37.5% of the full power operation, the expected total intensity was ~ 10⁷ n/s. The measured neutron counts were 1968 neutrons/1800 s and 1838 neutrons /1800s with/without water, respectively. From the difference between these counts, water was detected with 2.1σ confidence level. In this measurement, the background counts from the envi-

ronment were unfortunately very large and about 70% of the total counts. We still have room to improve signal to noise ratio by adding the detector shielding and collimator.

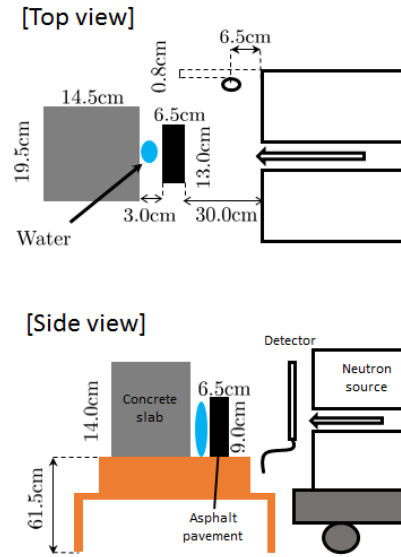


Figure 6: Experimental setup for water detection with 3.95 MeV electron linac based neutron source.

CONCLUSION

We have developed a new compact neutron source based on a 3.95 MeV X-band electron linac by utilizing photonuclear reaction on a beryllium target. With fast neutrons generated from this source, water in a concrete slab was indirectly identified. Our approach also realizes a mobile X-ray/neutron hybrid source system.

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REFERENCES

- [1] M. Uesaka *et al.*, “On-site nondestructive inspection by upgraded portable 950keV/3.95MeV X-band linac x-ray sources”, *J. Phys. B: At. Mol. Opt. Phys.*, vol. 47, p. 234008, 2014.
- [2] L. Auditore *et al.*, “Study of a 5 MeV electron linac based neutron source”, *Nucl. Instrum. Meth. B*, vol. 229, pp. 127-143, 2005.
- [3] M. Uesaka *et al.*, “Compact Neutron Sources for Energy and Security”, *Rev. Accel. Sci. Tech.*, vol. 8, pp. 181-207, 2015.
- [4] Hitachi Power Solutions Co., Ltd., http://www.hitachi-power-solutions.com/products/product02/p02_61.html