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30 MeV X-band electron linac neutron source for nuclear data study for Fukushima accident analysis

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Abstract

X-band (11.424GHz) electron linac as a neutron source for nuclear data study for the Fukushima nuclear plant accident is under development. Originally we developed the linac for Compton scattering X-ray source. Quantitative material analysis and forensics for nuclear security will start several years later after the safe settlement of the accident is established. For the purpose, we should now accumulate more precise nuclear data of U, Pu, TRU and MA (Cm, Am, etc.) especially in epithermal (0.1-10 eV) neutrons. Therefore, we have decided to suspend the Compton scattering X-ray experiment and move the linac in the core space of the experimental nuclear reactor "Yayoi" which is now under the decommission procedure. Due to the compactness of the X-band linac, the electron gun and accelerating tube and other components can be installed in a small space in the core. First we plan to perform the TOF (Time Of Flight) transmission measurement for study of the total cross sections of the nuclei for 0.1-10 eV neutrons. Therefore, if we adopt a TOF line of less than 10 m, the macro-pulse length of generated neutrons should be shorter than 100 ns. Electron energy, macro-pulse length, power and neutron yield are ~30 MeV, 100 ns - 1 μs, ~0.4 kW and ~10^{12} n/s, ~10^{3} n/cm^{2}/s at samples, respectively. Optimization of the design of a neutron target (Ta, W, ^{238}U), TOF line and neutron detector (Ce:LiCAF) of high sensitivity and fast response is underway. For the purpose, we are upgrading the electron gun and buncher to realize higher current and beam power with a reasonable beam size in order to avoid damage of the neutron target. Although the neutron flux is limited in case of X-band electron linac based source, we take advantage of its short pulse aspect and availability for nuclear data measurement with a short TOF system. We plan to perform the two phased development and measurement. First, we form a tentative configuration in the current experimental room for Compton scattering in 2014. Then, after the decommissioning has been finished, we move it the "Yayoi" room and perform the operation and measurement.

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1. Introduction

We plan to use our X-band electron linac (11.424GHz, 30 MeV) [1] as a linac based neutron source [2,3] for the nuclear data study for the Fukushima nuclear plant accident. Originally we developed the linac for Compton scattering X-ray source. Quantitative material analysis and forensics will start several years later after the safe settlement of the accident is established. For the purpose, we should now accumulate more precise nuclear data of U, Pu, TRU and MA especially in epithermal (0.1-10 eV) neutrons. Therefore, we have decided to suspend the Compton scattering X-ray experiment and allocate the linac in the core space of the experimental nuclear reactor "Yayoi" (see Fig. 1) which is now under the decommission procedure. Yayoi is the experimental fast neutron reactor (< 1 MeV neutron, 2 kW, 10^{11} neutrons/cm^2/s), which is now under decommission. Fig. 2 depicts the staged development of advanced and compact electron linacs at University of Tokyo. From the medium sized S-band (2.856 GHz) linacs to the portable X-band (9.3 - 11.424 GHz) 950 keV, 3.95, 6, 30 MeV linacs and the on-chip laser dielectric linac are under operation and development. Especially, due to the compactness of the X-band 30 MeV linac, it can be installed into the fuel core space. Therefore, we can reuse the whole shielding structure of the reactor, the neutron beam-lines and the control room. It is becoming more important to maintain the activity as a neutron source facility recently. This is because several old experimental reactors are going to be shut down.

Fig. 1. Fast Neutron Experimental Reactor "Yayoi".

Fig. 2. S-band, X-band and laser dielectric linac.

2. 30 MeV X-band (11.424GHz) electron linac

Accelerating structures of S-band (2.856 GHz, wavelength 105 mm), C-band (5.712 GHz, 50.3 mm) and X-band (9.3 GHz, 32.3 mm) linacs and cancer therapy systems using them are depicted in Fig. 3 in order to explain the dependence of the size of the medical device on the accelerating RF frequency. As the RF frequency is higher, it becomes smaller. Therefore, it can be installed in the smaller moving boxes. S-band linac is widely adopted for comformal RT and IMRT (Intensity Modulated Radiation Therapy). X-band and C-band linacs are adopted for stereotactic RT such as Cyberknife and dynamic tracking therapy due to their compactness, recently (see Fig. 3).

Recently, X-band linac is adopted such a backup for international linear collider, which is CLIC by CERN, and FEL by Elettra, Syncrotrone-Trieste and Compton scattering γ-ray system for nuclear physics in ELI (Extreme Light Infrastructure) [4].

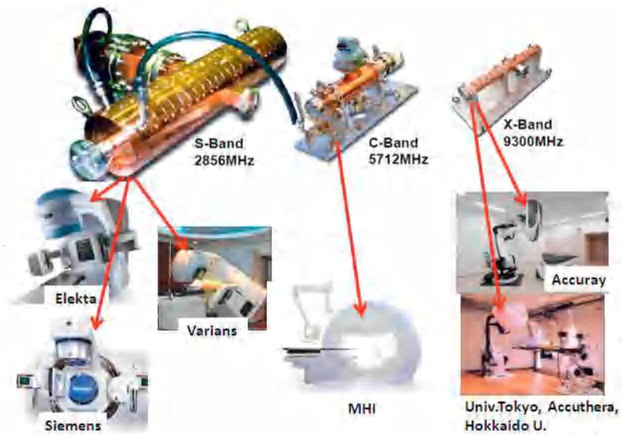


Fig. 3. S-band (2.856GHz), C-band (5.712GHz), X-band (9.3GHz) accelerating structures and cancer therapy systems.

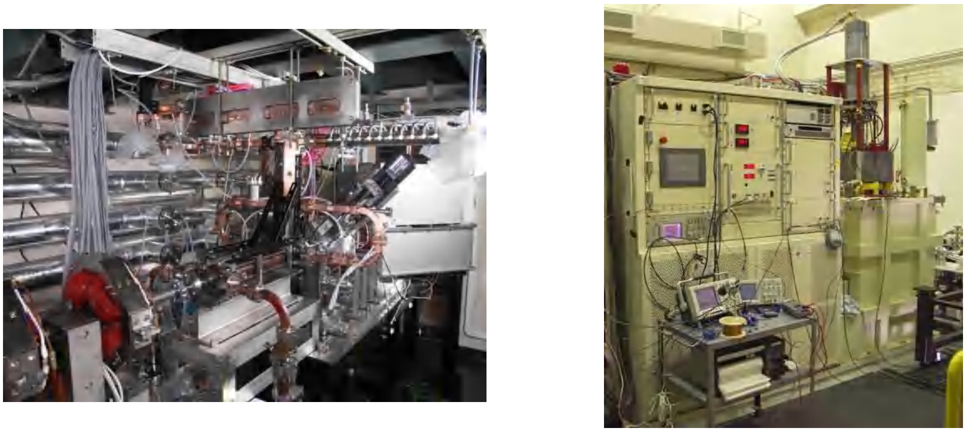


Fig. 4. 30 MeV X-band (11.424 GHz) Electron Linac. (a) Accelerating structure and magnets. (b) Modulator (500 kV, 1 ms:left) and klystron (50 MW:right).

It is basically designed and operated as a Compton scattering monochromatic X-ray source. The X-band linac (see Fig. 4 (a)) consists of the 3 MeV thermionic RF gun, solenoid magnet for focusing, α magnet as an energy filter, 700 mm accelerating tube and other components. 50 MW X-band klystron and 500 kV, 1 μs modulator are used as shown in Fig. 4 (b). ~10^4 micro-bunches of 20 pC and 1 ps (rms) forms 200 mA for 1 μs and 10 μA in average at 50 Hz. The macro-pulse length can be tuned down to 100 ns. 3 MeV thermionic RF gun, solenoid magnet and α magnet are adopted for low emittance beam with the radius of 0.1 mm (rms) at the collision point with our YAG laser. However, not low emittance but high average current is crucial as a neutron source. Therefore, the low energy part is replaced with 20 keV triode thermionic gun and 5 MeV traveling wave buncher to get ~0.4 kW beam output. The electron gun can emit a beam of up to 400 mA at 20 kV. The capture efficiency of the buncher is about 1/2-1/3 and the buncher accelerate to 5 MeV with 150 mA. The regular accelerating structure accelerates electrons up to 30 MeV. Average beam power is 375 W. The electron and X-ray beam spots are kept to be ~2 mmϕ in order to avoid the damage of the neutron target. Fig. 5 shows a block diagram of the system. The important specifications are summarized in Table 1.

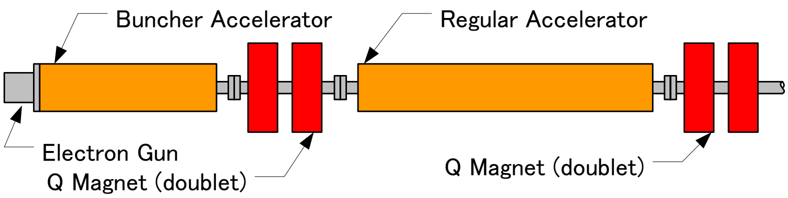


Fig. 5. Block diagram of the upgraded X-band 30 MeV linac specialized for neutron source.

Table 1. Specification of the upgraded X-band linac.

Linac					
Electron beam energy	30	MeV	Group velocity/c	4(average)	%
Beam current (at target)	150	mA	Attenuation coefficient	0.5(average)	Naper/m
Pulse width	0.1-1 (variable)	μsec	Regular accelerator		
Repetition rate	50	pps	Number of cells	60	
Average beam power	0.375	kW	RF section length	0.523	m
Electron Gun			Q (Quality factor)$_0$	6593	
Voltage	20	kV	Shunt Impedance	95.6(average)	MΩ/m
Beam current	400 (max)	mA	Group velocity/c	3.97(average)	%
Buncher accelerator			Attenuation coefficient	0.478(average)	Naper/m
Number of cells	30		RF source		
RF section length	0.26	m	Pulse width	1	μsec
Q_0	6000		Power in buncher acceleraotr	6	MW
Shunt Impedance	85(average)	MΩ/m	Power in regular accelerator	35	MW

Schematic drawing of allocation of the linac to the Yayoi area is shown in Fig. 6. The accelerating structure with the new 20 keV gun and 5 MeV buncher are inserted in the core space of the reactor. The klystron and modulator are put aside the shielding structure. 5, 10, 40 m long TOF lines are planned to be built step-by-step as shown in Fig. 6. The 5 m long TOF line can be set in the Yayoi room. Another experimental room exists next to the Yayoi room, which appears in the upper side in Fig. 6. The 10 m long TOF can be formed crossing across the wall between the two rooms via the beam port. The 40 m long TOF line is also available forward outside the building, which is depicted in the right-hand side in Fig. 6. We used to have and depose of this, but we plan to rebuild it with advanced detecting systems.

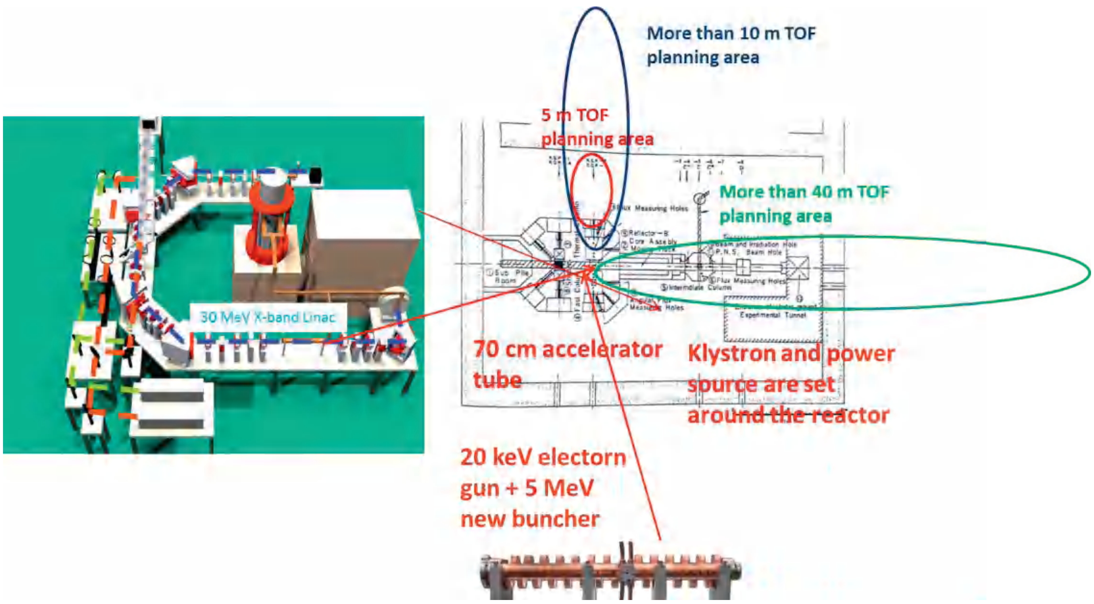


Fig. 6. Allocation of the linac to Yayoi area.

3. Design of TOF line and detector for Fukushima nuclear accident analysis

We should prepare more precise nuclear data of U, Pu and related nuclei for the quantitative material analysis and forensics of melted fuel and structural materials. Neutron active method is most promising for the purpose. First, we plan to perform the TOF transmission measurement for determining the total cross sections of the nuclei for 0.1-10 eV neutrons as shown in Fig. 7. Uncertainty of the data of Pu in this region contains ~5% [5] while less than 1% for thermal neutrons. We have to upgrade the precision down to a few %.

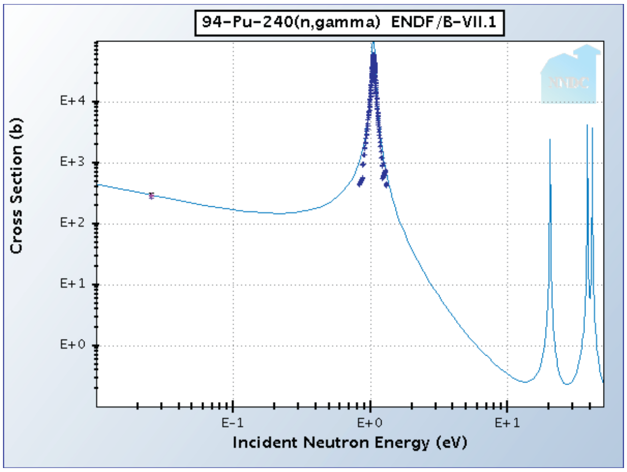


Fig. 7. (n, γ) cross section of 94-Pu-240 for 0.1-10 eV neutron.

We are working for the optimization of the design of a neutron target (Ta, W, depleted U) and moderator, TOF line and neutron detector (Ce:LiCAF) of high sensitivity and fast response. One example of the time-energy relation of neutron obtained by J-PARC is shown in Fig. 8. 0.1 - 10 eV energy range corresponds to ms time delay at TOF. In order to get this range and resolution at a TOF line of less than

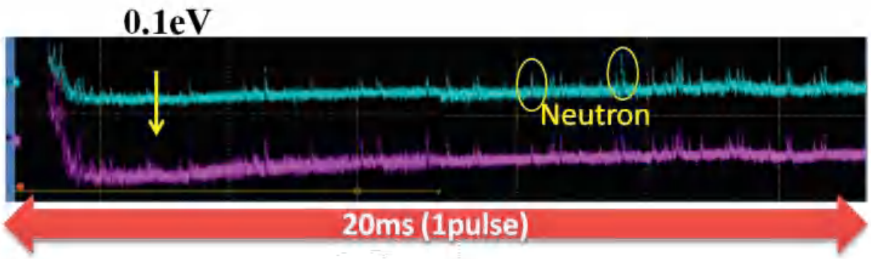
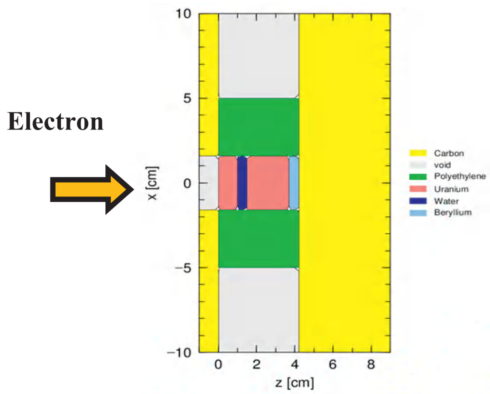
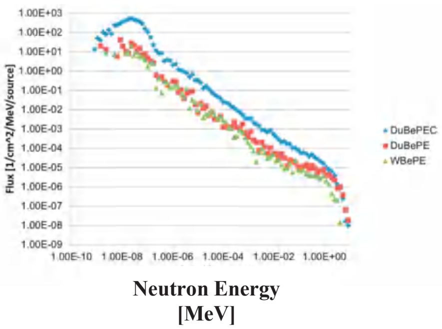


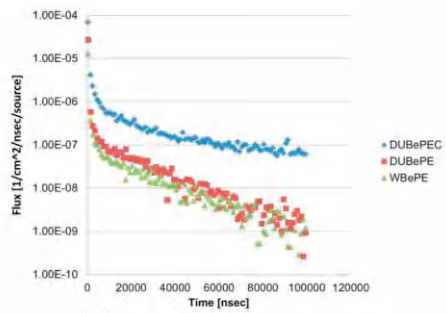
Fig. 8. Example of the time-energy relation of neutron obtained by J-PARC.



(a) Cross section of the neutron target.



(b) Neutron energy spectra.



(c) Relative neutron fluxes calculated by PHITS.

Fig. 9. Neutron target design and calculated relative flux.

10 m, the pulse length of electron and neutron should be around 100 ns. Electron energy, macro-pulse length, power and neutron yield are ~30 MeV, 100 ns - 1 μs, ~0.4 kW and < 10^{12} n/s, respectively. Cross section of the updated neutron target design, calculated energy spectra and fluxes by one electron by the PHITS code for several compositions are depicted in Fig. 9. We can observe the enhancement of neutron yield by using depleted Uranium (DU). Since we want 100 ns neutron pulse, all the time responses do not affect the pulse shape. The target consists of carbon (C), void, polyethylene (PE), depleted Uranium (DU), water (W) and Beryllium (Be) for neutron generation, modulation and finally control of energy spectrum.

Since the neutron yield for 100 ns short pulse is rather limited, we have to design highly sensitive detector. For the purpose, we adopt Ce:LiCAF as a scintillator. We are developing its detector system. One example of the signals for neutrons from Cf-252 and γ–rays from Co-60 is shown in Fig. 10. Moreover, we plan to form a large detection area to enhance the signal intensity. Finally, we expect to realize ~10 times more signal-to-noise ratio compared to a conventional BF_6 detector.

This project has been approved by the Japanese government and funded for 2013 - 2015. Now all components are designed and manufactured. Installation, commissioning and measurement start in 2014.

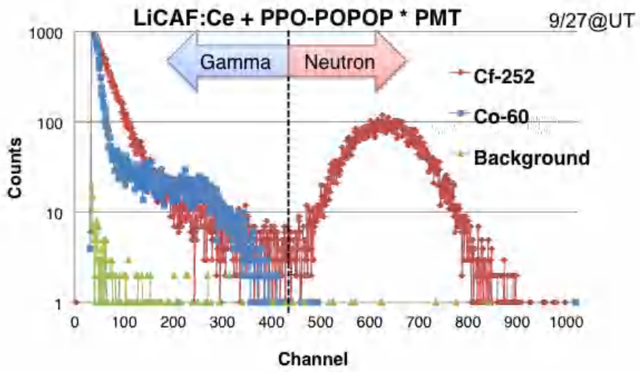


Fig. 10. Signals from for neutrons from Cf-252 and γ-rays from Co-60.

4. Operation and measurement in the preliminary configuration

We take the two phased development, operation and measurement. First, we form a tentative configuration in the current experimental room for the Compton scattering in 2014. Then, after the decommissioning of Yayoi has been finished, we move it to the "Yayoi" room and perform the operation and measurement. The preliminary configuration is shown in Fig. 11. The new 20 keV electron gun and 5 MeV buncher are replaced with the current 3 MeV thermionic RF gun. The new neutron target is installed just after the accelerating structure. Then, the samples and neutron detector for nuclear data measurement are set so as to realize ~5 m long TOF line as shown in Fig. 11, which is almost equivalent to the 5 m long TOF line in the Yayoi room (see Fig. 6). We plan to start neutron generation and experiment in early 2014. We shall start the nuclear data measurement with Au samples in the epithermal neutron energy region of 0.1-10 eV. This is because the nuclear data of Au in the neutron energy region pose sufficient precision and good for calibrating the whole system. Then, we shall move the linac and 5 m long TOF line to the Yayoi room after the Yayoi decommission. Then, we plan to use the sample of nuclear materials of U, Pu, Cm, Am, etc. there.

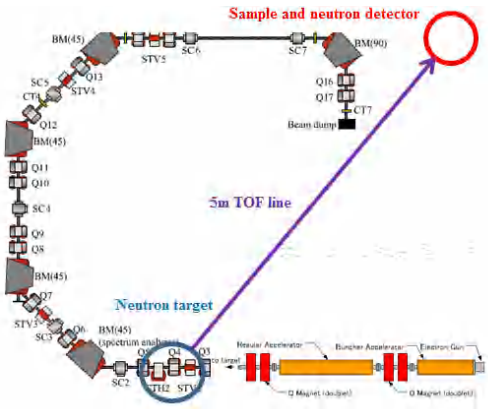
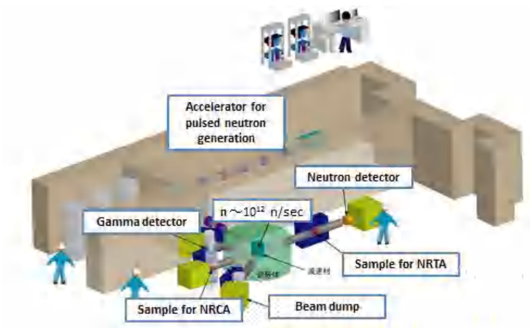


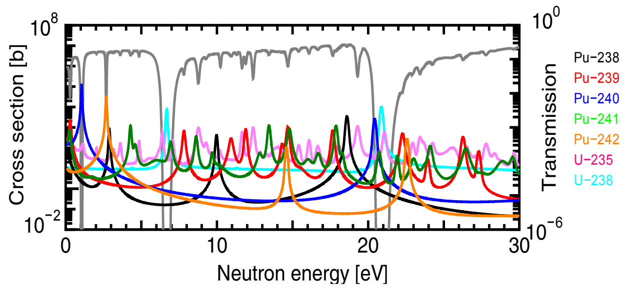
Fig. 11. Preliminary configuration in the current room of the X-band linac.

5. Future nuclear fuel debris analysis in Fukushima

Quantitative material analysis and forensics for nuclear security will start several years later after the safe settlement of the problems and decontamination are finished. Nuclear fuel debris analysis facility is now considered and designed by JAEA as shown in Fig. 12 (a) [6]. ~ 1 kW class electron linac based neutron source is assumed to be used there. Both the neutron resonance transmission analysis (NRTA) and nuclear resonance capture analysis (NRCA) are used. Typical numerical result of NRTA is given in Fig. 12 (b) [7, 8]. Furthermore, 1 kW 30 MeV S-band linac as a neutron source for the purpose is also designed. The fundamental parameters are shown in Table 2. The tube length is as short as 1.9 m.



(a) NRTA and NRCA facility (from Ref. 6)



(b) Typical numerical result of NRTA (from Refs. 7 and 8)

Fig. 12. Expected neutron transmission result by using the precise nuclear data.

Table 2. Specification of the proposed 50 kW class S-band linac for nuclear fuel debris analysis.

Beam energy	35 MeV		
Beam current	0-324 mA (continuously variable)	Klystron	
Pulse width	0.1-20 μsec (variable)	Type	Toshiba E3783
Repetition	0-250 (continuously variable)	Peak Power	4.5MW
Beam power	1 kW (short pulse mode)	Pulse width	0.5 μ sec (short pulse mode)
	50 kW (Generally) , 60kW (Max)		20 μ sec
Frequency	2856 MHz (S-band)	Repetition	250pps
Tube Length	1.9 m (traveling-wave type)		

6. Comclusion

X-band (11.424 GHz) 30 MeV electron linac as a neutron source (~10^{12} n/s, ~10^3 n/cm^2/s at samples) for the nuclear analysis for the Fukushima nuclear plant accident is developed. For the purpose, we are manufacturing the 20 keV triode electron gun and 5 MeV traveling wave buncher to realize higher current and beam power (~0.4 kW) with a reasonable beam size in order to avoid damage of the neutron target. Optimization of the design of the neutron target (Ta, W, U), TOF line and neutron detector (Ce:LiCAF) of high sensitivity and fast response is underway. We plan to perform the two phased development and measurement. Although the neutron flux is limited in case of X-band electron linac based source, we take advantage of its short pulse aspect and availability for nuclear data measurement with a short TOF system. First, we form the preliminary configuration in the current experimental room in 2014. Then, after the decommission has been finished, we move it the "Yayoi" room and perform the operation and measurement.

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