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# APPLICATIONS OF PARTICLE ACCELERATORS

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## *Abstract*

Applications of particle accelerators amid global policies of carbon neutrality and economic security. are reviewed. Downsizing of high energy large scaled accelerators by advanced technologies enables a variety of medical and industrial uses. One of the highlights is upgrade of sustainable supply chain of medical radioisotopes by the best mix of research reactors and accelerators. $^{99}$Mo/$^{99m}$Tc for diagnosis are going to be produced by low enriched U reactor and proton-cyclotron, electron rhodotron and electron linac. Moreover, the theranostics by $^{177}$Lu (beta) and $^{211}$At/$^{225}$Ac (alpha) are going to be realized. Proton-cyclotron and electron linac are expected to produce them soon. This new affordable radiation therapy should play an important role in the IAEA project of Rays of Hopes. Next, proof-of-principle trails of on-site bridge inspection of the portable X-band (9.3 GHz) electron linac X-ray/neutron sources are under way. The technical guideline for the practical inspection is to be formed in a couple of years. They are also expected to apply on-site material analysis at the decommissioning of TEPCO Fukushima Daiichi Nuclear Power Station.

## DOWNSIZING OF ACCELERATORS

Particle, energy and choice of accelerator are schematically described in Fig. 1. What kind of reaction is needed gives the choice of particle, energy and finally type of accelerator. If you induce chemical, atomic and nuclear reactions, the ranges of the energy become eV, keV and more than MeV, respectively. In order for the beam to penetrate into a macroscopic specimen, at least hundreds keV is necessary for the beam energy. Depending on the beam energy from hundreds keV to GeV, the choice of accelerator varies as electrostatic, linac, cyclotron and synchrotron, basically. Other new accelerators are now available, too. As for the linear collider, the linac is again chosen to reduce SR loss.

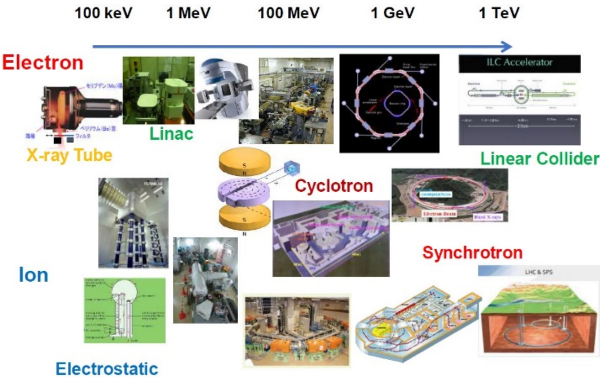

Figure 1: Particle, energy and choice of accelerator.

Downsizing of high energy big accelerator is crucial for saving the space, budget and so on. Higher RFs like S/C/X-bands are adopted for smaller electron linac. Even laser plasma acceleration (THz) and optical dielectric laser acceleration are under development. Concerning ion accelerators, superconducting magnet and optimization of alignment are the key techniques for downsizing. Laser plasma ion injector is expected to be used for the quantum knife, which is the carbon superconducting synchrotron, of QST (National Institutes for Quantum Science and Technology) in Japan.

This downsizing of accelerators offers a variety of applications in a limited space with a reasonable budget and further portability for on-site one-table-top operation [1, 2].

## MEDICAL RI PRODUCTION BY BEST MIX OF RESEARCH REACTORS AND ACCELERATORS

Most of medical radioisotopes are produced by highly enriched uranium (U) research reactors and supplied via air transportation in the world. Actually, those research reactors are facing the aging problem. Due to the security on nuclear and supply chain, the current supply chain of $^{99}$ Mo is expected to shift to regional supply chain based on low enriched U research reactors and accelerators such as electron rhodotron, linac and proton cyclotron (see Fig. 2).

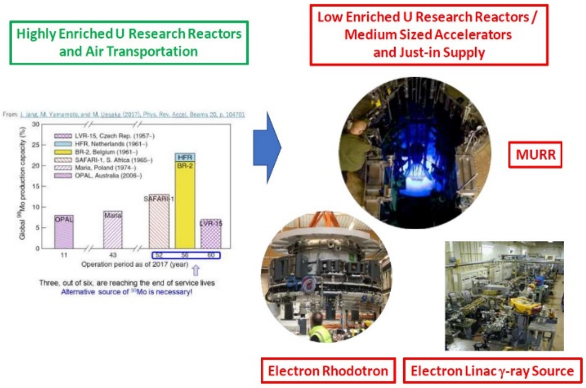

Figure 2: Supply chain shift of $^{99}$Mo.

Figure 3 explains theranostics ("therapeutic and diagnosis") by using $^{225}$Ac. These are the very famous and outstanding achievement of treatment of prostate cancer with multiple metastasis by Dr. Kratochwil's group of University Hospital Heidelberg [3]. Theranostics is a combination of therapy and diagnosis using the different RIs and the same carrier. Here, the $^{225}$Ac-PSMA (Prostate Specific Membrane Antigen) is used as therapy while the $^{68}$Ga-PSMA PET (Positron Emission Tomography) is used as diagnosis. Not only the prostate cancer but also multiple metastasis disappears remarkably.

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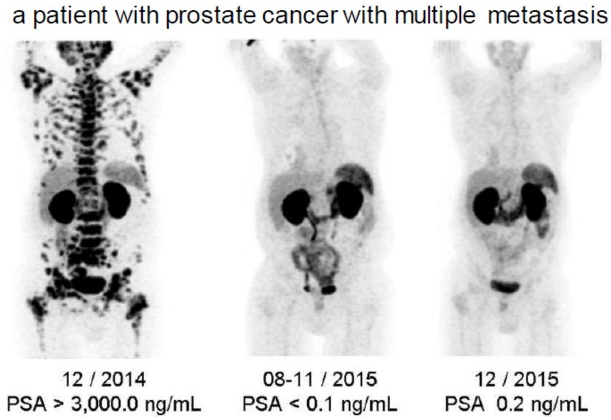

Figure 3: Theranostics by $^{225}$Ac for prostate cancer [3].

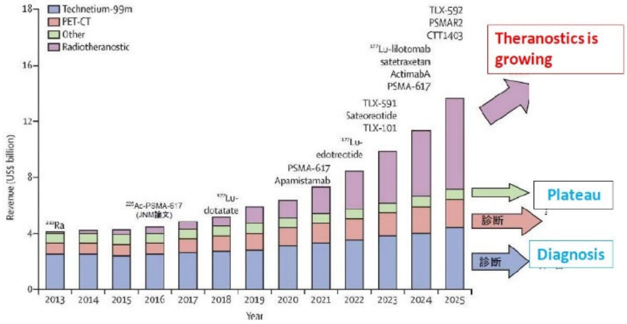

Figure 4: Growth of theranostics use [4].

Annual statistics and forecast of the medical RI market is given in Fig. 4. Although the diagnosis is in a plateau, theranostics is growing.

In promising manufacturing methods, there are three groups, namely high energy proton cyclotron and $^{232}$Th target, low energy proton cyclotron and $^{226}$Ra target, and medium-sizes electron linear accelerator γ-ray source and $^{226}$Ra target in the world. They are expected to supply $^{225}$Ac to the medical world in near future.

Research Fast Reactor, Joyo, of JAEA (Japan Atomic Energy Agency) is expected to restart in a couple of years. This fast neutron spectrum compared to that of Light Water Reactor is suitable to produce $^{225}$Ac by inserting solid $^{226}$Ra targets in the reactor core.

QST and Nihon Mediphysics Co. are performing basic research on $^{225}$Ac yield by solid $^{226}$Ra and proton cyclotron in Japan. They have developed this solid $^{226}$Ra target and successfully achieved about 200 μCi (tens kBq) $^{225}$Ac.

Moreover, 35 MeV 35 kW S-band Electron Linac γ-ray source for production of $^{99}$Mo/$^{99m}$Tc and $^{225}$Ac is proposed by University of Tokyo and others as shown in Fig. 5. Experimental verification of production and medical use of 99Mo / 99μTc by the linac has been performed [5–8]. In addition, Nihon Mediphysics Co. is constructing a similar system for $^{99}$Mo/$^{99m}$Tc production. They are planning to start supplying them very soon.

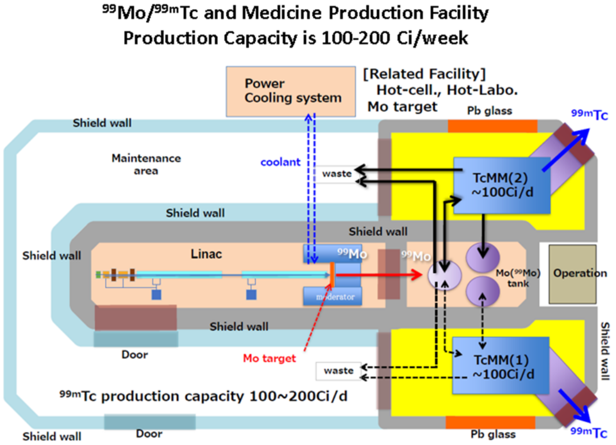

Figure 5: 35 MeV /35 kW Electron linac γ-ray source for medical RIs production [1].

The Japan Atomic Energy Commission (JAEC) launched its Advisory Committee for Promotion of Production and Utilization of Medical Radioisotopes last November and has finalized the Action Plan on May 31$^{st}$. The Action Plan aims to provide domestic radioisotopes to patients. The goals are to be achieved during this decade. As the Japan's stance toward radioisotope production, the JAEC's Action Plan has been included in the Basic Policy on Economic and Fiscal Management and Reform 2022 which has been approved by the Cabinet on June 7, 2022. That means the Action Plan will be realized as we move toward the future.

In the other hand, in February 2022, the IAEA has declared and started the new campaign named "Rays of Hope" initiative. Rays of Hope will integrate the breadth of the IAEA's expertise to support the member states in the diagnosis and treatment of cancer using radiation medicine. The JAEC and the IAEA are discussing on inclusion of Theranostics in Rays of Hope.

As one possibility, nuclear medicine from nuclear waste is proposed by the University of Tokyo. Even though the research reactors and accelerators and chemical processes are prepared, we have to import targets of high purity $^{100}$Mo, $^{98}$Mo, $^{226}$Ra and so on. On the other hand, there are a lot of $^{226}$Ra in U mining wastes and $^{100}$Mo and $^{98}$Mo in nuclear spent fuels, radioactive liquid wastes and nuclear fuel debris. From the point of view of chemical engineering, it is not so difficult to extract and form the target of $^{226}$Ra and $^{98/100}$Mo from the above nuclear wastes. However, we have to deal with several regulations on nuclear spent fuel and radioisotopes, of course. If we can utilize the target of $^{226}$Ra and $^{98/100}$Mo from the nuclear wastes, we can establish a perfect supply chain in Japan.

We are proposing the best mix of supply for both energy and medical RIs for the sustainable, safe, stable and secure society, as shown in Fig. 6.

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Figure 6: Best mix of supply for energy and medical RIs.

## SUSTAINABLE SOCIAL INFRASTRUCTURE

The University of Tokyo is attempting the quantitative evaluation of the aging stage of reinforced ion rods / wires and unfilled grout in prestressed concrete (PC) bridges by using the portable X-band (9.3GHz) electron linac 950 keV/3.95 MeV X-ray sources, which are shown in Figs. 7–10 [9–12]. We obtained the gray value profiles from the measured X-ray transmitted images and calculated the ratios of the gray values of the PC wires and grout.

In this measurement and analysis, iron PC wires, filled grout, concrete, and unfilled grout appeared to be black, very dark, dark, and bright, respectively [11]. As the image was darker, the gray value decreased in this analysis. It is possible that the stage of unfilled grout could be quantitatively evaluated as the gray value ratio between the PC wires and grout part by stacking more experiences and data. If the stage looks rather unfilled, further detailed inspection, such as destructive evaluation by boring surveys, for instance, should be performed.

This method is applicable to a wide range of scenarios and supports the overall strength evaluation of bridges for safety maintenance. Actual on-site inspection of PC highway bridges and analysis of the results are underway. We proposed a guideline for X-ray inspection using the 950 keV/3.95 MeV X-ray sources accompanied by visual and hammering-sound screenings, structural analysis, final repair, and / or reinforcement, as described in Fig. 11. The purpose is to extend the lifespan of PC bridges worldwide. The academic and industrial consortium is successfully performing the 950 keV/3.95 MeV X-ray inspection and evaluation of grout filling for a box-shaped PC girder highway-bridge in Japan. Detailed results will be presented in the near future.

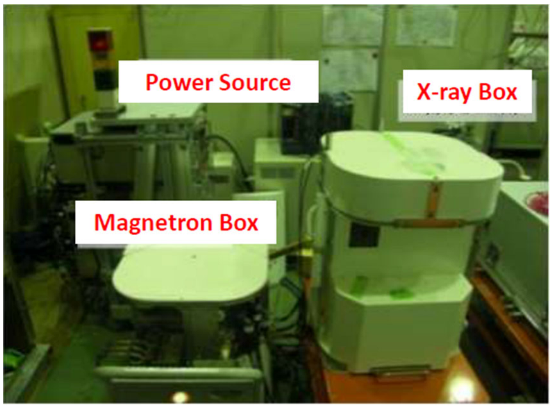

Figure 7: 950 keV portable X-band linac based X-ray source. The maximum X-ray energy is 950 keV. The system consists of three units: X-ray head, magnetron, and power units.

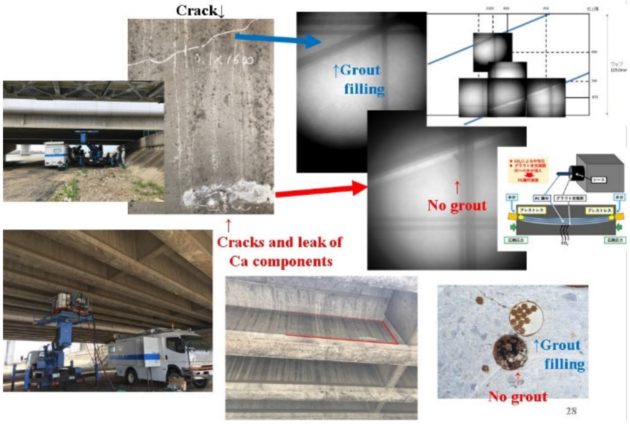

Figure 8: Updated results of on-site X-ray inspection of bridges of about 50 cm thick iron-reinforced concrete by the 950 keV source.

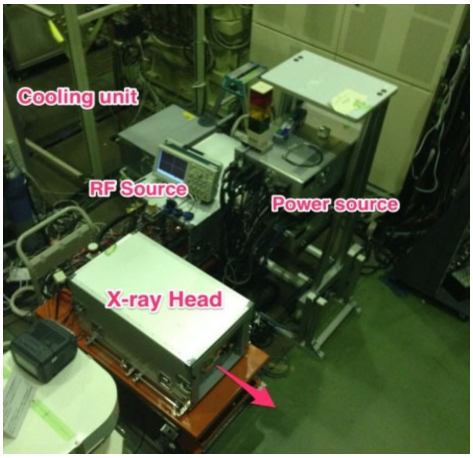

Figure 9: 3.95 MeV portable X-band linac based X-ray source. The system consists of four units: X-ray head, magnetron, power, and chiller units.

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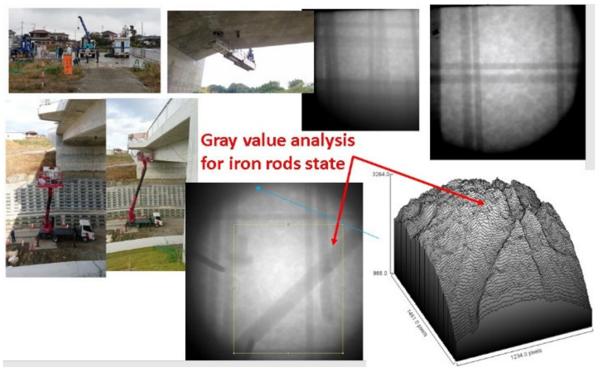


Figure 10: Updated results of on-site X-ray inspection of bridges of about 1 m thick iron-reinforced concrete by the 3.95 MeV source.

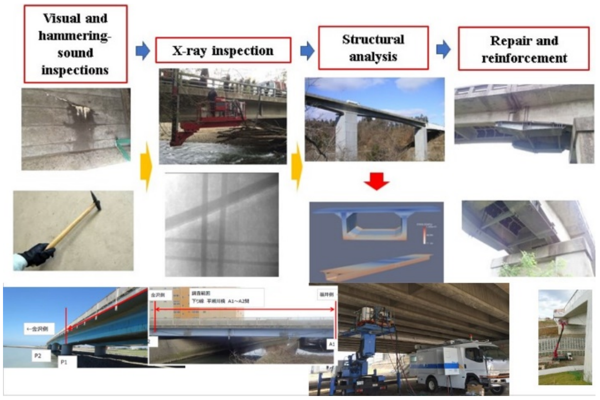
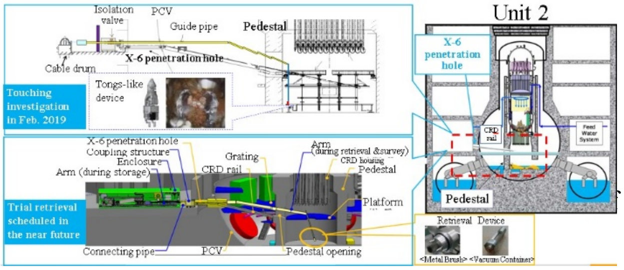


Figure 11: Guidelines for special X-ray transmission inspection using 950 keV/3.95 MeV X-ray sources accompanied with visual and hammering-sound inspections, structural analysis, final repair, and/or reinforcement.

## DECOMMISSION OF TEPCO FUKUSHIMA DAIICHI NUCLEAR POWER STATION (FDNPS)

On-site inspection system to estimate Uranium (U)/Plutonium (Pu) mass density in nuclear fuel debris in FDNPS is proposed by using the portable 950 keV/3.95 MeV X-ray and neutron sources by the University of Tokyo (see Figs. 12–14) [13, 14]. The two portable X-ray/neutron sources have been already applied to on-site transmission inspection of real bridges in Japan. 950 keV/3.95 MeV X-ray CT is applied to determine three dimensional (3D) atomic number distribution of the debris and nuclear resonance transmission absorption (NRTA) enables identification of U/Pu. Thus, we can estimate U/Pu mass density so that the criticality control is available for safe storage of the debris. We have successfully performed a proof-of-principle experiment using model melt debris samples. Figure 15 depicts the clear classification of the three groups of Pb, modelling U / Pu, and Zr / Fe (structural materials) and concrete, etc. for the model melt debris samples by the 3.95 MeV X-ray CT.



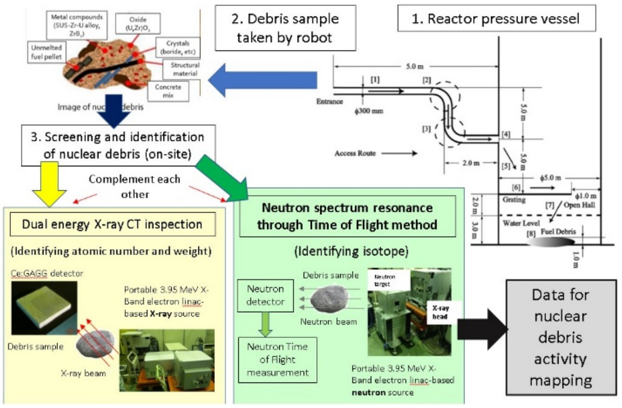


Figure 13: Proposal of debris sample acquisition and identification by the portable 950 keV/3.95 MeV X-ray and neutron sources.

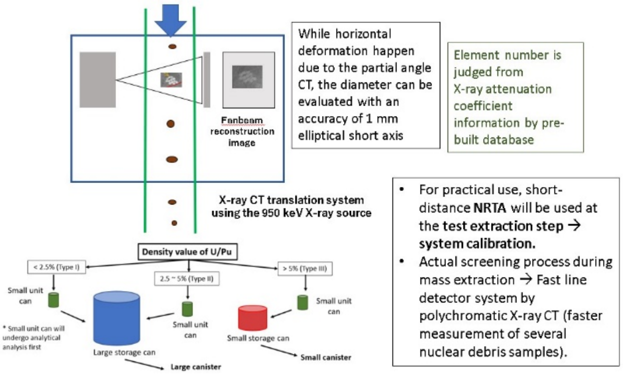


Figure 14: Latter phase of proposed scenario of on-site X-ray analyses for discriminating debris depending on U/Pu density for criticality safety.

The experiment using real nuclear fuel debris samples containing real natural U is planned in near future. Further, a prompt on-site U/Pu mass density estimation system for mass-extraction of large amount of fuel debris from the FDNPS is proposed.

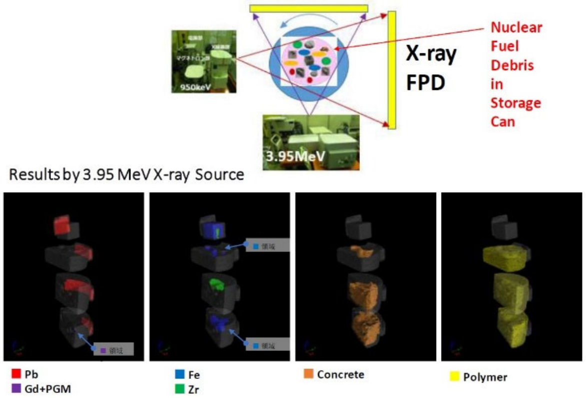


Figure 15: X-ray CT and Component Analysis for Classification of Nuclear Fuel Debris and Reasonable Storage.

## CONCLUSION

Downsizing of big accelerators enables portable accelerators for a variety of applications.

Medical RIs production is shifting to the best mix of accelerators and low enriched U research reactors.

Portable X-ray and neutron sources are expected to be applied to infrastructure maintenance and nuclear power plant decommissioning.

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