E-Journal of Advanced Maintenance Vol.5-2 (2013) 93-100
Japan Society of Maintenology

Commissioning of portable 950 keV/3.95MeV X-band linac X-ray sources for on-site transmission testing

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ABSTRACT

Development of portable 950keV/3.95MeV X-band (9.3GHz) linac X-ray sources has been almost successfully completed. Designed X-ray intensities of 0.05, 2 Gy/min at 1m have been achieved. Those intensities have been established with the portable three/four boxes with 182/386 kg in total, respectively, for the first time in the world. Equivalent commercial systems using S-band (2.856GHz) 950keV/3 MeV linac X-ray sources weighs about 1.5/1.7 tons, respectively. We have optimized the design with respect to the X-ray intensity, compactness and weight. By using the 950 keV system, we can get transmission views of artificial exterior wall thinning defects of petrochemical pipe of 8 mm thick and 300 mm diameter by 1 sec using the Perkin Elmer X-ray camera in the experimental room. By using a commercial 300 keV X-ray tube, the same transmission images are obtained by several minutes by an Imaging Plate (IP). 3.95 MeV system also enables 1 sec transmission test for 400 mm thick PC (Prestressed Concrete) bridge samples. By using 300 keV X-ray tube, it takes about one hour to get the similar image by IP. We have already performed the first on-site inspection using the 950 keV system at a certain chemical plant. The targets of the 950 keV system are chemical plants, petrochemical plants, impeller of pumps, wastaged pipes and iron bridge while those of the 3.95 MeV system are PC-, RC (Reinforced Concrete) - bridges. Partial CT technique and new X-ray detectors having better sensitivity for harder X-rays than 100 keV are under development.

KEYWORDS

Portable 950keV/3.95MeV X-band linac X-ray sources, on-site transmission testing

ARTICLE INFORMATION

Article history:
Received 19 November 2012
Accepted 4 April 2013

ARTICLE INFORMATION

1. Introduction

300keV X-ray tubes are mainly used for on-site transmission inspection so far. However, transmission of 150 mm thick iron is quite difficult and it takes about 1 hr for 400 mm thick PC bridges even by using highly sensitive IP. Under the law concerning prevention of radiation hazards due to radioisotopes and others, electron accelerators of less than 1 MeV can be used outside radiation controlled area and those of less than 4 MeV is available for only on-site inspection at bridges. Of course, we have to comply to the regulations on prevention of ionizing radiation hazards and confirm the radiation protection and safety. We have developed compact and portable 950keV/3.95MeV X-band linac X-ray sources in order to realize on-site transmission inspection based on the law and regulation. Inner structure of chemical reactors, off-line pipes with thermal shielding at petrochemical complex, impeller of pumps, iron-bridges are going to be inspected by the 950keV system. 3.95MeV system is suitable for PC/RC bridges.

Accelerating tubes of S-band (2.856GHz), C-band (5.712GHz) and X-band (9.3GHz)

linacs and cancer therapy systems using them are depicted in Figure 1 in order to explain the dependence of the size of the X-ray sources on the accelerating RF frequencies. As the RF frequency is higher, it becomes smaller so that it can be installed in the smaller moving cases.

Most common 300 keV tube X-ray source and S-band 950 keV linac X-ray source are introduced in Figure 2. Commercial systems using S-band 950keV/3 MeV linac X-ray sources weighs about 1.5/1.7 tons, respectively.

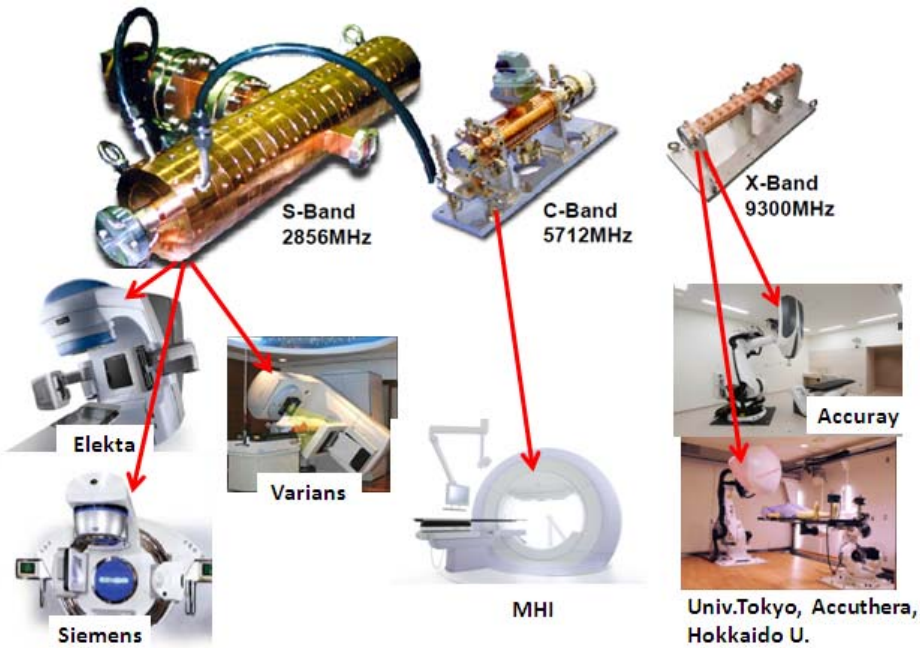


Figure 1. S(2.856GHz), C(5.712GHz), X-band(9.3GHz) accelerating tubes and cancer therapy systems

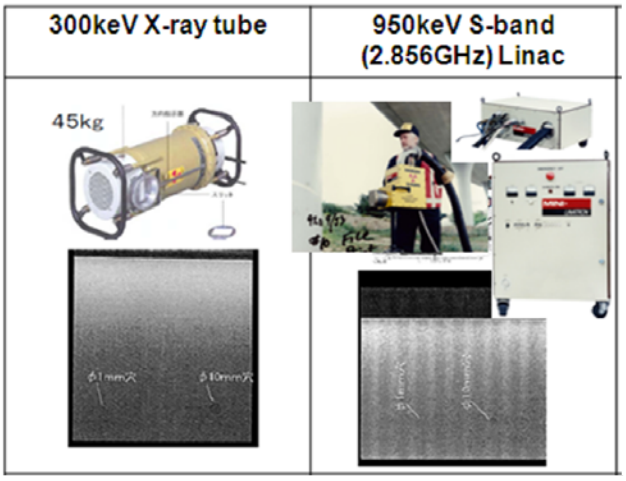


Figure 2. Commercial 300 and S-band 950 keV X-ray sources

2. 950 keV X-band linac X-ray source and on-site inspection

2.1. System upgrade and in-house verification

We have replaced the axial coupling cavities with the side-coupled ones for the accelerating structure and successfully solved the problems of RF power oscillation, beam current oscillation and reduction and lac of X-ray intensity [1]. The length of the accelerating tube is reduced to less than 25 cm, and the weight of X-ray source part with the local radiation shielding and magnetron are only 44kg and 49.5kg, respectively. The 950 keV

system [2] is shown in Figure 3 and the major parameters are given in Table 1. The biggest breakthrough in the design is the flexible waveguide which connect the magnetron to accelerating structure. Conventionally, a waveguide is made of copper so that it is rigid. The adoption of the flexible waveguide is for the purpose of on-site use in which the X-ray source part can move depending on the situation. Upgraded X-band 950keV linac X-ray source achieves almost all designed specifications. The most important is the X-ray intensity which is 50 mSv/min@1m for full magnetron RF power of 250kW. Thus, we have optimized the design with respect to the X-ray intensity, compactness and weight.

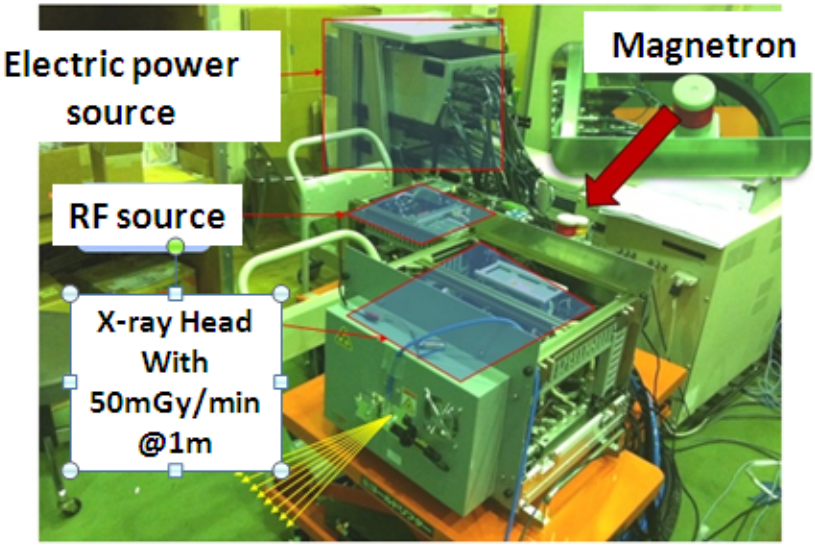


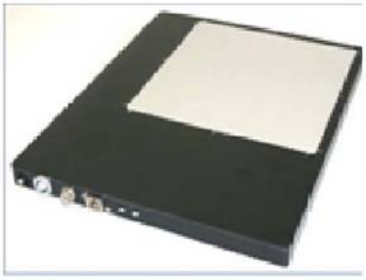
Figure 3. Upgraded X-band 950keV linac X-ray source.

Table 1. Parameters of Upgraded X-band 950keV linac X-ray source.

Operating frequency	9.3[GHz]
RF source	Magnetron
RF Power	250kW
Width and number of Repetitive of pulse	2[μs], 280[PPS]
Length of acceleration tube	25[cm]
Form of acceleration tube	Side coupled structure
Number of accelerating cell	Half1 + full8
Coupling between cells	3%
Filling time	0.18μs
Shunt impedance	110-130MΩ/m Regular part
Beam current	64mA or more
Focusing fashion	RF focusing
Intensity of X-ray	50[mGy/min] or more at 1[m]
Voltage of electron gun	20KV
Electron gun	Triode

In this experiment, we chose a 295 mm × 360 mm × 22 mm size scintillation type flat

panel detector, which is manufactured by Perkin Elmer Co. 0.2 mm thick Cd_2O_2S:Tb is used for the scintillator crystal. The photograph and important parameters are shown in Figure 4. The capable radiation energy range is 20 keV to 15 MeV. We also used a 200mm × 400mm size Fuji IP (Imaging Plate). The spatial resolution of the scintillation detector and IP (Imaging Plate) are 0.2mm and 0.05mm, respectively. The integration time of scintillation detector can be raised up to 20s by external pulse.



Perkin Elmer

Detector (Perkin Elmer)	
Scintillator + photodiode	
Pixel	1024 × 1024
Resolution	0.2mm, 0.4mm with 2 × 2 Binning
Size	204.8 × 204.8 mm^2
Scintillator	Gd_2O_2S:Tb
Energy range	20keV – 15MeV

Figure 4. Photograph and parameters of the X-ray camera.

Figure 5 shows the sample pipe where artificial defects were prepared at an exterior surface of an iron pipe cut from the off-line of the petrochemical complex in Kashima. Thickness and diameter of the pipe are 8, 300 mm, respectively, and surrounded by 5mm thick insulation material and outer layer of 0.5mm steel sheet. Artificial exterior wall thinning defects are of 3.5 mm in depth and 1,3,5,7,10 mm in diameter.

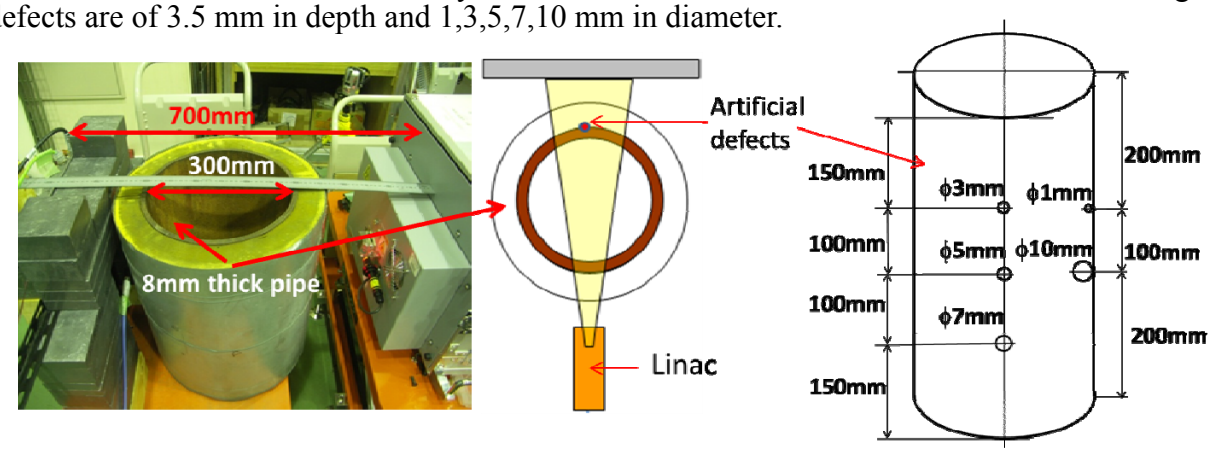


Figure 5. Pipe sample cut from the petrochemical complex with artificial defects

The results are shown in Figure 6. All data can be obtained by 1 sec by the Perkin Elmer X-ray camera. On-line visualization of X-ray transmission is available. Spatial resolution of 1 mm was confirmed here.

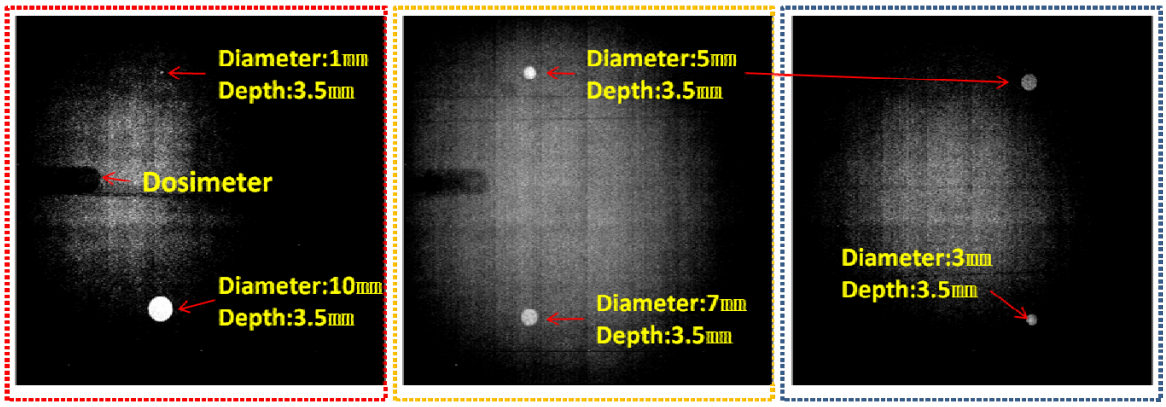


Figure 6. Artificial defects measured by the 950 keV system with scintillation detector for 1sec integration time.

By using a commercial 300 keV X-ray tube, the same transmission images are obtained by several minutes by an Imaging Plate (IP). Here, we have also optimized the design with respect to the X-ray intensity, compactness and weight.

2.2. On-site inspection

We have first performed the first on-site inspection using the 950 keV system at a certain chemical plant. Several transmission views of inner structure of a distillation tower of nitric acid were obtained by using the IP (Imaging Plate) within 20 seconds - 30 minutes. Horizontal projection view and detailed structures of the axis were got for 20 seconds. Oblique projection views whose iron-equivalent thickness was about 150 mm were obtained for 20-30 minutes. Even the inner structure, which have never been observed by the 300 keV X-ray source, can be first clarified in the oblique projection observation. Based on the success in the first trial, the next inspection is already scheduled in a commercial manner in end-2013.

3. 3.95 MeV X-band linac X-ray source and on-site inspection

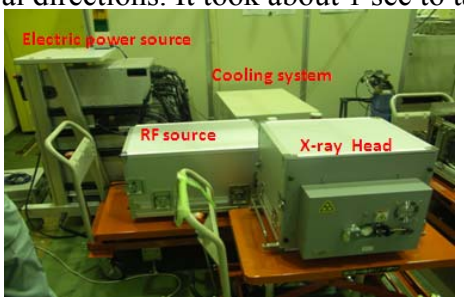
3.1. In-house verification

3.95MeV system appears in Figure.7 [3]. This system consists of 62 kg X-ray head with the target collimator 80 kg, the RF power source 62 kg, electric power sources 116 kg and water cooling system 30 kg. The X-ray intensity of this system is 2 Gy/min at 1m. We also adopted the side-coupled standing wave type accelerating structure [1]. For X-ray detection, we used the same Perkin Elmer X-ray camera and IP (Imaging Plate).

PC bridge means the bridge of concrete structure reinforced by many tensioned iron wires. About fifteen 7 mmϕ wires are set in a 30 mm diameter pipe and several pipes are put in the concrete. All wires are tension-loaded at the two edges of a bridge. 400mm thick concrete sample is shown in Figure 8. There is three 7mm ϕ wire pipes and one 10mm ϕ rod is set on the detector side as reference. The parts indicated by ①,②,③ are the cross sessions of pipes with the wires.

For improving the radiographic image quality, offset correction and gain correction are done. The offset correction of images is to eliminate the influence of pixel dark currents in the acquired image. The gain correction of images is to eliminate the influence of pixel sensitivities and influences of the used X-ray source in the acquired image. Image binning were also done to reduce the noise (binning size: 2×2).

The radiographic image of 400 mm concrete sample is shown in Figure 9. Three 7 mm ϕ wire blocks and reference rods are identified from these images. Since the X-ray source of this system is cone-beam and wire ② is closer to X-ray source than wire ①, so even the size of wire ② is the same as wire ①, wire ② in Figure 9(a) appears larger than wire ①. Wire ③ is far from the X-ray beam center, so wire ③ is difficult to identify from Figure 6(a). Each wire block consist several wires, but only three wires are identified in each wire block. That means if we want to identify every wire, we need to take radiographic image from several directions. It took about 1 sec to take this image.



Main unit	Accelerating Tube	RF Source	HVPS Control
Weight (kg)	80 + 62 (Collimator + Accelerating tube)	62	116
Parameters	Electron gun Output current 300mA	Frequency 9.3GHz	
	Electron gun Voltage 20kV	Pulse width 4μs	
	Beam current 100mA	Repetition rate 200pps	
		RF power output 1.5MW	

Figure 7. 3.95MeV linac X-ray source and major parameters.

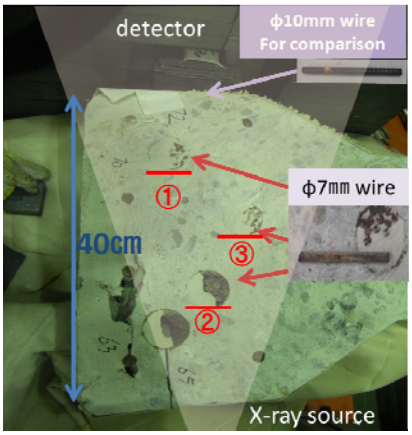
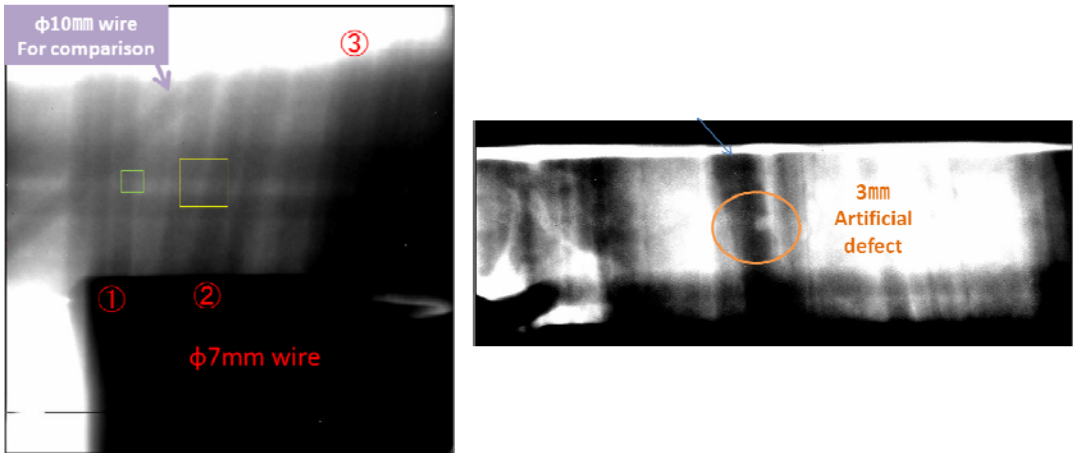


Figure 8. Cross section of PC bridge sample of 400 mm thickness



(a) (b)

- **Figure 9. Transmission views of the 400 mm PC bridge sample obtained by ~1 sec (a)② which is close to the radiation source is greater than ① for X-ray is a cone-beam. ③ is difficult to verify because it is far from the X-ray center. Only three wires can be confirmed in ① and ② despite the fact that they contain fifteen 7 mmϕ wires (b) 3mm artificial defect can be clearly observed.**

It takes about one hour to get the similar image by IP by using 300 keV X-ray tube.

3.2. On-site inspection

We are going to carry out the first on-site inspection for large degraded bridge parts at the Public Works Research Institute (PWRI) in Tsukuba-city in the spring, 2013. Since it is the first trial in Japan, the radiation safety scheme is carefully checked by the government.

4. Radiation Safety Control

Based on the law concerning prevention of radiation hazards due to radioisotopes and others of MEXT (Ministry of Education, Culture, Sports, Science and Technology) in Japan, less than 1 MeV system is available for on-site uses out of the radiation controlled area. However, we have to follow the regulations on prevention of ionizing radiation hazards of MHLW (Ministry of Health, labor, Welfare) in Japan. We have to complete our own radiation safety plan, confirm the local shielding and safety control area, and control the leakage radiation below 1.3 mSv/3 months at the safety control

area.

Amendment of the law was done in 2005, which allows use of below 4 MeV electron linac for only on-site bridge inspection. Here we should also obey the regulations on prevention of ionizing radiation hazards.

If 6 MeV linac X-ray source is available for on-site inspection, much thicker structures can be tested. However, it is not allowed to be used on-site yet now. We should accumulate the achievements with 950 keV and 3.95 MeV machines under the established radiation safety control scheme in these years and try to get the deregulation for on-site use of 6 MeV system in future.

5. Next subjects

Although we can observe the iron wires in the PC samples from a real bridge, the images are not clear enough (see Figure 9). Moreover, we cannot recognize all about fifteen 7mmϕ wires in the pipe in one projection. This mainly attributes to the effect of scattering low energy X-rays. Since the Perkin Elmer X-ray camera is developed for medical use, it is sensitive for X-rays below 100 keV. It is mainly because the scintillator is very thin and its thickness is just 200 μm. Hard X-rays more than 100 keV which penetrate thick and heavy targets cannot be detected by this camera.

Hence, the next subjects to be overcome are 1) to perform a partial CT to reconstruct the ROI (Region Of Interest) around reinforced iron components and 2) to develop a new X-ray camera which has rather high sensitivity for hundreds keV- few MeV hard X-rays. Necessity of the partial CT is schematically depicted in Figure 10. Full angle (180 degree) CT is impossible on-site due to spacing problem. We are also making the partial CT system. Details of the results and plans appear in [4]. Necessity of the new detector is schematically explained in Figure 11. There is no X-ray camera which has enough detection efficiency (detected energy/input energy) of more that 10 % for hundreds keV- few MeV hard X-rays. Only those hard X-rays can penetrate the thick metal pipes and bridge concrete structure. Proposed basic structure is shown in the right bottom of Figure 11. We use an array of scintillator plates which cross section is a few mm x tens mm. The hard X-rays are captured and detected in the tens mm length. Further, we put an array of collimators in front of the scintillators to reduce the scattering low energy X-rays. Now we plan to manufacture and verify the new detector within two years.

6. Conclusion

Two portable 950keV/3.95MeV X-band (9.3GHz) linac X-ray sources has been developed. Almost all designed parameters are fulfilled. Achived X-ray intensities of 0.05/2 Gy/min @1m have been established with the portable three/four boxes with 182/386 kg in total, respectively, for the first time in the world. Equivalent commercial systems using S-band (2.856GHz) 950keV/3 MeV linac X-ray sources weighs about 1.5/1.7 tons, respectively. By using the 950 keV system, we can get transmission views of artificial exterior wall thinning defects of petrochemical pipe of 8 mm thick and 300 mm diameter by 1 sec using the Perkin Elmer X-ray camera in the experimental room. 3.95 MeV system also enables 1 sec transmission test for 400 mm thick PC (Prestressed Concrete) bridge samples. By using 300 keV X-ray tube, it takes about one hour to get the similar image by IP. We have already started the first on-site inspection using the 950 keV system at a certain chemical plant. Compliance to the radiation safety law and regulation is confirmed. We plan to proceed to chemical plants, petrochemical plants, impeller of pumps, wastage pipes, bridges and nuclear power plants. The new X-ray detectors having better sensitivity for harder X-rays than 100 keV and the Partial CT technique are also under development.

Figure10. On-site Partial CT

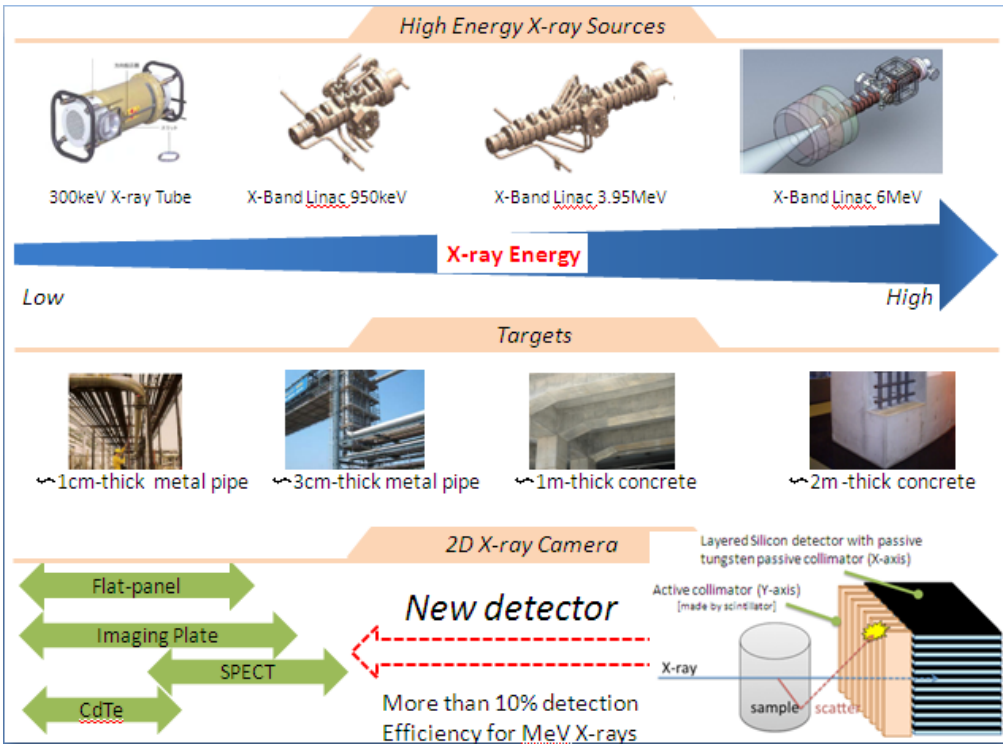


Figure11. Necessity of development of X-ray camera for hundreds keV-few MeV X-rays

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