The review and prospect of neutron radiography in China

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Abstract: Neutron radiography is one of radiography non-destructive testing. It is a valuable complementary of X and γ rays radiography. The present status and history of neutron radiography in China was described briefly, facilities of neutron radiography and their development were introduced in this paper.

Key words: China; neutron radiography; non-destructive testing; history; development

1 Introduction

As a non-destructive testing (NDT) technique based on the different sections of neutron-matter interactions, the neutron radiography obtains the internal structural information of the object by recording the spatial distribution of the neutron beams penetrating through it. It could be applied to the test of the hydric material, heavy metal subassembly, and radioactive matters to provide complementary advantages together with the application of other NDT techniques, such as X rays. The development of the neutron radiography in China was started in 1960s. In the early stage, the technical and applied study was developed by several institutes including Institute of Nuclear Physics and Chemistry (INPC) of China Academy of Engineering Physics (CAEP), Tsinghua University, China Institute of Atomic Energy (CIAE) and Northeast Normal University (NENU). As a result of their efforts, the testing platforms have been established to provide the quality control of weapons and new and high technology products in China. The development of the neutron radiography was promoted. This was regarded as the first upsurge for the development of the neutron radiography. However, due to various reasons, the study was continued by intervals and even to a standstill for a certain period. In recent years, driven by new rise of the neutron radiography study abroad and the internal requirements of quality assessment of certain products, the study of the neutron radiography in China was reactivated gradually. Other institutes have been involved successively into the related studies of this field such as Northwest Institute of Nuclear Technology (NWINT), Peking University, University of Science and Technology of China (USTC) and so on. The study of neutron radiography in China developed rapidly. Up to now, neutron radiography in China has been promoted from thermal neutron radiography to fast neutron radiography and cold neutron radiography. The neutron radiography facilities have been developed from fixed facilities based on reactor or accelerator neutron source to small-scale movable facilities. And the detecting techniques have been developed from using converters coupled with films to digital radiography and tomography. Besides, the study of the novel imaging techniques has been carried out, such as the neutron imaging on image plate and the phase contrast imaging. In a word, neutron radiography in the 21st century in China has been developed from a simplex technique only using the film to record the perspective neutron beams to an integrative neutron imaging technique which gathers various advanced techniques. The development of the neutron radiography in China is now undergoing another vigorous period.

2 The early development of neutron radiography in China

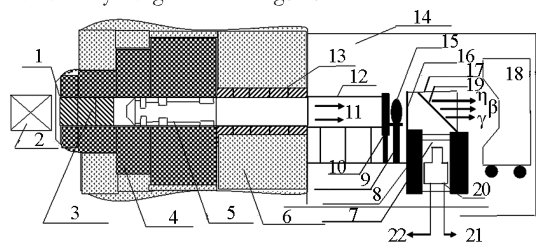
In 1960s, CIAE started its initial study of neutron radiography based on the research heavy water reactor, and finished the quality assessment of the ignition system of the first atomic bomb of China. This is the very beginning of the study of neutron radiography in China. Then, the technical and applied study of the thermal neutron radiography (TNR) was carried out successively in CAEP, Tsinghua University, NENU, NWINT and so on. By their efforts, several neutron radiography

Received 26 *August* 2009

facilities were established, including the thermal neutron radiography facility in SPRR (Swimming Pool Research Reactor)-300 reactor in CAEP, the thermal neutron radiography facility in 200# reactor in Tsinghua University, the neutron-tube-based mini thermal neutron radiography facility in NENU and the thermal neutron radiography facility in pulse reactor in NWINT. Such facilities had been used for the quality tests of the components of the spacecrafts, aircrafts, initiating explosive devices and nuclear weapons. The testing results demonstrated high quality, providing parameters for the quality assessment of the related products.

2.1 Brief introduction of the facility

The neutron radiography facility in CAEP is based on SPRR-300 reactor. The SPRR-300 is a light water-moderated swimming pool research reactor with beryllium and graphite reflector. The facility was built with the neutron beams derived from the thermal column in 6# horizontal channel. The 6# horizontal channel was started from the in-core pool, a 55 mm-thick lead plate was used as γ filter, while graphite was used as moderator. At the primal study, the major imaging techniques were Gd metal screen coupled with film and transfer imaging with In or Dy converter. In the end of 1990s, a real-time (~25 f/s) neutron radiography facility with the image intensifier coupled with CCD and high precision digital imaging facility with scientific level frame-transfer CCD were developed. The major parameters of the neutron beams applied in the facility are given in Table 1, while the scheme of the structure of the facility is given in Fig. 1.



1—Lead plate; 2—Reactor core; 3—Graphite plug;
4—Thermal column; 5—Inner collimato; 6—Concrete wall;
7—Lead glass; 8—Shielding materials; 9—Sample table;
10—Shutter; 11—Neutron; 12—Outer collimato;
13—Main shutter; 14—Shielding room; 15—Sample;
16—Converter; 17—Light tight box; 18—Neutron stoppe;
19—Mirror; 20—CCD; 21—Control computer;
22—CCD power supply

Fig. 1 The structure of the thermal neutron radiography facility in the 300# reactor in CAEP

Table 1 Major technical parameters of the thermal neutron radiography facility at SPRR-300 reactor

The max neutron fluence rate/ ($n\cdot cm^{-2}\cdot s^{-1}$)	Cadmium ratio	Neutron-gamma ratio /($kg\cdot cm^{-2}\cdot C^{-1}$)	Collimator ratio	ASTM-86 indicator parameter						
				NC / %	*S* / %	N / %	*P* / %	*H*	*G*	Imaging class
4.3×10^{7}	4 ~ 150	1.48×10^{14}	60 ~ 660	65.14	0.95	0.71	1.79	8	7	I

Note: *NC*—effective thermal neutron content; *S*—effective scattered neutron content; *N*—effective gamma content; *P*—effective pair production content; *H*—the closed visible value in the image; *G*—the smallest gap can be detected

The neutron radiography facility of Tsinghua University was installed in the 4# and 6# horizontal channel of the light water reactor in Institute of Nuclear and New Energy Technology (INET). The 4# channel is a radial horizontal chancel. And the neutrons were derived from the light water reflector with a relatively higher neutron flux. The 6# horizontal channel is tangential. The neutron beams were derived from graphite reflector, the radius of the channel was relatively big, and neutron spectrum was a little bit soft. Due to derivation from the channel of light water reactor, the γ rays were intense. Thus, a filter made of lead was installed at the front of the channel. And 3 neutron diaphragms made of boron nitride (replaceable) were also installed at the front of the channel to provide a better collimation ratio. Besides, an Al tube coated with boron nitride was installed inside the channel as inner liner to reduce the scattering neutrons. Then a neutron beam switch (valve) with multiple shielding was used to ensure the convenience and safety of the sample replacement. In order to minimize the interference of the scattering neutrons upon the image and guarantee the personnel safety in the hall, a small cell for neutron radiography and a small cell for neutron beam collection were built with precast concrete. The in-core neutron fluence was 1×10^{13} $n\cdot cm^{-2}\cdot s^{-1}$, the neutron fluence rate for the radiography was 5.3×10^{6} $n\cdot cm^{-2}\cdot s^{-1}$, the collimation ratio was 100, the cadmium ratio was 7.3 to 10, and *F* value was 0.085[1]. The image quality of the converter-film imaging system was as high as NC80-10-7 in accordance with ASTM E545-75. The porous characteristics of the concrete and the growth process of the corn root were studied by neutron radiography technique[2].. And the real-time images of water-gas two-phase flow were made with a real time neutron radiography facility consisting of NE-426 and silicon target tube. In addition, neutron radiography systems were developed with various converter options, including In, Gd, Gd_2O_2S, $ZnS-^{6}LiF$, barium fluobromide, ^{235}U converter and polyester film system. Fig. 2 is the scheme structure of the facility.

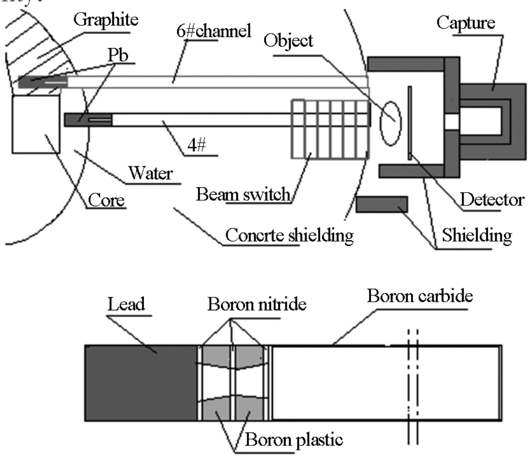


Fig. 2 The structure of the thermal neutron radiography facility at the 200# reactor in Tsinghua University (up: simplified scheme of the facility; down: the collimator structure)

Around 1990s, a small-scale thermal neutron radiography facility was set up with neutron tubes (D-T target, yield: 10^{10} n/s)[3] in NENU, whose structure was given in Fig. 3. In the facility, paraffin was used as moderator. A liner made of 1 mm-thick cadmium plate was installed axially inside the divergent collimator. The inlet diameter was 2.8 cm, collimation ratio was 18, and the thermal neutron fluence rate on the image surface was 3×10^3 n· cm^{-2}· s^{-1} with a cadmium ratio of ~ 2.0. Besides, the self-developed ^{6}LiFZnS (Ag) converter coupled with film was mostly used in the facility.

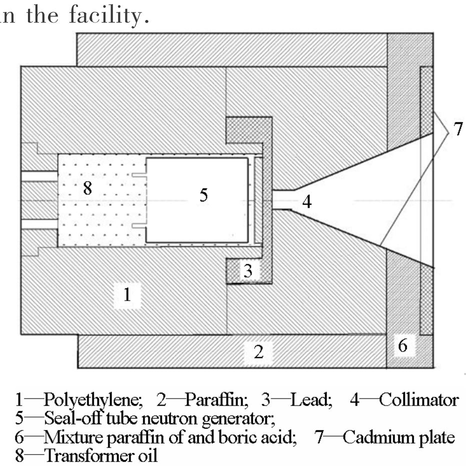


Fig. 3 The structural diagram of neutron radiography facility in NENU

The thermal neutron radiography facility[4,5] based on the Xi'an pulse reactor was built by NWINT. The moderator of the facility was graphite, and the channel structure for radiography was given in Fig. 4. At the front of the channel, a series of components were equipped, including bismuth γ filter, homogenization cabinet, diaphragm and so on. The collimation ratio was about 66 ~ 132, the cadmium ratio was 5, and the thermal neutron fluence rate was about 3.99×10^6 ~ 7.44×10^6 n· cm^{-2}· s^{-1}. As the major imaging technique, NIP (Neutron Imaging Plate) was used with BAs-1800 and BAS-ND screen produced by Fuji Co., Ltd. The inherent unsharpness obtained by NIP was about 0.15 mm.

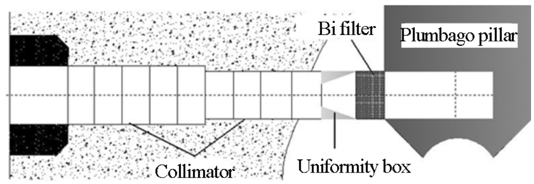


Fig. 4 The simplified diagram of the neutron radiography channel in Xi'an pulse reactor

2.2 Testing example

As a useful supplement to X rays and other NDT techniques, neutron radiography is used for the test of the hydric materials and the heavy metal components. As a matter of fact, the applications of the neutron radiography techniques in China have been focused on the quality control of the heavy metals and the initiating explosive device. Some testing examples obtained by neutron radiography in China are given in Fig. 5 to Fig. 8. As indicated in Fig. 5, the neutron beams of the thermal neutron radiography could easily penetrate a lead material up to 10 cm in thickness, which should be very difficult for X rays and γ rays. Fig. 6 presents a very clear venation of a cicada body, indicating a high sensitivity of the neutron radiography in dealing with hydric materials. Besides, the figures also give very clear displays of the loop and gear structure of the motor, the dial panel of the telephone and the cable joint, which demonstrated that neutron radiography could be used to provide a relatively effective identification of the structure and defect for such devices. As for the test of the initiating explosive device, the most principle testing object of the neutron radiography, Fig. 7 gives the actual photo and the testing image of the aviation fuses, which could be used to identify the defect in the explosive charges. Fig. 8 is an example image of the porosity test of the concrete. The leakage of the concrete is unacceptable in the construction of the underground storage. And this is another important application for the neutron radiography.

3 Status quo and development of neutron radiography in China

Along with the development of the neutron radio-

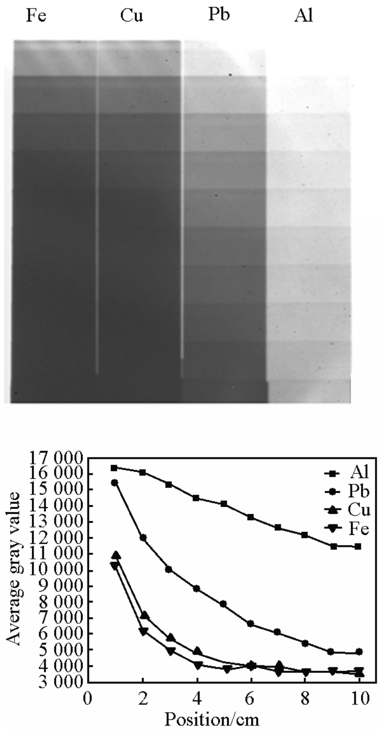


Fig. 5 The experimental diagram of the metal penetrating capacity of the thermal neutron digital radiography at SPRR - 300 reactor in CAEP

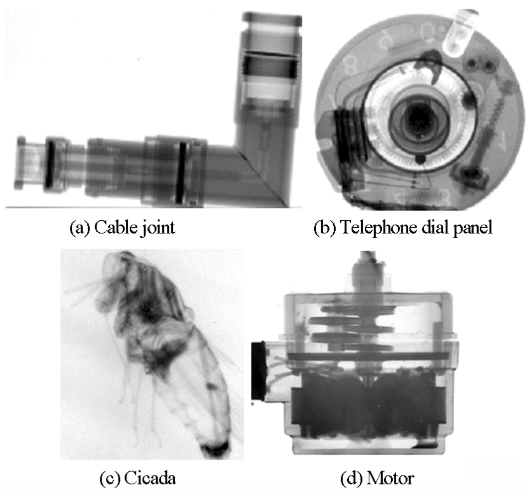
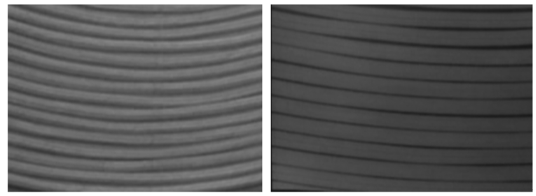


Fig. 6 The thermal digital radiography images obtained with the thermal neutron digital radiography in CAEP

graphy technology, there has been an increasing understanding in China about the unique performance and irreplaceability of the neutron radiography for certain applications. As a result, another rush for the development of the neutron radiography has come into being since 2000. At present, the R&D of both thermal and cold neutron radiography and their facility based on research reactor is undergoing in CAEP. And the technical study and facility development are also made for the



(a) (b)

Fig. 7 The actual photo (a) and test image (b) of the aviation fuses obtained with TNR facility in Tsinghua University

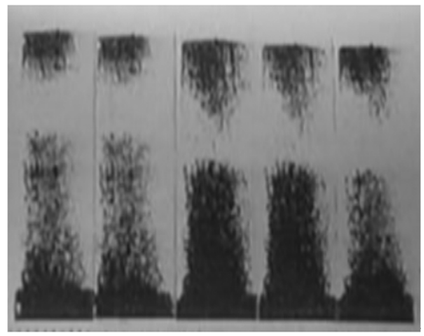
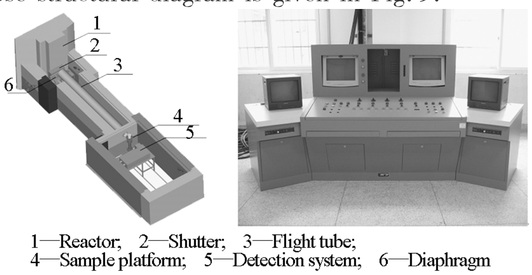


Fig. 8 The porosity testing image at various time obtained with the TNR facility in Tsinghua University

fast neutron radiography based on accelerator. Moreover, as another option, the investigation of fast neutron radiography with high yield fissile neutrons derived from reactor through the fissile target is also carried out in CAEP. At the same time, thermal and cold neutron radiography facilities are also proposed to build in China Advanced Research Reactor (CARR) in CIAE. In Peking University, the R&D of thermal neutron and fast neutron facilities[6-8] based on radio frequency quadrupole (RFQ) accelerator is in process, as well as the fast neutron resonance imaging for the material identification. In Lanzhou University, experts and scientists are researching and developing thermal and cold neutron radiography facilities[9] based on accelerator. While in USTC, the radiography technology based on Am-Be neutron source and fast neutron radiography technology based on accelerator have been studied[10].

3.1 Thermal neutron radiography

The thermal neutron radiography, with its best performance in material identification, has the greatest potential application. At present, the technical modification of CAEP 300# reactor is made to upgrade the reactor power and neutron fluence rate. And the new facility for thermal radiography is under installation and adjustment. The proposed imaging techniques for new facility would include film coupled with Gd, In and Dy metal screen, NIP of BAS-5000 with BAS-ND, real-time (25 f/s) neutron imaging and high precision digital imaging. Besides, the facility could also be used for both phase-contrast imaging and tomography imaging. The maximum thermal neutron fluence rate would be about 10^{9} n• cm^{-2} • s^{-1}, with a cadmium ratio of >100, and an adjustable collimation ratio of 100 ~ 3 000. The facility is planed to put into operation by the end of 2009. After that, the performance of the thermal neutron radiography facility in 300# reactor would be upgraded greatly with greater potential application in accordance the higher requirement. Meanwhile, the design of high speed (1 000 f/s) thermal neutron radiography system is being made in CAEP, whose structural diagram is given in Fig. 9.



(a) (b)

Fig. 9 3-D structure of the components distribution of the thermal neutron radiography facility under construction in CAEP (a) and the accomplished control console (b)

China Advanced Research Reactor (CARR) with a 60 MW power is now under construction in China Institute of Atomic Energy (CIAE). According to CIAE's program, the reactor would be equipped with neutron radiography facility. The proposed imaging techniques would be including NIP of Fuji-made FLA9000 and BAS-ND, and fluorescent screen coupled with high precision digital CCD. The facility could be used for digital imaging and tomography reconstruction with the maximum neutron fluence rate up to 2.3×10^{8} n• cm^{-2} • s^{-1}, an adjustable collimation ratio of 150 ~ 3 000, and a cadmium ratio of >100. The simplified diagram of the structure of the facility is given in Fig. 10.

Besides, a movable thermal neutron radiography facility based on RFQ accelerator is under construction in Institute of Heavy Ion Physics, Peking University. The accelerator uses D-Be target with a designed yield of $>10^{12}$ n/s. The thermal neutron imaging is achieved with water and polyethylene moderator. Fig. 11 shows the diagram of the moderator and collimator structure.

The accelerator which was planned to provide high-current neutrons in Lanzhou University has been

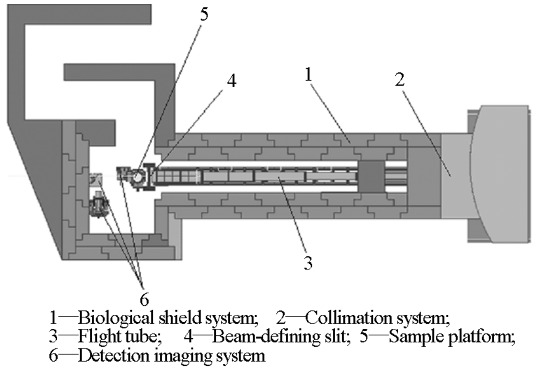


Fig. 10 The structural diagram of the proposed thermal neutron radiography facility in CIAE

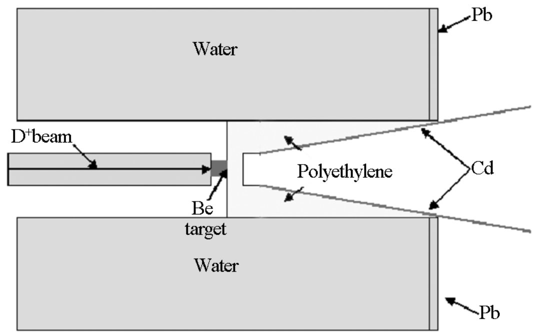


Fig. 11 The collimation and moderation structure of the thermal neutron radiography facility based on RFQ accelerator in Peking University

put forward into the final adjustment. The accelerator uses D-D target (yield: 5×10^{10} n/s) or D-T target (yield: 2×10^{12} n/s). Four Neutron beam lines are designed, one of which is deliberately used for thermal neutron radiography. Uranium and paraffin are used as moderator. Fig. 12 gives the structural diagram of the conceptual design of the collimation system of D-D target and D-T target. And the major technical specifications are given in Table 2.

3.2 Cold neutron radiography

The cold neutrons with appropriate energy have outstanding penetrating capacity in dealing with Fe, Be, Si, Ni, Zr, Pb, Bi and other metals. The cold neutron radiography could obtain fine structures inside such metals. Moreover, in dealing with hydrogen and most of other materials, such technique could be used to provide high mass- attenuation coefficient, higher sensitivity and higher resolution. Thus, the cold neutron radiography should have its own application and potential. And it's of great significance to develop the cold neutron radiography.

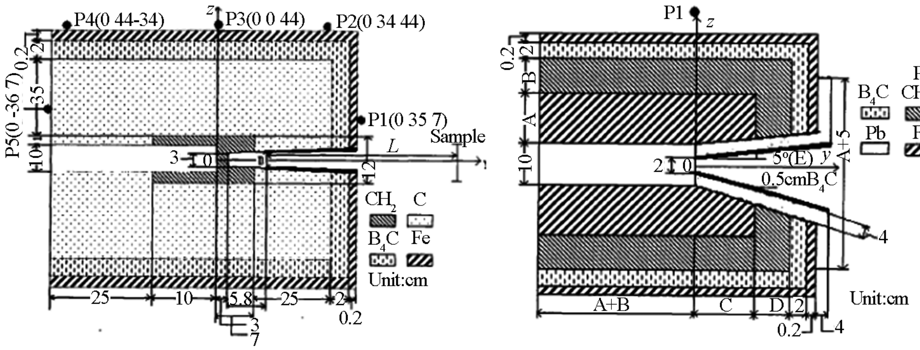


Fig. 12　The collimation and moderation structure of the thermal neutron radiography facility with D-D target and D-T target in Lanzhou University

Table 2　The major technical specifications of the proposed thermal neutron radiography facility based on accelerator in Lanzhou University

Specification	Neutron yield / ($n \cdot s^{-1}$)	Thermal neutron Φ /($n \cdot cm^{-2} \cdot s^{-1}$)	D / cm	L / cm	L/D	Visual field / cm	Cadmium ratio	n/γ /($n \cdot cm^{-2} sv^{-1}$)	Thermalization coefficient / cm^2	Φ_{fast}/ $\Phi_{thermal}$
D-D souce system	5×10^{10}	1.05×10^5	3.8	43.2	11.37	10	16.7	3.37×10^{10}	218	14
D-T source system	2×10^{12}	1.04×10^5	4.75	370	77.9	70	26.8	1.65×10^{10}	650	11

Limited by the fact that there's no cold neutron source in operation in China, the simulation study of the cold neutron radiography has been made in CAEP. And some of the research results are shown in Fig. 13 and Fig. 14. As indicated in Fig. 13, increasingly higher contrast of the sample image occurs with the lower energy, while Fig. 14 demonstrates the unique performance of monochromatic cold neutron differential imaging technique to identify the inside structure of such materials as beryllium. To some extent, with such technique, the impact of the matrix upon the image characteristics could be removed and the relatively fine structure could be identified.

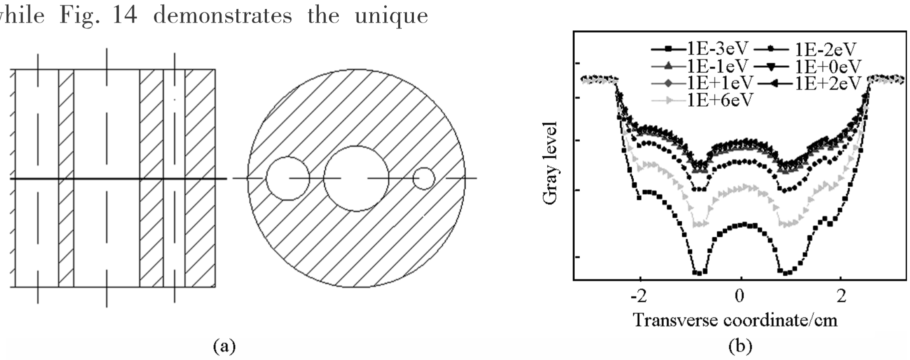


Fig. 13　The diagram of the Al sample (a) and the gray-scale curves of the images at various neutrons with different energy (b)

The construction of the cold neutron radiography facility has been started in CAEP. According to its design, the neutron beams would be derived through the neutron pipe and transmitted to the neutron diffraction hall. The maximum cold neutron fluence rate would be as high as 5×10^8 $n \cdot cm^{-2} \cdot s^{-1}$. The velocity selector would be used to select the neutron energy level. The facility could be used for the cold neutron radiography test both for continuous spectrum and monochrome spectrum. The structural diagram is given in Fig. 15. Up to now, the construction of the facility has been moved into engineering design stage, and the operation would have been available by the end of 2010 or at the beginning of 2011.

The cold neutron radiography facility in CARR of CIAE is now under planning. According to the design, the cold neutrons would be derived from moderator cell through the neutron pipe to the neutron diffraction hall.

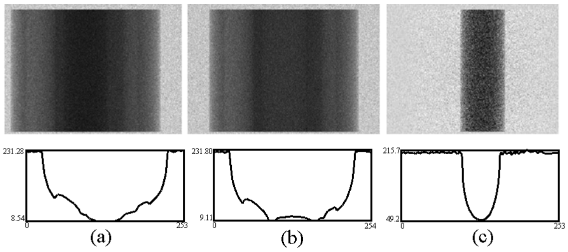


Fig. 14 The gray-scale curve of the MC method simulation neutron radiography(a); E_n = 2.15E-4 eV(b); E_n = 5.7E-3 eV(c), differential image material (matrix: beryllium, central material: titanium)

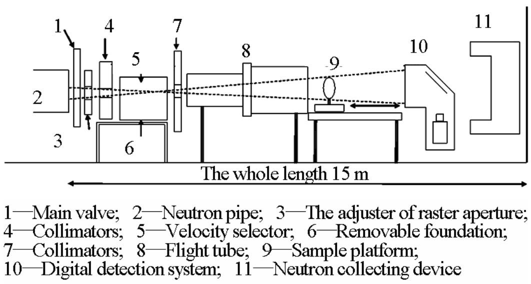


Fig. 15 The structure of the cold neutron radiography facility under construction in CAEP

The structural diagram is given in Fig. 16. And the parameters are similar with those of the facility under construction in CAEP.

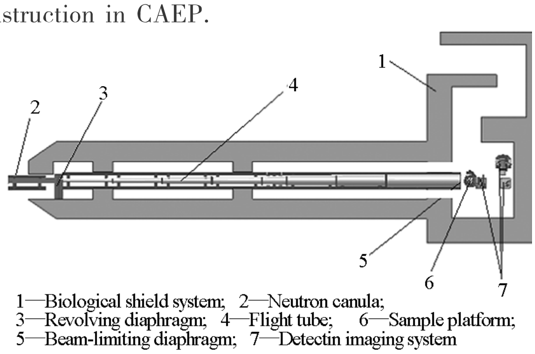


Fig. 16 The structure of the proposed cold neutron radiography facility in CIAE

3.3 Fast neutron radiography

With their outstanding penetrating capacity, the high energy neutrons play an irreplaceable role in the test of the big-size metal components and hydric materials. Great importance was attached in the last decade. And the major application of such technique has been focused on the assessment of the reliability and effectiveness of the stockpile weapon.

The initial investigation of the fast neutron radiography technique was made in CAEP with 14 MeV neutron beams generated from D-T accelerator. The imaging technique was fluorescent screen coupled with film and digital CCD. At present, the construction of the fast neutron radiography facility based on 14 MeV neutron source of small-scale moveable accelerator has been put into agenda. The yield of the neutron source is 10^{11} n/s, and the target is D-T target with an average energy of the 14 MeV. And the imaging technique is plastic organic scintillator coupled with high precision digital CCD. The diagrams of the experimental set-up and the system structure are given in Fig. 17. The proposed facility is mainly used in the locale NDT of certain key components. Moreover, another high performance fast neutron radiography facility based on high yield(10^{12} n/s, D-T target) and small target point (the FWHM in active region 2 mm) is planned.

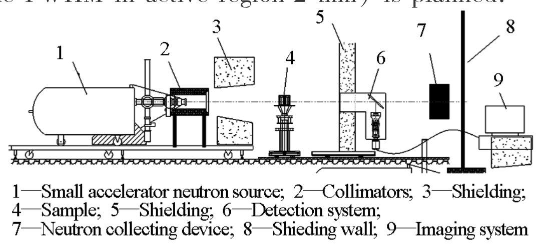


Fig. 17 The structure of the fast neutron radiography facility based on small-scale accelerator neutron source under construction in CAEP

The study of fast neutron radiography techniques was started in about 2002 in Peking University. As for the detector, the fast neutron converter for high efficiency CCD was separately studied with wave-shifted fiber technique. Fast neutron resonance imaging used to identify different matters is being carried out. The fast neutron radiography facility based on the RFQ accelerator is under empoldering. The facility was characterized by high intensity and small size.

Finally, the R&D the fast neutron radiography facility based on high current neutron generator in Lanzhou University is making.

4 Conclusion

The constant progress of the high yield neutron source technique in China leads to rapid rise of the development of neutron radiography. In 3 or 5 years, the high performance neutron radiography facilities under construction and in scheme would be put into operation. The R&D of neutron radiography will come to be a higher level. And these facilities can provide additional platforms for quality assessment of new and high technical products. In a word, China would be envisaged with another golden time for the development of the neutron radiography. At the same time, the R&D staff involved in the development of neutron radiography in China would make joint efforts with the rest of world, to study the novel neutron imaging techniques and to provide better performance of the neutron radiography. As a trend, the neutron radiography facility would be transformed from fixed facility to compact and moveable facility, and major application would be transferred from military into civilian use. In accordance with the increasing customers' requirement, the development of the neutron radiography would be greatly invigorated. In this way, a bright future would be very expectable for the development of the neutron radiography. However, neutron radiography is indeed a relatively "aristocratic" technique. Due to its big cost in the construction and operation of the neutron source, the price of the neutron radiography is very expensive, which is unacceptable for most of the potential customers. In this sense, the constant development and promotion of the neutron radiography could only available with the special concern and support from the country and concerned authorities. Otherwise, the development will duplicate a process with ups and downs.

References

[1] Mo Dawei, et al. Neutron radiography study in Tsinghua University[A]. 2nd World Conference on Neutron Radiography[C]. Paris: ISTP, 1986.

[2] Mo Dawei, et al. Application of neutron radiography to measurement of water-permeability of concret[A]. 2nd World Conference on Neutron Radiography[C]. Paris: ISTP, 1986.

[3] Hisao Kobayashi. The current state and perspective of the neutron radiography facility in Asia[J]. Nuclear Weapons & High Technology, 1997, 12(3):15-18.

[4] Yang Jun. Design and application of the collimated neutron radiography system[J]. Experiment & Study, 1998, 21(2): 10-14.

[5] Yang Jun, Chen Wei, Zhao Xiangfeng, et al. The system performance test and the applications of the neutron radiography facility [J]. Xi'an Pulse Reactor. Nuclear Power Engineering, 2002, 23 (6): 96-99.

[6] Pei Yuyang, Tang Guoyou, Guo Zhiyu, et al. Initial experiments of film imaging technique of fast neutron radiography[J]. Nuclear Physics Review, 2005, 22(1): 79-82.

[7] Yubin Zou, Li'an Guo, Zhiyu Guo, Guoyou Tang, et al. Development of a converter made of converter and wavelength-shifting fibers for fast neutron radiography [J]. Nuclear Instruments and Methods in Physics Research A, 2009, 28(2): 151-154.

[8] Pei Yuyang, Zhou Yubin, Guo Zhiyu, et al. Study of Neutron radiography of 9Be(d,n) accelerator neutron source[J]. Nuclear Technology, 2007, 30(4): 265-268.

[9] Cao Qinqin. Simulation design of the moderation collimation shielding system of neutron radiography with d-D and d-T neutron source[D]. Lanzhou: Lanzhou University. 2005.

[10] Jiang Shiping, Chen Liang, Chen Yang, et al. Experimental study of fast neutron radiography [J]. Nuclear Technology, 2005, 28(2): 151-154.

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