Design of Coded Neutron Source Based on a RFQ Accelerator by MCNP Simulation

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Abstract. In this paper, the influence of non-ideality factors of thermal neutron source for coded neutron source imaging has been studied by numerical calculation, in order to establish the design standard of coded neutron source. Then, the pinhole imaging detector (pinhole) of MCNP has been used to simulate the imaging process of the coded neutron source imaging, and the parameters such as the uniformity of the spatial distribution of the thermal neutron flux at the imaging plane and the uniformity of the angular emission of the coded neutron source are studied. The design results show that the spatial distribution of thermal neutron flux is less than 13% and the angular distribution is less than 10% with the optimized structure of moderator including a 4 cm thick polyethylene disk and a wedge of neutron absorbing layer closed to the junction surface of collimator and water tube.

1 Introduction

Coded neutron source imaging is a new imaging method which can solve the contradiction between neutron flux and L/D ratio\cite{1}. The projection image of sample by coded neutron source is the superposition of all the point source projections, so the inverse solution algorithm and the coded thermal neutron source that meets the requirements are the necessary condition to realize the imaging. At present, the coded neutron source is easy to be obtained by using the characteristics of large neutron emission surface and high thermal neutron purity of reactor neutron source in the world. However, the coded neutron source based on accelerator has not been reported\cite{2}. In this paper, we will study the influence of the non-ideality factors of the code source on the imaging, establish the requirements of the coded neutron source. Then the parameters of source can be calculated by using the pinhole-detector to simulate the coded source imaging process, in order to optimize the structure of moderator and extraction of the accelerator neutron source.

2 Coded neutron source imaging

Geometric inaccuracy is the main factor limiting the resolution of neutron imaging, which is determined by the L/D ratio of the imaging beam. As shown in the Fig.1, each point on the sample is expanded into an area on the imaging plane\cite{3}. Therefore, high quality neutron radiography requires high L/D ratio, that means reducing the size of the emitting surface of
the neutron source or increasing the distance between the sample and the neutron source, which will reduce the thermal neutron flux to the sample. In order to solve this problem, the coded neutron source imaging is proposed in recent years. Coded neutron source is to use neutron absorbing materials making a coded plate with a certain open distribution mode and place it on the neutron emission surface. Because the size of the opening hole on the coded plate is usually very small, each hole can emit an imaging beam with high $L/D$ ratio. At the same time, the neutron arriving at the sample has the contribution of all opening holes, so it can also ensure a high neutron flux. Using the coded neutron source imaging, every point on the sample projects the whole coded source, and the distribution mode of the projection image is same with the coded source. While the attenuation characteristic of the neutron is reflected in the different injection rate of the projection image. The internal information of sample can be obtained by the reconstruction of the projection image$^4$.

![Figure 1. Schematic diagram of coded neutron source imaging.](image)

The key of coded neutron source imaging is to meet the requirements of the coded neutron source and the reconstruction algorithm. The ideal coded neutron source requires that the neutron emission surface be divided into a certain pattern with 0 and 1 distribution, while 0 represents no neutron emission, 1 represents neutron emission with same flux and angular distribution. However, the actual coded neutron source is difficult to meet the ideal requirements. First of all, the coded plate is usually made of 0.1mm thick gadolinium foil, because gadolinium has a high thermal neutron absorption cross section (39000b). But the neutron absorption cross-section of gadolinium decreases with the increase of neutron energy, which will cause the 0.1mm thick gadolinium foil cannot fully absorb epithermal neutron and fast neutron. Therefore, there is a certain transmission in the coded plate material, and the ideal coded element of 0 cannot be obtained. In addition, generally, the size of the coding source is usually too large to obtain the neutron emission surface with the same parameters based on the accelerator neutron source, so it is also difficult to get the ideal coded element of 1.

### 3 Calculation of non-ideality factors

The coded neutron source may have the following non-ideality factors: (1) the material of the coded plate has a certain transmission; (2) the neutron flux distribution at the coded plate is uneven; (3) neutrons scatter to the imaging plane forming the scattering background. In order to study the influence of the above factors, the matlab program is used to calculate the influence of non-ideal factors on the reconstructed image compared with the ideal coded source. The calculation method is: set up the ideal sample and the coded source with certain non-ideal factors, simulate the projection and reconstruction, and evaluate the reconstruction effect by using the pixel average variance of the reconstructed image with the ideal sample. Definition of average variance of mean: the variance of single pixel is obtained by square of the difference between reconstructed image pixel substracts its
corresponding ideal image pixel, and the variance of all pixels is summed and divided by the total number of pixels. The square root value of the pixel mean variance represents the percentage value of the pixel deviation. The calculation condition is: coded mask adopts the MURA mode of $61 \times 61$ with 1mm aperture grid; the sample is a step with gradual gray level (gray value is from 1% to 99%); the pixel matrix is $300 \times 300$; the distance between the conversion screen and the coded mask is 2080mm; the 85mm lens is used; and the image is reconstructed by iterative algorithm.

(1) Effect of neutron transmission

The calculation results show the distribution of the average variance of mean with the penetration rate increasing from 0.05 to 0.5 in Fig.2. In order to make the average variance of mean less than 0.001, the penetration rate is required to be less than 20%.

(2) Effect of scattering background

On the basis of ideal projection, a certain proportion of Gaussian distribution noise is added to calculate the average variance of mean when scattering background accounts for different shares of effective signal. The result is shown in Fig.3. In order to make the pixel average variance less than 0.003, the background ration is required to be less than 10% of the effective signal.

![Figure 2](image1.png) ![Figure 3](image2.png)

Figure 2. Distribution of average variance of mean with penetration rate.  
Figure 3. Distribution of average variance of mean with background ration.

(3) Effect of neutron flux distribution at the coded source

The maldistribution of neutron flux distribution at the source is considered by two common models, which are: (a) high in center, linear attenuation to the surrounding; and (b) high in one direction, linear attenuation in the opposite direction. For these two models, the non-uniformity is defined as the percentage of the difference between the neutron flux at the edge and the center. The calculation results are shown in Fig.4. In order to make the average variance of mean less than 0.003, the non-uniformity is required to be less than 15% in case (a) and 20% in case (b).

![Figure 4](image3.png)  
(a)  
(b)

Figure 4. Distribution of average variance of mean with neutron flux maldistribution.
4 Code neutron source design

4.1 Calculation model

In order to meet the requirements of the coded neutron source imaging, the structure of PKUNIFTY target station has been modified with a new neutron emitting surface. PKUNIFTY target station was designed for thermal neutron radiography with $2.4 \times 10^{11}$ n/s of neutron yield, a polyethylene disk in front of Be target as main moderator, a water cylinder of $\Phi 13\text{cm} \times 26\text{cm}$ plays the role of both the secondary moderator and reflector, a combination of 8cm thick lead and 42cm boron containing polyethylene as neneutron shielding, and the collimator beam axis perpendicular to the D+ beam line in order to reduce the fast neutron and the gamma ray components in the imaging beam\[5\].

The spatial distribution and angular distribution uniformity of coded neutron source under different structure has been simulated by the pinhole detector of MCNP in order to modify the PKUNIFTY target station, shown as Fig.5. The simulation parameters are set as: coded neutron source and sample both with size of $7 \times 7\text{cm}^2$, distance between source and sample setting 70cm, imaging surface with size of $7 \times 7\text{cm}^2$ which is divided into $35 \times 35$ grid. In order to calculate the angular emission non-uniformity of the neutron emitting surface, three points are selected in the field of view to image the pinholes of the neutron emitting surface. The coordinates of the three pinholes are (83, 0), (83, -3.5), (83, 3.5). The angular emission non-uniformity can be obtained by comparing their projected images. The projection of the middle pinholes is used to calculate the spatial distribution uniformity of the neutron.

4.2 Design result

Because of the collimator beam axis perpendicular to the D+ beam line, the thermal neutron flux distribution at the emission surface decreases along the y-axis with a certain slope, while keep uniform along the z-axis. In order to improve the uniformity of the thermal neutron flux on the emission surface, the thermal neutron absorption material of boron containing polyethylene (2% by weight of boron carbide) was added to the moderator with wedge shape. The y-axis thickness of neutron absorption material changes with a certain slope, and the thickness of one side is 0, as shown in Fig.6.

![Figure 5. Schematic diagram of calculation model.](image)

In order to improve the calculation efficiency, the grid of the pinhole detector is no longer subdivided in the z-axis direction, recording the whole area of -3.5cm~3.5cm, while the y-axis direction is divided into 35 cells. The distribution of thermal neutron flux with
the maximum wedge thickness is shown in Fig.7, from which it can be seen that the uniformity of the neutron flux is 13% in 6.7cm and better than 10% in 5cm, with 1.5cm-thick wedge-shaped boron-containing polyethylene. The normalized thermal neutron flux on the imaging plane is about $1.4 \times 10^{-8}$n/s, and the equivalent normalized thermal neutron flux on the coding source is $8.6 \times 10^{-4}$. Simultaneously, distribution of thermal neutron flux on imaging plan with holes at different positions has been simulated to get the neutron emission angle distribution, as shown in Fig.8. It can be seen that the difference of thermal neutron flux of pinhole imaging at different positions is less than 10%, which means the non-uniformity of neutron emission angle distribution of coded source is less than 10%.

![Figure 7. Distribution of thermal neutron flux with the maximum wedge thickness.](image)

![Figure 8. Distribution of thermal neutron flux on imaging plan with holes at different positions.](image)

4 Conclusion

The coded neutron source imaging can solve the contradiction between neutron flux and L/D ratio. In order to meet the requirements of coded source imaging, the structure of PKUNIFTY target station has been modified with a new neutron emitting surface. The design standards have been proposed firstly by numerical calculations of the artifacts, which are brought to the reconstructed image by non-ideality factors of the coded source. Then the parameters of source can be calculated by using the pinhole-detector to simulate the coded source imaging process. The optimized structure of moderator includes a 4 cm thick polyethylene disk and a wedge of neutron absorbing layer closed to the junction surface of collimator and water tube. The variance of neutron distribution on the neutron emitting surface is better than 13%, and the variance of angular distribution is better than 10%.

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