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Design of moderator of a compact accelerator-driven neutron source for coded source imaging

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Abstract

Coded source imaging (CSI) is a possible method to solve the contradiction between neutron flux and L/D ratio. Peking University neutron imaging facility (PKUNIFTY) is a RFQ accelerator based facility. The CSI experiments were carried out on PKUNFTY to test the benefits that this technique might bring. The CSI technique gets more restricts on the moderator, especially the neutron distribution in the inner collimator, where the coded mask sampling the source. The effect caused by the non-uniformity of neutron distribution on the mask plane was investigated. The slope type non-uniformity should less than 20% to keep the artifact in the reconstructed image insignificant. The PKUNIFTY moderator was modified according to the above limit. The preliminary experiments shown the moderator design for coded source imaging is acceptable.

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Keywords: : Neutron Radiography, Coded Source Imaging, Compact Accelerator-driven Neutron Source, Moderator Optimization

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1. Introduction

Compared to neutron radiography (NR), taking projection with a small surface source, coded source imaging (CSI) uses a group of element sources, which are very tiny surface sources, arranged in a certain pattern (Fig.1) [1]. Each element of the coded source emits neutrons, which can project a figure of the object with high *L*/*D* ratio, where *L* is the distance between aperture and object, and *D* is the diameter of the aperture. Meanwhile, the neutron flux at the object plane is contributed from all the small aperture sources, so the CSI can achieve high neutron flux and *L/D* ratio which are contradictory during NR.

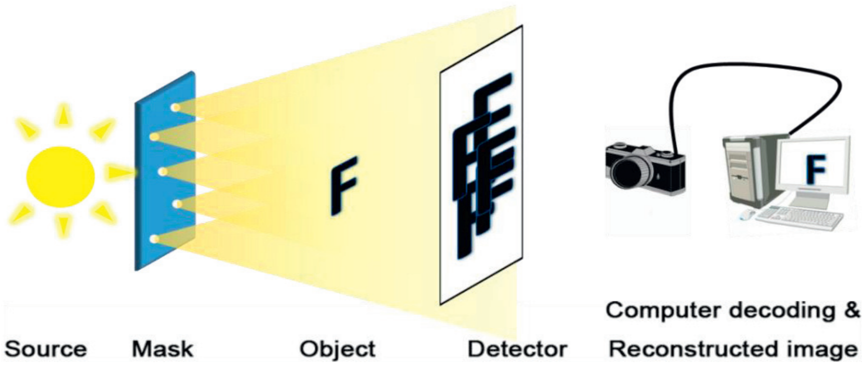

Fig.1 coded source imaging [1]

A coded neutron source is achieved by placing a mask in front of a neutron emitting surface. The mask is made of strong neutron absorbing materials with holes arranging at a certain pattern. The surface source can be sampled by the mask and becomes a coded source. The pattern of holes distributing on the mask determines the open factor and geometry arrangement of imaging. Several patterns have been studied, including random array (RA), non-redundant array (NRA), uniformly redundant array (URA), as well as modified uniformly redundant array (MURA) etc [2, 3].

In theory, the projections from elements of the coded source are just different in the position, and overlap each other on the detector. A reconstruction algorithm to retrieve the object imaging from the overlapped picture obtained on the detector is a key part for CSI. Several reconstruction algorithms have been proved to be effective for decoding the picture, including correlation decoding, wiener filter and Richardson-Lucy maximum likelihood (RLML) iteration algorithm etc [1, 4].

CSI demands all the element sources have the same parameters within the field of view, including the neutron flux, the energy spectrum and the isotropic emission, so that the image could be successfully reconstructed. Thus the neutron emitting surface should be uniformly distributed to make sure all the element sources have the same parameters. Usually, it is not a problem on reactor based facility. However, it is not easy to realize a uniform neutron distribution at the emitting surface on a neutron imaging facility based on a compact accelerator-driven neutron source (CANS).

Peking University Neutron Imaging Facility (PKUNIFTY) [5] is a thermal neutron imaging facility based on a radio frequency quadrupole (RFQ) accelerator-driven compact neutron source. The fast neutrons are produced by the 2 MeV deuterons bombarding a beryllium target with the neutron yield of 3×10^{12} n/s. The moderator, reflector, shielding and collimator have been designed for thermal neutron radiography (TNR). As shown in Fig.2, the neutrons are thermalized in a water cylinder of $\Phi 26\times 26$ cm^3 with a polyethylene (PE) disk in front of the Be target, and the thermal neutrons are emitted through a detachable collimator system. A combination shielding of a 8 cm thick lead layer and a 42 cm thick boron doped PE layer is around the target-moderator-reflector assembly to stop the γ rays and neutrons. The thermal neutron flux at the imaging plane is 1.5×10^5 n/cm^2/s with L/D = 100, which are lower compared with high quality TNR facility based on reactor neutron source [6]. In order to carry out CSI at PKUNIFTY, the original collimator system had to be taken out (Fig.2), and a coded mask would be placed in the position 13cm away from moderator centre. This paper describes the design of the moderator to meet the requirements of CSI.

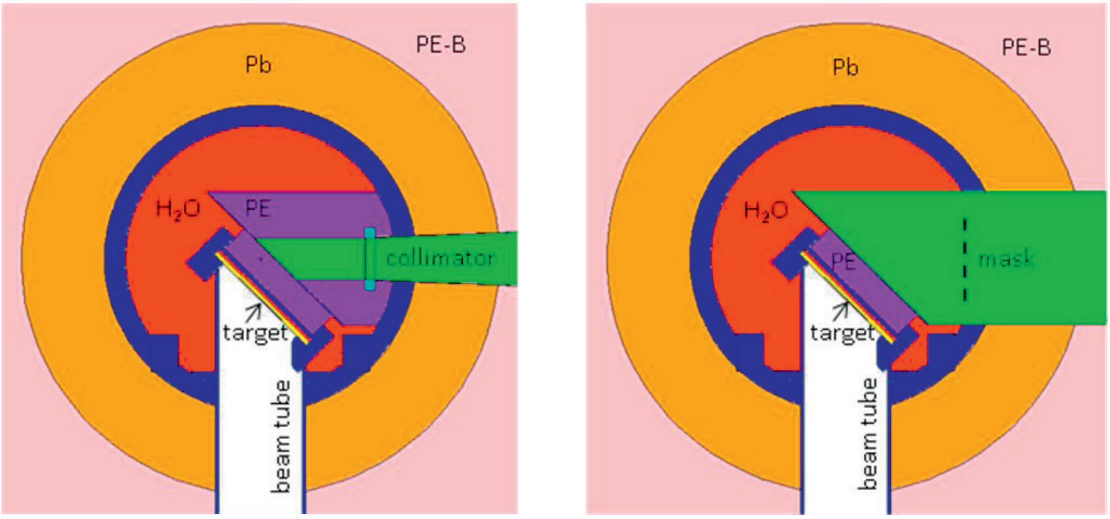

Fig.2 Central horizontal profile of original PKUNIFTY moderator (left) and with collimator drawn out and planned coded mask position (left)

2. The requirements of neutron source for coded source imaging

The ideal coded neutron source is a group of small element neutron sources with the same parameters on the dark background. For compact accelerator based neutron source such as PKUNIFTY, the fast neutrons emitted from the target cannot be fully moderated within several centimeter thick moderation materials, which means a large amount of fast and epithermal neutrons exist at the neutron emitting surface in addition to the thermal neutrons. However the mask material cannot fully absorb fast and epithermal neutrons. So a significant amount of epithermal neutrons can penetrate the mask and produced a non-coded background. Furthermore, the distribution of thermal neutrons in the moderator is non-uniform, which make the neutrons on coded source elements far from uniform distribution.

The impact of above factors on the reconstructed image has been numerically simulated. The simulation method is similar to that mentioned in [1], and RLML was used to reconstruct the image. Constructed image with non-ideal coded source projection results in the artifacts. The average pixel divergence was used to evaluate the artifacts from the non-ideality of the coded source. The average pixel divergence is defined as:

$$D = \frac{\sum (p_i' - p_i)^2}{n} \quad (1)$$

Where n is total number of pixels, P_i' and P_i are the ith pixel gray values of reconstructed image and object respectively, and i is 1, 2, …, n.

The coded pattern used in the simulation is 61×61 MURA. The dimensions of source and object are 6.1×6.1 cm^2 and 9.5×9.5 cm^2, respectively. The distance from source to detector is 208 cm, and the object is placed in the middle. A 0.1 mm thick gadolinium foil can absorb more than 99.9% thermal neutrons, which is good enough for the coded source. The simulation shows no visible artifacts with such a condition. However, the gadolinium foil is almost transparent to epithermal neutrons, which means the epithermal neutrons are not coded at all. When using a Li-6 based detector, the epithermal neutron cannot be neglected. The epithermal neutrons act in the samples in a different way from the thermal neutron, so adequate techniques, such as time-of-flight, should be used to remove the contribution of the epithermal neutrons, otherwise the significant artifacts would emerge [8].

In the simulation the non-uniform distribution of thermal neutron flux at the mask plane was categorized into two simple types: (a) A pyramid type, in which the neutron distribution is the highest in the center and decrease along the radius; (b) A slope type, in which the neutron flux is high near the target and decreases towards the opposite direction. The non-uniformity is defined as the percentage difference of thermal neutron flux between maximum and minimum, which can be calculated as (maximum-minimum)/maximum.

The reconstructed images of the simulated projection with non-uniform coded source are shown in Fig. 3. The artifacts become more obvious while the non-uniformity increases. The average pixel divergence is shown in Fig. 4. Artifacts still exist in the uniform coded source projection, which is caused by the near filed effect, as the simulation reflecting the true setup of PKUNIFTY.

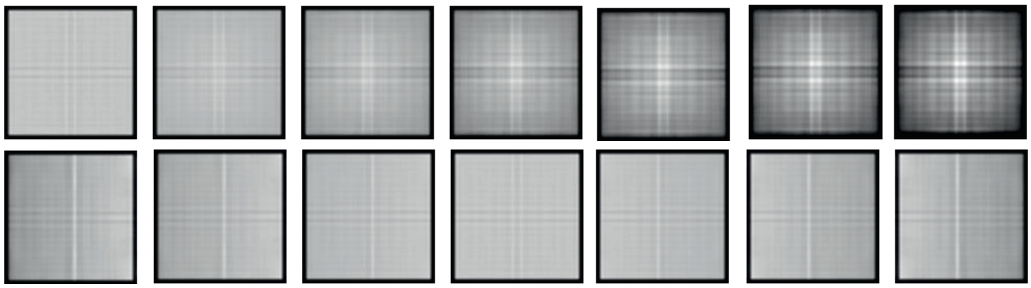

Fig.3 reconstructed image of non-uniform coded source. Upper row: Pyramid type. From left to right, the non-uniformity are 0, 10%, 20%, 30%, 40%, 50%, 60%; Lower row: Slope type. From left to right, the non-uniformity are -30%, -20%, -10%, 0, 10%, 20%, 30% (Negative value means the neutron distribution increase instead of decrease along the given direction).

The non-uniformity of 15% for pyramid type or 20% for slope type non-uniformity will make the average pixel divergence less than 0.3%. A real neutron distribution can be approximately described by the combination of these two types. Therefore, the designing goal of the coded neutron source was chosen, in which the non-uniformity should not exceed 15% on pyramid type and 20% on slope type.

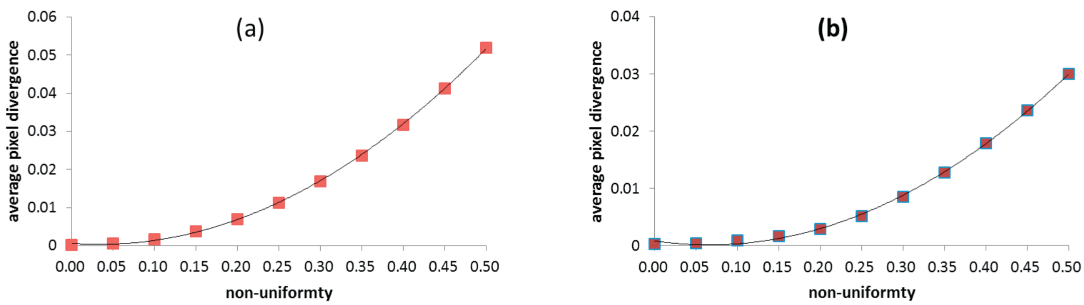

Fig.4 Average pixel variance of constructed image vs. non-uniformity of neutron distribution

3. Improvement of the neutron distribution at mask plane

The moderator structure was designed by three steps to satisfy the neutron flux uniform requirement on the mask plane.

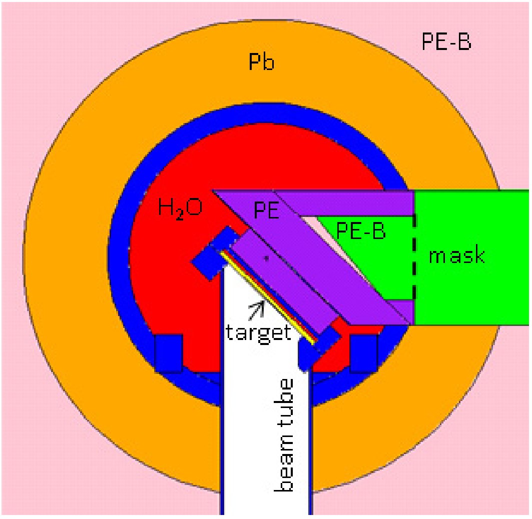

Fig.5 Central horizontal profile of moderator structure for CSI

- Choosing the size of inner collimator

The effective mask size was expected as 6×6 cm^2. Too large inner collimator size would reduce the amount of moderator materials and lead to a lower neutron flux. The size of inner collimator was chosen as 8×8 cm^2, just big enough to keep all the neutrons in the field of view from the same neutron emission surface instead of the wall of the inner collimator. Thus it is easier to control the neutron flux distribution.

- Increasing the thickness of the main moderation layer

The main moderation layer is the part between the target and the neutron emission surface. Most useful neutrons are moderated here. Increasing the thickness of this layer can bring two benefits. One is that the neutron was better moderated so that the thermal neutron content could be higher. The other is that the neutron flux distribution would be less affected by the shape of beam bombarding the target. Consequently the neutron distribution on the mask plane could be flater. The main moderation layer was chosen as 6 cm thick polyethylene.

- Adding an absorbing layer

Although the structure of the moderator has been adjusted, the neutron flux at the mask plane is still not uniform enough according to the simulation results. The neutron flux is higher at the far end along the deuteron beam direction, because the fast neutron yield at the deuteron beam direction is more than other direction. In order to adjust the flux distribution, a neutron absorbing layer with wedge shape was added to the neutron emission layer, as shown in Fig. 5. This layer is made of boron doped epoxy. Neutron flux distribution with different maximum thickness of absorbing layer is simulated with FLUKA code [9, 10]. The results are shown in Fig. 6. Choosing the absorbing layer maximum thickness as 1.5 cm is enough to adjust the goal we formerly set. However, the total neutron flux is decreased.

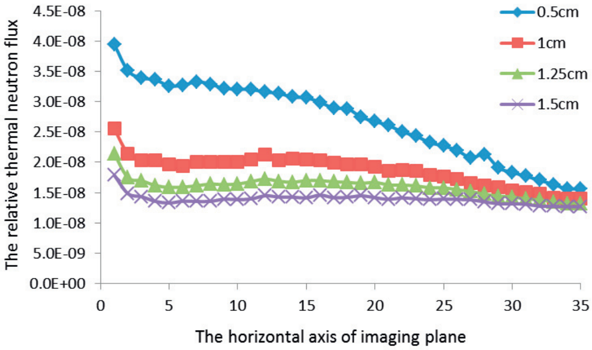

Fig.6 Distribution of thermal neutron flux at the mask plane with a wedge of boron doped epoxy resin

4. Imaging result

A preliminary imaging experiment was carried out based on the former desing. The used sample was shown in Fig. 7. The sample can be divided into four parts, and all the parts are made of 0.5 mm thich cadmium sheet. In two cadmium sheets a hole and some slots were cut. On the other two cadmium sheets a wedge and some strips were stuck. The neutron flux at the imaging plane is 3.17×10^4 n/cm^2/s and the exposure time is 15 min. The projection and the reconstructed image are shown in Fig. 8. The epithermal neutron is treaded as background as it penerate both the mask and the sample with little lose. Although the image is noisy and poor in resolution in this experiment, the artifacts caused by the non-uniformity of the coded source is not visible. The moderator design for the coded source imaging on PKUNIFTY is acceptable.

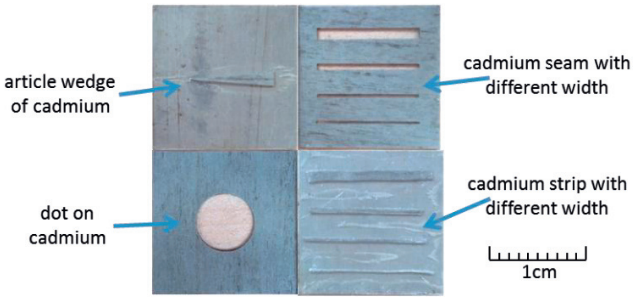

Fig 7. Photography of the sample

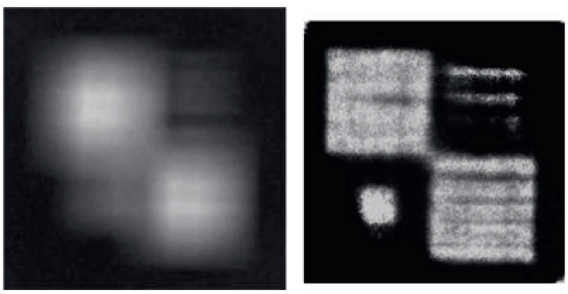

Fig 8. Coded source projection (left) and its reconstructed image (right).

5. Summary

The neutron moderator for coded source imaging gets more restricts than normal compact accelerator based NR facility. With the numerical simulation, we found that the non-uniformity neutron distribution at the mask plane, where is inside the inner collimation, would bring artifacts in the reconstructed coded source image. We proposed two types of distribution, pyramid and slope, to describe the non-uniformity approximately. For a CSI setup like PKUNIFTY, if one wants to keep the average pixel divergence below 0.3%, the neutron distribution non-uniformity on the mask plane should be less than 15% for pyramid type and 20% for slope type.

The moderator of PKUNIFTY was modified following former rules. To reduce the non-uniformity of the neutron distribution on the mask plane, the inner collimator size was reduced, the main moderation layer thickness was increased and an absorbing layer was added. The absorbing layer can decrease the total neutron flux, but it is necessary for adjusting the slope type non-uniformity to meet the requirement of less than 20%.

The new moderator was used to take the coded source image. As some noise sources have not been eliminated effectively so far, the image quality is not so good. However, the artifact caused by the non-uniformity of the neutron distribution on the mask plane is not visible in the image. The moderator design for coded source image is acceptable.

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