Neutron penumbral imaging simulation and reconstruction for Inertial Confinement Fusion Experiments

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(Dated: 2 May 2014)

Neutron penumbral imaging technique has been successfully used as the diagnosis method in Inertial Confinement Fusion. To help the design of the imaging systems in the future in CHINA. We construct the Monte Carlo imaging system by Geant4. Use the point spread function from the simulation and decode algorithm (Lucy-Richardson algorithm) we got the recovery image.

Inertial confinement fusion (ICF) has attracted much attention from all over the world. The National Ignition Facility (NIF) programs in America and Laser MegaJoule (LMJ) in France aim at reaching the inertial confinement fusion of a deuterium-tritium (DT) filled cryogenic target. China’s ICF program are also in progress, this paper’s aim is just study the neutron diagnosis system which will be used in the future ICF program in China.

The process of ICF can be divided into four steps as Fig 1: First step generate radiation to drive implosion. There are two approaches to drive implosion, one is laser direct driven, another is laser energy injected inside the cavity generates X-rays that heat the DT fuel. Under X-ray or laser compression, the target density as well as the mean ions’ temperature increases. Fusion reactions will occur within a hot spot generating 14 MeV neutrons and alpha particles1,2. If the density is sufficient to trap the energetic alphas or other radiation, these energy will be deposited on the surrounding cold DT medium. Then the chained thermonuclear reactions will lead to a combustion in the compressed target. For a well compressed target, combustion will last long enough to generate more energy than the injected energy. If ever, drive symmetry is poor or pulse shaping is imprecise, burning will be low. So we can use the neutrons escaped from the compressed cores of target to study the compressed process to make sure the drive be symmetrical.

There are several neutron imaging techniques for inertial confinement fusion (ICF) experiment to detect the size, shape, and uniformity of the compressed cores. The pinhole imaging is the easiest way, but the low neutron yield has an effect on the sensitivity. In NIF experiment a pinhole array is designed to increase the sensitivity3–7.

The another technique is the neutron penumbral imaging (NPI), which have been widely studied by LMJ8–13 and other groups14–19. Compared with other neutron imaging techniques, the sensitivity of neutron penumbral imaging is higher. Annular imaging is nearly the same as penumbral imaging, the only difference of the imaging process is aperture.

In this paper we just based on the simulation model in the reference20–23 to design a software package NG-PINEX which can be used to simulate the neutron imaging process and recovery the coded image. The imaging process simulation have been described in Geant4, and then the recover algorithm we used Lucy-Richardson method24,25, which have been successfully applied on decoding x-ray ring code image26. The whole program is written in C++, which can be run under the linux system with multi-core server.

In the program we simulated neutron penumbral imaging and Annular imaging, the pinhole imaging block is also included in the program. Based on the NIF and LMJ experiment we design an imaging system aiming to achieve 20µm resolution. At last we use the Lucy-Richardson method successfully got the recovered image.
I. THE IMAGING SYSTEM SIMULATION

The structure of neutron penumbral imaging system is shown in Fig.2. The source, aperture and detector composed the whole imaging system. The fast neutrons emitting from a burning target are scattered by the aperture materials, and form an penumbral image on the detector arrays. In our simulation the coded aperture is placed at 55\,mm from the source, the detector is placed at 7\,m from the aperture. The aperture is designed as a 50\,mm(h) thick 10\,mm diameter(tungsten) cylinder to achieve an effective absorption of the 14\,MeV neutrons in the opaque parts of the aperture. The pattern of the aperture is a disk (penumbr) which consists in a biconical hole, the diameters (D_1, D_2, D_3) of the biconical hole are 0.3\,mm, 0.38\,mm, 0.535\,mm. An enlarged coded image is projected on the neutron detector which is placed on the target bay floor, at 7895\,mm from the aperture. The image obtained from the detector is a convolution of the source spatial distribution with the aperture transfer function.

In the Fig.2 only the red annular of the coded image contains the effective information of the source shape changing. To achieve the high SNR we can place a plug inside the hole of an aperture of the same dimensions as the penumbral(Fig.2) to define a annular, which will be study in another paper. This pattern can shield a lot of background but also face the alignment tolerance problem and not enough neutron can be detected.

The neutron detector is composed of 255 \times 255 array of scintillating fibers Fig.3. Each scintillating fiber can be realized as a sub-detector, the structure was designed as the left figure of Fig.3. The core part is a tubes of scintillating fibers Fig.3. Each scintillating fiber can be study in another paper. This pattern can shield a lot of background but also face the alignment tolerance problem and not enough neutron can be detected.

The scintillating light interaction in the array of scintillating fibers. The material of the envelope is Polyvinyl alcohol(molecular formula CH2=CHOH, 1.26\,g/cm^3) and the thickness is 20\,\mu m. An optical relay then casts the scintillating light from the end of the array to an image intensifier tube (IIT) which gates the 14 MeV neutrons at their arrival time on the detector. The image is then reduced with a fibered optical taper onto a CCD. Overall spatial resolution of the system for both the annular and the penumbral apertures is the same, which is determined by the point spread functions (PSF) of the coded aperture and detector resolution (\Delta s_{\text{detector}}) scaled down the source plane as equation 1. In the paraxial approximation, the broadening of the apertures point spread function is identical, determined by the FOV and the aperture to target distance (L_0).

\[
\Delta s = \sqrt{\frac{\ln(2) \times \text{FOV}}{2 \times L_0 \times \mu} + \Delta s_{\text{detector}}^2 \times \left(\frac{L_0}{L_1}\right)^2} \quad (1)
\]

where \mu is the attenuation of the neutrons in tungsten and L_1 is the detector to the target distance. With this design, the overall spatial resolution of the system is about 20 \,\mu m in source plane.

In the GEANT4 simulation we used the physics list QGSP_BERT_HP which contains the high precision neutron package (NeutronHP) to simulate the process of neutrons’ transportation with the energy below 20 MeV down to thermal energies. The physical process neutron capture, fission, elastic and inelastic scattering (including absorption) are treated by referring to the ENDF-B VI cross-section data. Besides, in the ref[27] has demonstrated the validity of GEANT4 calculations in neutron generation and transportation which is the same as MCNP. Moreover, object-oriented programming and highly sophisticated processing of both electromagnetic interactions and ionization processes enhance GEANT4 capabilities for the study of mixed fields and complicated geometries.

In the ICF experiment the neutrons generated by hot spot spread in whole space. The idealized aperture only allow the neutrons in the solid angle as Fig.2 to deposit the energy on the detector. But actually because the neutrons have the high ability to penetrate the start part of the aperture, and also the neutrons will scatter with the

![FIG. 2. Penumbral imaging](image-url)

![FIG. 3. Fiber array](image-url)
wall of the aperture, these neutrons which hit the detector will become the background of the imaging. To simulate the complete imaging process and also save the calculation time we ask the program only generate random distribution neutron in the cone with \( R_i \) radius as Fig. 4. As equation 2 \( R_i \) is determined by \( R_0 \) which is the width of the detector project on the front face of the aperture.

With this design there are about one half of the events be scattered by the penumbral aperture. To get the high statistic sample we simulated 1 \( \times 10^{10} \) effective events of penumbral imaging.

\[
R_i = \begin{cases} 
   D_0/2, & R_0 > D_0/2 \\
1.3R_0, & D_3/2 \leq R_0 \leq D_0/2 \\
D_3/2, & R_0 < D_3/2 
\end{cases} \tag{2}
\]

II. RECONSTRUCTION OF THE CODED IMAGE

At present, there are a lot of reconstruction methods have been developed. Among them the simplest and quickest method is Wiener filter method, which is a linear reconstruction method. As we cannot get prior knowledge of the signal-noise ratio, wiener filter method cannot get good results. Therefore we can use this method as the reference or use the result as the input of some nonlinear reconstruction method. In these years there are some nonlinear reconstruct methods have been introduced to reconstruct penumbral image such as genetic algorithm and heuristic algorithm proposed by Chen et al.\textsuperscript{14}, and the classical molecular dynamics reconstruction method proposed by Liu et al.\textsuperscript{15,16}. In the experiment L. Disdier et al. had successfully used the filtered autocorrelation technique\textsuperscript{28} to get 20\( \mu \)m resolution reconstruction image from the penumbral imaging system with 22.3\( \mu \)m theoritical resolution. Filtered autocorrelation technique is different from other method which don’t need to rely on the simulation PSF in the reconstruction.

Another nonlinear method Lucy-Rechardson algorithm\textsuperscript{24,25} has been successfully used on X-ray ring coded imaging in experiment\textsuperscript{26}. And this algorithm has been most widely used for restoring images with noise from counting statistics and the data approximate Poisson statistics. In this program we first try to use the Lucy-Rechardson method to get reconstructed image. The process of the imaging can be described as a spatial intensity distribution \( g(x, y) \) convolved by a neutron source spatial intensity distribution \( f(x, y) \) with a point spread function (PSF) \( h(x, y) \). Add the noise \( n(x, y) \) the detector image can be expressed as

\[
g(x, y) = f(x, y) \otimes h(x, y) + n(x, y) \tag{3}
\]

Lucy-Rechardson algorithm is an iterative method. Based on the reference\textsuperscript{24,25}, the decode formulation can be expressed as 4. Where PSF(h) and image on detector(g) come from the simulation, the reconstructed image(f) can be extracted after k times iterate.

\[
f_{k+1} = f_k(h \otimes \frac{g}{h \otimes f_k}) \tag{4}
\]

The PSF for penumbral and annular imaging are presented in Fig. 5 respectively. In Fig. 6 we presented the raw images with a ‘F’ shape neutron source and the unfolded results with Lucy-Rechardson method. The width of the ‘F’ shape source is 20\( \mu \)m.

From the Fig. 6 we can see with this design the imaging system can achieve the aim to reconstruct the neutron source. With Lucy-Rechardson method the unfolded image of Penumbral aperture is clear. To get the real resolution of the system we simulate two point source with distance 20\( \mu \)m imaging on the detector. In the Fig. 7 present the raw image and unfolded image. For the annular imaging reconstruction and detail of the unfolding method we will present in further study.
FIG. 7. Two point source imaging for penumbral aperture(left), unfolded result(right).

III. CONCLUSION

We have successfully construct one software NG-PINEX which integrated the imaging system simulation and the reconstruction method. The simulation and reconstruction result show we can use this imaging system with these parameters to get 20µm resolution image of DT implore. To attend the aim of 3µm resolution in the future we can use this software to optimize the system parameter.

Acknowledgments: The authors would like to thank Ming Jiang and Bing-quan Hu for the help on the simulation model construction. This work was supported in part by the Fundamental Research Funds for the Central Universities under Grant No.CDJSX1102209 and the Program for New Century Excellent Talents in University under Grant No. NCET-10-0882, and by Natural Science Foundation of China under Grant No.10805082 and No.11075225.

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