Available online at www.sciencedirect.com

ScienceDirect

Physics Procedia 60 (2014) 118 – 124

Physics Procedia

3rd International Meeting of the Union for Compact Accelerator-driven Neutron Sources, UCANS III, 31 July–3 August 2012, Bilbao, Spain & the 4th International Meeting of the Union for Compact Accelerator-driven Neutron Sources, UCANS IV, 23-27 September 2013, Sapporo, Hokkaido, Japan

Three-dimensional (3D) Fast Neutron Tomography at the Low Energy Neutron Source (LENS)

S. Lee[a]*, T. Rinckel[a], J. Doskow[a], and P.E. Sokol[a,b]

[a]*Center for the Exploration of Energy and Matter, Indiana University, 2401 N Milo B. Sampson Lane, Bloomington, IN 47408, USA*
[b]*Department of Physics, Indiana University, 727 E Third St., Bloomington, IN 47405, USA*

Abstract

We have constructed a neutron imaging station at the Low Energy Neutron Source (LENS), located within the Center for the Exploration of Energy and Matter at Indiana University. In contrast to many existing neutron imaging stations, we utilize a broad range of neutron energies, extending into the fast neutron regime, to take advantage of the higher fluxes and larger penetrating power of these high-energy neutrons. The imaging station consists of a collimator to define the beam, a rotating sample stage, and a cooled charge-coupled device camera (Alta U6) using a scintillator. A LiF + ZnS screen is used to produce scintillation light. Typical image collection times are a few seconds for a aperture to sample distance ratio of 100, yielding a spatial resolution of 0.2 × 0.2 mm^2. Examples of the scanned and calculated image are presented.

Keywords: neutron tomography, MCNPX, radiography, scintillator.

doi:10.1016/j.phpro.2014.11.018

1. Introduction

In contrast to traditional X-ray or gamma-ray imaging technology, fast neutron tomography (FNT) provides significantly different internal information regarding materials. Materials with low atomic numbers, and particularly those containing high levels of hydrogen, such as water and organic materials, are clearly visible in neutron tomography. In particular, FNT promises a broad range of scanning power and faster scanning times than traditional thermal or cold neutron tomography. A fast neutron imaging station has been constructed at one of target stations of the Low Energy Neutron Source (LENS). Using a broad range of neutron energies, extending into the fast neutron regime, makes it possible not only to scan a broad range of samples, from palaeontology and geology collections, but also to shorten the scanning time, with the higher fluxes and larger penetrating powers of these high-energy neutrons. The imaging station consists of a 4-cm diameter steel collimator to define the beam, a rotating sample stage, and a cooled charge-coupled device (CCD) camera (Alta U6) [1]. A ^{6}Li-loaded ZnS screen is used for the scintillator screen where neutron signals are converted to visible light. Typical image collection times are a few seconds, the L/D value is 100, where D is the diameter of collimator aperture and L is the distance from a collimator to a camera, and the spatial resolution at the camera is 0.2×0.2 mm^2. In this paper, examples of a calculated and scanned image are presented.

2. FNT Beam Station and Image System

The LENS neutron source utilizes a high current pulsed proton accelerator and a beryllium target to generate neutrons. The accelerator generates 13 MeV proton pulses with a peak current of 25 mA and a variable pulse-width (from 10 µs to 1.4 ms). The proton beam is incident on a thin Be target and neutrons are generated via a (p,nx) reaction and generates neutrons with a spectrum extending to a maximum energy of 11 MeV. The neutron spectrum at the image station has been calculated using a Monte Carlo N-Particle, X (MCNP-X) 2.7.0 model [2], and is shown in Figure 1.

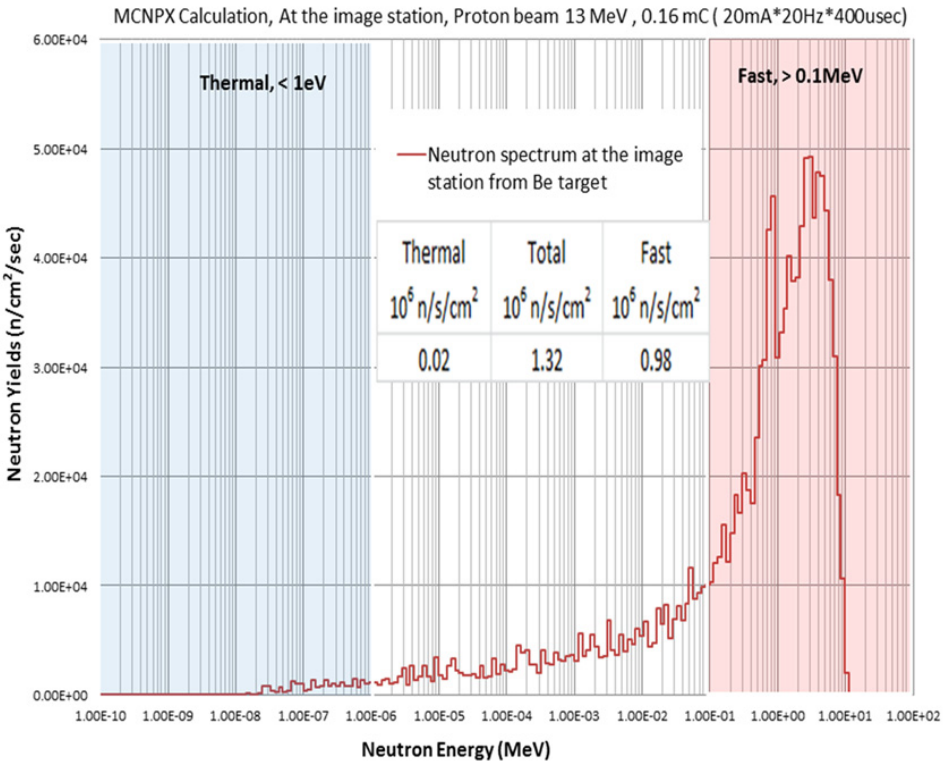

Fig 1. The neutron spectrum at the image station with 13 MeV, 20mA, a repetition rate of 20 Hz, and a 400 μs wide proton beam.

Total neutron flux at the sample station is approximately 1.4×10^6 **(**n/cm^2/s). The neutron spectrum consists primarily of fast neutrons with energies above 1 MeV and few thermal neutrons. Moderators can be downstream of the target to increase the flux of thermal neutrons [3]. An optical chopper phased to the neutrons source and located between the scintillator and camera allows the elimination of the signal from the fast neutrons. This allows conventional thermal neutron radiography studies to be carried out.

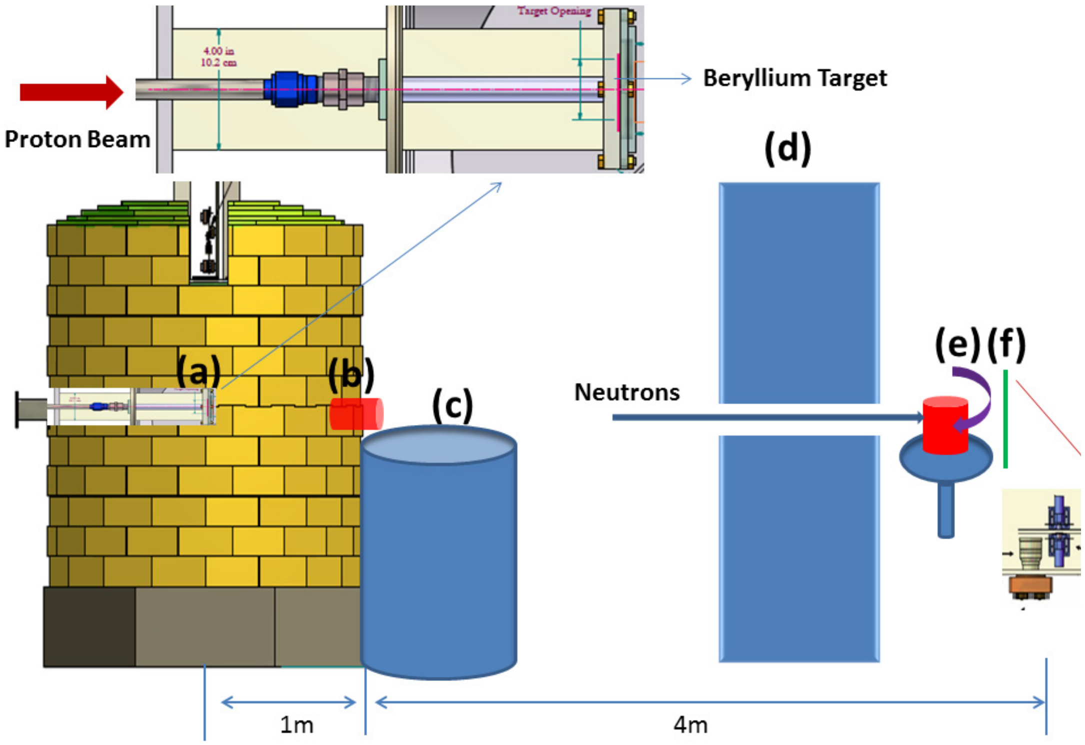

Fig 2. The schematic for the FNT beam station: (a) the beryllium target components, (b) the iron collimator, (c) the filter stage, (d) the secondary shielding, (e) high-precision rotary table, and (f) the scintillator screen.

The FNT beam station consists of three major components, as shown in Figure 2: 1. the beryllium target components, where the variable pulse-width proton beam is incident on the 1.2-mm-thick water-cooled beryllium target, producing fast neutrons, 2. the iron collimator, where various neutron beam sizes (from 0.5 up to 10 cm diameter) are defined and appropriate L/D values (100) can be selected. 3. the filter stage where the ratio of thermal and fast neutrons is controlled by applying moderating materials. The secondary shielding forming wall (2 m tall, 3.5 m wide, and 0.3 m think concrete) is between the FNT beam station and the image station to block possible background radiation, including scattered neutrons, gamma rays, and X rays. For the computed tomography studies, there are three major components at the image station: 1. a high-precision rotary table, where precise motor-driven rotary positioning and indexing is remotely controlled in conjunction with the Alta U6 CCD camera system. 2. a 6LiFZnS:Cu,Al,Au scintillator screen, where incident neutrons are converted into scintillation light in the reaction3. a cold CCD camera (Alta U6), which has a low dark current, a 1024 × 1024 pixels sensor array, 70% at 560 nm quantum efficiency, and 0.2 × 0.2 mm^2 spatial resolution [1].

3. Tomographic reconstruction and volume rendering

Tomographic reconstruction and volume rendering can be carried out by placing the sample on a rotating sample stage and collecting neutron images at different orientations. Scanned two-dimensional (2D) images were reconstructed using the Feldkamp filtered back-projection algorithm [4]. A three-dimensional (3D) image was produced using the slice volume rendering code [6] with a reconstructed 2D slice image. A typical full CT scan-collecting 400 slice images takes approximately one hour.

3.1 *Tomographic image simulation*

A tomographic 3D image can be produced by measuring the levels of brightness of the 2D image, which come from the attenuated neutron flux. One can calculate the attenuated neutron flux using a MCNP-X 2.7.0 model [2] if physical properties, such as the size and elements contained inside a volume are already known. A MCNP-X model was developed to calculate the attenuated neutron flux.

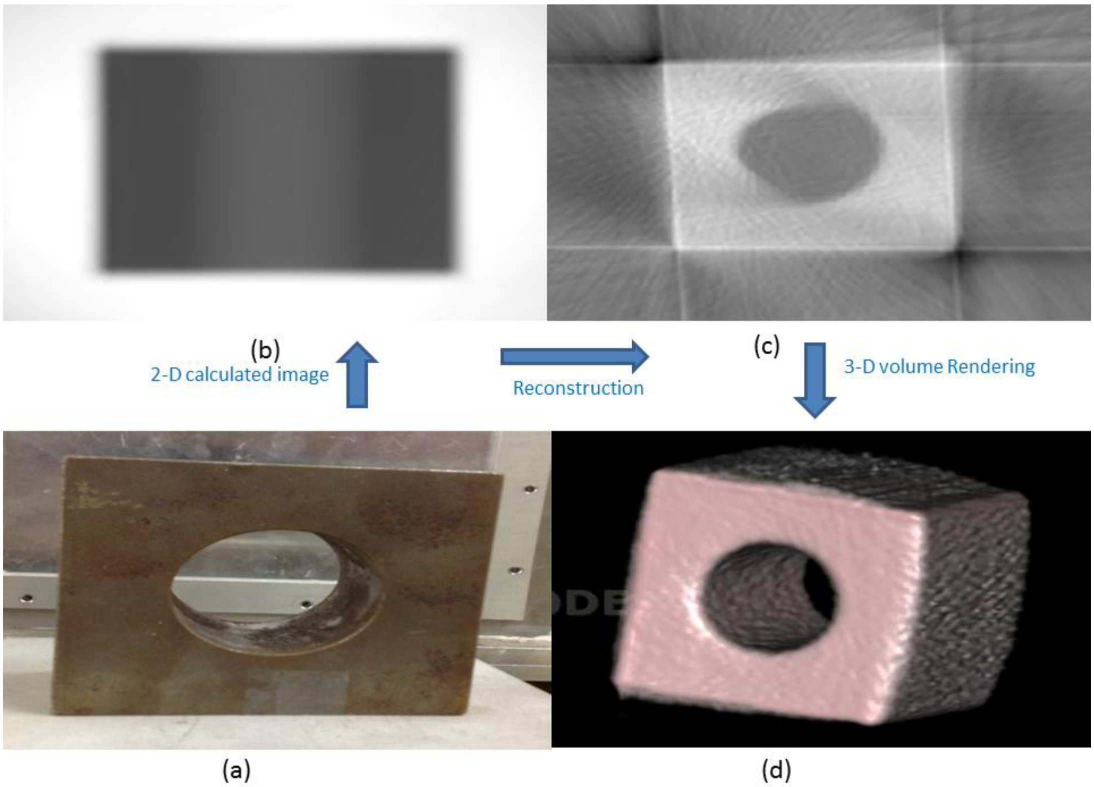

Fig 3. The procedure of tomographic image simulation: (a) the photo of a steel structure, (b) the 2-D calculated image using MCNP-X, (c) the reconstructed slice image, and (d) the volume rendered 3-D image.

Figure 3 shows the procedure for tomographic image simulation. Our test object is a 5 cm × 5 cm × 5 cm steel structure with a 2-cm diameter cylindrical hole in the middle the transmission through this object was simulated with MCNP-X. The transmission was calculated as the sample was rotated through 5 degree steps. Each simulation was 5^{10} histories using the Indiana University Parallel Quarry computing system [7]. The individual radiographs were then used to create the reconstructed slice images and the volume rendered 3-D image.

3.2 *Tomographic image measurement*

FNT was used to reproduce the 3D image, which revealed the internal structure of matter in scanning valuable and unusual scientific specimens at LENS, Indiana University. An automated procedure for collecting 400 slice images has been developed and a full CT scan can be completed in approximately 1 h.

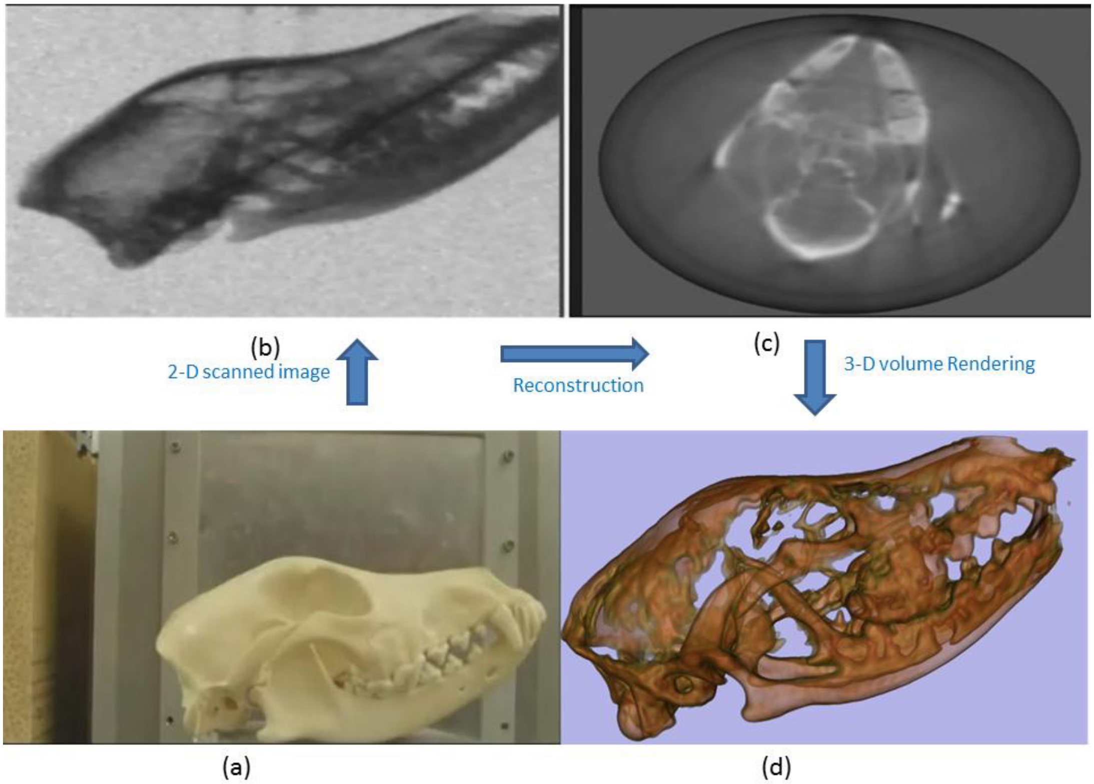

Fig 4. The procedure of tomographic image measurement: (a) the photo of a dire wolf fossil, (b) the 2-D scanned image, (c) the reconstructed slice image, and (d) the volume rendered 3-D image.

Figure 4 shows an example of the FNT procedure. A dire wolf fossil was placed on the high-precision rotary table and scanned into 400 degree deferent angle viewed images using a CCD camera with 5-s exposure times. The scanned 2D images were reconstructed into voxel images that contained the volume information using the Feldkamp filtered back-projection algorithm [4]. Voxel images can be visualized into one 3D image by a volume-rendering procedure using the slice volume rendering code [5]. A full FNT completion takes approximately 2.5 h, depending on computer power and sample size. Table 1 shows the full FNT procedure time.

Table 1. The full FNT procedure time

FNT procedure	Time
2-D image scanning	~ 1 hour
Reconstruction coding	~1 hour
Reconstruction Computer	10 sec
Volume Rendering Computer	15 sec
Mapping	0.5 hour
Total 3D Tomography time per one sample	~ 2.5 hour

4. Conclusions

We have developed a fast neutron imaging station at the LENS where an automated procedure for collecting 400 slice images has been developed and a full CT scan can be completed in approximately one hour. Several fossils have been successfully reconstructed into 3D FNT images in an appropriate scanning time (approximately 1 h) and reconstruction time (approximately 1 h). With known structure of matter, the neutron tomographic calculation has been developed and successfully reconstructed. High flux-fast neutrons (approximately 1.4×10^6 n/cm^2/s) at the FNT beam station and an automated scanning system make it possible to scan thousands of different digital images and use these collections as future cyber museum exhibits that students and researchers can study and compare remotely.

References

[1] Kun Chen, A STUDY OF SPECTROSCOPIC, COLD NEUTRON RADIOGRAPHY (Ph. D Thesis), 2006

[2] X-5 Monte Carlo Team, "MCNP-X A General Monte Carlo N-Particle Transport Code, Version 5," Los Alamos National Laboratory, User Manual LA-UR-03-1987, 2008.

[3] S. Lee, T. Rinckel, J. Doskow, and P. E Sokol, "New Neutron Radiation Effects Capabilities at The Low Energy Neutron Source (LENS) " in *Proceedings of the Union of Compact Accelerator-Driven Neutron Sources (UCANS) III*, 2013, Prepublished copy.

[4] L. A. Feldkamp, L. C. Davis, and J.W. Kress, “Practical conebeam algorithm,” *J. Opt. Soc. Am. A*, vol. 1, pp. 612–619, June 1984.

[5] 3D slicer, http://www.slicer.org/

[6] Quarry at Indiana University, http://kb.iu.edu/data/avkx.html, January 11, 2013.