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Development of neutron imaging beamline for NDT applications at Dhruva reactor, India

Mayank Shukla [a,b,*], Tushar Roy [a], Yogesh Kashyap [a], Shefali Shukla [a], Prashant Singh [a], Baribaddala Ravi [a], Tarun Patel [a], S.C. Gadkari [a]

[a] Technical Physics Division, Bhabha Atomic Research Centre, Mumbai 400085, Maharashtra, India
[b] Homi Bhabha National Institute, Mumbai 400094, Maharashtra, India

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ABSTRACT

Thermal neutron imaging techniques such as radiography or tomography are very useful tool for various scientific investigations and industrial applications. Neutron radiography is complementary to X-ray radiography, as neutrons interact with nucleus as compared to X-ray interaction with orbital electrons. We present here design and development of a neutron imaging beamline at 100 MW Dhruva research reactor for neutron imaging applications such as radiography, tomography and phase contrast imaging. Combinations of sapphire and bismuth single crystals have been used as thermal neutron filter/gamma absorber at the input of a specially designed collimator to maximize thermal neutron to gamma ratio. The maximum beam size of neutrons has been restricted to ~120 mm diameter at the sample position. A cadmium ratio of ~250 with L/D ratio of 160 and thermal neutron flux of ~4×10^7 n/cm^2 s at the sample position has been measured. In this paper, different aspects of the beamline design such as collimator, shielding, sample manipulator, digital imaging system are described. Nondestructive radiography/tomography experiments on hydrogen concentration in Zr-alloy, aluminium foam, ceramic metal seals etc. are also presented.

1. Introduction

Neutron radiography is a powerful tool for non-destructive evaluation of materials and finds numerous applications in material research and industry [1–9]. It produces a two-dimensional (2D) attenuation map of neutrons that have penetrated an object being examined, similar to the X-ray radiography. However, both X-ray and neutron imaging are often complementary techniques, especially when low-energy neutrons (thermal neutrons) are used. X-rays interact with orbital electrons and are strongly tied to the physical density of the examined object. Neutrons interact with an object's nucleus rather than its orbital electrons, so there is usually no tie to the object's electron density, but rather its elemental composition. Because the technique is based on attenuation from a well-collimated beam, either scattering or absorption will result in intensity variations to create an image. Low-Z materials such as hydrogen are easily imaged due to scattering, while boron and cadmium are readily imaged due to their strong absorption. This makes it possible to produce images of components containing light elements, like hydrogen, beneath a matrix of metallic elements, (lead or iron), which cannot be easily done with conventional X ray radiography. The interaction of X-rays with orbital electrons of the electronic shell gives rise to a near-monotonic increase of the mass attenuation coefficient with atomic number. Thus in general X-rays are preferred for high Z materials to achieve a good contrast radiography image. On the other hand, (thermal) neutron interaction with different elements is not a regular function of the atomic number and also differs for different isotopes of the same element. For example, it shows high attenuation for some low Z elements like hydrogen, carbon, lithium. At the same time, neutron shows low absorption in many high Z elements like iron, lead, zirconium. Neutron radiography has been especially used in applications requiring the identification of such low Z materials inside solid metallic samples. In particular, neutron radiography finds application in the detection of "O"-rings, gaskets, adhesives or sealants, hydrogenous liquids like water or petroleum products and corrosion inside high Z shielding materials like steel, lead or zircaloy. Besides this, strong absorption of neutrons in certain high Z elements like cadmium, gadolinium, dysprosium helps to distinguish between metals such as cadmium and iron or silver, rare earth metals such as gadolinium, samarium, europium, or dysprosium versus other rare earth metals, and iron, cobalt, and nickel versus

* Corresponding author at: Technical Physics Division, Bhabha Atomic Research Centre, Mumbai 400085, Maharashtra, India.
E-mail address: mayank@barc.gov.in (M. Shukla).

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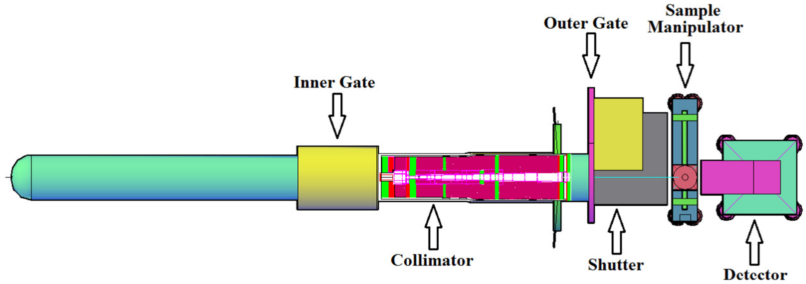

Fig. 1. Schematic setup of the neutron imaging beamline with collimator, shutter, sample manipulator and detector.

lead, tungsten or bismuth. An additional advantage is the ability to perform isotopic discrimination, i.e., that is the ability to image one isotope of an element in the presence of other isotopes of the same element. An example of this application that has proved useful is the radiography of nuclear fuels to image the fissionable ^{235}U content rather than the ^{238}U that is most prevalent in natural uranium. In addition, other isotopes such as ^{113}Cd, a material used in reactor control rods, can be imaged in the presence of other, less neutron absorbing cadmium isotopes.

Strong neutron sources like research reactors and accelerator-based spallation neutron sources [10] can provide intense neutron beams, required for efficient and practical neutron imaging. Such beams have been successfully used for neutron radiography during the last two decades and has found its greatest applications, for example, in the examination of nuclear fuels, engine turbines blades, and material characterization. Recently, neutron imaging has been used in new branches: fuel cell research, archaeological artefacts, geo-science etc. [11,12]. Although traditional transmission radiography still plays an important role, development of more sophisticated techniques like tomography [13,14], real-time analysis of systems including fluid flow and/or moving components, energy selective inspection have widened the scope of neutron imaging. Since wave-particle dualism (*de Broglie* postulate) allows us to treat the neutron beam as particles possessing a defined mass and a kinetic energy or to regard it as a propagating wave with corresponding amplitude and wavelength, another technique called phase contrast imaging has been useful for imaging objects with poor neutron absorption [15].

In this paper we describe a state-of-art neutron imaging beamline developed at Dhruva reactor for advanced imaging applications such as neutron radiography, tomography and phase contrast imaging. It incorporates an advanced collimator inserted in the beam port. A combination of sapphire (1 0 0) and bismuth (1 1 1) single crystals has been used as thermal neutron filter/gamma absorber at the input of collimator to maximize thermal neutron to gamma ratio [16–19]. Thicknesses of the sapphire and bismuth crystals were taken to be 90 mm each {as per Nieman etal [17] and other researchers [16,18,19] that suggest the use of more than 75 mm thickness}. This thickness was chosen so that high transmission (>85%) of thermal neutrons along with high neutron/gamma ratio can be achieved.

The collimator has been designed using reactor grade aluminium cone shaped housing with filled mixture of sand-B_4C powder, lead rings, boral rings for absorbing scattered neutrons and gamma radiation. Absorption based radiography/tomography studies can be performed using this fixed collimator. For phase contrast imaging studies, a specially fabricated thin walled cadmium-lined cone shaped structure with a pin hole that can be inserted in the conical space of the main collimator. The shielding is modular and has been placed around the beam-port. It also consists of a shielded motorized door for access to the hutch. We also present design details of a high sensitivity electronic imaging system that involves scintillator based imaging system combined with a high resolution CCD camera. This imaging system in combination with the data acquisition and image processing software has been used for neutron radiography, neutron 3D tomography and neutron phase contrast imaging. Neutron beam characterization along with experimental results of samples studied using this beamline are also presented. The phase contrast imaging studies on this beamline will be presented elsewhere. However, we present here the design details of collimator.

2. Neutron imaging beamline

Fig. 1 shows schematic view of neutron imaging beamline that includes collimator, shutter, sample manipulator and detector. The collimator has been placed in between the inner and the outer gate of the port whereas shutter, sample manipulator, detector have been placed inside a shielded experimental hutch made using borated polythene and lead blocks. This hutch also incorporates a motorized shielded door on a linear motion guide as presented in Section 2.2. Following sub-sections describe different parts of the beamline.

2.1. Collimator

A collimator is an essential part of any imaging beamline since it shapes the beam for optimized sharpness as well as reduces scattered neutrons and gamma. The essential parts of a neutron collimator are beam filters (to remove unwanted radiations), aperture that limits neutrons entering the collimator, gamma shielding and housing that helps define and shapes the beam. Fig. 2 shows the schematic diagram of the collimator that has been used in the beamline. The collimator has been designed using reactor grade aluminium cone shaped housing filled with mixture of sand-B_4C powder, lead rings and boral rings for absorbing gamma radiation and scattered neutrons. At the input end of the collimator facing the core, a sapphire (Al_2O_3) single crystal (100) in combination with a bismuth single crystal (111) is placed at the input of the collimator for filtering high energy neutrons and gamma radiation respectively. Since beam size of neutrons has been restricted to ~120 mm diameter at the sample position, annular housing has been used to fill the gap between the collimator and the port (diameter 300 mm). Sand-B_4C powder, cadmium sheets, lead rings and Boral has been used as filler materials in the annular housing. A 16 mm diameter (D) aperture, made in gadolinium disc, is placed just after the crystal to prevent thermal neutrons from entering the beam except through the hole. This aperture size was so chosen such that it gives a good collimation ratio with in the space between inner and outer gate of the port as well as not compromising the neutron flux at the sample position. The collimator (overall length-1567 mm) has been designed in such a way that both neutron absorption based radiography & tomography along with phase contrast imaging studies can be performed on the same setup. For phase contrast imaging application a special conical collimator (length-1537 mm) with a 0.5 mm pinhole (in gadolinium disc) is inserted in the main collimator. The collimators can be easily mounted or demounted depending upon the mode of the experiments.