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Neutron Tomography at INES: First experimental results

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Summary. — A neutron tomography apparatus has been designed and installed at the Italian neutron experimental station (INES) at ISIS (UK). The instrument has a double aim: an additional opportunity for the INES users and a "*bench test*" for an instrument component that will be proposed for installation on some of the new neutron scattering instruments of Target Station 2 (TS2) of ISIS. Here, we present the first experimental results achieved with this apparatus.

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1. – Introduction

Neutron imaging is a rapidly evolving non-invasive and non-destructive tool for material investigation [1]. Indeed, neutrons can be used almost like X-rays to produce images that reveal the inner structure of a sample. X-ray radiation is absorbed differently by diverse materials and the contrast they produce in an X-ray detector (*e.g.*, the usual photographic plate) gives rise to a familiar radiographic image. A similar technique can be applied using neutrons. Again, due to the different absorption properties of various materials it is possible, using a proper detector, to produce images of the interior of a sample.

Nevertheless, these peculiarities of neutrons would have not been of a significant importance, in practical terms, if they were not accompanied by a contemporary development of the detector technology. In fact, an important factor that has favored the development of neutron imaging techniques (as well as X-ray imaging, indeed) is related to the recent evolution of the CCD cameras that allow the digital recording of optical images. Thus, the simple coupling of a neutron scintillator with an optical CCD detector represents the basic ingredient for the development of neutron imaging techniques. Hence, thanks to the well-recognized complementarity between neutrons and X-rays, neutron radiography and tomography can shed light on a number of cases where conventional X-rays show their limitations.

It is worthwhile to recall that while the total X-ray cross-section grows monotonically as the square of the atomic number, the neutron cross-section is randomly distributed among elements. While it is difficult for X-rays to distinguish between elements of similar atomic number, this difficulty may be overcome when using neutrons. In addition, due to the inherent property of X-rays to interact with the electronic clouds of the atoms, there is an intrinsic weakness in detecting, by this technique, low-atomic weight components in a mixture with heavier atoms. On the contrary, this is not an insoluble problem for neutrons and it becomes even an advantage when considering hydrogen-containing materials, thanks also to the overwhelming neutron cross-section of this element with respect to the average value of all the others. As a result, the presence of even a small quantity of hydrogen can be detected and hydrogen-based materials situated behind a thick metal wall can be easily revealed.

Very intense neutron sources are required to obtain good quality images; this fact made reactors the primary choice for neutron imaging instrument construction in the past years [2]. Nowadays, accelerator-based pulsed neutron sources reach beam intensities that allow obtaining good quality imaging in short enough times; furthermore the pulsed nature of their neutron beam flux allows obtaining energy selective images of the investigated samples in a conceptually simple way. By selecting appropriate time windows for the image acquisition, it is possible to produce object images that are generated by neutrons with well-defined energy ranges. In such a way, tuning the energy of the probe near the Bragg edges characteristic of the different materials, it is possible to enhance the image contrast for the various substances that are present in the sample. As a result, materials that are indistinguishable under "white beam" illumination because of almost equal absorption coefficients can be easily discriminated [3].

Among the various possibilities, one of the main fields where the neutron imaging can be helpful is archaeometry. In fact, archaeological samples are delicate and often unique. Therefore, the investigation methods that can be used should be absolutely non-destructive and preferably non-invasive. In addition, since many archaeological samples contain interesting details that are hidden inside the investigated objects, or else, the interesting object itself is hidden into different enclosures, a technique that is able to detect and spatially localize such objects, in a non-destructive way, is extremely important. X-ray techniques have shown to be effective in these applications, even with limitations that are intrinsic and well recognized. Neutrons can be used to overcome these difficulties making the combination of the two radiographic techniques an extremely powerful tool to investigate almost any arrangement of materials.

2. – Experimental set-up

INES is the Italian experimental station at ISIS (UK); it was built in 2005 and since then it has been used for many experiments ranging from texture analysis of materials to a number of detector and neutron instrumentation tests. Recently, the INES station has been used to develop a portable imaging system to be used for beam monitoring and sample alignment on different instruments [4]. As the experimental station INES is involved in an international user programme, the installation of a neutron tomography camera had to be designed in such a way as to minimize changes to the standard configuration.

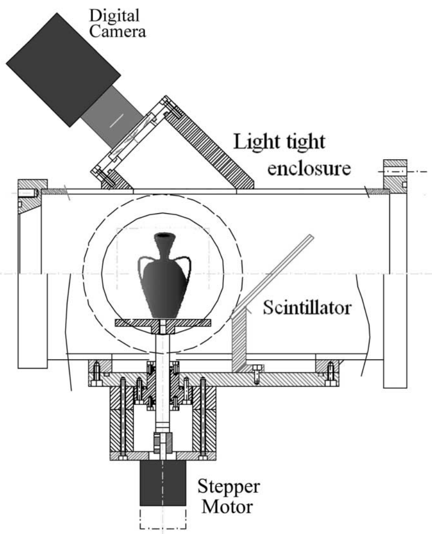

Fig. 1. – The neutron tomography chamber.

Consequently, this has been built as an extension of the INES sample container tank so as to maintain the earlier experimental configuration unaffected. In this arrangement the flight path length from the neutron source (room temperature water moderator) to the sample is $L = 23.84\,\mathrm{m}$ and the beam collimation, placed along the path, determines an effective size of the beam source, D, of $\simeq 8.5\,\mathrm{cm}$. The best theoretical image definition depends on the ratio L/D [5]. In our case, this is of about 280. The beam dimension, at the sample position, is about $\simeq 4.4\times4.4\,\mathrm{cm}^2$. A schematic view of the set-up is shown in fig. 1.

The incoming neutron flux is attenuated by the sample placed on a platform rotating around a vertical axis by means of a stepper motor. The beam transmitted through the sample reaches a scintillator screen, made of $ZnS/^6LiF$ layered on an aluminum substrate, which emits visible light centered at a wavelength $\lambda \approx 520\,\mathrm{nm}$. The mean distance, ℓ, between the sample rotation axis and scintillator is about 100 mm; this latter is tilted by an angle $\theta = 45°$. The values of the L/D ratio and the average distance ℓ allow to estimate an average spatial resolution d of about $340\,\mu\mathrm{m}$ [5]. Since the distance between the sample and scintillator is not constant, the spatial resolution is better at the bottom than at the top of the image ($0.261\,\mu\mathrm{m} < d < 0.421\,\mu\mathrm{m}$). The quantity d measures the dimension (diameter) of the projection of an object point onto the scintillator plane (see fig. 2) due to the finite size of the source.

The stepper motor used to rotate the platform is remotely controlled by a personal computer equipped with a homemade controller and a National Instrument USB-6211 interface; it can be operated at 1.8° step in full step mode or at 0.9°/step in half step mode giving a total of 100 or 200 steps for 180°, respectively. Future improvements will allow to considerably increase such number.

The light emitted by the scintillator is collected via a commercial black and white CCD camera (The Imaging Source model DMK 21BF04 [6]) equipped with a commercial objective (Computar M0814-MP, $f = 8\,\mathrm{mm}$, F 1.4). The camera is endowed with a digital trigger input, used by the software to start each single image acquisition, and it is controlled by a personal computer (PC) via an IEEE1394 interface. All the camera

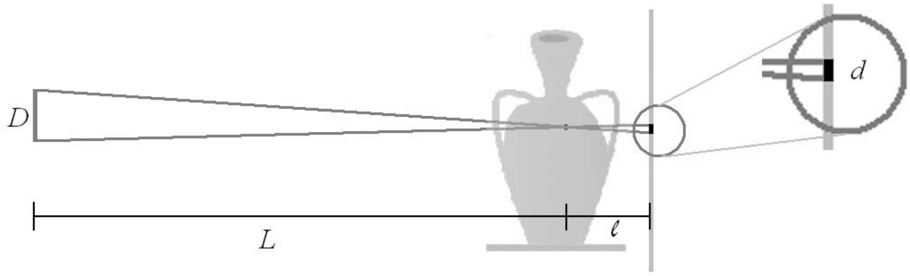

Fig. 2. – Finite source size effect.

parameters can be programmed through a class library (IC Imaging Control [7]), a software bundle that is sold with the camera. The CCD sensor is a Sony ICX098BL with a pixel size of $5.6 \times 5.6\,\mu\mathrm{m}^2$. It has 640×480 pixels and is equipped with a 10 bit ADC whose most significant 8 bits are sent as an output; it is operated at room temperature and, at present, without an image intensifier. The exposure times can be varied in the interval $100\,\mu$s–30 s, the frame readout frequency ranges from 3.75 Hz to 60 Hz and the camera gain could be changed from 0 dB to 36 dB.

One of the main problems we have to deal with when using a CCD sensor in a hostile environment, such as a neutron experimental enclosure, is to prevent or possibly reduce the damage that fast neutrons and γ-rays could produce in the electronic chips. To this aim, we have interposed a lead-glass window in front of the objective and we have wrapped the camera with a 10 mm thick neutron absorbing boron plastic. However, even using these protections, we have observed that a few white spots have developed onto the CCD sensor after some operation time. We are trying to overcome this problem by software techniques, for the time being, but we are also seeking for a more effective way to protect the sensor.

3. – Measurement procedure

Before each measurement we always recorded a series of dark images, needed to subtract the background noise contribution, and a series of the unobstructed beam pictures employed to normalize for the not perfectly uniform beam intensity along its cross-section (as shown in fig. 3).

Both the image sets are acquired in the same experimental conditions and with equal camera parameters as the related measurements. An *average* dark image and an *average* beam image have been calculated from the two sets and a 3×3 median filter has been applied to both the *average* images to remove the contribution due to damaged pixels.

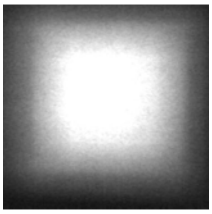

Fig. 3. – Beam cross-section.

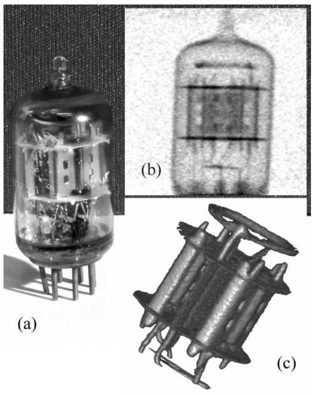

Fig. 4. – (a) Vacuum tube; (b) neutron radiography; (c) tube interior 3D rendering.

For each investigated sample 100 or 200 images were taken at different incident angles between the sample and the beam. The exposure time was varied together with the camera gain in order to optimize the image quality (low gain) *versus* the total acquisition time. Exposure times of 120 s and 22 s were used for the samples shown in this work. Since the camera has a maximum exposure time of 30 s, external accumulations, in the PC memory, were performed when needed. Each object image, subtracted of the dark contribution, was corrected for the beam intensity fluctuations by selecting an area free from sample and normalizing its intensity over the entire image set; the resulting images were then normalized to the open beam and finally a 3×3 median filter was applied.

To perform the tomographic reconstruction of the objects it is essential to precisely know the position and orientation of the rotation axis. However, since this axis does not coincide exactly with the optical axis of the camera, we applied a procedure to correctly estimate both the position and the inclination of one with respect to the other. To this aim, we used the images taken at 0° and 180°, that should be the mirror copy of each other, using the following procedure. A mirror copy of the 180° image is first obtained. For each row of both the 0° and the 180° mirror images, the cross-correlation function is computed and the location of its maximum, as a function of the shift, is recorded in a data array; thus, a linear fit is applied twice first to all the data in the array and then only to the data that are within a predetermined distance from the previous fitted line. This procedure has been proved to be robust enough against the presence of regions with uniform gray levels; in addition, the homemade developed software provides an interactive procedure that can be employed when the automatic one does not produce satisfactory results.

Because of the long primary path of the neutrons and the consequent almost parallel nature of the incident beam, a Filtered Backprojection algorithm with a Shepp Logan Filter [8] was applied to the obtained images in order to reconstruct the tomography slices of the investigated objects.

4. – Experimental results

The first examined object was a vacuum tube. Its optical image is shown in fig. 4a. In fig. 4b, we show one of its neutron radiographies, whose exposure time was set to 120 s. For the tomography reconstruction of this object, 200 images were acquired over 180°.

Fig. 5. – "*Black box*" composition.

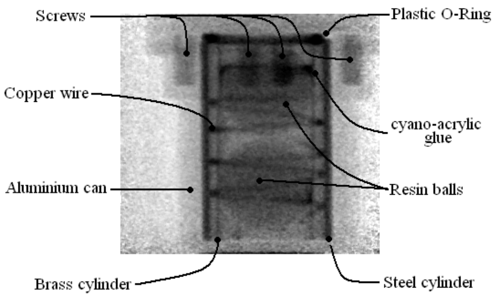

Fig. 6. – "*Black box*" neutron radiography.

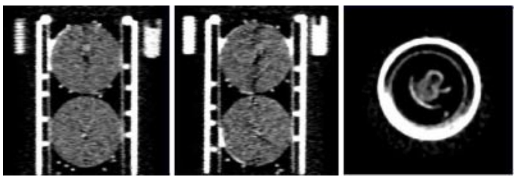

Fig. 7. – "*Black box*" tomography slices.

A three-dimensional rendering of the vacuum tube interior, reconstructed using a commercial software package [9], is shown in fig. 4c. We observe that the interior of the bulb is satisfactorily reproduced.

To check further the capability of neutron imaging techniques in penetrating metallic shells and in detecting organic (*i.e.* hydrogen-containing) materials, a special sample was built. This is a composite object, built on-purpose, which should represent a "black box" composed by various plastic and metallic objects. A sketch of the sample is shown in the various pictures of fig. 5. Two plastic balls were held together by means of a Cu-Ni wire and placed inside a brass tube. This, in turn, was wrapped by another piece of copper wire and enclosed into a second tube made by steel. The resulting object was then transferred into an aluminum container that has inserted four steel screws and that was air-tight closed with a screw cap also made of aluminum.

Fig. 8. – "*Black box*" 3D reconstruction.

The tomography was performed with the acquisition of 100 images, taken over 180°, with an exposure time of 22 s. The images were then processed, as described in the previous section, to reconstruct the 3D representation of the sample. One neutron radiography of the "black box" is shown in fig. 6. As we can see, all the components are clearly identified and evidenced, including the external aluminum container that, in spite of its thickness, appears almost transparent to neutrons, thanks to the very low absorption cross-section of aluminum. Tree slices of the "*black box*" tomography are shown in fig. 7 and a cut view of a 3D reconstruction is displayed in fig. 8. In this last picture, we have enhanced the contrast to make the internal components more visible and, in doing so, we have made transparent the external aluminum can.

5. – Conclusions

We report the results of the first experimental run carried out at the neutron tomography installation that has been recently tested on INES. The apparatus has been proven to be very effective in identifying the internal sample structure even in this basic configuration. Nonetheless, many different aspects can profit of major improvements to make this experimental facility an even more useful tool for Italian and international users of this instrument.

The use of a cooled and intensified camera should allow to obtain a drastic reduction of image noise and exposure times; this, in turn, will decrease sample activation. A larger dynamic range should permit a better distinction among different materials. Using the time structure of the neutron source and making a proper use of the Bragg edges, it will be possible to further enhance the image contrast also with materials characterized by similar integral absorption coefficients. An improvement of the platform rotation mechanism, with an increase of the angular step number, should allow a better spatial resolution on the object peripheric volume. Finally, the use of an x-z translation stage will allow studying samples with dimensions greater than the present beam size. A new neutron tomography chamber is in preparation that will address all these aspects.

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REFERENCES

[1] Lehmann E. H. *et al.*, *Physica B*, **385-386** (2006) 475.
[2] Lehmann E. H., *Facilities for neutron radiography in Europe: performance, applications and future use*, *Proceedings of 15th World Conference Non-Destructive Testing, Rome, Italy, 15-21 October 2000*, edited by AIPnD, Brescia.
[3] Kockelmann W. *et al.*, *Nucl. Instrum. Methods Phys. Res. A*, **578** (2007) 421.
[4] Bartoli L. *et al.*, *Nucl. Instrum. Methods Phys. Res. A*, **595** (2008) 643.
[5] Lehmann E. H. *et al.*, *Nucl. Instrum. Methods Phys. Res. A*, **576** (2007) 389.
[6] `http://www.theimagingsource.com`.
[7] `http://www.imagingcontrol.com`.
[8] Kak A. C. and Slaney M., *Principles of Computerized Tomography Imaging* (IEEE Press) 1988.
[9] `http://www.volumegraphics.com/products/vgstudiomax/index.html`.