COMMISSIONING TESTS OF THE NEW NEUTRON RADIOGRAPHY FACILITY AT THE LVR-15 REACTOR

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ABSTRACT

Neutron radiography represent a non-destructive testing imaging method, similar to X-ray radiography. Its application starts in cases where X-ray radiography may hit its limits. In recent years a neutron radiography facility has been built at one of the spare horizontal channel of the LVR-15 research reactor in Rez, Czech Republic. The present facility is a result of a pilot project of reintroduction of neutron radiography after 20 years at the LVR-15 reactor. The horizontal channel HK-1 was modified for this purpose, which was equipped by a neutron filter and an irradiation box. A Timepix based detector was developed for the facility and installed coupled with a sample positioning device. These can be fully remotely controlled via a computer and online measurements can be carried out and processed immediately. Before the facility was put into its full operation in 2016 several test measurements were done prior~~,~~ to test the limitations of the facility. The test measurements were focused on neutron imaging of test samples for various scientific fields like material science, structure engineering, geology, palaeontology, cultural heritage preservation, etc. The realized measurements have shown the limits of the facility caused mainly due to the level of beam collimation. This aspect require measurements where the sample is in near- contact geometry with the detector to achieve a reasonable image resolution. But despite this feature the new facility still provides unique non-destructive testing capabilities supplementary to X-ray radiography.

1. Introduction

The LVR-15 is a multipurpose tank-type light water moderated research reactor operated by the Research Centre Rez near Prague, Czech Republic. The reactor is operated at a maximum thermal power level of 10 MW. The utilization of the reactor is wide, covering material research, industrial and medical radioisotope production, neutron transmutation doping of silicon, neutron activation analysis, experimental boron neutron capture therapy, neutron diffraction experiments, prompt gamma activation analysis, etc. The reactor is equipped with nine horizontal channels (Fig. 1) and one thermal column providing ten neutron beams for further use. In scope of a research project, one of the formerly unused horizontal channels denoted as HK1, was adapted for the needs of a neutron radiography facility, which was reintroduced at the LVR-15 reactor after more than 20 years of absence. Neutron radiography represents a similar non-destructive examination method similar to standard X-ray radiography. It is however not a competing method, but a supplementary one, which can be successfully applied in many cases where x-ray radiography reaches its limits. In can be successfully applied in fields like material science, structure engineering, geology, palaeontology, cultural heritage preservation, etc. The facility was fully completed by the end of 2015. After the completion of the facility a series of commissioning measurements with several chosen test objects was carried out to test the limits of the facility and its possible application in applied research or industrial testing.

2. Facility description

2.1 Neutron beam

Before 2011 the HK1 horizontal channel was unused for many years. For the purposes of the neutron radiography facility several changes had to be done to the channel. One of the key conditions for operating an effective radiography facility is the delivery of a high intensity, parallel, homogeneous and collimated thermal neutron beam at the sample location. Additionally the intensity of fast neutrons has to be kept as low as possible as the fast neutrons may damage the detectors used for neutron imaging. As the spectrum in the empty horizontal channel roughly copies the spectrum in the reactor core, which has a high ratio of fast neutrons and reactor gamma radiation, neutron filter components have to be installed inside the channel in order to achieve desired beam parameters. The radial channel HK1 was, therefore, equipped with a silicon single crystal filter-collimator [1]. After the filter instalment it offers a neutron beam with a diameter of 10 cm with a high intensity of thermal neutrons and low fast neutron and gamma background (Tab. 1). As the beam exit surroundings was limited by other experimental or reactor maintenance devices a compact facility design was chosen. A shielded irradiation box (Fig. 2) was installed at the beam exit to house the samples while irradiation. The box is equipped with a detection system and a positioning device enabling the movement and rotation of the sample. Due to a compact design the L/D parameter of the facility is only 40.

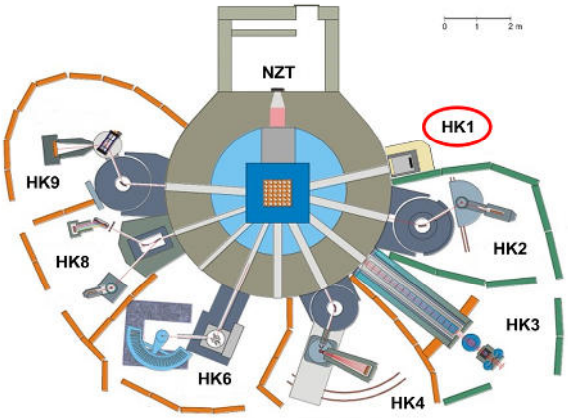

Fig. 1 LVR-15 reactor with its neutron beams

Fig. 2 Irradiation box at the HK1 beam

Tab. 1 Beam parameters overview at the HK1 neutron beam

Beam diameter	100 mm
Typical thermal neutron fluence rate	2.10^{8} $cm^{-2}.s^{-1}$
Typical fast neutron fluence rate	10^{5} $cm^{-2}.s^{-1}$
Typical gamma dose equivalent rate	200 $mGy.h^{-1}$

2.2 Detection system

The facility of the HK1 channel is equipped by large area Timepix [2] based pixel detector denoted as WIDEPIX4x5. The large-area neutron pixel detector is based on the adaptation of the large-area device originally developed for X-rays. The detector is formed by a matrix of Timepix assemblies (4×5 tiles with a total sensitive area of 71 × 57 mm2 comprising 1.3 mega pixels equipped with an edgeless silicon sensor forming the final device without image-disrupting gaps or insensitive areas. A thin film of 6LiF covering with the mass density ~ 4 mg/cm2 the sensitive area provides a detection efficiency for thermal neutrons of ~ 4%.

After the capture of a thermal neutron 6Li decays into an alpha particle and a triton, which are released in opposite directions with energies 2.05 MeV and 2.72MeV, respectively, causing a response in the detector. The read-out architecture is formed by the USB2.0-based FitPix3.0 read-out, developed by IEAP CTU in Prague. A brief overview of the detector parameters is listed in Tab. 2. The detector is mounted on a remotely adjustable positioning device (Fig. 3), which can be equipped with a rotational table. [3]

Tab. 2 Basic detector parameters

Detection area size	70,4 x 56,3 mm^2
	1280 x 1024 pixels (1,3 Mpx)
Timepix chips used	20
Timepix chip parameters	256 x 256 pixels, each chip is equipped with its own electronics supporting three operation modes: counter (Medipix mode), spectrometer (Time-over-Threshold mode) or timer (Time-of-Arrival mode)
Pixel size	55 µm (edge pixels of each chip 137,5 µm)
Sensor material	Si (thickness 300 µm)
Convertor material	^{6}Li (bounded in isotopically enriched LiF)
Thermal neutron detection efficiency	3 – 4 %
PC communication interface	USB 2.0
Read-out speed	0,6 s per frame
Thermal power	25 W
Cooling	Pump-powered water cooling circuit
Operating software	Pixelman

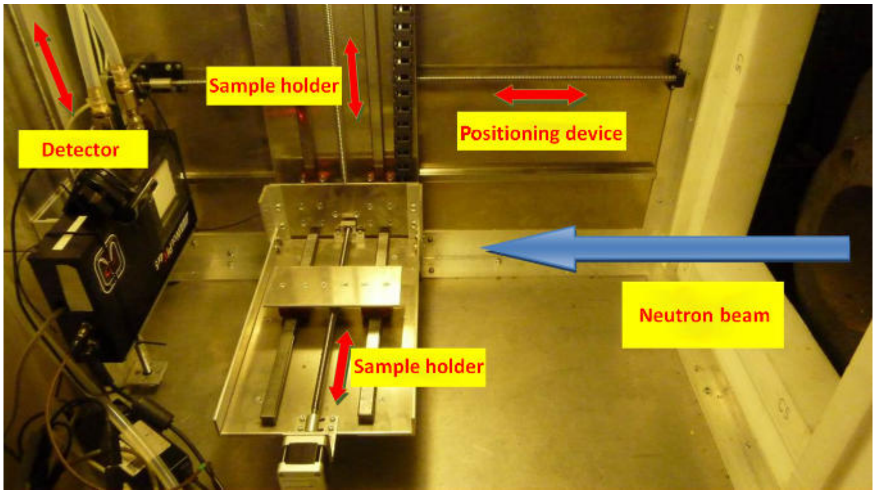

Fig. 3 Pixel detector and sample holder of the neutron radiography facility mounted inside the irradiation box

3. Pilot experiments

3.1 Spatial resolution determination

The spatial resolution of a radiography facility is one of the key aspects to evaluate its performance. Several approaches can be made to distinguish the spatial resolution using “semi-standardized” test patterns and objects. In case of the HK1 facility three thin partially holed foils, originally used to punch activation foils, from materials with a high thermal neutron attenuation factor have been used. These comprised holed foils made from gadolinium and dysprosium and a thin cadmium sheet. The test foils were assembled and placed in the neutron beam in 11 different distances from the detector, starting with a contact object-detector geometry (0 mm) and ending in a distance of 100 mm and an according radiograph was gathered (Fig. 4). In each of the radiographs there position were identified (denoted as L Vertical, R Vertical, and R horizontal) where the detection system response on the contrast sharp edge was evaluated (so called Edge Response Function). The sigmas of the error functions for each of the 3 evaluated positions for the distances up to 50 mm and the corresponding FWHMs are listed in Tab.3.

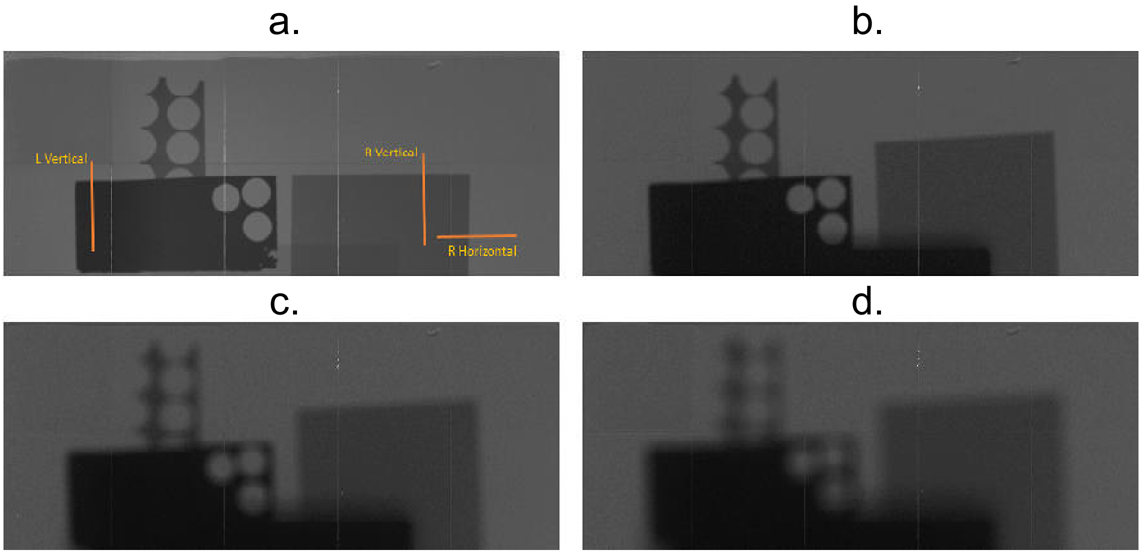

Fig. 4 A radiograph of a gadolinium, dysprosium and cadmium foil in several distances from the pixel detector – a) contact geometry (0 mm); b) 20 mm; c) 50 mm; d) 100 mm

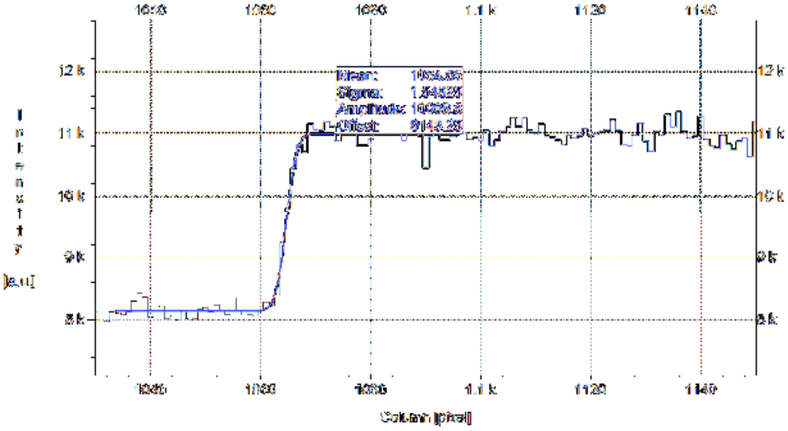

Fig. 5 The edge response function for the gadolinium (L Vertical) foil in the contact geometry.

Tab. 3 Image spatial resolution according to the distance of the object from the detector expressed as the sigma of the edge response function and the according FWHM

		Vertical - L		Horizontal - R		Vertical - R	
Distance [mm]	Time [s]	sigma [μm]	FWHM [μm]	sigma [μm]	FWHM [μm]	sigma [μm]	FWHM [μm]
0	20	86.90	205.08	85.25	201.19	85.80	202.49
20	20	220.55	520.50	261.80	617.85	235.40	555.54
30	20	305.80	721.69	342.65	808.65	298.10	703.52
40	20	388.30	916.39	496.10	1170.80	392.15	925.47
50	20	459.80	1085.13	600.05	1416.12	489.50	1155.22

As seen from the radiographs (Fig. 4) and their evaluation (Tab. 3) a reasonable spatial resolution of the facility is achievable only in close object-detector geometries. Due to this fact the facility is best suited for the examination of flat non-massive objects.

3.2 Real object examination

The series of test aimed to distinguish the facility resolution was followed by measurements with real object which are well suited for examination with neutrons. The chosen objects comprised a fossilized pine cone, a step motor, a clay tablet piece and a smartphone. The gathered radiographs of each of the objects are shown in Fig. 6 – 9.

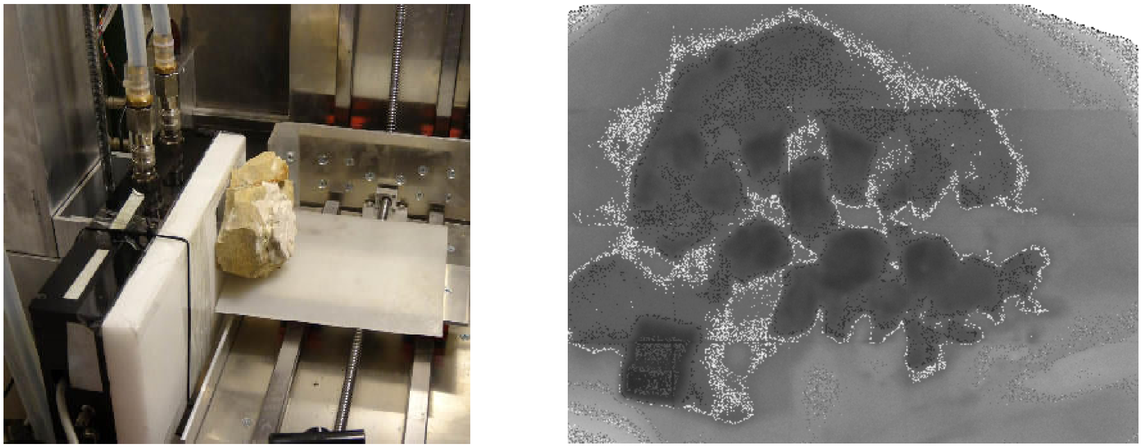

Fig. 6 A fossilized cone and its radiograph

The fossilized organic cone, from the collection of the National museum in Prague, is located in a massive stone matrices, and its visualization by the means of standard X-ray radiography is problematic. The radiographs demonstrates the potential of the method for similar types of samples (organic material sealed inside massive stone matrices), which can be found in palaeontology collections.

The radiograph of the step engine aims to demonstrate the potential of application of the method on the examination of inner structures of objects with a massive metallic cover. The radiograph of the clay tablet has shown hidden inscriptions in its structure (in archaeological collections can be found lots of similar coiled tablets). The radiograph of the smartphone shows a high contrast of the observed inner structures, which is limited mainly only by the exposure time. The exposition time of all the radiographs was 60 s.

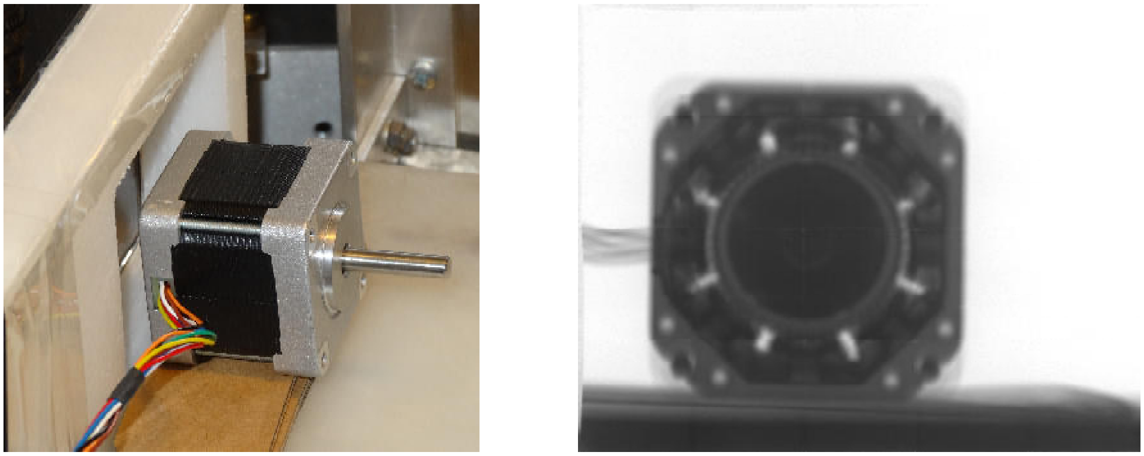

Fig. 7 A step motor and its radiograph

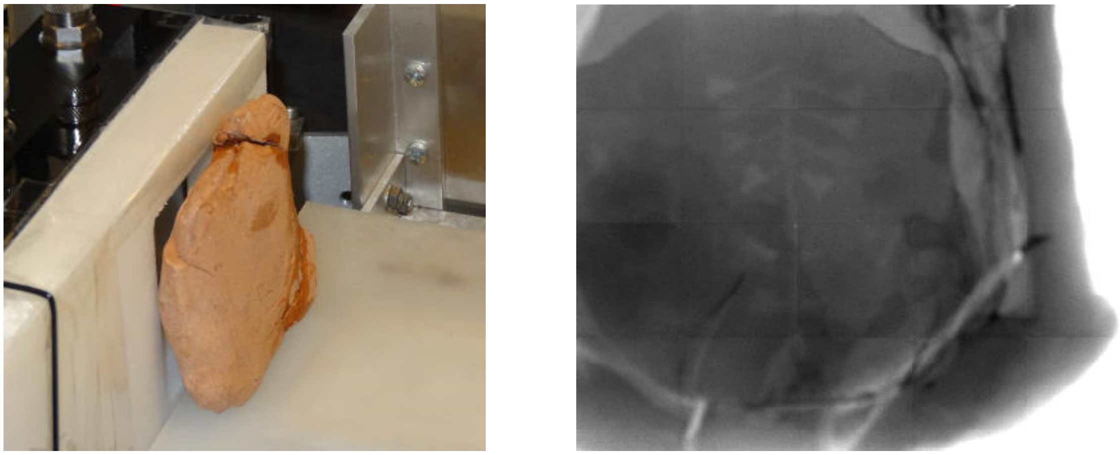

Fig. 8 A piece of a bent clay table, its radiograph shows a hidden ornament

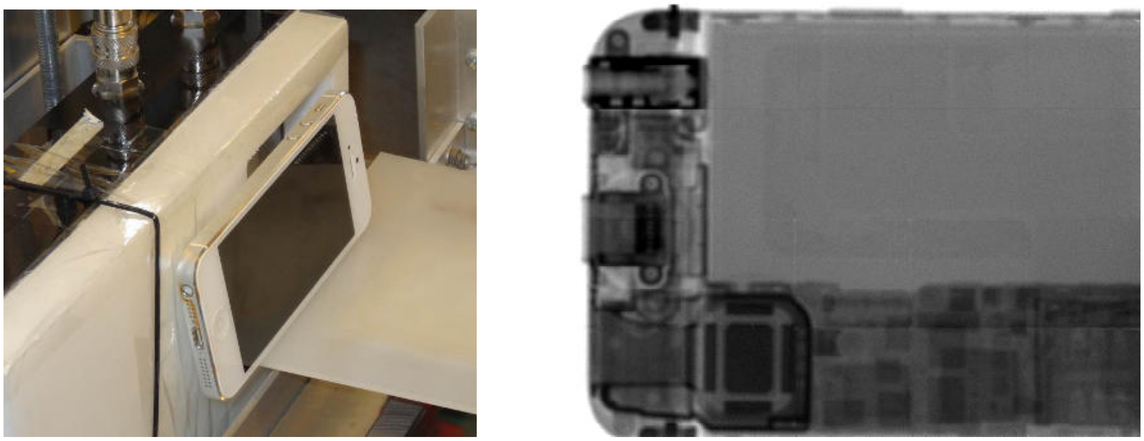

Fig. 9 A smartphone where its radiograph shows its detailed inner structure

Despite the lower resolution in non-contact geometries few attempts were done to realize a tomographic reconstruction of an object. A welded metallic pipe was chosen for this test. 180 projection were done in total, with a 15 s exposure time for each. The tomographic reconstruction was realized with the PIXELMAN software [4], using the OSEM reconstruction method with 3 iterations. Several cutting through the volume of the reconstructed volume of the pipe along with one radiograph are shown on Fig. 10. The application of neutron radiography for such kind of welded metallic structures is well suited compared to x-ray radiography, due to the high penetration of the neutrons trough metallic structures and characteristic interactions of thermal neutrons with the weld.

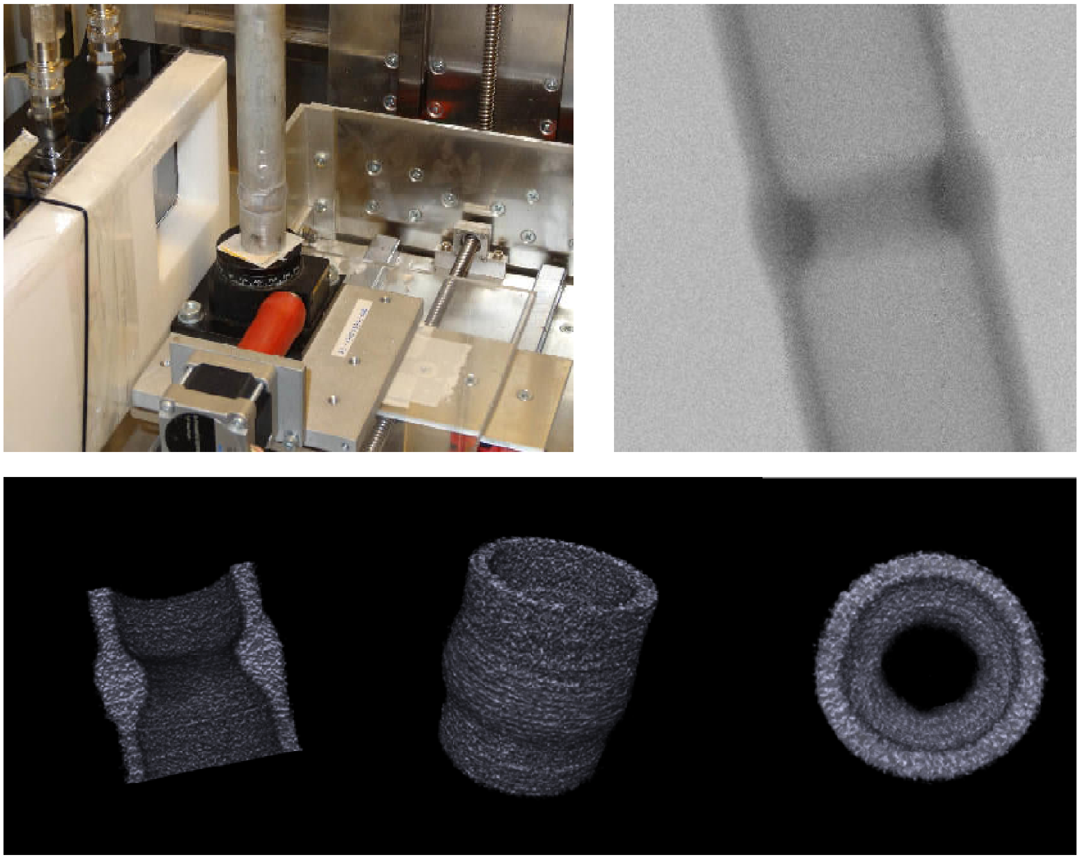

Fig. 10 A tomographic reconstruction of a welded aluminium pipe

4. Conclusion

Few representative of the first realized measurements on the newly built neutron radiography facility on the HK1 neutron beam of the LVR-15 reactor in Rez were presented. The realized measurements showed reasonable results with a decent resolution in the order of 100 μm in contact or close distance object-detector geometries. For with the increasing distance from the detector the image resolution of the examined object drops due to the lower level of collimation of the beam, which was mainly aimed on a high thermal neutron flux value with a low background, which can be applied also for other experiments, rather than a lower flux with better collimation. However, despite this limitation for certain kinds of radiographic examination the beam provides adequate results. Also the possibility of realizing 3D tomography reconstructions was proven.

Minor upgrades of the facility are considered for the facility by the extension of the flight neutron path or installing a pin-hole collimator adjacent to the neutron filter which could improve the beam collimation and thus beam quality, however at the cost of the beam intensity and thus extending the exposure time.

5. Acknowledgement

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