RADIOGRAPHY AND TOMOGRAPHY USING FISSION NEUTRONS AT FRM-II

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Abstract: Fission neutrons offer complementary information in radiography and tomography compared to the well established techniques using X-rays, gamma-rays, thermal or cold neutrons. They penetrate thick layers of high density materials with only little attenuation, while for light, specially for hydrogen containing materials, their attenuation is high.

In the past, fast neutrons for NDT (non-destructive testing) were only available at accelerator driven systems. These high energy neutrons have to be moderated to achieve acceptable detection efficiencies thus drastically reducing the available neutron intensities and either resulting in a high beam divergence or in additional losses in neutron intensities due to beam collimation.

The recently installed neutron computerized tomography and radiography system NECTAR at the Forschungsreaktor München-II (FRM-II) overcomes these disadvantages by using fission neutrons of about 1.7 MeV mean energy created in two converter plates set-up of highly enriched uranium. The beam quality, i.e. the neutron divergence can be adapted to the object to be measured by using different collimators, resulting in L/D-values up to 300. The available neutron beam intensity at the measuring position is up to 1.7E+08 cm^{-2} s^{-1} for a maximum beam area of 40 cm x 40 cm. For conventional imaging a two-dimensional detector system based on a CCD-camera is used, other more specialised systems are available.

Introduction: Radiography and tomography are well established methods in NDT of various samples, basically using X-rays or gamma-rays as transmission sources. Due to the increasing availability of intense and brilliant thermal or cold neutron beams at research reactors and spallation sources in recent years neutron radiography and tomography became a well accepted inspection technique, too, resulting in complementary information. This is based on the different type of interaction. X-rays and gamma-rays interact mainly with the electrons of the atoms, resulting in a direct dependency of the attenuation properties on the atomic number. Neutrons interact directly with the nucleus. This results in a completely irregular dependency on the atomic number for cold and thermal neutrons which have energies between 0.5 meV and ca. 100 meV. On the other hand fast (fission) neutrons with energies of ca. 1.7 MeV show a dependency which is nearly inverse to that of X-rays and gamma-rays. Thus the mass attenuation coefficients, a measure for the strength of interaction with matter, are completely different for X-rays, gamma-rays and neutrons (figure 1).

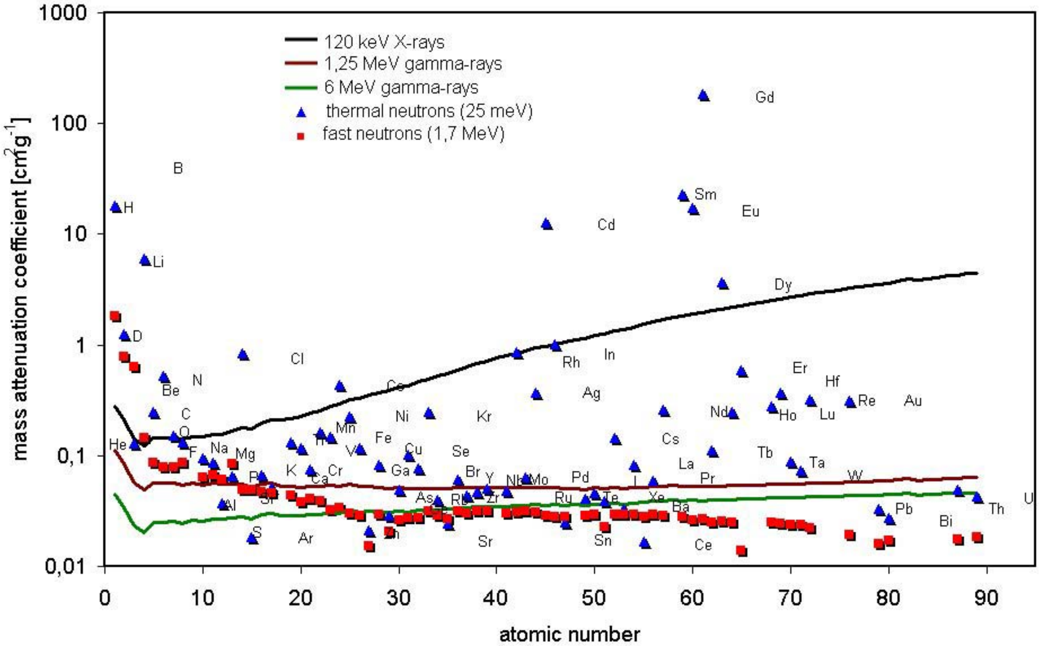
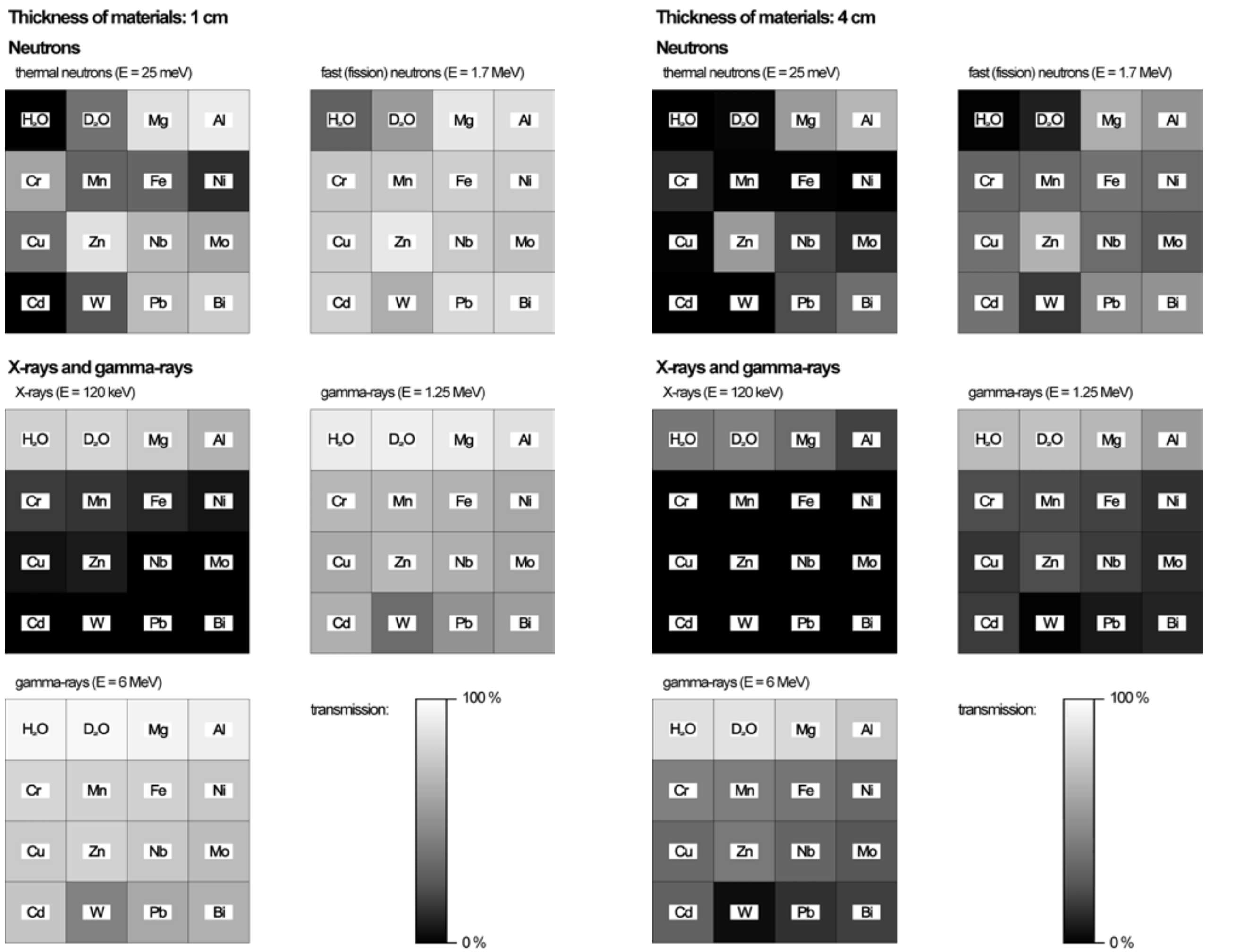


Figure 1: Mass attenuation coefficients for X-rays, gamma-rays, thermal and fission neutrons.

The often complementary results when applying different transmission sources become more obvious when considering figures 2 and 3. Here the corresponding transmitted intensities for different materials of 1 cm and 4 cm thickness, respectively, are plotted coded using the same grey scale. Bright areas signify, that this material can be penetrated easily by that radiation (i.e. high transmission), while dark areas indicate low or no transmission.

Figures 2 and 3 show the strong irregular transmission probabilities for thermal neutrons. Therefore materials having similar atomic numbers can very often be discriminated. X-rays and gamma-rays show a decreasing transmission probability with increasing atomic number. These transmission sources are complemented in an ideal way by fission neutrons: They penetrate thick and dense materials like iron, tungsten and lead, while being very sensitive to hydrogen containing materials.

Neutrons of this energy (1.7 MeV) can either be produced using accelerator based systems or by fission. The first usually generate neutrons of much higher energies (up to 14 MeV) which must be slowed down. This process is connected with an extreme loss in intensity and collimation, thus making successful application in NDT very problematic. On the other hand, fission neutrons only require collimation for being applicable in NDT. Therefore a neutron radiography and tomography facility using fission neutrons was planned and implemented at the new Forschungsreaktor München-II (FRM-II). The facility is actually tested and optimized.



Figures 2 (left) and 3 (right): Transmission properties for X-rays, gamma-rays, thermal and 1.7 MeV neutrons for different materials. In the individual areas the charge number is increasing from top left to bottom right, i.e. the densest material is located at bottom right. The darker an area the less its transmission.

The NECTAR facility: The schematic layout of the NECTAR (NEutron Computerized Tomography And Radiography) facility is shown in figure 4. Two converter plates containing highly enriched uranium (93 % ^{235}U) are placed in the moderator tank (filled with D_2O). Moderated thermal neutrons originating from fission in the single fuel element (compact core) of the FRM-II induce fission in these plates. Through an evacuated beam tube placed close in front of the plates the emitted fission neutrons can leave the moderator tank and further pass the H_2O-pool and the biological shield without moderation. The beam tube ends at the outer side of the biological shield and is equipped with four beam shutters. Next a small room ("Beckenwandnische") is passed by the fission neutrons. Here energy distribution of both neutron and gamma quanta can be manipulated by different polyethylene and lead filters. A permanent filter set-up of 2 cm polyethylene and 0.1 cm cadmium removes the undesired thermal neutrons from the beam. Collimators can be moved in the beam to optimize its geometry for neutron radiography and tomography. The filtered and collimated fission neutron beam then enters the room for medical applications trough an additional, variable collimator, which is mainly used for further discrimination of scattered neutrons and gamma-rays. Before leaving the room on the opposite side, the beam height can be adapted by the beam shutter used for the medical application. The adjacent room contains the detector systems, the manipulators for the sample and the detector systems and the beam dump (Figure 5).

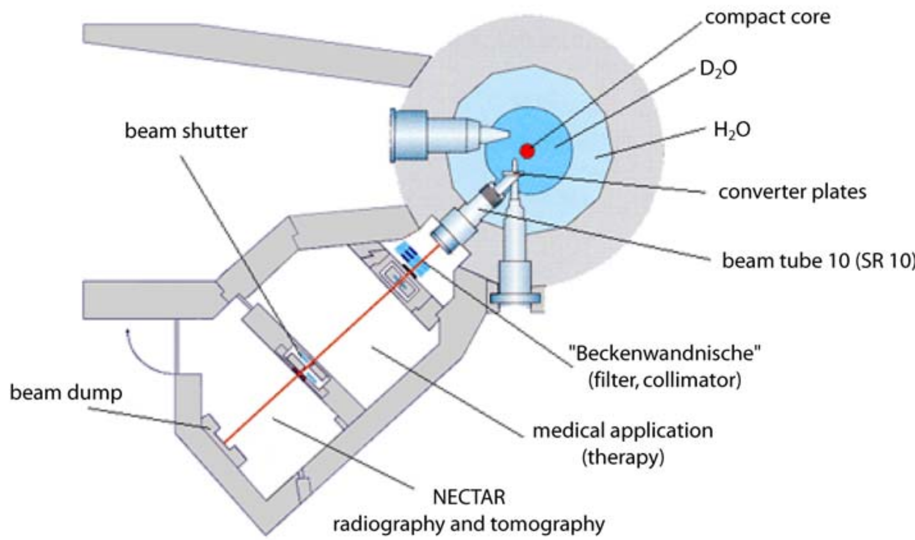


Figure 4: Schematic layout of the NECTAR facility.

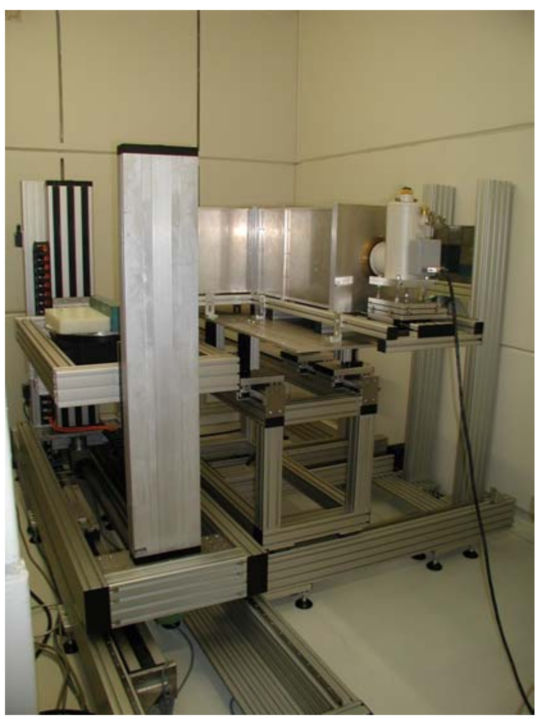


Figure 5: View of the measuring room for neutron radiography and tomography using fission neutrons. Left: Manipulator for samples. Centre: manipulator for detector systems with a CCD-camera based detector system.

The sample manipulator is a three-axis system for lifting, translating and rotating objects of 80 cm x 80 cm x 80 cm in dimension and up to 400 kg maximum burden. The axes are driven by servo motors being controlled by programmable controllers. In the actual set-up two detection systems are available which are positioned by the detector manipulator. The first detector system is based on a liquid nitrogen cooled CCD-camera [1]. The incoming neutrons are converted into visible light by a converter screen having low sensitivity to gamma-radiation. The light is then separated from the direct neutron beam by an aluminium coated mirror and focused on the CCD by a fast objective. The complete system is housed in a light tight box. The second system consists of a set of four single beam detectors. A four slit collimator cuts out four single beams of 0.1 cm x 0.5 cm (width x height) from the incoming neutron beam which are detected using NE-213 scintillators in combination with photomultipliers [2]. The applied electronics perform an excellent gamma-to-neutron discrimination and provide all information necessary for correction of beam hardening effects. The control units for the manipulators and detector systems are located outside of the bunker surrounding the NECTAR facility. The walls are 100 cm thick and made of heavy concrete (density 4.6 g/cm^3).

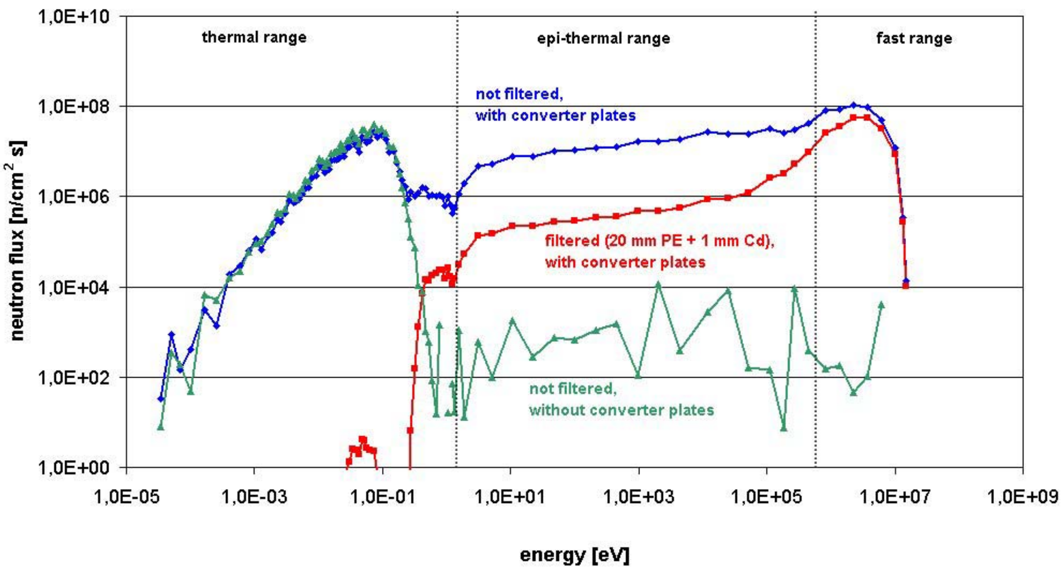


Figure 6: MCNP calculated energy distribution of the neutron flux at sample position without collimation. Blue line: Neutron beam is not manipulated. In this case undesired thermal neutrons are present, too. Red line: Permanent filter is applied, cutting of contribution of thermal neutrons. Green line: Distribution when converter plates are not in front of the beam tube [1].

Beam area and neutron flux available at the sample position are determined by the collimators in the “Beckenwandnische”. The layout of the main collimator is based on extensive MCNP calculations resulting in a sandwich structure composed of cadmium, borated polyethylene, iron and lead placed in an aluminium housing. While cadmium is used for suppressing the background of thermal neutrons, lead is required for reducing the high gamma-radiation background created by the fission process in the converter plates. These two materials cover the complete beam area. Collimation of the neutron beam is performed by the other materials having an opening of 2.5 cm in diameter in beam direction. This results in a L/D-value (L: distance collimator-sample, D: diameter of collimator opening) of 100 and a calculated neutron flux at the sample position of about 6.4E+07 cm^{-2} s^{-1}. An additional collimator made out of iron, having an opening of 1.5 cm in diameter further improves the L/D-value to 300 with a calculated neutron flux of about 7.2E+06 cm^{-2} s^{-1}. The corresponding beam diameters (FWHM) at the detector position are

37 cm and 31 cm, respectively. Figure 6 shows the MCNP calculated neutron spectra without collimation for different working situations. For neutron radiography and tomography using fission neutrons the permanent filter must be applied to avoid the undesired contribution from thermal neutrons.
Putting into Service: The putting into service of the FRM-II was delayed for administrative reasons. In the meantime, an extensive testing of the CCD-camera based detector system was performed using a ^{244}Cm spontaneous fission source. The results of these measurements are summarized in table 1.

Table 1: Results of the test measurements on the CCD-detector system using a ^{244}Cm source.

detection efficiency	(0.46±0.21) %
gamma-to-neutron sensitivity	(4.6±2.9)E-6
signal-to-noise ratio	ca. 30
linearity	excellent up to 3.5E+4 neutrons/pixel[1]
optical resolution	up to 562 μm

[1]data for higher fluences is not measured due to the limited neutron intensity of the ^{244}Cm neutron source.

The first neutrons were generated by the FRM-II on 2 March 2004 running at a thermal power of about 1 kW [3]. During the stepwise increase of the thermal power actually performed to the final value of 20 MW, the individual instruments set-up at the FRM-II can be put into service, too. In the first phase this includes the inspection by the radiological health and safety officers of the FRM-II assuring that the requirements for radiation protection are fulfilled (i.e. dose-rate on the outer side of the instruments (bunker) must be less than 5 μSv/h). For this purpose a simple beam-dump made of iron is installed at the NECTAR facility. Based on the results of these dose-rate measurements an optimized version is under construction, not only reducing the dose-rate at the outer side of the bunker, but also reducing the increase of background in the measuring room due to absorption and scattering effects in the beam-dump [4]. First background measurements with closed beam shutters were performed while the reactor was running at 10 % of its maximum power (i.e. ca. 2 MW). The measured background being about 0.8 % of the maximum peak signal of the CCD-camera system is caused by electronic noise in the CCD-detector system and some spallation effects in the bunker walls proofed to be stable during an integral measuring time of 12 hours. Thus the system is now ready for operation. First radiographs are expected within the next two weeks, tomographs within the next few months.

References: [1] T. Bücherl, Ch. Lierse von Gostomski, E. Calzada, The NECTAR Facility at FRM-II: Status of the Set-Up of the Radiography and Tomography Facility using Fast Neutrons, Proceedings of the 7th World Conference on Neutron Radiography, September 15 to 21, 2002, Roma, Italy, will be published.
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[4] R.M. Ambrosi, J.I.W. Watterson, B.R.K. Kala, A Monte Carlo study of the effect of neutron scattering in a fast neutron radiography facility, Nucl. Instr. and Meth. B 139 (1998) 286-292.