MICHAEL SCHULZ · BURKHARD SCHILLINGER · ELBIO CALZADA · DOMINIK BAUSENWEIN
PHILIPP SCHMAKAT · TOMMY REIMANN · PETER BÖNI

THE NEW NEUTRON IMAGING BEAM LINE ANTARES AT FRM II

Neutron imaging (NI) has a wide range of applications in the field of nondestructive testing. The different interaction mechanisms of neutrons and X-rays with matter yield complementary information, which frequently makes NI the method of choice for difficult cases which cannot be addressed with X-rays. Especially the high contrast for hydrogen and other light elements obtained with neutrons results in a high sensitivity for organic materials. The combination with the high penetration of most metals makes NI a valuable tool particularly in the fields of Archaeology and Cultural Heritage research (Manescu et al. 2008; Grolimund et al. 2011; Berger et al. 2013).
The NI beam line ANTARES was operational at FRM II in Garching, Germany from 2005 to 2010 (Grünauer/Schillinger/Steichele 2004; Schillinger et al. 2004; Calzada/Schillinger/Grünauer 2005). In this period, a huge variety of successful experiments was performed in many different fields of applications including nondestructive testing (Schillinger/Brunner/Calzada 2006; Joos et al. 2010; Tremsin et al. 2010; Grosse et al. 2011; Beyer et al. 2011; Butler et al. 2011; Hungler et al. 2011), basic research (Schulz et al. 2011), biology (Metzke et al. 2011) as well as archaeology and cultural heritage research (Festa et al. 2009).
However, due to an internal redistribution of beam lines at FRM II, the instrument ANTARES had to be dismantled and completely rebuilt at a different beam position of FRM II. The experience gained in the six years of operation of ANTARES was used to define a new beam line concept, which resulted in a major upgrade of the facility with increased possibilities and flexibility for non-standard experiments (Calzada et al. 2009). In this paper we will discuss the performance and features of the new ANTARES beam line which is now operational after three years of construction starting in 2010 and ready to perform user experiments.

The new beam line concept

The new ANTARES beam line is located at the same beam tube SR4 as before but has moved to the other of the two available beam channels, which are both facing the FRM II could source under symmetric angles and therefore provide the same spectrum and flux. Using cold neutrons has the advantage of higher neutron absorption cross sections in the sample compared to the thermal neutron cross sections, which leads to higher sensitivity and better contrast. The spectrum, which was measured at the old ANTARES beam line (Lorenz et al. 2006) is shown in **figure 1**. Since there are no neutron guides installed along the beam, the spectrum of the cold source remains essentially unchanged except for the aluminum Bragg edge visible at approx. 4 Å, which results from the transmission of the aluminum beam tube and various Al beam windows of the beam tube and flight tubes. Furthermore, the maximum of the wavelength distribution is at a thermal wavelength of approx. 1.4 Å, which shows that the cold source does not fully moderate the spectrum but rather increases the flux in the cold neutron range compared to a typical thermal spectrum.
Due to the manifold sample geometries and requirements for sample environment in NI experiments a NI instrument requires a high degree of flexibility. A key design goal of the new ANTARES beam line was therefore to offer high flexibility for the diverse fields of applications of NI in standard user experiments as well as for basic research, where often bulky sample environment is required. This resulted in a beam line

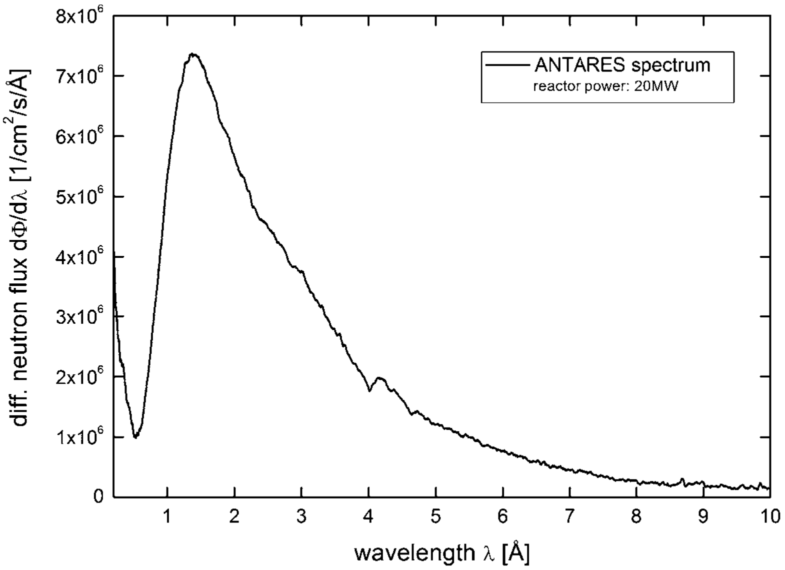

Fig. 1 Cold neutron spectrum of the ANTARES beam line. The spectrum was measured using a TOF detector at the old ANTARES beam line. However, because the new ANTARES beam line remains at the same beam tube, the spectrum is unchanged. The maximum of the wavelength spectrum lies at approximately 1.4 Å. A dip at 4 Å is visible which results from the Al beam tube and windows. – (TU München – FRM II).

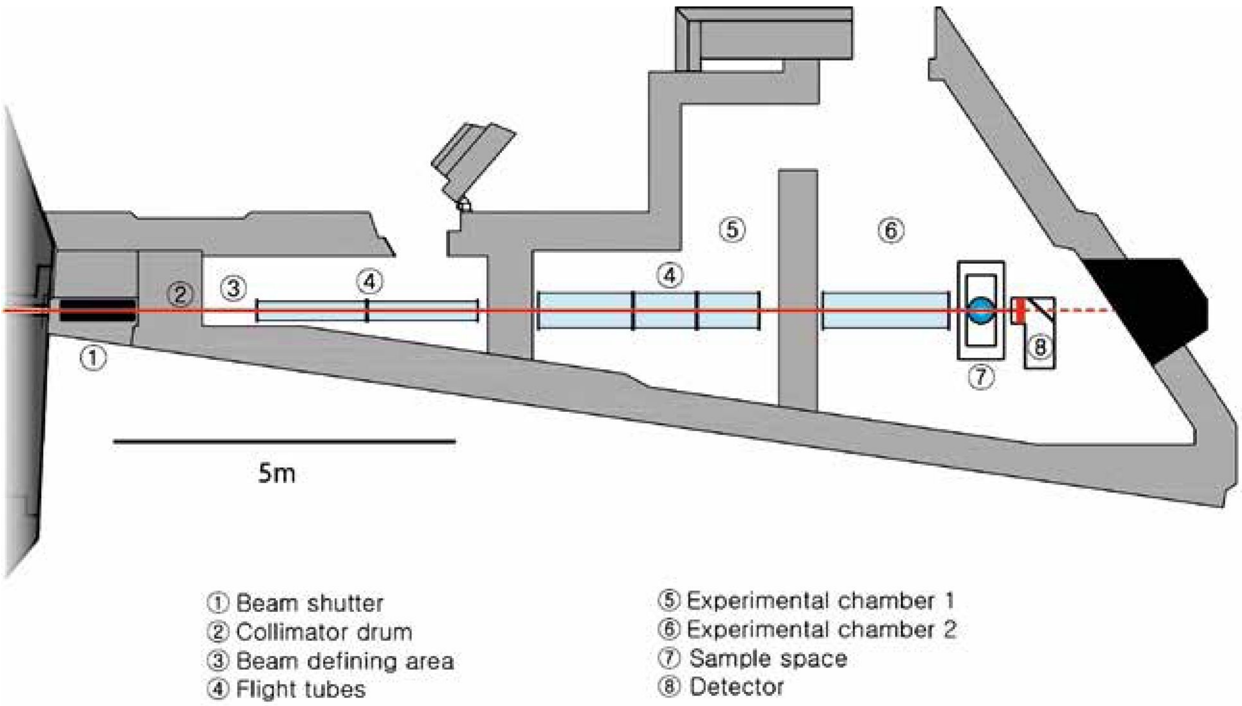

Fig. 2 Schematic of the new ANTARES beam line layout. The beam line offers three separate chambers. The beam defining area (3) hosts devices to manipulate the neutron wavelength spectrum. The user can choose for experiments between two experimental chambers (5 and 6) depending on the requirements for beam size, flux, resolution, etc. – (TU München – FRM II).

concept, which combines a beam which is accessible along the entire flight path together with a larger variety of available collimators.
The beam line traverses three subsequent chambers as shown in figure 2. The first chamber is separately accessible by a massive shielding door and is used as a beam defining area which provides the possibility to mount various kinds of beam and spectrum shaping devices. As standard devices, ANTARES offers a filter selector wheel, a neutron velocity selector and

a double crystal monochromator which will be described in more detail below, but also devices provided by the user can be mounted here.

The six different collimators are mounted in a rotary selector drum in the shielding block just before the beam defining area as indicated by (2) in **figure 2**. The massive 800 mm long collimators (cf. **fig. 3**), which effectively stop fast neutrons and gamma rays from the source are machined from borated steel to reduce activation and facilitate future disposal. Pinhole sizes range from 2 mm to 71 mm, providing a large variety in flux and collimation.

The user can choose between two experimental chambers depending on the requirements of the experiment. Detectors and sample manipulation stages are available in both of these chambers.

Experimental chamber 1 is separated from the beam defining area by a shielding wall with a small beam window which suppresses the gamma and fast neutron background. Due to the relatively short distance to the pinhole, the beam cross section is less than 20 × 20 cm², which renders this chamber ideal for experiments on smaller samples. Consequently, a small high precision sample manipulation stage is available at this position with a load capacity of approx. 10 kg (**fig. 4**), which allows accurate horizontal and vertical positioning of the sample in front of the detector. Furthermore, for tomography experiments the sample manipulation stage provides a rotary stage, which is mounted on two goniometers for alignment of the rotation axis with respect to the detector. The fact that the beam dump is located in the following chamber which is separated by another shielding wall from the first experimental chamber in combination with the effective use of the small beam largely reduces the amount of gamma and scattered neutron background in experimental chamber 1. The detector position in this chamber is approx. 9 m from the collimator pinhole, which results in L/D ratios between 127 and 4500 with a calculated flux between $9.9 \cdot 10^8$ n/cm^2/s and $7.9 \cdot 10^5$ n/cm^2/s, respectively. A roof elevation is available above the sample position to host even high sample environment components including all standard FRM II cryostats with which temperatures as low as 50 mK can be reached.

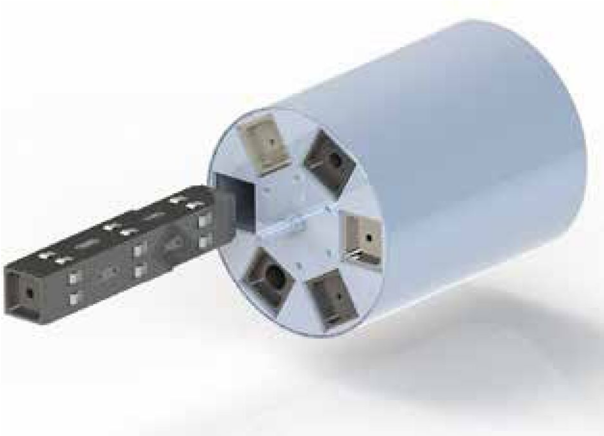

Fig. 3 The rotary drum containing six different collimators with pinhole diameters from 2 mm to 71 mm. The collimators have a length of 800 mm, which effectively stop fast neutron and gamma background and are fabricated from borated steel to minimize activation through neutron capture. – (TU München – FRM II).

Fig. 4 The sample position in experimental chamber 1. The sample can be accurately positioned in the horizontal and vertical direction in front of the detector. Furthermore, a rotary stage is available for tomography, which is mounted on two goniometers for exact alignment of the rotation axis with respect to the detector. – (TU München – FRM II).

Experimental chamber 2, which follows another massive shielding wall with a window is much larger and offers abundant space for bulky samples and complex sample environment. This chamber was designed to offer similar beam size, collimation and flux as the old ANTARES beam line to make measurements easily comparable. In addition to this, the LD ratio can be chosen between 200 and 7200 resulting in a calculated flux between $4.0 \cdot 10^8$ n/cm^2/s and $3.1 \cdot 10^5$ n/cm^2/s, respectively. The sample manipulation stage in this chamber can handle large and heavy samples of up to 1 m^3 in volume and 500 kg of weight and also provides a rotary stage for tomography.

Features of the new ANTARES beam line

As discussed above, in the beam defining area, ANTARES offers various devices to change the effective wavelength spectrum of the neutrons. A selector wheel containing four different filter crystals and a separate 10 mm lead filter to suppress low-energy gamma radiation is mounted just after the collimators where the beam cross section is still small. This filter wheel has already been used at the old ANTARES beam line (Lorenz et al. 2006) and was reinstalled at a similar position. Additionally, an Astrium neutron velocity selector (Friedrich/Wagner/Wille 1989; Wagner/Friedrich/Wille 1992) is available which can be moved into the beam path on demand. The wavelength resolution provided by the selector is $\Delta\lambda/\lambda = 10\,\%$ which is well suited for monochromatic tomography and imaging with polarized neutrons. The shortest accessible wavelength is 2.95 Å.

If an even finer wavelength resolution is required e.g. for Bragg edge imaging, the pyrolytic graphite double crystal monochromator from the old ANTARES beam line (Schulz et al. 2009) will soon be reinstalled and will provide a wavelength resolution between 1 and 3 % depending on the selected wavelength in a wavelength range from 2.7 to 6.5 Å.

In contrast to the old beam line all flight tubes at ANTARES are now filled with Helium at a slight overpressure of 15 mbar which avoids the danger of implosion and allows using much thinner aluminum windows resulting in less attenuation and scattering of the beam. The flight tubes in the beam defining area and in the experimental chambers have a diameter of 300 and 550 mm, respectively. The arrangement of the flight tubes is flexible since tubes with different lengths are available, which can be connected to each other to form a long tube of the desired length, therefore avoiding windows in-between the various tubes.

Both experimental chambers are equipped with adjustable beam slits, which use 5 mm thick plates of boron nitride to limit the beam to the minimum necessary cross section in order to avoid activation of parts of the sample that are not of interest for the user as well as surrounding material and the sample environment. The beam limiters also help to reduce the gamma radiation produced close to the detector by neutrons which are absorbed in structural material.

A variety of different detectors suited for all types of applications are available at ANTARES and further detectors are under development. These range from high resolution detectors with a pixel size of 13.5 μm for small samples up to ~2.5 cm over large field-of-view detectors (up to 40×40 cm^2) to very fast detectors for either dynamic or stroboscopic imaging of fast processes. These detectors are based on cooled scientific CCD or CMOS cameras which provide very low noise and a high dynamic range in combination with neutron sensitive scintillation screens. Furthermore, an imaging plate system is available which provides high resolution radiographs for larger samples of up to 25 cm.

All flight tubes and all other components in the experimental chambers are precisely movable along the beam direction on a rail system which is embedded in the floor of the instrument. The rail system is equipped with a measuring tape, which provides the distance of each component with respect to the pinhole and therefore allows a reproducible repeating of measurements in exactly the same setup even after a long time.

A video surveillance system allows the observation of all sample movements during an experiment from the air conditioned instrument control room. The instrument control software is a server/client based system, which allows scripting of even complex experimental programs with simple commands and provides an automatically generated electronic logbook in which all instrument parameters at any time of the experiment are recorded.

Conclusion and outlook

Along with a complete rebuild of the ANTARES beam line a major upgrade of the experimental possibilities has been performed. The new ANTARES beam line offers now a much higher flexibility and adapted beam positions for high resolution experiments on small samples as well as for large and bulky samples. The user can choose between two experimental chambers which both have sufficient space for even bulky sample environment or experimental setups. The collimation can be tuned to the needs of each experiment via a selector drum which provides six different pinhole sizes between 2 and 71 mm. A maximum flux of $9.9 \cdot 10^9$ n/cm^2/s is provided in experimental chamber 1 using the largest pinhole, which allows the direct visualization of fast processes. With a choice of several detectors for different resolutions and sample sizes in combination with the possibility to modify the neutron spectrum, ANTARES offers unique possibilities for experiments in nondestructive testing, basic research and particularly in archaeology and cultural heritage as well as basic research.

References

Berger et al. 2013: D. Berger / K. Hunger / S. Bolliger-Schreyer / D. Grolimund / S. Hartmann / J. Hovind / F. Müller / E. H. Lehmann / P. Vontobel / M. Wörle, New insights into early Bronze Age damascene technique north of the Alps. The Antiquaries Journal 93, 2013, 25-53.

Beyer et al. 2011: K. Beyer / T. Kannengiesser / A. Griesche / B. Schillinger, Study of hydrogen effusion in austenitic stainless steel by time-resolved *in situ* measurements using neutron radiography. Nuclear Instruments and Methods in Physics Research Section A 651 (1) 2011, 211-215.

Butler et al. 2011: L. G. Butler / B. Schillinger / K. Ham / T. A. Dobbins / P. Liu / J. J. Vajo, Neutron imaging of a commercial Li-ion battery during discharge: Application of monochromatic imaging and polychromatic dynamic tomography. Nuclear Instruments and Methods in Physics Research Section A 651 (1) 2011, 320-328.

Calzada/Schillinger/Grünauer 2005: E. Calzada / B. Schillinger / F. Grünauer, Construction and assembly of the neutron radiography and tomography facility ANTARES at FRM II. Nuclear Instruments and Methods in Physics Research A 542 (1) 2005, 38-44.

Calzada et al. 2009: E. Calzada / F. Gruenauer / M. Mühlbauer / B. Schillinger / M. Schulz, New design for the ANTARES-II facility for neutron imaging at FRM II. Nuclear Instruments and Methods in Physics Research A 605 (1) 2009, 50-53.

Festa et al. 2009: G. Festa / C. Andreani / M. P. De Pascale / R. Senesi / G. Vitali / S. Porcinai / A. M. Giusti / R. Schulze / L. Canella / P. Kudejova / M. Muhlbauer / B. Schillinger / The Ancient Charm Collaboration, A nondestructive stratigraphic and radiographic neutron study of Lorenzo Ghiberti's reliefs from paradise and north doors of Florence baptistery. Journal of Applied Physics 106/7, 2009. DOI:10.1063/1.3204514.

Friedrich/Wagner/Wille 1989: H. Friedrich / V. Wagner / P. Wille, A high-performance neutron velocity selector. Physica B: Physics of Condensed Matter 156, 1989, 547-549.

Grolimund et al. 2011: D. Grolimund / D. Berger / S. Bolliger Schreyer / C. N. Borca / S. Hartmann / F. Müller / J. Hovind / K. Hunger / E. H. Lehmann / P. Vontobel / H. A. O. Wang, Combined neutron and synchrotron X-ray microprobe analysis: attempt to disclose 3600 years-old secrets of a unique Bronze Age metal artifact. Journal of Analytical Atomic Spectrometry 26 (5) 2011, 1012-1023.

Grosse et al. 2011: M. Grosse / M. Van Den Berg / C. Goulet / E. Lehmann / B. Schillinger, *In-situ* neutron radiography investigations of hydrogen diffusion and absorption in zirconium alloys. Nuclear Instruments and Methods in Physics Research A 651 (1) 2011, 253-257.

Grünauer/Schillinger/Steichele 2004: F. Grünauer / B. Schillinger / E. Steichele, Optimization of the beam geometry for the cold neutron tomography facility at the new neutron source in Munich. Applied Radiation and Isotopes 61 (4) 2004, 479-485.

Hungler et al. 2011: P. C. Hungler / L. G. I. Bennett / W. J. Lewis / M. Schulz / B. Schillinger, Neutron imaging inspections of composite honeycomb adhesive bonds. Nuclear Instruments and Methods in Physics Research A 651 (1) 2011, 250-252.

Joos et al. 2010: A. Joos / G. Schmitz / M.J. Mühlbauer / B. Schillinger, Investigation of moisture phase change in porous media using neutron radiography and gravimetric analysis. International Journal of Heat and Mass Transfer 53 (23-24) 2010, 5283-5288.

Lorenz et al. 2006: K. Lorenz / E. Calzada / M. Mühlbauer / B. Schillinger / B. Schillinger / M. Schulz / K. Zeitelhack, The new multi-filter at ANTARES: TOF measurements and first applications. In: M. Arif / R. G. Downing (eds), Neutron radiography. Proceedings of the 8th world conference; WCNR-8; Gaithersburg, Maryland, USA, October 16-19, 2006 (Gaithersburg 2006) 58-66.

Manescu et al. 2008: A. Manescu / F. Fiori / A. Giuliani / N. Kardjilov / Z. Kasztovszky / F. Rustichelli / B. Straumal, Non-destructive compositional analysis of historic organ reed pipes. Journal of Physics: Condensed Matter 20 (10) 2008, 104250.

Metzke et al. 2011: R. W. Metzke / H. Runck / C. A. Stahl / B. Schillinger / E. Calzada / M. Mühlbauer / M. Schulz / M. Schneider / H.-J. Priebe / W. A. Wall / J. Guttmann, Neutron computed tomography of rat lungs. Physics in Medicine and Biology 56 (1) 2011, 1-10.

Schillinger/Brunner/Calzada 2006: B. Schillinger / J. Brunner / E. Calzada, A study of oil lubrication in a rotating engine using stroboscopic neutron imaging. Physica B: Physics of Condensed Matter 385, 2006, 921-923.

Schillinger et al. 2004: B. Schillinger / E. Calzada / F. Grünauer / E. Steichele, The design of the neutron radiography and tomography facility at the new research reactor FRM-II at Technical University Munich. Applied Radiation and Isotopes 61 (4) 2004, 653-657.

Schulz et al. 2009: M. Schulz / P. Böni / E. Calzada / M. Mühlbauer / B. Schillinger, Energy-dependent neutron imaging with a double crystal monochromator at the ANTARES facility at FRM II. Nuclear Instruments and Methods in Physics Research A 605 (1) 2009, 33-35.

Schulz et al. 2011: M. Schulz / P. Schmakat / Ch. Franz / A. Neubauer / E. Calzada / B. Schillinger / P. Böni / Ch. Pfleiderer, Neutron depolarisation imaging: Stress measurements by magnetostriction effects in Ni foils. Physica B: Physics of Condensed Matter 406 (12) 2011, 2412-2414.

Tremsin et al. 2010: A. S. Tremsin / M. J. Mühlbauer / B. Schillinger / J. B. McPhate / J. V. Vallerga / O. H. W. Siegmund / W. B. Feller, High resolution stroboscopic neutron radiography at the FRM-II ANTARES facility. IEEE Transactions on Nuclear Science 57, 2010, 2955-2962.

Wagner/Friedrich/Wille 1992: V. Wagner / H. Friedrich / P. Wille, Performance of a high-tech neutron velocity selector. Physica B: Physics of Condensed Matter 180, 1992, 938-940.

Summary / Zusammenfassung

The New Neutron Imaging Beam Line ANTARES at FRM II

Neutron imaging comprises a multitude of methods which are being used in many different applications in the context of nondestructive testing. After six years of operation during which excellent experiments have been performed, the neutron imaging beam line ANTARES at FRM II has been completely rebuilt. Together with the rebuild a major upgrade has been performed and the beam line has now come back to operation with new features, lower background and higher flexibility. ANTARES now offers three separate chambers along the beam. The first chamber contains the collimators, instrument shutter as well as all beam formation devices such as filter crystals, double crystal monochromator, velocity selector, etc. Following this chamber the user can choose between two experimental chambers. The first one offers a smaller beam for high resolution/high flux and low background experiments with an adjustable L/D ratio (collimation) of 100-3600. A maximum flux of $1.9\times10^9 n/cm^2 s$ can be achieved for time resolved imaging. The second chamber has a larger beam size and ample space for even large sample environment. Here the L/D ratio can be varied between 200 and 7100. In this contribution the new ANTARES beam line and its performance and features will be shown.

Die neue Anlage ANTARES für Neutronenbildgebung am FRM II

Neutronenbildgebung oder Neutron Imaging beinhaltet eine Vielzahl von Methoden zu verschiedenen Anwendungen im Kontext von zerstörungsfreier Prüfung. Nach sechs Jahren Betrieb, während denen hervorragende Experimente durchgeführt wurden, erfuhr die Anlage ANTARES für Neutronen-Bildgebung einen kompletten Neuaufbau. Zusammen mit diesem Neuaufbau wurden auch wesentliche Verbesserungen installiert. Die neue Anlage ist inzwischen wieder in Betrieb, mit neuen Möglichkeiten, geringerem Untergrund und größerer Flexibilität. ANTARES bietet nun drei getrennte Kammern entlang der Strahlachse. Die erste Kammer enthält die Kollimatoren, den Instrument-Strahlverschluss sowie alle Einrichtungen, um den Strahl zu beeinflussen wie Filterkristalle, einen Doppelkristall-Monochromator, einen Geschwindigkeitsselektor etc. Nach dieser ersten Kammer kann der Nutzer zwischen zwei Experimentkammern wählen. In der ersten gibt es einen kleineren Strahl für Experimente mit hoher Auflösung und hohem Neutronenfluss sowie niedrigem Untergrund mit einem einstellbaren L/D-Verhältnis (Kollimation) von 100-3600. Ein maximaler Fluss von $1{,}9\times10^9 n/cm^2 s$ lässt sich für zeitaufgelöste Experimente verwenden. Die zweite Kammer hat einen größeren Strahlquerschnitt und bietet Platz selbst für große Probenumgebungen. Hier kann das L/D-Verhältnis zwischen 200 und 7100 variiert werden. In diesem Beitrag wird die neue Anlage ANTARES mit ihrer Leistung und ihren Möglichkeiten vorgestellt.

Keywords

neutron imaging / beam lines / cultural heritage / energy selective imaging