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A new transmission based monochromator for energy-selective neutron imaging at the ICON beamline

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ABSTRACT

A new type of monochromator has been developed for energy-selective neutron imaging at continuous sources. It combines the use of a mechanical neutron velocity selector with pyrolytic graphite crystals of different mosaicity. The beam can be monochromatized to similar levels as a standard double crystal monochromator. It can flexibly produce different desired spectral shapes, even an asymmetric one. Intrinsically, no higher order contamination of the spectrum is present. Working with the transmitted beam, the beam divergence (and thus the spatial resolution) is uncompromised. The device has been calibrated, characterized and its performance demonstrated with the measurement of Bragg edges for iron and lead, resolving them more sharply than if solely a mechanical velocity selector was used.

1. Introduction

Neutron imaging relies on the attenuation of a neutron beam depending on the traversed thickness and material types in a sample of interest. In general the full polychromatic spectrum or *white beam* from the neutron source is used, resulting in a high flux on the sample and short exposure times. It has been used to investigate topics in numerous fields, ranging from quantification of the amount of water in porous media with technical applications such as fuel cells to cultural heritage [1–3].

However, imaging with a monochromatic beam has several advantages, though at the cost of increased exposure times due to a reduction of the total flux on sample. In general, the cross-section is energy-dependent. Thus, different materials in a sample may appear similar using a white beam, with their cross-section averaged out over the full incoming beam spectrum, but very different when the energy is chosen appropriately. Polycrystalline materials for instance exhibit sharp Bragg edges in their energy-dependent cross-section. Neutrons can be removed from the direct beam because of diffraction from the *hkl* crystal lattice planes for all wavelengths $\lambda \le 2d_{hkl}$, after which no diffraction can occur and the cross-section decreases sharply. As these Bragg edges are dependent on the crystal structure, imaging at energies above and below the Bragg edge of a particular crystallographic phase can be used to enhance its contrast w.r.t other phases [4]. Moreover, the presence of residual stresses will result in small changes in the local d_{hkl} spacing. The spatial distribution of these changes can be mapped at high spatial resolution using neutron imaging [5,6]. The use of a monochromatic beam allows for a more quantitative approach to neutron imaging as it reduces beam-hardening effects. Scattering contributions are also greatly reduced for energy-selective imaging past the last Bragg edge or Bragg cut-off [7] where coherent elastic scattering from the crystal lattice planes (Bragg diffraction) is not possible anymore.

The required energy-selection can be achieved in several ways. At pulsed sources, one can simply use the time lag between the source pulse and the neutron arrival at the detector, which is representative for the neutron velocity i.e. its energy. At continuous neutron sources however, one has to use a monochromator device to select the desired wavelength out of the incident polychromatic spectrum that is provided by the neutron source.

There are several options to select the neutron energy, the simplest one being a filter of a material (typically Be and Cd) that cuts off part of the spectrum.

A mechanical neutron velocity selector (MVS) consists of a rotating drum with twisted lamellae coated with a strong neutron absorber. Depending on its rotation speed, only neutrons of the right velocity or energy will pass through the device [8]. The resulting wavelength band is quite wide, with $\Delta\lambda/\lambda \approx 15\%$, meaning however reasonably high flux and limited increase in exposure time. The field of view is usually large ($\sim$10 cm), though the spectrum is not entirely uniform across it [9].

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Some applications (e.g. residual stress mapping), need a higher energy-resolution. Here, a double crystal monochromator (DCM) might be used instead. It is based on obtaining the desired wavelength by Bragg reflection from a crystal

$$2d\ \sin\ \vartheta = n\lambda, \quad (1)$$

d being the used crystal plane spacing, θ the set crystal angle, λ the reflected wavelength of order $n=1, 2, 3$ …. A second crystal is then used to diffract the beam back to its original direction, be it displaced. In neutron imaging, generally pyrolytic graphite's (002) reflection is used with higher order reflections $\lambda/2$, $\lambda/3$, … ($n=2$, 3, …, in Eq. (1)) suppressed with a Be filter [10,11]. The monochromaticity is in general 2–5% depending on the set wavelength and mosaicity of the crystals used.

In this paper, we present a new type of monochromator, named *TESI* (*Transmission-based Energy-Selective Imaging*), where a set of crystals is used to flexibly filter the MVS spectrum of $\Delta\lambda/\lambda \approx 15\%$ further down to $\Delta\lambda/\lambda \approx 2$–5% through the out-scattering of undesired wavelengths. As such, one can work with the transmitted beam of high monochromaticity without higher order contamination and keeping the original divergence (and thus spatial resolution). The beam is not displaced which eases compatibility with other present imaging plugin devices (e.g. for grating interferometry). The main principle, its design and properties for imaging are described in the following sections, together with first experimental results.

2. TESI: A transmission-based monochromator for energy-selective imaging

2.1. Principle

A schematic representation of the TESI principle can be found in Fig. 1. First the rotation frequency of the MVS is set to the desired central wavelength λ. The resulting Gaussian wavelength pass-band is still quite wide with $\Delta\lambda/\lambda \approx 15\%$ (Fig. 1a). Adding a pair of crystals of low mosaicity $\Delta\theta_1$, set to diffract a small wavelength band before and after the peak in MVS spectrum at $\lambda \pm \delta\lambda_1$ (Fig. 1b) will reduce the width of the central peak in the transmitted beam spectrum. However, two secondary wavelength peaks or side lobes at $\lambda \pm \delta\lambda_2$ are still present as the remainder of the original broad MVS spectrum. By adding a second pair of crystals and set them to diffract these wavelengths out of the original beam direction (Fig. 1c). Being further away from the central peak, one can use crystals of higher mosaicity $\Delta\theta_2$ that can diffract out a larger wavelength range without compromising the central peak. A third and a fourth crystal pair can be added to further suppress the induced side lobes (particularly at long wavelengths). Using the beam transmitted through matched pairs of crystals in combination with a MVS, the collimation of the monochromatized beam that reaches the sample are unchanged and its spectrum does not contain higher-order contributions.

2.2. Design

TESI is designed as a plug-in device that can easily be mounted in front of the MVS at the ICON beamline for imaging with cold neutrons [12] at the Swiss spallation neutron source SINQ at Paul Scherrer Institut. It has capacity for ten crystals, mounted on independently controllable rotation stages with an accuracy of 0.005°. The control of the stages is integrated in the beamline operating system for user-friendly remote manipulation of the positions. Unused crystals can be flipped out of the beam instead of being removed from the device, so as to preserve calibration. Currently eight highly oriented pyrolytic graphite crystals of varying mosaicity (see Section 2.3) are installed, measuring 40 mm × 10 mm × 5 mm (width × height × thickness). A shielding

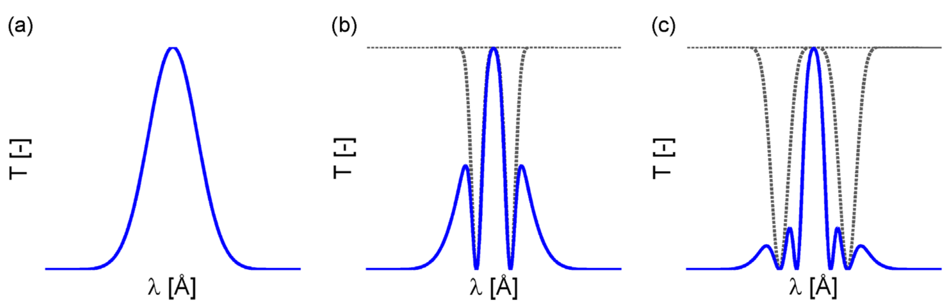

Fig. 1. TESI principle: starting from the transmission spectrum of the mechanical velocity selector (a), a first crystal pair of low mosaicity is added (b) after which a second crystal pair of higher mosaicity is added to lower the side lobes (c). The total transmission spectrum is indicated by the solid blue line and the crystal transmission spectra by the dashed gray one. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

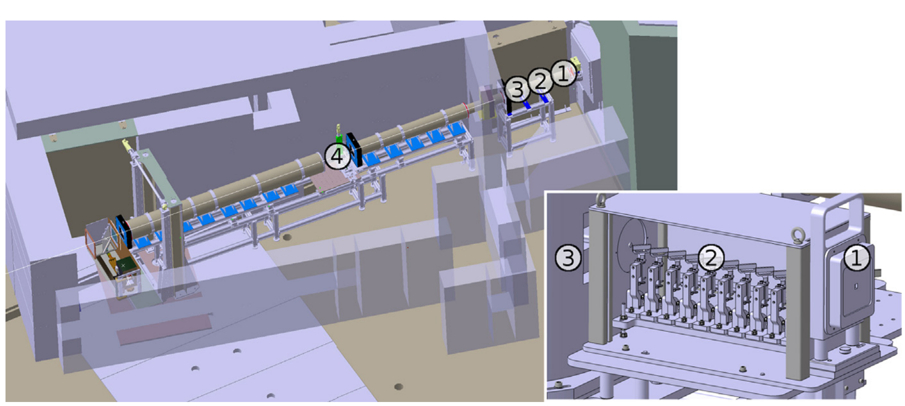

Fig. 2. TESI (right, inset) device installed at the ICON beamline (left). Neutrons enter the device from the right, passing through shielding aperture (1), crystals (2), mechanical velocity selector (3) and detected at position (4).