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A large-area double rotating-crystal monochromator for time-focusing neutron instruments

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Abstract. We present the principle and the first prototypes of a double rotating-crystal monochromator, based on an assembly of smaller rotating elements. Such a device was developed as the key element to implement a parallel-beam modification of the time-focusing technique for neutron spectrometers. This concept is particularly promising for long-pulse sources and can bring specific advantages on continuous sources as well. Neutron tests performed on the first prototypes validate the mechanical reliability of the proposed design and the feasibility of a large-area double rotating-crystal monochromator based on this technology.

1. Introduction

The idea of a neutron monochromator based on a rotating crystal was first proposed by Brockhouse in the early age of neutron research [1]. An instrument based on this principle was the Rotating Crystal Spectrometer RXS, installed at Hanford (USA) [2, 3]. The use of rotating crystals was also considered for pulsed sources, an example is the rotating crystal analyzer of ROTAX at ISIS (UK) [4]. A major limitation to this design originates from the request of an accurate rotational stability, which prevents the use of large-area crystals. On the other hand, double crystal configurations have also been largely exploited in several instruments. An historical example is the hybrid spectrometer at the CP-5 reactor of the Argonne National Laboratory [5], which was employed by Copley and Rowe for their seminal researches on liquid metals [6]. Double crystal instruments are currently operational at several facilities, e.g. three axis spectrometers at LLB (Saclay, France) and BARC (Mumbay, India), and the imaging station ANTARES at FRMII (Garching, Germany). A combination of these two configurations, namely a double rotating-crystal monochromator (DRCM), was used at the IN4 beamline of the Institut Laue Langevin (Grenoble, France) in order to get rid of the unwanted Bragg diffraction orders [7].

In this paper, we discuss the construction and tests of a large-area rotating-crystal monochromator, based on an assembly of small rotating elements. This device was developed to build a DRCM with the aim to implement a modification of the well-known time-focusing technique for neutron spectrometers. In fact, a couple of properly phased rotating-crystal monochromators can be used to extract a wider wavelength band from a white beam of neutrons, in such a way that faster and slower neutrons reach the detector at the same time, i.e. are time-focused at the detector position. As compared to standard chopper instruments, this configuration exploits a longer extraction time, so that it is particularly effective for continuous or long-pulse sources. Moreover, the intensity gain due to time-focusing can be further boosted by using large-area beams. Finally, a DRCM has the advantage of shifting the monochromating beam well away from the primary white beam, thus avoiding a direct view of the neutron source from the sample position, with consequent background reduction. In addition, when installed in non-dispersive configuration, the DRCM fully preserves the incoming beam divergence. A more detailed conceptual description of a full time-focusing instrument based on this principle will be reported elsewhere [8].

2. Monochromator development

Our target is a rotating monochromator with ideally a large surface, of the order of 20×20 cm^2, that can rotate at frequencies up to about 100 Hz (6000 rpm). It is evident that the rotation of such a large-surface device implies facing considerable mechanical difficulties. In addition, it can introduce Doppler shift effects on neutrons diffracted by the peripheral regions of the monochromator. Although this can bring some advantages in specific conditions, for the time being we prefer to consider only cases where Doppler effects can be neglected. To this end, the large-area crystal can be partitioned into a suitable number of smaller rotating elements, thus reducing the peripheral speed of the single element. Each element would contain a subset of small crystals conveniently held and aligned by a proper mechanical support.

Having these considerations in mind, we designed a 2 cm-diameter cylindrical crystal holder where slab-shaped crystals lay on the cylinder axis and cut the cylinder along its diameter into two symmetric halves. A suitable number of such cylindrical elements can be easily disposed with parallel axes one next to each other, to cover the desired total monochromator area. An external supporting frame to hold the cylinder ends can be machined with high enough precision to obtain both thorough axial alignement and very small mechanical separations between adjacent cylinders. Spacings of few tenths of mm can be easily realized, thus covering most of the incoming beam area and minimising reflected beam losses. Finally, the cylindrical shape allows a great mechanical stability during rotation, which can thus be operated even in air, given the low frequencies into play. Proper phasing of all the rotating cylinders will result in simultaneous Bragg reflection from all the crystals of the array, thus reproducing the effect of a full large-area monochromator.

More specifically, each cylindrical holder is made of an aluminum alloy of the 6000 series. After cutting the cylinder along its diameter into two symmetric halves, most of the inner material is also removed until the cylinder external wall is reduced to less than 1 mm. In this way, neutron attenuation and background due to scattering by the supports are strongly reduced, while the necessary mechanical stability is preserved. The two halves are then assembled with the crystals in a sandwich structure and tightened together by M2 screws inserted along the cylinder diameter. Although the screws pierce the crystals perpendicularly to their surface, they do not constitute a real problem because the mounting system guarantees a negligible crystal damage during screws insertion.

As a first possible choice for the crystals, we considered Highly Oriented Pyrolitic Graphite (HOPG) that provides a high peak reflectivity even at relatively short wavelengths ($R_0 \simeq 0.7$ at about 1.3 Å [9]), with a clean reflected beam and no spurious components due to multiple reflections. In particular, a high reflectivity is crucial to minimize intensity losses due to the double monochromator configuration.

Fig. 1(a) shows a prototype assembly of three rotating elements. Each cylinder is 240 mm high with a diameter of 20 mm and hosts five $40 \times 20 \times 2$ mm^3 HOPG crystals. The overall weight of each rotating element is about 100 g, so that it can be easily rotated using a direct-drive small

DC motor or a stepper motor. The latter is preferable since it guarantees a digitally controlled velocity up to at least 112 Hz. It is worth noting that the present design exploits both faces of the rotating crystal for neutron reflection, hence the frequency f_M of the monochromatic neutron pulses is twice the *real* rotation frequency f_R. For special applications, it can be envisaged to realize a vertically focusing monochromator, by installing properly tilted crystals inside each cylinder. Of course, this implies the use of only one of the crystal faces, which yields a neutron pulse frequency $f_M = f_R$.

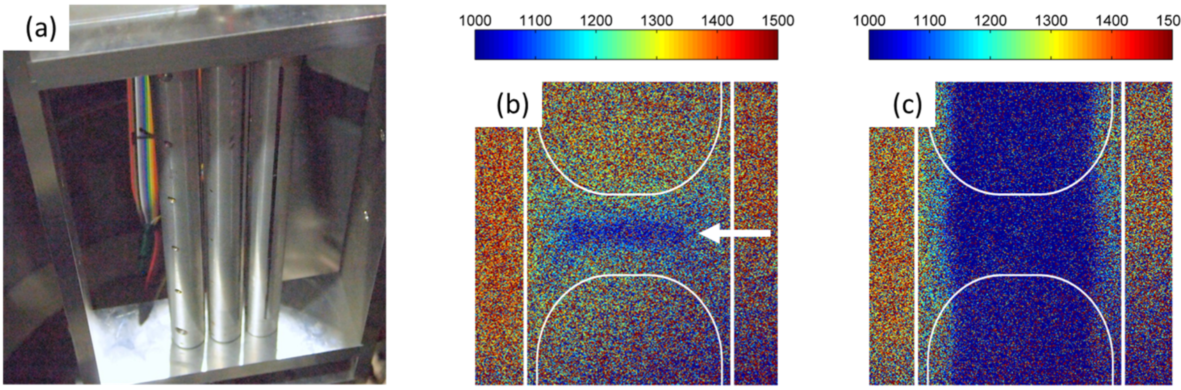

Figure 1. (a) Picture of one of the monochromator prototypes employed in the neutron tests, composed of three rotating elements. The thin 2 mm edge of the HOPG crystals appears as a vertical black line along the rightmost cylinder, whereas the heads of the horizontal screws holding the crystals are visible on the leftmost one. A neutron radiography of a 20×30 mm^2 portion of one cylinder shows the neutrons transmitted by the crystal when the latter is set off (b) and in Bragg reflection (c). White lines highlight the contours of the thickest parts of the cylinder aluminum structure. The white arrow in (b) marks the position of one of the brass screws.

3. Tests and results

In order to define the real performance of a DRCM, we produced and tested different prototypes using HOPG crystals with a typical mosaic spread of 0.5°. Neutron tests were performed at the Institut Laue Langevin (Grenoble, France) using the beamlines IN3 and T13A, and at the Laboratoire Léon Brillouin (Saclay, France) with the cold beam of the G4.3 three-axis spectrometer.

3.1. Transmission tests

Figures 1(b) and 1(c) show neutron radiographies obtained on IN3 using a CCD camera coupled to a thin (0.2 mm) lithium glass scintillator. Images were acquired in transmission geometry, using a monochromatic incident beam. The contours of the thickest parts of the aluminum cylindrical structure are highlighted by white lines: the vertical lines depict the external walls of the cylinder, the U-shaped lines delimit one of the inner parts hosting a screw. As expected, when the crystal is off Bragg reflection like in Fig. 1(b), the cylinder is almost completely transparent and the only absorbing detectable part is the horizontal brass screw marked by a white arrow. Conversely, when the graphite crystal is set into Bragg reflection, like in Fig. 1(c), the majority of the incident neutrons are scattered away and the transmitted intensity drops over all the crystal surface. Brass screws were used in this prototyping phase to allow frequent assembling and disassembling of the system. However, in a final design, the same aluminum alloy employed for the cylindrical holders would be used everywhere in the beam area, including screws. This is also useful to reduce the radiological activation of the device.

3.2. Crystal alignment

The alignment of the different crystals was checked using the test diffractometer T13A with an incident wavelength $\lambda_i = 2.27$ Å. Rocking curves were acquired along the cylinder vertical axis with a vertical step $\Delta h = 10$ mm. Results are reported in the intensity map of Fig. 2(a). The crystals appear well-aligned and the peak intensity shows only minor fluctuations that are compatible with the crystal size and with the presence of the brass screws. This qualitative impression is confirmed by the results of a Gaussian fit of the rocking curves. Fig. 2(b) and (c) show the peak position and intensity along the length of the holding cylinder. The average position is $108.63° \pm 0.02°$, that is a very good alignment compared to the typical rocking curve width of about 0.5°. The same results were obtained for the other prototype devices, thus confirming that the holding system is valid and perfectly suitable to build a large-area device.

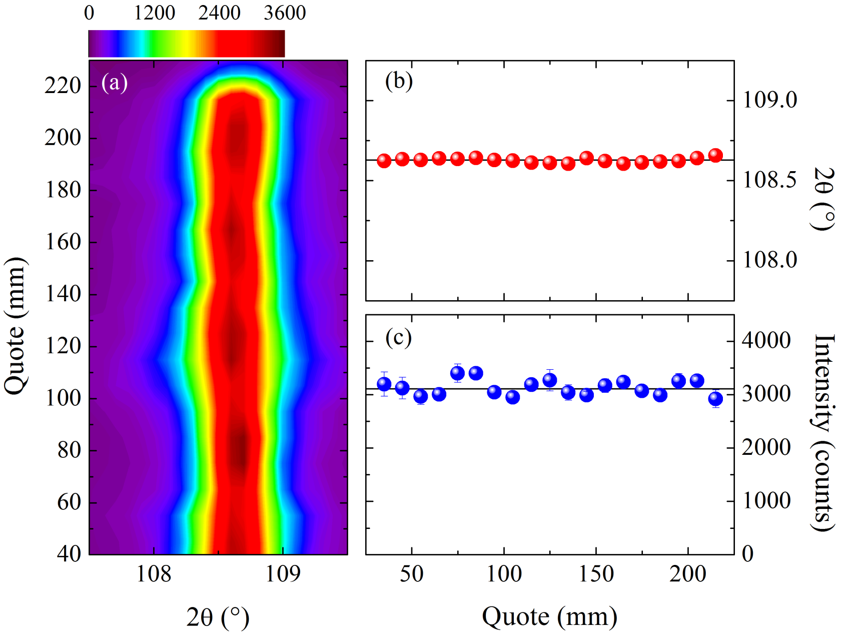

Figure 2. Intensity map produced from the rocking curves measured as a function of the vertical position along one of the cylinders (a). Measurements are performed with 10 mm steps. Peak angular position (b) and intensity (c) as a function of the height along the cylinder axis, as obtained by a Gaussian fit of the rocking curves.

3.3. Phasing and ToF measurements

An *in-operando* test of a complete DRCM was performed on the IN3 spectrometer, by acquiring time-of-flight (ToF) spectra. The test setup is shown in Fig. 3(a). It includes a single rotating monochromating element (M1), followed by an assembly of three rotating monochromating elements, like those depicted in Fig. 1(a), that constitutes the second monochromator (M2).

Each cylinder was rotated using a stepper motor having a step of 1.8° with a stability better than 0.09°. The rotation velocity was driven by a set of computer-controlled signals generated by means of a FPGA card (National Instrument single board RIO-9606) via the Labview environment. The same card was employed for the neutron ToF data acquisition. The use of the stepper motors coupled to the FPGA card has the advantage of a very precise control of the motor rotation, provided that the motors are correctly powered. The control clock of the system was operated at 40 MHz, thus allowing to drive the motor phase with time steps of 25 ns. Such short time steps ensure a more accurate phasing of all the rotating cylinders in the DRCM. Since the motors were controlled by a single clock, there was no relative difference in the velocity of the various motors and the overall phasing was well undemanding. This is a very important issue, as it allows a straightforward implementation of a device made up of several rotating elements.

The first monochromator was installed at the IN3 sample position, downstream a 0.67° collimator. Conversely, the second element of the DRCM replaced the spectrometer analyzer. In this configuration the distance between the two monochromators was about 1.12 m. Neutrons were acquired using the IN3 detector – a vertically-mounted 3 cm-diameter ^{3}He tube located at 2.02 m from the sample position – using a single-event ToF acquisition system [10]. As rotation control and acquisition exploited the same clock signal, there was no need for a ToF trigger from the motors to the acquisition system.

The fundamental wavelength selected by the IN3 graphite monochromator was $\lambda_1 = 4.26$ Å, that corresponds to a Bragg angle of 39.4°. Fig. 3(b) shows the ToF spectrum after the first rotating monochromator with $f_M = 28$ Hz. In addition to λ_1, three further harmonics are visible: $\lambda_2 = 2.13$ Å, $\lambda_3 = 1.42$ Å, and $\lambda_4 = 1.065$ Å.

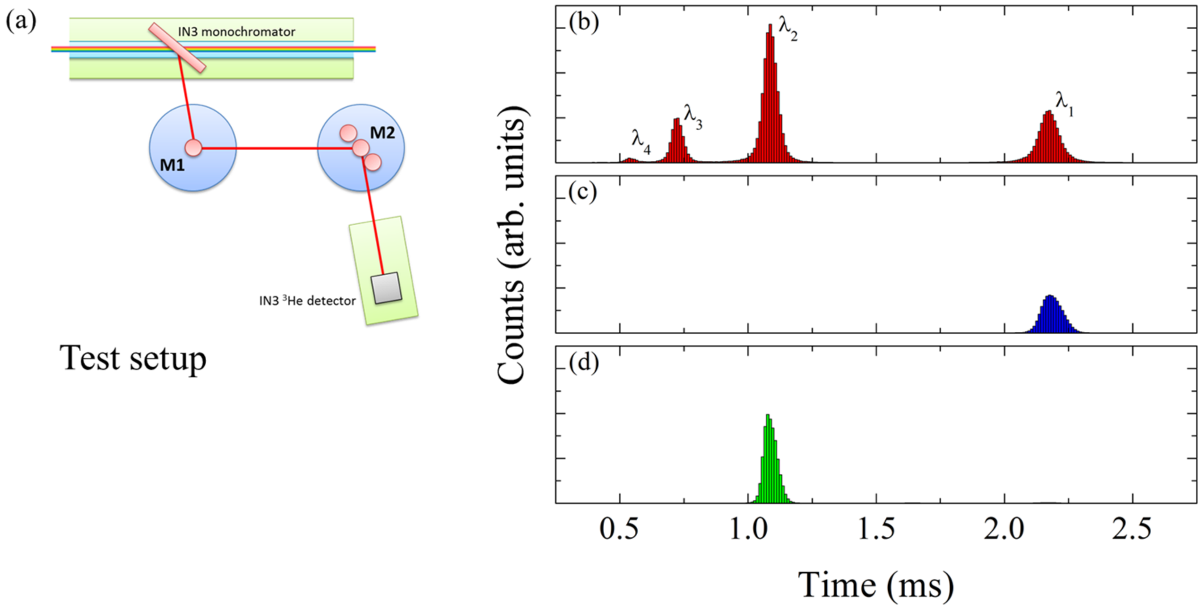

Figure 3. (a) Setup employed to test the DRCM. M1 and M2 indicate respectively the first and the second rotating-crystal monochromators, as explained in the text. ToF histograms measured at $f_M = 28$ Hz downstream M1 (b) and M2 ((c) and (d)). In (b) and (c), the second rotating-crystal monochromator was phased on λ_1 and λ_2 respectively.

Figs. 3(c) and (d) show two typical ToF spectra measured downstream the second rotating monochromator, that is using the whole DRCM. By phasing the first and the second monochromators an efficient selection of the different wavelengths can be achieved, even if the distance between the two monochromators is relatively short. All the data shown in Fig. 3 were acquired in fixed-event-number configuration, with the number of counts fixed to (2.5×10^5). The present acquisition system also allows operation in fixed-time mode, or in fixed-event-number mode controlled by a source other the acquisition detector itself, e.g. a beam monitor. ToF runs lasted several hours and showed that the phase stability is perfect. In fact, the relative phases of the various cylinders remained constant without any need of adjustment during each run. Similar tests, performed at the G4.3 beamline of the Laboratoire Léon Brillouin with wavelengths of 4.65 and 2.33 Å, fully confirmed the previous results of IN3.

4. Conclusions

The presented tests show the feasibility of a large-area rotating crystal monochromator. The flexibility of the proposed design allows to easily modify the size of the monochromator by adding or removing a rotating element. Similarly, the use of stepper motors coupled with a FPGA card allows to easily control and phase a large number of rotating devices, keeping their relative velocity constant up to frequencies of about 100 Hz (6000 rpm).

It is worth noting that HOPG is only one of the possible candidate materials for the crystals. Indeed, the HOPG does not allow for mosaic spreads narrower than 0.5°. Other possible candidates with this respect are Si, Cu, Ge and Pb. However, HOPG is known to provide the best performance in terms of reflectivity and quality of the beam.

Finally, the described tests also show that there are no fundamental mechanical problems in attempting to implement a time-focusing method, based on a large-area DRCM. On a long-pulse source, such as the forthcoming European Spallation Source, a spectrometer exploiting this concept could collect a large time slice of the source neutron pulse and thus allow significant intensity gains at the sample.

Acknowledgments

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