A combined radial collimator and cooled beryllium filter for neutron scattering

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Abstract

A flexible, combined, radial collimator and beryllium (Be) filter have been designed and manufactured at the Paul Scherrer Institut (PSI), Switzerland. The Be is integrated in the radial collimator by placing thin Be slices between the collimator lamellas. The filter/collimator is mounted within a vacuum vessel and dry cooled. The flexible design allows for different degrees of collimation and for different Be lengths. Results of measurements carried out at the BOA beamline at PSI are presented. These experiments include rotation scans determining the focal full width half maximum (FWHM), transmission measurements, test of different collimator lamellas and performance tests of the cooling of the filter. This new combined device will be a crucial part of the CAMEA spectrometer at SINQ, PSI.

Keywords: neutrons, radial collimator, Beryllium filter, neutron optics, neutron scattering

1. Introduction

Inelastic neutron scattering experiments, e.g. at three-axis-spectrometers, require a good signal-to-noise ratio and it is crucial to keep the background as

low as possible to be able to detect even very weak excitations. Thus, collimation and filter elements are commonly used in experiments.

Most experiments use complex sample environments (SE), e.g for parametric studies under extreme conditions (temperature, high magnetic fields, pressure). Cryo-magnets for example are stabilized by concentric aluminum rings, which generate additional background. Therefore, collimation is required to reduce the background arising from these SE [1]. In the case of instruments with a larger acceptance in scattering angle this would be a radial collimator (RC). The best performance of a RC is achieved by placing it as close to the sample as possible. Therefore, the optimal solution would be to include the RC directly into the SE. However, most instruments are designed to work with an existing SE suite, which often does not include such collimation. Thus, the RC should be placed immediately after the SE.

Monochromator/analyzer based instruments measuring in the cold neutron regime ($E = 0 - 20$ meV), which do not employ a velocity selector, have to take contamination by $\lambda/2$ neutrons into account. Second order scattering by the monochromator would not only contaminate the analyzed signal itself, but likewise increase the background [2]. In the case of highly oriented pyrolytic graphite (HOPG) analyzer crystals the analyzers scatter neutrons of higher energies due to parasitic reflections [3–5]. To avoid this effect a filter of polycrystalline, sintered Be is employed. Polycrystalline Be scatters neutrons with wave vectors $k > \frac{\tau}{2}$, with $\tau_{100} = 3.19 \text{ \AA}^{-1}$, $\tau_{002} = 3.51 \text{ \AA}^{-1}$ and $\tau_{101} = 3.64 \text{ \AA}^{-1}$ [6, 7]. Smaller neutron wave vectors are transmitted with little attenuation. Thus, to avoid this effect, a Beryllium filter is needed. Since the wavelength transmission of a Be filter above the cut-off is significantly improved at low temperatures, such filters are generally cooled to liquid nitrogen (LN) temperatures [6, 8]. The suppression of $\lambda/2$ improves with increasing length of the filter. However, simultaneously the transmission worsens for wavelengths greater than $4 \text{ \AA}$ [9]. A Be filter length of 120 mm gives a satisfying compromise between a $\lambda/2$ suppression of the order of 10^{-3} and overall transmission of roughly 90 %. Here, a new implementation of a RC combined with a Be filter in one compact

35 device is presented. Combining both element has two advantages. First, the
 36 final device becomes shorter and more compact. Second, the longer collima-
 37 tor blades reduce the poisoning of the filter, i.e. the diffuse leakage of neutrons
 38 through the filter, by simply decreasing the open solid angle for neutrons leaking
 39 through the filter. Note that there are existing Be filters which employ a coarse
 40 collimation, e.g. at RITA-II at SINQ, PSI. However, in conventional filters the
 41 coarse collimation is restricted to the dimensions of the Be and allows a simple
 42 pressing of the complete stack.
 43 In the design presented here the Be filter is integrated in the front part of the
 44 RC (see Fig. 1). Hence, the complete housing of the combined device needs to
 45 be cooled to LN temperatures for a good transmission quality. This is especially
 46 challenging due to the different thermal expansion coefficients of the various ma-
 47 terials used[10, 11]. Most Be filters are conventionally cooled with LN, while the
 48 device presented here is dry cooled by a free-piston Stirling cryocooler. Since
 49 the performance of such a cooler only slightly depends on its orientation, the
 50 cooler can be mounted anywhere around the device. This allows to optimize the
 51 position of the cooler for each instrument. Furthermore, the dry cooling opens
 52 the possibility to easily construct such collimator/filters with a larger angular
 53 coverage. This makes the device especially interesting for the upcoming gener-
 54 ation of wide-angle multiplexing spectrometers, e.g. CAMEA [12], BIFROST
 55 (formerly CAMEA ESS) [13] and BAMBUS [14], where radial collimation and
 56 Be filtering are needed, and spatial restrictions apply. The combined device
 57 presented here will be used in the CAMEA spectrometer at PSI.

59 **2. Description of components**

60 The design parameters of the filter collimator were chosen in agreement
 61 with the requirements specified for the CAMEA spectrometer. Here, dictated
 62 by existing SE the front of the collimator has a distance of 550 mm to the sample
 63 position, a length of 280 mm and a height of 80 mm. A sketch of the assembly is

Figure 1: Cut sketch of the combined device. Neutrons are scattered from the sample (S) towards the collimator. The distance between sample and beginning of the collimator is $a = 550$ mm (not to scale). Be wedges (orange, length $b = 80$ mm and $c = 40$ mm) can be inserted between the coated lamellas (red, length $d = 280$ mm) to allow for different total Be lengths of 80 mm and 120 mm. The device is connected to the cooling head (dashed circle), which is mounted on top of the vacuum vessel.

64 shown in Fig. 1. The whole device was mounted within an aluminum housing.
 65 The 0.3 mm-thick absorbing lamellas were inserted into the aluminum housing
 66 in 0.5 mm-wide notches, ensuring enough space to compensate for the stronger
 67 thermal contraction of aluminum [10, 11]. The lamella notches were designed
 68 such, that a collimation of 0.5° could be realized, while collimation could be
 69 increased to 1° by only equipping every second notch. Throughout the tests
 70 two different lamella materials, Si and boronated glass (Borofloat33 by Schott
 71 AG), were tested. The lamellas were sputtered with an absorbing Gd layer.
 72 Future lamellas will have a layer of ^{10}B .

73 The filter was prepared for two different Be lengths, 80 mm and 120 mm. The Be
 74 was purchased from Materion. The compound used (S200FH: min. 98.5% Be,
 75 max. 1.5% BeO), gives a satisfying combination of low BeO content (optimizing
 76 desired transmission) and small grain size (max. $12\ \mu\text{m}$, the smaller the grain
 77 size, the better the scattering of unwanted wave vectors). The trapezoidal-
 78 shaped Be pieces were mounted between the lamellas and fixed with screws
 79 from the top. The fixation by screws and the stronger thermal contraction of
 80 the aluminum ensured a good thermal contact of the Be with the ground plate

Figure 2: Prototype temperature as a function of cooling time for different heat shield configurations. According to the specifications of the cooling head the heat shield saves a heat load of 2.5 W on the collimator fins. The calculations (green) were done for a filter with a mass of 12 kg.

of the housing. The prototype was mounted within a vacuum vessel and fixed to the cooling head (Cryotel GT, Sunpower, nominal cooling power of 16 W at 77 K).

3. Experimental results

The characterization experiments were performed at the multi-purpose neutron beamline BOA at SINQ, PSI [15, 16]. The cooling performance, different collimator configurations and transmission measurements are described in the following sections.

3.1. Cooling

In order to monitor the cooling process, thermometers were placed at the housing and directly on the Be. The temperatures as a function of cooling time is shown in Fig. 2. The initial arrangement (black) had neither heat shields at the front nor at the back of the collimator and the temperature stabilizes after 25 hours around 72 K. In this configuration the collimator fins are exposed

95 to heat radiation from the vacuum vessel. Therefore, further cycles were done
 96 with radiation shielding (out of thin aluminum foil attached to the frame) only
 97 at the front (blue) and shielding at the front, the back and the sides (red). The
 98 first configuration stabilizes at a temperature of 63 K corresponding to a cooling
 99 power of 10 W according to the specifications of the cooling head used. The sec-
 100 ond configuration stabilized at a temperature of 56 K corresponding to a cooling
 101 power of 7.5 W. Thus, shielding the collimator fins from the heat radiation of
 102 the surrounding vessel reduces the heat load by 2.5 W. This seems little, how-
 103 ever, in the case of CAMEA the collimator will be 8 times larger resulting in a
 104 saving of 20 W cooling power at LN temperature. Calculations were performed
 105 using a lumped heat capacity model. Here, a point mass of 12 kg of aluminum
 106 and the manufacturer's data on the temperature dependent cooling power of
 107 the cooler were used. The radiative heat load from the surrounding vessel at
 108 RT was considered assuming a surface area of 1800 cm² with an emissivity of
 109 $\epsilon = 0.18$. The calculated cooling time (green line in Fig. 2) as well as the base
 110 temperature are in excellent agreement with the measurements.
 111 The whole arrangement (equipped with Si and glass lamellas) was thermally cy-
 112 cled between room temperature (RT) and 60 K several times in order to check
 113 the reliability of the components, mainly the lamellas and the coating. Af-
 114 ter more than 15 cycles, no damage due to thermal contraction/tension was
 115 observed.

116 3.2. Transmission Measurements

117 The performance of the Be filter was tested using the time-of-flight (ToF)
 118 option of BOA. The prototype was mounted in the direct beam and ToF spec-
 119 tra were recorded for Be lengths of 80 mm and 120 mm, with the filter at RT
 120 and cooled to LN temperatures. The spectra were compared to the same open
 121 collimator with no Be mounted. The transmission results for the different se-
 122 tups are shown in Fig. 3. As expected, the transmission improves drastically
 123 by cooling the Be, e.g. for an incoming wavelength of $\lambda = 4.4 \text{ \AA}$ from 48.2%
 124 to 85.1% (120 mm Be) and from 61.6% to 86.6% (80 mm Be). At LN tem-

Figure 3: The transmission of the different Be arrangements as a function of incoming wavelength. Cooling the Be (blue, red dashed) shows a significant improvement in transmission compared to Be at room temperature (green, black).

125 peratures, the normal operation temperature of the filter, the transmission for
 126 wavelengths above $4.05 \text{ \AA}$ is similar for both Be lengths. The experimentally
 127 determined absolute transmission above the cut-off is slightly less than the the-
 128 oretical predictions of $\sim 94\%$ (80 mm) and $\sim 92\%$ (120 mm) [6], while the ratio is
 129 in good agreement. Note that the theoretical calculations do not consider any
 130 BeO content of the filter. Any BeO content reduces the transmission above the
 131 normal Be cut-off due to the shifted cut-off at $\lambda = 4.6 \text{ \AA}$ [17].
 132 There is no sharp cut-off for the suppression of unwanted wavelengths below
 133 $4.05 \text{ \AA}$ but due to several Bragg cut-offs a clear shoulder region is visible. The
 134 suppression below the shoulder region is almost temperature independent and
 135 it is improved by factors in the range of 3 to 4.5 in the investigated region by
 136 increasing the Be length from 80 mm to 120 mm. A suppression of $\lambda/2$ neutrons
 137 of the order of 10^{-3} is achieved. Although cooling the filter improves the trans-
 138 mission the effect is smaller in the shoulder region compared to the region above
 139 the cut-off. In the shoulder region an increase in Be length still improves the
 140 suppression while above the cut-off almost no effect is visible. However, due to

Figure 4: Temperature dependent transmission for wavelengths below and above the Be cut-off (4.05 Å).

the temperature dependent variations in transmission the device should not be operated in the shoulder region.

Additional temperature dependent transmission measurements were performed with a different arrangement using the ToF option of BOA. Here, a smaller piece of Be (length 40 mm, width 10 mm) was mounted in a sample holder and attached to a cryocooler. Spectra were measured for a temperature range of $T = 20 - 290$ K and normalized to the direct beam spectra. The results for wavelengths below and above the cut-off and in the shoulder region are shown in Fig. 4. Here, several time bins were combined to obtain better statistics. For a wavelength below the cut-off ($\lambda = 2.37 \pm 0.17$ Å, red) the transmission is almost temperature independent. In the shoulder region ($\lambda = 3.80 \pm 0.08$ Å, blue) and above the cut-off ($\lambda = 4.39 \pm 0.035$ Å, black) the relative improvement in transmission is roughly the same ($\tau_{max}/\tau_{min} \sim 1.2$). Above the cut-off the transmission significantly improves until a temperature of $T = 120$ K is reached. Further cooling does not improve the transmission within the statistics. This is far above LN temperatures and demonstrate the advantage of the dry cooling of the filter. Dry cooling allows to optimize the cooling temperature, which

Figure 5: Sketch of the instrument configuration used for the rotation scans. The device (detailed sketch in Fig. 1) is centered to a scattering angle of -25° while a Perspex rod was used as an incoherent scatterer. To minimize background from air scattering the direct beam was shielded (blue).

reduces running costs by saving energy consumption and reduced maintenance cycles.

3.3. Rotation Scans

Figure 6: Rotation scans for different collimator configurations using an incoherent scatterer. A triangular function was fitted to the background corrected data. Due to the white beam configuration and changes of the slit opening, the peak intensities cannot directly be compared with each other and are not indicative for the filter performance.

A Perspex rod (diameter 5 mm, length 40 mm) was used as an incoherent scatterer in the white beam. Due to strong background arising from air scat-

Figure 7: Calculated intensity distribution for a collimation of 1° . The y-axis is parallel to the sample-collimator axis. During a rotation scan the sample (black circle) moves along the solid black line.

163 tering, the direct beam was shielded towards the detector. The collimator con-
 164 figuration was characterized by rotation scans with the collimator centered to
 165 a scattering angle of -25° (see Fig. 5). The results of the rotation scans are
 166 shown in Fig. 6, which displays the results for an empty collimator (collimation
 167 of 0.5° (red) and 1° (blue)) and 80 mm Be mounted with 0.5° collimation at RT
 168 (black) and LN temperatures (green). All data were corrected for background
 169 and a triangular function was fitted to all data sets. The fitting results are
 170 shown in Tab. 1.

171 The measurements were compared to geometrical calculations of the intensity
 172 distribution around the sample region. Here, the opening angle through a single
 173 radial collimator channel (focused on the sample position) is calculated for each
 174 point around the sample position within the scattering plane. By normalizing
 175 the resulting map to the sample position the intensity distribution of an inco-
 176 herent scatterer through one radial collimator channel is obtained. Neighbored
 177 collimator channels are taken into account by adding the same map rotated by
 178 the opening angle of the collimator. Fig. 7 shows a calculated example for the
 179 1° arrangement with a total number of 6 collimator channels. Here, the sample

Configuration	FWHM [mm], fit	FWHM [mm], calc
0.5°	13.65(4)	13.81
1°	27.44(5)	27.61
0.5°, 80 mm Be, RT	13.64(6)	13.81
0.5°, 80 mm Be, LN	13.48(7)	13.81

Table 1: Fitting results of the different rotation scans using a triangular function. The results are in excellent agreement with the values calculated geometrically.

position is in the center. The y-axis is parallel to the sample-collimator-axis. The beginning of the collimator is located at $y = 550$ mm. By performing a rotation scan, the sample position (black circle) w.r.t. the collimator rotation axis is moved along the black solid line. The calculated FWHM values are in excellent agreement with the experimental values (see Tab. 1). The presence of Be within the collimator does not affect the focal width of the collimator. Note that the rotation scans were performed to characterize the collimator performance. Since the measurements were done using a white beam, the peak intensities of these measurements cannot be directly taken as an indicator for the filter performance. In the case of Be inserted into the RC a large part of the incoming spectrum is cut off by the filter resulting in a larger drop in peak intensity. Furthermore, the slit configuration changed for the Be arrangements at RT and LN temperatures. Thus, these intensities should likewise not be compared directly.

3.4. Lamellas

Two lamella materials, Si wafers and boronated glass (Borofloat33, Schott AG), were tested. The lamellas had a thickness of 0.3 mm and were coated with a $1\ \mu\text{m}$ thick, absorbing Gd layer by sputtering. At the center position of the rocking scans (scattering angle of -25°) the collimator without Be was illuminated for 30 min. The results for the intensity of the 1° configuration integrated over the vertical detector channels are shown in Fig. 8. The intensity structure for the Si lamellas (black) is slightly less pronounced compared to the

Figure 8: Integrated intensities for different lamella configurations: Si (red) and glass (black). The structure is slightly more pronounced for the glass configuration.

one of the glass lamellas (red). The glass lamellas are less stiff than the Si wafers, which results in a small bending of the lamellas due to their own weight. This increases the effective thickness of the lamellas resulting in a slightly more pronounced intensity structure. The effect is small and in a spectrometer the structure will be smeared out by the mosaicity of the analyzers. Glass lamellas are less expensive compared to Si wafers ($\sim$ factor of 10). Thus, for the future CAMEA spectrometer glass lamellas coated with ^{10}B will be used.

4. Conclusion

A new, compact, combined device of a radial collimator and a dry cooled Be filter has been successfully tested. It can be shown that such a combined device with the radial collimator much longer than the filter can be realized without sacrificing the performance of the instrument. The achieved collimation is only limited by the manufacturing tolerances of the Be wedges inserted into the radial collimator allowing flexibility in positioning. Furthermore, the dry cooling allows a more flexible operation and installation of the easily extendable layout. This device will be included in the currently constructed CAMEA spectrometer

219 at SINQ, PSI. The minimum space requirements are especially interesting for
220 wide angle instruments where spatial restrictions apply, e.g. the upcoming gen-
221 eration of multiplexing neutron spectrometers currently developed at different
222 institutes [12–14].

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