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A new type of wide-angle supermirror analyzer of neutron polarization

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Abstract. We describe here a new type of wide-angle supermirror-based multichannel analyzer configured in the fan orientation. The increased channel width allows for reflections only from one of the channel's walls, so that the overlap of beams propagating through neighboring channels is avoided. However the straight beam, which is unavoidably propagating through the channels with the increased width, is blocked by an absorbing mask at the entrance of the analyzer. The neutron transmission of such analyzer is 22% higher and the number of the supermirrors needed to cover the same beam cross section is 16% less in comparison with a conventional fan analyzer. Results of the calculations and first tests of the analyzer at the Magnetism Reflectometer at Oak Ridge National Laboratory, USA, are presented.

1. Introduction

In the past few years, two-coordinate position sensitive detectors (2d-PSD) with the sensitive area greater than 400 cm^2 have been widely used at polarized neutron instruments. Therefore, there is an urgent need in wide-angle polarization analyzers allowing for polarization analysis (PA) over the whole large area of the detected beam. The use of wide-aperture fan type multichannel supermirror analyzer (MSA) (see Fig. 1) is one of the possible choices that suites well the requirements of neutron reflectometry.

Two wide-angle fan type supermirror analyzers have been manufactured in recent years in the PNPI. The first one, designed for the use with a 1-dimensional (linear) PSD at the TOF reflectometer REMUR (JINR, Dubna) [1], consists of 94 channels and has the following characteristics: the angular acceptance of scattered beam is about 1.5 degrees, the cross-section of the entrance window is (40×120) mm^2 (w × h) and is optimized for the neutron wavelength band of $\lambda = 1.5 - 10$ Å. The analyzing (polarizing) efficiency averaged over the wavelength band is about 0.95 - 0.96.

Another wide-angle fan type MSA designed for the neutron reflectometer NeRo (HZG, Germany) [2] has been used for a monochromatic beam of cold neutrons with a wavelength of 4.35Å.

This analyzer has been installed in front of the 2d-PSD with the sensitive area of 250 × 250 mm^2. It consists of 90 channels, has an entrance window of (90×160) mm^2 (w × h) and provides an anglular acceptance of about 6.1 deg. The analyzing (polarizing) efficiency of such analyzer is about 0.98 at above the given wavelength.

In the present paper we describe a wide-angle MSA designed for the Magnetism Reflectometer at the SNS (ORNL, USA) [3, 4] that operates in a wavelength range from 2.5 - 8Å.

2. Generic fan supermirror analyzer

The design of the analyzer for the Magnetism Reflectometer at the SNS is based on two MSAs mentioned in Ch.1, whose generic layout is depicted in Fig. 1.

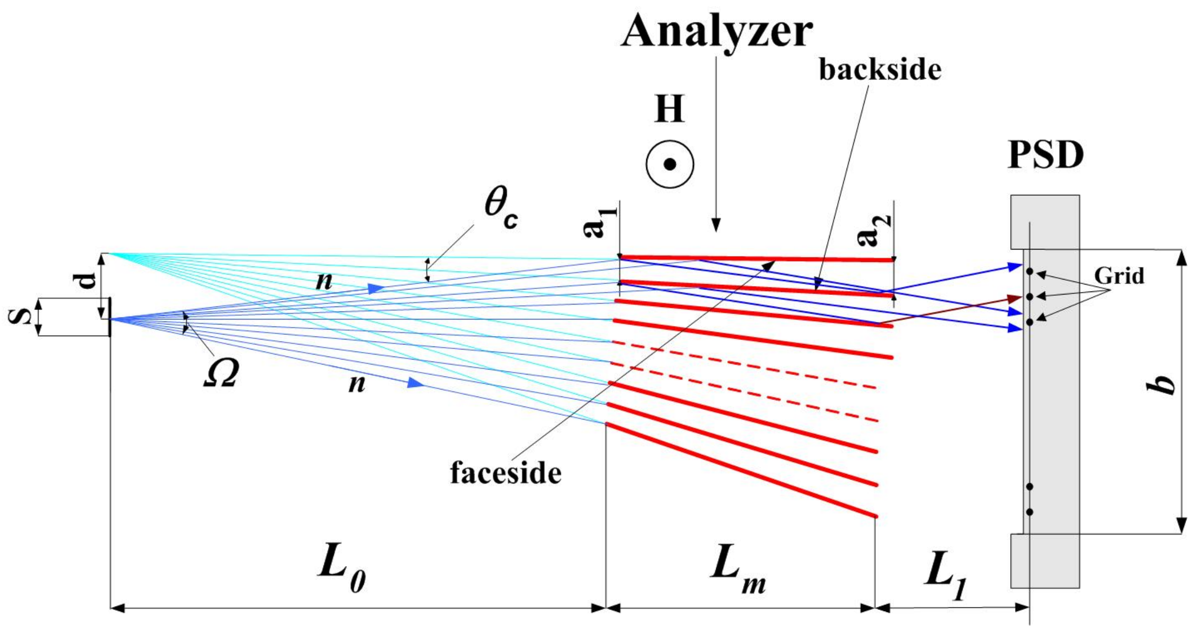

Figure 1. Sketch of the layout of a generic fan type MSA.

The entrance of the analyzer is at the distance L_0 from the center of the sample and covers a beam of the width s. Each channel of the analyzer consists of two supermirrors of projected length L_m labeled as "*faceside*" (FS) and "*backside*" (BS). They are separated by wedge-shaped spacers, widening from the entrance to the exit of the analyzer and are installed above and below the supermirrors along the channels. The supermirror coatings for FS and BS are m_1 and m_2, respectively. The channel widths at the entrance is a_1, the width at the exit is a_2 and the constant channel height is h. The neighboring channels of the analyzer are turned relative to each other by the angle $\Delta\theta = (a_1 - a_2)/L_m$. The exit of the analyzer is placed at a distance L_1 from the surface of a 2d-PSD with a width of b, so that the illuminated area of the detector is (b x h). The analyzer is placed in the external magnetic field H parallel to the plane of the supermirrors; the magnitude of the magnetic field should be close to the saturation field of the supermirrors. The turquois solid lines, which are the prolongation of the channel walls, are crossing in one point, the analyzer focus, at the distance L_0 from the analyzer entrance. The focus is shifted by distance d from the sample axis. The maximal glancing angle θ_{max} under which the neutron beam impinges on the walls of the channel shouldn't exceed θ_c, which is the critical angle of the supermirror coating for neutrons with the minimal used wavelength. Ω is the acceptance angle of the analyzer. Further on, we will call such analyzer "a conventional fan MSA": The parameters of such an conventional fan MSA optimized for an analyzer-detector distance of 110 mm are calculated according the algorithm described in Ref. [2] and given in Table 1.

Table 1. Parameters of the conventional fan MSA optimized for analyzer-detector distance of 110mm.

Length of supermirrors	L_m = 100 mm
Height of supermirrors	h_0 = 150 mm
Height of analyzer channel	h = 120 mm
Strength of magnetizing field	H = 650 G
Number of supermirrors in analyzer	N = 185
Polarizing Fe/Si supermirror coating: FS BS	m_1 = 4.0 m_2 = 2.5
Distance from sample to entrance of analyzer	L_0 = 2220 mm
Maximal glancing angle in the channel	θ_c = 12.6 mrad
Thickness of glass substrate	d_0 = 0.4 mm
Width of the beam blocked by sample	s = 2 mm
Channel width at the entrance	a_1 = 0.942 mm
Channel width at the exit	a_2 = 1.0 mm
Displacement of the analyzer focus relative to sample axis	d_0 = 6.4 mm
Distance from analyzer exit to detector	L_1 = 110 mm,
Sensitive width of 2d-PSD	b = 220 mm
Acceptance angle for the beam reflected from sample	$\Omega = 6.36°$
Entrance cross-section of analyzer	(120 x 247) mm^2

Q-dependences (Q is the momentum transfer) of the reflection coefficients of supermirrors for the spin-up component of the neutron beam are shown in Fig. 2. Using them one can calculate [5] the transmission function of a single channel of the analyzer (Fig. 3).

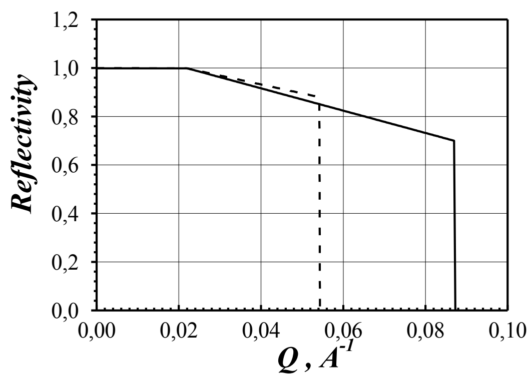

Figure 2. Reflection coefficients for the spin-up neutrons for supermirrors with m_1 = 4 at the FS wall (solid line) and m_2 = 2.5 at the BS wall (dash line) as functions of Q.

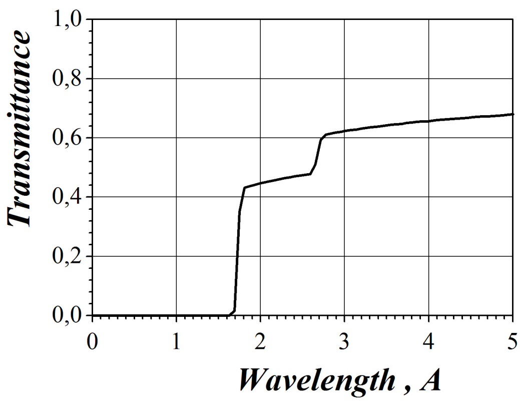

Figure 3. The calculated spectral transmission for the spin-up neutrons for a single channel of the conventional fan analyzer with m_1 = 4 at the FS wall and m_2 = 2.5 at the BS wall.

The calculated spatial distribution of the beam transmitted through a single channel of the conventional fan MSA at the detector surface separated by 110 mm is shown in Fig. 4. One can see that neutrons with the wavelengths λ=2Å and 3Å are transmitted to one peak of 0.85 mm width. However, there is also a second peak for λ=3Å, so that the full width of the reflected beam becomes 3.07 mm. Thus, there is a double reflection (from the BS wall) for neutrons with a wavelength larger than 3Å because of the small (about 1mm) channel width at the analyzer exit that results in the peak at 3mm (Fig.4). This leads to the undesirable overlap of beams propagating through the neighboring channels. The simplest solution of this problem would be to place the detector sensitive area very close to the exit of the analyzer. However, practically this distance could only be reduced to 66 mm that is not sufficient to avoid the overlap.

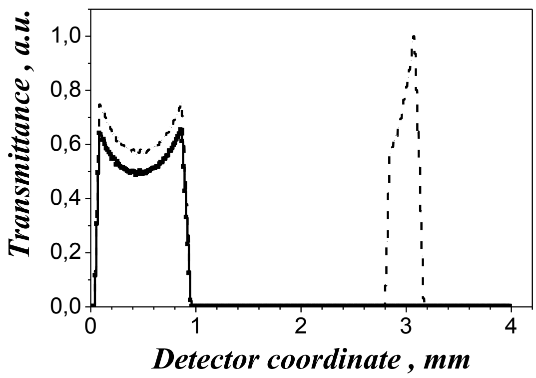

Figure 4. Calculated intensity distributions for one channel of the conventional fan analyzer. The solid line corresponds to spin-up neutrons λ=2Å, the dash line corresponds to spin-up neutrons with the wavelength λ=3Å.

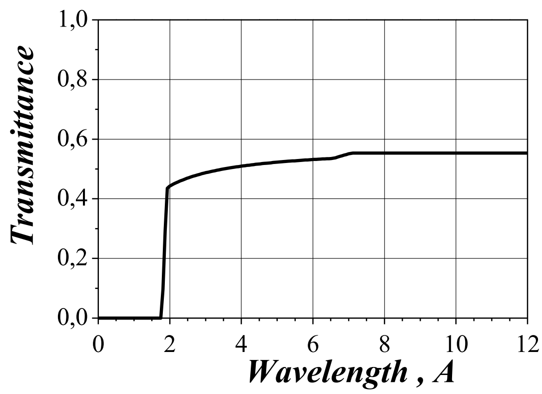

Figure 5. The spectral transmission of a single channel of the conventional fan analyzer (m_1 = 3.7 (FS) and m_2 = 0 (BS)).

Trying to solve the situation with the reflection from the BS wall, we painted it with an absorbing layer with m_2 = 0 (e.g. a gadolinium oxide layer). This allows for suppression of the parasitic reflection from the BS wall (peak at 3mm), however the width of the transmitted beam for both wavelengths is decreased to 0.8 mm. The transmission of spin-up neutrons through one channel of the conventional MSA as a function of the neutron wavelength is presented in Fig. 5. The maximum transmission of 0.55 is achieved for neutrons with wavelengths above 7.1Å.

3. The fan analyzer with an absorbing mask at the channel entrance

As it was shown in Ch.2, the neutron reflection from the BS of the narrow analyzer channel results in undesirable broadening of the outgoing beam (see also Fig. 6a), however this effect can be suppressed by painting the backside of the channel with an absorbing layer. In this chapter we will describe another approach that allows us to obtain even better results.

The idea is to increase the width of the analyzer channels, so that any double reflection will be avoided and simultaneously to block the part of the neutron beam, which can propagate through the channel without touching its walls and therefore will not be analyzed (see Fig. 6b). This can be achieved by using a neutron absorbing mask at the entrance of the analyzer. This mask is made of stripes of a thin polyester film coated with gadolinium oxide. The thickness of the mask is calculated using simple geometrical considerations and is equal to $a_1^* - a_1$ where a_1^* is the width of the channel at the entrance and a_1 is the effective channel width with the accounting for the mask thickness:

$$a^*_1 = L_{m2} \cdot (\theta_c - s/L_0)/(1+L_{m2}/L_0); \qquad a_1 = L_m \cdot (\theta_c - d_0/L_0)/(1+L_m/L_0),$$

The parameters of such improved analyzer and adopted to the requirements of the Magnetism Reflectometer at the SNS, with a wavelength range of (2.5-8)Å and an entrance cross-section of 250×120 mm^2 (w × h), are given in Table 2. One can see, that the thickness of the mask should be not less than 0.12 mm to block the straight beam. The calculated spatial distribution in the beam transmitted through a single channel for s=2 mm is presented in Fig. 7: the straight beam is fully blocked and the width of the reflected beam is about 1.3 mm, which is less than a_2+d_0=1.65 mm, the period of the channels at the exit of the analyzer. It means that the overlap of neutron beams passing through neighboring channels is avoided. The calculated spectral transmission through one channel for spin-up neutrons is presented in Fig. 8; the SM coatings of walls of the analyzer are m_1 = 3.7 (FS) and m_2 = 0 (BS).

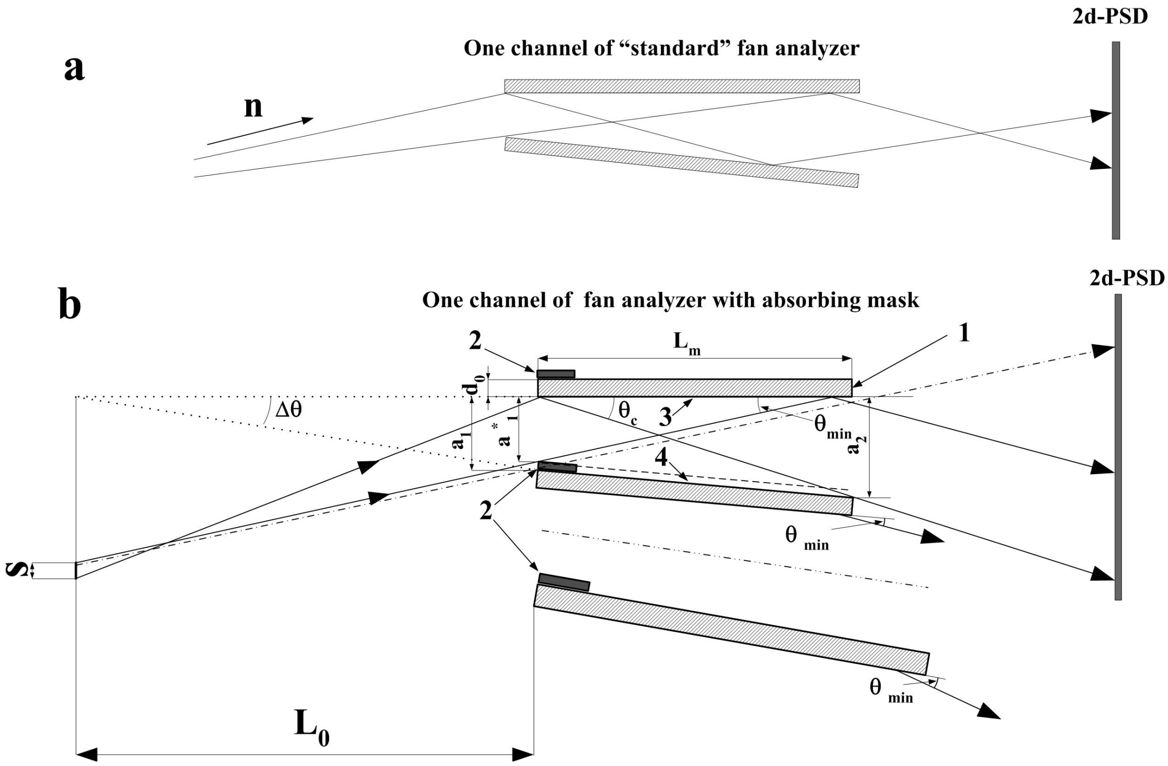

Figure 6. Layout of a conventional analyzer (a) and the analyzer with the neutron absorbing mask at the entrance (b). 1 – glass substrate with thickness d_0; 2 – absorbing mask; 3 – FS wall; 4 – BS wall.

Table 2. The optimized parameters of the new variant of fan analyzer with absorbing mask.

Length of supermirrors	L_m = 100 mm
Height of supermirrors	h_0=150 mm
Height of the analyzer channel	h = 120 mm
Strength of a magnetizing field	H = 650 G
Number of supermirrors in the analyzer	N = 159
Polarizing *Fe/Si* supermirror coating: FS BS	m_1 = 3.7 m_2 = 0
Distance from a sample to an entrance of the analyzer	L_0 = 2260 mm
Maximal glancing angle in the channel	θ_c = 12.5 mrad
Thickness of a glass substrate of supermirror	d_0 = 0.4 mm
Width of the beam blocked by sample	s = 2 mm
Channel width at entrance with spacer	a_1 = 1.180 mm
Actual width of channel at entrance including mask	a^*_1 = 1.059 mm
Channel width at the exit	a_2 = 1.25 mm
Distance from the analyzer exit to the detector	L_1 = 66 mm
Sensitive width of 2d-PSD	b = 220 mm
Acceptance angle for the beam reflected from a sample	$\Omega = 6.36°$
Entrance cross-section of the analyzer	(120 x 250) mm^2

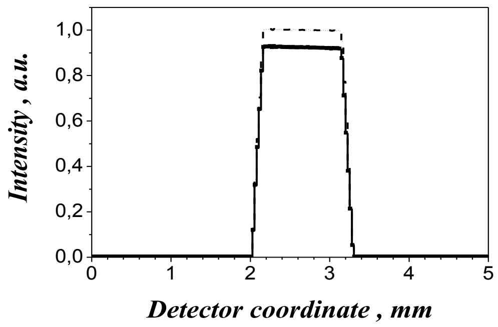

Figure 7. The calculated spatial distribution of spin-up neutron intensity passing through the analyzer with a mask at its entrance. The solid line corresponds to neutron intensity for λ=2Å, the dash line for λ=3Å.

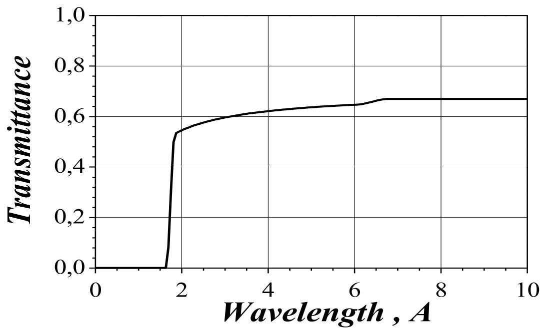

Figure 8. The calculated spectral transmission through one channel of analyzer with the mask at its entrance for spin-up neutrons.

As one can see from Fig. 8, the maximal value of the transmission for this analyzer is 0.67 for λ>6.7 Å, i.e. about 22 % higher than for a conventional fan analyzer (Fig. 5) over the whole used wavelengths range. It should be noted that due to the increased width of the channel's exit for this version of the analyzer one needs 16% less supermirrors than for a conventional analyzer covering the neutron beam of the same cross-section.

Principally, because of the use of an absorbing mask, no coating of the BS wall is necessary. However, the deposition of a supermirror coating only on one side of a thin glass substrate results in mechanical tensions and in the deformation of the flat substrate [6]. To compensate for this effect, one can cover the BS wall with a layer of the gadolinium oxide, as in the conventional fan MSA.

4. Results of test experiments

The analyzer improved by absorbing masks has been designed in the PNPI for the Magnetism Reflectometer at the SNS on the basis of the above presented design using 159 polarizing neutron Fe/Si supermirrors made by SwissNeutronics [7]. The magnetic system of the analyzer [8] has been built on the basis of permanent rare-earth NdFeB magnets. In this way a magnetic field of up to 65mT (at the middle of the magnetic system) are achieved over the a height of 120mm of the super mirror channels and with a high uniformity of the magnetic field over the supermirror's area.

The test of the analyzer has been carried out at the polarized neutron beam in a wavelength band from 2.2 – 4.7 Å. The detector surface has been separated from the analyzer exit face by 66 mm. The polarization efficiency of each 10^{th} analyzer channels has been measured using a highly efficient radio-frequency adiabatic spin-flipper. The wavelength dependency of the polarizing efficiency for the central (0) and the two side channels (40). (-50) are presented in Fig. 9, showing a very high level of polarizing efficiency: (40): 0.988±0.002, (0): 0.987±0.002 (-50): 0.989±0.002, respectively. The spectral transmission of spin-up neutrons for the central channel is shown in Fig. 10: as it is seen the transmission is rather close to the calculated values (cf. Fig. 8). The results of the measurements on other the analyzer channels will be presented elsewhere [9].

5. Conclusions and acknowledgements

We present a new version of wide-angle high efficiency supermirror fan polarization analyzer with a neutron absorbing masks at the entrance designed for the operation with a large size 2d-PSD. The first analyzer has been designed and manufactured in the PNPI for the use at the Magnetism Reflectometer (SNS, Oak Ridge National Laboratory) that operates with a wide neutron wavelength

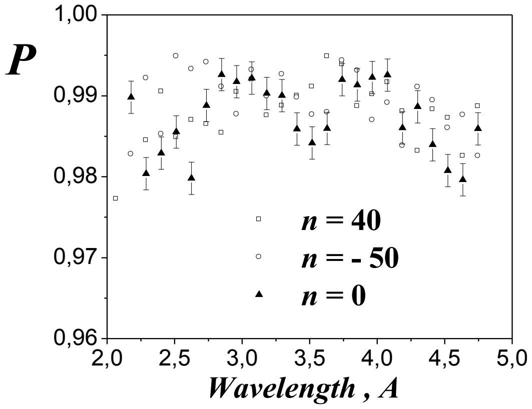

Figure 9. Spectral polarizing efficiency for three analyzer channels (*n* = 40, 0, -50).

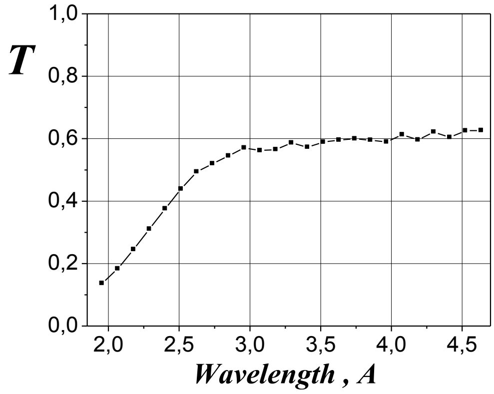

Figure 10. Wavelength dependence of transmission through the central analyzer channel for spin-up neutrons.

band of (2.2 – 4.7) Å. In comparison with the conventional type of fan analyzer, the presented analyzer requires 16% less supermirrors and demonstrates significant improvements in the neutron beam transmission that is 22 % higher in the whole range of used wavelengths.

Test measurements on 10 selected channels have demonstrated a very high analyzing power and high luminosity of the analyzer: the averaged level of polarizing efficiency over the wavelengths band (2.2 – 4.7) Å is about 0.99 and the transmission for spin-up neutrons is close to the calculated value and approaches 60% for wavelengths above 3.7 Å (has been only tested for the central channel).

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