High performance, large cross section S-bender for neutron polarization

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Abstract

An 80 mm long polarizing S-bender with a large cross section of 30 mm x 100 mm for the instrument MIRA at the FRM II has been simulated, built and tested. The results of the experiment show for the wavelength of 4.4 Å a homogenous polarization of more than 98% across the bender cross section and a high transmission of above 65% of the spin up component of the neutron beam. The bender design has the advantage of delivering the polarized beam in the direction of the incoming beam.

Keywords: Neutron polarizer, bender, S-shaped bender, supermirror

1. Introduction

The instrument MIRA [1] at the FRM II in Munich requires for several instrument options like polarized small angle scattering, neutron reflection and quasi-elastic measurements with the spin-echo method MIEZE [2,3] a highly polarized beam with a large beam cross section. Due to the restricted space there are mainly two approaches to this goal: the ^{3}He polarizing gas cell [4] or a supermirror polarizer. The former has the advantage of providing a homogenous polarization across the beam with very low small angle scattering while the main disadvantage is the relative low transmission for a good polarization. A supermirror polarizer provides a stable high polarization and a reasonable transmission but creates small angle scattering at a significant order. Therefore the choice for a polarizer is the supermirror version provided the instrument operates in the cold neutron range, while for an analyzer in small angle scattering experiments the ^{3}He polarizer is the preferred solution.

For MIRA additional requirements were to provide the polarized beam over the short distance of 8 cm and in the direction of the incoming beam. Three devices fulfilling these requirements were considered: the S-bender, a system of parallel V-shaped cavities (“V cavity”) and of cavities with two V cavities behind each other (“2V cavity”). The required wavelength range was 3 – 6 Å.

Monte-Carlo simulations were performed to compare these systems.

2. Simulations

McStas software [5] version 1.12c has been used to carry out simulations to investigate the performance of the three polarizing devices, each with a length of 8 cm. The cavities have purely absorbing walls. All other simulation parameters are shown in Table 1.

Table 1: Simulation parameters for the different polarizing devices for m = 3 supermirrors. d is the distance between the two V in the 2V cavity and r the radius of curvature of the S-bender.

	S-bender	V-cavity	2V-cavity
Length [mm]	80	80	80
d [mm]	-	-	20
r [mm]	2100	-	-
Wafer thickness [mm]	0.15	0.3	0.3
Channel width [mm]	0.15	3	3
Wafer angle to the walls	-	1.07°	1.43°
Absorbing wall width [mm]	-	0.3	0.3

For each of the three devices two different incoming angular and wavelength distributions were simulated to compare their angular acceptance: distributions at the end of a neutron guide behind the cold source of the Munich reactor coated with supermirrors with either m=1.2 or with m=3, where m is the multiple of the critical angle of natural Ni.

The value m=1.2 corresponds to the divergence distribution at the end of the neutron guide of MIRA. The value m=3 was chosen to show the transmission of the devices at the end of a neutron guide coated with m=3.

Figure 1 shows the simulated polarization for the three devices. The S-bender has for the wavelength range from 2 to 10 Å a very high polarization above 97.5%.

The cavities exhibit much worse polarizations values. They are very short and thus the angle of the wafers is so large that a polarization above 95% is reached only for the small divergence of m=1.2 and only at wavelengths above 7.5 Å for the 2V cavity and 9.2Å for the V cavity. For the large divergence of m=3 their polarization values stay below 70% (2V cavity) and 60% (V cavity), even at 10 Å. A smaller angle for the wafers would result in smaller channel widths and increased absorption for the whole system which would lower the quality factor (see below) as well.
The S-bender was found to clearly surpass the polarization of the two other devices in the required wavelength range from 3 to 6 Å.

(Insert Figure 1 here)

Figure 2 shows the simulated transmission values for the spin up component of the neutron beam through the three devices, again for the two different divergence values. The cavities show for wavelengths below 5 Å a slightly larger transmission than the S-bender for the m=1.2 divergence. For the m=3 divergence the same is true up to 3 Å. However, the high transmission of the cavities cannot be used since there the polarization is too small.

(Insert Figure 2 here)

The usefulness of a polarizer is often assessed by the quality factor $Q = P^2 * T_{up}/I_{up}$, where P is the polarization of the transmitted beam and T_{up}/I_{up} the transmitted fraction of the spin up component. Figure 3 shows the quality factor for the three devices, again for two different divergence values. Here the S-bender shows the largest quality factors for all wavelengths; especially for the large incoming divergence its performance is much better.
In conclusion, we found a clear advantage of the S-shaped bender over the other considered systems. The tests of such a system, supplied by the company NOB, are described below.

(Insert Figure 3 here)

3. The working principle of an S-bender

An S-bender consists of a set of parallel S-shaped channels which are coated on both sides first with a polarizing and then with an absorbing layer. A proof-of-principle was realized at the ILL by Stunault et al. using a bender prototype with a cross section of 6 mm x 70 mm [6]. The system we report on here has a cross section of 30 mm x 100 mm and channels formed by 0.15 mm thick silicon wafers in which the neutrons propagate. The polarizing coating is realized by Fe-Si supermirrors with m=3 which reflect only the spin up component of the neutron beam. The supermirrors are magnetically saturated by permanent magnets creating a field of 300 G. The absorbing coating is made from Gd and absorbs the unwanted spin down state, which is transmitted through the supermirrors.

It is an important feature of the S-bender that the average direction of the transmitted polarized beam is in the same direction as the incoming beam. This is advantageous compared to a bender which deflects the beam and thus requires a readjustment of the instrument when the polarizer is inserted. The conservation of the average flight direction is a result of typically two reflections of the neutrons inside the S-bender. Simulations show that these most often occur at a large and a small angle between neutron flight path and supermirror. This results in a very high reflectivity for the low angle reflection. Furthermore the two reflections lead to a multiplication of the flipping ratios and thus result in very high polarization values.

4. Polarization measurements

First the S-Bender was adjusted at the instrument MIRA with the bender mounted at the sample table of the instrument. A beam with the wavelength of 4.4 Å and a cross section of 5 x 5 mm^2 collimated to 0.5° hit the middle of the polarizer and was analyzed by a ^3He polarizer (99.9% polarization with 10% transmission) before being detected with a CSACADE 20 x 20 cm^2 boron GEM detector [7]. The polarizer bending was adjusted during a series of rocking scans of the bender where the transmitted intensities of the two spin components were measured. The transmission of the polarizer was determined from a comparison to the empty beam. These values were determined at 12 positions across the polarizer showing a good homogeneity of the system to within 6% in transmitted intensity and 0.4% in polarization. The axes of incoming and transmitted beam coincided within less than 0.1°.

Figure 4 shows a rocking curve of the S-Bender in the beam, giving the values for the transmitted spin up and spin down neutron beam intensities T_{up} and T_{down} together with the flipping ratio $FR= T_{up}/T_{down}$, the polarization $P = (FR - 1)/(FR + 1)$ and the quality factor Q. Due to the high polarization of the ^3He cell no corrections were applied to the incoming polarization. Background corrections were made due to detector noise in the order of 1% of the direct beam.

(Insert Figure 4 here)

Polarization values above 98.7% at all angles where the transmission values were above 6% of the spin up component indicate the excellent polarization capability of the S-bender. The total transmission values were between 67% and 70% depending on the size of the beam. The linear absorption length for neutrons at the wavelength of 4.4 Å is μ_l=0.03 cm^{-1} [8] and gives a transmission of 78.7% through 80 mm Si. Hence the losses due to incomplete reflection at the supermirrors are in the order of 10%.

The FWHM amounts to 1.85° which corresponds to an m-value of ± 2.1for the wavelength of 4.4 Å. Within this FWHM the average transmitted intensity is 58%, the average quality factor is 57%.

Figure 5 shows a comparison of the experimental values to a simulation. The simulated intensity reaches 70% in the maximum and is for all angles a few percent higher than the experimental values. It should be noted that the simulated maximum value shown here is higher than that in Figure 2. This is due to different incoming divergence values. In the simulations for Figure 2 the full divergence at the end of a neutron guide with a nearly rectangular distribution was used because the polarizing device will be applied at this position. The experiment and the corresponding simulation were done with two slits which transmit a triangular distribution. This favors angles close to 0° which have a higher transmission probability through the S-bender.

The flipping ratio in the simulation is for most angles higher than in the experiment except for a small dip below the experimental values in the interval from -0.4° to -0.9°. This is due to the model for the spin down reflectivity, which uses the simulated reflectivity of the spin down component of a neutron moving through Si and hitting a thick Fe layer. Obviously, this underestimates the real reflectivity and thus only a qualitative agreement could be reached.

(Insert Figure 5 here)

After adjustment the polarizer was installed at the exit of the monochromator shielding of MIRA. A black ^{3}He cell was used as analyzer to determine the total polarization of the beam.

At the same wavelength of 4.4 Å and the same set of slits, which were used for the experiments, we found a transmission of the spin up component of the neutron beam of 68% ±2% and a flipping ratio of 150 ±10.

5. Conclusion

The tested solid state S-bender with a length of 80 mm showed for neutrons with the wavelength of 4.4 Å polarization values above 98.7%. The maximum transmission value was above 65%, the average value within the FWHM 58% of the incoming spin up intensity. The quality factor for the spin up component P^2*T was 68% in the maximum, the average value within the FWHM 57%. The polarized beam is delivered in the direction of the incoming beam and the system is maintenance free. With these excellent features an S-bender can be used to polarize and analyze cold neutrons beams in a broad range of applications.

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Figure Captions:

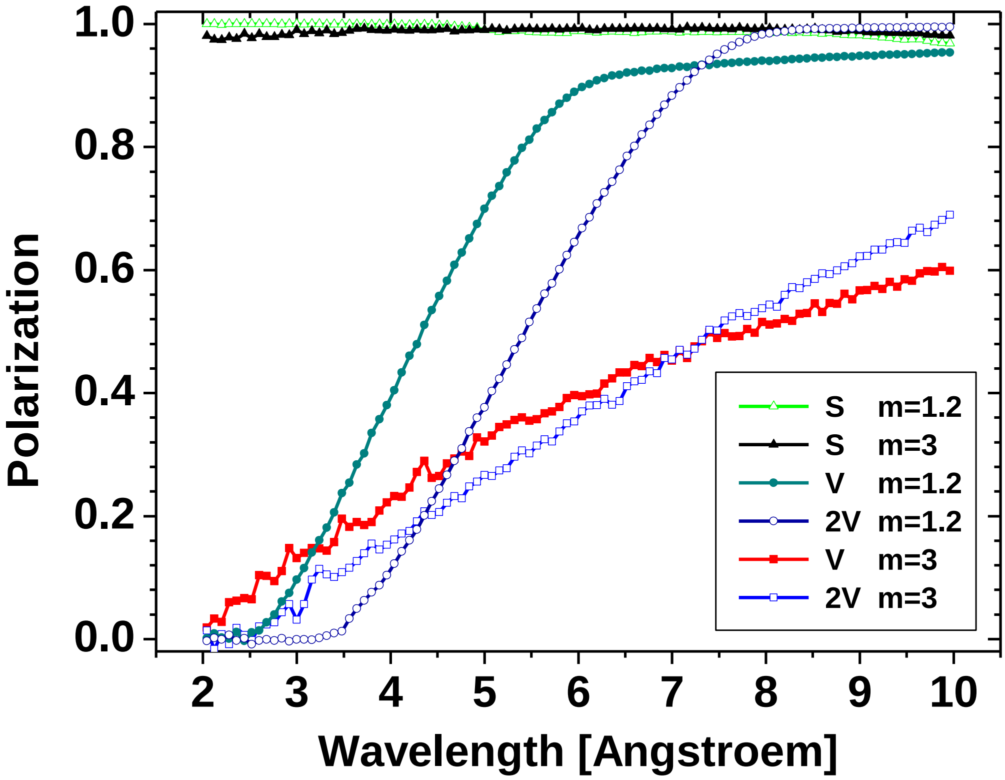
Figure 1: Simulated polarization performance of the three devices: S-bender (S), 2V-cavity (2V) and V-cavity (V), each for two incoming divergence values of m=3 and m=1.2.

Figure 2: Simulated transmission of the spin up component through the three devices: S-bender (S), 2V-cavity (2V) and V-cavity (V), each for two incoming divergence values of m=3 and m=1.2.

Figure 3 Simulated quality factor Q = $P^2 * T_{up}/I_{up}$, where P is the polarization of the transmitted beam and T_{up} /I_{up} the transmitted fraction of the spin up component for the three devices: S-bender (S), 2V-cavity (2V) and V-cavity (V), each for two incoming divergence values of m=3 and m=1.2.

Figure 4 Experimental transmission through the S-bender of the two spin components of a neutron beam with the wavelength of 4.4 Å together with the quality factor Q, the polarization P and the flipping ratio FR.

Figure 5 Comparison of experimental, Exp_{up}, Exp_{down}, and simulated, Sim_{up}, Sim_{down}, transmission values for the two spin components of a neutron beam with the wavelength of 4.4 Å through the S-bender together with the flipping ratios FR_{exp}, FR_{sim}. Experimental values as in Figure 4.



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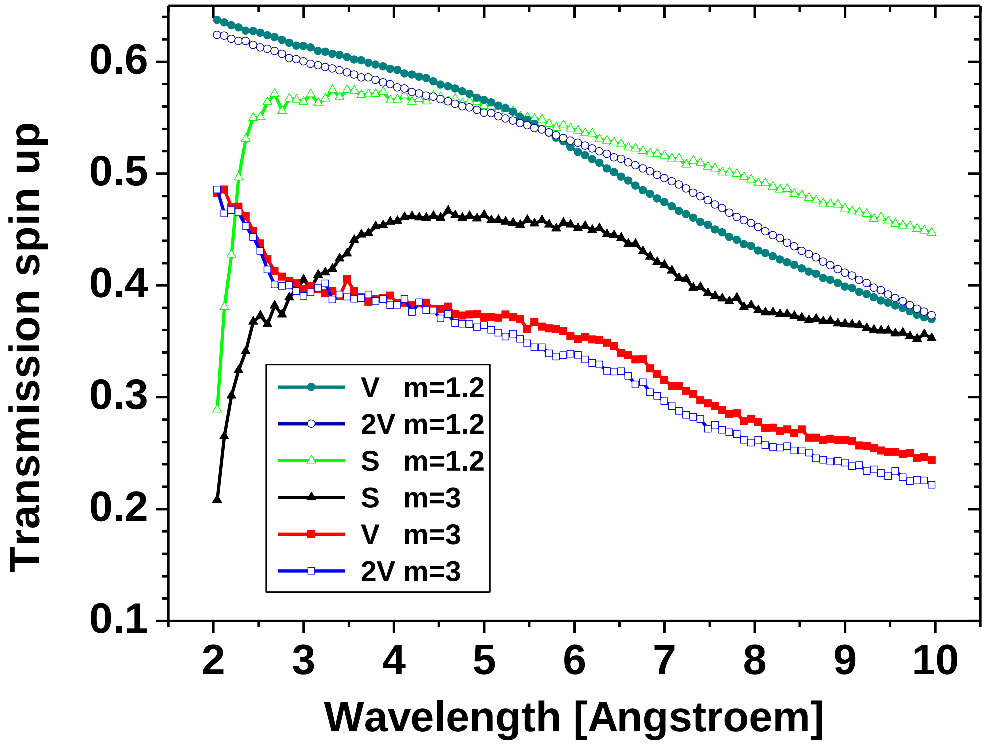

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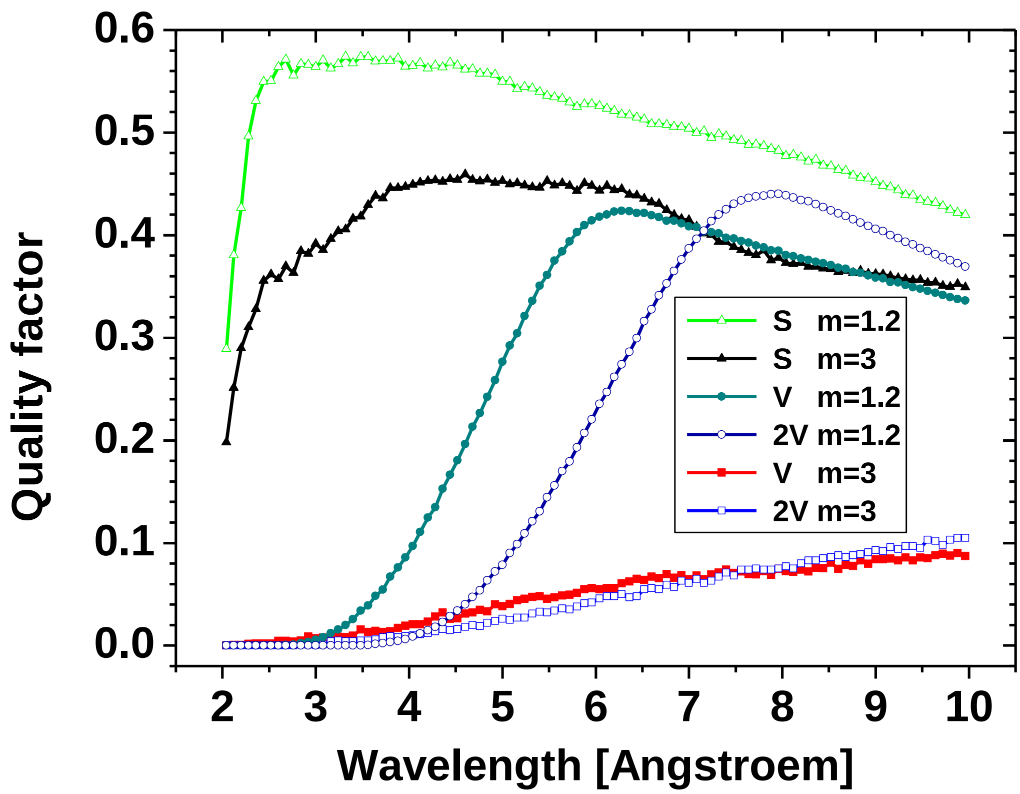

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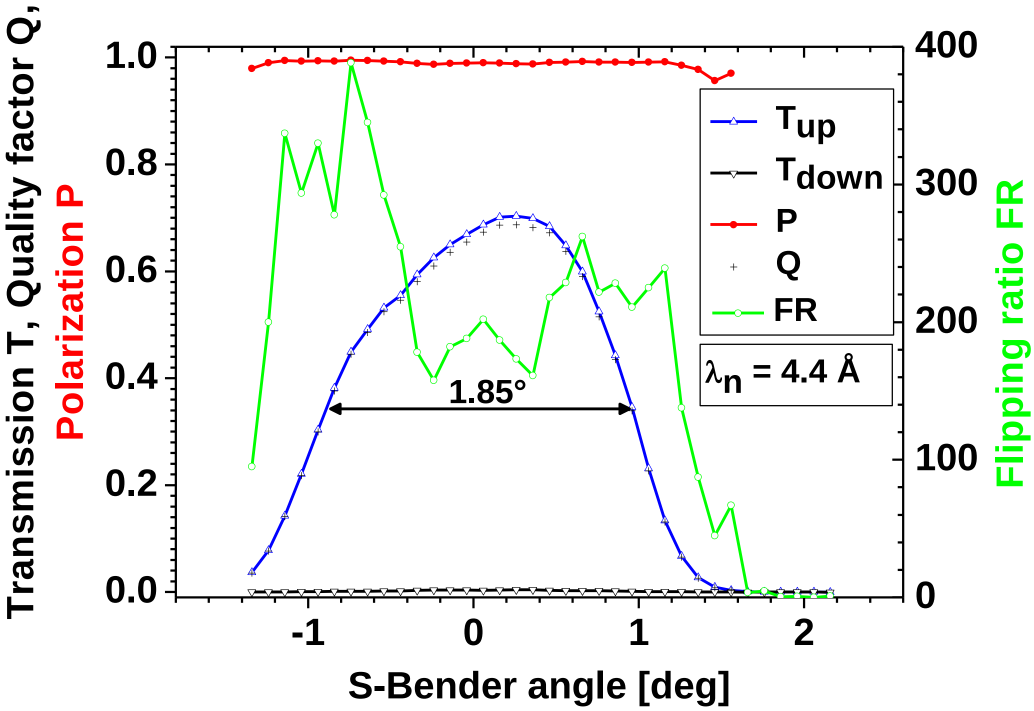

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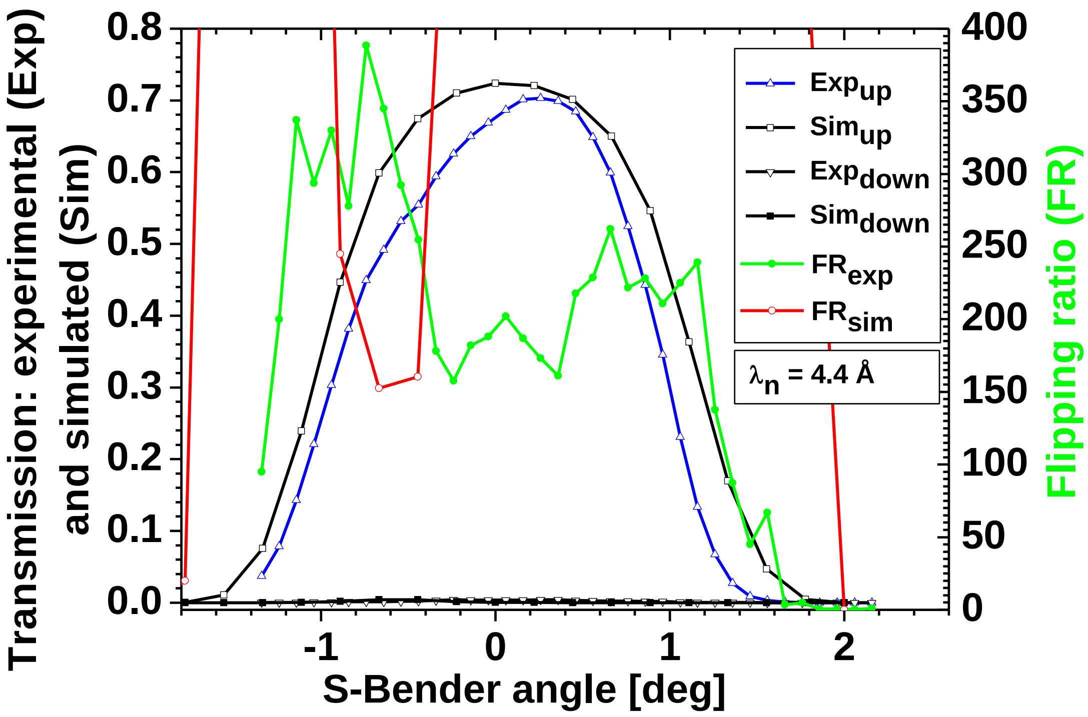

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