ODIN – Neutron optics preliminary design report

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Contents

List of Figures

Motivation

The neutron optics system of ODIN has been optimized for neutron imaging experiments. The requirements were set in the proposal and endorsed by the STAP and the ESS management. The aim of this system is to fulfill the high level scientific requirements by providing:

1. Large and homogeneously illuminated Field of View (± 0.7 deg transported divergence)
2. Bi-spectral extraction to increase the usable bandwidth (1-10 Å or more)
3. Spectrally homogeneous FoV

Due to the many changes in moderator design, correspondingly many designs were optimized. We present here the optimization for the 3 cm butterfly moderator (with the current and seemingly final design). Several others optics layouts were tested, such as bent guides, guides with a constant or tapering cross sections and more (see for instance [Hilger et al., Optic Express, 23, (2015)] or, more recently, presentation about ODIN at various IKON and topical meetings), as a result we concentrated our efforts on a direct-line-of-sight ballistic-based design.

ODIN coordinate system

Parameters given below refer to the ODIN axis. This axis is defined starting from the beamport coordinate system (BPCS) which in turn is defined in terms of the target coordinate system (TCS) with a translation from the origin of (-54,-89,0) mm and a rotation around the z-axis of -144.70 degrees (South sector, beamport 2). From the BPCS we define the ODIN axis with a rotation around the z axis of -0.86 degrees with pivot point (0,0,2120)mm in the BPCS and a translation of 27 mm in the direction of S3 (Figure 1). In the new coordinate system, z will be in beam direction, while x and y are the horizontal and vertical coordinate respectively.

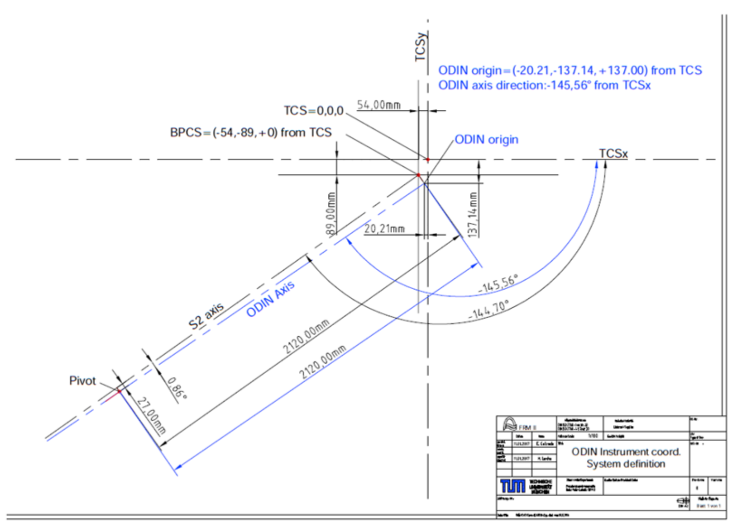

Figure 1: ODIN coordinate system.

The rotation angle and shift have been chosen in order to extract the highest flux from the thermal moderator while minimizing the conflicts between neighboring beamlines and still fitting the extraction system in the monolith insert (Figure 2).

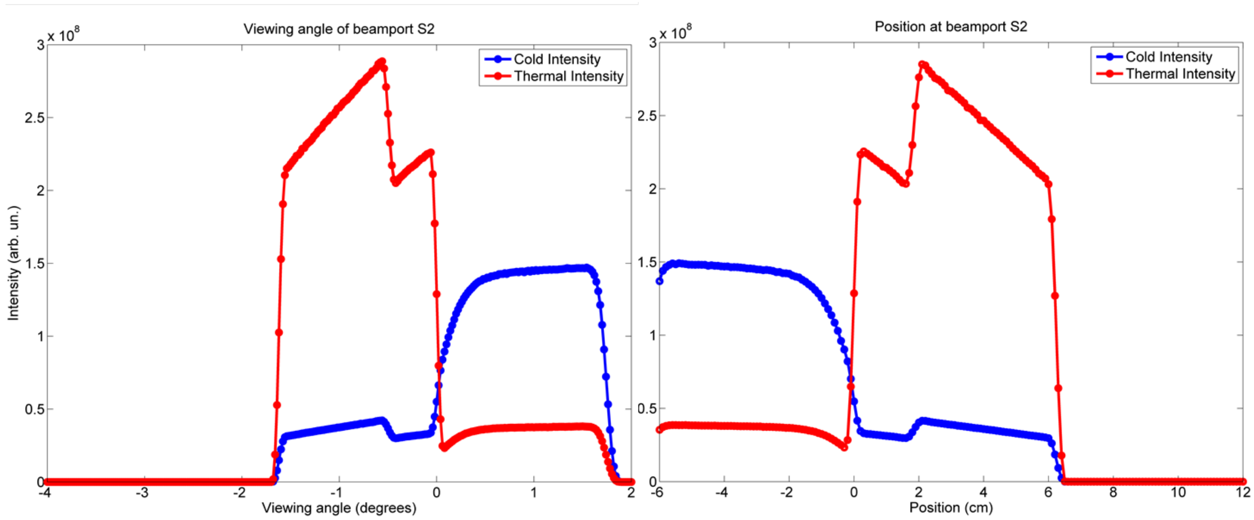

Figure 2: Rationale for the choice of the ODIN coordinate system. Left: Thermal and cold moderator intensities as function of the viewing angle, obtained without any shift. Right: Thermal and cold moderator intensities as function of the beamline axis shift, obtained without any rotation. The actual choice is made in order to point the beamline to the maximum of the thermal extraction.

Overview

The basic components of the ODIN neutron optics systems are shown in Figure 3 and listed here:

1. The extraction system (G1). Except for the light shutter insert it is situated in the monolith with the multi-channel bi-spectral component at the front end.
2. The beam expansion system (G2 in the horizontal, G2 and G3 in the vertical profile). It is situated entirely in the bunker.
3. The beam transport system (G3, G4 and G5 in the horizontal, G4 in the vertical profile). It is situated in partly in the bunker and partly in the instrument shielding.
4. The beam compression system (G6 in the horizontal, G5 and G6 in the vertical profile). It is situated completely in the instrument shielding that leads to the instrument cave.

The sizes and parameters of all these guides are given in appendix A.

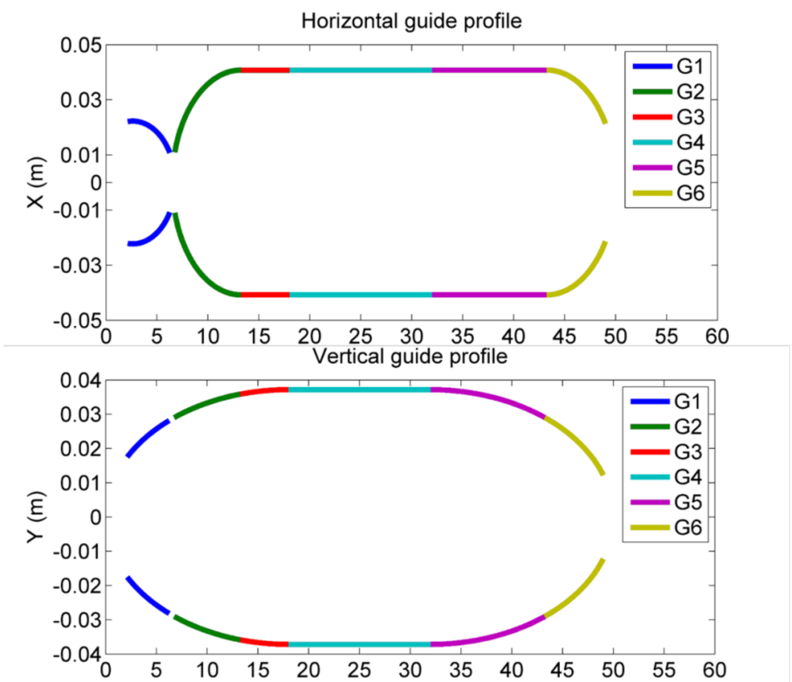

Figure 3: Schematics of the ODIN neutron optics system. Not shown here are the bi-spectral mirrors.

The design of the guide system is based on a ballistic approach, with the addition of a feeder in the horizontal profile. Two eye-of-the-needles are defined, one at 6.75 m and one at 50 m. The first one is 15 x 60 mm^2 (w x h) and it defines the center of the Wavelength Frame Multiplication Chopper ensemble. It is used to reduce the size of the beam to allow for a fast chopping in the direction of the chopper motion (horizontal). It is also the focus of the beam expansion system. The second eye-of-the-needle has dimension 30 x 30 mm^2 and is at the entrance of the instrument cave (50 m). It is used to manipulate the beam in order to define a precise geometry for the experiments carried at the sample position. The main sample position is defined to be 10 m after the cave entrance (60 m), but the option to move the sample and the detector closer or further away is open in order to have some freedom to choose the best experimental conditions in terms of tradeoff between flux and size of the FoV/collimation.

There are other components that are not strictly neutron optics, but are still relevant for the proper performance of the optical system, such as the graphite diffuser for smoothing out any sharp inhomogeneities and the slit systems in both eye-of-the-needles, but they will not be discussed here.

Bi-spectral mirrors

The bi-spectral mirrors are an insert to the feeder used to extract neutrons from the cold moderator and reflect them in-line with the thermal ones.

The generic design is based on [Zendler et al, NIMA, 704, (2013)], in which its superior design is demonstrated compared to simpler alternatives. A number of neutron supermirrors are stacked inside the elliptical feeder. An overall tilt angle is given to the stack in order to reflect the chosen part of the cold moderator parallel to the instrument axis. To improve the collection and the reflected divergence, each of the mirrors is divided in sections (5 in our case) of equal length. Each section is given an additional incremental angular offset such that the central section is parallel to the original stack direction, sections closer to the moderator are at a steeper angle, section further away from the center are at a shallower angle (Figure 4).

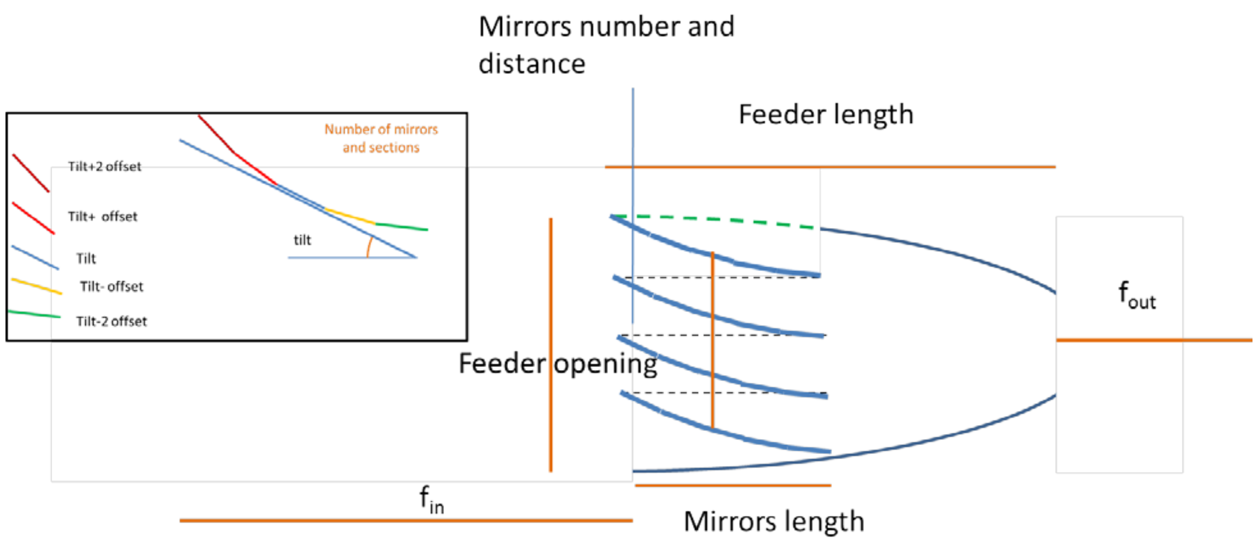

Figure 4: Schematics of the bi-spectral feeder components. All the parameters in orange are variables for the McStas component.

Based on this design, we developed a McStas component with all the degrees of freedom shown in the previous picture.

The current design has been optimized with regard to geometry using a maximization software coupled with a swarm particle algorithm capable of scanning a very wide phase space of parameters (GuideBot).

The result is an ensemble of 12 single-coated, 0.3 m long, m=5 supermirrors on monocrystalline silicon substrate.

We will avoid using a bent substrate in order not to incur significant extinction effects due to the smoothly-varying lattice spacing in bent silicon. The mirrors will be pressure mounted via slots precisely made in the vertical walls of the feeder and glued with radiation-hard glue. The choice of Silicon has been made due to its transparency to low wavelength neutrons coupled with its radiation hardness. The temperature expected at the very entrance of the monolith insert is ~60° C according to the calculation presented at IKON 11, making a special cooling of this component not strictly necessary, but cooling channels are foreseen in the insert anyways.

Performance of the bi-spectral mirrors

To assess the performance of the bi-spectral mirror arrangement, we compare the current version of the ODIN neutron optics (including bi-spectral extraction) to two fictitious instruments, a "thermal ODIN" and a "cold ODIN" each pointing respectively to the thermal and cold moderator only, without bi-spectral extraction but having all the remaining optics untouched. This comparison is visible in Figure 5.

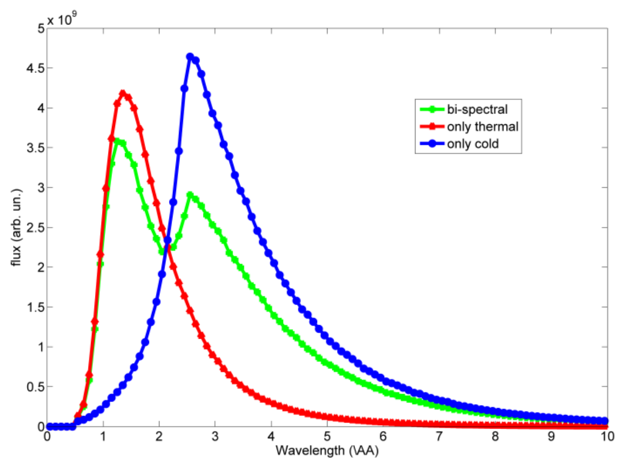

Figure 5: Comparison of the spectra of the current bi-spectral ODIN's optics (pink) to a thermal only (red) and cold only (blue) version of the guide system.

An ideal dual beam extraction would provide a spectrum equal to the maximum of the two fictitious instruments for each wavelength. When comparing the resulting spectrum of ODIN with such an ideal extraction, we obtain Figure 6.

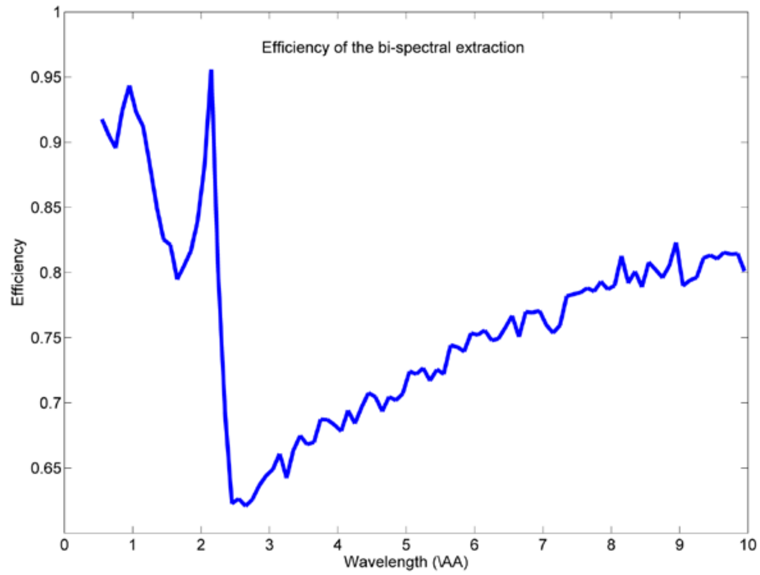

Figure 6: Efficiency of the bi-spectral extraction compared to the ideal case.

In this figure we see that for short wavelengths we have a high efficiency of more than 80%, which decreases as the wavelength increases due to the more efficient reflection of neutrons coming from the thermal moderator. As the wavelength increases, we reach the crossover point where the thermal and the cold moderator have the same intensity, after which the extraction efficiency has a discontinuity given by the binary nature of the max function, and as expected for colder regions the current extraction performs at a satisfactory level of about 75% of a “pure cold” instrument.

The gain in having a bi-spectral extraction is apparent in the next figure (Figure 7), where the expected ODIN spectrum is compared to either the spectrum of the “thermal ODIN” or the “cold ODIN”.

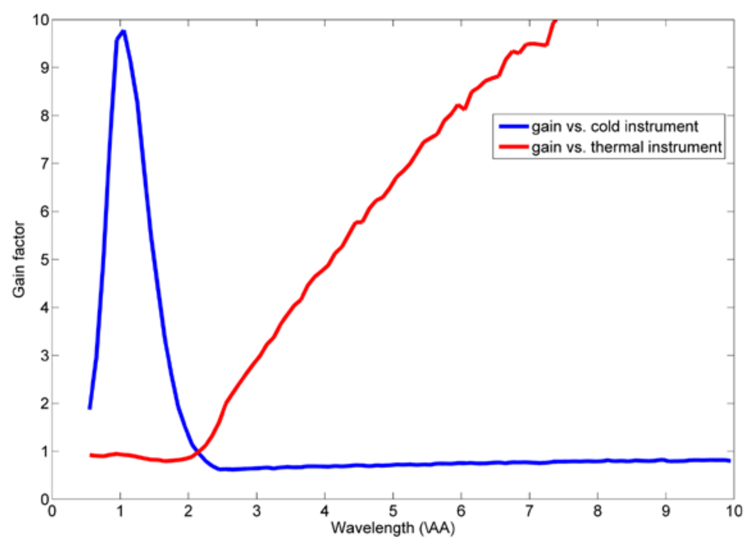

Figure 7: Gain factors by using a bi-spectral extraction on the purely cold and thermal instruments.

As can be seen, we can expect an order of magnitude increase in intensity around 1 A compared to a cold only instrument and a factor of 2-10 for the cold wavelength region (2.5-8 Å) compared to the case of a thermal only instrument.

Feeder system

The feeder system starts at 2.12 m and it is 4.13m long. It extends outside the monolith and reaches the closest position to the WFMC ensemble. The feeder has a focusing shape in horizontal direction and defocusing in vertical direction. The focusing part is needed to achieve proper chopping at the focal spot of the feeder itself, where the WFMCs will be placed. This is the part that has the highest m-coating after the bi-spectral mirrors.

The vertical direction is defocusing in order to relax the m-coating needs and increase the transported flux without affecting the chopping.

In this section of the guide system, the curved guides will be approximated with straight segments of 300 mm each. This will allow the use of thicker substrates and improve the thermal stability of the whole structure. No significant effect on the performances is expected with this choice (Figure 8). The rest of the guide will feature truly curved guides.

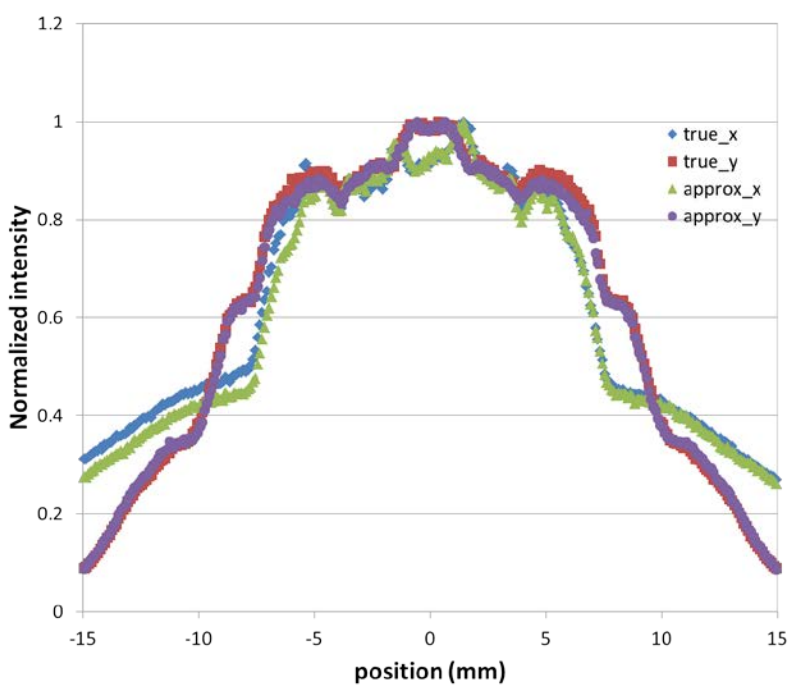

Figure 8: Comparison of the beam profile at sample position with a truly curved substrate as feeder (blue and red, respectively horizontal and vertical) and with a polygonal approximation with 30 cm long segments (green and purple, respectively horizontal and vertical). As can clearly be seen, no substantial differences can be seen.

The substrate of choice in this area, in accordance with the NOSG handbook (ESS-0039408), will be either Al or Cu, depending on the results of background simulations.

Expansion system

The expansion system is composed by G2 and by the vertical part of G3, In this area, the substrate will be the same metal that was used for the extraction system. G2 starts immediately after the WFMC ensemble at 6.75 m and has a length of 6.5 m. G3 starts at 13.25 m and has a length of 4.75 m. It will also have a metallic substrate.

Transport system

The transport system is composed by the horizontal part of G3, G4 and the horizontal part of G5. G4 starts at 18 m and is 14 m long and has a section of 82 x 74 mm^2. This guide, in accordance with the NOSG, will have a metallic substrate where needed, and an appropriate radiation hard Borkron substrate after. G5 starts at 32 m and is 11.25 m long.

Compression system

The compression system is composed by the vertical part of G5 and G6. The latter starts at 43.23m and extends for 5.75 m all the way to the entrance of the cave at the 50 m position. It focuses the beam on a 30 x 30 mm^2 area, where the beam can be manipulated the pinhole exchanger and the filter bank.

Guide vacuum

Except for the front end, inside the monolith, the whole guide system will be operated in vacuum. Operation inside the monolith may be in He atmosphere due to the higher heat load in that area. In particular, the concept of “outside vacuum” will be employed, where the optics will be mounted and aligned inside long vacuum chambers, as opposed to “inside vacuum” where only the inner space within the guide system is evacuated and the guide substrate itself provides the vacuum chamber. This will ensure the least amount of deformation to the shape of the guide thus increasing its durability and performance, albeit at a slight cost penalty.

Coating optimization

The coating of the entire guide system has been optimized for the transport of the minimum required wavelength (1 Ȧ) along the whole length of the instrument. To do so, a specially developed Matlab program has been devised in order to apply a “brute force” approach, as described below, to the coating optimization. The approach has been benchmarked to the instrument where the coating for the entire length is m=5. The algorithm divides the guide system in user defined number of sections (in the case of ODIN, the parts were approximately 1 m long) and, starting from the section closest to the moderator, it changes the coating of that part in user defined steps (in our case, in steps of 0.5) and proceeds to simulate the resulting instrument. It then compares the intensity at the end of the guide to the benchmark and decides if the loss (if any) are acceptable or not, according to a user defined criteria (for ODIN, no more than a total of 5% loss of 1 Å neutrons). When the software finds the minimum m-coating that satisfies the criterion, it fixes it and it moves on with the next pieces, alternating vertical and horizontal profile. After the run, it produces the instrument with the optimized m-coating. At this point user interaction is needed to check if the resulting FoV is acceptable. The result of this procedure is shown in Figure 9, where the color coding reflects the m-coating of each section.

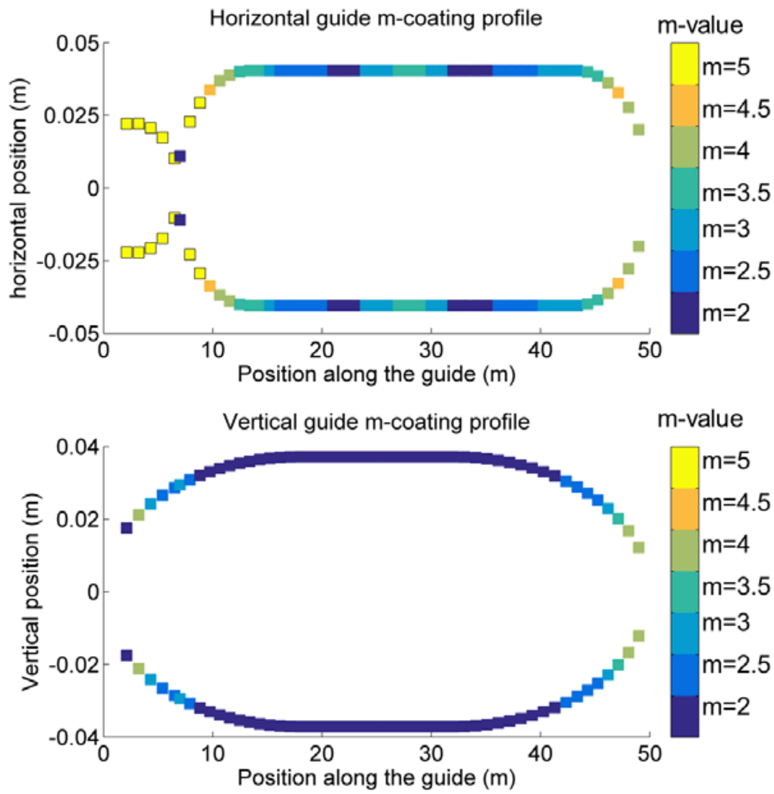

Figure 9: m-coating profile of the ODIN neutron optics.

The bi-spectral mirrors were treated separately, but with a similar approach. The results (Figure 10) confirm the needs to employ high m-coating in this very delicate section.

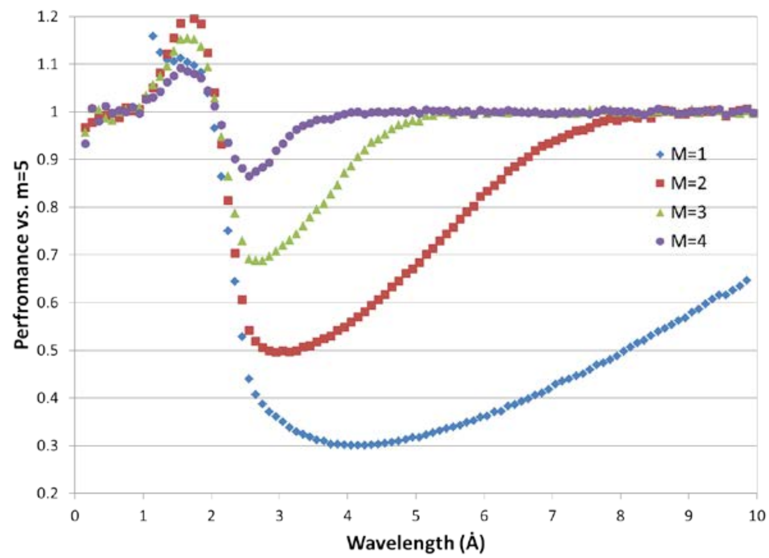

Figure 10: Performances of the ODIN guide system with varying m-coating of the bi-spectral mirrors compared to m=5.

Overall performances

Finally, we discuss the overall performances of the entire guide system.

The first and foremost measure of the performance of the ODIN guide system is arguably the size and homogeneity of the FoV. This impacts directly the imaging capability of the beamline. There is no agreed-upon definition of FoV, but after discussion with imaging experts and the STAP, we settled for a rather conservative approach of defining the limits of the FoV as those being within 75% of the maximum intensity. With the optics system described above, at the main sample position (60 m), the resulting FoV is ~ 140 x 150 mm^2 (Figure 11), extending to ~ 200 x 200 mm^2 at the end of the cave.

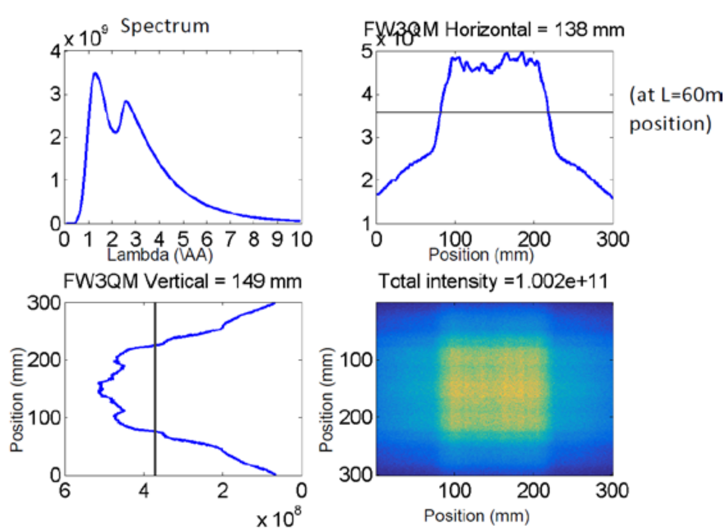

Figure 11: FoV resulting from the neutron transport with the ODIN optics system. This image is simulated using a graphite filter at the 50 m position.

From the previous picture we can see how the intensity variations within the defined FoV are in the order of less than 5% of the maximum, a value considered acceptable. We can also notice that the vertical profile is perfectly symmetrical, while the horizontal one has some slight asymmetry, due to the asymmetric placement of the bi-spectral mirrors. The asymmetry is minute enough, however, not to hinder the performances.

Another important parameter is the spectral homogeneity, i.e. how well the FoV is illuminated by the entire spectrum. It would not be acceptable, for instance, to have one side of the FoV illuminated by a consistently colder spectrum than the other, as that would hinder the possibility of imaging extended objects. In Figure 12, we see two different ways to visualize this.

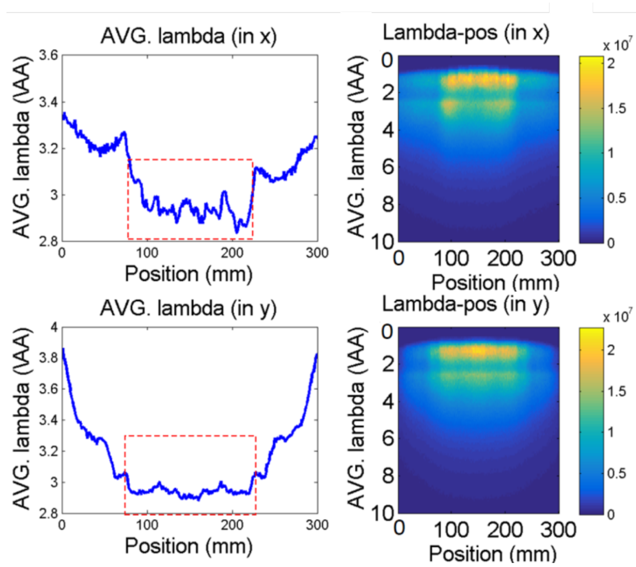

Figure 12: Spectral homogeneity resulting from the transport of the neutrons via the ODIN neutron optics system.

In the previous figure, on the left we can see the averaged wavelength across the horizontal (top) and vertical (bottom) direction. The boxed area is a guide for the eye to identify the previously defined FoV. As before, the vertical direction is completely symmetric, while as expected, the horizontal one less so. However, the magnitude of this asymmetry and of the overall wavelength variation is considered more than acceptable. On the right side of the previous figure, we have the output of the specially implemented lambda-position monitor in McStas. The y-axis is the wavelength, the x axis is the horizontal (top) and vertical (bottom) direction in the FoV, while the color coding represent the intensity. This way of visualizing the simulated performances conveys more information compared to the previous one, but the results are analogous.

To further measure the spectral homogeneity of the FoV, we selected two wavelength bands, one at 2 Å ± 0.3% and one at 4 Å ± 0.3%, to verify if the FoV is homogeneously illuminated (within 75%). The results are shown in Figure 13.

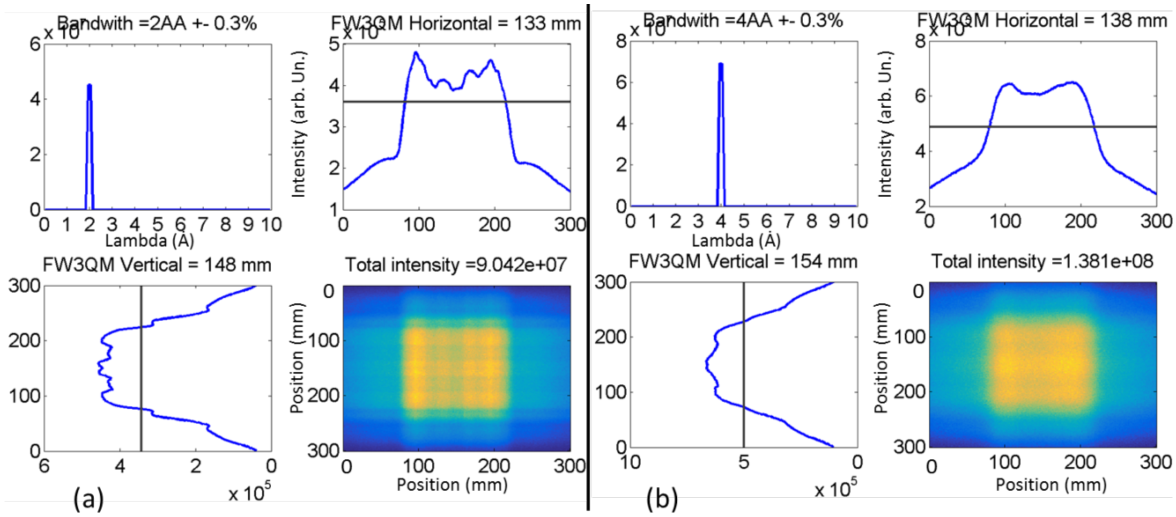

Figure 13: Illumination of the FoV by a wavelength band centered at 2 Å (left) and 4 Å (right).

As can be clearly seen, the illumination is homogeneous across almost all the FoV, meeting (and actually exceeding) the high level scientific requirements for high energy resolution imaging set during the proposal.

A useful figure of merit to compare the performances of the guide system of ODIN to other imaging beamlines (that usually do not feature neutron optics) is to compare the transfer function of the entire neutron guide system from source to cave to a shorter instrument where only the optics up to the first eye-of-the-needle is considered. This is because an optic-less beamline would have only one pinhole a few meters away from the moderator and the sample position a few meters further downstream. Hence, to assess the performance of the guide system after the first eye-of-the-needle as compared to a more traditional neutron imaging beamline layout, we compare the spectrum of the beam 10 m after the first 15 x 60 mm^2 eye-of-the-needle without any additional neutron optics to the full guide system at the main sample position. This comparison can be found in Figure 14.

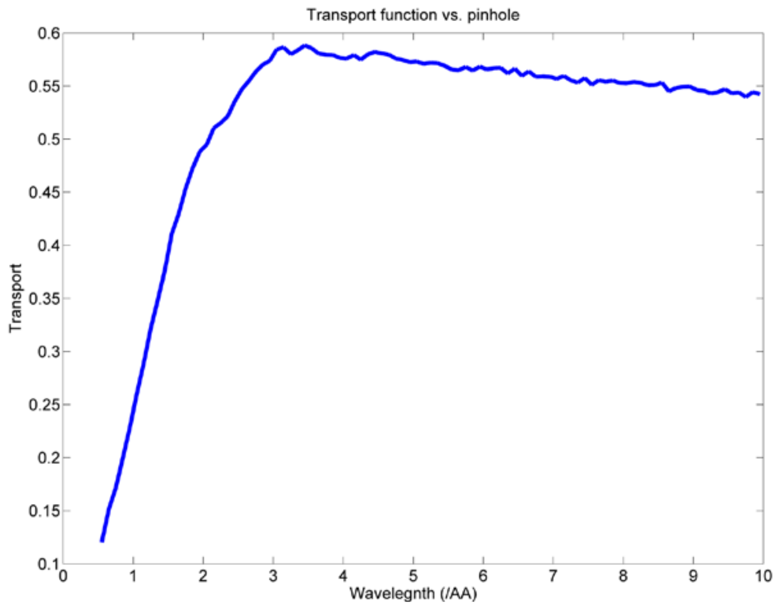

Figure 14: Transport function of the full ODIN neutron optics compared to a pinhole configuration.

As can be expected, the substantial length of the neutron optics hinders the transport of low-wavelength neutrons compared to a ~18 m long instrument, but of course with the added benefit of the longer time structure for ToF applications.

Finally, we show the brilliance transfer function of the entire guide system (Figure 15). By this, it is possible to calculate the expected time-averaged neutron flux at the sample position, which results to be ~3*10^9 neutrons/s/cm2 for an L/D of 200, which would put ODIN at roughly 8 times more flux than the current most intense facility available (ANTARES @ TUM), even though it has to be noted that ANTARES is a purely cold instrument without view on the thermal moderator.

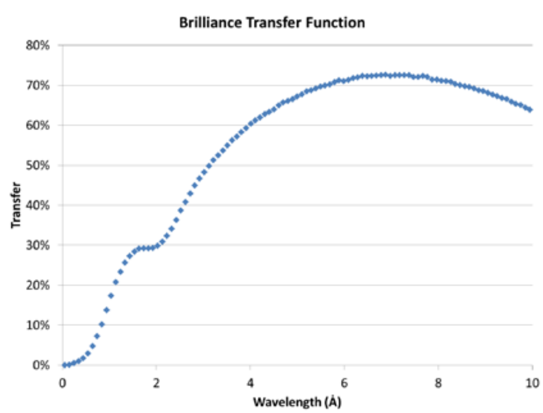

Figure 15: Brilliance transfer function of the ODIN neutron optics system.

Appendix A: Parameters of the guides

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******  HORIZONTAL GUIDES PARAMETERS ***************

Guide 1 (bi-spectral extraction system)
a = 4.155059 , b =  0.022274 , f = 4.155
Start @: 2.120000 , length = 4.13
Opening = 0.044230

Guide 2 (elliptical)
a = 6.750123 , b =  0.040787 , f = 6.750000
Start @: 6.750000 , length = 6.5
Opening = 0.022000

Guide 3 (straight)
Start @: 13.25 , length = 4.750000
Opening = 0.081573

Guide 4 (straight)
Start @: 18.00000 , length = 14.000000
Opening = 0.081573

Guide 5 (straight)
Start @: 32.000000 , length = 11.25
Opening = 0.081573

Guide 6 (elliptical)
a = 6.750123 , b =  0.040787 , f = 6.750000
Start @: 43.250000 , length = 5.75
Opening = 0.081573

*******  VERTICAL GUIDES PARAMETERS ***************

Guide 1 (bi-spectral extraction system)
a = 18.000038 , b =  0.037168 , f = 18
Start @: 2.120000 , length = 4.13
Opening = 0.035000

Guide 2 (elliptical)
a = 18.000038 , b =  0.037168 , f = 18.000000
Start @: 6.750000 , length = 6.5
Opening = 0.058028

Guide 3 (elliptical)
a = 18.000038 , b =  0.037168 , f = 18.000000
Start @: 13.25 , length = 4.750000
Opening = 0.071701

Guide 4 (straight)
Start @: 18.000000, length = 14.000000
Opening = 0.074336

Guide 5 (elliptical)
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a = 18.000038 , b =  0.037168 , f = 18.000000
Start @: 32.000000 , length = 11.245
Opening = 0.074336

Guide 6 (elliptical)
a = 18.000038 , b =  0.037168 , f = 18.000000
Start @: 43.250000 , length = 5.75
Opening = 0.058028
```