DESY Summer Student Report – Study of Magnetic Domain Patterns of Co/Pt Using SAXS

Miriam Martínez Flórez, University of Oviedo, Spain

September 4, 2019

Abstract

This report describes the data analysis of a small-angle X-ray scattering experiment on a $(Co_{10\mathring{A}}\,Pt_{12\mathring{A}})6$ in order to study the magnetic domain-size distribution using Matlab as programming language. The relation between the fit parameters and the effect of an out-of-plane and in-plane magnetic field on the scattering pattern is studied.

This analysis is a precharacterization of the samples for XFEL experiments, where the study of the dynamics of the magnetic domains could have a great influence in the development of large scale data storage devices in order to make them more efficient.

Contents

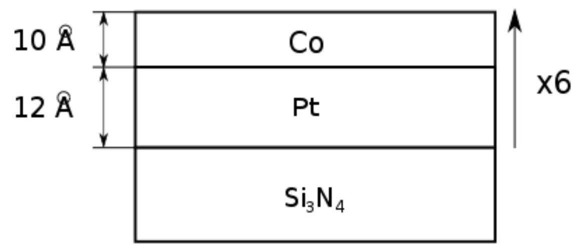
1 Introduction

The aim of this project is to characterise the size of the magnetic domains in a cobalt-platinum multilayer on length scales of 100 nm using small-angle X-ray scattering, and check homogeneity and stability of the sample.
The report analyse the data of an X-Ray experiment conducted in BESSY, Berlin, January 2019 at the VEKMAG station.

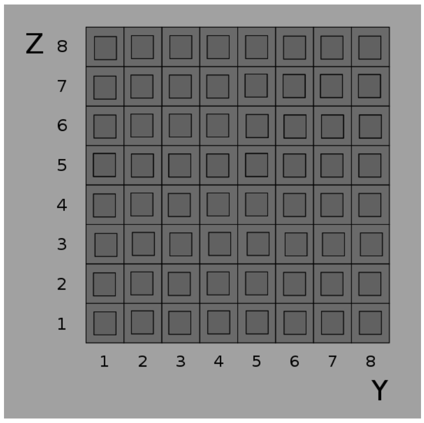
2 Description of the experiment

2.1 Cobalt-Platinum Sample

The cobalt-platinum multilayer sample ($Co_{10\mathring{A}}Pt_{12\mathring{A}}$)6, where the last number indicates how many times the layers are repeated and the numbers that accompany the compounds represents the thickness of each layer. The multilayer is grown on a non-magnetic substrate (Si_3N_4), as cobalt has an out-of-plane anisotropy, it can only be deposited on a platinum (1,1,1) surface. The description of the composition of the layer is shown in the Figure 1a.



(a) Multi-layer structure.



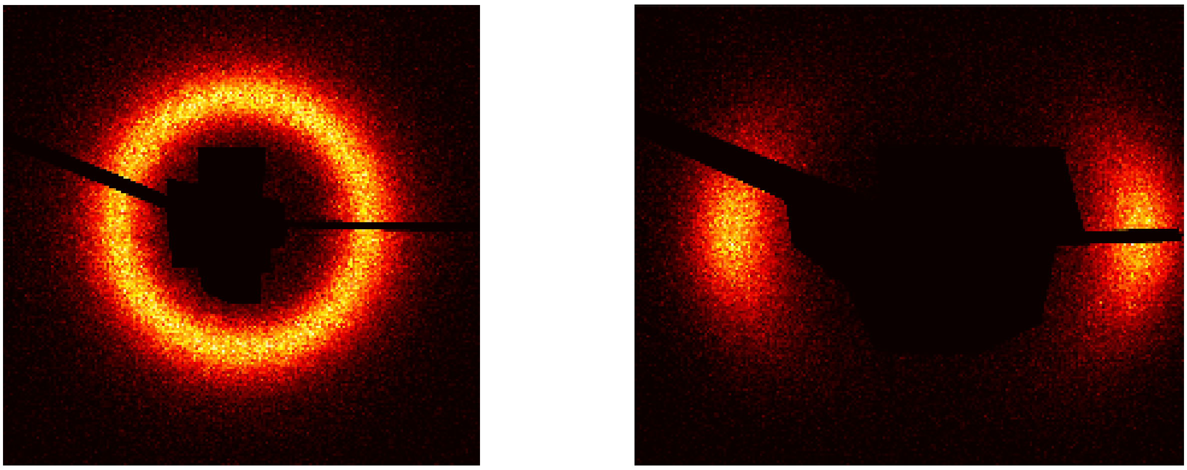
(b) Sample structure.

Figure 1: Cobalt-Platinum sample.

Nevertheless, the sample is not composed uniformly, but it is formed by membranes as it is shown in Figure 2b. The main point of the experiment is to study a number of membranes and its scattering pattern in reciprocal space.

2.2 Magnetic domains

In the course of this experiments two kinds of scattering patterns were studied. The first one is found after the sample has been demagnetized in out-of-plane direction and it corresponds to random magnetic domains, whose scattering pattern is a scattering ring



(a) Scattering ring of magnetic domains.

(b) Scattering pattern of aligned magnetic domains.

Figure 2: Cobalt-Platinum scattering patterns.

(Figure 2a). When an out-of-plane magnetic field is applied, the ring degrades into a disc for sample-specific field strength.

The magnetic domains are aligned in stripes, when a magnetic field is applied in the direction of the plane of the sample, and the scattering pattern has the shape of two high intensity poles symmetric to the origin ($q = 0$ position) (Figure 2b).

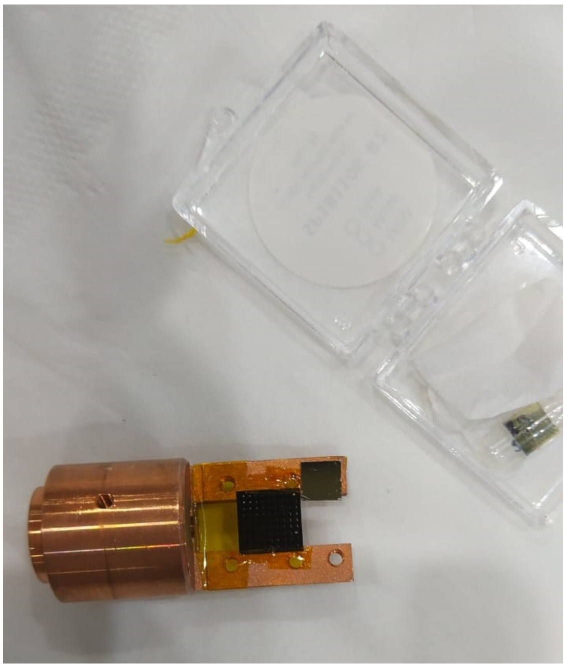
2.3 Experiment's structure

The following pages show the results of measurements obtained in BESSY (Berlin) on the beam time January 2019.

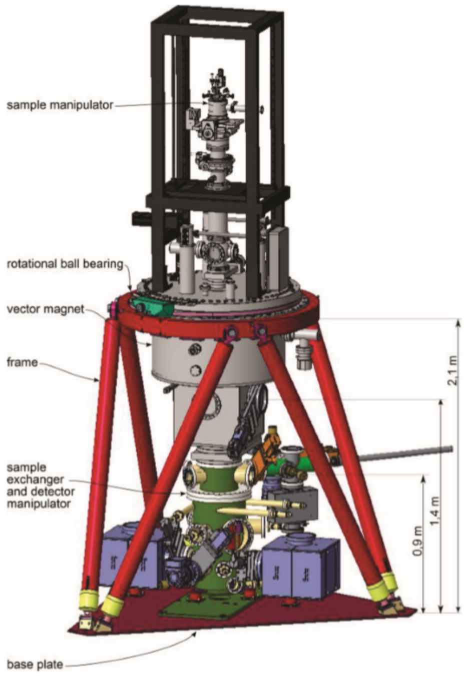
The measurements obtained at BESSY were taken at the VEKMAG station (Figure 3b) using a soft X-ray beam. The end station has a Tesla vectorial magnet chamber which can introduce a magnetic field in a chosen direction (9 T in the beam direction, in the direction perpendicular to the beam or in the vertical direction), as well as a cryostat, a deposition chamber and a UHV detector chamber [1].

Measurements were taken from a number of membranes and the scattering pattern obtained was studied. The detector is a photo-sensitive device, whose sensitivity can be damage if he X-ray is not stopped with a mask suspended in front of the detector. They can be seeing as black bars that cut the images (Figure 2). It is going to be crucial to mask using the program any residual-visible light caused by vacuum. Further, X-ray radiation passing through neighbouring membranes has also to be masked.

Apart from that, the sample has also a polycrystal structure. As the typical domain size is in the range of 100 nm and the crystallites about 10 nm, their respective scattering patterns do not overlap.



(a) CoPt sample.



(b) VEKMAG station.

Figure 3: Cobalt Platinum sample and BESSY experiment.

3 Data Analysis

There were three types of measurements:

- Scattering patterns of different membranes of the sample.
- The effect of an out-of-plane magnetic field.
- The application of a in-plane magnetic field and its effect on the alignment of the domains.

The structure factor is represented in terms of the scattering vector q in reciprocal space and counts of intensity obtained from the averaging of pixels of equivalent q in the scattering pattern (Figure 4).

The fit of the structure factor is done using a split Pearson type VII function, used also in crystallography. The continuous function has two parts joint in the maximum. The fit matrix contains the values of the peak position and the amplitude of the curve, as well as the parameters a_i and m_i with $i \in \{1, 2\}$ that characterize the shape of the fit. The width at half maximum is calculated by

$$w = \frac{\sqrt{m_1} a_1 + \sqrt{m_2} a_2}{2}, \tag{1}$$

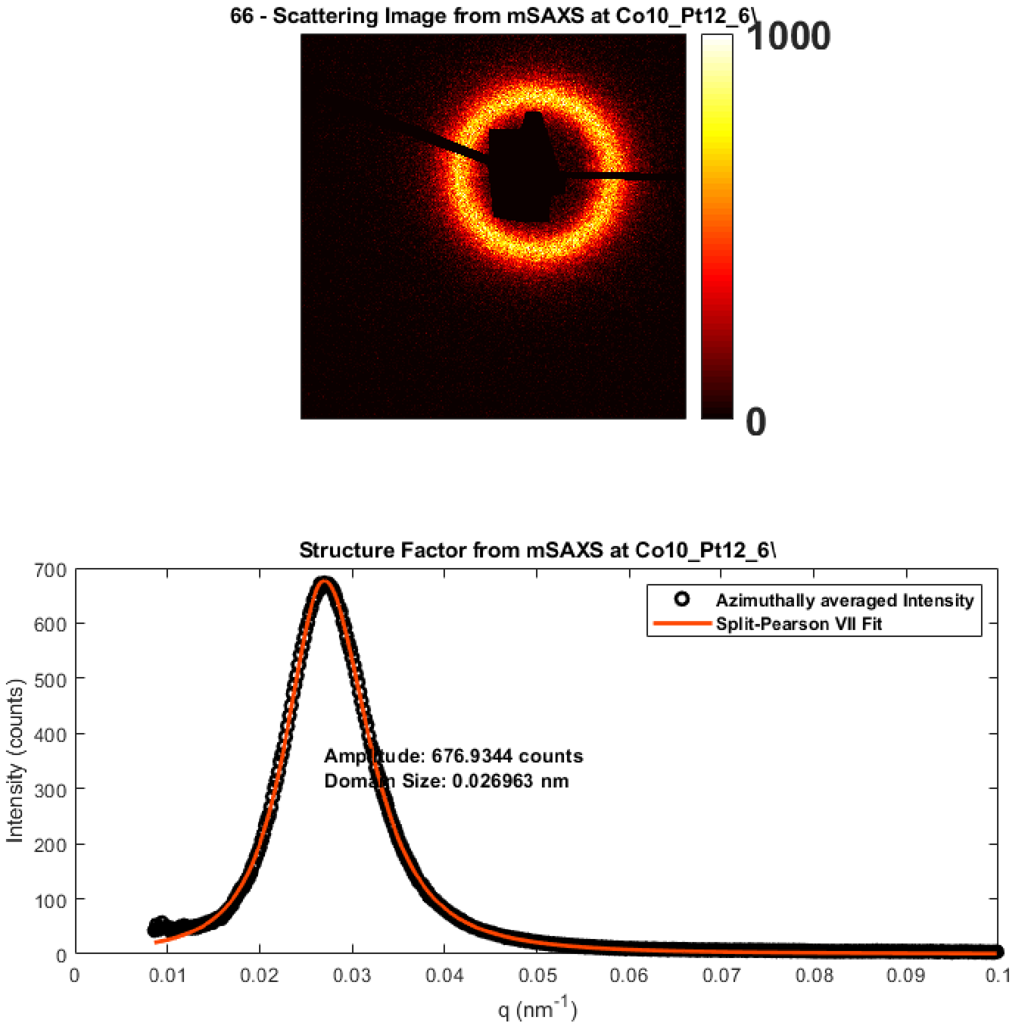


Figure 4: Scattering ring pattern and its structure factor fitted with split Pearson type VII function.

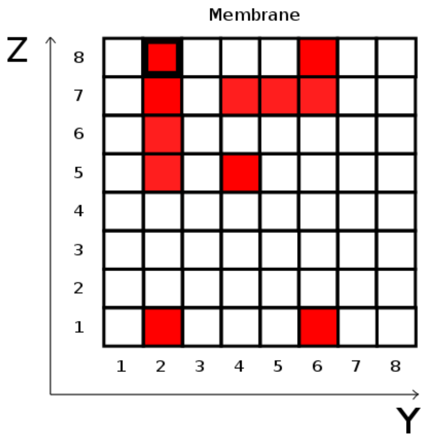


Figure 5: Membranes used in the experiment.

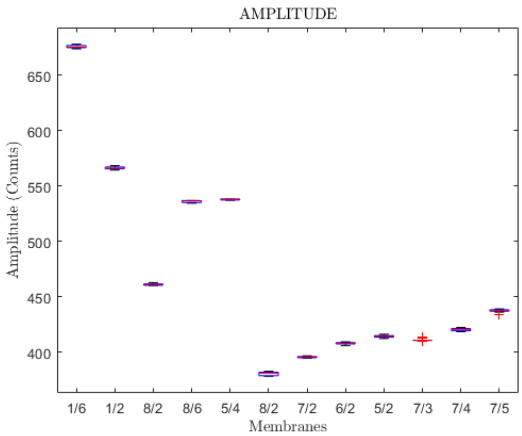
where $w_i = \sqrt{m_i} a_i$ is the width of the non-split Pearson type VII function [2]. The fit matrix contains also the measurement's error. Applying error theory and error propagation the error of the width is obtained.

3.1 Analysis of the scattering patters of some of the membranes of the sample

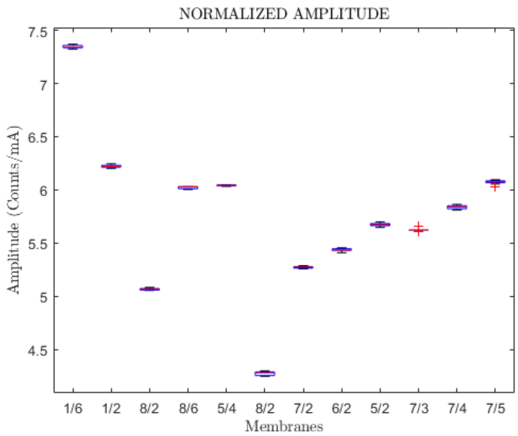
The study of sample's membranes shows the variation and relation between fit parameters. For all measurements an exposure time of 5 s was used and the external magnetic field was switched off. Figure 5 shows the position of the membranes in the sample with the notation Z/Y. The residual-visible light is masked in the program in order to obtain a correct integration value of the scattering ring.

The main results obtained are presented in the following table.

Membranes	Amplitude (counts)	Peak Position (nm^{-1})	Width (nm^{-1})	Current (mA)
1/6	675.65	0.026961	0.010426	92
1/2	566.18	0.029243	0.011307	91
8/2	461.05	0.033806	0.012546	91
8/6	535.98	0.031264	0.011732	89
5/4	537.72	0.030672	0.011649	89
8/2	380.43	0.033897	0.012635	89
7/2	395.49	0.033184	0.012373	75
6/2	407.78	0.032662	0.012155	75
5/2	414.17	0.031794	0.011917	73
7/3	410.88	0.032441	0.012058	73
7/4	420.34	0.031902	0.011832	72
7/5	437.27	0.031115	0.011570	72



(a) Amplitude.



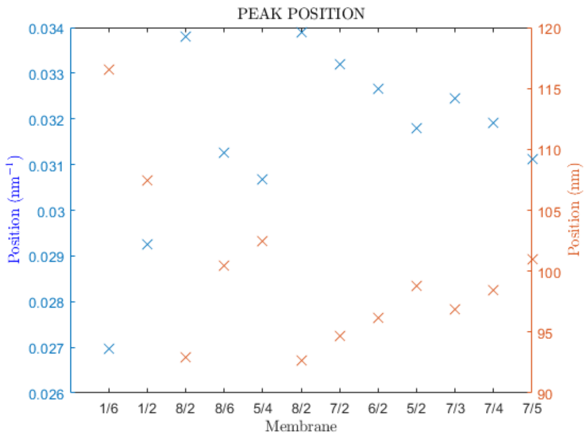
(b) Normalized amplitude.

Figure 6: Box plots for the amplitude of the split Pearson fit VII function for a number of membranes.

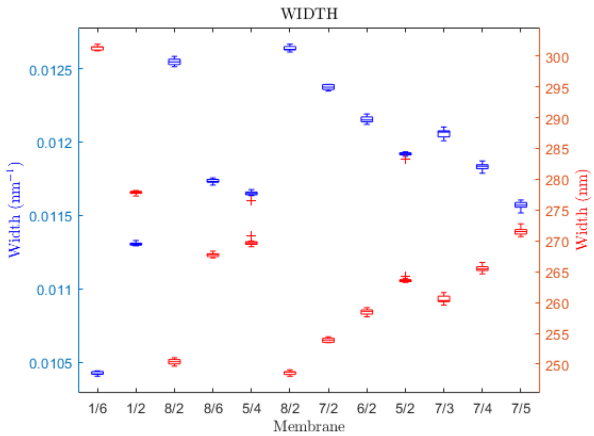
Amplitude, peak position, and width are calculated as the mean values of 10 images corresponding to each membrane. The normalized amplitudes used in this section are obtained by normalizing the amplitude by the current.
The variation between the membrane's amplitudes is shown in figure 6 as box plots. This plot visualizes the mean value and the distribution in quartiles, i.e, it shows how the values distributed.

The position of the membrane in the sample plays an important role in the behaviour of the material. The membrane 1/6 show a high amplitude for a membrane that is quite far from the center. There are similar values fro the amplitude for the membranes situated closed to each other for last 6 measurements, in contrast to the other membranes situated on the opposite side of the sample. The irregularities could come from the fact that the sample is not as uniform as expected. As the current decreases with time, the amplitude values are normalized.

A plot with the mean values of the peak position in the real and reciprocal space is shown, as there is not a remarkable variation of the values to use a box plot (Figure 7.a). The width box plot (Figure 7b) seems to follow the same distribution as the peak position.
Looking for a relation between fit parameters, the Figures 8a and 8b are obtained. The figure 8a indicates the relation between normalized amplitude and peak position,that seems to follow a linear tendency. However, the error bars, that come from the fit do not reach the tendency line. For the normalized intensity there is not an accurate error known. The intensity normalization is nor accurate, as only beam current is known, but none of the influences on the intensity. The figure 8b symbolized the relation between width and peak position. This two parameters follow a directly proportional relation, when we the width of the function increases, the peak position is further from the origin.



(a) Peak Position plot.



(b) Width Box Plot.

Figure 7: Peak position plot and width box plot for a number of membranes.

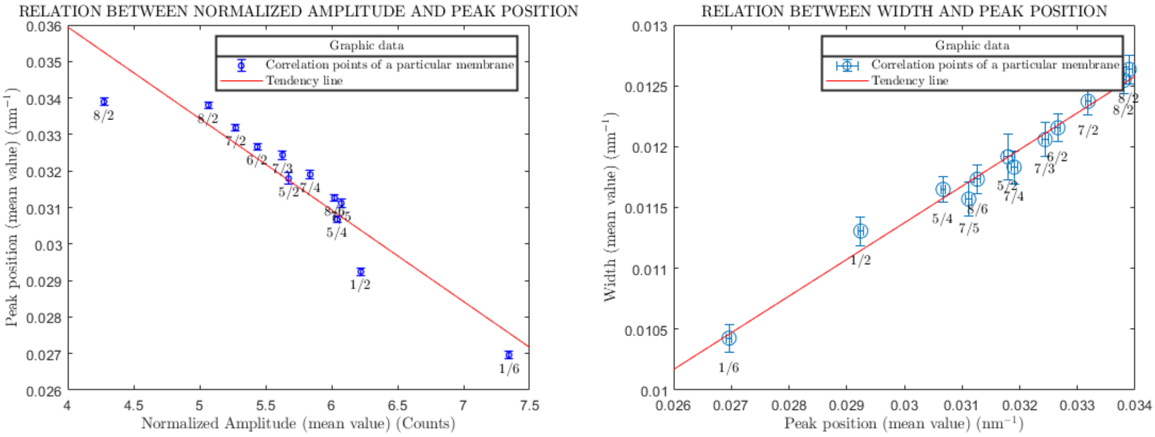
In this case both of the parameters are well defined, as they do not depend on the intensity and come directly from the fit function.

3.2 Analysis of the action of an out-of-plane magnetic field in the intensity of a fixed membrane

The application of an out-of-plane magnetic field in the X direction in the domain system was studied in a range of [0 mT, 370 mT]. The measurement was done at membrane 7/5. The aim of this measurement is to understand the effect on domain orientation.

The increase of the magnetic field leads to a decrease in scattering intensity of the sample. Above 100 mT a change in the form of the scattering pattern occurs. It evolves from a scattering ring to a scattering pattern with a disk-like shape (Figure 9).
Until the magnetic field values reach 110 mT, the split Pearson type VII function is able to find a maximum. As the magnetic field increases, the intensity of the scattering pattern decreases. Above 140 mT, almost all the light intensity disappears.
With 10 measurements per magnetic field, the box plot for the amplitude, peak position and width are represented. For magnetic fields stronger than 110 mT the fit does not find a maximum.

The Figure 10a shows how the intensity is decreased as the magnetic field increases, and so does the normalized amplitude in Figure 10b. When the magnetic field is smaller than 40 mT, the system compensate this external magnetic field, and the amplitude is only slightly decreased. Nevertheless, when the magnetic field reaches bigger values, the system is not able to compensate and the amplitude reduces. The two last values correspond to a magnetic field of 0 mT.



(a) Correlation between normalized amplitude and peak position.

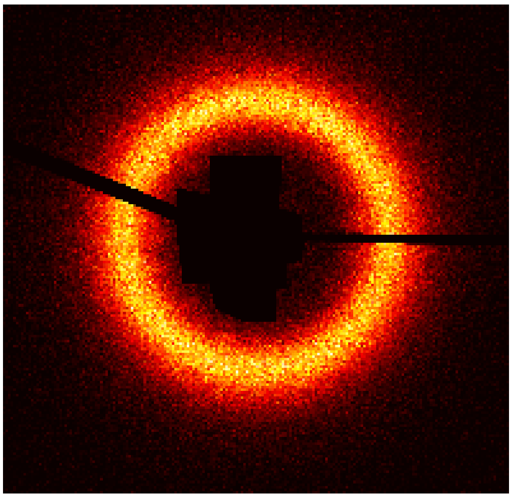
(b) Correlation between the width and the peak position.

Figure 8: Correlation function between fit parameters.

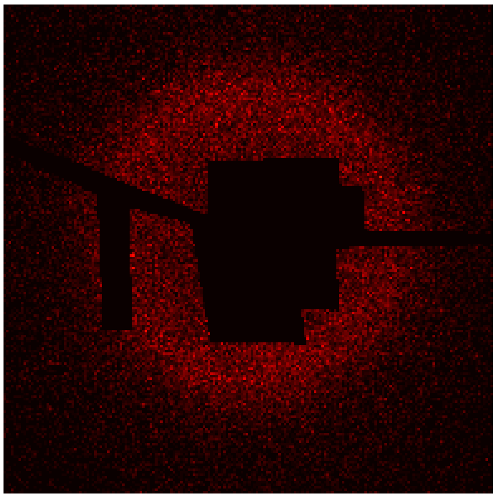
In Figure 10c it is show the percentage in the change of the value of the peak position with respect to the one in $B = 0$. The values corresponding to weak magnetic fields only suffer slight changes, whereas for values above 80 mT the changes are remarkable. It is clear that the increase of magnetic field suppose a smaller peak position value of the function in the q space (Figure 10d). For this two parameters it is represented all the data taken. However, for the width only take the data that could be fitted is shown.

As it is shown in the figure 11a, the width increases with the magnetic field, with the limit occurring when the scattering ring degrades into a scattering pattern with the shape of a disc.

The values of the analysis are shown in the following table.

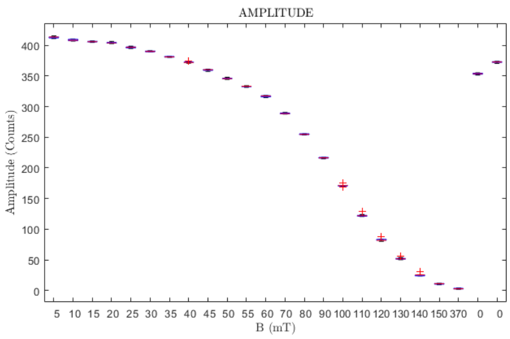


(a) Scattering ring of a random distribution of magnetic domains with a 0 mT magnetic field.

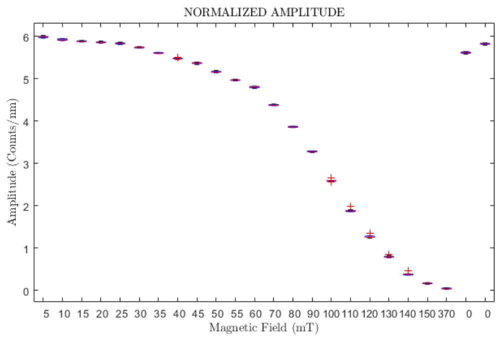


(b) Scattering pattern of random distributon of magnetic domains with a magnetic field of 110 mT in the X direction.

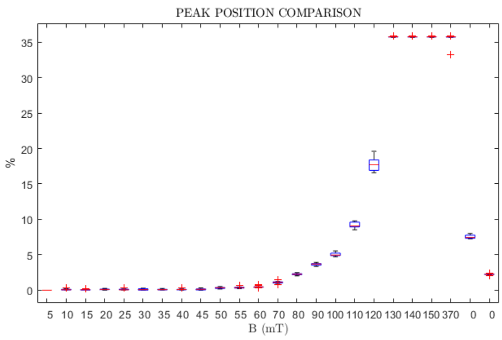
Figure 9: Cobalt Platinum Scattering patterns with out-of-plane magnetic field.



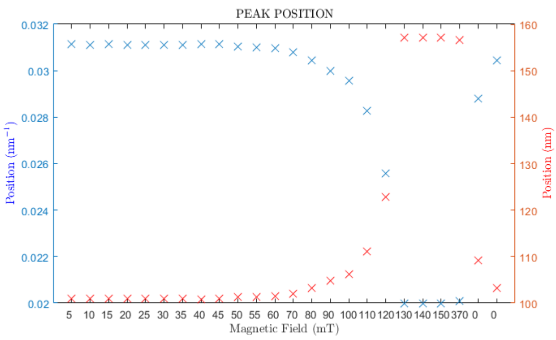
(a) Amplitude box plots.



(b) Box plot of normalized amplitude by the current.

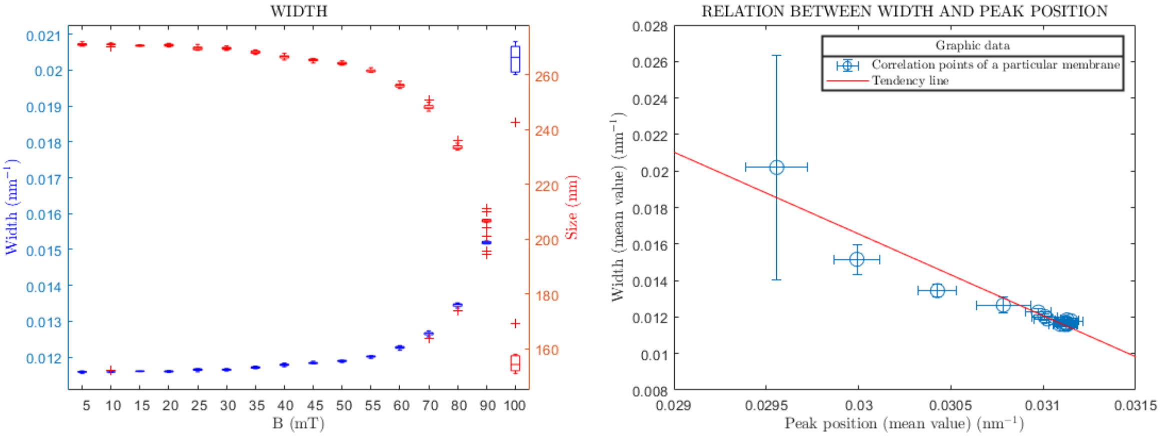


(c) Peak position values with respect to peak position in 0 mT.



(d) Mean values of peak position in q and real space.

Figure 10: Fit parameters for different values of magnetic field.



(a) Width box plots for the values when the fit of the function behaves correctly.

(b) Relation between the mean values of the width and peak position.

Figure 11: Analysis of the width and its relation with the peak position

B (mT)	Amplitude (counts)	Peak Position (nm^{-1})	Width (nm^{-1})	Current (mA)
5	412.96	0.031127	0.011590	69
10	408.46	0.031113	0.011594	69
15	405.79	0.031132	0.011612	69
20	403.97	0.031091	0.011606	69
25	396.53	0.031125	0.011650	68
30	389.96	0.031118	0.011652	68
35	381.03	0.031122	0.011712	68
40	372.15	0.031150	0.011789	68
45	359.66	0.031128	0.011841	67
50	345.73	0.031021	0.011897	67
55	332.73	0.031009	0.012019	67
60	316.84	0.030973	0.012268	66
70	288.94	0.030784	0.012654	66
80	254.83	0.030428	0.013443	66
90	216.41	0.029991	0.015162	66
100	171.21	0.029557	0.020196	66
110	122.69	0.028266	0.072745	65
120	82.77	0.025597	Inf	65
130	52.11	0.020000	Inf	65
140	25.40	0.020000	Inf	65
150	11.07	0.020000	Inf	64
370	3.15	0.020073	Inf	64
0	353.53	0.028782	0.014180	63
0	372.55	0.030426	0.012094	64

The relation between the width and the peak position are shown in the figure 11b. The data used was the one where the width had sense, so in the range of [5 mT, 110 mT] and it follows a linear fit with a negative slope. The majority of the values are situated around a point, which means that the values are proportional to a fixed constant for weak magnetic fields. However, as the magnetic field taken higher values, the constant proportionality changes and move ascendant in the fit curve.

3.3 Application of an in-plane magnetic field and its effect in the alienation of the domains

In this section the analysis of the effect of an in-plane magnetic filed over the sample is studied. This is going to affect in the alignment of the domains in the sample and consequently with the scattering pattern obtained. In the previous cases, where the domains were randomly distributed, the scattering pattern was a scattering ring. However for this case were there exist a progressive alignment of the domains the scattering pattern obtained is formed by two opposite high intensity poles, as it was shown in picture 2.b. As an in-plane magnetic field is applied, the magnetic domains got aligned. The scattering pattern changes accordingly, so there is not going to present a scattering ring anymore. The new scattering pattern is composed by two poles of high intensity.
As seen previously, the progressive increase of the magnetic field in the X direction produces a progressive decrease in the intensity of the scattering pattern. This phenomena also occurs for the increase of in-plane magnetic field, as well as the change in the behaviour of the scattering pattern. The values of the fit parameters obtained in the measurement can be shown in the following table.

B (mT)	Amplitude (counts)	Peak Position (nm^{-1})	Width (nm^{-1})	Current (mA)
20	299.58	0.032484	0.008233	59
40	216.76	0.034190	0.008681	59
60	164.61	0.037581	0.008713	59
80	136.46	0.040051	0.008776	59
100	109.54	0.042590	0.009446	59
120	84.38	0.045800	0.010431	59
140	62.84	0.049019	0.010585	59
160	45.63	0.050552	0.011989	59
180	29.65	0.052305	0.013729	59
200	21.42	0.052743	0.013599	59
220	15.27	0.050000	0.014897	59
240	9.96	0.056170	0.024278	59
260	6.81	0.056434	0.023361	59
280	4.73	0.050000	0.021693	59
300	3.95	0.050000	0.023329	59
0	155.63	0.045152	0.008865	59

It is remarkable that in this case the current in the sample is remaining constant. It is possible to normalize the amplitude in terms of the current. The q vector (the distance of the reciprocal space) is also normalized by the peak position of every measurement. This is shown in the figure 11 for every value of magnetic field.
It is clear that all the fits, for every value of magnetic field, follows the same behaviour. However, even though the normalized peak position has always the same value, the shape

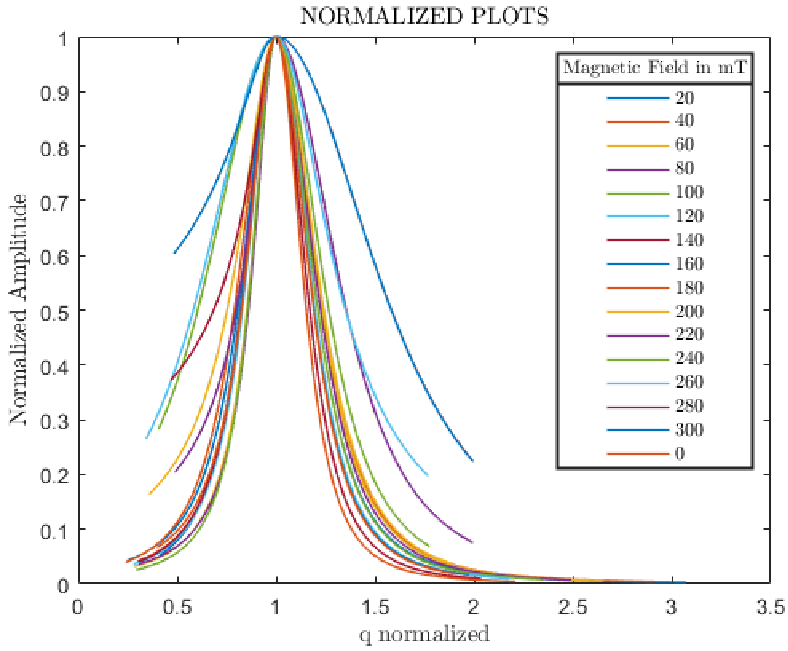


Figure 12: Relation between amplitude and peak position

of each curve changes, what means that the a_1, a_2, m_1 and m_2 values from the fit are changing with the magnetic field. It can be seen that for low values of magnetic field, the curve has already the same shapes, but as for the stronger values of the magnetic field the shape of the curve gets wider.

4 Conclusion

The use of the small angle X-ray scattering allows the study of magnetic domains in samples of ferromagnetic materials such as CoPt. This alignment can be produced with the application of an in plane magnetic field over the sample, that produces a different scattering pattern as the one where the magnetic domains were aligned. This scattering patterns allow to form the hologram of the distribution of the magnetic domains in the sample. In the figure 12 it is shown how this distribution is in the real space.

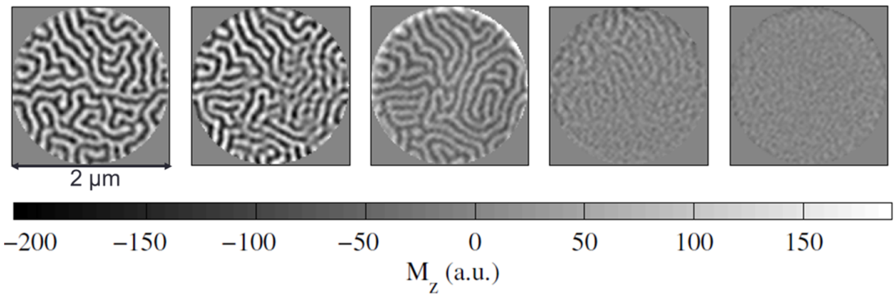


Figure 13: Progressive alignment of the magnetic domains of the sample.

It is also remarkable that the usage of this magnetic domain and the study of its behaviour, as a magnetic field is applied, could help n the development of high scale storage devices.

References

[1] The Mechanis of the Vekmag experiments *T.Noll, F.Radu*

[2] Peak Decomposition using Pearson Type VII Function *s.k. Gupta*

[3] High-resolution magnetic-domain imaging by Fourier transform hoography at 21 nm wavelenght.