# A W/$B_4$C Transmission Multilayer as an Achromatic Phase Shifter in the XUV: Some Experimental Aspects

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**Abstract.** Completing previous investigations we study a W/$B_4$C transmission multilayer with 350 periods each 1.74 nm as a phase shifter for polarization analysis between 720 eV and 1020 eV. The FWHM of the Bragg curve is as small as 0.18° = 3 mrad and thus smaller than the inherent accuracy of most polarimeters. We discuss some of the experimental implications and limitations. We obtain a phase shift of up to $\Delta$=24° through out the spectral range.

**Keywords:** Multilayer, phase shifter, soft x-ray
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Multilayers, i.e. systems with a large number of layers of alternating materials are in themselves fascinating objects. Additionally they are used in different branches of physics and technology. We use multilayers to characterize the state of polarization of XUV radiation, in particular the circular polarization. This is motivated by the interest in magnetic properties of the transition elements Fe, Co and Ni with L-edges at 707 eV, 778 eV, and 859 eV. To this end two optical components are needed rotating around the light axis: The first one, called polarizer, introduces a phase shift of ideally 90° between two orthogonal directions while the second one, called analyzer, filters out one direction of linear polarization. The detector measures the intensity as function of azimuthal angles of the two optical components. We use free standing transmission multilayers and reflection multilayers on a substrate, respectively. Energy tuning is achieved by varying the angle of incidence [1]. For such multilayers to work the indices of refraction of the two materials must differ as much as reasonable which favors operation near an absorption edge of one of the constituents [2]. While phase shift and analyzing power are large operation is limited to few photon energies only (e.g. 397 eV and 573 eV for a Cr/Sc multilayer). Material combinations like e.g. W/$B_4$C [3] exhibit no resonance structure in the soft x-ray range and can thus continuously be used in a broad energy range. However, the difference of the indices of refraction of the two materials is small and a large number of bi-layers is needed for acceptable optical performance leading to sharp Bragg features (angular width below 1°).

In this note we report on measurements using such an achromatic transmission multilayer made of 350 bi-layers W/$B_4$C [4] of thickness d=1.74 nm to be used as phase shifter in polarization measurements up to 1020 eV (corresponding to the L-edge of Zn, the last first row transition element, see fig. 1 and fig 2). The multilayer period has been chosen to have as grazing a Bragg angle as reasonable to decrease the roughness to layer thickness ratio. Here we concentrate on experimental aspects leaving the interpretation of the data to a forthcoming publication [5].

The experiments are performed at the 1.7 GeV electron storage ring BESSY II having an emittance of $6 \cdot 10^{-9}$ m rad, and a vertical to horizontal coupling of 2%. The horizontal and vertical betatron functions at the source point are 13 m/rad and 3 m/rad, respectively. The source is the APPLE II undulator UE56/2 [6] having 30 periods each 56 mm long allowing for emission of linearly and circularly polarized radiation. The PGM-1 beam line [7] is designed to preserve the state of polarization. It uses a 1200 l/mm plane grating in collimated light [8] at a focusing constant of $c_{ff}$ =2.25. An exit slit setting of 100 µm yields an energy resolution of 300 meV at 900 eV which is small compared to the width of the Bragg resonance. The measured fractional contamination by second order radiation is less than $1 \cdot 10^{-3}$.

We employ the BESSY polarimeter (see fig 3) [1]. It mainly consists of two goniometers labeled α and β mounted back to back rotating the transmission polarizer in the α-stage and the reflection analyzer in the β-stage

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around the optical axis. The angles of incidence $\theta_P$ and $\theta_A$ of the two multilayers are independently controlled with a resolution better than 10 µrad.

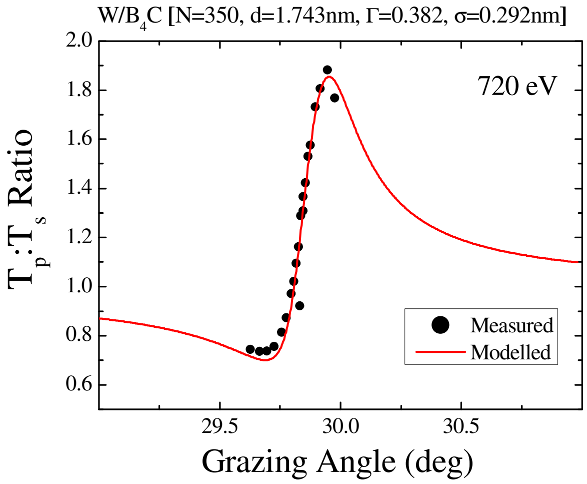

**Figure 1**: Ratio of transmission for p-geometry to s-geometry of an achromatic phase shifter versus incident angle.

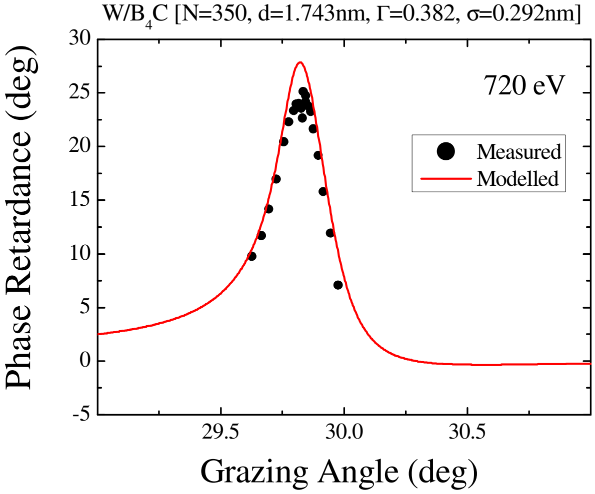

**Figure 2**: Phase shift of an achromatic phase shifter versus incidence angle.

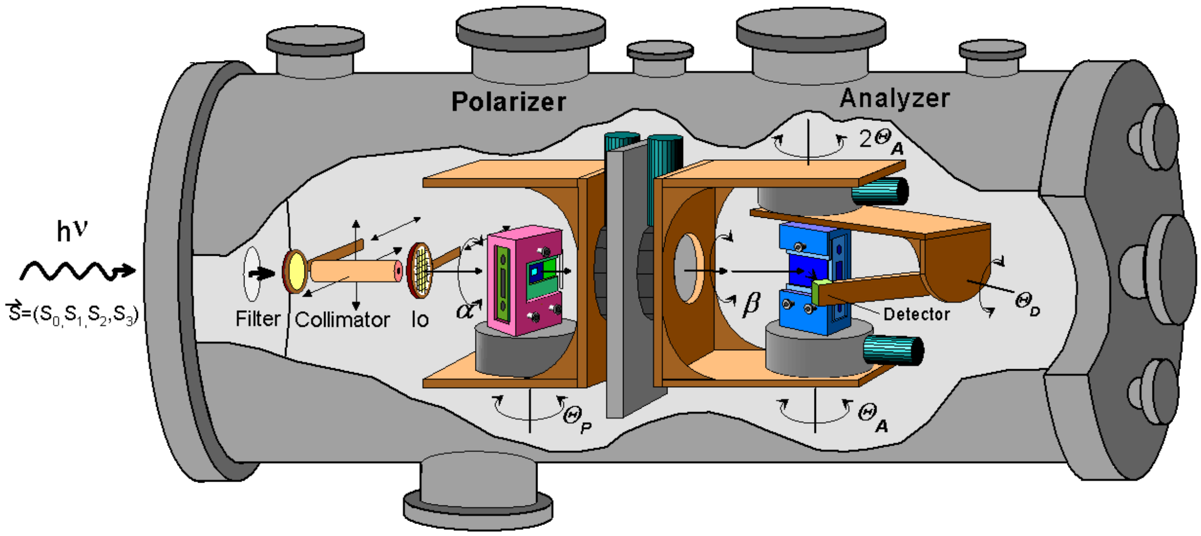

**FIGURE 3.** The BESSY 6 axis Polarimeter, schematic. The sketch shows $\alpha = 90^\circ$ and $\beta = 90^\circ$.

The intensity recorded by the photodiode during a polarimetry scan (see [1,3,9,10] and references therein) contains terms proportional to $\cos 2\alpha$, $\cos 2\beta$, $\cos 4\alpha$ etc and product of them, but no term that varies as $\cos \alpha$ or $\sin \alpha$. When the rotation axis and the light axis do not coincide the rotation around e.g. $\alpha$ introduces a modulation of the angle of incidence $\theta_P$ with a period of $2\pi$. A linear dependence of $T_p/T_s$ on $\theta_P$ then introduces the same functional variation of the intensity. The fit function containing only functions orthogonal to this perturbation is almost insensitive. However, the non-linear dependence of $T_p/T_s$ and phase retardance on $\theta_P$ (see fig. 1 and 2) introduces terms which can not be separated out and which thus interfere with the fit procedure. Thus, the alignment of the polarimeter must be much better than the width of the Bragg resonance of the 350 period multilayer.

The Bragg resonance width is of the order of 3 mrad (see fig. 1 and fig 2) requiring an angular accuracy of 300 µrad and better. The beam divergence due to diffraction limitation and including emittance is of the order of FWHM 100 µrad. For intensity reasons the acceptance of the beam line (hard edge) is set to 160 µrad / 140 µrad (horizontal /

vertical) which translates into 240 μrad / 270 μrad at the end of the beam line due to the de-magnifying optics. The focus has a measured size FWHM of 60 μm / 65 μm. Thus the entrance aperture of the polarimeter (see fig. 3) of 0.5 mm diameter located 300 mm upstream of the focus is underfilled by the beam. Nevertheless, we observe an alignment sensitivity of about 200 μrad by maximizing the transmitted intensity.

The necessary alignment is tighter than the inherent accuracy of the polarimeter. The polarimeter is characterized prior to the experiment using a theodolite with auto-collimation having a repeatability of 10 μrad. As reference we define the (geometrical) axis of the polarimeter as the line connecting the two intersection points of the rotation axis with the planes of the optical components. These planes are separated by 480 mm. This defines the axis within 50 μrad. The entrance aperture, a precision circular pinhole of 0.5 mm diameter located 200 mm upstream of the α-stage, is adjusted onto this axis with a comparable accuracy. A gravity induced bending of the β stage is evident when tracing the motion of the detector entrance aperture (not shown). Since the polarimeter is aligned to the midway position of the detector for β = 90° and β = 270° this makes the light axis pointing at an angle of +25 μrad horizontal and -200 μrad vertical (in short (+25/-200) μrad) with respect to the geometrical axis.

Tracing the auto-collimation direction of a mirror occupying the sample position as function of α and β the data in fig. 4 are obtained. The rotation axis is obtained as the center of these circles. The α-axis is at an angle of (-70 / 285) μrad with respect to the geometrical axis which is a significant deviation. The orientation of the β axis is at (170 / -450) μrad which is unimportant due to the much larger width of the analyzer Bragg resonance (not shown).

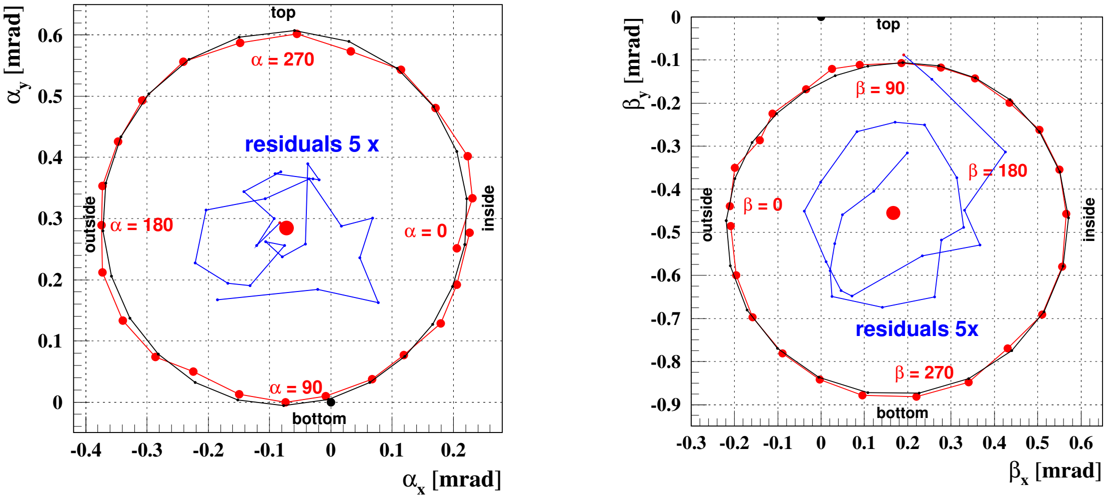

**FIGURE 4.** Auto-collimation of α-stage (left panel) and β-stage (right panel) (big dots). Residuals (small dots) of β-stage show systematic structure due to gravitational induced bending of the frame holder. The geometrical axis is the origin.

Experimentally we observe a reasonable stability of the set-up. However, there is a significant angle of about 300 μrad between the optical axis and the α-axis which causes systematic variation of angle of incidence with α. We thus introduce an on-line α-depending correction of $\theta_P$ of the form $\theta_P = \theta_{P0} + \Delta\theta_P \cos(\alpha-\alpha_o)$ where $\Delta\theta_P$ and $\alpha_0$ are chosen to minimize any term with a period of 2π in α. The applied function is an approximation which is correct in the limit $\theta_P \rightarrow 0$. This procedure is most sensitive for incidence angles where $T_p/T_s$ varies most strongly. We typically obtain $\Delta\theta_P = 260$ μrad and $\alpha_0 = -70°$. This indicates a mostly horizontal misalignment probably partially due to the incomplete filling of the entrance aperture. We then arrive at a situation depicted in fig. 5 which shows a data set taken at maximum slope of $T_p/T_s$ and the fit residuals. The fit considers all scans simultaneously that are taken at the same source setting (i.e. identical Stokes parameters) and the same analyzer setting while only the angle of incidence of the polarizer is varied. For example there are 21 data sets considered simultaneously at 720 eV. The fit results with respect to the multilayer for one energy are summarized in fig. 1 and 2. The absolute uncertainty of the simultaneously determined normalized Stokes parameters is estimated to be ±0.02. Details are found in [5].

In this experiment we show that using an achromatic transmission multilayer as polarizer with as much as 350 periods we can characterize the full polarization state with an absolute uncertainty of ±0.02 at any photon energy in the soft x-ray range between 700 eV and 1020 eV. The unavoidable imperfections of the polarimeter are compensated by an on-line α-depending correction of the angle of incidence at the multilayer. This experiment also indicates limits that will be difficult to overcome: Even more grazing incident angles at the phase shifter will reduce transmission and a more sensitive detector technology is required; the individual layers are composed of only a few atoms in thickness and a reduction in layer thickness and roughness while maintaining amorphous structures is not plausible; a significant improvement in mechanical accuracy and alignment precision will require a strategically different approach to the mechanical design and fabrication of polarimeters.

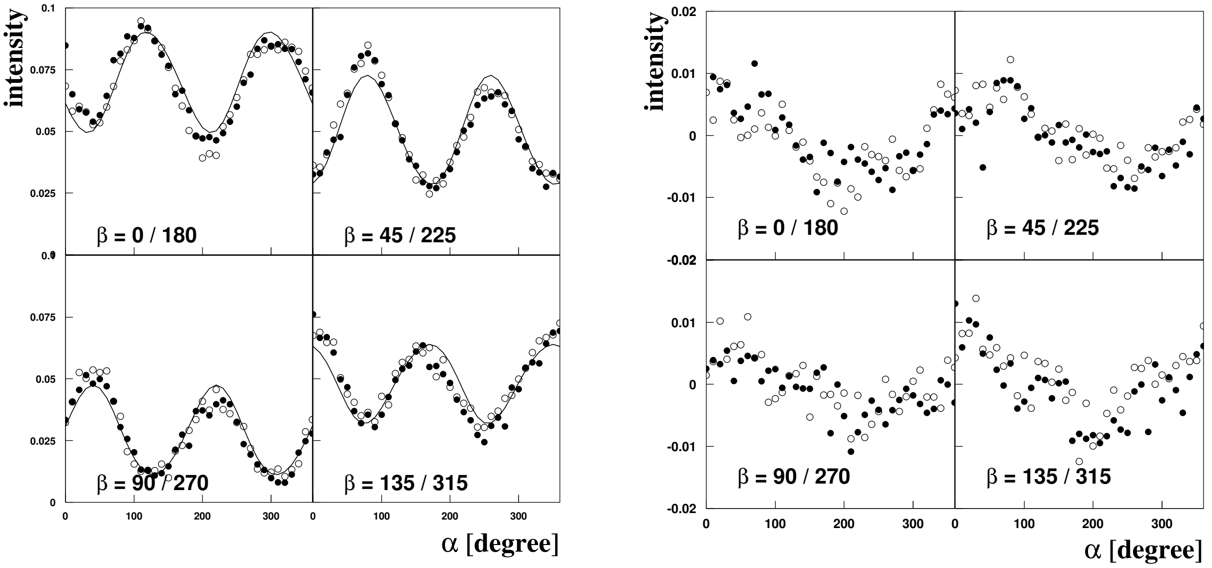

**FIGURE 5.** Typical polarimeter-scan, experimental data (points) and fit (line) (left) and residuals (right). Each window shows data for two $\beta$ values separated by $\pi$ (filled and open symbols). For each of 8 values of $\beta$ the intensity is recorded as function of $\alpha$ while $\theta_P$ is continuously adjusted as explained in the text. All data sets taken at the same energy (not shown) are simultaneously fit. These data are taken with circularly polarized light, a beam line acceptance of 140 μrad x 140 μrad, photon energy of 820 eV, and a grazing angle of incidence of $\theta_P = 25.908^o$. The residuals show a modulation with sin $\alpha$ indicating not yet perfect correction of the alignment error.

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