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2010 J. Phys.: Conf. Ser. 211 012030

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## Description of the new I1011 beamline for magnetic measurements using synchrotron radiation at MAX-lab

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**Abstract.** We report on the characterization of the new I1011 beamline at the MAX-II storage ring, in the MAX-lab synchrotron radiation laboratory and give examples of first results. This beamline is using an Elliptically Polarizing Undulator source, producing soft x-rays of a variable polarization state. It delivers high flux and high brightness circularly polarized x-rays in the energy range 0.2 to 1.7 keV, covering the L-edges of the late 3d elements. The new beamline will operate with an octupole magnet endstation. It is specially engineered to solve the problem of the limited optical access typically associated with magnetic fields and synchrotron radiation endstations. Eight water-cooled magnets allow the application of the magnetic field of up to 1 T in any direction. X-ray absorption spectroscopy, X-ray resonant reflectivity and the corresponding magnetic variants, i.e., XMCD, XMLD and XRMS experiments are possible also under an applied magnetic field. The high flux allows working with dilute magnetic systems such as ultra-thin films and nano structures.

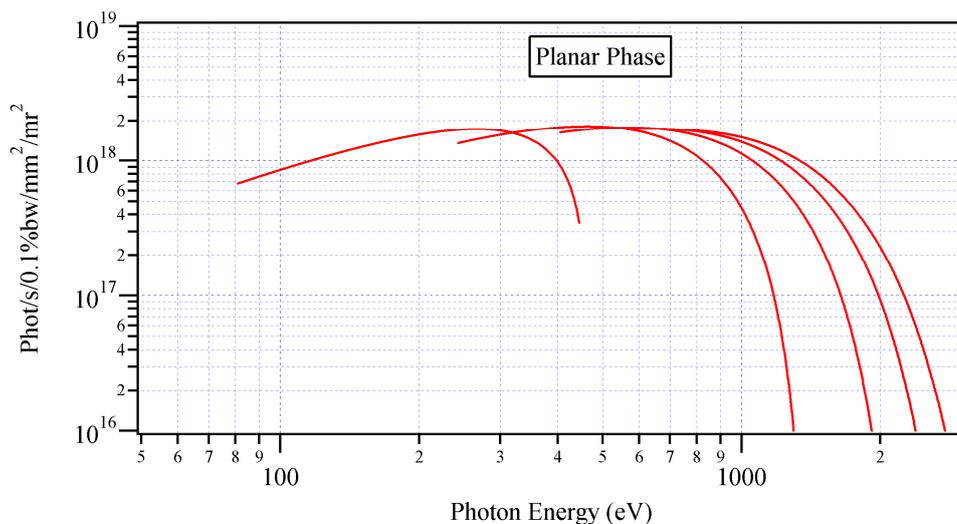
### 1. Introduction

The I1011 beamline at MAX-lab, located at the MAX II ring [1], uses an Elliptically Polarizing Undulator (EPU) light source, which produces soft x-rays of a variable polarization state. This beamline delivers, in particular, high flux and high brightness x-ray light covering the L-edges of the 3d elements and is therefore useful for elementally resolved magnetic investigations of technologically relevant samples. Also, the M edges of the rare earth elements can be reached in the spectral region between 1 and 2 keV. The EPU source can be used to produce linearly polarized light in the vertical and horizontal planes, as well as left and right handed circularly polarized x-rays. Comparing the spectral areas of core level spectra while varying the x-ray light polarization allows in particular for X-ray Magnetic Linear Dichroism (XMLD) and X-ray Magnetic Circular Dichroism (XMCD) spectroscopy. Both XMCD and XMLD make possible the element specific characterization of the magnetic properties of both ferromagnetic and anti-ferromagnetic materials.

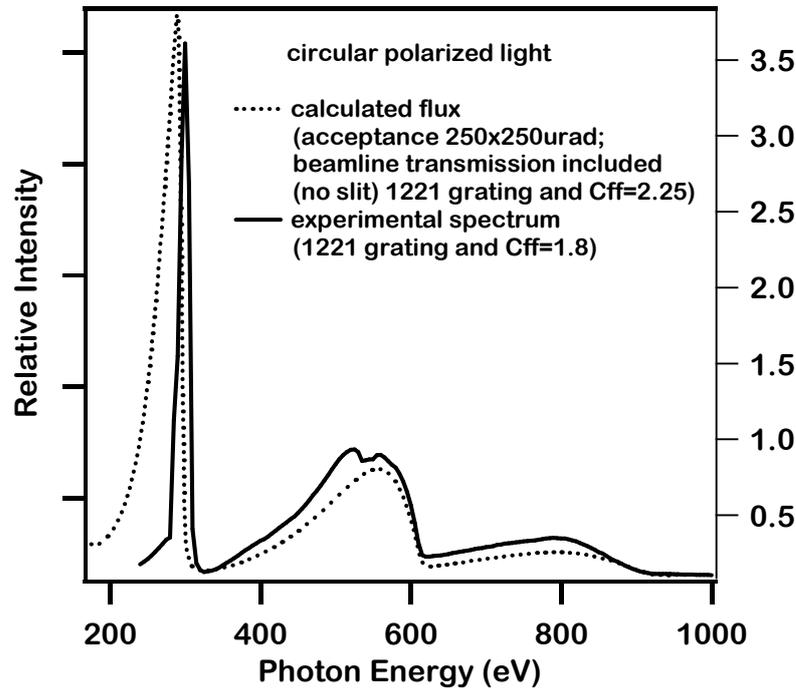
An important issue for magnetic measurements by means of the XMCD technique using synchrotron radiation is, among other things, the full control of the degree of polarisation over the whole energy range covering the absorption edges of all relevant elements, in combination with good energy resolution and sufficient photon flux. For the endstation a variable direction of the applied magnetic field vector is very useful, allowing for measurements in both the easy as well as the hard direction, without a sample rotation or any other type of sample motion. These aspects concerning new I1011 beamline will be described below.

## 2. A linearly and circularly polarised x-ray light source: the EPU

To reveal the spin-dependence of the x-ray absorption process, best is to use an x-ray light source capable of delivering variable polarisation. In particular, the XMCD technique requires a well defined degree of circular polarisation. Advanced Design Consulting USA Inc. (ADC) together with the MAX-lab machine group staff has optimized the design and manufactured the variable polarization EPU x-ray source, with four moveable sub-girders, for the MAX II (1.5 GeV) storage ring. The total length of the EPU is 2.14 m, with a period length of 46.6 mm. It produces soft x-rays with sufficient flux and brilliance over the important energy range, 100 to 2000 eV, with variable polarization: linear (vertical and horizontal) to circular, depending on the phase of the undulator magnet sub-girders. A user-friendly interface provided by ADC allows for control of the undulator gap and the EPU phase with almost no impact on orbit of the electron beam and the stored beam life-time. The high photon flux makes possible to measure even dilute magnetic samples and nanostructures. As seen in Fig. 1, the third harmonic of the undulator radiation covers the full range of the L-edges of the 3d transition metal series, allowing for element specific investigations of most technologically important materials. This situation can still be improved by increasing the energy of the stored electron beam, to 3 GeV, such as in future the MAX IV storage ring, where one will be able to reach the L-edge 3d transition metal series within the 1<sup>st</sup> undulator harmonic.



**Figure 1.** The Elliptically Polarizing Undulator calculated brightness curves for the 1st, 3rd, 5th, 7th and 9th harmonics for linearly polarized light in the horizontal plane light.

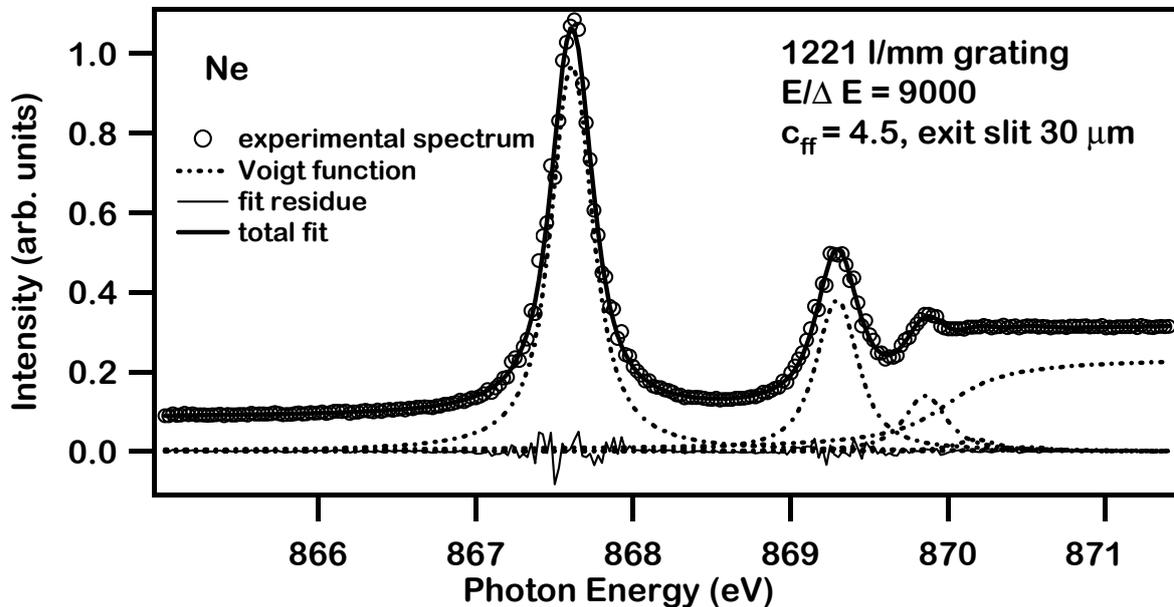


**Figure 2.** The  $I_0$  photocurrent measured from Au mesh on grating 1221 l/mm compared with theoretical predictions for circular polarized light. 1<sup>st</sup> and 2<sup>nd</sup> harmonic clearly visible. The minimum in the measured spectrum around 530 eV, is due to oxygen contamination of the optical elements of the beamline. The carbon minima can also be observed, here not so clearly, as they are located in the low energy side of the first harmonic. These features can be normalized out in the measured spectra using the  $I_0$  flux reference monitor of the beamline.

### 3. The beamline: a cPGM for optimal photon flux and energy resolution

The beamline is based on a collimated Plane Grating Monochromator (cPGM) which covers under high photon flux and good energy resolution, the energy range of 0.1 -1.7 keV. The cPGM and several other beamline components were provided by the BESTEC company (Berlin, Germany). The cPGM contains three blazed gratings, which can be exchanged in vacuum: 336, 1221, or 1400 l/mm. A plane grating solution is used for the x-ray monochromatization, which maintains the polarization state over the whole energy range covered by the monochromator. The possibility of selecting the so-called  $c_{ff}$ -parameter allows balancing between energy resolution, photon flux or higher order suppression [2,3,4]. The energy resolution was characterized using a gas cell, by measuring the photo ion yield. Various gases were used to cover the energy range of about 0.2 to 1 keV. Here we show the case of Ne gas using the 1221 l/mm grating. The energy range probed using the K-edge of Ne is close to the Co L-edge and characteristic of the performance of the I1011 BL for the late 3d series ferromagnets. The cPGM is designed to deliver a resolution of 10 000 over the whole energy range of operation but even with rather relaxed conditions ( $c_{ff} = 4.5$ , slit 30  $\mu\text{m}$ ), the resolving power which we reached is more than 9000 for  $\text{N}_2$  and 6000 for Ne gas, while the flux at the sample is about  $10^{11}$  photons/sec. The flux, within an order of magnitude, is estimated using the photocurrent from a fine electroformed Au mesh in the beam path. The quantum efficiency of gold is obtained from Ref. [5]. The transmission of the gold mesh, is reported by the manufacturer. The geometry of the mesh was checked using an optical microscope. This mesh is also used as an  $I_0$  reference monitor. The confirmed high energy resolution and flux means that the alignment of the optical elements is satisfactory. The resolving power and flux at I1011 compares favourably to the other beamlines at MAX-lab [6]. To maximize energy resolution the beam is focused onto the exit slit. The spot size of the diverging beam, after the exit slit, into the

experimental station at the sample position is about 1 mm both in the vertical and horizontal directions.



**Figure 3.** Photo ion yield spectrum recorded at Ne 1s ionization threshold. The spectrum is dominated by the 1s to 3p absorption peak, between 867 and 868 eV. A Voigt profile analysis is shown; the instrumental width corresponds to the resolving power of 6000.

#### 4. Element specific magnetic measurements using an “octupole” magnet endstation

We present the first results obtained with the endstation we designate as the “octupole” magnet endstation. The “octupole” endstation has been specially engineered to solve the problem of the limited optical access typically arising from magnetic measurements using synchrotron radiation [7]. An octupole Ultra High Vacuum chamber contains eight water-cooled electromagnets, spaced equidistantly over the surface of a sphere, which allows the application of the field in any direction [8,9]. This solution together with the possibility to rotate the whole chamber allows measuring the magnetic properties with a variable geometry of applied magnetic field, electromagnetic radiation and sample orientation. These high current magnets generate a field in the sample space of up to 1T. Such possibilities allow to optimize the measuring conditions for various magnetic systems studied by the XMCD method [10]. XMCD relies on spin selective photo excitation of the  $2p_{3/2}$ ,  $2p_{1/2}$  electrons to the empty 3d band, in case of 3d transition metals. Circularly polarised light transfers its angular momentum  $\hbar$  for right helicity ( $\sigma+$ ) or  $-\hbar$  for left helicity ( $\sigma-$ ) to a spin-orbit-split core electron, from the  $2p_{3/2}$  or  $2p_{1/2}$  level, allowing for spin selectivity in the XAS process. By applying the magneto optical sum rules the orbital ( $m_l$ ) and spin ( $m_s$ ) moments can be determined directly from the experimental XMCD signal [11]. We assume that the amount of depolarized x-ray light is negligible. The experiments can be carried out both in remanence and under magnetic field, in particular with a constant applied magnetic field (dc mode). Another method available at the “octupole” endstation is x-ray resonant magnetic scattering (XRMS) known also as resonant x-ray reflectivity. A photodiode detector travels along a  $\pm 90$  deg arc perpendicular to the beam axis. This motion, coupled with the entire system rotation of  $\pm 90$  deg and incoming light polarization allows for the diode to be placed anywhere on a hemisphere perpendicular to the beam for any light polarization. The XMCD or XRMS

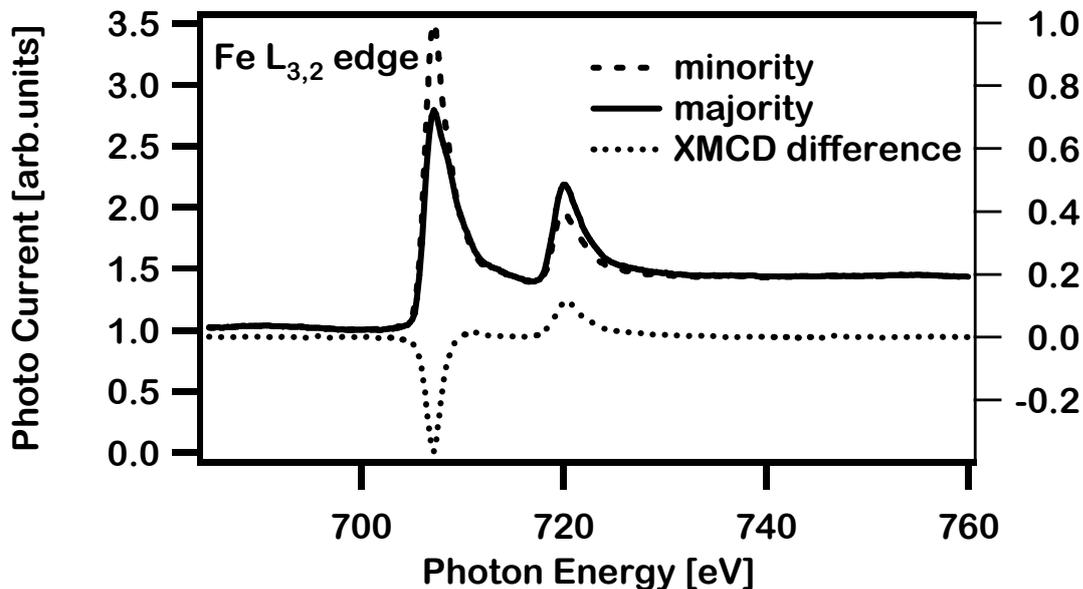
experiments can be combined with element specific magnetic hysteresis loops taken in total electron yield mode or using the photodiode. This allows for a full magnetic characterization of the specimen (measurements of saturation moment, coercive force, magnetic anisotropy) in an elementally resolved manner. A cryogenically cooled rod allows the XMCD and XRMS signals to be measured as a function of temperature - down to 20 K.

We now turn to measurements of magnetic standards and the use of the XMCD technique as a means to perform a characterization of the degree of circular polarization of the EPU x-rays. The x-ray absorption spectroscopy can be measured in different ways, using various secondary channels. Of importance is to stay in such conditions where the signal chosen is proportional to the absorption coefficient. Here we use the photocurrent of the sample and work in the Total Electron Yield (TEY) mode, avoiding grazing incidence angles to avoid saturation effects in the TEY mode. We measure the difference in absorption of circularly polarized x-rays between parallel and anti-parallel orientation of the photon spin in the TEY mode. After proper normalization the XMCD signal is obtained. We give as an example data obtained for a thick bcc Fe film. The Fe film is protected from oxidation by means of a protective cap layer. We cover the photon energies around the Fe L-edges with the 1221 1/mm grating. The data are shown in Fig. 4. Here elliptical x-rays are used using an energy range close to the 3rd EPU harmonic maximum. The angle of x-ray incidence is 45 degrees to avoid saturation effects in the secondary channel. The data are taken in the remanent state after a 0.2T magnetic field pulse was applied along the magnetic easy direction. Clear XMCD contrast is seen.

The XMCD in the XAS mode is taken by measuring the sample photocurrent with the sample in the remanent state. The data can be analyzed using the magneto optic sum rules, which allows in particular to determine the orbital and spin magnetic moments, on a per an atom basis. Here we focus on the spin moment by assuming the known number of holes for bulk Fe (3.8) and neglecting the dipole term, which is small for the Fe bulk. Knowing the experimental geometry and assuming that the remanent magnetization is to a good approximation equal to the full saturation magnetization, the degree of circular polarization can be deduced: we obtain a value of about 0.75(10). The error of order 10-15% is due in part to the imperfect knowledge of the background function introducing an uncertainty in the determination of the spin moment by means of the XMCD sum rules. This is close to the predicted value for the 3<sup>rd</sup> EPU harmonic for the chosen beamline acceptance.

## 5. Summary

Beamline I1011 at MAX-lab is dedicated for magnetism related investigations. With an EPU as the source of linear and circular polarized x-ray light this beamline delivers high flux and high brightness light covering the L-edges of the late 3d elements and M edges of the rare earths. The so-called "octupole" endstation has been specially engineered to solve the problem of the limited optical access typically associated with magnetic fields and synchrotron radiation, in a UHV environment, allowing to fully exploit the vector character of the XMCD technique. The electron yield measurement with a diode detector makes at present possible the element specific characterization of the magnetic properties of various types of dilute magnetic samples using XMLD, XMCD and X- XRMS.



**Figure 4.** The photocurrent of a thick bcc Fe film is shown (left scale), using the 1221 1/mm cPGM grating. Here elliptical x-rays are used, see text. The XMCD difference is clearly seen (right axis). The angle of x-ray incidence is 45 degrees. The data are taken in the remanent state.

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