X-RAY PULSE LENGTH CHARACTERIZATION USING THE SURFACE MAGNETO OPTIC KERR EFFECT

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Abstract

It will be challenging to measure the temporal profile of the hard X-ray SASE beam independently from the electron beam in the LCLS and other 4th generation light sources. A fast interaction mechanism is needed that can be probed by an ultrafast laser pulse in a pump-probe experiment. It is proposed to exploit the rotation in polarization of light reflected from a thin magnetized film, known as the surface magneto optic Kerr effect (SMOKE), to witness the absorption of the x-ray pulse in the thin film. The change in spin orbit coupling induced by the x-ray pulse occurs on the subfemtosecond time scale and changes the polarization of the probe beam. The limitation to the technique lies with the bandwidth of the probe laser pulse and how short the optical pulse can be made. The SMOKE mechanism will be described and the choices of materials for use with 1.5 Å x-rays. A schematic description of the pump-probe geometry for x-ray diagnosis is also described.

INTRODUCTION

An important measurement at the LCLS will be the temporal characterization of the SASE X-ray pulse. Electro optic techniques are being developed to measure the temporal profile and arrival time of the electron bunch via its Coulomb field. However, in a SASE radiation source not all parts of the electron bunch will lase equally and the duration of the x-ray pulse can be much shorter and have a very different temporal profile compared to the electron bunch in the undulator.

An x-ray pulse can be temporally profiled with an ultra-short visible laser pulse providing a suitable pump-probe mechanism can be found, whereby the x-rays produce a prompt process in some material that can in turn be detected by the visible laser. In the analogous case of the electro optic measurement of the electron bunch Coulomb field this is done by measuring the fast change in birefringence of a material by probing it with an ultra-short pulse from a high-bandwidth source, such as a Ti:Sapphire laser. The Coulomb field of the sub-picosecond electron bunches produces THz radiation which changes the refractive index along one axis of an electro optic material.

The challenge with using pump-probe techniques to measure the x-ray pulse length is to find an analogous interaction between the shorter wavelength x-ray radiation and matter that can be probed by a visible laser.

The effect considered here is the Magneto Optic Kerr Effect (MOKE) in which the polarization of a light ray is rotated according to the magnetization state of a surface from which the ray is reflected. The principal is illustrated in figure 1, where a plane-polarized ray is shown incident on a magnetized sample. A plane-polarized ray is the superposition of left and right circularly polarized beams. The circularly polarized photon will interact more strongly with an electron whose spin is in the same direction, resulting in a difference in the refractive index for the left and right circular polarizations. A plane-polarized ray is therefore observed to undergo a Faraday rotation when transmitted through a magnetized medium. The effects considered here are special forms of magnetic dichroism, which is a general term describing the way in which light is absorbed in a material according to its polarization.

Magneto optic detection using the Faraday Effect has been used to measure the time profile of terahertz radiation [1]. The time resolution can be a few picoseconds, but since the Faraday rotation is a bulk effect for the transmitted ray it is inherently limited by the geometry of the perpendicular pump and probe beams.

The change in polarization of the reflected ray was first observed by Kerr, where a plane-polarized ray is converted to elliptically polarized light, and rotated upon reflection from a magnetized sample. This is not to be confused with the electro optic Kerr Effect in which the amount of birefringence changes quadratically with the electric field.

The magneto-optic Kerr Effect depends on the surface properties, and was applied to the study of the properties of thin magnetic films by Moog and Bader [2]. The technique has been extensively developed and is referred to as the surface magneto optic Kerr Effect, or SMOKE.

The spin-orbit coupling interaction responsible for the SMOKE Effect is extremely fast and can therefore be used to probe changes in thin film magnetic properties brought about by the pump action of an x-ray beam. The

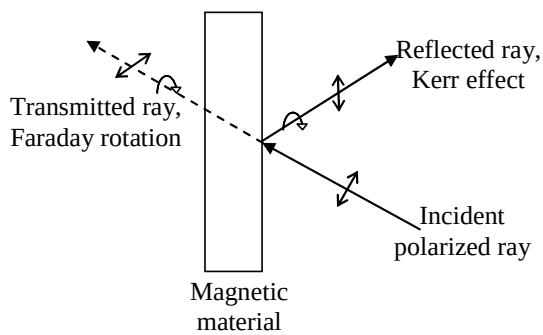

Figure 1: Change in polarization of light either transmitted through (Faraday effect), or reflected from (Kerr effect) a magnetic material.

pump action of the x-ray beam is caused by the resonant absorption of a photon causing a demagnetization of the sample. This happens on the femtosecond time scale of the spin precession velocity.

This process is of inherent interest to the study of fast magnetic switching in thin films and it is studied, for example by resonant scattering from the Cobalt L-Edge in a sample. Soft x-rays of the correct energy promote a spin-polarized electron from the 2p state into an empty 3d state. The excited electron then drops back into the empty 2p state emitting a photon of the same energy.

Beaurepaire et al have observed ultra fast transitions at the 60 fs time scale from the ferro- to the paramagnetic state in thin Ni films [3] and transitions at the 120 fs time scale from the ferro- to the paramagnetic state in epitaxial $CoPt_3$ alloy films [4].

The femto-slicing project at the BESSY storage ring in Berlin proposes to use soft x-rays (850 eV) at the L edge in Co systems to study fast switching in films [5]. In order to apply this technique to hard x-rays at energies up to 10 keV in the LCLS it would be necessary to use magnetic materials made up of rare earth elements where the L edge is in the 5 to 10 keV range. A significant difference in the L edge for rare earth systems is that the inner shell transition is a quadrupole transition and not a dipole transition as is the case for lighter elements. This suggests that the contrast might be reduced to as little as 10% relative to dipole transitions. However, recent work by Goulon and Rogalev et al [6] shows strong signals for dichroic effects in the hard x-ray regime. They have also come up with an elaborate set of sum rules for such transitions [7].

An interesting candidate material for LCLS applications would be holmium with its L-shell at 9.394 keV. Incidentally, it has the highest magnetic moment (10.6μB) of any naturally occurring element. Because of this it has been used to create the highest known magnetic fields by placing it within high strength magnets as a pole piece or magnetic flux concentrator. The Kerr rotation of thin films of Fe-Ho has been measured [8] to be 0.43 deg at 800 nm.

SMOKE PUMP PROBE GEOMETRY

The SMOKE process allows an ultra-fast laser to probe the x-ray induced change in magnetization of a thin film with femtosecond resolution. The SMOKE reflection geometry can be exploited to translate the temporal profile of the pump x-ray pulse into a spatial profile as shown in figure 2.

The incident laser pulse is plane polarized and incident on the magnetized surface of a sample at 45º. For a 1 mm diameter laser beam the transit time across the surface of the sample is approximately 3 ps, which is long compared to the nominal 20 fs duration of a short-pulse laser. The reflected ray passes through an analyzer that is adjusted to block the polarized light reflected from the sample when no x-rays are present. An x-ray beam is normally incident on the sample and will alter the instantaneous magnetization at the surface. The magnetic material is in the form of a thin film so that only surface effects need be considered and there is no broadening from bulk effects. For the duration time that the x-ray pulse is intercepting the surface film the magnetic state is altered and the Kerr rotation of the reflected ray changes in proportion to the intensity of the x-rays. The light transmitted through the analyzer is therefore proportional to the instantaneous x-ray intensity. The 45º geometry of the probe laser pulse means that the position at which it intersects the surface is a function of time so that the temporal structure of the x-rays is translated into position at the detector. The temporal to spatial correlation is a function of the probe laser incidence angle and a greater temporal resolution can be achieved with an angle larger than 45º.

The magnitude of the Kerr rotation is proportional to the projection of the magnetization in the direction of the incident ray. The magnetization, m, in the material causes a change in the dielectric, which when written as a tensor produces off-diagonal elements,

$$\mathbf{D} = \varepsilon_0 \varepsilon_x \begin{bmatrix} 1 & iQm_z & -iQm_y \\ -iQm_z & 1 & iQm_x \\ iQm_y & -iQm_x & 1 \end{bmatrix} \mathbf{E}$$

where **D** is the electric displacement, **E** the electric field and ε the dielectric tensor. The magneto optical constant is given by the Voigt parameter [9],

$$Q = i\frac{\varepsilon_{xy}}{\varepsilon_{xx}}$$

The Fresnel equations for the reflection coefficients, *r*, lead to an expression for the Kerr rotations of the *s* and *p* polarizations [10]:

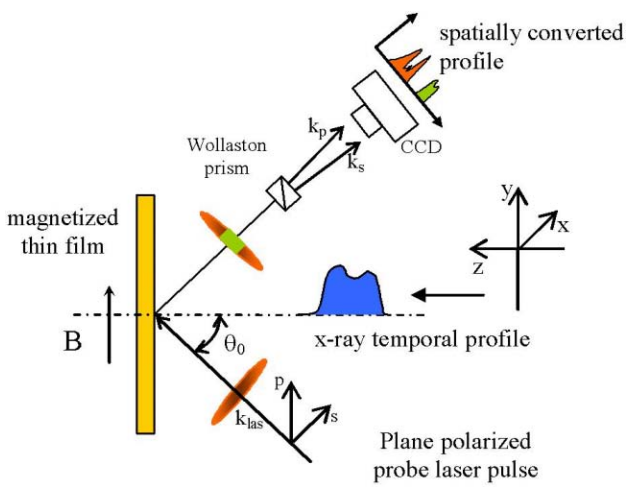

Figure 2: A circularly polarized ultra-short laser pulse is incident at 45º on a magnetized film. A polarization analyzer detects the temporal overlap between x-ray and laser incident on the magnetized film and spatially translates it in this geometry.

$$\theta_K^p = \frac{r_{sp}}{r_{pp}} = \frac{\cos\theta_0\left(m_z + m_y \tan\theta_1\right)}{\cos\left(\theta_0 + \theta_1\right)} \cdot \frac{in_0 n_1 Q}{\left(n_1^2 - n_0^2\right)}$$

$$\theta_K^s = \frac{r_{ps}}{r_{ss}} = \frac{\cos\theta_0\left(m_z - m_y \tan\theta_1\right)}{\cos\left(\theta_0 - \theta_1\right)} \cdot \frac{in_0 n_1 Q}{\left(n_1^2 - n_0^2\right)}$$

where n_0 and n_0 are the refractive indices for vacuum and of the magnetic material, and θ_0 and θ_1 are the angles of the incident and transmitted ray in the magnetic medium.

FURTHER DEVELOPMENTS

For most materials the magnitude of the Kerr rotation is quite small but this is offset by good detection sensitivity for changes in polarization so that changes in the magnetic field at the level of a milligauss can be observed. Several enhancements to the technique can also be considered. The analysis above predicts a linear increase in Kerr rotation with magnetization. At high probe laser power densities there can be a nonlinear increase in the Kerr rotation, for example in the second harmonic generation magneto optic Kerr effect (SHMOKE) [11], which is a technique developed specifically for thin magnetic films. Thin films made from multilayers (superlattices) also promise to give larger Kerr rotations, especially at shorter wavelengths. Kerr rotation formulae for superlattices have been derived by Zak et al [12].

The development of a pump-probe using the SMOKE technique to profile the x-ray pulse length begins with selecting a suitable magnetic material that will respond to x-rays at the LCLS wavelengths down to 1.5 Å. The sensitivity of a material at this wavelength could be tested at a storage ring based SMOKE facility. Our group already has considerable experience with ultra-fast lasers and in particular the timing and synchronization of the laser pulse with the electron beam used to generate the x-rays. The electro-optic experiments [13] at the SPPS [14] demonstrated that pump probe measurements with spatial crossing angles can effectively resolve ultra-fast phenomena in the sub-picosecond regime. The SMOKE experiment will extend this technique to measuring ultra-fast hard x-ray phenomena.

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