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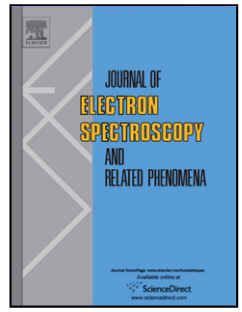


Title: Time-resolved x-ray detected ferromagnetic resonance of spin currents


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# Time-resolved x-ray detected ferromagnetic resonance of spin currents

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**Abstract**

X-ray detected ferromagnetic resonance (XFMR) has recently emerged as a powerful synchrotron-radiation-based tool able to study the element-selective magnetization dynamics. Magnetic and chemical contrast in XFMR is obtained by x-ray magnetic circular dichroism (XMCD), while the phase difference between the magnetization precessions is monitored using stroboscopic probing. A unique property of time-resolved XFMR is the visualization of the magnetization precession for each individual layer in a magnetic device. Measurement of the amplitude and phase response of the magnetic layers gives a clear signature of spin-transfer torque (STT) coupling between ferromagnetic layers due to spin pumping.

*Keywords:* FMR, XMCD, spin pumping, spin-transfer torque



## 1. Introduction

Improved understanding of precessional magnetization dynamics is essential for the continuing development of high frequency magnetic devices such as hard disk drives and spin oscillators. In the past, conventional ferromagnetic resonance (FMR) has been used extensively to determine fundamental parameters that affect magnetism in thin films using resonance frequencies (related to internal and applied fields) and relaxation (determined by damping of the resonance). However, the growing complexity of many modern magnetic materials and devices requires the development of new measurement techniques that reveal in a more direct fashion the microscopic origin of magnetic interactions.

The novel technique of x-ray detected FMR (XFMR) enables to study the element-selective magnetization dynamics. Magnetic and chemical contrast in XFMR is obtained by x-ray magnetic circular dichroism (XMCD). Time-dependent XFMR can be used to measure the amplitude and phase of the spin precession of each layer. The challenge of such experiments is that for ferromagnets the precession frequency in the order of GHz and the precession cone angle is $<1°$. The solution is to do stroboscopic measurements utilising the time structure of the synchrotron ($\sim$500 MHz). The radio frequency (RF) field that drives the spin precession is synchronised with the x-ray pulses using the clock of the synchrotron. Each x-ray pulse measures the magnetization cone at precisely the same point in the cycle. In brief, XFMR combines FMR and XMCD as follows: The magnetization of the sample in a magnetic field is pumped by an RF field to generate a precessing moment (i.e., FMR), which is probed using the XMCD effect.

As will be shown in this paper, XFMR is a unique probe to study spin-transfer torque (STT) and spin currents. STT is the effect in which the orientation of a magnetic layer in a spin valve can be modified using a spin-polarized current [1, 2]. By passing a current through a thick magnetic layer (usually called the 'fixed layer') a spin-polarized current can be produced. If this spin-polarized current is directed into a second, thinner magnetic layer (the 'free layer'), angular momentum can be transferred to this layer, changing its magnetic orientation. This can be used to excite oscillations or even flip the magnetization direction. The effects are usually only seen in nm scale devices. An example is spin-torque induced domain-wall motion, which can be used in race-track memory devices.

Spin pumping is due to the precessing magnetization vector of a ferromagnet (FM) emitting a pure spin current when in contact with a normal metal (NM) [3]. The magnetization precession is generated by FMR using RF radiation. A spin current differs from a spin-polarized current in that there is no net transfer of charge, i.e., equal amounts of electrons with spin-up and spin-down flow in opposite directions, so that only angular momentum is transferred.

Spin currents are generally probed using measurements of the effects they produce in the metals through which they flow. For instance, they can create an electrical voltage drop perpendicular to the spin current direction, or a torque that bends the magnetization direction of a magnetic film. However, such indirect measurements are often ambiguous because they are influenced by factors other than the spin current, such as magnetic proximity effects at the interface.

Since the first demonstration just over a decade ago, several XFMR studies in time-averaged and time-resolved mode have been reported [4–40] The first element-specific measurement of magnetization dynamics by pump-probe XMCD was reported by Bailey *et al.* [4] on permalloy