ELECTRICAL MEASUREMENT OF AN ION INDUCED THERMOMAGNETIC EFFECT ON A NANOSECOND TIME SCALE

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1. Introduction

The effect of ultrafast particle induced demagnetization on a femtosecond and nanometer scale was experimentally confirmed in 2004 [1]. The ultrafast demagnetization is a result of an electron temperature spike, caused by power loss of the traversing ion. A following lattice spike, which occurs significantly later in time, is responsible for an increase of lattice temperature due to electron-phonon interaction. Simulations of the thermal spike in a particle track of alpha particles and swift heavy ions in water have yielded a temperature increase of 400K and 10^4K respectively on the particle track axis [2]. The time constant of the temperature drop on the order of 10^{-11} s makes it potentially measurable using high frequency electronic equipment. In this work we discuss the expected transient thermomagnetic effect due to ion stopping and propose a detection scheme for induction-based electrical measurement of the particle induced demagnetization.

1.1 Ultra-fast demagnetization dynamics

Although the particle induced demagnetization has not yet been observed on a picosecond, or nanosecond time scale, numerous experiments using nanosecond to femtosecond laser pulses were conducted, examining transient magnetization processes on these timescales [3-6]. In order to phenomenologically describe the spin dynamics of thin films after laser irradiation, a three temperature model has been proposed. In the model, electron, spin and lattice subsystem are all assigned their own temperature as it can be seen in the figure 1. The electronic system is heated by the optical excitation almost instantaneously. Its energy is rapidly transferred to the spin system causing the initial rapid demagnetization on the order of hundreds of femtoseconds. The subsequent thermalization of the electron and spin system with the lattice after several picoseconds results in a partial recovery of the magnetization. On a timescale of a few nanoseconds, the three subsystems cool down because of heat transfer to the surrounding material, and the magnetization recovers completely [3].

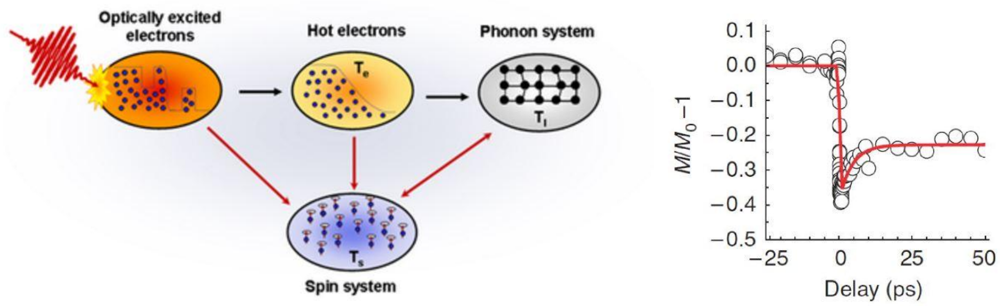

Fig.1: *A graphical representation of the three temperature model, where T_e is electron temperature, T_s spin system temperature and T_l lattice temperature [4] and an actual demagnetization characteristic of a CoPd multilayer film [3].*

2. Particle induced demagnetization

Similar processes can be expected to take place even if the source of the initial excitation is an ion stopping. The initial rapid demagnetization due to an electronic spike, has been experimentally confirmed by means of spin precession measurement of probe ions on the femtosecond time scale [1]. The well known phenomenon of radiation heating suggests conversion of initial ionization and electronic excitation into heat on longer time scales, however the exact processes of relaxation as well as the corresponding change of magnetic properties are still a matter of research and a transient magnetic field change due to the lattice temperature spike induced by ion stopping has not been experimentally observed. The ion induced demagnetization dynamics is expected to differ from that of the laser induced demagnetization due to the different nature of interaction of the radiation with the magnetic material as well as different geometries of the heated region. The femtosecond laser pulse heats the surface area more or less uniformly and the heat profile reaches depth of just a few hundreds of nm within the first 1-2ps [5]. The heat deposition from ion stopping takes place along the particle track, which might penetrate much deeper into the material. For example, the average range of an alpha particle emitted by ^{238}Pu in Iron is 11.3 μm as shown in the table 1.

However, the sample surface area heated by a single ion impact has a heat profile with diameter of just a few tens or hundreds of nanometers, depending on the type of the ion and energy transfer per unit length near the surface.

Tab. 1. *Comparison of average ^{238}Pu alpha and 1MeV per nucleon ^{132}Xe ranges and energy deposition per unit length in different materials, calculated using TRIM.*

Material	^{238}Pu alpha		^{132}Xe	
	Particle range [μm]	Average LET [keV/μm]	Particle range [μm]	Average LET [keV/μm]
Fe	11.3	495.0	7.24	18 232
Ni	10.7	522.7	6.75	19 555
Gd	18.8	297.5	12.2	10 820

The differences in energy deposition do not end with geometry. The amount of energy deposited per unit length changes with the ion energy and is different for different ions as it can be seen in the figure 2.

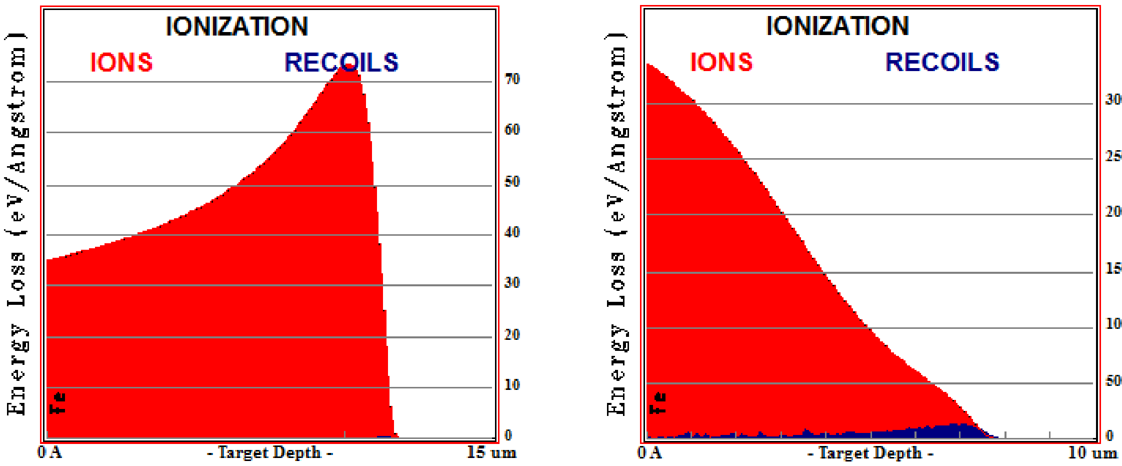

Fig.2: *Comparison of the energy loss of ^{238}Pu alpha and 1MeV per nucleon ^{132}Xe calculated using TRIM program.*

On the time scale of tens of picoseconds to nanoseconds, the heat is removed from the track volume by conduction and radiant losses. The time constant of the temperature drop depends on the heat conductivity of the sample material and has been counted to be on the order of 10^{-11}s for 4 MeV alpha particle in water [2]. The volume of the sample demagnetized by the heat, deposited in the particle track, can be increased if the temperature of the sample is near its Curie point. Increasing the demagnetized volume enhances the chance to detect the field change.

3. The electrical measurement

The electrical measurement relies on the ability to pick-up the field change induced by ion stopping in the ferromagnetic material. The upper limit of temporal resolution of an electrical measurement of laser induced demagnetization reported in literature is on the order of microseconds and has been achieved thanks to a hall effect in a cross-like microstructure [6]. However, due to limitations of the Hall Effect in terms of time resolution, it is necessary to use a different approach for electrical measurements of processes on picosecond and nanosecond domain. Induction-based measurements seem like a good alternative as there is a fast change of magnetic properties involved. However, the signal strength from induction measurement of a single ion induced thermomagnetic effect is limited by the relative efficiency of the thermomagnetic effect itself, which reaches 3% for a bulk Iron and up to 12% for a bulk Gd under ideal conditions [7]. Due to further practical limitations of the field change pick-up efficiency in the case of particle induced thermomagnetic effect, we first propose a time-resolved measurement, taking advantage of summation of the signals to identify the influencing factors and improve the detector design in order to increase the efficiency. The proposed solution takes advantage of a relatively long time interval needed to discharge a high capacity capacitor through a resistor and a biased diode. The time interval can be precisely set by adjusting the capacitance of the capacitor and by using an appropriate resistor. The measurement loop would be in series with the diode. The electrical impulse generated in the measurement loop due to the thermomagnetic effect will be rectified by the diode, thus decreasing the overall time needed for the capacitor to discharge. By measuring a discharge characteristic of the capacitor, we should be able to see a combined effect of the individual signals resulting in slowing down the discharge process compared to a discharge without pulses. By extrapolating the characteristics measured under alpha irradiation and comparing with the control ones, a difference in the capacitor discharge time should be evident. A schematic layout of the experimental setup is shown in the figure 3.

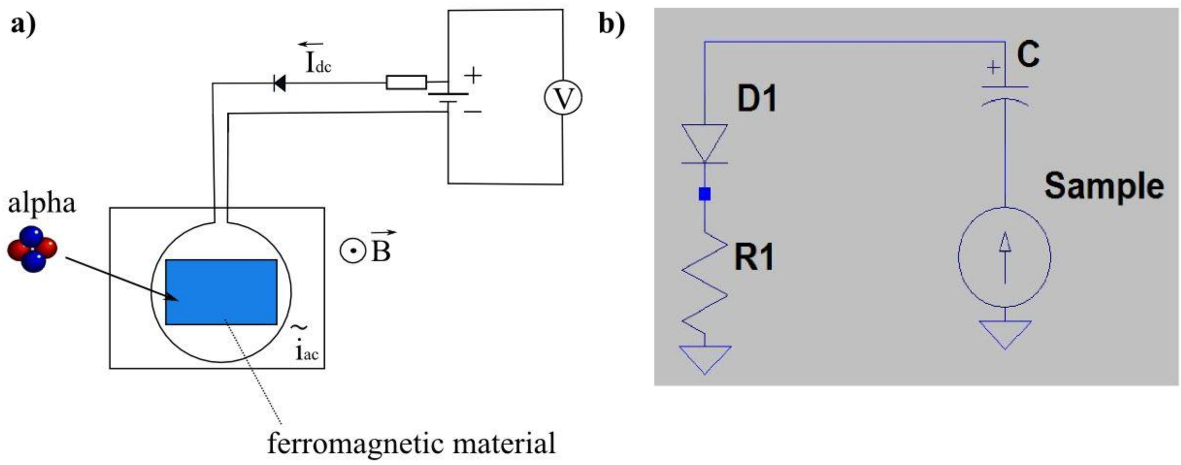

Fig.3: *a) A diagram of the measurement set-up b) the scheme of the detection circuit made in LTSpice program, where C is a capacitor, D1 a diode and R1 a resistor.*

To increase the signal strength a suitable pre-amplifier and amplifier might be used. Before employing the proposed scheme, the sample electrical response should be tested with a high power impulse heat source, such as an impulse laser, in order to determine the efficiency and estimate the signal strength of the ion induced thermomagnetic effect. A simulation of the measurement circuit response to a DC and an AC signal using LTSpice has proved the scheme viable for detection of a series of both DC and AC pulses.

3.1 Samples

The first series of samples was prepared using a commercial Permalloy, NiZn ferrite powder with grain size of 200μm, nanocrystalline $(Fe_1Ni_3)_{81}Nb_7B_{12}$ alloy and Fe_3O_4 nanoparticles with 8nm diameter. The samples were prepared in the form of a thin layer deposited inside a copper loop with 2mm inner diameter prepared on a printed circuit board by means of photolithography. The scheme of the measurement loop and the whole sample is shown in the figure 4a. The thickness of the layer varied from several micrometers for the nanoparticle film up to several hundred micrometers for the NiZn ferrite powder.

In order to prevent the charged particles to enter the measurement circuit, the measurement loop and the pin of a connector were covered by a several hundred micrometer thick layer of an insulating paste.

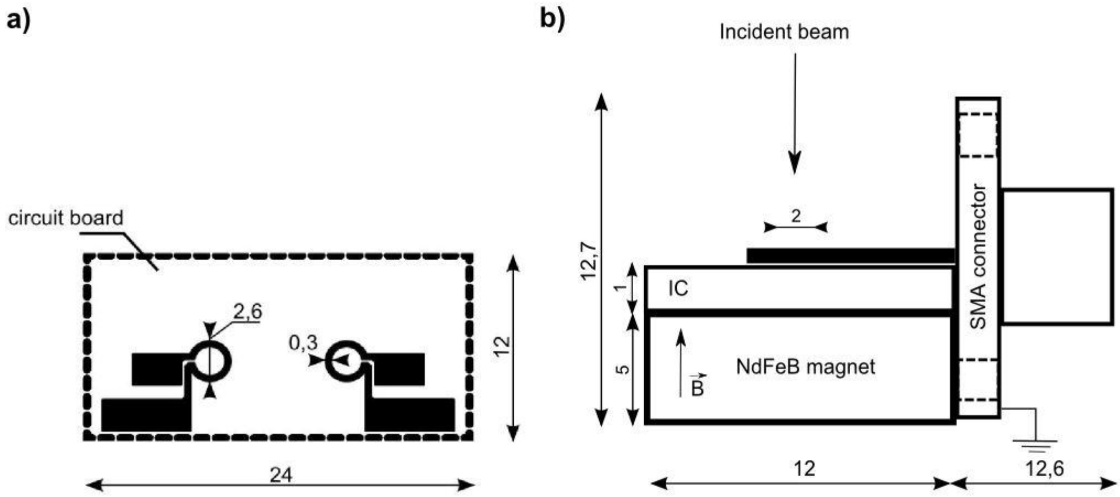

Fig. 4: *a) Circuit board layout (top view) b) Total sample layout with dimensions (side view), all dimensions in milimeters – not to scale*

3.2 Initial tests and results

The samples were first tested under the laser irradiation by a 10mW laser with the pulse width of 10ns and repetition rate of 60Hz. Samples were directly connected to Tektronix TDS 3032C oscilloscope by a short coax cable, however, no observable signal was detected, even after amplification by a charge sensitive preamplifier with a gain of 1 V/pC.

The laser pulse width provided enough power to make direct observation of the signal on the oscilloscope feasible, however the noise level of up to 1mVpp without amplification and up to 100mVpp after amplification and the signal strength lower than expected, has made observation of the signal impossible. The main sources of noise were found to be connectors and cables. Other potential sources include for example background EM radiation picked-up by the measurement loop.

In case of Permalloy and nanocrystalline sample a high reflection coefficient might have caused a decrease of the signal strength. However a much lower reflection coefficient of NiZn ferrites and the nanoparticle film suggests the reflection coefficient not being the solely cause. Among other factors, low penetration depth of the heat profile after laser irradiation, compared to the sample thickness, seem to be universal for all the samples. As a result of heating just a few hundred nanometers of the multi-micrometer layer, the change of magnetic flux through the loop can be expected to be small. A relatively large loop-wire diameter of 0.3mm, might have caused a further reduction of the amount of flux escaping the loop.

A direct observation of an alpha radiation induced signal has also not yielded any results, as anticipated due to lower power compared to the laser source.

4. Conclusions

Based on theoretical considerations and experimental data, an expected transient thermomagnetic effect due to ion stopping has been described and a detection scheme for an induction-based electrical measurement of the particle induced demagnetization proposed.

Direct electrical measurements of various ferromagnetic sample materials prepared in the form of several micrometer - up to several hundred micrometer thick layer deposited inside of the measurement coil irradiated with 10mW, 10ns pulse width laser, has however not provided a clear evidence of a signal, due to the high noise level and low signal strength.

One of the reasons for low signal strength is a low penetration depth of the laser heating with regards to the sample thickness. A lower thickness of the ferromagnetic layer on the order of not more than hundred nanometers might be necessary for impulse laser testing. A test with an impulse heat source, such as laser, is a vital step towards preparing samples for measurements of the ion induced demagnetization.

Acknowledgement

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