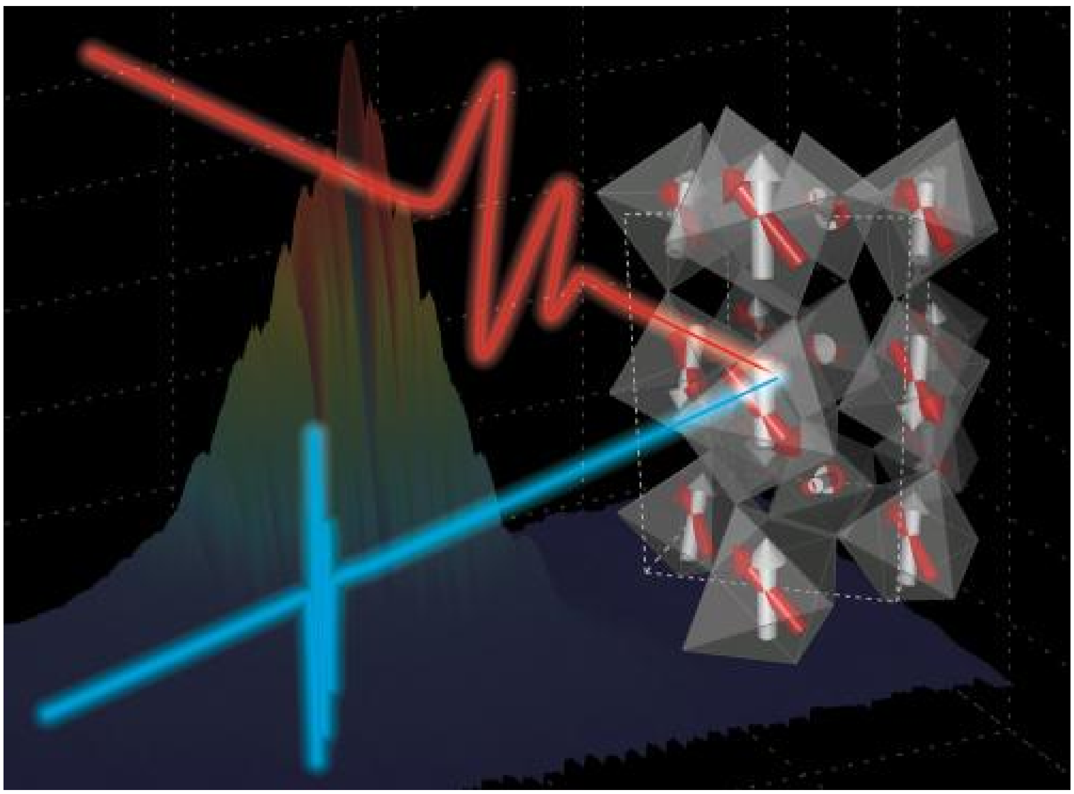
Observed live with X-ray laser: Electricity controls magnetism

March 7 2014, by Paul Piwnicki



Principle of the experiment. The motion of the magnetic moments in TbMnO3 (shown as arrows on the right hand side) is excited by a terahertz pulse (red beam) and probed by a pulse from the x-ray laser LCLS (blue beam). Credit: Teresa Kubacka

Researchers from ETH Zurich and the Paul Scherrer Institute PSI demonstrate how the magnetic structure can be altered quickly in novel materials. The effect could be used in efficient hard drives of the future.

Data on a hard drive is stored by flipping small magnetic domains. Researchers from the Paul Scherrer Institute PSI and ETH Zurich have now changed the magnetic arrangement in a material much faster than is possible with today's hard drives. The researchers used a new technique where an electric field triggers these changes, in contrast to the magnetic fields commonly used in consumer devices. This method uses a new kind of material where the magnetic and electric properties are coupled. Applied in future devices, this kind of strong interaction between magnetic and electric properties can have numerous advantages. For instance, an electrical field can be generated more easily in a device than a magnetic one. In the experiment, the changes in magnetic arrangement took place within a picosecond (a trillionth of a second) and could be observed with x-ray flashes at the American x-ray laser LCLS. The flashes are so short that you can virtually see how the magnetisation changes from one image to the next - similar to how we are able to capture the movement of an athlete with a normal camera in a series of images with a short exposure time. In future, such experiments should also be possible at PSI's new research facility, the x-ray laser SwissFEL.

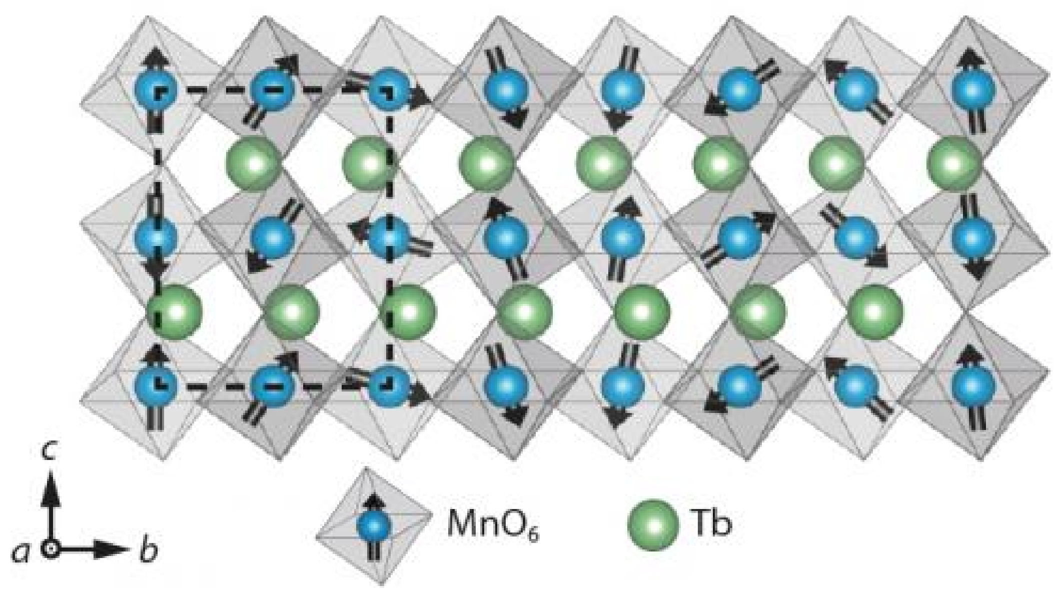
The results will be published in the journal *Science*. They appear online in advance of print in *Science Express* on 6 March.

One common method of data storage uses materials in which different magnetic domains can be oriented in different directions. In other words, the tiny elementary magnets inside the material are aligned along two possible directions, which enables one bit to be saved in the material. A bit is the smallest unit of information, for which there are two possibilities, often referred to as 0 and 1. In the storage device, these correspond to the two different magnetic directions. In a real hard drive, which must store a large amount of information, there are many small areas that correspond to single bits. To change the information on the hard drive, the direction of the magnetism in one domain must be flipped. In modern consumer devices this is achieved using a small magnetic field.

An electric field can be generated in a small space more easily than a magnetic field, which means that, in principle, smaller storage devices can be constructed if magnetism is switched by electric fields. A strong connection between magnetic and electric properties is exhibited by so-called multiferroic materials, which have been one of the hottest topics in materials research for a number of years. Researchers from the Paul Scherrer Institute PSI and ETH Zurich have now studied the material TbMnO3 and demonstrated that its magnetic arrangement can be changed by an electric field in a matter of picoseconds (10-12 s = one trillionth of a second), which is considerably shorter than the time it takes for today's hard drives to be switched. "This shows that multiferroic materials can be switched quickly enough electrically for them to be used in magnetic storage devices," explains Urs Staub, a research group leader at PSI and one of the research project supervisors. "Electric switching could have numerous advantages. In order to generate a magnetic field, you need a coil through which a current flows. An electric field can be generated without current.

"The material we studied can't be used in technical devices - you need very low temperatures and strong electrical fields to observe the relevant phenomena. However, the basic result probably also applies for materials that are more suitable for applications and will presumably consist of a combination of thin layers of different materials."

Exposure time: 0.000 000 000 000 1 seconds



The arrangement of magnetic moments in TbMnO3.Neighbouring moments are tilted in respect to each other. There are two possible directions in which the moments can turn that might correspond to the two values of a bit in future storage devices. Credit: Kubacka et al., Science Express (2014) DOI: 10.1126/science.1242862

The experiment is based on the interaction between pulsed light produced by two lasers - terahertz light generated by a laser which can easily fit into a lab, and the radiation from the x-ray laser Linac Coherent Light Source (LCLS), a large-scale research facility located at SLAC National Accelerator Laboratory in Menlo Park, California, that is roughly three kilometres in length. In the experiment, the material was illuminated with short flashes of terahertz-frequency light which were only a few picoseconds long. Light consists of an electric and a magnetic field, which periodically become stronger and weaker. The terahertz flashes were so short that the electric fields in them were only able to perform a few oscillations. With experiments at the LCLS, the researchers were able to demonstrate that the magnetic arrangement was distorted by the flash of light and - with a slight delay - this distortion followed the oscillation of the electrical field within the flash. The magnetic component of the light was too weak to influence the magnetic structure. The x-ray laser generates very short (100 femtoseconds = 0.000 000 000 000 1 seconds) and intense flashes of x-ray light which are so much shorter than the terahertz flash. This allows the x-rays to measure the magnetic distortion along the different stages of its motion, similar to how a camera with a fast shutter speed captures still images of rapid motions. Today, the LCLS is one of two facilities where such experiments are possible. In the future, they will also be possible at the x-ray laser SwissFEL, which is currently under construction at the Paul Scherrer Institute. "An experiment like this can only be conducted at an x-ray laser because only the pulses from the x-ray laser show the magnetic order and are short enough for you to follow the chronological sequences," explains Staub.

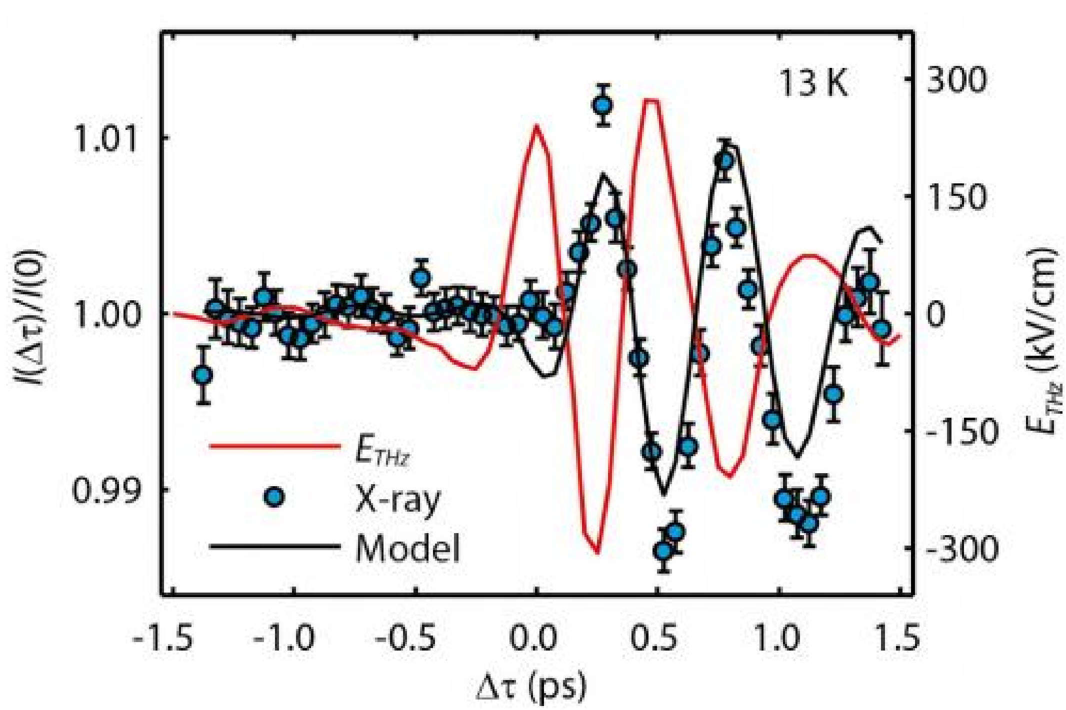
Tilted elementary magnets

Magnetic materials which can be used to store data can have different magnetic arrangements. In today's hard drives, the magnetic areas are arranged ferromagnetically, which means that the elementary magnets or, to use the technical term, magnetic moments are all pointing in same direction within the area encoding one bit. In the material studied in the experiment, the moments are arranged in rows but in such a way that two neighbouring moments are slightly rotated with respect to each other as opposed to being parallel. If you move from one moment to the next, the direction of the moments keeps turning and overall the sequence of magnetic moments forms a cycloid. Generally speaking, there are two directions in which the moments can turn, clockwise and anticlockwise - and these could correspond to the two values of a bit. To change between "0" and "1", the magnetic moments would have to change the turning direction within the sequence, which is equivalent to rotating the entire sequence of magnetic moments by 180 degrees.

Positive and negative - offset from each other

The multiferroic material also has another property: electric polarisation, which means that the positive and negative charges are shifted slightly against each other. The interior of the material is constructed from atoms that have fixed positions in a three-dimensional structure. As there are just as many negative charges (electrons) as positive ones (atomic nuclei) in the atoms, the entire material is electrically neutral. Some of the electrons, however, are not bound rigidly to the atomic nuclei. These electrons can be displaced with respect to the atomic nuclei, which means that one side of the material is positively charged, the other negatively. In other words, the material is electrically polarised. In everyday life, electrically polarised materials are primarily known thanks to the piezoelectric effect used to produce sparks in lighters or sound in loudspeakers, for instance.

Electrically and magnetically linked



The deflection of the magnetic moments (black line) follows the electric field of the terahertz pulse (red line) with a short delay. The blue dots show the results of the measurement. Credit: Kubacka et al., Science Express (2014) DOI: 10.1126/science.1242862

In TbMnO3, the electrical polarisation is linked to the magnetic arrangement, which means that if the magnetic moments turn in one direction, this always corresponds to an alignment of the electric polarisation; if you reverse the polarisation, the rotational direction of the magnetic moments also turns around. The researchers studied this coupling in their experiment. Using the alternating electric field of the terahertz pulse, they influenced the electric polarisation and observed the extent to which the magnetic arrangement followed the alternating field. Although the electric field was too weak to actually turn the sequence of magnetic moments by 180 degrees, the scientists were able to observe that it was turned by around four degrees in time with the electrical field. "This procedure is also important for possible applications," explains Teresa Kubacka, a doctoral student in the Ultrafast Dynamics Group at ETH Zurich and first author of the paper. "The terahertz pulse is designed in such a way that it influences the magnetic arrangement only in this particular way. If the magnetic arrangement in a device could be changed so specifically, much less energy would be wasted and the material would not heat up as much."

Precision measuring

It is the first time that it was possible to measure such a rapid change in a multiferroic material so precisely. The angle by which the magnetic moments were turned was determined using the short flashes from the LCLS x-ray laser in a scattering experiment. It involved sending the x-ray beam through the sample studied and observing the directions in which the x-ray light was deflected by the sample. In the case of this material, there are directions in which the light is deflected by the atomic structure and others where the deflection is caused by the magnetic moments. If the magnetic arrangement is changed, the intensity of the deflected x-ray light changes. In the experiment, the researchers measured the intensity of the deflected x-ray beam at different times for a selected direction. Then they calculated how the magnetic moments react to the electric field within the terahertz flash.

Experimental challenges

"One of the challenges of the experiment was to create the terahertz flashes with the correct frequency and guarantee that enough of their intensity reaches the sample. Such pulses were not created directly by a laser, but rather with the aid of special organic crystals hit by laser pulses with another frequency. At ETH Zurich, we are also working on facilities that generate terahertz pulses and working together with the specialists from PSI and LCLS we were able to adapt the lasers available at the LCLS to our experiment's needs," says Kubacka.

More information: "Large-Amplitude Spin Dynamics Driven by a THz Pulse in Resonance with an Electromagnon." T. Kubacka, et al. *Science* DOI: 10.1126/science.1242862

Provided by Paul Scherrer Institute