Speed Limit of Magnetic Recording

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Two important goals of technology are: smaller and faster. In line with this goal the 50 billion dollar per year magnetic recording industry has been wondering where it would run into obstacles set by basic physical principles. The basic questions concern the lateral sizes at which the magnetic domains that define the "1" and "0" bits become unstable and whether there is speed limit for the writing process of the bits.

It is well established that the ***size limit*** of the bits is determined by a phenomenon called super-paramagnetism. At this limit the direction of the magnetization of a bit is no longer stable in space and may switch erratically between "1" and "0". The physical origin of this instability is that the thermal energy becomes comparable to the magnetic anisotropy energy which holds the bit magnetization in a certain fixed direction. The thermal energy is determined by the room temperature environment in the computer while the magnetic anisotropy energy scales with the volume of the bit or the number of magnetic atoms. Today's bits have about 10 million magnetic atoms and if one requires a magnetic memory to be reliable for 10 years, one can estimate from the above considerations that one will run into trouble when the number of atoms is reduced by a factor of about 1000.

Much less has been known until recently about potential ***speed limits*** of the recording process. Today's technological limit is about 1 nanosecond per bit and in research and development (R&D) laboratories bits have been switched ten times faster at about 100 picoseconds (ps). But how much faster can one hope to reliably write a bit?

An experiment performed at the Stanford Linear Accelerator Center has now provided an answer to this fundamental problem. The experimental geometry is illustrated in Fig. 1. The linac's beam, made of tightly packed bunches of electrons traveling close to the speed of light, creates magnetic pulses that are some of the world's strongest – at up to 10 Tesla, or 200,000 times the strength of the Earth's magnetic field – and briefest, as short as about 100 femtoseconds.

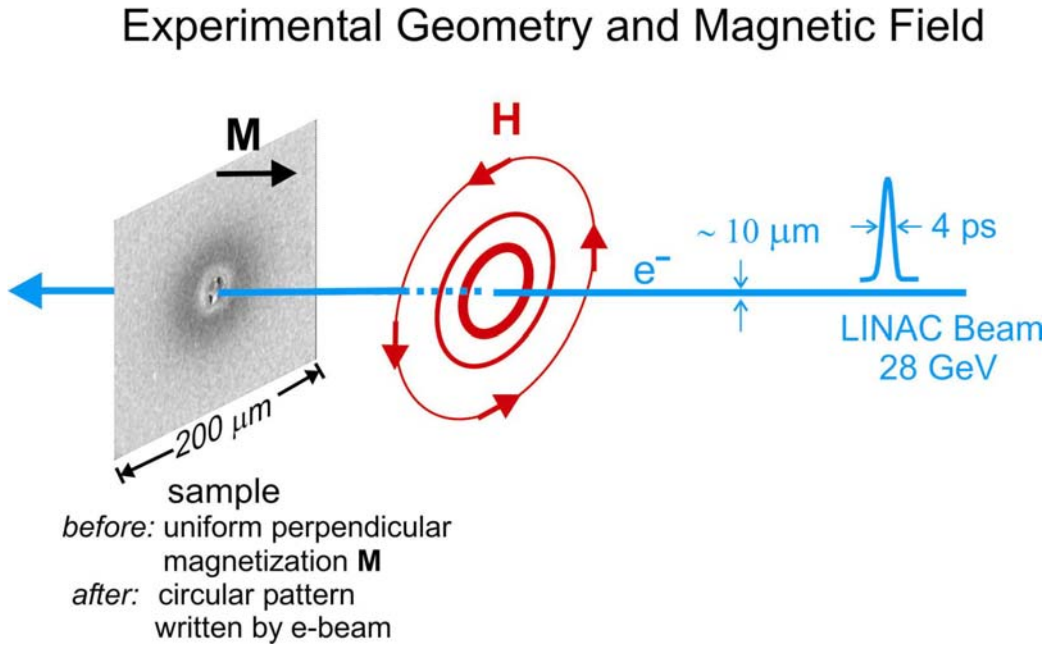

Fig. 1

When the SLAC beam with magnetic pulses of about 5 ps length (full width at half maximum) is shot through a uniformly magnetized magnetic sample with the magnetization along the surface normal, the magnetic field of the beam writes a ring-shaped magnetic pattern that reflects the symmetry of the magnetic field. When the magnetic pattern around the beam impact point is imaged some time after the SLAC experiment, deviations from the original magnetization direction can be distinguished as changes in the grey scale contrast. In our images the original magnetization direction corresponds to light grey (**M** pointing to the right in Fig. 1), the opposite magnetization direction corresponds to dark grey. Regions where the magnetization direction is ill-defined, i.e. where there are some microscopic domains with **M** pointing to the right and some with **M** pointing to the left, have an in-between shade of grey.

It is difficult to draw definitive conclusions from the image in Fig. 1 alone. The exquisite control of the linac beam position also allows one to record multiple shot images. Such images are of particular importance in the interpretation of the experimental data. The resulting patterns are extremely sensitive to whether the magnetic switching process is reversible or not, which is a key requirement for magnetic recording in technology. The experiment shows that with an increasing number of shots the magnetic pattern becomes increasingly diffuse, as illustrated in Fig. 2 by comparison of the magnetization pattern after 1 shot and 7 shots. This indicates that with increasing number of magnetic write-pulses the magnetization direction becomes ill-defined over a large region of the sample.

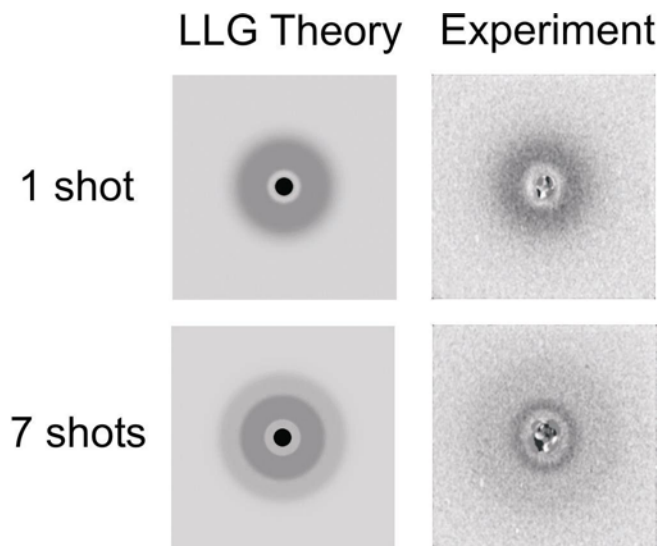

Fig. 2

After the first shot the observed pattern consists of a large light region on the outside where no switching has occurred. Closer to the center is a dark ring where the magnetization has switched to a direction that is opposite from the initial direction. The dark ring has a fuzzy outside boundary which indicates a transition region where the magnetization direction is ill-defined, i.e. it has opposite directions over microscopic dimensions of the grain size of the material. Next to the center, where beam damage prevents an analysis, one observes a light ring, where the magnetization has switched back (360^o rotation) to the original magnetization direction. After 7 shots the light center ring is still present and the dark ring, indicating well-defined switching has collapsed to a narrow ring, while the medium grey region has grown significantly and now dominates in size. This indicates that with increasing number of magnetic pulses a large chaotic zone grows where some grains have switched, but others not. Similar results were observed with different types of magnetic grains, or even with a continuous magnetic film.

The observed behavior is in stark contrast to the patterns calculated with the well-known materials parameters by micromagnetics theory, the Landau-Lifshitz-Gilbert (LLG) theory, also shown in Fig. 2. The theory also predicts an ill-defined zone, which arises from the finite thermal fluctuations of the magnetization, but the zone is much smaller than that observed by experiment.

The experiment thus showed that the switching becomes non-deterministic when the switching time is shortened to about 5 ps. A new mechanism must be operative that leads to a fracture of the magnetization at very fast time scales and requires a new theory which goes beyond the uniform precession model. This sets the speed limit to equal or longer than 5 ps and means that, at best, one can hope to write faster by a factor of about 20 than in today's most advanced R&D studies and a factor of about 200 faster than in today's computers. At faster speeds things become unpredictable.

For the original publication see: I. Tudosa et al., *Nature* **428**, 831 (2004)

More information can be found be found on the following websites:

http://www-ssrl.slac.stanford.edu/stohr/index.htm
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