Soft X-ray microscopy – a powerful analytical tool to image magnetism down to fundamental length and time scales

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Acknowledgements

This work was supported by the Director, Office of Science, Office of Basic Energy Sciences, Materials Sciences and Engineering Division, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

The author wants to thank M-Y. Im, B.L. Mesler, W.L. Chao, A. Sakdinawat, E. Anderson, D. Attwood (CXRO), K.-D. Lee, S.-H. Lee, S.-Ch. Shin (KAIST Korea), D.-H. Kim (Chungbuk NU, Cheongju, Korea), G. Meier, L. Bocklage, M. Bolte, R. Eiselt B. Krueger (U Hamburg Germany) for their collaboration on this topic. The continuous help of the staff of CXRO and ALS is highly appreciated

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Abstract

The magnetic properties of low dimensional solid state matter is of the utmost interest both scientifically as well as technologically. In addition to the charge of the electron which is the base for current electronics, by taking into account the spin degree of freedom in future spintronics applications open a new avenue.

Progress towards a better physical understanding of the mechanism and principles involved as well as potential applications of nanomagnetic devices can only be achieved with advanced analytical tools. Soft X-ray microscopy providing a spatial resolution towards 10nm, a time resolution currently in the sub-ns regime and inherent elemental sensitivity is a very promising technique for that. This article reviews the recent achievements of magnetic soft X-ray microscopy by selected examples of spin torque phenomena, stochastical behaviour on the nanoscale and spin dynamics in magnetic nanopatterns. The future potential with regard to addressing fundamental magnetic length and time scales, e.g. imaging fsec spin dynamics at upcoming X-ray sources is pointed out.

Challenges to modern magnetic microscopies

Research of magnetism in low dimensions has not only led to important fundamental discoveries, such as the Giant Magnetoresistance (GMR) effect [1][2] which has been awarded with the Noble Prize Physics in 2007, but has also tremendously changed current technologies, particularly in the field of magnetic sensor and storage technologies. Manipulating the spin on the nanoscale, its fundamental understandiung and applications thereof is furthermore considered to be one of the grand challenges in nanoscience [3].

Solid state magnetism is also a showcase in the way scientific research is performed, i.e. the classical method of observation and interpretation of physical phenomena is extended by the capability and the desire to functionalize and control magnetism down to fundamental length and time scales and also to create novel materials such as multiferroics, which envision revolutionary ways to tailor magnetism.

While fundamental length scales, such as magnetic exchange length in magnetism, which are in the sub-10nm regime can be approached to a large extent both experimentally and theoretically with a variety of techniques, the corresponding fundamental time scales down to the fs regime can be approached by means of optical laser techniques [3], but unfortunately with a limited spatial resolution.

The ultimate question, how magnetism behaves when both the fundamental magnetic length and time scales will be approached cannot be addressed today. A thorough understanding of e.g. the nature and origin of the exchange interaction is therefore still missing.

Imaging magnetic structures and the corresponding fast and ultrafast spin dynamics in novel and advanced magnetic materials is a very appealing analytical approach and therefore a manifold of powerful imaging techniques have been developed and flourished recently.

To name just a few, Spin polarized Scanning tunneling microscopy provides static images with almost atomic spatial resolution [4]. On the other hand time resolved Kerr microscopy using the magneto-optical Kerr effect images with a time resolution down to fs regime, however, with an (diffraction) limited spatial resolution in the sub-micrometer range only. None of these techniques is able to distinguish the magnetic response from individual components in multicomponent novel materials, which is of paramount interest in the development of novel materials.

The grand challenge to modern magnetic microscopues is to approach a sub-10nm spatial resolution with elemental specificity and, at the same time a fsec time resolution with the capability to take instantaneous snapshot images of ultrafast spin dynamics.

Magnetic soft X-ray microcopy offers a unique potential. It not only combines X-ray magnetic circular dichroism as element specific contrast with a high spatial resolution due to Fresnel zone plates used as imaging X-ray optical elements, but can be foreseen to add at upcoming high brilliant X-ray sources such as Free Electron Lasers (FELs) a fsec time resolution, that will expand the capabilities of current third generation sources where due to the inherent time structures an only sub-100ps temporal resolution can be used in stroboscopic pump-probe experiments.

Magnetic soft X-ray microscopy

Although immediately after the discovery of X-rays by W.C. Roengen in 1885 the short wavelength of X-rays has been used to determine e.g. crystal structures, the lack of appropriate X-ray optics has prevented X-ray microscopy for more than 80 years until it became clear that Fresnel zone plates (FZP), which are circular gratings with a radially increasing line density can be used as diffractive optics to build X-ray microscopes [5]. FZPs can be designed and customized for specific purposes and applications. Varying a few parameters, such as Δr, which is the outermost ring diameter, N, the number of zones, and λ, the photon wavelength at which the FZP is operating one obtains a spatial resolution which is proportional to Δr, a focal length, which is $\sim 4N(\Delta r)^2/\lambda$ and a spectral bandwidth which is ~1/N. The most advanced FZPs for soft X-ray microscopy have achieved a spatial resolution better than 15nm [6], and the current developments seem to make the 10nm spatial resolution regime become feasible in the near future.

The optical setup of the full-field soft X-ray microscope endstation XM-1, located at the Advanced Light Source in Berkeley CA, where the data presented in this review have been obtained is shown in Fig. 2 and described in detail elsewhere [7].

The principle of this instrument follows that of an optical microscope, consisting of

a) a light source, which is the bending magnet source at a third generation X-ray synchrotron such as the ALS,

b) a condenser part, which here comprises of the first FZP, the condenser zone plate (CZP) and acts as both monochromator and illuminating optic,

c) an objective lense, the so-called micro zone plate (MZP) and

d) a two dimensional detector, which is a commercially available CCD system.

The spatial resolution is provided by performance of the MZP, i.e. the smaller the outermost zones can be fabricated by nanolithography, the better the spatial resolution will be. Elemental specificity is determined by the spectral resolution of the illuminating part, which here is dominated by the CZP-pinhole arrangement. The time resolution is limited by the time structure of the X-ray source, therefore progress towards better time resolution requires X-ray sources with shorter time structures.

The magnetic contrast is provided by X-ray magnetic circular dichroism (XMCD), i.e. the fact that the absorption of circularly polarized X-rays depends strongly on the relative orientation between the photon helicity and the photon propagation direction. The XMCD effect occurs predominantly in the vicinity of X-ray absorption edges, such as the spin-orbit coupled L_2 and L_3 edges. They refer to the element specific binding energies of inner core electrons, which adds an inherent elemental sensitivity to this analytical tool. XMCD effects with large values up to 25% [8] occur e.g. for 3d transition metals such as Fe, Co, Ni, which are the most prominent materials for magnetic specimens.

The transmission geometry probes the volume of the sample with a thickness up to few 100nm, which matches perfectly most of the systems of interest..

As a pure photon-in/photon-out based technique magnetic fields of in principle any strength and pointing in any direction can be applied during the recording of X-ray images. At XM-1 typical magnetic fields up to 2-3kOe in perpendicular geometry and about 1-2kOe along the plane of the sample can be applied. Samples with both perpendicular and in-plane anisotropy can be investigated. To image in-plane components the sample has to be tilted at an axis perpendicular to the photon beam propagation.

Time resolution, i.e. the observation of spin dynamics benefits from the inherently pulsed structure of X-ray synchrotron storage rings. At the ALS electrons having a typical energy of 1.9GeV circulate in so-called bunches at a velocity close to the speed of light. The typical bunch length corresponds to about 70ps, therefore the emitted X-ray flashes have the same length. Setting up a stroboscopic pump-probe scheme one can study with soft X-ray microscopy spin dynamics on the sub-100ps time scale in nanoscale magnetic elements [9]. The time resolved studies shown in this review have been in the so-called 2-bunch mode operation, where two electron bunches, each 70ps in width circulate at a 3MHz frequency, i.e. separated by 328ns. The low intensity per bunch implies prevents single shot time resolved imaging and therefore only the perfectly repeatable part of spin dynamics processes can be studied so far.

In the following a few selected examples of previously published work will demonstrate the current achievements of magnetic soft X-ray microscopy.

Manipulating spins on the nanoscale

The conventional interaction with magnetic moments is performed by applying external magnetic fields to the specimen. The magnetic microstructure, which in general is not the single domain state, but rather splits into a multidomain structure, forms in such a way that the total Gibbs's Free energy density, which contains mainly anisotropy, exchange and dipolar terms is minimum.

A typical example of the domain structure in a nanogranular CoCrPt thin alloy film is shown in Fig. 3 [10]. These films exhibit a pronounced perpendicular magnetic anisotropy and are therefore candidates for perpendicular magnetic recording. The question as to whether the nucleation during a hysteresis cycle in such a system is deterministic or exhibits a stochastical character is of high scientific and technological interest.

The image shown was obtained at the Co L_3 edge with a 15nm spatially resolving X-ray optics, which can be seen from the intensity profile across a domain following a standard knife edge analysis procedure. The dark/ bright areas in the image are a direct measurement of the direction of the local magnetic moments. Transmission electron microscopy analysis of this sample showed a grain size distribution around 20nm, and therefore the high spatial X-ray microscopy shows the magnetization reversal behaviour at the grain size level [11].

Analyzing images recorded in repeated hysteresis cycles provides a thorough insight in the stochastic character of the magnetic reveral process. Correlation coefficient derived from these studies are shown in Fig. 4 [11] and clearly reveal a stochastic character in nanogranular system, which might have a serious impact to future developments towards higher storage densities in those films.

The demand for scalability favors a different approach to manipulate spins on the nanoscale. Instead of reversing magnetization by applying external magnetic (Oersted) fields, one can use directly the spin torque exerted by a spin polarized current onto a non-linear domain configurations to switch the magnetization on a nanoscale. This effect has been described by Berger [12] and Sloncewski [13] a while ago but ony recently these effects have attracted not only significant scientific interest , but are also discussed as novel pathways for memory [14] and logic [15] devices. The spin torque induced magnetization reversal effect can be considered as the reversed GMR effect, where the transport properties, i.e. the current of electrons is impacted by the relative orientation of two magnetic layers, while for the spin torque process, the electron current acts directly on the magnetization of the layers.

Current-driven domain wall motion in magnetic nanowires, particularly the question how fast and how reliable such a domain wall can be moved upon spin current injection is of paramount importance.

The capability of magnetic soft X-ray microscopy to image directly the magnetic domain wall is shown in Fig 5. Curved 60nm thin permalloy wires with a radius of 25µm were prepared by e-beam lithography. Two contact pads were added to the structure to inject 1ns short current pulses and comparing Fig 5 a and b, i.e. before and after the injection of the pulse gives clear evidence that the domain wall was moved along the wire by the pulse [16].

Analysing repeated processes gives interesting insight into the stochastic character of the current induced domain wall motion. Fig. 6 displays the effiency of the spin torque effect derived from the X-ray microsopic images. Plotted as a power law, there is strong evidence for a stochastic character in the current induced process [16].

Spin dynamics in ferromagnetic elements

Time resolved studies of spin dynamics with soft X-ray microscopy takes advantage of the inherent time structure of current synchrotron storage rings. At the ALS the so-called 2-bunch mode operation, where two electron bunches, each 70ps in width circulate at a 3MHz frequency, i.e. separated by 328ns (Fig. 7) are used for the studies shown here. The clock signal of the synchrotron triggers a fast electronic pulser, which launches pulses with a rise time of about 100ps into a waveguide structure. These pump pulses create either a local Oersted field pulse or, if the current is sent through the magnetic element exhibits a spin torque onto the magnetic microstructure They can be delayed relative to the X-ray probe pulse to follow the time development of the excited magnetic domain pattern. The advent of the X-ray pulse onto the sample is monitored by a fast Avalanche photo diode giving an accurate measure of the arrival time of the photons on the sample.

One example for imaging fast spin dynamics is shown in Fig. 8. The groundstate configuration in PY nanoelements are Landau patterns and their perfect repeatability and various features (domain walls, vortices) makes them the ideal candidates for time resolved magnetic soft X-ray microscopy.

A sequence of images taken at several delay times between 0-5ns between the pump and the probe pulse are shown in Fig. 8 indicating both a gyrotropic vortex motion as well as the bulging of domain walls. The vertical dashed line serves as a guide to the eye, since the displacement of the vortex amounts to a few 100nm only.

Future challenges for magnetic soft X-ray microscopy

Magnetic soft X-ray microscopy is a powerful tool that combines the capability to image magnetic nanostructures and their spin dynamics in multicomponent materials combining high spatial resolution due to the advancements of X-ray optics, a high temporal resolution provided by the X-ray source and inherent elemental sensitivity due to X-ray magnetic circular dichroism as magnetic contrast.

While the current developments of the optics are enabling a sub-10nm spatial resolution in the near future and therefore will be able to image spins at fundamental magnetic length scales, the upcoming ultrafast fsec X-ray sources will add fundamental magnetic time scales and with the high brilliance at these sources single shot images of spin dynamics seems to come within reach.

The development and analysis of novel and advanced magnetic materials, such as multiferroic materials can be foreseen to open a huge variety of interactions and applications, but they will require state-of-the-art analytical tools.

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Figure Captions

Fig. 1 Modern magnetic microscopies have to tackle fundamental magnetic length and time scales as well as identifying the contribution of individual components in multicomponent novel materials.

Fig. 2. Optical setup of the full-field high resolution soft X-ray microscope XM-1 at the ALS in Berkeley, CA

Fig. 3. Left: High resolution soft X-ray microscopy image of the magnetic domain structure in a nanogranular CoCrPt thin alloy film. Right: Intensity scan showing the obtained spatial resolution of 15nm [11].

Fig. 4. Correlation coefficients derived from a statistical analysis of field induced magnetization reversal in CoCrPt nanogranular thin alloy films revealed a stochastical character in the reversal process [11].

Fig. 5. Magnetic X-ray microscope image of a domain wall in a PY microwire before (a) and after (b) the injection of a 1ns short spin polarized current pulse showing the effect of spin current induced domain wall motion [16].

Fig. 6. Analysis of repetitive attempts to move the domain wall by injecting short current pulses shows a power law behaviour, which is indicative for a stochastic character of the process [16]

Fig. 7. Schematics of the stroboscopic pump probe scheme to image spin dynamics with magnetic soft X-ray microscopy [17].

Fig. 8 Time resolved magnetic soft X-ray microscopy images of a 2x4 μm^2 *PY element upon injection of 1ns short spin current pulses. The deviation of the vortex position(marked by the red circle) from the dashed line for various delay times between the pump and the probe pulse (a-d) can be clearly seen.*

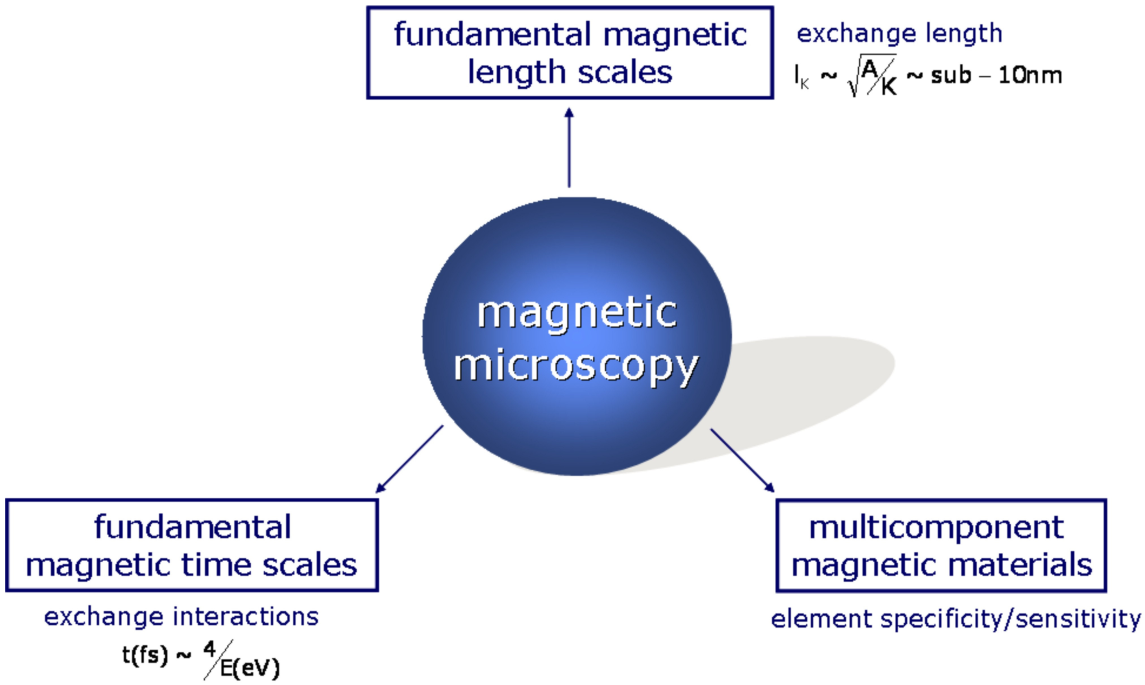


Fig 1 P. Fischer

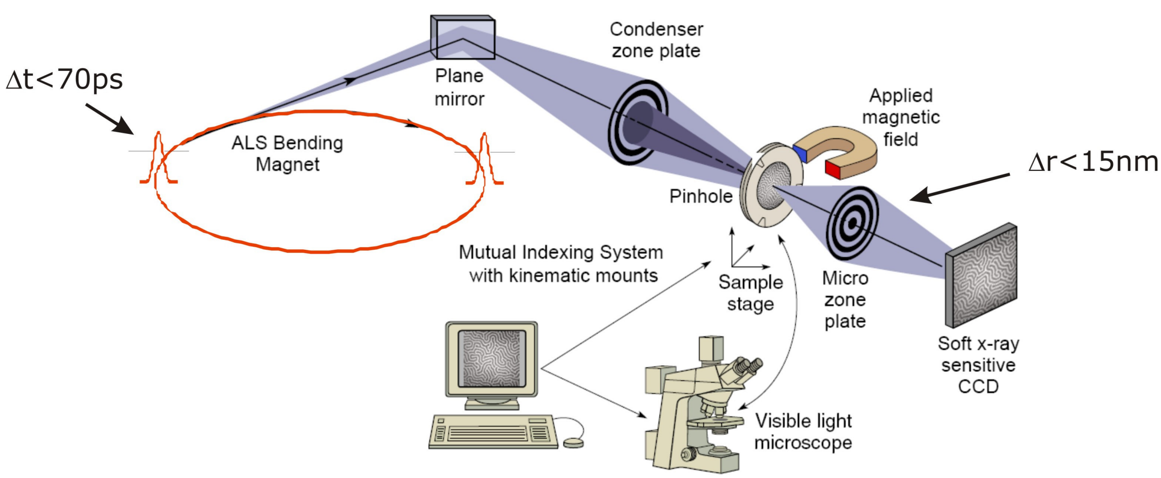


Fig 2 P. Fischer

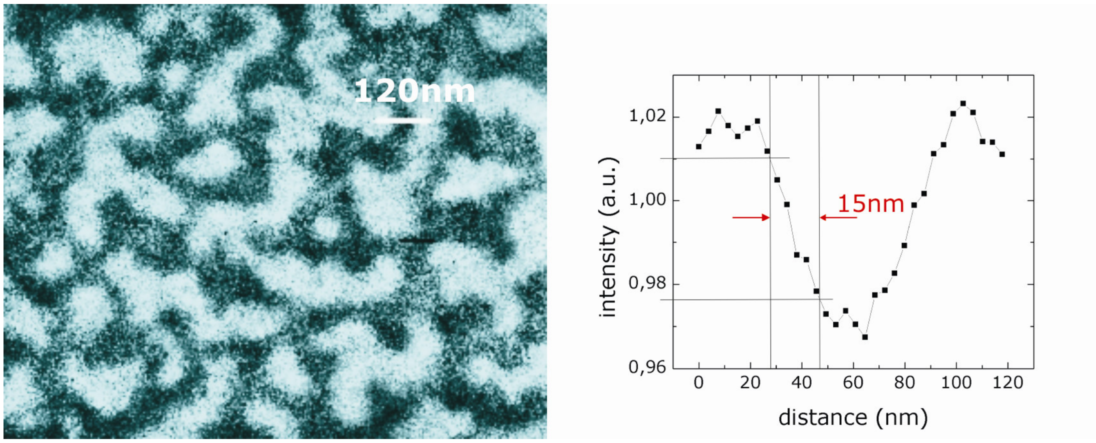
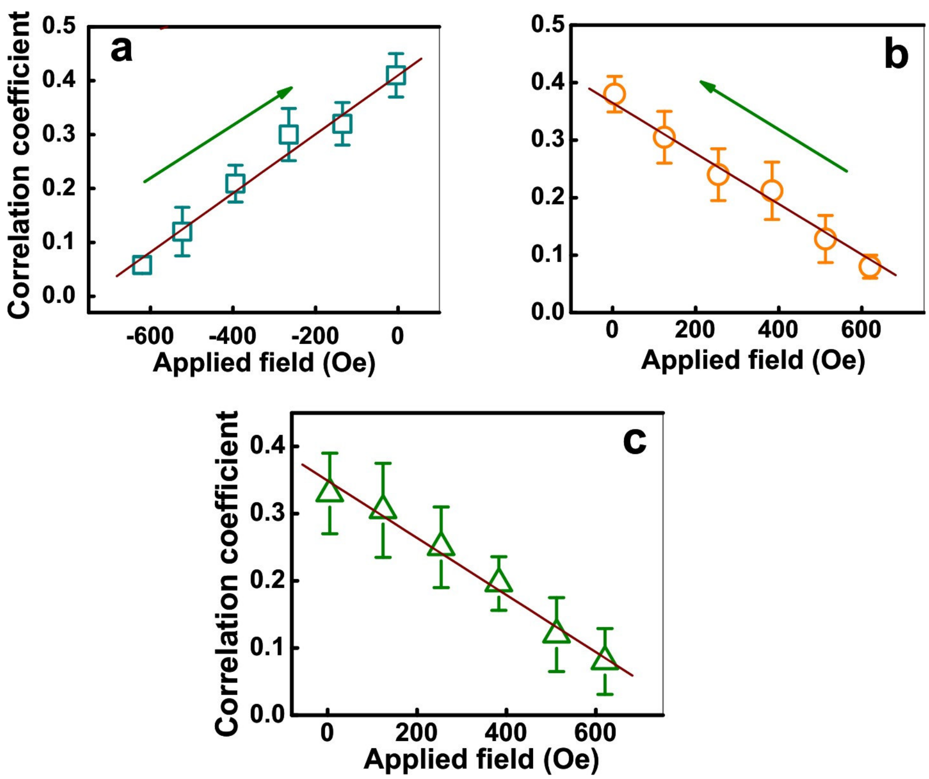


Fig 3 P. Fischer



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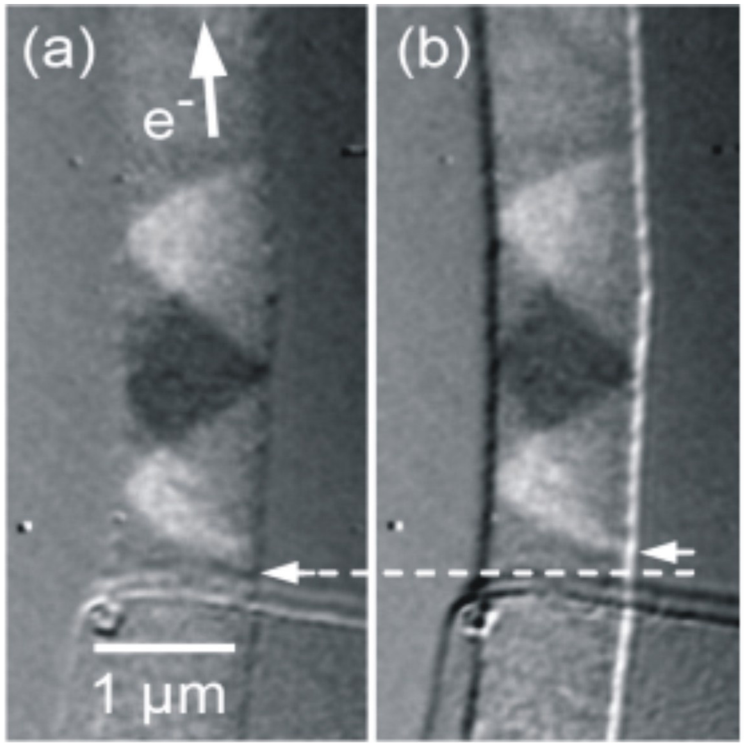

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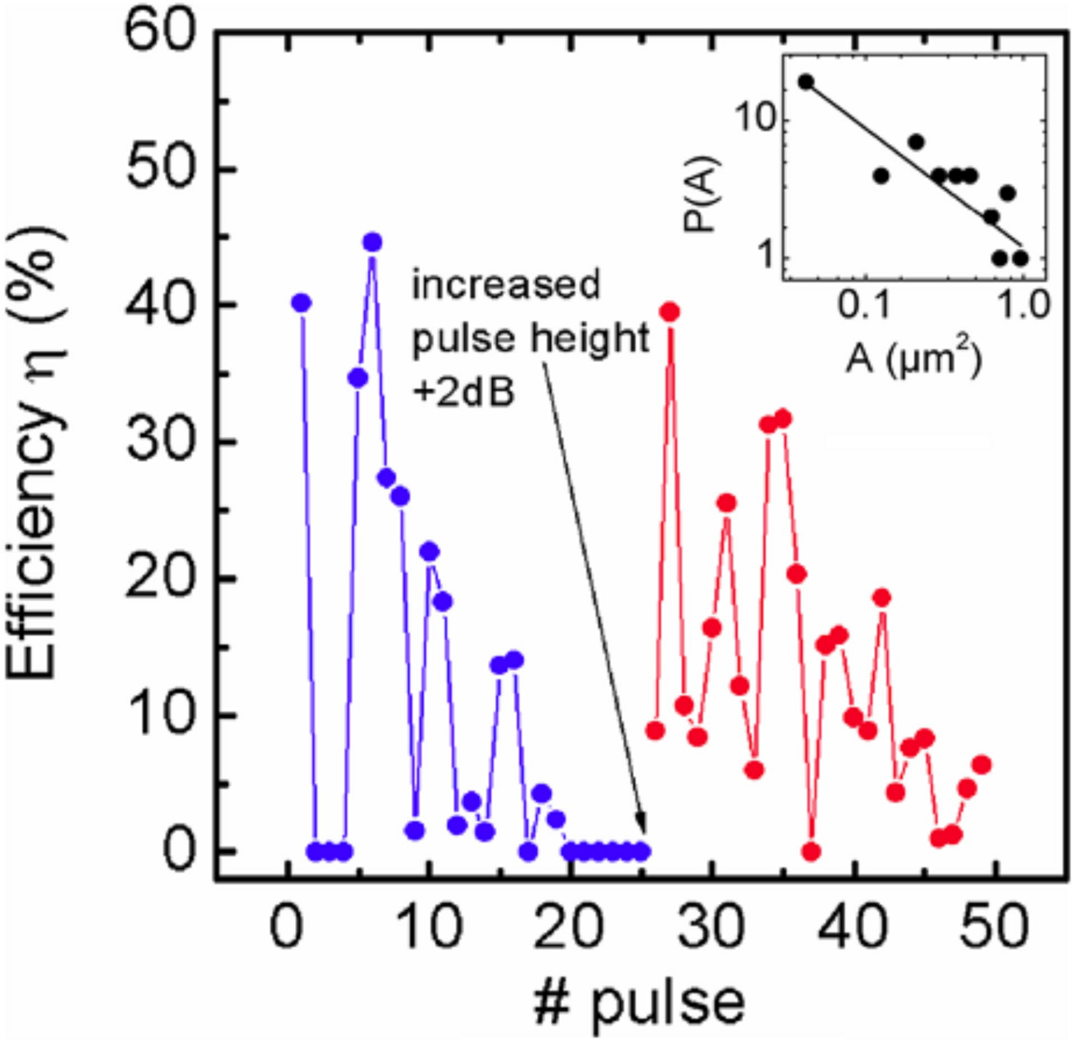

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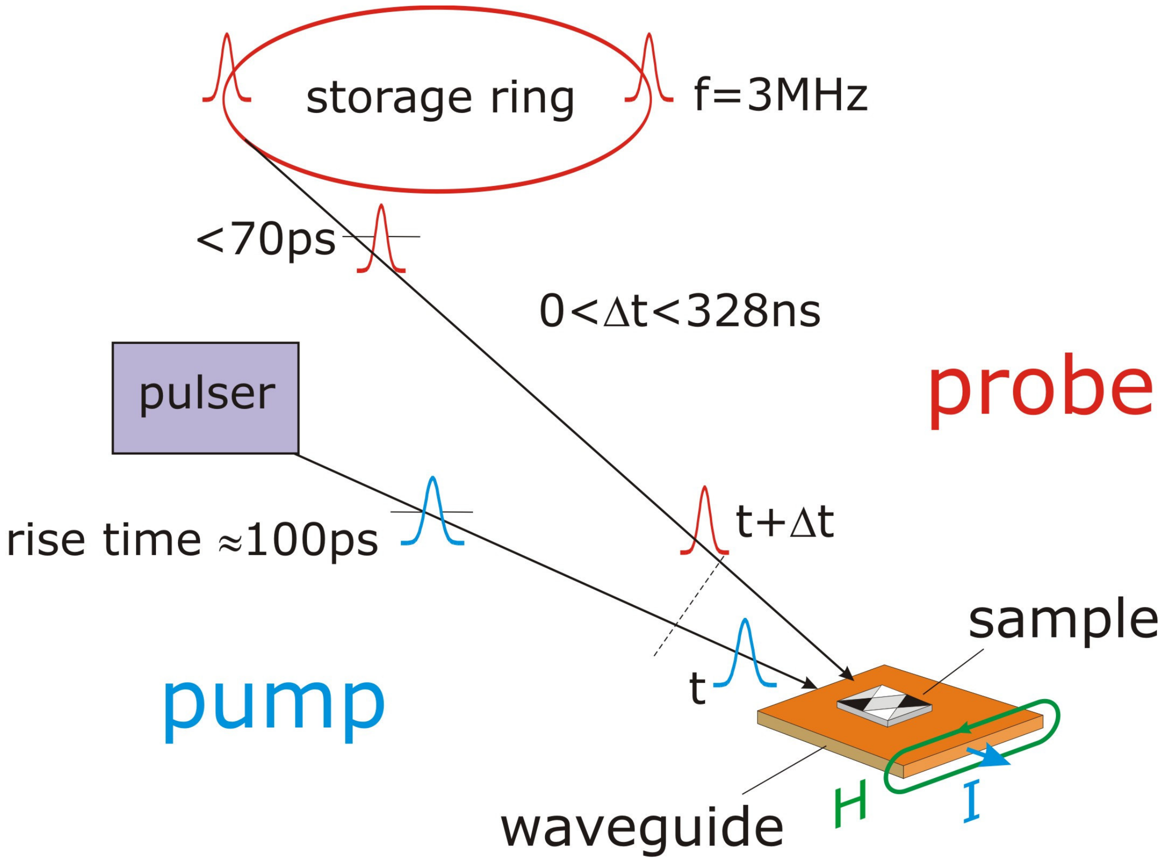
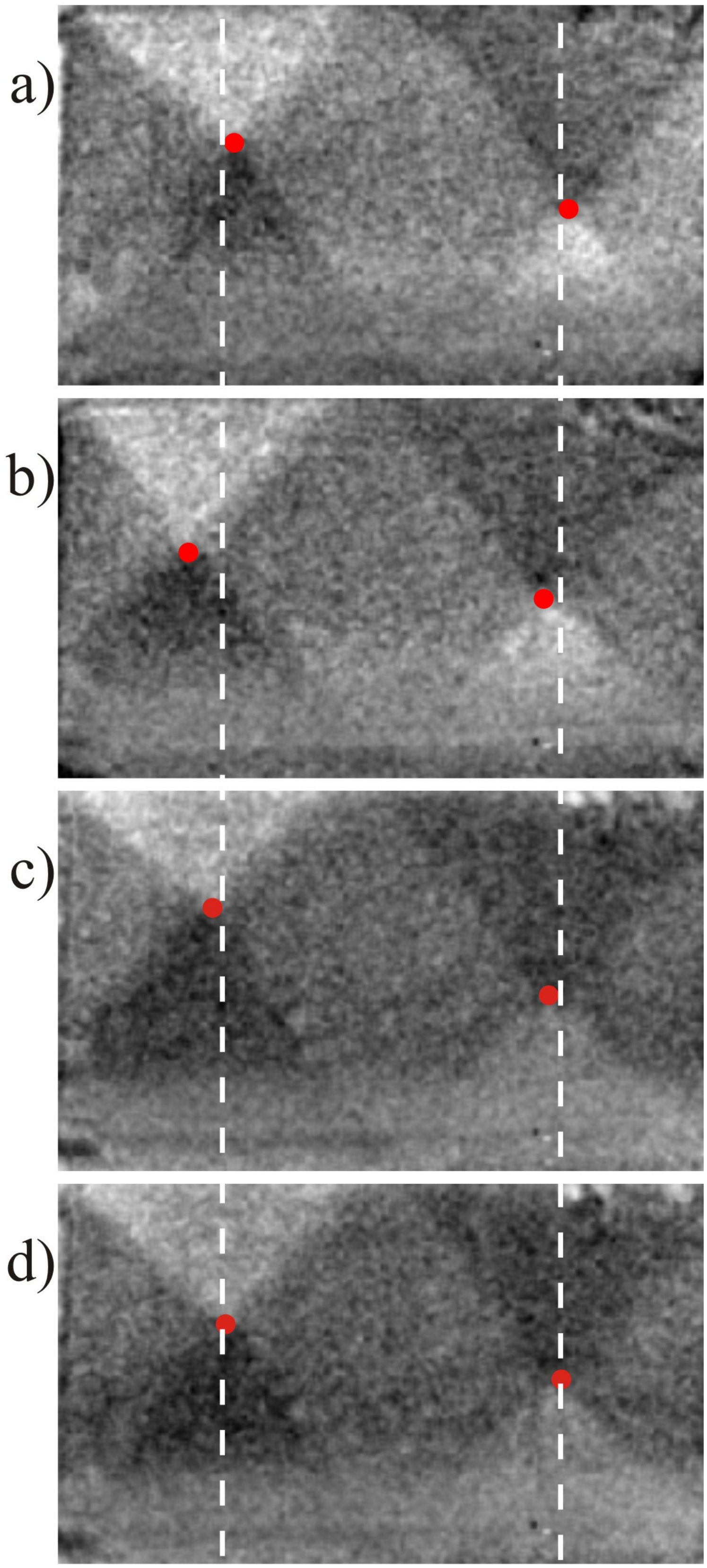


Fig 7 P. Fischer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b)
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Fig 8 P. Fischer