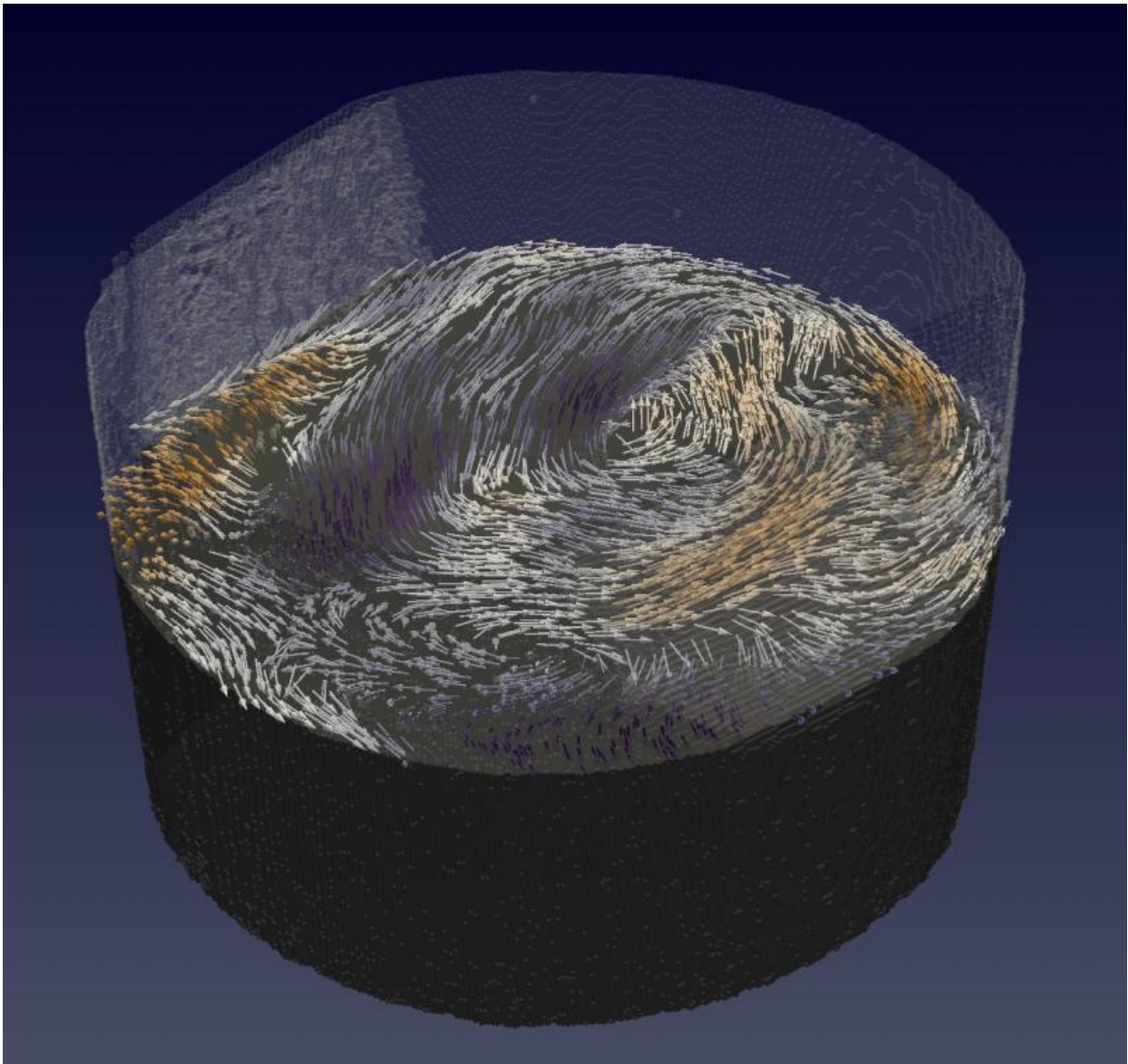


First-time 3-D imaging of internal magnetic patterns

July 20 2017, by Laura Hennemann



Swirling internal magnetic structure. A section of the investigated sample, which

is a gadolinium-cobalt pillar of diameter 0.005 millimetres (5 micrometres), is shown. With magnetic tomography, scientists determined its internal magnetic structure. Here, the magnetisation is represented by arrows for a horizontal slice within the pillar. In addition, the colour of the arrows indicate whether they are pointing upwards (orange) or downwards (purple). Credit: Paul Scherrer Institute/Claire Donnelly

Magnets are found in motors, in energy production and in data storage. A deeper understanding of the basic properties of magnetic materials could therefore impact our everyday technology. A study by Scientists at the Paul Scherrer Institute PSI in Switzerland, the ETH Zurich and the University of Glasgow has the potential to further this understanding.

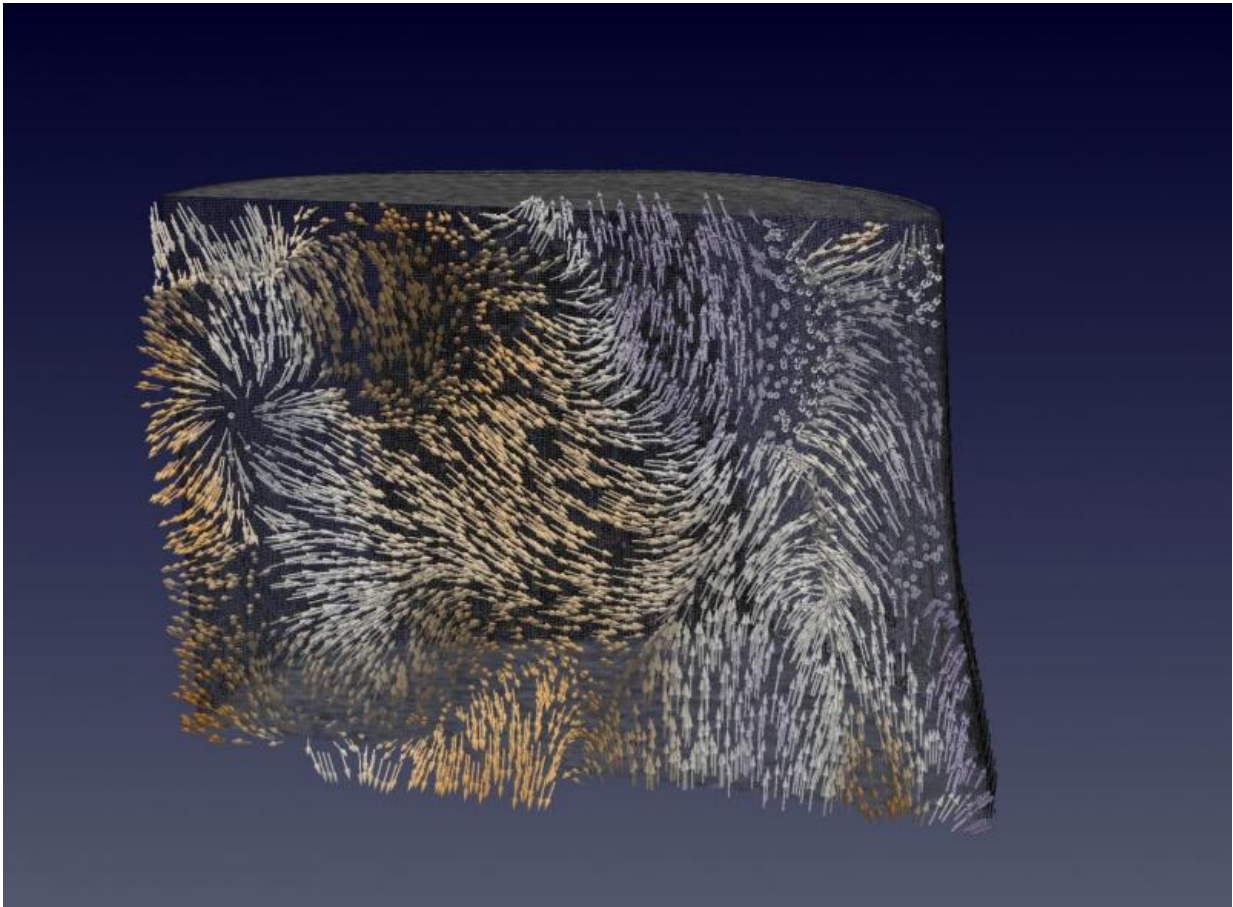
The researchers have for the first time made visible the directions of the magnetisation inside an object thicker than ever before in 3-D and down to details ten thousand times smaller than a millimetre (100 nanometres). They were able to map the three dimensional arrangement of the [magnetic moments](#). These can be thought of as tiny magnetic compass needles inside the material that collectively define its magnetic structure. The scientists achieved their visualisation inside a gadolinium-cobalt magnet using an experimental imaging technique called hard X-ray magnetic tomography which was developed at PSI. The result revealed intriguing intertwining patterns and, within them, so-called Bloch points. At a Bloch point, the magnetic needles abruptly change their direction. Bloch points were predicted theoretically in 1965 but have only now been observed directly with these new measurements. The researchers published their study in the renowned scientific journal *Nature*.

A team of scientists from the Paul Scherrer Institute PSI, the ETH Zurich and the University of Glasgow have for the first time been able to image the magnetic structure within a small 3-D object on the nanometre

scale. The [magnetic structure](#) is an arrangement of magnetic moments, each of which can be thought of as a tiny magnetic compass needle. The studied object was a micrometre-sized pillar (thousandth of a millimetre in diameter) made of the material gadolinium-cobalt, which acts like a ferromagnet. Within it, the scientists visualised the magnetic patterns that occur on a scale ten thousand times smaller than a millimetre – in other words, the smallest detail they could make visible in their 3-D images was around 100 nanometres. The sophisticated imaging was achieved by a technique called hard X-ray magnetic tomography that was newly developed at PSI in the course of this proof-of-principle study.

Up to now, imaging magnetism and magnetic patterns at this small scale could only be done in thin films or on the surfaces of objects, explains Laura Heyderman, principal investigator of the study, researcher at PSI and professor at ETH Zurich. We really feel like we are diving inside the magnetic material, seeing and understanding the 3-D arrangement of the tiny magnetic compass needles. These tiny needles 'feel' each other and hence are not oriented randomly, but instead form well-defined patterns throughout the magnetic object.

Basic magnetic structures and first-time visualisation of Bloch points



A vertical slice of the internal magnetic structure of a sample section. The sample is 0.005 millimetres (5 micrometres) in diameter and the section shown here is 0.0036 millimetres (3.6 micrometres) high. The internal magnetic structure is represented by arrows for a vertical slice within it. In addition, the colour of the arrows indicate whether they are pointing towards (orange) or away from the viewer (purple). Credit: Paul Scherrer Institute/Claire Donnelly

The scientists quickly realised that the magnetic patterns consisted of tangled fundamental magnetic structures: They recognised domains, in other words, regions of homogenous magnetisation, and domain walls, the boundaries separating two different domains. They also observed magnetic vortices, which have a structure analogous to that of tornadoes,

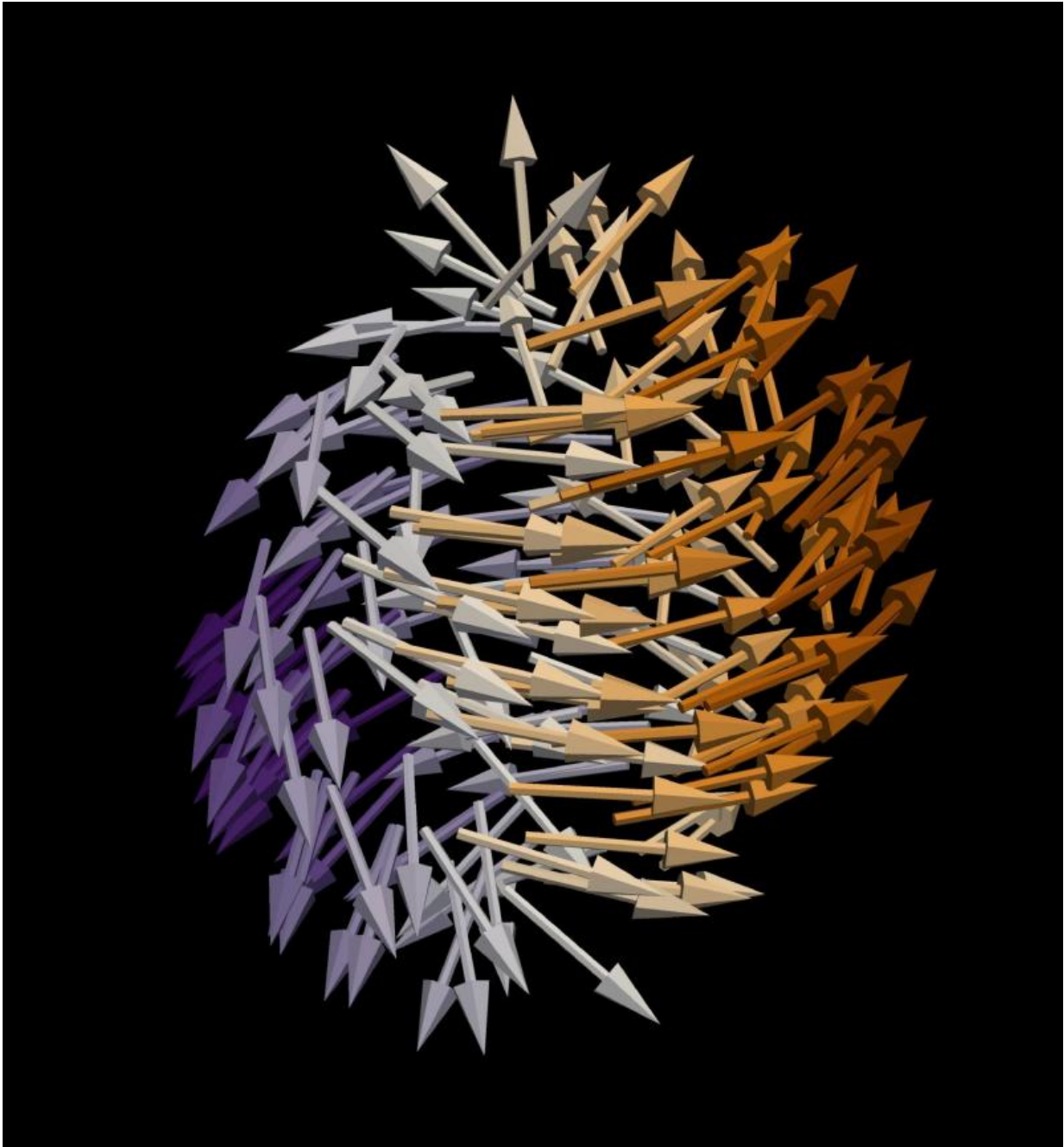
and all of these structures intertwined to create a complex and unique pattern. Seeing these basic and well-known structures come together in a complex 3-D network made sense and was very beautiful and rewarding, says Claire Donnelly, first author of the study.

One specific kind of pattern stood out and gave additional significance to the scientists' results: a pair of magnetic singularities, so-called Bloch points. Bloch points contain an infinitesimally small region within which the magnetic compass needles abruptly change their direction.

Singularities in general have fascinated scientists in a variety of research fields. Well known examples are black holes in space. In ferromagnets, the magnetisation can generally be considered continuous on the nanoscale. At these singularities, however, this description breaks down, says Sebastian Gliga of the University of Glasgow and visiting scientist at PSI. Bloch points constitute monopoles of the magnetisation and although they were first predicted over 60 years ago, they have never been directly observed.

Magnetic X-ray tomography: 3-D mapping with nanoscale resolution

The experimental technique of magnetic X-ray tomography employed in this study draws on a basic principle from computer tomography (CT). Similar to medical CT scans, many X-ray images of the sample are taken one after the other from many different directions with a small angle in-between adjacent images. The measurements were carried out at the cSAXS beamline of the synchrotron light source SLS at PSI using advanced instrumentation for X-ray nanotomography under the OMNY project and a recently developed imaging technique called ptychography. Employing computer calculations and a novel reconstruction algorithm developed at PSI, all of the data collected this way was combined to form the final 3-D map of the magnetisation.



Representation of a Bloch point which the scientists found in their data. A Bloch point contains a magnetic singularity at which the magnetisation abruptly changes its direction. Within the Bloch point shown here, this change of direction is from upward pointing magnetic needles – visualised by arrows – to downward pointing ones. This singularity is surrounded by a swirling

magnetisation pattern which is analogous to the structure of a tornado. Credit: Paul Scherrer Institute/Claire Donnelly

The scientists employed so-called 'hard' X-rays from the SLS at PSI. In comparison with 'soft' X-rays, hard X-rays have higher energy. Lower energy soft X-rays have already very successfully been used to achieve a similar map of the magnetic moments, Claire Donnelly explains. But soft X-rays hardly penetrate such samples so you can only use them to see the magnetisation of a thin film or at the surface of a bulk object. In order to really dive inside their magnet, the PSI scientists chose hard X-rays of higher energy, at the price of obtaining a much weaker signal: Many people did not believe that we would be able to achieve this 3-D magnetic imaging with hard X-rays, Laura Heyderman recalls.

Tailoring the magnets of the future

The researchers see their achievement as a contribution to a deeper understanding of the basic properties of magnetic materials. Moreover, the ability to image inside magnets could be applied to many of today's technological problems: Magnets are found in motors, in energy production and in data storage – creating better magnets thus has a huge potential of improving many every-day applications.

More information: Claire Donnelly et al. Three-dimensional magnetization structures revealed with X-ray vector nanotomography, *Nature* (2017). [DOI: 10.1038/nature23006](https://doi.org/10.1038/nature23006)

Provided by Paul Scherrer Institute

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