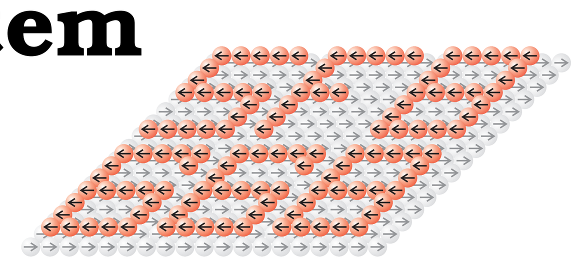
Investigation of the chiral spin structure of the double layer Fe on Ir(111) using SP-STM in a 3D vector magnetic field system



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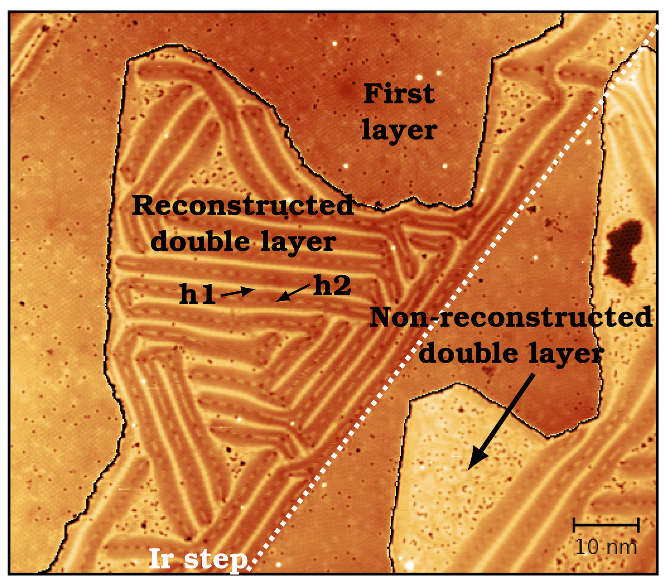
Summary

The double layer Fe on Ir(111) exhibits a non collinear chiral magnetic structure which consists of spin spirals. Their properties (wavevector and wavefront) are strongly influenced by the reconstruction of the Fe surface.
Understanding this system could be a first step in controlling the morphology of spin spirals and offer new possibilities for spintronic technology applications.

Structural properties of the double layer Fe on Ir(111)

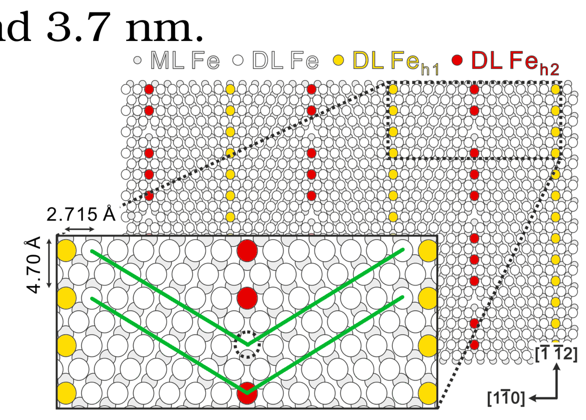
Sample preparation

The Ir(111) surface is cleaned by sputtering and subsequent annealing.
Fe is deposited onto the clean Ir(111) surface at about 200 °C.



Topography (colors adjusted separately for terraces), $B = 0$ T, $U = 200$ mV, $I = 1$ nA, $T = 4$ K, W tip

- The growth of the first layer is pseudomorphic [1].
- The second layer exhibits both reconstruction lines, due to uniaxial strain relief induced by lattice mismatch of bcc(110) Fe growth, and non-reconstructed areas.
- These **reconstruction lines appear in the 3 equivalent crystallographic directions** of the Ir(111) surface with periodicities between 3.3 and 3.7 nm.
- The proportion between reconstructed and non-reconstructed areas can be modified by changing the Fe deposition temperature.

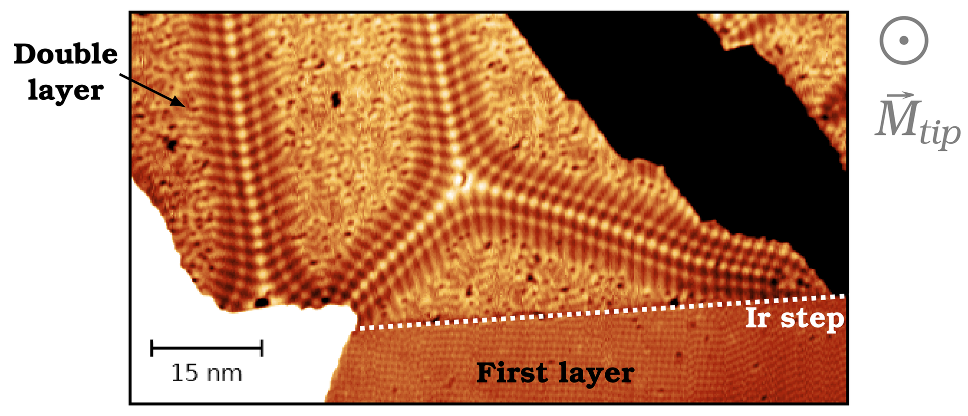


Structure model

[1] New J. Phys. 9, 396 (2007)

Magnetic structure

- The three-dimensional magnetic spin structure of the double layer Fe is probed using spin-polarized STM [1].
- **Spin spirals with a periodicity of about 1.1 nm are propagating along the reconstruction lines**.
- In the non-reconstructed areas, the spirals are not guided anymore and they propagate isotropically.



$B = 0$ T, $U = 1$ V, $I = 1$ nA, $T = 8$ K, Cr bulk tip

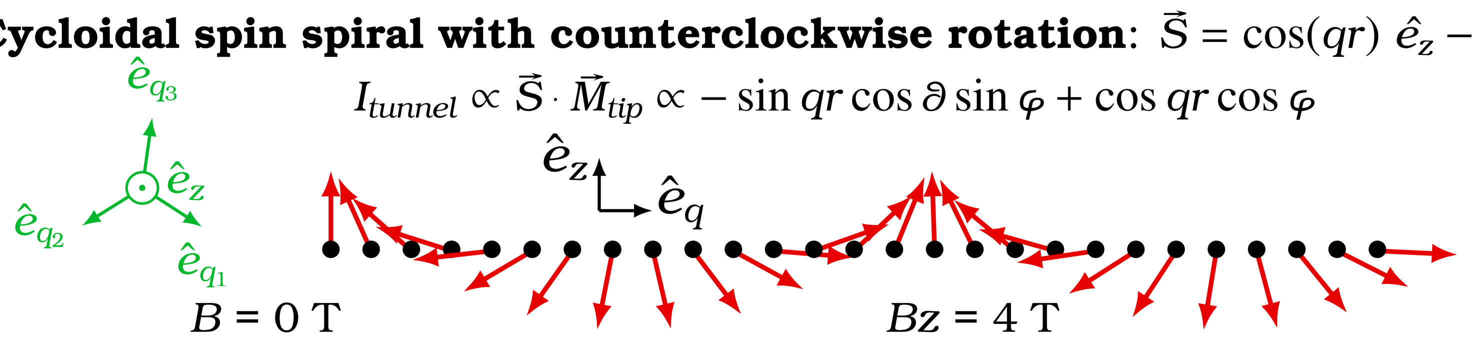
[1] Rev. Mod. Phys. 81, 1495 (2009)

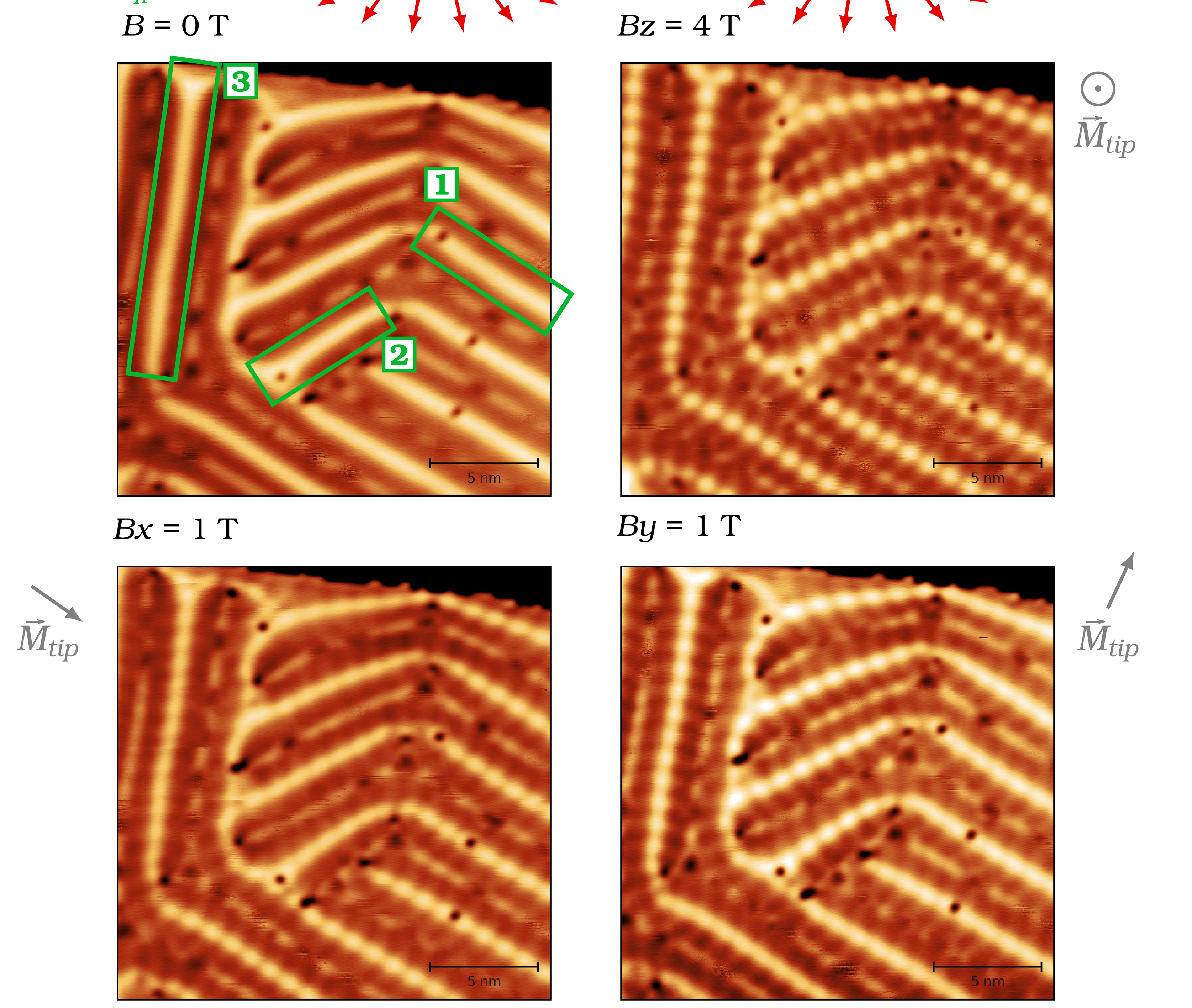
Detailed investigation of the cycloidal spin spirals

In SP-STM, the tunnel current depends on the relative angle between the tip magnetization and the local magnetization of the sample.

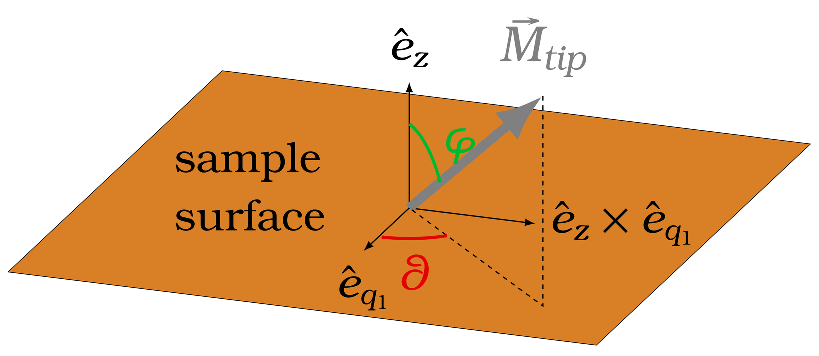
Cycloidal spin spiral with counterclockwise rotation: $\vec{S} = \cos(qr)\,\hat{e}_z - \sin(qr)\,\hat{e}_q$

$I_{tunnel} \propto \vec{S} \cdot \vec{M}_{tip} \propto -\sin qr \cos\vartheta \sin\varphi + \cos qr \cos\varphi$



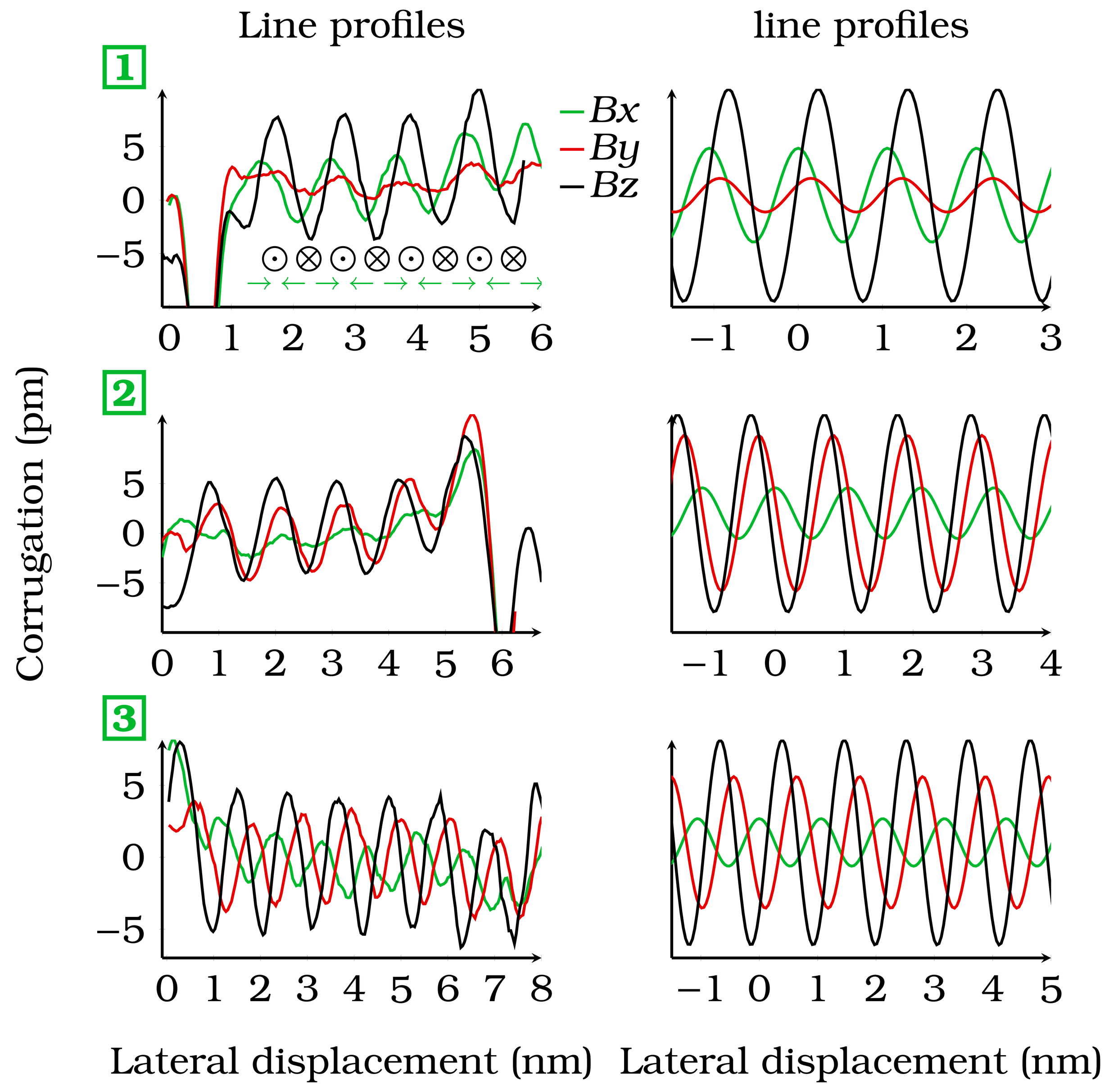


$U = +200$ mV, $I = 1$ nA, $T = 4$ K, W tip with a magnetic cluster at the end



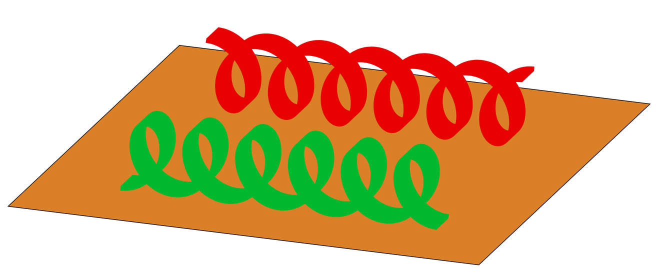
Magnetic field	Orientation of the tip magnetization (from fit)	
	ϑ	φ
$Bx = 1$ T	-2 °	90 °
$By = 1$ T	98 °	76 °
$Bz = 4$ T	4 °	47 °

For this experiment, a superparamagnetic cluster is located at the end of the tip. Without magnetic field, the magnetization of this cluster is switching and the measured signal is spin-averaged.



However, the cluster magnetization aligns with an external magnetic field (whereas the spirals do not react, see below), thus it can be controlled with the 3D vector field. In principle, **any direction of the tip magnetization can be obtained**.
The presence of 3 equivalent propagation directions of the spirals allows to determine experimentally the actual orientation of the tip magnetization. For each STM image, the line profiles of the 3 cycloids were fitted together, the angles ϑ and φ being left as free parameters.

The Dzyaloshinskii-Moriya interaction



The measurements show that **all the spin spirals are cycloids with the *same* rotational sense**. This chirality of the magnetic structure indicates that, in addition to Heisenberg exchange or other symmetrical interactions, the Dzyaloshinskii-Moriya (DM) interaction [1,2] has to be considered.

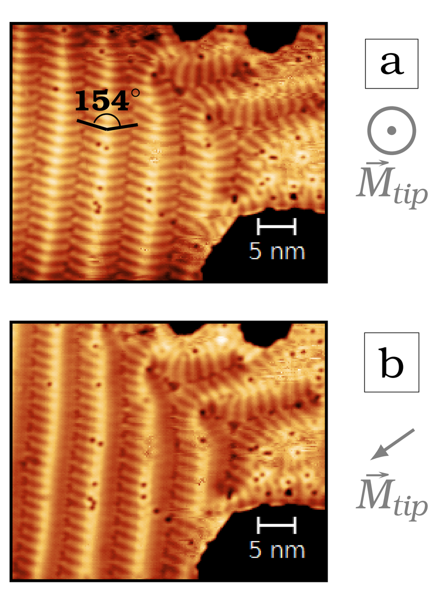
The DM interaction is an **antisymmetric** magnetic interaction originating from spin-orbit coupling and its energy is given by: $\mathcal{E}_{DM} = \sum_{ij} \vec{D}_{ij} \cdot (\vec{S}_i \times \vec{S}_j)$

For this interaction to appear, a lattice inversion symmetry breaking is needed, coming here from the interface between Fe and Ir. The two types of cycloids, when they are placed on a surface (cf drawing) cannot be linked by a symmetry operation [3]. Hence, they can have different energies and one rotational sense is favoured by the DM interaction.

[1] J. Phys. Chem. Solids, 4, 241 (1958) ; [2] Phys. Rev, 120, 91 (1960) ; [3] J. Phys. Cond. Mat, 26, 394002 (2014)

Zig-zag shape of the spirals wavefront

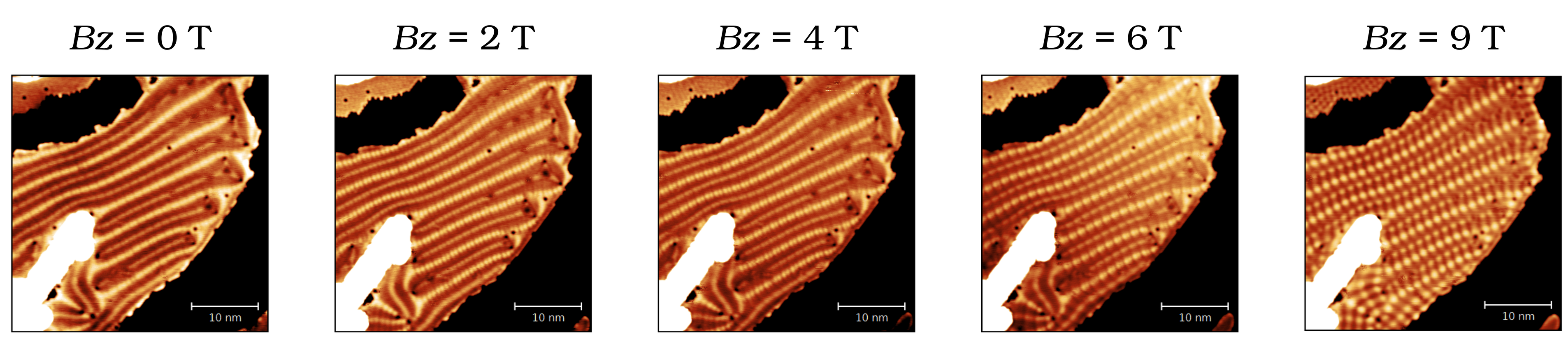
- The spin spiral wavefront has a **zig-zag shape**.
- This wavefront follows the lines marked in green on the structure model.
- There is an **angle between the spins on adjacent tracks**: no magnetic contrast on half of the tracks with a specific in-plane tip (image b).
- The measured angle of 154° is bigger than the one expected from the structure model (116°)
$\Longrightarrow$ competition between coupling to the atomic lattice and energy loss due to the kinks in the wavefront.



$U = +500$ mV, $I = 1$ nA, $T = 8$K, $B = 2.5$ T, Cr bulk tip

Effect of out-of-plane magnetic field

An out-of-plane magnetic field was applied to the sample and no significant change in the magnetic structure was observed (the magnetic contrast increases with the external magnetic field). There is **no magnetic phase transition up to 9 T.**



$U = +200$ mV, $I = 1$ nA, $T = 4$ K, Cr bulk tip