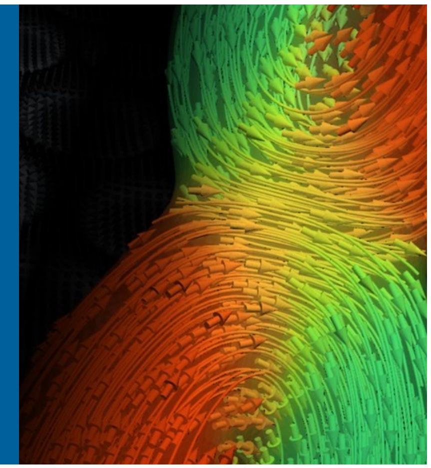
WORKSHOP: NANOMAGNETISM IN 3D

FRONTIERS OF IMAGING AND UNDERSTANDING 3D NANOSCALE MAGNETIC STRUCTURES



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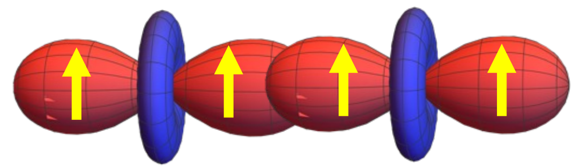
Materials Science Division, Argonne National Laboratory

Department of Materials Science and Engineering,
Northwestern University.

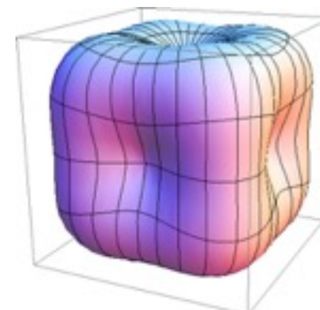
May 1, 2024
Ingelheim, Germany

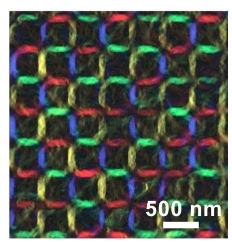
MAGNETIC NANOSTRUCTURES

Exploring the energy landscape

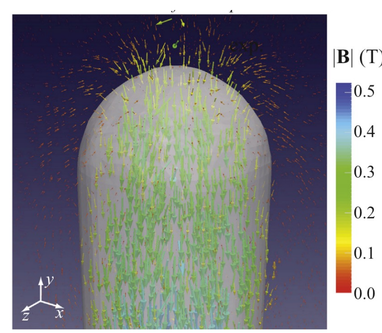


- Exchange Energy
- Magnetocrystalline anisotropy
- Shape anisotropy
- .....

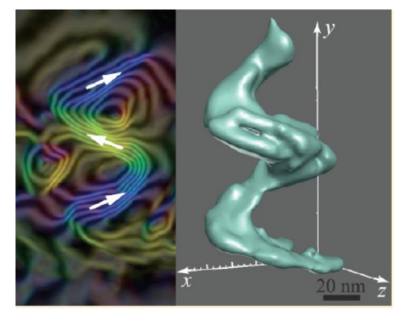




C. Phatak, et al. Phys. Rev. B **83**(17), 174431 (2011).



C. Phatak, et al. Ultramicroscopy **164**, 24–30 (2016).



C. Phatak, et al. Nano Letters **14**(2), 759–764 (2014).

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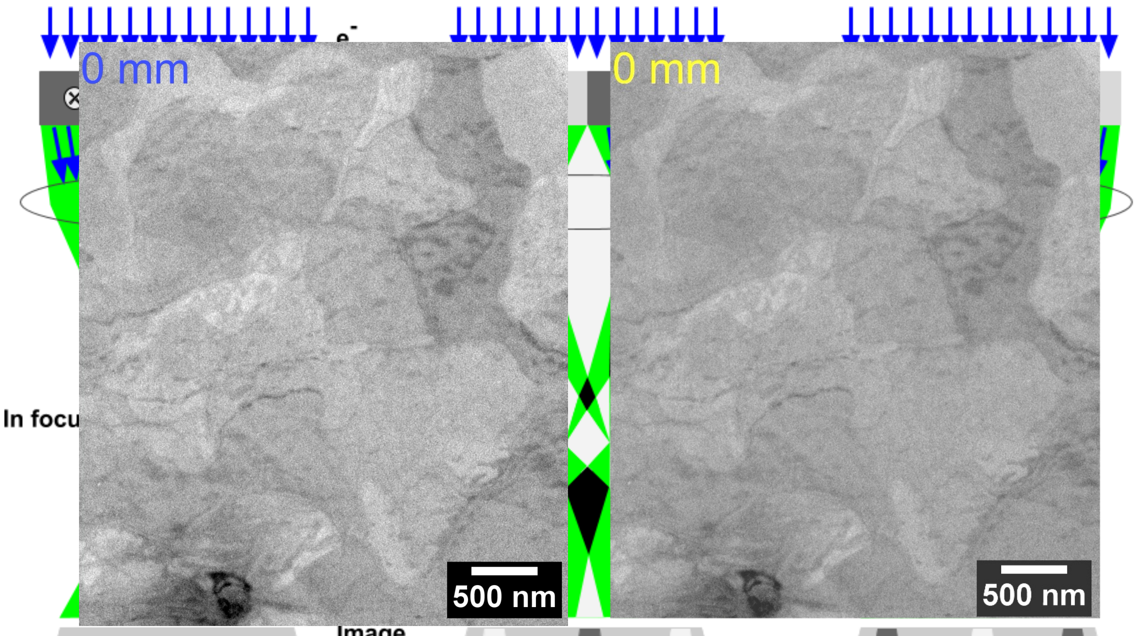
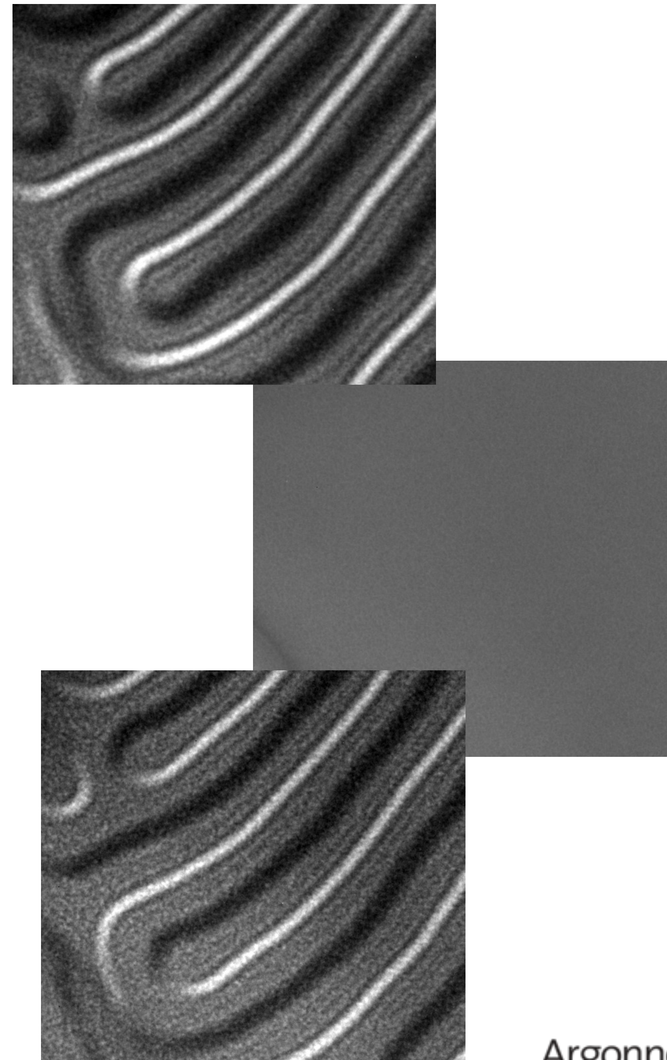
LORENTZ TEM

LORENTZ TEM – IMAGING

Fresnel Mode:

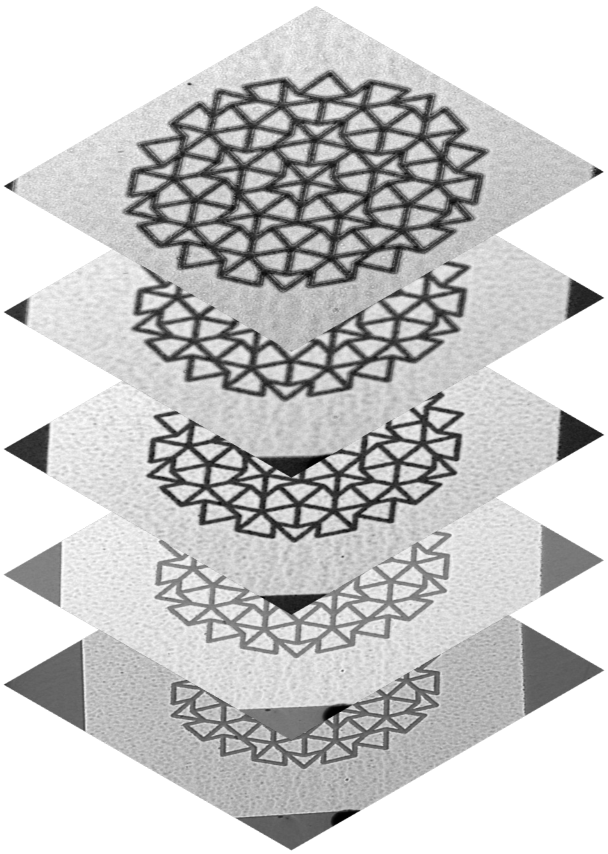


Fe_5GeTe_2: T=100 K, 600 Oe field, tilt=24º



- Out-of-focus images highlights regions of change in magnetization
  - Domain walls, Vortices, Skyrmions

PHASE RETRIEVAL USING TIE



Through-Focus Series of TEM images

Transport of Intensity Equations (TIE)

$$\varphi(\mathbf{r}_\perp, z) = -\frac{2\pi}{\lambda}\nabla_\perp^{-2}\left[\nabla_\perp \cdot \left(\frac{1}{I(\mathbf{r}_\perp,0)}\nabla_\perp\left\{\nabla_\perp^{-2}\left[\frac{\partial I(\mathbf{r},0)}{\partial z}\right]\right\}\right)\right], \quad I(\mathbf{r}_\perp,0) \neq 0$$

In-focus image

Approximated by difference between the over- and under-focus images

$$\nabla\varphi = \frac{2\pi e t}{h}(\mathbf{B} \times \mathbf{n})$$

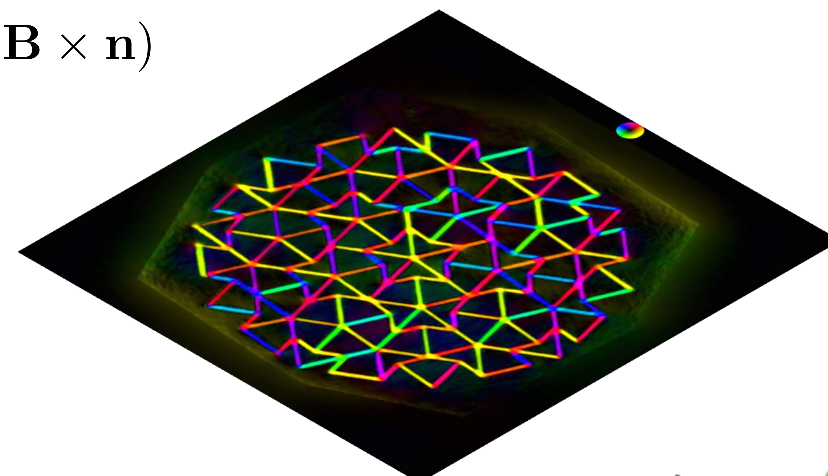


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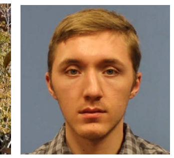
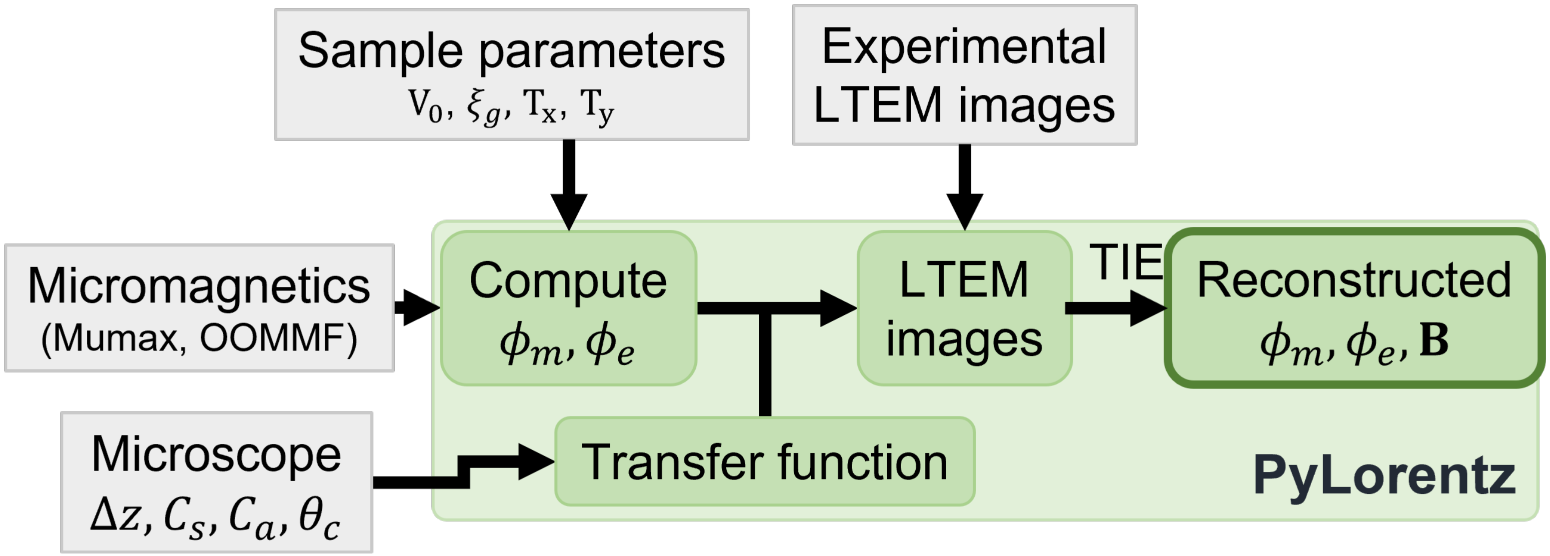
IMAGE ANALYSIS AND SIMULATION

Simulating LTEM images from micromagnetics output

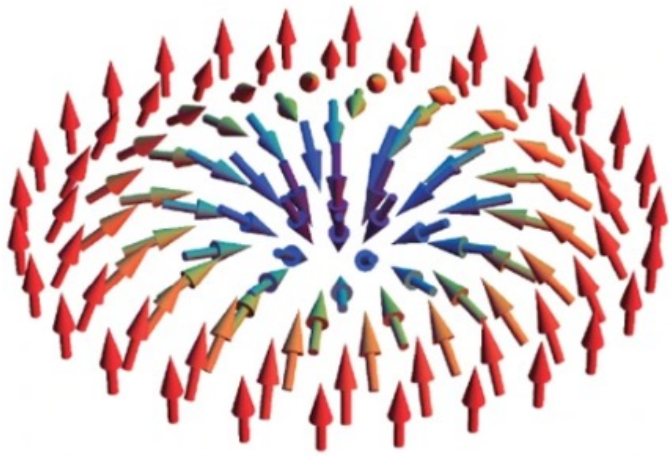




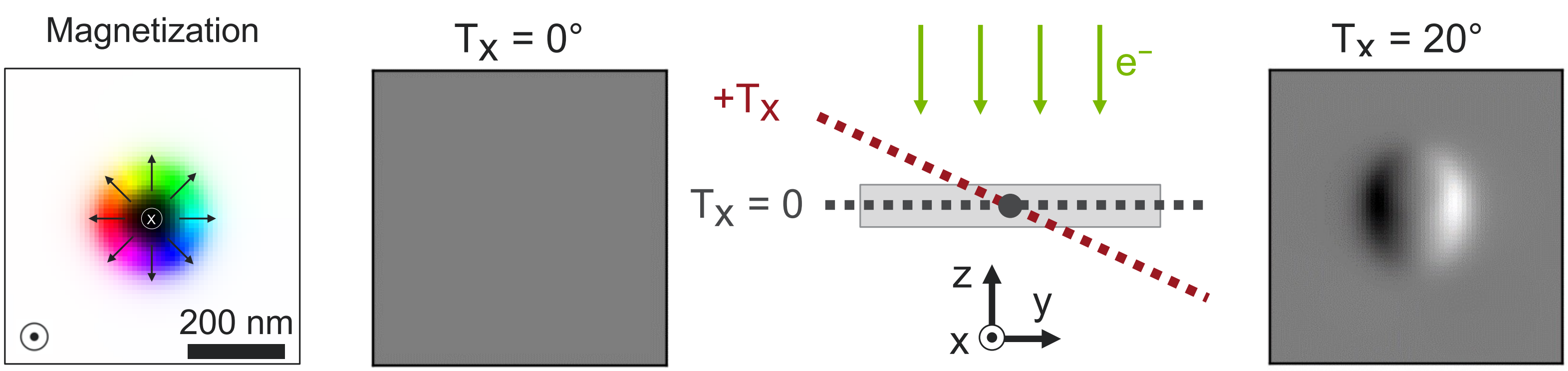
- We developed a new method for calculating electron phase shift through a magnetic material, using the linear superposition method
  - This works for 3D magnetization at any image tilt

McCray *et al. Phys. Rev. Appl.* **15**, 044025 (2021).
https://github.com/PyLorentz/PyLorentz

NÉEL SKYRMION: 3D MAGNETIC STRUCTURE



- Néel skyrmions must be tilted to create contrast



Simulated LTEM images at Δz = −25 μm, for 0° tilt and rotated 20° about the x axis

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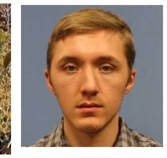
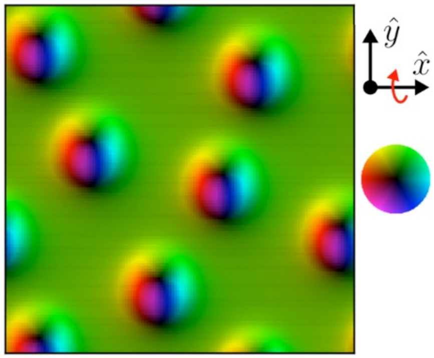
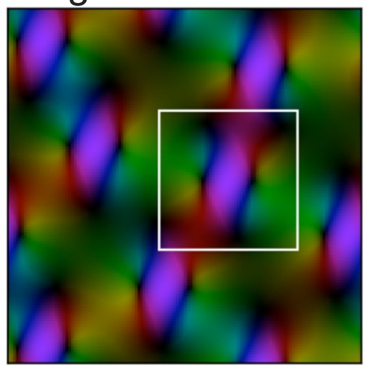
NÉEL SKYRMIONS

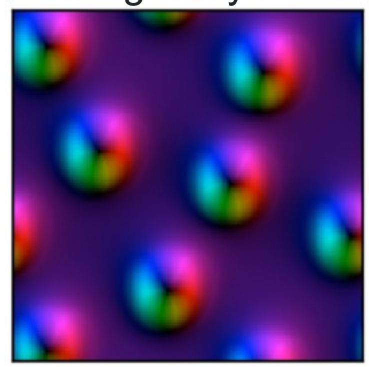
Magnetization



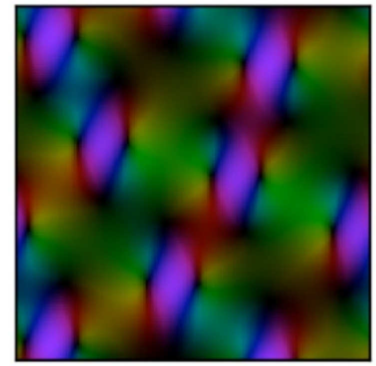
Reconstructed Magnetic Induction



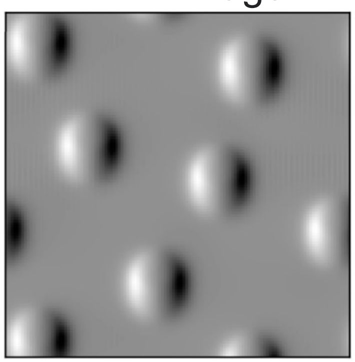
Demag/Stray Field



$B = \mu_0(M + H)$



LTEM Image



These do not match!!

In LTEM, we measure the total projected magnetic induction which includes the stray fields

Simulation is critical to account for tilt and stray fields

It allows us to interpret the magnetization from the magnetic induction

McCray *et al. Phys. Rev. Appl.* **15**, 044025 (2021).

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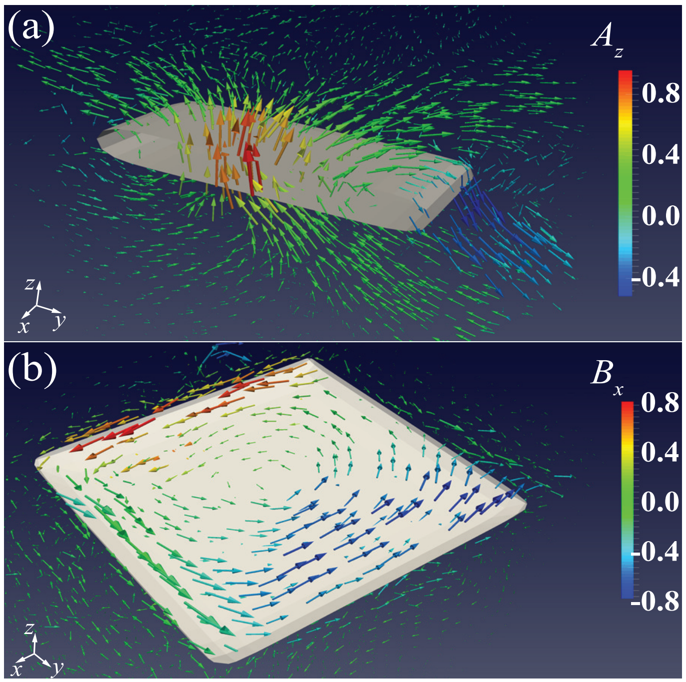
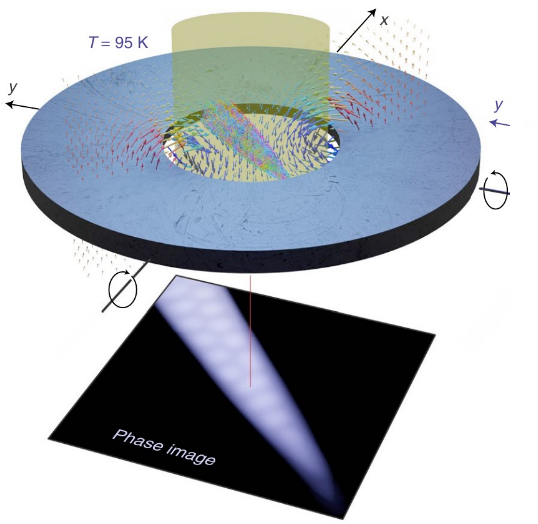
VECTOR FIELD ELECTRON TOMOGRAPHY

Reconstructing 3D Magnetic Fields

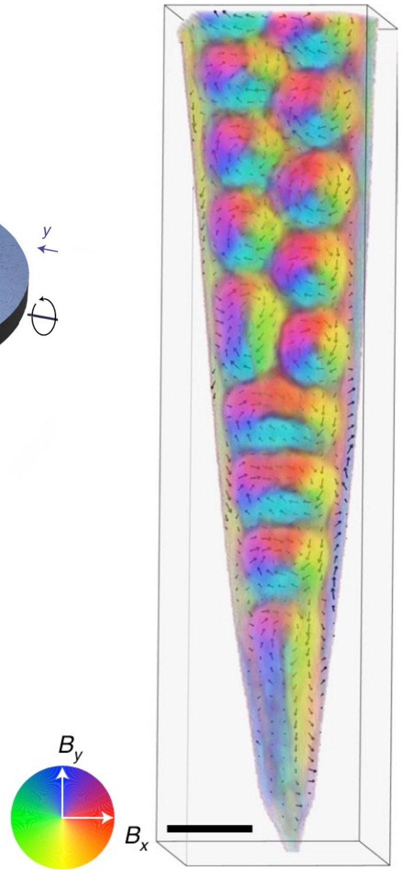
Patterned Permalloy



C. Phatak, et al., Phys. Rev. Lett. **104**, 253901 (2010).



3D Skyrmion tubes



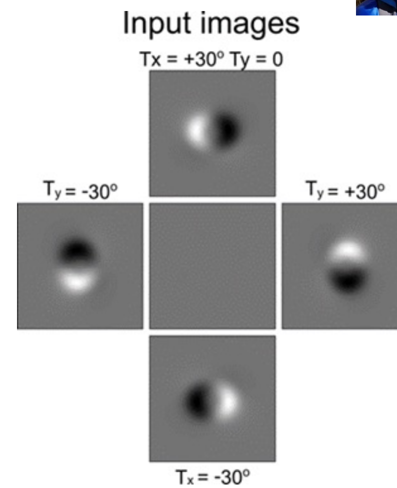
D. Wolf, et al., Nat. Nanotechnol. **17**(3), 250–255 (2022).

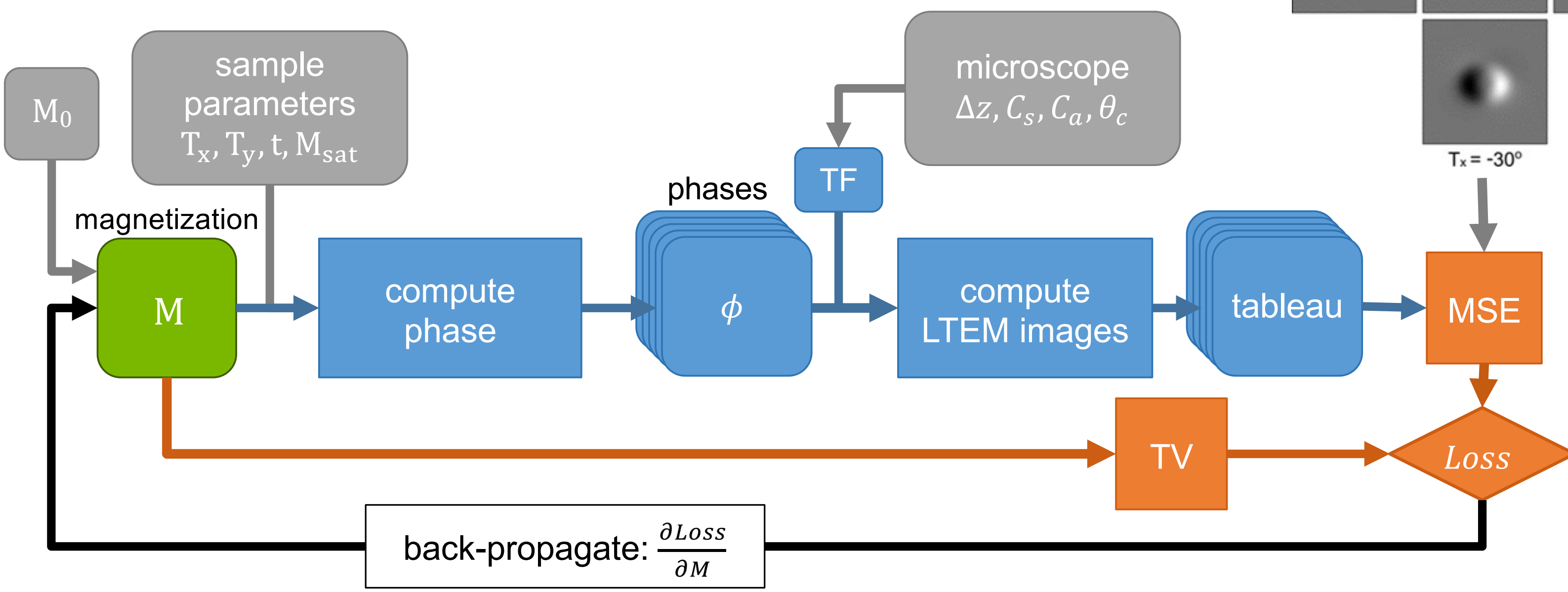
Can we reconstruct the sample magnetization from LTEM data?

3D MAGNETIZATION RECONSTRUCTION

Automatic differentiation (AD) of a forward model

- The forward model is composed of two steps: **M** → ϕ → images
- Input is a tilt tableau of defocused LTEM images
- Iteratively learns the magnetization that creates those images



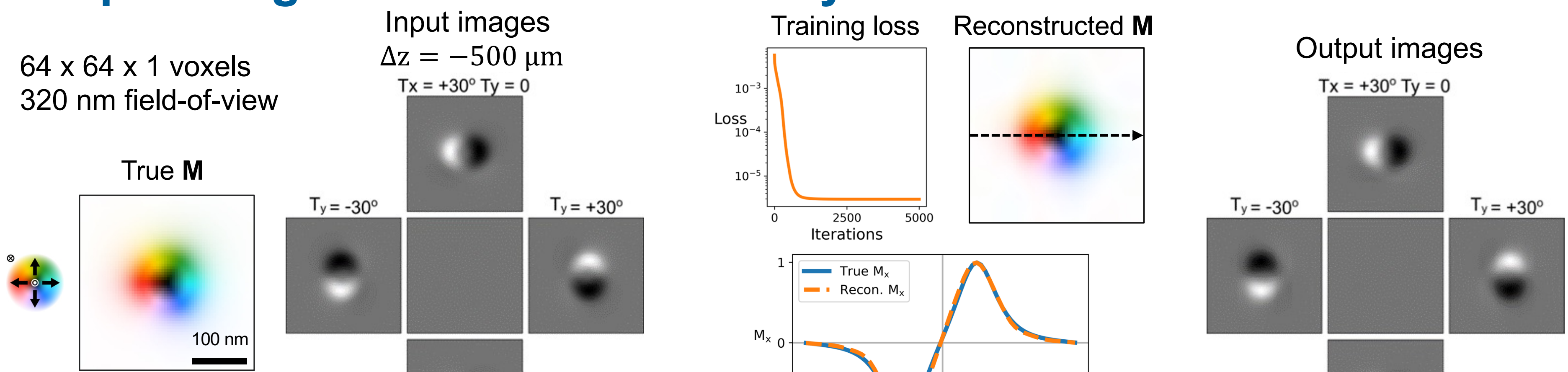


PyTorch

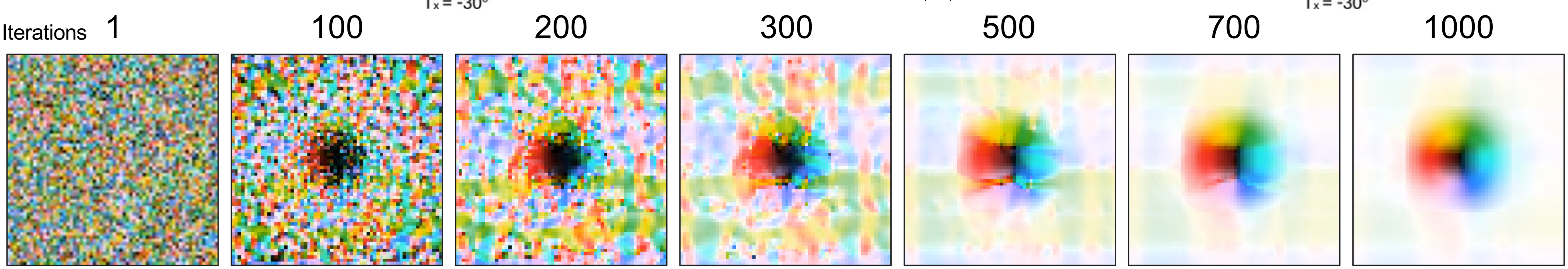
[1] A.R.C. McCray, et al. Micro. and Microanal. **29**(S1), 1756–1757 (2023). © Oxford University Press 2023.

RECONSTRUCTING A NÉEL SKYRMION

5 input images from a simulated skyrmion

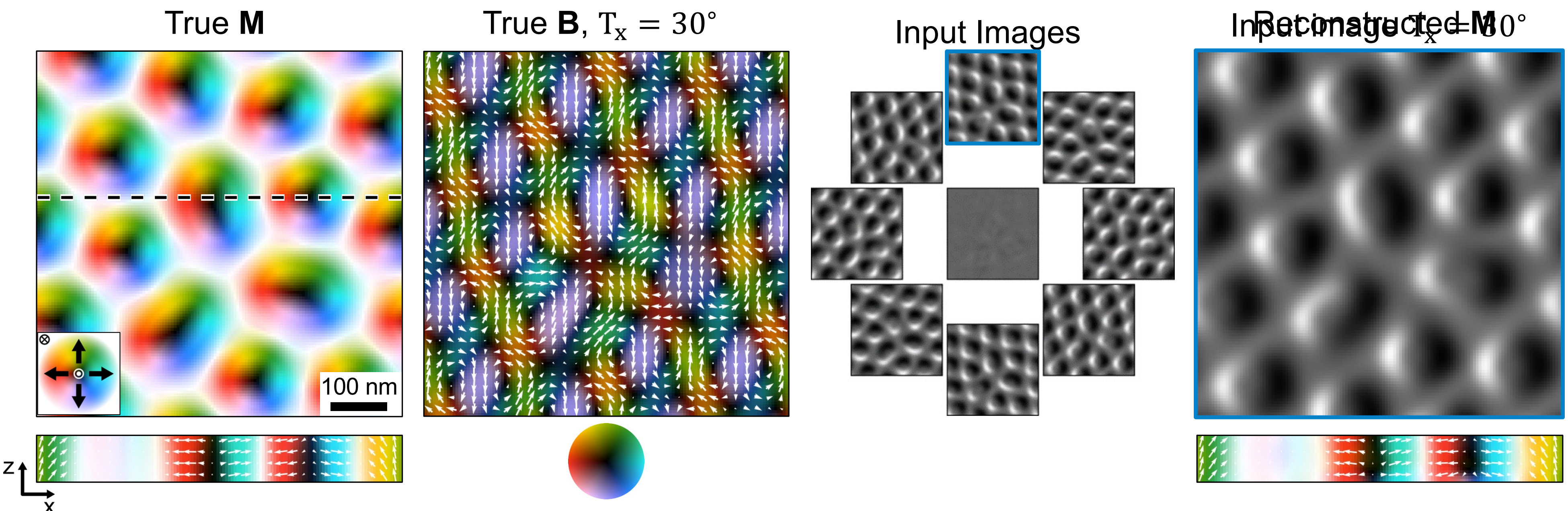


We accurately reconstruct the skyrmion chirality!

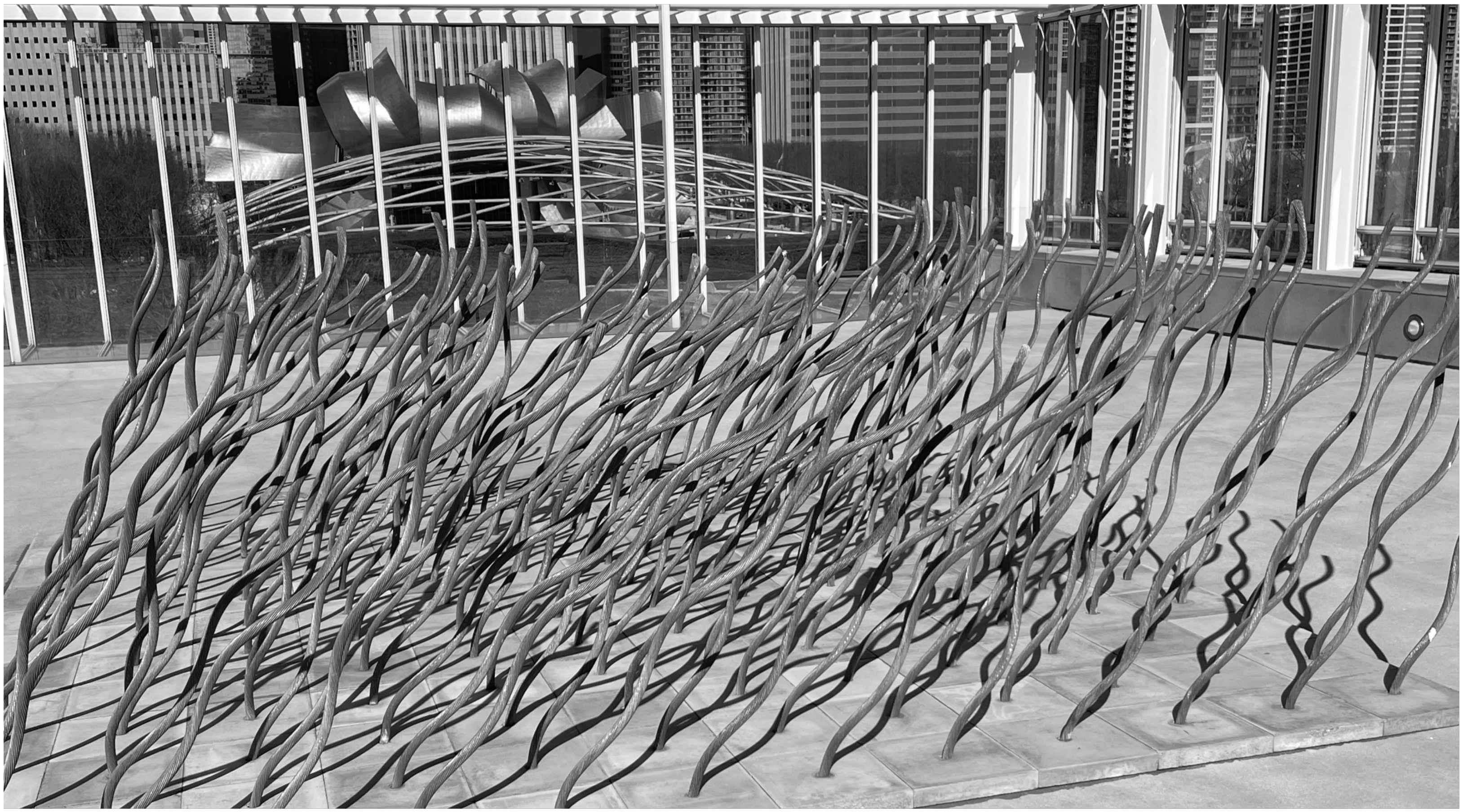


NÉEL SKYRMION LATTICE RECONSTRUCTION

- Magnetization reconstruction is more important in cases with many spin textures
  - Skyrmions are often distorted and have complex integrated induction maps
- Skyrmion lattice region: $(128 \text{ x } 128 \text{ x } 16)$, 5 nm^3 cell size
  - 9 input images (conical tilt series, $\theta = 30°$) for reconstructing 3D samples



COBALT NANOHELICES



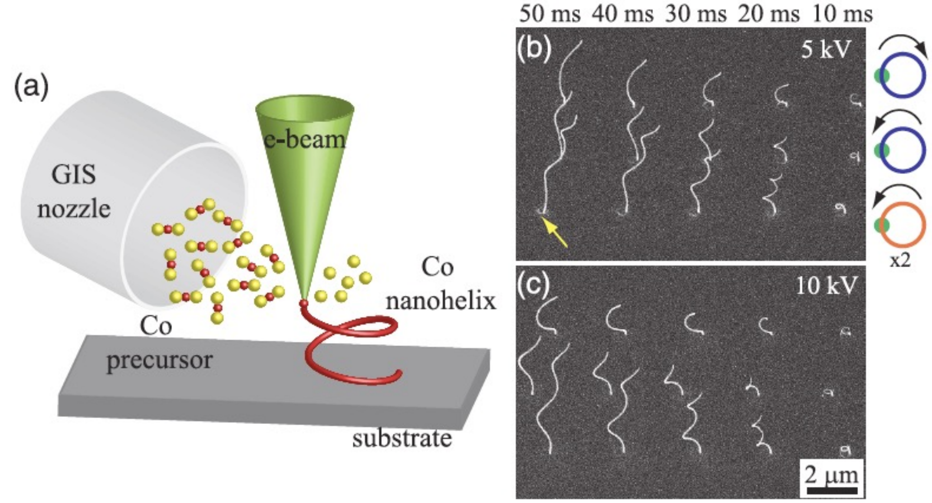
Maren Hassinger: This Is How We Grow

Art installation at Art Institute of Chicago titled “Paradise Regained (2020)” shows industrial rope curved towards Lake Michigan

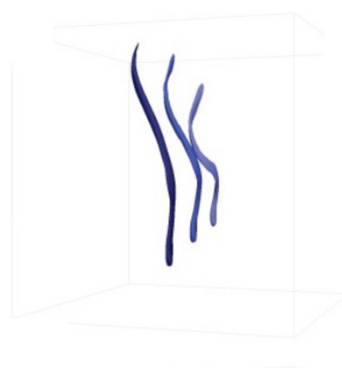
CREATING MAGNETIC NANOHELICES

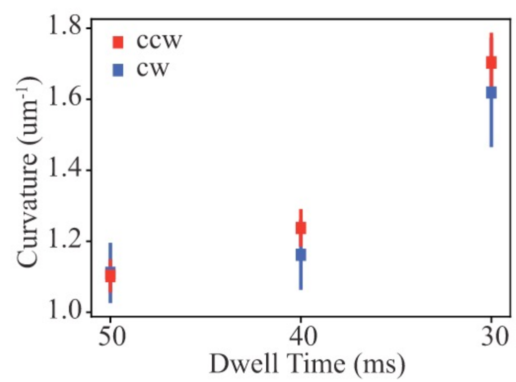
Controlling curvature and torsion

- Creating magnetic nanostructures with controlled curvature can be challenging
- We use direct-write technique via focused electron beam-induced deposition (FEBID)
- This enables growth of helices with different curvature and torsion



Schematic of FEBID process for fabrication of Co nanohelices with different curvature and torsion





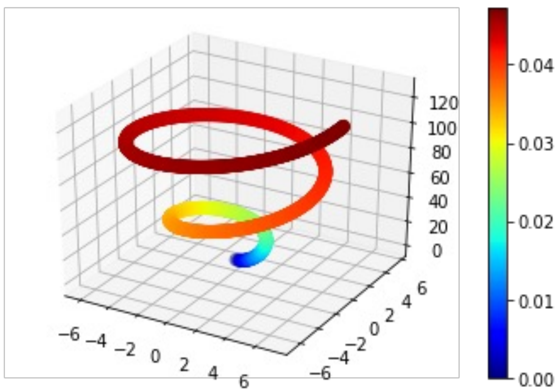
C. Phatak et al., *ACS Appl. Nano Mater.* **3**, 6009 (2020). © American Chemical Society 2020

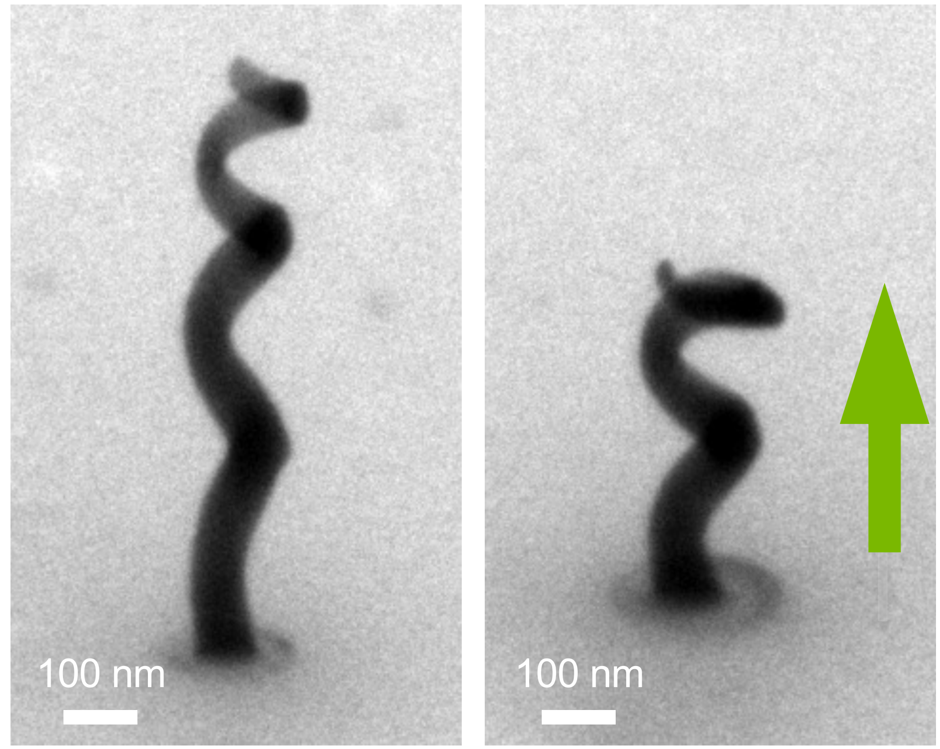
NANOHELICES

Changing curvature in a single nanohelix

- The radius of the nanohelix changes with the height.

$$\kappa = \frac{|r|}{r^2 + c^2}, c = \frac{Pitch}{2\pi}$$



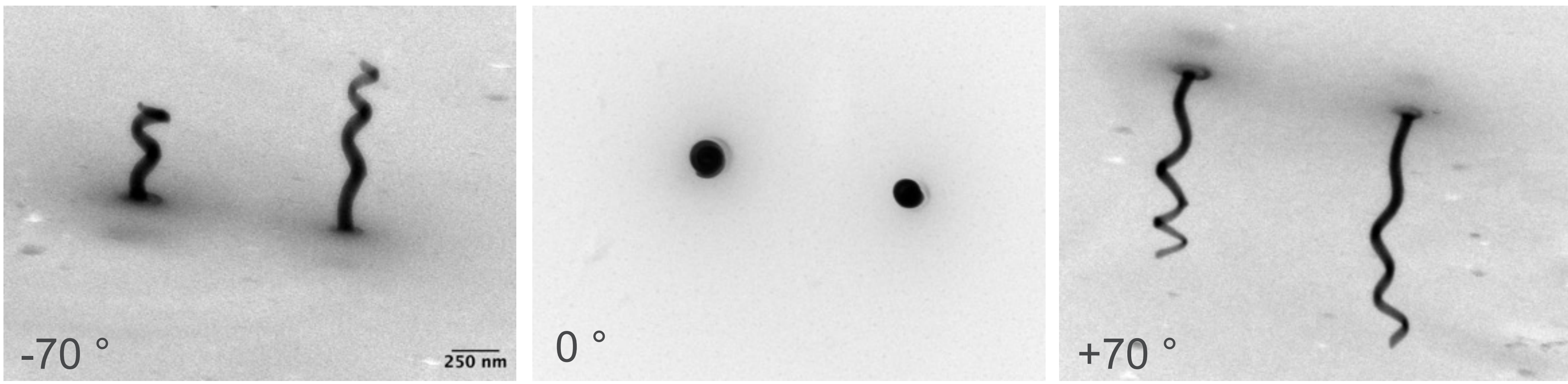


- Varying curvature and torsion with height of the nanostructure.

J. Fullerton, et al., Nano Lett., **24**, 2481-2487 (2024).

ELECTRON TOMOGRAPHY OF MAGNETIC NANOHELICES

- Depositing nanohelices directly on C-coated SiO_x TEM membranes allows for electron tomography and LTEM experiments



Tilt series of images showing the orientation of two different Co nanohelices grown using FEBID.

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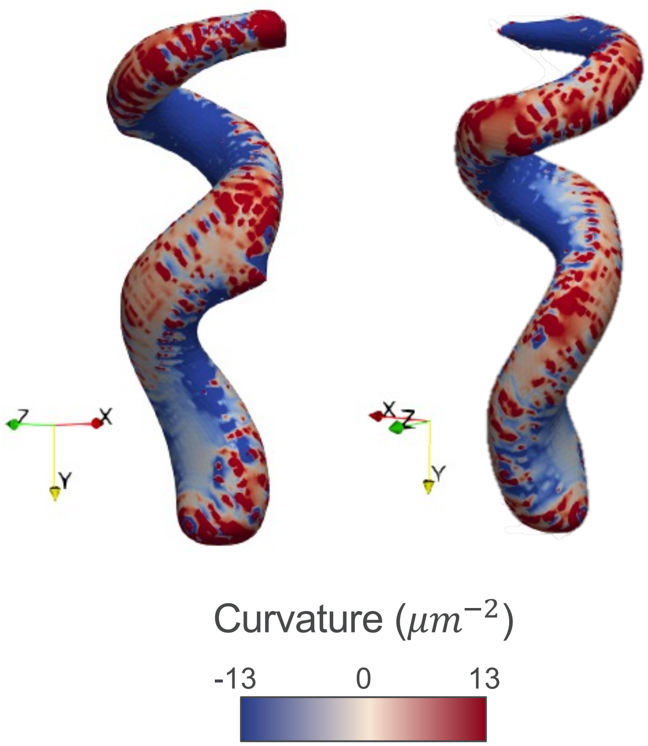
GAUSSIAN CURVATURE OF 3D NANOHELICES

Helix 1:



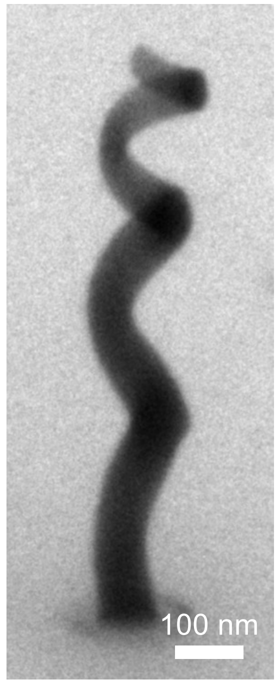
Helix 2:

Increasing magnitude of curvature with height

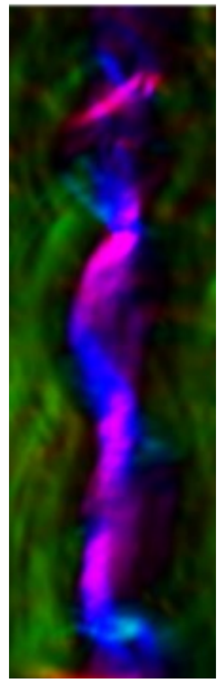
Co FEBID NANOHELIX 1: RECONSTRUCTED PHASE

- Experimental LTEM data used to reconstruct magnetic induction map
- Experimental tomography data were used as the input for the helix shape in micromagnetic simulation (first time we have done this)
- Micromagnetic simulation used to reconstruct simulated magnetic induction map

Experimental data

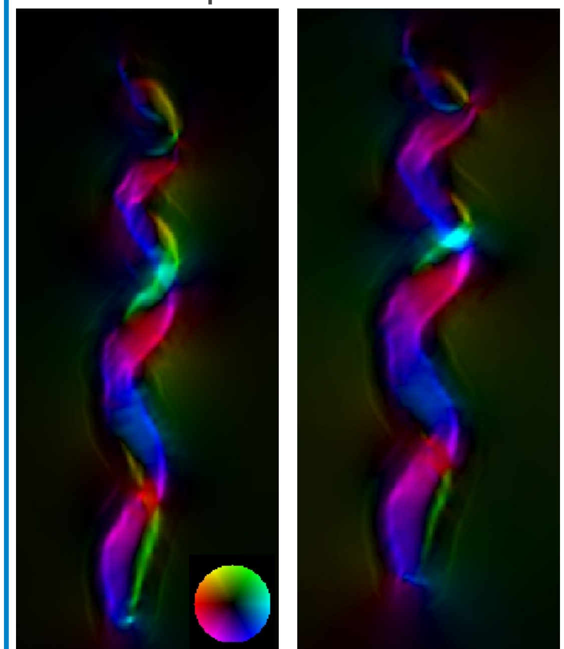


BF image



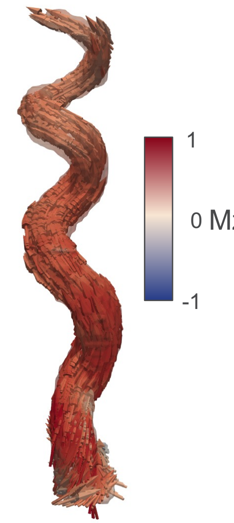
Magnetic induction map

Simulated phase reconstruction



45° rotation

Micromagnetic simulation



Magnetic induction maps for this nanohelix match a single domain state with magnetization following the length of the helix

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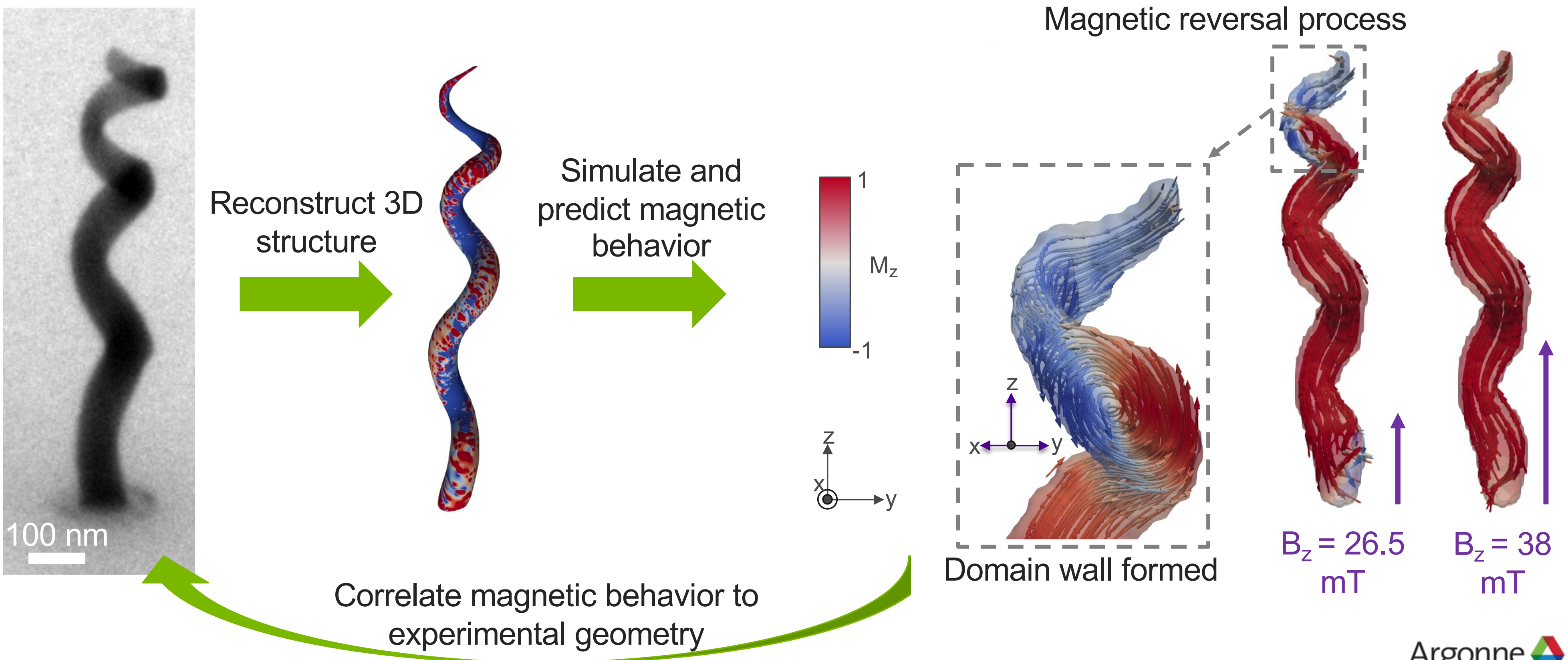
SIMULATED MAGNETIC REVERSAL



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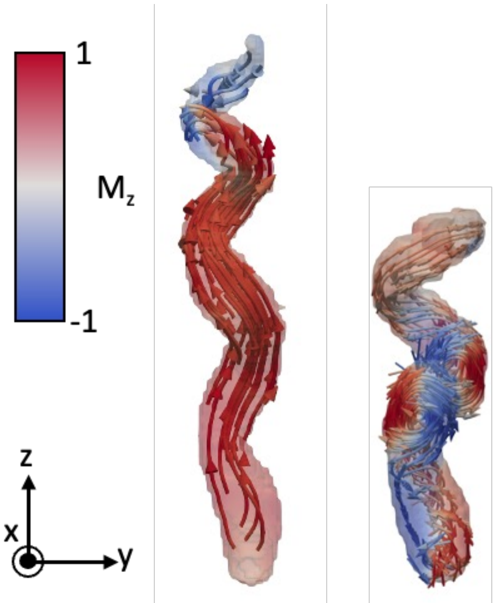
NANOHELICES

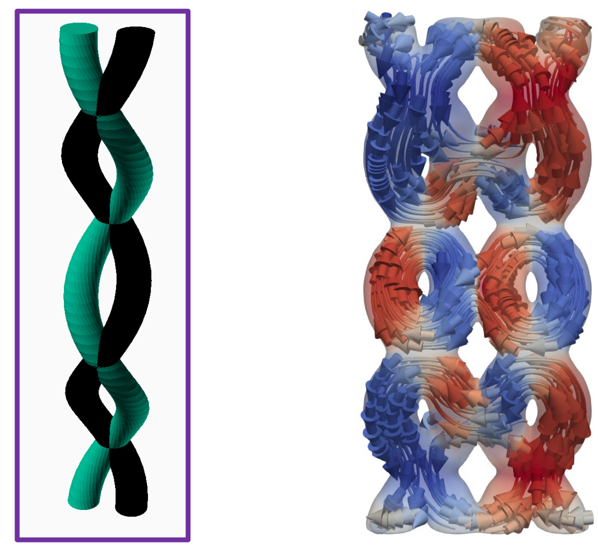
Beyond the single nanohelix

Domain walls appear with higher curvature and under applied field



But single domain states are favored at remanence for single, non-interacting helices

Designing interconnected nanowires – curvature, overlap



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- D. Czaplewski

Northwestern University

Materials Science & Engineering Dept
- E. B. Gulsoy
- Z. Thompson

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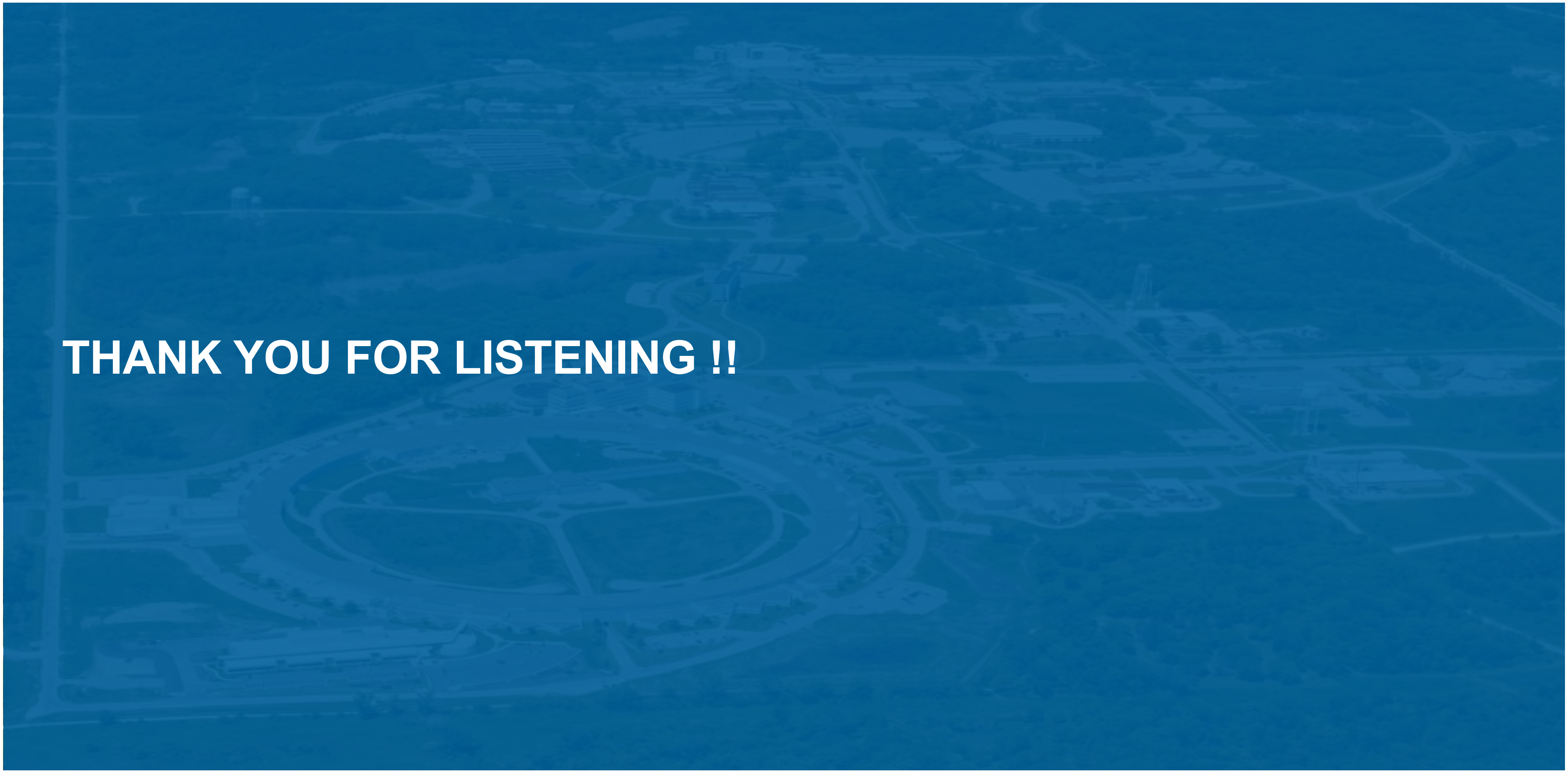

THANK YOU FOR LISTENING !!

https://www.anl.gov/msd/functional-nanoscale-heterostructures

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