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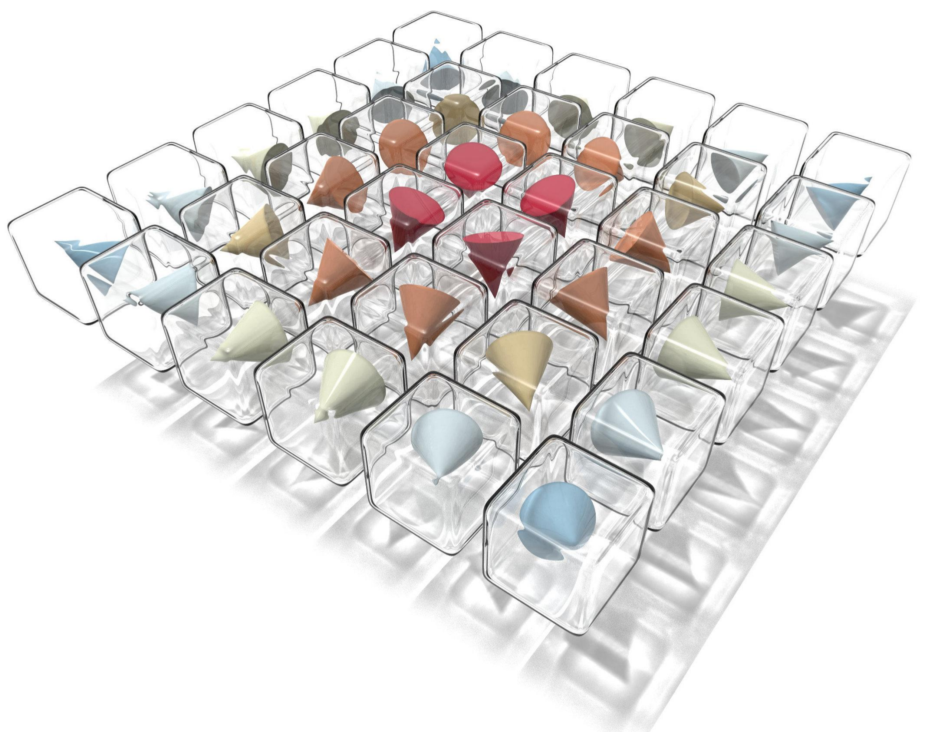
Search for a Bloch point using the Mean-field model



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PART 0 - MOTIVATION

- **WHY BLOCH POINT?**

Bloch point

nanoscale singularity[1] .... high data density

H-H & T-T Bloch points stably exist[2] .... two stable states

Hysteresis[2] .... can switch between each other

competitive memory

[1] W Döring. Point singularities in micromagnetism. Journal of Applied Physics, 39(2):1006–1007, 1968.
[2] Beg, Marijan, et al. "Stable and manipulable Bloch point." Scientific reports 9.1 (2019): 1-8.

PART 0 - MOTIVATION

- **WHY SIMULATIONS?**

  - More efficient
  - Easy to use
  - Get results quickly

...

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PART 1 - OBJECT OF STUDY

- Material: Cubic B20 FeGe
- Parameters: $M_s = 384\mathrm{kAm}^{-1}$ [1] $A = 8.78\mathrm{pJm}^{1}$ [1] $|D| = 1.58\mathrm{mJm}^{-2}$ [1]

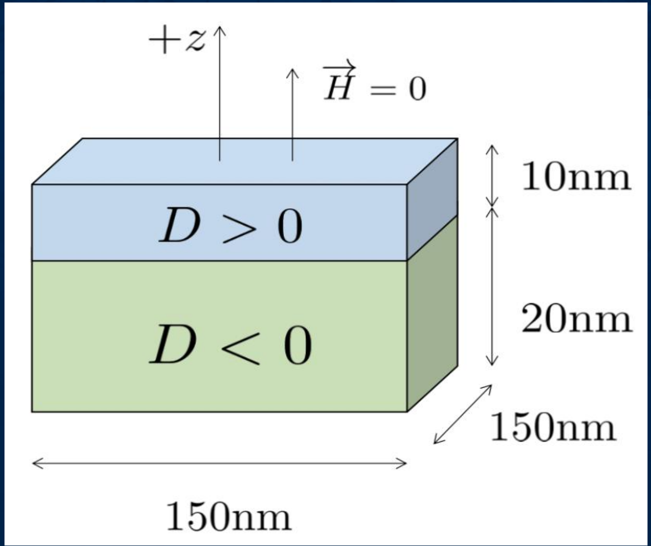

Fig1 The geometry of the studied system

Initialize the system

the Mean-field model used to

Reach the equilibrium state

Study the stability of Bloch points

Study the hysteretic behaviour of Bloch points

[1] Beg, Marijan, et al. "Stable and manipulable Bloch point." Scientific reports 9.1 (2019): 1-8.

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PART 2 - MEAN-FIELD MODEL

Algorithm 1 Relax the system using the Mean-field model

Require : temperature T, max iterations max_{iters}, changing rate λ

Require : Initialize the system with a uniform magnetisation configuration in $+z$ or $-z$ direction.

$iter \leftarrow 0$

$\mathbf{M}_{\text{old}} \leftarrow \mathbf{M}_{\text{ini}}$

do

Calculate effective field: $\mathbf{H}_{\text{eff}} = \frac{2\text{A}}{\mu_0 \text{M}_s} \nabla^2 \mathbf{m} - \frac{2\text{D}}{\mu_0 \text{M}_s} \nabla \times \mathbf{m} + \mathbf{H}$ Part A

Update the length: $\mathbf{M}_{\text{len}} = M_s \cdot \mathcal{L}\left(\beta \mu_0 \left|\mathbf{H}_{\text{eff}}\right|\right) \cdot \frac{\mathbf{H}_{\text{eff}}}{\left|\mathbf{H}_{\text{eff}}\right|}$

where $\mathcal{L}(x) = \coth x - \frac{1}{x}$ is the Langevin function and the parameter $\beta = \frac{1}{\text{K}_\text{b} T}$ introduces temperature to the algorithm.

Update the direction: $\mathbf{M}_{\text{dir}} = \mathbf{M}_{\text{old}} + \lambda \cdot (\mathbf{M}_{\text{len}} - \mathbf{M}_{\text{old}})$

Compute update: $\mathbf{M}_{\text{new}} = |\mathbf{M}_{\text{len}}| \cdot \frac{\mathbf{M}_{\text{dir}}}{|\mathbf{M}_{\text{dir}}|}$

Apply update: $\mathbf{M}_{\text{old}} = \mathbf{M}_{\text{new}}$

Part B

Update the counter of iterations: $iter \leftarrow iter + 1$

Calculate new effective field: $\mathbf{H}_{\text{eff}_{\text{new}}} = \frac{2\text{A}}{\mu_0 \text{M}_s} \nabla^2 \mathbf{m}_{\text{new}} - \frac{2\text{D}}{\mu_0 \text{M}_s} \nabla \times \mathbf{m}_{\text{new}} + \mathbf{H}$

while $iter \geq max_{\text{iters}}$ or $\mathbf{m}_{\text{new}} \times \mathbf{H}_{\text{eff}_{\text{new}}} = 0$ Part C

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PART 2 - MEAN-FIELD MODEL

A. EFFECTIVE FIELD

- Definition of effective field

$$\mathbf{H}_{\mathrm{eff}} = -\frac{1}{\mu_0 \mathrm{M_s}} \frac{\delta E(\mathbf{m})}{\delta \mathbf{m}}$$

- Effective field points in the opposite direction of the system energy gradient.

- Calculation of effective field

$$\mathbf{H}_{\mathrm{eff}} = \underbrace{\boxed{\frac{2\mathrm{A}}{\mu_0 \mathrm{M_s}} \nabla^2 \mathbf{m}}}_{\text{Exchange}} \underbrace{\boxed{- \frac{2\mathrm{D}}{\mu_0 \mathrm{M_s}} \nabla \times \mathbf{m}}}_{\text{DMI}} + \underbrace{\boxed{\mathbf{H}}}_{\text{Zeeman}}$$

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PART 2 - MEAN-FIELD MODEL

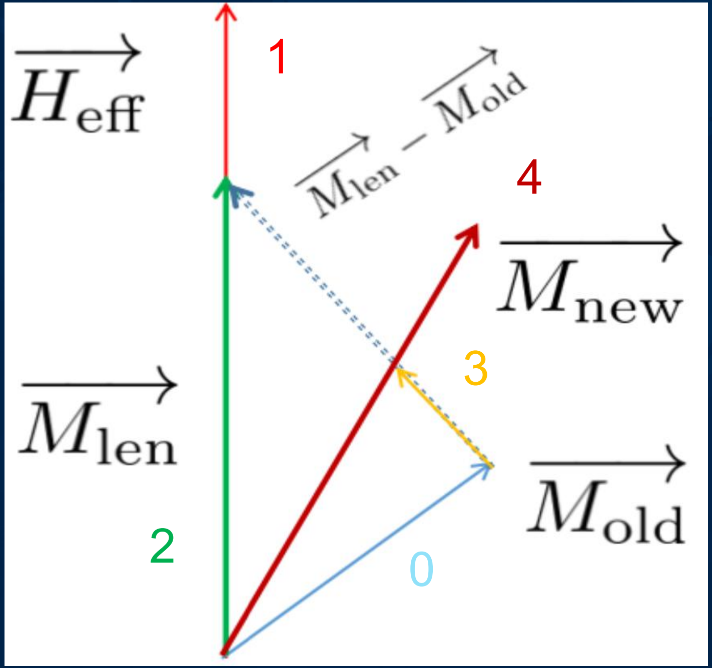

Fig2: The Geometric schematic of updating magnetization

B. Update Magnetization

1 **Calculate effective field**: $\mathbf{H}_{\mathrm{eff}} = \frac{2A}{\mu_0 M_s}\nabla^2\mathbf{m} - \frac{2D}{\mu_0 M_s}\nabla \times \mathbf{m} + \mathbf{H}$

2 **Update the length**: $\mathbf{M}_{\mathrm{len}} = M_s \cdot \mathcal{L}\left(\beta\mu_0 |\mathbf{H}_{\mathrm{eff}}|\right) \cdot \frac{\mathbf{H}_{\mathrm{eff}}}{|\mathbf{H}_{\mathrm{eff}}|}$

3 **Update the direction**: $\mathbf{M}_{\mathrm{dir}} = \mathbf{M}_{\mathrm{old}} + \boxed{\lambda} \cdot (\mathbf{M}_{\mathrm{len}} - \mathbf{M}_{\mathrm{old}})$

4 **Compute update**: $\mathbf{M}_{\mathrm{new}} = |\mathbf{M}_{\mathrm{len}}| \cdot \frac{\mathbf{M}_{\mathrm{dir}}}{|\mathbf{M}_{\mathrm{dir}}|}$

PART 2 - MEAN-FIELD MODEL

C. EQUILIBRIUM STATE

- Energy minimization can be reprsent by the Brown's condition:

$$\mathbf{M} \times \frac{\delta E}{\delta \mathbf{M}} = 0$$

- The ideal stopping criteria of the simulation:

$$\mathbf{M} \times \mathbf{H}_{\text{eff}} = 0$$

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PART 2 - MEAN-FIELD MODEL

C. STOP CRITERIA

1. Stop when arriving at the maximum iterations $iter > max_{\text{iters}}$
   - represents the maximum computational cost we can accept

2. Stop when the magnetization and its effective field are in the same direction
   - If the algorithm convergent before the max iteration, we can save computing resources. $\mathbf{M} \times \mathbf{H}_{\text{eff}} = 0$

3. Stop according to the physical meaning of the Bloch point $107^\circ \leq \theta_{\text{interface}} \leq 180^\circ$
   - The Mean-field model cannot convergent when there is a singularity in the system, because the magnetization is discontinuous and not differentiable
   - when the angle of the magnetization at the interface is greater than 107 degrees.

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PART 2 - MEAN-FIELD MODEL

- **ADVANTAGE**

  - High efficiency
    - along the defined direction(effective field)
    - update all lattice at once
  - Introduce the influence of temperature
  - Show the detailed structures of Bloch points

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PART 3 - RESULTS

RESULT: STABILITY

Two types of Bloch points appear at the interface, when the system is relaxed to the equilibrium state using **the Mean-field model**

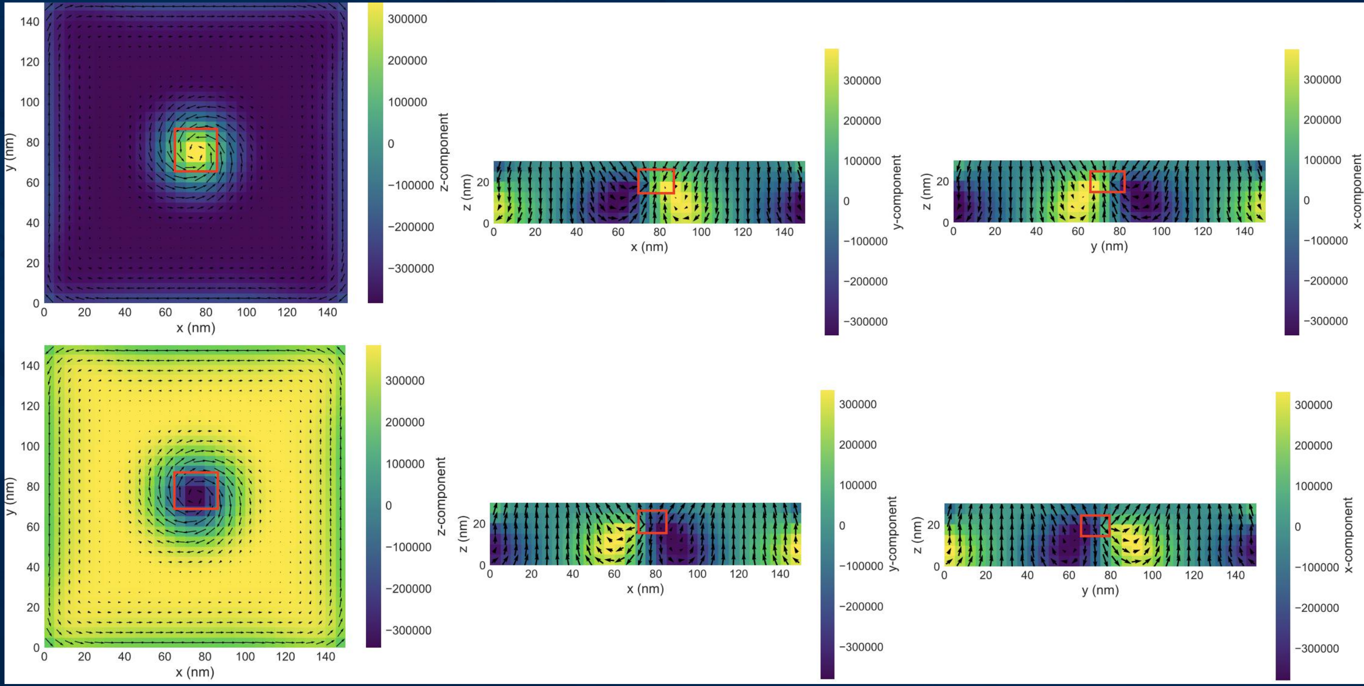

Fig3: The structures of two types of Bloch points

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PART 3 - RESULTS

RESULT: STABILITY

The magnetization at the centre of the interface offset each other, resulting in a stable Head-to-Head Bloch point.

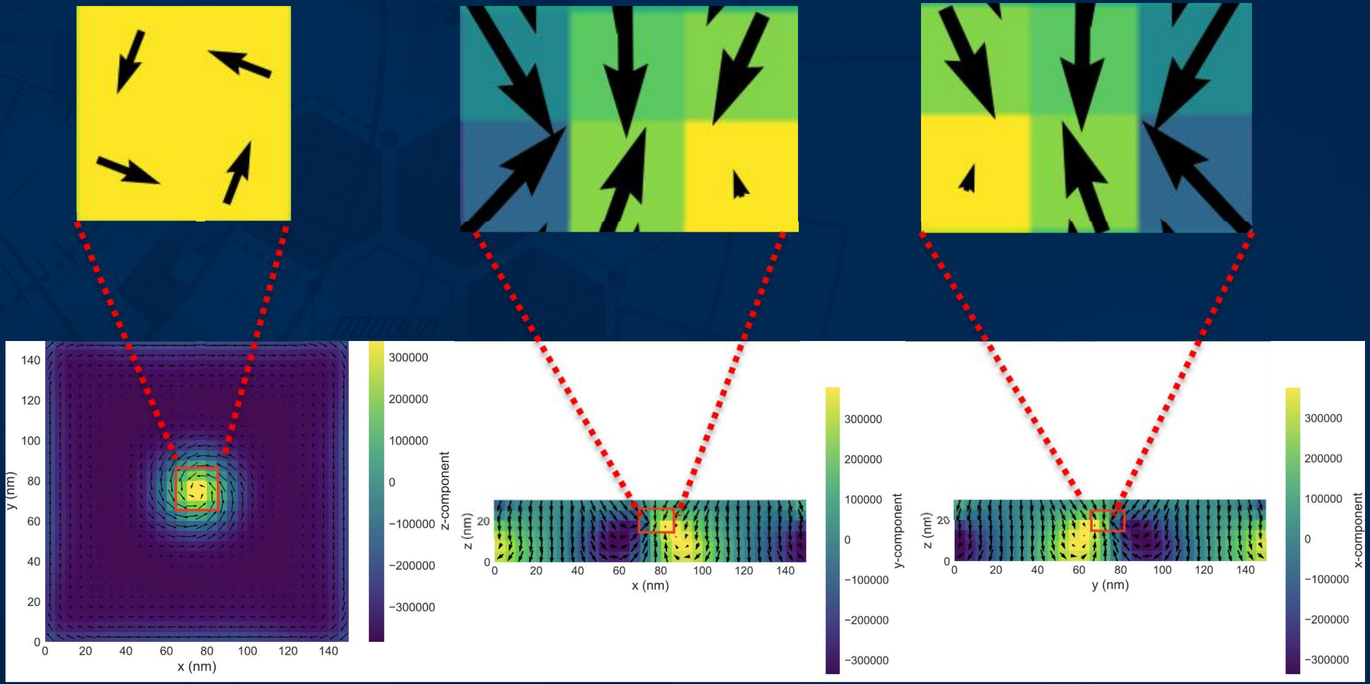

Fig4: The detailed structure of Head-to-Head Bloch points

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PART 3 - RESULTS

RESULT: HYSTERESIS

- H-H to T-T:
  - increase to 1T
  - decrease to -0.1T
- T-T to H-H:
  - decrease to -1T
  - increase to 0.1T

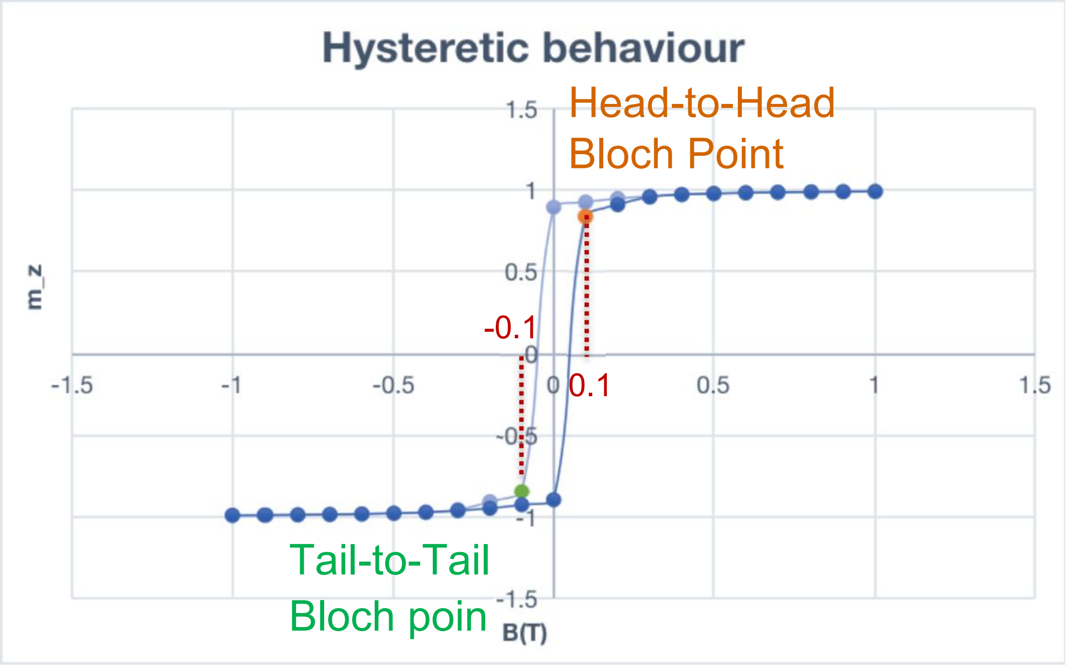

Fig5: The hysteretic behaviour of the system

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PART 4 - CONCLUSION

- This project implements the Mean-field model
- Using the Mean-field model, the stability and hysteretic behaviour of Bloch points are studied.
  - Stability: the detailed structures of two Bloch points
  - Hysteresis: the two can be switched between when changing the external magnetic field
- In summary, this project demonstrates that Bloch point is a very promising topological quasiparticle for data storage.

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Q&A

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Thanks for listening!