MSE 464 PROJECT 3: DOMAIN WALLS

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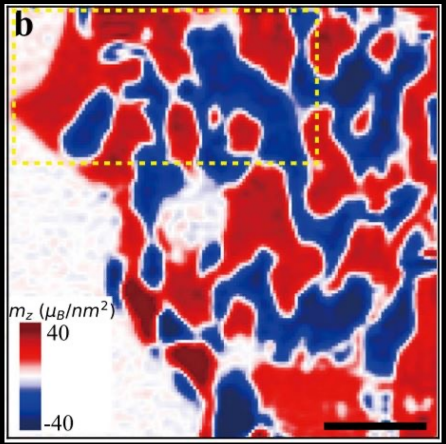
INTRODUCTION

- Domain walls are exceedingly common in magnetic systems as they form energetically favorable configurations
- They could be anywhere, even in your house right now
- Beyond physical curiosity, the deterministic control of domain walls has applications in devices, most notably racetrack memory



Fu, K. M. C., Santori, C., Barclay, P. E. & Beausoleil, R. G. *Appl. Phys. Lett.* **96**, 1–4 (2010).

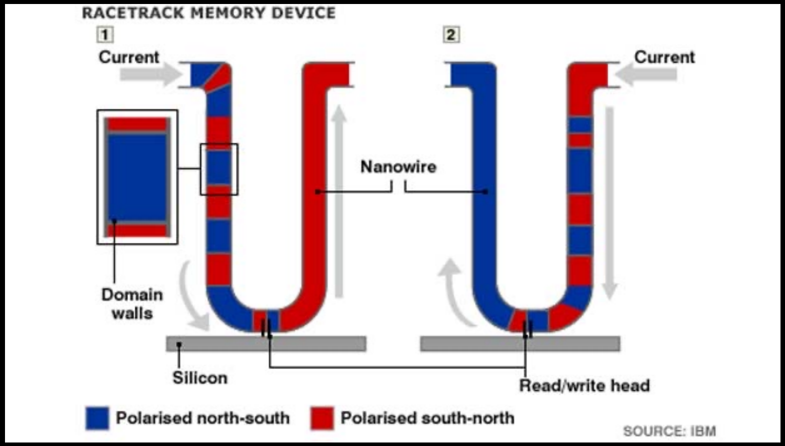


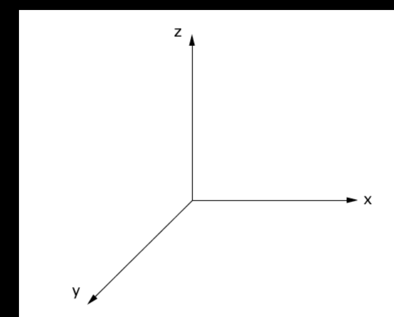
Image from:https://www.ibm.com/ibm/history/ibm100/us/en/icons/racetrack/

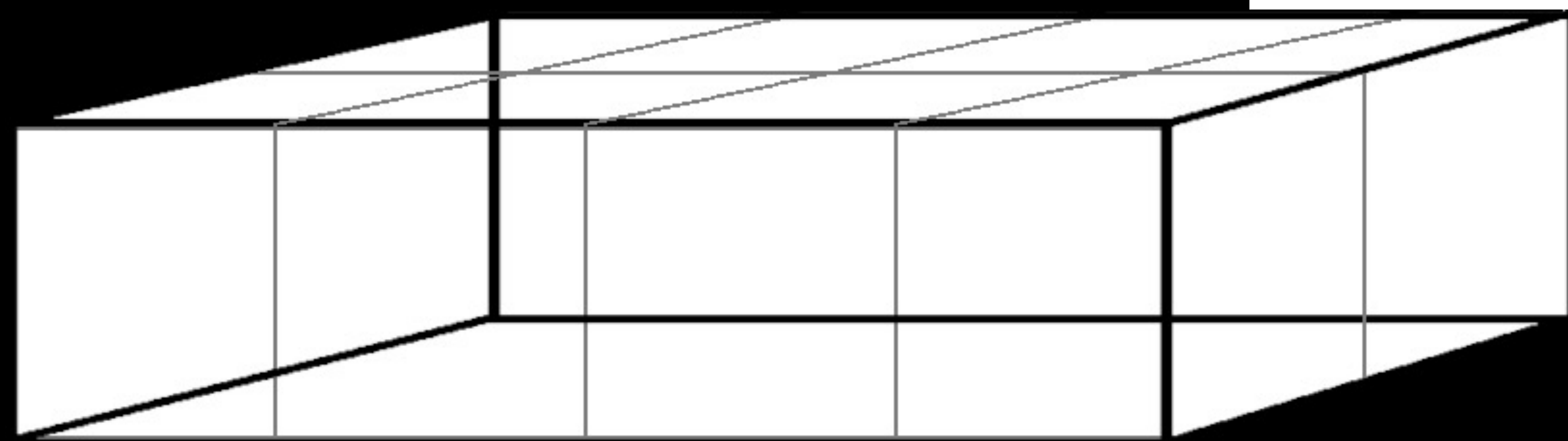
DOMAIN WALL MICROMAGNETIC SYSTEM

- A rectangular system:
  - L = 500 nm, w = 20 nm, h = 2.5 nm
  - Cells: x: 200, y: 8, z: 1

- Discretization dimensions: 2.5 nm in all directions (image not to scale)
- Will be used for all parts of the project*

=> Top-down visualization useful





PART 1: STATIC PROPERTIES OF A DOMAIN WALL IN A MAGNETIC STRIP

- Using Ubermag to initialize and visualize domain walls
- System energy terms:

$$-A\mathbf{m} \cdot \nabla^2 \mathbf{m} - \frac{1}{2}\mu_0 M_s \mathbf{m} \cdot \mathbf{H}_d$$

- System parameters:

$M_s = 5.8 \times 10^5$ A/m

$A = 13 \times 10^{-12}$ J/m

- Defined domain structure:
  1. 0 – 250 nm, +x
  2. 250 – 500 nm, -x

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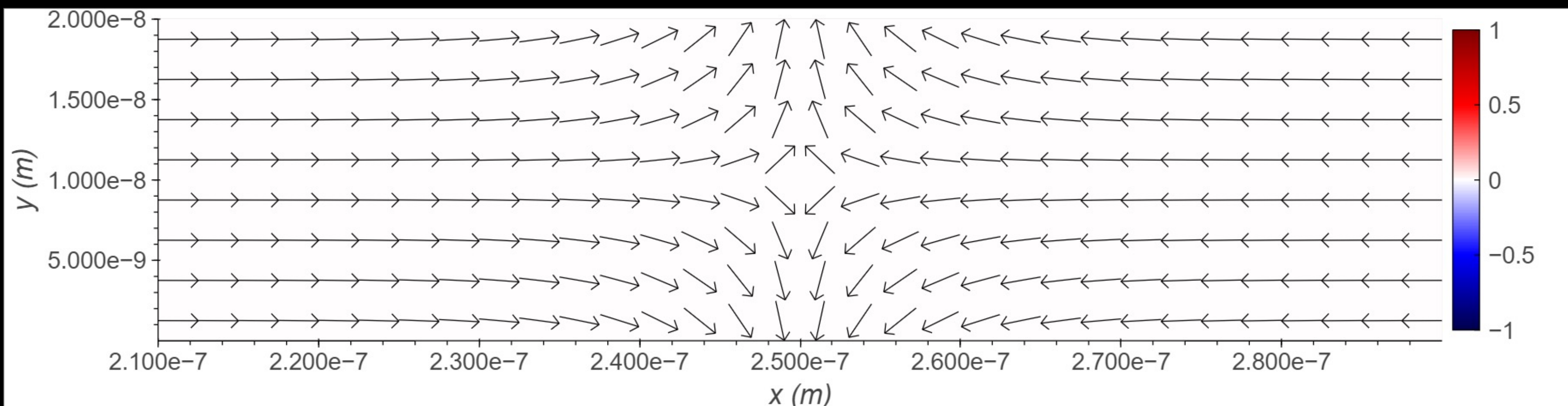
$$-A\mathbf{m} \cdot \nabla^2 \mathbf{m} - \frac{1}{2}\mu_0 M_s \mathbf{m} \cdot \mathbf{H}_d$$



$M_s = 5.8 \times 10^5$ A/m

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PART 1: STATIC PROPERTIES OF A DOMAIN WALL IN A MAGNETIC STRIP

- System energy terms:

$$-A\mathbf{m}\cdot\nabla^2\mathbf{m}-\frac{1}{2}\mu_0 M_s\mathbf{m}\cdot\mathbf{H}_\mathrm{d}$$

- System parameters:

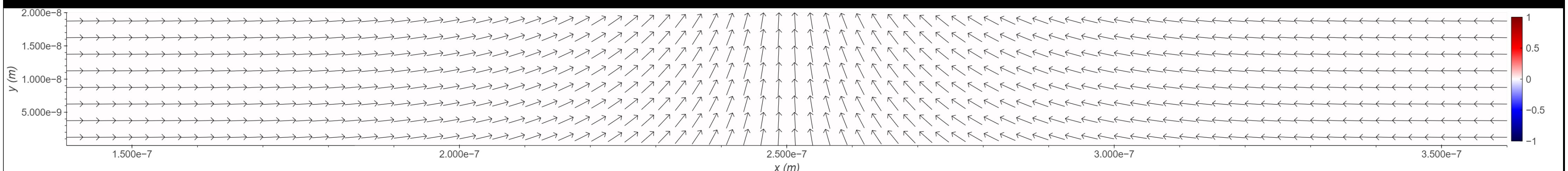
$$M_s = 5.8 \times 10^5 \text{ A/m}$$

$$A = 13 \times 10^{-12} \text{ J/m}$$

- Defined domain structure:
  1. 0 – 245 nm, +x
  2. 255 – 500 nm, -x
  3. **245 – 255 nm, +y**

PART 1: STATIC PROPERTIES OF A DOMAIN WALL IN A MAGNETIC STRIP

$$-A\mathbf{m}\cdot\nabla^2\mathbf{m} - \frac{1}{2}\mu_0 M_{\mathrm{s}}\mathbf{m}\cdot\mathbf{H}_{\mathrm{d}}$$



$M_s = 5.8 \times 10^5$ A/m

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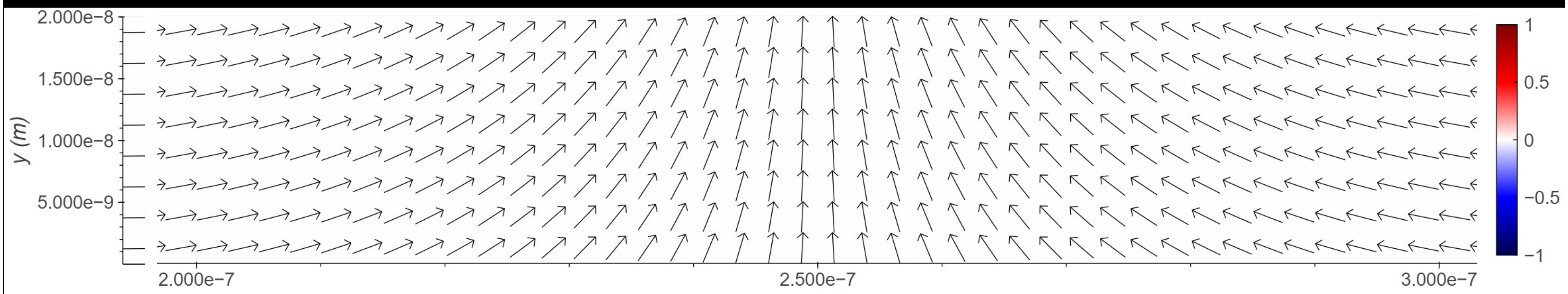
$$-A\mathbf{m}\cdot\nabla^2\mathbf{m} - \frac{1}{2}\mu_0 M_{\mathrm{s}}\mathbf{m}\cdot\mathbf{H}_{\mathrm{d}}$$



$M_s = 5.8 \times 10^5$ A/m

$A = 13 \times 10^{-12}$ J/m

PART 1: STATIC PROPERTIES OF A DOMAIN WALL IN A MAGNETIC STRIP

- System energy terms:

$$-A\mathbf{m}\cdot\nabla^2\mathbf{m} - \frac{1}{2}\mu_0 M_s \mathbf{m}\cdot\mathbf{H}_d - K(\mathbf{m}\cdot\mathbf{u})^2$$

- System parameters:

$M_s = 5.8 \times 10^5$ A/m

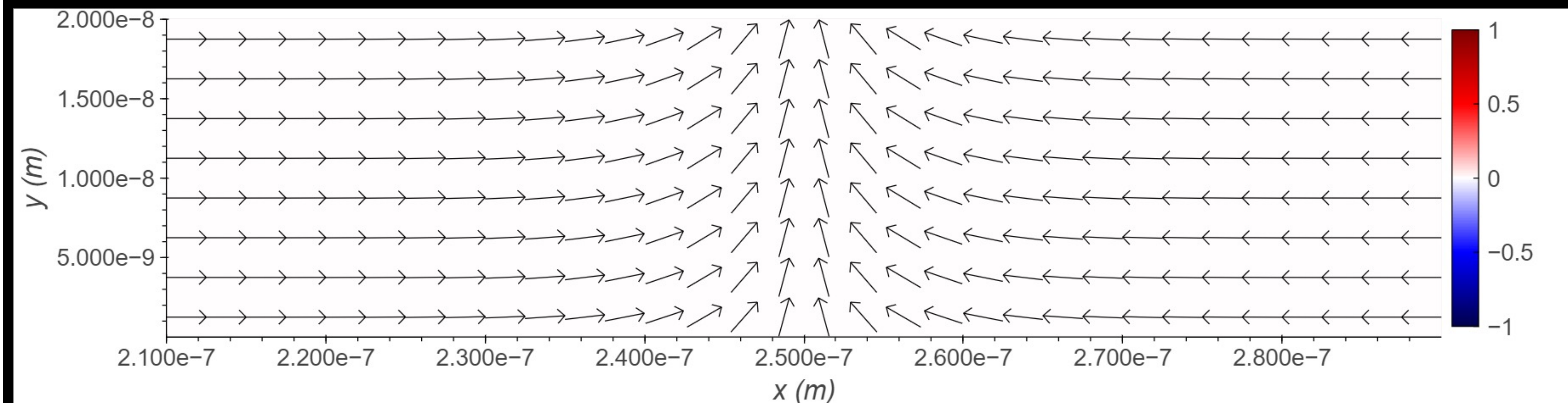
$A = 13 \times 10^{-12}$ J/m

$K_u = 0.5 \times 10^6$ J/m^3 x-direction

- Defined domain structure:
  1. 0 – 245 nm, +x
  2. 255 – 500 nm, -x
  3. 245 – 255 nm, +y

PART 1: STATIC PROPERTIES OF A DOMAIN WALL IN A MAGNETIC STRIP

$$-A\mathbf{m}\cdot\nabla^2\mathbf{m} - \frac{1}{2}\mu_0 M_{\mathrm{s}}\mathbf{m}\cdot\mathbf{H}_{\mathrm{d}} - K(\mathbf{m}\cdot\mathbf{u})^2$$



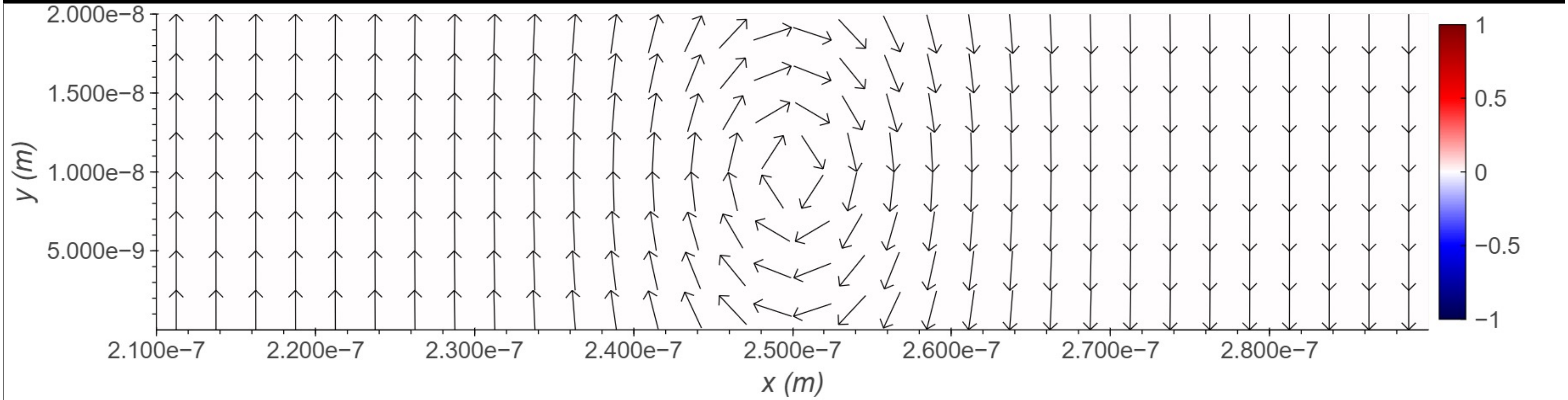
$M_s = 5.8 \times 10^5$ A/m

$K_u = 0.5 \times 10^6$ J/m^3

$A = 13 \times 10^{-12}$ J/m

PART 1: STATIC PROPERTIES OF A DOMAIN WALL IN A MAGNETIC STRIP

$$-A\mathbf{m}\cdot\nabla^2\mathbf{m} - \frac{1}{2}\mu_0 M_s \mathbf{m}\cdot\mathbf{H}_d - K(\mathbf{m}\cdot\mathbf{u})^2$$



- Defined domain structure:
  1. 0 – 250 nm, **+y**
  2. 250 – 500 nm, **-y**

$M_s = 5.8 \times 10^5$ A/m

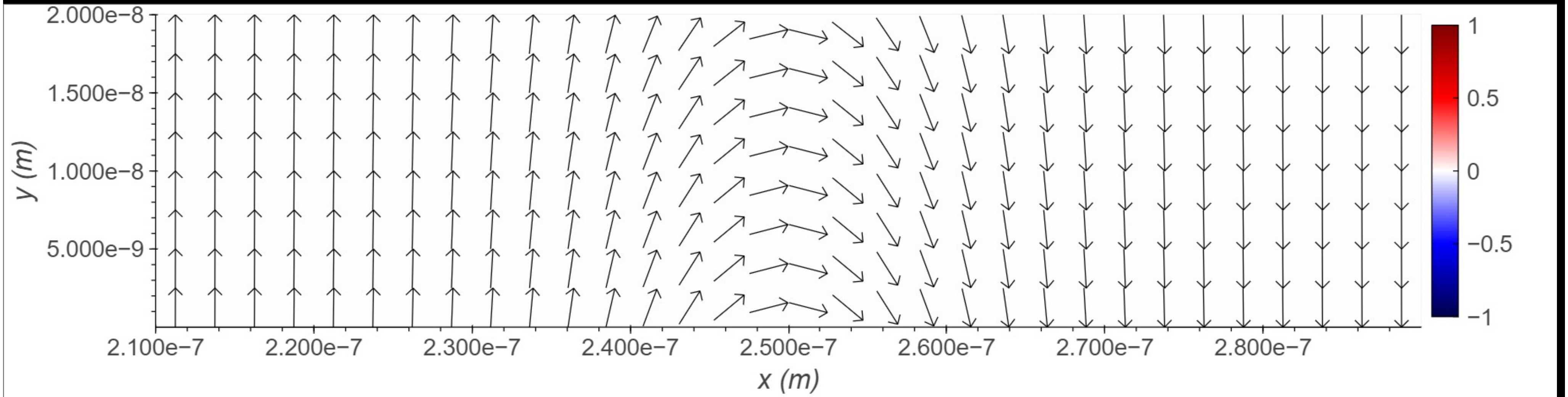
$K_u = 0.5 \times 10^6$ J/m^3

y-direction

$A = 13 \times 10^{-12}$ J/m

PART 1: STATIC PROPERTIES OF A DOMAIN WALL IN A MAGNETIC STRIP

$$-A\mathbf{m}\cdot\nabla^2\mathbf{m} - \frac{1}{2}\mu_0 M_s \mathbf{m}\cdot\mathbf{H}_d - K(\mathbf{m}\cdot\mathbf{u})^2$$



- Defined domain structure:
  1. 0 – 245 nm, **+y**
  2. 255 – 500 nm, **-y**
  3. 245 – 255 nm, +x

$M_s = 5.8 \times 10^5$ A/m

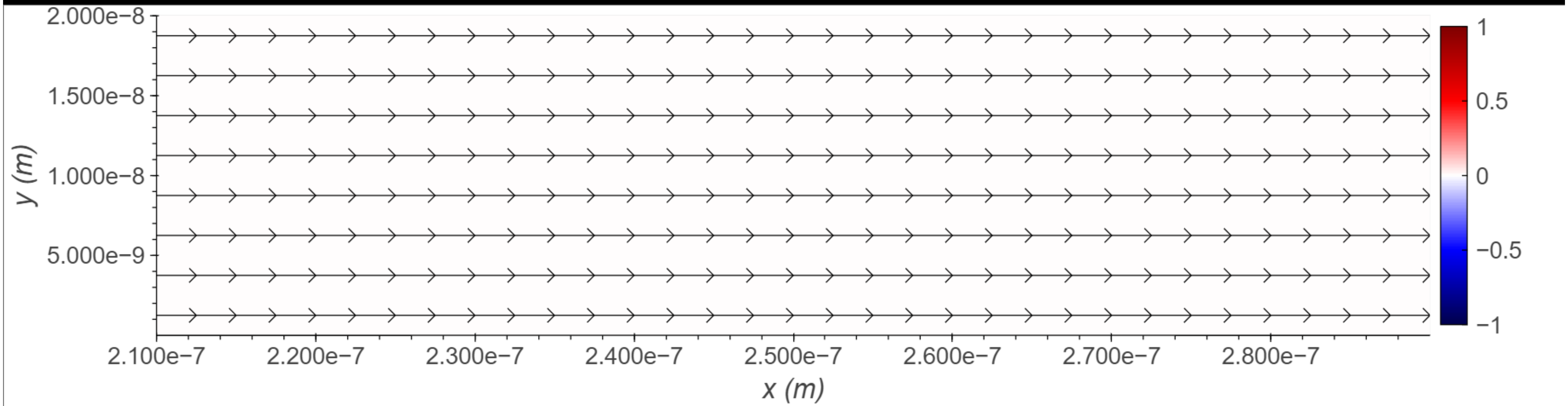
$K_u = 0.5 \times 10^6$ J/m^3

y-direction

$A = 13 \times 10^{-12}$ J/m

PART 1: STATIC PROPERTIES OF A DOMAIN WALL IN A MAGNETIC STRIP

$$-A\mathbf{m}\cdot\nabla^2\mathbf{m} - \frac{1}{2}\mu_0 M_s \mathbf{m}\cdot\mathbf{H}_d - K(\mathbf{m}\cdot\mathbf{u})^2$$



- Defined domain structure:
  1. 0 – 245 nm, **+y**
  2. 255 – 500 nm, **-y**
  3. 245 – 255 nm, +x

$M_s = 5.8 \times 10^5$ A/m

$K_u = 0.5 \times 10^6$ J/m^3

y-direction

$A = 13 \times 10^{-12}$ J/m

PART 1: STATIC PROPERTIES OF A DOMAIN WALL IN A MAGNETIC STRIP

- Thus far we've only been looking at in-plane magnetizations
- Let's see some colors!

PART 1: STATIC PROPERTIES OF A DOMAIN WALL IN A MAGNETIC STRIP

- System energy terms:

$$-A\mathbf{m} \cdot \nabla^2 \mathbf{m} - \frac{1}{2}\mu_0 M_s \mathbf{m} \cdot \mathbf{H}_d$$

- System parameters:

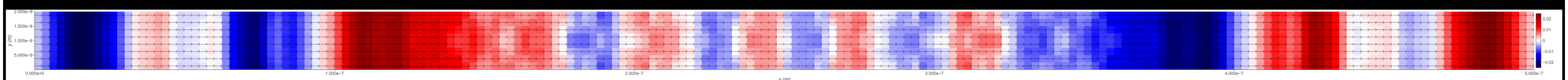
$$M_s = 5.8 \times 10^5 \text{ A/m}$$

$$A = 13 \times 10^{-12} \text{ J/m}$$

- Defined domain structure:
  1. 0 – 245 nm, +z
  2. 255 – 500 nm, -z
  3. 245 – 255 nm, **+x**

PART 1: STATIC PROPERTIES OF A DOMAIN WALL IN A MAGNETIC STRIP

$$-A\mathbf{m} \cdot \nabla^2\mathbf{m} - \frac{1}{2}\mu_0 M_s \mathbf{m} \cdot \mathbf{H}_d$$

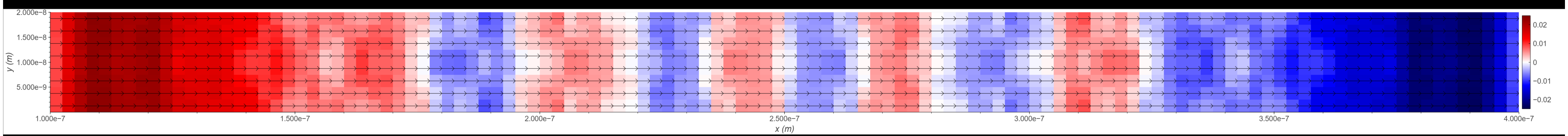


$M_s = 5.8 \times 10^5$ A/m

$A = 13 \times 10^{-12}$ J/m

PART 1: STATIC PROPERTIES OF A DOMAIN WALL IN A MAGNETIC STRIP

$$-A\mathbf{m}\cdot\nabla^2\mathbf{m}-\frac{1}{2}\mu_0 M_{\mathrm{s}}\mathbf{m}\cdot\mathbf{H}_{\mathrm{d}}$$

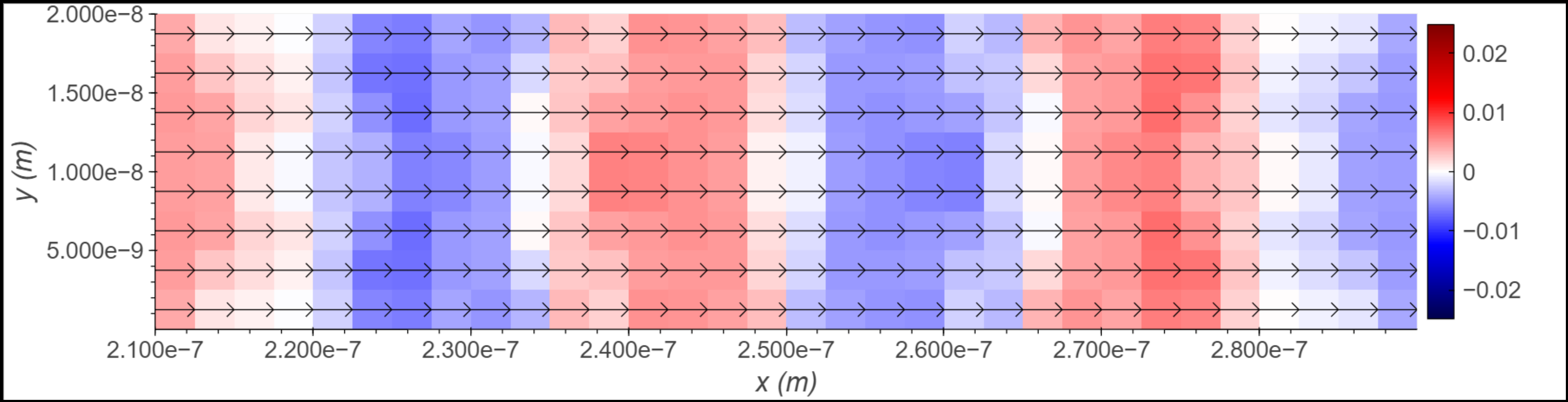


$M_s = 5.8 \times 10^5$ A/m

$A = 13 \times 10^{-12}$ J/m

PART 1: STATIC PROPERTIES OF A DOMAIN WALL IN A MAGNETIC STRIP

$$-A\mathbf{m}\cdot\nabla^2\mathbf{m} - \frac{1}{2}\mu_0 M_\mathrm{s}\mathbf{m}\cdot\mathbf{H}_\mathrm{d}$$



$M_s = 5.8 \times 10^5$ A/m

$A = 13 \times 10^{-12}$ J/m

PART 1: STATIC PROPERTIES OF A DOMAIN WALL IN A MAGNETIC STRIP

- System energy terms:

$$-A\mathbf{m}\cdot\nabla^2\mathbf{m}-\frac{1}{2}\mu_0 M_\mathrm{s}\mathbf{m}\cdot\mathbf{H}_\mathrm{d}-K(\mathbf{m}\cdot\mathbf{u})^2$$

- System parameters:

$M_s = 5.8 \times 10^5$ A/m

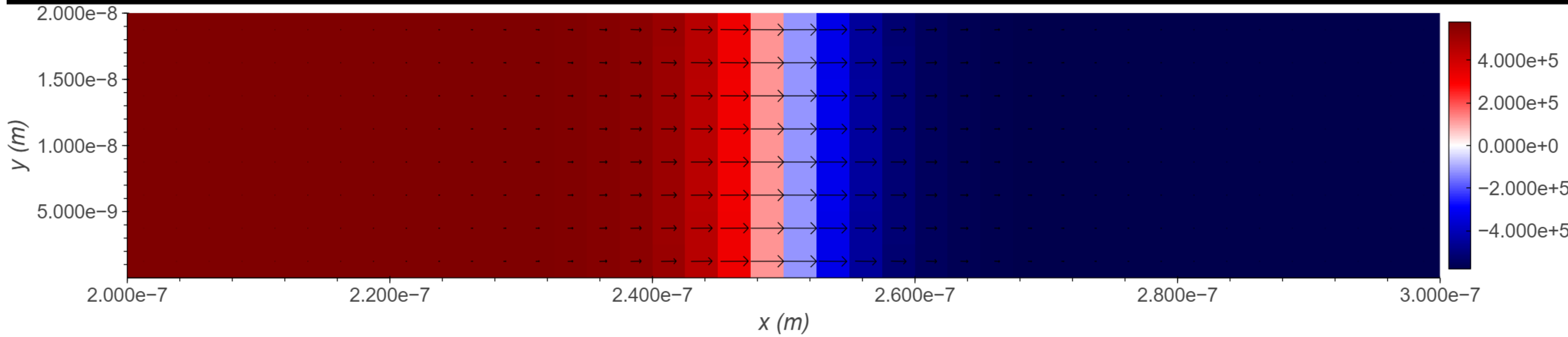
$A = 13 \times 10^{-12}$ J/m

$K_u = 0.5 \times 10^6$ J/m^3 z-direction

- Defined domain structure:
  1. 0 – 245 nm, +z
  2. 255 – 500 nm, -z
  3. 245 – 255 nm, +x

PART 1: STATIC PROPERTIES OF A DOMAIN WALL IN A MAGNETIC STRIP

$$-A\mathbf{m}\cdot\nabla^2\mathbf{m} - \frac{1}{2}\mu_0 M_s \mathbf{m}\cdot\mathbf{H}_d - K(\mathbf{m}\cdot\mathbf{u})^2$$



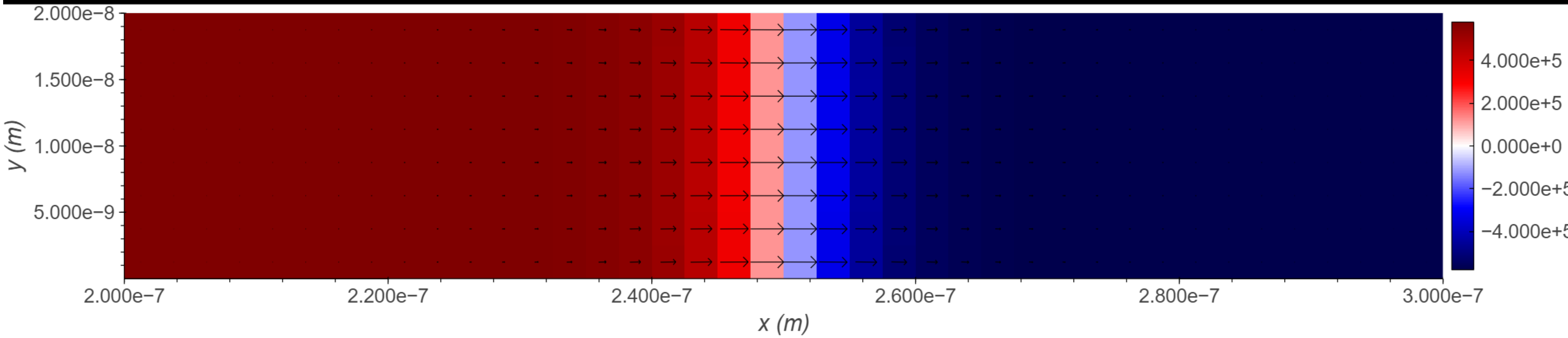
$M_s = 5.8 \times 10^5$ A/m

$K_u = 0.5 \times 10^6$ J/m^3

$A = 13 \times 10^{-12}$ J/m

PART 1: STATIC PROPERTIES OF A DOMAIN WALL IN A MAGNETIC STRIP

A Néel wall!



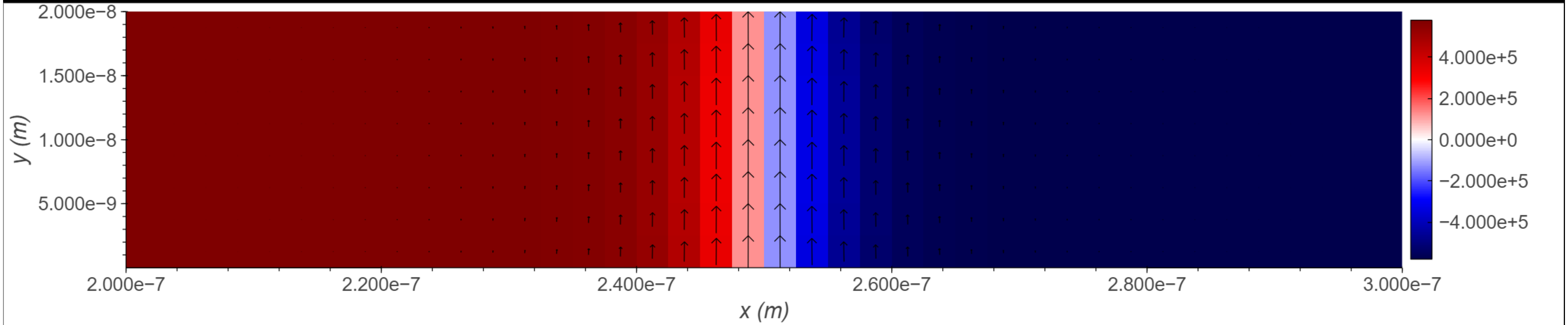
$M_s = 5.8 \times 10^5$ A/m

$K_u = 0.5 \times 10^6$ J/m^3

$A = 13 \times 10^{-12}$ J/m

PART 1: STATIC PROPERTIES OF A DOMAIN WALL IN A MAGNETIC STRIP

A Bloch wall!



- Defined domain structure:
  1. 0 – 245 nm, +z
  2. 255 – 500 nm, -z
  3. 245 – 255 nm, **+y**

$M_s = 5.8 \times 10^5$ A/m

$K_u = 0.5 \times 10^6$ J/m^3

$A = 13 \times 10^{-12}$ J/m

PART 1: STATIC PROPERTIES OF A DOMAIN WALL IN A MAGNETIC STRIP

- Thus far we've needed to specify in our initializations a third domain to get coherent domain walls

- Can add another energy term: Dzyaloshinskii-Moriya interactions (DMI)

$$\mathcal{H} = -\mathcal{D} \cdot (\boldsymbol{S}_i \times \boldsymbol{S}_j), \tag{5.27}$$

- Unlike regular exchange (prefers parallel alignment), DMI prefers perpendicular alignment of neighboring spins

PART 1: STATIC PROPERTIES OF A DOMAIN WALL IN A MAGNETIC STRIP

- System energy terms:

$$-A\mathbf{m}\cdot\nabla^2\mathbf{m} - \frac{1}{2}\mu_0 M_{\mathrm{s}}\mathbf{m}\cdot\mathbf{H}_{\mathrm{d}} - K(\mathbf{m}\cdot\mathbf{u})^2 + D(\mathbf{m}\cdot\nabla m_z - m_z\nabla\cdot\mathbf{m})$$

- System parameters:

$M_s = 5.8 \times 10^5$ A/m

$K_u = 0.5 \times 10^6$ J/m^3 z-direction

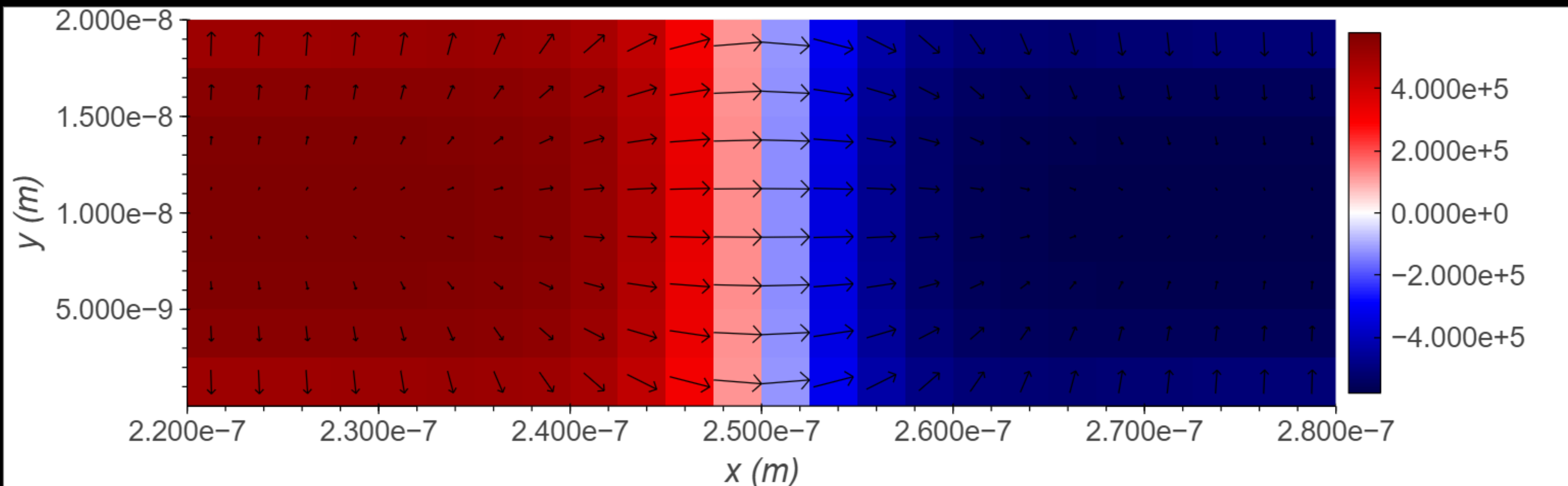
$A = 13 \times 10^{-12}$ J/m

$D = 3 \times 10^{-3}$ J/m^2

- Defined domain structure:
  1. 0 – 250 nm, +z
  2. 250 – 500 nm, -z

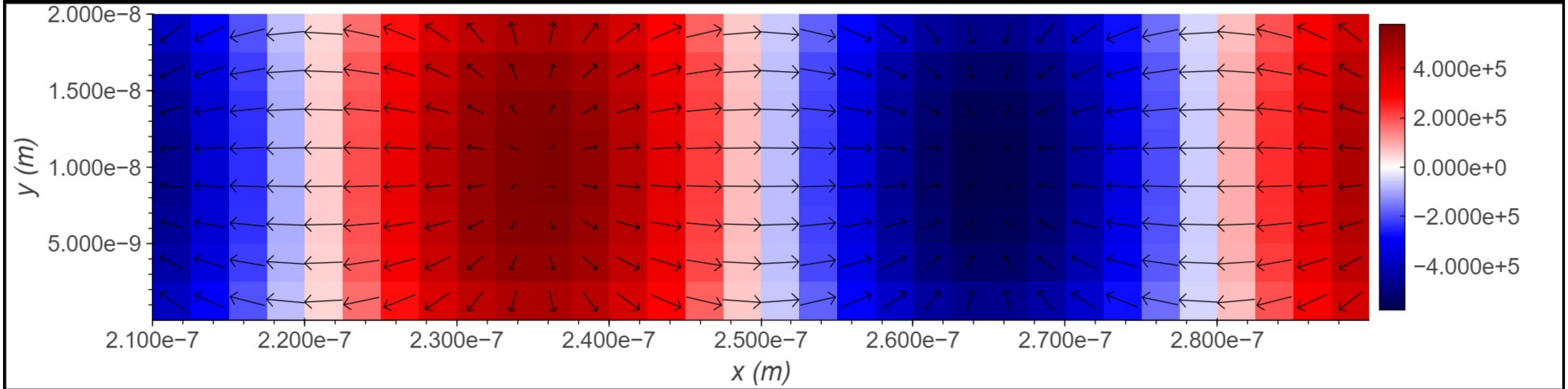
PART 1: STATIC PROPERTIES OF A DOMAIN WALL IN A MAGNETIC STRIP

$$-A\mathbf{m}\cdot\nabla^2\mathbf{m} - \frac{1}{2}\mu_0 M_\mathrm{s}\mathbf{m}\cdot\mathbf{H}_\mathrm{d} - K(\mathbf{m}\cdot\mathbf{u})^2 + D(\mathbf{m}\cdot\nabla m_z - m_z\nabla\cdot\mathbf{m})$$



PART 1: STATIC PROPERTIES OF A DOMAIN WALL IN A MAGNETIC STRIP

$$-A\mathbf{m}\cdot\nabla^2\mathbf{m} - \frac{1}{2}\mu_0 M_s \mathbf{m}\cdot\mathbf{H}_d + D(\mathbf{m}\cdot\nabla m_z - m_z\nabla\cdot\mathbf{m})$$



PART 1: STATIC PROPERTIES OF A DOMAIN WALL IN A MAGNETIC STRIP

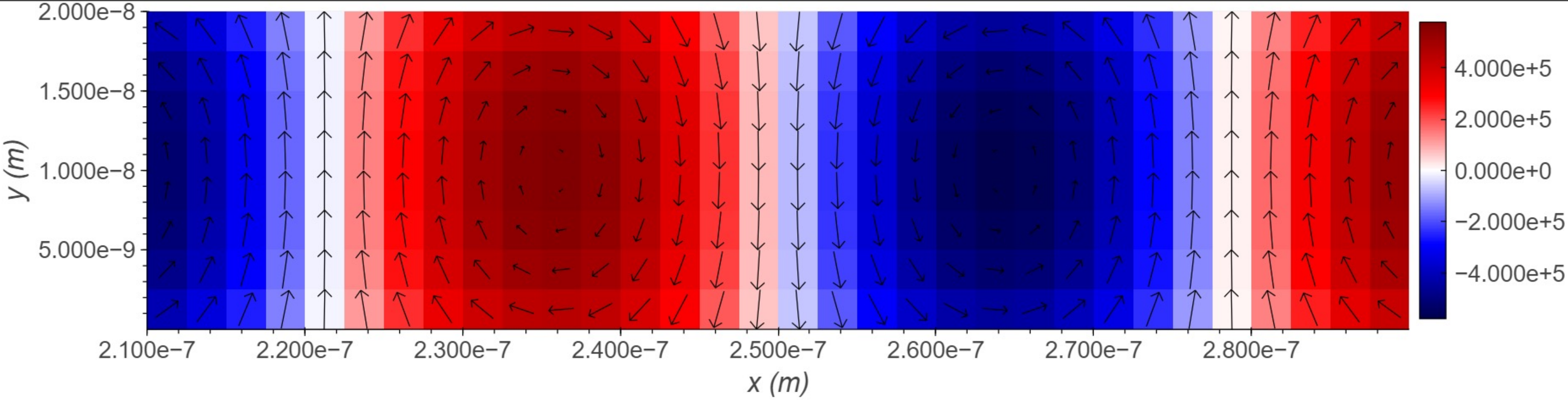
- DMI requires specification of the crystal class
  - So far saw class 'Cnv_z'
  - Impacts energy term, and has drastic effect on spin orientations within domains

$$-A\mathbf{m} \cdot \nabla^2\mathbf{m} - \frac{1}{2}\mu_0 M_\mathrm{s}\mathbf{m} \cdot \mathbf{H}_\mathrm{d} + D(\mathbf{m} \cdot \nabla m_z - m_z \nabla \cdot \mathbf{m})$$

PART 1: STATIC PROPERTIES OF A DOMAIN WALL IN A MAGNETIC STRIP

$$-A\mathbf{m}\cdot\nabla^2\mathbf{m} - \frac{1}{2}\mu_0 M_s \mathbf{m}\cdot\mathbf{H}_d + D\mathbf{m}\cdot(\nabla\times\mathbf{m})$$

Class T



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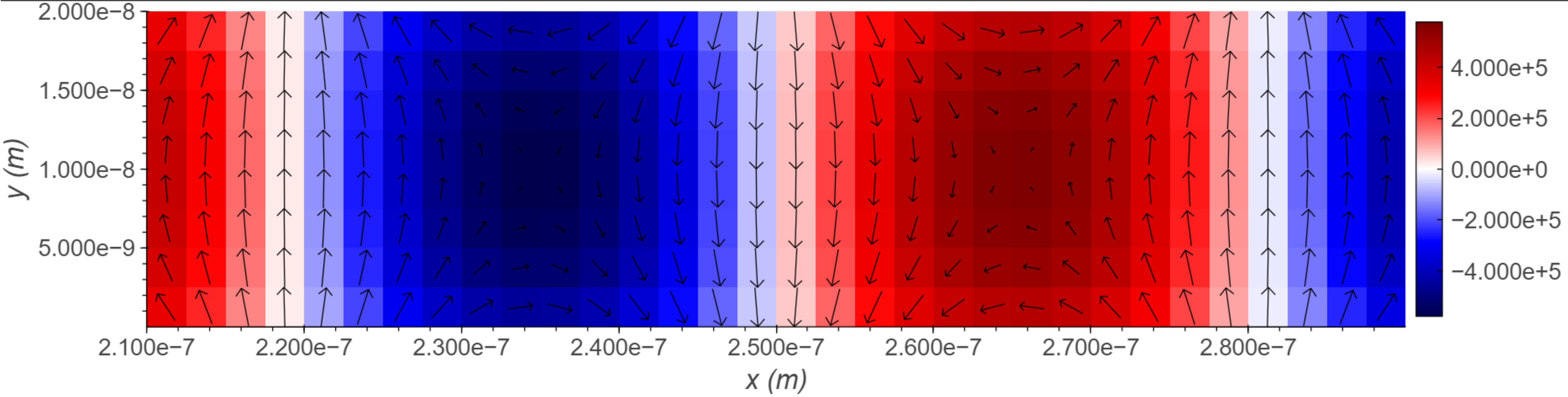
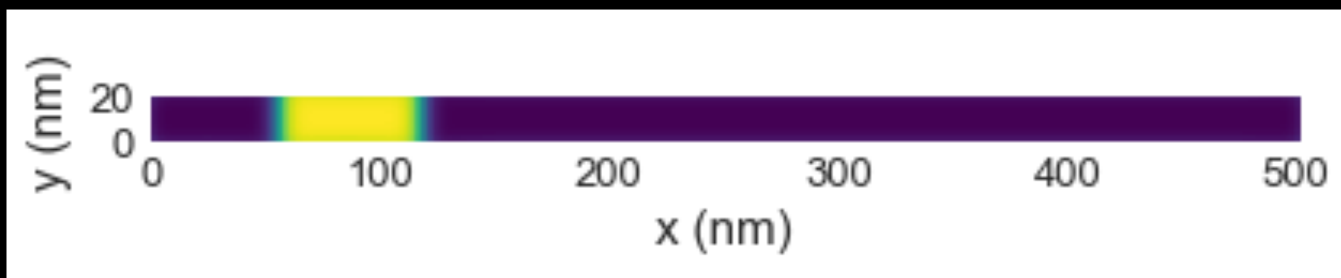
$$-A\mathbf{m}\cdot\nabla^2\mathbf{m}-\frac{1}{2}\mu_0 M_\mathrm{s}\mathbf{m}\cdot\mathbf{H}_\mathrm{d}+D\mathbf{m}\cdot\left(\frac{\partial\mathbf{m}}{\partial x}\times\hat{x}-\frac{\partial\mathbf{m}}{\partial y}\times\hat{y}\right)$$

Class D2d_z



PART 2: DOMAIN WALL MOTION

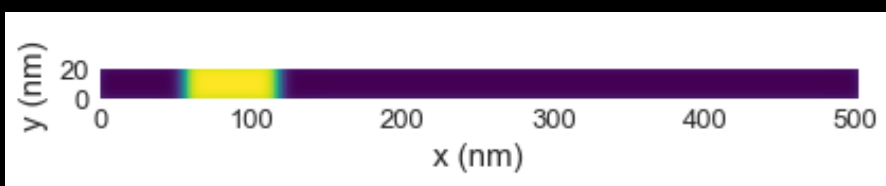
- There are multiple techniques available for the manipulation of domain walls, including the use of an external field and applied current. Here, we show the effects of both on domain walls in a small permalloy strip. We first consider a pair of domain walls initialized as shown below:



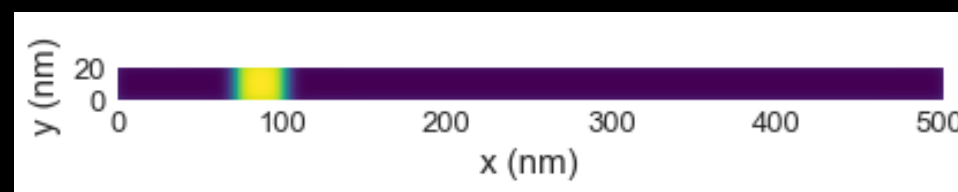
EXTERNAL FIELD (ZEEMAN ENERGY)

- Applying a field of 10 kA/m in the negative z-direction and driving the system for 5 ns while considering the Zeeman energy contribution ($\mu_0 \boldsymbol{M_s} \mathbf{m} \cdot \mathbf{H}$) changes the system as shown below:

Initial State



After time drive

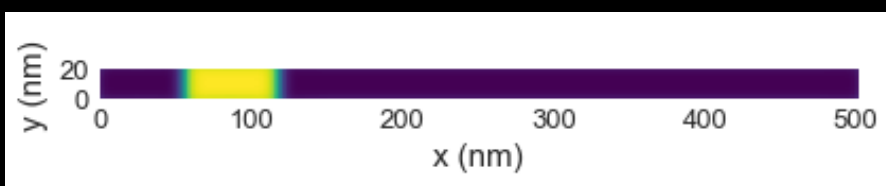


- The application of a field to the system moved the domain walls in opposite directions to one another, effectively shrinking the size of the positively magnetized region

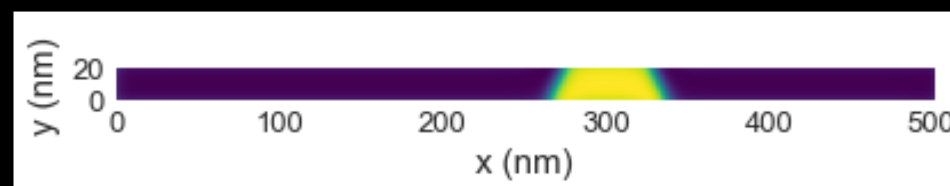
ELECTRICAL CURRENT (SLONCZEWSKI PRECESSION)

- An electrical current applied to the strip can also drive domain wall motion via spin transfer torque (STT). Utilizing the Slonczewski dynamics term ($\gamma_0 \beta \epsilon (\mathbf{m} \times \mathbf{m}_\mathrm{p} \times \mathbf{m}) - \gamma_0 \beta \epsilon' (\mathbf{m} \times \mathbf{m}_\mathrm{p})$) in the simulation and applying a current density of 10e12 A/m and a spin polarization of 0.4 yields the following results after driving for 0.5 ns:

Initial State



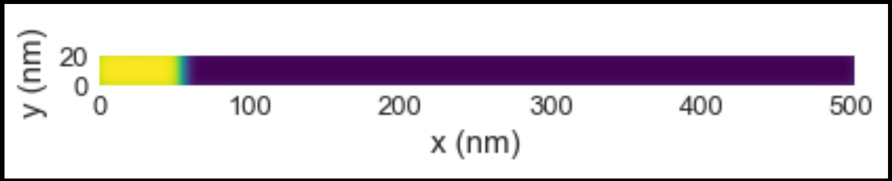
After time drive



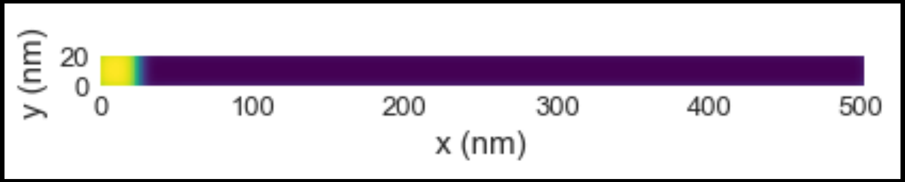
- Compared to an applied field, the use of STT moves domain walls much faster. Additionally, the walls moved together with the width of the positively magnetized region roughly preserved

SINGLE DOMAIN WALL

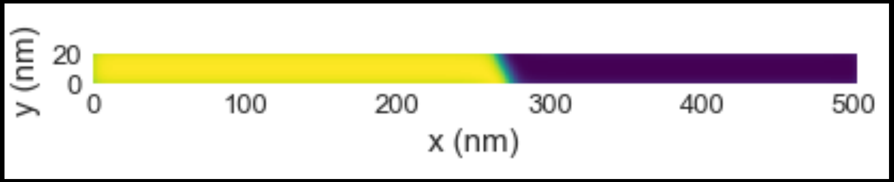
Initial State



Field Driven



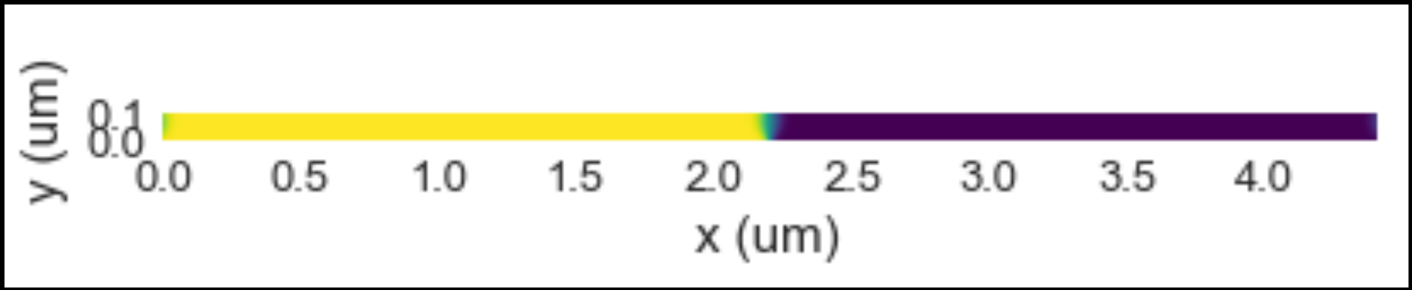
Current driven



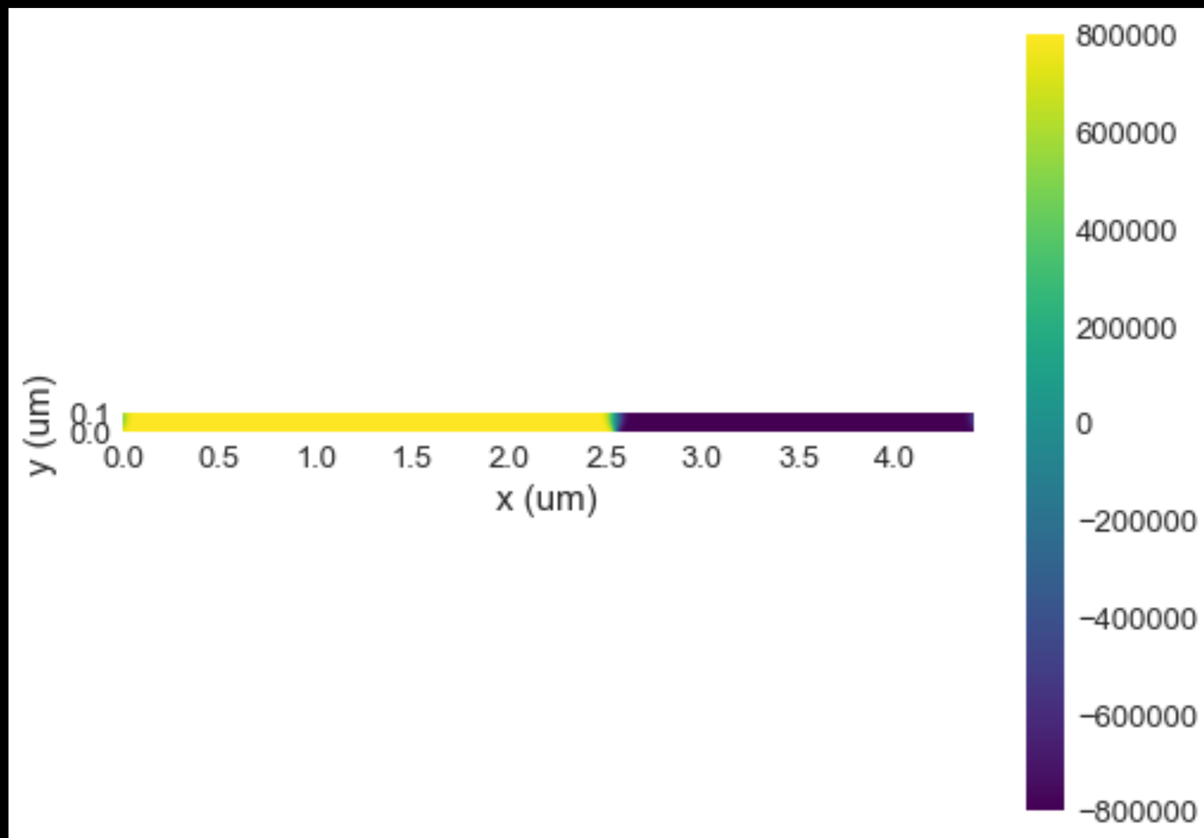
- Results are similar when using a single domain wall instead of two, with the current driven wall still far outpacing the field driven wall

WALKER BREAKDOWN

- As was discussed in class, moving domain walls are susceptible to Walker breakdown. We study this here by initializing a long strip containing two domains magnetized in the +/- x direction separated by a domain wall pointing in the y-direction as shown below:

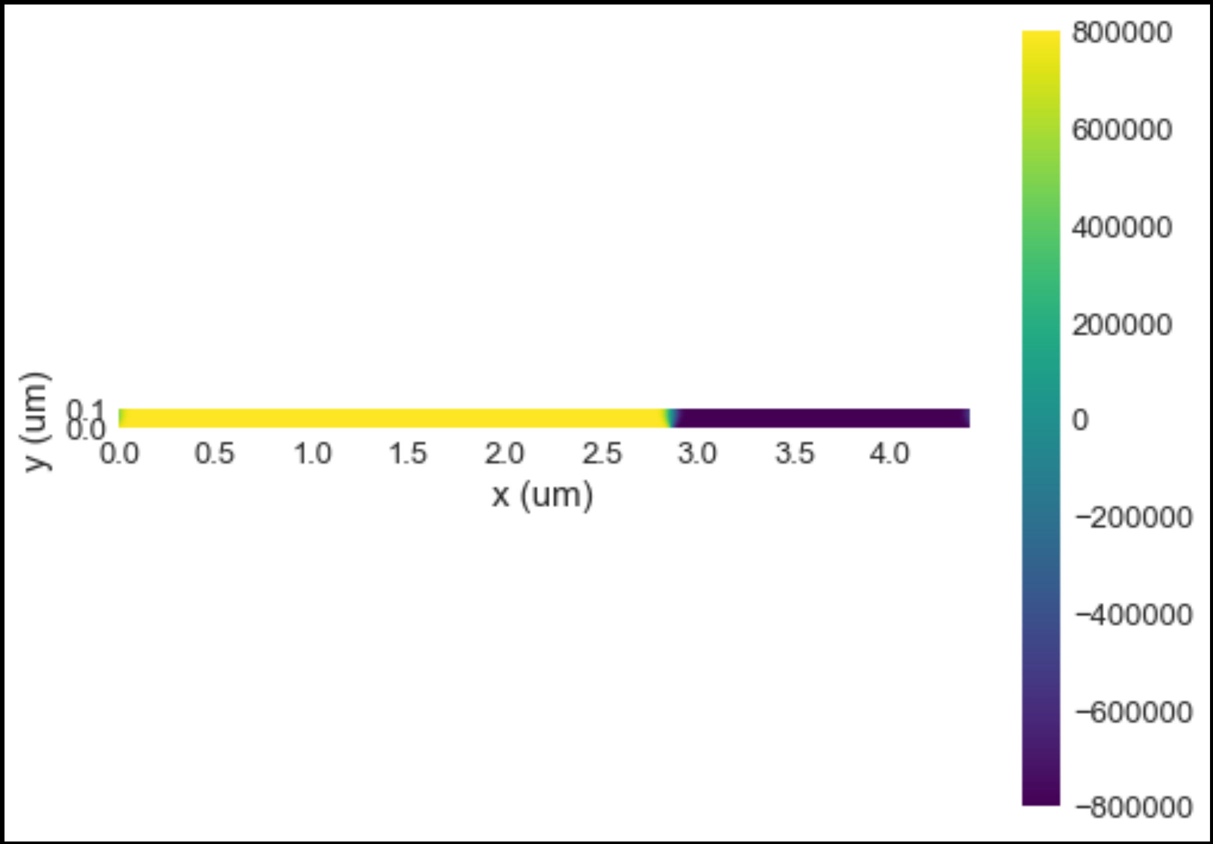


5 OE FIELD



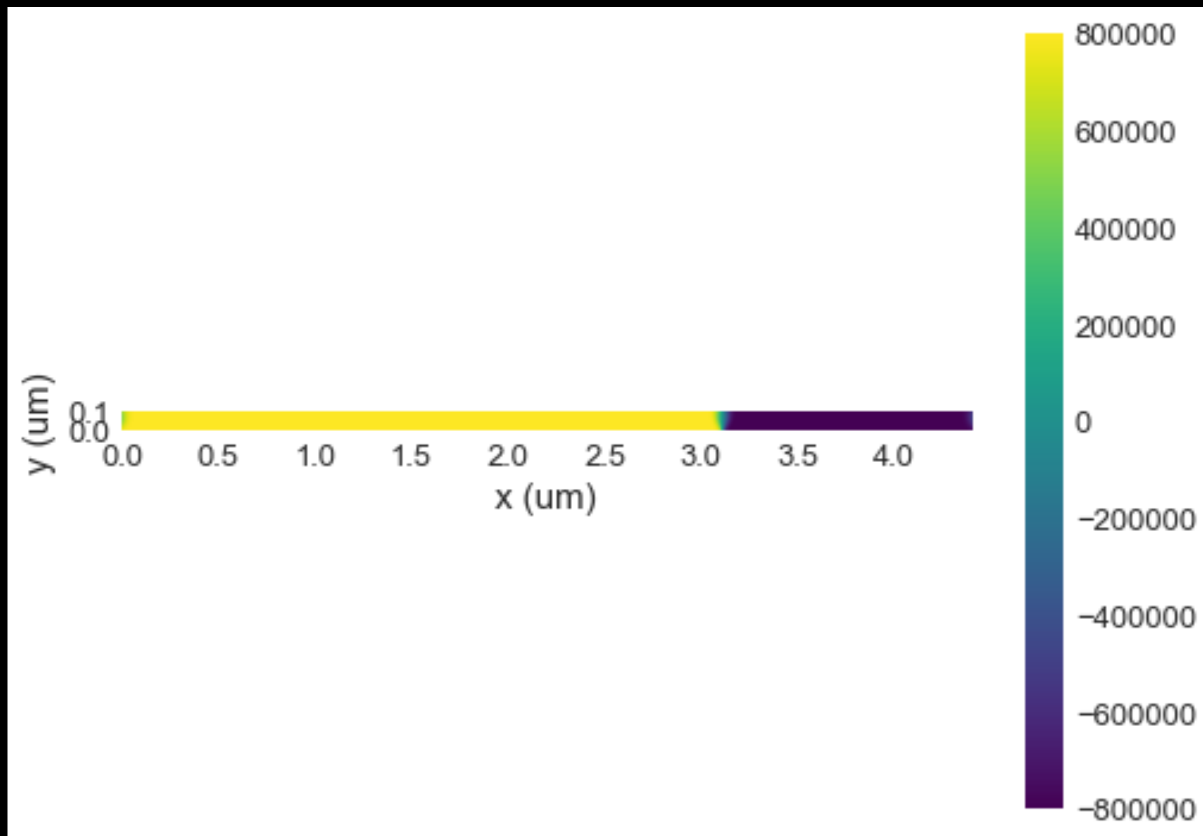
800000
600000
400000
200000
0
−200000
−400000
−600000
−800000
y (um)
0.1
0.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
x (um)

10 OE FIELD

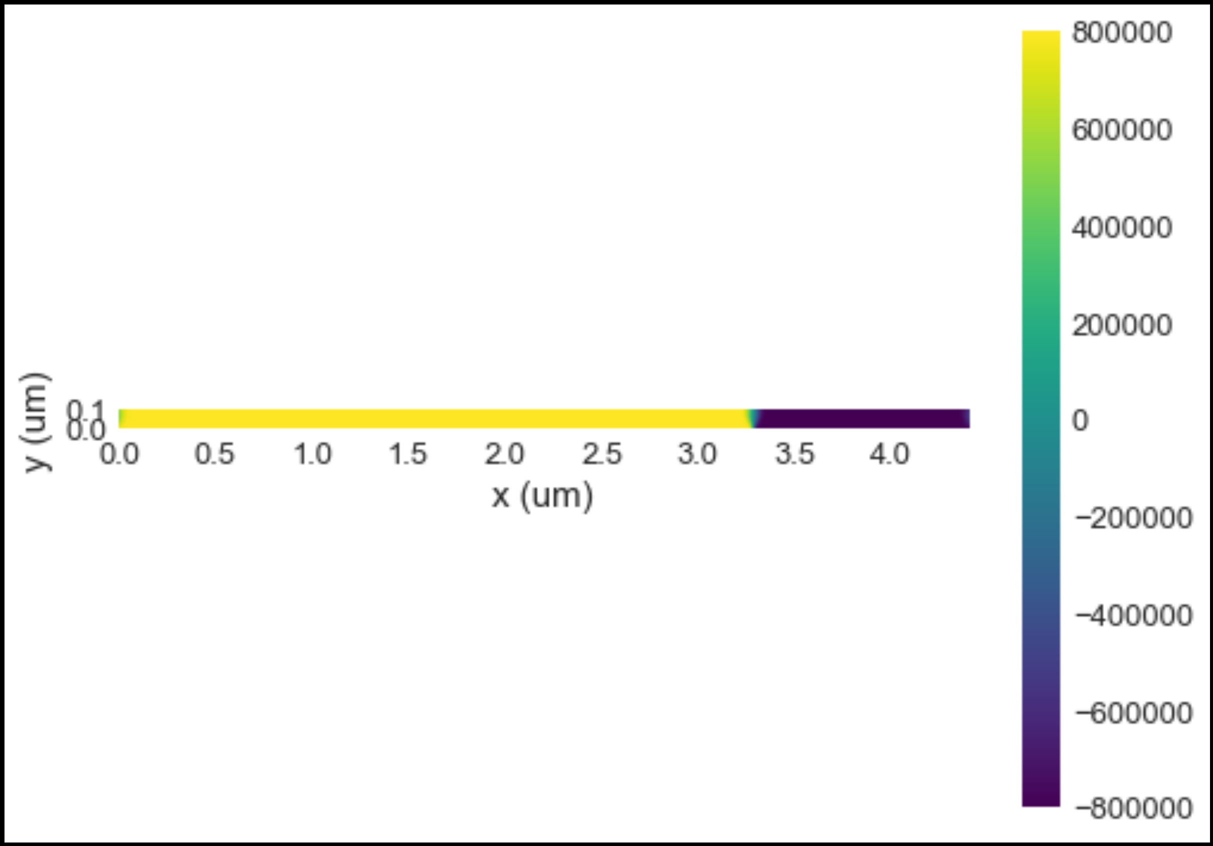


y (um)
0.1
0.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
x (um)
800000
600000
400000
200000
0
−200000
−400000
−600000
−800000

15 OE FIELD

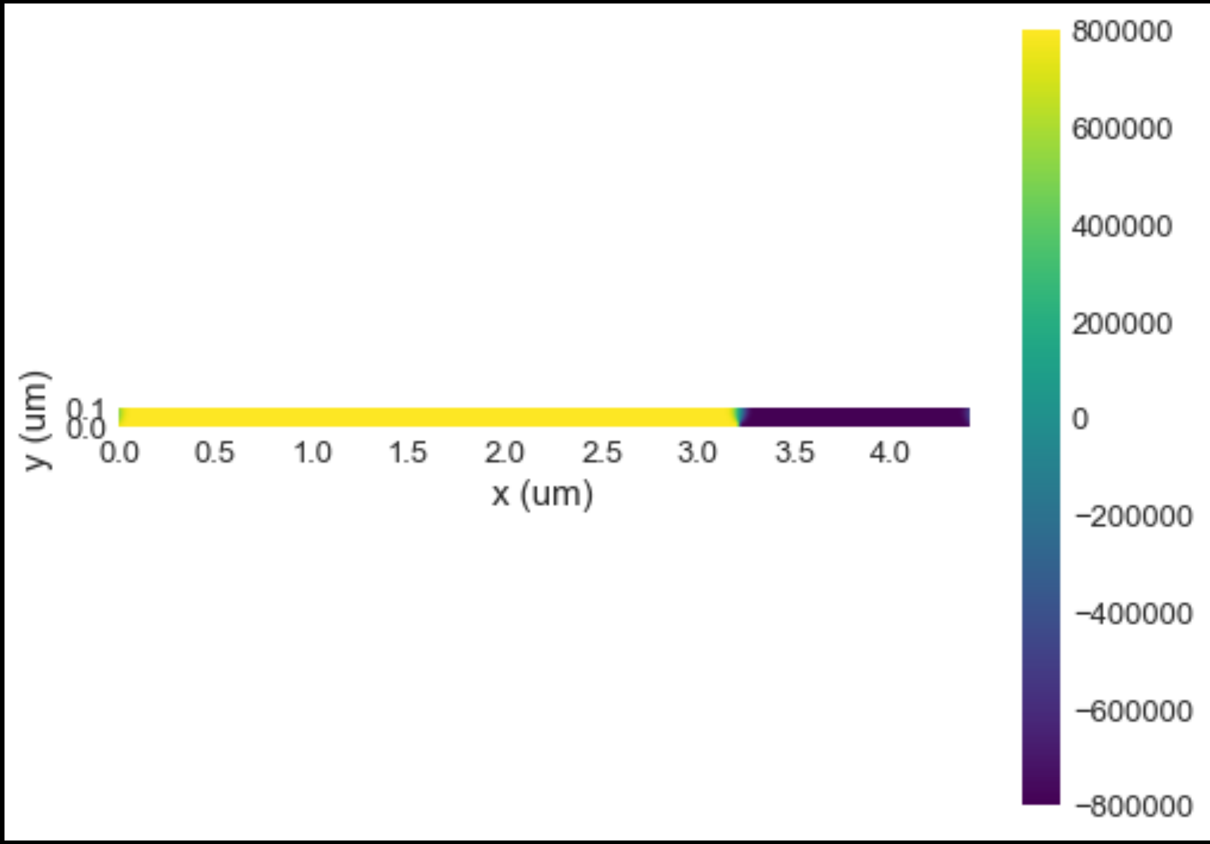

800000
600000
400000
200000
0
−200000
−400000
−600000
−800000
y (um)
0.1
0.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
x (um)

20 OE FIELD



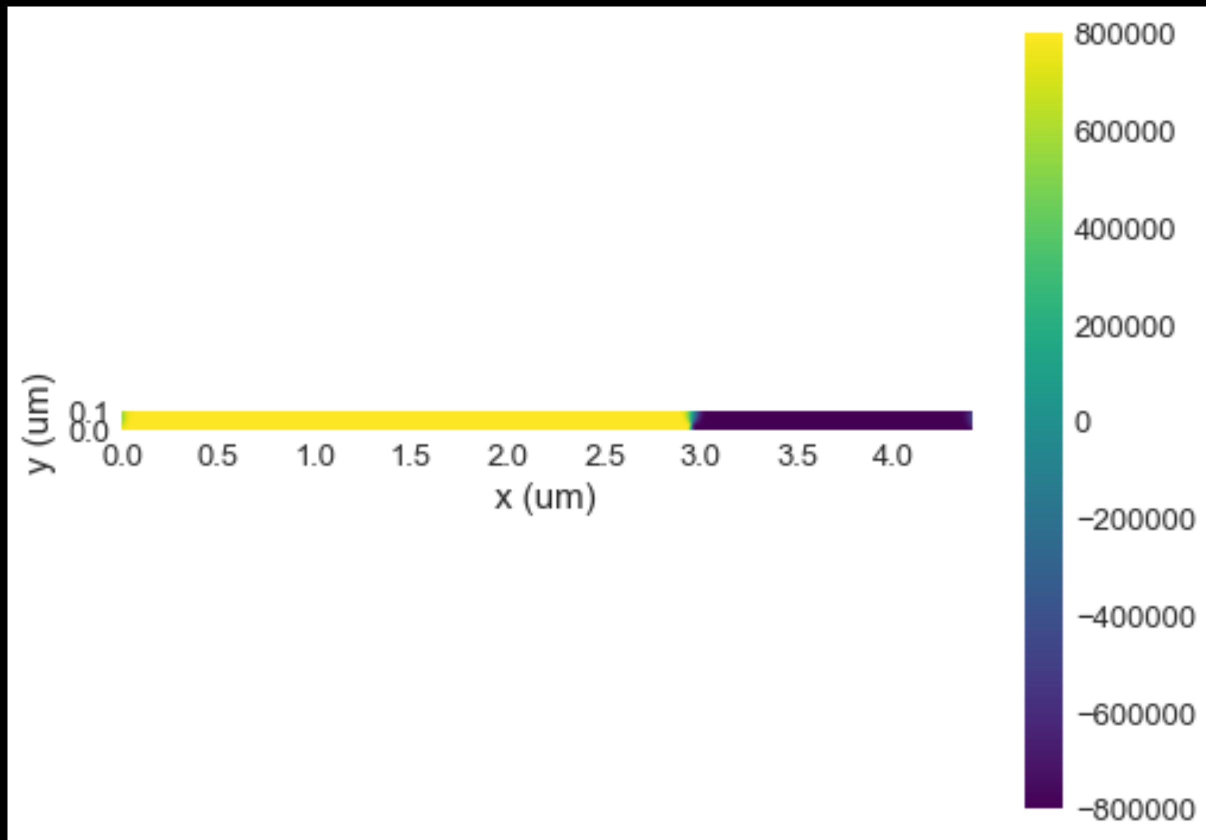
y (um)
0.1
0.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
x (um)
800000
600000
400000
200000
0
−200000
−400000
−600000
−800000

25 OE FIELD



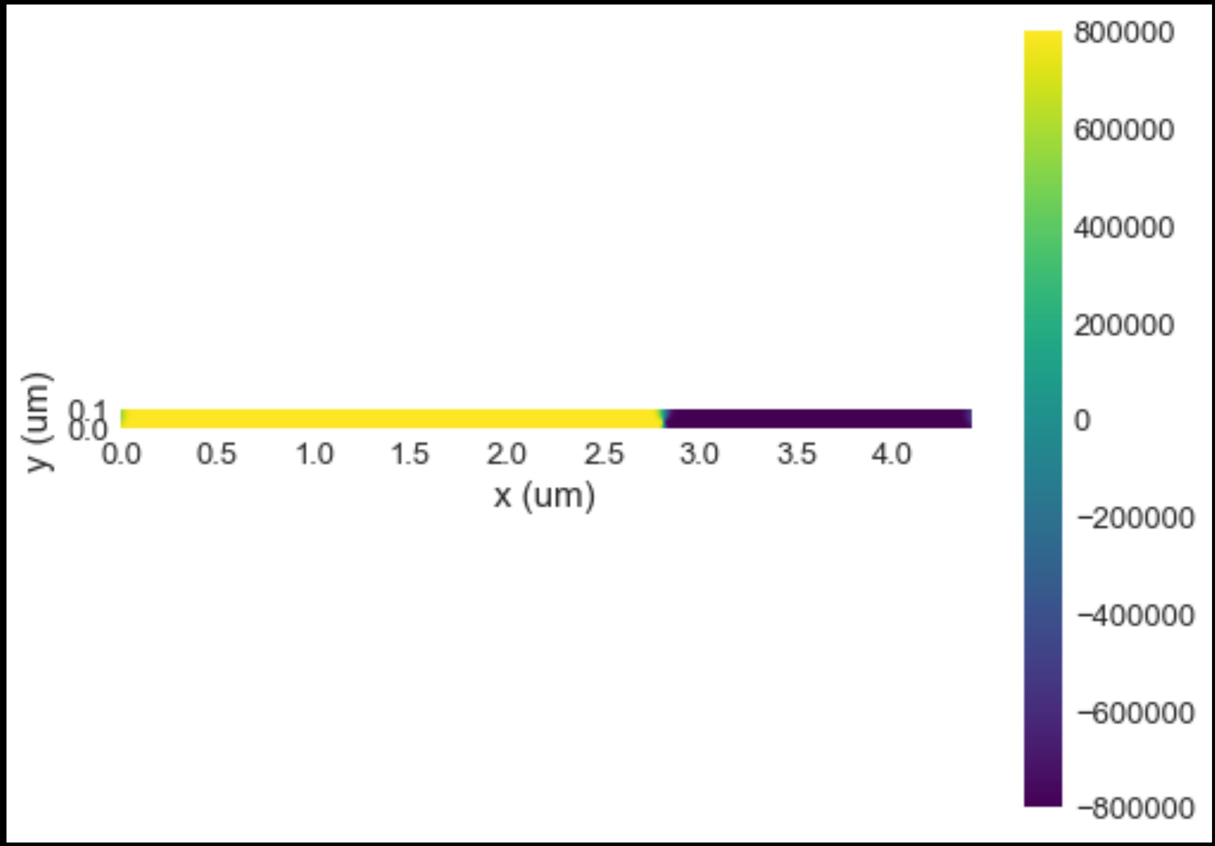
y (um)
0.1
0.0
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0
x (um)
800000
600000
400000
200000
0
−200000
−400000
−600000
−800000

30 OE FIELD



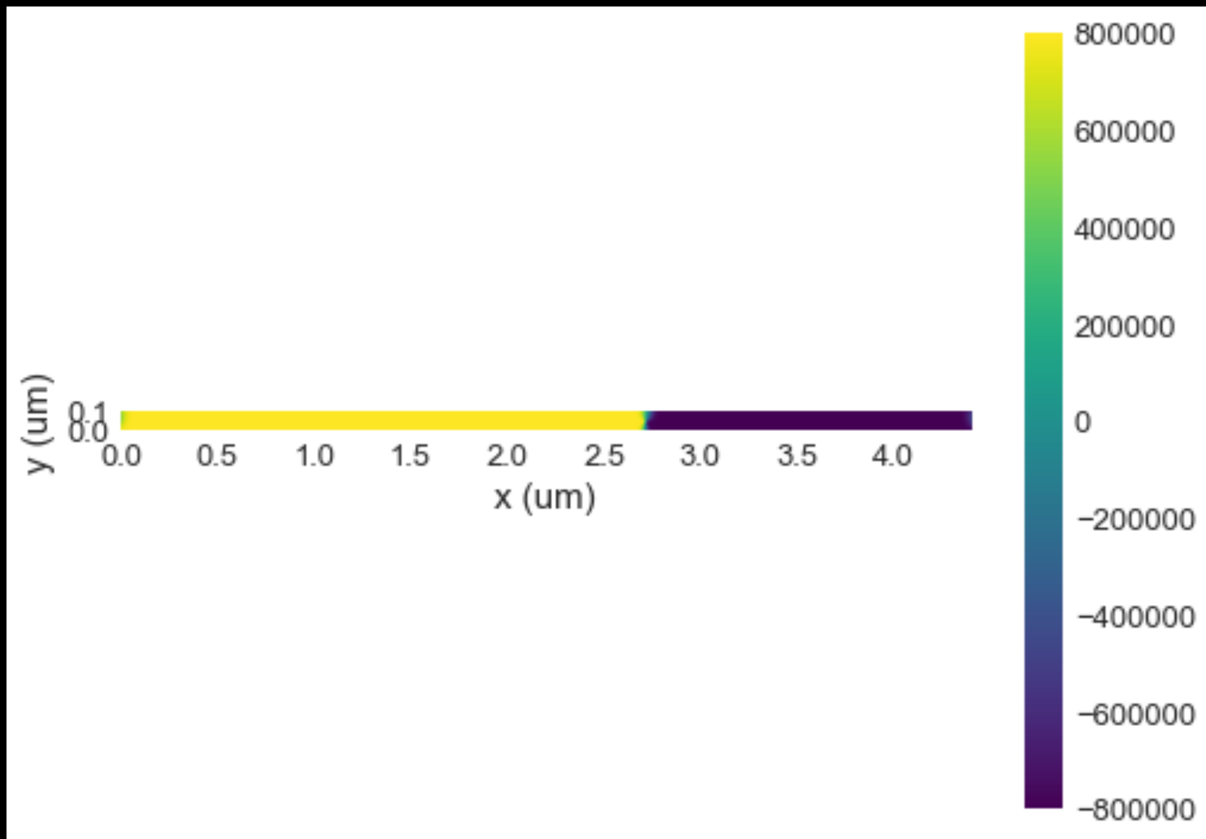
y (um)
0.1
0.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
x (um)
800000
600000
400000
200000
0
−200000
−400000
−600000
−800000

35 OE FIELD



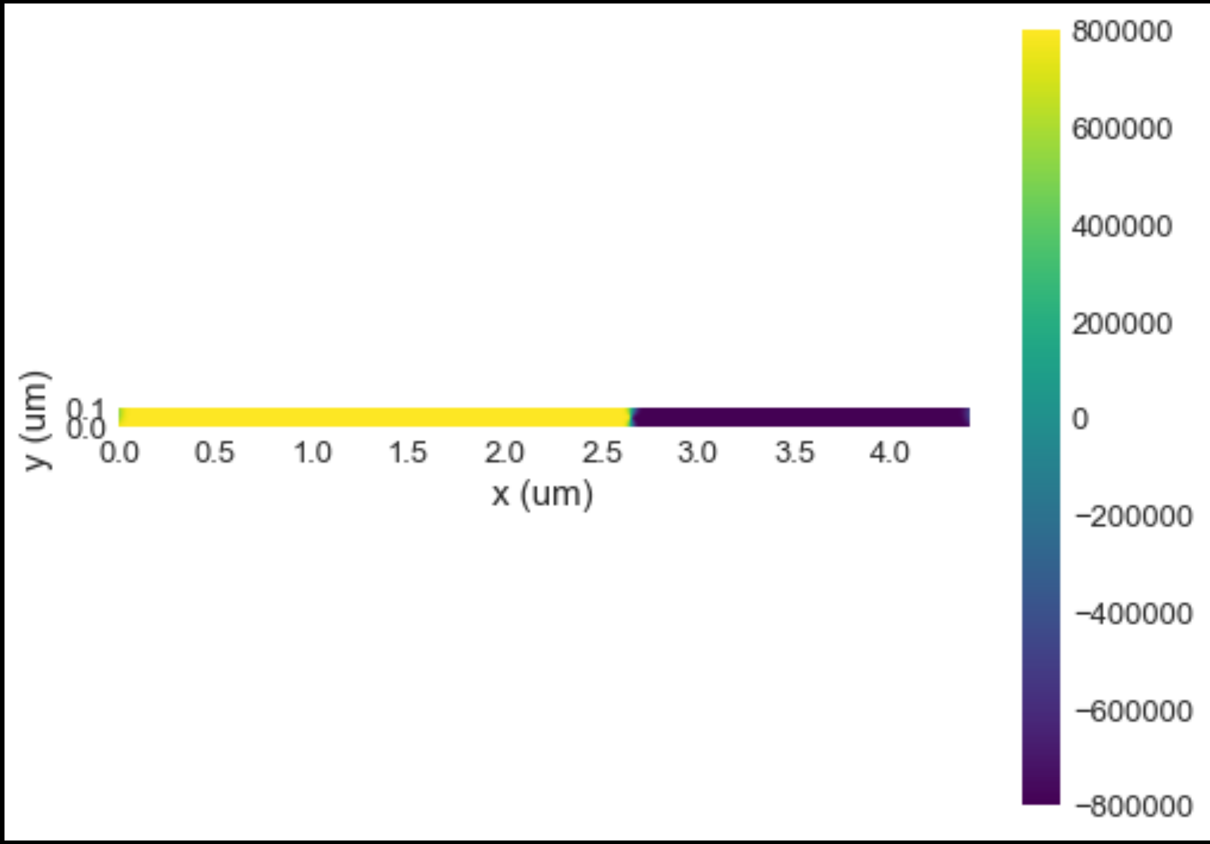
y (um)
0.1
0.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
x (um)
800000
600000
400000
200000
0
−200000
−400000
−600000
−800000

40 OE FIELD



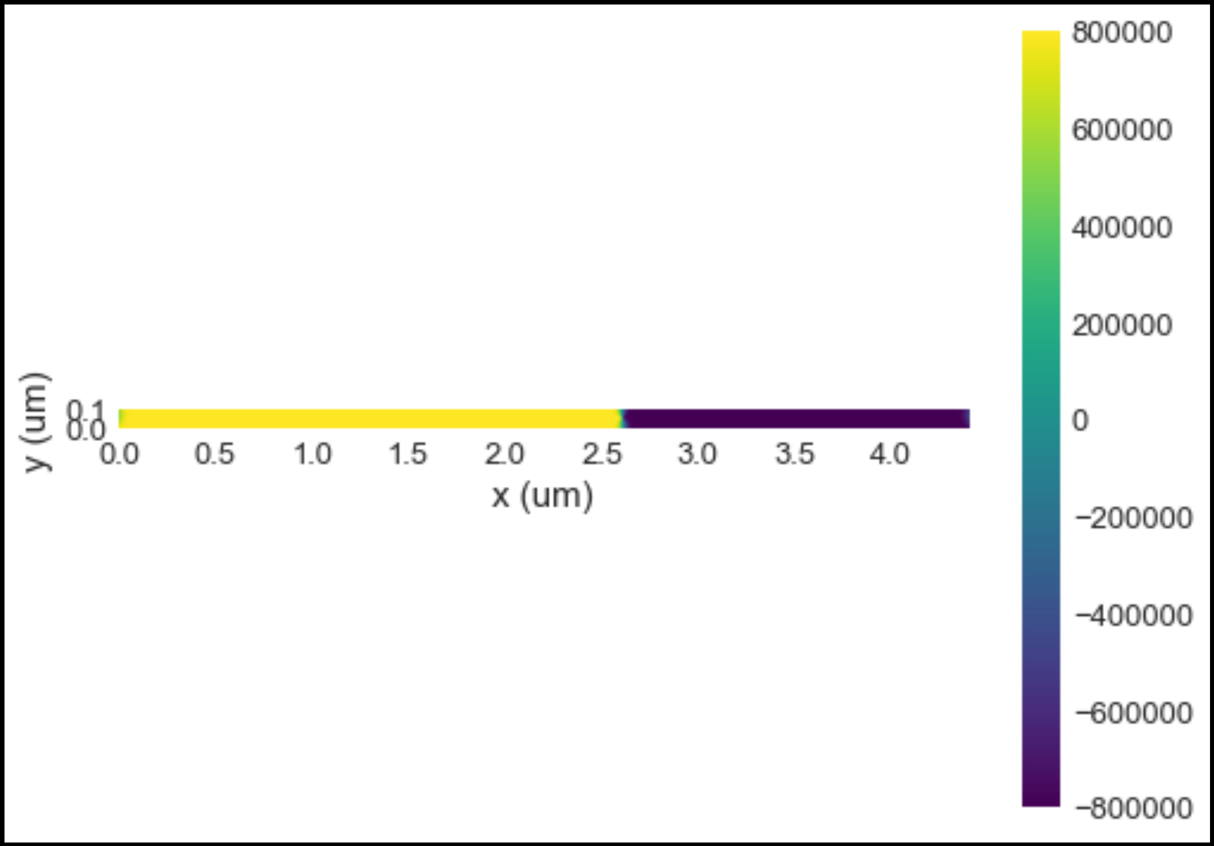
y (um)
0.1
0.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
x (um)
800000
600000
400000
200000
0
−200000
−400000
−600000
−800000

45 OE FIELD



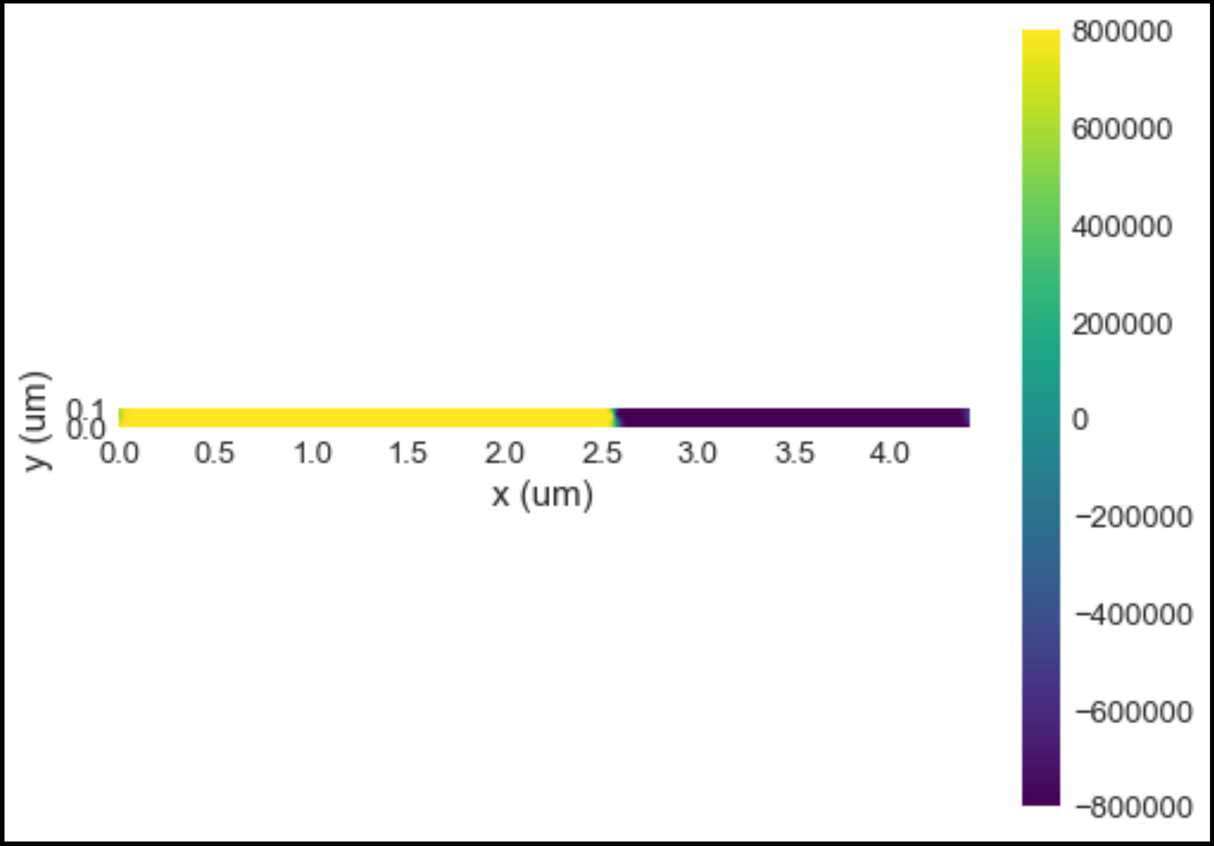
y (um)
0.1
0.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
x (um)
800000
600000
400000
200000
0
−200000
−400000
−600000
−800000

50 OE FIELD



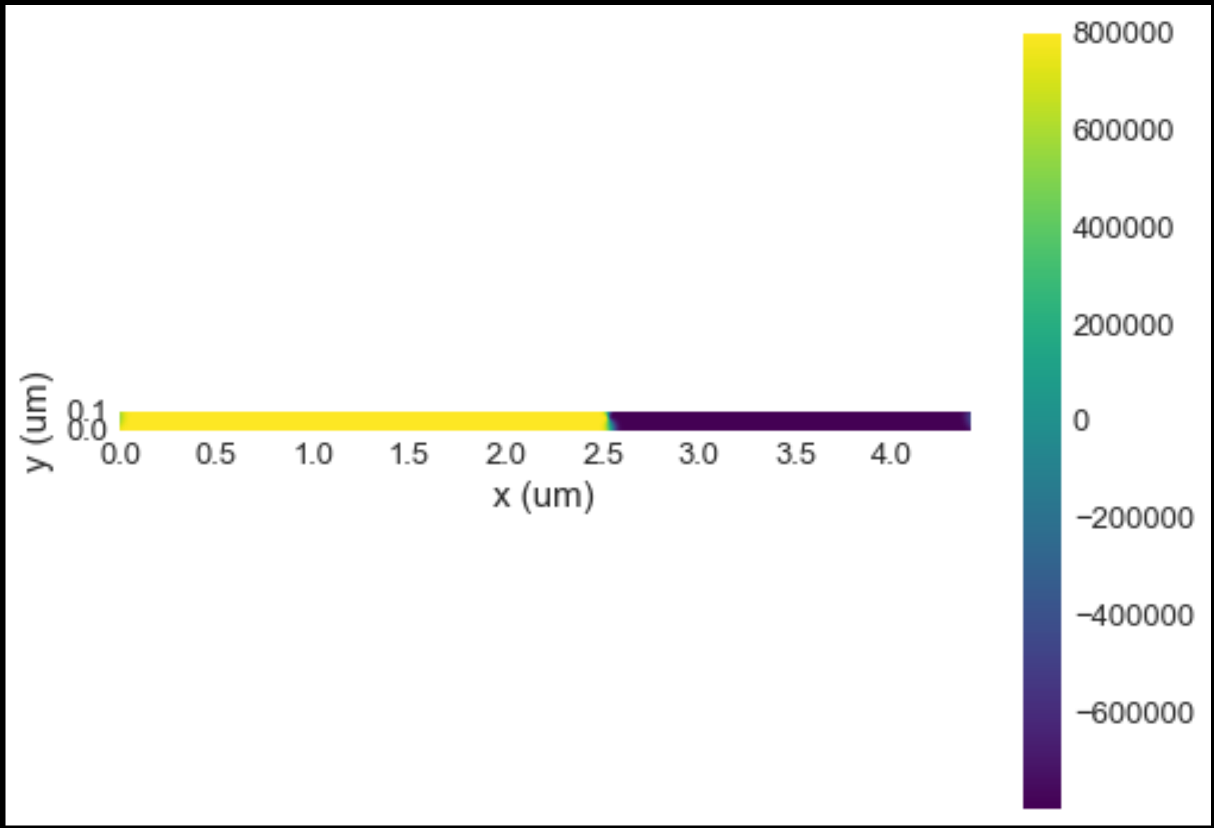
800000
600000
400000
200000
0
−200000
−400000
−600000
−800000
y (um)
0.1
0.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
x (um)

55 OE FIELD



800000
600000
400000
200000
0
−200000
−400000
−600000
−800000
0.1
0.0
y (um)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
x (um)

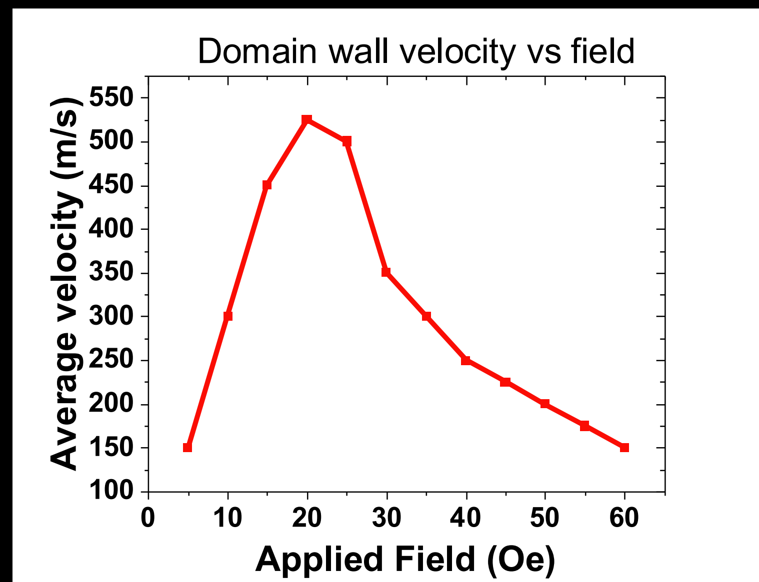
60 OE FIELD



y (um)
0.1
0.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
x (um)
800000
600000
400000
200000
0
−200000
−400000
−600000

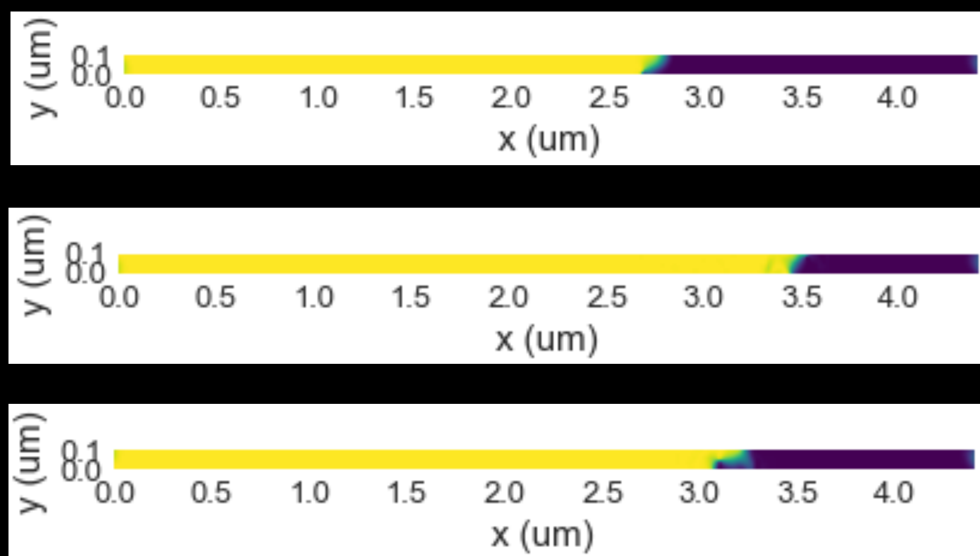
WALKER BREAKDOWN

- Average domain wall velocity was calculated by dividing the change in position by simulation time
- Domain wall velocity peaked at an applied field of about 20 Oe for this system



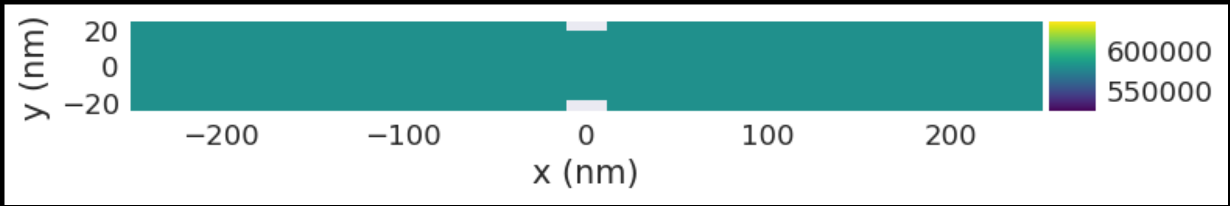
WALKER BREAKDOWN

- After this regime, domain wall velocity remains steady until beginning to oscillate at higher fields. The shape of the domain wall becomes irregular, and the strip eventually saturates in 2 ns at about 300 Oe. Shown below are simulations from 150 Oe to 170 Oe.



PART 3: DOMAIN WALL PINNING

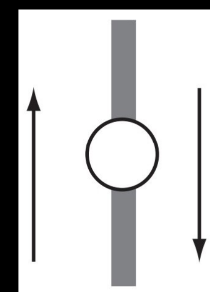
- Defects can change the energy of a domain wall, blocking its motion
- We introduce a defect in the form of notches in the sides of the strip
- This local energy minimum can be overcome by applying an external field



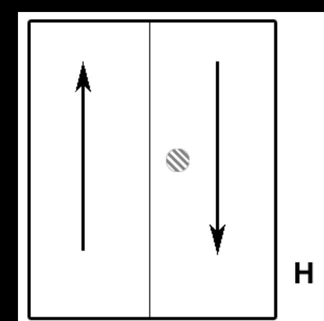
Magnet strip with notches (one domain)

500 nm long, 50 nm wide, 1 cell thick

RECAP ON PINNING



- Energy per unit area of domain wall: $\gamma_w = 4\sqrt{AK}$
- When a defect has values A and K which differ from bulk, pinning can occur
- The contrast is highest at voids, where K and A are zero
  - The size of the defect also matters, larger pins more easily!
- Applying a large enough field can overcome the local minimum created by the defects

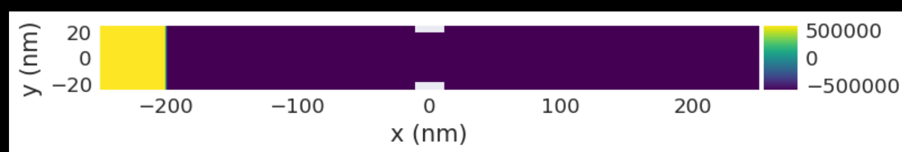


Zeeman Energy of Wall: $2\mu_0 M H \delta x$ Therefore, pressure on wall: $2\mu_0 M H$

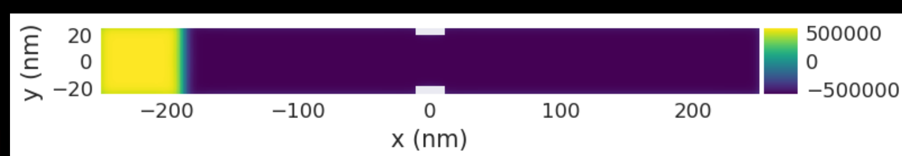
PINNING THE WALL

- We make two notches of 5 nm depth on each side of the strip
- Create a domain wall on the left, minimize the energy
- Now attempt to drive the wall across the film using a magnetic field pointing along the z-axis
- A field too weak cannot get the wall beyond the notch, a local minimum for energy

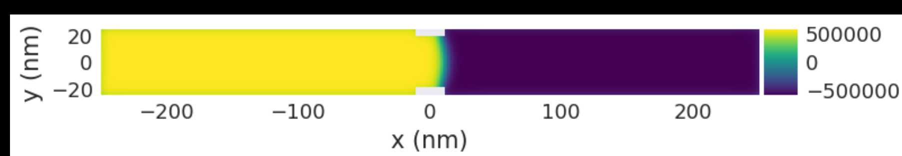
$$\delta_w = \pi\sqrt{\frac{A}{K}}$$



Minimize energy



Apply Field in
+z direction



Zeeman Energy:

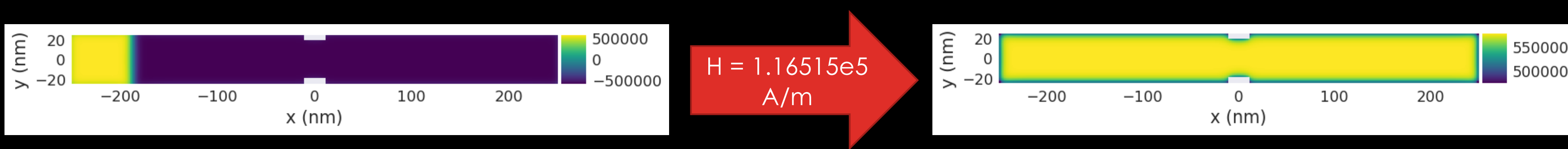
$$2\mu_0 M H \delta x$$

Therefore, pressure on wall:

$$2\mu_0 M H$$

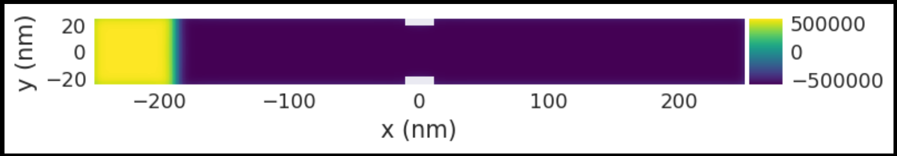
DRIVING WALL ACROSS NOTCH

- After some trial and error, for notches of 5 nm it was found that a field of approximately **H = 1.16515e5 A/m** applied in the +z direction is needed at minimum to drive the wall all the way across the strip

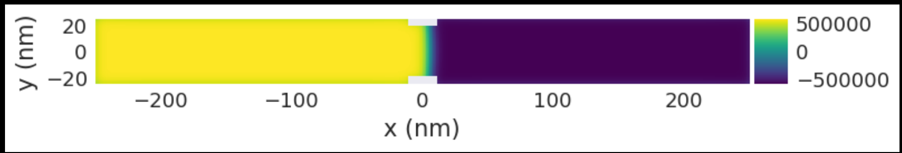


DEPINNING THE WALL

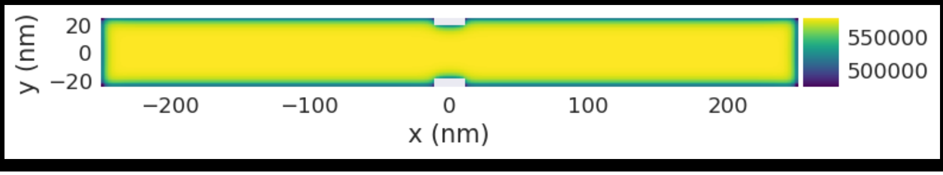
- Now, apply a weaker field to pin the wall on the notch
- What minimum field is now required to unpin from the wall?
- Turns out, the same minimum field when the wall was not first moved!



Apply field resulting in pinned wall



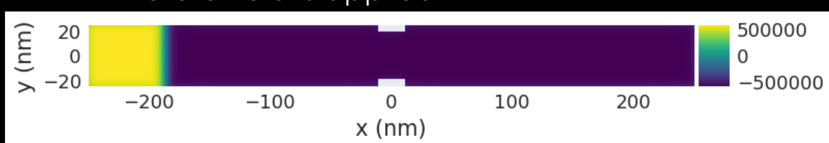
Apply H = 1.16515e5 A/m to unpin and make it across



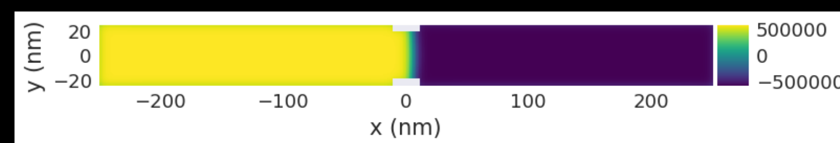
LOCAL ENERGY MINIMA

- A weaker field can be applied to get the wall beyond the notches but not all the way across the strip
- At this point, if the magnetic field is turned off, the wall will move back towards the notches

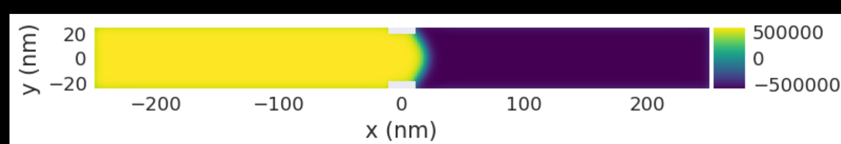
Before field is applied



Wall moves back to notches



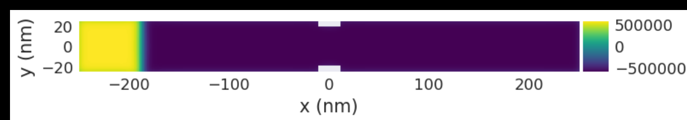
Apply field to move wall just beyond notches



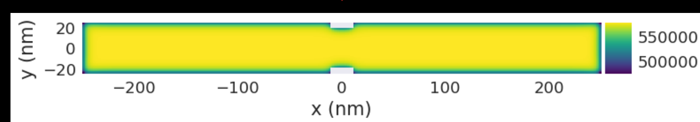
Remove magnetic field and minimize again

LOCAL ENERGY MINIMA

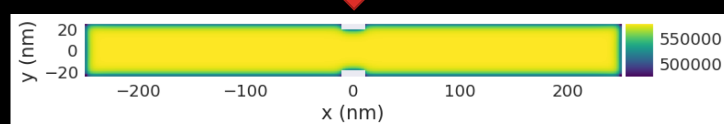
- After the domain wall has been driven to the end of the strip, it remains there even if the magnetic field is removed. This is another local minimum.



Drive to end of strip



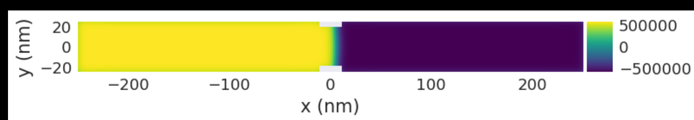
Remove field and minimize again



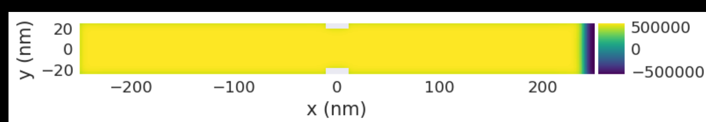
The wall does not move back

LOCAL ENERGY MINIMA

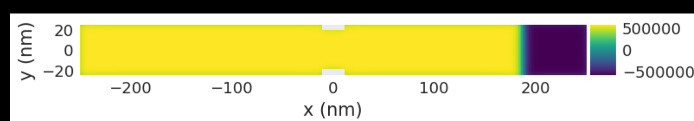
- Another energy minimum found along the strip?



Apply field

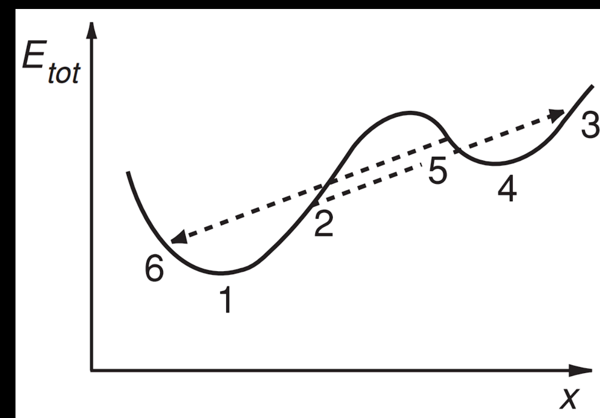


Remove field



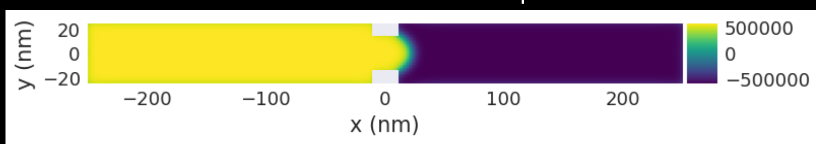
LOCAL ENERGY MINIMA

- These results can be explained using the energy landscape
- There are local energy minima along the strip
- The notches are one location of a minimum
- Getting beyond a given energy barrier requires a minimum field strength

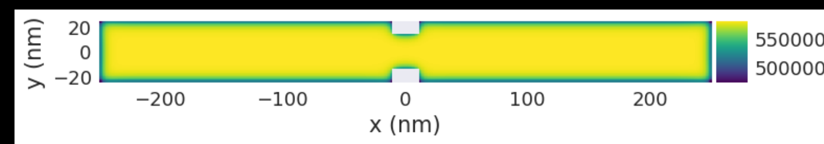


OTHER SIZED NOTCHES

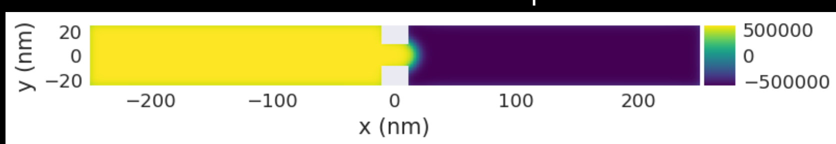
10 nm notch depth



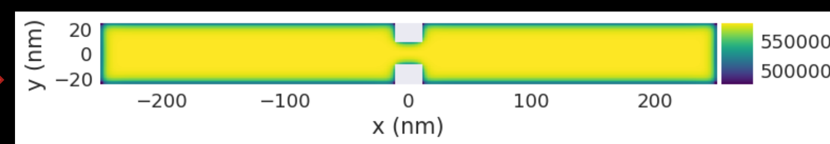
H = 1.2238e5 A/m



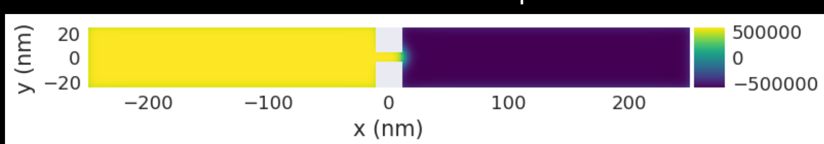
15 nm notch depth



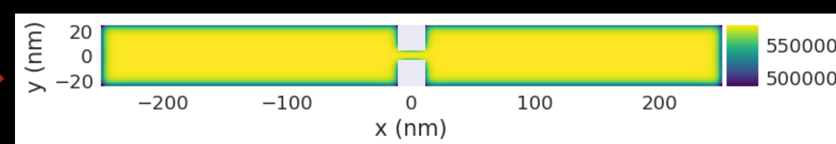
H = 1.52643e5 A/m



20 nm notch depth

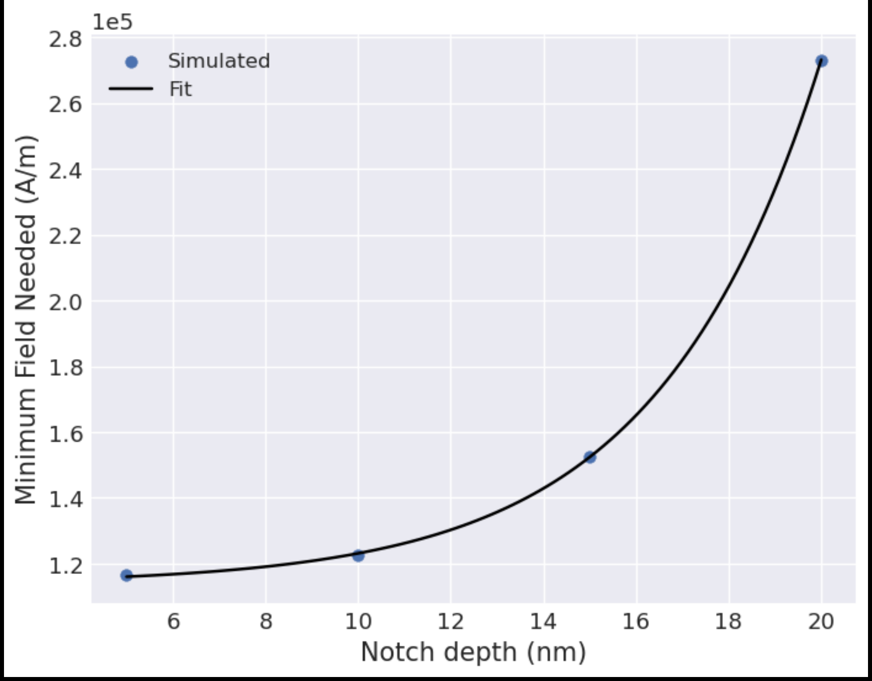


H = 2.7313e5 A/m



OTHER SIZED NOTCHES

- The minimum field needed was found for notches of 10, 15, and 20 nm depths as well
- It was found that the field varied exponentially with a linear increase in notch depth: **a * Exp(b * t) + c**
  - t = notch depth in nm
  - a = 549.12
  - b = 0.2835
  - c = 113759



QUESTIONS?