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Shape anisotropy effects on magnetic domain wall dynamics in spintronic devices

Samuel Liu

University of Minnesota-Twin Cities, University of Texas at Austin

Department of Electrical and Computer Engineering

Sponsors:

- Sandia National Laboratories
- O-REU at TAMU

Collaborators:

- Matthew Marinella
- Christopher Bennett
- Tianyao (Patrick) Xiao
- INC Lab at UT Austin

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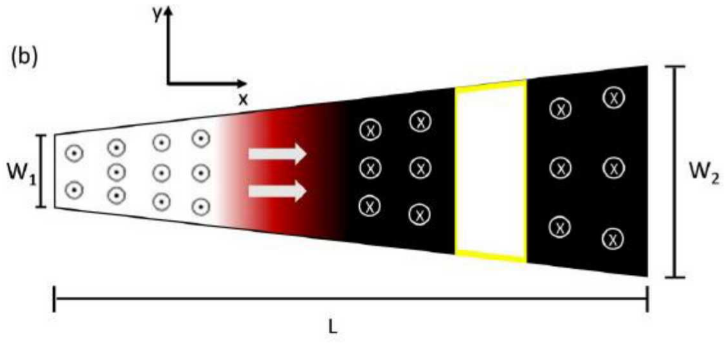
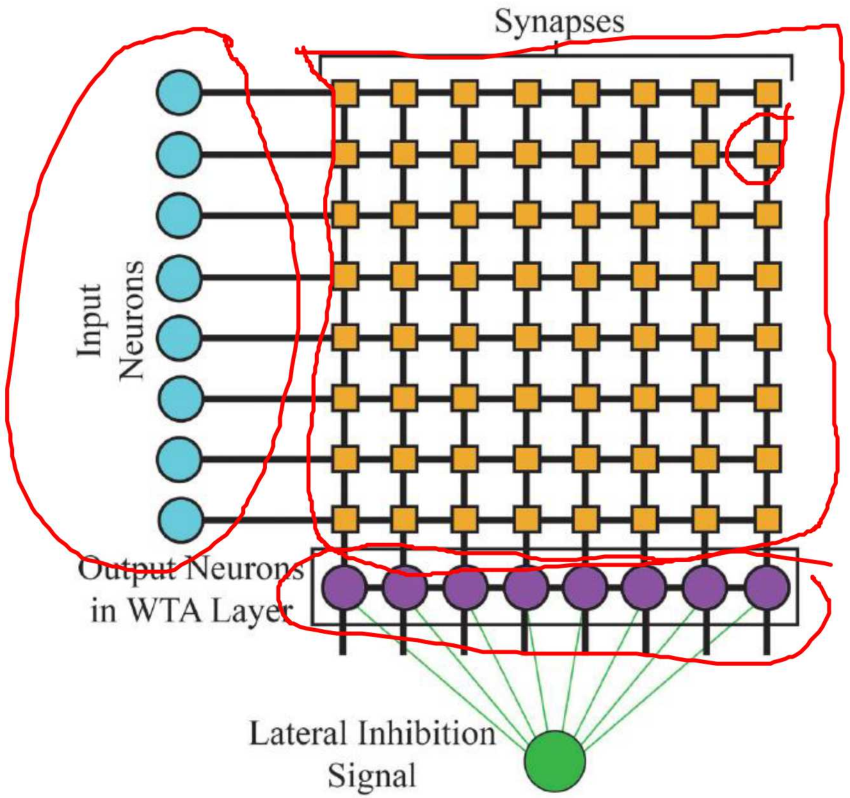
Nanomagnetic Neural Networks

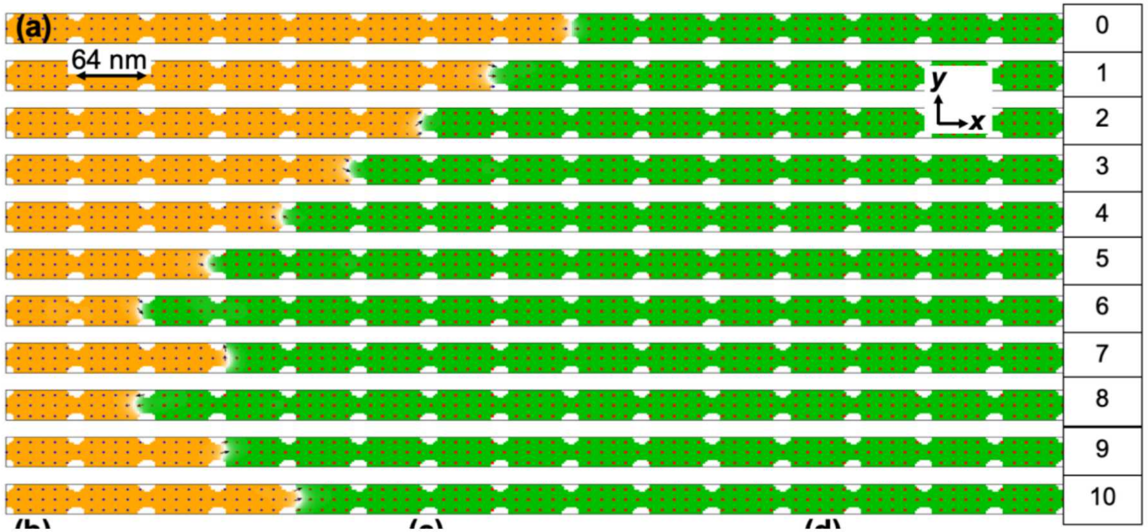


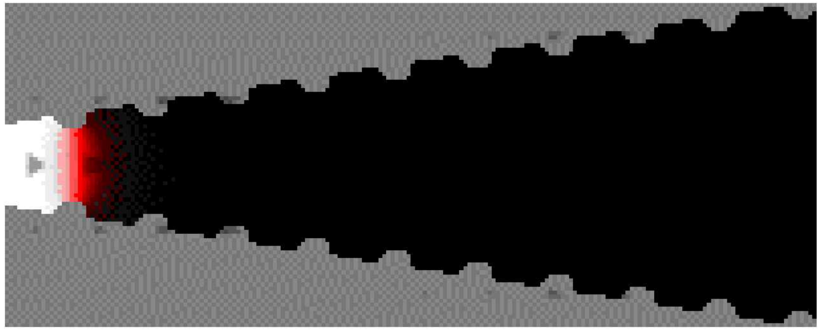
- Neural networks (NNs) are useful for pattern recognition tasks that humans are traditionally better at like speech and image recognition
- Synapses and neurons of a neural network can be implemented using spintronic domain wall devices
- Magnetic domain wall device current density vs synapse change linearity can be tuned to optimize NN training
- Goal: model shape-based nonlinear synaptic behavior at device and system level
  - Nonlinear synaptic behavior implement unsupervised learning



Hassan et al., *Magnetic domain wall neuron with lateral inhibition*

Domain Wall Synapses





- Linear synapses implemented by rectangular channel
- Notches provide the fixed states/positions for the domain wall

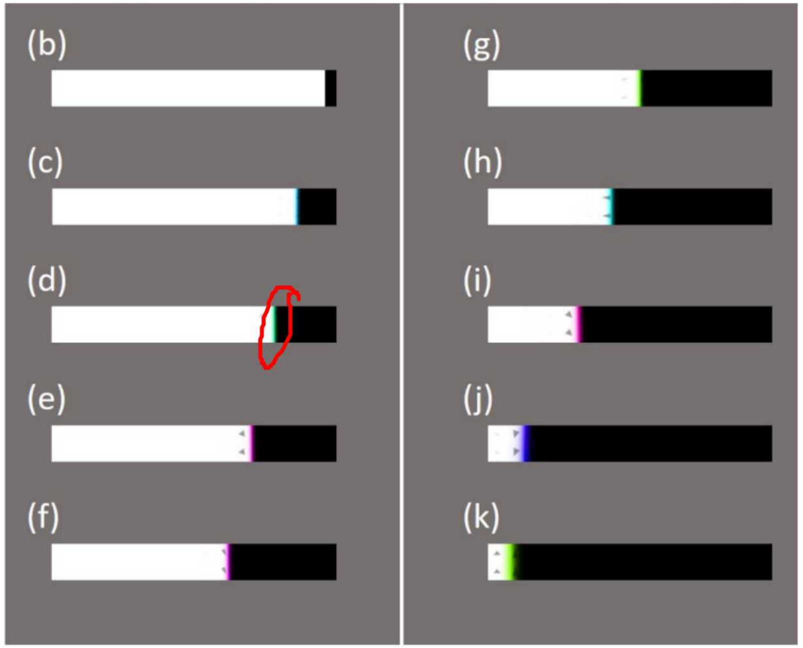
- Nonlinear tuning can be implemented by using sloped channel

Micromagnetics and Analytical modeling

- Develop non-linear synapse model using micromagnetics simulation software MuMax3
- Produce SPICE compatible analytical device model
- Emphasis on ways to minimize leaking behavior in synapses

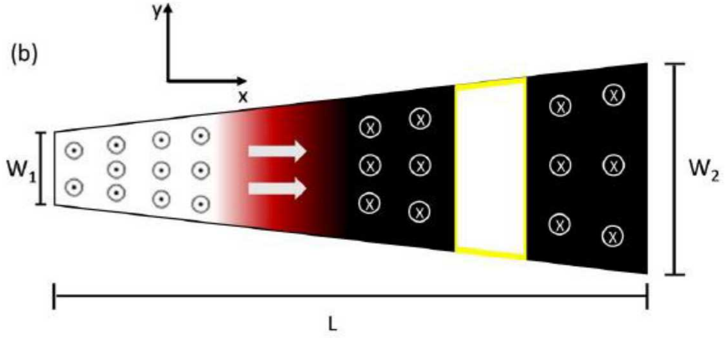
$$\vec{\tau}_{\mathrm{ZL}} = \frac{1}{1+\alpha^2}\left((1+\xi\alpha)\,\vec{\mathbf{m}}\times(\vec{\mathbf{m}}\times(\vec{\mathbf{u}}\cdot\nabla)\vec{\mathbf{m}}) + (\xi-\alpha)\,\vec{\mathbf{m}}\times(\vec{\mathbf{u}}\cdot\nabla)\vec{\mathbf{m}}\right)$$

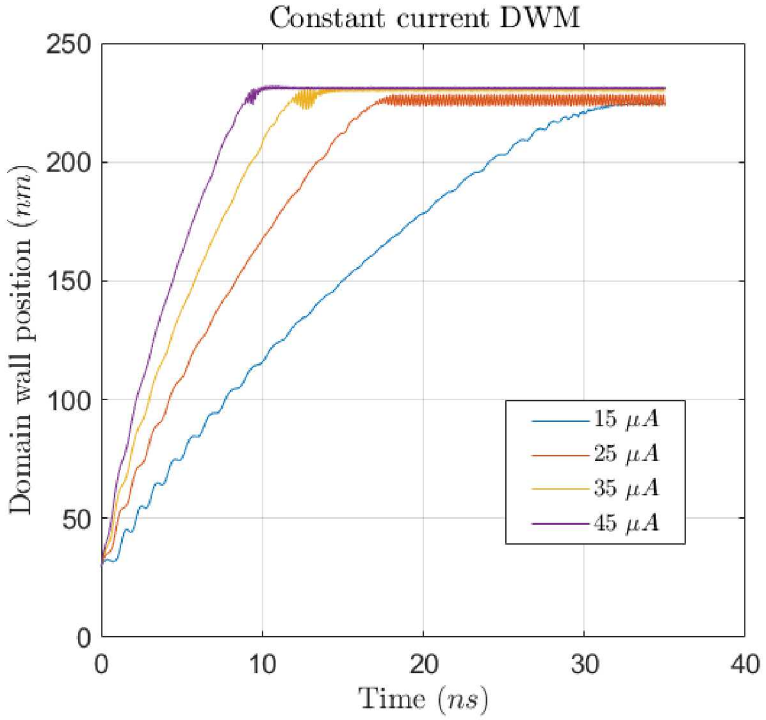
$$\vec{\mathbf{u}} = \frac{\mu_B\mu_0}{2e\gamma_0 B_{\mathrm{sat}}(1+\xi^2)}\vec{\mathbf{j}}$$

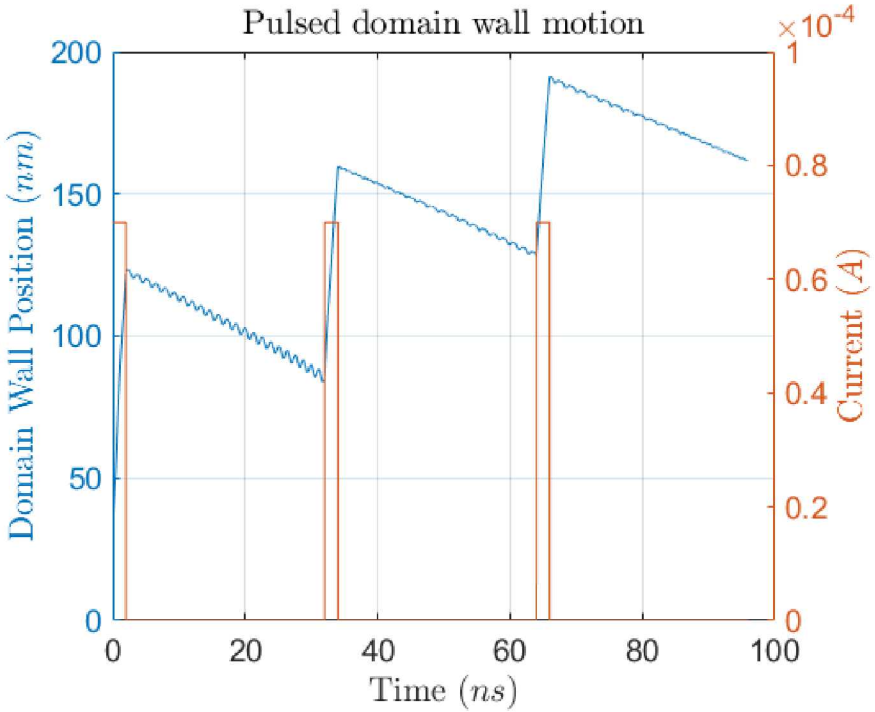


Brigner et al., *Graded-Anisotropy-Induced Magnetic Domain Wall Drift for an Artificial Spintronic Leaky Integrate-and-Fire Neuron*

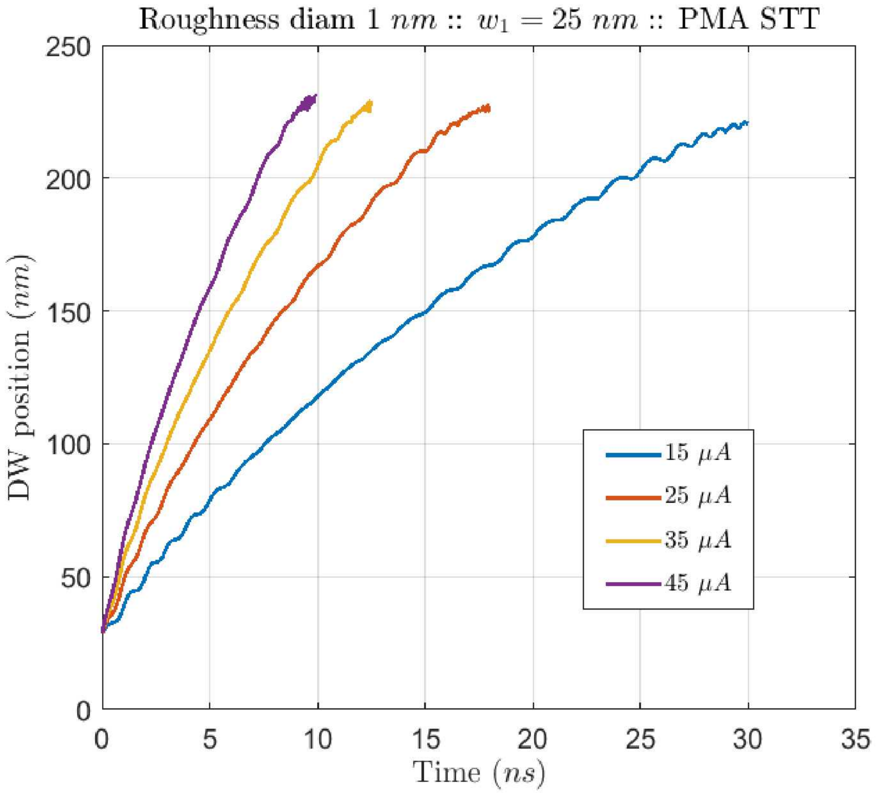
Benchmark results for smooth synapse

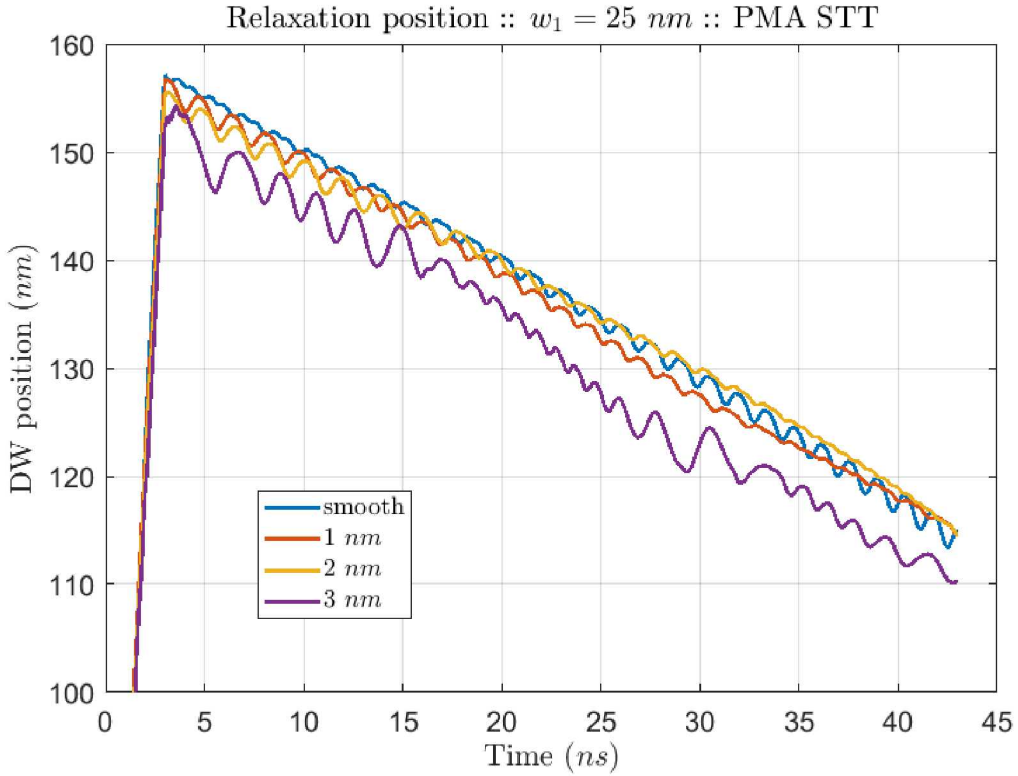




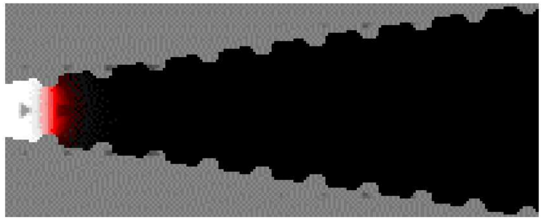


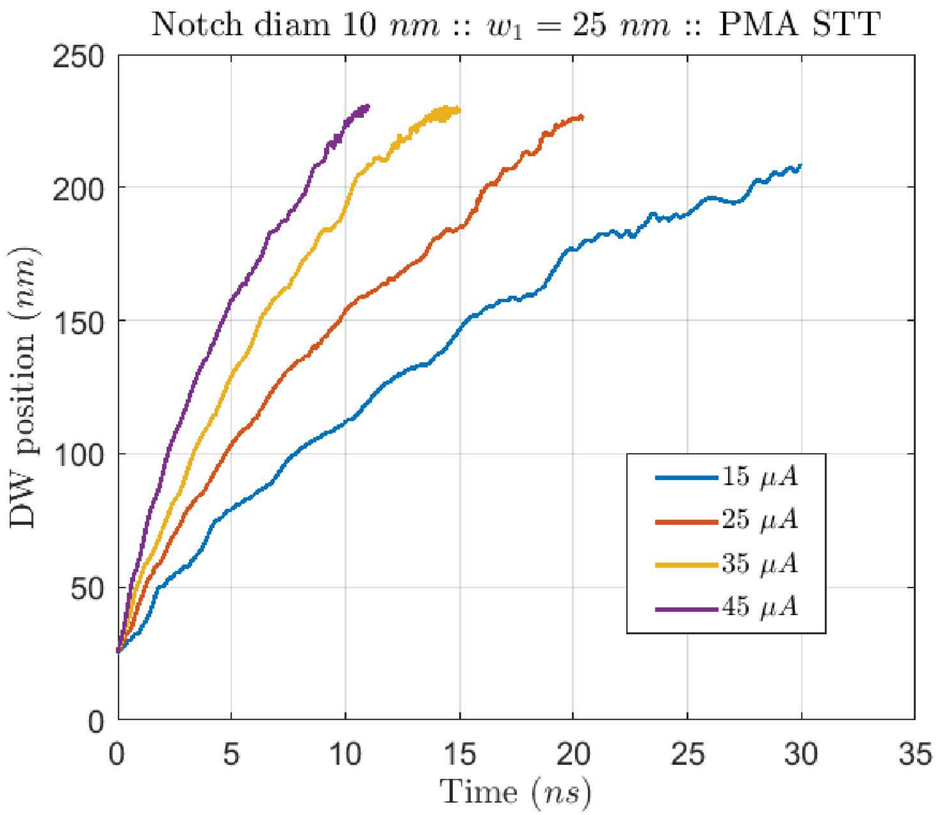
Edge roughness does not impact synapse behavior

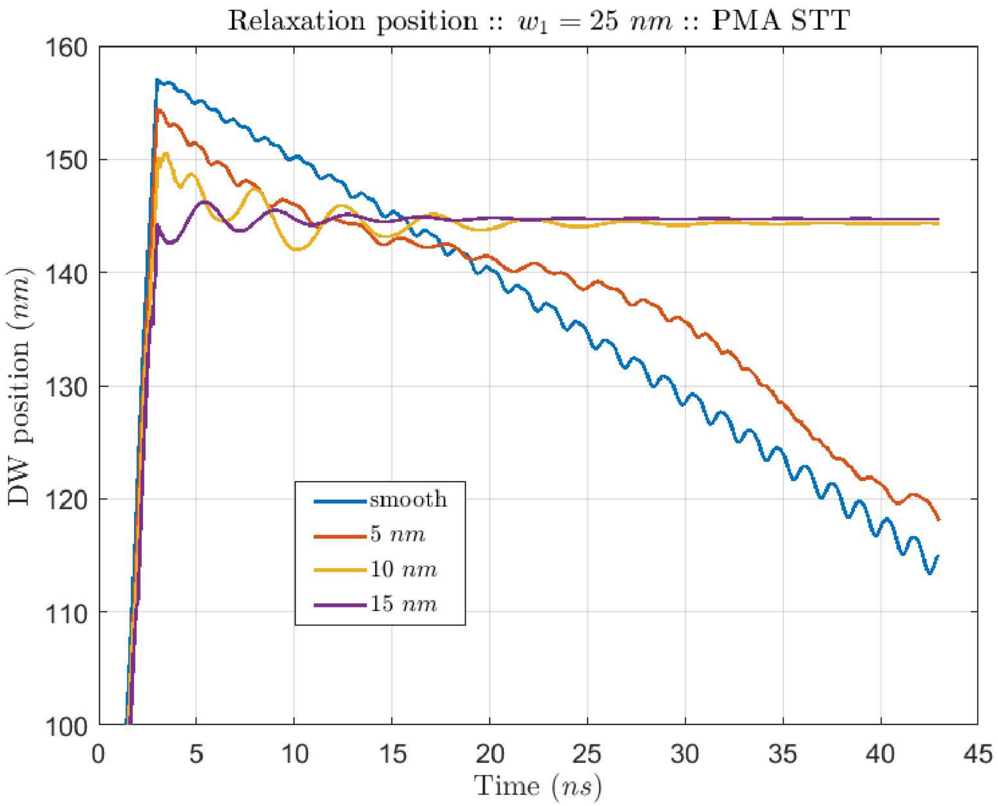




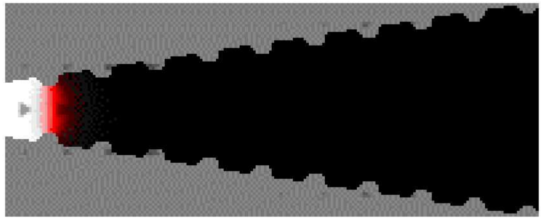
Notches prevent leaking

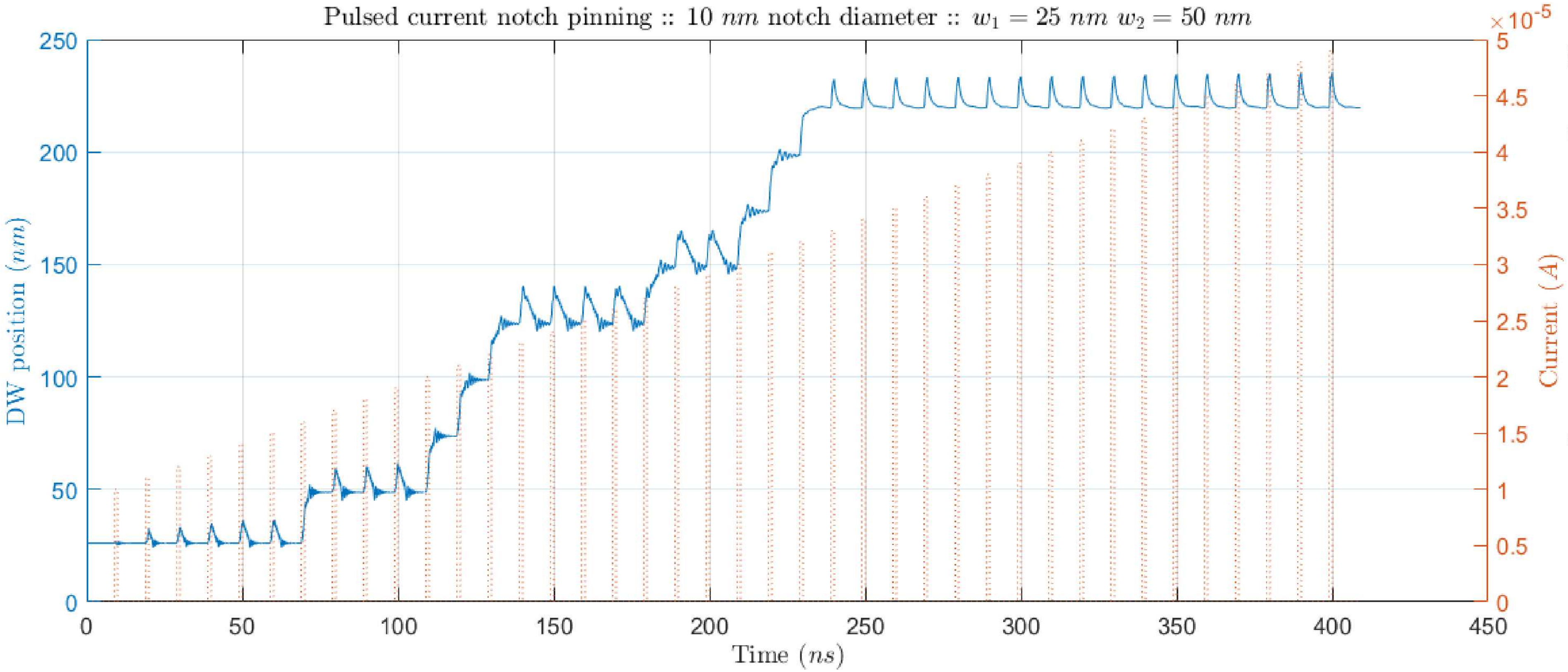






Notch pinning verification





Observations:

- Pinning dependence likely dependent on Walker breakdown precession of domain wall
- Domain wall at wide end hard to pin, likely because of stronger edge effect

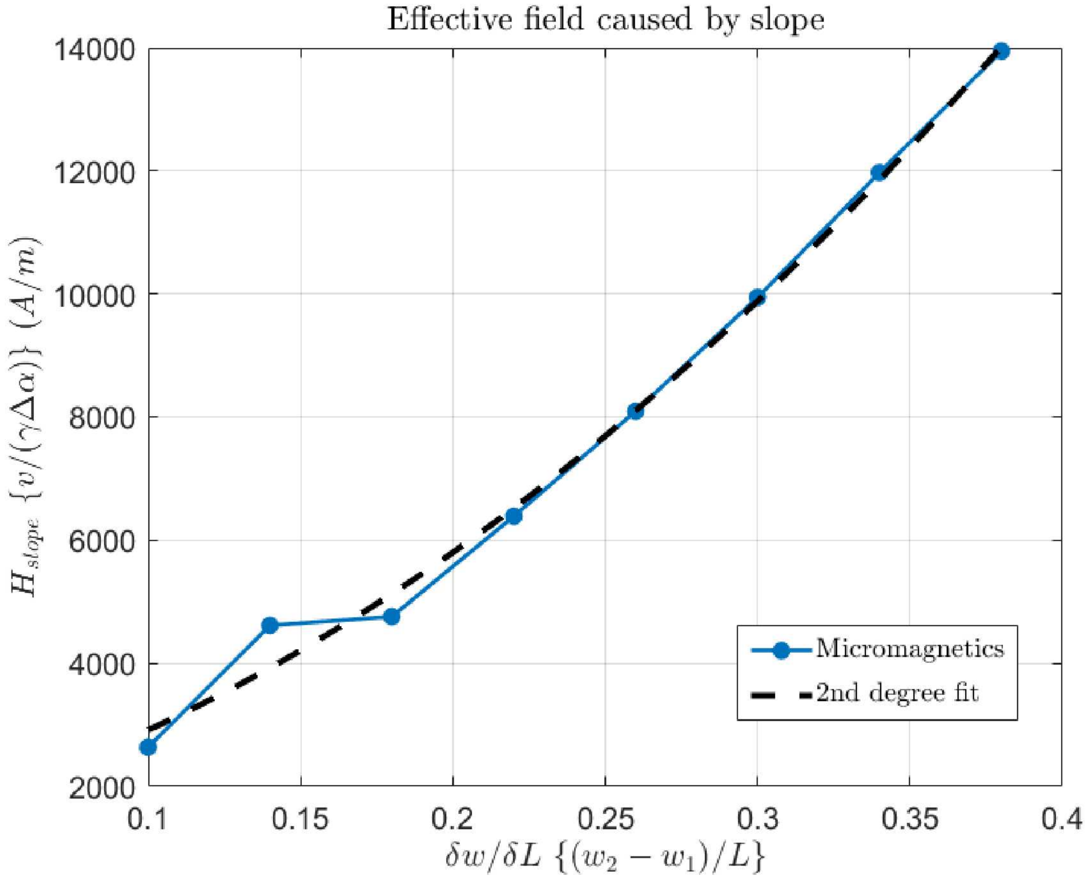
Analytical modeling

- Approach: use 1D solution for DW motion in Walker breakdown regime
- Subsume all geometry based effects (slope, notches) into field term (H)

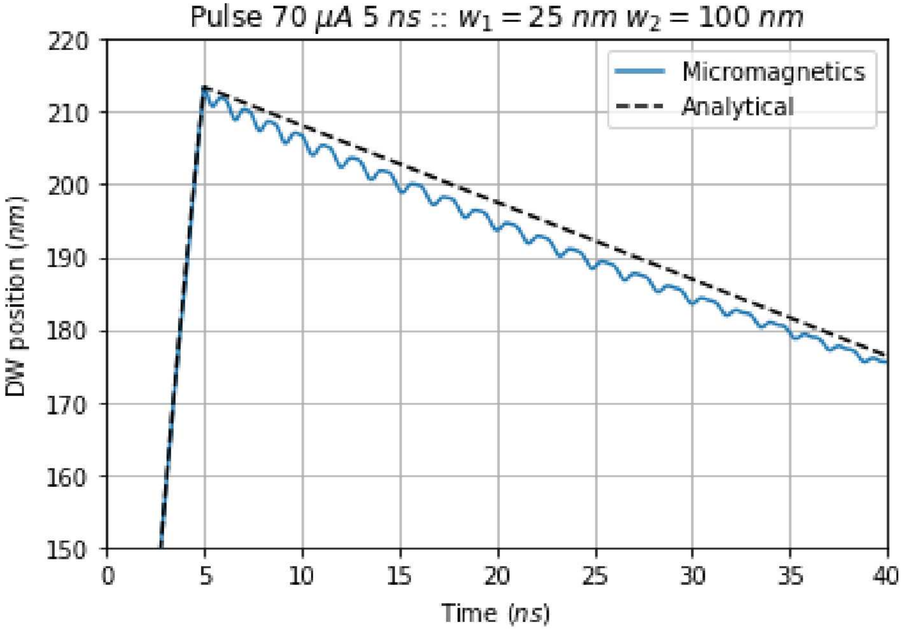
$$\overline{v} = \gamma\Delta\frac{\alpha}{1+\alpha^2}\left(H + \frac{\beta u}{\gamma\Delta}\right) + \frac{u}{1+\alpha^2}$$

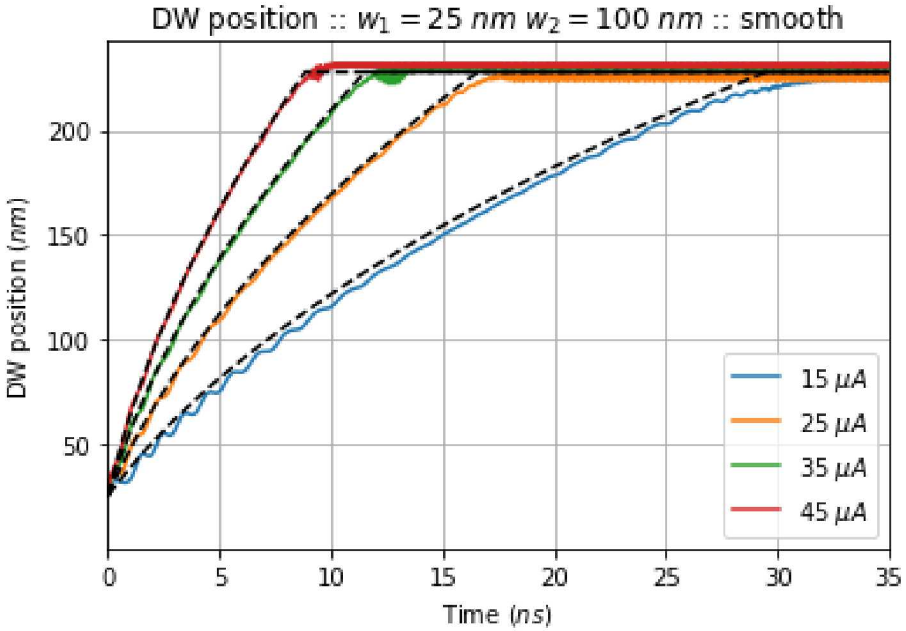
$$u = \frac{gJ_e\mu_B P}{2eM_s} \qquad \beta = 0$$

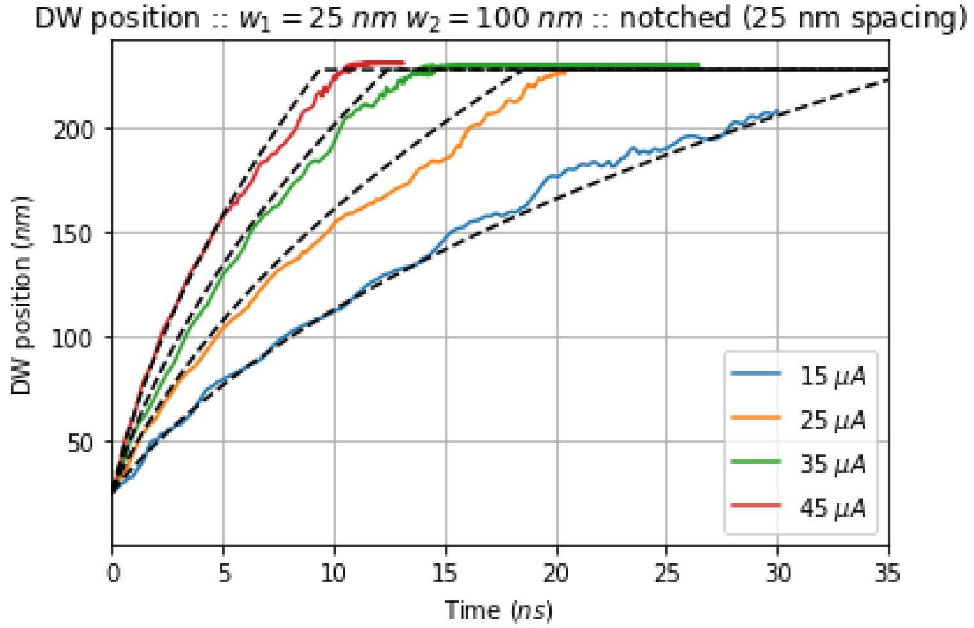
$$H = H_{slope} + H_{notch} + H_{demag}$$



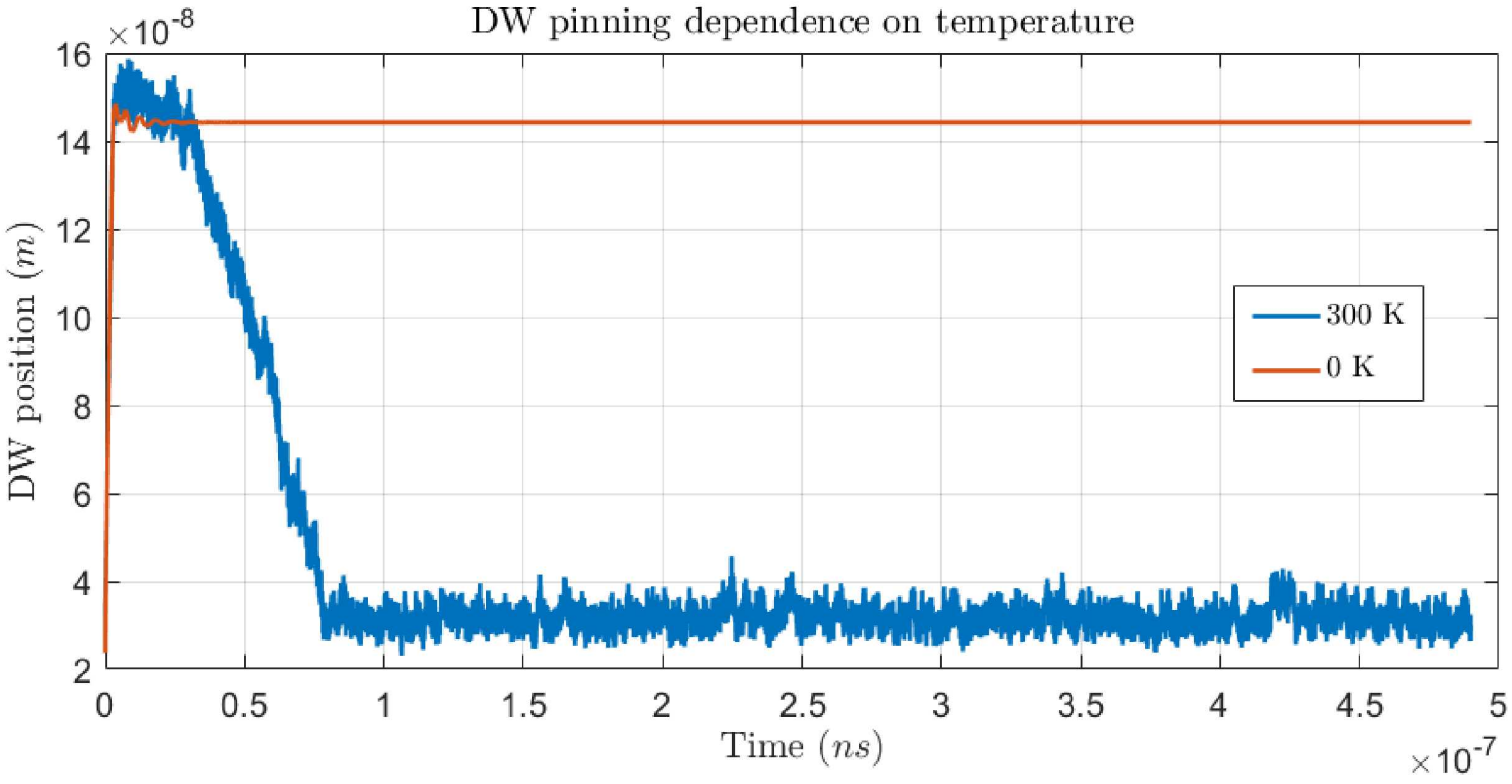
Analytical results







Temperature Considerations



- Temperature causes noise, random motion for each spin in the system
- Random magnetization fluctuations due to heat cause gradual depinning
- Notches must provide energy well exceeding energy of heat fluctuation

Conclusion

- Set up micromagnetics model of trapezoidal synapse using CoFeB material parameters with implementation of:
  - Spin transfer torque, spin Hall effect, Rashba effect
  - Notches and surface roughness
  - PMA vs IMA materials
- Notches were identified as a shape-related way to prevent leaking
- Analytical model useful for circuit-level simulations developed, with effects of geometry consumed into effective magnetic field term
- Limitations identified:
  - Resolution of device limited due to notches
  - Pinning effect dependent on temperature
  - Notches in different positions have different thresholds due to demagnetizing field

Future Research

- Investigation into required notch depth to prevent depinning due to thermal fluctuations
- Improvement of notch field effects in analytical model
- Analyze multiple interacting devices and neural network update behavior