Stochastic Resonance and Negative Inductance in Square-loop FM Core

Midterm Presentation

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Under the guidance of
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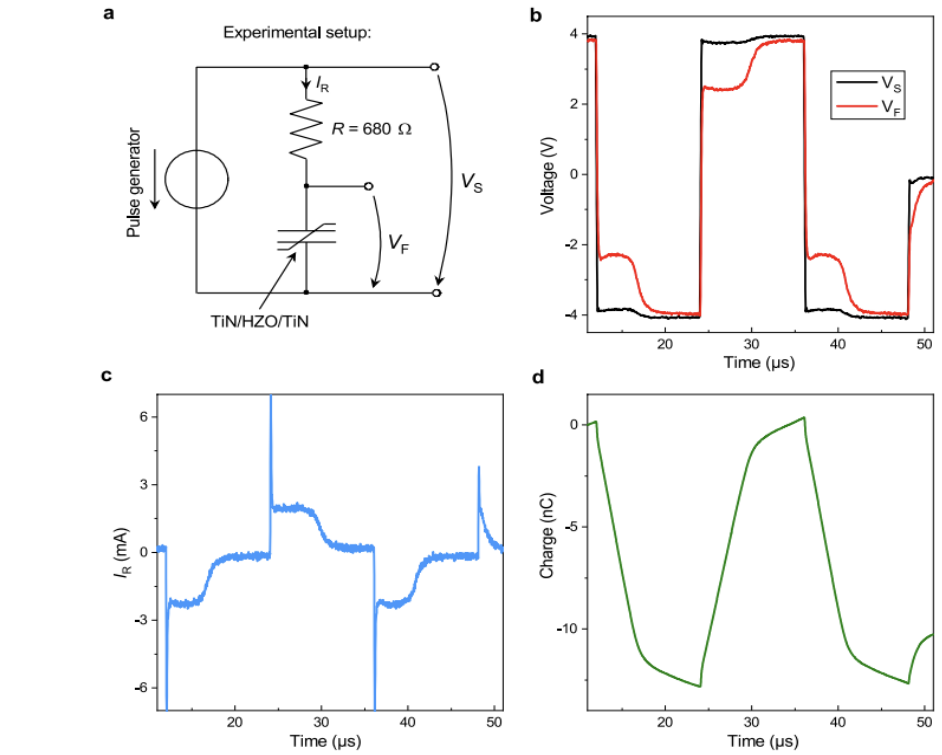
Continuation from the previous semester OELP …

Key words

FM	–	Ferro Magnet
FE	–	Ferro Electric
NI	–	Negative Inductance
NC	–	Negative Capacitance
SR	–	Stochastic Resonance
VCCS	–	Voltage controlled Current source
PCB	–	Printed Circuit Board
SMU	–	Source Meter Unit

What is Negative Inductance ?

- In recent years, negative capacitance has risen in popularity with its effect manifesting in ferroelectric materials
- This discovery holds promise for paving the way to create more energy-efficient electronics.
- This prompts the question of existence of a dual, which is negative inductance (NI)



Extended Data Fig. 1 | Direct measurement of transient negative capacitance with hysteresis in a TiN/HZO/TiN capacitor. **a**, Experimental set-up with resistor in series. See Methods for details. **b**, Transient applied voltage (V_S) and ferroelectric voltage (V_F) measured via an oscilloscope. **c**, Calculated transient current I_R flowing through the resistor R. **d**, Transient charge on the capacitor from integration of I_R.

Source link : https://doi.org/10.1038/s41586-018-0854-z

What is Negative Inductance ?

$$\epsilon = L\frac{dI}{dt} \Rightarrow L = \frac{\varepsilon}{\frac{dI}{dt}} = \frac{\frac{d\phi}{dt}}{\frac{dI}{dt}} = \frac{d\phi}{dI}$$

$$\frac{d\phi}{dI} < 0$$

If L is negative, this implies that for an **increase in flux**, the **change in current** is **negative**.

OR,

this implies that for an **increase in current**, the **change in flux is negative**.

What is Stochastic Resonance ?

- Observed in Subthreshold systems and Double well systems

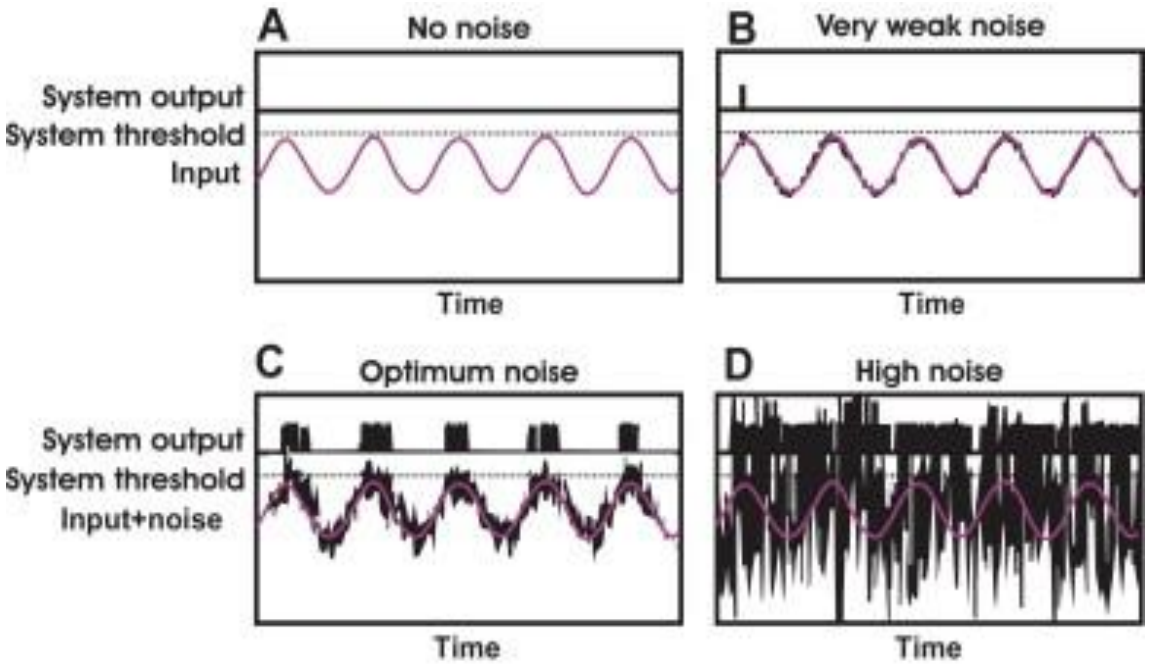


Image source :
https://www.researchgate.net/publication/245537925_Modelling_Non-Invasive_Brain_Stimulation_in_Cognitive_Neuroscience/figures?lo=1

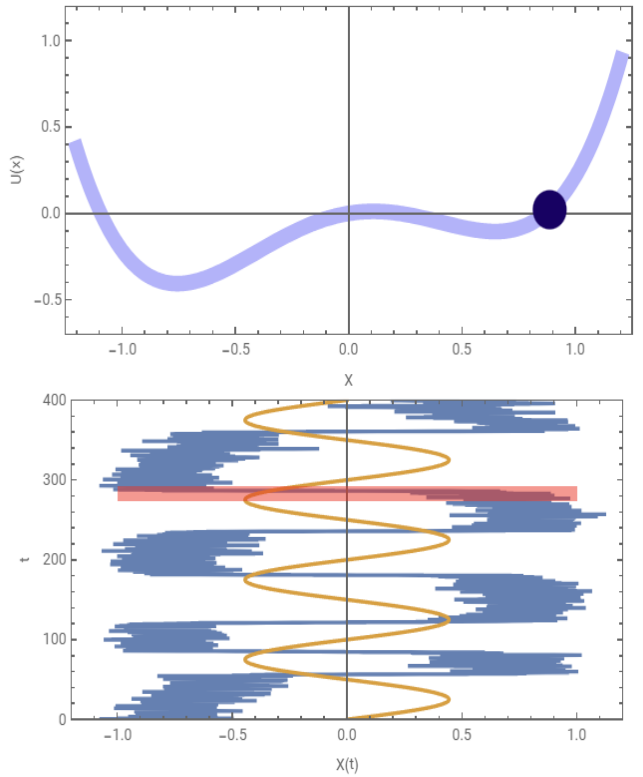
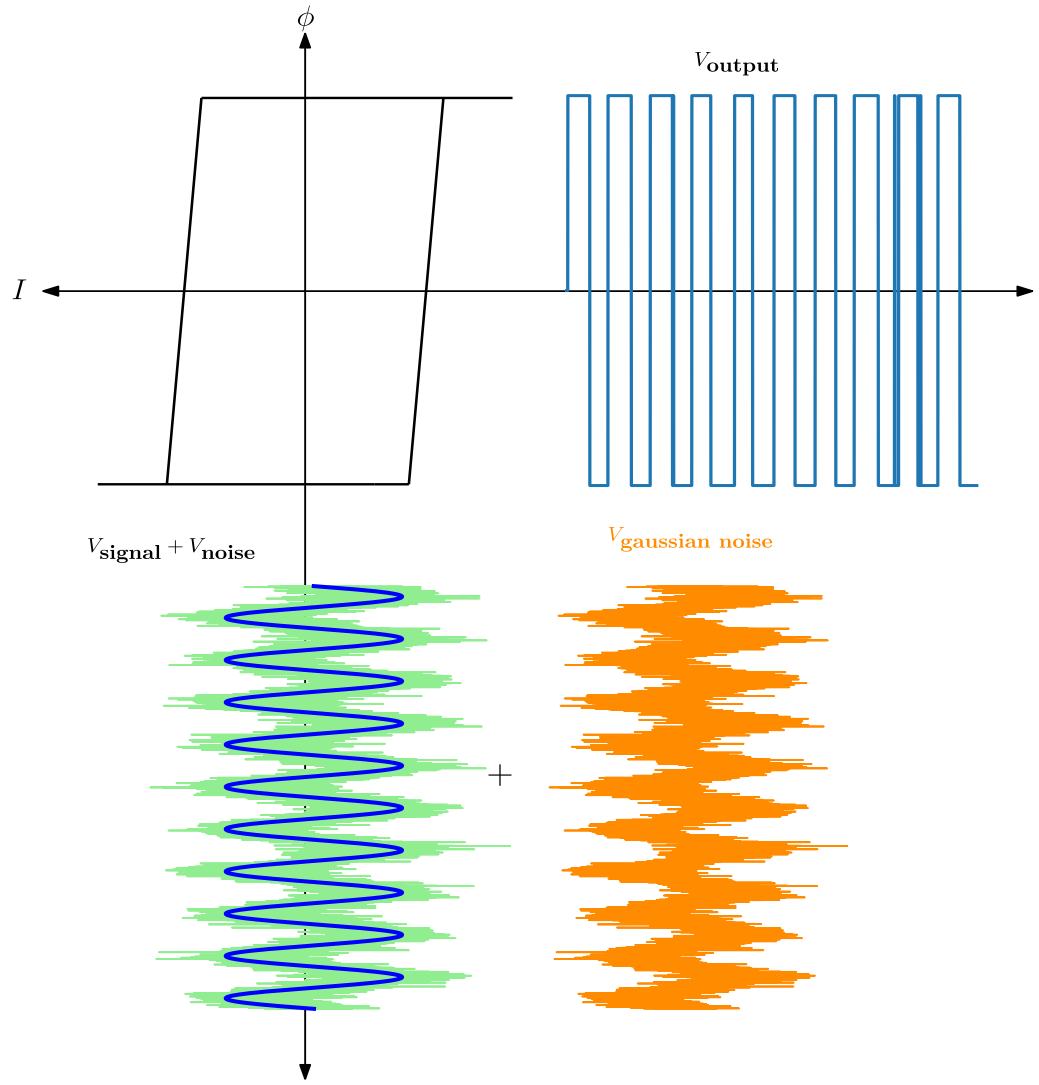


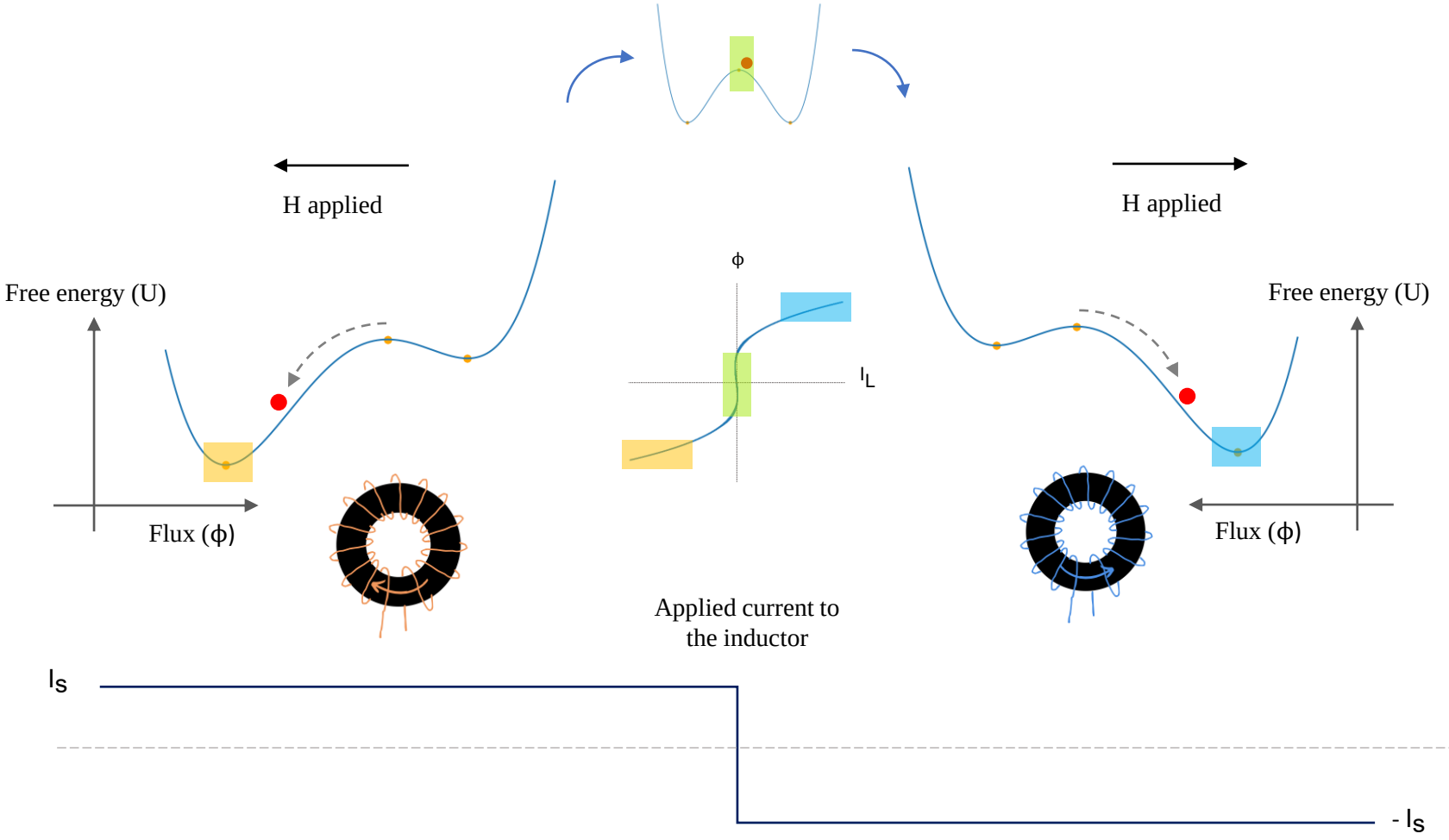
Image source :
https://demonstrations.wolfram.com/StochasticResonance/

Stochastic Resonance Using FM Inductor

Inductor is a Clipper !



Double well system, Origin of NI and SR



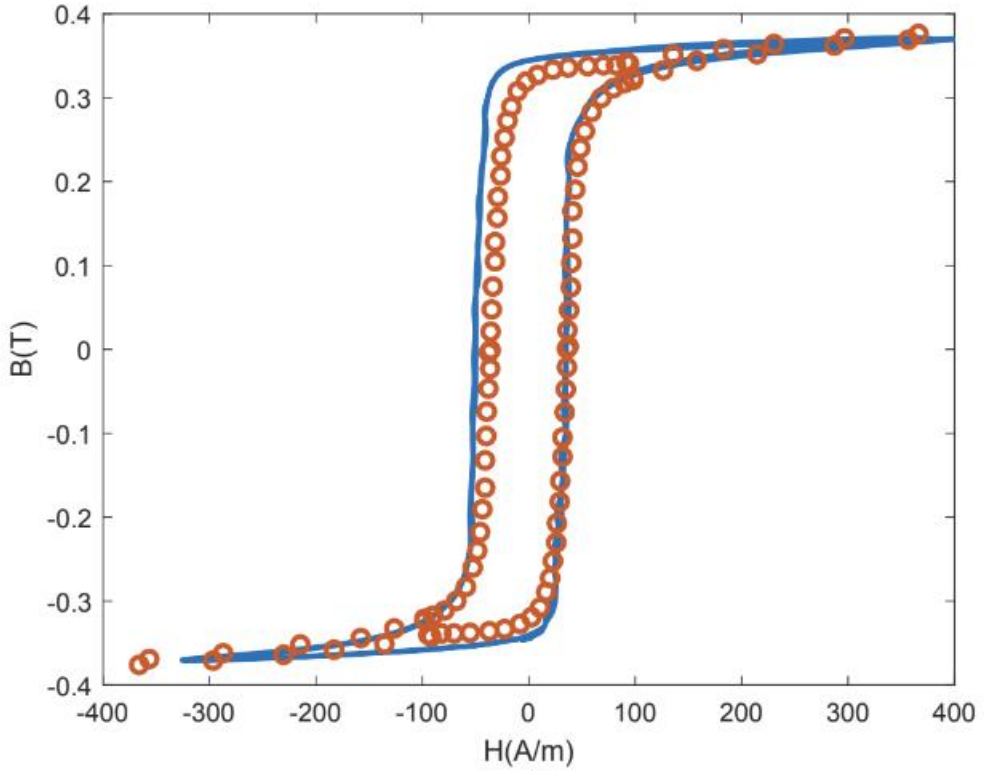
Ferromagnetic Toroid - the “CORE” of this Project

- Ferrite toroid (TN/9/6/3) from Ferroxcube

SYMBOL	PARAMETER	VALUE	UNIT
$\Sigma(l/A)$	core factor (C1)	5.17	mm^{-1}
V_e	effective volume	102	mm^3
l_e	effective length	22.9	mm
A_e	effective area	4.44	mm^2
m	mass of core	≈ 0.5	g

Ferromagnetic Toroid - the “CORE” of this Project

- The core has this characteristic square loop hysteresis which is critical for observing NI and SR



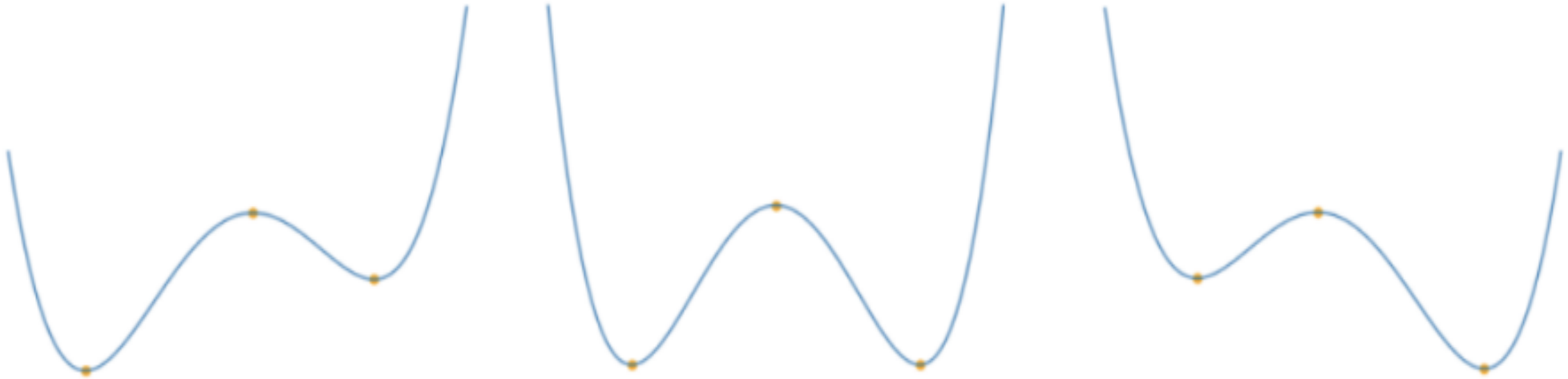
Landau Theory

- FM energy landscape proposed by Landau

$$U = \alpha\phi^2 + \beta\phi^4 - \phi I_L$$

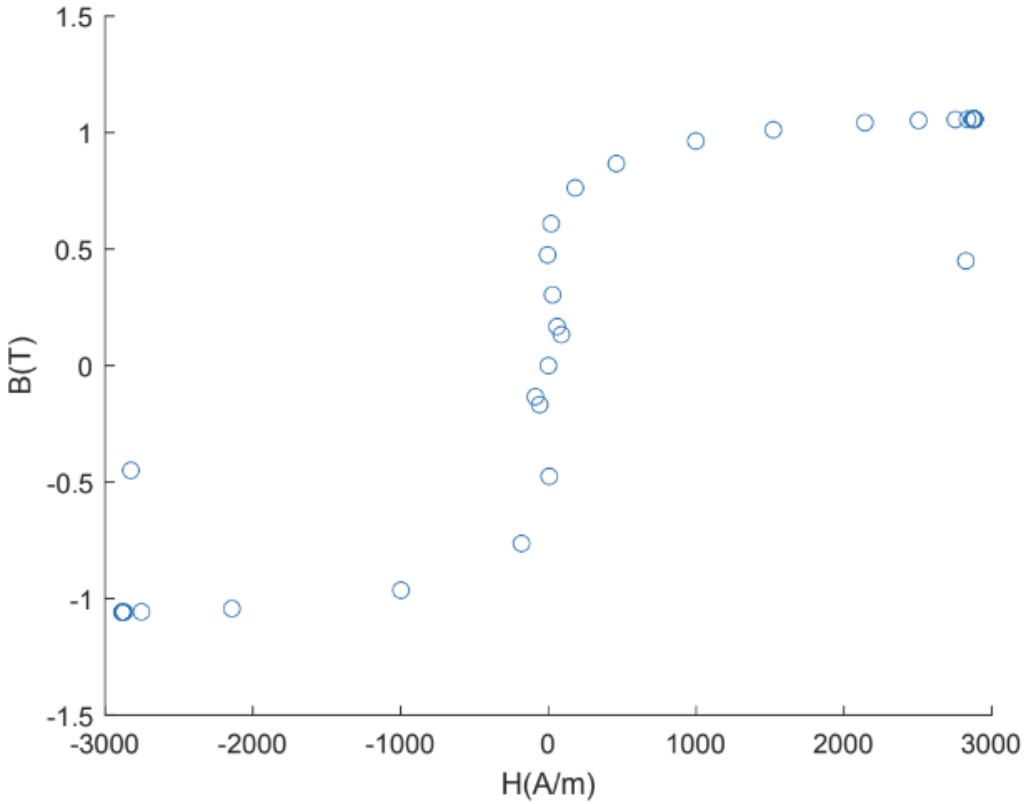
- Time dependent Landau-Ginzburg equation

$$\rho\frac{d\phi}{dt} = -\frac{dU}{dt}$$

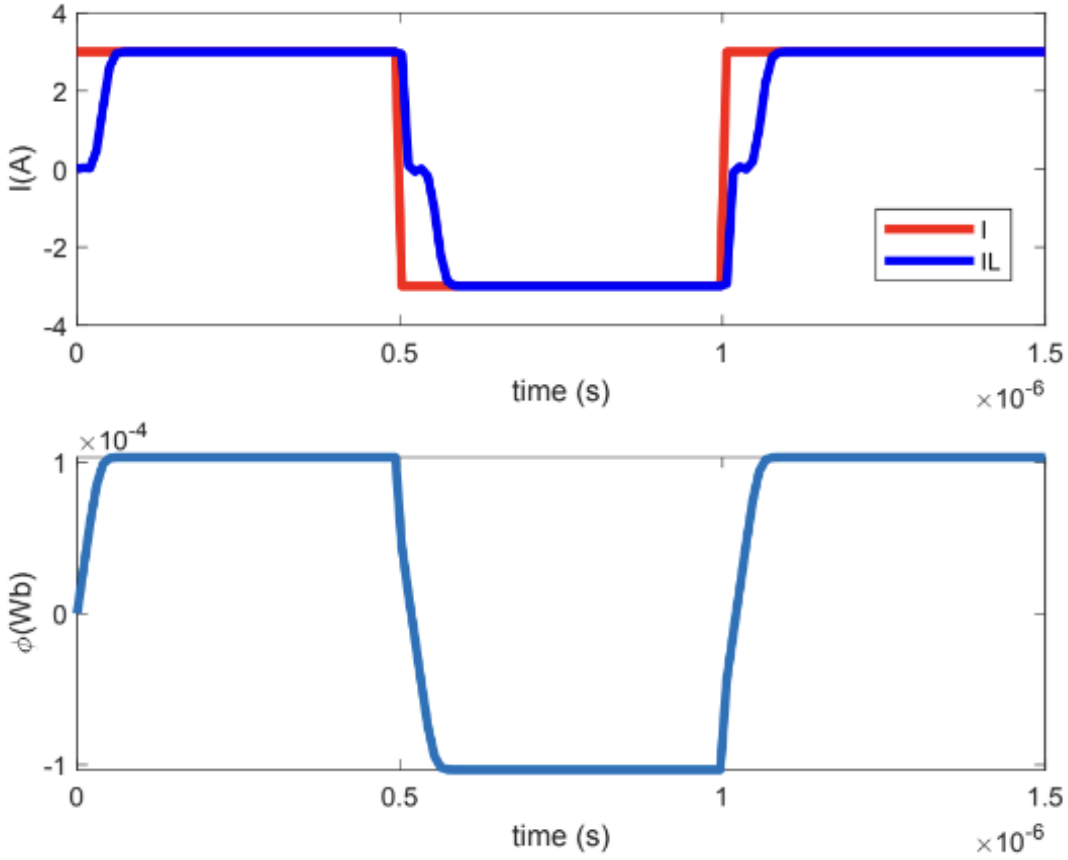


Double well energy landscape of single domain ferromagnet, the change illustrates the polarization switching on applied external magnetic field

Landau Theory



The B-H loop when plotted will trace the S-curve



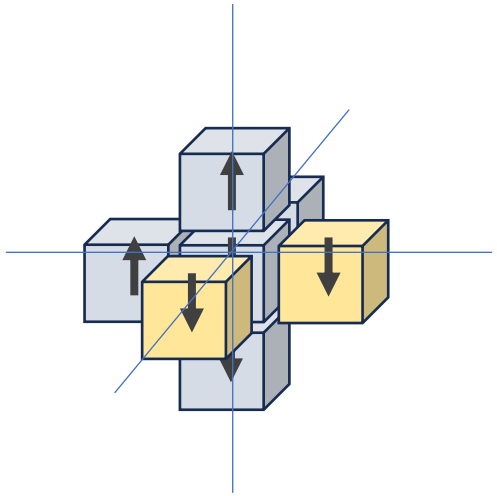
The region with negative slope we expected to see negative inductance

Ising Model for FM materials

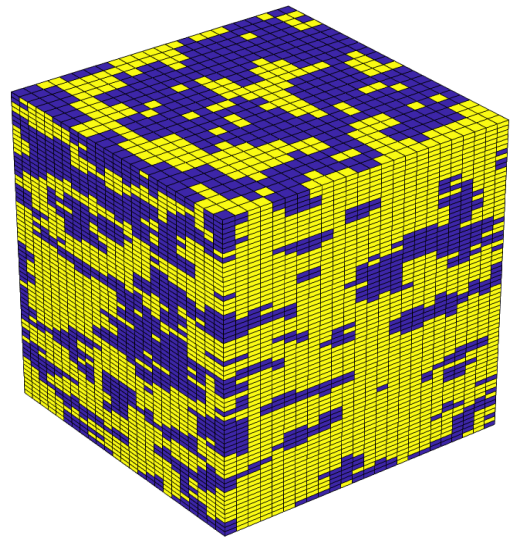
- Ising model is a multi-domain model for ferromagnetic materials which consider each dipole in the FM to be an individual entity.

- A 3D Ising model with circular boundary condition is used to simulate the toroid used in the work.

Circular boundary condition



Nearest neighbor spin interaction



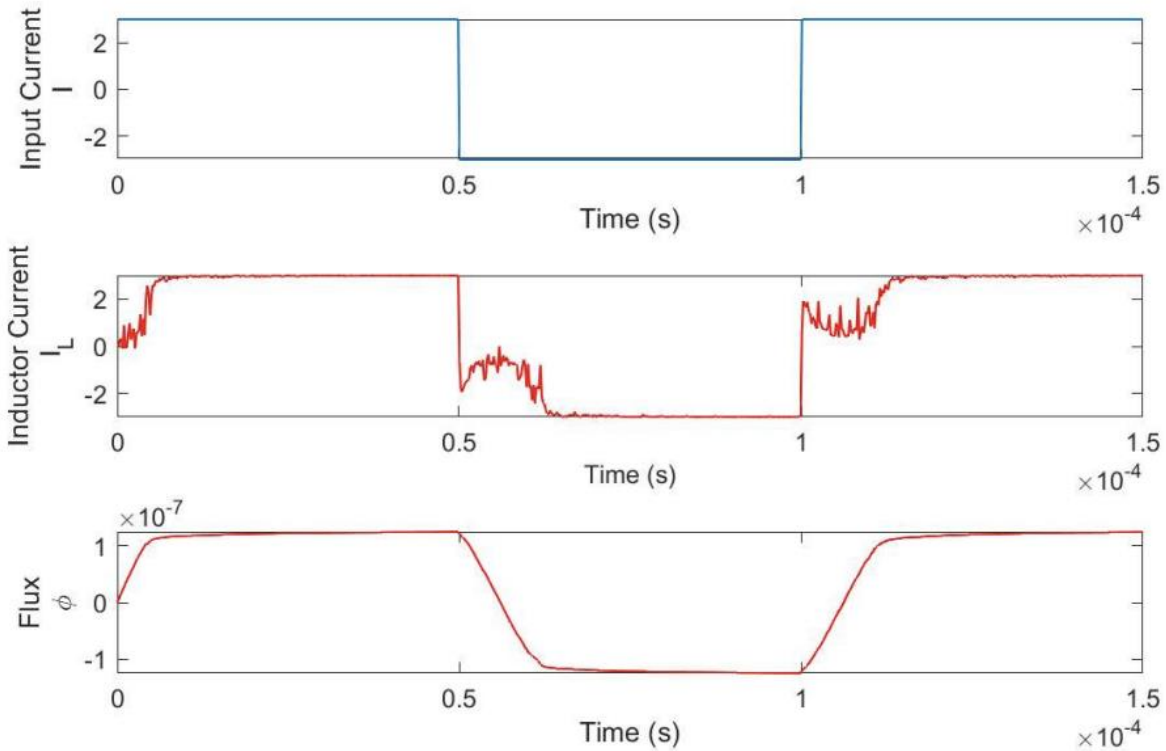
Applied external magnetic field

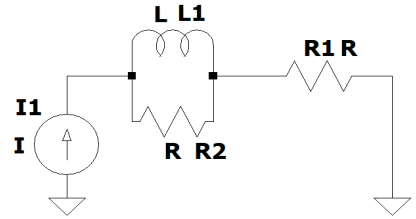
Hamiltonian of the system

$$\hat{\mathrm{H}}(\sigma) = \sum_i \sum_{<i,j>} J_{(i,j)}\, \sigma_i\, \sigma_j + \sum_i H \sigma_i$$

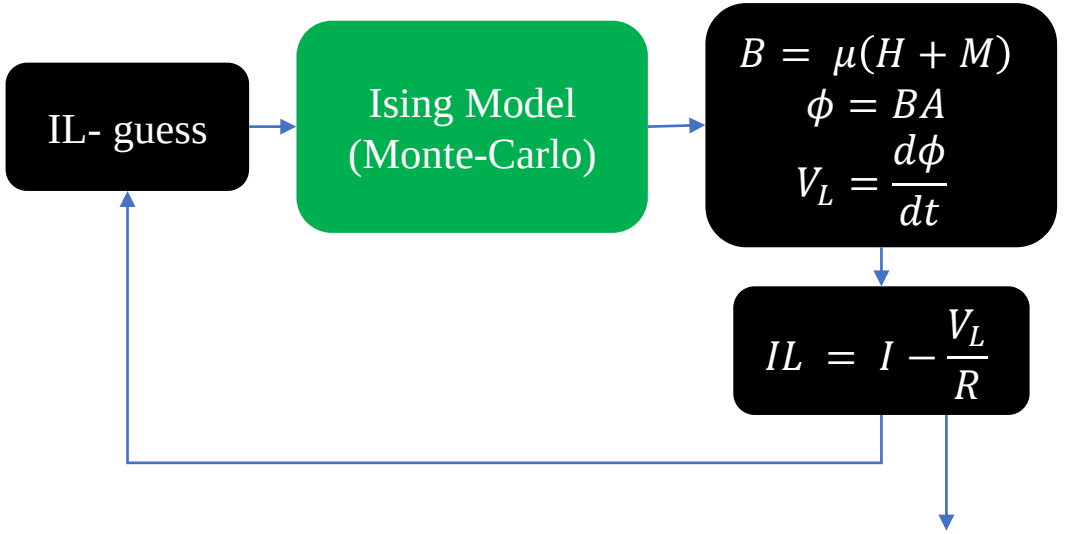
Ising Model Results which Shows NI

- Simulation results..





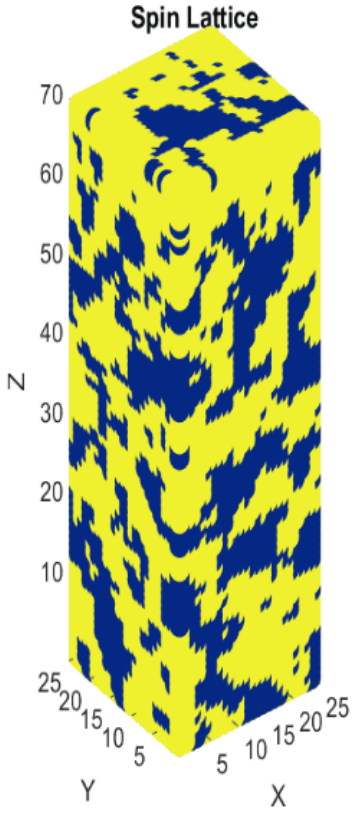
Simulating circuit

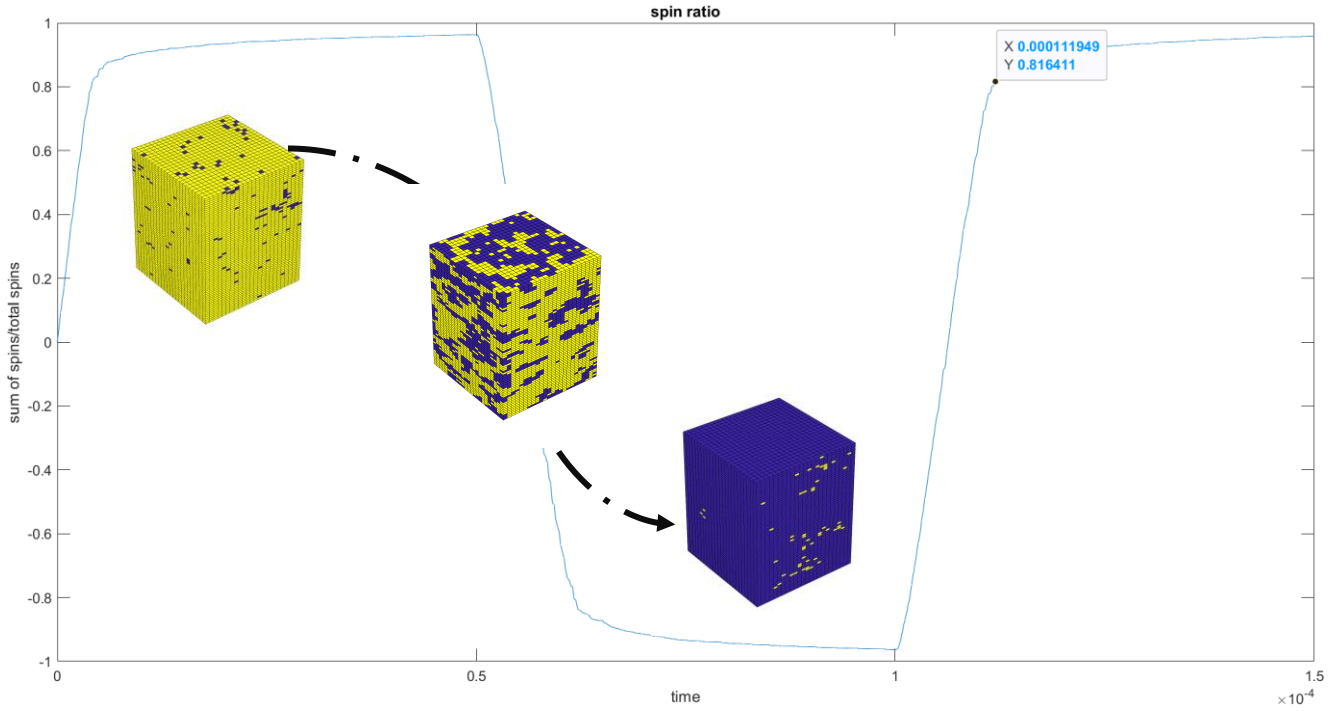


Stop at convergence

Switching Behaviour of the Ising Spin Structure

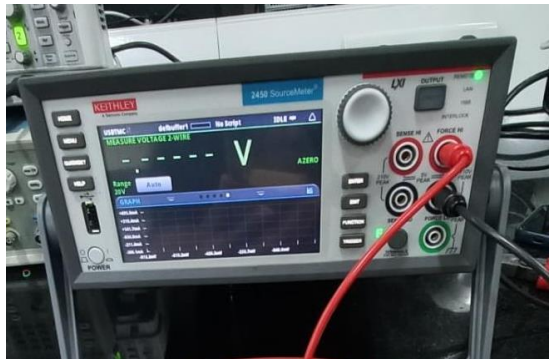
- Simulation result from The Ising Model



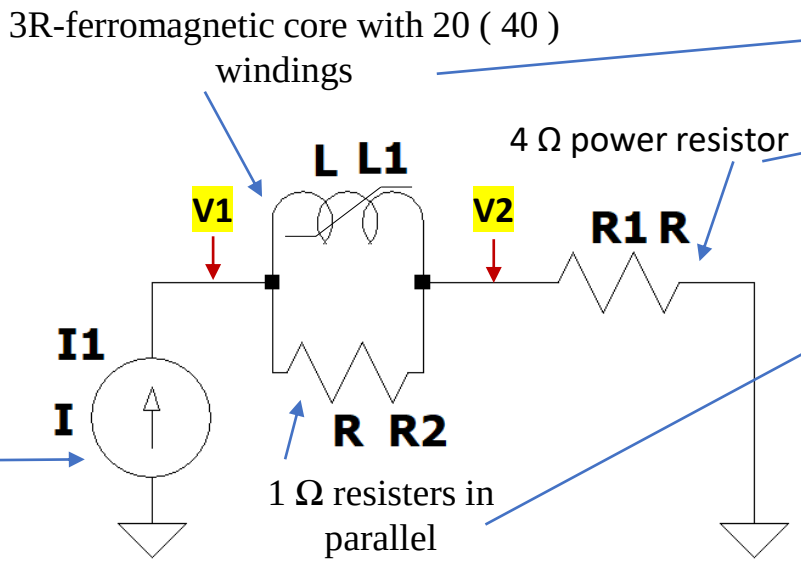


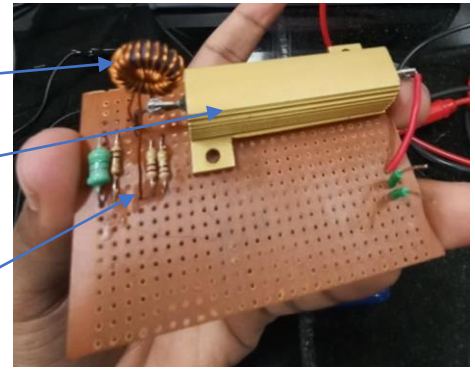
Experimental Results which Confirms NI

- Experiment setup



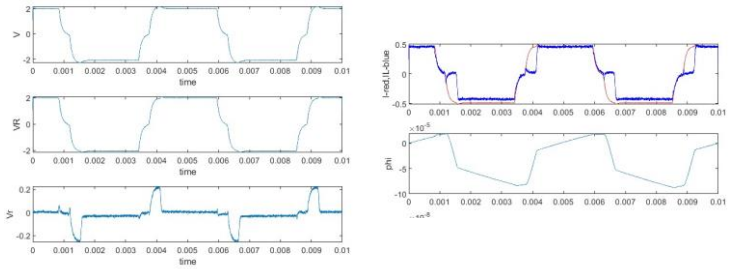
SMU



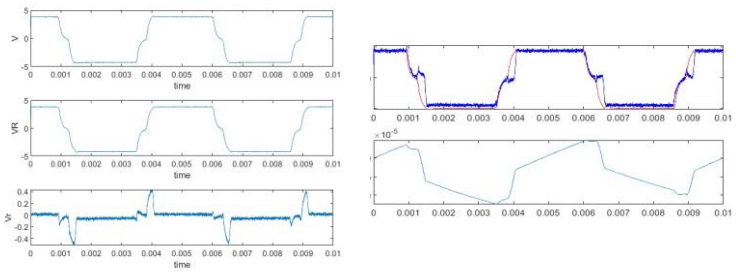


Experimental Results Which Confirms NI

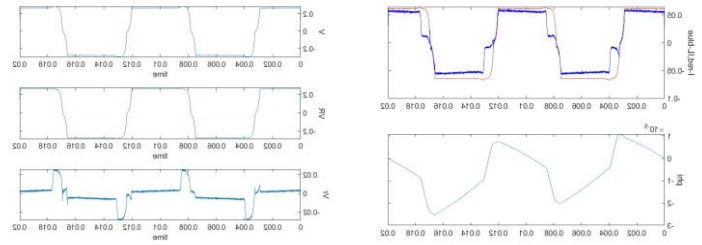
I = 0.5 A, Rp = 0.5, t = 4e-3, N = 20



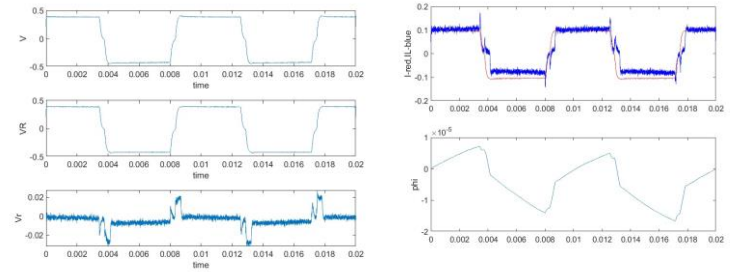
I = 1 A, Rp = 0.5, t = 4e-3, N = 20



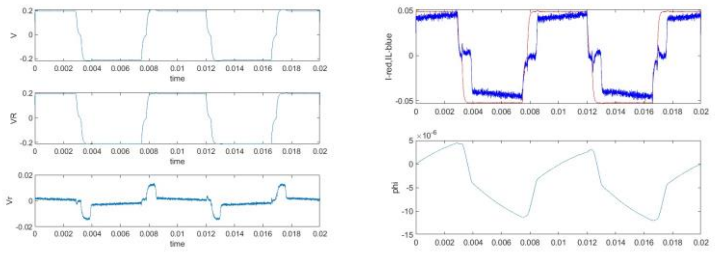
I = 0.5 A, Rp = 0.5, t = 4e-3, N = 40



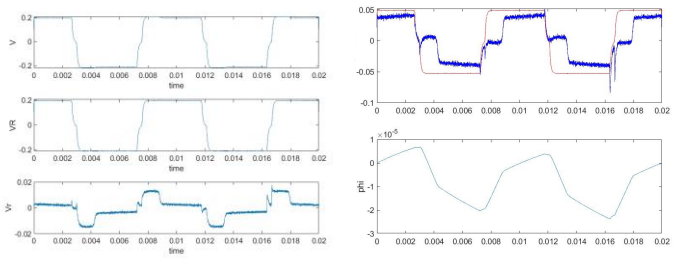
I = 1 A, Rp = 0.25, t = 4e-3, N = 20



I = 0.5 A, Rp = 0.25, t = 4e-3, N = 20



I = 0.5 A, Rp = 0.25, t = 4e-3, N = 40

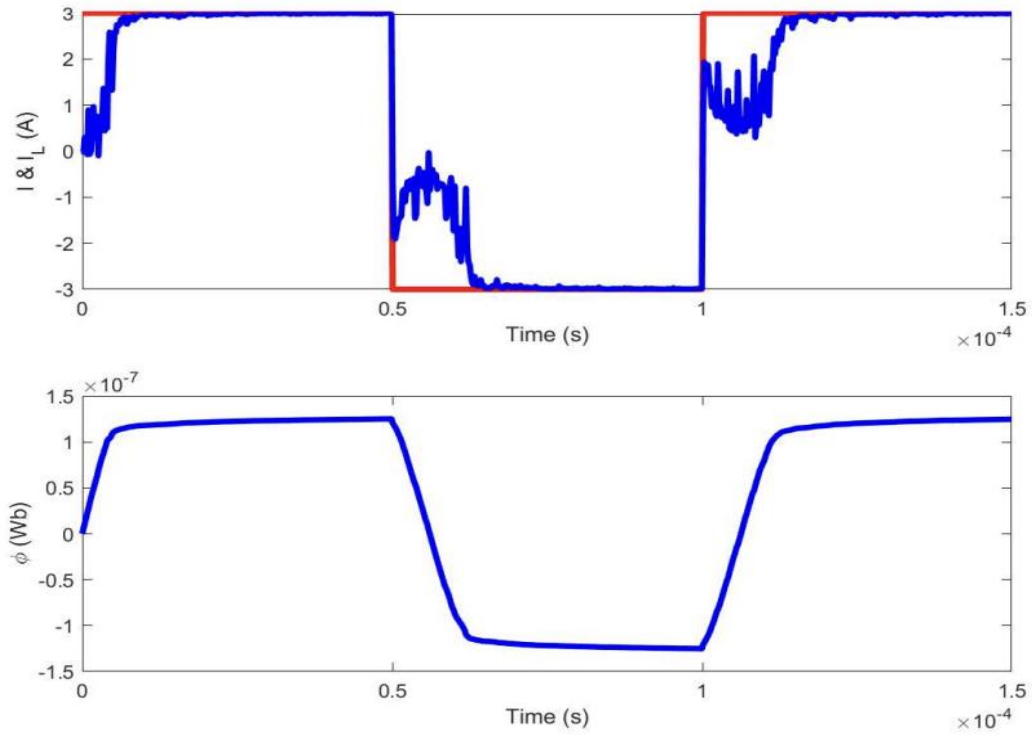


Measurements with SMU

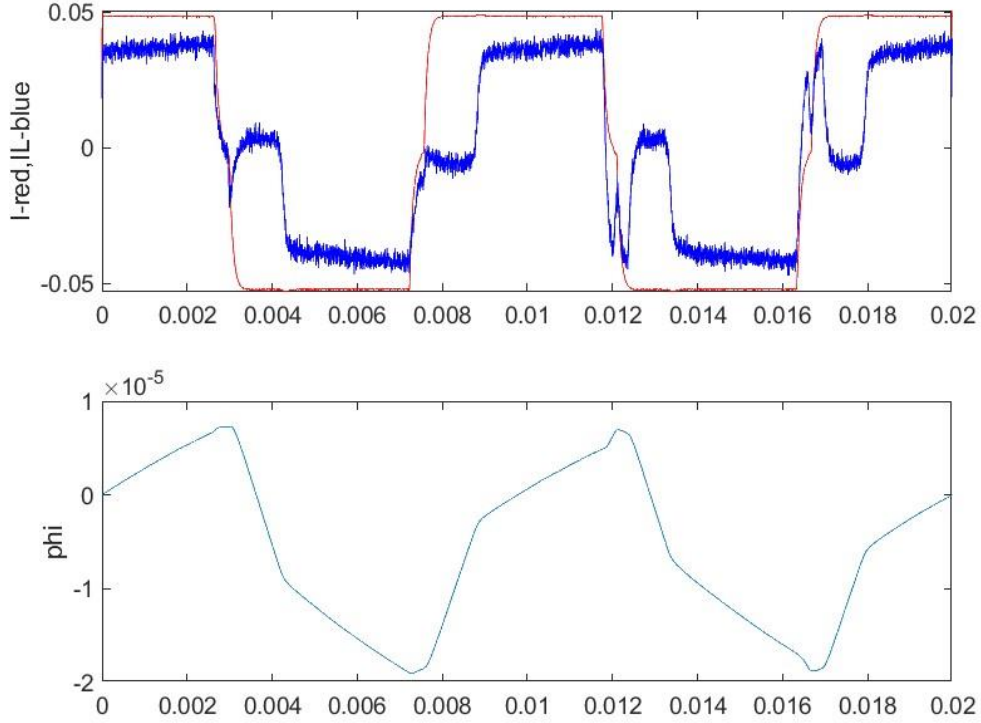
A variety of parameters such as the Parallel resistance, Number of turns and Current Amplitude were varied. Measurement are taken using Keysight DSO_x1102G.

Comparison with Simulation Results

Ising Model

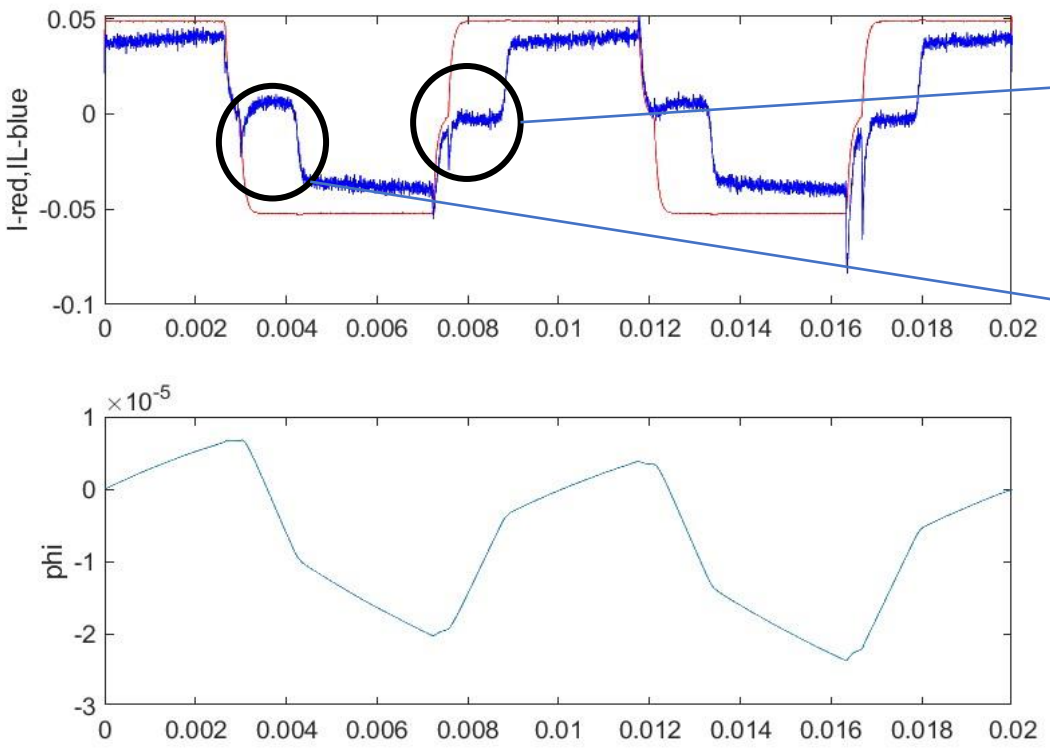


SMU measurement

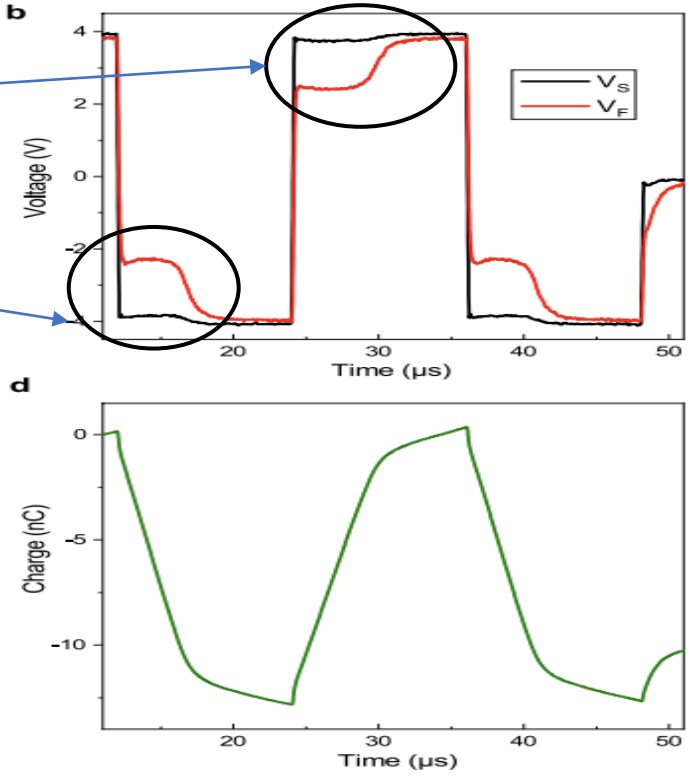


Comparison with NC Results

Our SMU results & Asif Khan's paper (NC)



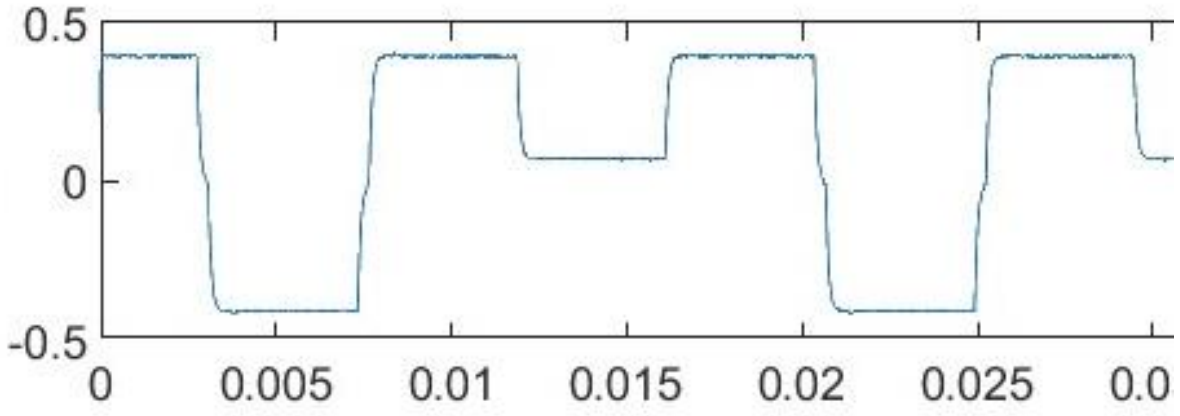
FM - Inductor response in input square current waveform



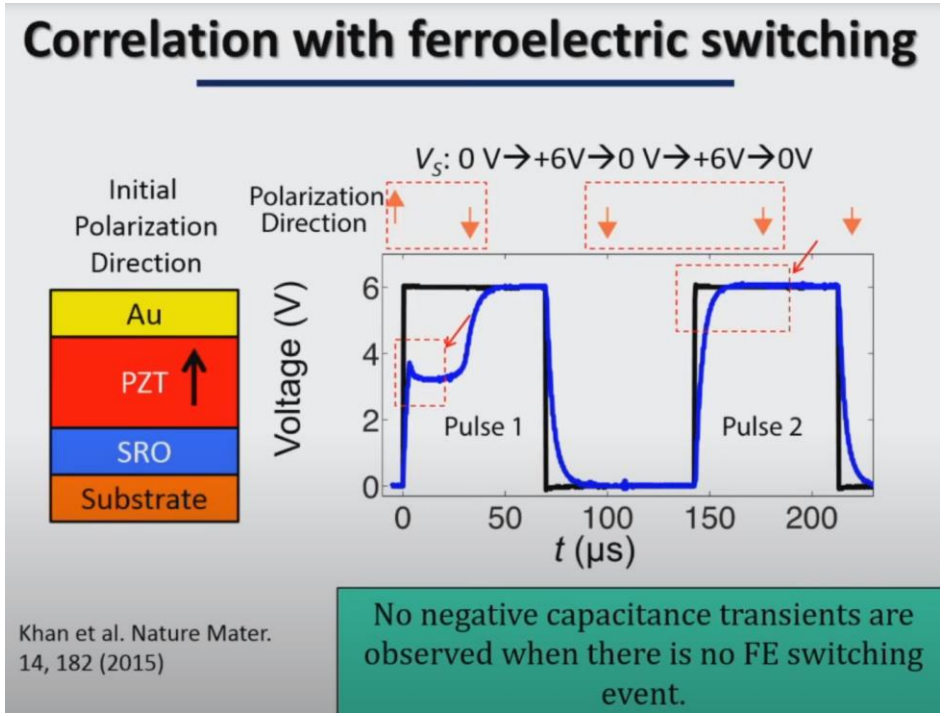
FE Capacitor response in square Voltage waveform

Comparison with NC Results

- We tried one switching and non switching pulse..

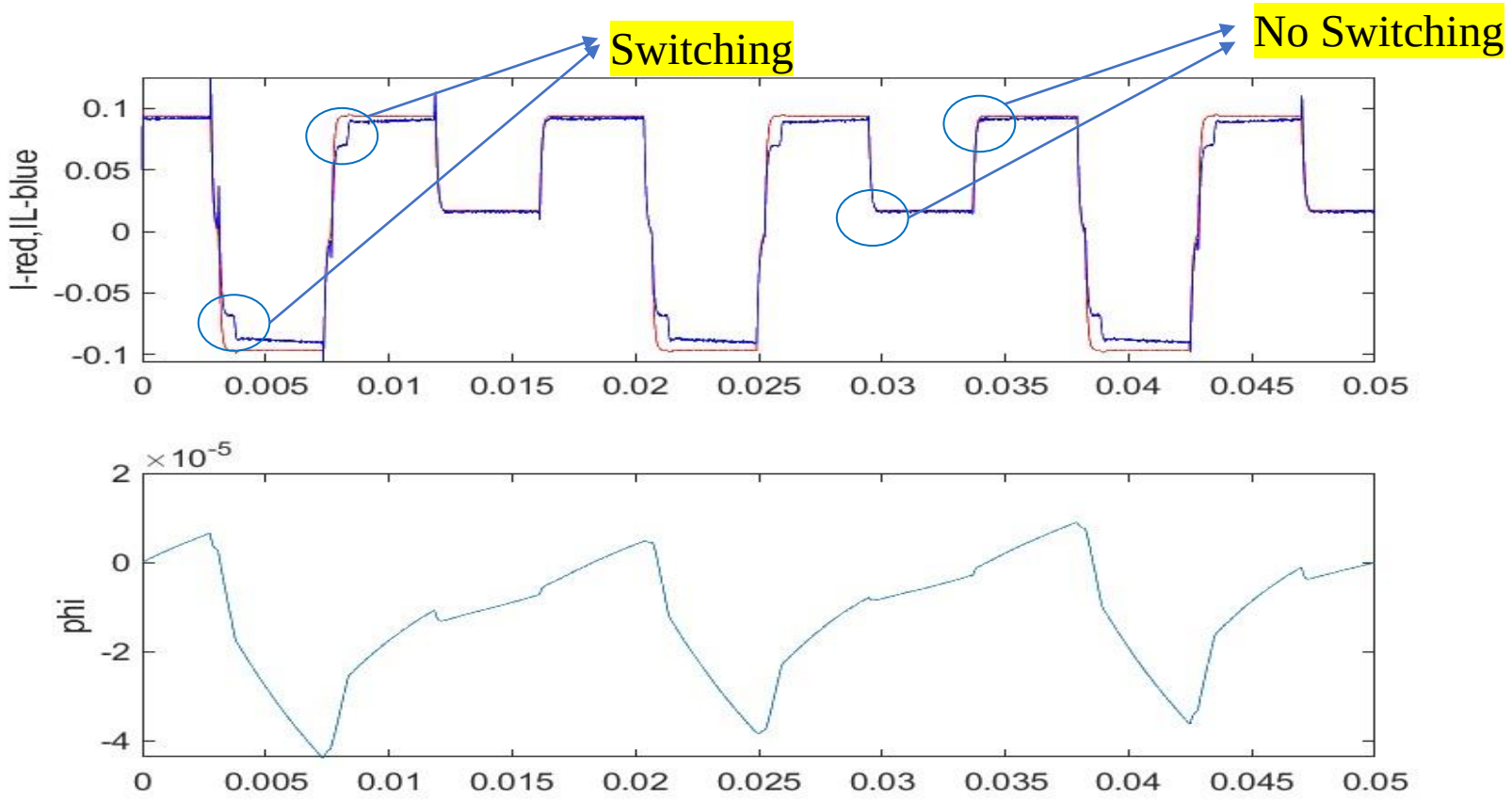


Trying to apply the similar check done by the NC experiment



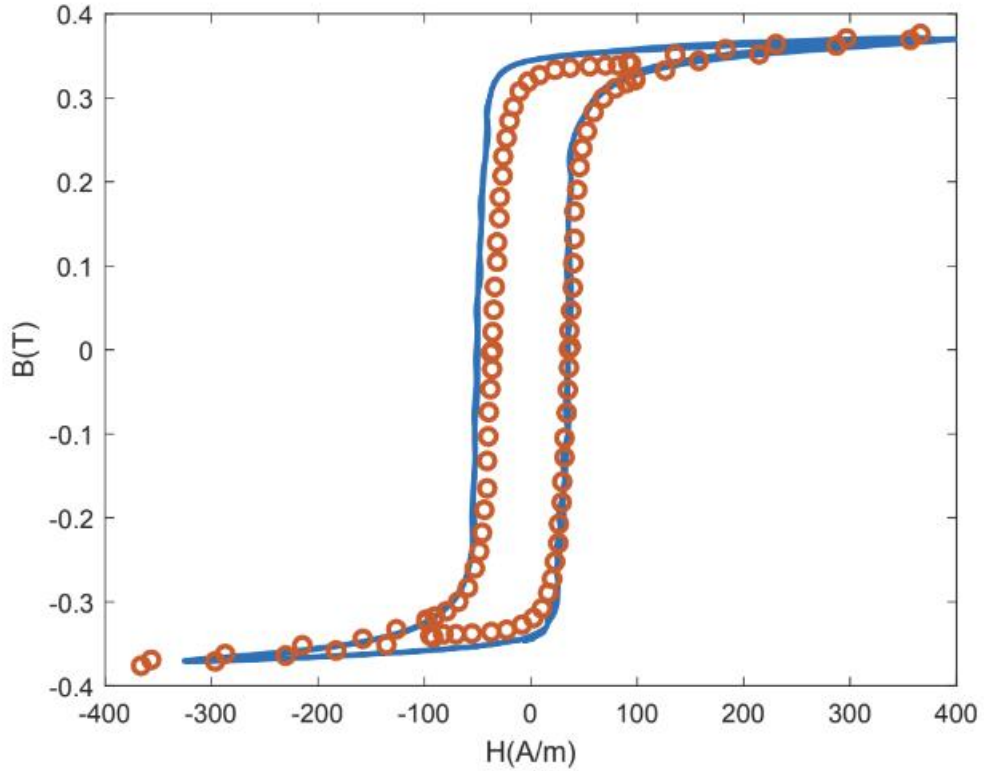
Source link: https://www.youtube.com/watch?v=jIaxc1RfNM0&t=538s

Comparison with NC Results

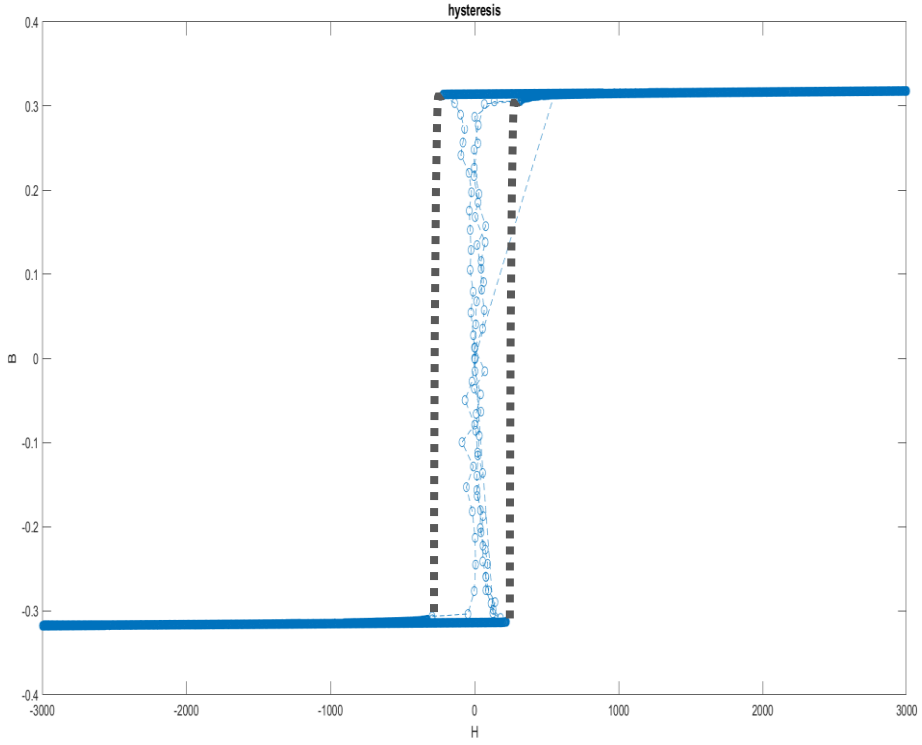


Benchmarking the Results with the Experiment Data

Tuning the Ising model hysteresis to the inductor hysteresis



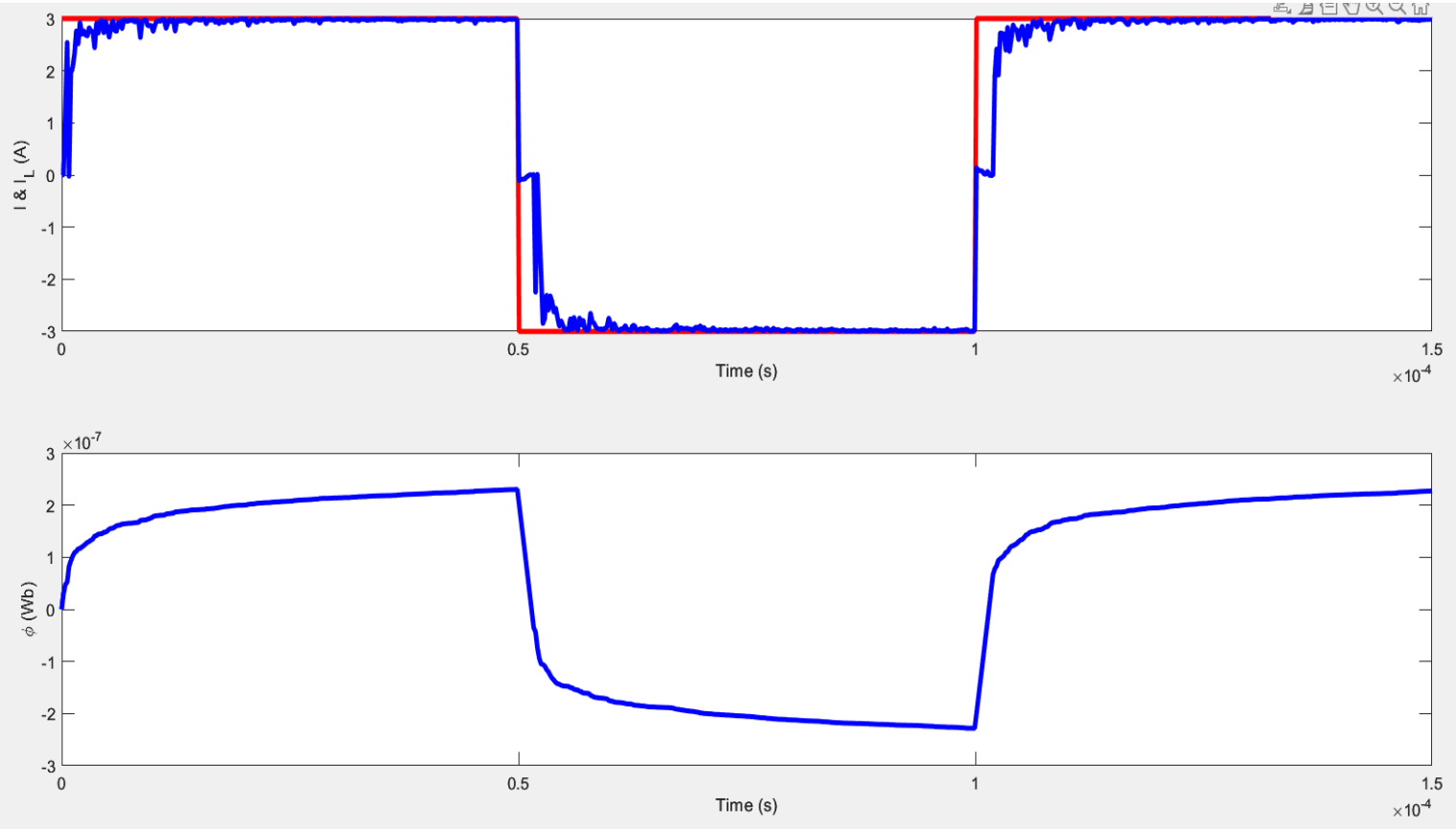
Experimentally verified hysteresis loop



Tuned the model parameters to match the core's hysteresis loop

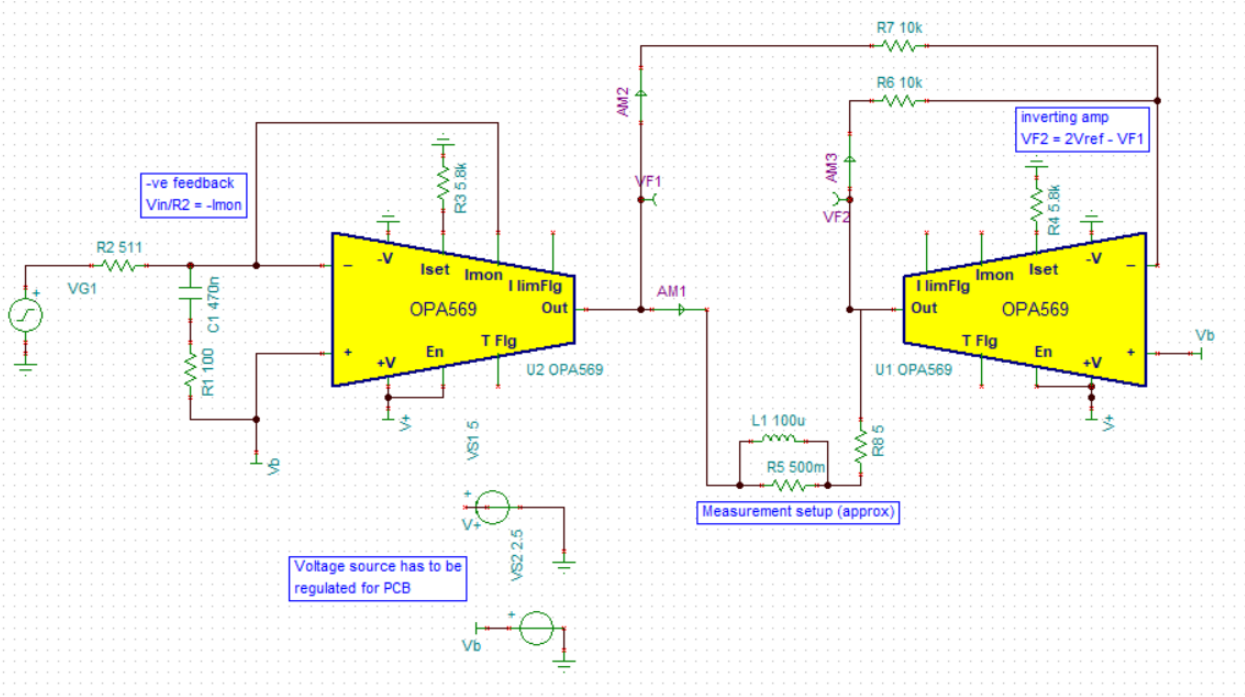
Benchmarking the Results with the Experiment Data

Now used the updated model to run the Ising simulation

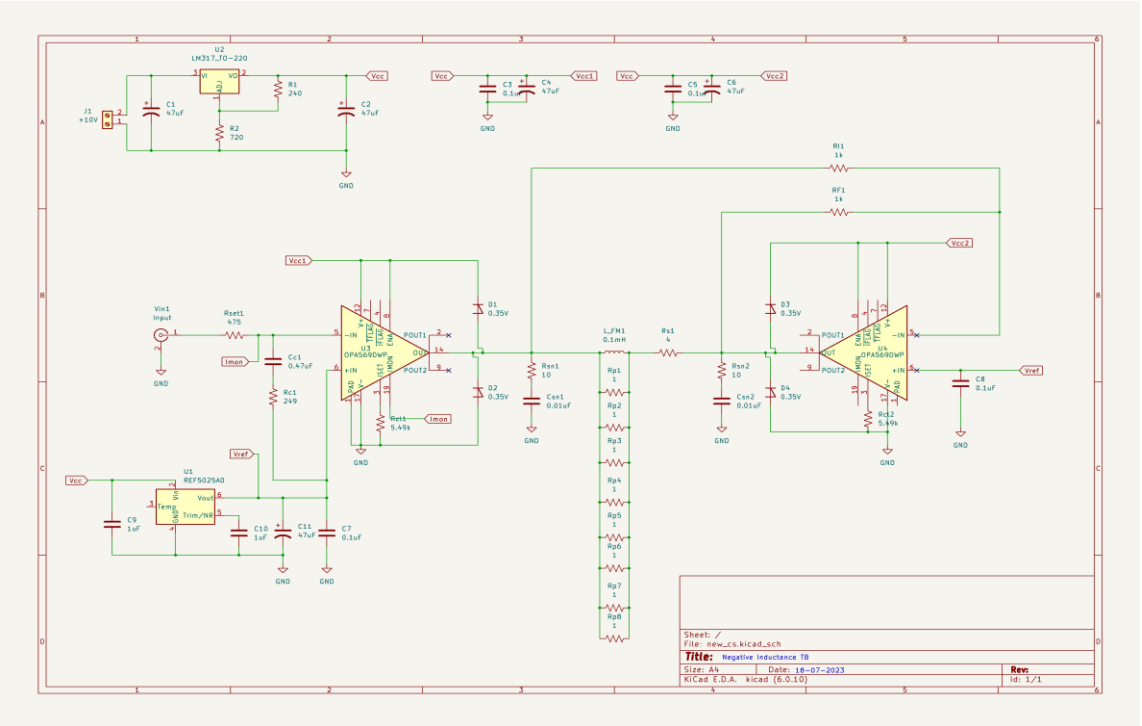


More Robust Setup to Clean Up the Results

- Voltage controlled Current Source - a design from TI



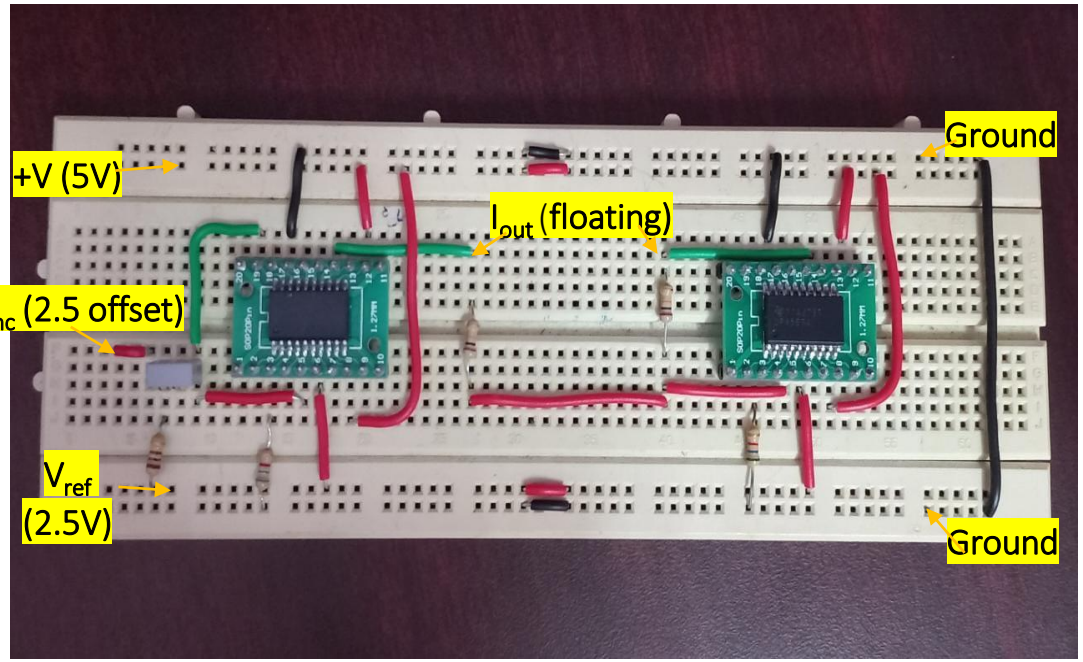
Simulation and verification of the design are done on Tina-Cloud simulator (circuit simulator of Texas)



Schematic designed in KiCAD

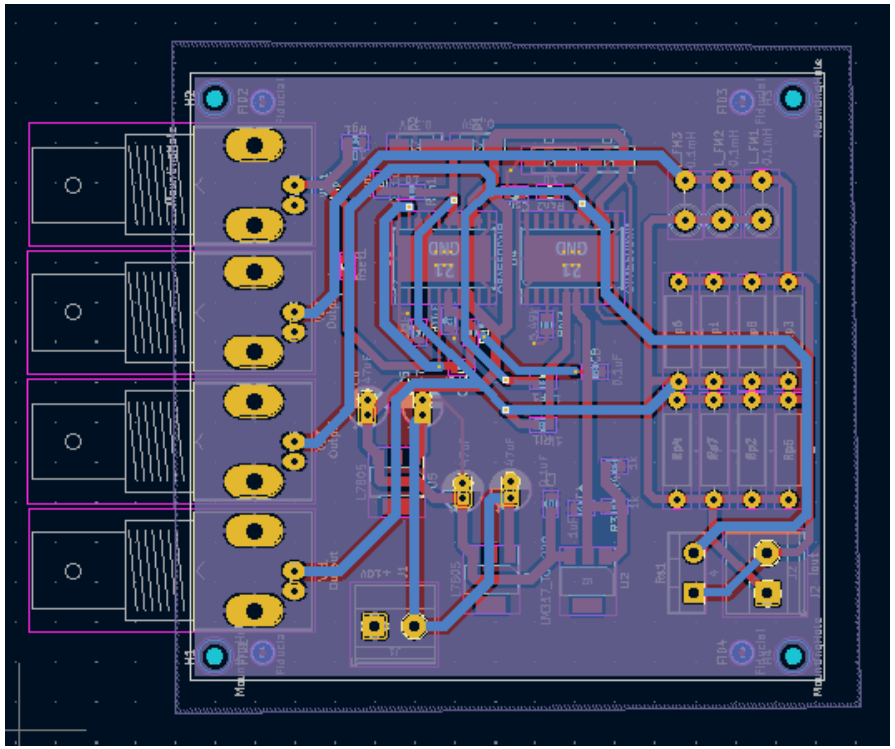
Tested in Breadboard

- Voltage controlled Current Source - a design from TI

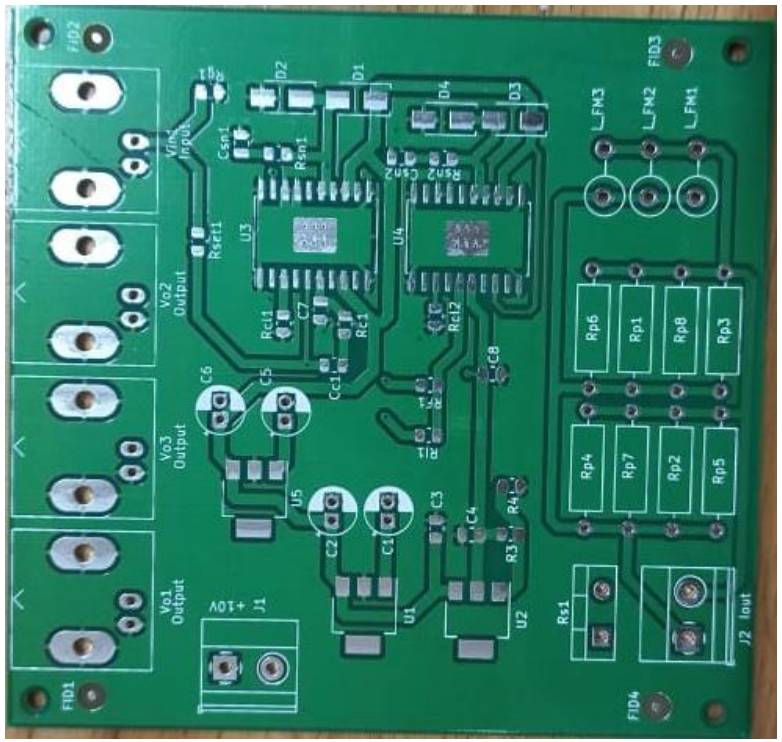


VCCS PCB

- PCB design and the printed board



Layout in KiCAD



PCB ordered from Lionscircuit

Modification in the current source for SR measurement & Future Plans

- PCB population and testing
- Measure S – Curve that characterise the NI
- A additional input to add noise to the input
- The characteristics of noise will vary at the output so the we need to find a way to get the desired noise induced current in the output
- We will try to experimentally obtain SR with our setup, and then move to simulation for benchmarking

Thanks to …

Priyankka G. R.

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Rekha S. S.

Abhinav Rajeev

&

our faculty advisor

Dr. Arvind Ajoy

For helping us in this project