2nd IEEE International Challenge in Design Methods for Power Electronics

2025 IEEE Power Electronics Society

MagNet Challenge 2

"From Steady-State to Transient Models!"

Tutorial Session 1, May 16, 2025

Shukai Wang, Hyukjae Kwon, Haoran Li, Thomas Guillod, Minjie Chen, Charles R. Sullivan

GitHub Repository: https://github.com/minjiechen/magnetchallenge-2
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MagNet 2025 Organizing Team

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Agenda

- **Webinar 1 – Data and Neural Network Methods**
  - May 16th Friday, 9 AM EST
- **Webinar 2 – Analytical Methods (by Dr. Thomas Guillid)**
  - May 23th, Friday, 9 AM EST
- **Webinar 3 – Model Testing and Evaluation Rules**
  - May 30th, Friday, 9 AM EST
- **Webinar 4 – Brainstorm and Q&A**
  - June 6th, Friday, 9AM EST

Registered Teams

Nagoya Institute of Technology
The Hong Kong Polytechnic University 香港理工大學
TU/e Eindhoven University of Technology
Nanyang Technological University Singapore
Huazhong University of Science and Technology
Aalborg Universitet
Tokyo Metropolitan University
Hefei University of Technology
ASU
Universidade Federal de Santa Catarina
National Institute of Technology Calicut
Fuzhou University
The University of Sydney
TUM
SAL Silicon Austria Labs
Southeast University 東南大學
Politecnico di Torino
UNIKASSEL VERSITÄT

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Universität Siegen
University of Bristol
Fujian University of Technology
Hangzhou Dianzi University
UTS University of Technology, Sydney
Georgia Tech
Princeton University
Dartmouth
University of Leeds
भारतीय प्रौद्योगिकी संस्थान धारवाड Indian Institute of Technology Dharwad
Xi'an Jiaotong University
University of Cambridge
Mizzou University of Missouri
Xiamen University of Technology
Universität Paderborn
Tianjin University (Peiyang University)
NVIDIA
Texas Instruments
WE Würth Elektronik
ITG Trusted Innovation Magnetics & EMI Filters
tsmc
pSemi A Murata Company

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Timeline of the MagNet Challenge 2

Feb 13st, 2025	Initial Call for Participation Announcement
Feb 26th, 2025	MagNet Challenge 2 Information Session
March 18th, 2025	APEC Official Announcement
April 1st, 2025	Online Q&A Session
May 1st, 2025	1-Page Letter of Intent Due with Signature [Attached]
June 1st, 2025	2-Page Proposal Due for Eligibility Check [TPEL Format]
July 1st, 2025	Notification of Acceptance [Eligibility Check]
Nov 1st, 2025	Preliminary Submission Due, Finalists Selected
Dec 24th, 2025	Final Submission Due
March 1st, 2026	Winner Announcement and Presentation

April 1st - Large amount of data for 10 materials released

May 1st – 1-Page letter of intent due

June 1st – 2-Page proposal due

July 1st – All participating teams confirmed

Nov 1st – Release small training data for 5 new materials

Dec 24th – Callable models and predicted core loss (P_v) for 10+5 materials under a variety of {B(t), f, T} conditions, and a 5-page TPEL format report due

March 1st , 2026 – Winner Announcement

MagNet Methodology
- Develop methods on **old** materials
- Test methods on **new** materials
- Train models with **small** datasets
- Test models with **large** datasets

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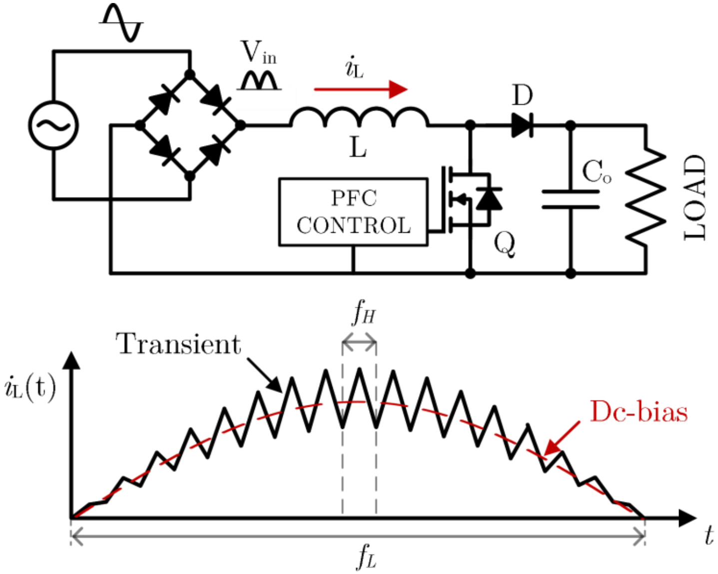
Motivation for the MagNet Challenge 2

- No good method to design magnetics in transient.
- **Imprecise material ↔ imprecise model ↔ imprecise design.**
- Unnecessary design margins (thermal, B_{sat}, batch-to-batch variation, …).
- Opportunities to reduce the size of all magnetics by 20%~50%?

An example PFC converter



Make every AC-DC adapters 30% smaller?

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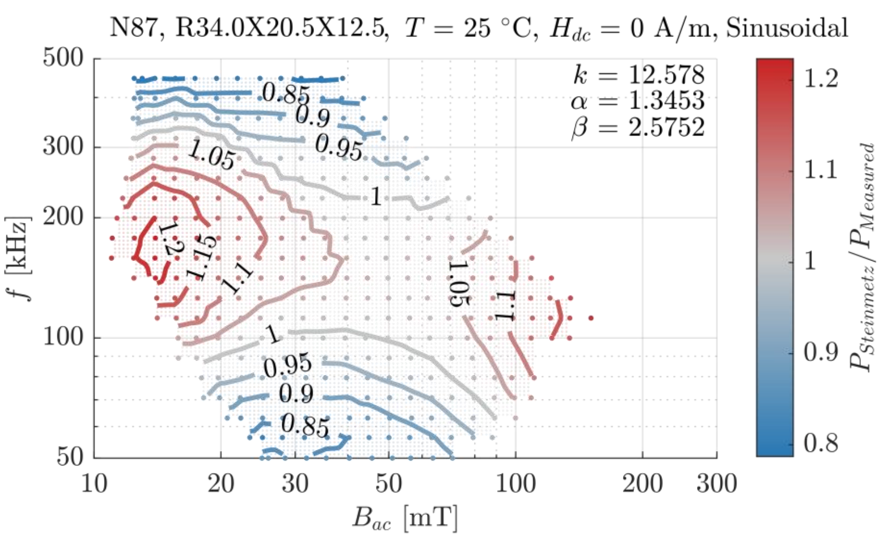
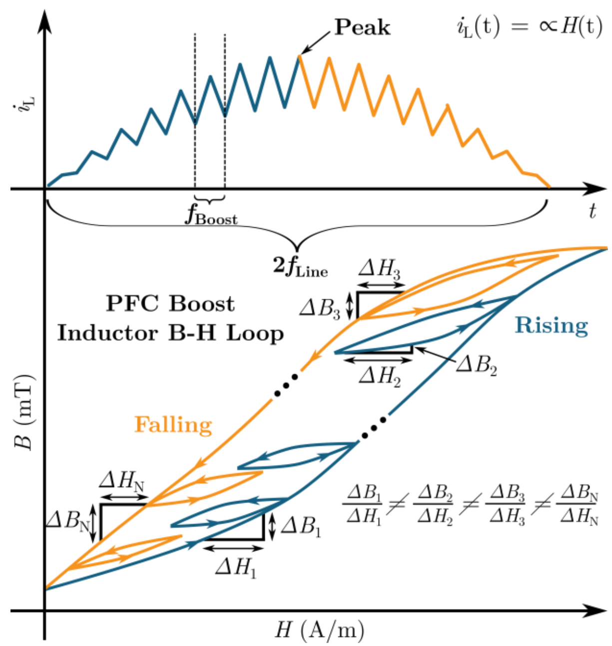
MagNet 2025 – A Transient Challenge





Steinmetz Equation (1890s)

Preisach Model & J-A Model (1930s) & (1980s)

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Foundation Model for Power Magnetics

Read history and predict future based on new inputs

Foundation Model

Frequency agnostic

- Any arbitrary / non steady state waveforms

Universal time step

- Long- or short-time steps

Initial state impact

- Hypothesis: impact of initial state has finite time horizon

Rigorous Mathematical Framework

- Flexible, Accurate
- Converge over time to steady state condition
- Explainable modeling framework
- Physics-based, data-driven, or hybrid …

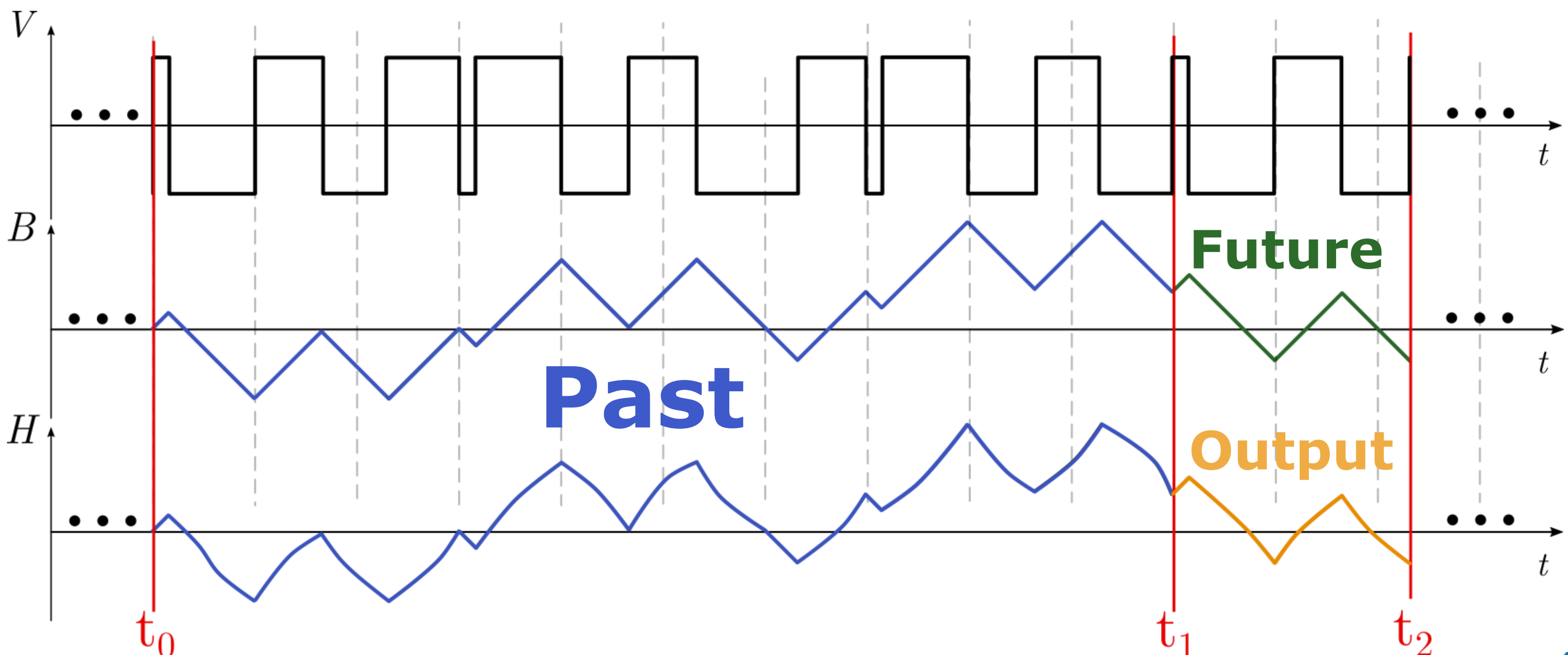
Outcome: A Callable Prediction Function

Training data:
- 10 training materials
- Lots of long B(t)-H(t) pairs
- Temperature

Testing data:
- 5 new materials
- Temperature
- Practicing: plenty of long B(t) and H(t) pairs
- Testing:
  - B(t) and H(t) pairs from t_0 to t_1
  - B(t) from t_1 to t_2

Output:
  - H(t) from t_1 to t_2

Evaluate:
- Total core loss from t_1 to t_2
- H(t) RMS error from t_1 to t_2
- Model size (# of parameters)

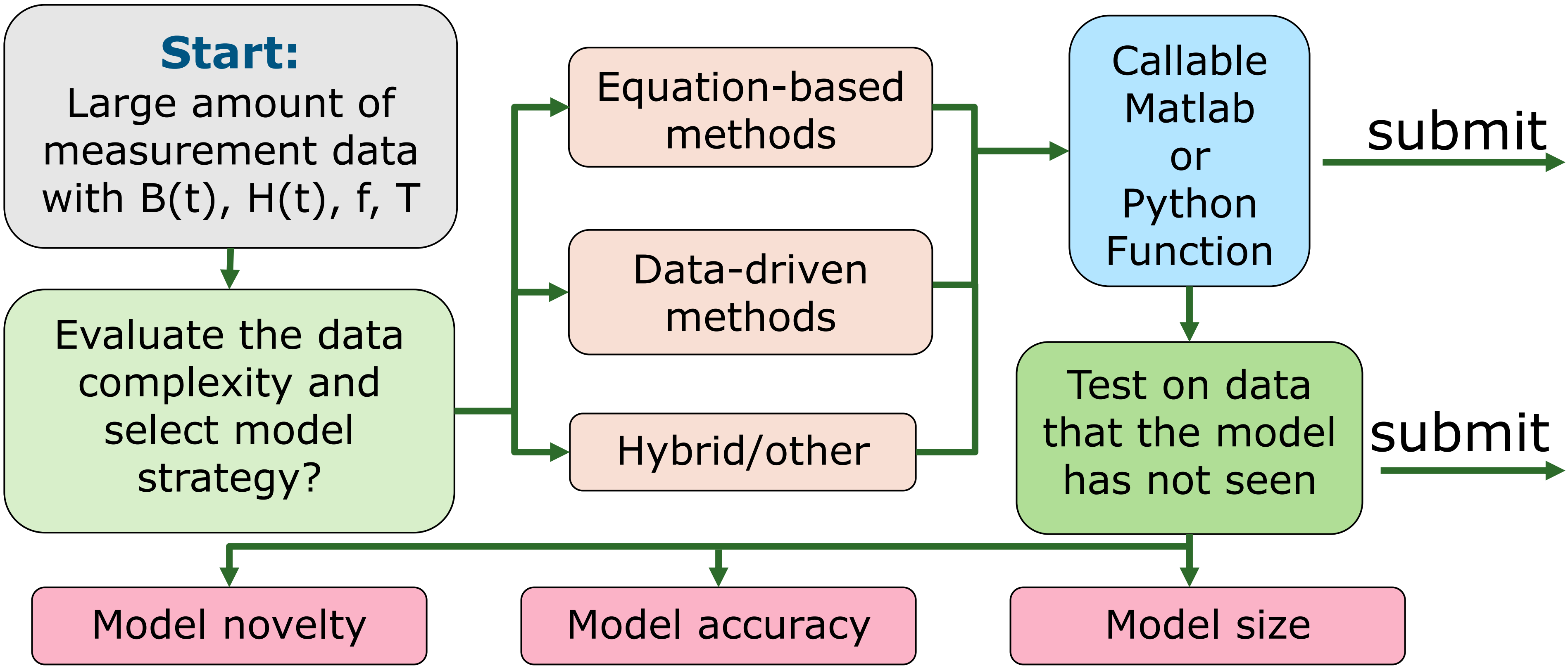


- Hyukjae Kwon, Shukai Wang, Haoran Li, et al. "**MagNetX: Extending the MagNet Database for Modeling Power Magnetics in Transient**," *TechRxiv*. December 11, 2024. Accepted to APEC 2025.

Information Flow of MagNet Challenge 2

Next step: $$H_{t+1} = function\,(B(t), H(t), B_{t+1}, T)$$

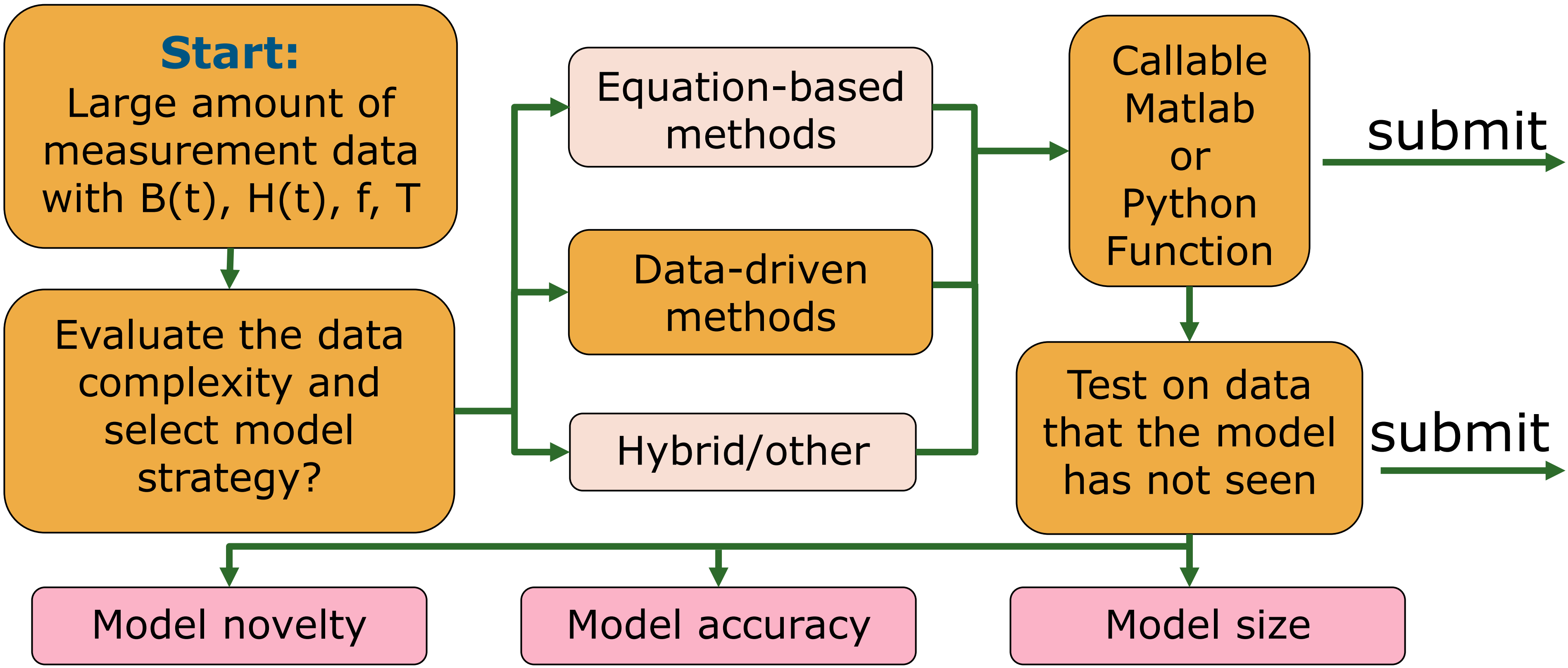
Long cycle: $$H_{t_1\rightarrow t_2} = function\,(B(t), H(t), B_{t_1\rightarrow t_2}, T)$$



Information Flow of MagNet Challenge 2

Next step: $H_{t+1} = function\,(B(t), H(t), B_{t+1}, T)$

Long cycle: $H_{t_1 \to t_2} = function\,(B(t), H(t), B_{t_1 \to t_2}, T)$



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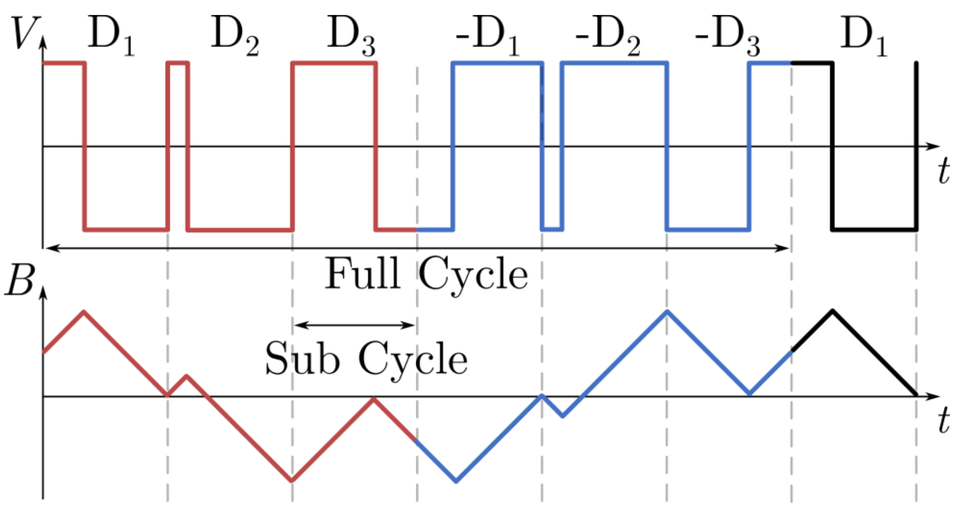
New MagNetX Dataset for Transient Dynamics

- How to collect transient data?
  - A mix of high frequency transient and low frequency steady state
  - Applicable to PFC converters, etc.

Example symmetric magnetizing and demagnetizing sequences



15 ferrite materials

13,587 sequences per material

Fixed sampling frequency: 16 MHz

Duty cycle step changes D = 0.2~0.8, min step size = 0.1

Fixed 7 subcycle frequency f = 50kHz~800kHz

Three temperatures: 25°C, 50°C, 70°C

100 subcycles per sequence

- Hyukjae Kwon, Shukai Wang, Haoran Li, et al. "**MagNetX: Extending the MagNet Database for Modeling Power Magnetics in Transient**," *TechRxiv*. December 11, 2024. Accepted to APEC 2025.

Data Structure

For Training

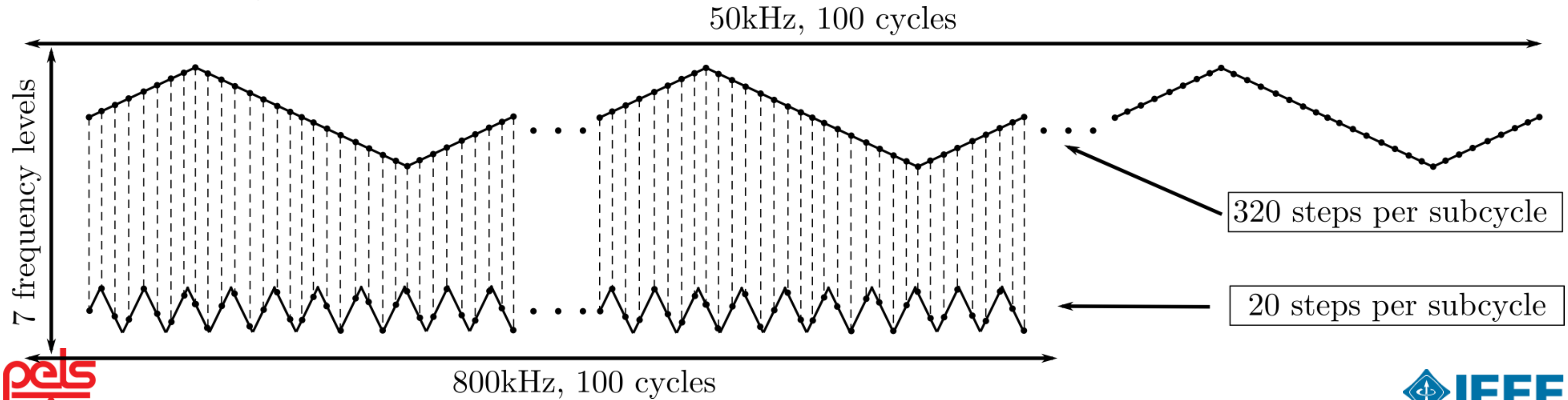
- Material format:
    - 7 sets of B(t), H(t), T for each material
    - Frequency information not provided
- Sampling frequency for all sequences: 16MHz
    - 50kHz: 32016 steps
    - 80kHz: 20016 steps
    - 125kHz: 12816 steps
    - 200kHz: 8015 steps
    - 320kHz: 4975 steps
    - 500kHz: 3216 steps
    - 800kHz: 2016 steps

Testing

- Same length for all sequences (TBA)

Material Folder: 3C90

3C90_1_B	3C90_3_H	3C90_5_T
3C90_1_H	3C90_3_T	3C90_6_B
3C90_1_T	3C90_4_B	3C90_6_H
3C90_2_B	3C90_4_H	3C90_6_T
3C90_2_H	3C90_4_T	3C90_7_B
3C90_2_T	3C90_5_B	3C90_7_H
3C90_3_B	3C90_5_H	3C90_7_T



MagNetX Database

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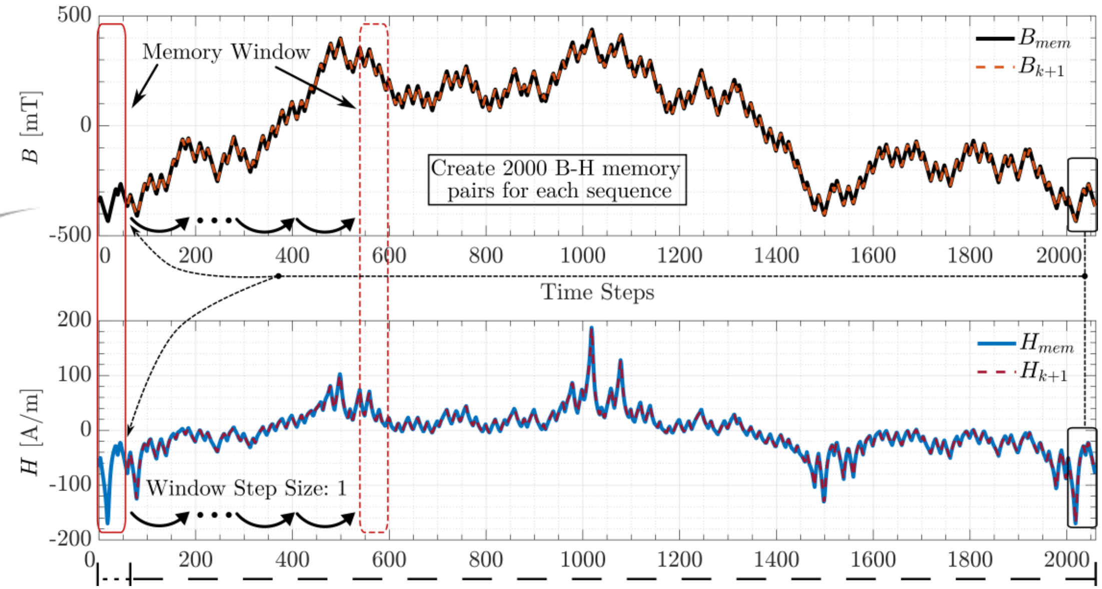
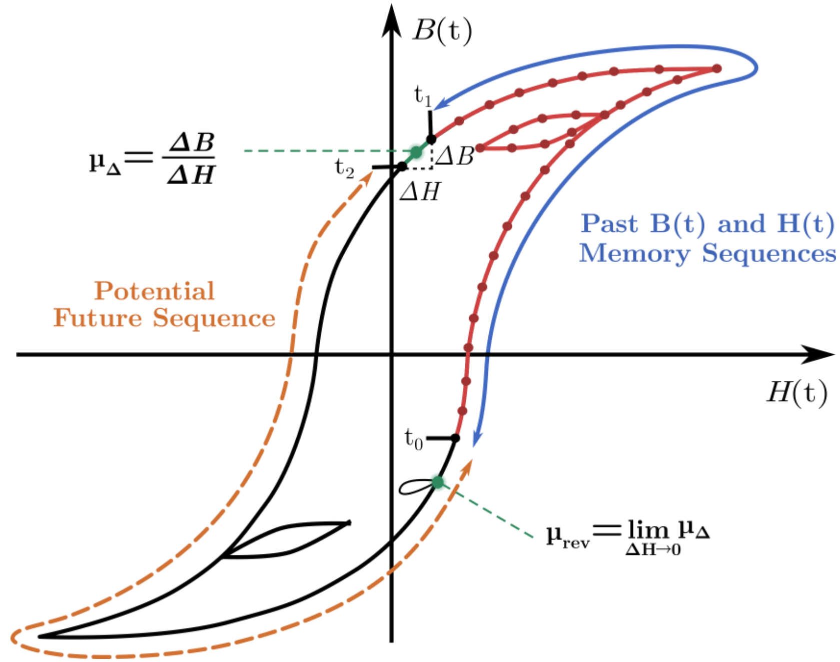
Material	Data Sequence
Ferroxcube 3C90	13,587
Ferroxcube 3C94	9,224
Ferroxcube 3E6	7,407
Ferroxcube 3F4	10,714
Fair-Rite 77	10,726
Fair-Rite 78	9,845
TDK N27	11,456
TDK N30	10,580
TDK N49	7,266
TDK N87	12,313
Total	103,118

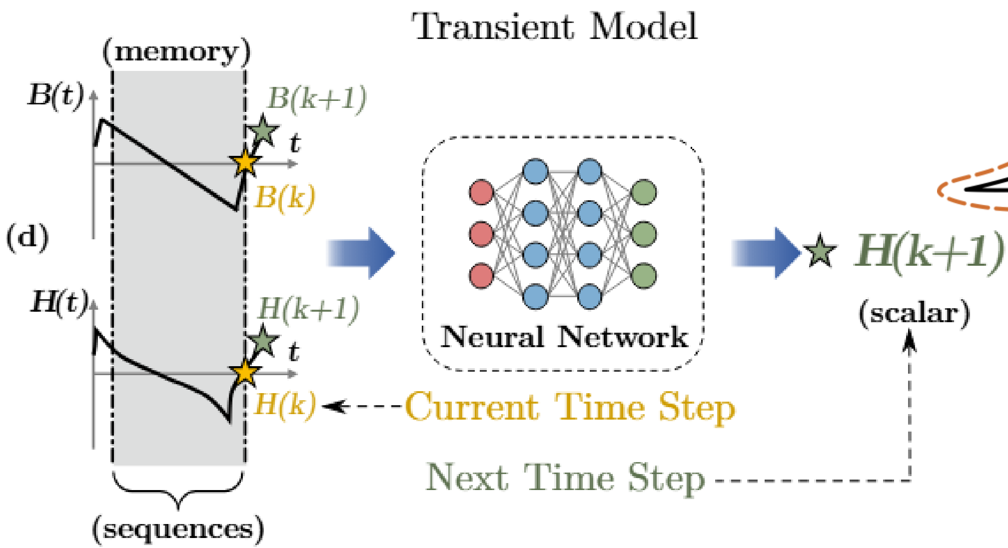


- Collected 10 materials, including 103,118 sequences

What we have developed (as tutorials)

Input: B(t) in the past 80 steps
H(t) in the past 80 steps
future B(t) from t_1 to t_2
Output: future H(t) from t_1 to t_2

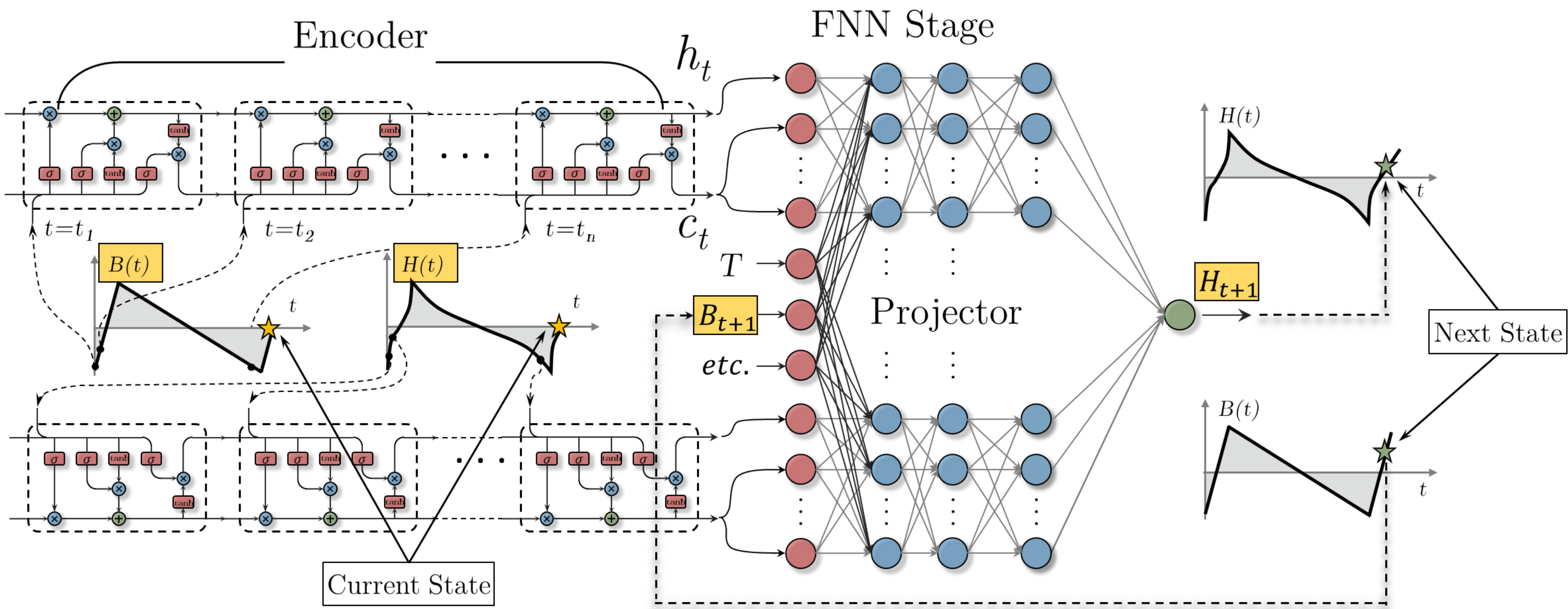




- Shukai Wang, Hyukjae Kwon, Haoran Li, et al. "**MagNetX: Foundation Neural Network Models for Simulating Power Magnetics in Transient**." *TechRxiv.* December 11, 2024. Accepted to APEC 2025.

Machine Learning Foundation Models

Single next step: $H_{t+1} = function\,(B(t), H(t), B_{t+1}, T)$



What B(t) and H(t) memory information to acquire?

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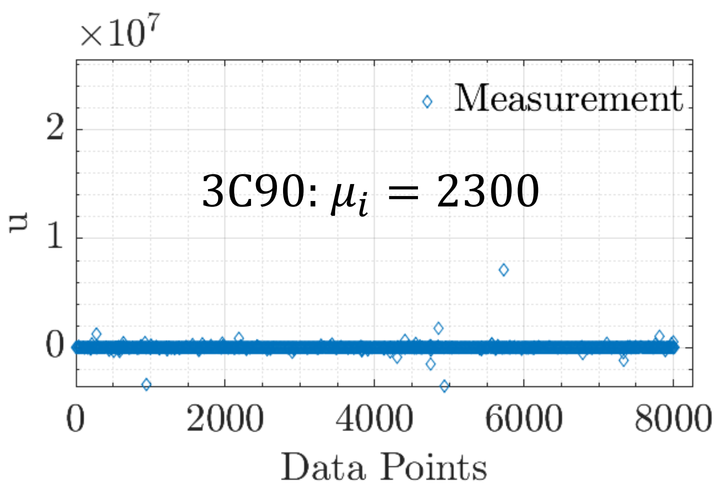
Dataset Setup

Original Dataset: 54 GB-sized file with full training

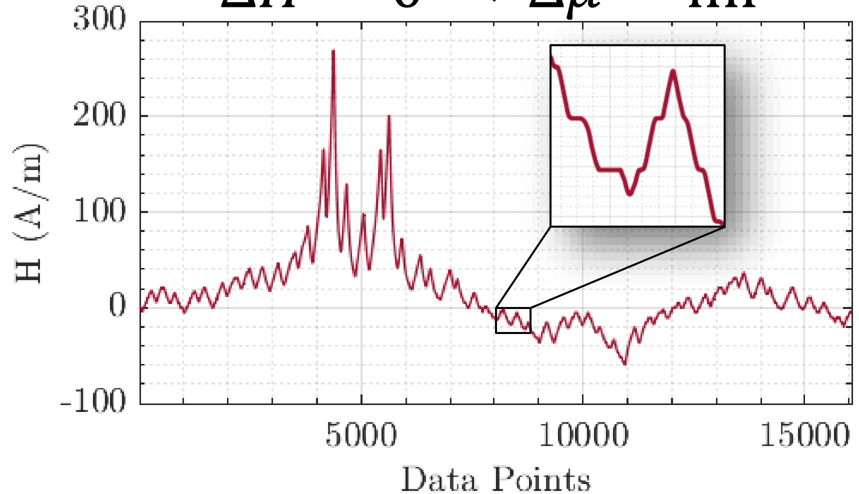
Freq (kHz)	50	80	125	200	320	500	800
No. of Seqs (M)	647	1459	2252	3252	3269	3300	3090
Seq Length (N)	32016	20016	12816	8015	5008	3216	2016

- Every data point prediction requires information about two memory sequences of *B(t)* and *H(t)*
  - What are the important points?
  - How long of a memory?

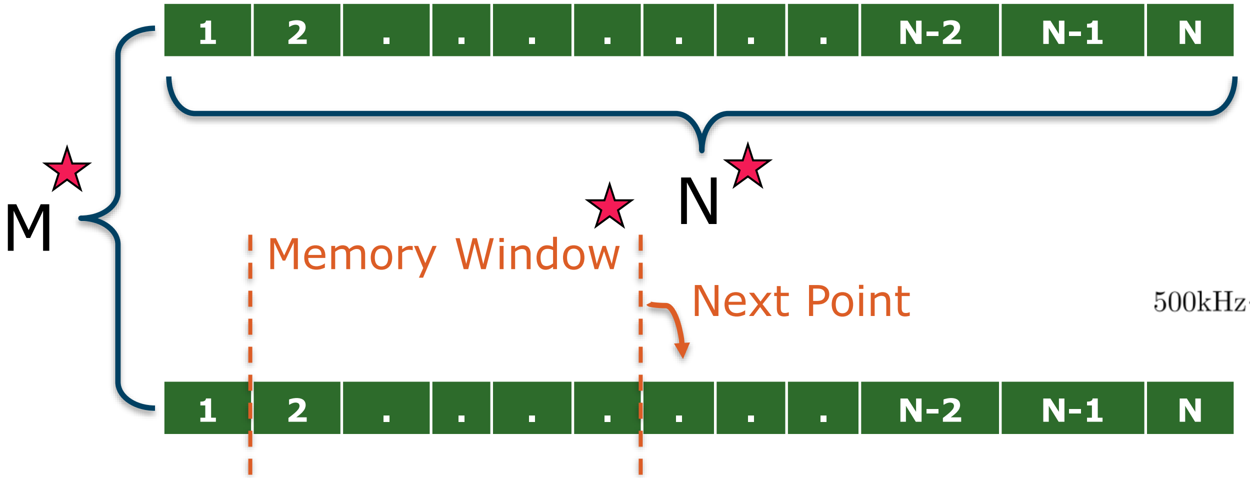
Select training points that is in a good range?

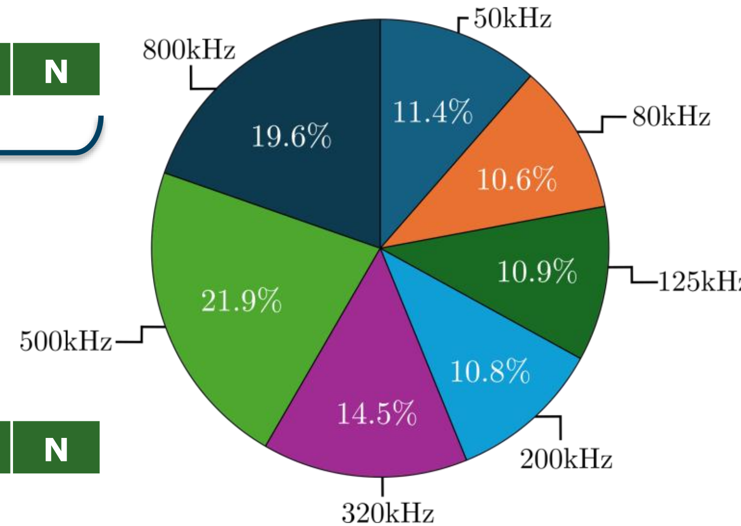


$\Delta H = 0 \rightarrow \Delta\mu = \text{inf}$



Dataset Setup





Training Dataset:

Freq (kHz)	50	80	125	200	320	500	800
No. of Seqs (M)	53	82	85	501	1123	1698	2277
Seq Length (N)	10000	6000	6000	1000	600	600	400
No. of Points	530000	492000	510000	501000	673800	1018800	910800
Percentage	11.4%	10.6%	10.9%	10.8%	14.5%	21.9%	19.6%

Training Tutorial

- Please visit MagNet Challenge GitHub: https://github.com/minjiechen/magnetchallenge-2
- Or MagNetX GitHub: https://github.com/PaulShuk/MagNetX

Network Training

This tutorial demonstrates how to train the double LSTM-based model for the seqeunce-to-scalar future hysteresis step prediction. The model may serve as a good starting point for the neural network based transient magnetic modeling. The network model will be trained based on 3C90_Training_Tutorial.h5 file and saved as a state dictionary (.sd) file. The training data is a all frequency inclusive, 50-sequences per freqeuncy dataset with each seuqence containing only 1000 randomly selected time steps for training, operating under all availble temepratures, and flux excitations.

Step 0: Import Packages

In this step we import the important packages that are necessary for the training.

In [1]:

```
from google.colab import drive
drive.mount('/content/drive')

import torch
from torch import Tensor
import torch.nn as nn
import torch.nn.functional as F
import torch.optim as optim
import random
import numpy as np
import json
import math
import csv
import time
import h5py
```

```
Mounted at /content/drive
```

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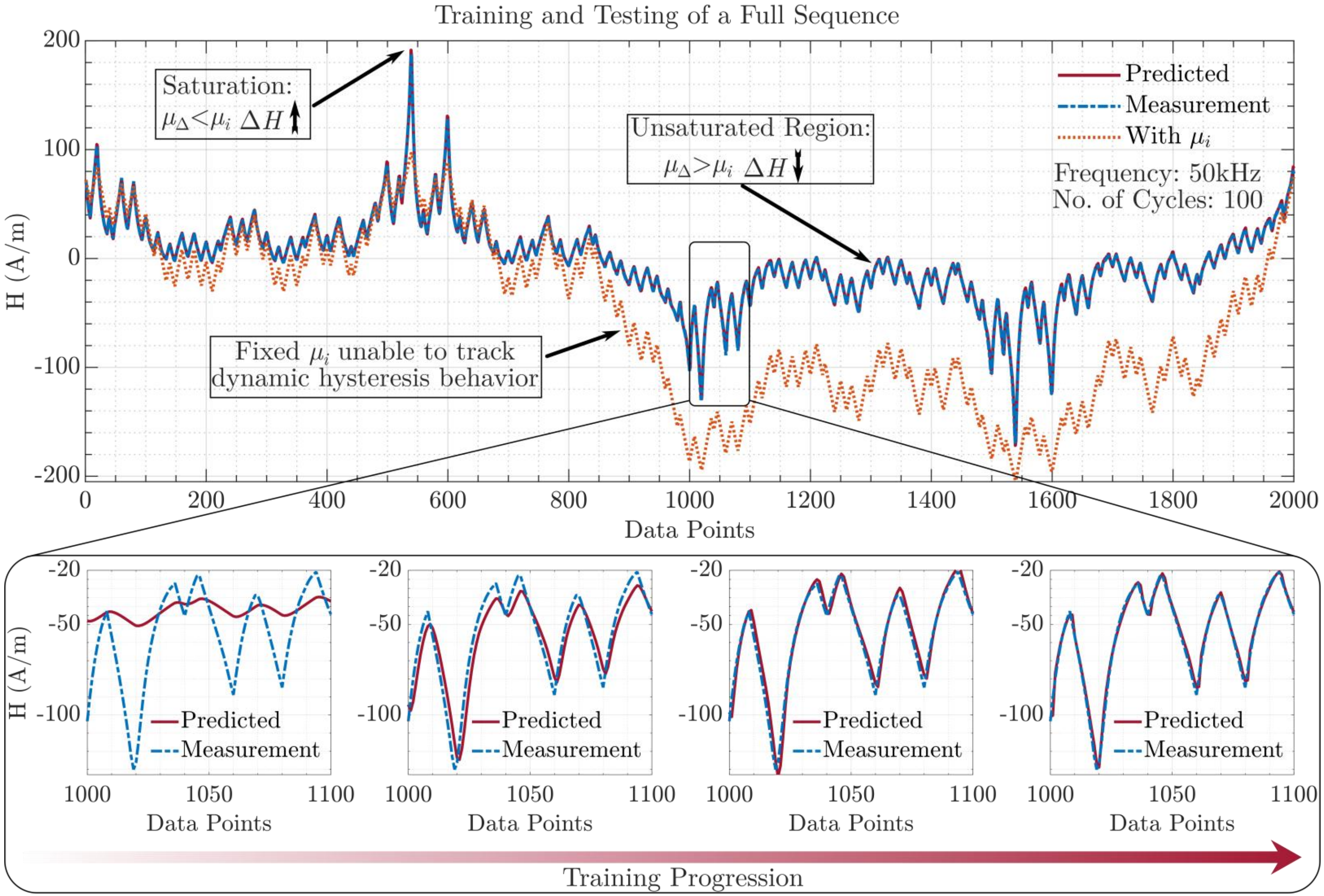
Model Evaluation



Single-Step Prediction

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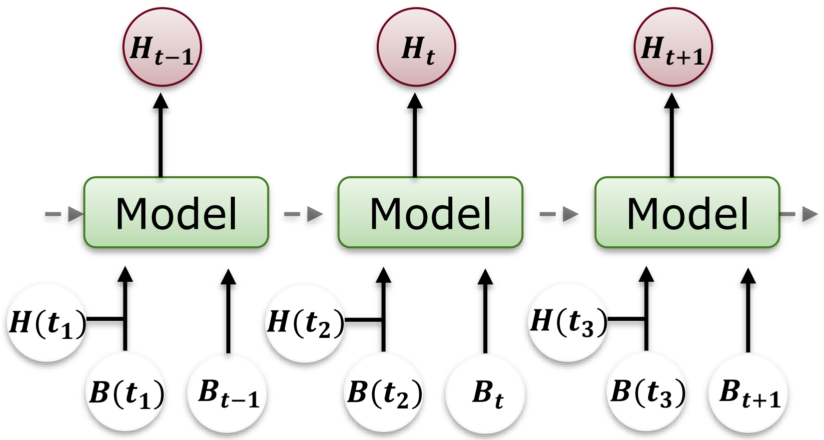
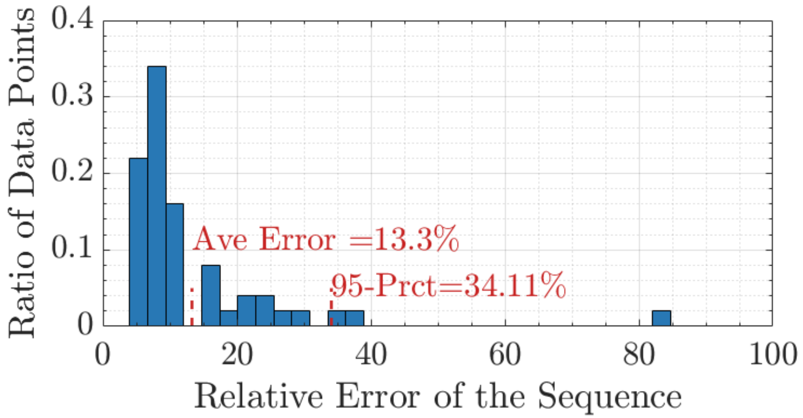
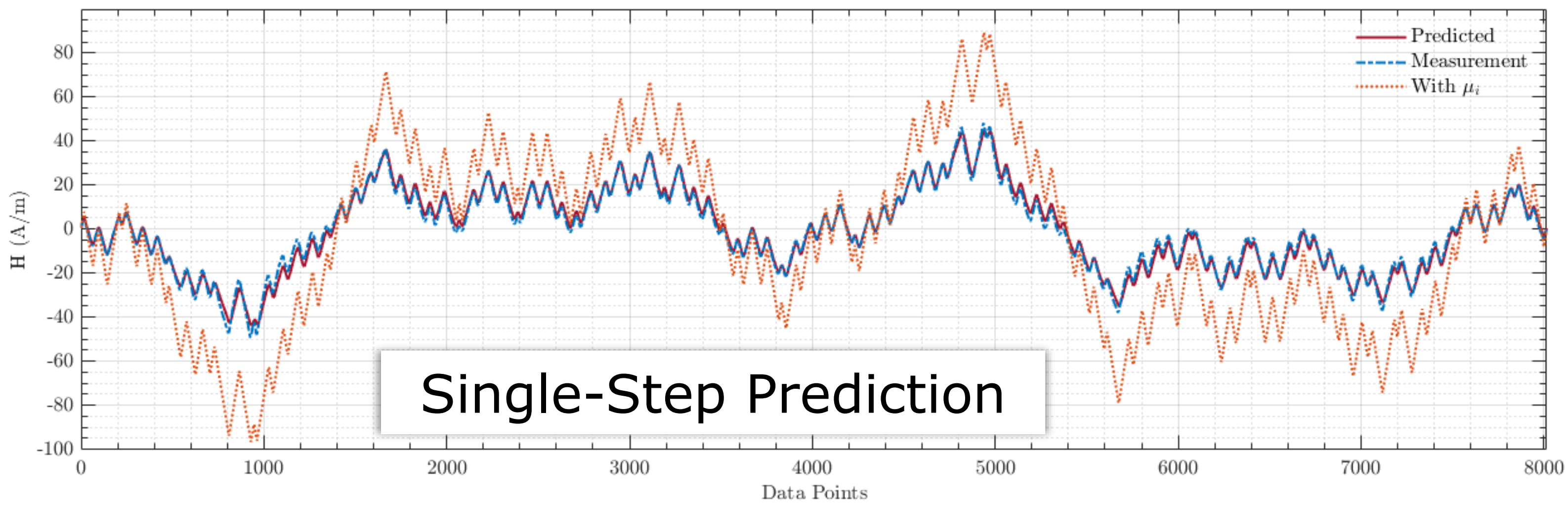
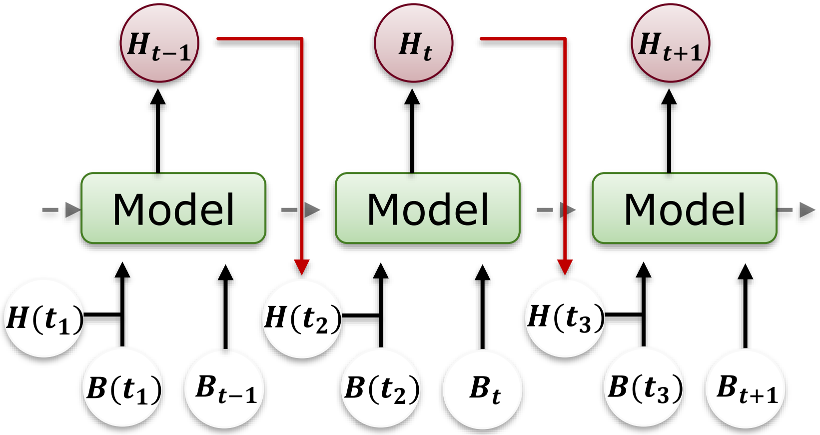
Single-Step Prediction

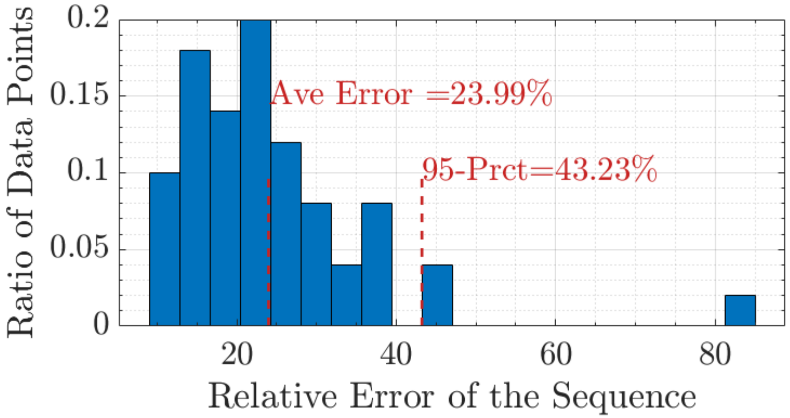


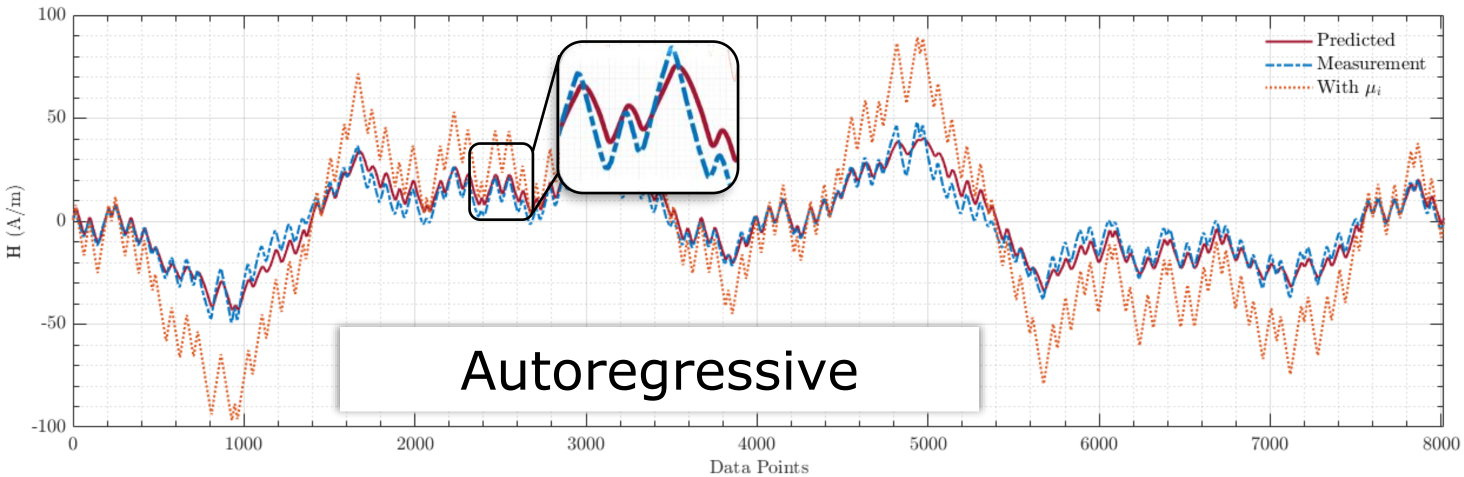




Autoregressive Prediction







Training Tutorial

- Please visit MagNet Challenge GitHub: https://github.com/minjiechen/magnetchallenge-2
- Or MagNetX GitHub: https://github.com/PaulShuk/MagNetX

1: Network Testing

This tutorial demonstrates how to test the double LSTM-based model for the sequence-to-scalar future hysteresis step prediction. The testset seqeunces include data that has the same sampling time steps as the training dataset. The testing data is a single frequency 200kHz data sequence at 25C. Sequence length = 8015 data points

Step 0: Import Packages

In this step we import the important packages that are necessary for the testing.

```
[24] from google.colab import drive
     drive.mount('/content/drive')

     import torch
     from torch import Tensor
     import torch.nn as nn
     import torch.nn.functional as F
     import torch.optim as optim
     import random
     import numpy as np
     import json
     import math
     import csv
     import time
     import h5py
     import matplotlib.pyplot as plt
```

Opportunities for Innovation

- How do we determine the training data
  - Sample freq, temp, material
- Model architecture
  - Input (length, format of data, etc.)
  - Output (time series, core loss, etc.)
  - Hidden parameters (physics-informed)
- Model implementation
  - Data driven
  - Analytical
  - Hybrid
- Model generality and scalability
  - Transfer learning
  - General algorithm that works across materials

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Extended Reading – MagNet Challenge 2

- **J-A Model –** D. Jiles and D. Atherton, “Theory of ferromagnetic hysteresis,” Journal of Magnetism and Magnetic Materials, vol. 61, no. 1, pp. 48–60, 1986.
- **Preisach Model –** F. Preisach, “Uber die magnetische Nachwirkung,” Zeitschrift fur Physik,vol. 94, no. 5-6, pp. 277–302, May 1935.
- **LLG Model –** H. H. Cui, S. Dulal, S. B. Sohid, G. Gu, and L. M. Tolbert, “Unveilingthe microworld inside magnetic materials via circuit models,” IEEEPower Electronics Magazine, vol. 10, no. 3, pp. 14–22, 2023.
- **iGSE-PFC –** M. J. Jacoboski, A. de Bastiani Lange and M. L. Heldwein, “Closed-Form Solution for Core Loss Calculation in Single-Phase Bridgeless PFC Rectifiers Based on the iGSE Method,” in IEEE Transactions on Power Electronics, vol. 33, no. 6, pp. 4599-4604, June 2018.
- **Why MagNet –** D. Serrano et al., “Why MagNet: Quantifying the Complexity of Modeling Power Magnetic Material Characteristics,” in IEEE Transactions on Power Electronics, vol. 38, no. 11, pp. 14292-14316, Nov. 2023.
- **How MagNet –** H. Li et al., “How MagNet: Machine Learning Framework for Modeling Power Magnetic Material Characteristics,” in IEEE Transactions on Power Electronics, vol. 38, no. 12, pp. 15829-15853, Dec. 2023.
- **MagNet-AI –** H. Li, D. Serrano, S. Wang and M. Chen, “MagNet-AI: Neural Network as Datasheet for Magnetics Modeling and Material Recommendation,” in IEEE Transactions on Power Electronics, vol. 38, no. 12, pp. 15854-15869, Dec. 2023.
- **MagNet Challenge –** M. Chen et al., “MagNet Challenge for Data-Driven Power Magnetics Modeling,” in IEEE Open Journal of Power Electronics, accepted.

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Extended Reading – MagNet Challenge 2

- **iGSE** - K. Venkatachalam, C. R. Sullivan, T. Abdallah and H. Tacca, “Accurate prediction of ferrite core loss with nonsinusoidal waveforms using only Steinmetz parameters,” Proc. IEEE Workshop Comput. Power Electron., pp. 36-41, 2002.
- **iGSE** - Matlab Implementation https://www.mathworks.com/matlabcentral/fileexchange/39995-magnetic-core-loss-evaluation-for-arbitrary-flux-waveforms
- **i2GSE** - J. Muhlethaler, J. Biela, J. W. Kolar and A. Ecklebe, “Improved Core-Loss Calculation for Magnetic Components Employed in Power Electronic Systems,” in IEEE Transactions on Power Electronics, vol. 27, no. 2, pp. 964-973, Feb. 2012.
- **iGSE-CD** - D. Menzi et al., “iGSE-CD—An Electric-/Displacement-Field Related Steinmetz Model for Class II Multilayer Ceramic Capacitors Under Low-Frequency Large-Signal Excitation,” in IEEE Open Journal of Power Electronics, vol. 4, pp. 107-116, 2023.
- **Stenglein Model -** E. Stenglein and T. Dürbaum, “Core Loss Model for Arbitrary Excitations With DC Bias Covering a Wide Frequency Range,” in IEEE Trans. on Magnetics, vol. 57, no. 6, pp. 1-10, June 2021.
- **IGCC -** T. Guillod, J. S. Lee, H. Li, S. Wang, M. Chen, C. R. Sullivan, “Calculation of Ferrite Core Losses with Arbitrary Waveforms Using the Composite Waveform Hypothesis,” IEEE Applied Power Electronics Conference (APEC), 2023.
- **MagNetX Models -** S. Wang, H. Kwon, H. Li, et al. “MagNetX: Foundation Neural Network Models for Simulating Power Magnetics in Transient,” TechRxiv. December 11, 2024.
- **MagNetX Database -** H. Kwon, S. Wang, H. Li, et al. “MagNetX: Extending the MagNet Database for Modeling Power Magnetics in Transient,” TechRxiv. December 11, 2024.