

2nd IEEE International Challenge in Design Methods for Power Electronics

2025 PELS MagNet Challenge

MagNet Challenge 2

“From Steady-State to Transient Models!”

Kickoff Meeting, January 5, 2025

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

MagNet 2025 Organizing Team
pelsmagnet@gmail.com



A Very Successful MagNet Challenge 1



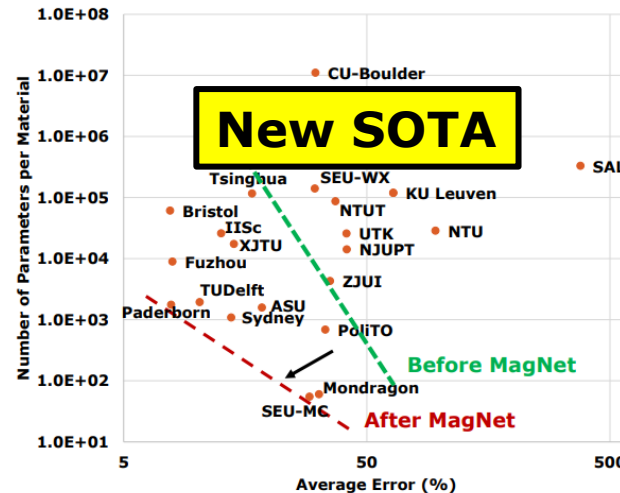
MagNet Challenge for Data-Driven Power Magnetics Modeling

Minjie Chen¹, Haoran Li¹, Shukai Wang¹, Thomas Guillod², Diego Serrano¹, Nikolas Förster³, Wilhelm Kirchgässner², Till Piepenbrock³, Oliver Schweins³, Oliver Wallscheid³, Qijue Huang⁴, Yang Li²⁰, Yu Dou²¹, Bo Li²¹, Sinan Li⁴, Emmanuel Havugimana⁵, Vivek Thomas Chacko⁵, Sritharini Radhakrishnan⁵, Mike Ranjram⁶, Bailey Sauter⁶, Skye Reese⁶, Shivangi Sinha⁷, Lizhong Zhang⁷, Tom McKeague⁷, Binyu Cui⁷, Navid Rasekh⁷, Jun Wang⁷, Song Liu⁷, Alfonso Martinez⁸, Xinyu Liu⁹, Chaoying Mei⁹, Rui Zhao⁹, Gaoyuan Wu⁹, Hao Wu⁹, Rui Zhang¹⁰, Hao Song¹⁰, Lie Zhang¹⁰, Yibo Lu¹⁰, Lijun Hang¹⁰, Neha Rajput¹¹, Himanshu Bhushan Sandhibigraha¹¹, Neeraj Agrawal¹¹, Vishnu Mahadeva Iyer¹¹, Xiaobing Shen¹², Fanghao Tian¹², Qingcheng Sui¹², Jiaze Kong¹², Wilmar Martinez¹², Asier Arruti¹³, Borja Alberdi¹³, Anartz Agote¹³, Iosu Aizpuru¹³, Minmin Zhang¹⁴, Xia Chen¹⁴, Yuchen Dong¹⁴, Duo Wang¹⁴, Tianming Shen¹⁴, Yan Zhou¹⁴, Yaohua Li¹⁵, Sicheng Wang¹⁵, Yue Wu¹⁵, Yongbin Jiang¹⁵, Ziheng Xiao¹⁵, Yi Tang¹⁵, Yun-Shan Hsieh¹⁶, Jian-De Li¹⁶, Li-Chen Chen¹⁶, Alessio Giuffrida¹⁷, Nicolo L... Luigi Solimene¹⁷, Carlo Stefano Ragusa¹⁷, Xiang Ma¹⁹, Boyu Zhang¹⁹, Zheng Wang¹⁹, Puskar Neupane²², Mecon Joshi²², Shahabuddin Khan²², Bowen Su²⁰, Yunhao Xiao²⁰, Min Yang²⁰, Kai Sun²⁰, Zhengzhao Li²³, Reza Mirzadaran²³, Ruijun Liu²³, Lu Wang²³, Tianming Luo²³, Dingsihao Lyu²³, Mohamad Ghaffarian Niasar²³, Zian Qin²³, Syed Irfan Ali Meerza²⁴, Kody Froehle²⁴, Han Helen Cui²⁴, Daniel Costinett²⁴, Jian Liu²⁴, Zhanlei Liu²⁵, Cao Zhan²⁵, Yongliang Dang²⁵, Yukun Zhang²⁵, Na Wang²⁵, Yiting Chen²⁵, Yiming Zhang²⁵, Chushan Li²⁵, Yinan Yao²⁶, Tianxiang Hu²⁶, Lumeng Xu²⁶, Yiyi Wang²⁶, Sichen Wang²⁶, Shuai Jiang²⁷, David Shumacher²⁸, Dragan Maksimović⁶, Ron S. Y. Hui²⁹, Johann W. Kolar³⁰, David J. Perreault³¹ AND Charles R. Sullivan²

133 co-authors



Charles Steinmetz
(1865-1923)



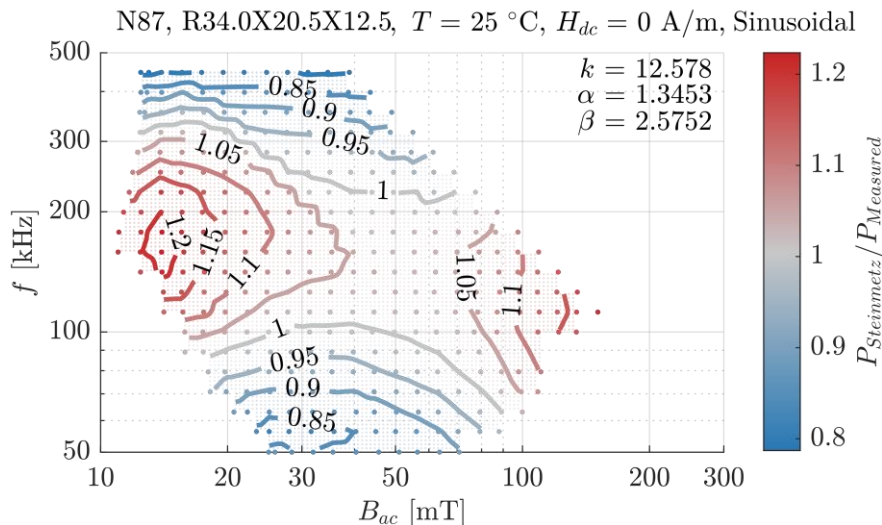
24 teams

Many theses

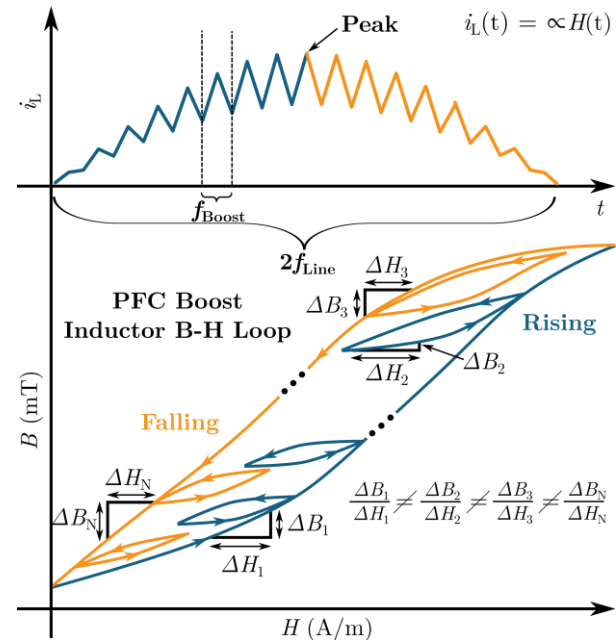
- Arizona, USA
- Fuzhou, China
- Hangzhou, China
- Bangalore, India
- Leuven, Belgium
- Hernani, Spain
- Nanjing, China
- Cambridge, USA
- Singapore, Singapore
- Taipei, Taiwan
- Hong Kong, China
- Paderborn, Germany
- Princeton, USA
- Hanover, USA
- Piscataway, USA
- Torino, Italy
- Graz, Austria
- Lalitpur, Nepal
- Beijing, China
- Fremont, USA
- Delft, Netherlands
- Boston, USA
- Santa Clara, USA
- Manchester, UK
- Sydney, Australia
- Knoxville, USA
- Xi'an, China
- Mountain View, USA

MagNet 2023 - IEEE International Challenge in Design Methods for Power Electronics

MagNet 2025 – A Transient Challenge



Steinmetz Equation
(1890s)



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

2025: from Racetrack to Open Path

Periodic Steady State Excitations



Non-Periodic Excitations



Foundation Model for Power Magnetics

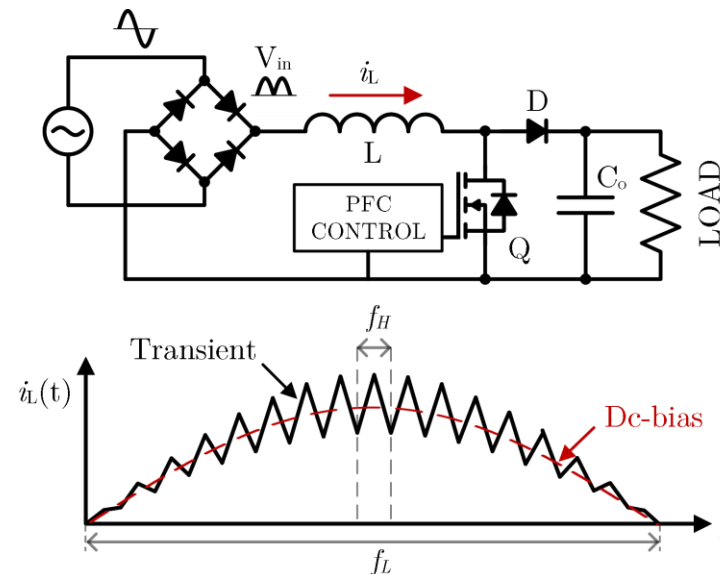
- Foundation Model for Magnetic Materials?
 - Frequency agnostic (non-steady-state)
 - Universal time step (long- or short-time steps)
 - Finite memory system (damping all initial impacts)
 - Long term convergence (long term converging)
 - ...
- A Rigorous Mathematical Framework?
 - A compact and efficient, hopefully explainable modeling framework which will converge over time to the material's steady state condition

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, ...).
- Future chips, vehicles, and robotics need miniaturization and precision.
- Opportunities to reduce the size of all magnetics by 20%~50%?
- Need a better way to document, compress, and share information.
- Help the manufacturers to improve repeatability, control the quality, and share better data in better ways.



An example PFC converter

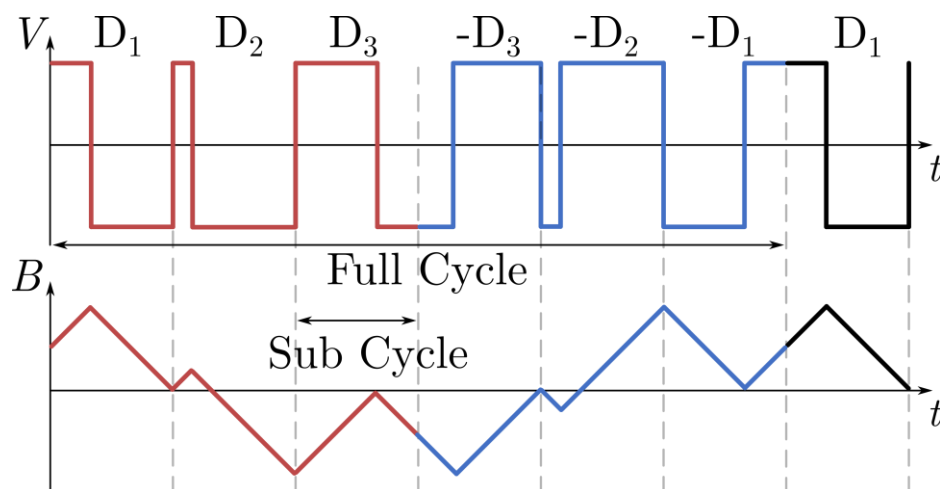


Make every AC-DC adapters 30% smaller?

New MagNetX Dataset for Transient Dynamics

- Duty cycle step changes $D = 0.2 \sim 0.8$, min step size = 0.1
- Fixed frequency sequences $f = 50\text{kHz} \sim 800\text{kHz}$, 7 frequency levels
- Three temperatures: 25°C , 50°C , 70°C
- ~ 7 voltage levels
- 100 subcycles per sequence

Example symmetric magnetizing and demagnetizing sequences



Symmetric magnetizing and demagnetizing sequences

15 ferrite materials

>5,000 sequences per material

Fixed sampling frequency: 16 MHz

50 kHz: 320 steps per subcycle

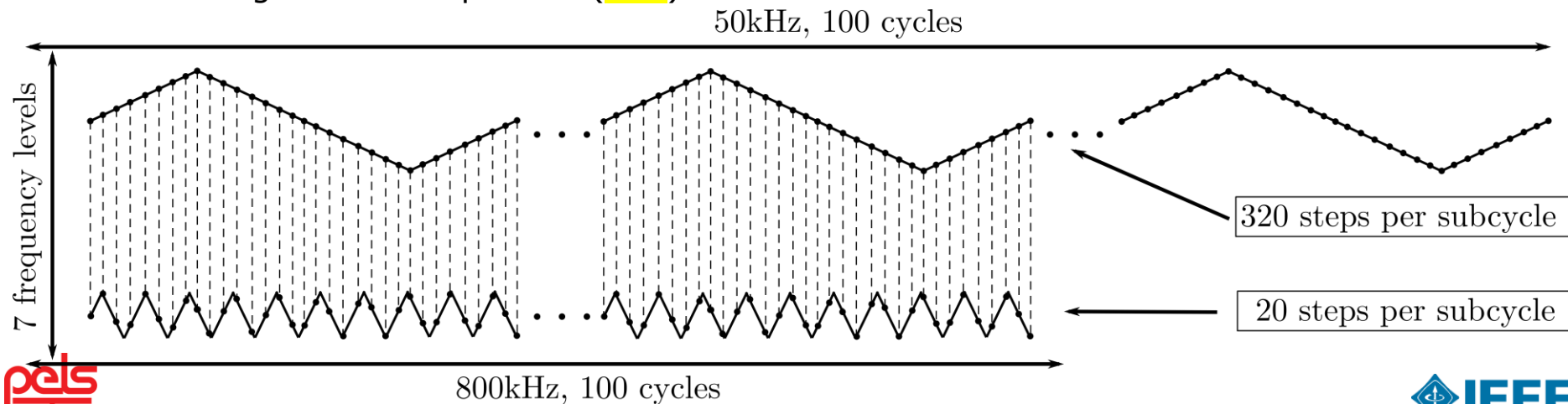
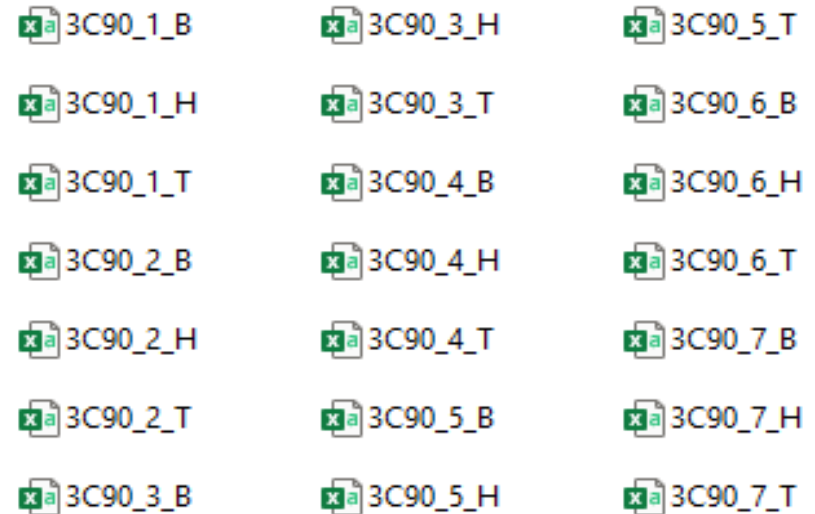
500 kHz: 32 steps per subcycle

- 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.

Material Folder: 3C90

- 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: 1967 steps

- Same length for all sequences (TBA)



MagNet 2025 – A Transient Challenge

Training data:

- 10 training materials
- Lots of long $B(t)$ - $H(t)$ pairs
- Temperature



Testing data:

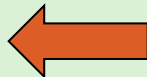
- 5 new materials
- Temperature
- Practicing: plenty of long $B(t)$ and $H(t)$ pairs
- Testing:

- $B(t)$ and $H(t)$ pairs from t_0 to t_1
- $B(t)$ from t_1 to t_2



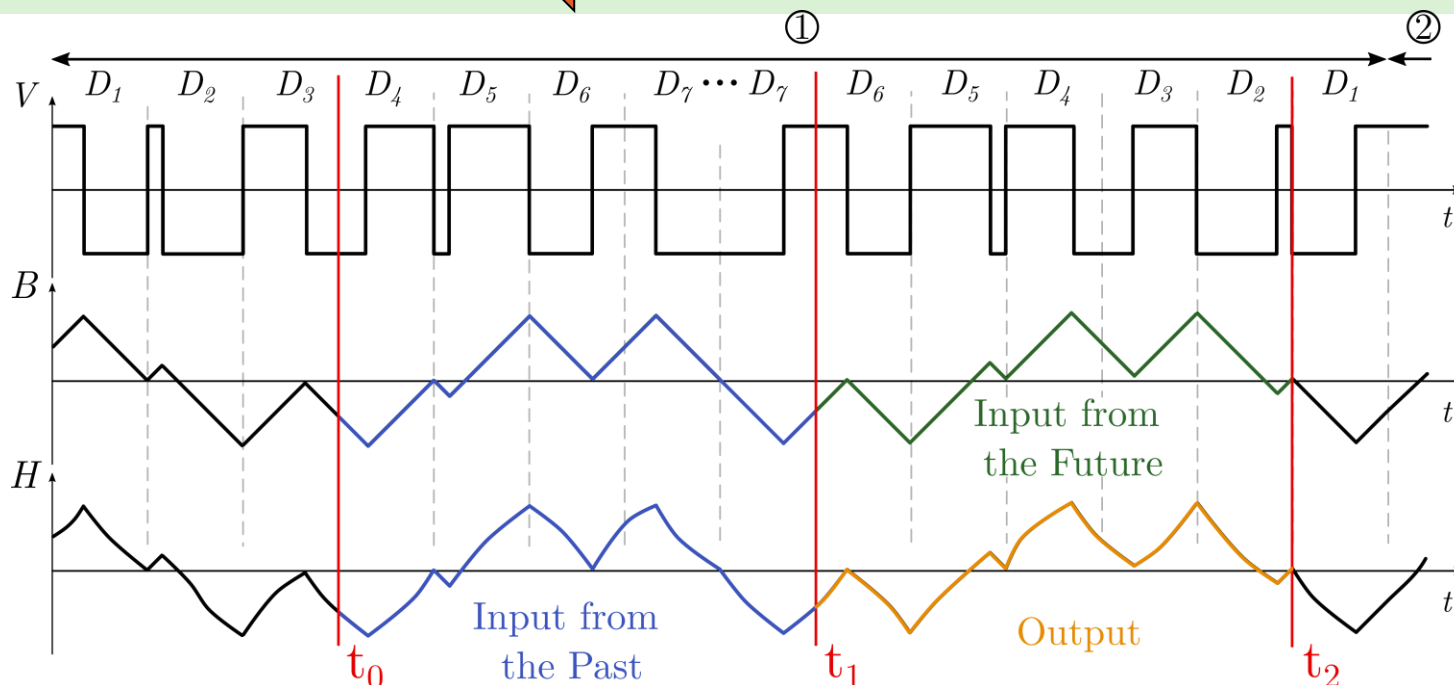
Evaluate:

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



Output:

- $H(t)$ from t_1 to t_2



- 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.

Strategies to win the Challenge?

- **Understand physics and understand data**
 - Model / method should be reasonably explainable
 - Balancing model generality and model accuracy
- **Understand materials and understand design**
 - What manufacturers provide? – modeling framework
 - What designers need? – software engineering
- **Respect legacy and challenge legacy**
 - Understand what has been done
 - Challenge existing understanding
 - Leverage modern methods and tools
- **Winning team structure:**

**Power Electronics
Magnetics**

**Data Science
Software Engineering**

MagNet 2025 – A Transient Challenge

MagNet 2025 Organizing Committee:

- **Shukai Wang**, Princeton, USA
- **Hyukjae Kwon**, Princeton, USA
- **Haoran Li**, Princeton, USA
- **Minjie Chen**, Princeton, USA
- **Charles Sullivan**, Dartmouth, USA
- **Thomas Guillod**, Dartmouth, USA

Judge Committee:

- **Charles Sullivan**, Dartmouth, USA
- **David Perreault**, MIT, USA
- **Jürgen Biela**, ETH Zurich, Switzerland
- **Dragan Maksimovic**, CU Boulder, USA
- **SY Ron Hui**, NTU, Singapore

Liaison Committee:

- **Han Cui**, Tianjin, China
- **Sinan Li**, Sydney, Australia
- **Oliver Wallscheid**, Paderborn, Germany

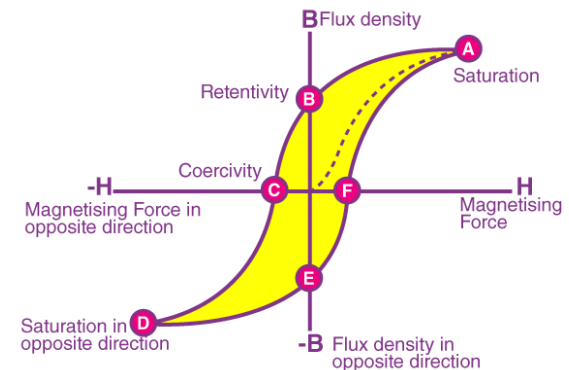
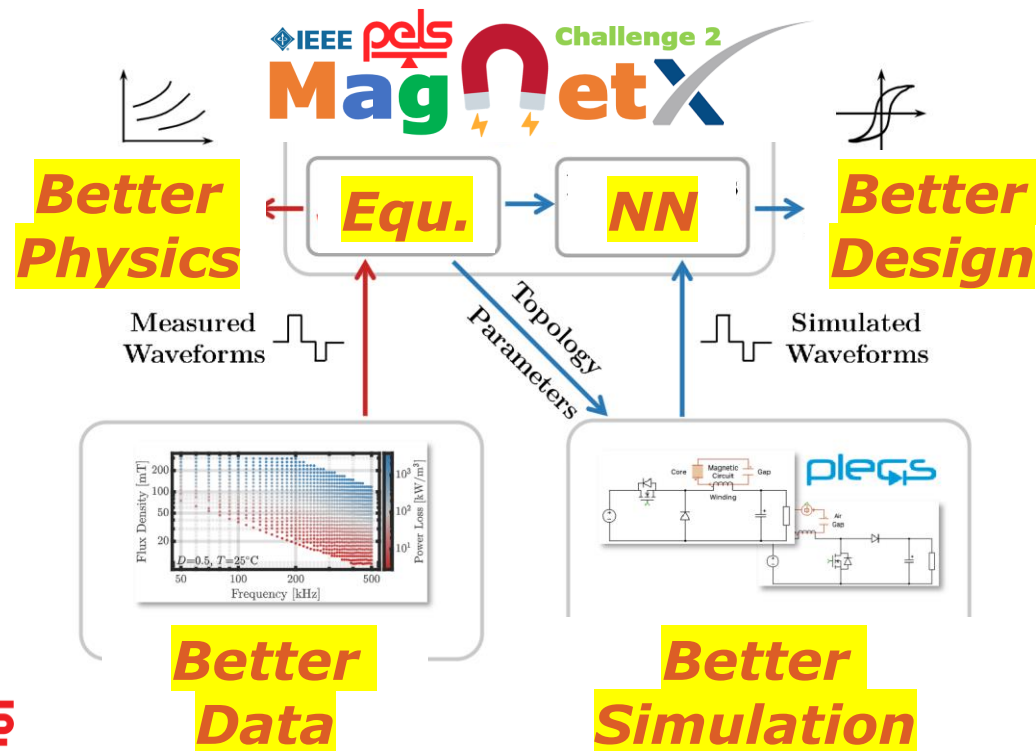
Advisory Committee:

- **Gerard Hurley**, National University of Ireland, Ireland
- **Maeve Duffy**, National University of Ireland, Ireland
- **Khai Ngo**, Virginia Tech, USA
- **Edward Herbert**, PSMA, USA
- **Wei Chen**, Fuzhou University, China
- **Brad Lehman**, Northeastern University, USA
- **Matt Wilkowski**, Würth Electronics, USA
- **George Slama**, Würth Electronics, USA
- **Mike Ranjram**, Arizona State University, USA
- **Alex Hanson**, UT Austin, USA
- **Frede Blaabjerg**, Aalborg Uni., Denmark
- **Ouyang Ziwei**, DTU, Denmark
- **Yenan Chen**, Zhejiang Uni., China



Outcomes of the MagNet Challenge 2

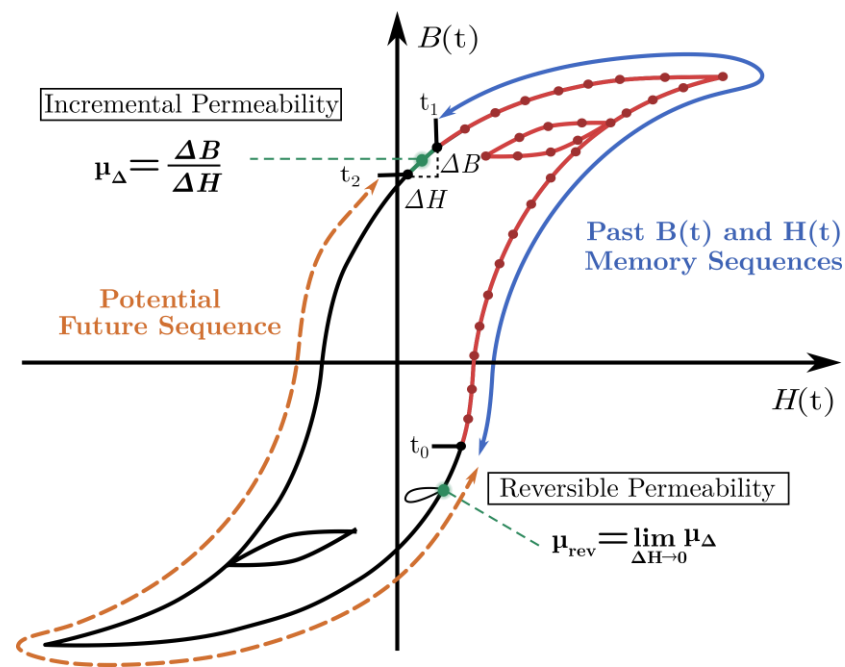
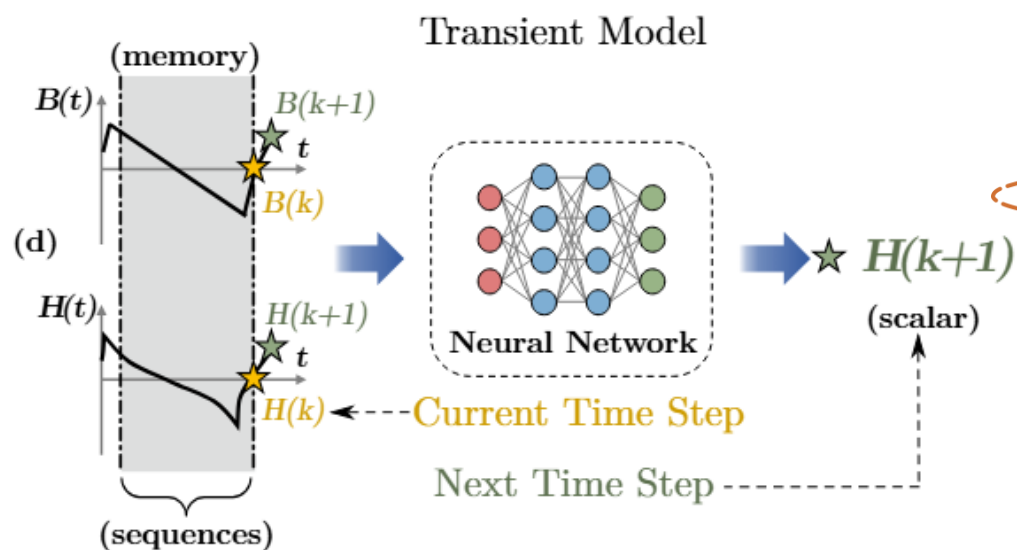
- Better understandings about power magnetics.
- Better tools for power magnetics design.
- Better ways of sharing information (digital/interactive datasheet).
- Cultivate an open-source community.
- Better impact on practical design.



- Hysteresis loop exists for almost all energy materials
- Magnetics, capacitors, piezoelectric, batteries, etc.

A Miniaturized Model for the Next Step

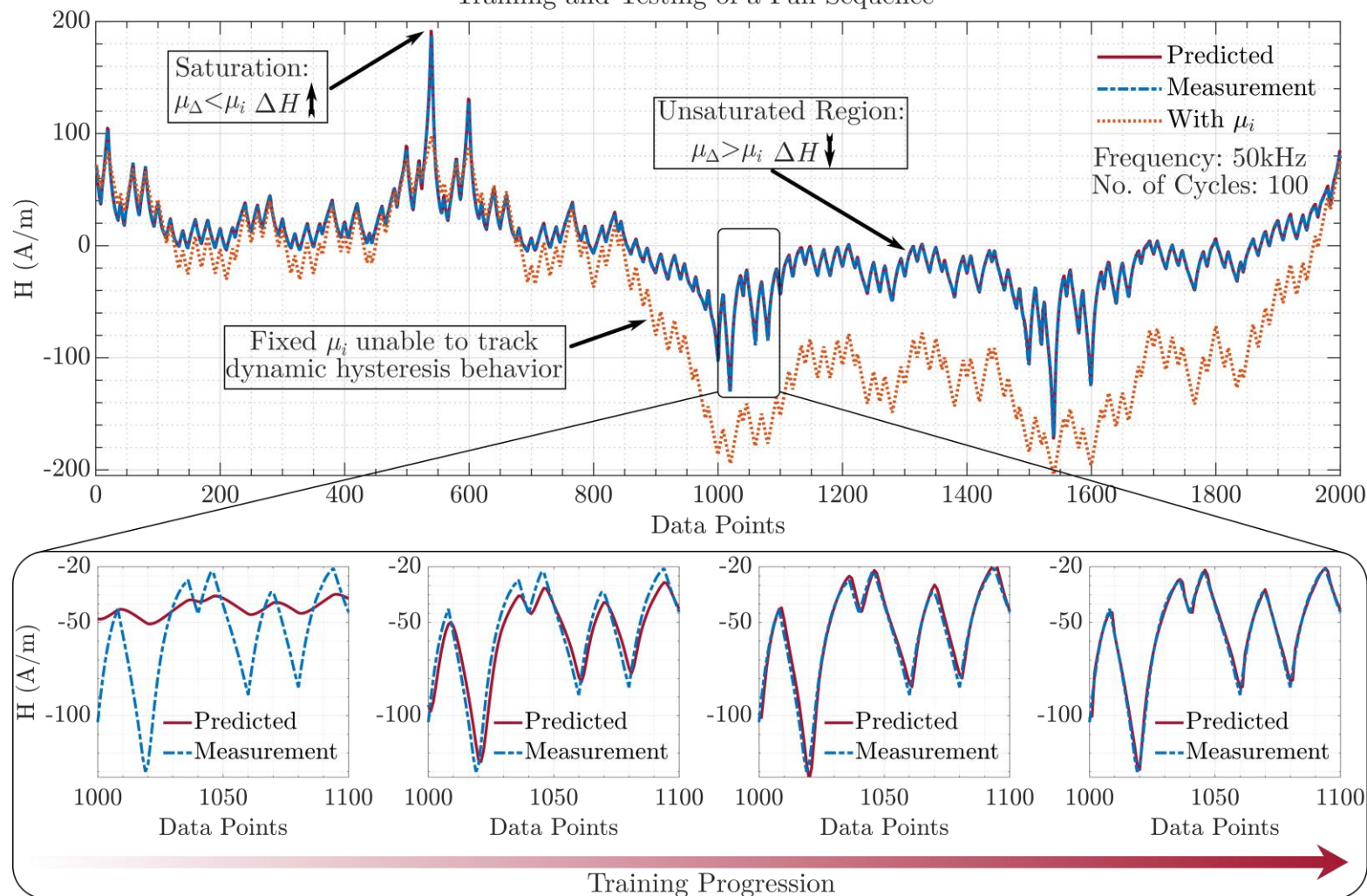
Input: $B(t)$ in the past 80 steps
 $H(t)$ in the past 80 steps
 future $B(t)$ from t_1 to t_2
 Output: future $H(t)$ from t_1 to t_2



- 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.

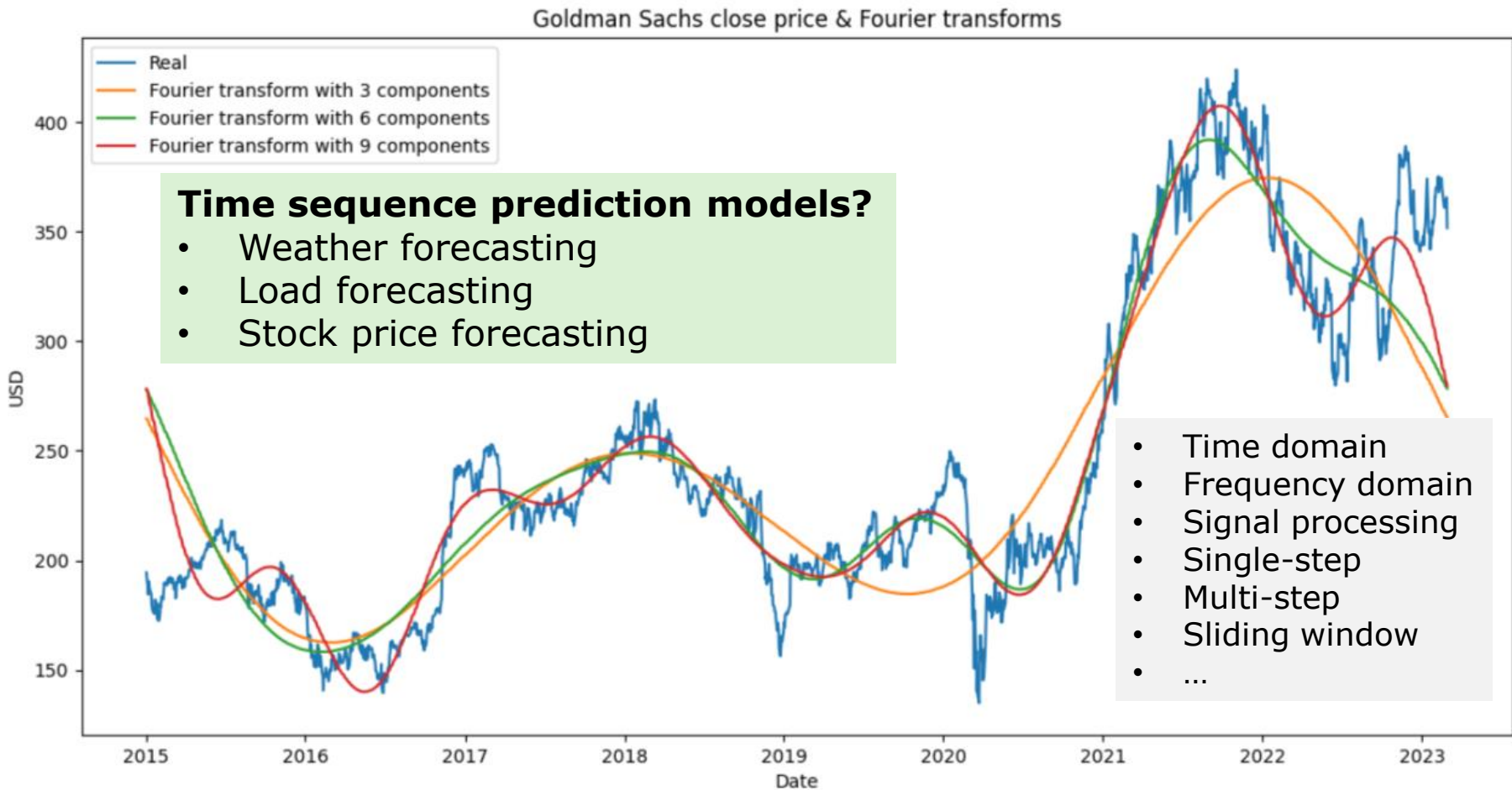
A Large Model for the Long Sequences

Training and Testing of a Full Sequence



Goal: Autoregressive Prediction

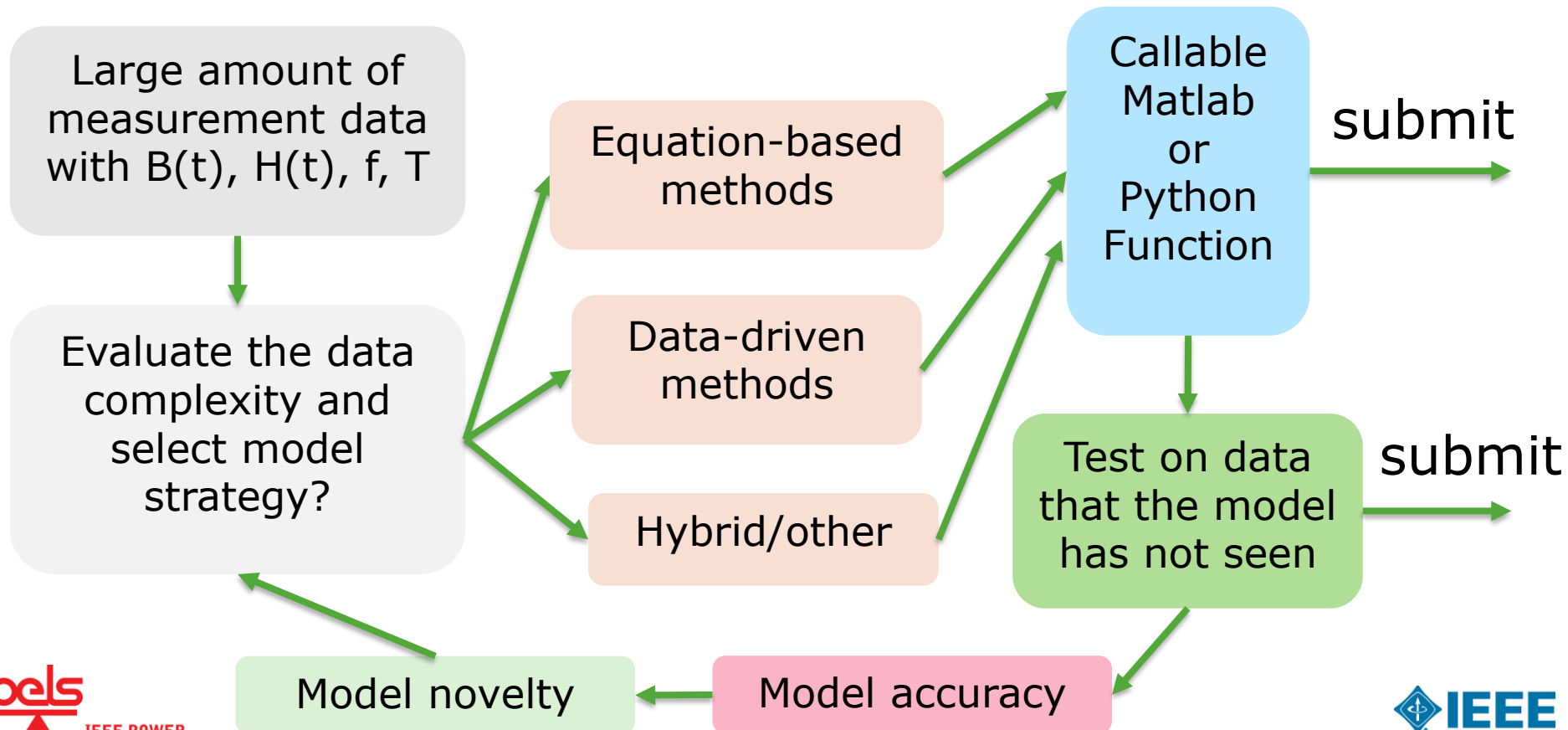
Separate Fast Details and Slow Trends



Information Flow of MagNet Challenge 2

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

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



Evaluation Criteria

- **Winning solution:** a **simple, robust, and trustworthy** method to
 - (1) **accurately** predict power magnetic behaviors
 - (2) **efficiently** use the training data
 - (3) provide **useful design insights**
 - (4) **advance** understanding about power magnetics
 - (5) other novel contributions to the field
- **Model performance:** 95th percentile error on RMS error in B-H sequence.
- **Model size:** number of material-specific parameters that need to be kept in the model. Jointly evaluated by submitted package size and code review.
- **Model novelty:** new insights and new methods in physical understanding, data processing, model development, and anything else related to power magnetics.
- **Model generality:** extending the developed model to different materials.

Final Winners selected by the Academic Advisory Committee:

- Charles Sullivan, Dartmouth, USA
- David Perreault, MIT, USA
- Jürgen Biela, ETH Zurich, Switzerland
- SY Ron Hui, NTU, Singapore
- Dragan Maksimovic, UC Boulder, USA

Timeline of the MagNet Challenge 2

Feb 10st, 2025	Initial Call for Participation Announcement
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

Nov 1st – Callable models for 10 materials due

MagNet Methodology

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

May 1st – 1-Page letter of intent due

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

June 1st – 2-Page proposal due

July 1st – All participating teams confirmed

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

Student Team Eligibility

- **Eligibility:** To confirm eligibility, potential participating schools must submit a Letter of INTENT (attached) by **May 1st, 2025**, to pelsmagnet@gmail.com, for better coordination.
- For each team, the minimum student number is **three (3)** and the maximum student number is **five (5)** to qualify for the competition. Each team should consist of between **one (1) to two (2)** undergraduate students (B.S. or equivalent), between **two (2) to three (3)** graduate students (M.S./Ph.D. or equivalent), and at least **one (1)** faculty advisor and optionally **one (1)** industry mentor. Interdisciplinary and diversified teams are highly encouraged.
- Note: We will try to host as many teams as possible. We can perhaps host **2-3 teams per university** depending on the final total participating team numbers and the quality of the proposals.
- Members of the judging committee will be replaced if there is a conflict from the same university. Student teams will NOT be judged by experts with conflicts of interest.
- We will invite **20-30 prominent researchers** from academia and industry as scientific advisors to student teams.

Award Structure (TBD)

Tesla Award for Model Performance 1 st Place \$10,000	Google Award for Model Novelty 1 st Place \$10,000	Princeton Award for Outstanding Software Engineering \$5,000
PELS Award for Model Performance 2 nd Place \$5,000	PELS Award for Model Novelty 2 nd Place \$5,000	PELS Honorable Mentions \$1,000 x multiple

- Performance
- Model size
- Novelty
- Model generality
- Software implementation
- Other contributions

Intellectual Property

- MagNet Challenge 2 has no restrictions on intellectual property.
- We encourage open-source culture and open-source licenses.
- Presenting the models to MagNet team is considered as public disclosure.
- Student teams should take actions before disclosure if IP protection is needed.

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, "Über die magnetische Nachwirkung," Zeitschrift für 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, "Unveiling the microworld inside magnetic materials via circuit models," IEEE Power 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.

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.