LIÈGE université
Sciences Appliquées

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Fast and accurate Neural-Network-based Ferromagnetic Laminated Stack Model for Electrical Machine Simulations in Periodic Regime

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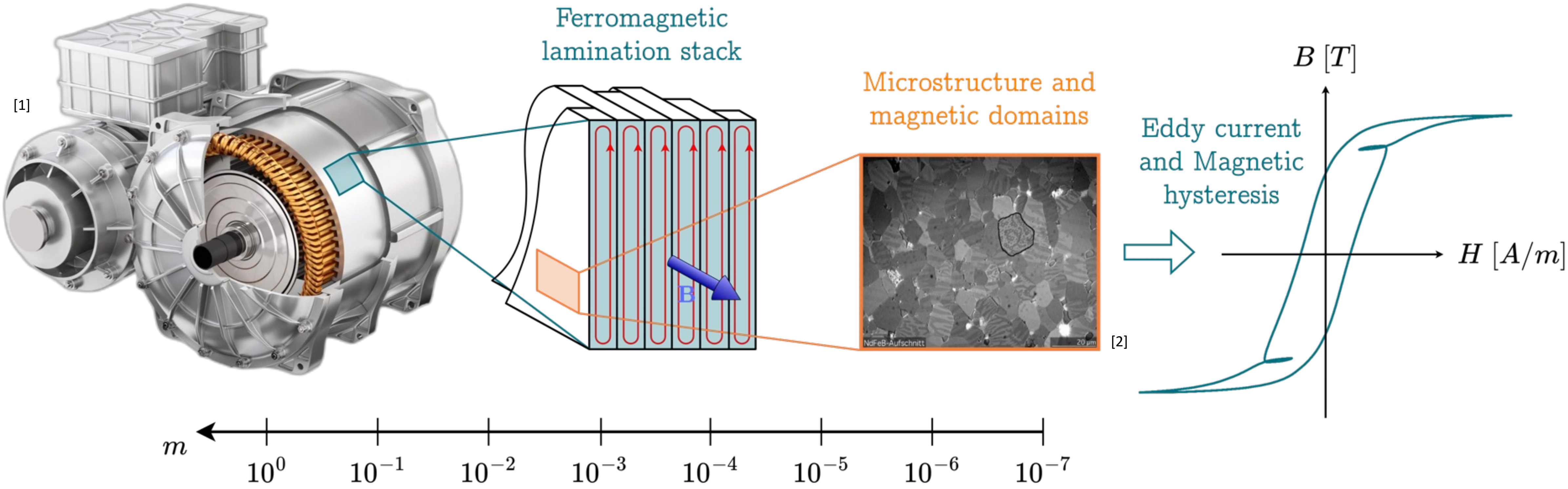
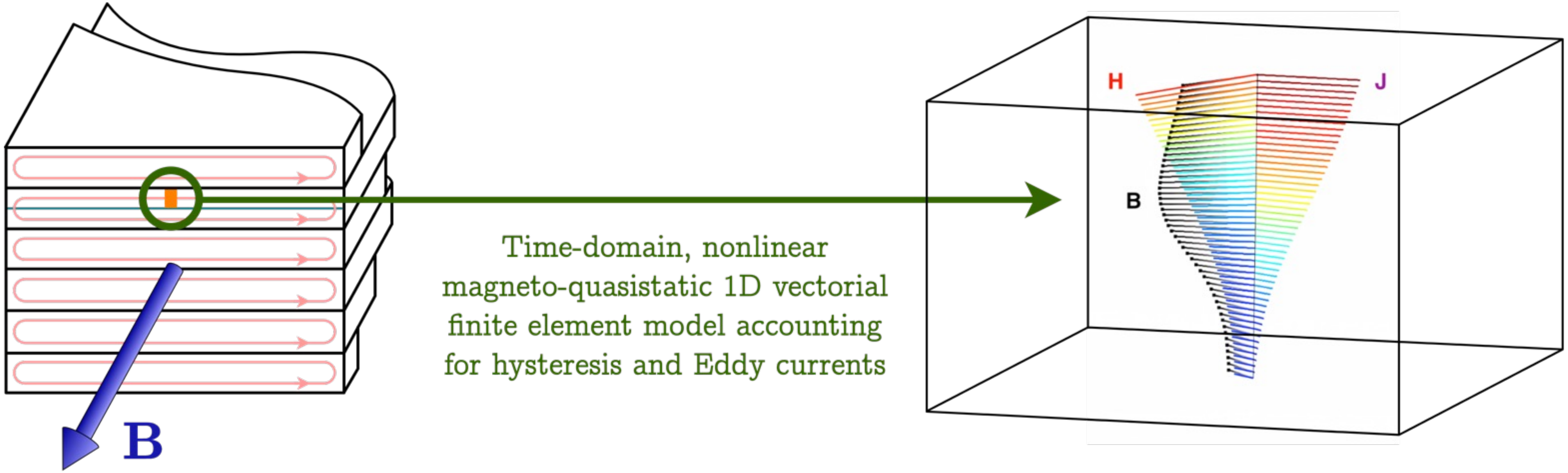
Ferromagnetic stacks are multi-scale



- Ferromagnetic materials exhibit eddy currents and hysteresis
- Both phenomena induce losses

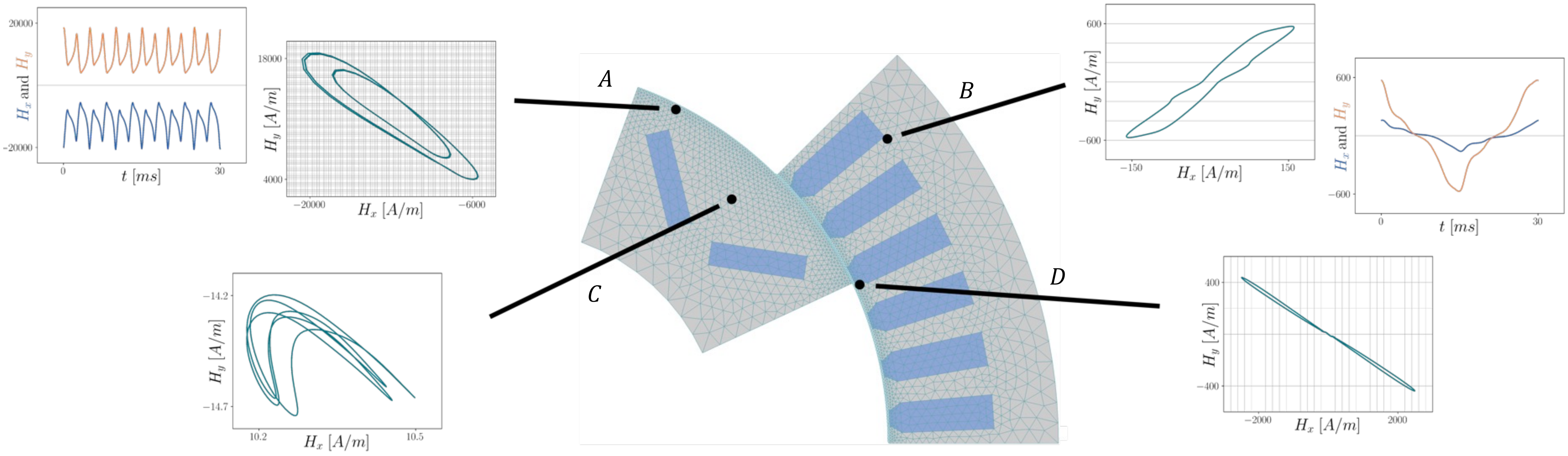
[1] Testamatic Labs © 2023 (Unico Graphix), [2] Photomicrograph of NdFeB (Wikipedia – Magnetic domain)

What happens inside a ferro lamination



- The response of a lamination accounting for hysteresis and Eddy currents is very complex (Magnetodynamics, skin effect, vector hysteresis coupled together)
- 3D simulation is way to expensive ➔ **Homogenization** is required
- Invoking the homogenized lamination model in each element of a 2D model is also too slow
- Hence, 2D conventional approaches often disregard hysteresis and Eddy currents

$\boldsymbol{H}(t)$ excitation varies from place to place



- Local magnetic fields $\boldsymbol{H}(t)$ are very different from place to place
- To account for hysteresis and Eddy currents, one has to compute the lamination response to every local $\boldsymbol{H}(t)$
- We introduce a new parametric homogenized irreversible $\widetilde{\boldsymbol{H}}(\boldsymbol{B})$ material law extended to account for the ferromagnetic behaviour

Parametric homogenized material law (p_k law)

$$\widetilde{\boldsymbol{H}}(\boldsymbol{B}, \dot{\boldsymbol{B}}, p_k) = \boldsymbol{B}\left(p_0 + \left(p_1\, |\boldsymbol{B}|^2\right)^{p_2}\right) + p_3\, \dot{\boldsymbol{B}} + \frac{p_4}{\sqrt{p_5^2 + \left|\dot{\boldsymbol{B}}\right|^2}}\, \dot{\boldsymbol{B}}$$

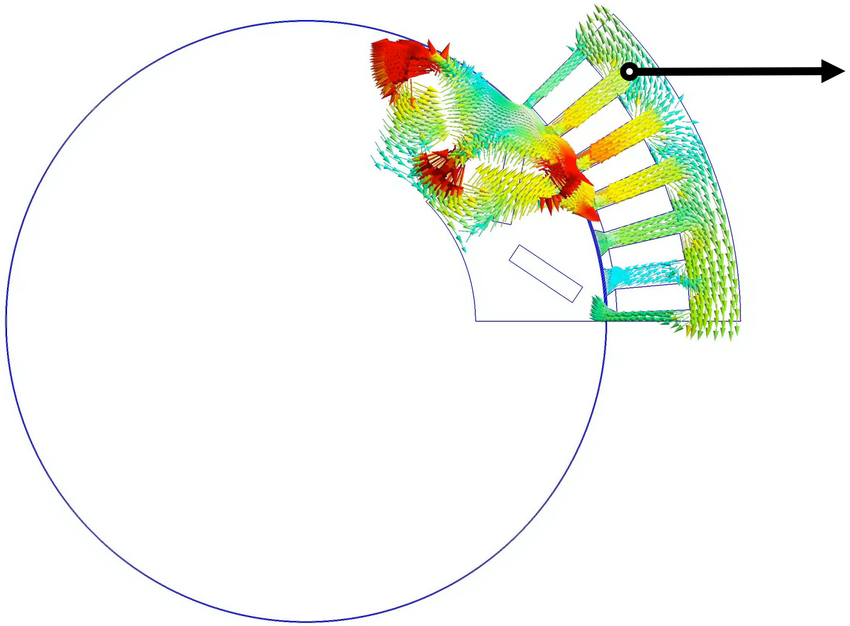
Reversible (anhysteretic) saturation curve

Irreversible dynamic eddy current (viscosity-like) term

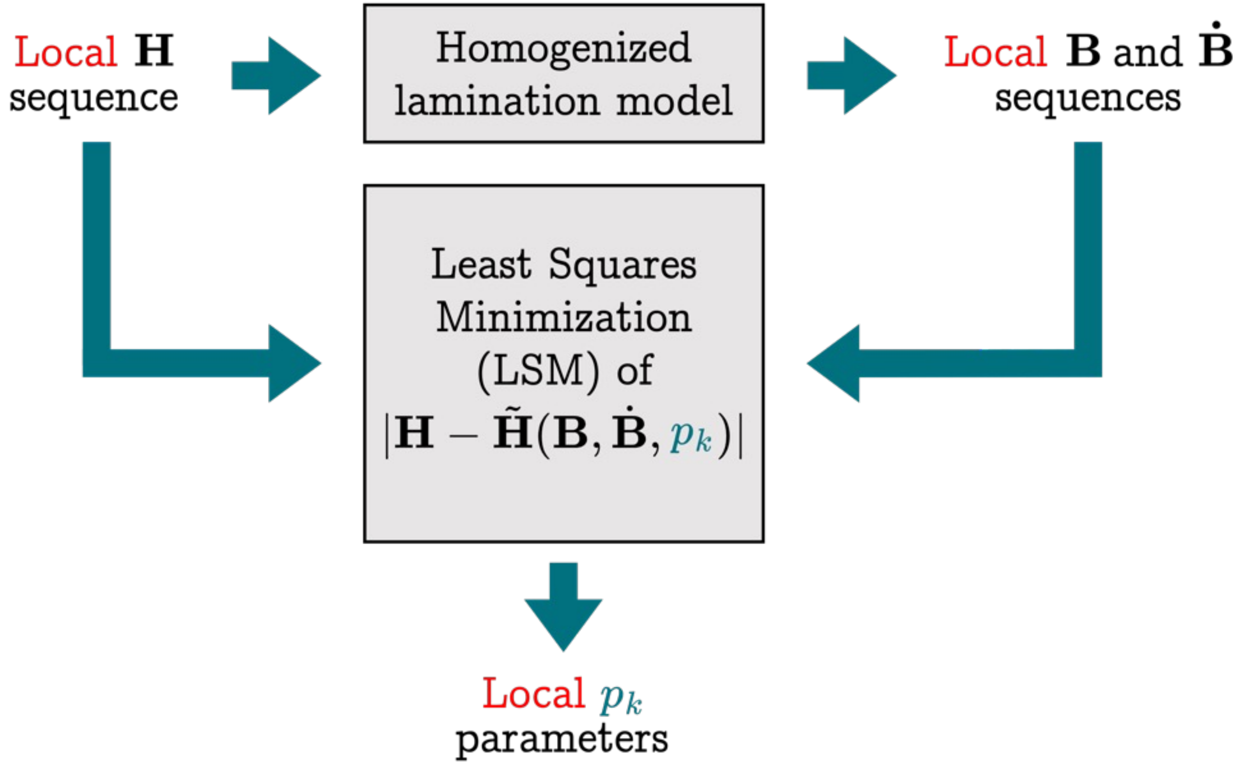
Irreversible hysteresis (dry friction-like) term

- Local p_k parameters to adapt to the local fields
- How to identify the right p_k's? Identification per region or per element?

p_k identification with Least Squares Min.



2D anhystertic
FEM simulation

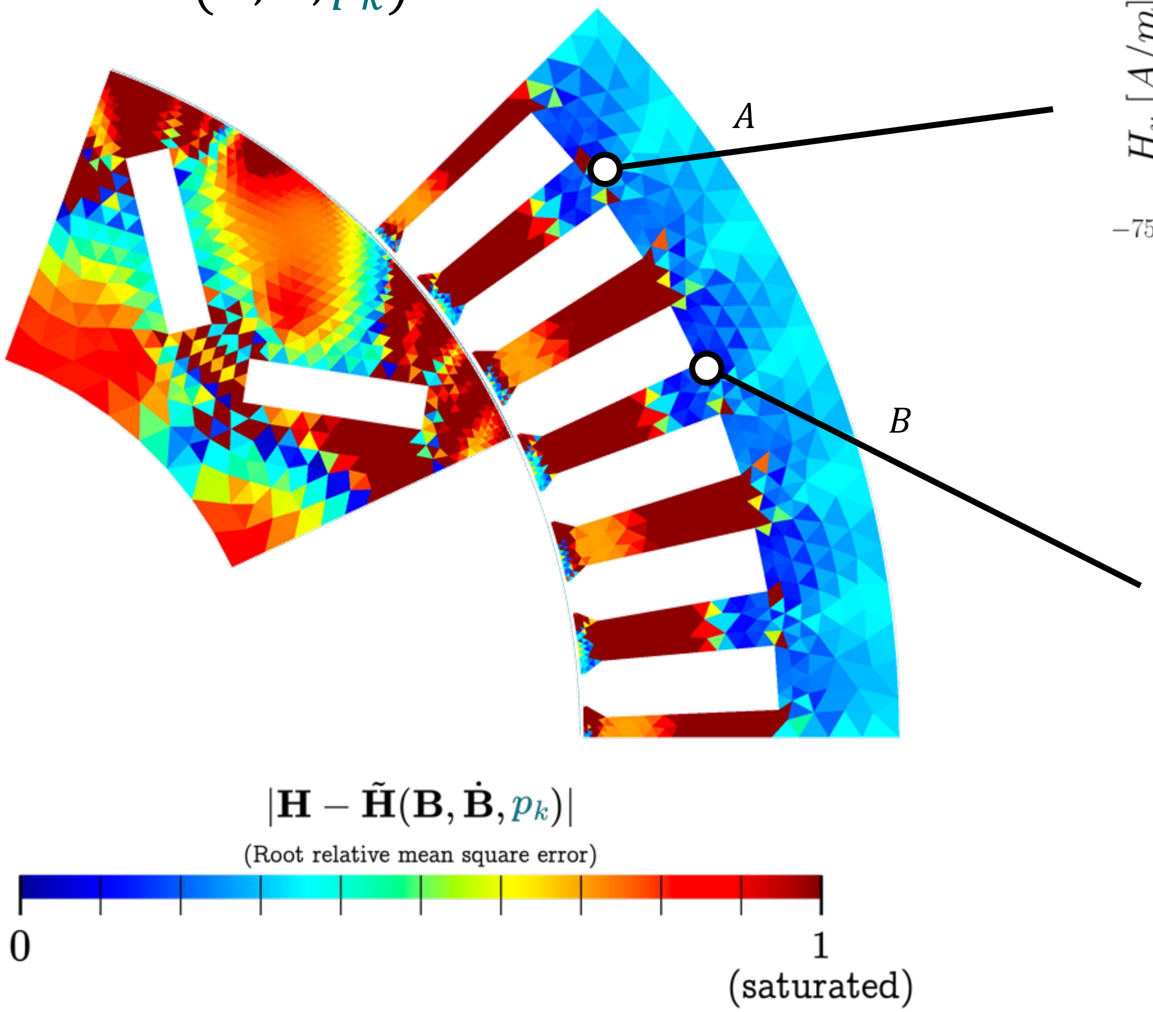


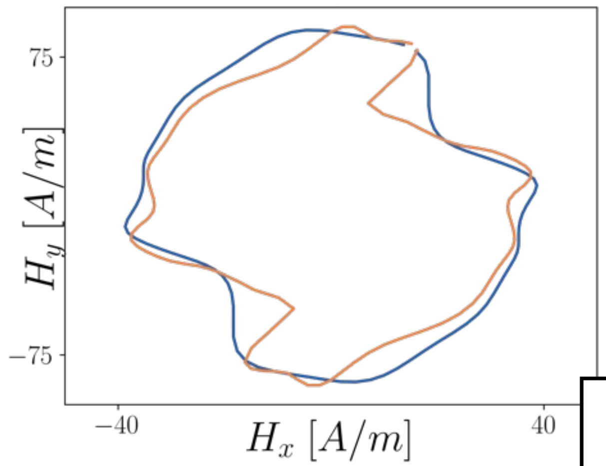
- One has to first perform a 2D anhystertic macro simulation to generate local $\boldsymbol{H}(t)$ sequences
- Homogenized lamination model: Any efficient code that solves Magnetodynamics, skin effect and vector hysteresis coupled together to obtain the corresponding $\boldsymbol{B}(t)$
- Least Squares Minimization (LSM) of the error $\left|\boldsymbol{H} - \widetilde{\boldsymbol{H}}\left(\boldsymbol{B}, \dot{\boldsymbol{B}}, p_k\right)\right| \longmapsto p_k$ (e.g. python scipy.optimize.leastsq)

p_k identification, per element or region?

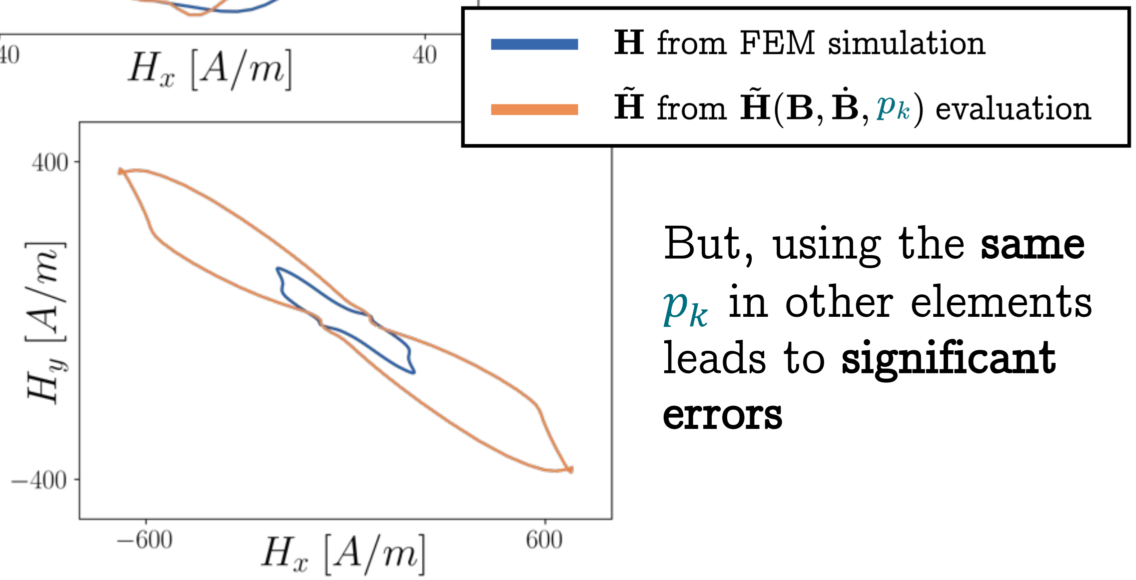
LSM of $\left|\boldsymbol{H} - \widetilde{\boldsymbol{H}}(\boldsymbol{B}, \dot{\boldsymbol{B}}, p_k)\right| \longmapsto p_k$

$\widetilde{\boldsymbol{H}}(\boldsymbol{B}, \dot{\boldsymbol{B}}, p_k) \longmapsto \widetilde{\boldsymbol{H}}$





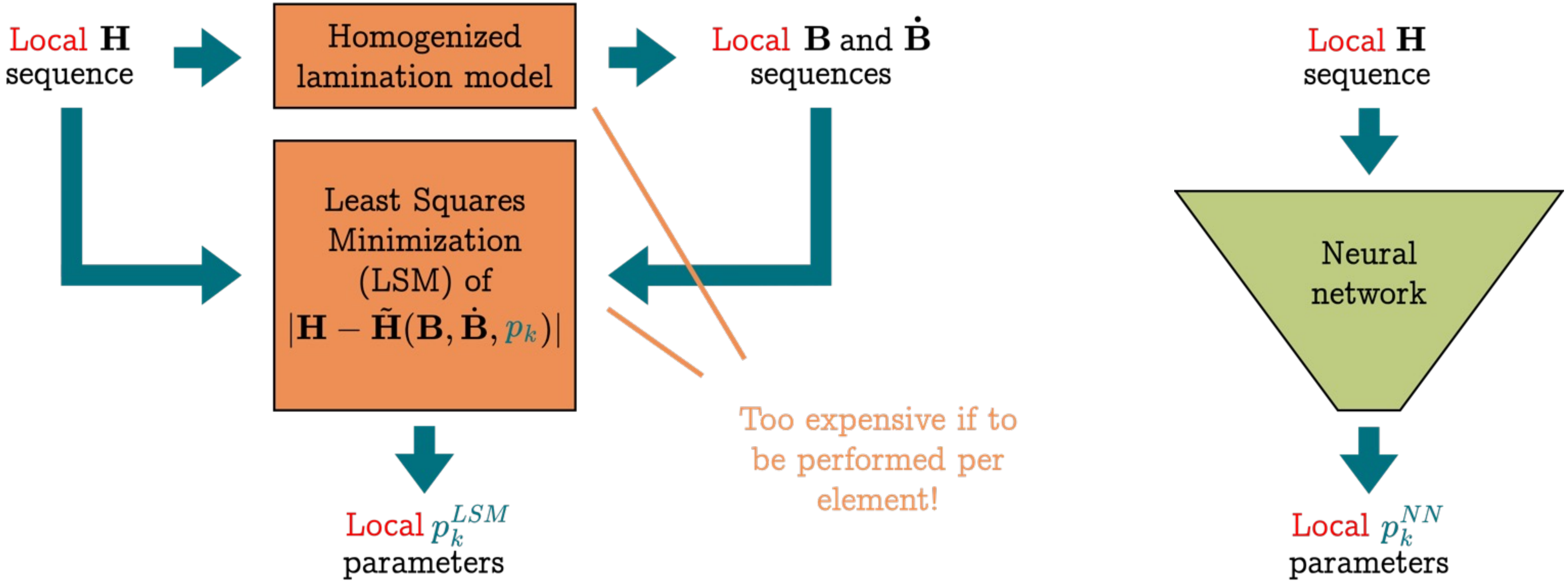
After LSM identification of the p_k for one local element, the $\widetilde{\boldsymbol{H}}(\boldsymbol{B}, \dot{\boldsymbol{B}}, p_k)$ law captures the essential features of the corresponding local fields



But, using the **same** p_k in other elements leads to **significant errors**

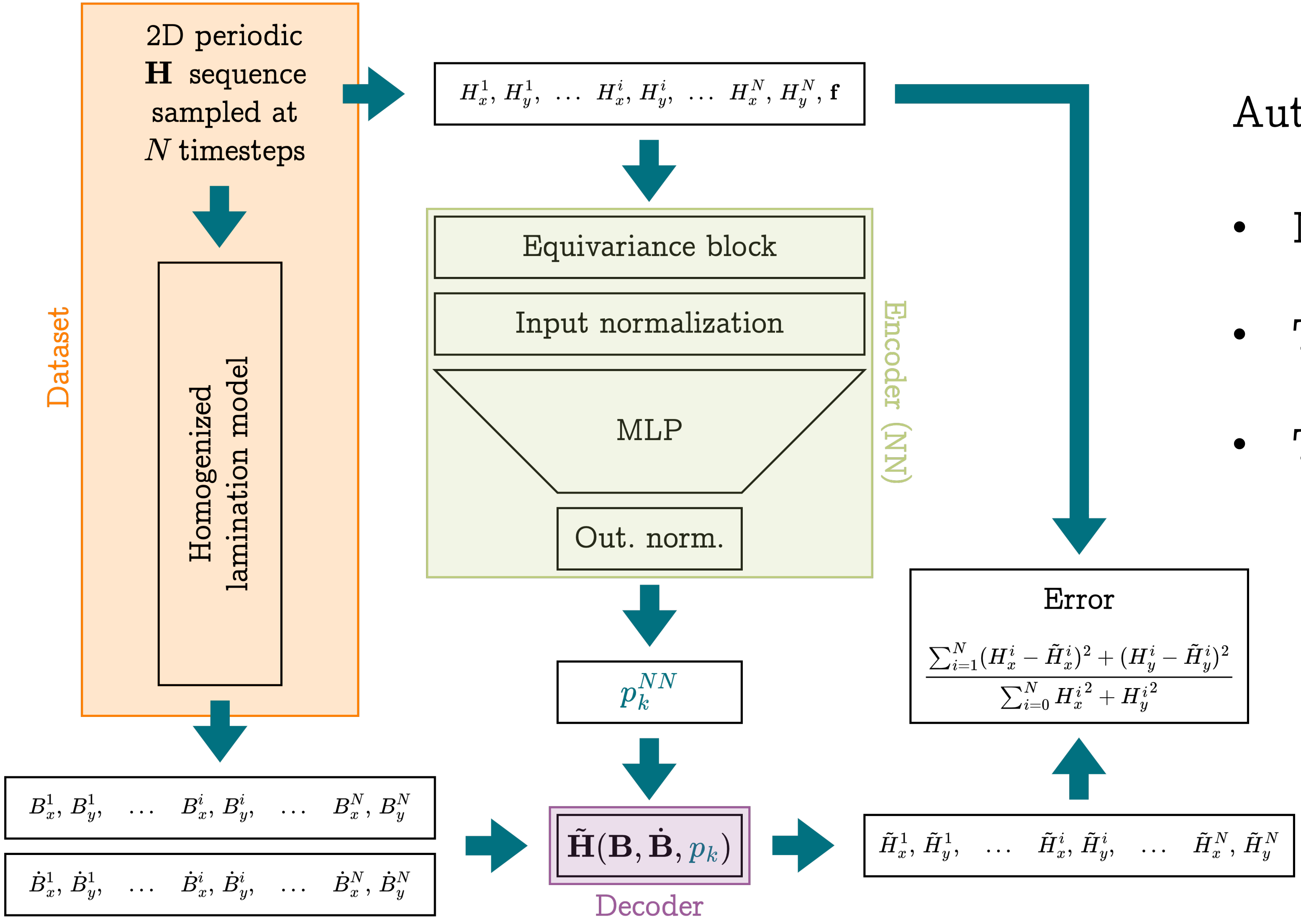
- Better to identify p_k's per element
- We need an efficient mapping $\boldsymbol{H}(t) \longmapsto \mathrm{p_k}$

LSM p_k identification vs. NN p_k identification



- Neural networks (NN) can efficiently perform regressions
- The dataset generation and the NN training is costly but done only once
- The NN evaluation is much faster
- Considering periodic sequences, the mapping $\boldsymbol{H}(t) \longmapsto \mathrm{p_k}$ can be efficiently handled by a neural network

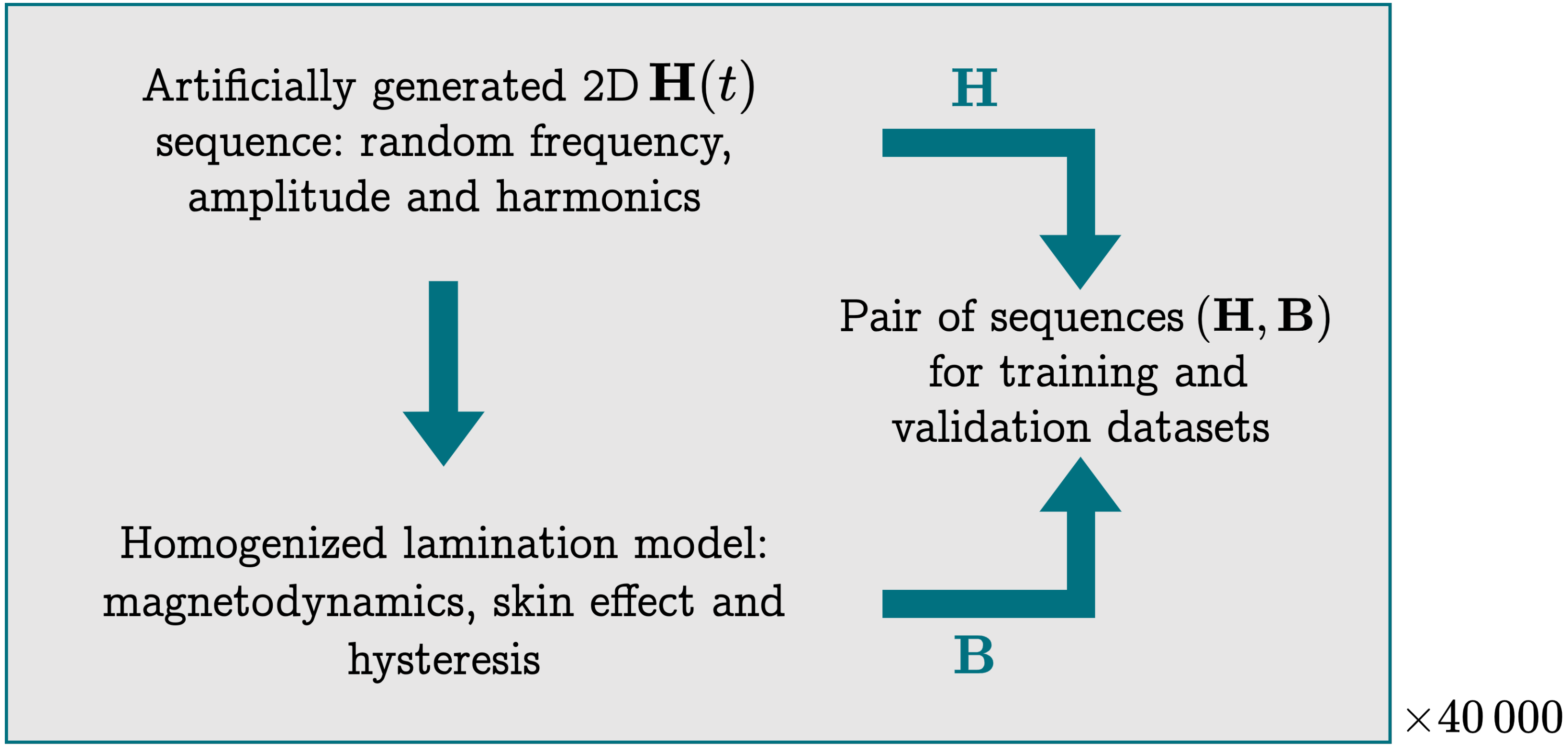
Dedicated NN architecture



Auto-encoder-like learning:

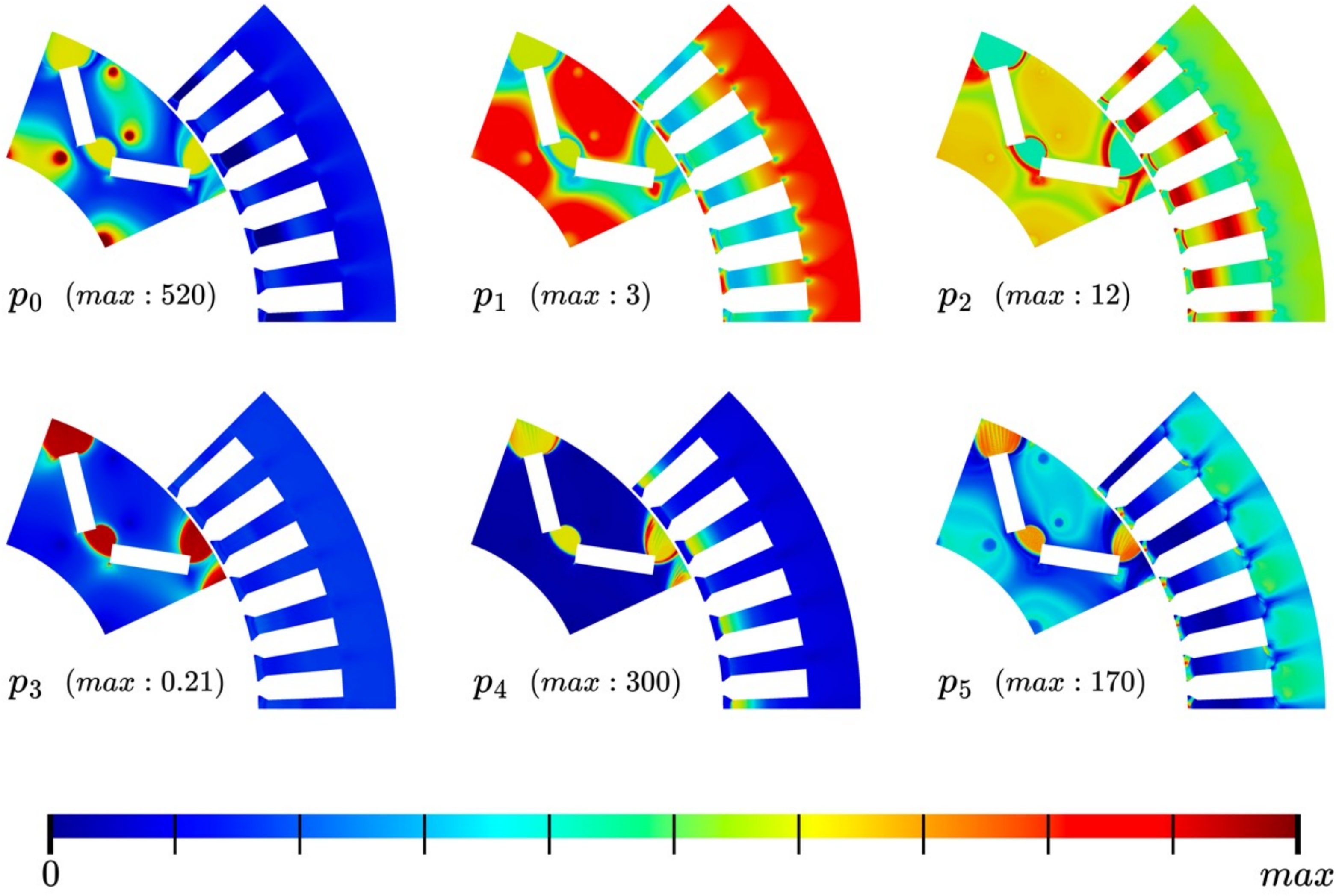
- Minimization of $|\boldsymbol{H} - \widetilde{\boldsymbol{H}}(\boldsymbol{B}, \dot{\boldsymbol{B}}, p_k)|$:
- The p_k law is the decoder
- The p_k^{NN}'s are extracted features

Artificial training dataset



- Training datasets should be populated by a sufficient number of pairs of sequences $(\mathbf{H}, \mathbf{B})$ similar to those encountered in electrical machine simulations
- I.e., 40 000 artificial sequences are generated for the training and validation datasets

NN-predicted $\mathbf{H}_{\mathrm{FEM}} \longmapsto p_k^{NN}$



- Run anhysteretic FEM to generate local $\boldsymbol{H}_{FEM}$ sequences and evaluate the NN:

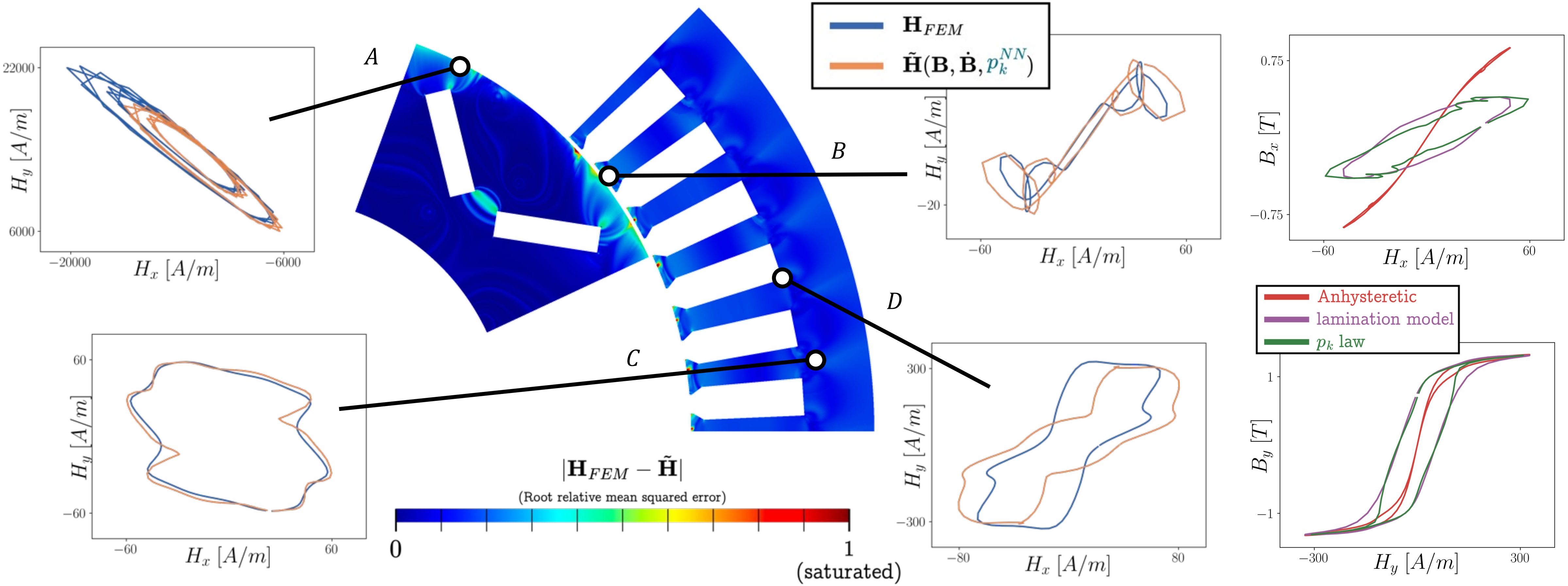
$$\boldsymbol{H}_{FEM} \longmapsto p_k^{NN}$$

- The identified p_k^{NN}'s are coherent with the physics of the machine

- Despite p_k^{NN} are evaluated elementwise, the spatial distributions are smooth
  ➔ The $\boldsymbol{H} \longmapsto \mathrm{p}_k^{NN}$ mapping is well-conditioned

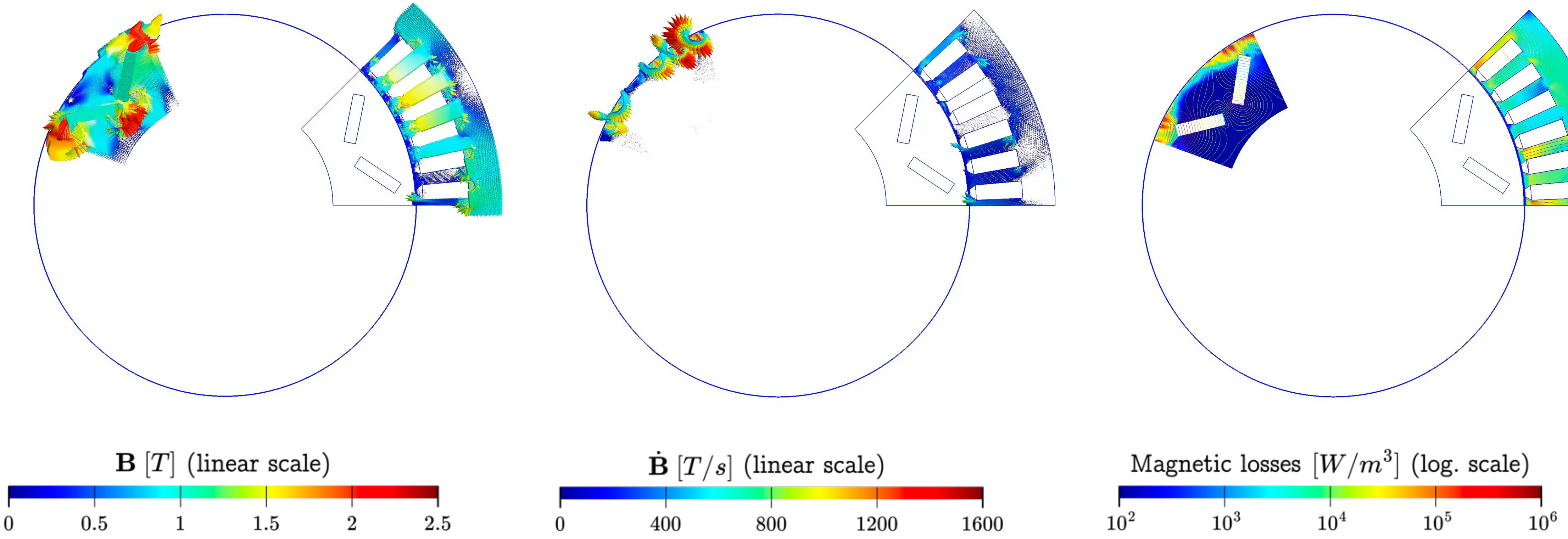
Mean rel. error $\left|\boldsymbol{H}_{FEM} - \widetilde{\boldsymbol{H}}_{FEM}\right|$ is ~15%

Solve lamination model: $\boldsymbol{H}_{FEM} \mapsto \boldsymbol{B}$, evaluate p_k law: $\widetilde{\boldsymbol{H}}(\boldsymbol{B}, \dot{\boldsymbol{B}}, p_k^{NN}) \mapsto \widetilde{\boldsymbol{H}}$, evaluate error: $\left|\boldsymbol{H}_{FEM} - \widetilde{\boldsymbol{H}}\right|$



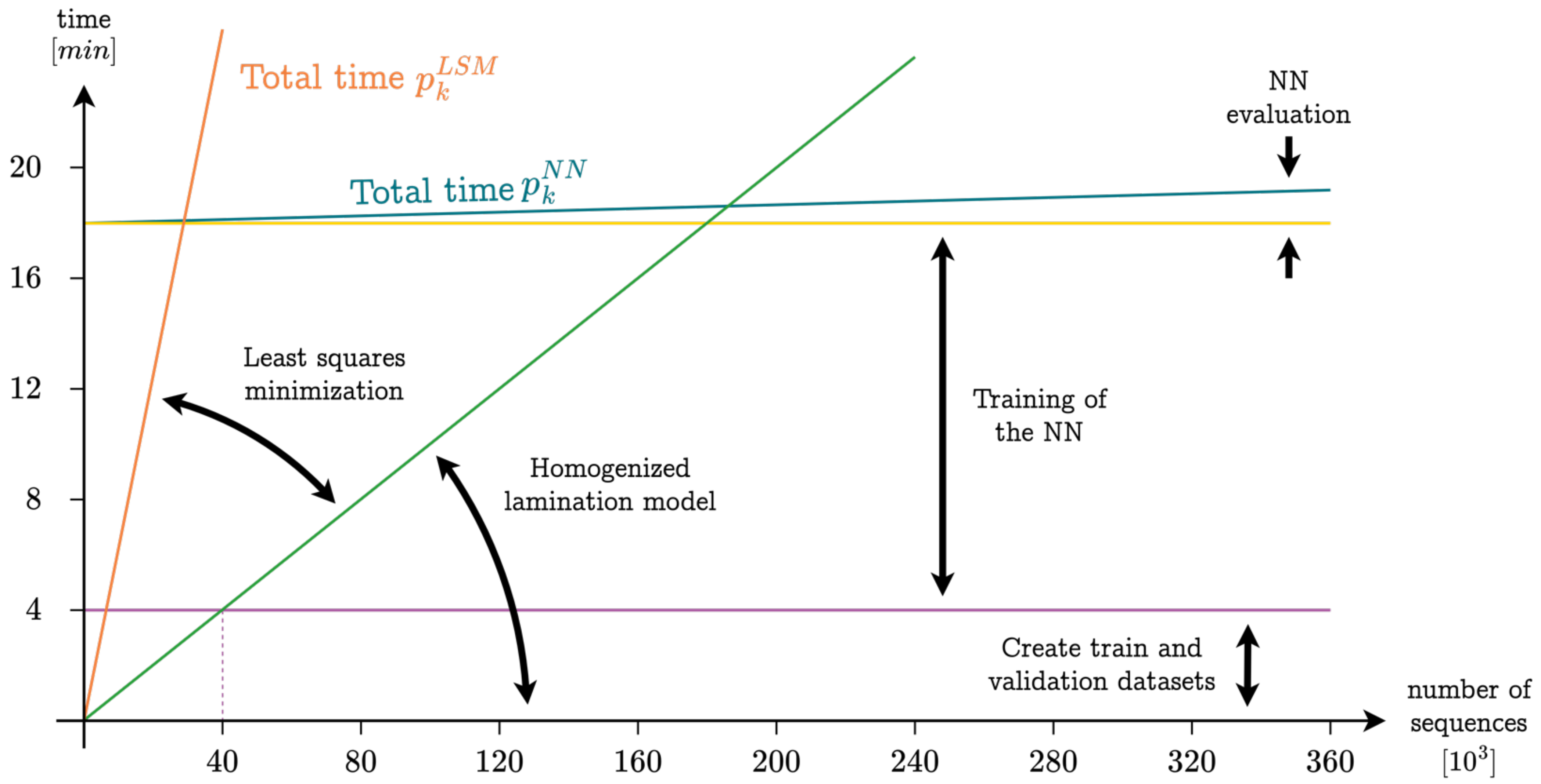
The p_k law captures the essential features of the local fields (compared to the lamination model), with an average error of 15% for the sequences $\boldsymbol{H}_{FEM}(t)$ issued from the FEM simulation

Fields $\boldsymbol{B}$ & $\dot{\boldsymbol{B}}$ & iron loss distribution



- The p_k law is differentiable ➔ exact Jacobian can be computed ➔ non-linear convergence is ensured
- The identified p_k law is used as material law in the FEM model
- Instantaneous iron losses in laminated cores are simulated and can be visualized

Computational time breakdown



Conclusions

- We introduced a new method to include Eddy currents and hysteresis in 2D FEM simulations of electrical machines at a cost similar to a conventional 2D anhysteretic simulation
- The homogenized lamination model, the p_k law and the NN all introduce approximations, but the trade-offs are worth it:
  - The p_k law has an exact Jacobian, it is easily included in a classical Newton-Raphson scheme
  - **The cost is very low** compared to the direct inclusion of a homogenized lamination model in macro simulations
- The method is currently designed for periodic regime, the extension to fully transient is coming

(Don't hesitate to get in touch if you have questions: florent.purnode@uliege.be)