Integration of magnetic measurement data in magnetic field simulations by BEM-based discrepancy modeling

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Agenda

Learning from data through the lens of models is a way to exploit structure in an otherwise intractable problem [1]

- The lifecycle of the accelerator magnet
- Hybrid modeling (Newton to Kepler)
  - Calibrated models
  - Delta models
- Integration in the life cycle management
- Conclusion

[1] K. Wilcox, Predictive data science for physical systems – from model reduction to scientific machine learning. ICIAM – international congress on industrial and applied mathematics. 2019

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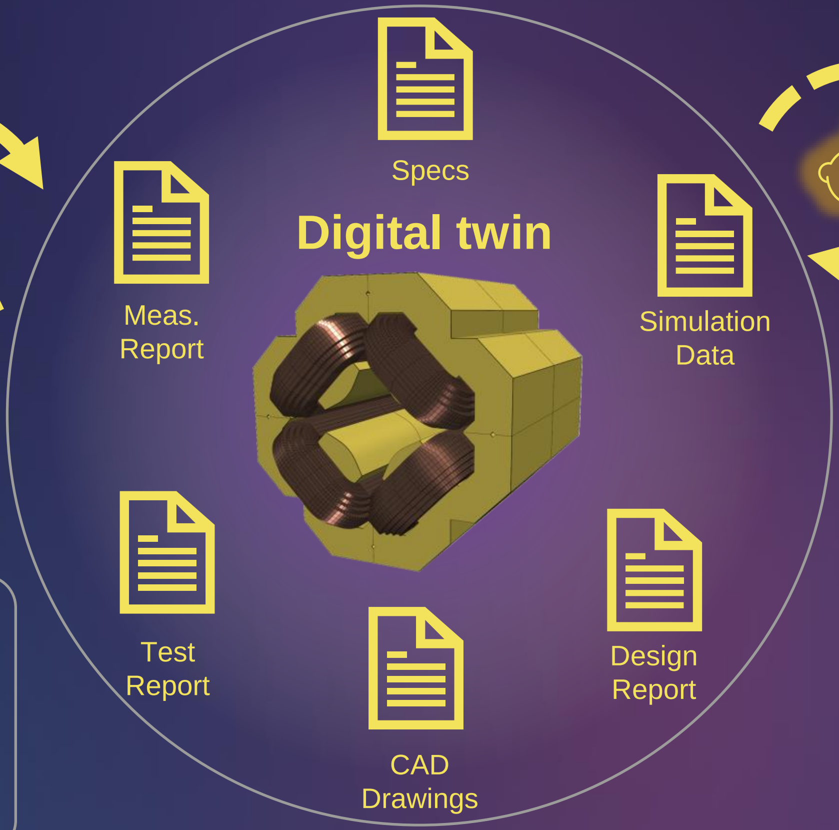
Accelerator magnet life cycle

Magnet operation

- State observation
- Prediction
- Maintenance

Virtual prototyping

- Coupled multi-physics optimization
- Integration in virtual environment
- Multiscale modeling



Prototype manufacturing/testing

- Calibrating material properties
- Optimal experimental design

Series manufacturing

- Quality assurance
- Fault detection and correction procedures
- Magnet alignment data
- Magnet transfer function

Communication frequency

slow fast

Product life cycle

Development life cycle

Principles of systems modeling

→ Document based information exchange

→ Communication frequency depends on the application

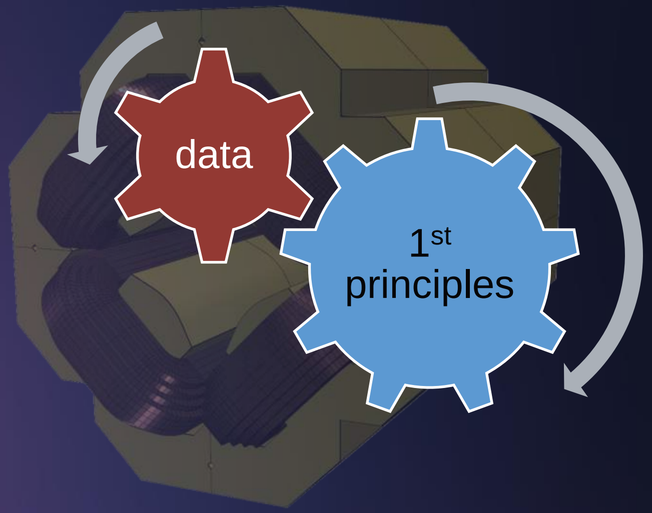
→ Data management services: EDMS, EAM, INFORMA, PLM

Document based → Model based

Challenges

- *Complex (non-linear) dynamic system*
  - Interplay of iron saturation, hysteresis and eddy currents
  - Superconductor magnetization
  - Temperature effects
- *Computational costs*
  - A complete 3D magnet simulation does not allow for fast predictions
- *Tough requirements for machine operation*
  - Field stability at 1 unit in 100 000
  - Field quality at 1 unit in 10 000

Digital representation
a.k.a. numerical system model



→ ***Measurement data*** *needs to be* ***integrated*** *in the numerical model to enable* ***accurate predictions***

→ ***Hybrid models integrate first principle and data driven models in a joint architecture***

The field simulation software ROXIE

Routine for the **O**ptimization of Magnet **X**-sections, **I**nverse Field Computation and Coil **E**nd Design

- *Developed for the design of the superconducting magnets for the LHC*
- *The standard tool for the design of cos(θ) magnets*
- *Features the calculation of 3D fields and iron magnetization*
- *Based on the coupling of boundary and finite elements (BEM-FEM), see [4]*

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   RRRRRRRRRRR    OOOOOOOOO XX      XXXX   IIII   EEEEEEEE
    RRR   RRR    OOO   OOO  XXX   XXXX    IIII   EEEE
   RRR   RRR    OOO   OOO    XXX XXX     IIII   EEEE
  RRRRRRRRR    OOO   OOO      XXXXX     IIII   EEEEEEE
 RRR RRR      OOO   OOO     XXXXXX     IIII   EEEE
RRR   RRR    OOO   OOO    XXXX  XXX   IIII   EEEE
RRR     RRR  OOOOOOOOO   XXXX     XXX IIII   EEEEEEEEE 23.6

      Routine for the Optimization of magnet X - sections,
        Inverse field calculation and coil End design
                 VERS.22, UPDATE 0.1, 2022

                (C) BY STEPHAN RUSSENSCHUCK,
         B. AUCHMANN, M. ALEKSA, M. BONORA, P. HAGEN,
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              CERN, 1211 GENEVA 23, SWITZERLAND
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ROXIE default output

[4] S. Russenschuck, “ROXIE: Routine for the optimization of magnet X-sections, inverse field computation and coil end design.,” in 1st International ROXIE Users Meeting and Workshop, Geneva, Switzerland, CERN Yellow Reports: Conference Proceedings, 3 1998.

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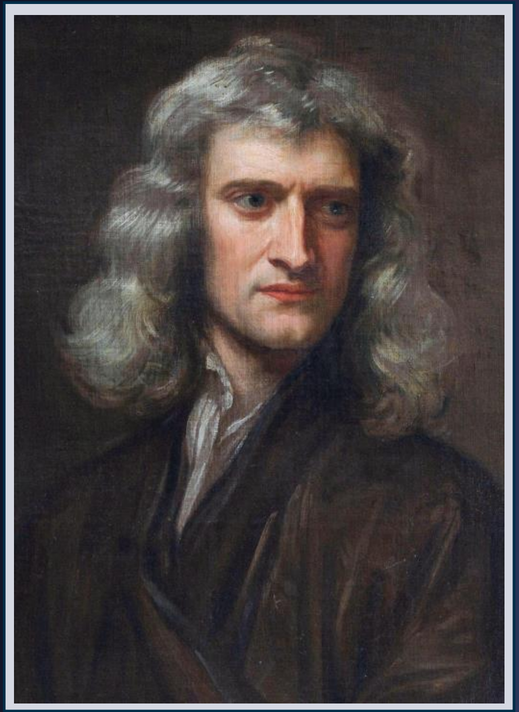
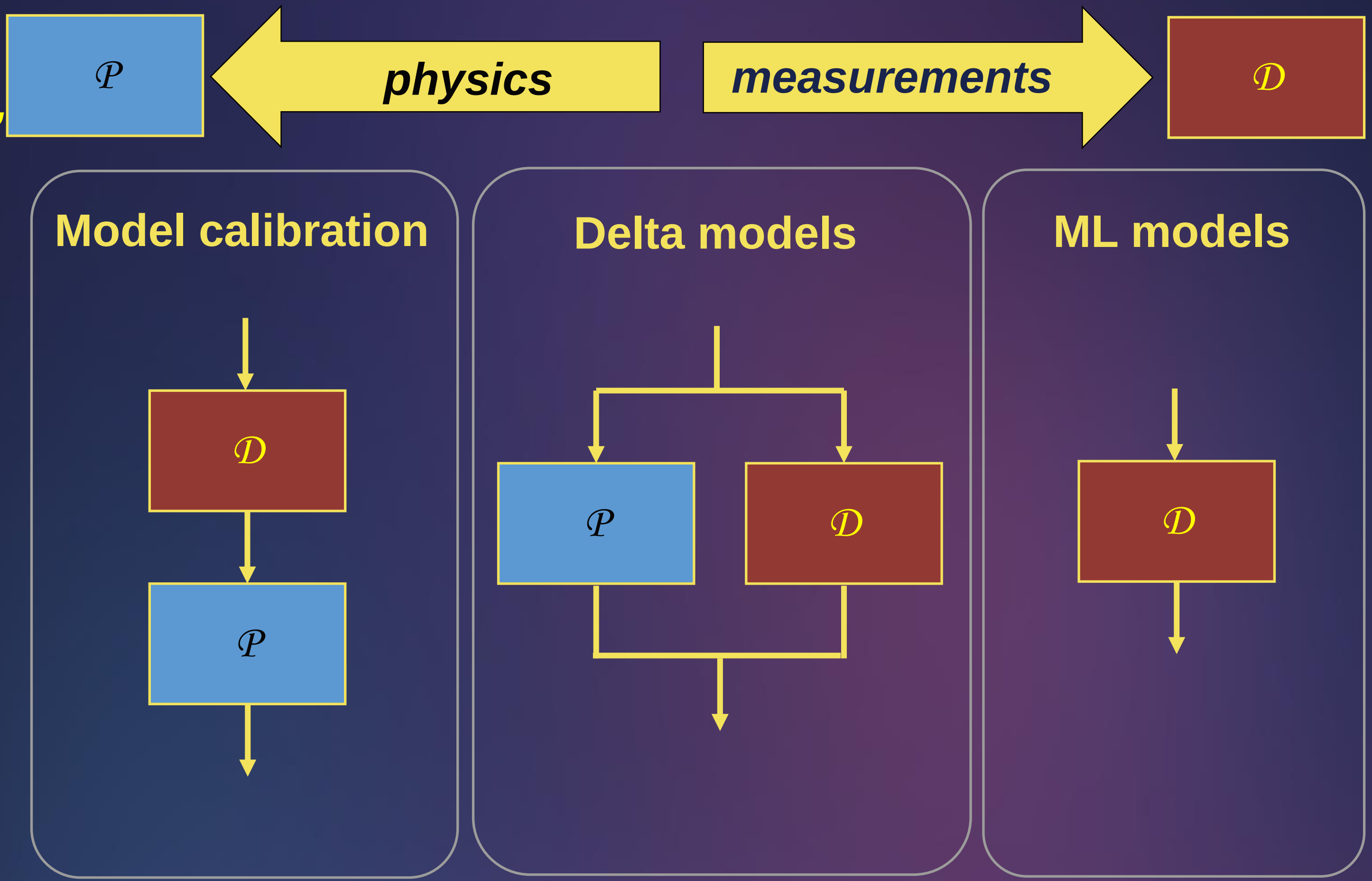
Hybrid modeling [5]

1st principle modeling

"Newtonian paradigm"



https://commons.wikimedia.org/wiki/File:Sir_Isaac_Newton_by_Sir_Godfrey_Kneller,_Bt.jpg



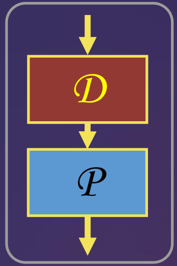
Machine learning (ML)

"Keplerian paradigm"

https://de.wikipedia.org/wiki/Johannes_Kepler#/media/Datei:Portrait_Confused_With_Johannes_Kepler_1610.jpg

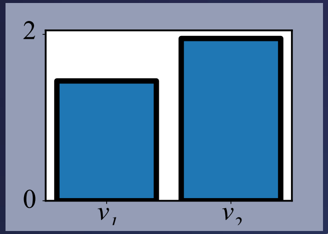
[5] Rudolph M., Kurz S. and Rakitsch B. *Hybrid modeling design patterns,* Journal of Mathematics in Industry, 2024, DOI: 10.1186/s13362-024-00141-0

Model calibration [6]



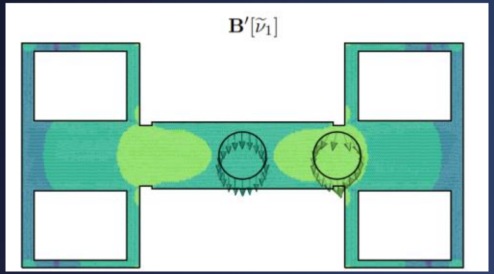
Calibration test campaign

Resulting parameters

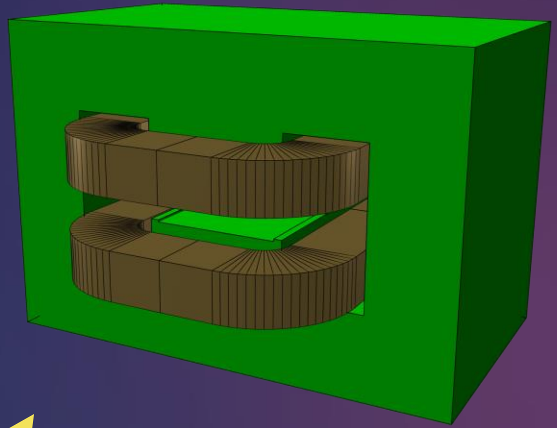


Design of a test campaign

Design of experiment (DOE)
optimal sensor placement



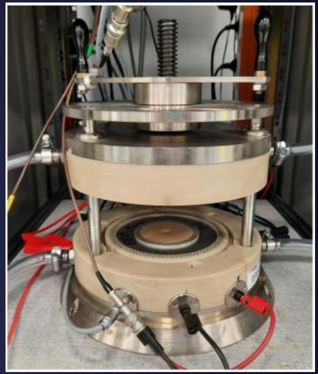
Digital twin



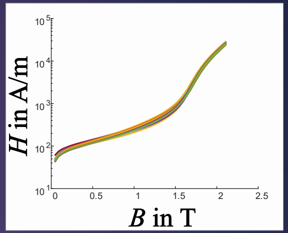
Magnet manufacturing QA

Material Specimen

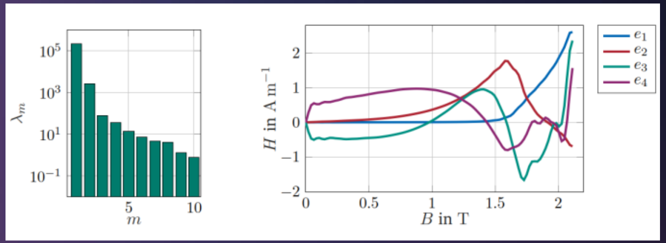
Permeameter



H(B)-curve

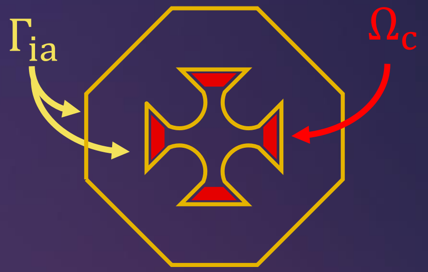


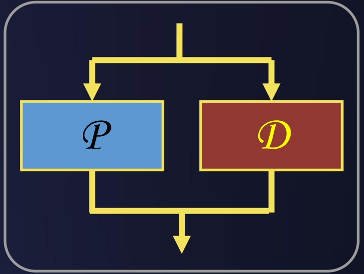
Pattern recognition (KLE)



[6] L. Fleig, M. Liebsch, S. Russenschuck and S. Schöps, "Identification of B(H) Curves Using the Karhunen Loève Expansion," in IEEE Access, vol. 12, pp. 59441-59449, 2024, doi: 10.1109/ACCESS.2024.3393348

Delta models





- ***The discrepancy*** between measurement and simulation ***may not vanish*** after magnet calibration
- ***The discrepancy*** drives the delta model
- *The delta model may be used to understand the* ***origin of the discrepancy***
- *The predictions of the updated model are* ***matching our observations***

ROXIE boundary integral equation for field evaluation

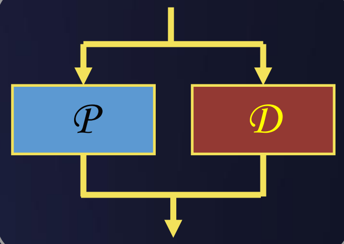
$$\boldsymbol{A}(\boldsymbol{r}) = \int_{\Gamma_{ia}} \underbrace{\boldsymbol{A}(\boldsymbol{r}')}_{\substack{\text{MVP}\\ \text{ROXIE}\\ \text{BEM-FEM}}} \partial_n u^*(\boldsymbol{r},\boldsymbol{r}')\,\mathrm{d}r' - \int_{\Gamma_{ia}} \underbrace{\partial_{\boldsymbol{n}}\boldsymbol{A}(\boldsymbol{r}')}_{\substack{\text{normal}\\ \text{derivative}\\ \text{ROXIE}\\ \text{BEM-FEM}}} u^*(\boldsymbol{r},\boldsymbol{r}')\,\mathrm{d}r'$$

$$+ \int_{\Omega_c} \underbrace{\boldsymbol{J}(\boldsymbol{r}')}_{\substack{\text{Current}\\ \text{density in}\\ \text{coil domain}}} u^*(\boldsymbol{r},\boldsymbol{r}')\,\mathrm{d}r'$$

Data driven update

$$+ \int_{\Gamma_{ia}} \underbrace{\mathrm{curl}_{\Gamma_{ai}}\, v}_{\substack{\text{ficticious}\\ \text{sources}}} u^*(\boldsymbol{r},\boldsymbol{r}')\,\mathrm{d}r'$$

u^* Greens function $\qquad \Delta u^*(\boldsymbol{r},\boldsymbol{r}') = \delta(\boldsymbol{r}-\boldsymbol{r}')$



Delta models - Data driven model update

Minimum energy solution

minimize $E(v)$

subject to: $\boldsymbol{H}(v) = \boldsymbol{y} - \tilde{\boldsymbol{y}}$

Discretized on boundary mesh

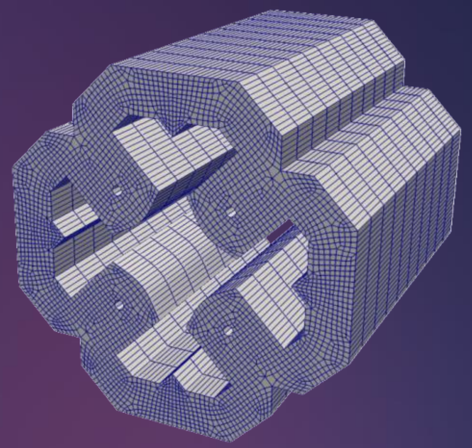
minimize $\frac{1}{2}\boldsymbol{v}^T \boldsymbol{W}\, \boldsymbol{v}$

subject to: $\boldsymbol{H}\, \boldsymbol{v} = \boldsymbol{y} - \tilde{\boldsymbol{y}}$

→ ***Model update is obtained by quadratic programming***

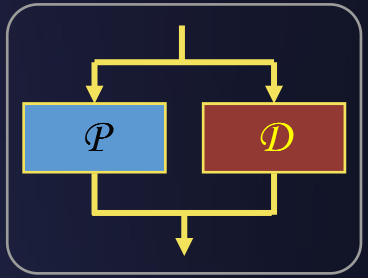
→ ***We use the python software for convex optimization "cvxopt"***

Boundary mesh



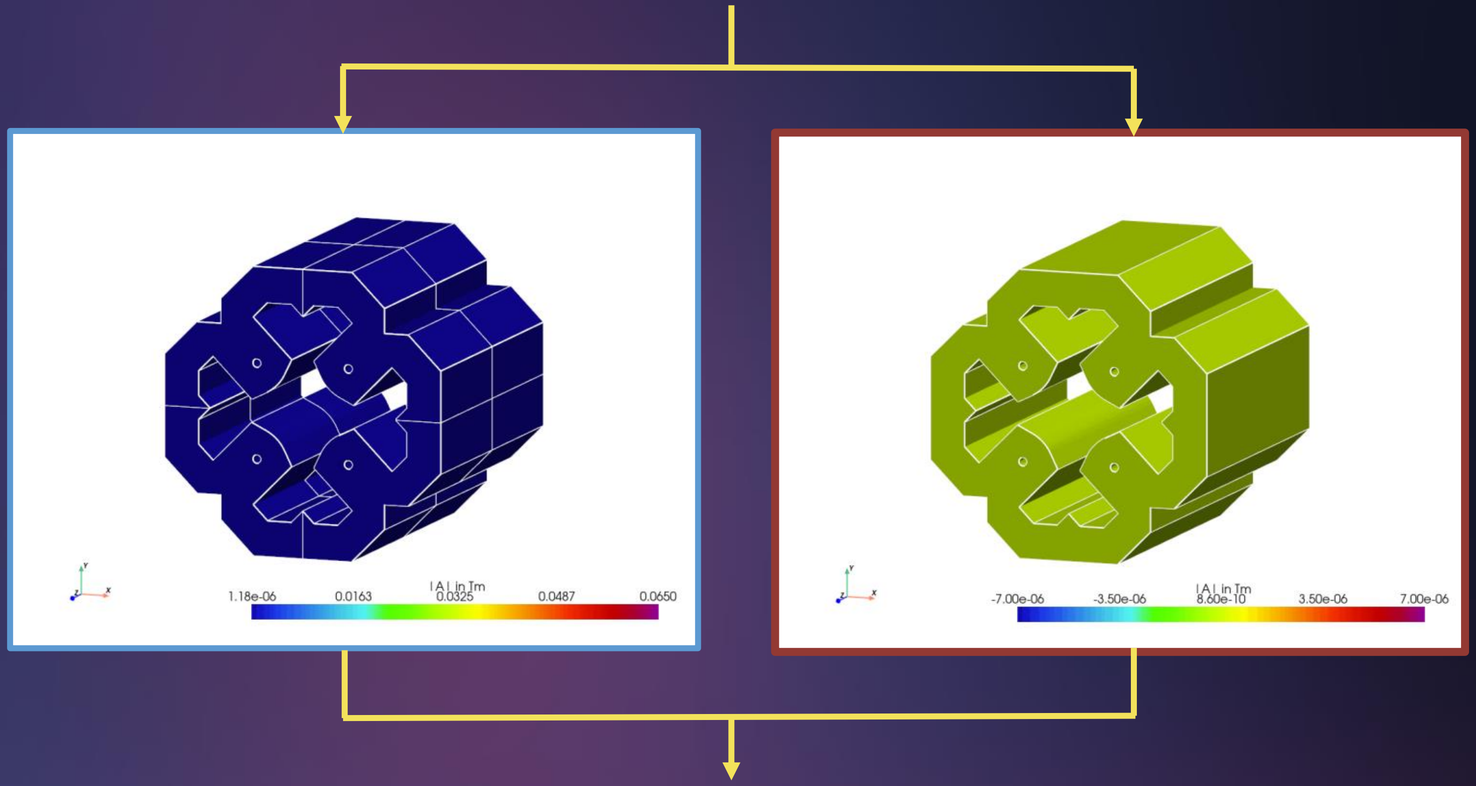
$E(\cdot)$	Energy functional
$\boldsymbol{W}$	Energy matrix
$\boldsymbol{H}(\cdot)$	Observation operator
$\boldsymbol{H}$	Observation matrix
$\boldsymbol{y}$	Measurement data
$\tilde{\boldsymbol{y}}$	Predicted measurements

Example integrated field measurement



Quadrupole magnet on test bench

Rotating coil measurement system



Example 3D field mapping [7]

Curved dipole magnet on test bench

Model update ($v_0 \rightarrow v_1$) by means of a linear Kálmán filter

$$Q_1 = (H^T R^{-1} H + Q_0^{-1})^{-1}$$

$$(H^T R^{-1} H + Q_0^{-1})\, v_1 = H^T R^{-1} y + Q_0^{-1} v_0$$

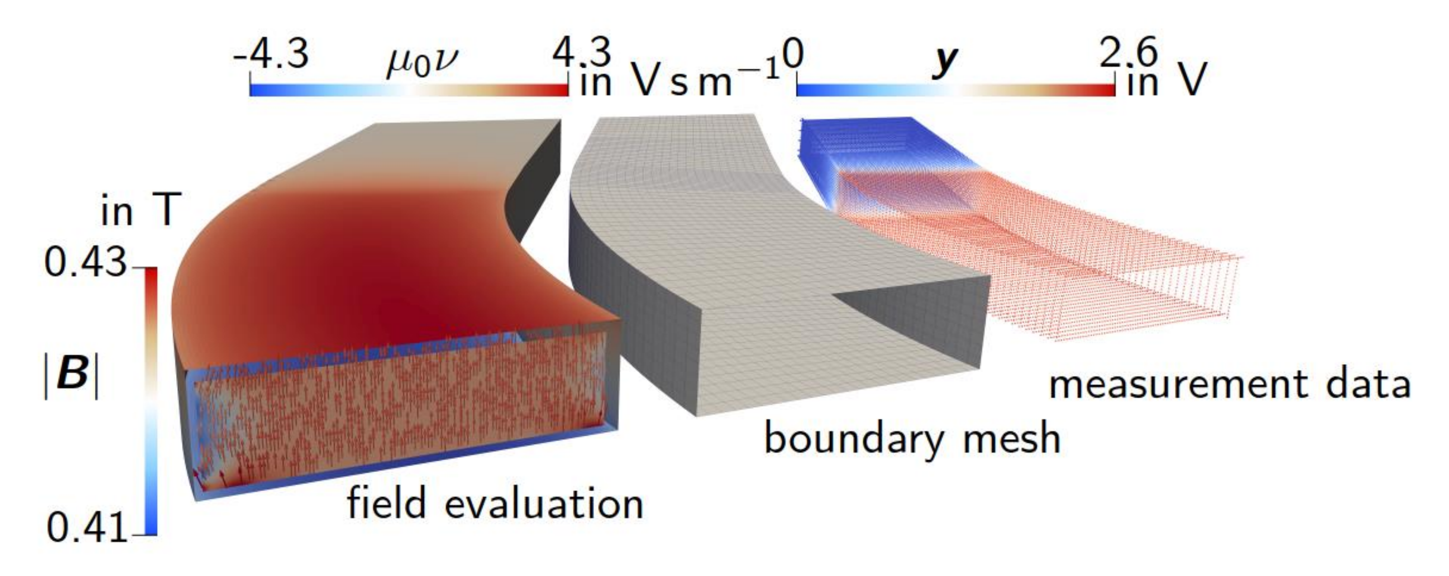
Q_0	Prior covariance matrix
Q_1	Posterior covariance matrix
H	Observation matrix
R	Measurement covariance matrix
y	Measurement data

[7] Liebsch, Melvin, Russenschuck, Stephan and Kurz, Stefan. "BEM-Based Magnetic Field Reconstruction by Ensemble Kálmán Filtering" *Computational Methods in Applied Mathematics*, vol. 23, no. 2, 2023, pp. 405-424. https://doi.org/10.1515/cmam-2022-0121

Example 3D field mapping [7]

Curved dipole magnet on test bench

Measurement data, boundary mesh and model update



[7] Liebsch, Melvin, Russenschuck, Stephan and Kurz, Stefan. "BEM-Based Magnetic Field Reconstruction by Ensemble Kálmán Filtering" *Computational Methods in Applied Mathematics*, vol. 23, no. 2, 2023, pp. 405-424. https://doi.org/10.1515/cmam-2022-0121

Example 3D field mapping [7]

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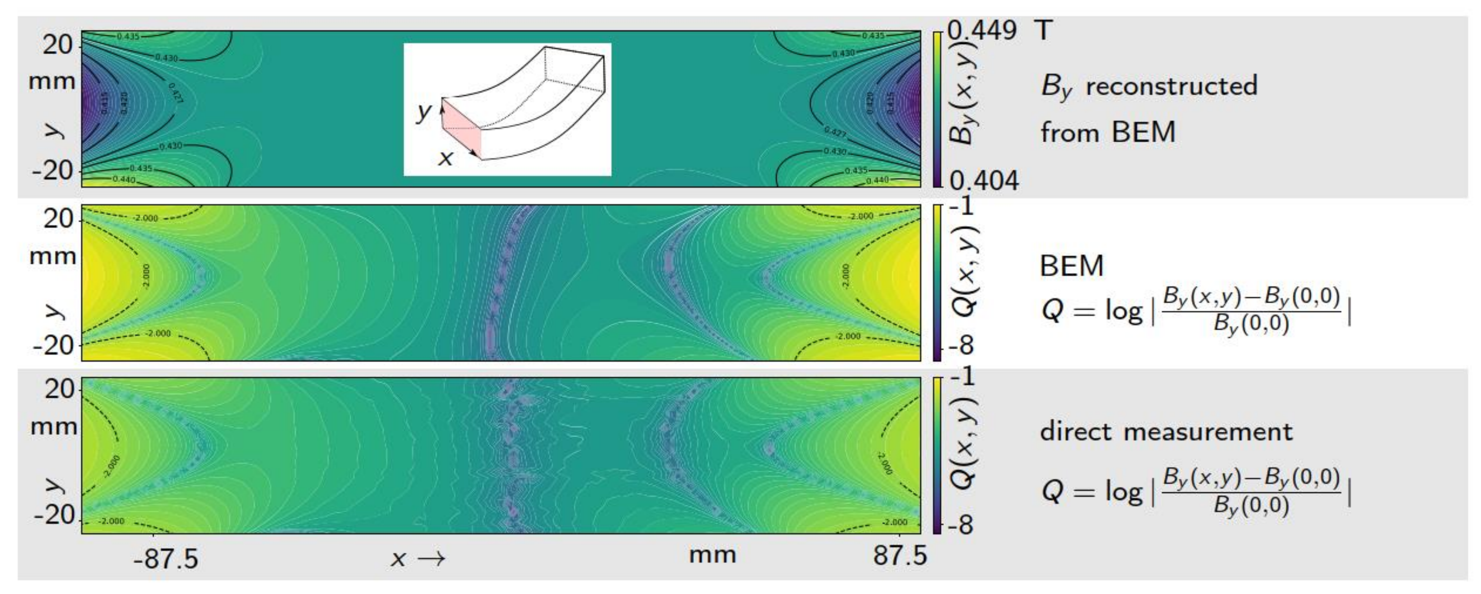
Validating the field evaluation



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The ROXIE evaluator

- The ROXIE evaluator is python package for the ***advanced post-processing and reverse engineering***

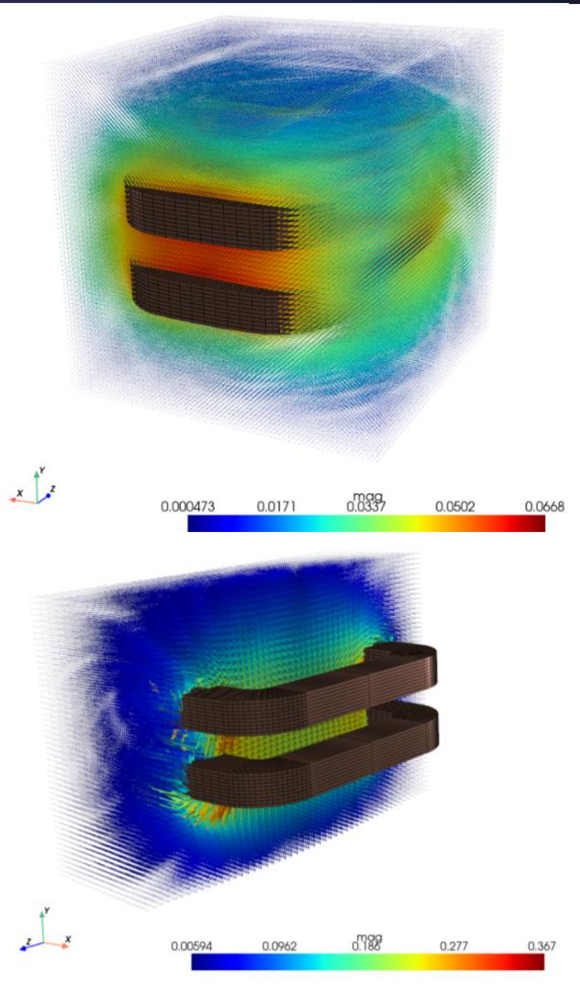
- We make extensive use of GMSH ***for mesh operations and shape functions***

- ***Performant C++ extensions*** are used for the BEM matrix assembly

- The C++ code leverages on
  vectorization (EigenC++)
  parallelization (OpenMPI)

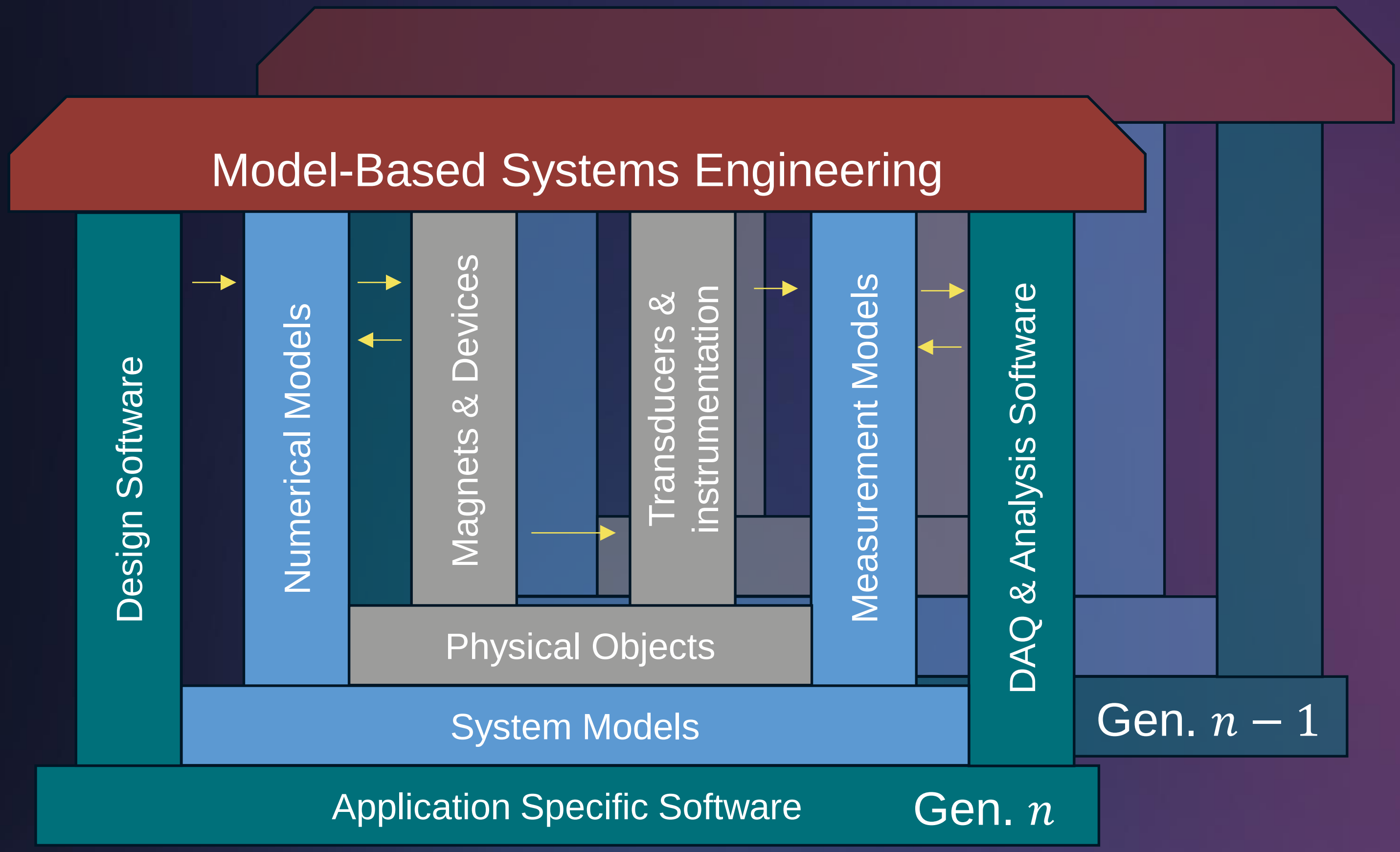
- It features a ***Multi Level Fast Multipole Method (MLFMM) for accelerated field evaluation***

- The ***poetry packaging manager*** is used for platform independence and dependency tracking



https://github.com/MelvinLie/roxie_evaluator

Integration



All systems models must be:

- ***Exchangeable***
- ***Versioned***
- ***Integratable***

Application specific software for ROXIE
- ***ROXIE API***
- ***ROXIE evaluator***

The goal is to integrate our models in ***pyMBSE*** [8], a python toolbox for the self-contained ***multi model execution***

[8] PyMBSE User Documentation, Accessed: Oct. 03, 2024. [Online]. Available: https://chart-magnum.github.io/pymbse-docs/intro.html

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Conclusion

- We use ***hybrid modeling*** to integrate magnetic measurement data in numerical field simulations
- Model calibration techniques alone are ***sometimes not sufficient to find a match*** between measurements and simulations
- Delta models are used to ***compensate for discrepancies***
- They can provide an ***indication of the cause of the differences***
- Our post-processing techniques leverage on ***boundary integral equations***
- We follow the principles of model-based systems engineering to integrate the numerical models and simulation data in the ***development and product lifecycle***