ENTSO-E European R&D meeting

Developing Digital Twins for Accelerator Magnets

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- TE-MSC-TM -

Agenda

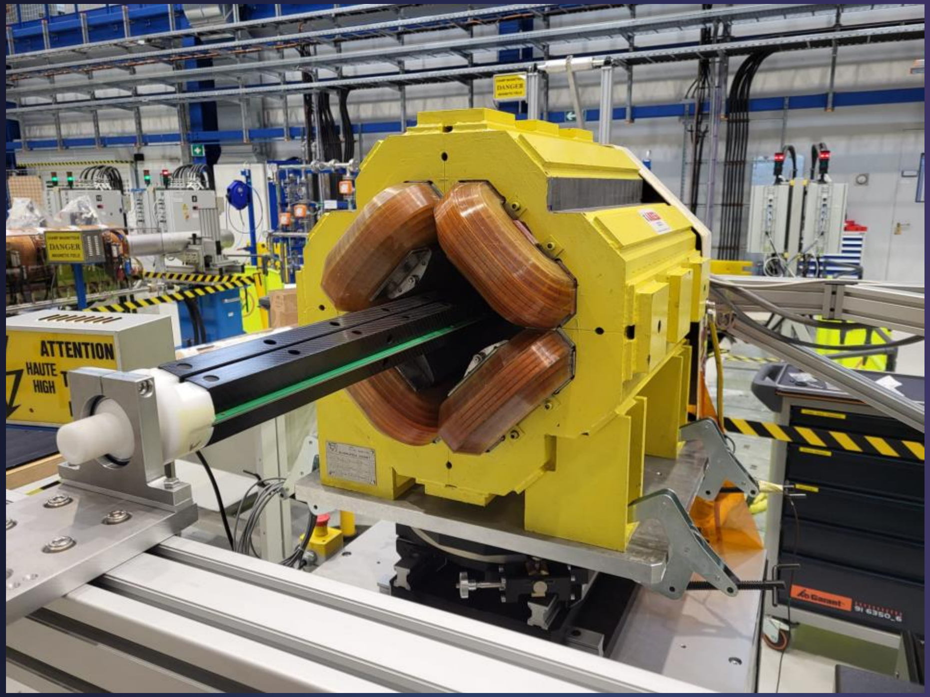
Learning from data through the lens of models is a way to exploit structure in an otherwise intractable problem [6]

- The digital twin of the accelerator magnet
- Challenges
- Integration in the life cycle management
- Conclusion

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

The digital twin [1]

Physical object
a.k.a. accelerator magnet

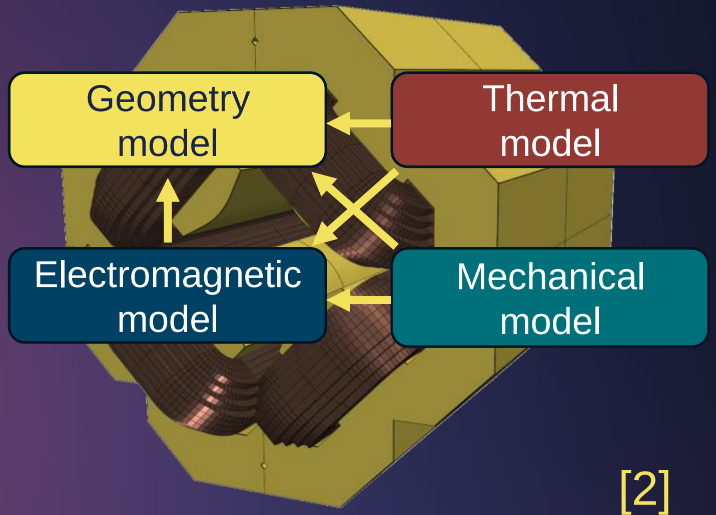


Communication channel

Data
Measurements and inputs
→

Information
Prediction
State observation
←

Digital representation
a.k.a. numerical system model



[2]

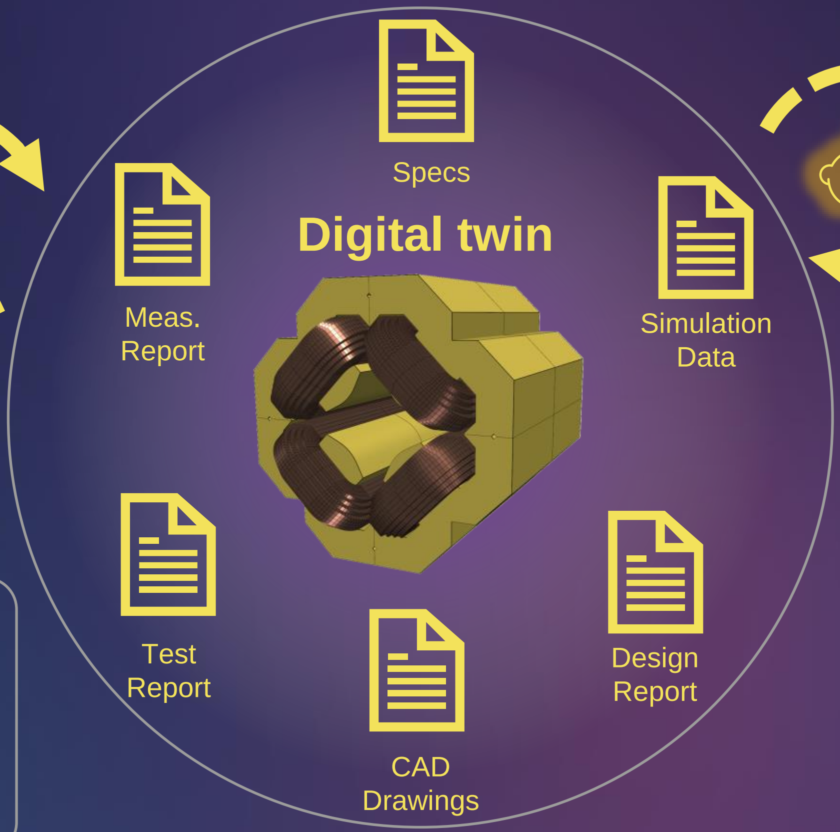
→ The digital twin requires multi-physical modeling

[1] Piascik, R., et al., *Technology Area 12: Materials, Structures, Mechanical Systems, and Manufacturing Road Map*. 2010, NASA Office of Chief Technologist.
[2] M. Maciejewski, B. Auchmann, D. M. Araujo, G. Vallone, J. Leuthold and J. Smajic, "Model-Based System Engineering Framework for Superconducting Accelerator Magnet Design," in IEEE Transactions on Applied Superconductivity, vol. 33, no. 5, pp. 1-5, Aug. 2023, Art no. 4003105, doi: 10.1109/TASC.2023.3249647

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

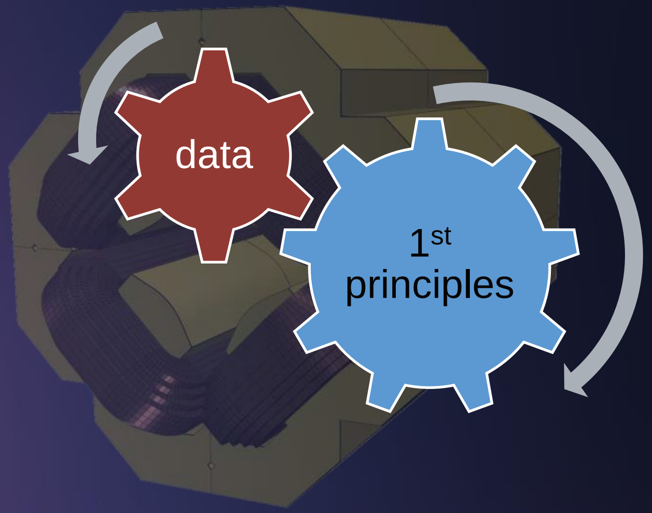
→ Data management services: EDMS, EAM, NORMA, PLM

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



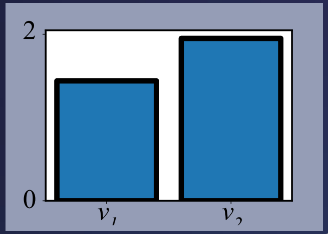
→ ***Measurement data*** *needs to be* ***integrated*** *in the numerical model to enable* ***accurate predictions***

→ ***The digital twin is a hybrid model***

Example – Model Calibration [3]

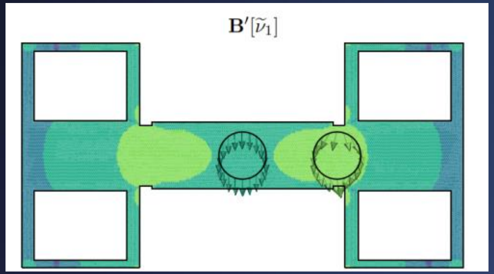
Calibration test campaign

Resulting parameters

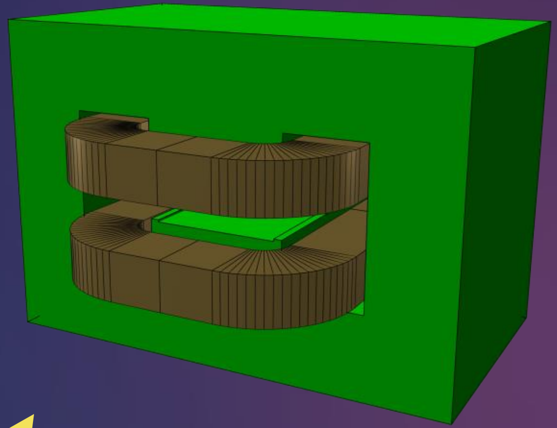


Design of a test campaign

Design of experiment (DOE)
optimal sensor placement



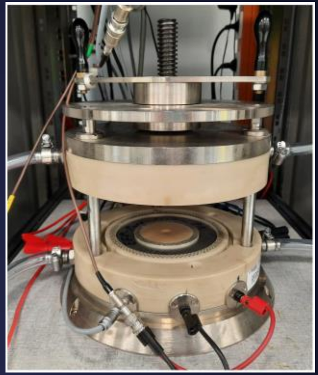
Digital twin



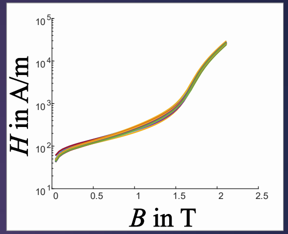
Magnet manufacturing QA

Material Specimen

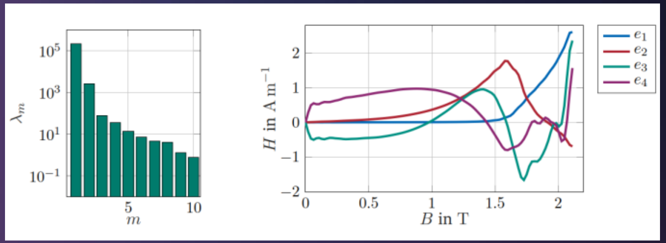
Permeameter



H(B)-curve

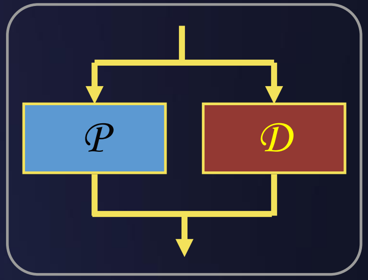


Pattern recognition (KLE)



[3] 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

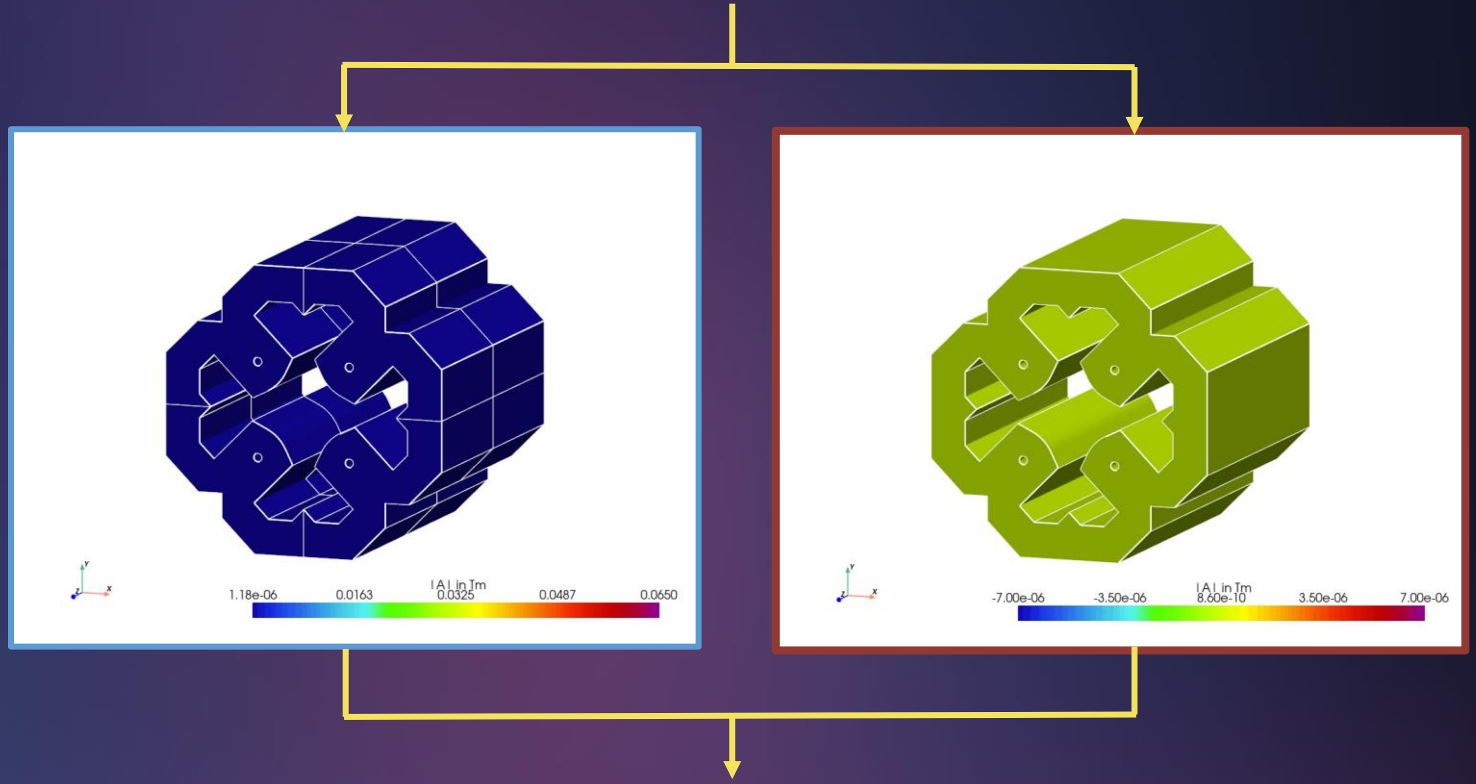
Example – Discrepancy Models



- ***Discrepancy*** between measurement and simulation ***may not vanish*** after magnet calibration
- ***Discrepancy*** drives the delta model
- Delta model ***implies Maxwell's equations*** in the vacuum domain

$$\text{curl}\,\boldsymbol{H} = \boldsymbol{0},\ \text{div}\,\boldsymbol{B} = 0$$

- ***Boundary element*** or ***volume integral methods*** have been used



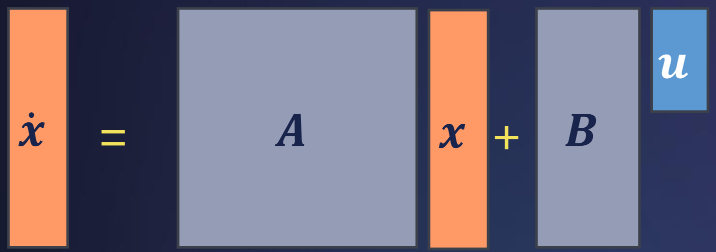
Magnet operation

Requires rapid information exchange

Model order reduction (MOR) [5]

$$\dot{x}(t) = \boldsymbol{A}\,x(t) + \boldsymbol{B}\,u(t)$$

High fidelity model

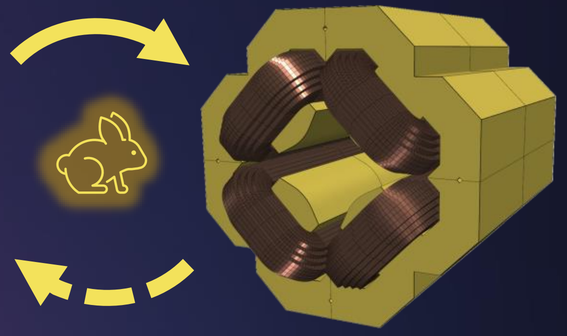


Reduced order model (ROM)

x: State vector, u: Input vector, $\hat{x}$: ROM state

Magnet operation

- ***State observation***
- ***Prediction***
- Maintenance

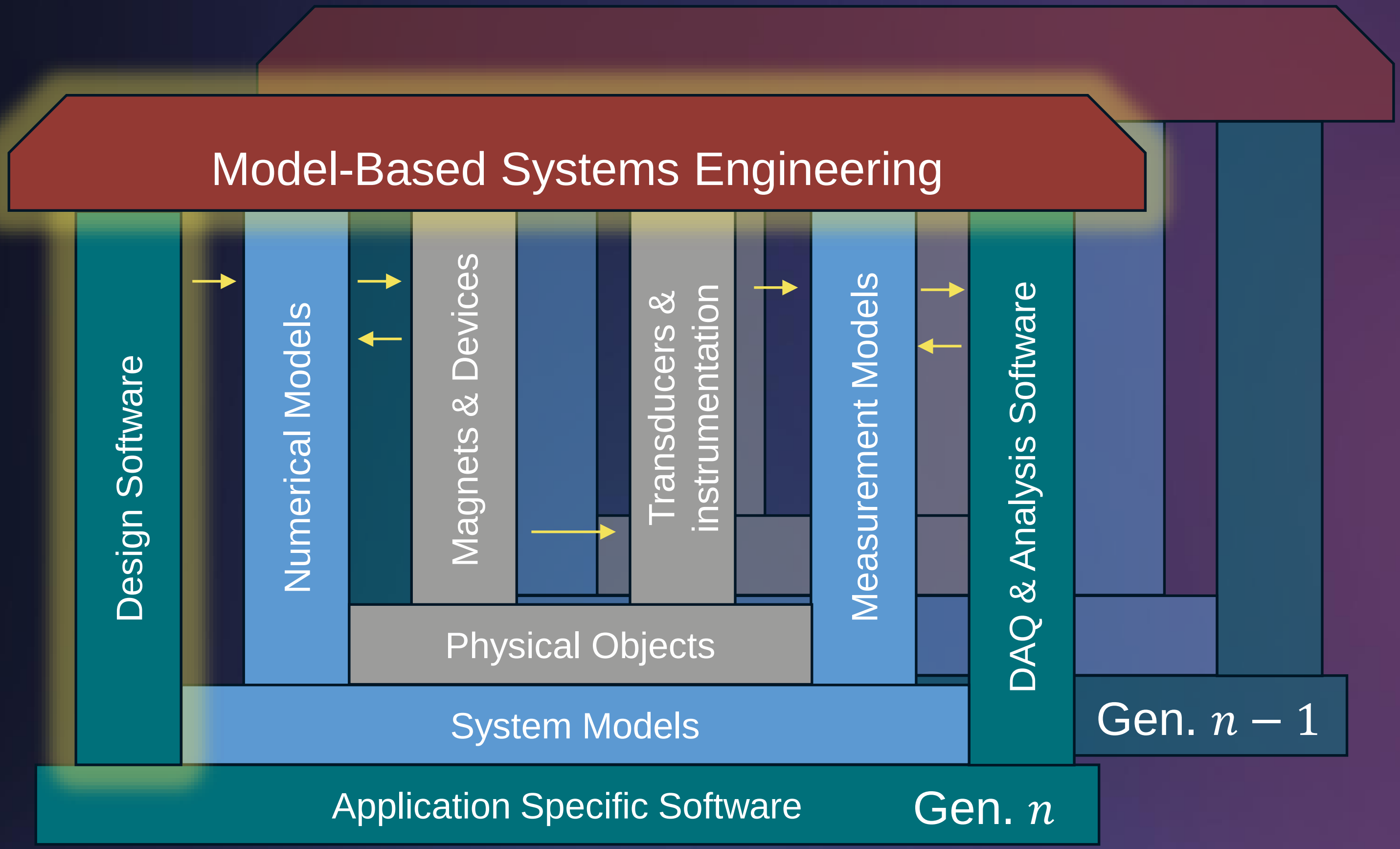


- ***Nonlinear dynamics*** and ***hysteresis*** need to be observed
- ***High accuracy*** is required
  - *Field integral better than 1 unit in 10 000*
- Objective conflict: ROM is faster, but ***less accurate*** than the full model!
- ***Solution:*** Field integrals ***are measured at run-time***
  - *c.f. B-train online monitoring systems*
- ***Domain knowledge is derived from the digital twin***
  - ***e.g. Local versus integral field***

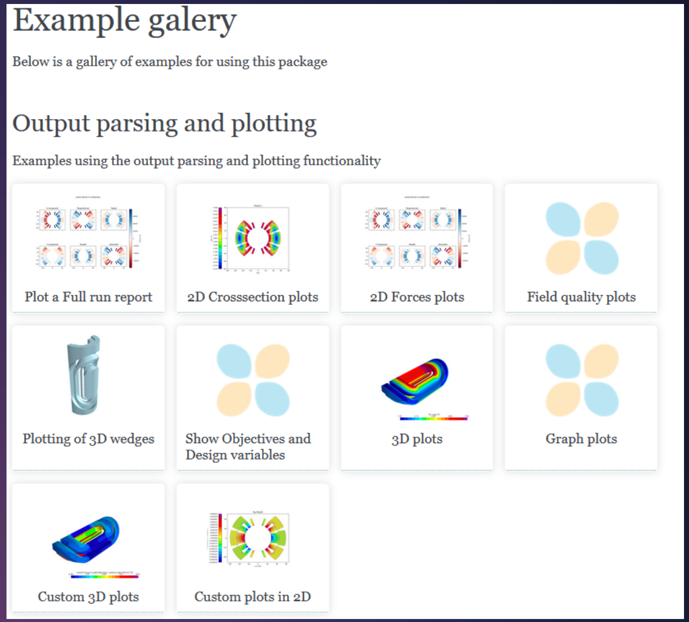
[5] Sorti, S., Petrone, C., Russenschuck, S., Braghin, F.: Data-driven simulation of transient fields in air-coil magnets for accelerators, Nuclear Instruments and Methods in Physics Research Section A, 2021

Integration

*Integrating the digital twin with **M**odel **B**ased **S**ystems **E**ngineering*

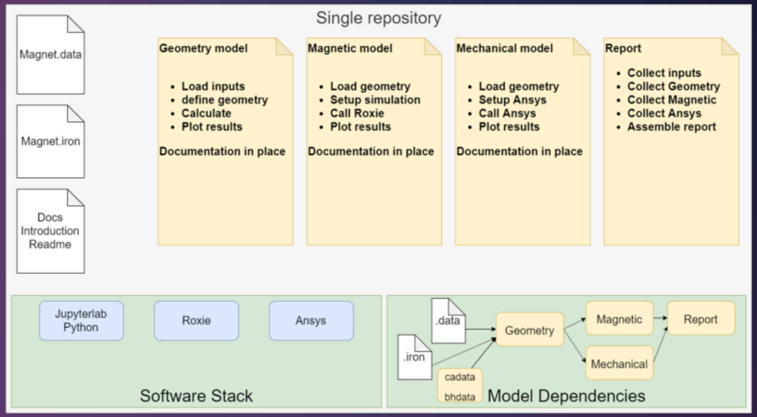


ROXIE API* for integration in MBSE



code available

***pyMBSE**: self-contained multi model execution*



**Developed by M. Bonora (TE-MSC-TM)*

Conclusion

Developing the digital twin of the accelerator magnet

- Numerical models and simulation data ***need to be integrated*** in the ***development and product lifecycle management***
- We must use ***hybrid modeling*** to design ***application specific*** digital twins
- In doing so we must follow the principles of ***model-based systems engineering***
  → ***Traceability, platform independence, versioning***
- A ***collaborative effort in the ATS sector*** is requited to integrate data from various sections and working groups