DITET
Institute of Electromagnetic Fields

CHART Magnet Numerics (MagNum) Sustainable and Consistent Integrated Modelling of Superconducting Magnets

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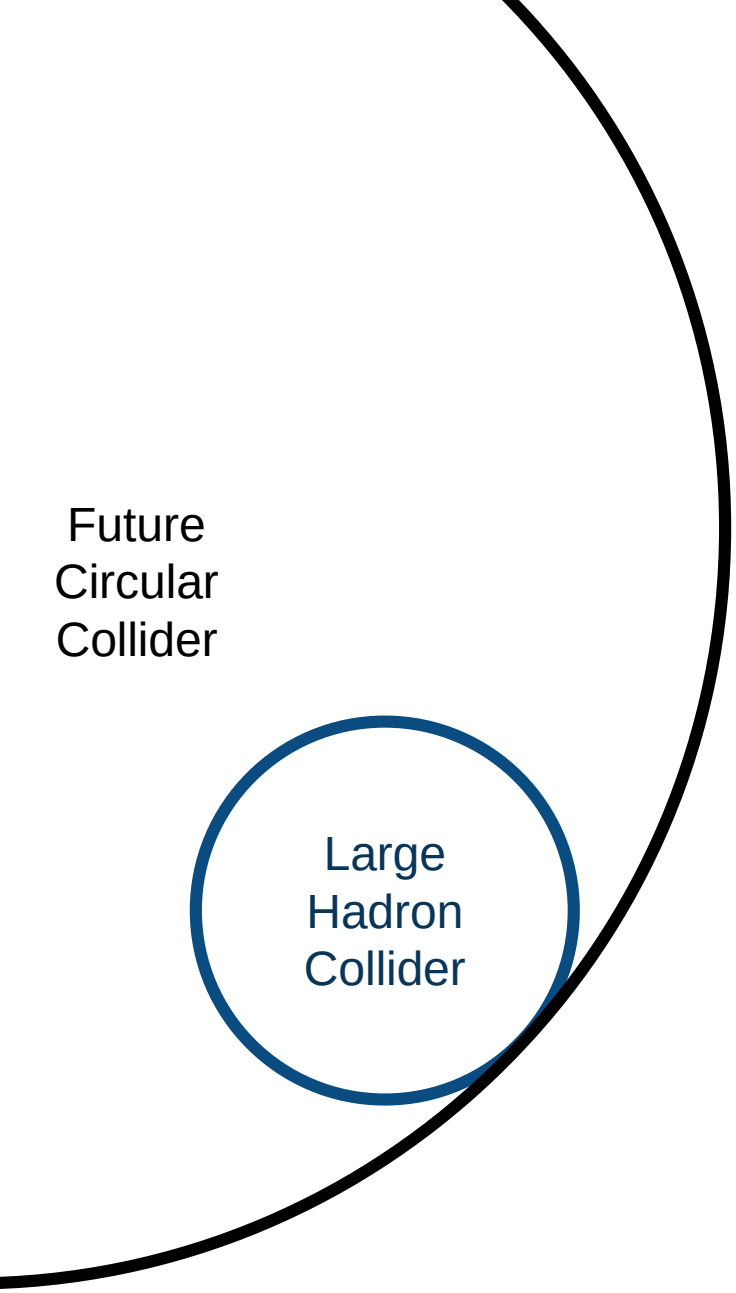
Motivation



Projects in superconducting magnet R&D for future accelerators:

- are intrinsically multi-stage, iterative processes involving various disciplines,
- feature changing teams of experts, and software tools that are subject to updates or replacement
- last from several years to several decades,

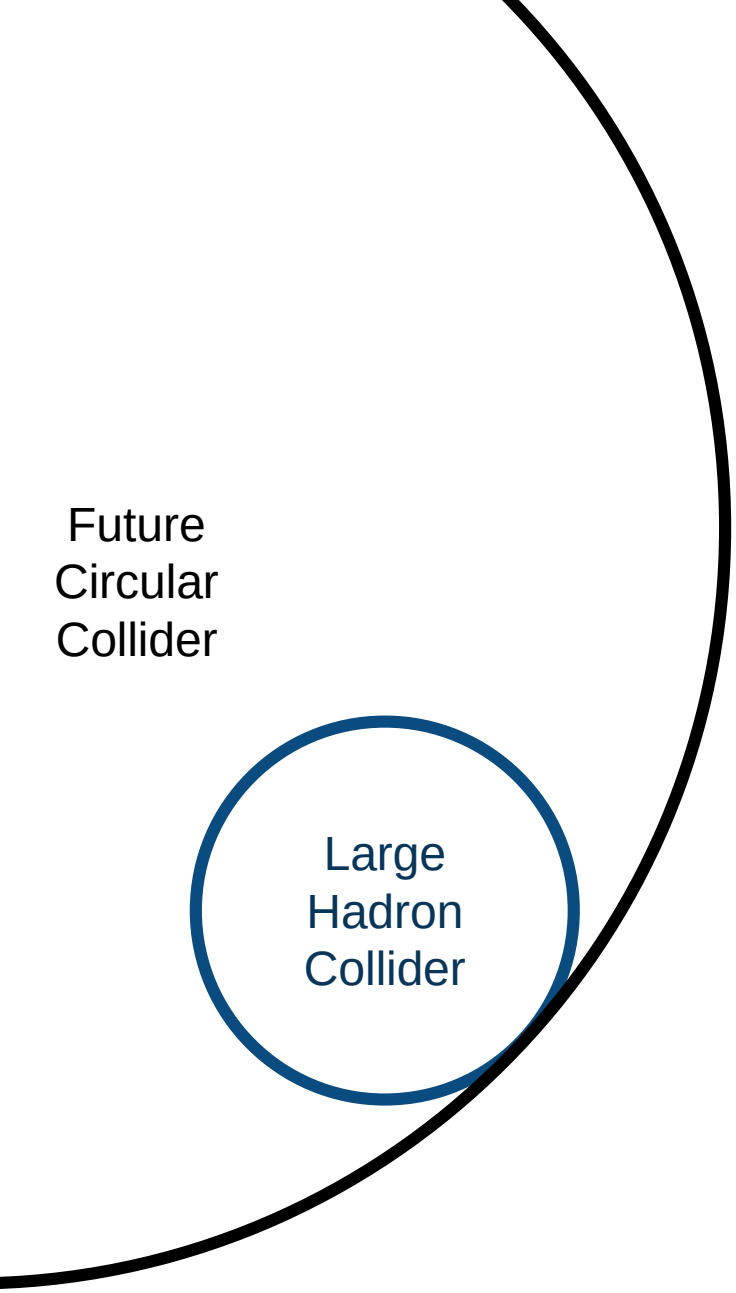
Therefore, a consistent, sustainable, and reproducible organization of numerical models, construction and validation data, and tools used in the process, **is of the essence**.

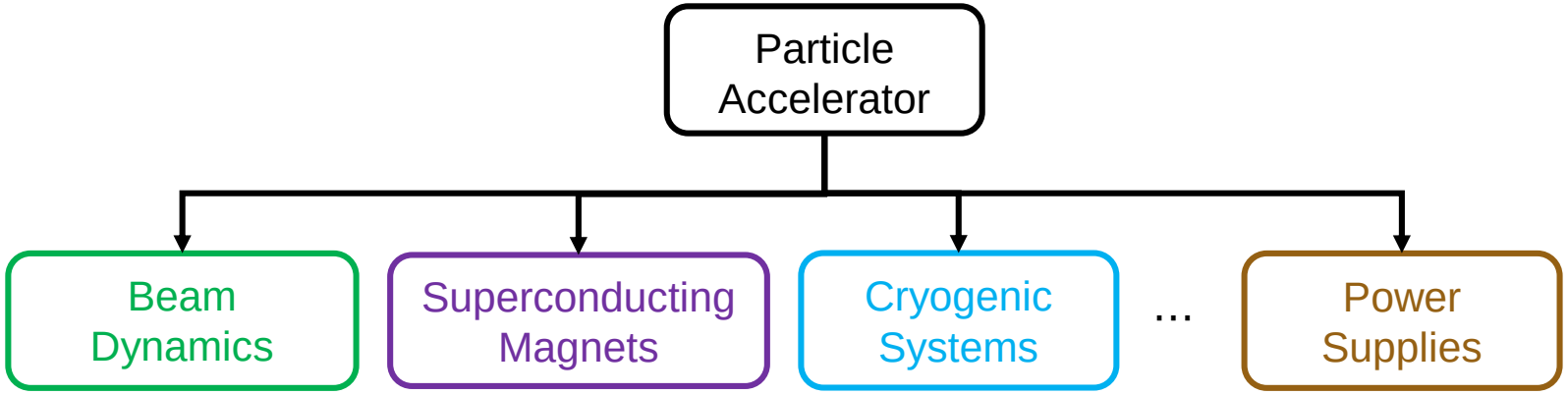
Inspiration

"**Model-based systems engineering (MBSE)** is the formalized application of modelling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases."

https://www.incose.org/incose-member-resources/corporate-advisory-board

Particle Accelerator – System of Systems



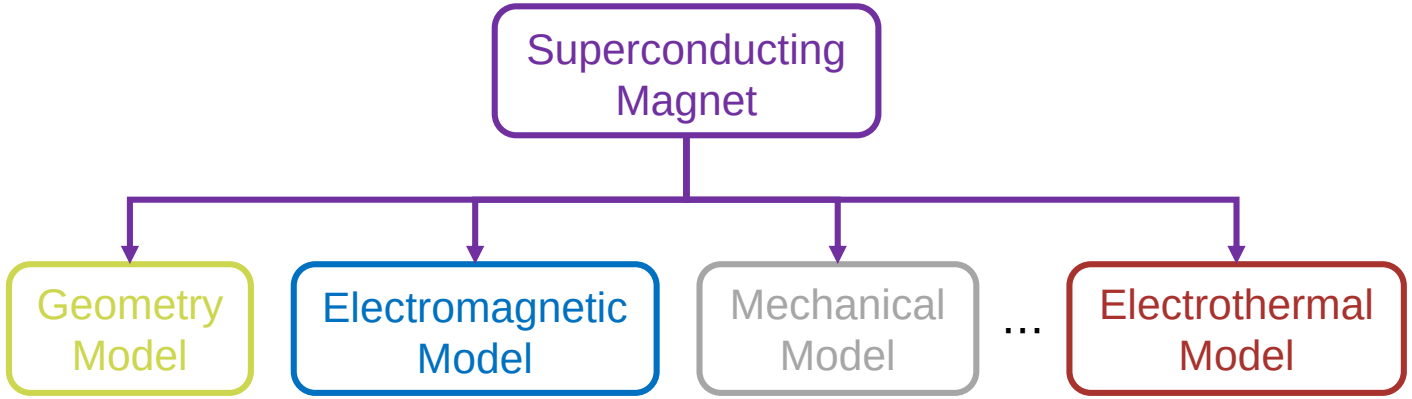


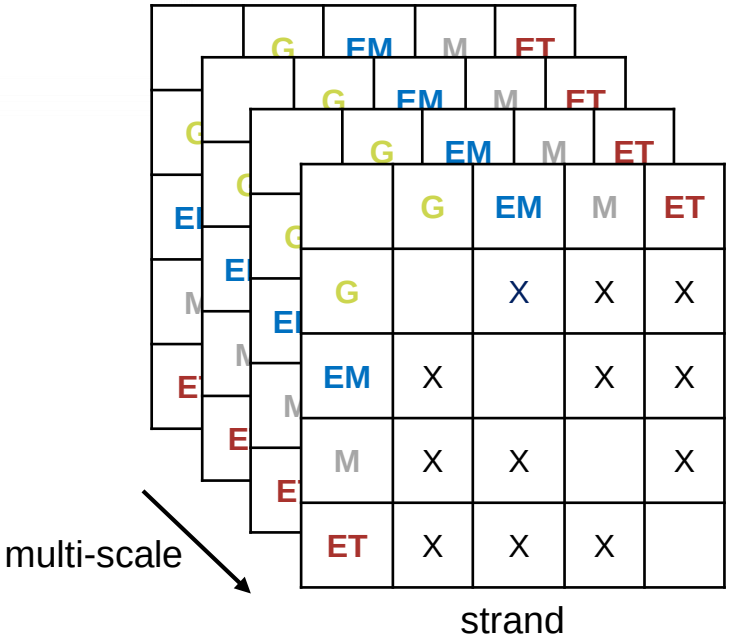
	BD	SM	CS	PS
BD		X		
SM	X		X	X
CS		X		
PS	X	X		

Design System Matrix

- Magnetic field guides beams of particles
- EM losses impact the cryogenic systems
- Magnet inductance influences power supply
- Power supplies are synchronised with the beams

Superconducting Magnet – System of Components





	G	EM	M	ET
G		X	X	X
EM	X		X	X
M	X	X		X
ET	X	X	X	

- All models rely on the geometry model
- Lorentz force acts on the mechanical structure
- EM energy is safely discharged by quench protection system
- Excessive mechanical strain deteriorates magnet performance

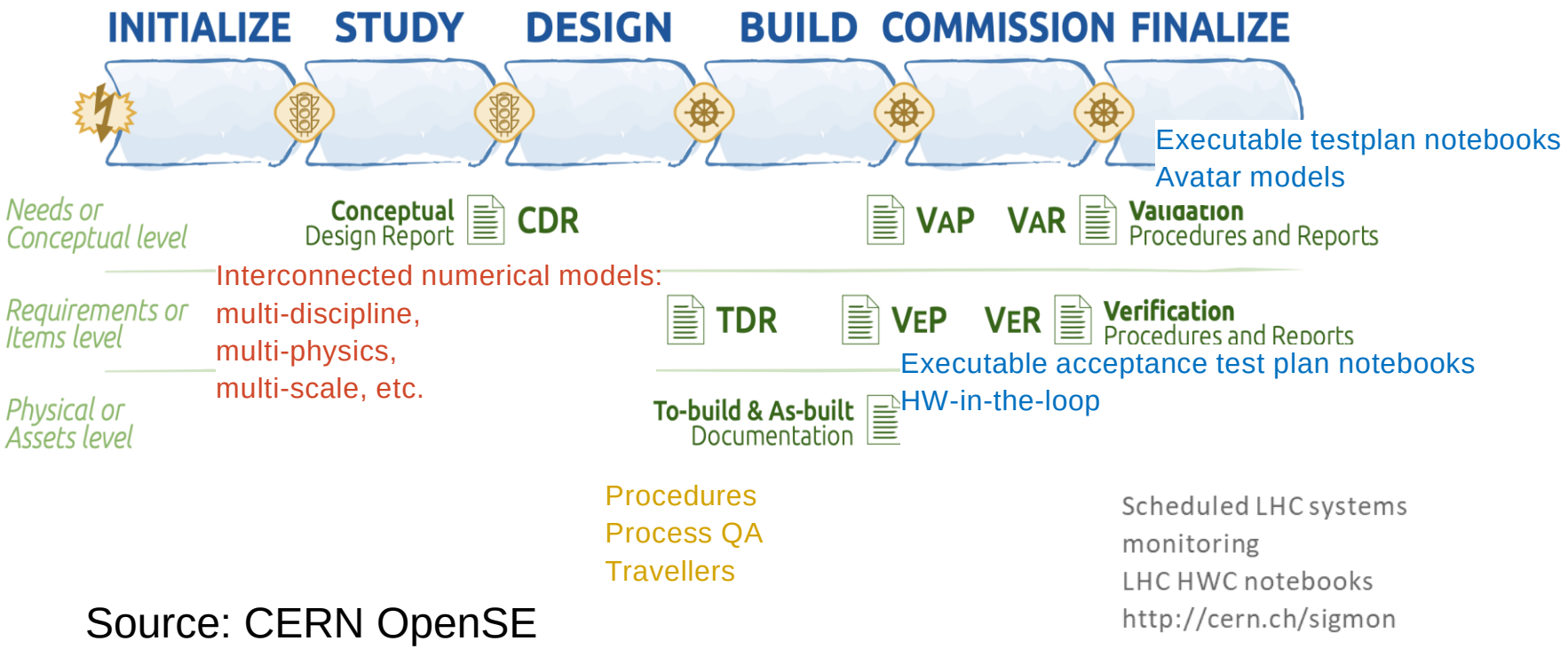
Paradigm Shift to Model-Based Systems Engineering

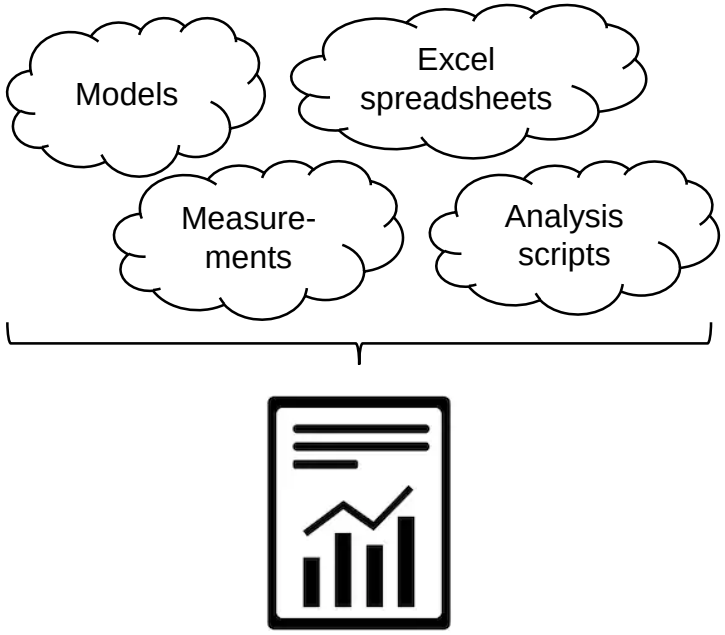
A model is a simplified version of something:

a graphical, mathematical, or physical representation that abstracts reality to eliminate some complexity

MBSE shifts SE focus on documents to interconnected models.

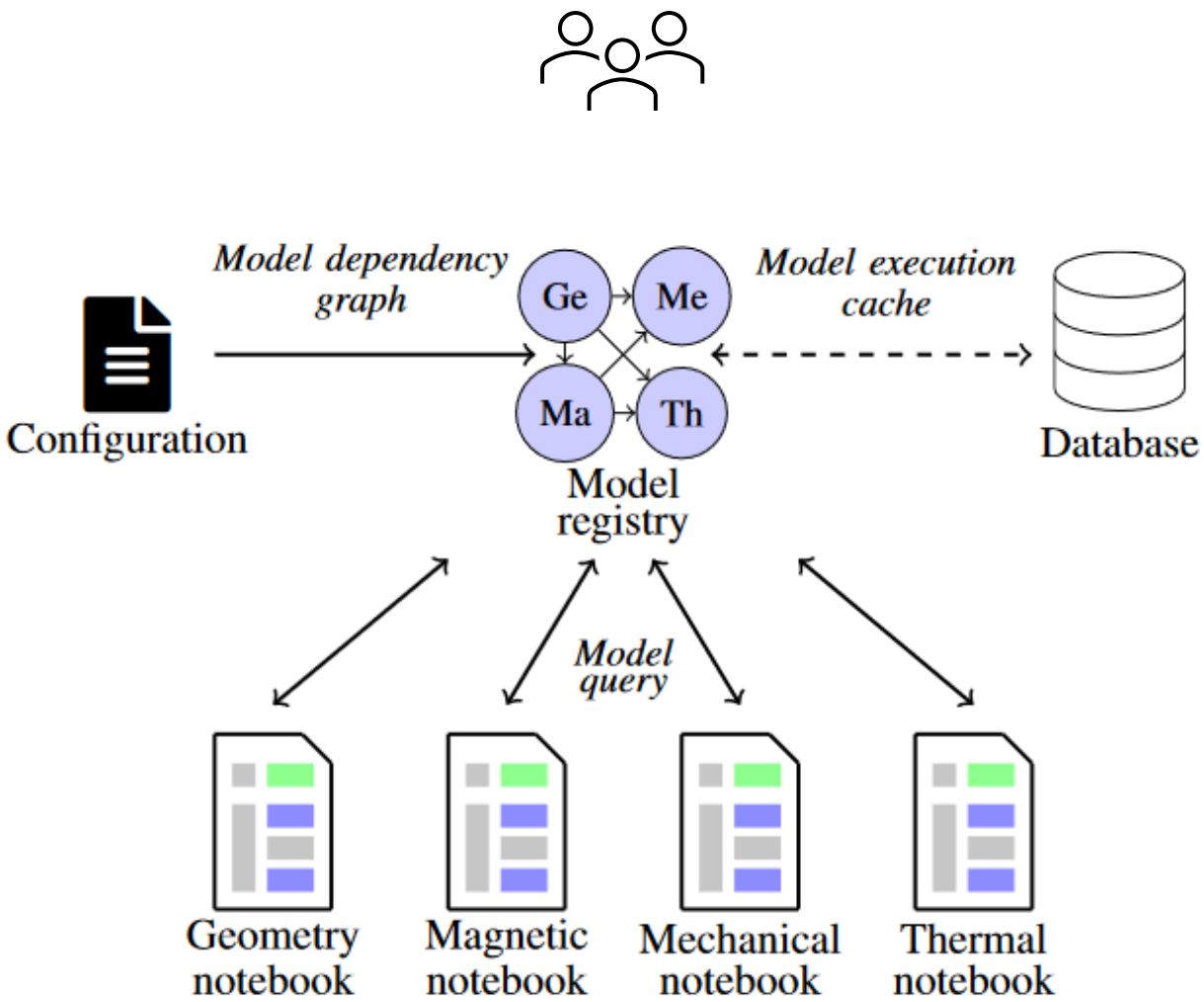
Models are queried, generate views, are traceable and repeatable.





Source: CERN OpenSE

Implementation
Models and Services

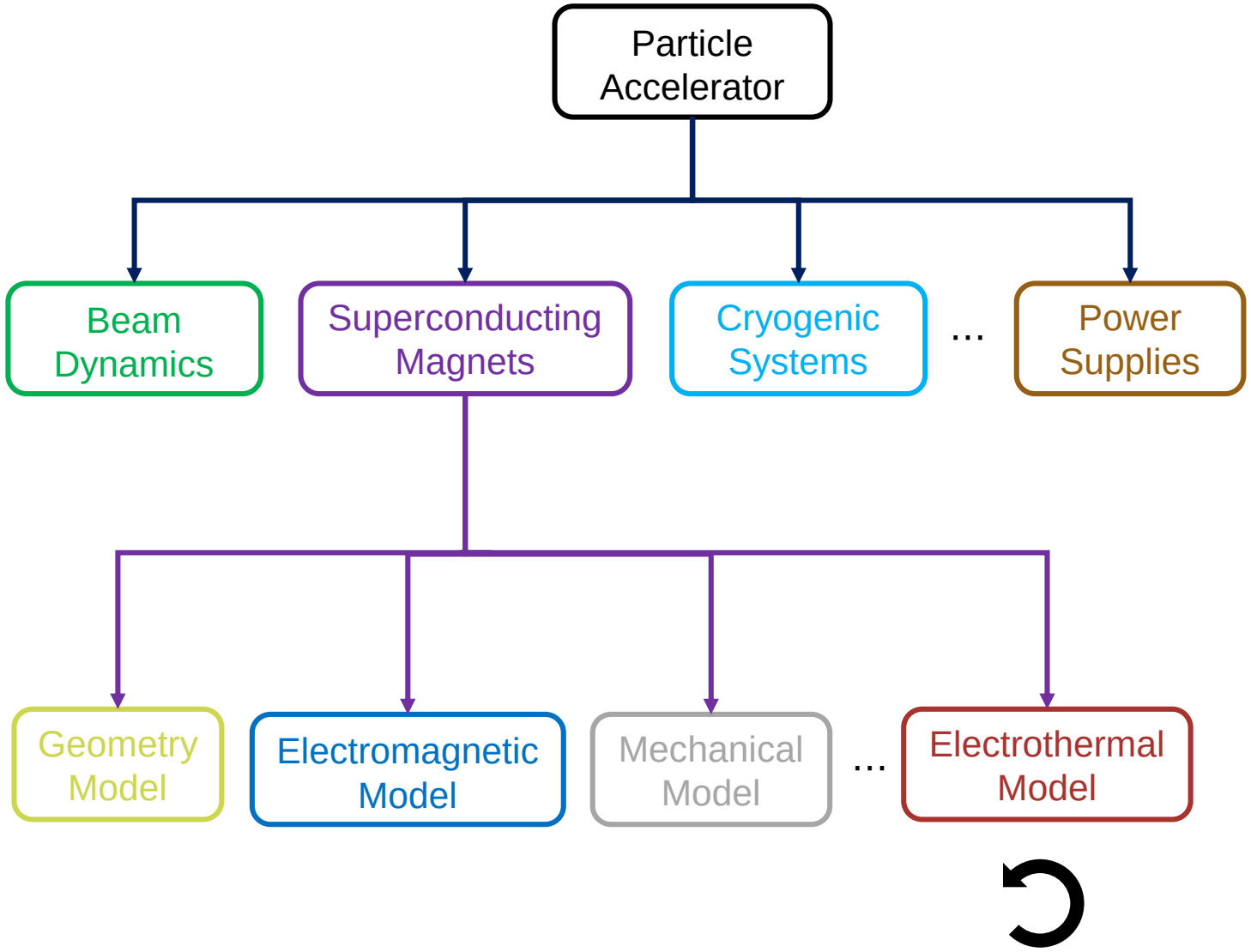


- Users may query models for results
- Models may query models
- Notebook models are handy but not mandatory

- Model configuration describes dependencies
- Model dependencies form a DAG (directed acyclic graph)
- DAG is linearized to detect model changes

- A database keeps track of model execution
- Results are cached to avoid redundant calls and enable model queries

Change Propagation



A model is executed again, when:

- its content changed
- its input parameter(s) changed
- its input file(s) changed
- any of its dependent model changed

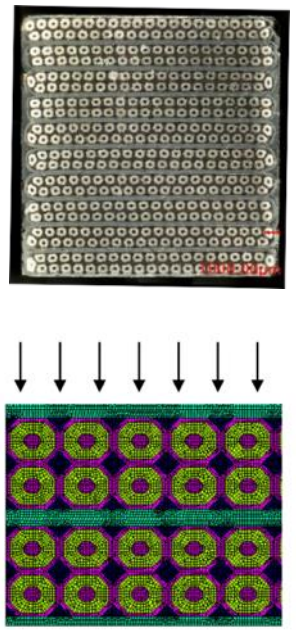
If a model did not change, cached results are immediately returned

After re-execution, a report from all models is automatically updated

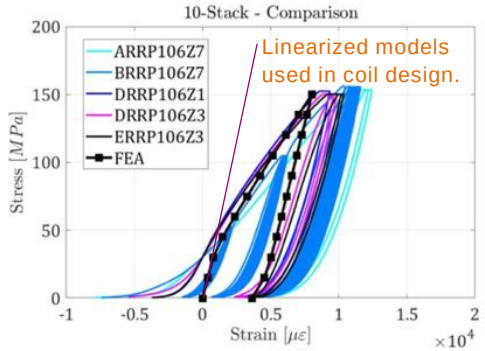
https://chart-magnum.github.io/compumag-cdr-example/intro.html

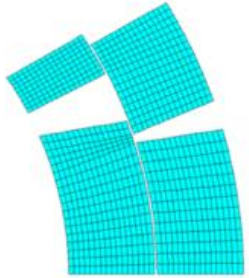
Example 1: Interconnection of Physical and Numerical Models

- Multi-scale Mechanical workflows:
  - Up-scaling (homogenization) moves from local models to a larger scale.
  - Down-scaling (sub-modelling) analyzes local effects based on averaged results from large-scale models.

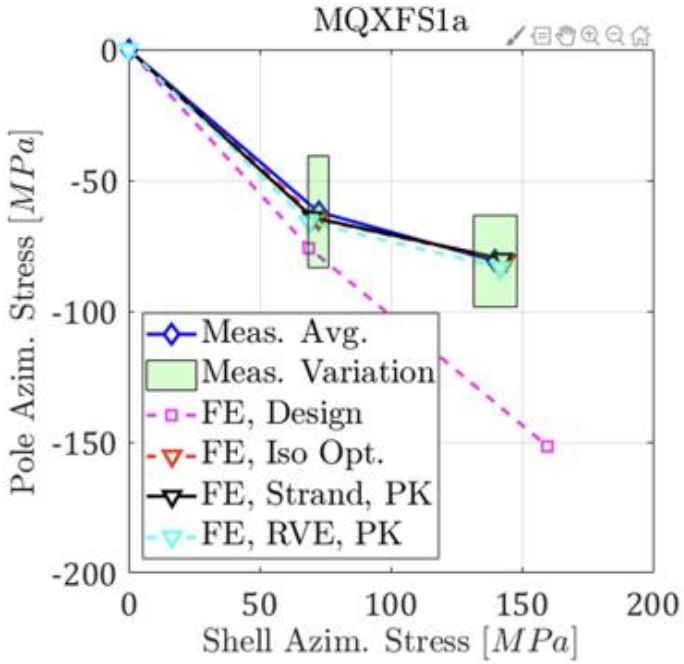


Strand Model



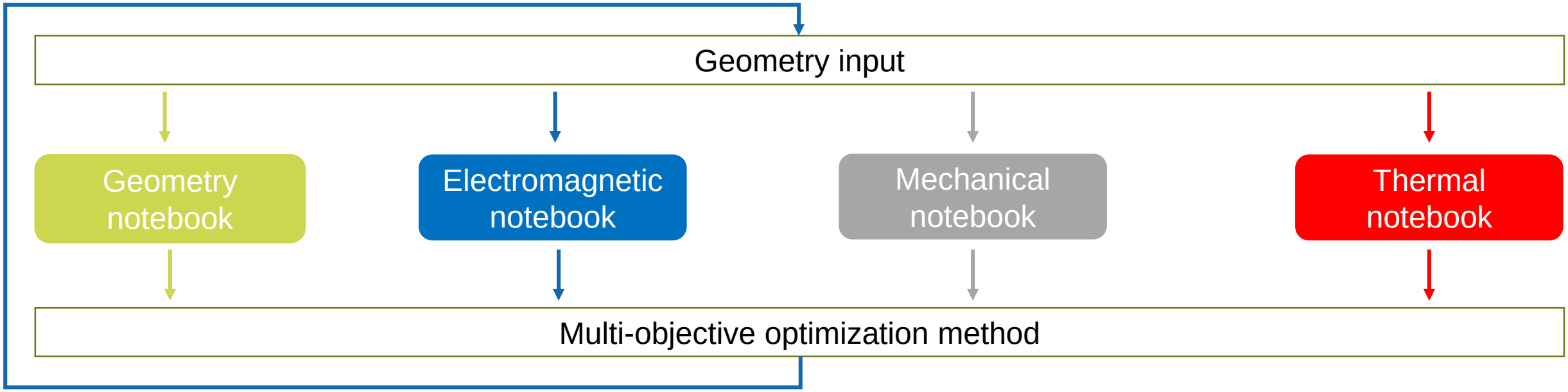


Block 'RVE' Model



See G. Vallone, HFM State of the Art Workshop, 2021;
For FE, Design curve: G. Vallone et al. Mechanical Performance of Short Models for MQXF, the Nb3Sn Low-beta Quadrupole for the Hi-Lumi LHC, IEEE Trans. On Appl. SC, 27(4), 2017.

Example 2: MBSE Trade Study



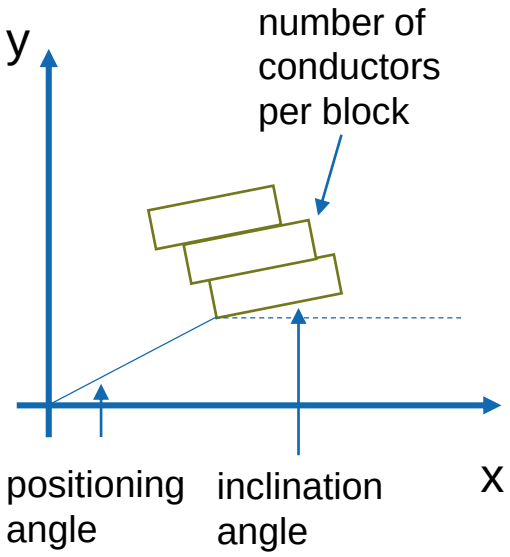
For a given operating field and magnet aperture, we minimize:

- absolute value of the magnetic field multipoles (field quality)
- position on the superconductor load line (safety margin)
- peak stress in the coil (superconductor degradation)
- adiabatic hot-spot temperature (insulation degradation)

by adjusting:

- positioning angle
- inclination angle
- number of conductors per block

which, for a wide range of the design variables, may lead to an inconsistent geometry



Conclusion

- ✓ *Model data* is being gathered and exchanged in thousands of places and circumstances in an accelerator project such as the FCC feasibility study
- ✓ Consistent trade studies (system-wide optimizations) are extremely difficult
- ✓ MBSE is an established concept for systems architecture and requirements engineering
- ✓ We introduce model-based information exchange among subsystems, e.g., magnet design, cryogenics, etc
- ✓ The same MBSE methodology lends itself to drastically improve all domains of systems engineering (verification, validation, commissioning, operations domains)
- ✓ With our framework a system-wide model-based CDR becomes a living document

On-going work:

- ➢ We focus for now on collaborative modeling, simple update of modeling chains upon specification changes
- ➢ The framework will be introduced into manufacturing and testing at PSI over the coming 1-2 years