Finite Element Thermal Thin Shell Approximation for Simulation of Transients in Accelerator Magnets

Andrea Vitrano, Erik Schnaubelt, Mariusz Wozniak, Emmanuele Ravaioli, Arjan Verweij

Machine Protection and Electrical Integrity Group (TE-MPE-PE)

4th May 2023 - CHATS AS 23 - Torino, Italy

Outline

1. Introduction to STEAM
2. Introduction to FiQuS
3. FiQuS Structure & Features
4. Thermal Thin Shells

STEAM framework

Conductor	Magnet	Circuit
LEDET	FiQuS	XYCE*
PyBBQ	LEDET	
	ProteCCT	
BBQ	SIGMA	PSPICE**
Materials properties	Component library	

CHALLENGES

- ✓ Need of trusted simulation tools.
- ✓ Time consuming validation process.
- ✓ Dealing with diverse physics phenomena at different scales.

Simulation of **T**ransient **E**ffects in **A**ccelerator superconducting **M**agnet circuits

*Free tools from Sandia Labs. **Commercial circuit solver from Cadence Design Systems

STEAM framework

Conductor	Magnet	Circuit
LEDET	FiQuS	XYCE*
PyBBQ	LEDET	
	ProteCCT	
BBQ	SIGMA	PSPICE**
Materials properties		Component library

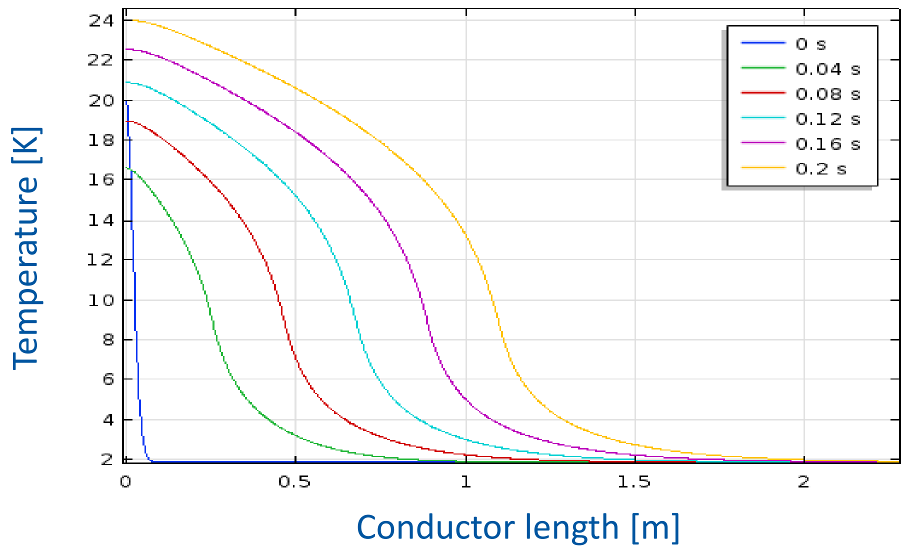
Simulation of Transient Effects in Accelerator superconducting Magnet circuits

BusBar Quench

→ Simulate 1D quench propagation in superconducting busbars.

→ Legacy: BBQ (COMSOL model, finite elements solver).

→ New development: PyBBQ (Python program, FDM).

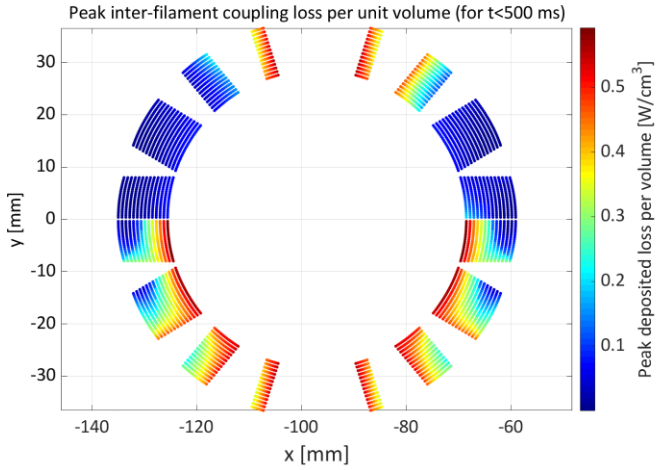


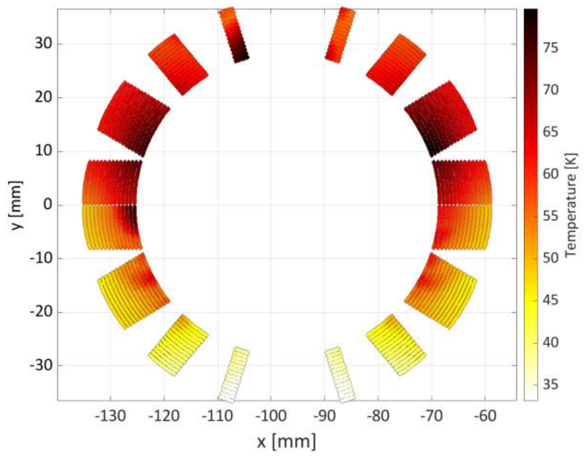
*Free tools from Sandia Labs. **Commercial circuit solver from Cadence Design Systems

STEAM framework

Conductor	Magnet	Circuit
LEDET	FiQuS	XYCE*
PyBBQ	LEDET	
	ProteCCT	
BBQ	SIGMA	PSPICE**
Materials properties	Component library	

Lumped-Element Dynamic Electro-Thermal
→ Simulate electro-magnetic and thermal transients in superconducting magnets in 2D and 3D geometry using the finite-differences method.





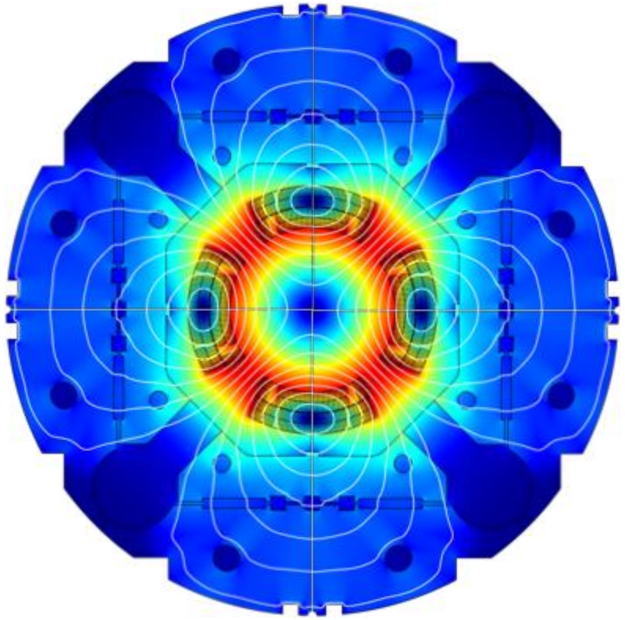
Simulation of **T**ransient **E**ffects in **A**ccelerator superconducting **M**agnet circuits

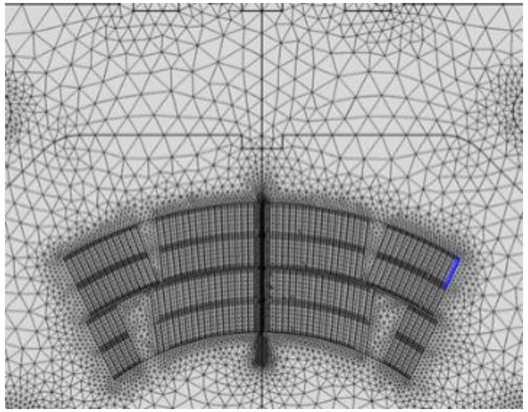
*Free tools from Sandia Labs. **Commercial circuit solver from Cadence Design Systems

STEAM framework

Conductor	Magnet	Circuit
LEDET	FiQuS	XYCE*
PyBBQ	LEDET	
	ProteCCT	
BBQ	SIGMA	PSPICE**
Materials properties		Component library

STEAM Integrated Generator of Magnets for Accelerators
→ Simulate electro-magnetic and thermal transients in superconducting magnets in a 2D geometry using a COMSOL finite-elements (FE) model.





Simulation of **T**ransient **E**ffects in **A**ccelerator superconducting **M**agnet circuits

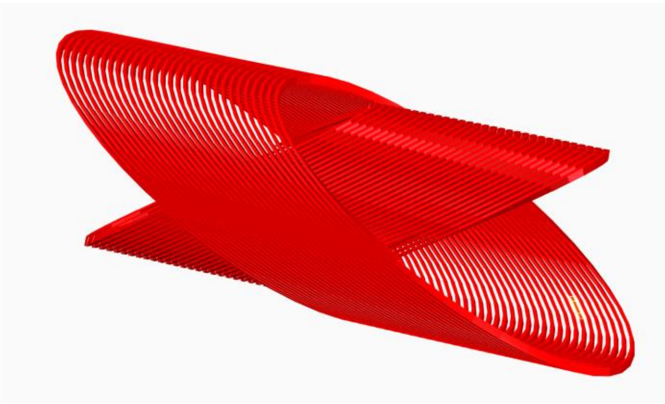
*Free tools from Sandia Labs. **Commercial circuit solver from Cadence Design Systems

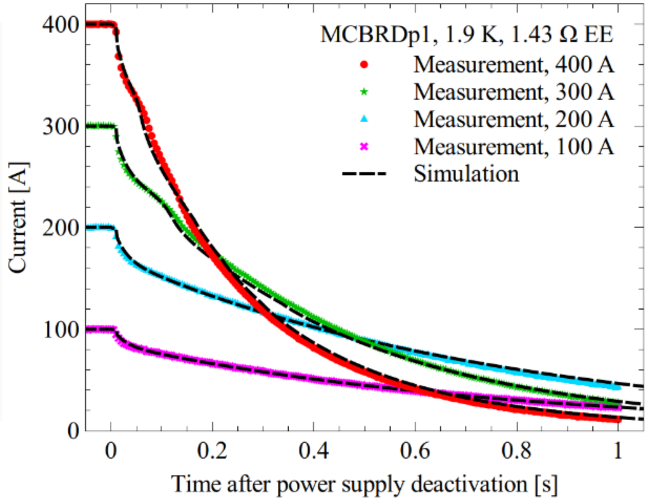
STEAM framework

Conductor	Magnet	Circuit
LEDET	FiQuS	XYCE*
PyBBQ	LEDET	
	ProteCCT	
BBQ	SIGMA	PSPICE**
Materials properties	Component library	

Protection of Canted-Cosine-Theta

→ Simulate electro-magnetic and thermal transients in canted-cosine-theta (CCT) using finite-differences method.

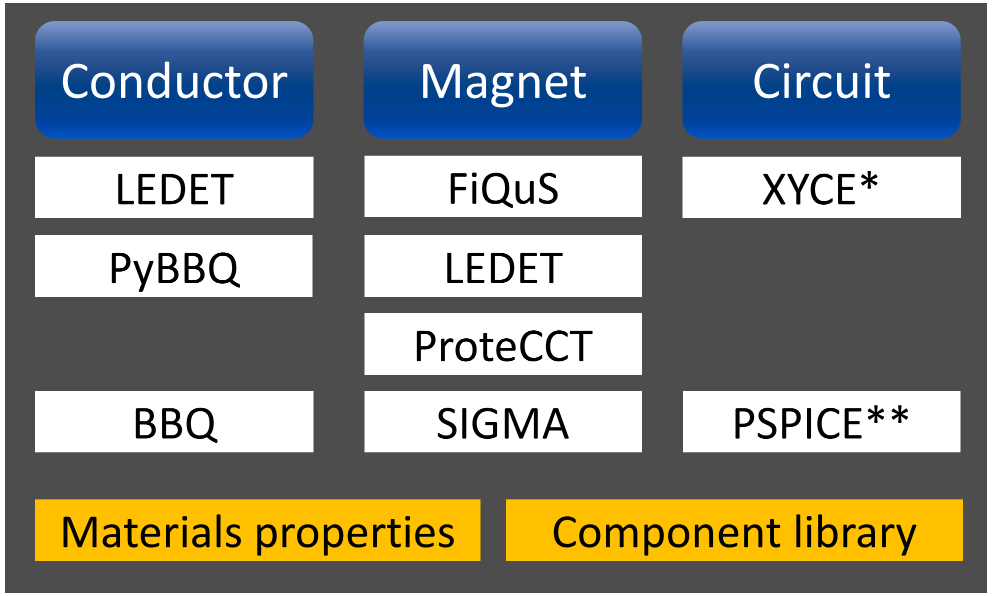




Simulation of **T**ransient **E**ffects in **A**ccelerator superconducting **M**agnet circuits

*Free tools from Sandia Labs. **Commercial circuit solver from Cadence Design Systems

STEAM framework



CHALLENGES

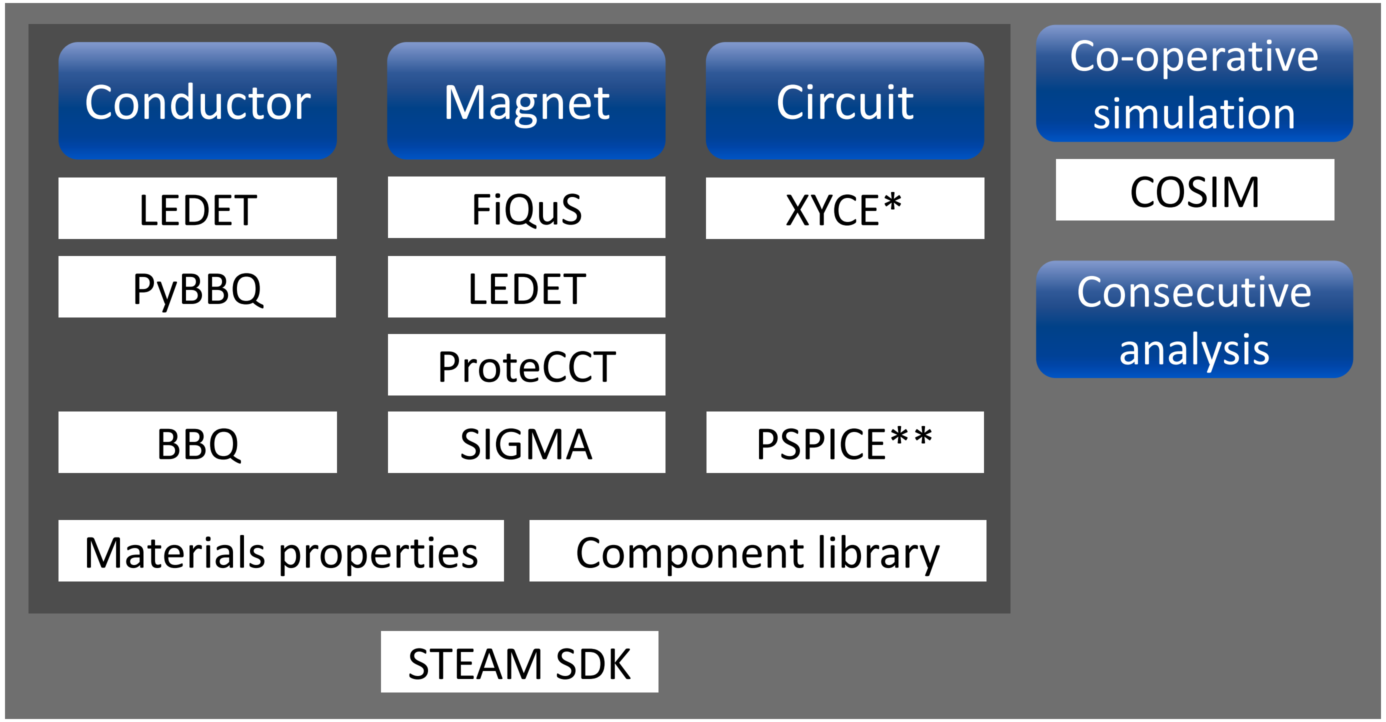
- ✓ Maintain consistency across simulation tools.
- ✓ Use the same material properties.
- ✓ Duplication of the same inputs.
- ✓ Maintain a library of validated reference models.

→ Unified material properties coded in C.
→ Unified model library for different programs.
→ GitLab-versioned code and library.

Simulation of **T**ransient **E**ffects in **A**ccelerator superconducting **M**agnet circuits

*Free tools from Sandia Labs. **Commercial circuit solver from Cadence Design Systems

STEAM framework



Simulation of **T**ransient **E**ffects in **A**ccelerator superconducting **M**agnet circuits

Co-operative Simulations

→ Run co-operative simulations of models developed in different software.

Consecutive Analysis

→ Maintain long-term reproducibility.

→ Programmatically setup folders, change parameters, and run models.

→ Record software versions.

→ Typical steps in YAML analysis files:

Setup folder;

↳Load reference model;

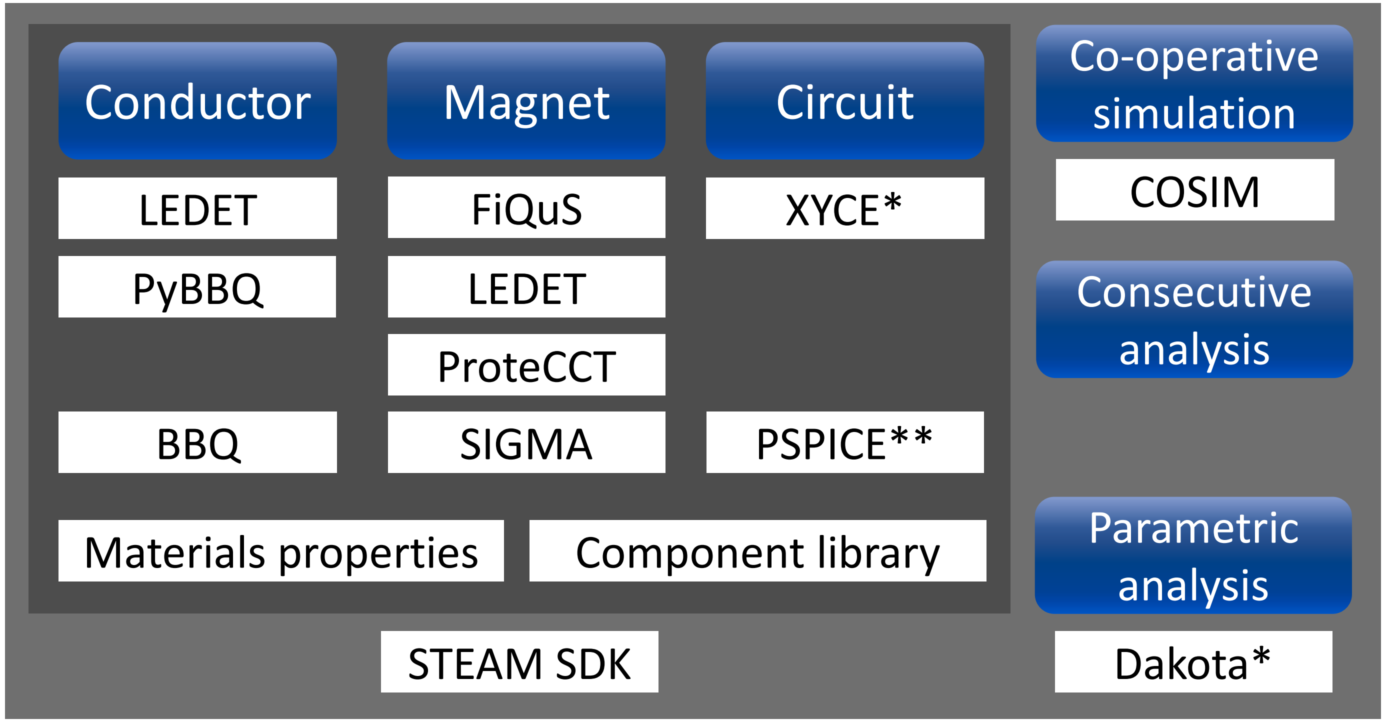
↳Change parameters for new model;

↳Change other parameters for another model;

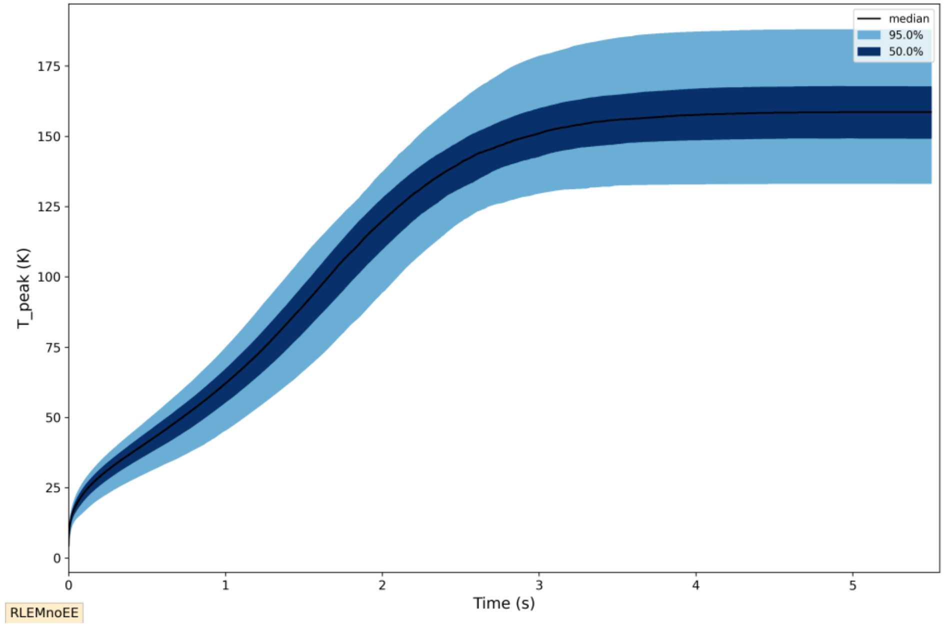
↳ Run all simulations.

*Free tools from Sandia Labs. **Commercial circuit solver from Cadence Design Systems

STEAM framework



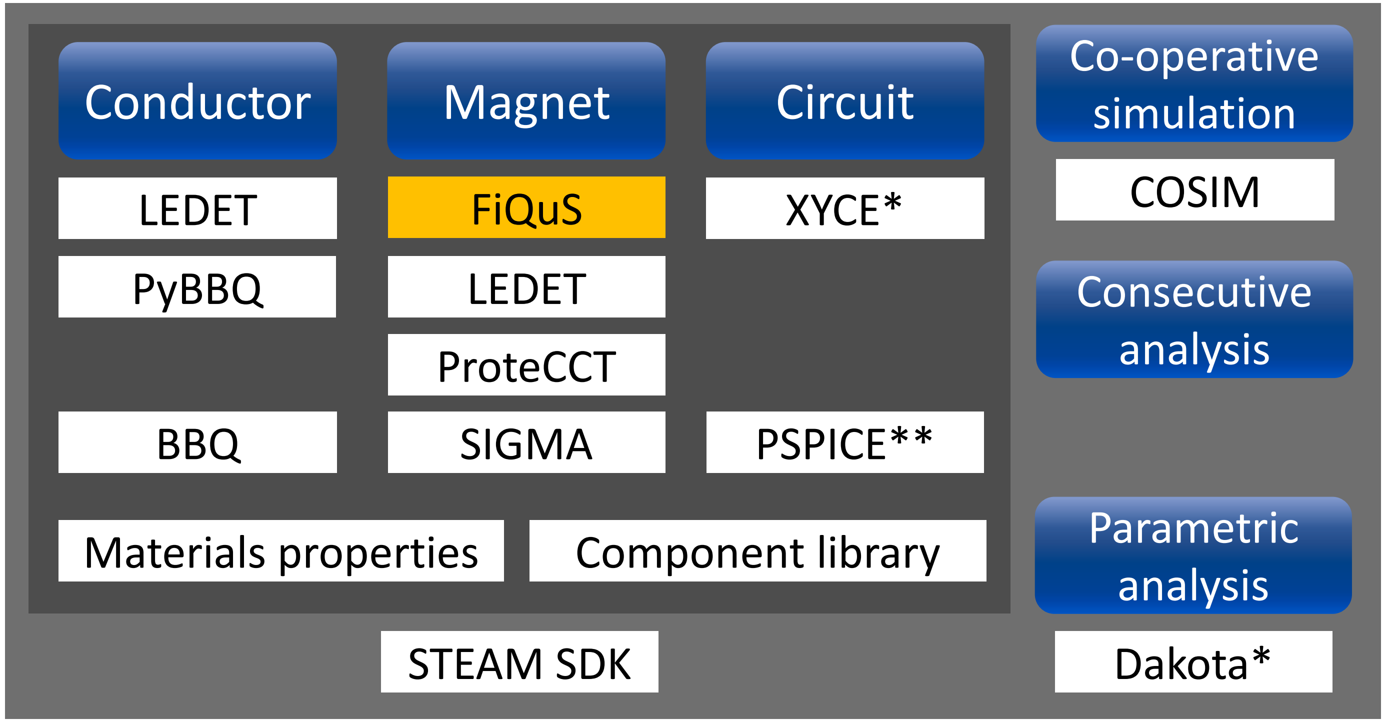
Parametric Analysis
→ Run sensitivity studies, multi-objective optimization, uncertainty quantification.
→ Directly coupled to model data files.
→ Compatible with consecutive analysis.



Simulation of **T**ransient **E**ffects
in **A**ccelerator superconducting
Magnet circuits

*Free tools from Sandia Labs. **Commercial circuit solver from Cadence Design Systems

STEAM framework



Simulation of **T**ransient **E**ffects
in **A**ccelerator superconducting
Magnet circuits

Finite Element **Qu**ench **S**imulator

→ Coded in Python and uses its libraries.
→ Based on Gmsh and GetDP.

onelab.info

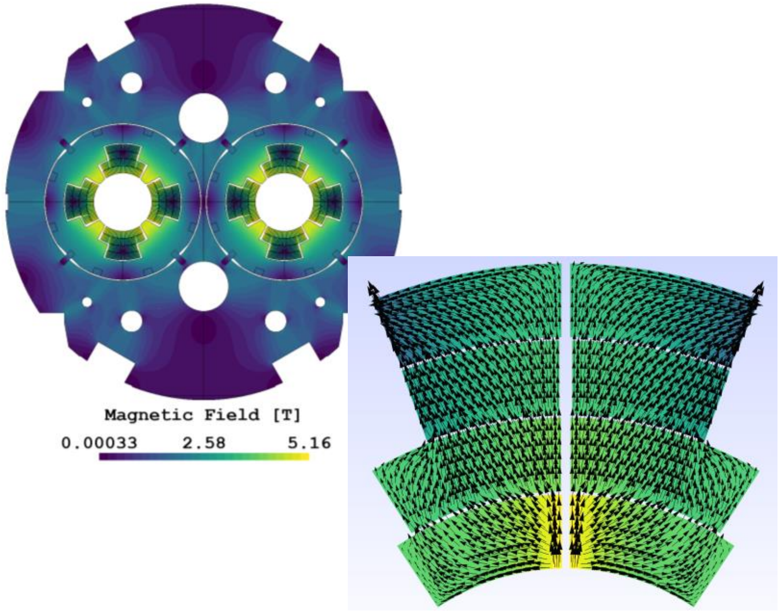
→ Lives in CERN GitLab and uses CI/CD.
→ Free and open-source!

cern.ch/fiqus

*Free tools from Sandia Labs. **Commercial circuit solver from Cadence Design Systems

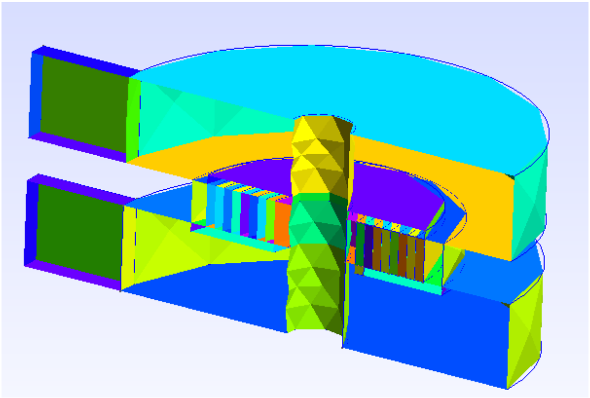
FiQuS applications

2D multi-pole magnets



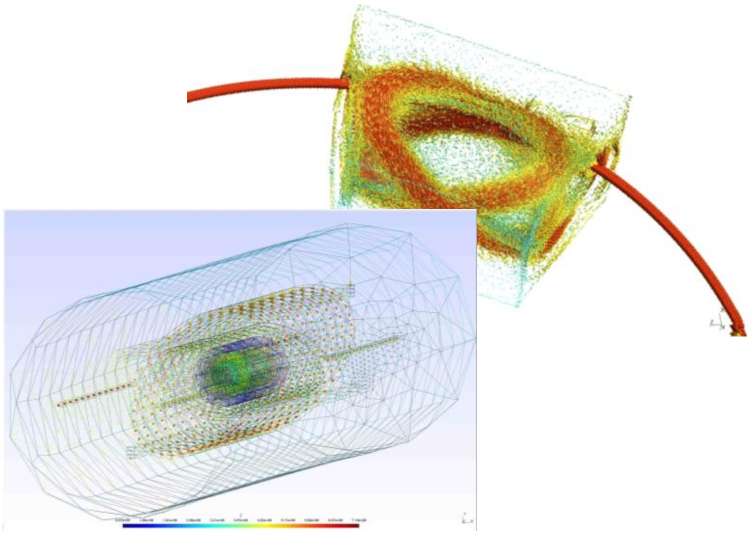
- B and M calculation.
- Thermal transient and steady state sim.
- Stand-alone quench simulations.

3D NI HTS coils



- HTS coils ramp up and down simulations.
- HTS coils quench simulations.
- Coils with insulation, no-insulation, partial-insulation.

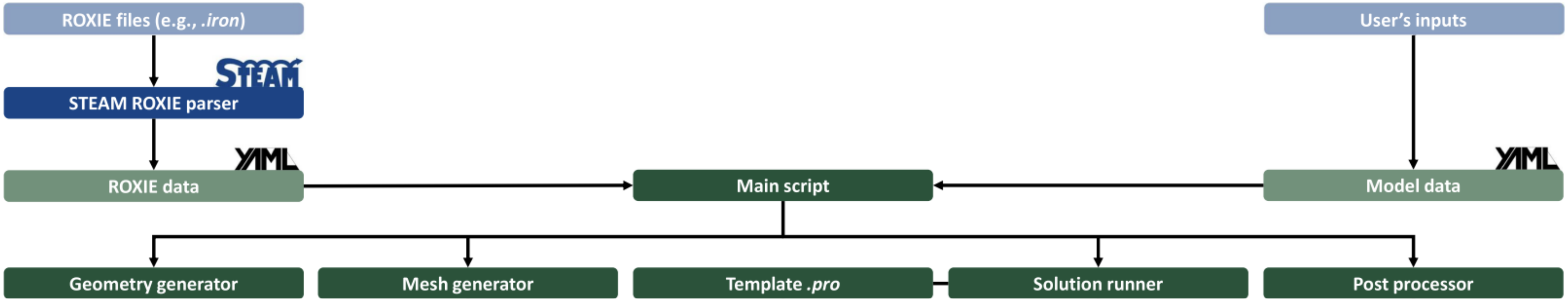
3D CCT magnets



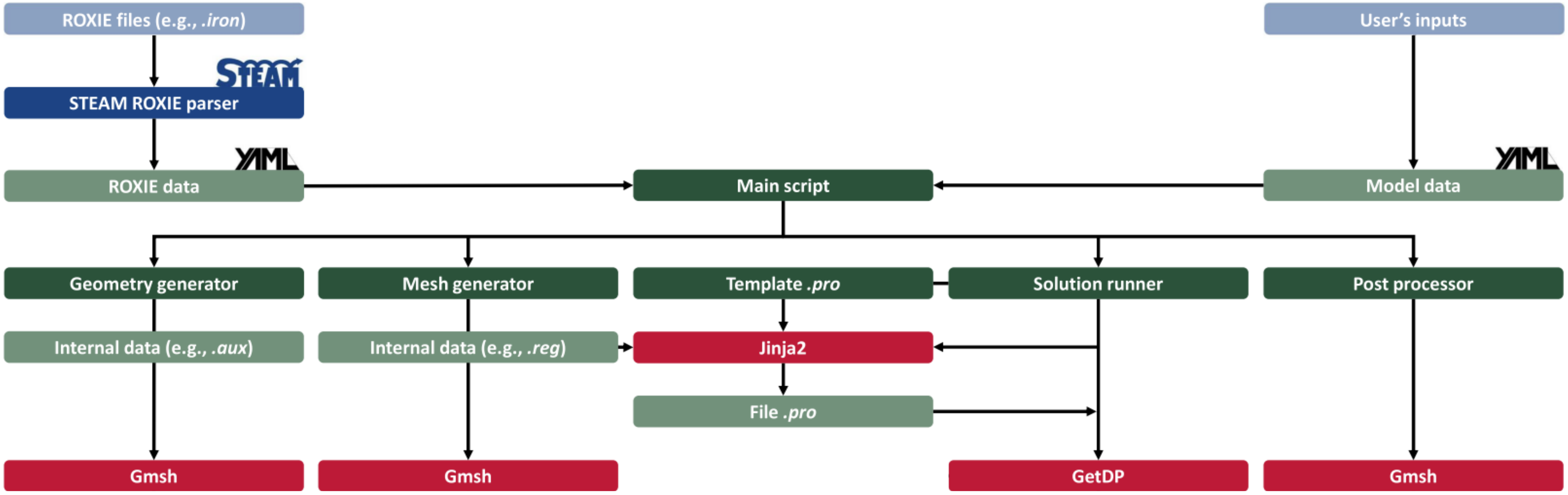
- B, M, V, T calculation.
- Eddy currents in the formers.
- Temperature of the formers.
- Co-simulation with LEDET.

FiQuS code structure

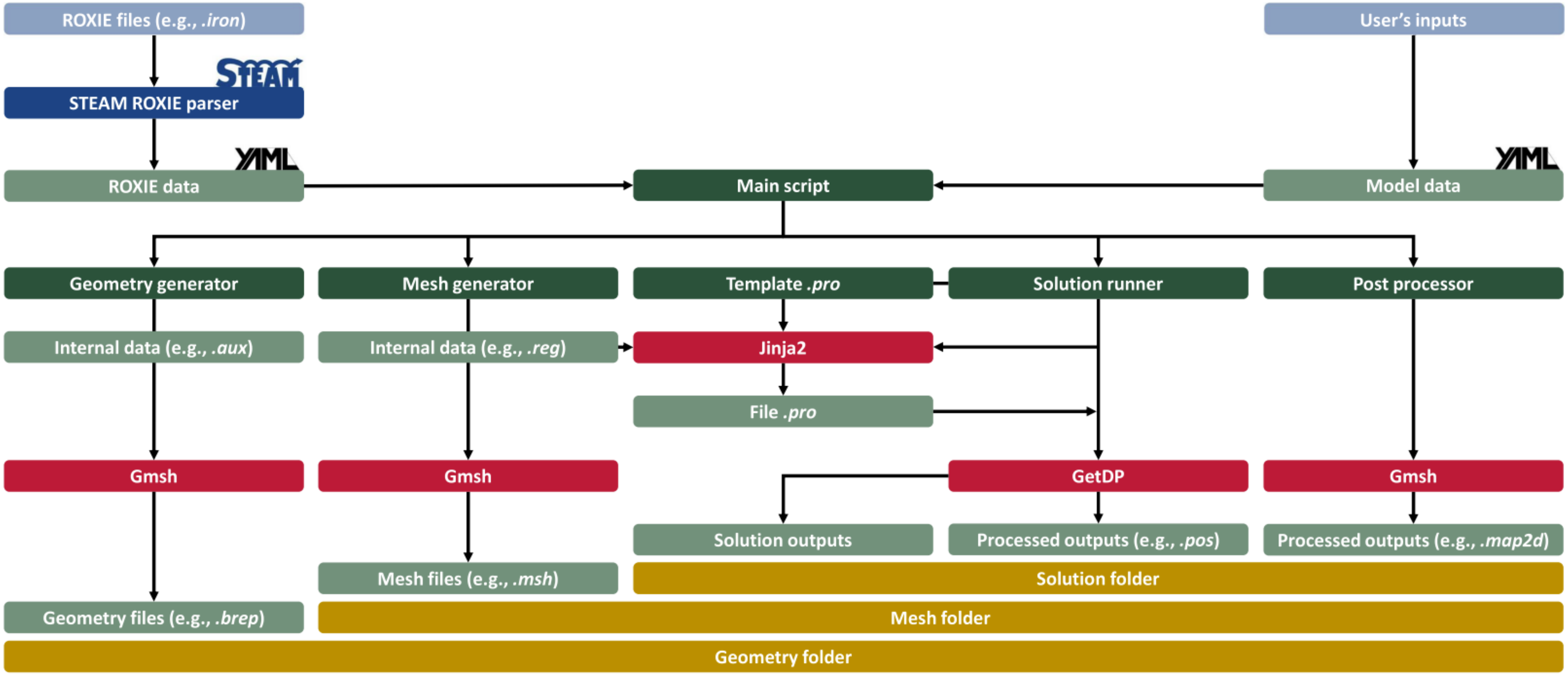
FiQuS code structure



FiQuS code structure

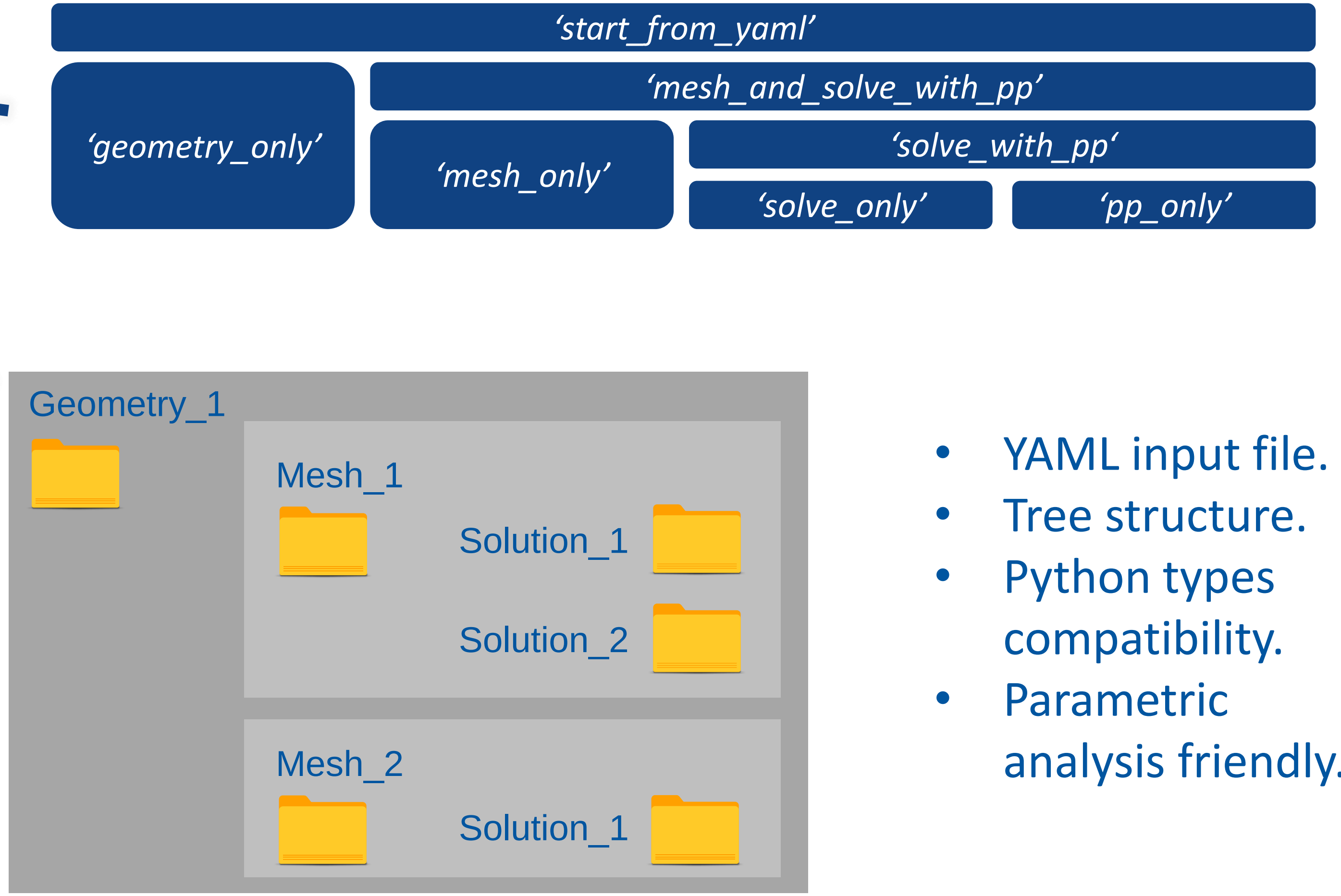


FiQuS code structure



FiQuS input file, run types, and folder structure

```yaml
general:
  magnet_name: MQXA
run:
  type: mesh_and_solve_with_pp
  geometry: 1
  mesh: null
  solution: null
  launch_gui: true
  overwrite: false
magnet:
  type: multipole
  geometry:
    with_iron_yoke: false
    with_wedges: true
  mesh:
    default_mesh: true
    mesh_iron:
    mesh_coil:
  solve:
    thermal:
      solved: 'transient'
      coolant_temperature: 4.2
      boundary_conditions:
        temperature:
        heat_flux:
        cooling:
      transient:
        time_pars:
        initial_temperature: 4.2
        quench_initiation:
    electromagnetics:
      solved: ''
      boundary_conditions:
      transient:
    thin_shells: true
    pro_template: Multipole_TH_TS_template.pro
  postproc:
```



- YAML input file.
- Tree structure.
- Python types compatibility.
- Parametric analysis friendly.

FiQuS current status

FiQuS project started in 2022 and is under active development.

FiQuS code is released for these magnet types:

1. **Magnetostatic** solution of **2D multipole** magnets with iron and integrated with STEAM SDK [1].
2. **Magnetostatic** solution of **3D CCT** magnets and integrated with STEAM SDK [2].

We are working on and plan to release:

3. **Transient** electromagnetic + **thermal** of **2D multipole** magnets
4. **Transient** electromagnetic + **thermal** of **3D CCT** and co-simulation with other STEAM tools.
5. **Full integration** of **3D pancake HTS coils** in FiQuS.

[1] Vitrano, A., et al. (2023). An open-source finite element quench simulation tool for superconducting magnets. *IEEE Transactions on Applied Superconductivity*, 33(5), 1-6.

[2] Wozniak, M., et al. (2023). Fast Quench Propagation Conductor for Protecting Canted Cos-Theta Magnets. *IEEE Transactions on Applied Superconductivity*, 33(5), 1-5.

FiQuS current status

FiQuS project started in 2022 and is under active development.

FiQuS code is released for these magnet types:

1. **Magnetostatic** solution of **2D multipole** magnets with iron and integrated with STEAM SDK [1].
2. **Magnetostatic** solution of **3D CCT** magnets and integrated with STEAM SDK [2].

Thermal Thin Shell approximation

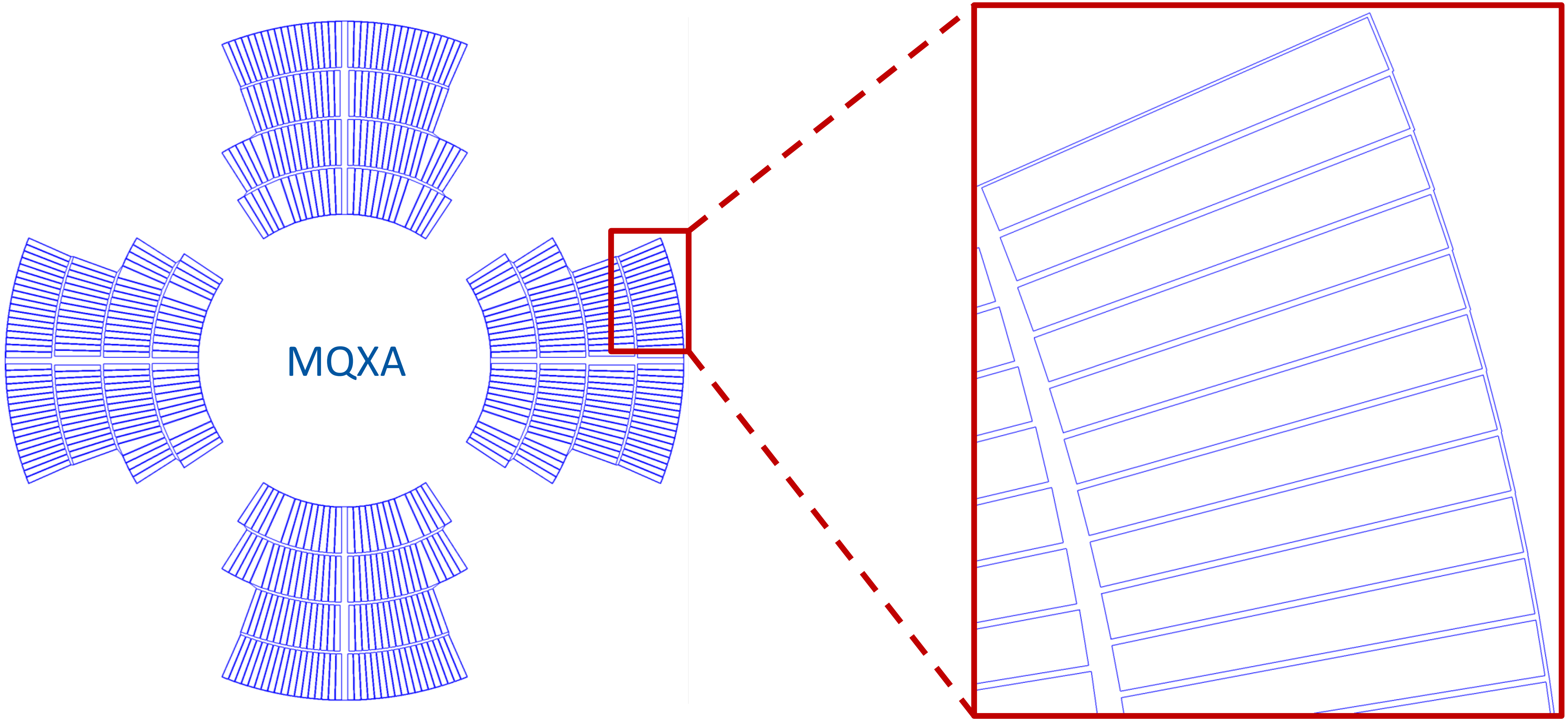
We are working on and plan to release:

3. **Transient** electromagnetic + **thermal** of **2D multipole** magnets
4. **Transient** electromagnetic + **thermal** of **3D CCT** and co-simulation with other STEAM tools.
5. **Magnetothermal** solution for **3D pancake HTS coils** and with full integration with FiQuS.

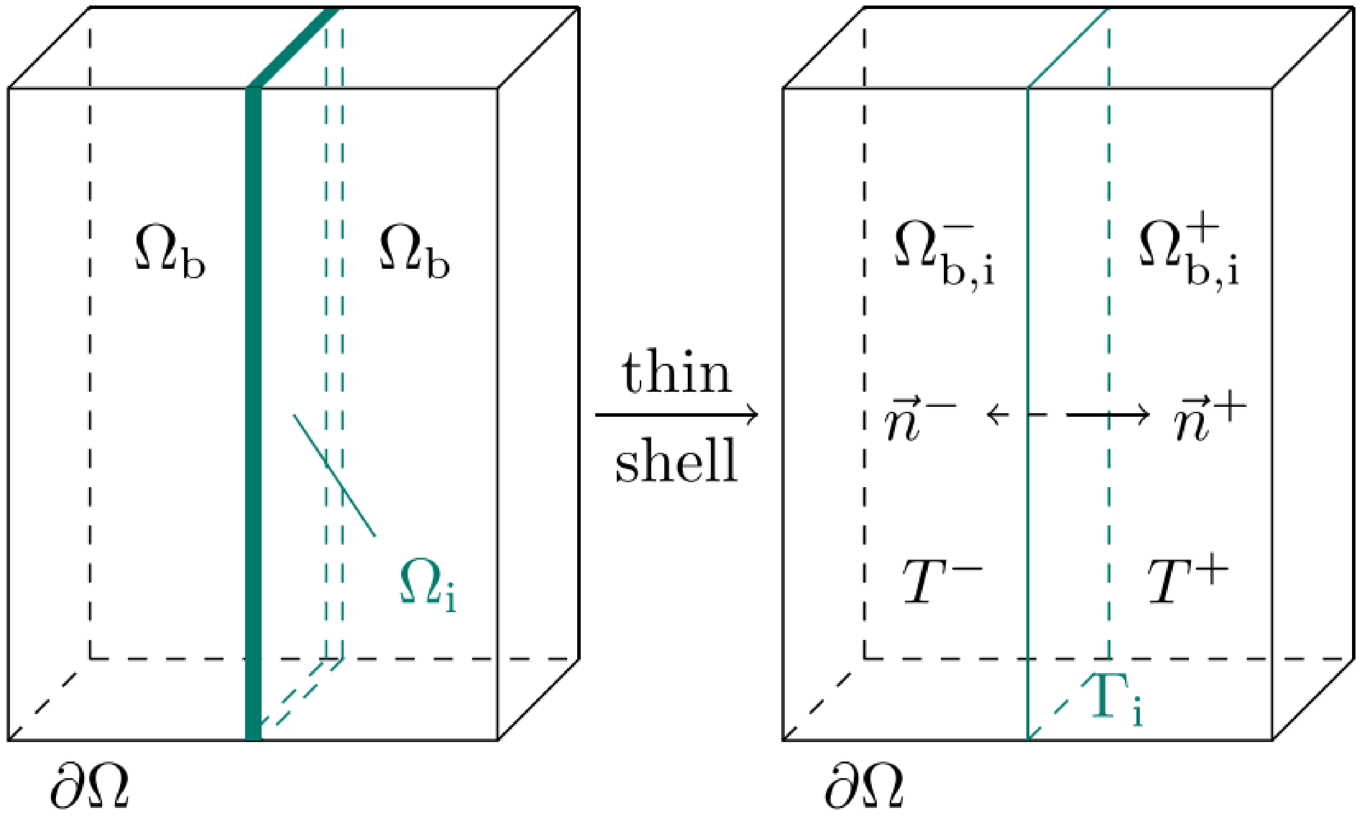
[1] Vitrano, A., et al. (2023). An open-source finite element quench simulation tool for superconducting magnets. *IEEE Transactions on Applied Superconductivity*, 33(5), 1-6.

[2] Wozniak, M., et al. (2023). Fast Quench Propagation Conductor for Protecting Canted Cos-Theta Magnets. *IEEE Transactions on Applied Superconductivity*, 33(5), 1-5.

Thin shell approximation motivation



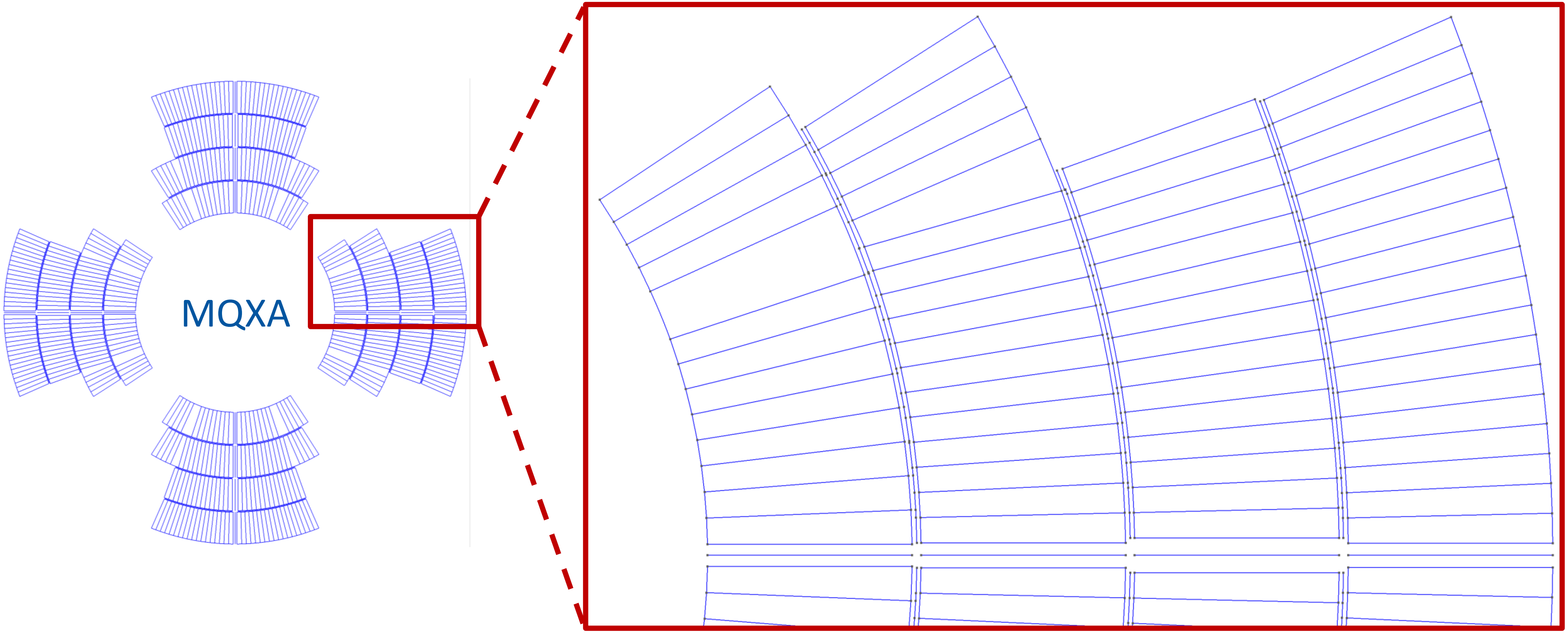
Thin shell approximation basics



- Volume Ω_i → Surface Γ_i .
- Internal 1D FE discretization of Ω_i :
  - ➢ Able to handle non-linearities;
  - ➢ Supports classical BCs;
  - ➢ Supports quench heaters;
  - ➢ Supports multiple layers.

Schnaubelt, E., Wozniak, M., & Schöps, S. (2023). Thermal thin shell approximation towards finite element quench simulation. *Superconductor Science and Technology*, 36(4), 044004.

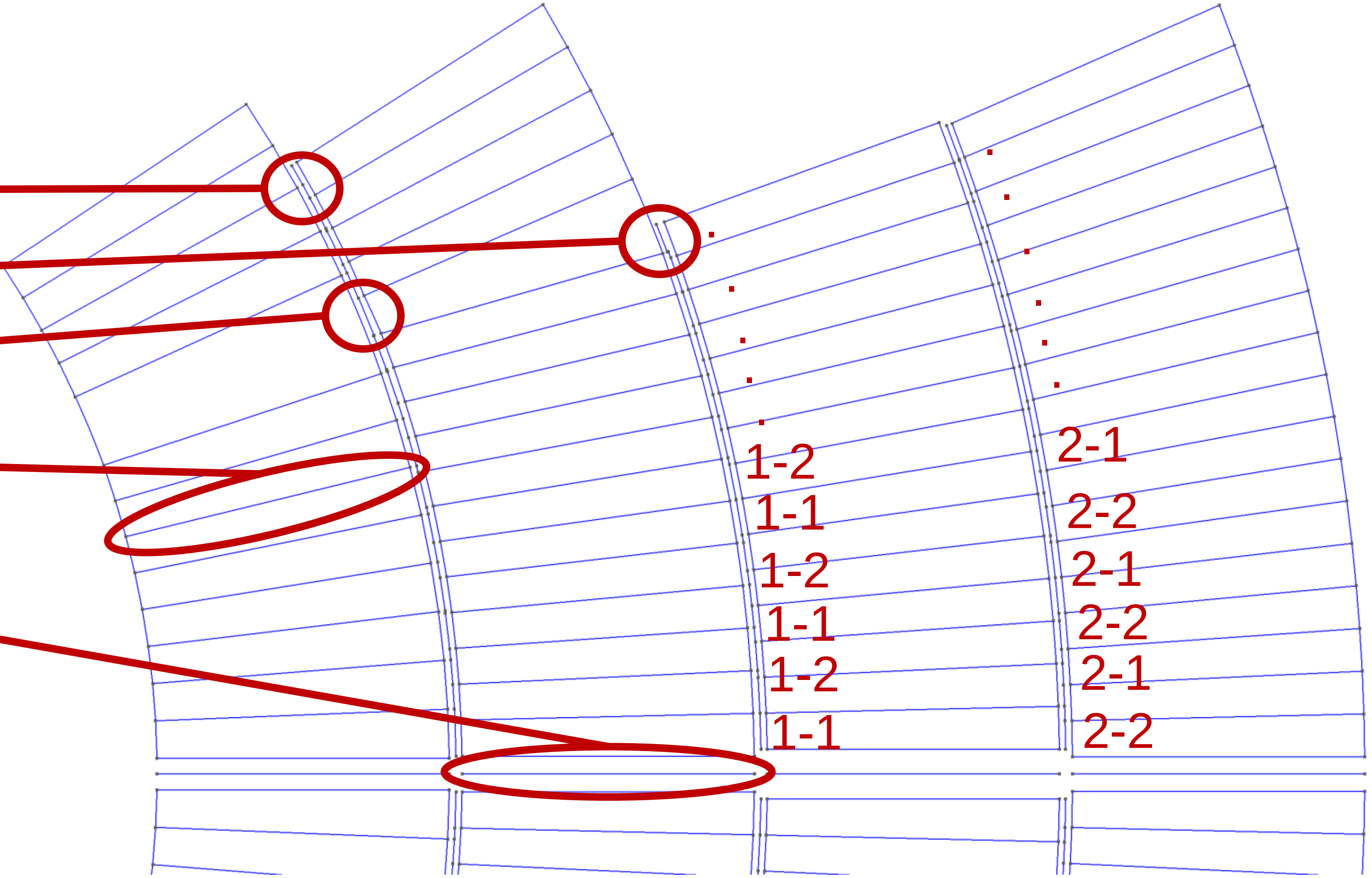
Thin shells in multi-pole magnets



Thin shells in multi-pole magnets

Thin shell geometry requirements:

- Turn-to-turn (mid-layer)
- Wedge-to-turn
- Wedge-to-wedge
- Turn-to-turn (in block)
- Mid-pole
- Specific line grouping



Needs to work for all the magnets!

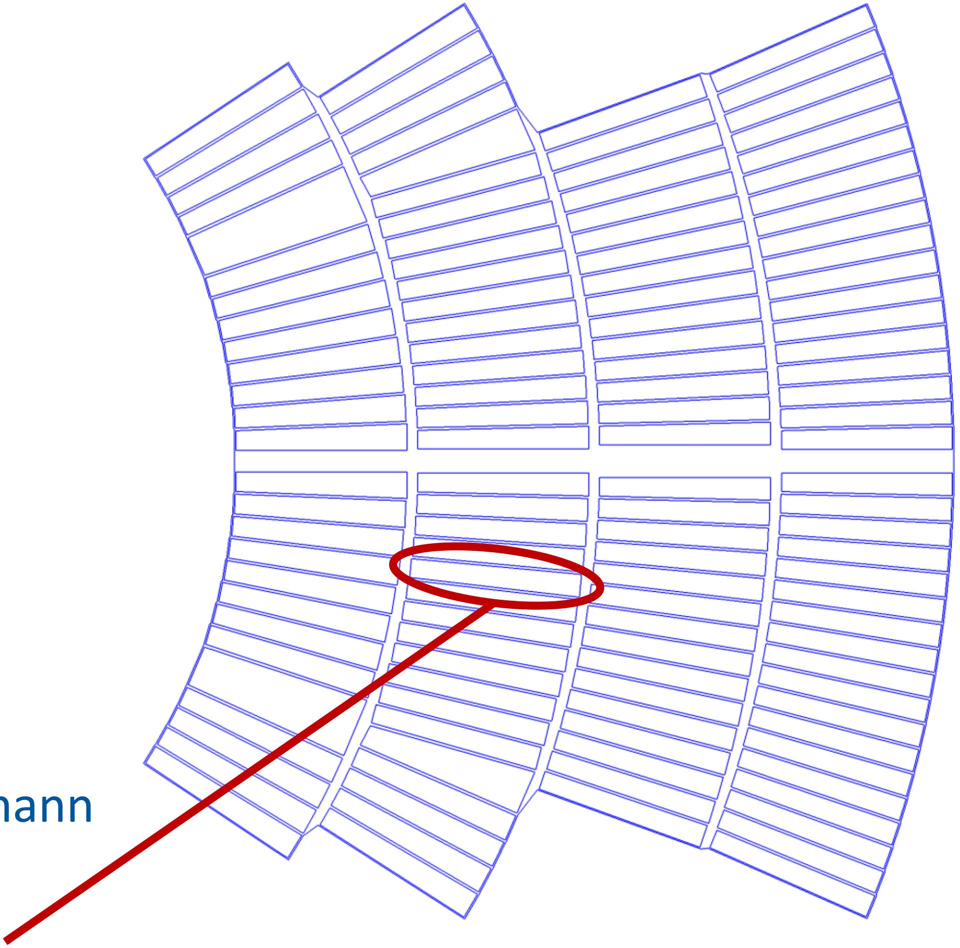
Comparison test case for verification

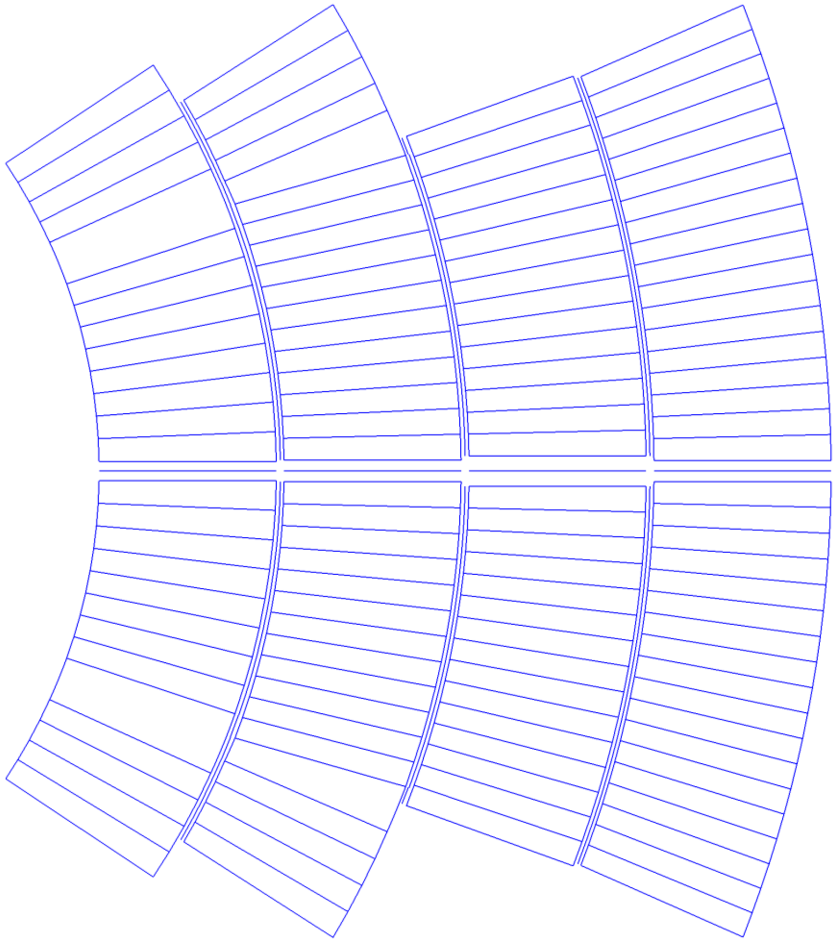
FiQuS

MQXA:
- Nb-Ti / Cu cables
- Cu wedges
- Kapton insulations

Assumptions:
- Constant current
- Constant field

Simulation:
- Thermal transient
- Homogeneous Neumann
- Non-linear model
- Quenching half-turn

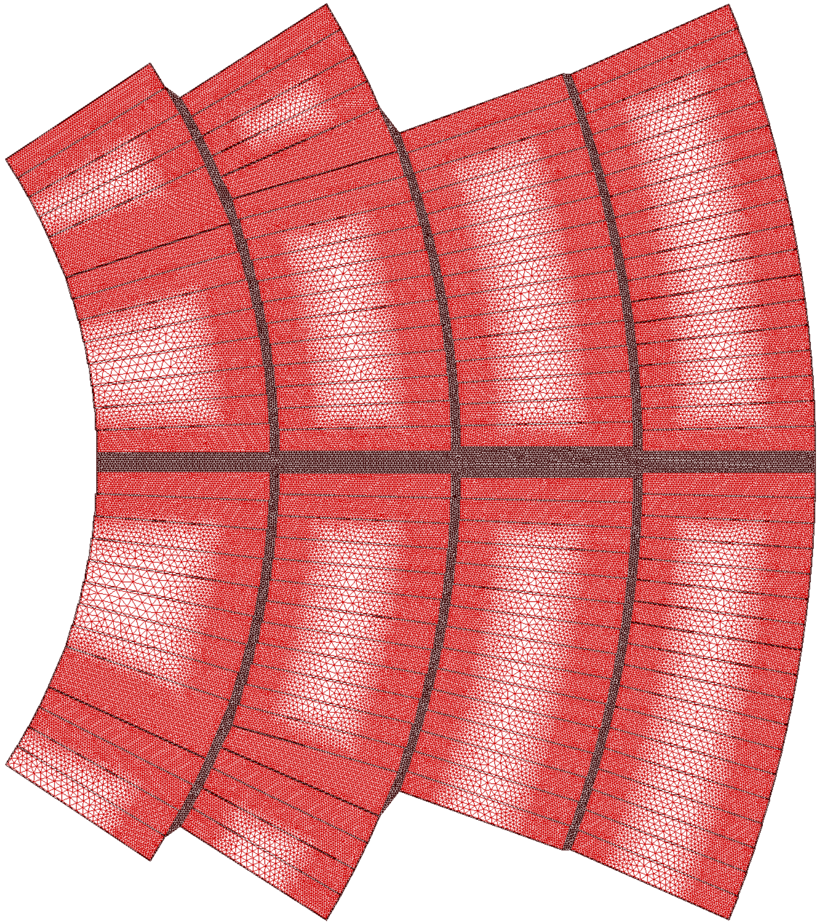

Reference (meshed insulation)


Thin shell model

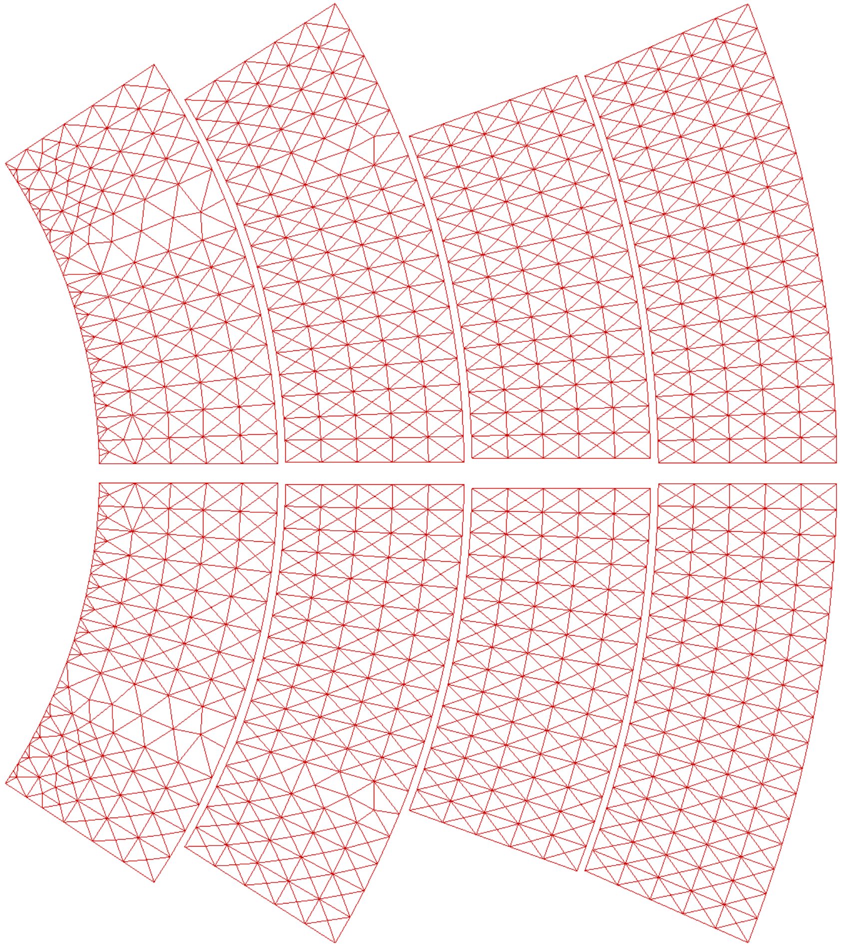
Space discretization

FiQuS

- Mesh-free insulation
- Correction factors



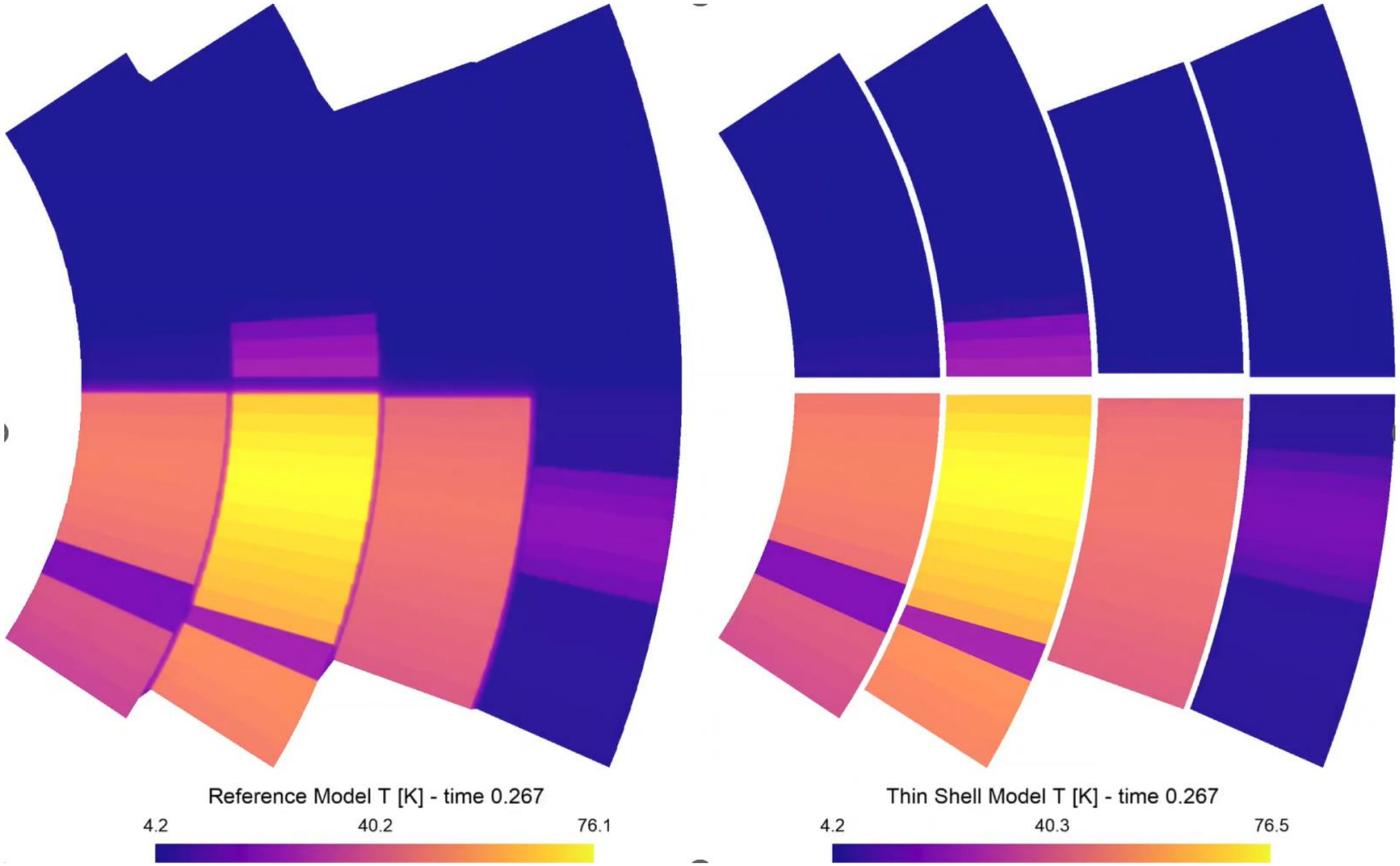
Reference (meshed insulation)



Thin shell model

Thin shell model verification

77’380
DoFs



13’143
DoFs

~10 times shorter solution time!

Conclusions and outlook

- New FE tool called **FiQuS** is being developed within the STEAM framework.
- FiQuS is intended for **quench** simulations of accelerator magnets.
- Specific functionalities developed for 2D **multi-pole** magnet geometries.
- Thermal **thin shell** approximation is used to decrease DoFs and meshing effort.
- Promising preliminary results with good degree of accuracy and **decreased computational cost**.
- Needs to be extended:
  - Further **refinement of geometries** required to decrease reliance on correction factors;
  - Enable **EM-TH coupling** and coupling to circuit parameters;
  - Include **iron-yoke** in thermal solution.
- **Verify** quench simulation results against other STEAM framework tools.

Thank you for your attention

Questions?

cern.ch/steam steam-team@cern.ch cern.ch/fiqus