





The CERN STEAM Simulation Platform

- *short introduction*

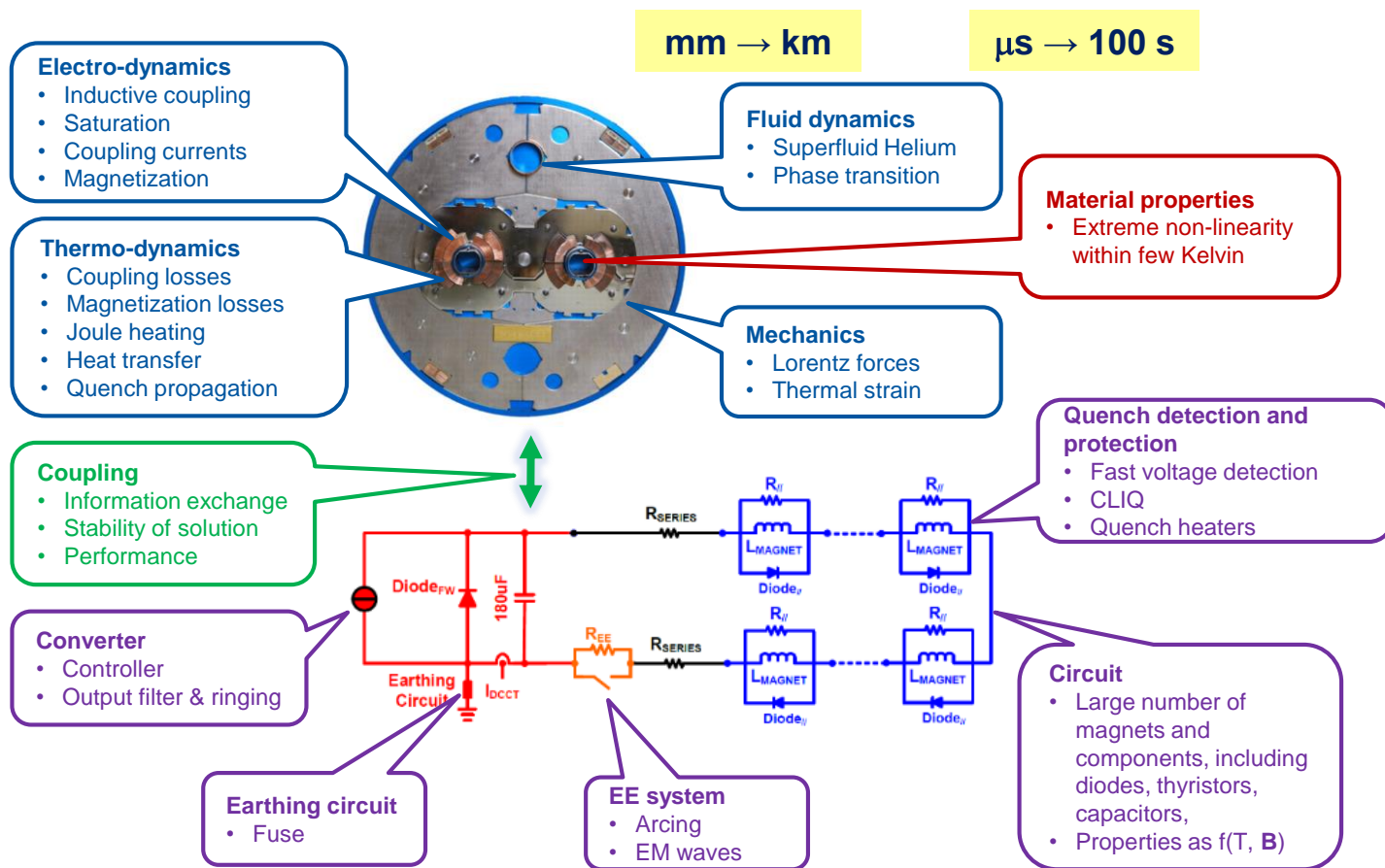
Bernhard Auchmann, Lorenzo Bortot, I. Cortes-Garcia, J. Ghini, Akrivi Liakopoulou,
Michał Maciejewski, Matthias Mentink, Dimitri Pracht, Marco Prioli,
Emmanuele Ravaoli, S. Schöps, Arjan Verweij
TE-MPE-PE

<http://www.cern.ch/STEAM>



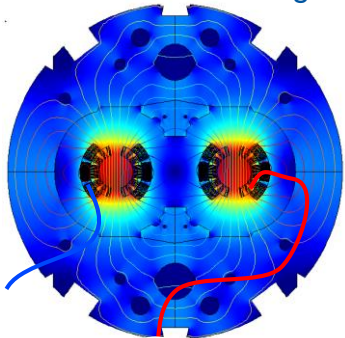
Lodz University of Technology

Simulation of Transient Effects in Accelerator Magnets

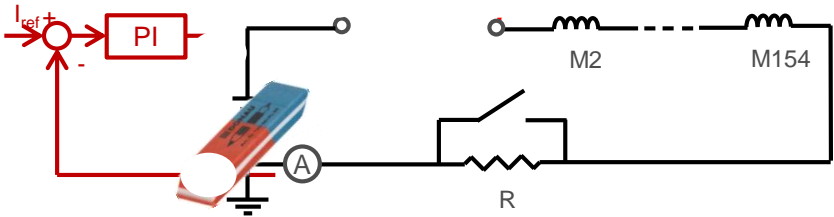


Heterogeneous Domain Decomposition and Coupling

Field model of a magnet



Controller Model



Automatic Generation:

Meta-methods:

	Controller	Superconducting Circuit	Superconducting Magnet
Equation type	Differential-algebraic	Differential-algebraic	Differential-algebraic Partial-differential
Time-stepping	fixed	adaptive	adaptive
# DOF	~10	~10-10k	~1k-10k
Dimension	0D	0D	0D, 1D, 2D
Physical domains	-	Electric	Magnetoquasistatic Thermal Mechanical

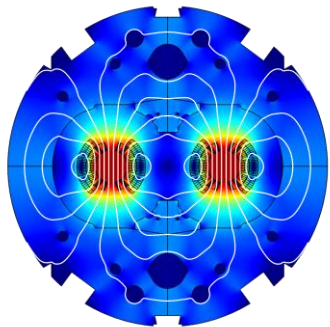
SING	SIGMA
------	-------

Cooperative Simulation
Optimization
Parametric Sweep

Outline

1. Workflows for automatic generation of models
 - a) SIGMA for magnet models
 - b) SING for circuit models
2. Meta-methods
 - a) Co-Simulation for model coupling
 - b) Optimization routine for parameter identification
3. Continuous Integration Pipeline
4. Selected Applications
5. Conclusion

2D FEM Model in COMSOL



Magnetic Vector Potential

$$\nabla \times (\mu^{-1} \nabla \times \vec{A})$$

$$= \vec{j}_s + \sigma \partial_t \vec{A} + \nabla \times \vec{M}$$

Iron yoke
saturation

Eddy
currents

IFCC

$$\mu_0 \mu_r \vec{M}_{\text{IFCC}} = -\tau_{\text{IFCC}} \partial_t \vec{B}$$

ISCC

$$\mu_0 \mu_r \vec{M}_{\text{ISCC}} = -\tau_{\text{ISCC}, \alpha} \partial_t \vec{B}_\alpha$$

Thermal Balance Equation

$$\sigma C_p \partial_t T - \nabla \cdot \lambda \nabla T = Q$$

Quench

Electrical network

$$\Sigma I = 0, \Sigma U = 0$$

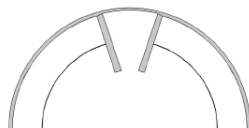
CLIQ

Coil Insulation (Polyimide, Gass Fiber $f(T)$)

- Ampère's Law Linear
- Thermal Balance (Passive)

Wedges (Copper, Steel, $f(T)$)

- Ampère's Law Linear
- Weak constraint ($I_{\text{tot}} = 0$)
- Thermal Balance (Eddy Currents)

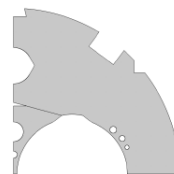


Outer Shell (Steel – Aluminum, $f(T, B)$)

- Ampère's Law Linear
- Thermal Balance (Eddy Currents)

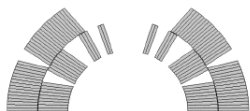
Iron Yoke (Laminated Iron, $f(B, T)$)

- Ampère's Law Non Linear
- Thermal Balance (Hysteresis)



Coil (Nb₃Sn, NbTi, Copper, $f(T, B)$)

- Ampère's Law Equivalent Magnetization
- Persistent Magnetization
- Thermal Balance (Dynamic Losses)
- Quench transition

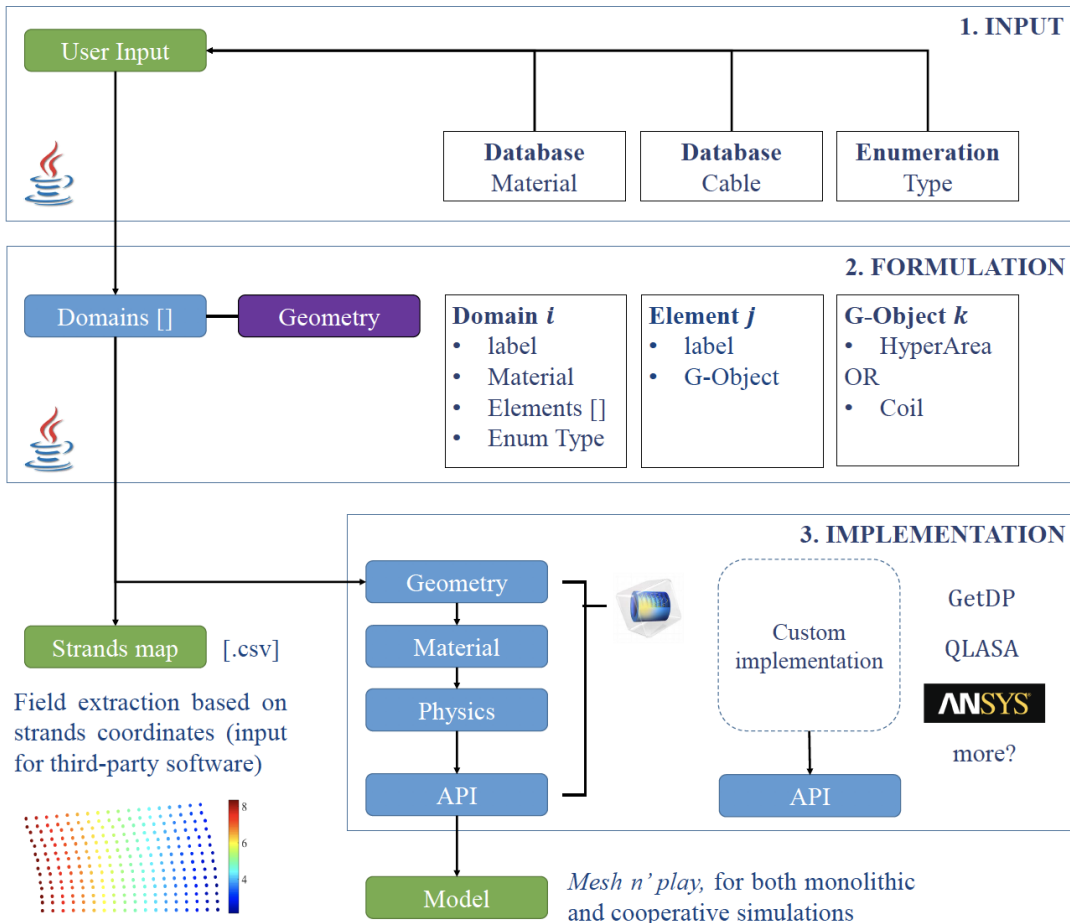


Collars (Laminated Steel $f(T)$)

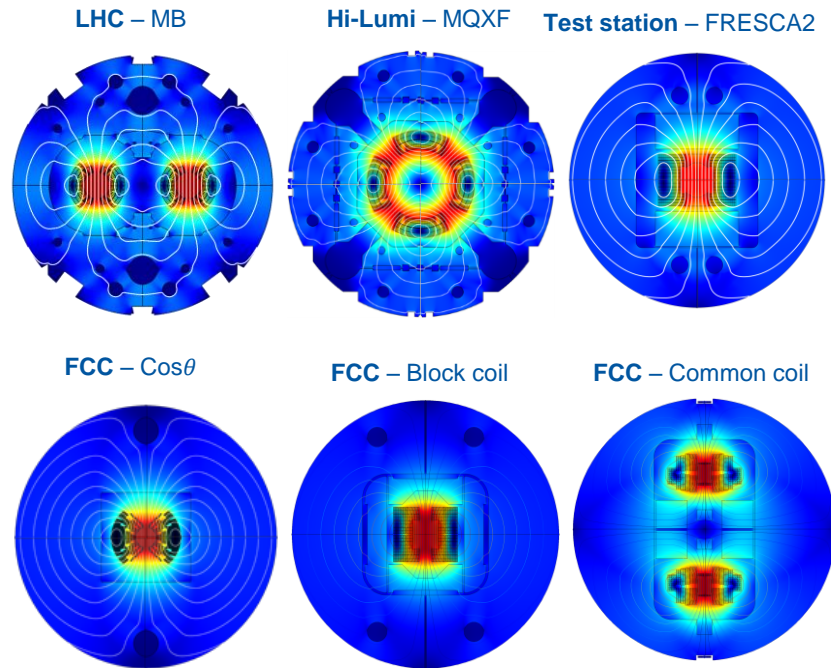
- Ampère's Law Linear
- Thermal Balance (Passive)



STEAM Integrated Generator of Magnets for Accelerators



- *Mesh & play* models
- Construction time of minutes
- Automation against error-prone, manual work

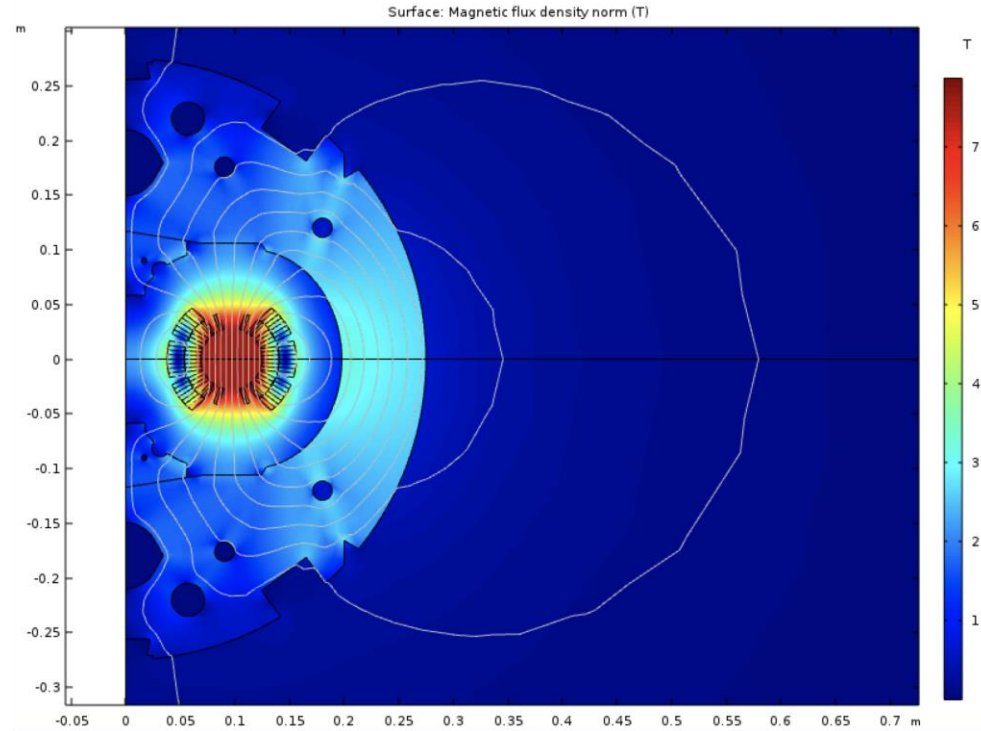


Other models: 11 Tesla, D1, ... and many more!

STEAM SIGMA - Demo

LHC Main Dipole Magnet

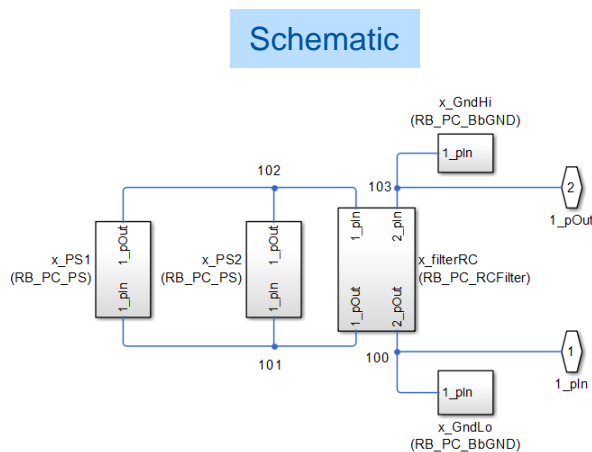
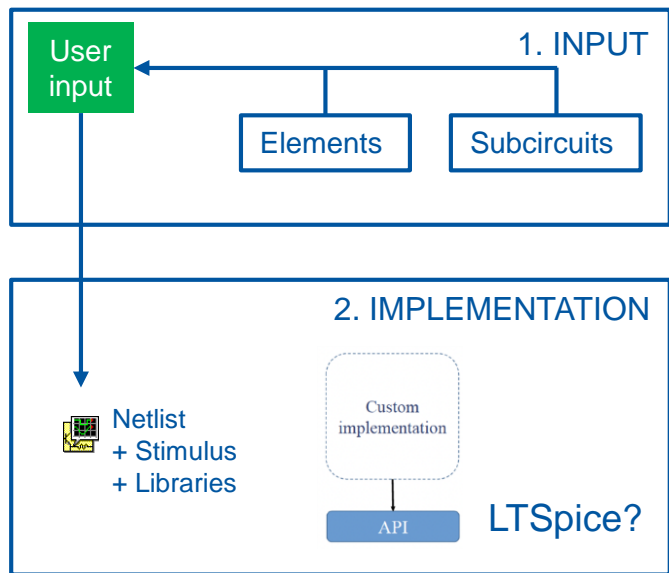
- Single Aperture
- Magneto-static study
- # 45k mesh elements
- # 10k LoC – operations in COMSOL



Release status: In the process of the first release

STEAM Integrated Network Generator

- **Use of netlists**, i.e., textual description of circuit elements and interconnections (topology).
- **Automatic generation of netlists**, useful for parametric studies including changes to circuit topology.
- A “for loop” for PSpice to build models of large circuits (~10 k elements)



Netlist

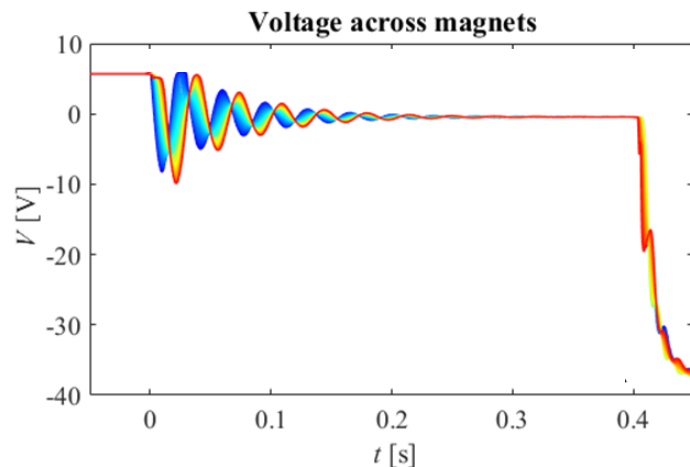
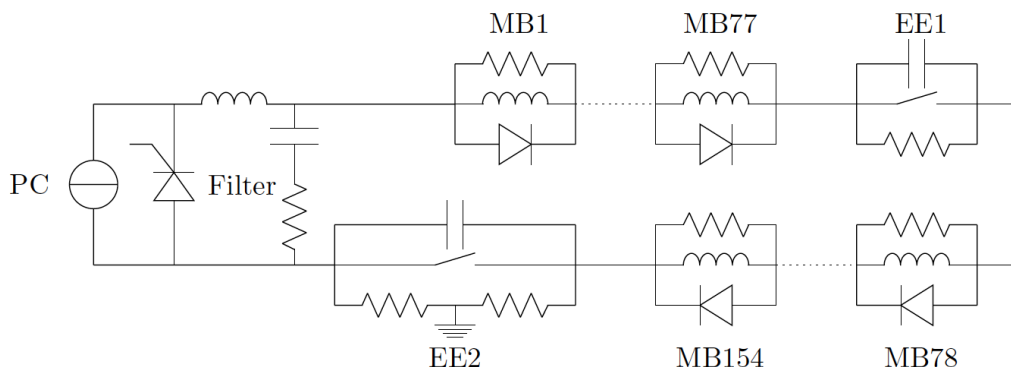
```
.subckt RB_PC_Full 1_pIn 1_pOut
v1_bbIn_PH (1_pIn 100) 0
x_GndLo (100) RB_PC_BbGND
x_filterRC (102 101 103 100) RB_PC_RCFilter
x_PS1 (101 102) RB_PC_PS
x_PS2 (101 102) RB_PC_PS
x_GndHi (103) RB_PC_BbGND
v2_bbOut_PH (1_pOut 103) 0
.ends
```

- Modular, expandable, versioned 😊
- Static libraries of main components are available 😊
- Netlist more difficult to interpret than a schematic 😞

STEAM SING - Demo

LHC Main Dipole Circuit

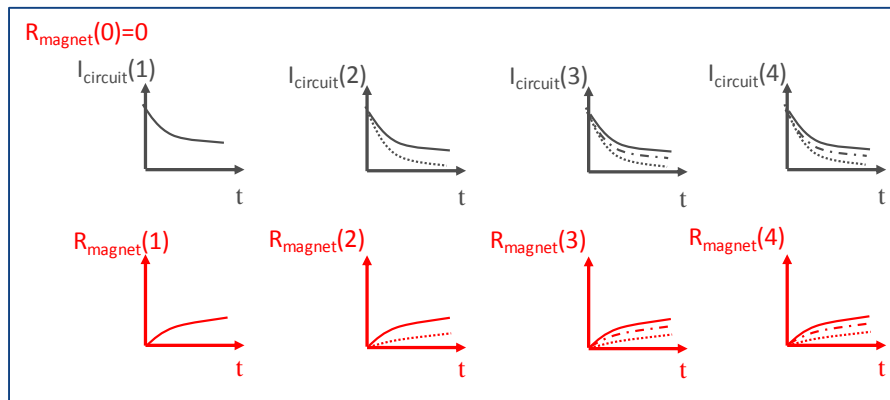
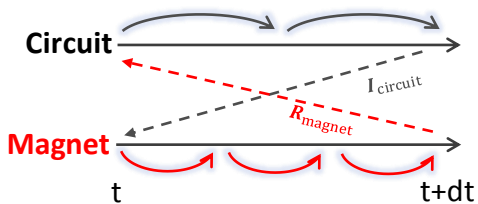
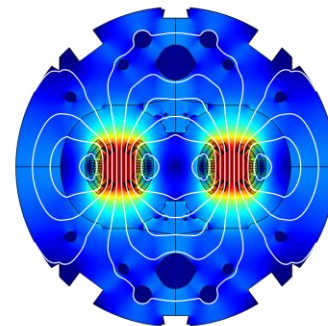
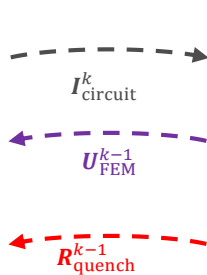
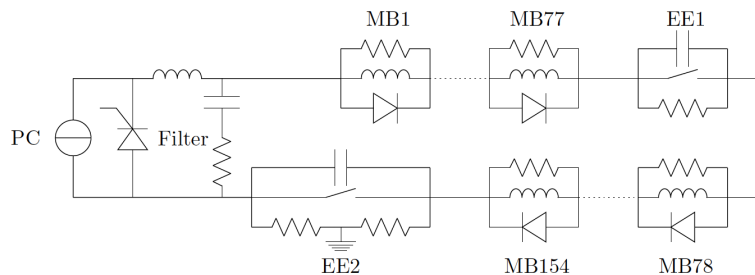
- Chain of 154 magnets
- Voltage distribution during a power abort
- # 6072 elements
- # 1324 LoC – operations in SPICE



Release status: released internally, external release on demand

Cooperative Simulation - Motivation

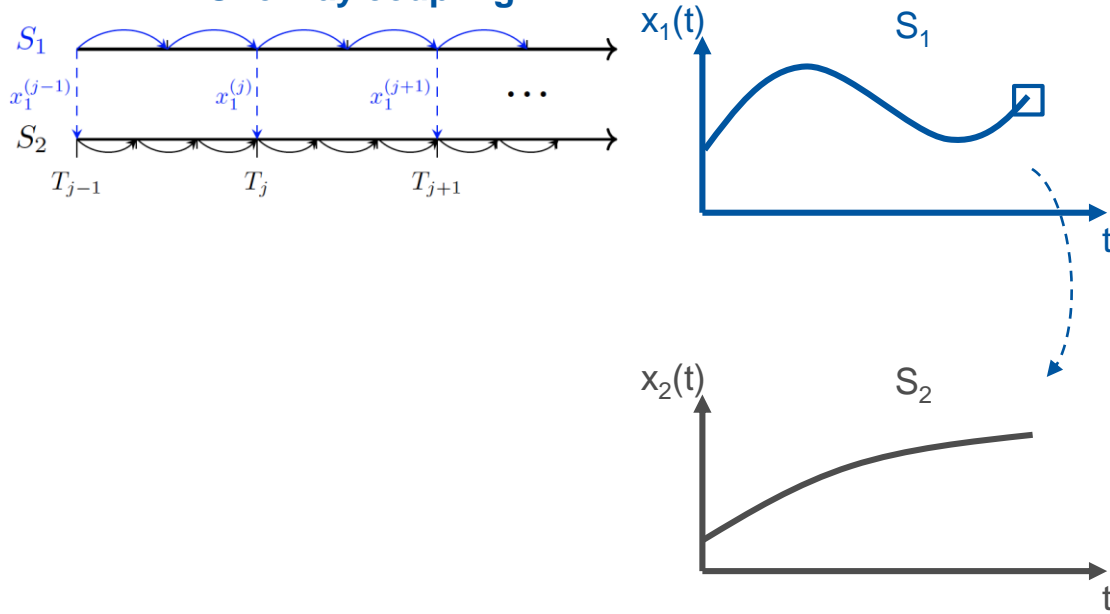
At this stage we have automatically created the LHC main dipole circuit and a main dipole itself.



Iteration until convergence is reached

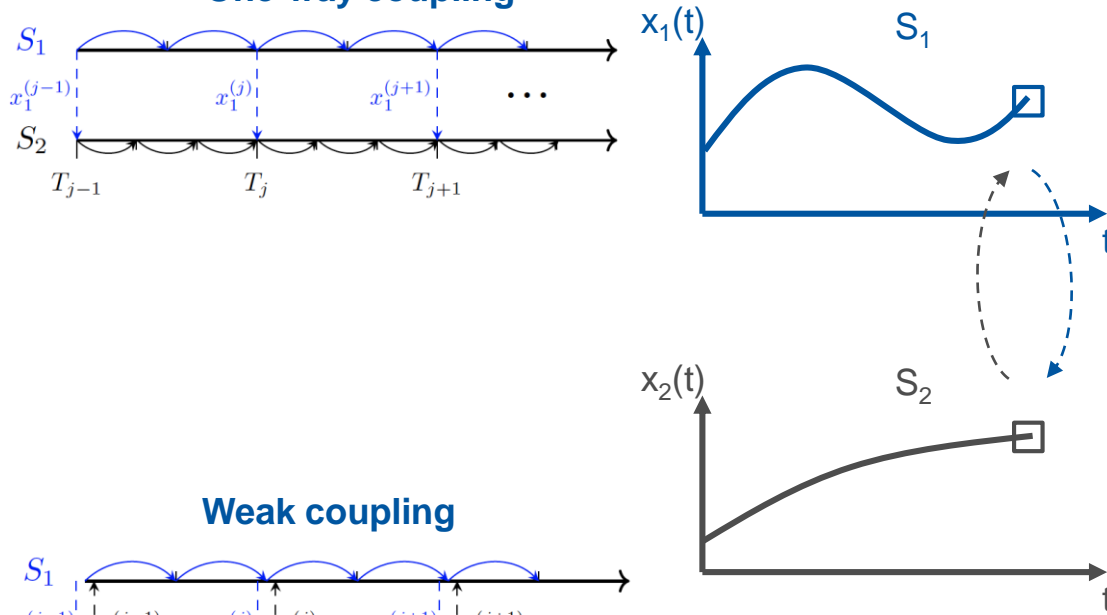
Co-Simulation Algorithms* (1/4)

One-way coupling

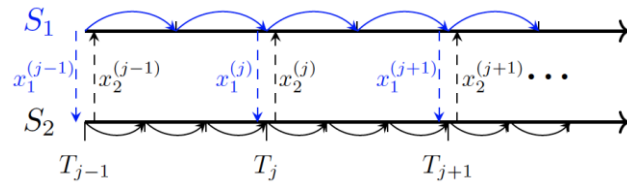


Co-Simulation Algorithms* (2/4)

One-way coupling

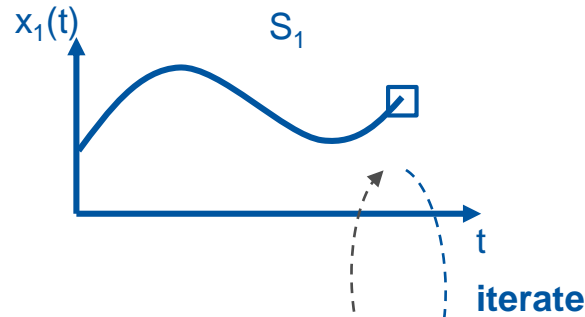
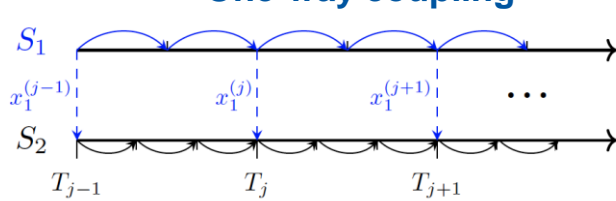


Weak coupling

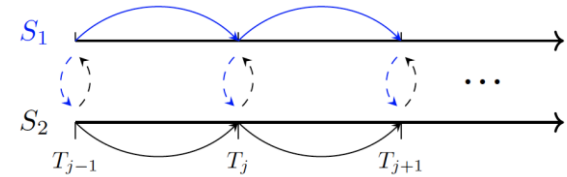


Co-Simulation Algorithms* (3/4)

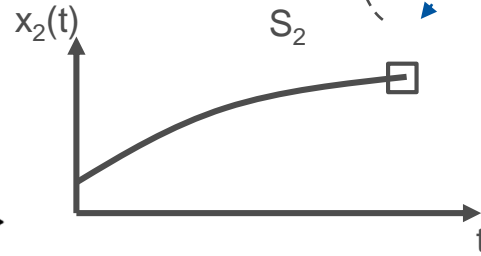
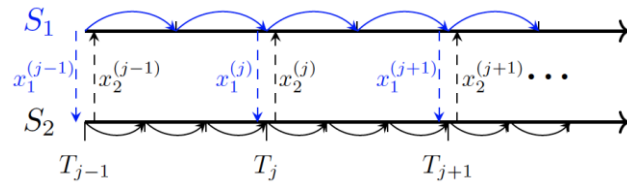
One-way coupling



Strong coupling

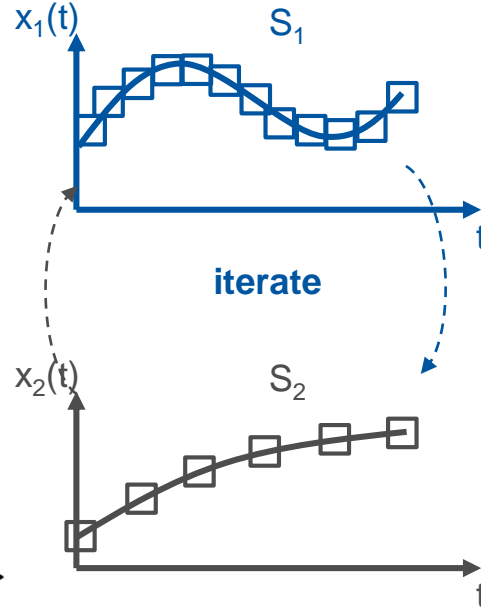
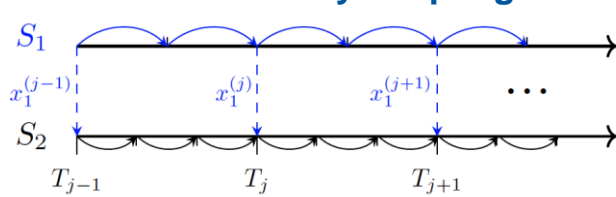


Weak coupling

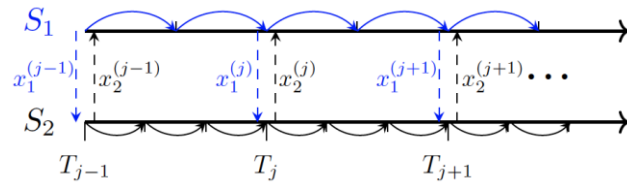


Co-Simulation Algorithms* (4/4)

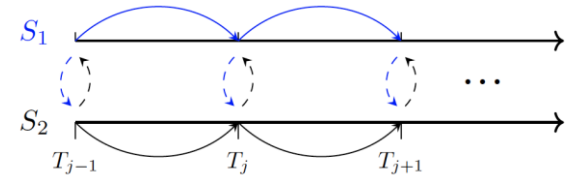
One-way coupling



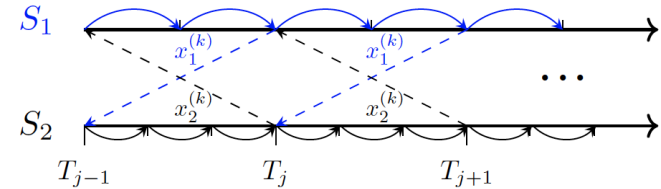
Weak coupling



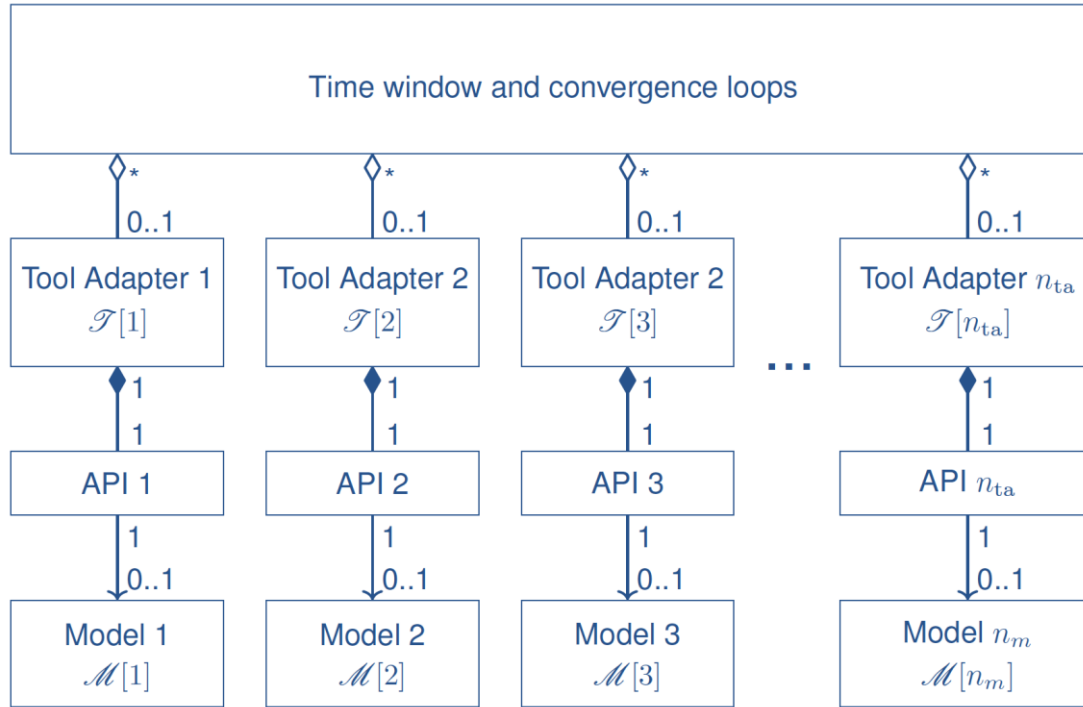
Strong coupling



Waveform Relaxation



Co-Simulation Framework Architecture



Each tool adapter implements a *ToolAdapter* abstract class

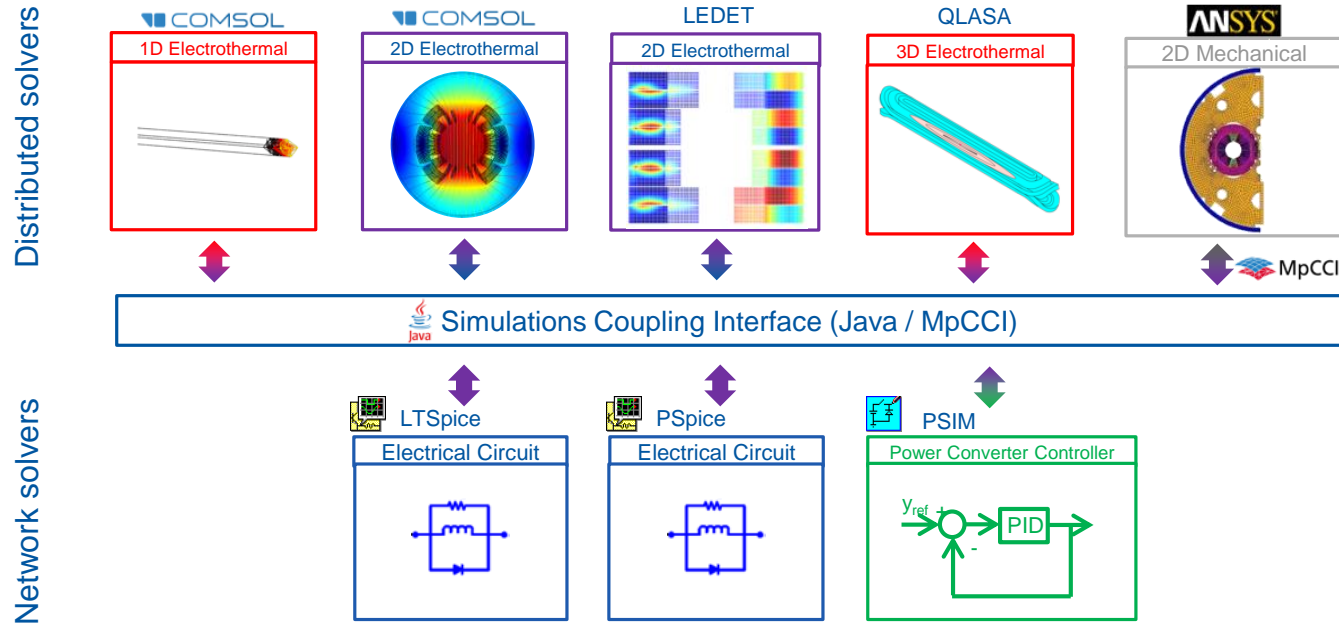
<i>ToolAdapter</i>
<ul style="list-style-type: none"> - IOPort array - time window definition array - absolute tolerance array - relative tolerance array - maximum iteration array - convergence signal label
<ul style="list-style-type: none"> + <i>set simulation time</i> + <i>set initial conditions</i> + <i>exchange signals</i> + <i>set input</i> + <i>execute study</i> + <i>get output</i> + <i>check convergence</i>



The proposed data structure and algorithm enable execution of all four co-simulation algorithms.

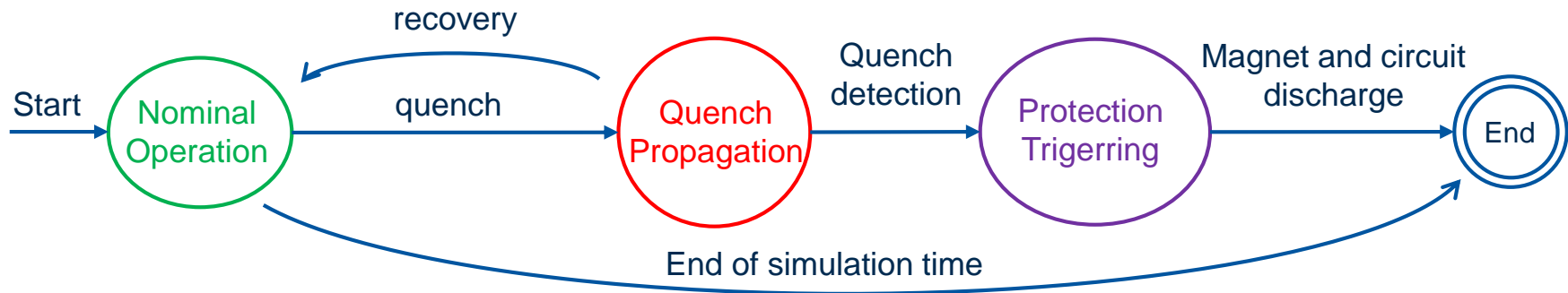
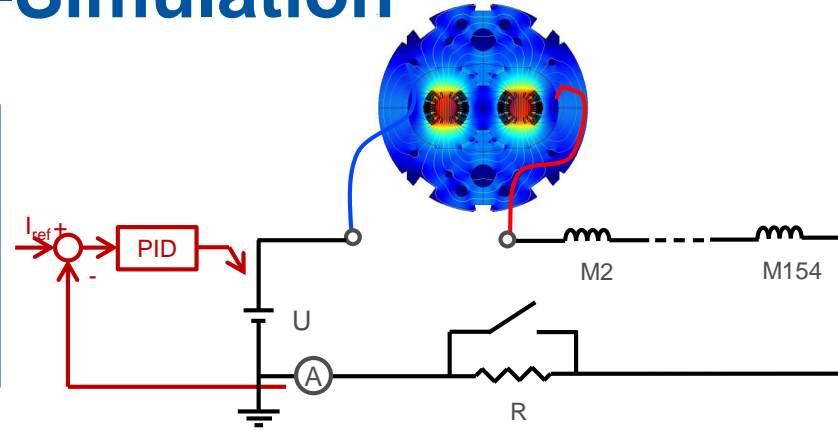
STEAM Co-Sim: Cooperative Simulation Platform

Flexible co-simulation environment for Multi-physics, Multi-rate, Multi-scale problems



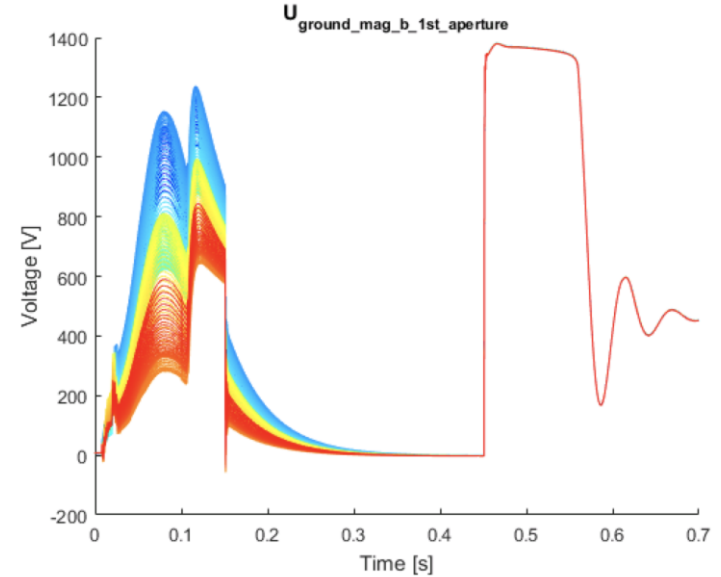
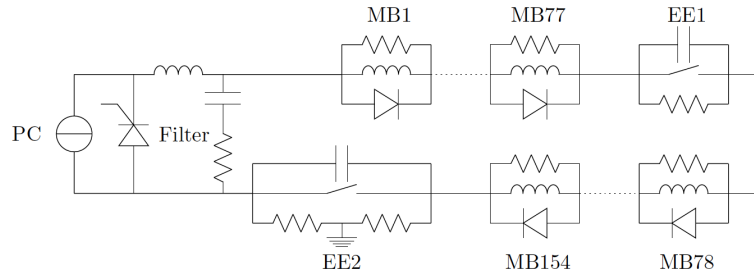
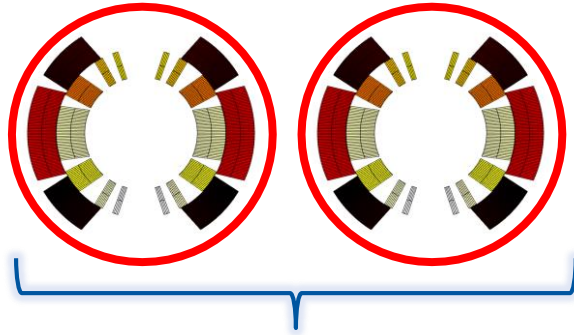
Hierarchical Co-Simulation

1. Single analysis may involve a hierarchy of magnet models (lumped inductor, 1D model, 2D model)
2. Circuit operation involves several states (Controller/Circuit coupling, Field (1D, 2D)/Circuit coupling)



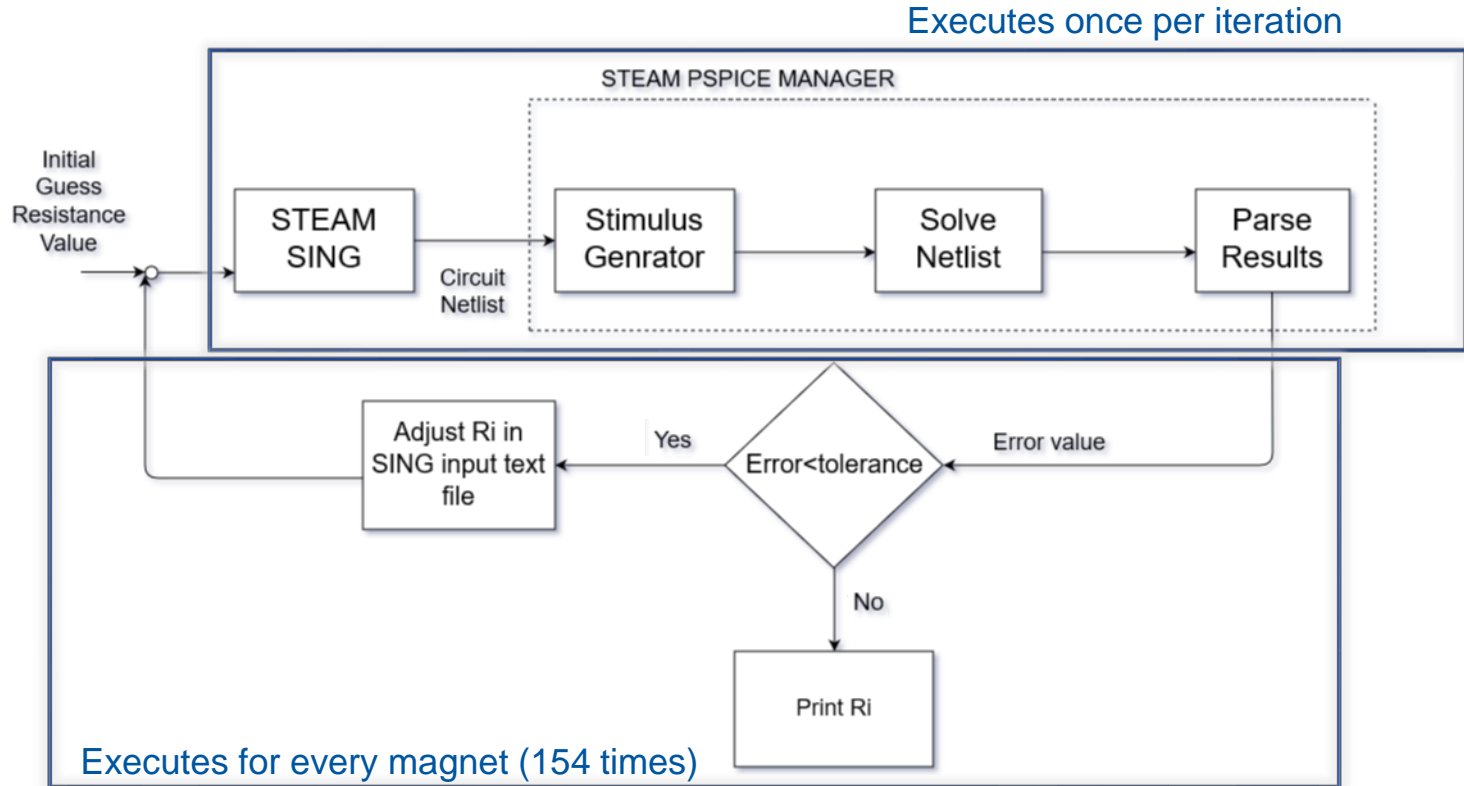
It is necessary to switch between coupled models and coupling algorithms (state machine)

STEAM Co-Sim Demo – Modified Main Dipole Circuit

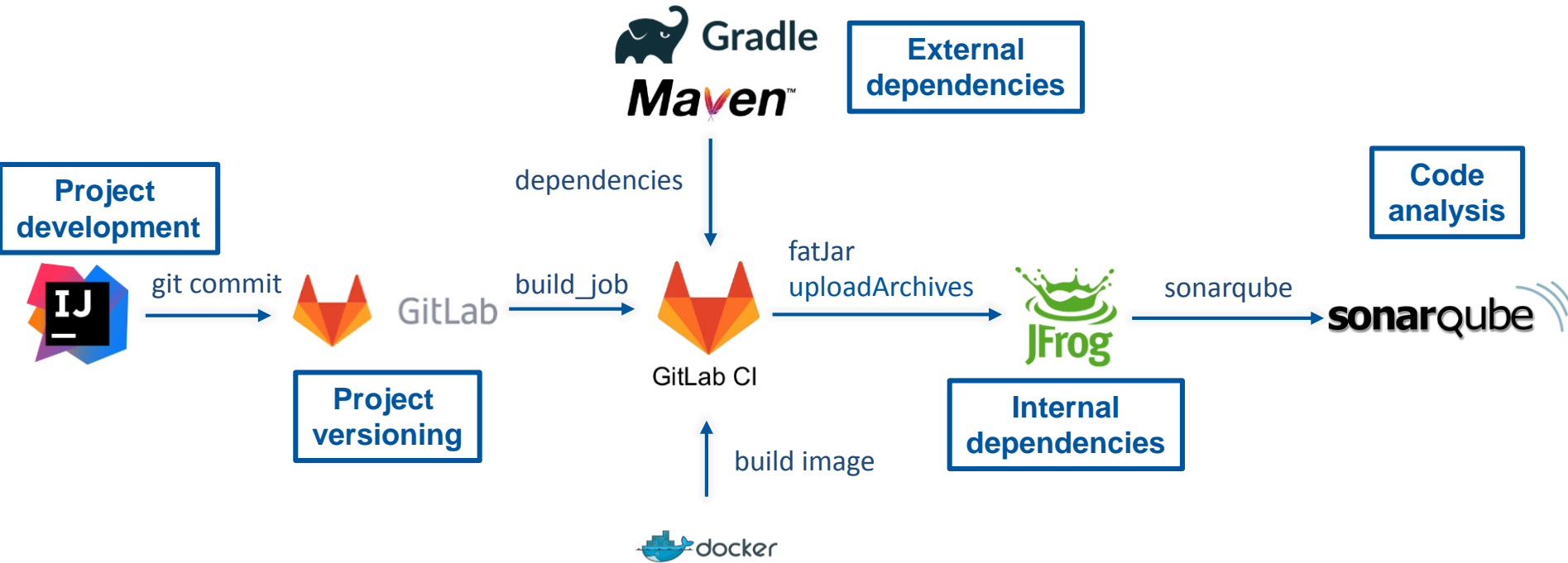


Release status: currently fifth version released internally and externally

Identification of the Main Dipole Circuit Parameters



Continuous Integration Pipeline



The pipeline automatically executes project build, testing, sharing, and analysis. This ensures the maintainability of the project.

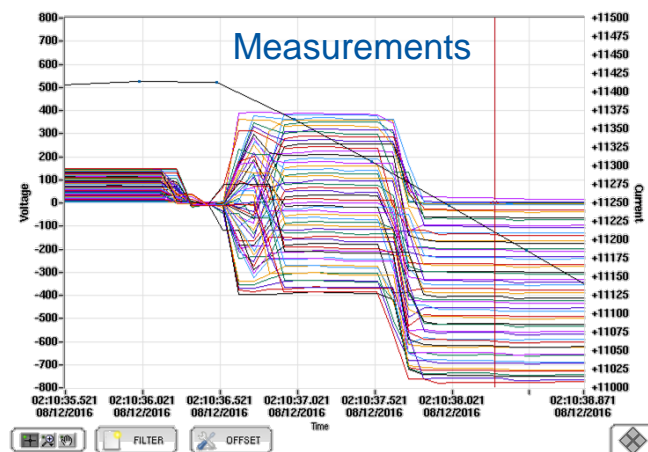
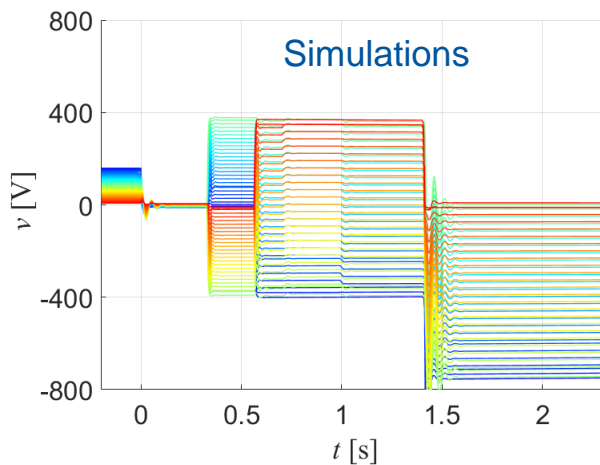
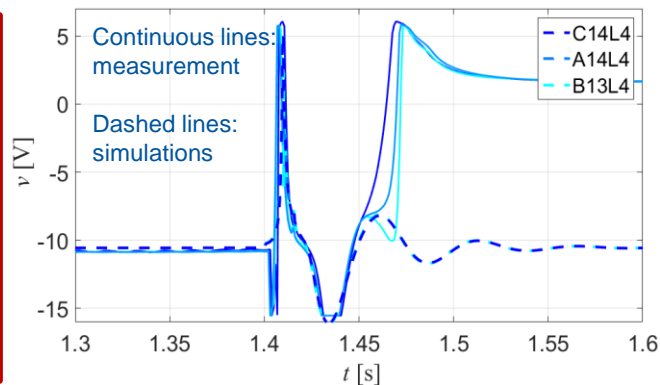
What STEAM has been used for so far

	Part	Study	
LHC	RB circuit	Transients during Fast Power Abort and earth failures.	Ex. 1
		Inter-turn shorts.	
		Operation of the power converter controller.	Ex. 2
		Effect of unbalanced dipoles.	
		Optimisation of the damping.	
LHC	600 A circuits	Protection studies (quench-back, need of EE). Earth fault analysis/localisation.	
LHC & HL-LHC	Triplet and RB	Effect of spurious QH or CLIQ firing on the beam.	
HL-LHC	Triplet	Protection studies.	Ex. 3
HL-LHC	Triplet with beam screen	Coupling currents and forces during a quench.	Ex. 4
HL-LHC	RB+11 T	Protection studies, CLIQ. Functioning of trim PC.	
FCC	SC magnet	Use of quench absorption coils.	Ex. 5
FCC	16 T dipole designs	Quench protection (incl. CLIQ). Mechanical response during quench.	Ex. 6
SM-18	FRESCA2	Quench, MIIts, hot spot, field errors during ramp.	Ex. 7
...			

Ex 1: Short in the RB Circuit

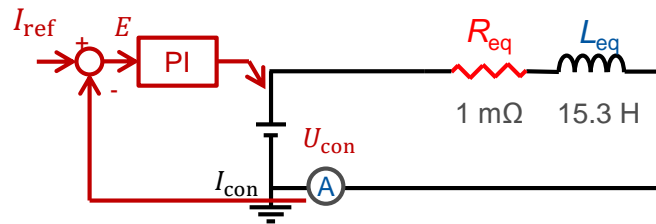
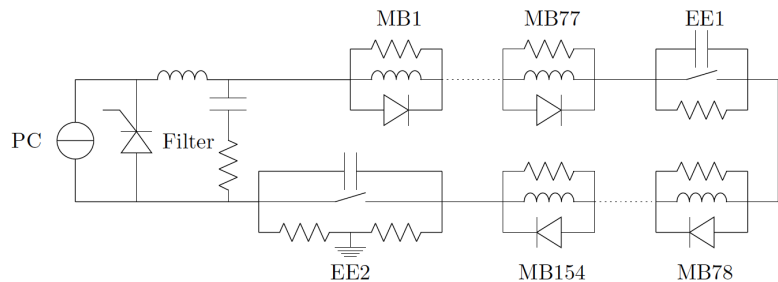
Used to:

- Localize the short by parametric studies
- Understand the transients \Rightarrow Validate model
- Run the validated model for other use cases (double short, ...)

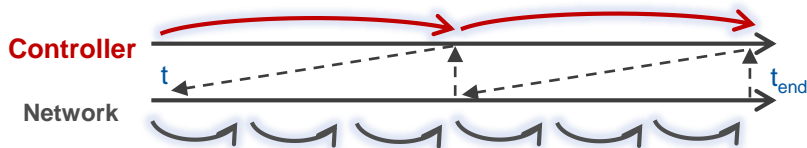


Ex 2: Controller/Circuit Coupling

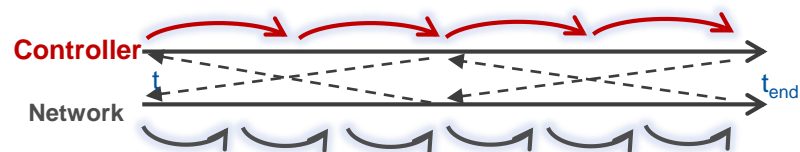
- An ideal current source is used for the studies of the LHC main dipole circuit (and others as well)
- A first order model is used to design the power converter controller



Discrete controller is a weak coupling scheme

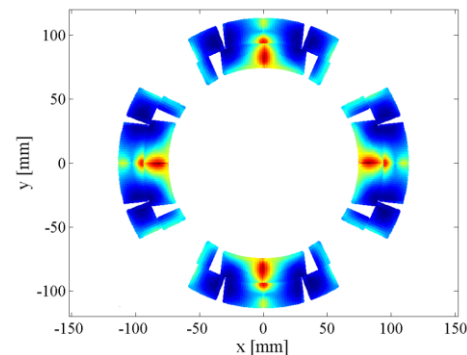
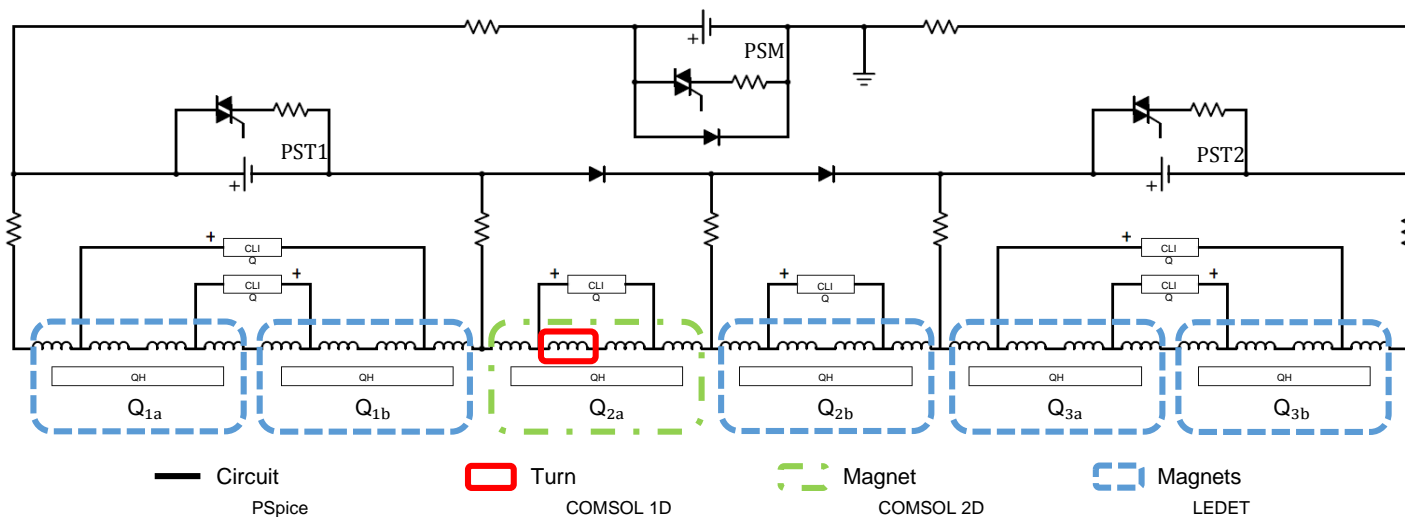


Waveform relaxation scheme can speed-up the computation



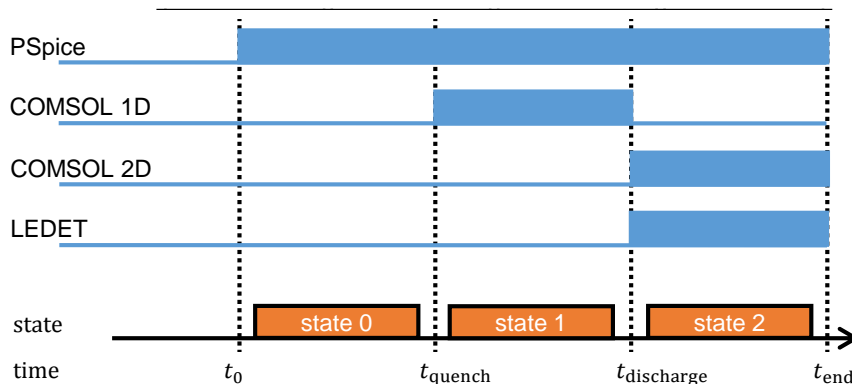
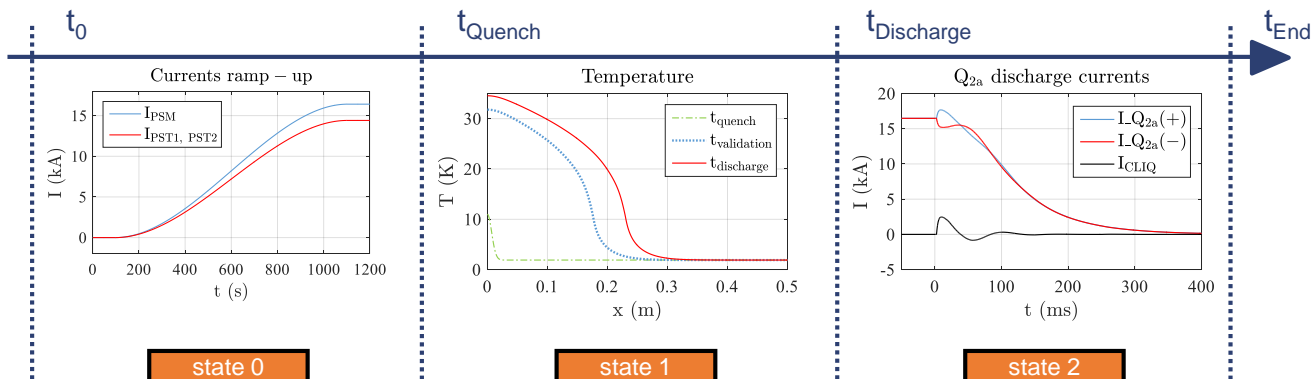
Ex 3: HL-LHC triplet

- Very complex circuit with CLIQ and quench heaters as baseline.
- Co-simulation with Comsol1D + Comsol2D + 5xLEDET + Pspice
- 142 signals are being exchanged between the models.



Ex 3: HL-LHC triplet

- Models activated according to the system state (hierarchical co-simulation)



Used to:

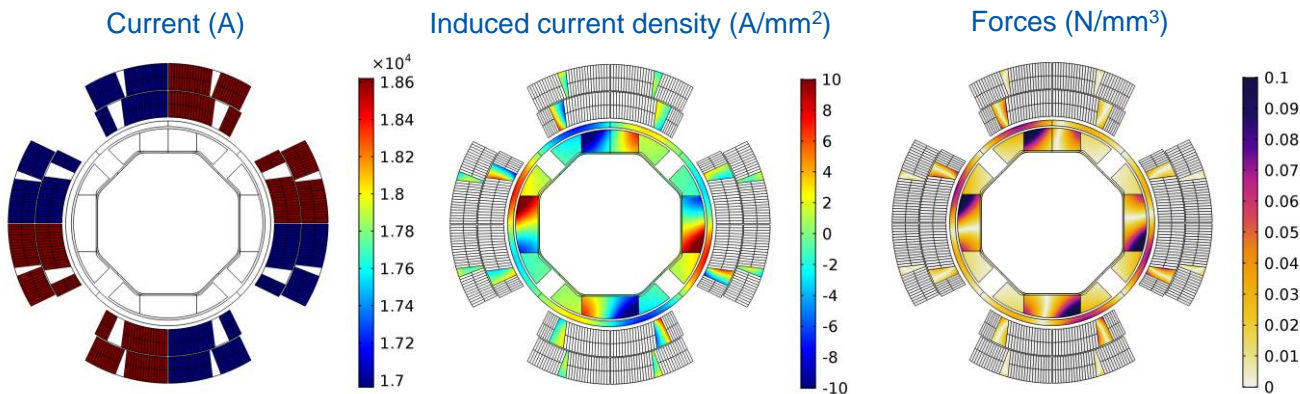
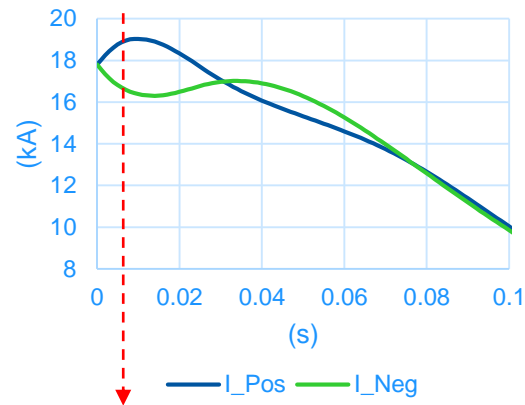
- Validate the circuit layout.
- Optimise the protection system.
- Dimension the busbars and current leads.

Ex 4: HL-LHC Beam Pipe in the Triplet

Used to:

- Calculate the eddy currents and electrodynamic forces acting on the beam screen during a quench with CLIQ.
- Dimension the beam tube.

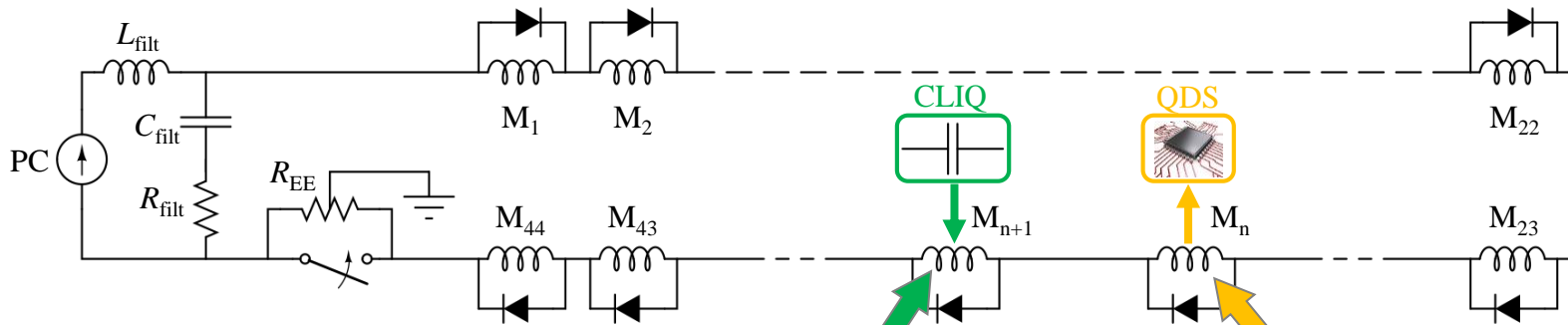
With: *TE-VSC-DLM*



Ex 5.Co-simulation of the FCC Dipole Circuit

Circuit model
2800 components

PSpice

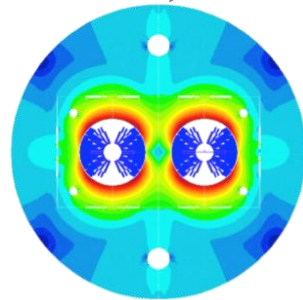


Used to:

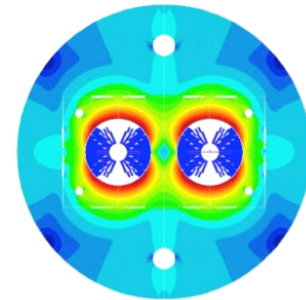
- Study voltage waves during protection scenarios involving CLIQ
- Study quench detection system.

Electro-thermal
magnet model
400 turns

COMSOL



Quenching magnet:
CLIQ simulation



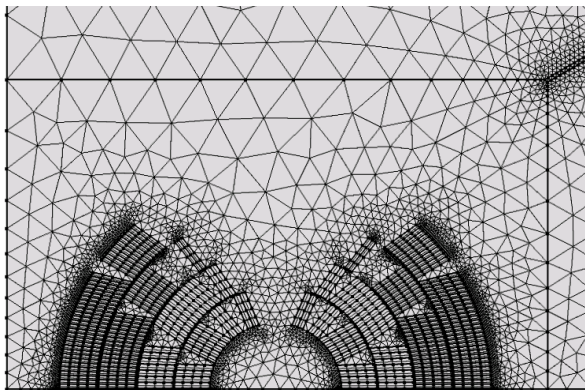
Neighbouring magnet:
Simulation of voltage response

Ex 6: Mechanical Stress During Quench

- COMSOL used for magneto-thermal simulation, ANSYS used for mechanical simulation
- FE models with different mesh (physics driven) can be coupled via mesh-based interpolation

CLIQ quench simulation

COMSOL



Coupling Environment



T

\vec{F}_L

Mesh-based
interpolation

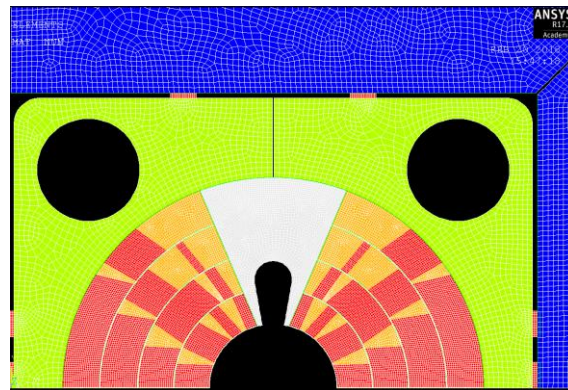
\hat{T}

$\widehat{\vec{F}}_L$

Fraunhofer
SCAI

Mechanical simulation

ANSYS



Integrated circuit and magnet design was applied to three FCC designs.

Example 7: FRESCA2 Analysis App

Used to:

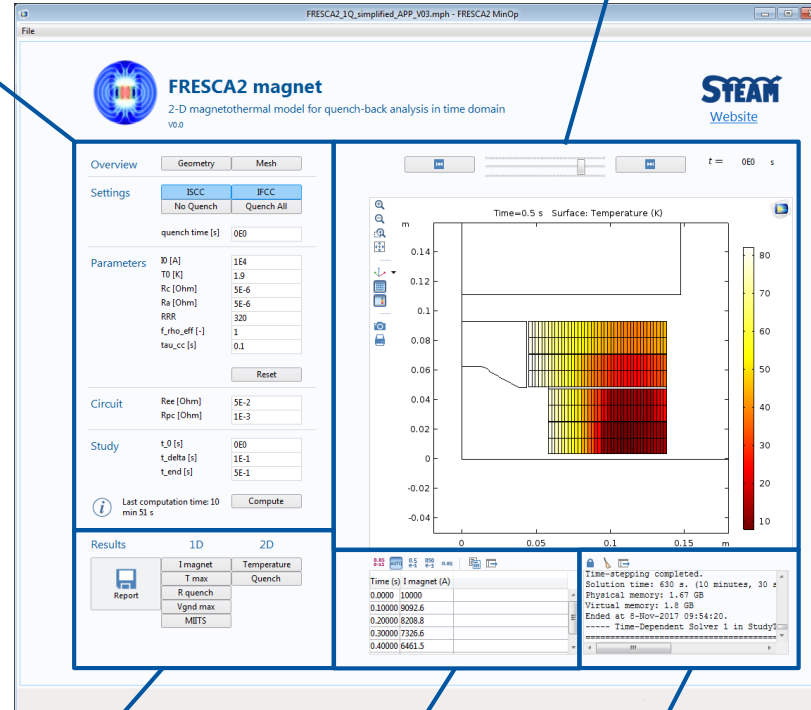
Provide test station with a user-friendly tool to quickly compare measurements with simulations.



Faster & better understanding of the measurements.

User's settings

Graphics



Post-process

Data export

App Log

Conclusion

- A solid base of the STEAM framework is now established and ready to be used for all kinds of simulations on SC circuits for actual and future accelerators.
- STEAM has already been used for many studies, especially:
 - Fault scenario's in the LHC
 - HiLumi triplet circuit
 - FCC magnet and circuit protection
 - “RB+11T” circuit
 - ...
- With the foreseen increase in number of *magnet models*, *circuit models*, *tools/physics*, *users*, *case studies*, and *validations*, STEAM will become an invaluable tool to study a broad variety of applications in the field of accelerator magnet circuits.
- We have acquired a lot of competence in the MPE-PE section in co-simulation and individual tools which could be profitable for people in other groups.
- Implementation of the Model-Based System Engineering framework for integrated modelling (models as repositories of data, notebooks with versioned inputs)



References

A Consistent Simulation of Electrothermal Transients in Accelerator Circuits

Lorenzo Bortot¹, IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 27, NO. 4, JUNE 2017

Abstract—Transients in accelerator circuits consistently account between the magnet network. We present a simulation framework, combining this modularity with the framework, to provide a consistent simulation of the field-circuit coupling.

Index Terms—Computational analysis, accelerator analysis, Large Hadron Collider

CIRCUITS of complex systems from several interactions. For our functional domains systems, Network transient leads, and bus coupling to other LC resonances that work. Magnets can be subject to coupled eddy currents in systems, such as

Coupling of Magneto-Thermal and Mechanical Superconducting Magnet Models by Means of Mesh-Based Interpolation

M. Maciejewski, P. Bayrasy, K. Wolf, M. Wilczek, B. Auchmann, T. Griesemer, L. Bortot, M. Prioli, A.M. Fernandez Navarro, S. Schöps, I. Cortes Garcia, and A.P. Verweij

STEAM: A Hierarchical Co-Simulation Framework for Superconducting Accelerator Magnet Circuits

L. Bortot, B. Auchmann, I. Cortes Garcia, A.M. Fernandez Navarro, M. Maciejewski, M. Mentink, M. Prioli, E. Ravaoli, S. Schöps, and A.P. Verweij

Abstract—Coupling of models representing mechanical structure as under nominal conditions, initiation, quenching in of new prototype. We use and electron models. These quantum models. Therefore, we exchange on with a small field dipole in Quench) test.

Index Terms—Computational analysis, Superconducting components, considerable of a small

Abstract—Simulating the transient effects occurring in superconducting accelerator circuits requires to resolve the mutual electro-thermo-dynamic interaction between the circuit, the magnets and the protection systems. We present STEAM, a hierarchical co-simulation framework which allows to decompose a complex system into simpler, independent sub-units. The convergence of the coupling algorithm, based on the waveform relaxation scheme, ensures the consistency of the solution between the sub-units forming the coupled problem. The modularity of the framework allows to integrate both commercial and in-house tools. A state-management algorithm ensures that each tool contributes to the simulation only when needed, ensuring an efficient use of computational resources. The capabilities of the workflow are applied to co-simulate a quench scenario that could occur in the Inner Triplet Circuit for the future High Luminosity

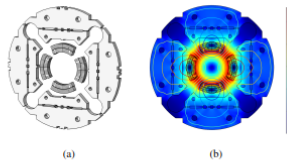


Figure 1: (a) MQXF geometry, and (b) magnetic flux density

Optimized Field/Circuit Coupling for the Simulation of Quenches in Superconducting Magnets

IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 27, NO. 4, JUNE 2017

Quench Protection System Optimization for the High Luminosity LHC Nb₃Sn Quadrupoles

E. Ravaoli, G. Amb...

Abstract—In this paper, an optimized Schwarz coupling approach for simulations in superconducting magnets is presented. The convergence of the magnetothermal part lumped-element circuit model is studied. A framework to tackle the problem requires a framework to tackle it at both the circuit and in case of faults, at the circuit side for the convergence of the optimized Schwarz approach is illustrated dipole magnet with ac

Index Terms—Computational analysis, circuits, eddy currents

SUPERCONDUCTING fields used in high particle beams, see Fig. 1. The magnets are kept at 1.9 K. Since the he

Application of the Waveform Relaxation Technique to the Co-Simulation of Power Converter Controller and Electrical Circuit Models

M. Maciejewski¹, I. Cortes Garcia²

¹Technical University of Lodz, Poland
²Technical University of Lodz, Poland

Reduced Order Modelling for the Simulation of Quenches in Superconducting Magnets

Sebastian Schöps¹*, Idolo Cortes Garcia², Michał Maciejewski² and Bernhard Auchmann^{2,3}

PHYSICAL REVIEW ACCELERATORS AND BEAMS 20, 032401 (2017)

Quench protection analysis integrated in the design of dipoles for the Future Circular Collider

Tiina Salmi^{1,2}, Antti Stenwall¹, Marco Prioli², Janne Ruuskanen¹, Arjan Verweij², Bernhard Auchmann², Davide Tommasini², Daniel Schoerline², Clement Lorin², Fernando Fernandez Navarro², and A.P. Verweij²

Simulation of Electro-Thermal Transients in Superconducting Accelerator Magnets with COMSOL Multiphysics®

L. Bortot¹, M. Maciejewski^{1,2}, M. Prioli¹, A.M. Fernandez Navarro³, S. Schöps¹, I. Cortes Garcia¹, B. Auchmann¹ and A.P. Verweij¹

¹CERN, Geneva, Switzerland, ²Lodz University of Technology, Lodz, Poland

A 2-D Finite-Element Model for Electro-Thermal Transients in Accelerator Magnets

L. Bortot¹, B. Auchmann^{1,2}, I. Cortes Garcia⁴, A.M. Fernandez Navarro³, M. Maciejewski^{1,3},

¹CERN, Geneva, Switzerland, E-mail: lorenzo.bortot@cern.ch

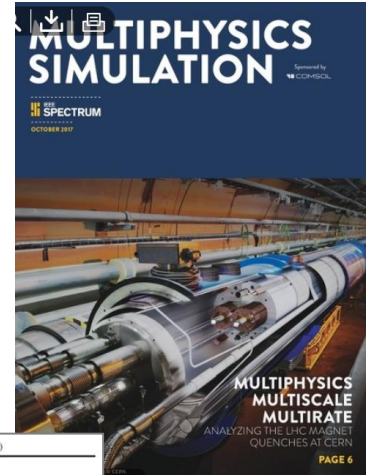
²Paul Scherrer Institut, Villigen, Switzerland

³Lodz University of Technology, Lodz, Poland

⁴Technische Universität Darmstadt, Darmstadt, Germany

Abstract: Superconducting magnets are a cutting-edge technology in the case of superconducting magnets. Numerical simulation is a powerful tool to understand the electro-thermo-dynamic interaction between the circuit, the magnets and the protection systems. We present a 2-D FEM model for the simulation of electro-thermal transients occurring in superconducting accelerator magnets. The magnetization problem is solved with a modified magnetic vector potential formulation, where the cable eddy currents are resolved in terms of their equivalent magnetization. The heat balance equation is then investigated, and the relevant heat sources are discussed. The model implements a two-part component interface and is resolved, as part of an electrical circuit, in a cooperative simulation scheme with a lumped-parameter network.

Index Terms—Superconducting Accelerator Magnet, Quench, Finite Element Method, Equivalent Magnetization, Eddy Currents.



References

Transient Effects in Superconducting Magnet Systems

1. F. Rodriguez-Mateos and F. Sonnemann, "Quench heater studies for the LHC magnets," in Particle Accelerator Conference, 2001. PAC 2001. Proceedings of the 2001, vol. 5. IEEE, 2001, pp. 3451–3453.
2. E. Ravaioli, "CLIQ. A new quench protection technology for superconducting magnets," Ph.D. dissertation, Universiteit Twente, 2015.
3. E. Ravaioli, et al., "Impact of the voltage transients after a fast power abort on the quench detection system in the LHC main dipole chain," IEEE Transactions on Applied Superconductivity, vol. 22, no. 3, pp. 9 002 5049 002 504, 2012.

The STEAM framework

4. S. Schops et al., "A cosimulation framework for multirate time integration of field/circuit coupled problems," IEEE Trans. Magn., vol. 46, no. 8, pp. 3233–3236, 2010.
5. C. Garcia et al., "Optimized field/circuit coupling for the simulation of quenches in superconducting magnets," IEEE Journal on Multiscale and Multiphysics Computational Techniques, 2017.
6. L. Bortot et al. "A Consistent Simulation of Electrothermal Transients in Accelerator Circuits." *IEEE Transactions on Applied Superconductivity* 27.4 (2017): 1-5.
7. M. Maciejewski et al., "Application of the waveform relaxation technique to the co-simulation of power converter controller and electrical circuit models," Paper submitted in 22nd International Conference on Methods and Models in Automation and Robotics (MMAR2017), 28-31 August 2017, Miedzyzdroje, Poland.
8. L. Bortot et al., "STEAM: A Hierarchical Co-Simulation Framework for Superconducting Accelerator Magnet Circuits," Paper submitted to the 25th International Conference on Magnet Technology MT25. August 26 - September 1 2017, Amsterdam, The Netherlands.
9. M. Maciejewski et al., "Architecture of a Hierarchical Co-Simulation Framework for the Simulation of Transient Effects in Superconducting Accelerator Circuits," Paper submitted to Computer Physics Communications Journal.

2-D FEM model for electro-thermal transients in accelerator magnets

10. M. N. Wilson, Superconducting magnets. Clarendon Press Oxford, 1983.
11. Morgan, G. H. "Theoretical Behavior of Twisted Multicore Superconducting Wire in a Time-Varying Uniform Magnetic Field." *Journal of Applied Physics* 41.9 (1970): 3673-3679.
12. A. P. Verweij, "Electrodynamics of superconducting cables in accelerator magnets," Ph.D. dissertation, Universiteit Twente, 1995.
13. H. De Gersem and T. Weiland, "Finite-element models for superconductive cables with finite inter-wire resistance," *IEEE trans. mag*, vol. 40, no. 2, pp. 667–670, 2004.
14. B. Auchmann, S. Russenschuck, and R. de Maria. *Comparative study of inter-strand coupling current models for accelerator magnets*. No. CERN-AT-2006-011-MEL. 2006.
15. L. Bottura and B. Bordini, "Jc(B, T, ϵ) Parameterization for the ITER Nb3Sn Production," IEEE Trans. Appl. Supercond., vol. 19, no. 3, pp.1521–1524, 2009.
16. M. Sorbi, and V. Marinuzzi. "Magnetization Heat in Superconductors and in Eddy Current Problems: A Classical Thermodynamic Approach." *IEEE Transactions on Applied Superconductivity* 26.6 (2016): 1-9.
17. Russenschuck, Stephan. *Field computation for accelerator magnets: analytical and numerical methods for electromagnetic design and optimization*. John Wiley & Sons, 2011.
18. L. Bortot et al "A 2-D Finite-Element Model for Electro-Thermal Transients in Accelerator Magnets," Paper submitted in 21st International Conference on the Computation of Electromagnetic Fields (COMPUMAG2017), 18-22 June 2017, Daejeon, Korea.

Case Study: High-Luminosity LHC Inner Triplet Circuit

19. H. L. Collaboration et al., "HL-LHC Preliminary Design Report," FP7 High Luminosity Large Hadron Collider Design Study, CERN-ACC-2014, vol. 300, 2014.
20. P. Ferracin et al., "Development of MQXF: The Nb3Sn Low- β Quadrupole for the HiLumi LHC," IEEE Transactions on Applied Superconductivity, vol. 26, no. 4, pp. 1–7, 2016.
21. E. Ravaioli et al., "Quench protection system optimization for the High Luminosity LHC Nb3Sn quadrupoles," IEEE Transactions on Applied Superconductivity, vol. 27, no. 4, pp. 1–7, 2017.

