Circuit protection aspects, CLIQ simulations and STEAM

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Outline

1. Circuit protection aspects
   - Circuit protection @ FCC week 2016
   - Circuit layouts for the latest magnet designs

2. The STEAM project
   - New perspectives for circuit and quench simulations
   - Main STEAM features
   - First results of CLIQ simulations

THE STEAM **S**imulation of **T**ransient **E**ffects in **A**ccelerator **M**agnets

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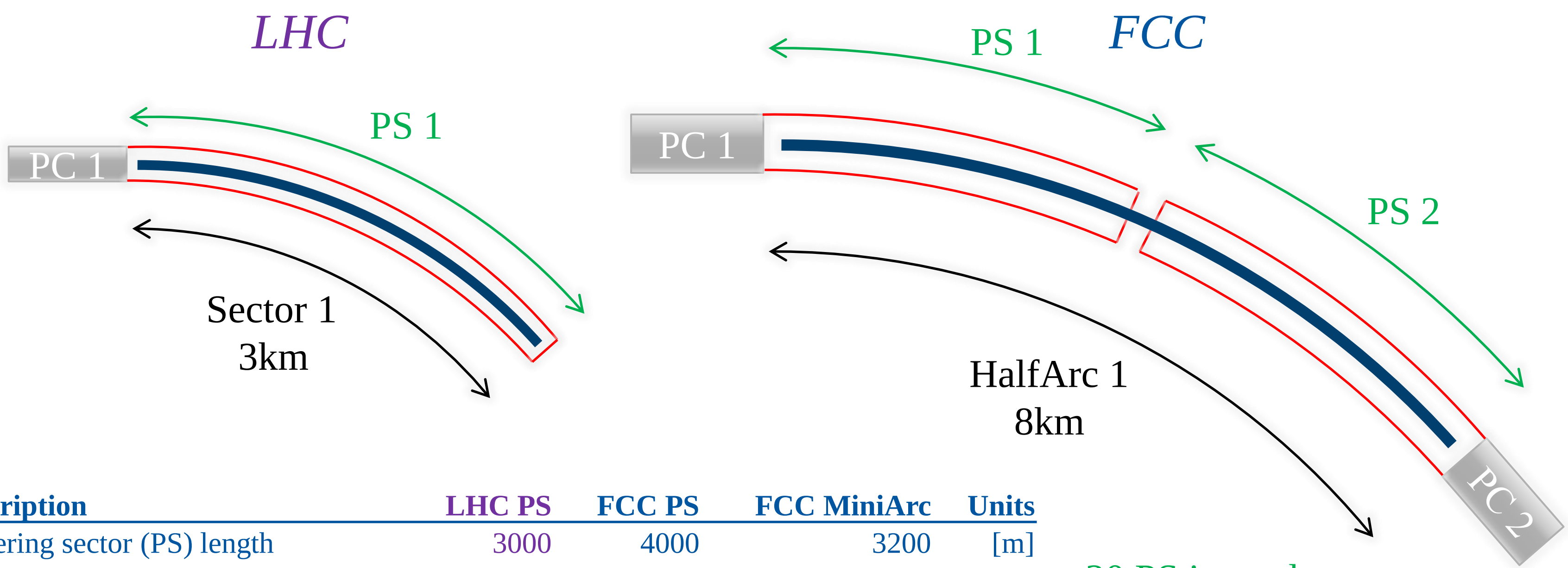
Simulation of **T**ransient **E**ffects in **A**ccelerator **M**agnets

Circuit protection @ FCC week 2016*

- Definition of the FCC powering sector (PS)

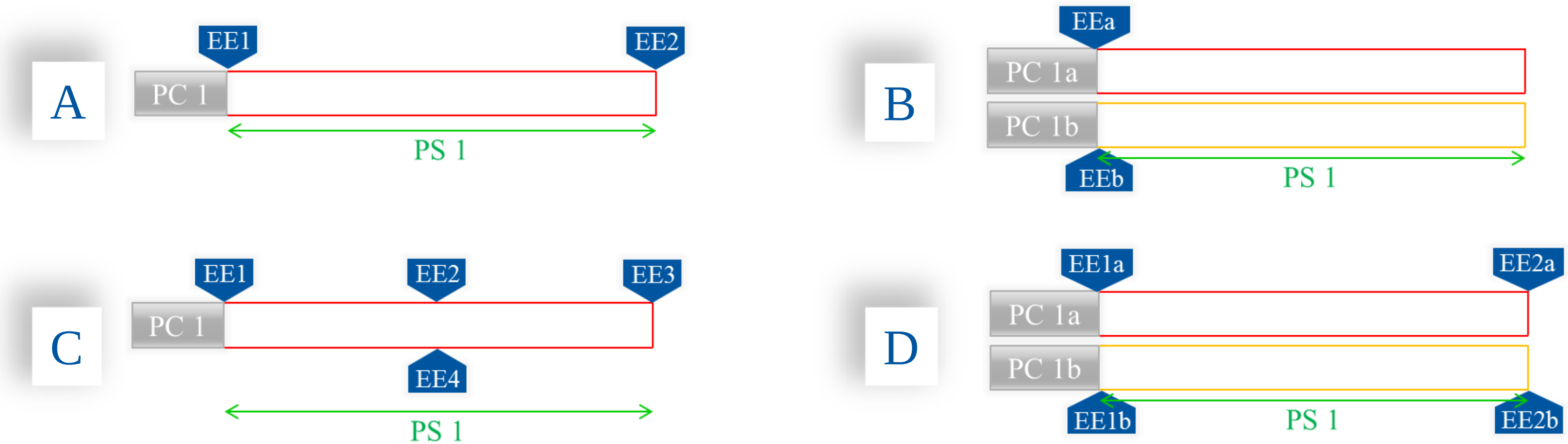


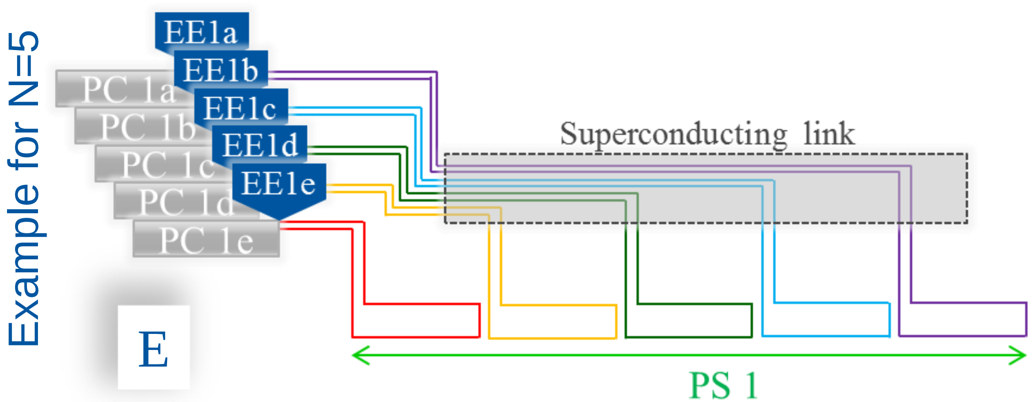
Description	LHC PS	FCC PS	FCC MiniArc	Units
Powering sector (PS) length	3000	4000	3200	[m]
Number of PS in the accelerator	8	16	4	-
Filling factor	74%	77%	77%	-
Number of dipole magnets per PS	**154**	**215**	**172**	-
Inductance per PS	**15**	**272**	**218**	[H]
Stored energy per PS	**1**	**10**	**8**	[GJ]

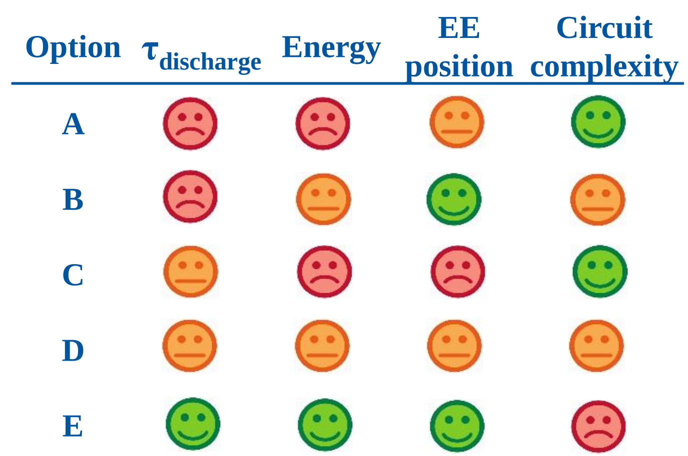
20 PS in total

*Concepts for magnet circuit powering and protection (M. Prioli) (Link)

Circuit protection @ FCC week 2016*



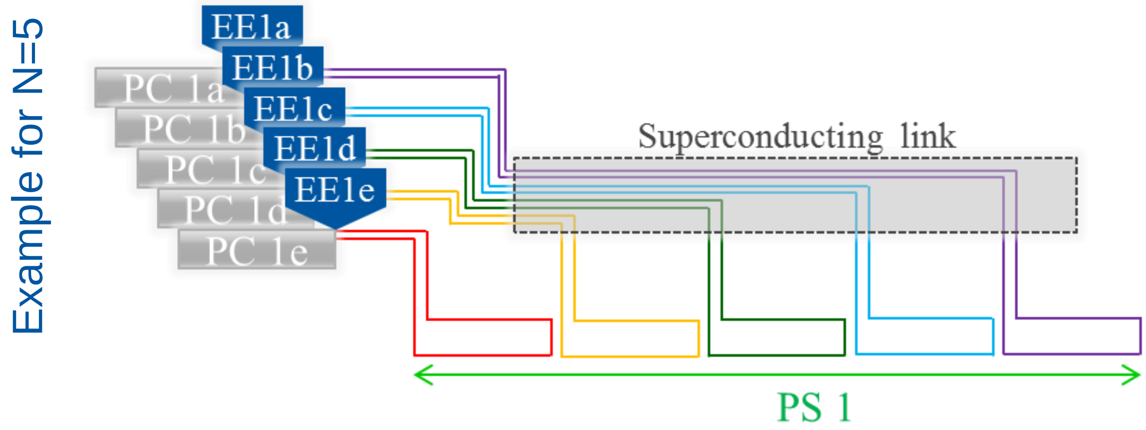




*Concepts for magnet circuit powering and protection (M. Prioli) (Link)

Circuit protection @ FCC week 2016*

- A string of magnets can ***always*** be protected, for any magnet design and given constraints, by adapting the number of circuits, so by subdividing a powering sector in multiple circuits

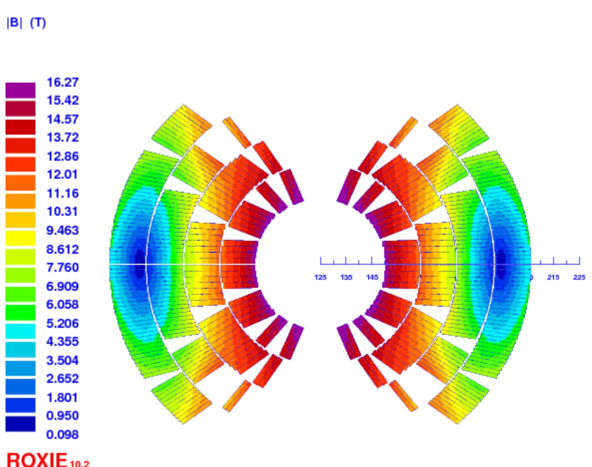


- Magnets can be compared analysing the resulting circuit complexity
  - Number of circuits N in one Powering Sector (PS)
  - 20N circuits for the entire machine

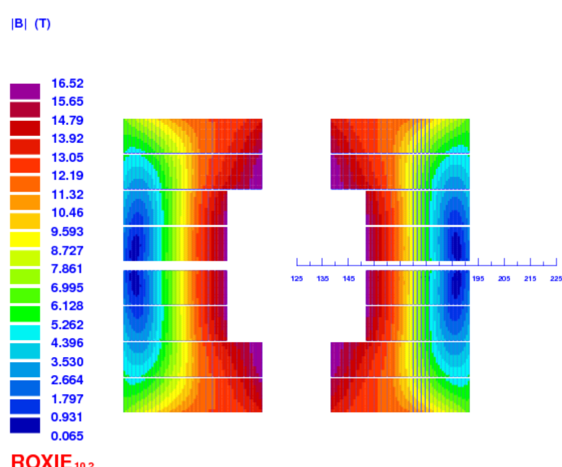
*Comparison of magnet designs from a circuit protection point of view (A. Verweij) (Link)

New magnets parameters

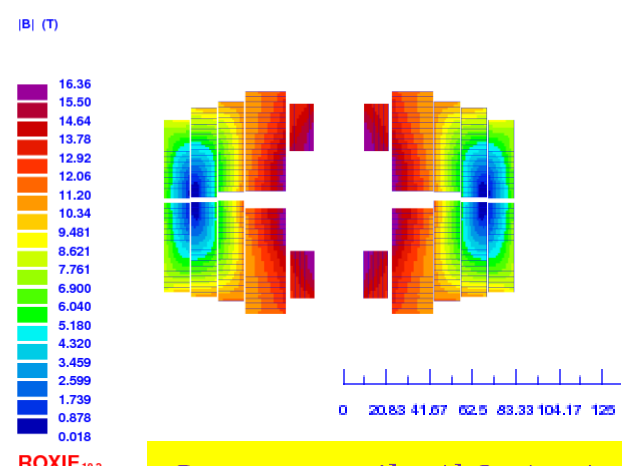
	Load line margin	Current @ B_{nom} [kA]	Differential inductance (2 apertures) [mH]	Stored energy @ I_{nom} (2 apertures) [MJ]
Cos-theta 28b38 v.5	18%	10.275	734	39
Cos-theta v22b	**14%**	**11.23**	**566**	**38**
Block coil v26cmag	18%	8.47	1265	45
Block coil v20ar	**14%**	**10.99**	**571**	**36**
Common coil v1h_intgrad	18%	9.025	1824	74
Common coil v1h2_1ac1	**14%**	**16.80**	**287**	**43**
Canted cos-theta	**14%**	**18**	**254**	**44**



Cos-theta v22b



Block coil v20ar



Common coil v1h2_1ac1

Circuits layouts for Cos-theta 18% LL*

N. of circuits per PS	1	2	3	4	6	8
N. of circuits entire FCC	20	40	60	80	120	160
Magnets per circuit	215	108	72	54	36	27
Inductance per circuit [H]	158	79	53	39	26	20
Stored energy per circuit [GJ] (<1.6) (>3)	8.3	4.2	2.8	2.1	1.4	1.0
Ramp time [min]	20	20	20	20	20	20
V_{PC} [V] (<500) (>1000)	1352	676	451	338	225	169
$V_{FPA,max}$ [kV]	1.0	1.0	1.0	1.0	1.0	1.0
$V_{FPA,max,fault}$ [kV]	3.3	2.6	2.4	2.3	2.2	2.2
τ_{circ} [s] (<150) (>250)	811	406	270	203	135	101
MIITS [A^2s]*10^9 (<10) (>20)	43	21	14	11	7	5
A_{busbar} [mm^2], ΔT=300K	550	390	310	270	220	190

*Comparison of magnet designs from a circuit protection point of view (A. Verweij) (Link)

Circuits layouts for Cos-theta 14% LL

N. of circuits per PS	1	2	3	4	6	8
N. of circuits entire FCC	20	40	60	80	120	160
Magnets per circuit	215	108	72	54	36	27
Inductance per circuit [H]	122	61	41	30	20	15
Stored energy per circuit [GJ] (<1.6) (>3)	8.1	4.1	2.7	2.0	1.4	1.0
Ramp time [min]	20	20	20	20	20	20
V_{PC} [V] (<500) (>1000)	1139	570	380	285	190	142
$V_{FPA,max}$ [kV]	1.0	1.0	1.0	1.0	1.0	1.0
$V_{FPA,max,fault}$ [kV]	3.3	2.6	2.4	2.3	2.2	2.2
τ_{circ} [s] (<150) (>250)	684	342	228	171	114	85
MIITS [A^2s]*10^9 (<10) (>20)	43	22	14	10	7	5
A_{busbar} [mm^2], ΔT=300K	550	390	320	270	220	190

Circuits layouts for Block coil 18% LL*

N. of circuits per PS	1	2	3	4	6	8
N. of circuits entire FCC	20	40	60	80	120	160
Magnets per circuit	215	108	72	54	36	27
Inductance per circuit [H]	272	136	91	68	45	34
Stored energy per circuit [GJ] (<1.6) (>3)	9.7	4.9	3.2	2.4	1.6	1.2
Ramp time [min]	20	20	20	20	20	20
V_{PC} [V] (<500) (>1000)	1920	960	640	480	320	240
$V_{FPA,max}$ [kV]	1.0	1.0	1.0	1.0	1.0	1.0
$V_{FPA,max,fault}$ [kV]	3.3	2.6	2.4	2.3	2.2	2.2
τ_{circ} [s] (<150) (>250)	1152	576	384	288	192	144
MIITS [A^2s]*10^9 (<10) (>20)	41	21	14	10	7	5
A_{busbar} [mm^2], ΔT=300K	540	380	310	270	220	190

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*Comparison of magnet designs from a circuit protection point of view (A. Verweij) (Link)

Circuits layouts for Block coil 14% LL

N. of circuits per PS	**1**	**2**	**3**	**4**	**6**	**8**
N. of circuits entire FCC	20	40	60	80	120	160
Magnets per circuit	215	108	72	54	36	27
Inductance per circuit [H]	123	61	41	31	20	15
Stored energy per circuit [GJ] (<1.6) (>3)	7.8	3.9	2.6	1.9	1.3	1.0
Ramp time [min]	20	20	20	20	20	20
V_{PC} [V] (<500) (>1000)	1124	562	375	281	187	141
$V_{FPA,max}$ [kV]	1.0	1.0	1.0	1.0	1.0	1.0
$V_{FPA,max,fault}$ [kV]	3.3	2.6	2.4	2.3	2.2	2.2
τ_{circ} [s] (<150) (>250)	674	337	225	169	112	84
MIITS [A^2s]*10^9 (<10) (>20)	41	20	14	10	7	5
A_{busbar} [mm^2], ΔT=300K	540	380	310	270	220	190

Circuits layouts for Common c. 18% LL*

N. of circuits per PS	**1**	**2**	**3**	**4**	**6**	**8**
N. of circuits entire FCC	20	40	60	80	120	160
Magnets per circuit	215	108	72	54	36	27
Inductance per circuit [H]	392	196	131	98	65	49
Stored energy per circuit [GJ] (<1.6) (>3)	16.0	8.0	5.3	4.0	2.7	2.0
Ramp time [min]	20	20	20	20	20	20
V_{PC} [V] (<500) (>1000)	2952	1476	984	738	492	369
$V_{FPA,max}$ [kV]	1.0	1.0	1.0	1.0	1.0	1.0
$V_{FPA,max,fault}$ [kV]	3.3	2.6	2.4	2.3	2.2	2.2
τ_{circ} [s] (<150) (>250)	1771	886	590	443	295	221
MIITS [A^2s]*10^9 (<10) (>20)	72	36	24	18	12	9
A_{busbar} [mm^2], ΔT=300K	710	500	410	360	290	250

*Comparison of magnet designs from a circuit protection point of view (A. Verweij) (Link)

Circuits layouts for Common c. 14% LL

N. of circuits per PS	1	2	3	4	6	8
N. of circuits entire FCC	20	40	60	80	120	160
Magnets per circuit	215	108	72	54	36	27
Inductance per circuit [H]	62	31	21	15	10	8
Stored energy per circuit [GJ] (<1.6) (>3)	9.2	4.6	3.1	2.3	1.5	1.1
Ramp time [min]	20	20	20	20	20	20
V_{PC} [V] (<500) (>1000)	863	432	288	216	144	108
$V_{FPA,max}$ [kV]	1.0	1.0	1.0	1.0	1.0	1.0
$V_{FPA,max,fault}$ [kV]	3.3	2.6	2.4	2.3	2.2	2.2
τ_{circ} [s] (<150) (>250)	518	259	173	130	86	65
MIITS [A^2s]*10^9 (<10) (>20)	73	37	24	18	12	9
A_{busbar} [mm^2], ΔT=300K	720	510	410	360	290	250

Circuits layouts for CCT 14% LL

N. of circuits per PS	1	2	3	4	6	8
N. of circuits entire FCC	20	40	60	80	120	160
Magnets per circuit	215	108	72	54	36	27
Inductance per circuit [H]	55	27	18	14	9	7
Stored energy per circuit [GJ] (<1.6) (>3)	9.6	4.8	3.2	2.4	1.6	1.2
Ramp time [min]	20	20	20	20	20	20
V_{PC} [V] (<500) (>1000)	819	409	273	205	136	102
$V_{FPA,max}$ [kV]	1.0	1.0	1.0	1.0	1.0	1.0
$V_{FPA,max,fault}$ [kV]	3.3	2.6	2.4	2.3	2.2	2.2
τ_{circ} [s] (<150) (>250)	491	246	164	123	82	61
MIITS [A^2s]*10^9 (<10) (>20)	80	40	27	20	13	10
A_{busbar} [mm^2], ΔT=300K	750	530	430	370	300	260

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Circuit protection aspects: conclusions

- For all magnet designs:
  - Reduction in the circuit complexity 🙂
  - The layout with 6 circuits per powering sector fulfils the largest number of constraints

	Cos-theta	**Block coil**	**Common coil**	**Canted cos-theta**
Circuit complexity	😐	😐	😐	😐
Circuit energy	🙂	🙂	🙂	🙂
Ramp-up, V_{PC}	🙂	🙂	🙂	🙂
FPA, τ_{circ}	🙂	🙂	🙂	🙂
FPA, MIITS	🙂	🙂	😐	😐

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THE STEAM **S**imulation of **T**ransient **E**ffects in **A**ccelerator **M**agnets

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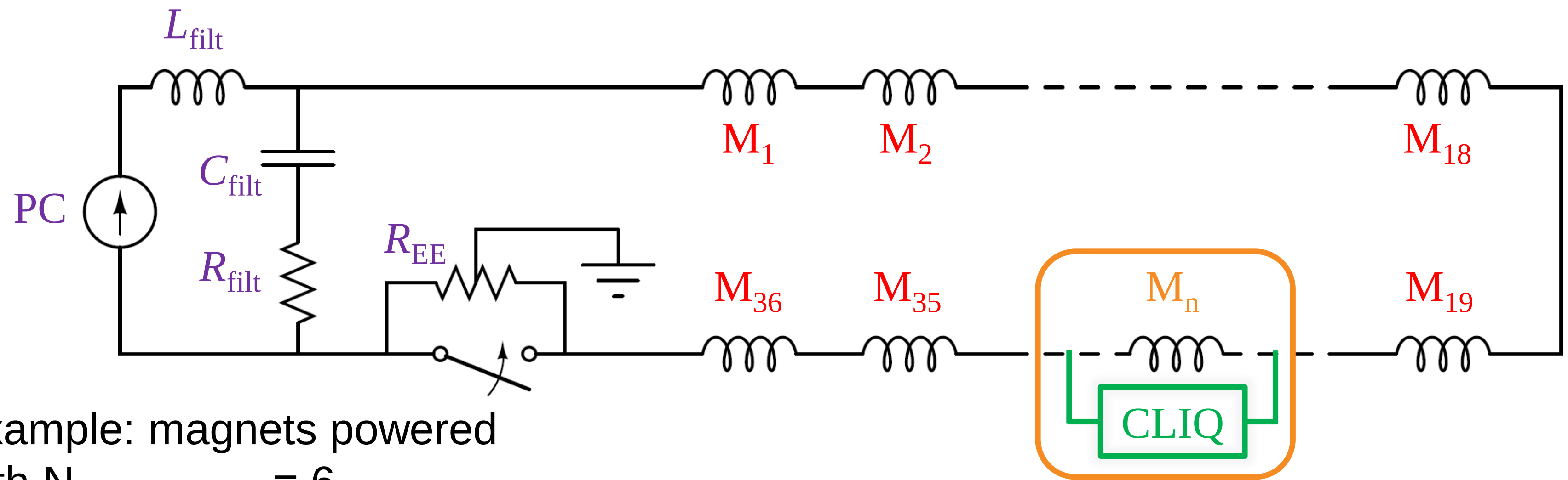
Outlook for circuit and quench simulations



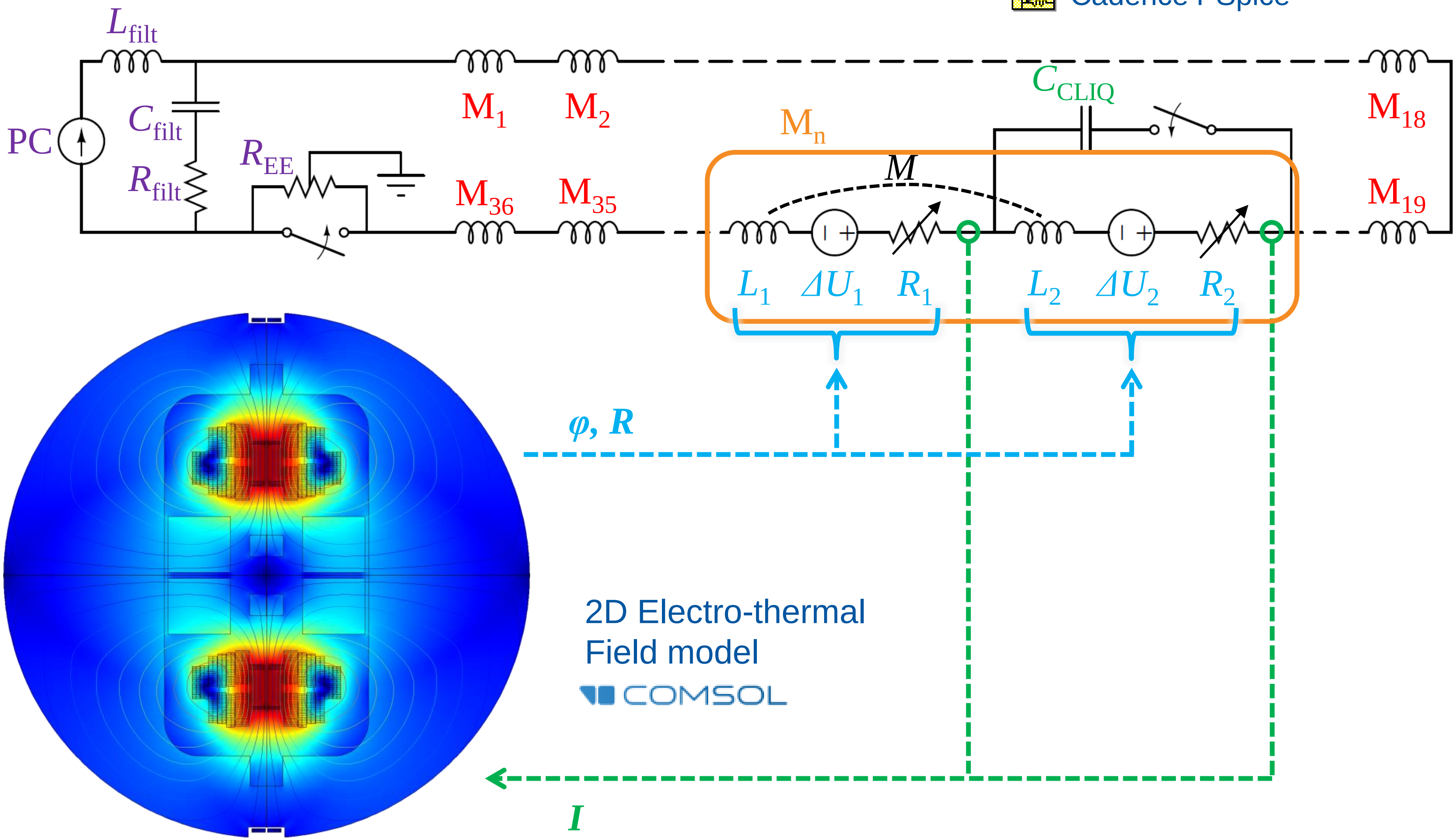
Example: magnets powered with $N_{\text{circuits per PS}} = 6$

- To understand if this proposal is feasible, circuit simulations are needed
  - Quenching magnet
  - CLIQ protection system
  - Lumped element model of the other magnets in the chain
  - Other components (e.g. Power Converter (PC), nonlinear switches)
  - … Quench protection system, controller of Power Converter
- CLIQ introduces a coupling between circuit and quench simulations

Field-circuit coupling

Circuit model

Cadence PSpice



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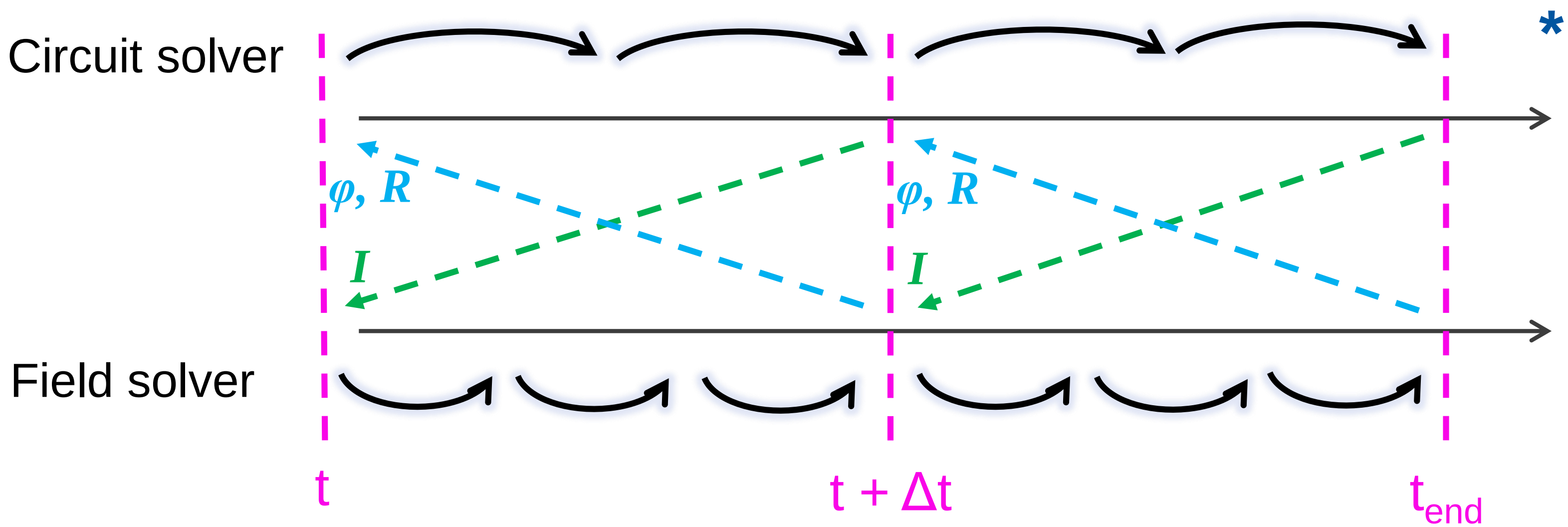
Field-circuit coupling

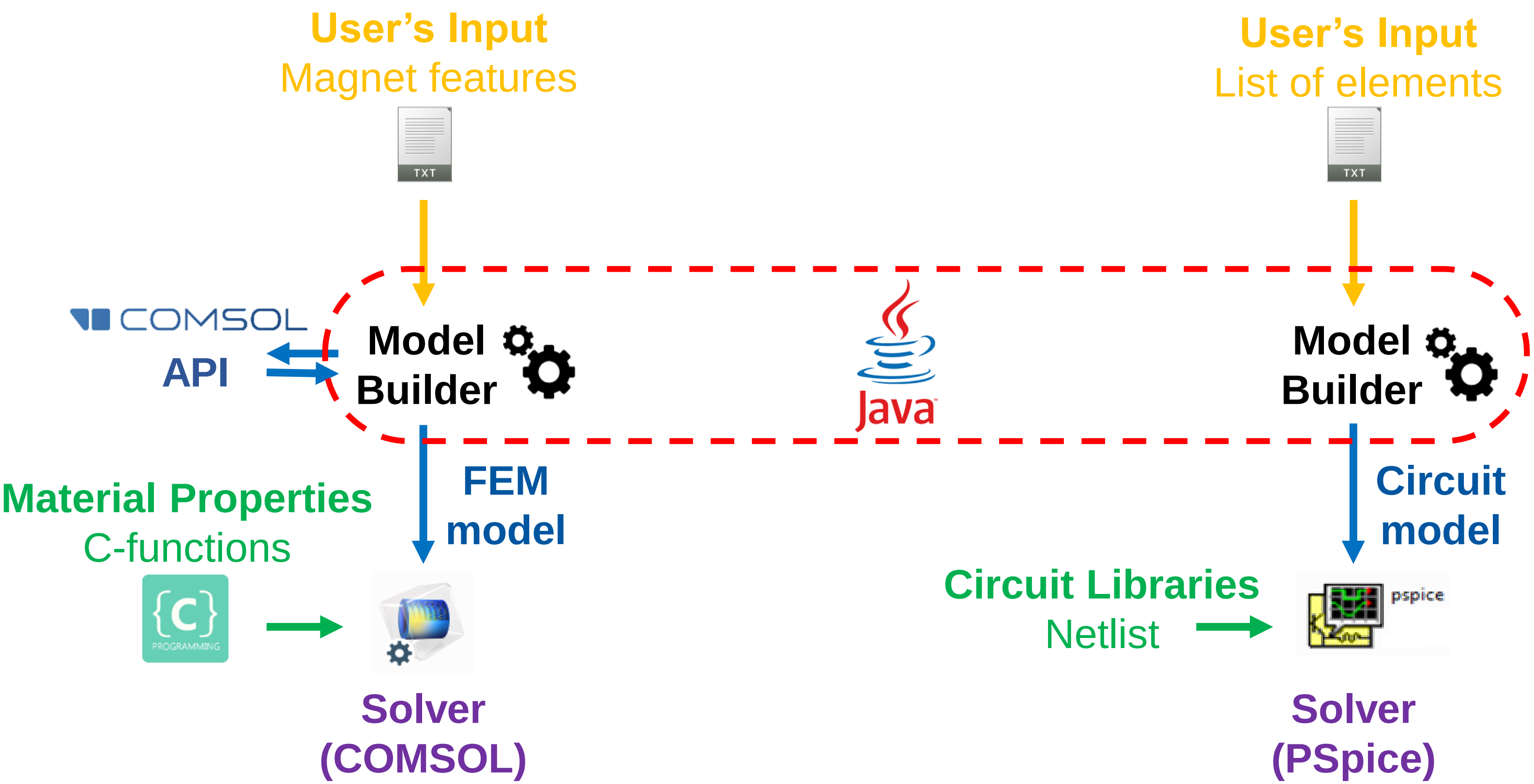
- Coupling scheme: Waveform Relaxation – Gauss-Siedel scheme



- Advantages
  - Multiple solvers with individual adaptive time stepping
  - No assumptions about current decay
  - No assumptions about field and inductance evolution
  - Convergence error under control

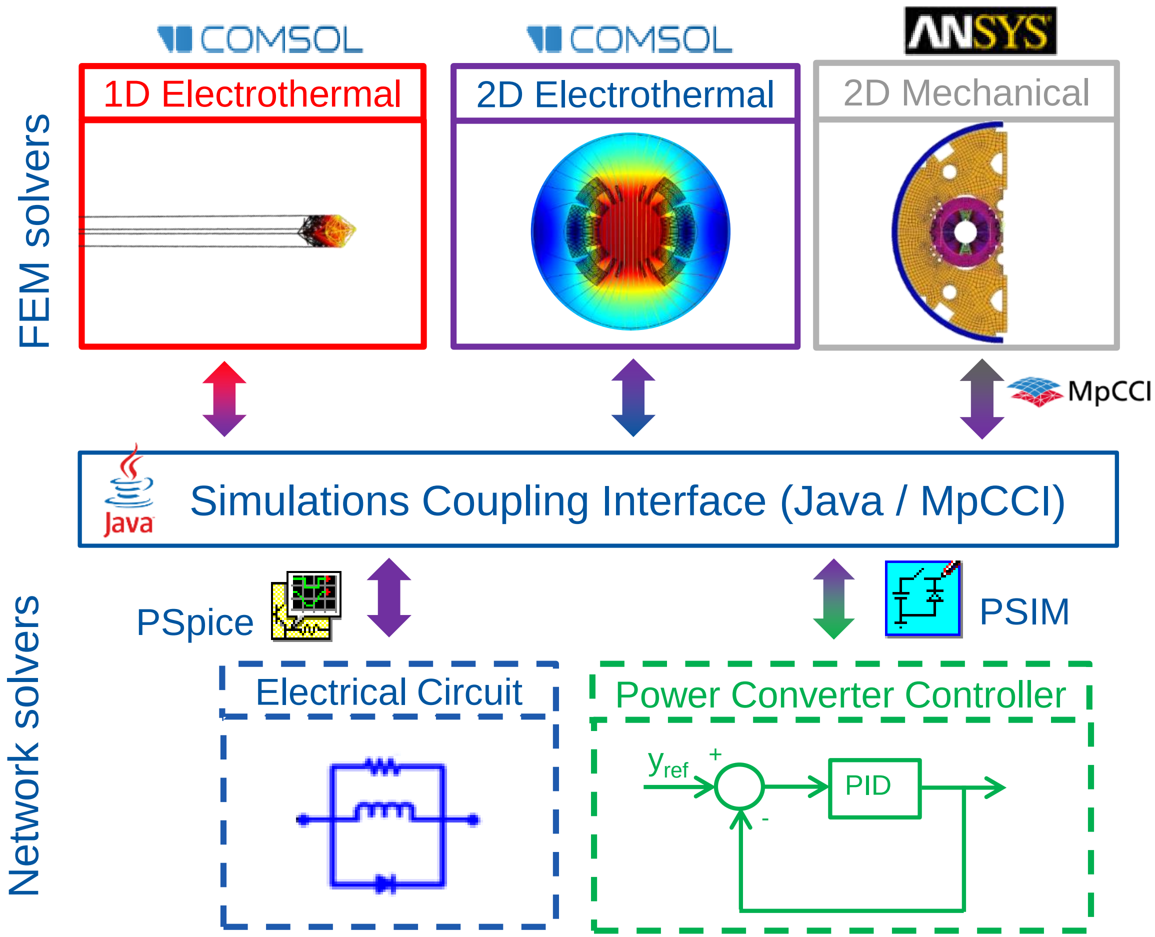
Field and Circuit automated workflows

- 400 FEM domains* for common coil
- Potentially 5000 elements for circuit (slide 15)



* Element with assigned geometry, materials and physical laws

STEAM architecture



Motivation for simulation coupling:

Multi-physics
- Multiple coupled physical domains

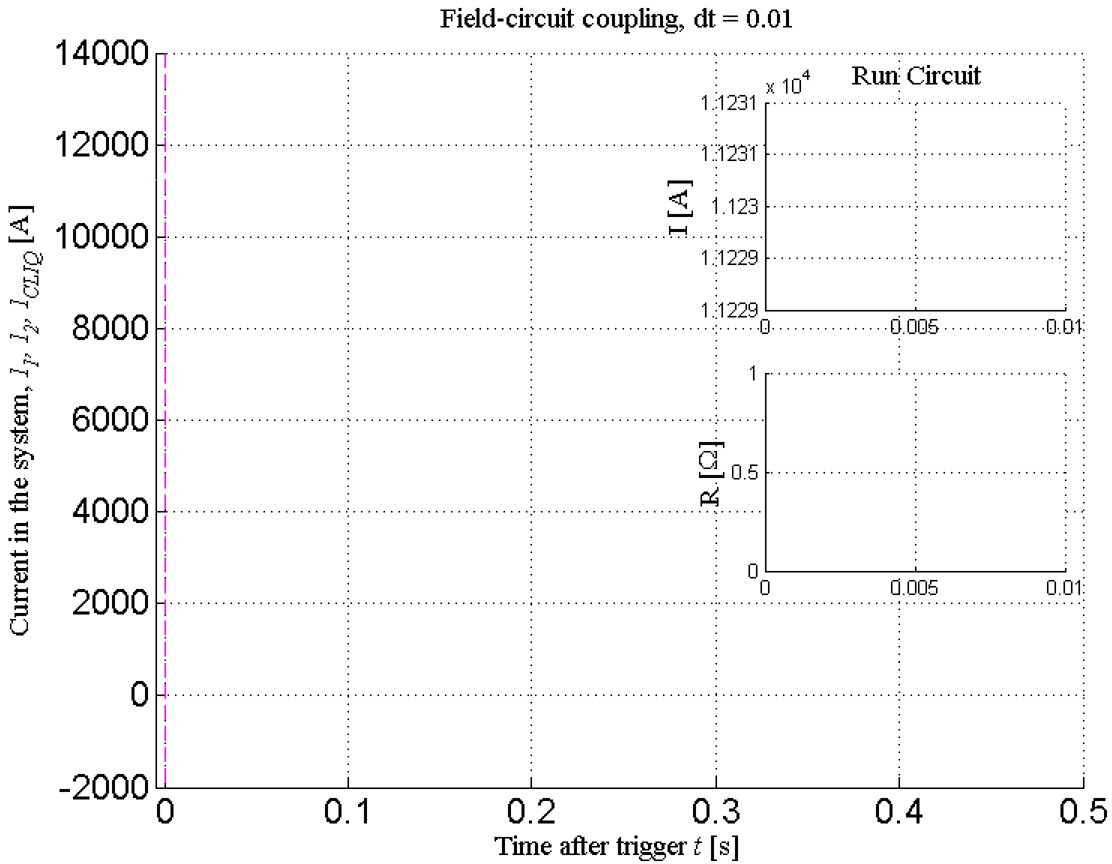
Multi-rate
- Time constants ranging from µs to minutes

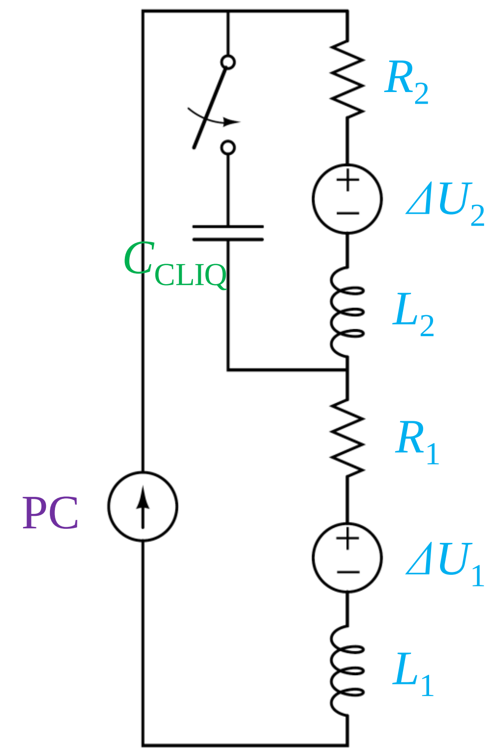
Multi-scale
- Geometrical dimensions differ by several orders of magnitude µm to km

CLIQ simulations

Cos-theta v22b

l_{tp} [mm]	14
ρ_0 [ohm*m]	1.334e-10
ρ_1 [ohm*m/T]	4.2e-11

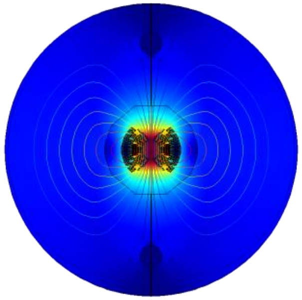




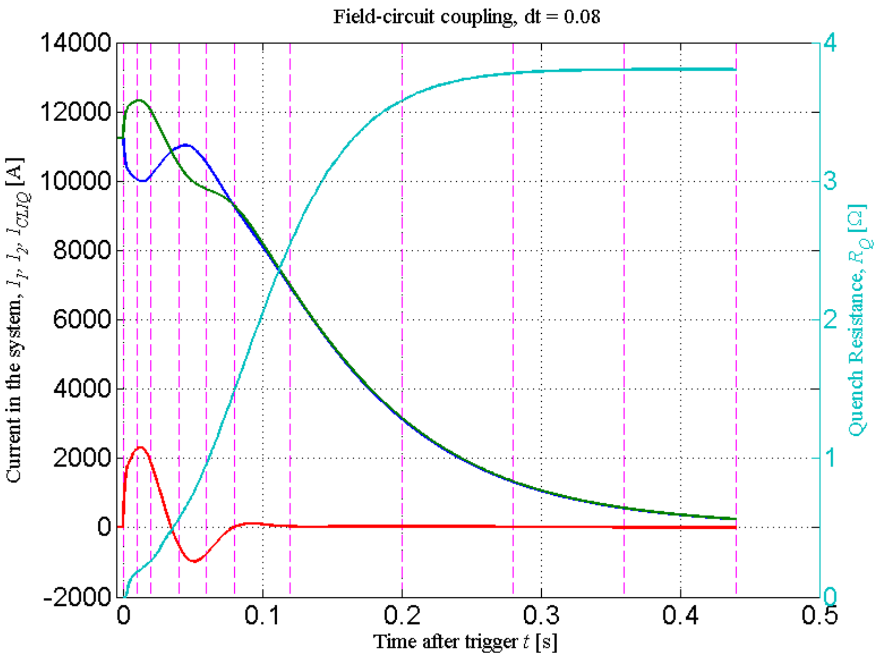
C_{CLIQ}=20 mF, U_{CLIQ}=2 kV

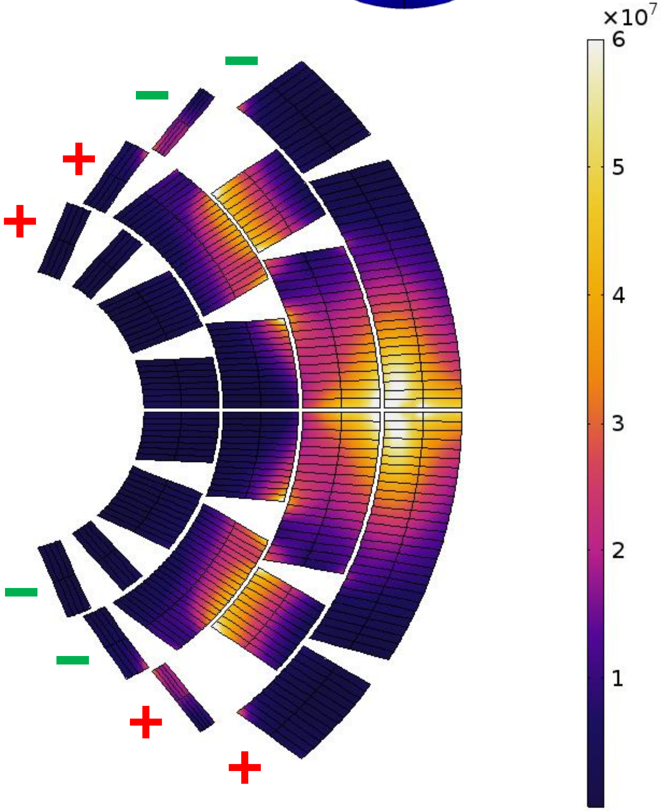
CLIQ simulations

Cos-theta v22b



C_{CLIQ}=20 mF, U_{CLIQ}=2 kV



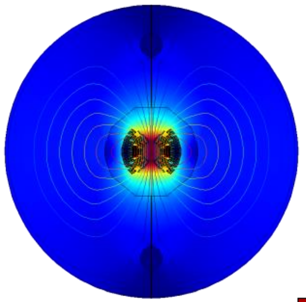


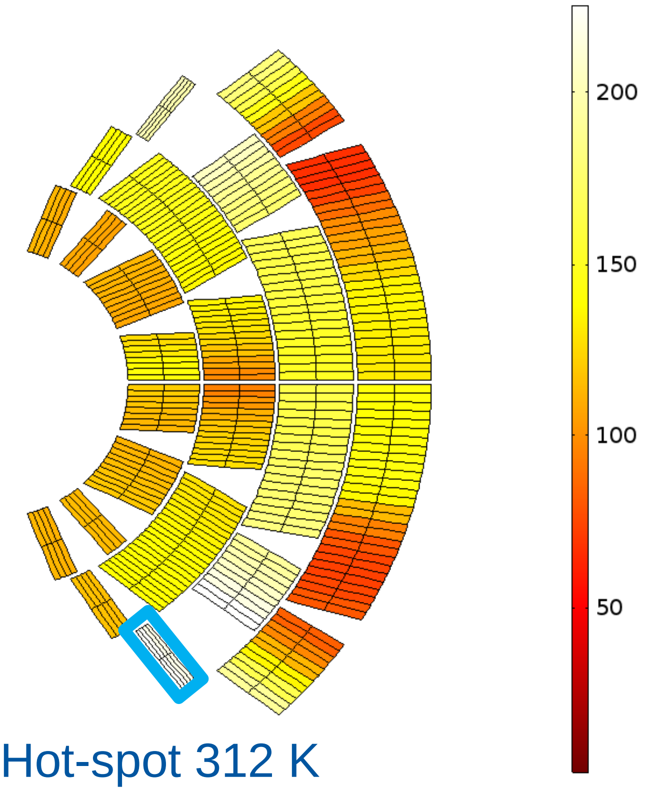
- Current [A] and resistance [Ω] evolution
- Coupling losses [W/m³]

CLIQ simulations

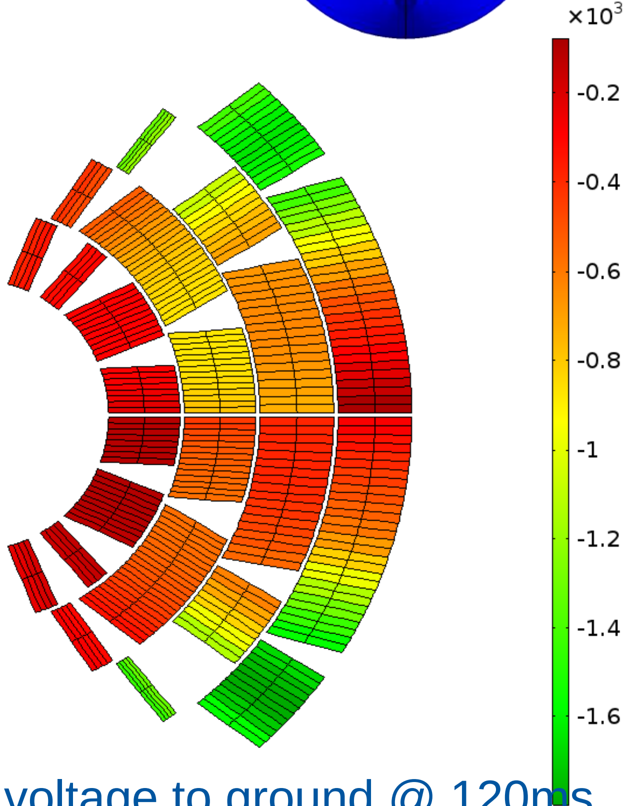
Cos-theta v22b

C_{CLIQ}=20 mF, U_{CLIQ}=2 kV





Hot-spot 312 K

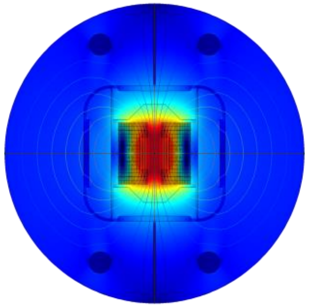


Peak voltage to ground @ 120ms

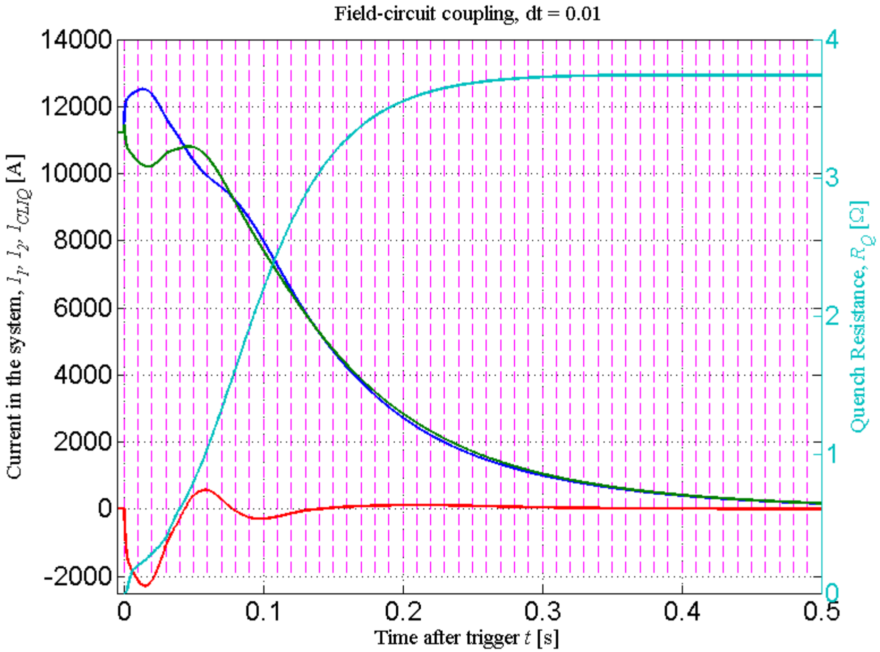
- Temperature [K]
- Voltage to ground [V]

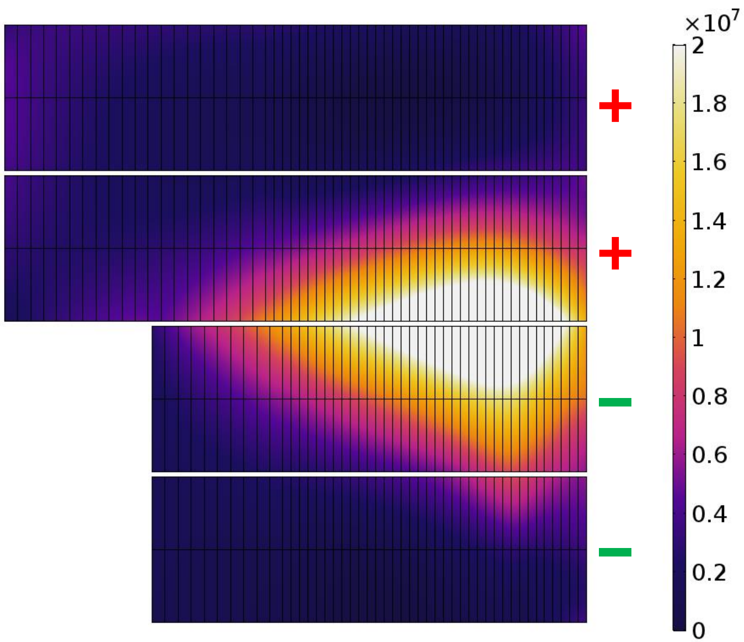
CLIQ simulations

Block coil v20ar



C_{CLIQ}=20 mF, U_{CLIQ}=2 kV

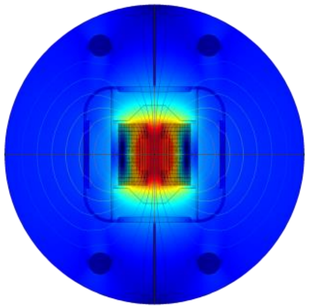




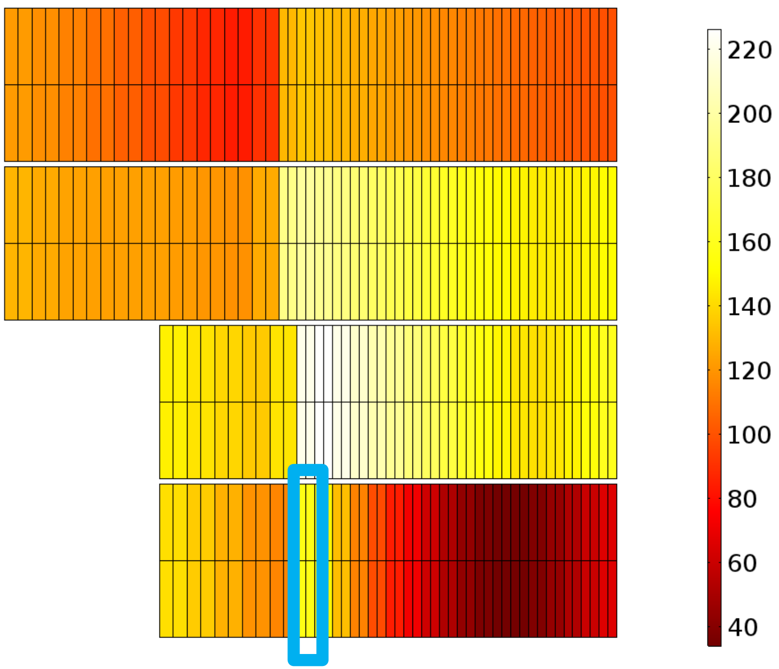
- Current [A] and resistance [Ω] evolution
- Coupling losses [W/m³]

CLIQ simulations

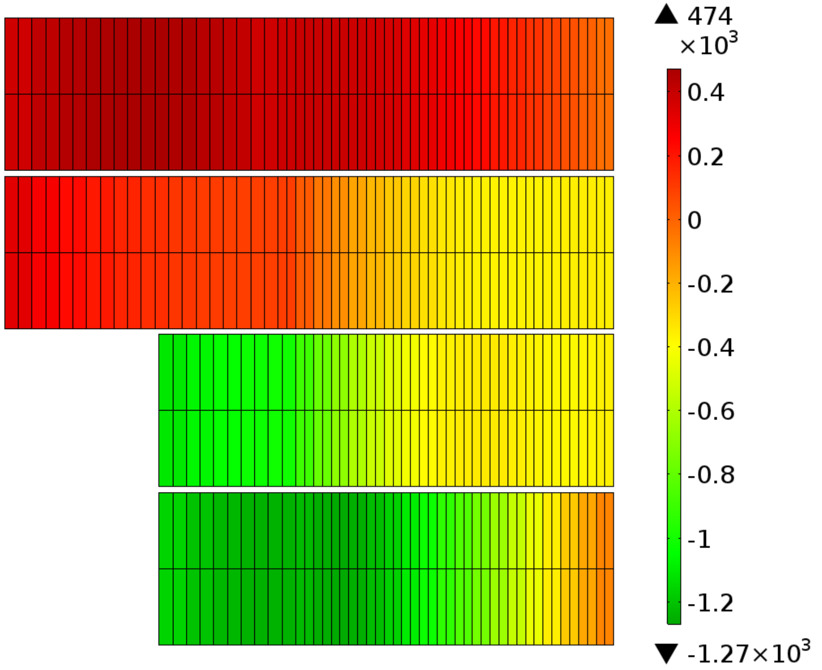
Block coil v20ar



C_{CLIQ}=20 mF, U_{CLIQ}=2 kV



Hot-spot 338 K



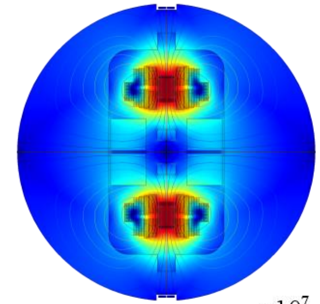
Peak voltage to ground @ 110ms

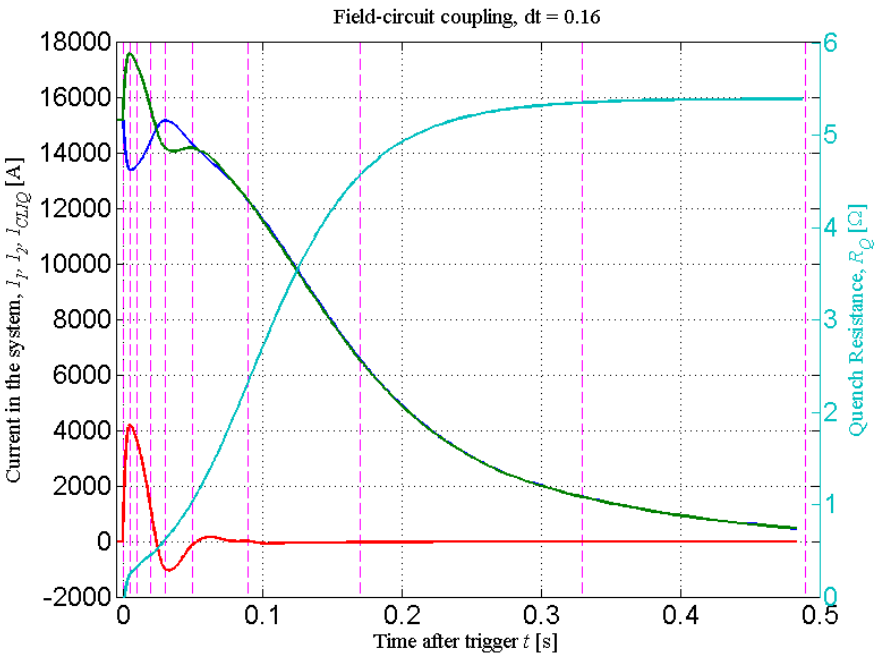
- Temperature [K]
- Voltage to ground [V]

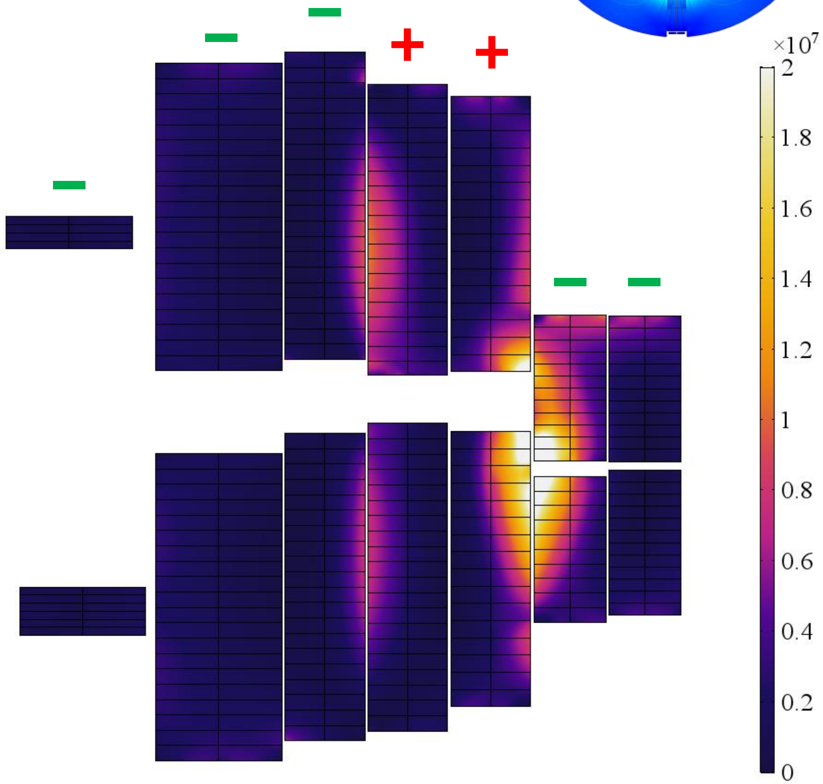
CLIQ simulations

Common coil v1h2

2 × C_{CLIQ}=20 mF, U_{CLIQ}=2 kV





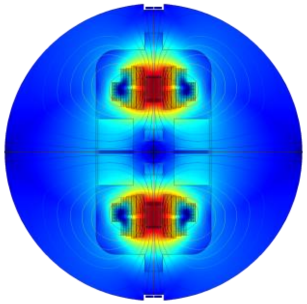


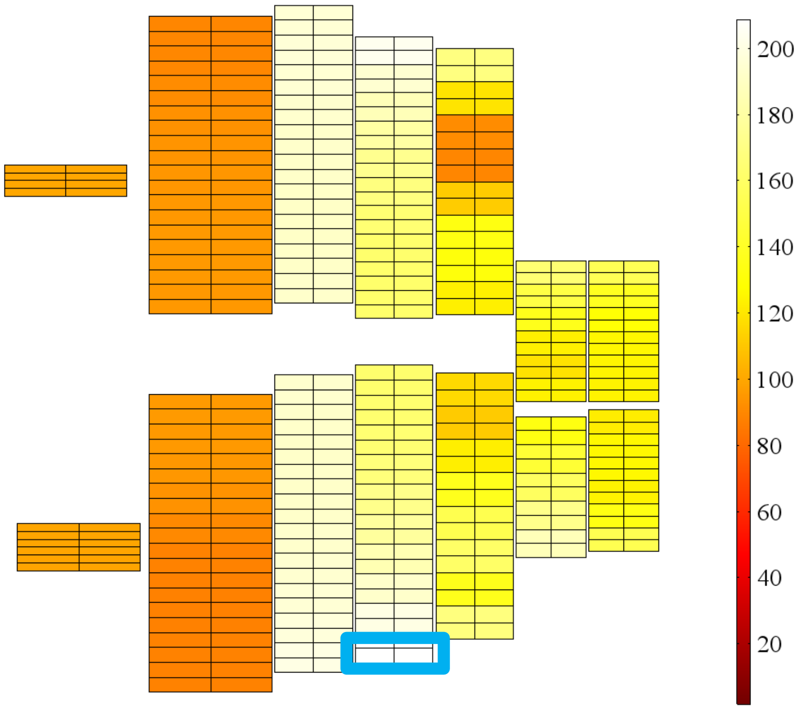
- Current [A] and resistance [Ω] evolution
- Coupling losses [W/m³]

CLIQ simulations

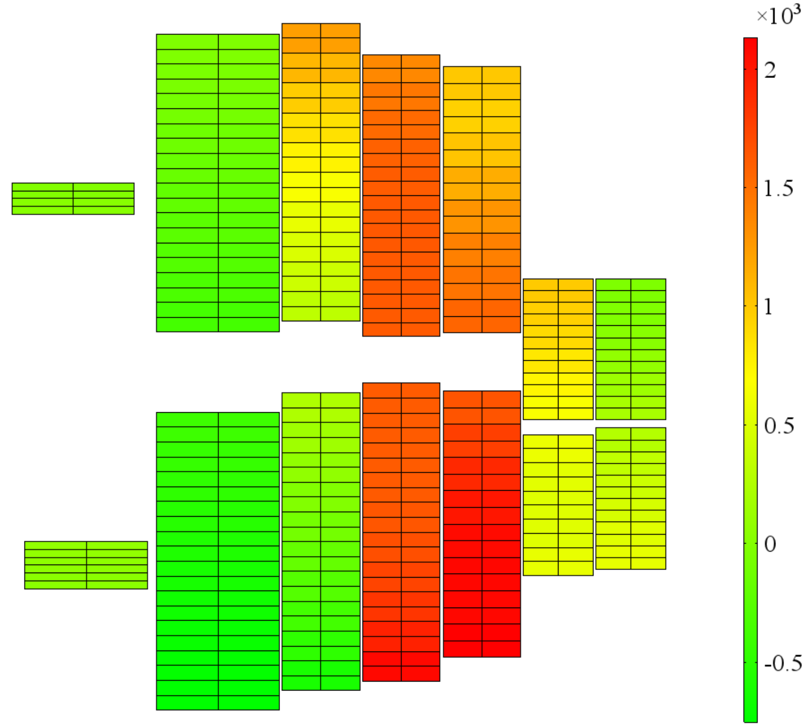
Common coil v1h2

2 × C_{CLIQ}=20 mF, U_{CLIQ}=2 kV





Hot-spot 354 K



Peak voltage to ground @ 130ms

- Temperature [K]
- Voltage to ground [V]

Conclusions and future work

- A new tool for circuit and quench protection simulations
- First fully consistent CLIQ simulations
- Flexibility enables study of complex circuits/magnets without additional effort

- Next steps
  - Analyse a magnet quench in the full FCC circuit
  - Test new ideas for magnet powering: e.g. separate circuits for inner and outer layers, or subdivision diodes

  - Build two apertures model for all magnet designs
  - Optimize CLIQ configuration considering different current levels
  - Include heaters model

  - Share the tool with TAMPERE colleagues