CERN

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How to bring STEAM power into FCC protection studies

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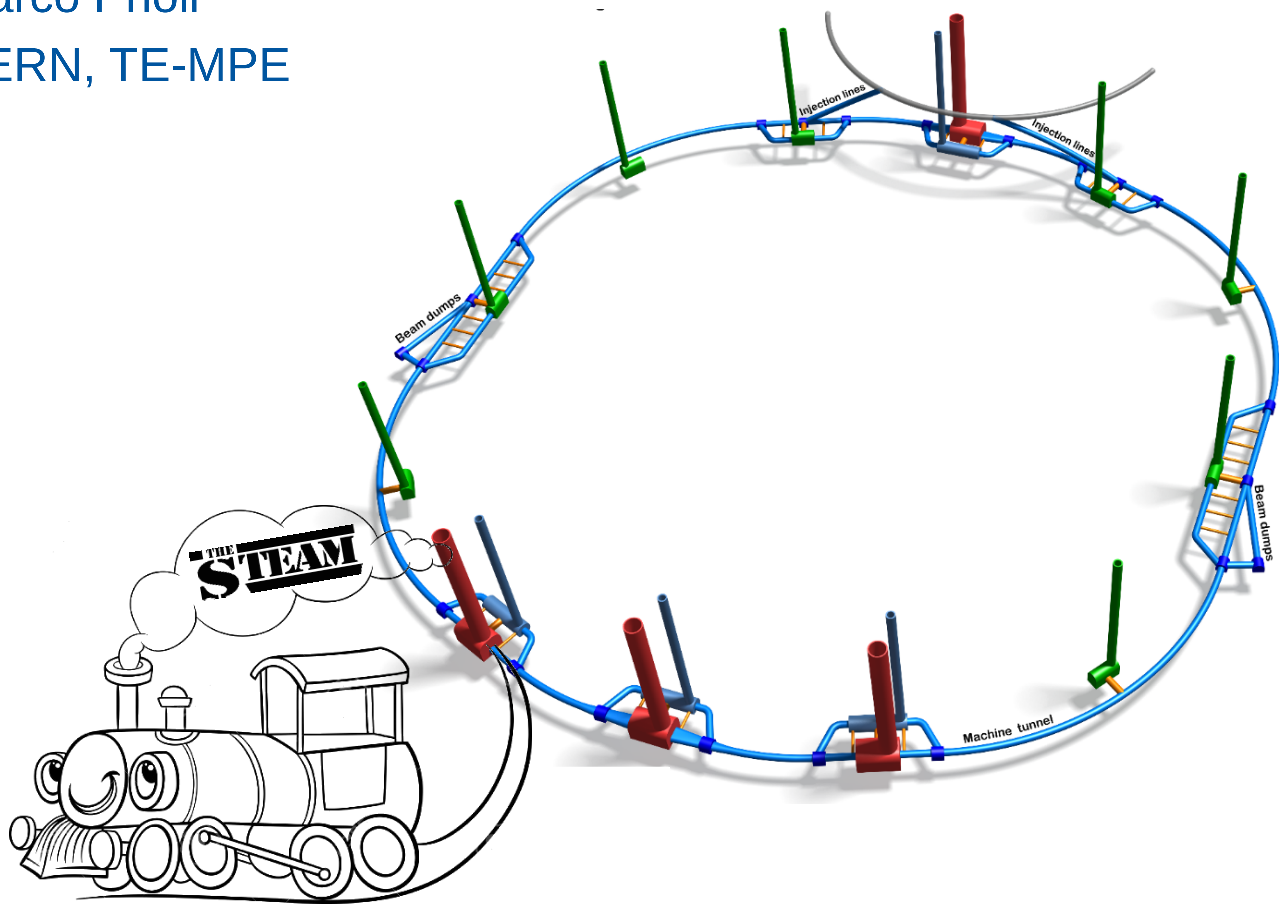
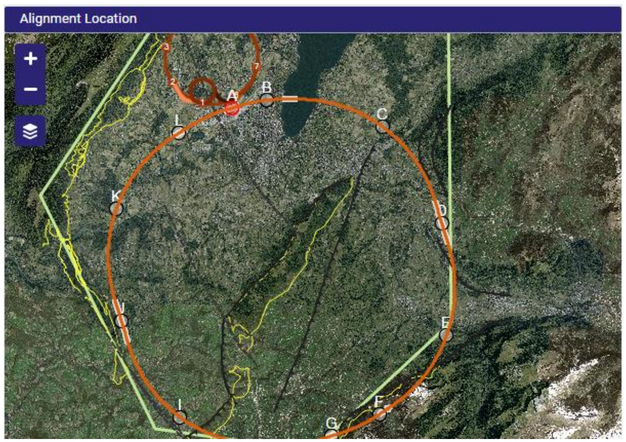
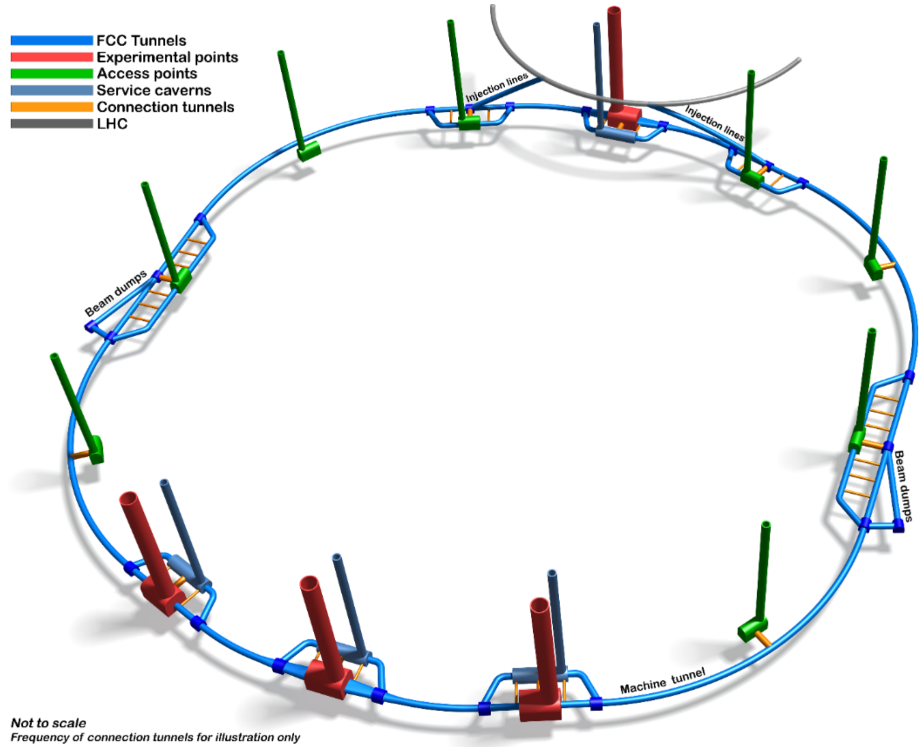
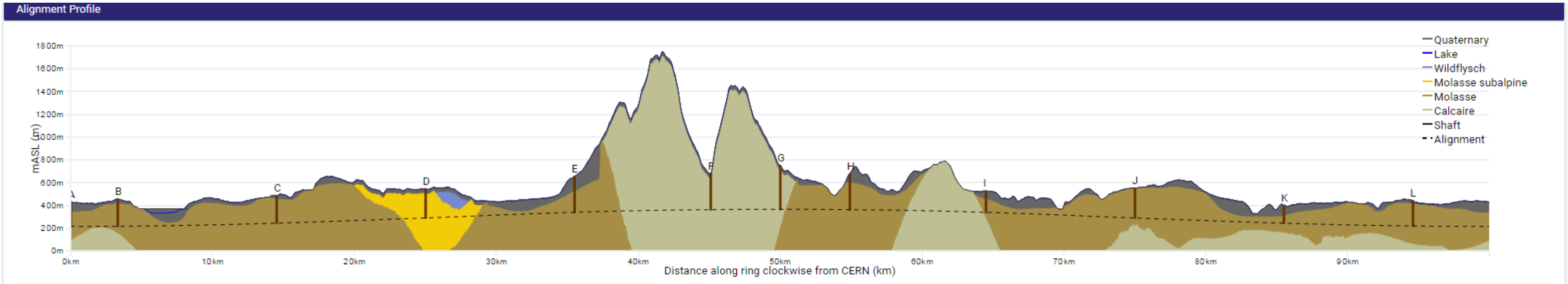


The Future Circular Collider

- 100 km accelerator
- 16 T dipole field
- 100 TeV energy at collision

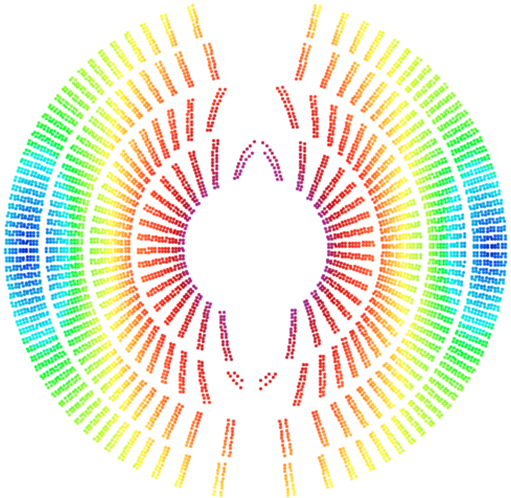




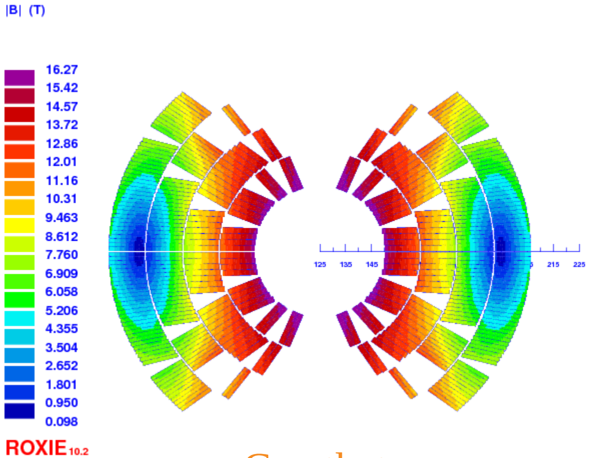


Dipole magnets

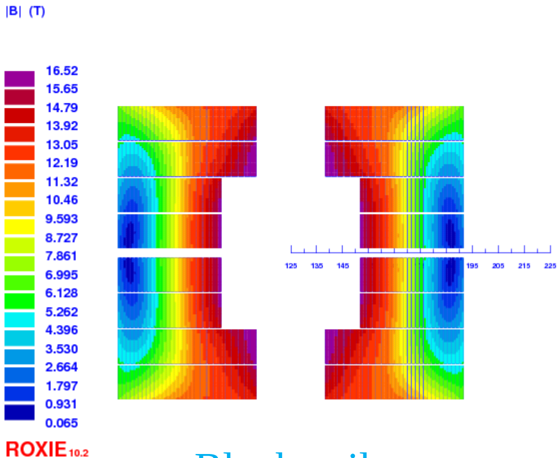
	Current @ B_{nom} [kA]	Differential inductance (2 apertures) [mH]	Stored energy @ I_{nom} (2 apertures) [MJ]
Cos-theta	11.23	566	38
Block coil	10.99	571	36
Common coil	16.80	287	43
Canted cos-theta	18	254	44
Dipoles in LHC	11.85	98	7



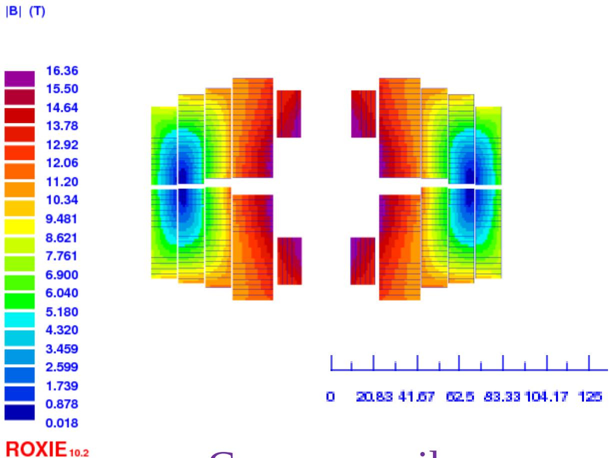
Canted Cos-theta



Cos-theta



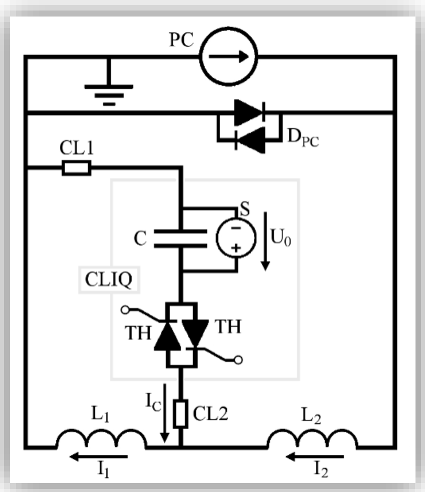
Block coil



Common coil

Magnet protection

- Magnets need to be protected in case of quench
  - The key is to lead most of the magnet into the resistive state as *fast* and *uniform* as possible
- The design of the protection system is challenging
  - High specific energy and inductance → high temperatures and voltages
  - The simple extrapolation of the present protection technology (Quench Heaters) could not be enough



Coupling-Loss Induced Quench (CLIQ) is a new technology for the protection of superconducting magnets. The core component is the capacitor bank that generates:

- An alternated transport current in the magnet
- A variable magnetic field in the coils
- High inter-filament and inter-strand coupling losses
- Heat on the superconductor
- Quick spread of the normal zone after a quench

Schematic courtesy of E. Ravaioli

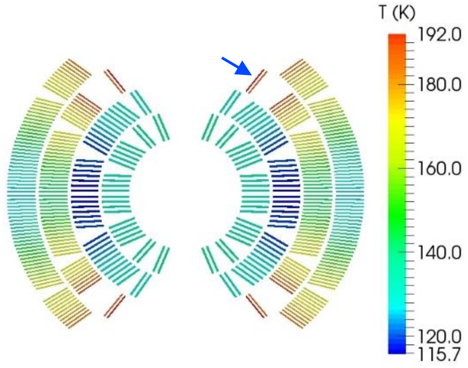
Quench simulations: TAMPERE

40 ms uniform protection delay: Temperatures

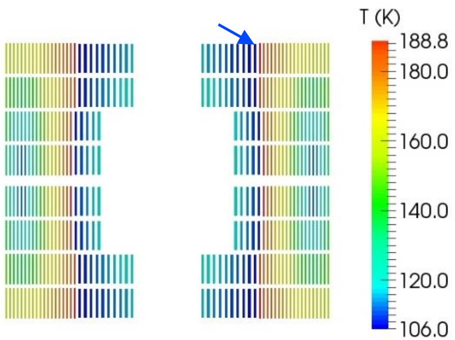
Protection delay includes the detection, etc.

	T_{max} (K)	Δ*T* (incl. HS) (K)	Δ*T* (excl. HS) (K)
Cos*θ*	345	~140	~60
Block	356	~250	~80
CC*	353	~250	~120

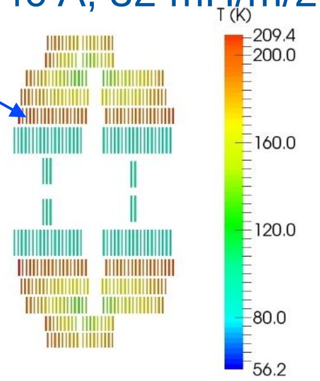
16T_22b-37-optd6f6
11790 A, 20 mH/m/ap



V20ar
12040 A, 18 mH/m/ap



V1h2
15940 A, 32 mH/m/2-ap



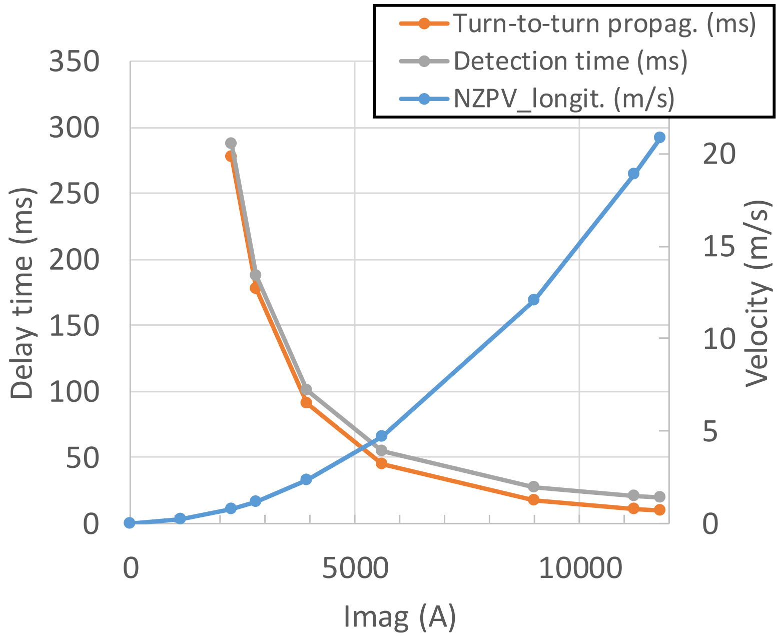
*CC winding order and induct. tbc

From T. Salmi, EuroCirCol WP5 Workshop 2016 (link)

Quench simulations: TAMPERE

Hotspot temperature simulation assumptions

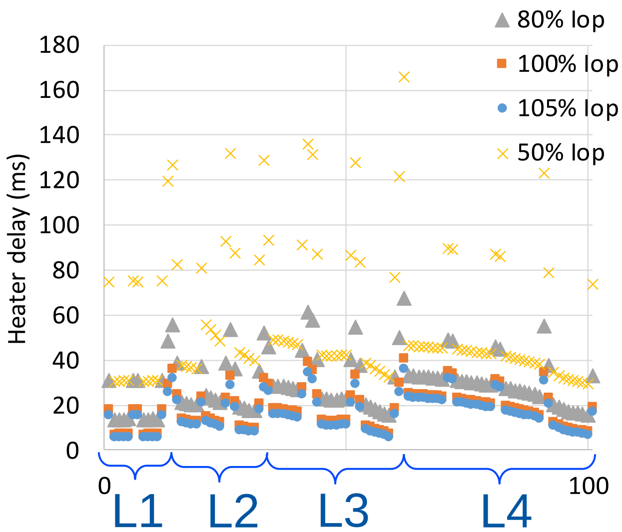
- 20 ms for quench detection (10+10ms)
- 20 m/s longit. NZPV, 10 ms turn-to-turn
  - QLASA: Average longit. 18 m/s, turn to turn: ~4-10 ms
  - Remember pre-heating from heaters!
- At lower current scaled proportionally to I_{mag}^2

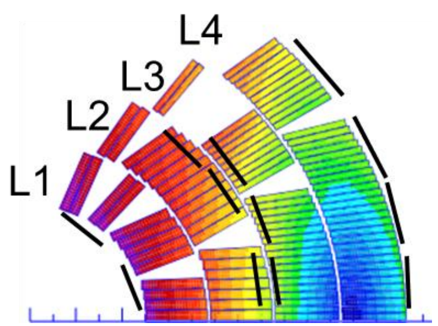


Quench simulations: TAMPERE

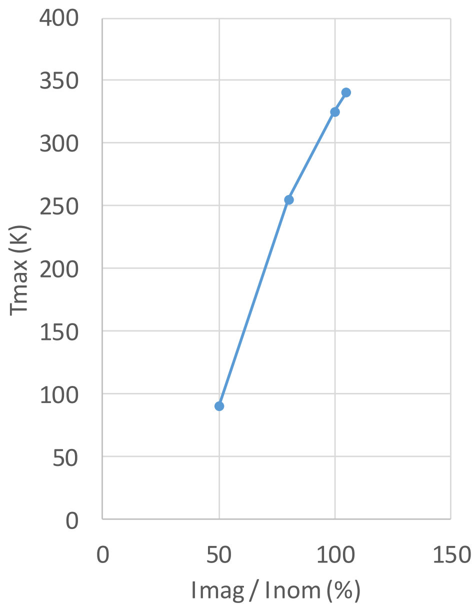
Results with heater based protection

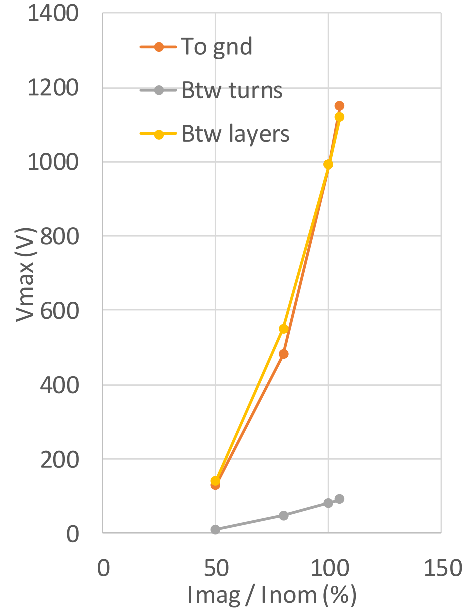
Turn heater / quench delays vs. I_{mag}





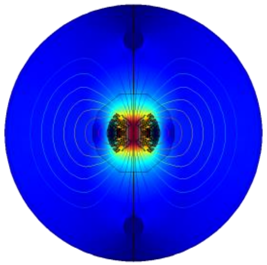
Hotspot temperature and voltages vs. I_{mag}



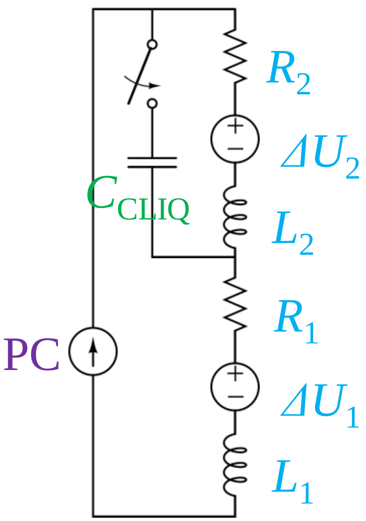


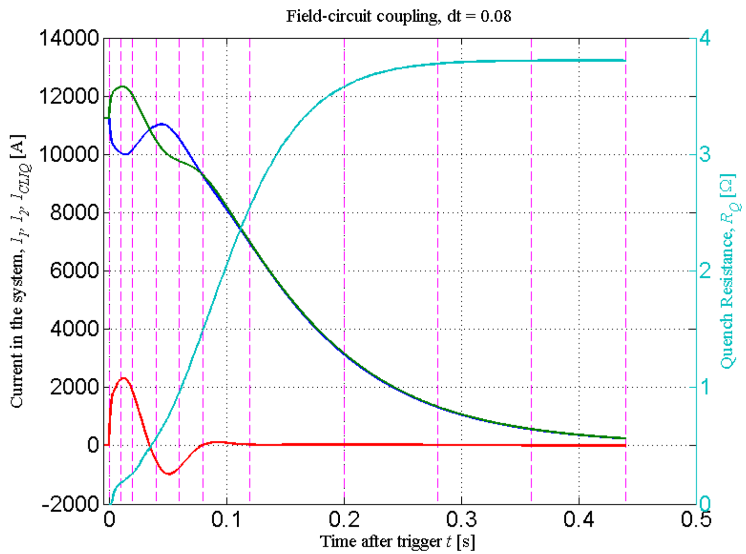
⇒ High current the most critical
⇒ Protection at all currents
⇒ Very small margin at high current

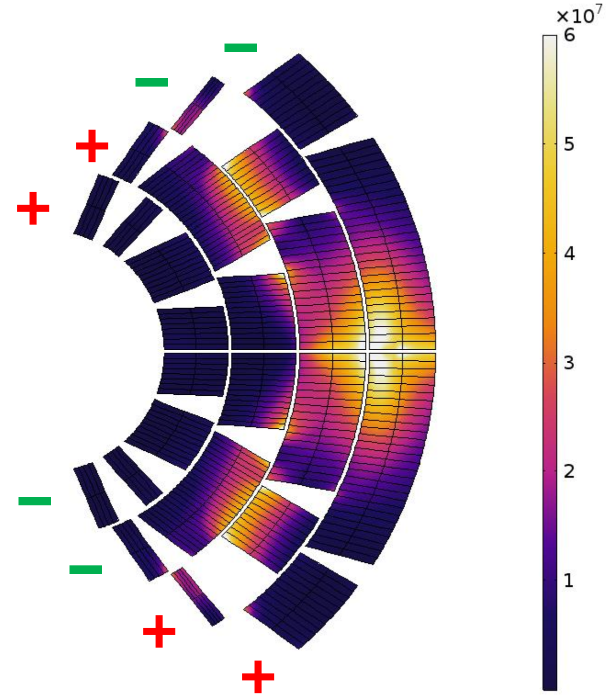
Quench simulations: STEAM



CLIQ simulations



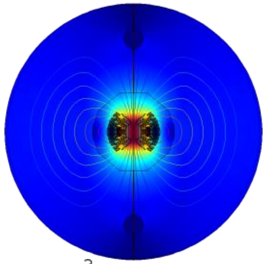




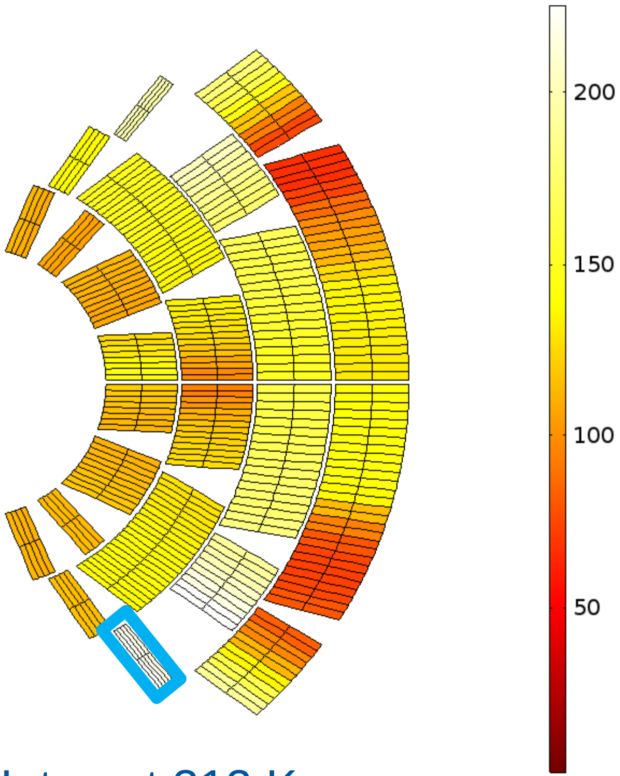
C_{CLIQ}=20 mF,
U_{CLIQ}=2 kV

- Current [A] and resistance [Ω] evolution
- Coupling losses [W/m^3]

Quench simulations: STEAM

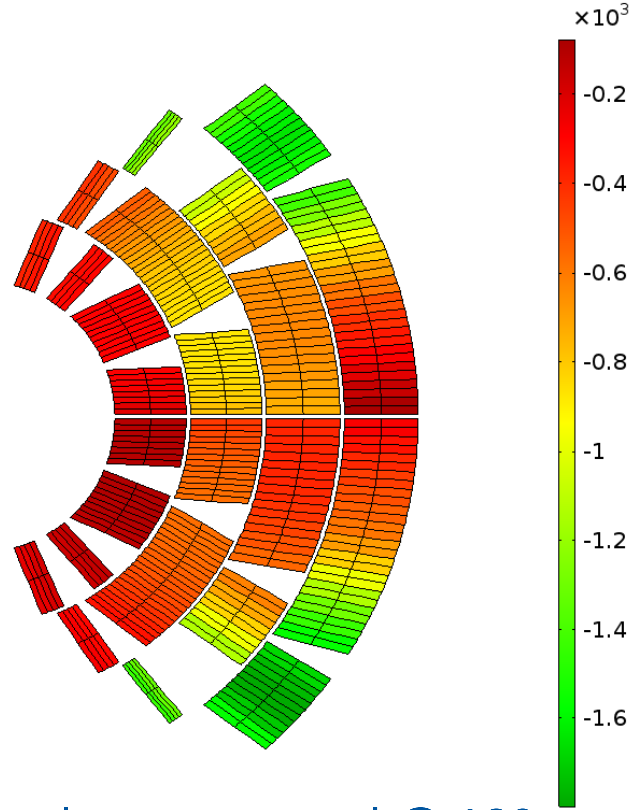


CLIQ simulations



Hot-spot 312 K

- Temperature [K]



Peak voltage to ground @ 120ms

- Voltage to ground [V]

Common strategy for quench simulations

- Many actors and tools involved
  - Tampere, CoHDA + Coodi
  - CERN, STEAM
  - LBNL, LEDET
  - INFN, QLASA

- Crosscheck and validation of the tools
  - Table of features and assumptions
  - Crosscheck with uniform protection delay (adiabatic, no iron, no losses)
  - Simulations adding incrementally all the tools features

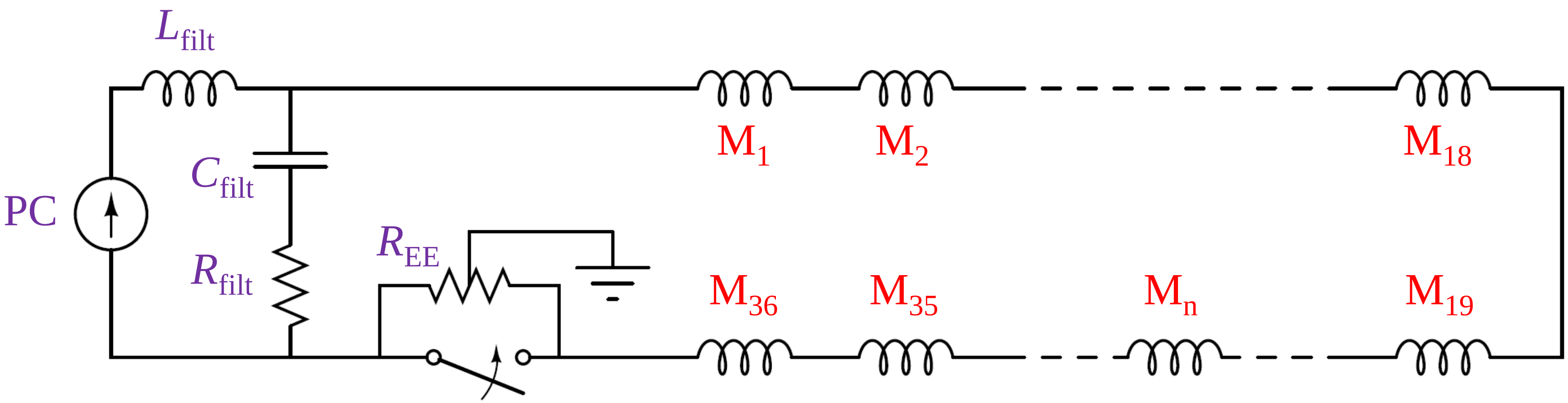
  - Validation against measurement in MQXF

STEAM strategy for quench simulations

- Prove that our tool for CLIQ simulations is robust and easy to use, and receive feedbacks
  - STEAM release
- In many cases, parametric studies are needed: current sweep, optimization of CLIQ + QH, sensitivity analysis
  - Integration in STEAM of faster tools for quench simulations (QLASA, LEDET, …)
- Hybrid protection scenario of CLIQ + QH has to be simulated
  - QH model in COMSOL
- Each tool needs to prove its capabilities for extrapolation of results
  - The consistent physics formulation in STEAM is the key

Circuit protection

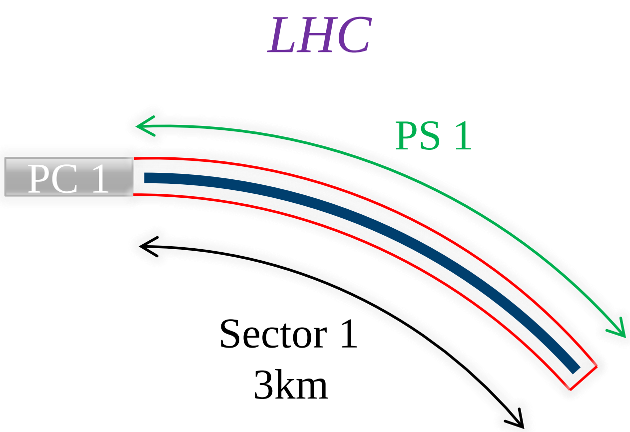
- Magnets are powered in a chain
- The circuit design is challenging
  - High specific energy and inductance → high circuit energy and voltages
  - The simple extrapolation of the present LHC design is not feasible

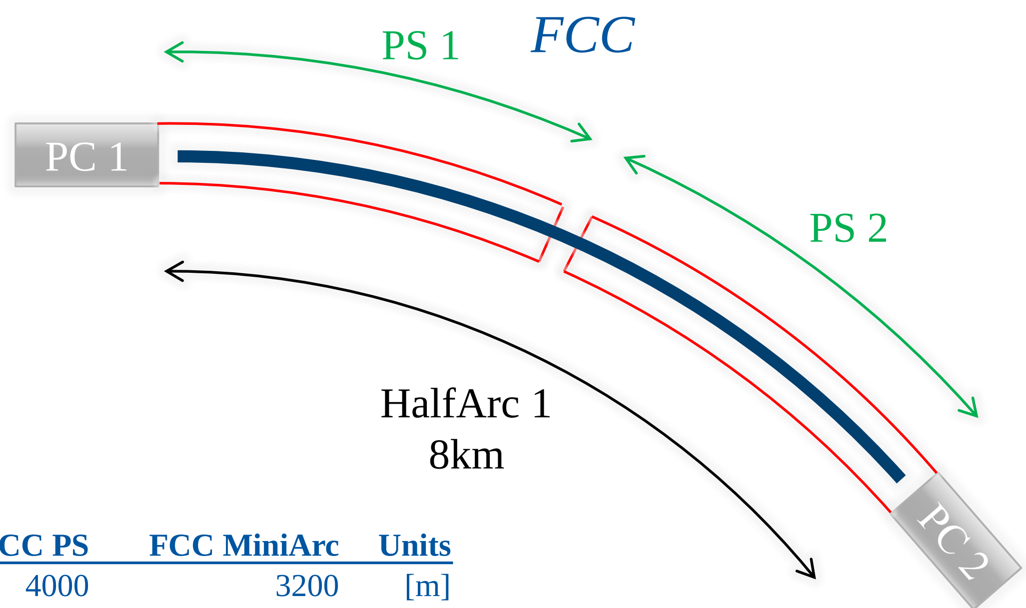


Example: chain of 36 magnets

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

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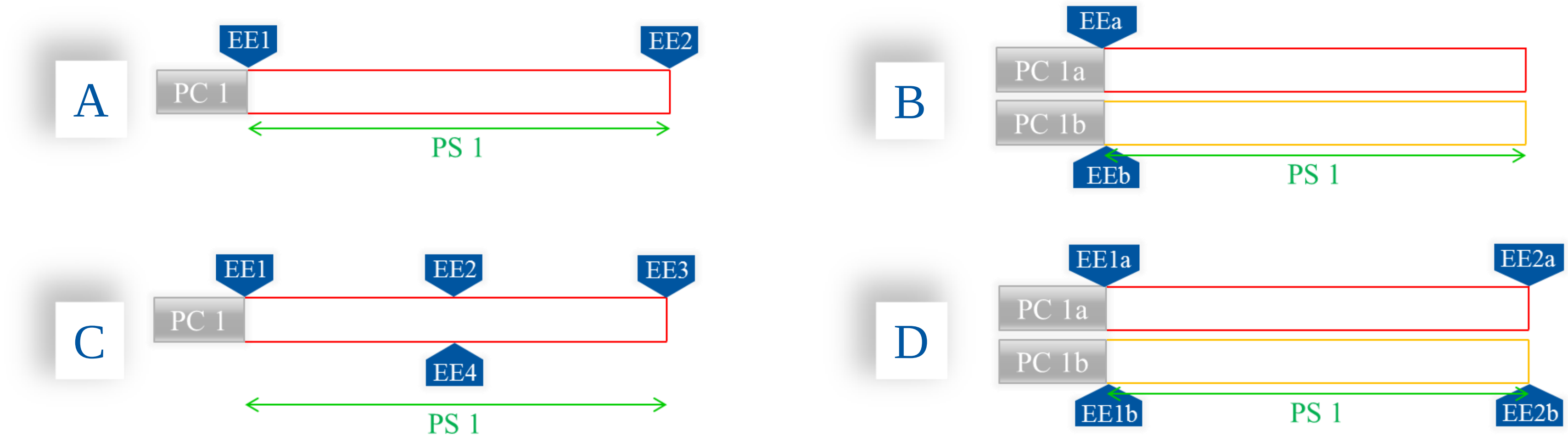
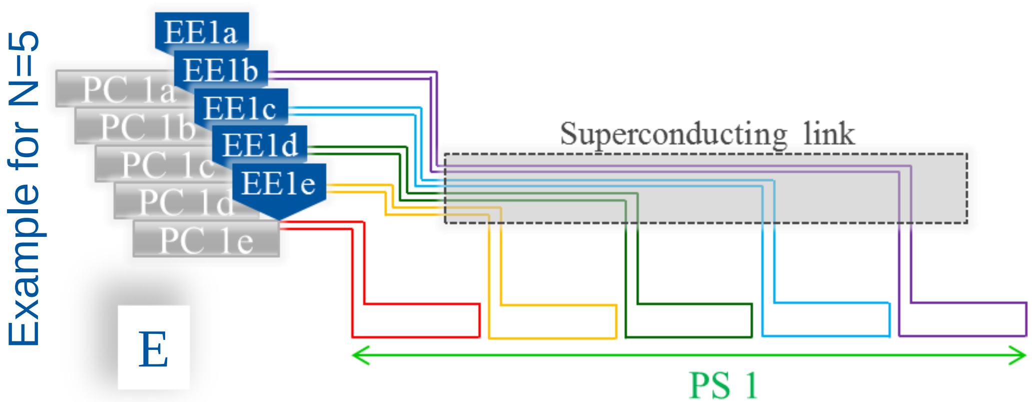
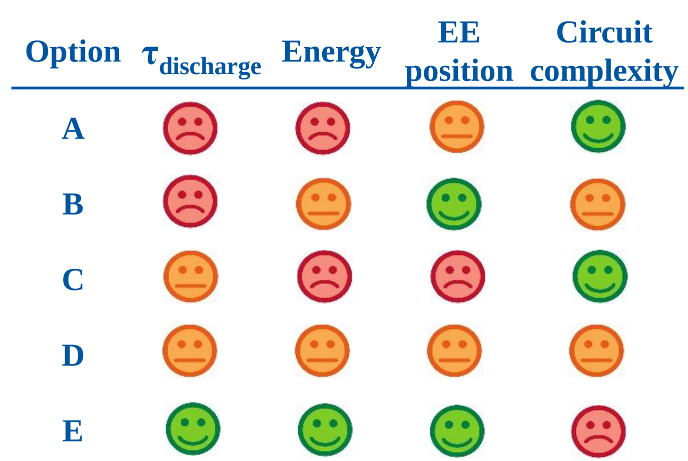
* M. Prioli, Concepts for magnet circuit powering and protection (Link)

Circuit protection @ FCC week 2016*





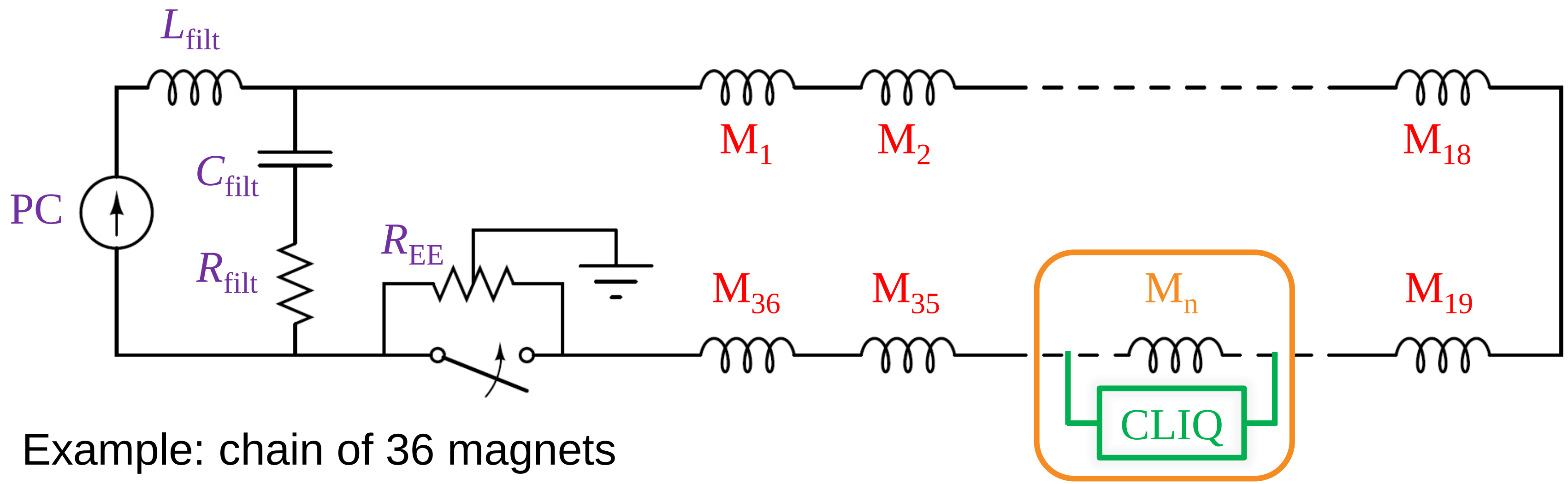


Circuits layouts E for Cos-theta

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

More details in M. Prioli, EuroCirCol WP5 Workshop 2016 (link)

Outlook for circuit and quench simulations



Example: chain of 36 magnets

- 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

STEAM strategy for circuit simulations

- Thanks to field-circuit coupling, STEAM can provide the first consistent tool for circuit and quench simulations
  - STEAM release
- CLIQ effect on the circuit
  - Create and couple the PSpice netlist of the full FCC circuit
- Voltage is the most severe limiting factor in the circuit design
  - Test new ideas for magnet powering as coil subdivisions, internal diodes, …
- For the circuit, lumped elements magnet models are needed
  - Possibly obtained from FEM?