Magnet protection considerations for FCC-hh

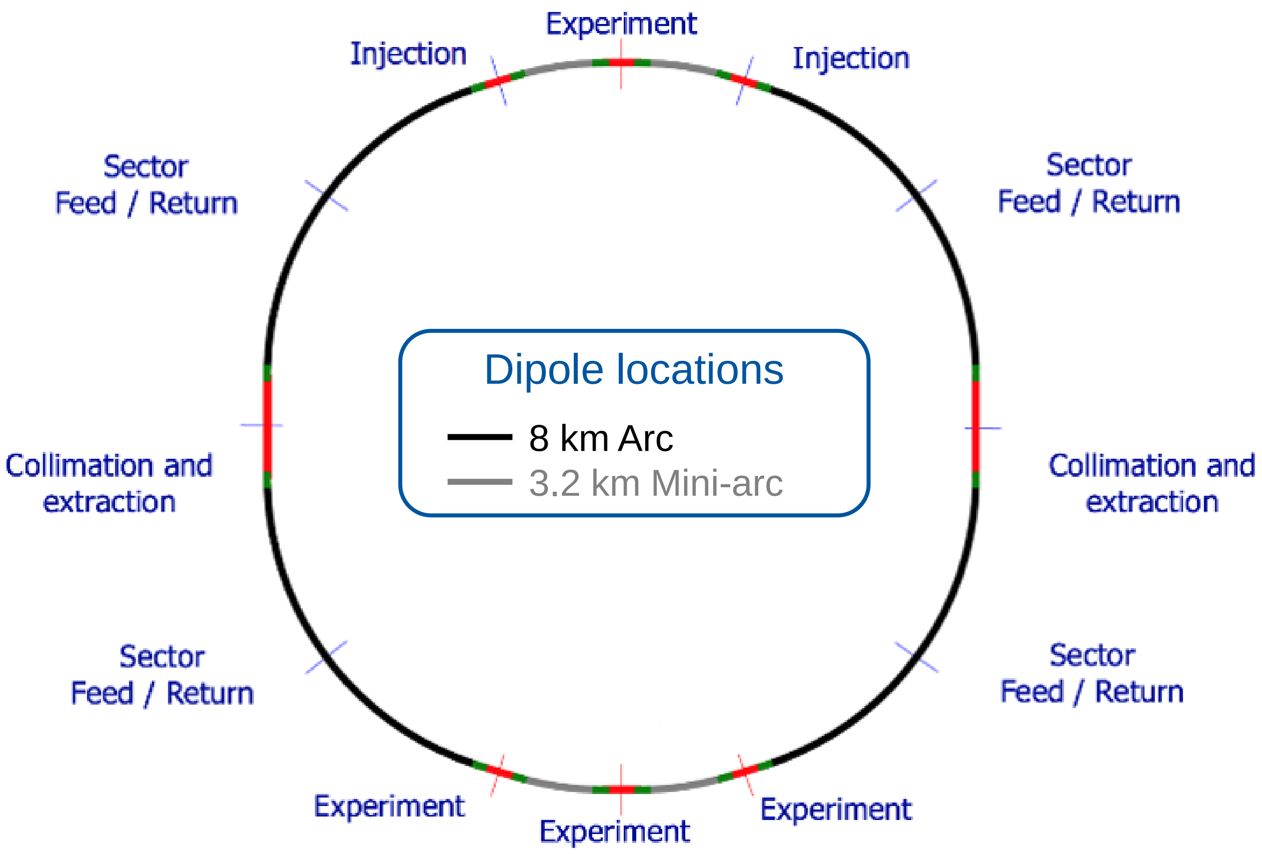
Emmanuele Ravaioli (CERN)
with acknowledgments to the colleagues who previously worked on this topic,
in particular B. Auchmann, L. Bortot, M. Maciejewski, M. Prioli, T. Salmi, R. Schmidt, A. Siemko, A. Verweij,
and to the colleagues in the STEAM team, in particular M. Wozniak

2024.06.13 FCC Week

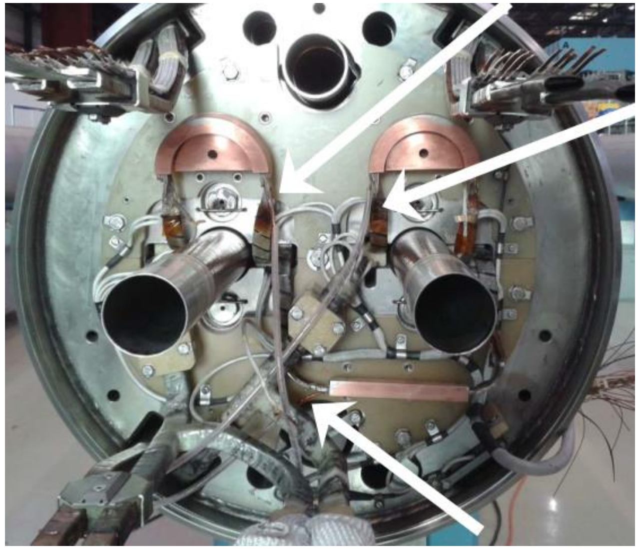
GOALS OF MAGNET/CIRCUIT PROTECTION

Safer magnets and circuits	• Lower peak temperature • Lower peak voltage to ground • Lower peak thermal stress • Lower risk (i.e. higher redundancy and less severe consequences) • Lower downtime (i.e. higher availability)
More efficient magnets and circuits	• Lower construction cost • Lower use of conductor • Lower operating cost • Lower operating voltage • Lower cryogenic loss

CIRCUIT OPTIMIZATION



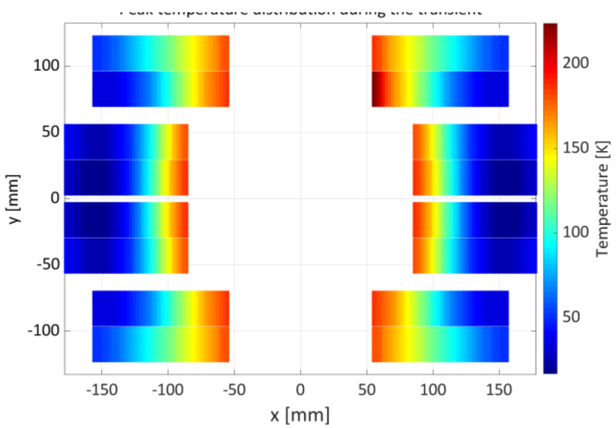
MAGNET QUENCH PROTECTION METHODS



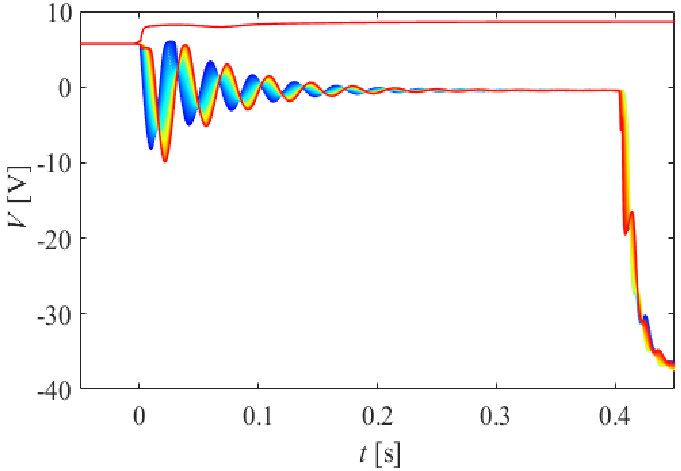
2

[1]Courtesy of D. Cheng [2]Courtesy of T. Mulder

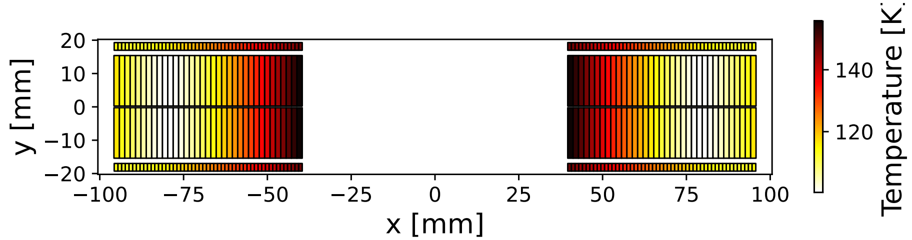
MODELING



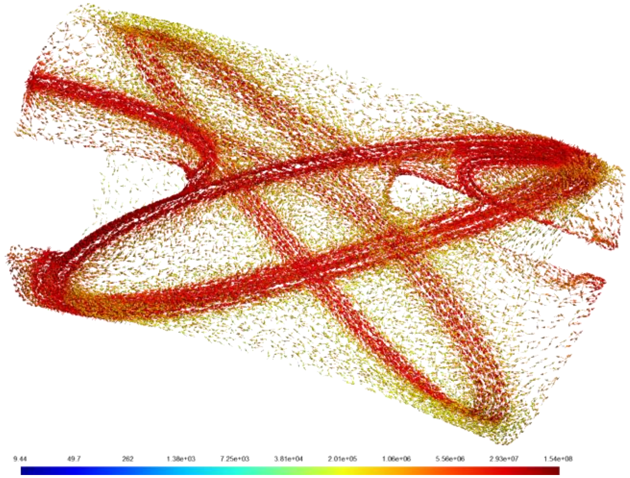
100
50
0
-50
-100
y [mm]
-150
-100
-50
0
50
100
150
x [mm]
200
150
100
50
Temperature [K]

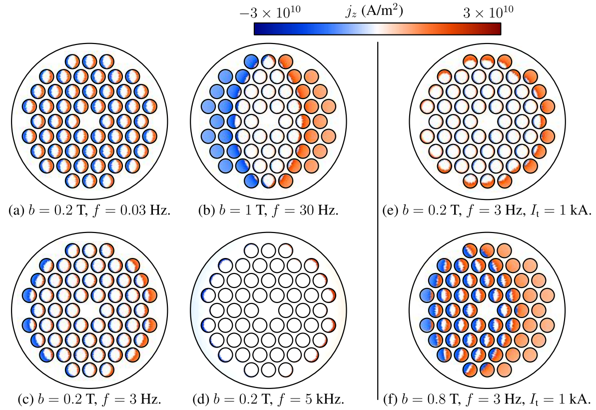


10
0
-10
-20
-30
-40
V [V]
0
0.1
0.2
0.3
0.4
t [s]

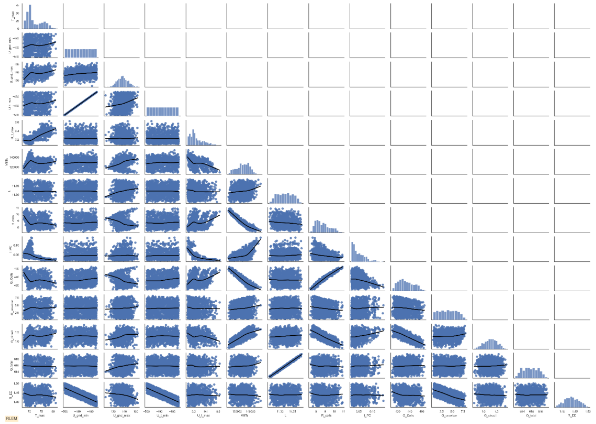


20
10
0
−10
−20
y [mm]
−100
−75
−50
−25
0
25
50
75
100
x [mm]
140
120
Temperature [K]

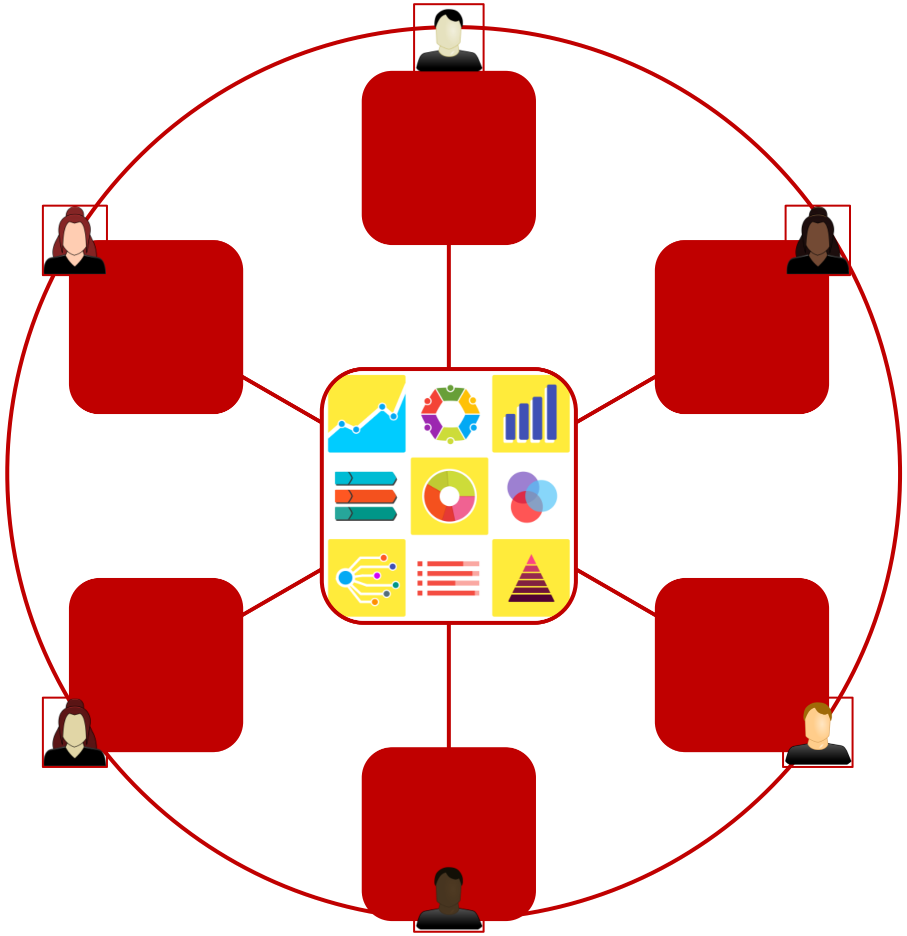




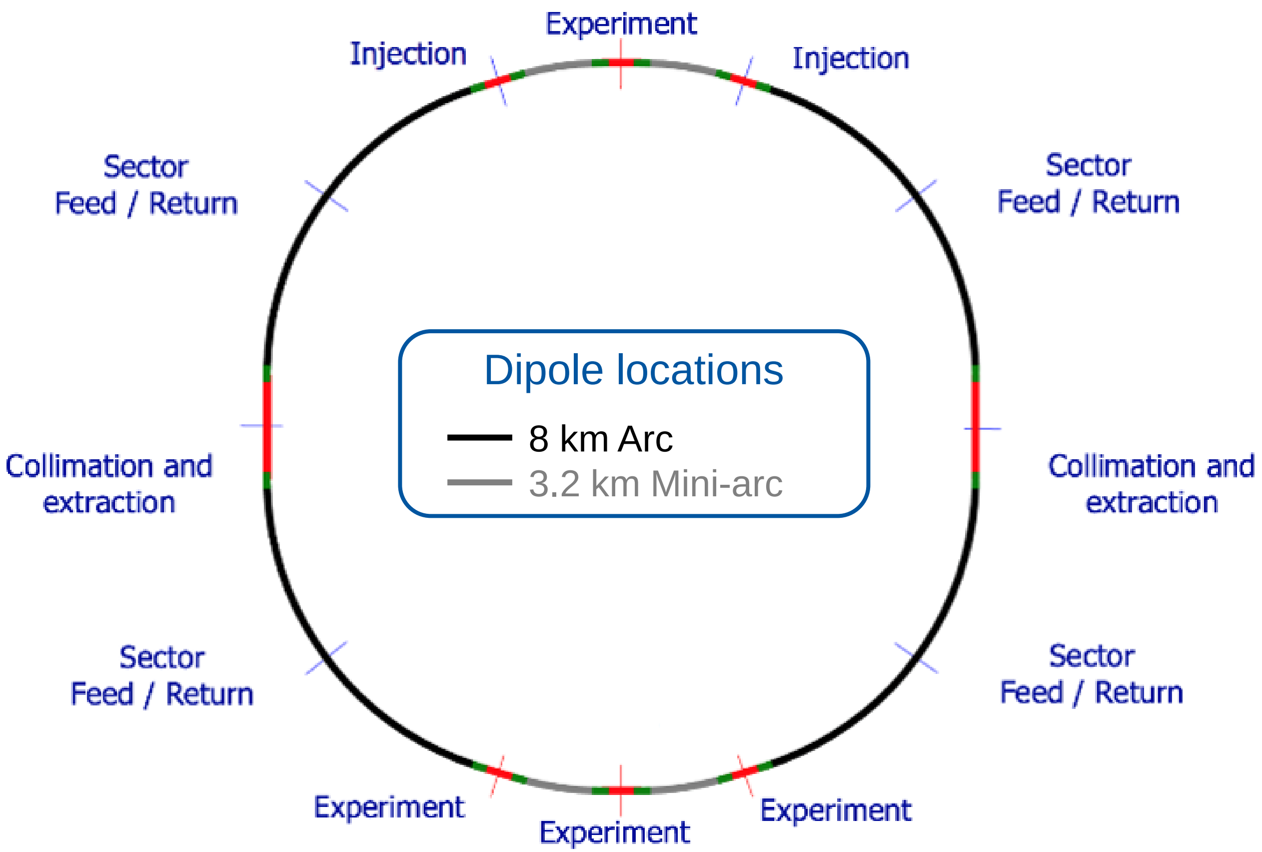
-3×10^{10}
j_z (A/m^2)
3×10^{10}
(a) $b = 0.2$ T, $f = 0.03$ Hz.
(b) $b = 1$ T, $f = 30$ Hz.
(e) $b = 0.2$ T, $f = 3$ Hz, $I_t = 1$ kA.
(c) $b = 0.2$ T, $f = 3$ Hz.
(d) $b = 0.2$ T, $f = 5$ kHz.
(f) $b = 0.8$ T, $f = 3$ Hz, $I_t = 1$ kA.



COLLABORATION



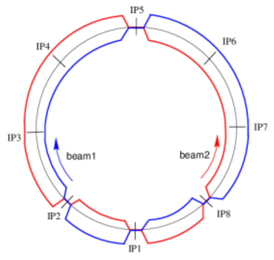
CIRCUIT OPTIMIZATION



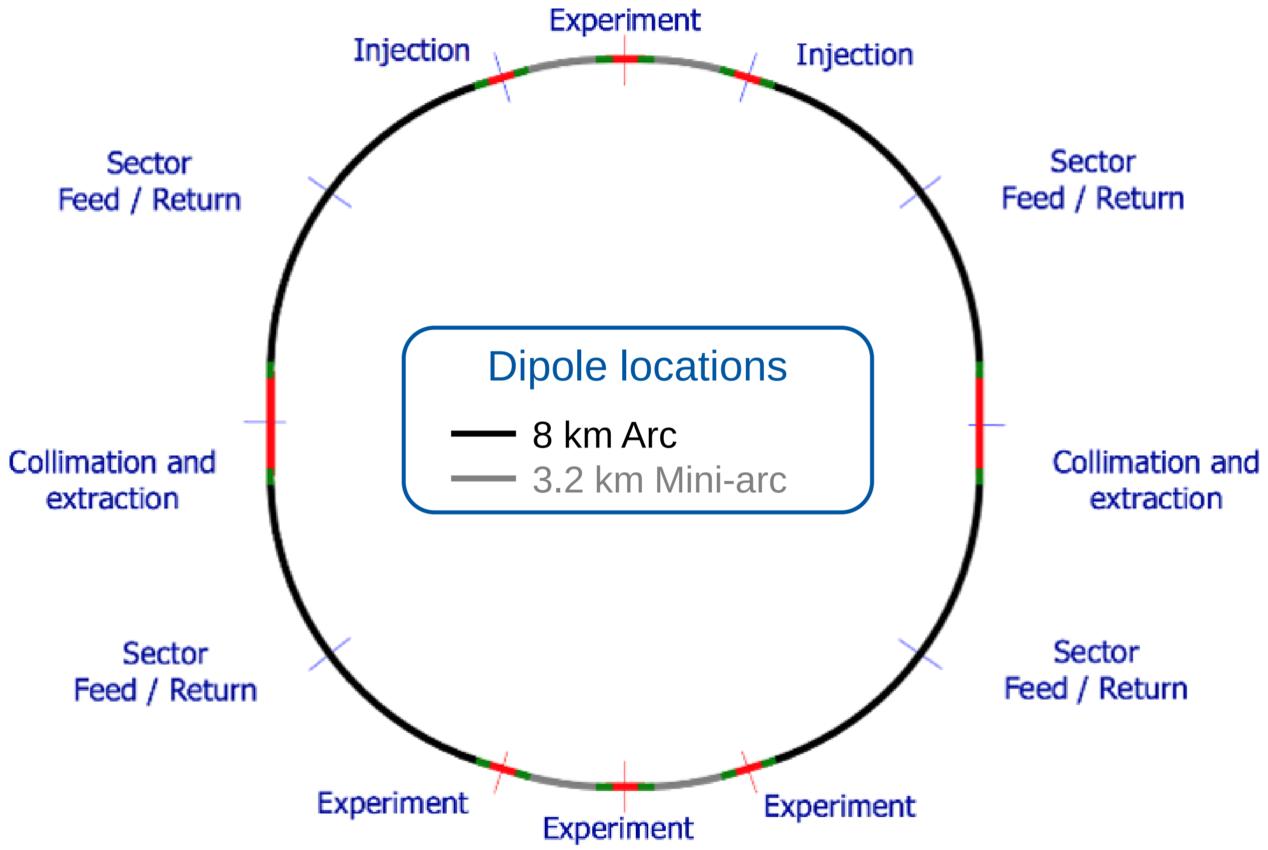
Studies have been performed in 2015-2020 mainly by M. Prioli and A. Verweij, with input from: B. Auchmann, L. Bortot, M. Maciejewski, T. Salmi, R. Schmidt, A. Siemko.

MAIN DIPOLE CIRCUIT PARAMETERS

	LHC	FCC
Number of arcs	8	8
Length arc	3 km	8 km
Number of dipoles per arc	154	438
Nominal current of the dipoles	11.9 kA	10-18 kA
Stored energy per arc	1.1 GJ	16-20 GJ
Number of mini-arcs	-	4
Length mini-arc	-	3.2 km
Number of dipoles per mini-arc	-	180
Stored energy per mini-arc	-	7-8 GJ
Total stored energy in the dipoles	8.8 GJ	108-176 GJ



LHC



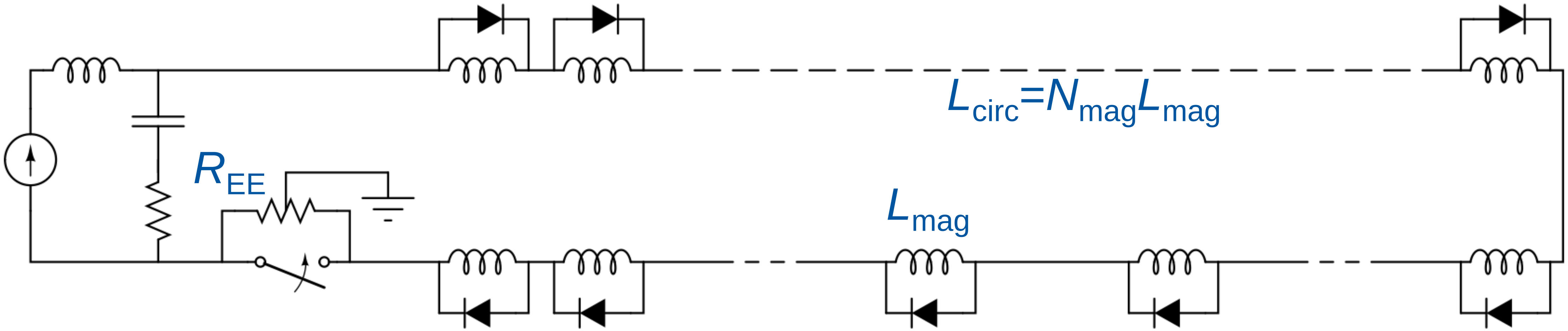
FCC

From A. Verweij's FCC Week 2019 presentation

CIRCUIT POWERING AND PROTECTION STRATEGY

For the FCC-hh we consider LHC-type of powering and protection:

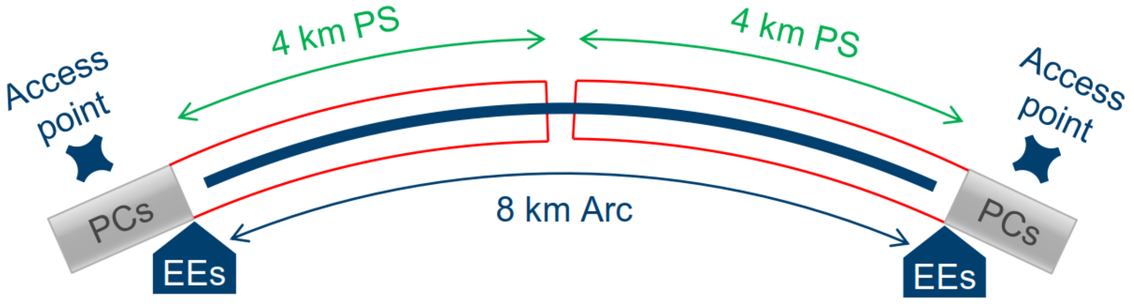
- Series connection of magnets to limit the number of power converters and current leads.
- Quench detection of individual magnets based on differential voltage.
- CLIQ units (and/or quench heaters) and cold bypass diodes to protect individual quenching magnets.
- Warm Energy Extraction (EE) units to protect the circuit, including bypass diodes, busbar and current leads. LHC uses a passive R_{EE} (i.e. circuit ~exponential decay $t_{decay}=L_{circ}/R_{EE}$). For FCC we consider an active $R_{EE}(I)$ (i.e. ~linear decay $t_{decay}=L_{circ}/R_{EE,0}$) to reduce the quench load for the same maximum circuit voltage.
- Grounding of the circuit in the centre of one of the EE resistances.

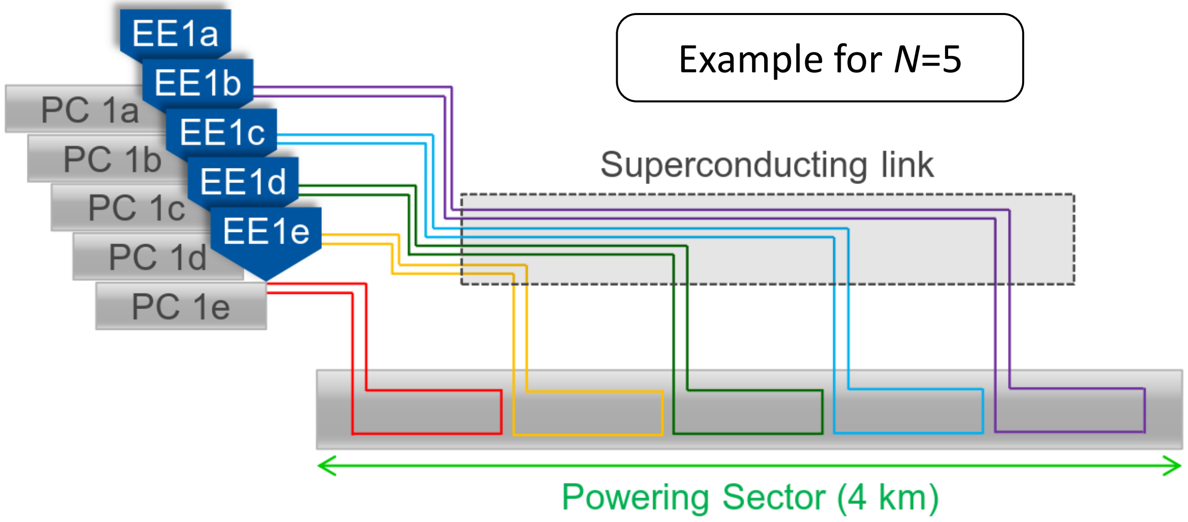


CIRCUIT TOPOLOGY

Power converters (PC) and energy extraction systems (EES) **close to the 12 access points**
- Space optimization and easier maintenance

1. Power each 8 km long Arc from two sides, obtaining in total 16 powering sectors (PS) of 4 km
2. Power each 3.2 km long Mini-arc from one side, obtaining in total 4 mini powering sectors (PS_{mini}) of 3.2 km
3. Subdivide each PS in N circuits ($16N$ circuits in total)
4. Subdivide each PS_{mini} in N_{mini} circuits ($4N_{mini}$ circuits in total)
5. Equip each circuit with one PC and one energy-extraction unit (EES)
6. Power the circuits through superconducting links





From A. Verweij's TE FCC-ee 2024 presentation

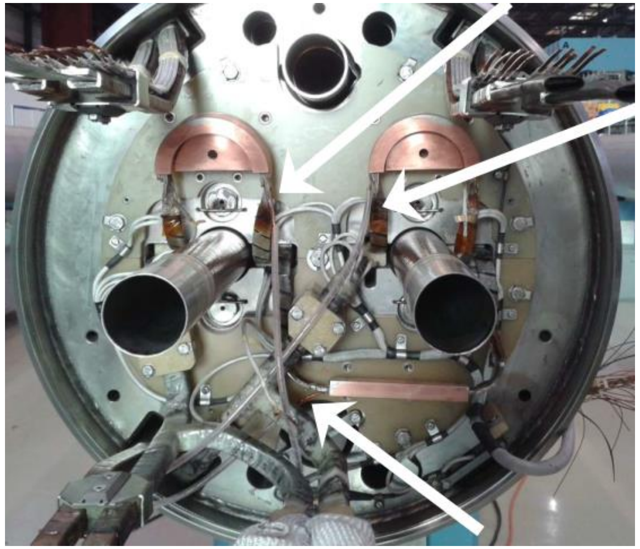
CIRCUIT DESIGN TARGETS

Design target	**N, N_{mini}**	**I_{magnet}**
Minimize the Voltage Withstand Level; VWL+f *($U_{quench,max}$+$U_{circuit,max}$)	↑	↑
Minimize the discharge time τ during a Fast Power Abort and hence cross-section of the busbars; $\tau = L_{circ}/R_{EE,0}$	↑	↑
Minimize the stored energy in a circuit (risk scenario's)	↑	
Minimize the number of SC links	↓	
Minimize the thermal heat inleak	↓	↓
Reduce number of EES and current rating EES	↓	↓
Minimize ramp time and the required peak voltage and power of the PC	↓	↑
Minimize the time needed for HWC & training campaign	↑	

This circuit topology is very flexible. Optimum values for N and N_{mini} have to be defined depending on type of magnet and various design targets, resulting in about 80-120 powering circuits (see Annex)

From A. Verweij's TE FCC-ee 2024 presentation

MAGNET QUENCH PROTECTION METHODS



2

[1]*Courtesy of D. Cheng* [2]*Courtesy of T. Mulder*

EVOLVING QUENCH PROTECTION REQUIREMENTS

8 T

- ✓ Nb-Ti
- ✓ Quite some margin in terms of hot-spot temperature, peak voltages to ground, peak stresses
- ✓ Often quenching ~20% of the coil volume is enough to protect the magnet

12 T

- ✓ Nb_3Sn
- ✓ Tighter margin in terms of hot-spot temperature and peak voltages to ground
- ✓ New quench protection method introduced
- ✓ Peak stresses are an issue as Nb_3Sn is quite sensitive to stress/strain

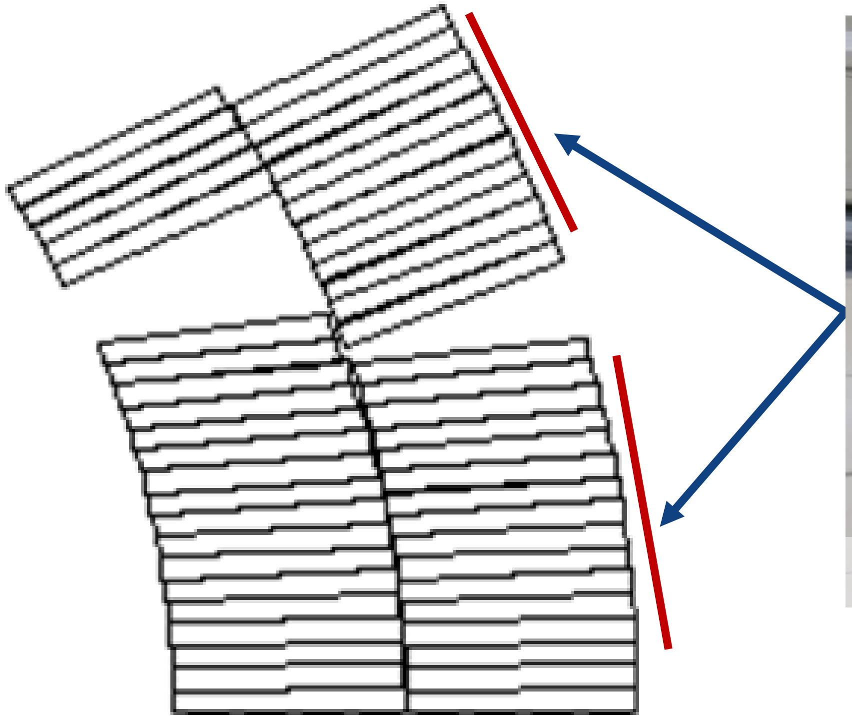
14-16 T

- ✓ Nb_3Sn
- ✓ Even tighter margins
- ✓ Typical target: 90-100% coil quenched in 1-5 ms
- ✓ Peak stresses are a significant issue and require rethinking the support structure

20+ T

- ✓ HTS
- ✓ New quench protection methods needed
- ✓ Screening currents during transients can cause very high stresses
- ✓ If LTS+HTS, insert/outsert solution is possible

QUENCH HEATERS (QH)

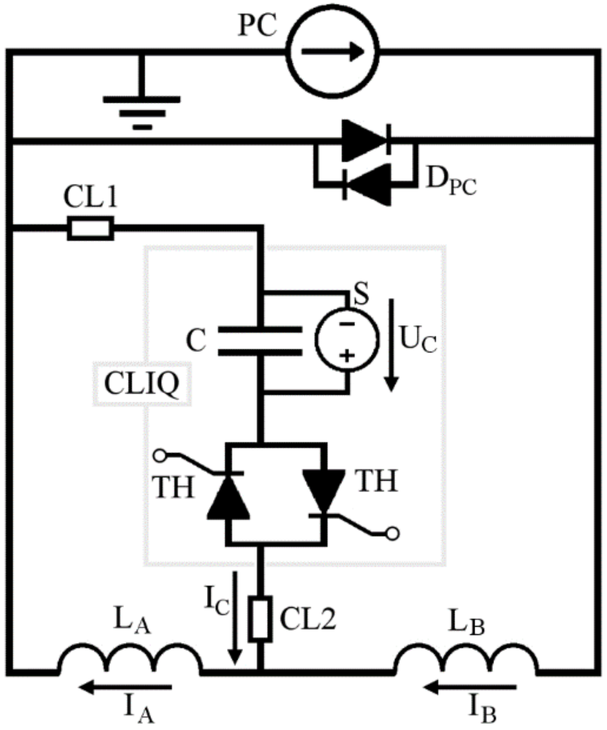


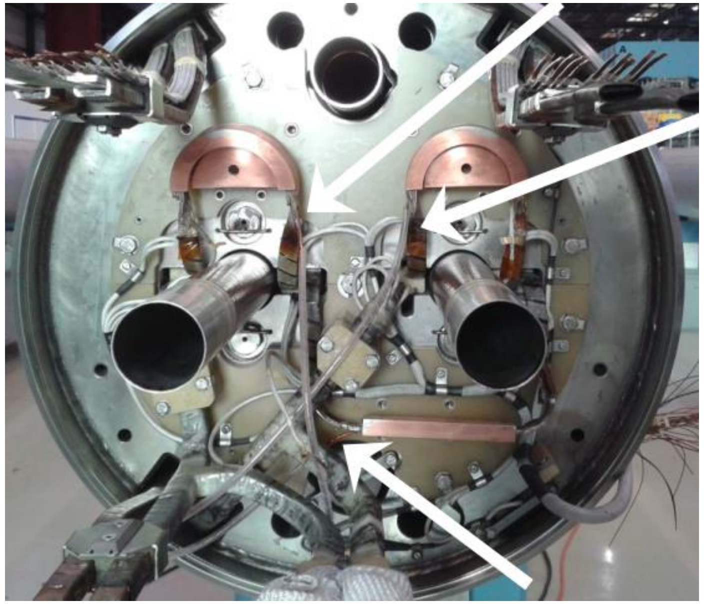
Courtesy of D. Cheng

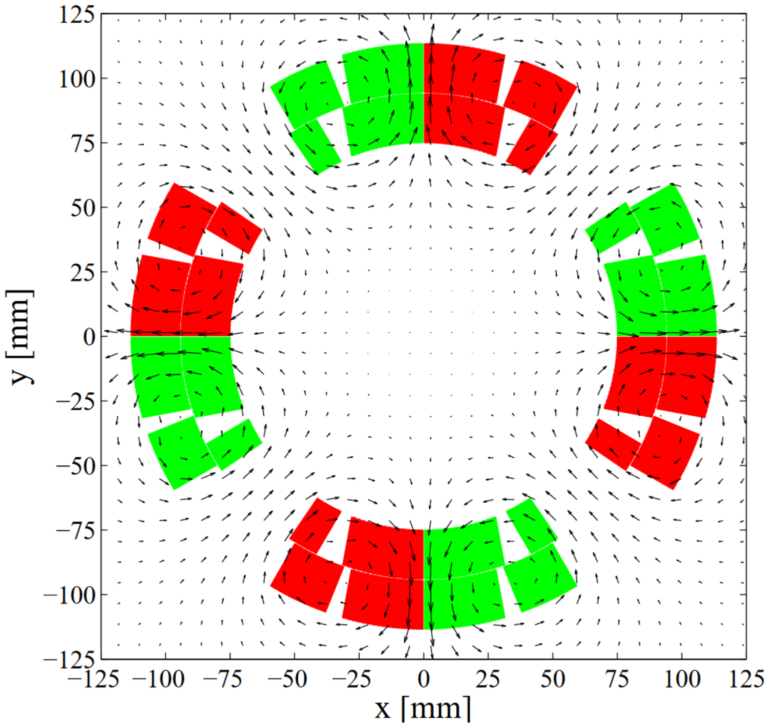
Advantages
- Scales well with the magnet length
- Doesn't impose a voltage on the magnet coils
- Well known and established technology

Disadvantages
- Thin insulation between QH and conductor is risky
- Challenging to cover all turns and layers
- Challenging to cover all length (heating stations)

COUPLING-LOSS INDUCED QUENCH (CLIQ)





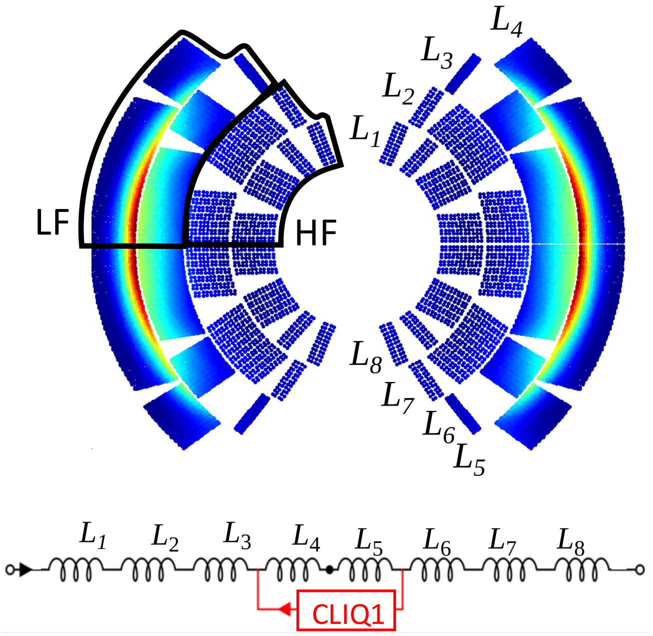


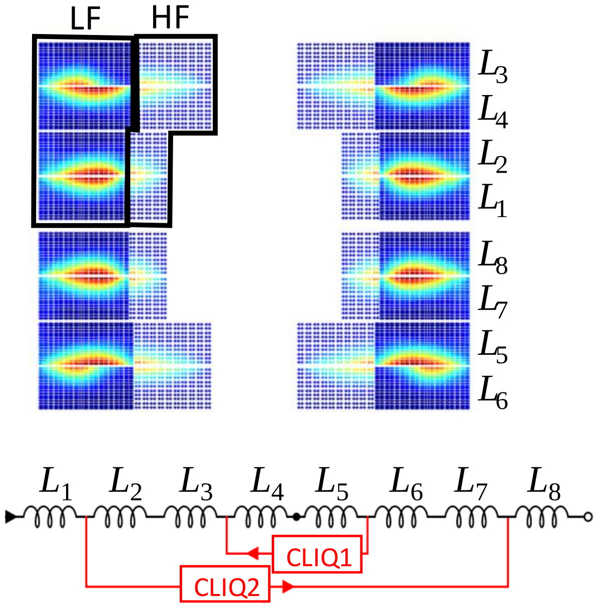
Advantages
- Fast and effective heat deposition
- Heat deposited simultaneously in all the coil volume
- Electrically robust system

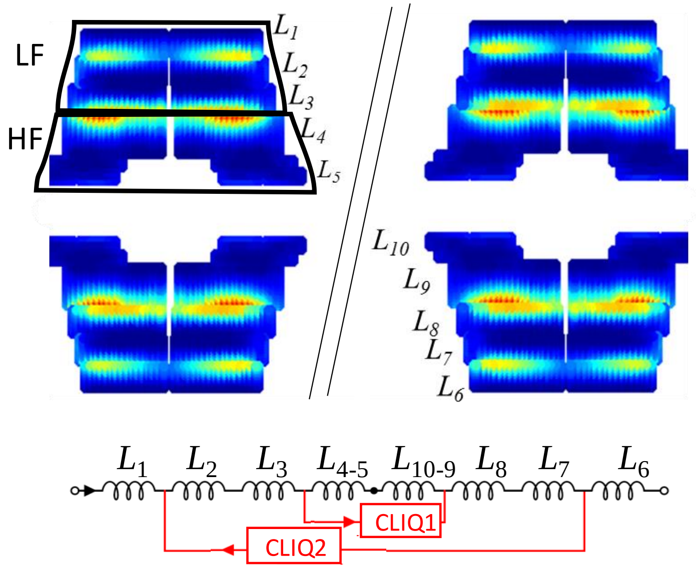
Disadvantages
- Direct electrical connection to the magnet circuit
- Challenging to make it redundant
- Additional asymmetric forces on the magnet coils

EuroCirCol 16 T MAGNET QUENCH PROTECTION STUDY

STEAM simulations	$T_{Hotspot}$ [K]		U_{ground} [V]		N_{units} per magnet	
	CLIQ	QH	CLIQ	QH	CLIQ	QH
Cos-θ	286	322	800	870	2	14
Block	281	321	730	870	4	13
Common-coil	284	330	1100	1040	2	15







Tiina Salmi, et al., Quench Protection of the 16 T Nb_3Sn Dipole Magnets Designed for the Future Circular Collider, 2019

Cross-sections are not in scale

From T. Salmi and M. Prioli's FCC Week 2019 presentation

THE CHALLENGE FOR HIGH-FIELD MAGNET PROTECTION

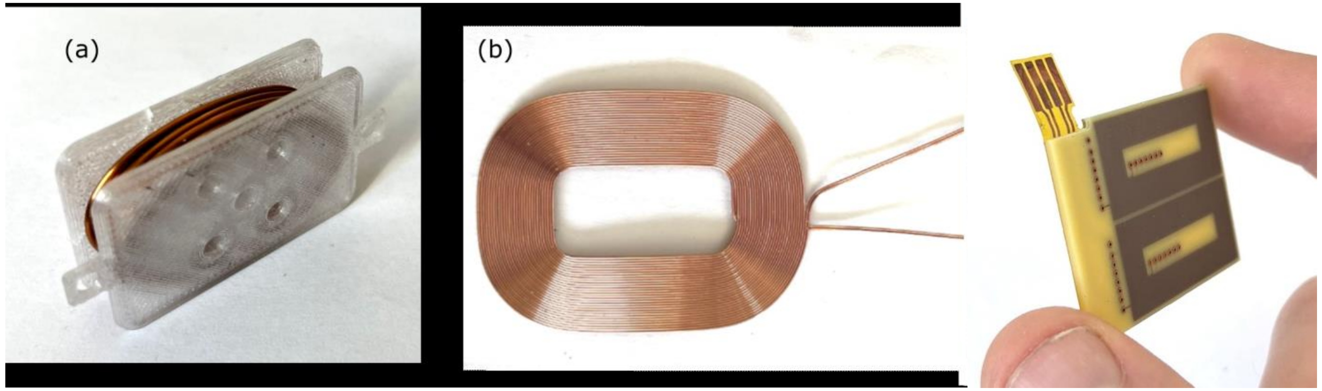
Achieve very fast quench initiation

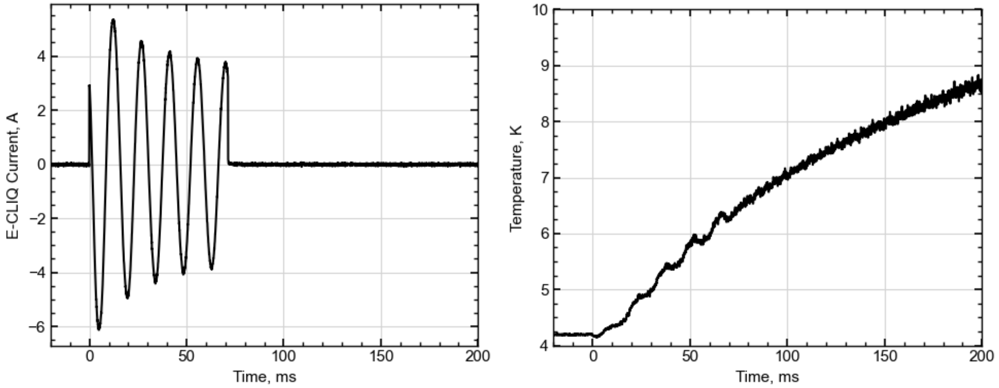
(target 90-100% coil quenched in 1-5 ms)

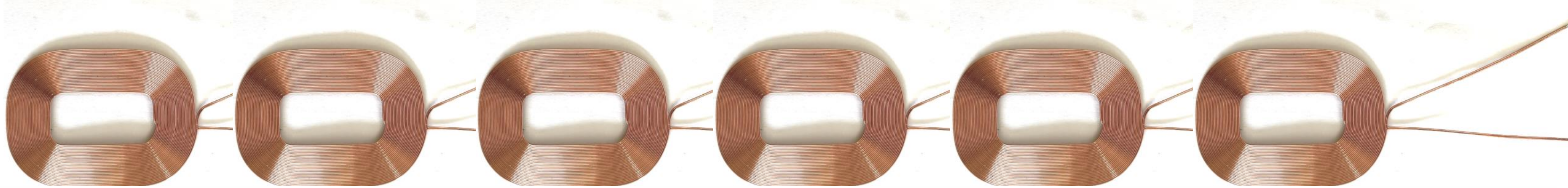
Without physical contact to the coil

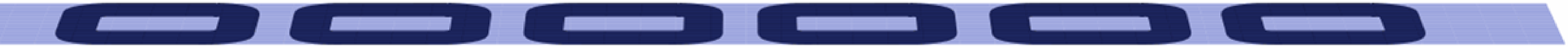
Without electrical contact to the coil

EXTERNAL COIL COUPLED LOSS INDUCED QUENCH (E-CLIQ)





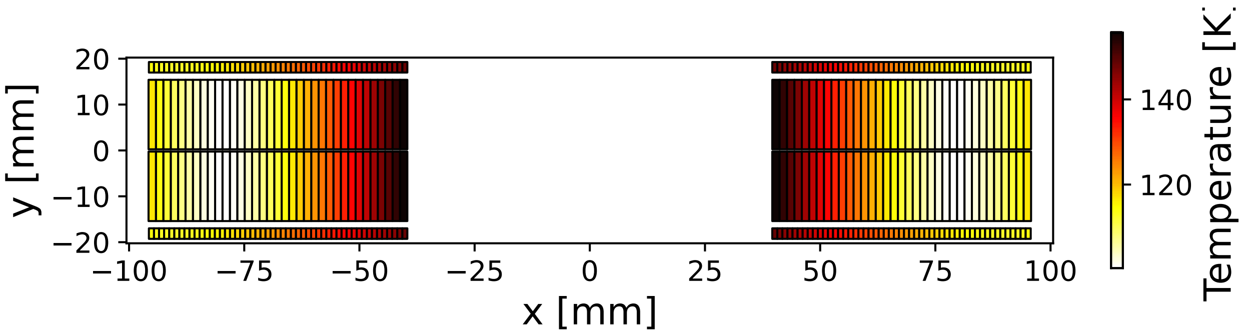


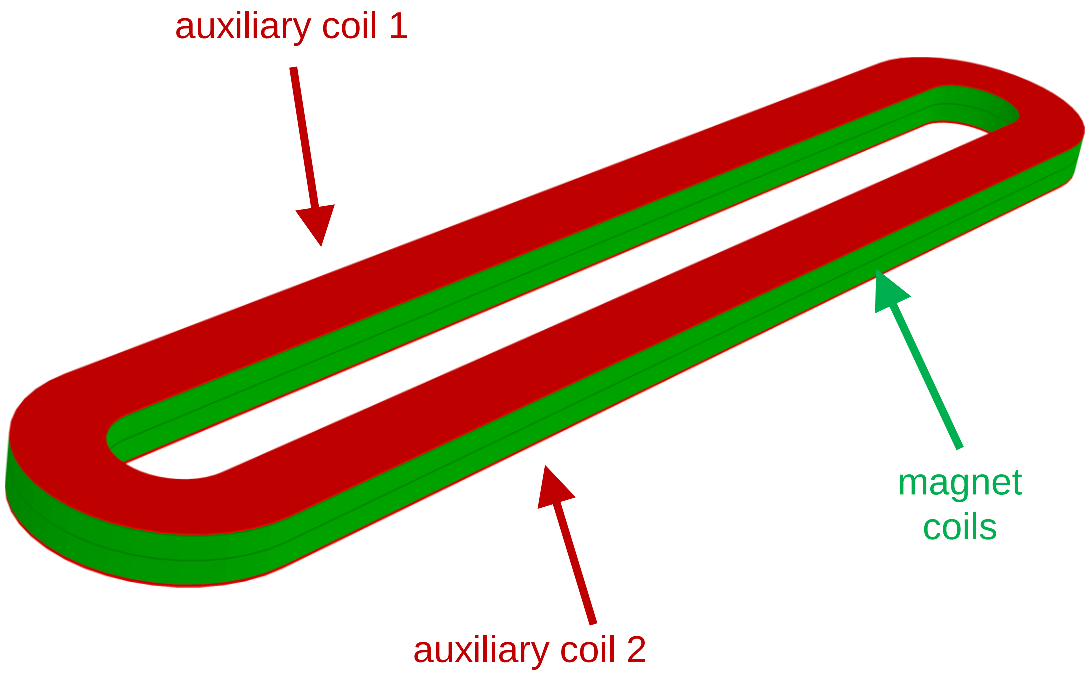


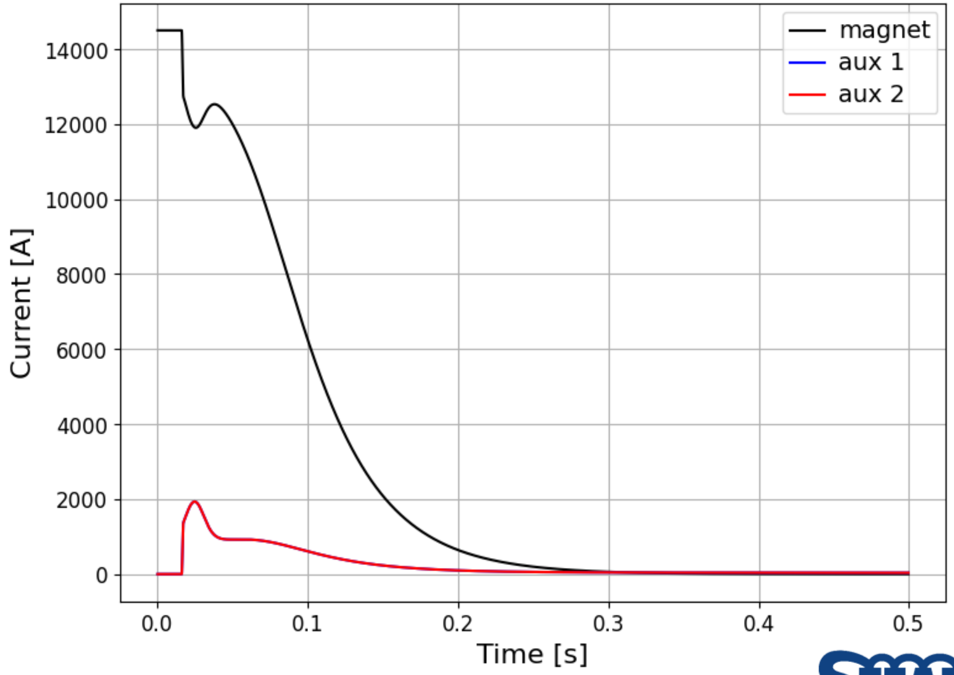
T. Mulder et al., “External Coil Coupled Loss Induced Quench (E-CLIQ) System for the Protection of LTS Magnets”, IEEE Trans. Appl. Supercond. 2022, https://cds.cern.ch/record/2856850.

ENERGY SHIFT WITH COUPLING (ESC)

- ✓ As fast as CLIQ or faster
- ✓ Extracts part of the magnet energy
- ✓ Sudden current drop → lower ohmic loss
- ✓ Electrically insulated from coil
- ✓ Easier redundancy

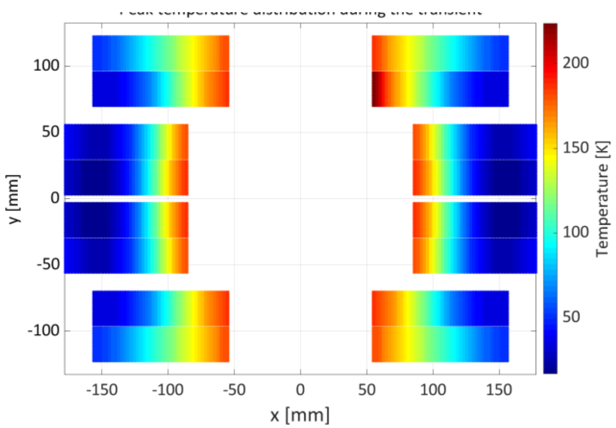


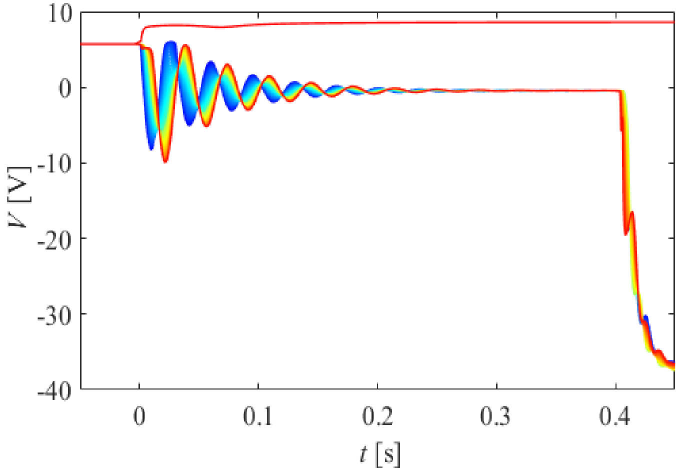


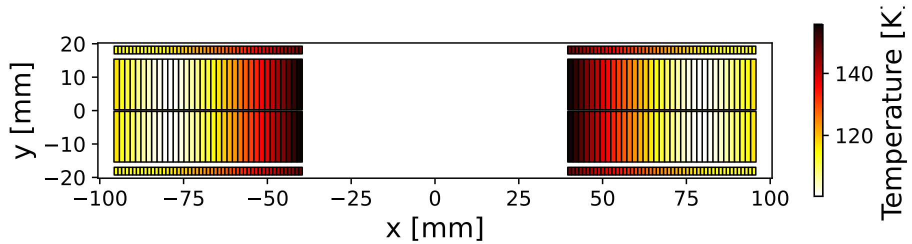


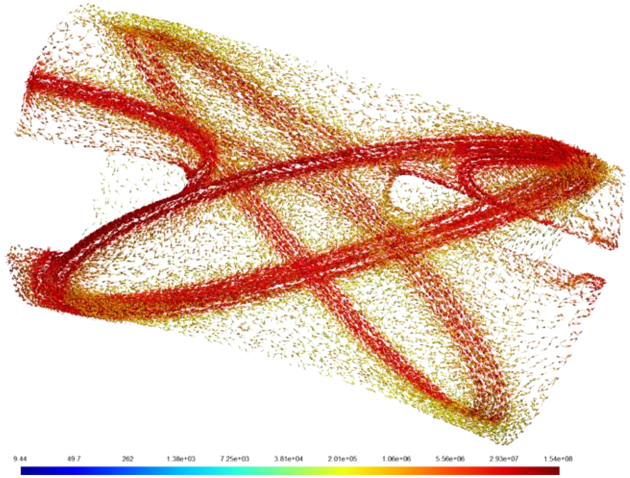
Pic courtesy of M. Dumas, I. Garcia-Aguirrebeitia Sanchez

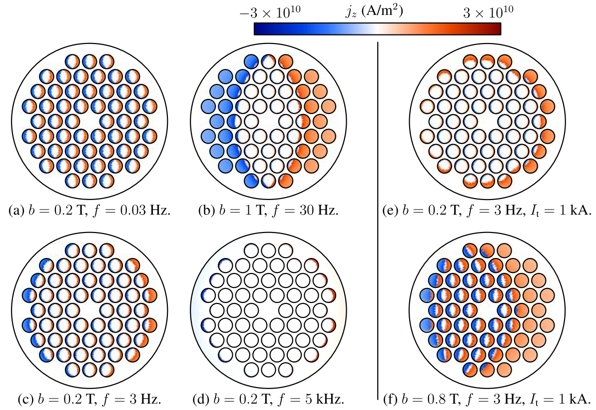
MODELING

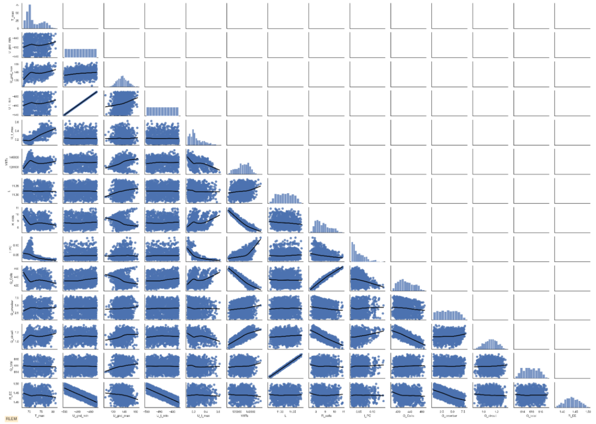

y [mm]
x [mm]
Temperature [K]


V [V]
t [s]


y [mm]
x [mm]
Temperature [K]




-3×10^{10}
j_z (A/m^2)
3×10^{10}
(a) $b = 0.2$ T, $f = 0.03$ Hz.
(b) $b = 1$ T, $f = 30$ Hz.
(e) $b = 0.2$ T, $f = 3$ Hz, $I_t = 1$ kA.
(c) $b = 0.2$ T, $f = 3$ Hz.
(d) $b = 0.2$ T, $f = 5$ kHz.
(f) $b = 0.8$ T, $f = 3$ Hz, $I_t = 1$ kA.



MODELING

Transient losses

- They will likely be key for protecting high-field magnets
- Transient effects also affect magnet powering, beam dynamics, mechanics

Stress during quench

- Thermal stress could result in the highest stress experienced by the conductor
- Especially important for stress-managed magnets

Fast, integrated tools

- Target: a few minutes per transient simulation
- Important to couple different design and simulation tools
- Can AI take over?

HTS

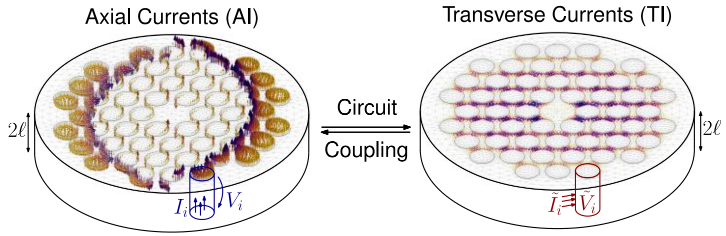
- Material properties
- Various cable architectures (Roebel, CORC©, STAR©, Spiral Cu-plated Striated Coated (SCSC), 6-in-1,…)
- Various loss types

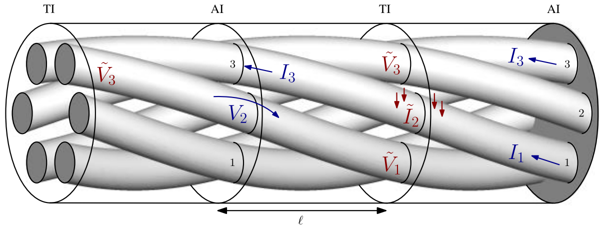
These topics will provide very exciting R&D opportunities in the coming years

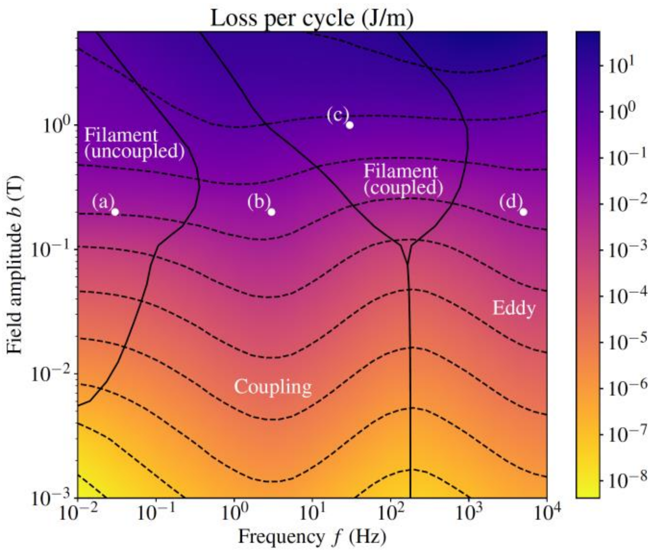
- Accurate and efficient model for AC losses in multifilamentary LTS strands
  - Two 2D problems coupled via circuit equations
  - **C**oupled **A**xial and **T**ransverse currents (**I**): **CATI**
  - Coupling currents, eddy, and hysteresis losses

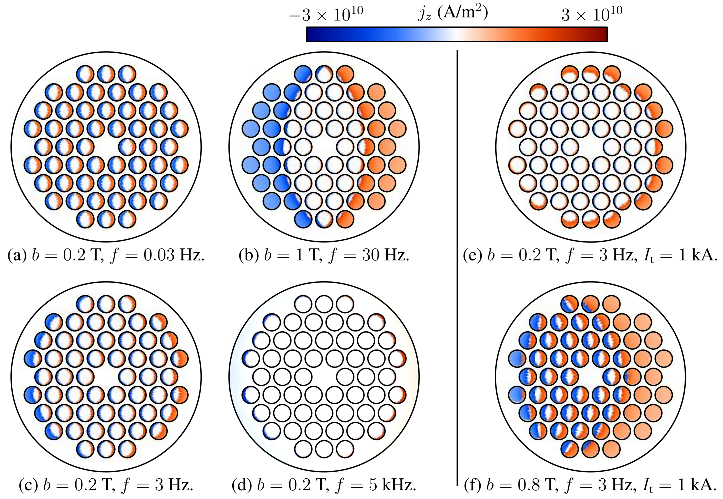
[J. Dular, et al., arxiv.org/abs/2404.09775]

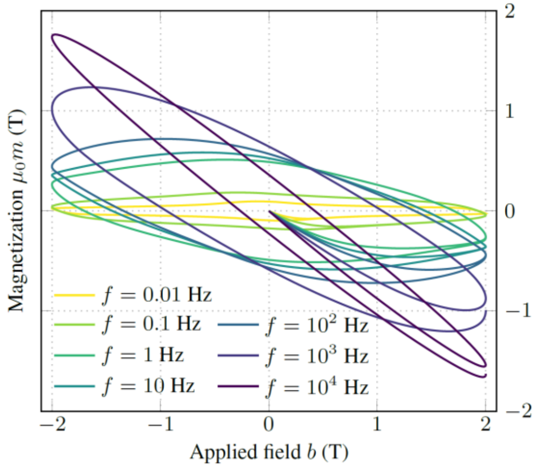
- Here for 54-filament strand with transverse field:







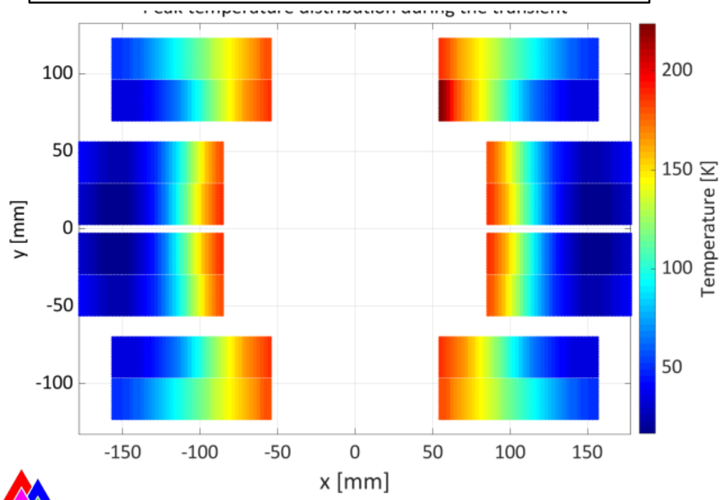




Slide courtesy of J. Dular, F. Magnus, M. Wozniak

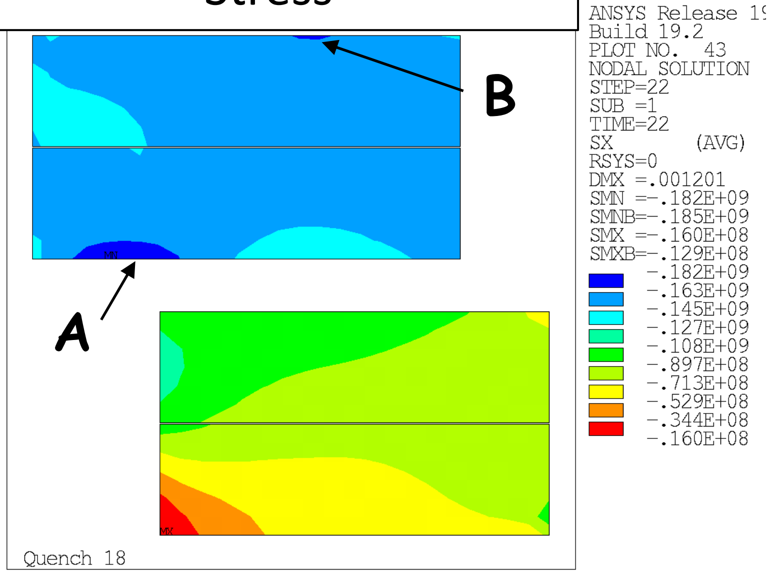
MODELING STRESS DURING QUENCH

Temperature

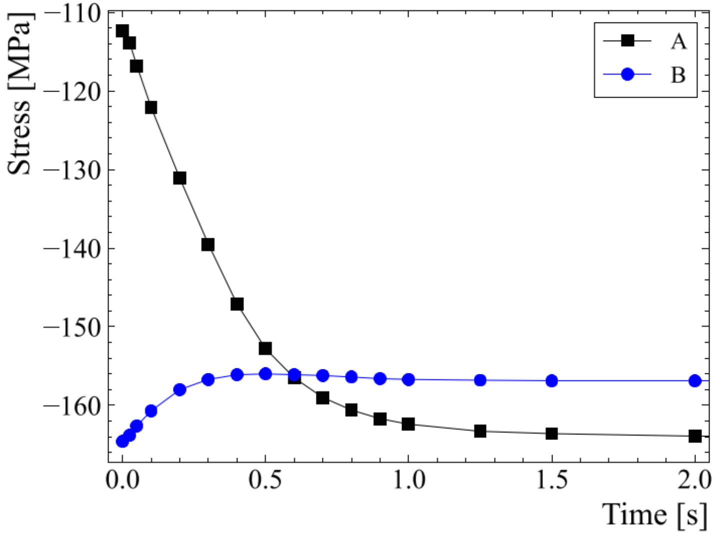


LEDET

Stress



Stresses versus time



STEAM-LEDET

Electrical domain
Magnetic domain
Thermal domain

Temperatures
e.m. forces

ANSYS

Mechanical domain

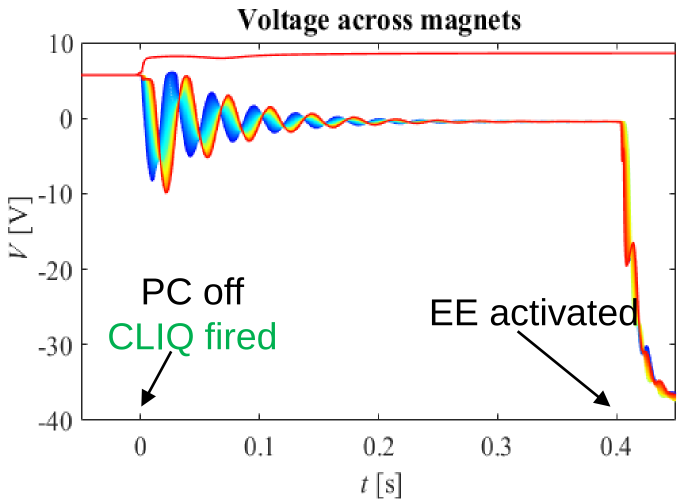
G. Vallone, E. Ravaioli, et al., "Simulation of thermo-mechanical stresses after a quench in the 15 T Test Facility Dipole magnet", IEEE Trans Appl SC, 2024.

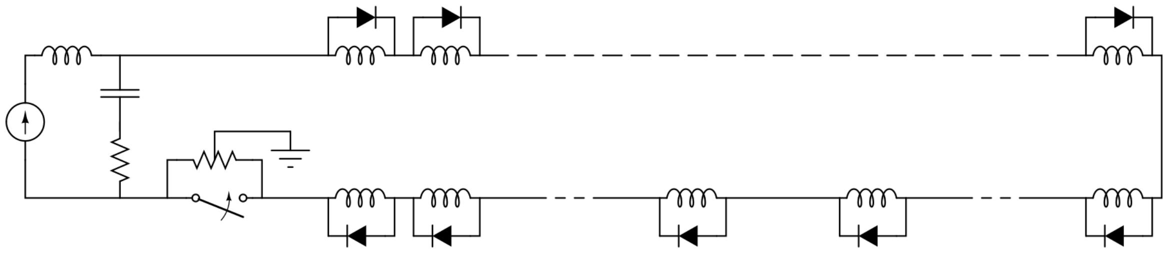
This workflow was developed with G. Vallone (LBNL)

COOPERATIVE SIMULATION (CO-SIM)

CLIQ in full circuit:
PSPICE + LEDET

LEDET



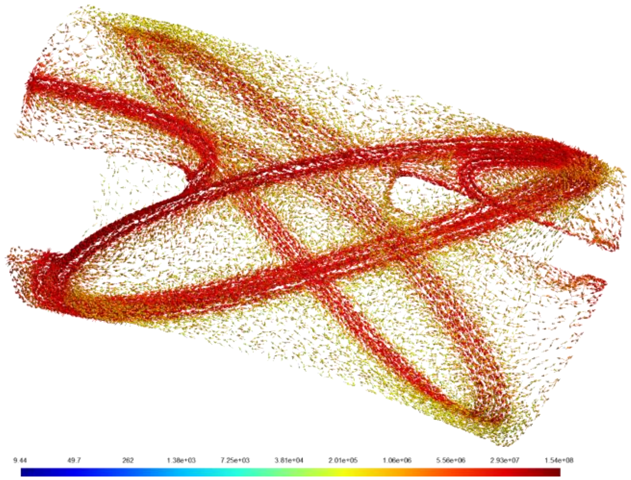


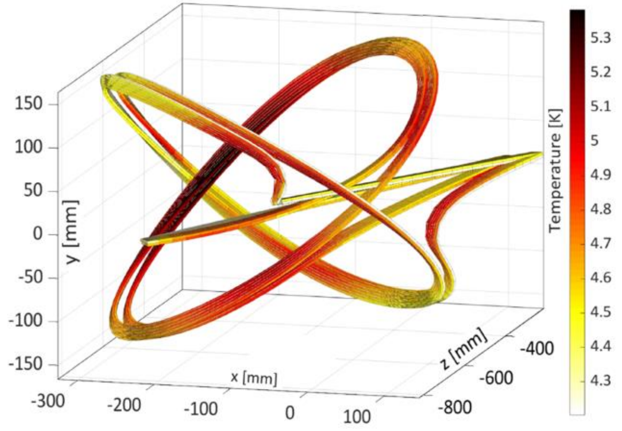
Work of M. Prioli and STEAM team
Plot from A. Verweij's FCC Week 2019 presentation

CCT magnet transient:
FiQuS + LEDET

LEDET

Magnet design courtesy of Fusillo design team at CERN



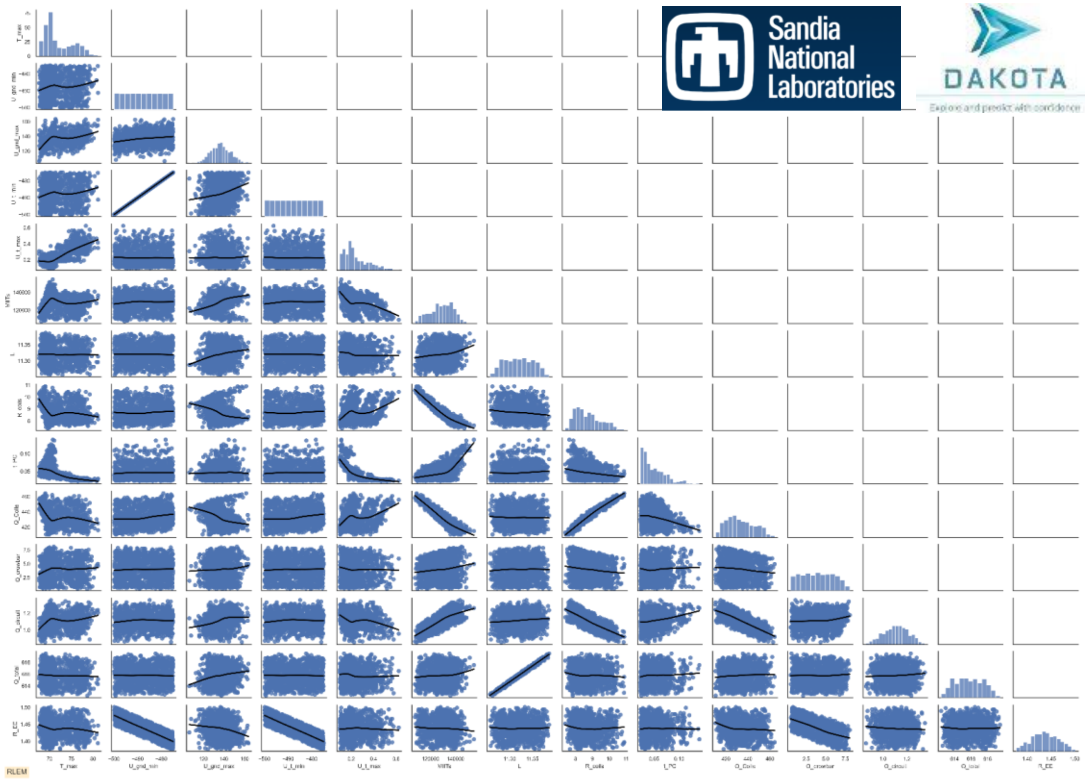


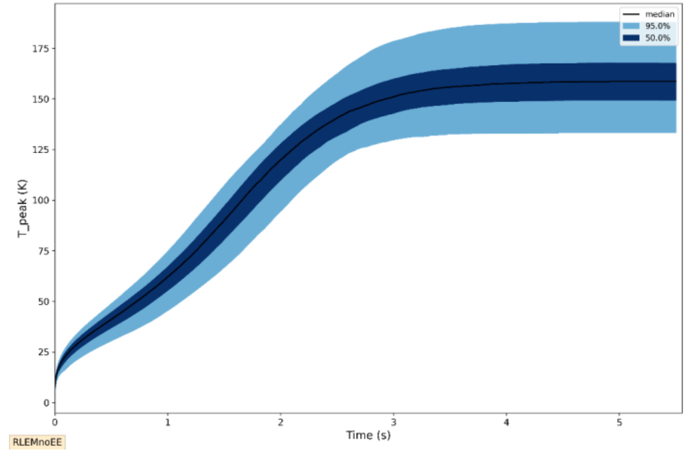
M. Wozniak, et al., "Quench Co-Simulation for Canted Cos-Theta Magnets", IEEE Trans Appl SC, 2024.
M. Wozniak, et al., "Quench Behaviour of Fusillo sub-scale curved CCT magnet", IEEE Trans Appl SC, 2024.

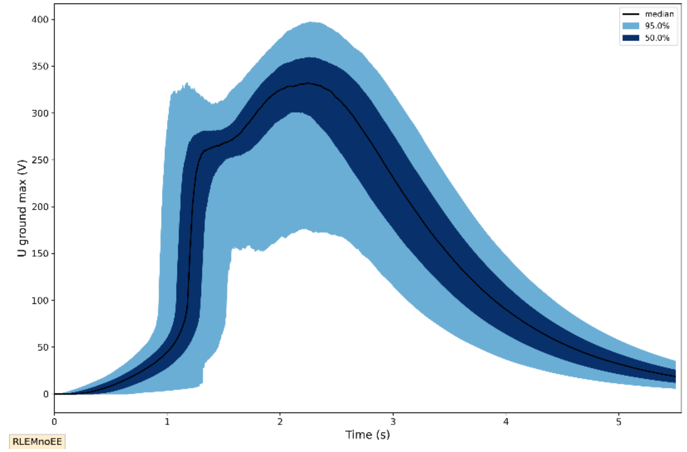
FAST AND BROAD PARAMETRIC STUDIES

Variation or uncertainty on input parameters

Impact or uncertainty on quench protection results







M. Wozniak, et al., "Quench Protection of the HL-LHC Hollow Electron Lens Superconducting Solenoid Magnets", IEEE Trans. on Appl. SC, 2022.

Slide courtesy of M. Wozniak

HIGH TEMPERATURE SUPERCONDUCTORS (HTS)

Screening currents

- Effect on field quality (both transient and persistent)
- Effect of additional forces (both during powering and after quench)

Quench detection

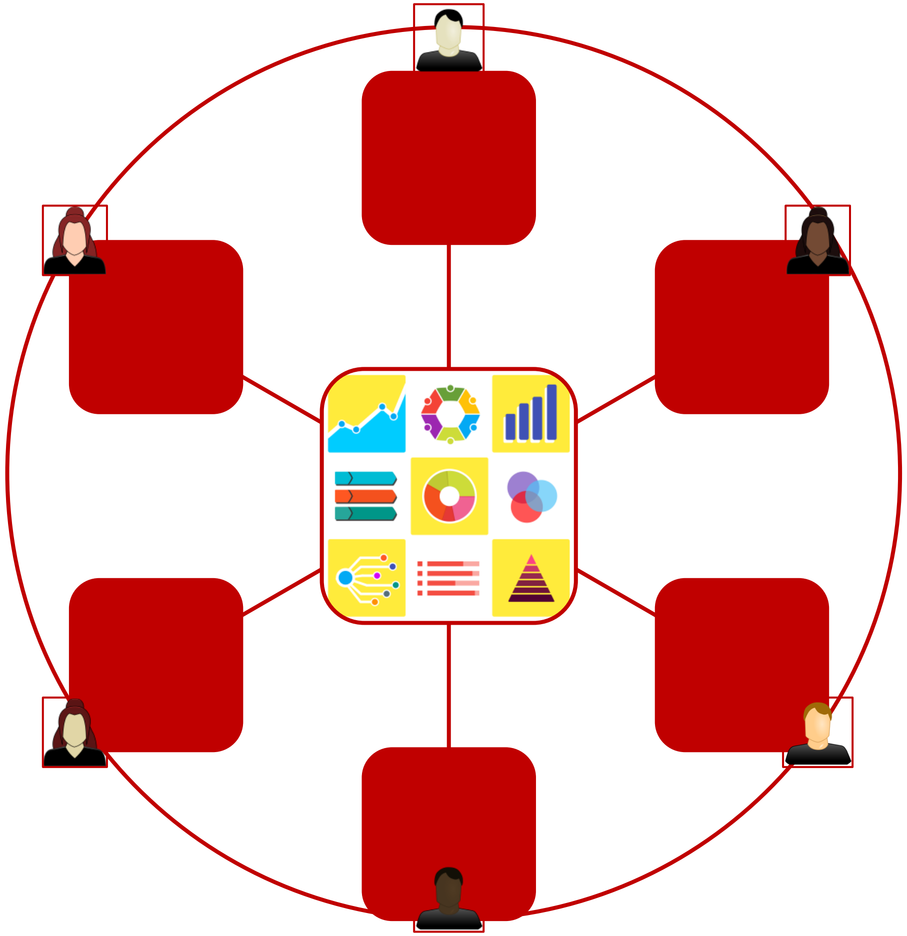
- Novel techniques (acoustic, fiber optics, RF-based techniques, current redistribution, stray capacitance, acoustic thermometry,…)
- Combine multiple methods?
- Detect before thermal runaway?

Quench protection

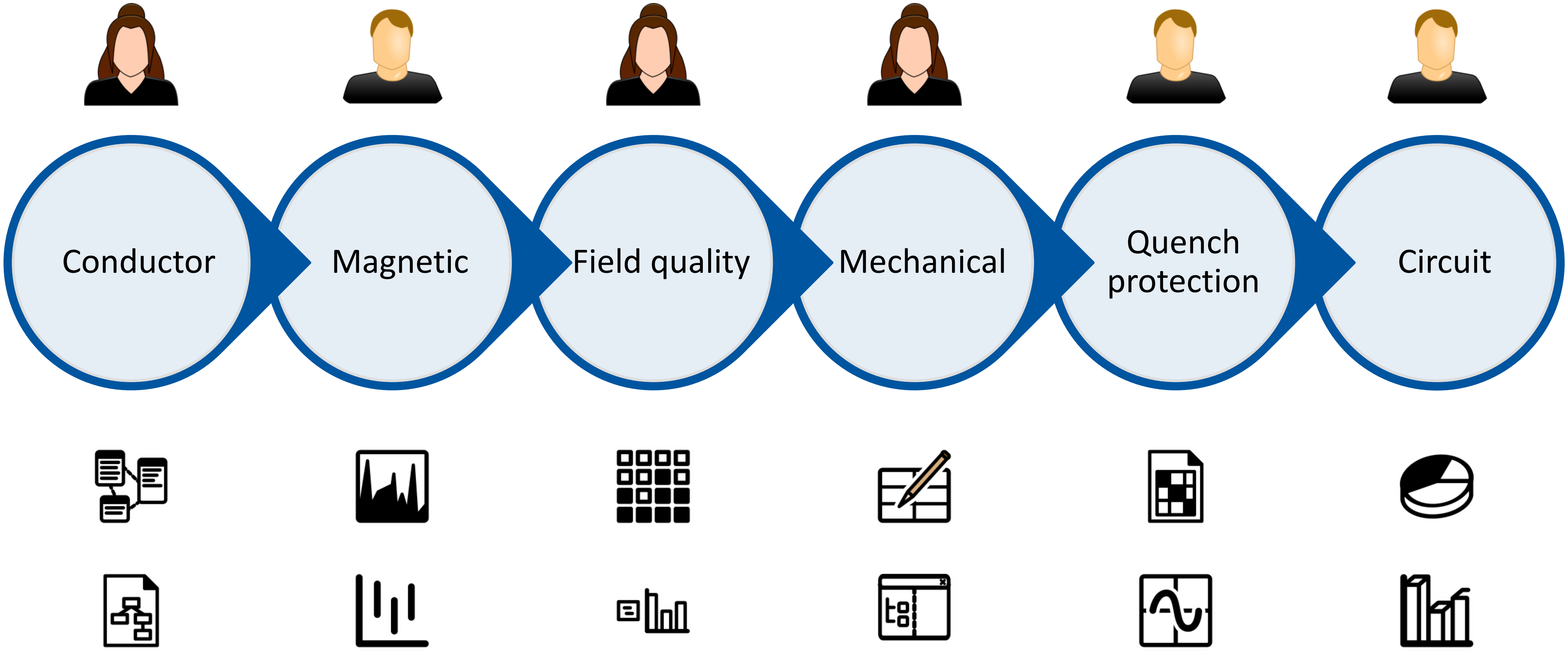
- Very slow quench propagation
- Very high quench energy margin
- Novel techniques (S-CLIQ, E-CLIQ, ESC,…)
- Alternatives to active quenching?

These topics will provide very exciting R&D opportunities in the coming years

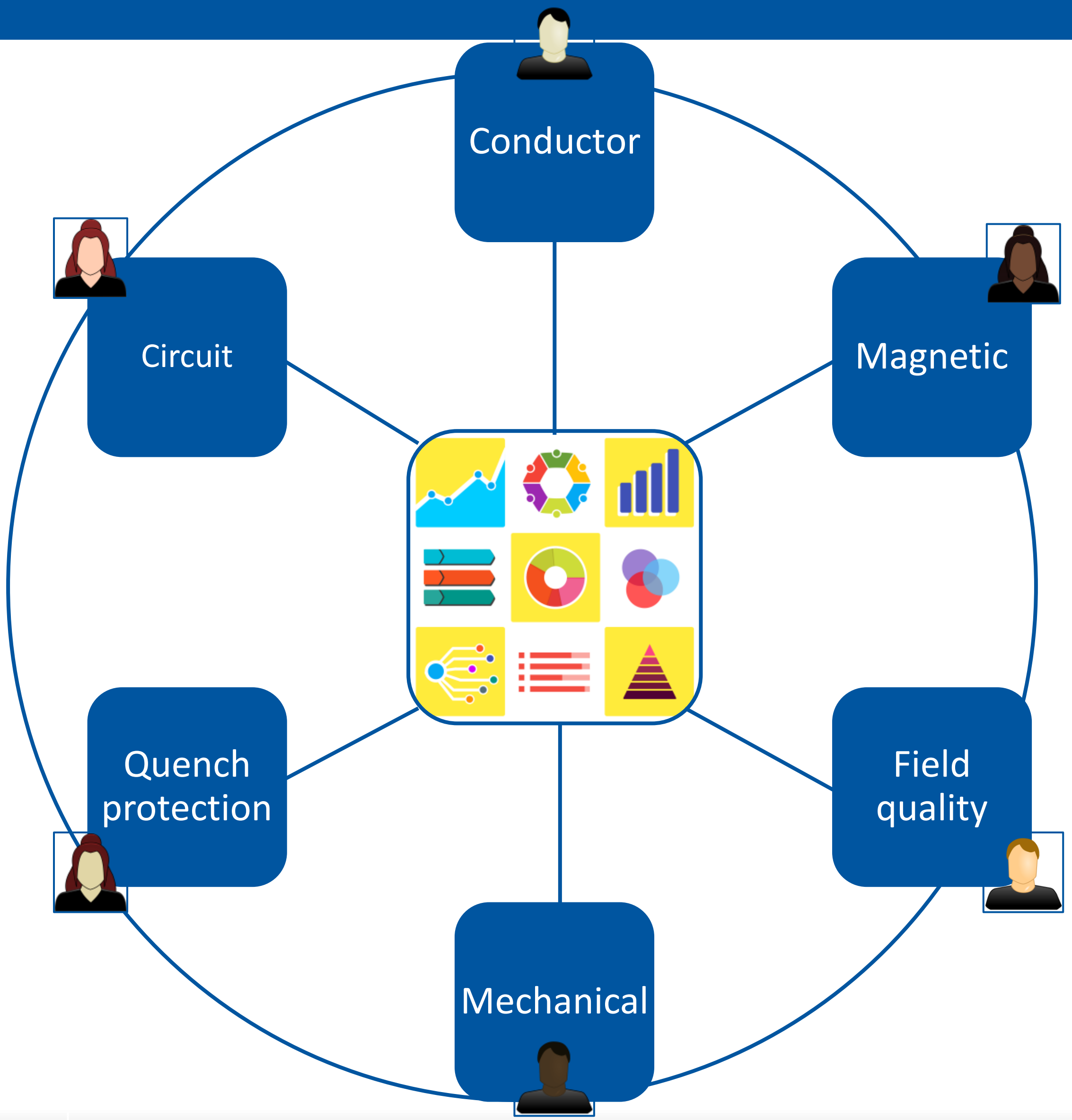
COLLABORATION



ACCELERATOR MAGNET DESIGN



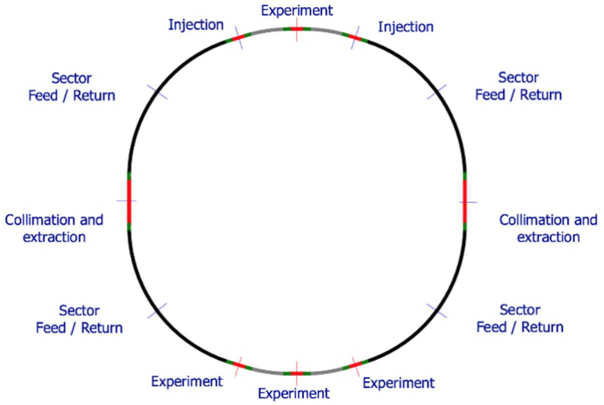
INTEGRATED ACCELERATOR MAGNET DESIGN

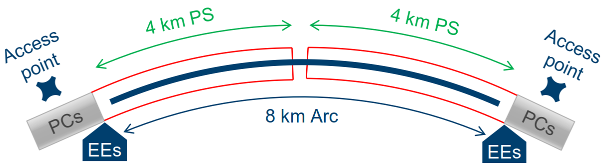


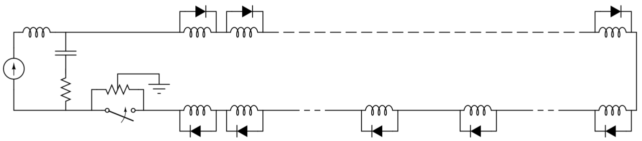
Real examples from recent collaborations between CERN, PSI, US MDP

- ✓ Is it easier to protect a magnet with more turns and higher current?
- ✓ Let's optimize grading for increasing margin and decreasing hot-spot temperature!
- ✓ Which conductor types would help quench protection?
- ✓ Where could we fit special protection coils in the magnet cross-section?
- ✓ What can we do to reduce the peak voltages during quench?
- ✓ How will this change affect peak stress during quench?
- ✓ Can we make the magnet smaller if we use a different quench protection method?

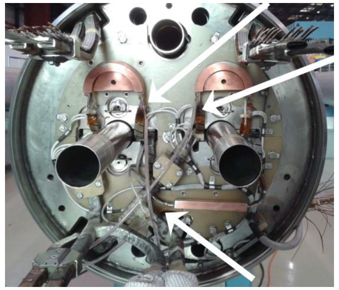
CIRCUIT OPTIMIZATION

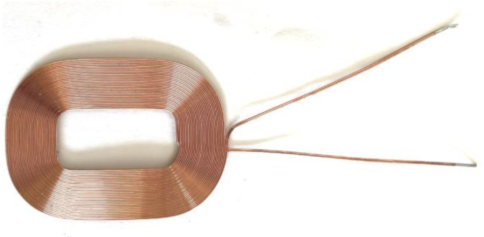




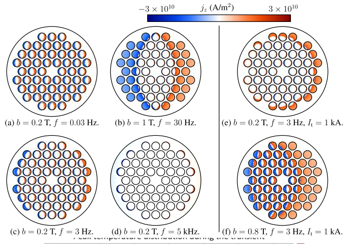


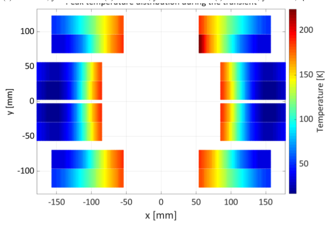
PROTECTION METHODS

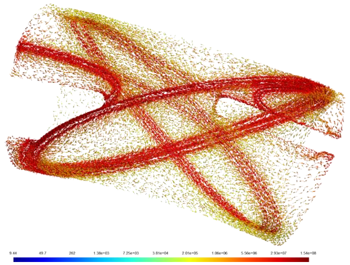


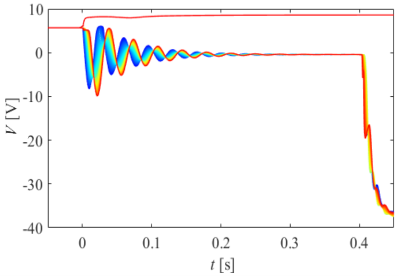


MODELING

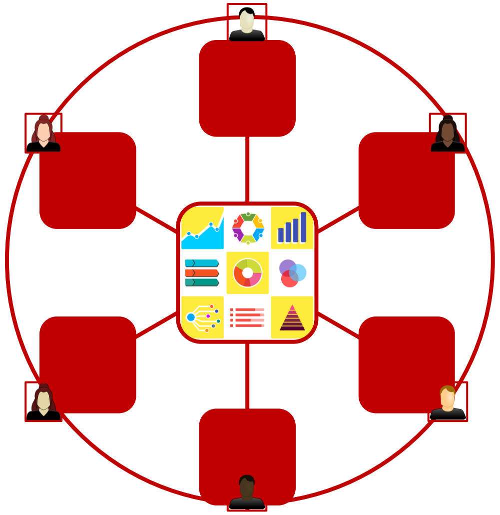








COLLABORATION



Let's research, design, build, test magnets keeping in mind the full-scale accelerator machine

ANNEX

MAGNET PROTECTION STRATEGY

The **individual magnet protection** is based on a similar concept as the LHC:

- Quench detection based on differential voltage;
- CLIQ or Quench heaters;
- Cold bypass diodes.

Four different FCC magnet designs (LTS, LHe) were considered, varying significantly in terms of inductance and current. ***HTS designs were not yet considered***

The 'allowed' internal quench voltage $U_{q,max}$ was about 1.2 kV.

	Cosθ (baseline)	Block	Common Coil	CCT
L [H]	0.591	0.745	0.339	0.284
I [A]	11390	10100	16100	18000
E [MJ]	38	38	44	46

From A. Verweij's TE FCC-ee 2024 presentation

Circuit decay time (t_{decay})

Minimizing t_{decay} (after a Fast Power Abort or magnet quench) reduces:

- dissipated energy in the SC busbars and current leads ⇒ reduces the required cross-section,
- dissipated energy in the diode heat sinks of a quenched magnet ⇒ reduces the required volume of the heat sink,
- probability of quench propagation to neighbouring magnets ⇒ less frequent thermal stress in the magnets; faster cryogenic recovery; smaller probability of failures.

$t_{dec}=L_{circ}/(N_{EE}*R_{EE,0})$ with: N_{EE}: the number of EE systems in the circuit

For the LHC: τ_{decay}=100 s, copper cross-section busbar = 270 mm^2, heat sinks of about 30 kg per diode. At nominal current, a quench propagates to typically 5 adjacent magnets.

For the FCC we target t_{decay}=120 s.

Nr of magnets in a circuit

A **small number of magnets** in a circuit:

- Reduces the stored energy in the circuit and hence the damage potential in case of accidents;
- Reduces the ramp voltage for given ramp rate;
- Reduces the duration of a training campaign. Imagine a circuit of 438 magnets, each needing 1 training quench with a cryogenic recovery time of 12 hours. Such a campaign would take more than 7 months!
- Increases the number of power converters and current leads.

From A. Verweij's FCC Week 2019 presentation

Circuit topology

Reducing the VWL ($\Rightarrow$ reducing R_{EE}) and reducing as well t_{decay} ($\Rightarrow$ increasing $N_{EE}R_{EE}$) can be met by two circuit topologies:

1. Increase the number of EE systems per circuit (uniformly distributed along the circuit) in order to have an acceptable decay time.

2. Subdivide each circuit in *N* sub-circuits, each with one EE system, located close to the power converter.

Also taking into account the advantages of having less magnets per circuit (smaller damage potential, smaller ramp voltage of the converter, shorter training campaign) makes option 2 the preferred topology.

From A. Verweij's FCC Week 2019 presentation

Circuit topology

Setting t_{decay}=120 s, and requiring $U_{circ,max}$<1300 V, gives:

		Cosθ	Block	Common Coil	CCT
	L [H]	0.591	0.745	0.339	0.284
	I [A]	11390	10100	16100	18000
	E [MJ]	38	38	44	46
Arc	Nr of circuits *N*	5	6	4	4
	$U_{circ,max}$ [V]	1230	1140	1250	1170
Mini-arc	Nr of circuits N_{mini}	4	5	4	3
	$U_{circ,max}$ [V]	1260	1130	1020	1280
Total	Total nr of circuits	96	116	80	76

From A. Verweij's FCC Week 2019 presentation

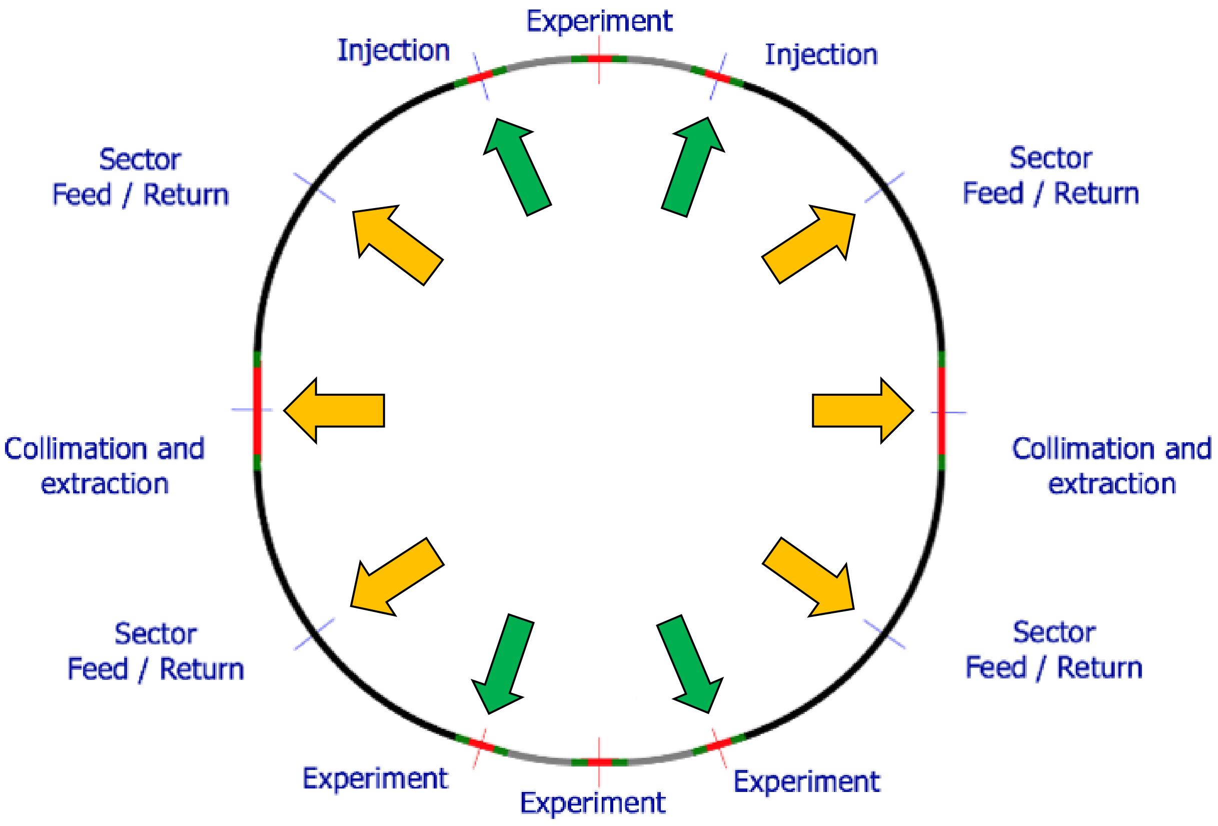
Circuit topology

Setting t_{ramp}=1200 V, constant ramp rate, gives:

		Cosθ	Block	Common Coil	CCT
	L [H]	0.591	0.745	0.339	0.284
	I [A]	11390	10100	16100	18000
	E [MJ]	38	38	44	46
	$U_{M,ramp}$ [V]	5.6	6.3	4.5	4.3
Arc	Nr of circuits N	5	6	4	4
	$U_{Circ,ramp}$ [V]	246	229	249	233
	Max P_{PC} [MW]	2.8	2.3	4.0	4.2
Mini-arc	Nr of circuits N_{mini}	4	5	4	3
	U_{ramp} [V]	252	226	205	256
	Max P_{PC} [MW]	2.9	2.3	3.3	4.6

From A. Verweij's FCC Week 2019 presentation

Distribution of peak power



t_{ramp}=1200 s

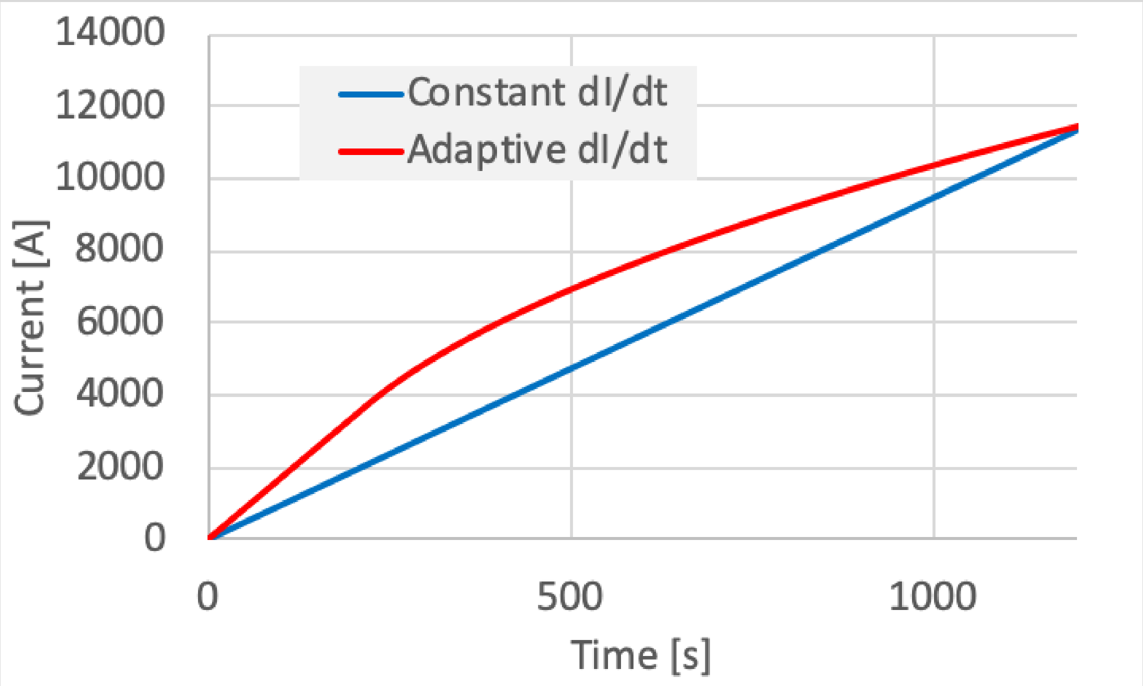
	Cosθ	Block	Common Coil	CCT
[MW]	25.5	25.3	29.1	30.6
[MW]	28.0	27.7	32.1	33.6

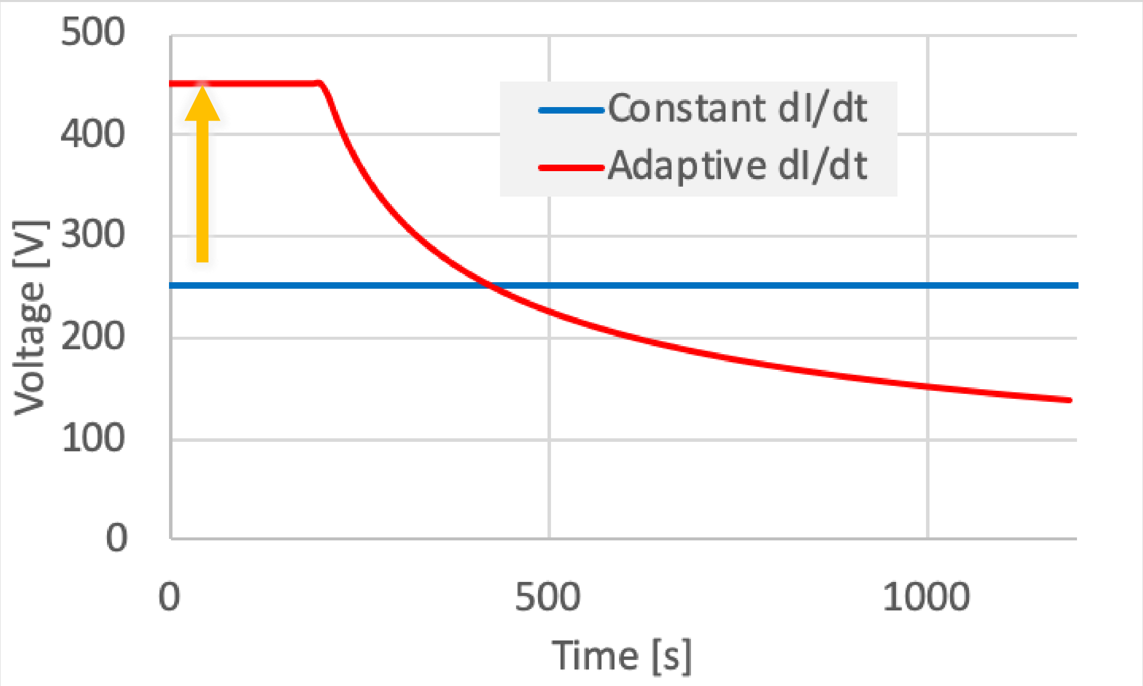
Values do not take into account losses and inefficiency

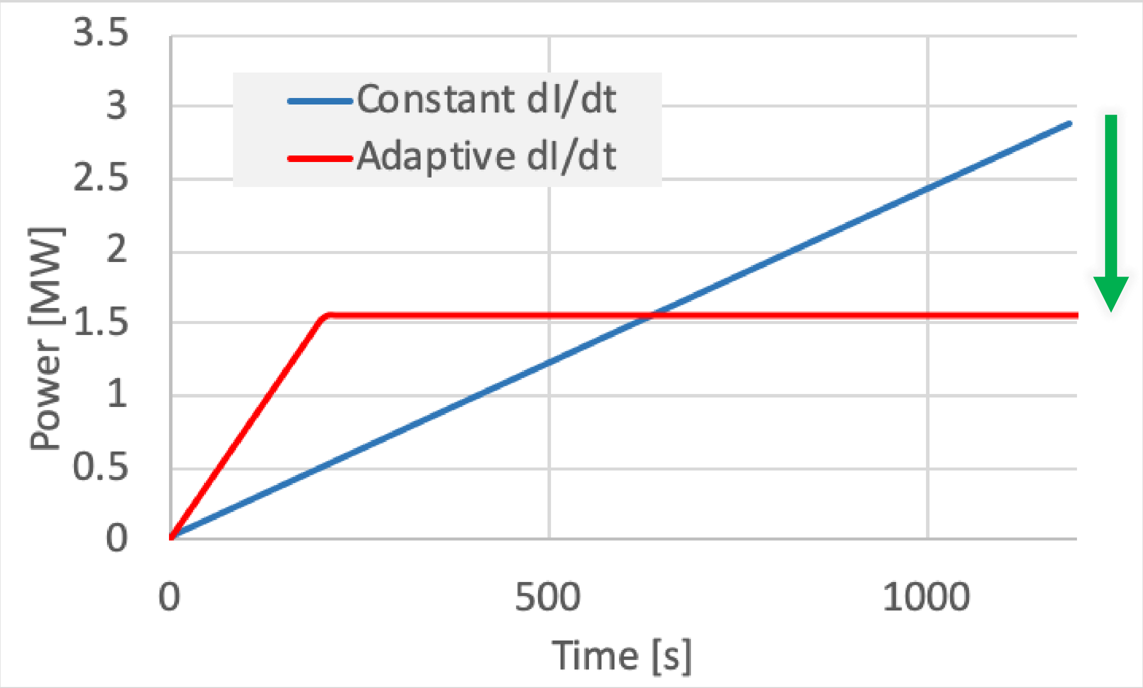
From A. Verweij's FCC Week 2019 presentation

Peak power

Peak powers can be reduced significantly using an adaptive ramp rate, requiring however a higher voltage (to keep t_{ramp} constant).



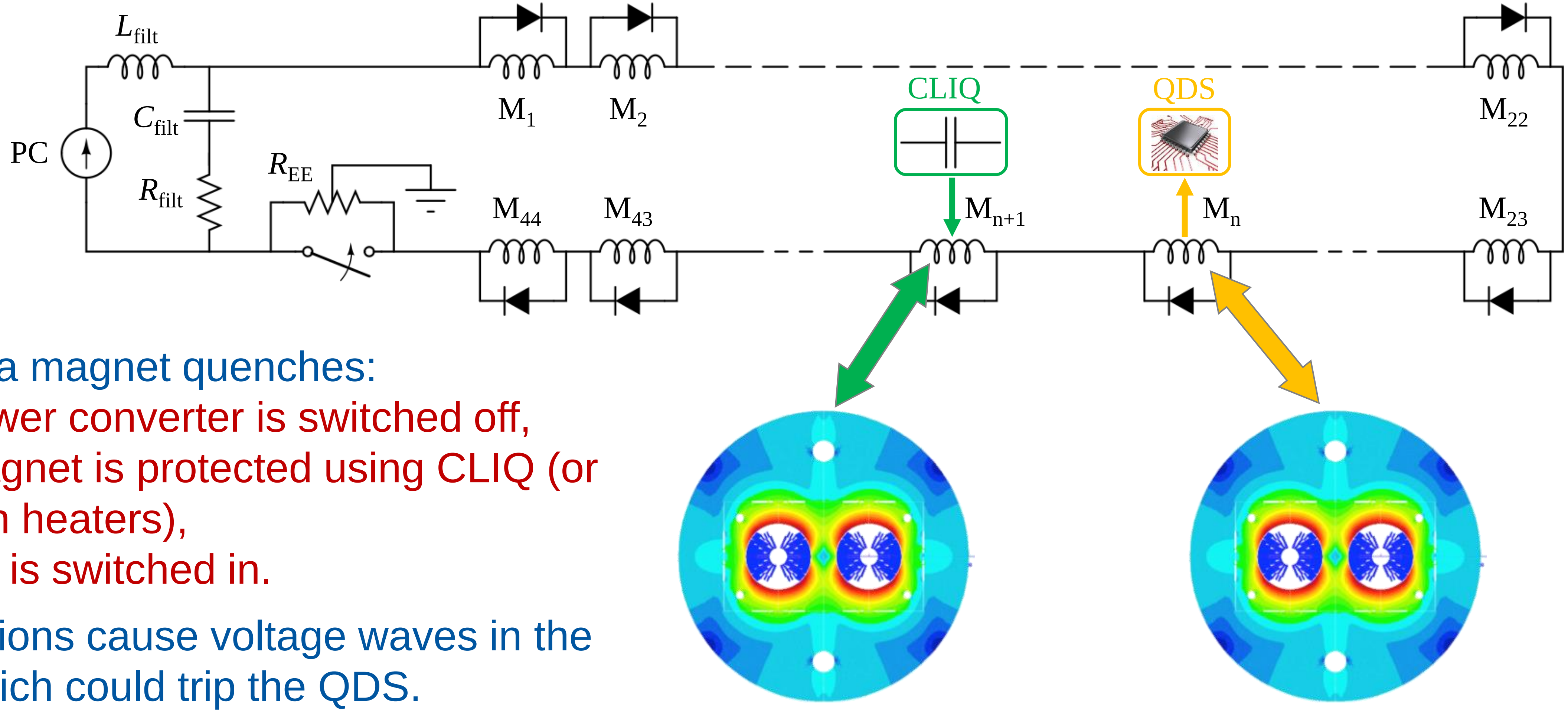




From A. Verweij's FCC Week 2019 presentation

Simulations performed using the STEAM framework

Response of the QDS if a neighbouring magnet quenches



Quenching magnet: *CLIQ simulati*

Neighbouring magnet: *...se*

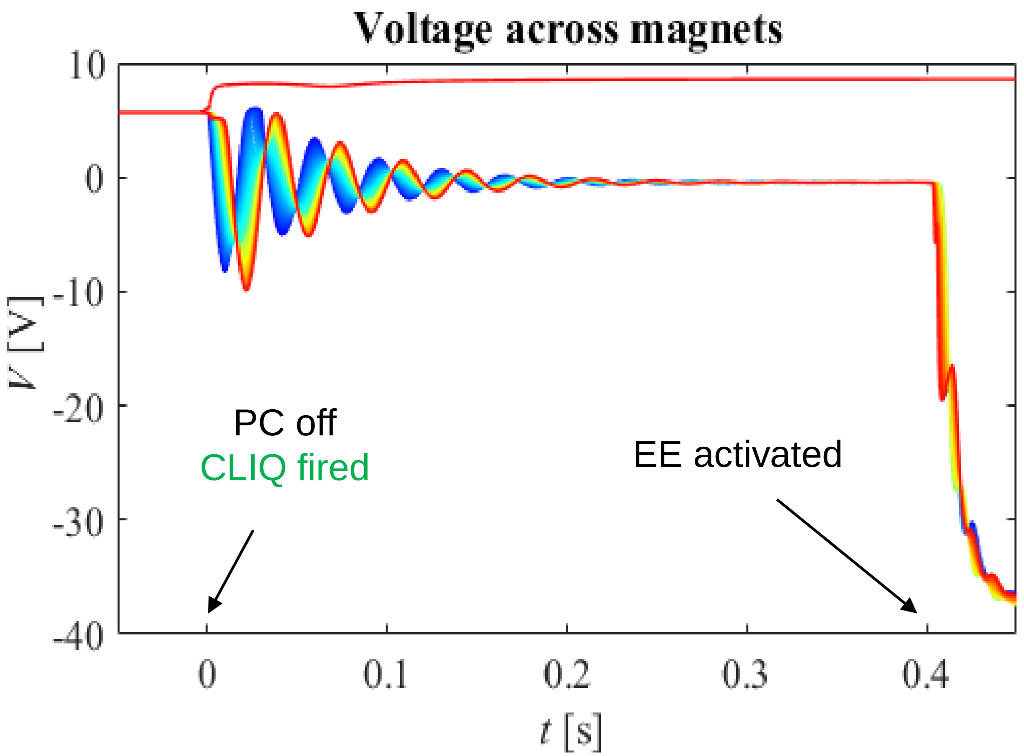
Actions if a magnet quenches:

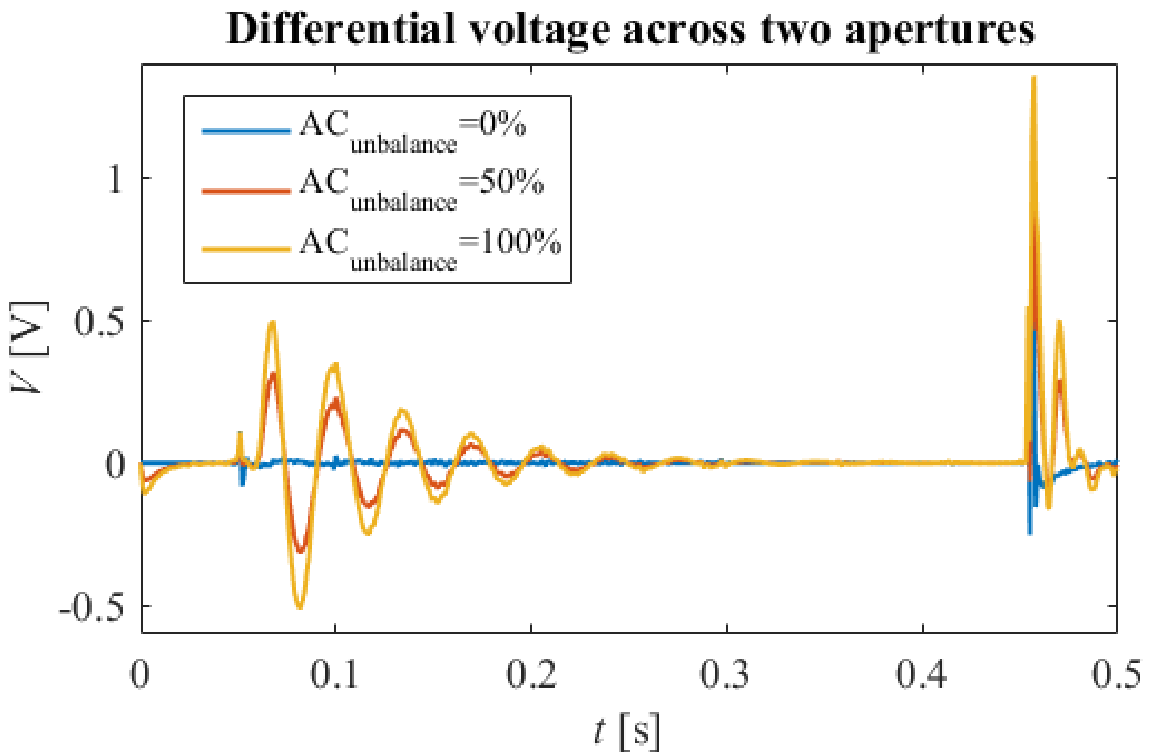
- the power converter is switched off,
- the magnet is protected using CLIQ (or quench heaters),
- the EE is switched in.

These actions cause voltage waves in the circuit, which could trip the QDS.

From A. Verweij's FCC Week 2019 presentation

Response of the QDS if a neighbouring magnet quenches





Differential voltages increase for larger ‘AC imbalance’ between the 2 apertures,

→ assure that the voltage transient remains below the QD threshold, by:

- Circuit optimization (adding components to reduce the voltage waves)
- QDS optimization (adding filters, subdividing voltages)
- Conductor development (homogeneous AC behaviour)