FCC WEEK 2019
BRUSSELS, BELGIUM
24 - 28 JUNE 2019
Crowne Plaza Brussels
Le Palace

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STEAM

Status of FCC-hh main magnet circuit layout, powering and protection

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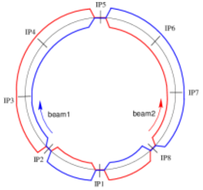
The European Circular Energy-Frontier Collider Study (EuroCirCol) project has received funding from the European Union's Horizon 2020 research and innovation programme under grant No 654305. The information herein only reflects the views of its authors and the European Commission is not responsible for any use that may be made of the information.

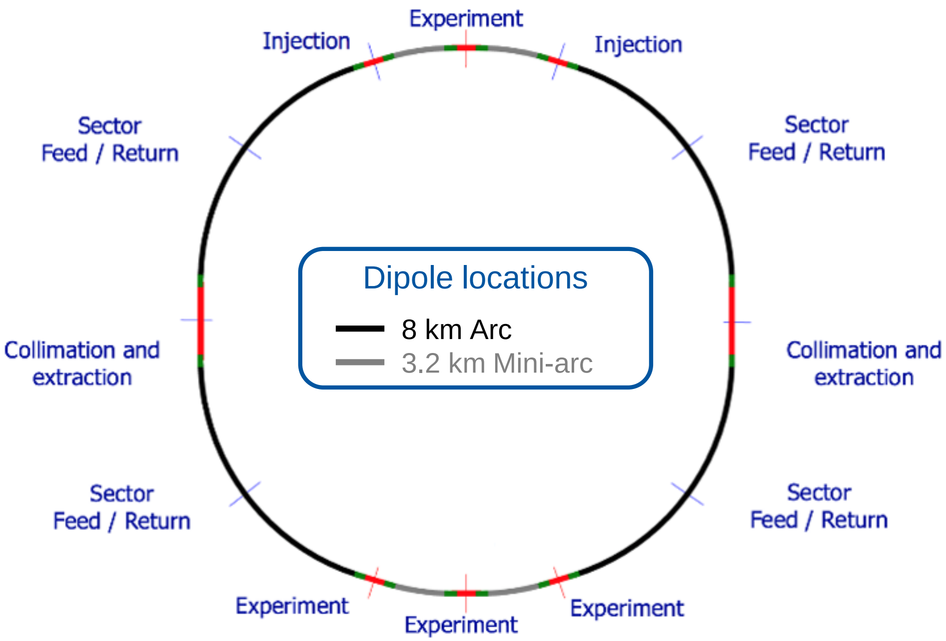
EuroCirCol

Intro

	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

Equivalent of 140 GJ

15’000 trucks of 20 ton at 110 km/hr

35 ton of TNT

Magnet protection

The individual magnet protection has been presented by Tiina Salmi (THU 8h50).

For EuroCirCol we consider a maximum voltage to ground of an individually quenched magnet equal to $U_{Q,max}$=1.2 kV.

Four different FCC magnet designs (Cosθ, block, common coil, CCT) are considered, varying significantly in terms of inductance and current.

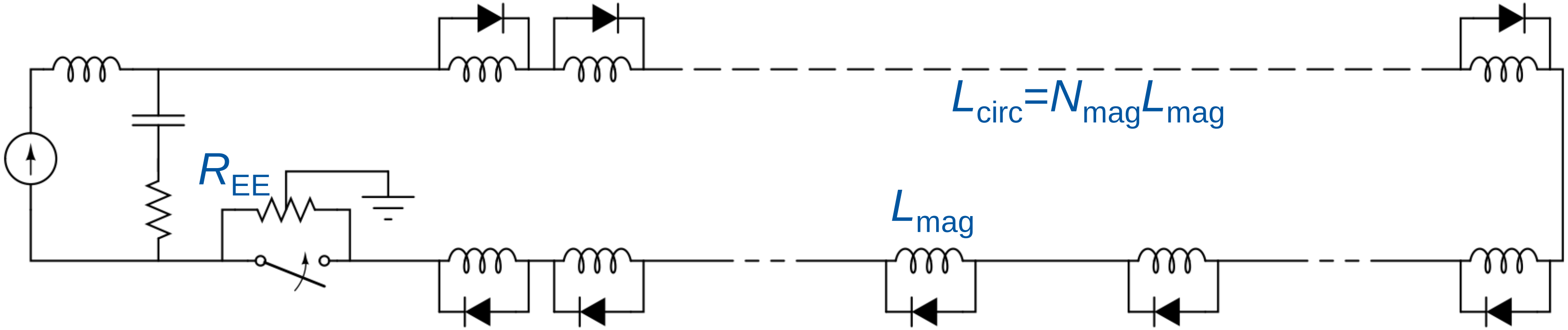
	Cosθ	**Block**	**Common Coil**	**CCT**
L [H]	0.591	0.745	0.339	0.284
I [A]	11390	10100	16100	18000
E [MJ]	38	38	44	46

PS: small deviations are possible compared to the latest designs

Circuit protection

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

- series connection of magnets to limit the number of power converters and current leads;
- cold bypass diodes, to protect a quenching magnet;
- warm Energy Extraction (EE) systems to protect the circuit, including bypass diodes, busbar and current leads. LHC uses a passive R_{EE} ($\Rightarrow$ exp. decay $\tau_{decay}=L_{circ}/R_{EE}$). For FCC we consider an active $R_{EE}(I)$ ($\Rightarrow$ lin. decay $t_{decay}=L_{circ}/R_{EE,0}$) to reduce the MIIts for the same maximum circuit voltage.
- grounding of the circuit in the centre of one of the EE resistances.



Circuit design targets

Minimize the peak voltage to ground during a Fast Power Abort
Minimize the discharge time during a Fast Power Abort
Minimize the number of magnets in series in a circuit
Minimize the complexity of the circuits
Minimize the thermal heat inleak
Minimize the required peak voltage and power of the power converters
Minimize the number of spurious triggers of the quench detection system (QDS)

Some of these targets are contradictory and a good balance has to be found.

Voltage Withstand Level (VWL)

Minimizing the VWL level has a positive impact on the insulation and testing of the magnets, and also on all the auxiliary equipment (voltage taps, other sensors, quench detection electronics)

$\mathrm{VWL}=f*(U_{\mathrm{Q,max}}+U_{\mathrm{circ,max}})$ with:
f: safety factor
$U_{\mathrm{Q,max}}$: max. magnet quench voltage
$\underline{U}_{\mathrm{circ,max}}$: max. circuit voltage after a FPA

$U_{\mathrm{circ,max}}=I_{\mathrm{max}}*R_{\mathrm{EE,0}}/2$ with:
$R_{\mathrm{EE,0}}$: initial resistance of one EE system

In EuroCirCol we consider VWL=3 kV, f=1.2, $U_{\mathrm{Q,max}}$=1.2 kV and $U_{\mathrm{circ,max}}$=1.3 kV not taking into account failure scenario's.

Note: various plausible failure scenario's can add a significant voltage, for example a short-to-ground in the circuit, resulting in blowing up of the grounding fuse.

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.

Circuit topology

Reducing the VWL (⇒ reducing R_{EE}) and reducing as well t_{decay} (⇒ 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.

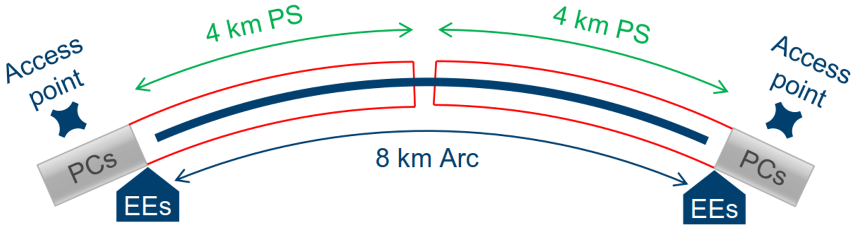
2. Subdivide each circuit in N sub-circuits, each with one EE system, located close to the power converter.

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.

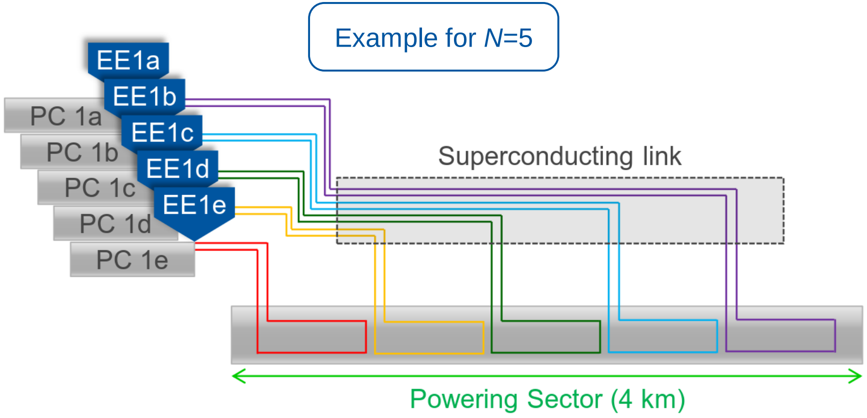
Circuit topology

Power converters (PC) and energy extraction (EE) systems close to access points

- ➢ Space optimization and easier maintenance



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



Circuit topology

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

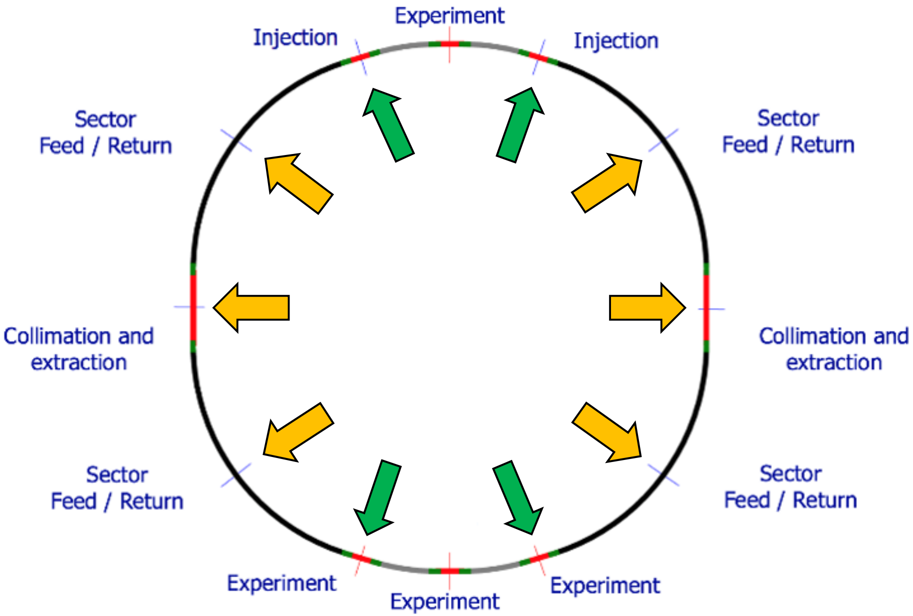
		Cosθ	**Block**	**Common Coil**	**CCT**
	L [H]	0.591	0.745	0.339	0.284
	I [A]	11390	10100	16100	18000
	E [MJ]	38	38	44	46
Arc	Nr of circuits N	5	6	4	4
	$U_{circ,max}$ [V]	1230	1140	1250	1170
Mini-arc	Nr of circuits N_{mini}	4	5	4	3
	$U_{circ,max}$ [V]	1260	1130	1020	1280
Total	Total nr of circuits	96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

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
	$U_{M,ramp}$ [s]	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

Distribution of peak power



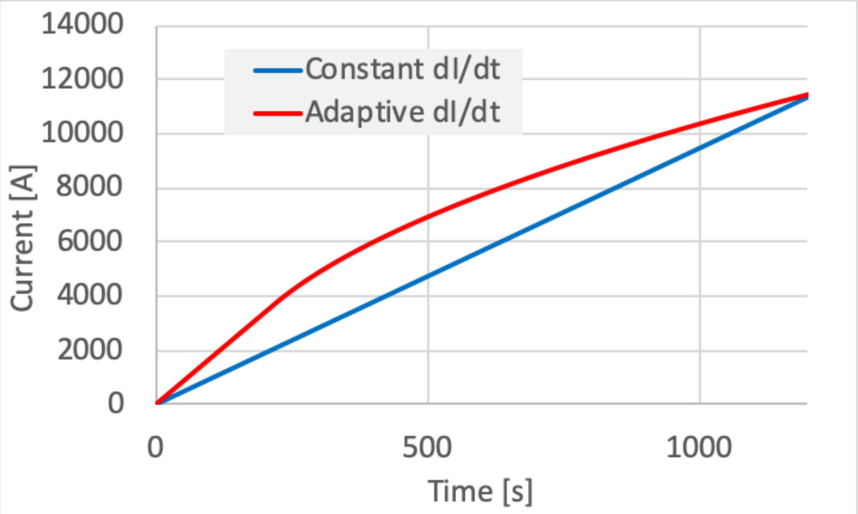
t_{ramp}=1200 s

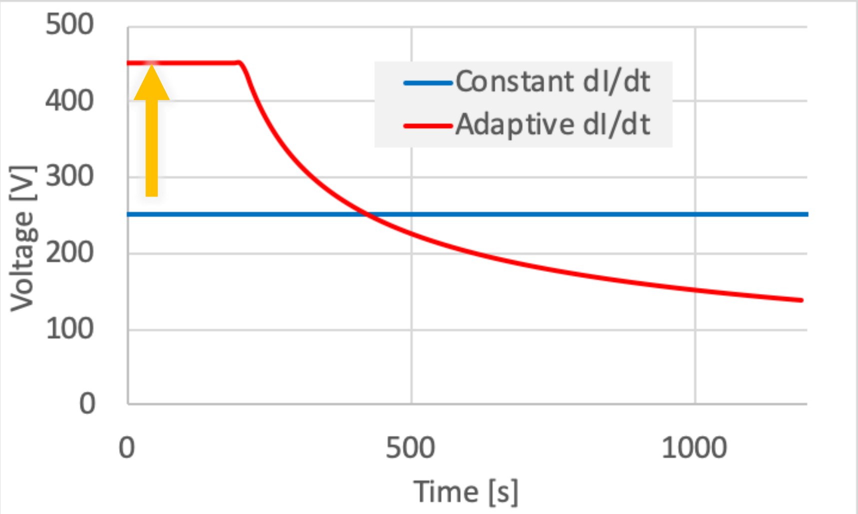
	Cosθ	Block	Common Coil	CCT
🟩 [MW]	25.5	25.3	29.1	30.6
🟨 [MW]	28.0	27.7	32.1	33.6

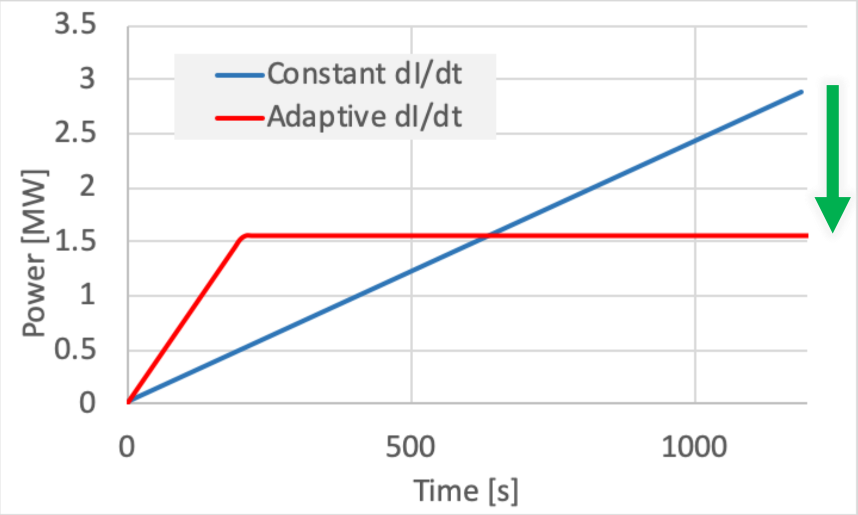
Values do not take into account losses and inefficiency

Peak power

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

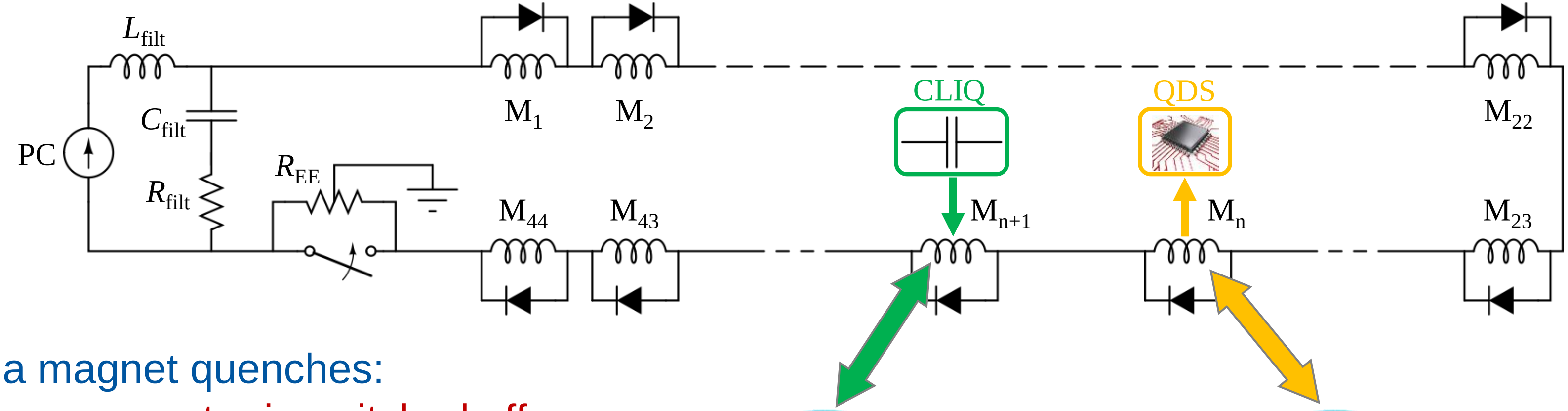






Simulations performed using
the STEAM framework

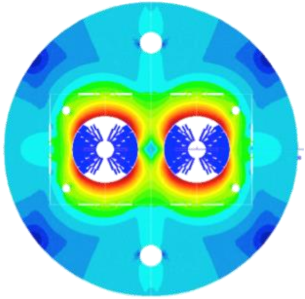
Response of the QDS if a neighbouring magnet quenches



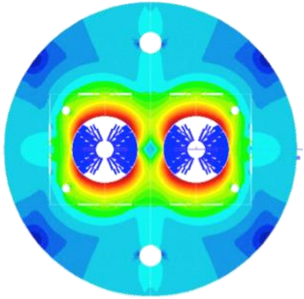
Actions if a magnet quenches:

- 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.

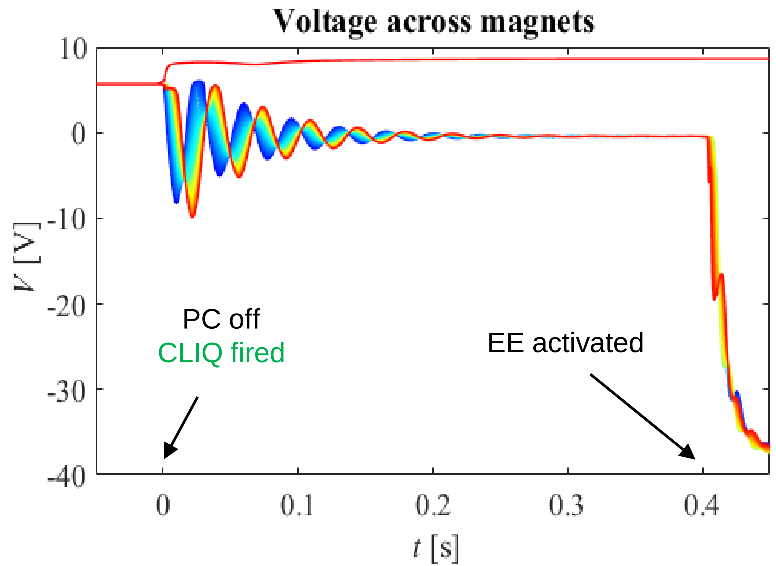


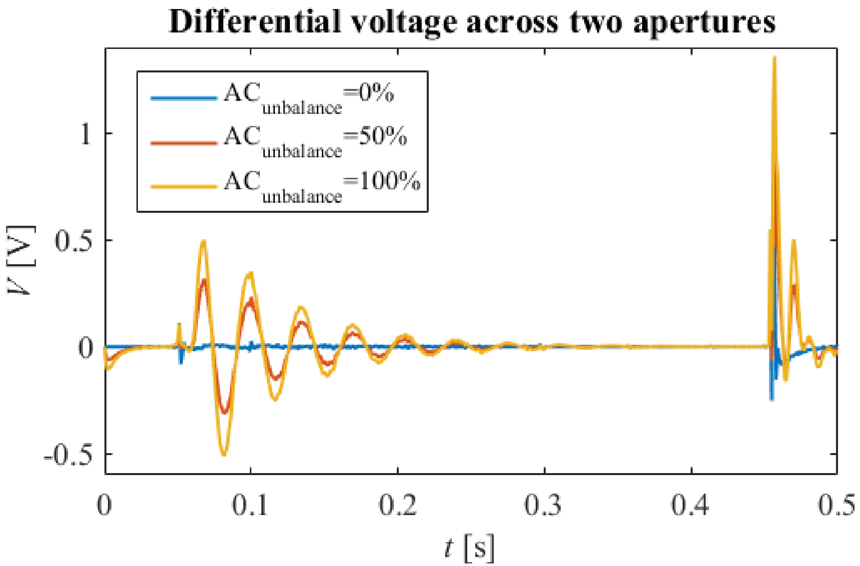
Quenching magnet:
CLIQ simulation



Neighbouring magnet:
Simulation of voltage response

Response of the QDS if a neighbouring magnet quenches


Voltage across magnets


Differential voltage across two apertures

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)

Conclusion

- The main dipoles of the FCC-hh have to be powered in about 80-120 circuits, each with one power converter and one active EE system.
- The converters and EE systems will be located in the access points, hence an additional cryogenic distribution line, in parallel to the dipole cryostats, is needed to house the SC busbars that feed the current to all the circuits.
- The ramp time, max circuit voltage, max power from the grid, busbar dimensions, diode characteristics, etcetera depend on the magnet current and inductance. However, all these parameters can be kept within the allowed limits by tuning the number of circuits. The first focus should be on defining the most reliable/feasible/cost-efficient magnet design. Circuit topology and protection will follow/adapt, ultimately with an additional cost (being much less than the magnet cost).
- All other type of circuits can be powered & protected in a similar way as done in the LHC.

Further study & Optimization

- Protection: several mitigation measures have to be studied to:
  - minimize spurious triggering of the QDS,
  - reduce probability and consequences of failures ⇒ redundancy,
  - increase reliability & optimize availability.
- Optimization of the ramp time, taking into account:
  - maximum ramp voltage and power ⇒ converter specifications / cost,
  - maximum voltage per magnet ⇒ number of diodes,
  - optics requirements.
- Reduction of the quench propagation along the chain of magnets, e.g. by means of:
  - quench stoppers in the busbars,
  - reduced helium heat flow between magnets.
- Optimization of the Cryogenic Distribution Line.