STEAM

Dipole circuit layout and protection for FCC-hh

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with contributions from: B. Auchmann, L. Bortot, M. Maciejewski, T. Salmi, R. Schmidt, A. Siemko, A. Verweij

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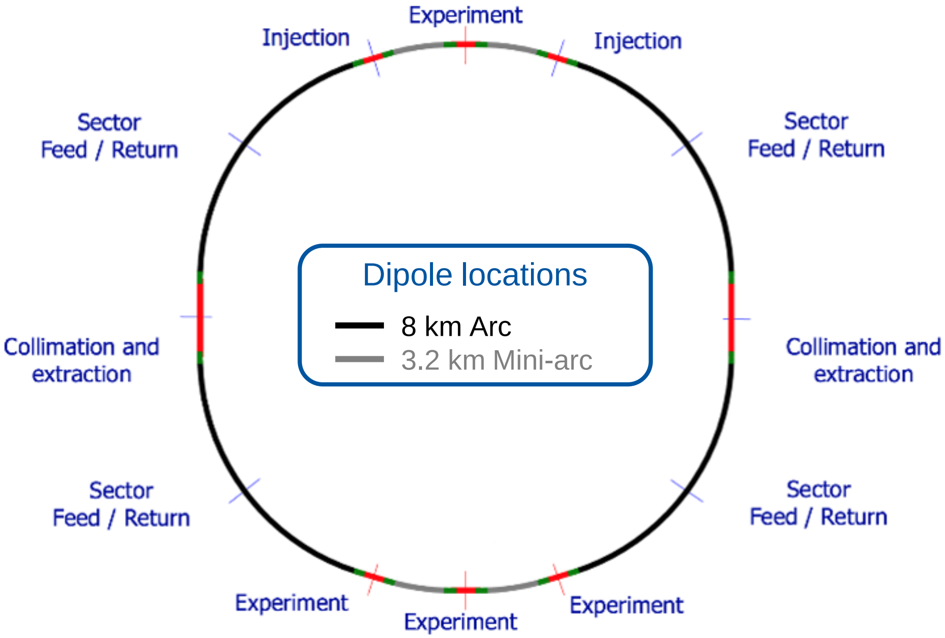
EuroCirCol

Motivation and input parameters

	Nominal current I_{nom} [kA]	Stored energy @ I_{nom} (2 ap.) [MJ]
Cos-theta	11.4	37
Block coil	10.1	38
Common coil	16.1	44
Canted cos-theta	18.0	46
LHC MB	11.9	7

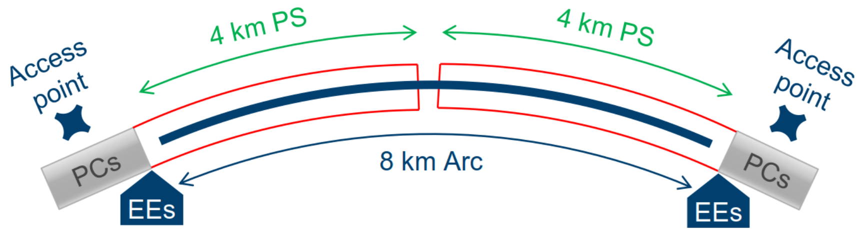
	Length	Number	Number of magnets
Arc	8 km	8	438
Mini-arc	3.2 km	4	180
LHC arc	3 km	8	154



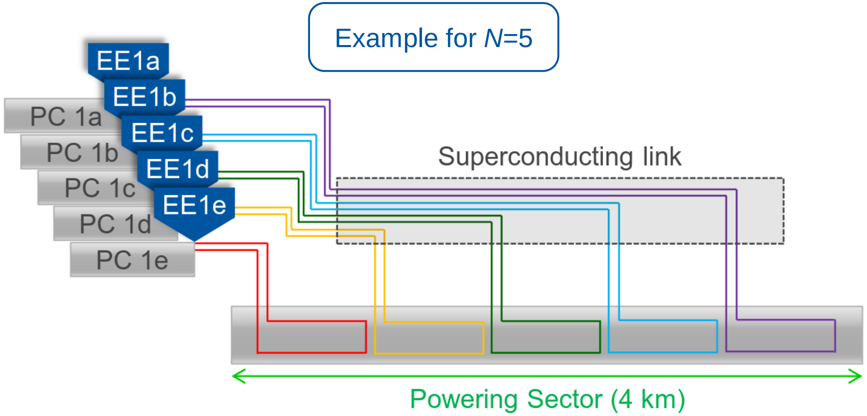
Circuit design strategy

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

- ➢ Space optimization and easier maintenance



1. Subdivide each 8 km long Arc in two powering sectors (PS) of 4 km
2. … and each powering sector in *N* circuits (20*N* circuits in total including mini-arcs)
3. Equip each circuit with one PC and one EE system
4. Power the circuits through a Superconducting link



Circuit design inputs

- Ramp-up in 20 min
  - Limit the turnaround time

- Fast Power Abort (FPA) with 1.3 kV voltage to ground budget for the circuit
  - Limit the required Voltage Withstand Level… $f \cdot (V_{Cir} + V_{Mag,quench}) = VWL$
  - … following the EuroCirCol specifications $1.2 \cdot (1.3\ kV + 1.2\ kV) = 3\ kV$

Circuit design targets

	Target: to minimize the…	Condition: During…	Result: to improve the…
1	Total number of circuits	-	Reliability
2	No. of magnets in series in a circuit	-	Training campaign
3	Circuit energy	Nominal operation	Fault scenarios
4	Peak voltage of power converters	Ramp-up	Power converter design
5	Peak power of power converters	Ramp-up	Accelerator power demand
6	Discharge time constant	Fast Power Abort	Cryo-recovery time due to neighbouring quenching magnets
7	$\int i^2 dt$ (MIITs)	Fast Power Abort	Diode design
8	Busbar copper cross section	Fast Power Abort	Layout inside the cryostat
9	Number of spurious triggers of the quench detection system (QDS)	Fast Power Abort	Availability

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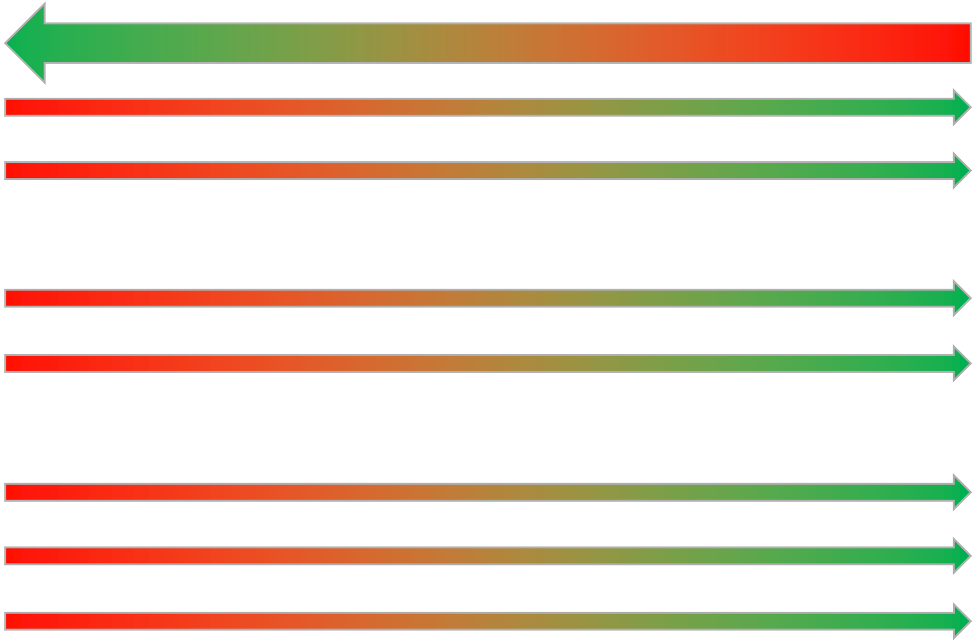
Circuit design targets

Number of circuits per Powering Sector (N)	1	2	3	4	5	6	7	8

1. Total number of circuits
2. No. of magnets in series
3. Circuit energy
4. PC peak voltage
5. PC peak power
6. Discharge time constant
7. MIITs
8. Busbar copper cross section



Circuit design

Number of circuits per Powering Sector (N)	1	2	3	4	5	6	7	8	LHC
1. Total number of circuits	20	40	60	80	100	120	140	160	8
2. No. of magnets in series	219	110	73	55	44	37	32	28	154
3. Circuit energy [GJ]	8.2	4.1	2.7	2.1	1.6	1.4	1.2	1.0	1.1

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4. PC peak voltage [V]	1200	600	400	300	240	200	175	150	150
5. PC peak power [MW]	14	6.8	4.5	3.4	2.7	2.3	2.0	1.7	1.8

t_{ramp} = 20 min

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t_{ramp} = 20 min	4. PC peak voltage [V]	1200	600	400	300	240	200	175	150	150	t_{ramp} = 20 min
	5. PC peak power [MW]	14	6.8	4.5	3.4	2.7	2.3	2.0	1.7	1.8	
V_{gnd} = 1.3 kV	6. Discharge time constant [s]	550	280	180	140	110	90	80	70	100	V_{gnd} = 450V
	7. MIITs [MA^2*s]	36e3	18e3	12e3	9e3	7e3	6e3	5e3	4e3	7e3	
	8. Busbar copper cross section [mm^2]	600	430	350	300	270	250	230	210	270	

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Rows 4–5: t_{ramp} = 20 min (LHC: t_{ramp} = 20 min)

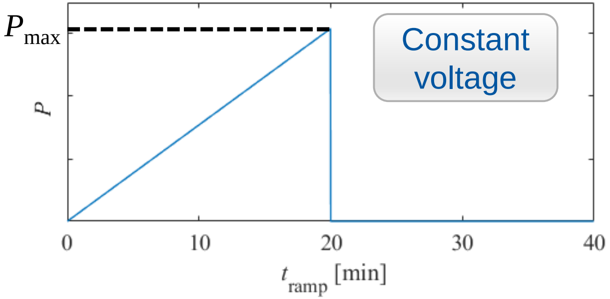
Rows 6–8: V_{gnd} = 1.3 kV (LHC: V_{gnd} = 450V)

Proposal for ramp-up and EE strategies

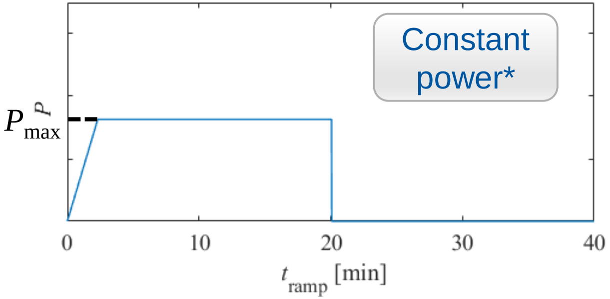
<u>Target 5</u>

PC peak power during ramp-up

LHC



FCC



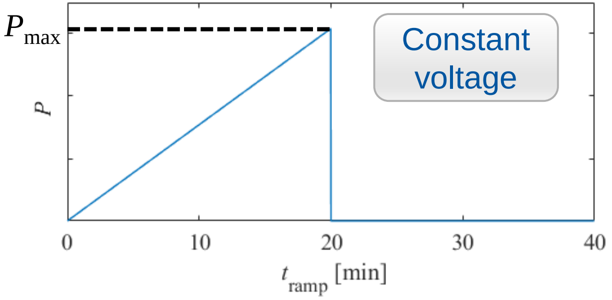
*See presentation of F. R. Blánquez in this session

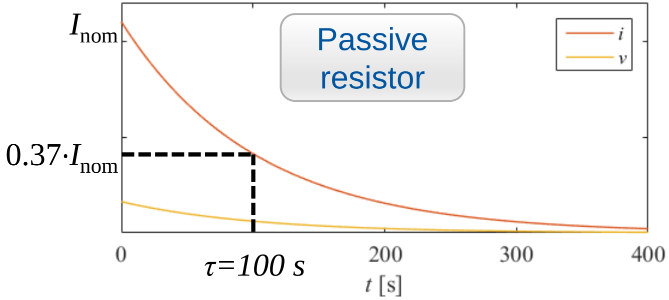
Proposal for ramp-up and EE strategies

Target 5
PC peak power during ramp-up

Target 6
Discharge time constant during FPA

LHC





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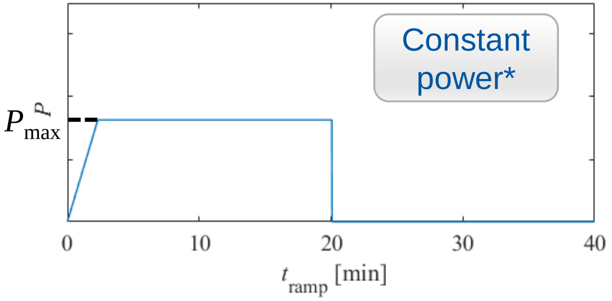

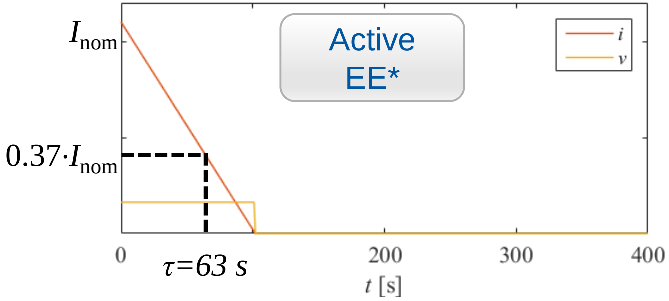

*See presentation of F. R. Blánquez in this session

*See presentation of V. Karaventzas in this session

Circuit design

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	3. Circuit energy [GJ]	8.2	4.1	2.7	2.1	1.6	1.4	1.2	1.0
t_{ramp} = 20 min	4. PC peak voltage [V]	2400	1200	800	600	480	400	350	300
t_{ramp} = 20 min	5. PC peak power [MW]	7.3	3.7	2.4	1.8	1.5	1.2	1.1	0.9
V_{gnd} = 1.3 kV	6. Discharge time constant [s]	350	175	120	90	70	60	50	45
V_{gnd} = 1.3 kV	7. MIITs [MA^2*s]	24e3	12e3	8e3	6e3	5e3	4e3	3.5e3	3e3
V_{gnd} = 1.3 kV	8. Busbar copper cross section [mm^2]	480	340	280	240	210	190	180	170

Circuit design

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t_{ramp} = 20 min	4. PC peak voltage [V]	2400	1200	800	600	480	400	350	300	+100%
	5. PC peak power [MW]	7.3	3.7	2.4	1.8	1.5	1.2	1.1	0.9	-46%
V_{gnd} = 1.3 kV	6. Discharge time constant [s]	350	175	120	90	70	60	50	45	-37%
	7. MIITs [MA^2*s]	24e3	12e3	8e3	6e3	5e3	4e3	3.5e3	3e3	-33%
	8. Busbar copper cross section [mm^2]	480	340	280	240	210	190	180	170	-21%

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t_{ramp} = 20 min	4. PC peak voltage [V]	2400	1200	800	[illegible]	[illegible]	400	350	300
t_{ramp} = 20 min	5. PC peak power [MW]	7.3	3.7	2.4	1.8	1.5	1.2	1.1	0.9
V_{gnd} = 1.3 kV	6. Discharge time constant [s]	350	175	120	90	70	60	50	45
V_{gnd} = 1.3 kV	7. MIITs [MA^2*s]	24e3	12e3	8e3	6e3	5e3	4e3	3.5e3	3e3
V_{gnd} = 1.3 kV	8. Busbar copper cross section [mm^2]	480	340	280	240	210	190	180	170

+100%

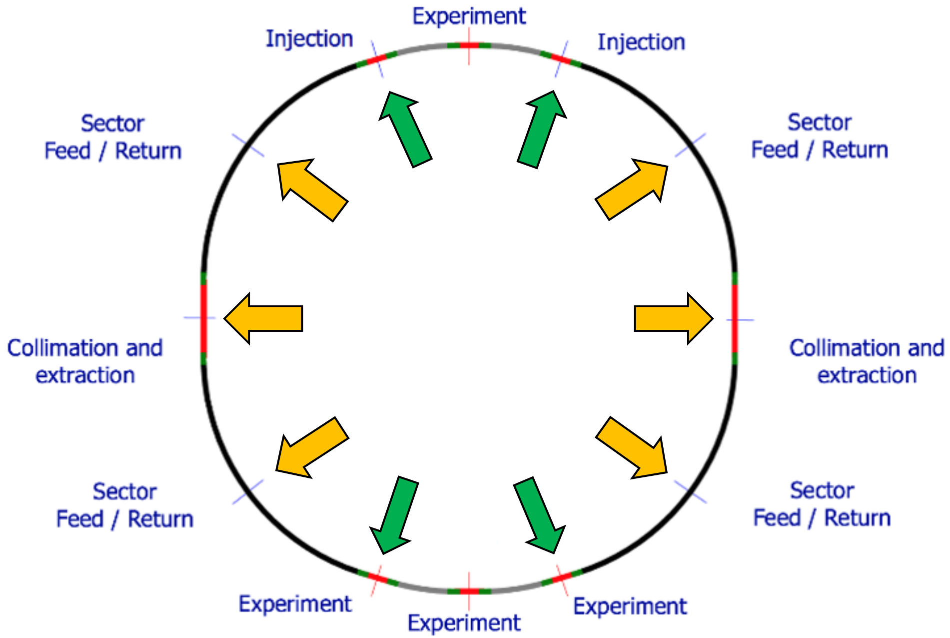
-46%

-37%

-33%

-21%

Distribution of peak power



Ramp-up strategy:

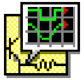
	Constant voltage	Constant power
Yellow arrow	27 MW	15 MW
Green arrow	25 MW	13 MW

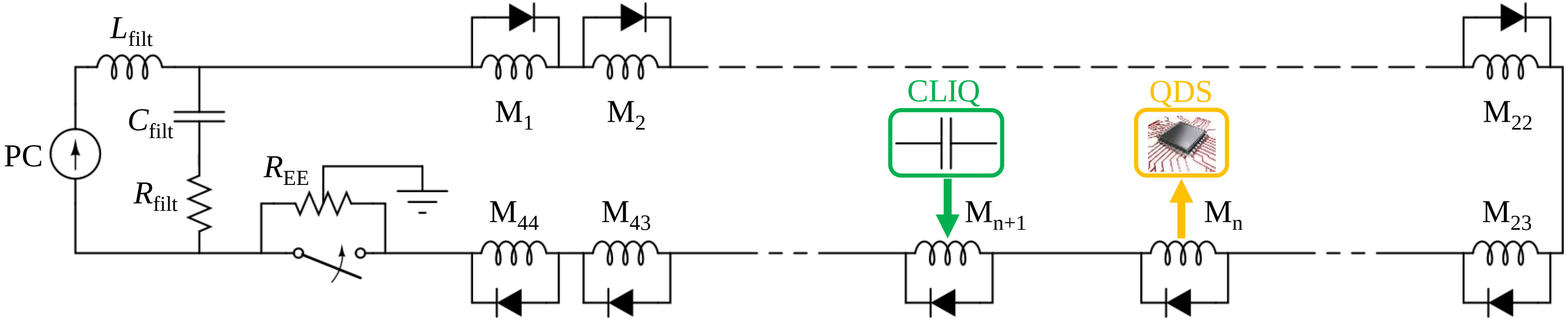
- Ramp-up of FCC dipole magnets
- Net power: no losses and inefficiency

Co-simulation of circuit and magnets

Circuit model
2800 components

PSpice





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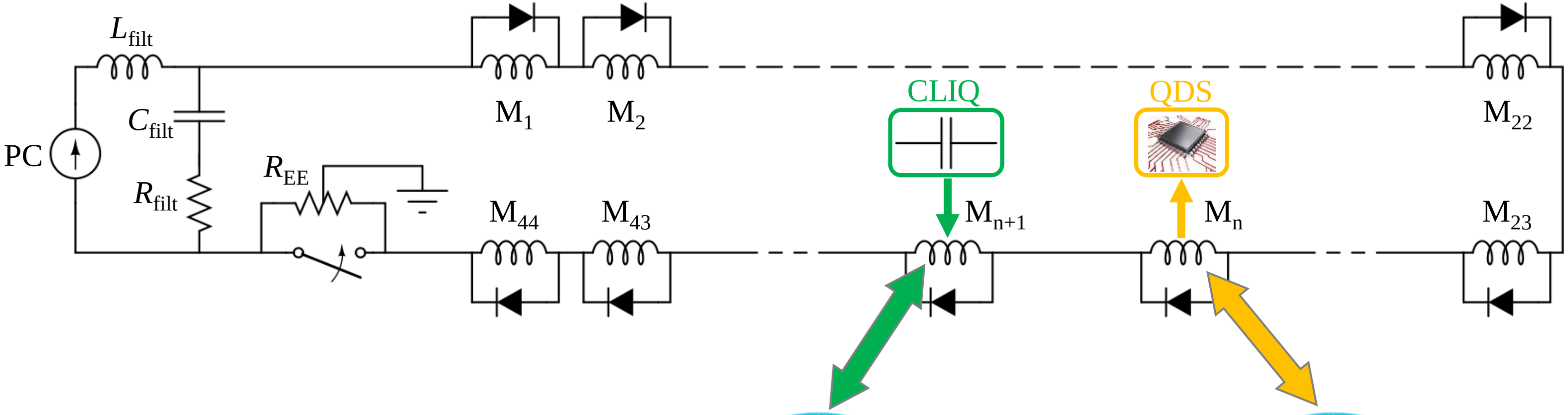
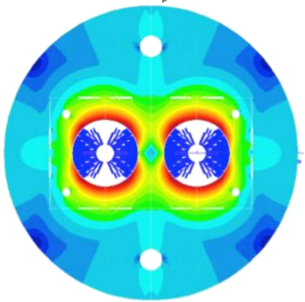
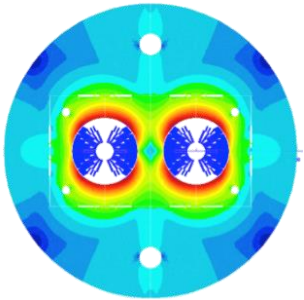


Electro-thermal magnet model
400 turns

COMSOL



Quenching magnet:
CLIQ simulation

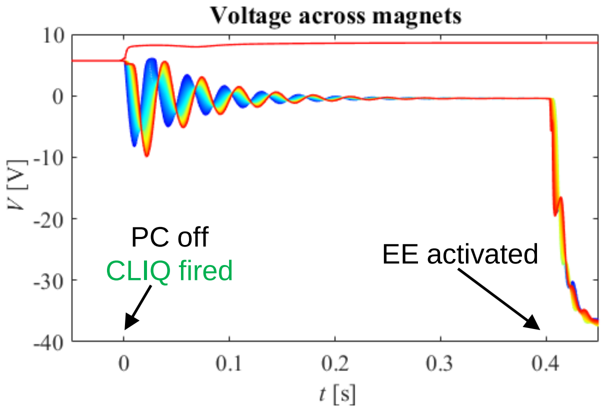


Neighbouring magnet:
Simulation of voltage response

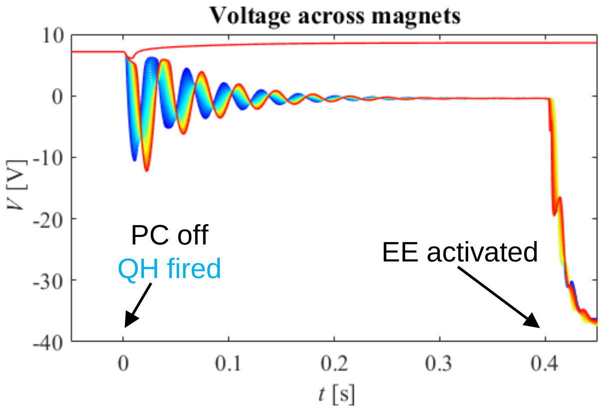
Target 9: reduce spurious triggers of the QDS

One magnet of the chain is quenching:

2. CLIQ is activated
   (Baseline)



1. Quench-heaters are activated
   (Heaters delays from CoHDA, T. Salmi)

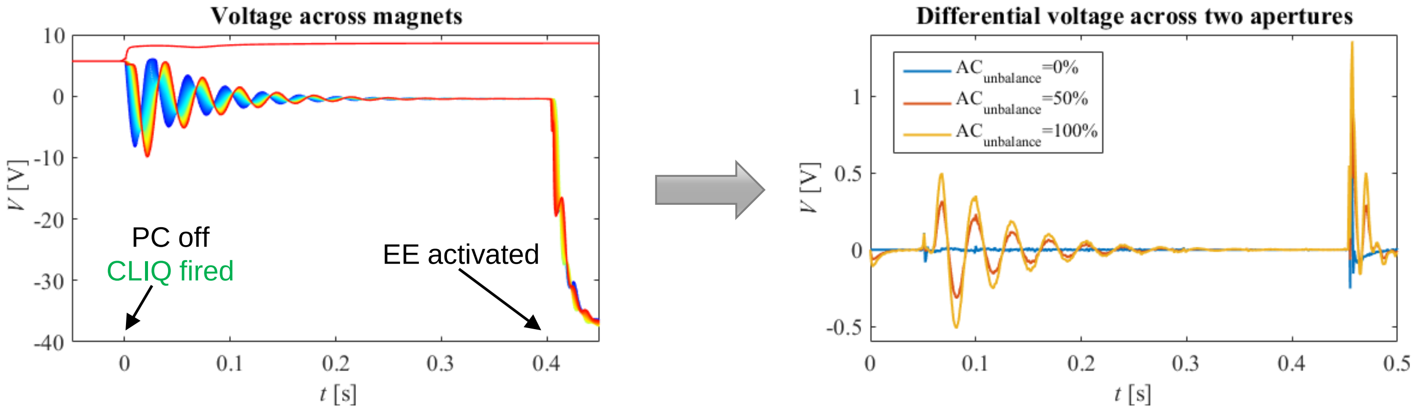


QH and CLIQ result in the same voltage transients

- ➢ CLIQ does not affect the voltage distribution on neighbouring magnets

Target 9: reduce spurious triggers of the QDS

Considering case 2 (CLIQ protection), the differential voltage across the two apertures of the neighbouring magnet can be calculated



The differential voltage is larger than the foreseen quench detection thresholds

Voltage transient could be reduced through:

- Circuit optimization
- QDS optimization
- Conductor development

Conclusion

- The subdivision of the 4 km Powering Sector in multiple circuits is required from the protection point of view
- Following standard ramp-up and EE strategies
  - 5 circuits per Powering Sector
  - 100 dipole circuits for full accelerator, each with one power converter and one energy extractor
- Alternative strategies are proposed to optimize ramp-up and EE
  - 3 circuits per Powering Sector
  - 60 dipole circuits for full accelerator, each with one power converter and one energy extractor
- CLIQ and QH protection systems have the same effect on quench detection signals
  - CLIQ can be safely operated in a long chain of magnets
- Transient effects are significant for the FCC dipole circuits due to the high voltages
  - Mitigation strategies have to be foreseen