# Circuit protection for FCC

## 1. Recap of FCC-hh circuit protection

## 2. Conditions for FCC-ee circuit protection

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# 1. Recap of FCC-hh circuit protection

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

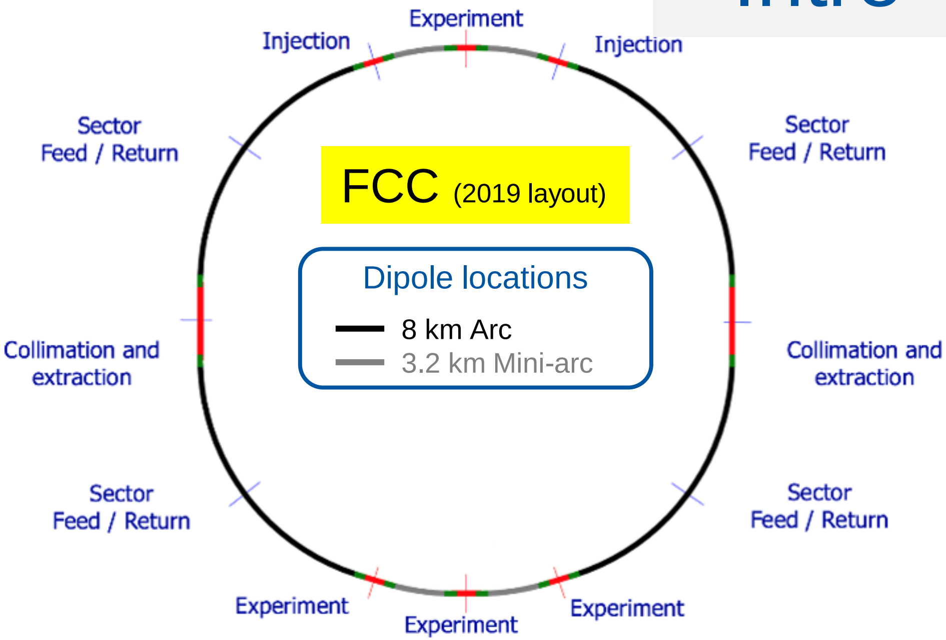
Outcome of the studies has been presented at various occasions, especially at FCC week in Rome in 2016 and FCC week in Brussels in 2019.

Since 2020, we have stopped working on the topic due to low priority, and since no major changes in the designs of the FCC layout and SC magnets were introduced.

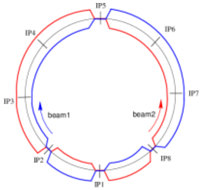
# Intro

| | 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** |

11’500-10’000 trucks of 20 ton at 110 km/hr




LHC



# Magnet protection

The **individual magnet protection** is based on a similar concept as the LHC:
- Quench detection based on differential voltage;
- 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***

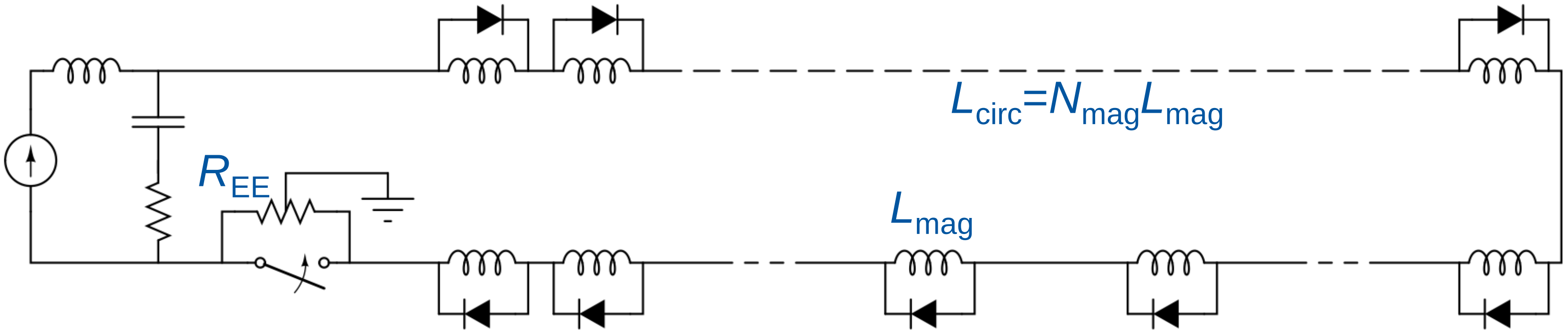
The ‘allowed’ internal quench voltage $U_{q,max}$ was about 1.2 kV.

| | 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 |

# Circuit protection

**The circuit powering and protection is based on a similar concept as the LHC:**

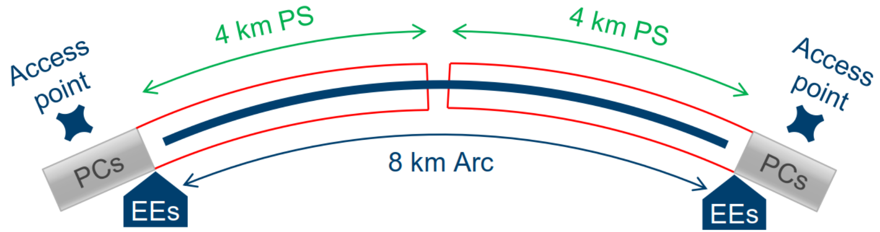
- Series connection of magnets to limit the number of power converters and current leads;
- Warm Energy Extraction Systems (EES). LHC uses two passive EES per circuit (expon. decay). For the FCC we consider one active EES per circuit (lin. decay to reduce the MIIts for the same maximum circuit voltage).
- Grounding of the circuit in the centre of the EE resistance to reduce maximum voltage to ground. Max. circuit voltage $U_{circ,max}$ at FPA was set to 1.3 kV.



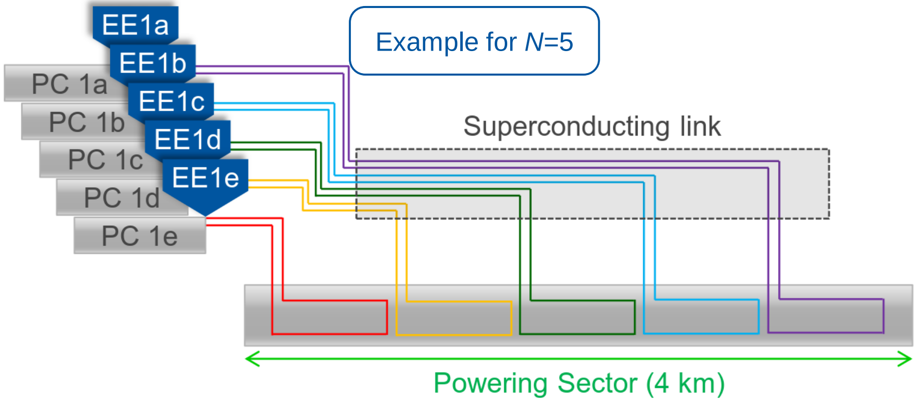
# Circuit topology

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 (16$N$ circuits in total)
4. Subdivide each $PS_{mini}$ in $N_{mini}$ circuits (4$N_{mini}$ circuits in total)
5. Equip each circuit with one PC and one EES
6. Power the circuits through superconducting links



# Circuit design targets

| **Design target** | **N, $N_{mini}$** | **$I_{magnet}$** |
|---|---|---|
| Minimize the Voltage Withstand Level; $VWL+f*(U_{Q,max}+U_{circ,max})$ | ↑ | ↑ |
| Minimize the discharge time during a Fast Power Abort and hence cross-section of the busbars; $t=L_{circ}/R_{EE,0}$ | ↑ | ↑ |
| 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)

# Conclusion

- Studies for the protection of the main dipole circuit (based on $Nb_3Sn$) for the FCC-hh have been made in 2015-2020. Depending on the magnet design, the baseline is to power all dipoles 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, separate or incorporated in the magnets cryostats, is needed to house the SC links that feed the current to all the circuits.
- Protection and powering of HTS magnets is very different w.r.t. $Nb_3Sn$ magnets. FCC-hh based on HTS is in my opinion a very promising option. Should we not quickly increase ***much*** more the R&D on HTS tapes/cables/magnets?
- The circuit powering and protection for the quads and all other circuit types is much simpler but of course has to follow somehow the dipole circuit topology, which will impact the complexity and size of the SC link and current leads.

# Further studies (to name a few)

- Study quench detection & protection of HTS magnets/circuits through modelling and experimental work.
- Increase performance and reliability of the protection (use of CLIQ or variants of it, new EES concepts, …). Note that CLIQ units are large and have to be placed next to each magnet.
- Optimize availability (minimize probability of spurious triggering of the QDS, …)
- Reduce probability and consequences of failures (fail-safe design, …)
- Reduce quench recovery time (quench stoppers, …)
- Optimize the SC link (incorporated/separate, LTS/HTS/$MgB_2$, …)

# 2. Conditions for FCC-ee circuit protection

- Warm magnets will be protected by the WIC.
- I am not aware of the design of any SC magnet or circuit for the collider part of the FCC-ee. I am not considering the final focus Nb-Ti magnets that are positioned at 2.2 m from the IR.
- Hence, we have not performed any study for the SC magnet/circuit protection.
- In case the FCC-ee will comprise SC magnets/circuits, then MPE should be involved from the beginning in the magnet design and circuit layout, so that both magnet and circuit are protectable in an effective and reliable way.

# Annex

# Circuit topology

Setting $t_{decay}$=120 s, and requiring $U_{circ,max}$<1.3 kV, 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 s, 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 |