# Comparison of magnet designs from a circuit protection point of view

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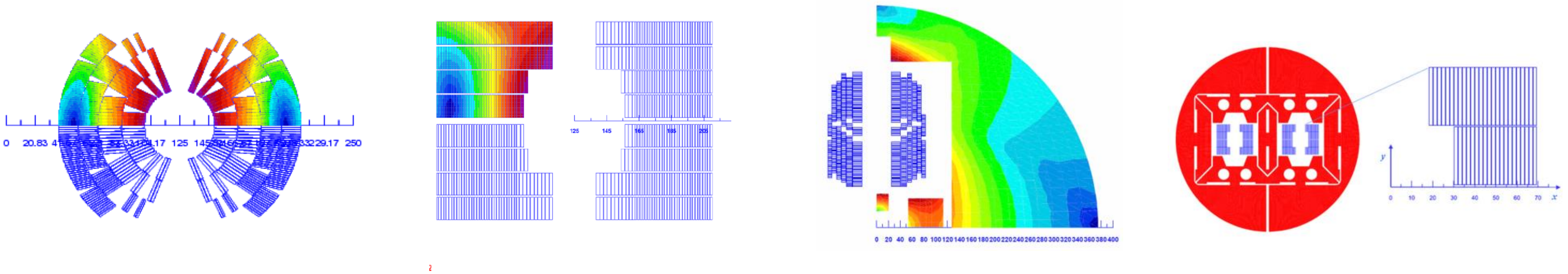
with input from M. Prioli, R. Schmidt, and A. Siemko



# Reminder

Sept 2008: damage caused in the LHC by 0.6 GJ stored energy

The stored energy of all main dipoles in the FCC is about 200 GJ.

⇒ Circuit protection is extremely important

# Intro

The FCC main dipole magnets have to be powered in strings, and the magnet design has therefore a strong impact on the protection and configuration of the string.

The following magnet designs are compared from a circuit protection point of view:

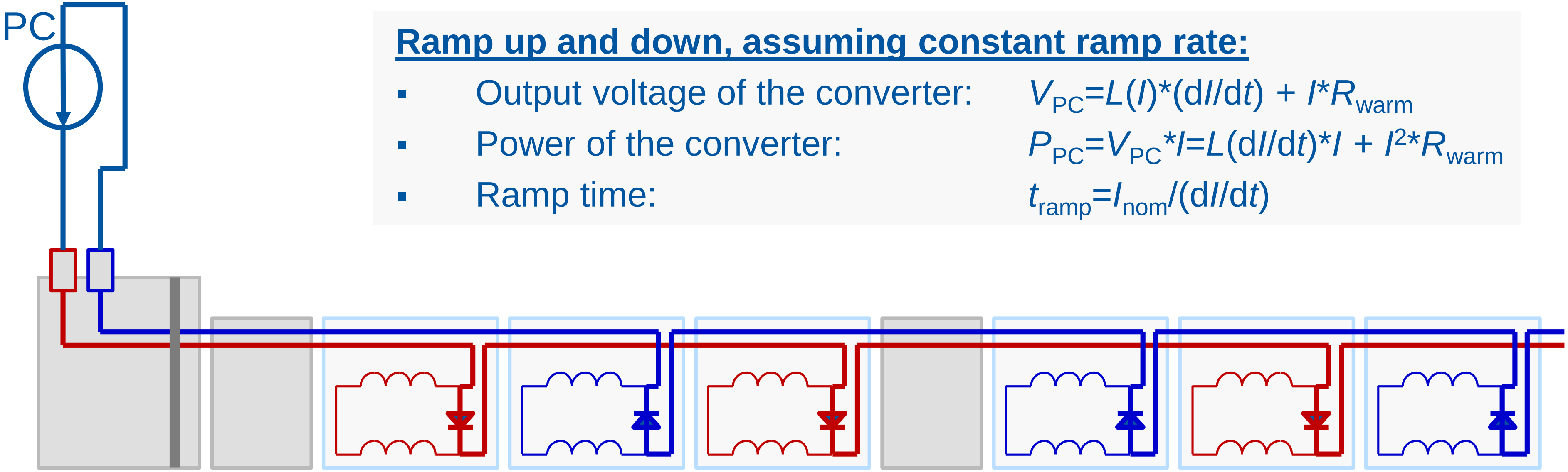
- **Cos-θ**, INFN, EuroCirCol collaboration
- **Block**, CEA, EuroCirCol collaboration
- **Common coil**, CIEMAT, EuroCirCol collaboration
- **Block**, LBNL

Quench protection of the magnet itself (mainly characterised by the hot-spot temperature and maximum voltage-to-ground is not discussed here.

(see presention T. Salmi).

# Typical powering of the dipole circuit

Magnets are powered in series and each magnet has a **bypass diode** to decouple the current decay of a *quenching* magnet from the current decay of the circuit.



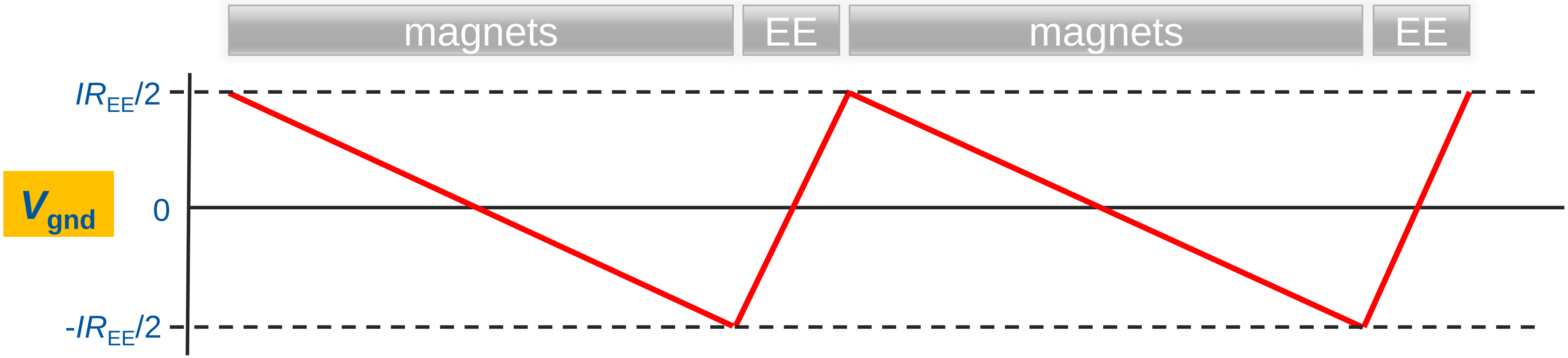
**Ramp up and down, assuming constant ramp rate:**

- Output voltage of the converter: $V_{PC}=L(I)*(\mathrm{d}I/\mathrm{d}t) + I*R_{warm}$
- Power of the converter: $P_{PC}=V_{PC}*I=L(\mathrm{d}I/\mathrm{d}t)*I + I^2*R_{warm}$
- Ramp time: $t_{ramp}=I_{nom}/(\mathrm{d}I/\mathrm{d}t)$

**$N_{EE}$** energy extraction (**EE**) systems, each with a resistor **$R_{EE}$**, are present, equally spaced along the circuit, to ensure a sufficiently fast decay of the circuit current in case of a Fast Power Abort (**FPA**) triggered by a quench/trip.

# Quench/trip ⇒ Fast Power Abort (FPA)

- the power converter is switched off,
- the switches of the EE system(s) are opened,
- quench heaters (or CLIQ) are activated,
- the current in the quenching magnet(s) transfers into the bypass diode,
- the voltage over the quenching magnet(s) equals the forward voltage of the bypass diode,
- the circuit current decays ‘exponentially’ with $\tau_{\mathbf{circ}}=L_{circ}/(N_{EE}*R_{EE})$,



# Required voltage withstand level

For a circuit with grounding in the centre of the EE resistor, the maximum voltage-to-ground ***without faults*** equals:

$$\boxed{V_{\mathrm{gnd,max}} = V_{\mathrm{Q,max}} + V_{\mathrm{FPA,max}} = V_{\mathrm{Q,max}} + 0.5{*}I{*}R_{\mathrm{EE}}}$$

$V_{\mathrm{Q,max}}$ is given by the layout of the coils and magnet protection system.

(see presentation T. Salmi)

**Fault scenario's** (for a circuit with one or two EE systems):

- ➢ Malfunctioning of part of the magnet protection can give an increased $V_{\mathrm{Q,max}}$.
- ➢ An ***intermittent short (before the circuit fuse blows)*** could give:

$$\boxed{V_{\mathrm{FPA,max,fault}} = I{*}R_{\mathrm{EE}} + N_{\mathrm{mag}}{*}V_{\mathrm{diode}}/N_{\mathrm{EE}}}$$

(private comm. E. Ravaioli)

$N_{\mathrm{mag}}$: the number of magnets in the circuit

$V_{\mathrm{diode}}$: the opening voltage of the cold bypass diode (6 V).

A safe ***voltage withstand level*** of the circuit is:

$$\boxed{VWL = f * (V_{\mathrm{Q,max}} + V_{\mathrm{FPA,max,fault}})}$$

with $f$ a safety margin (for example $f$=1.2)

# Circuit configuration

In general it is preferable to reduce the number of circuits ⇒ less power converters, warm busbars, electrical Distribution Feed Boxes (DFB), and current leads.

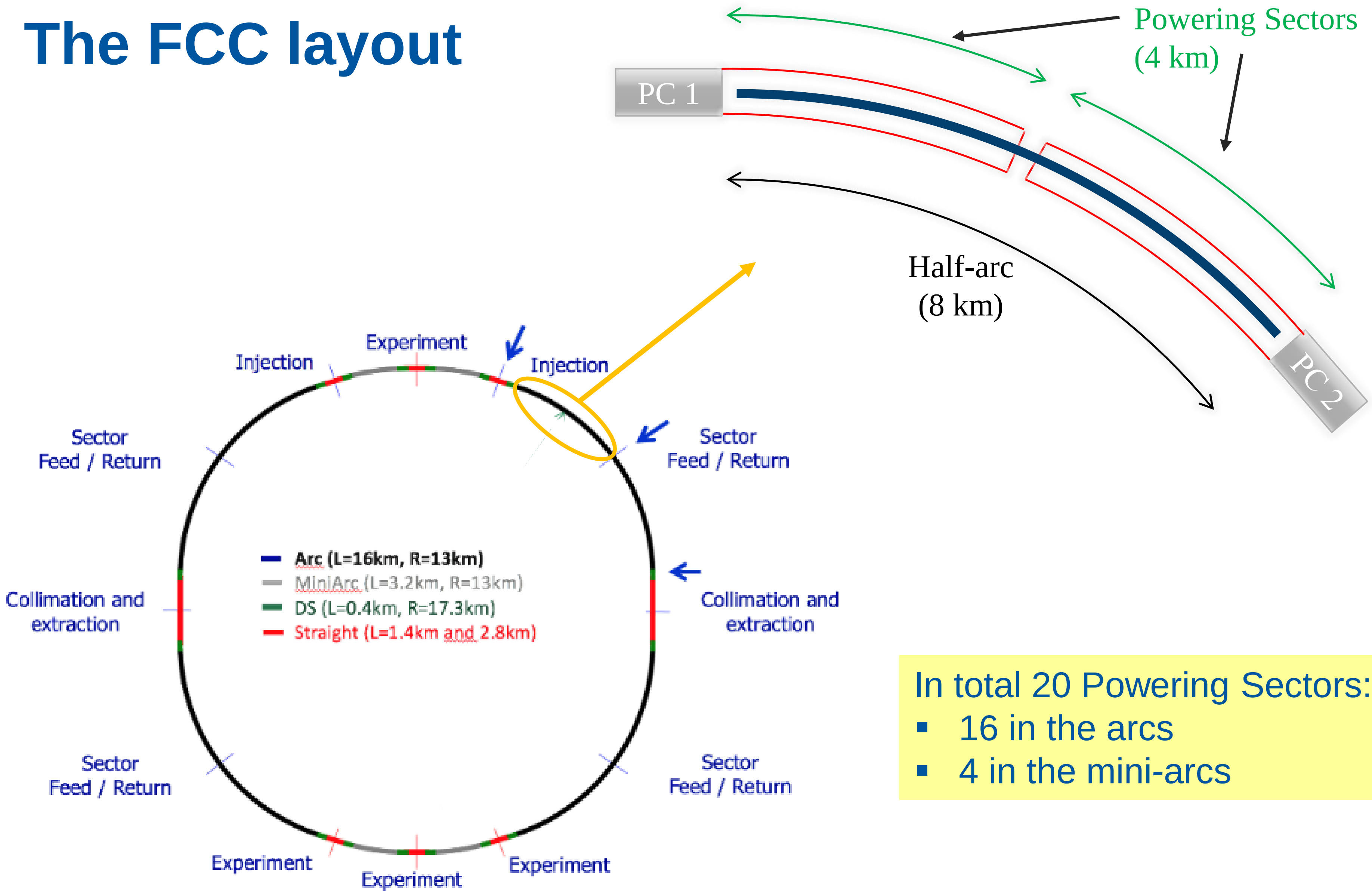
**For a circuit one would like to reduce:**

- **current in the circuit** → smaller size DFB & current leads, lower cost PC
- **$V_{PC}$ and $P_{PC}$** → lower cost and smaller size of the converter
- **ramping time** → increased availability for beam physics
- **$V_{FPA,max}$** → reduced voltage withstand level
- **$\tau_{circ}$** → faster cryo recovery, less quench propagation
- **dimensions cold busbars** → ‘easier’ layout inside the cryostats
- **number of EE systems** → lower cost, less maintenance, lower heat inleak
- **current rating of EE systems** → lower cost, smaller size
- **stored energy per circuit** → reduced risk in fault scenario’s
- **heating in the bypass diode** → smaller diode heat sinks, faster cryo recovery

And of course, the EE systems and PC’s should be located in easily accessible areas.

Unfortunately, many of these demands are contradictory...

# The FCC layout

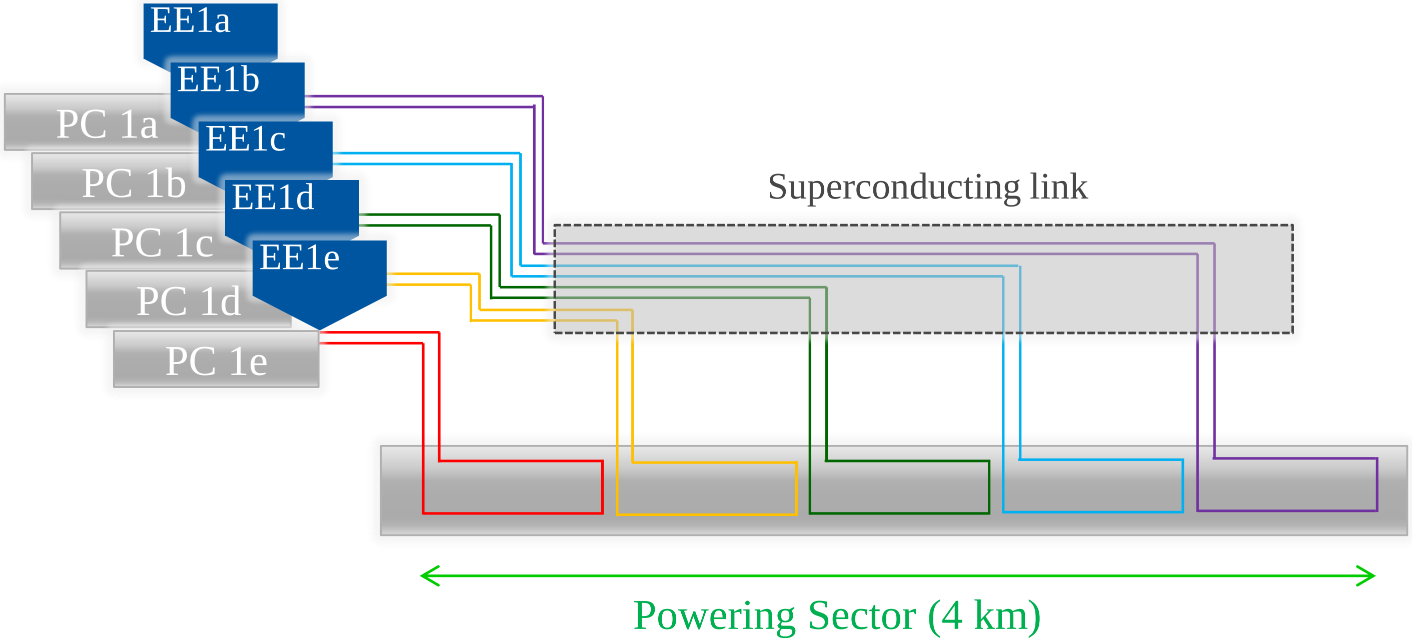


In total 20 Powering Sectors:
- 16 in the arcs
- 4 in the mini-arcs

# Strategy for circuit configuration

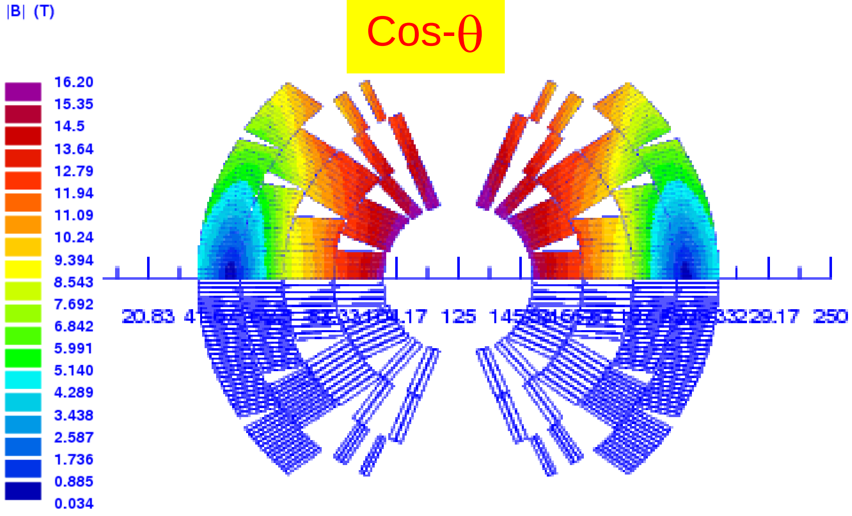
1. Locate power converters and EE systems in the access points.
2. Subdivide each Powering Sector in N circuits ⇒ 20N circuits for the entire machine
3. Power both apertures of the dipoles in series, independently from the quads.
4. Power the circuits via a superconducting link.
5. Use one EE system per circuit, located near the converter.

Example for N=5

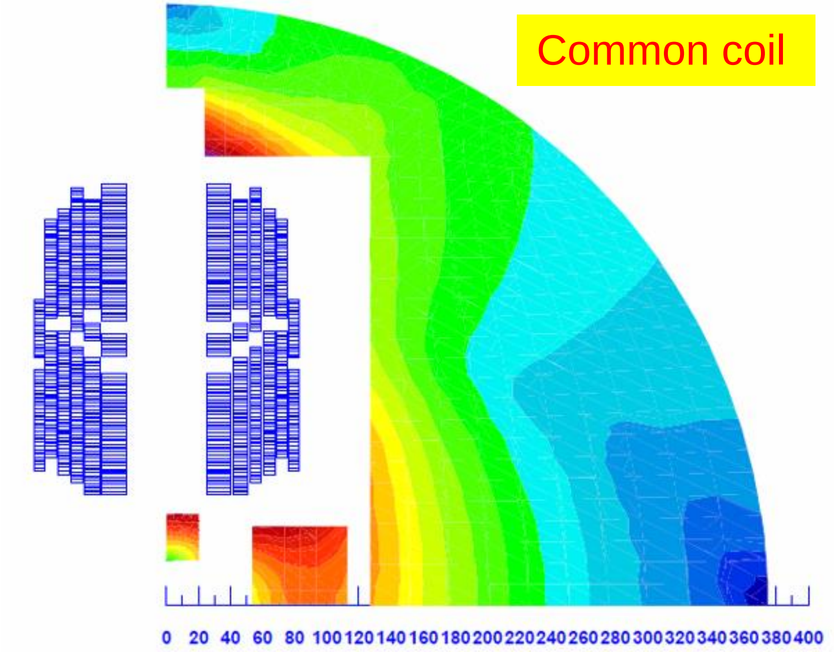


# FCC magnet designs

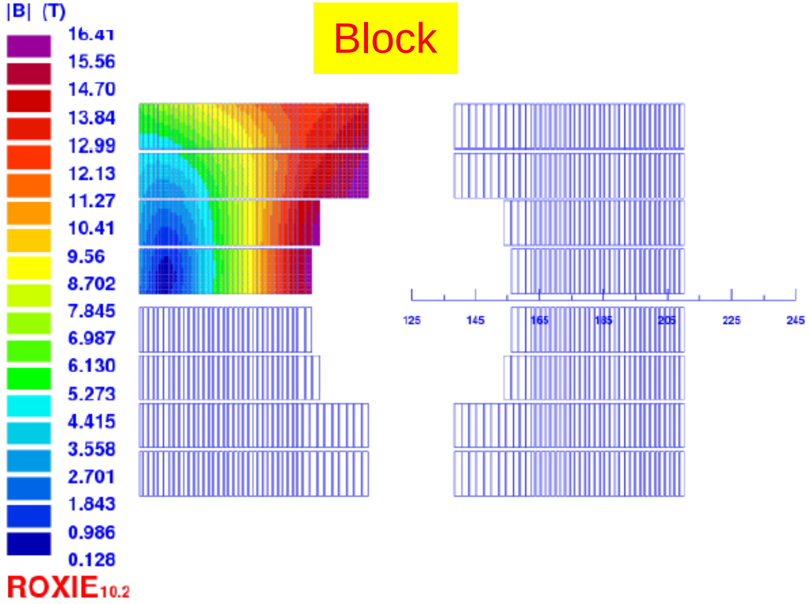
Cos-θ



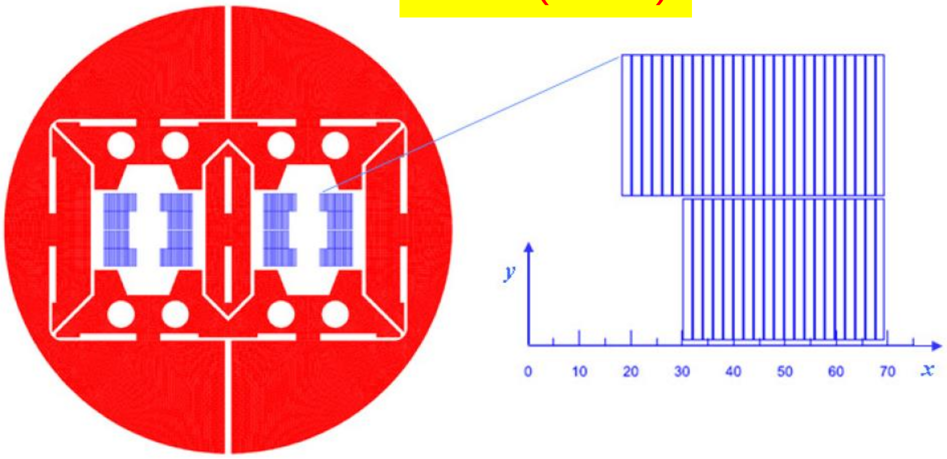
Common coil



Block



Block (LBNL)



# FCC magnet designs ($B_{nom}$=16 T, 14.3 m)

**50 mm** aperture
**~82%** on loadline at 1.9 K
$J_c$=1500 A/mm$^2$ at 16 T, 4.2 K

**60 mm** aperture
**90%** on loadline at 1.9 K
$J_c$=1500 A/mm$^2$ at 16 T, 4.2 K

| Description | Cos-θ [1] | Block [2] | Common Coil [3] | Block - LBNL [4] | Units |
|---|---|---|---|---|---|
| Nr of turns per aperture | 230 | 306 | 394 [5] | 92 | - |
| Current @ nominal field | 10.275 | 8.47 | 9.03 | 25.8 | [kA] |
| Inductance (double aperture) | 734 | 1264 | 1824 | 120 | [mH] |
| Stored energy at nominal (double aperture) | 39 | 45 | 74 | 40 | [MJ] |

[1] G. Bellomo, P. Fabbricatore, S. Farinon, V. Marinozzi, M. Sorbi, G. Volpini, INFN, Version 28b-38 v5, Minutes EuroCirCol WP 5 meetings.
[2] C. Lorin, M. Dunante, CEA/IRFU, Version v26cmag, Minutes EuroCirCol WP 5 meetings
[3] T. Martinez, J. Munilla, F. Toral, CIEMAT, Version v1h_intgrad, Minutes EuroCirCol WP 5 meetings.
[4] G.L. Sabbi et al, "Design study of a 16 T Block-Dipole for FCC", EUCAS 2015.
[5] Total for a double aperture divided by 2

# Assuming 2x larger stored energy with same current

**Same:**

- cable
- circuit
- ramp time
- nr of EE systems ($N_{EE}$)
- $V_{FPA,max}$

| | **Circuit powering** |
|---|---|
| $L_{circ}$ | 2x larger |
| $V_{PC}$ | 2x larger |
| $P_{PC}$ | 2x larger |
| $A_{warm\text{-}leads}$ | equal |
| $A_{current\text{-}leads}$ | equal |

**High priority: Minimize stored energy**

| | **Magnet protection** |
|---|---|
| $L_M$ | 2x larger |
| MIIts | larger |
| $V_{Q,max}$ | larger |
| $T_{hot}$ | larger |

⇒ More copper in cable

| | **Circuit protection** |
|---|---|
| $E_{circ}$ | 2x larger |
| $\tau_{circ}$ | 2x larger |
| $A_{busbar}$ | √2x larger |
| $Q_{diode}$ | 2x larger |
| EE switch | equal |
| EE dump | 2x larger |

⇒ Increase nr of circuits or number of EE systems

# Assuming 2x larger cable (half number of turns) with same stored energy

**Same:**

- circuit
- ramp time
- nr of EE systems ($N_{EE}$)
- $V_{FPA,max}$

| | Magnet protection |
|---|---|
| $L_M$ | 4x smaller |
| MIIts | 4x larger |
| $V_{Q,max}$ | smaller |
| $T_{hot}$ | equal |

| | Circuit powering |
|---|---|
| $I_{nom}$ | 2x larger |
| $L_{circ}$ | 4x smaller |
| $V_{PC}$ | 2x smaller |
| $P_{PC}$ | equal |
| $A_{warm\text{-}leads}$ | larger |
| $A_{current\text{-}leads}$ | larger |

| | Circuit protection |
|---|---|
| $E_{circ}$ | equal |
| $\tau_{circ}$ | 2x smaller |
| $A_{busbar}$ | $\sqrt{2}$x larger |
| $Q_{diode}$ | equal |
| EE switch | 2x higher current rating |
| EE dump | equal |

**Not obvious what is preferable:**

**Low-$I_{nom}$ & High-$L_M$ versus High-$I_{nom}$ & Low-$L_M$**

# Are there hard limits for the magnet design?

A string of magnets can ***always*** be protected, for any magnet design and given constraints (voltage withstand level, $\tau_{\mathrm{circ}}$, …), by adapting the number of circuits, so by subdividing a powering sector in multiple circuits.

**Magnet powering:**

| | |
|---|---|
| Trade-off between: | Number of circuits |
| | Converter voltage rating ($V_{\mathrm{PC}}$) |
| | Ramp time ($t_{\mathrm{ramp}}$) |

**Circuit protection**

| | |
|---|---|
| Trade-off between: | Number of circuits |
| | $\tau_{\mathrm{circ}}$ (busbar & diode size & quench propagation) |
| | $V_{\mathrm{FPA,max}}$ |

# Layouts for the EuroCirCol Cos-$\theta$ design

| **Nr of circuits per half-arc** | **1** | **2** | **3** | **4** | **4** | **8** |
|---|---|---|---|---|---|---|
| Nr of circuits entire FCC | 20 | 40 | 60 | 80 | 80 | 160 |
| Magnets per circuit | 215 | 113 | 72 | 54 | 54 | 27 |
| Inductance per circuit [H] | 158 | 79 | 53 | 39 | 39 | 20 |
| Stored energy per circuit [GJ] | 8.3 | 4.2 | 2.8 | 2.1 | 2.1 | 1.1 |
| Ramp time [min] | 20 | 20 | 20 | 20 | 20 | 20 |
| $V_{PC}$ [V] | 1350 | 676 | 450 | 338 | 338 | 169 |
| | | | | | | |
| $V_{FPA,max}$ [kV] | 1 | 1 | 1 | 1 | 0.5 | 0.5 |
| $V_{FPA,max,fault}$ [kV] | 3.3 | 2.6 | 2.4 | 2.3 | 1.3 | 1.2 |
| $\tau_{circ}$ [s] | 810 | 405 | 270 | 203 | 405 | 203 |
| $A_{busbar}$ [mm$^2$] | 539 | 387 | 316 | 273 | 387 | 273 |
| $Q_{diode}$ [MJ] | 8.3 | 4.2 | 2.8 | 2.1 | 4.2 | 2.1 |

# Layouts for the EuroCirCol Block design

| **Nr of circuits per half-arc** | **1** | **2** | **4** | **6** | **6** | **12** |
|---|---|---|---|---|---|---|
| Nr of circuits entire FCC | 20 | 40 | 80 | 120 | 120 | 240 |
| Magnets per circuit | 215 | 108 | 54 | 36 | 36 | 18 |
| Inductance per circuit [H] | 272 | 136 | 68 | 45 | 45 | 23 |
| Stored energy per circuit [GJ] | 9.7 | 4.9 | 2.4 | 1.6 | 1.6 | 0.8 |
| Ramp time [min] | 20 | 20 | 20 | 20 | 20 | 20 |
| $V_{PC}$ [V] | 1920 | 960 | 480 | 320 | 320 | 160 |
| | | | | | | |
| $V_{FPA,max}$ [kV] | 1 | 1 | 1 | 1 | 0.5 | 0.5 |
| $V_{FPA,max,fault}$ [kV] | 3.3 | 2.6 | 2.3 | 2.2 | 1.2 | 1.1 |
| $\tau_{circ}$ [s] | 1150 | 575 | 288 | 192 | 384 | 192 |
| $A_{busbar}$ [mm$^2$] | 538 | 380 | 269 | 220 | 310 | 220 |
| $Q_{diode}$ [MJ] | 9.7 | 4.9 | 2.4 | 1.6 | 3.2 | 1.6 |

# Layouts for the EuroCirCol Common coil design

| **Nr of circuits per half-arc** | **1** | **4** | **6** | **8** | **8** | **12** |
|---|---|---|---|---|---|---|
| Nr of circuits entire FCC | 20 | 80 | 120 | 160 | 160 | 240 |
| Magnets per circuit | 215 | 54 | 36 | 27 | 27 | 18 |
| Inductance per circuit [H] | 392 | 98 | 65 | 49 | 49 | 33 |
| Stored energy per circuit [GJ] | 16 | 4 | 2.7 | 2 | 2 | 1.3 |
| Ramp time [min] | 20 | 20 | 20 | 20 | 20 | 20 |
| $V_{PC}$ [V] | 2950 | 740 | 492 | 370 | 370 | 246 |
| | | | | | | |
| $V_{FPA,max}$ [kV] | 1 | 1 | 1 | 1 | 0.5 | 0.5 |
| $V_{FPA,max,fault}$ [kV] | 3.3 | 2.3 | 2.2 | 2.2 | 1.2 | 1.1 |
| $\tau_{circ}$ [s] | 1770 | 443 | 295 | 221 | 443 | 295 |
| $A_{busbar}$ [mm$^2$] | 710 | 355 | 290 | 251 | 355 | 290 |
| $Q_{diode}$ [MJ] | 16 | 4 | 2.7 | 2 | 4 | 2.7 |

# Layouts for the LBNL Block design

| **Nr of circuits per half-arc** | **1** | **2** | **3** | **4** | **4** | **8** |
|---|---|---|---|---|---|---|
| Nr of circuits entire FCC | 20 | 40 | 60 | 80 | 80 | 160 |
| Magnets per circuit | 215 | 108 | 72 | 54 | 54 | 27 |
| Inductance per circuit [H] | 26 | 13 | 8.6 | 6.5 | 6.5 | 3.2 |
| Stored energy per circuit [GJ] | 8.6 | 4.3 | 2.9 | 2.1 | 2.1 | 1.1 |
| Ramp time [min] | 20 | 20 | 20 | 20 | 20 | 20 |
| $V_{PC}$ [V] | 555 | 277 | 185 | 139 | 139 | 69 |
| | | | | | | |
| $V_{FPA,max}$ [kV] | 1 | 1 | 1 | 1 | 0.5 | 0.5 |
| $V_{FPA,max,fault}$ [kV] | 3.3 | 2.6 | 2.4 | 2.3 | 1.3 | 1.2 |
| $\tau_{circ}$ [s] | 333 | 166 | 111 | 83 | 166 | 83 |
| $A_{busbar}$ [mm$^2$] | 880 | 622 | 508 | 440 | 622 | 440 |
| $Q_{diode}$ [MJ] | 8.6 | 4.3 | 2.9 | 2.1 | 4.3 | 2.1 |

# Conclusion 1/2

- Magnet designers should try to minimize the stored energy. ***Cos-$\theta$*** and ***block*** designs have clear advantages as compared to the ***common-coil*** design.
- Subdivision of a 4 km long half-arc in several dipole circuits seems the most feasible solution for proper circuit protection within the required constraints, while at the same time having all converters and EE systems at the access points (using a SC link).
- Assuming $t_{ramp}$=20 min, $V_{FPA,max}$=1 kV, $\tau_{circ}$≈200 s, gives:

| | **Cos-θ** | **Block** | **Common coil** | **LBNL block** |
|---|---|---|---|---|
| **Nominal current [kA]** | 10.275 | 8.47 | 9.03 | 25.8 |
| **Nr of circuits** | 80 | 120 | 160 | 40 |

Changing $t_{ramp}$ (10-30 min) affects the rating of the converters ($V_{PC}$ and $P_{PC}$) but not the number of circuits.

# Conclusion 2/2

- High voltage withstand levels of the circuits and all its components are needed to reduce the number of circuits and hence reduce the complexity of the layout.

- High-current low-inductance magnets are favourable in terms of quench voltage and number of circuits, which seem to outweigh the drawbacks (larger busbars, larger diode heat sink, larger current rating for the converters and current leads).

- I suggest to design several cos-$\theta$ and block dipoles with the usual EuroCirCol requirements, but with $I_{nom}$=15-25 kA.

- The possibility of independent powering of the dipole apertures, each in series with a RQD/F circuit, should be explored from optics point-of-view. This might significantly reduce the number of busbars, power converters, DFB's, and current leads.