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

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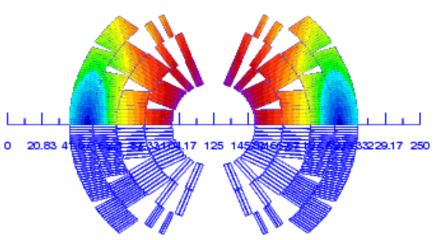
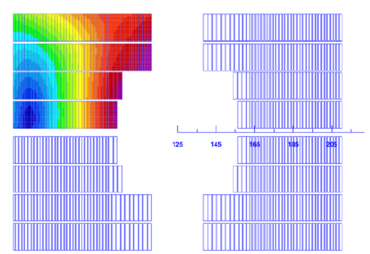
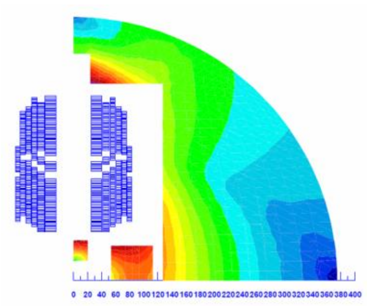
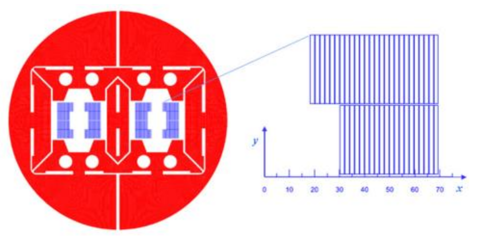








Reminder

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.

$\Rightarrow$ Circuit protection is extremely important

Intro

The FCC main dipole magnets have to be powered in strings, so:

- the magnet design has an impact on the protection and configuration of the string,
- the string layout has an impact on the magnet requirements.

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

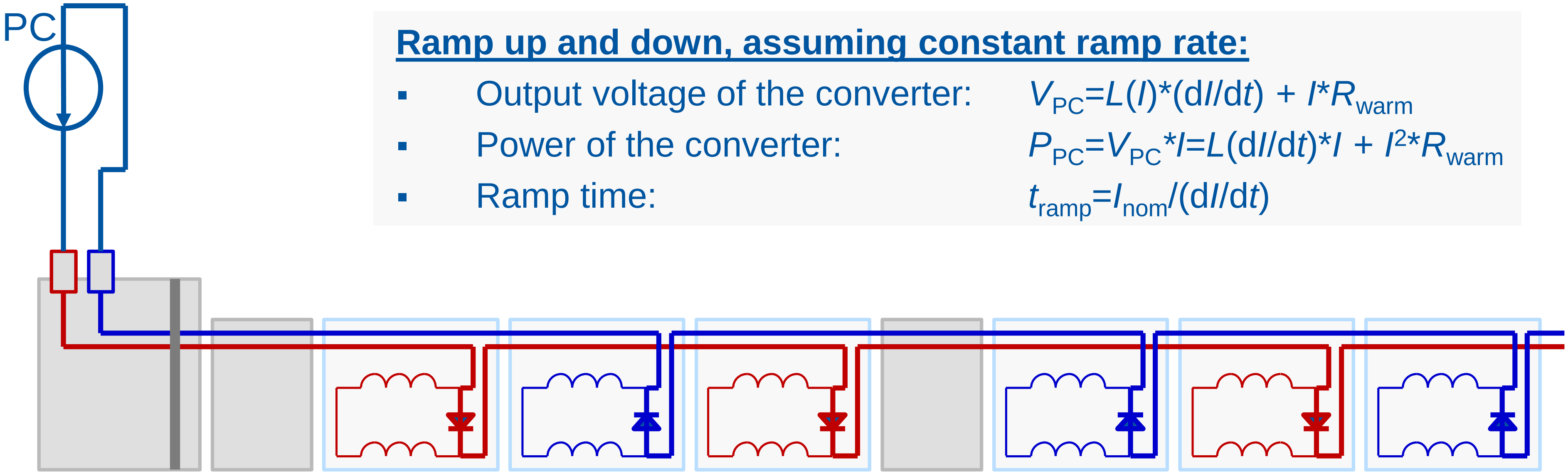
- **Cos-θ**, INFN, EuroCirCol collaboration
- **Block**, CEA, EuroCirCol collaboration
- **Common coil**, CIEMAT, EuroCirCol collaboration
- **Block**, LBNL

Quench protection of the magnet itself (characterised by the hot-spot temperature, voltage-to-ground, thermal gradients) is not discussed here.

(see presention T. Salmi).

Recap: Powering of the LHC dipole circuits

The 154 twin-aperture magnets in each of the 8 sectors of the LHC 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:

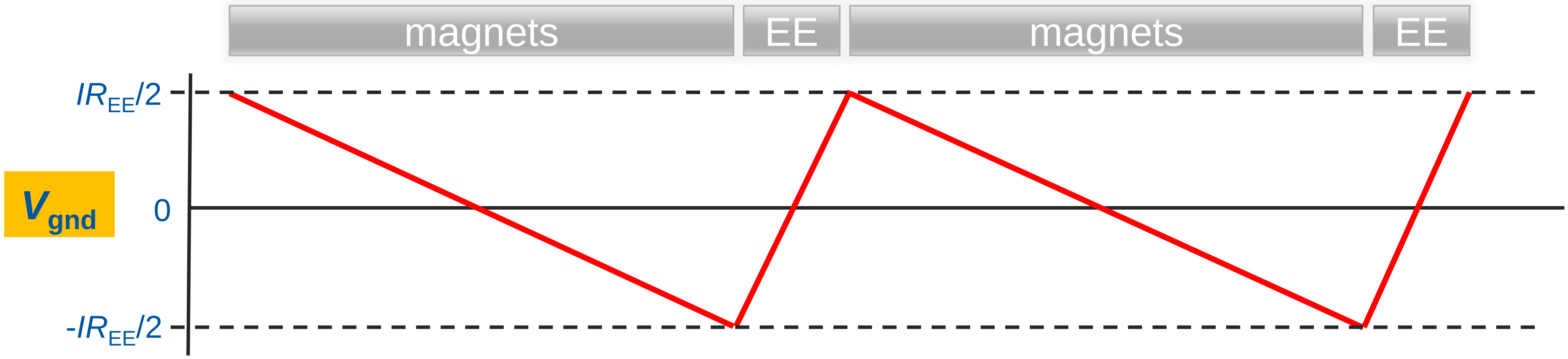
- Output voltage of the converter: $V_{PC}=L(I)*(dI/dt) + I*R_{warm}$
- Power of the converter: $P_{PC}=V_{PC}*I=L(dI/dt)*I + I^2*R_{warm}$
- Ramp time: $t_{ramp}=I_{nom}/(dI/dt)$

Two room-temperature energy-extraction (**EE**) systems, each with a switch and a 75 mΩ resistor (***R*$_{EE}$**) are present, to ensure a sufficiently fast decay of the circuit current (τ=100 s) in case of a Fast Power Abort (**FPA**) triggered by a quench/trip.

Diodes and (possibly non-SC) busbars therefore have to withstand this current decay.

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 $\boldsymbol{\tau_{circ}}=L_{circ}/(N_{EE}*R_{EE})$,



Required voltage withstand level

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

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

$V_{Q,max}$ 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 $V_{Q,max}$.
- An ***intermittent short (before the circuit fuse blows)*** could give:

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

(private comm. E. Ravaioli)

N_{mag}: the number of magnets in the circuit

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

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

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

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

Powering of the FCC dipole circuits

An “LHC-type” powering seems also for the FCC the best configuration.

However, some modifications could be envisaged:

- Independent powering of the two apertures.
- Powering of dipoles and quadrupoles in series.
- More than one circuit per sector.
- Different number of EE systems per circuit.
- Cold EE systems.
- Cold EE switches (persistent mode).
- More than one diode per magnet.

The diode by-pass should preferably also cover the magnet-to-magnet busbar to avoid a ‘2008-like accident’.

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.

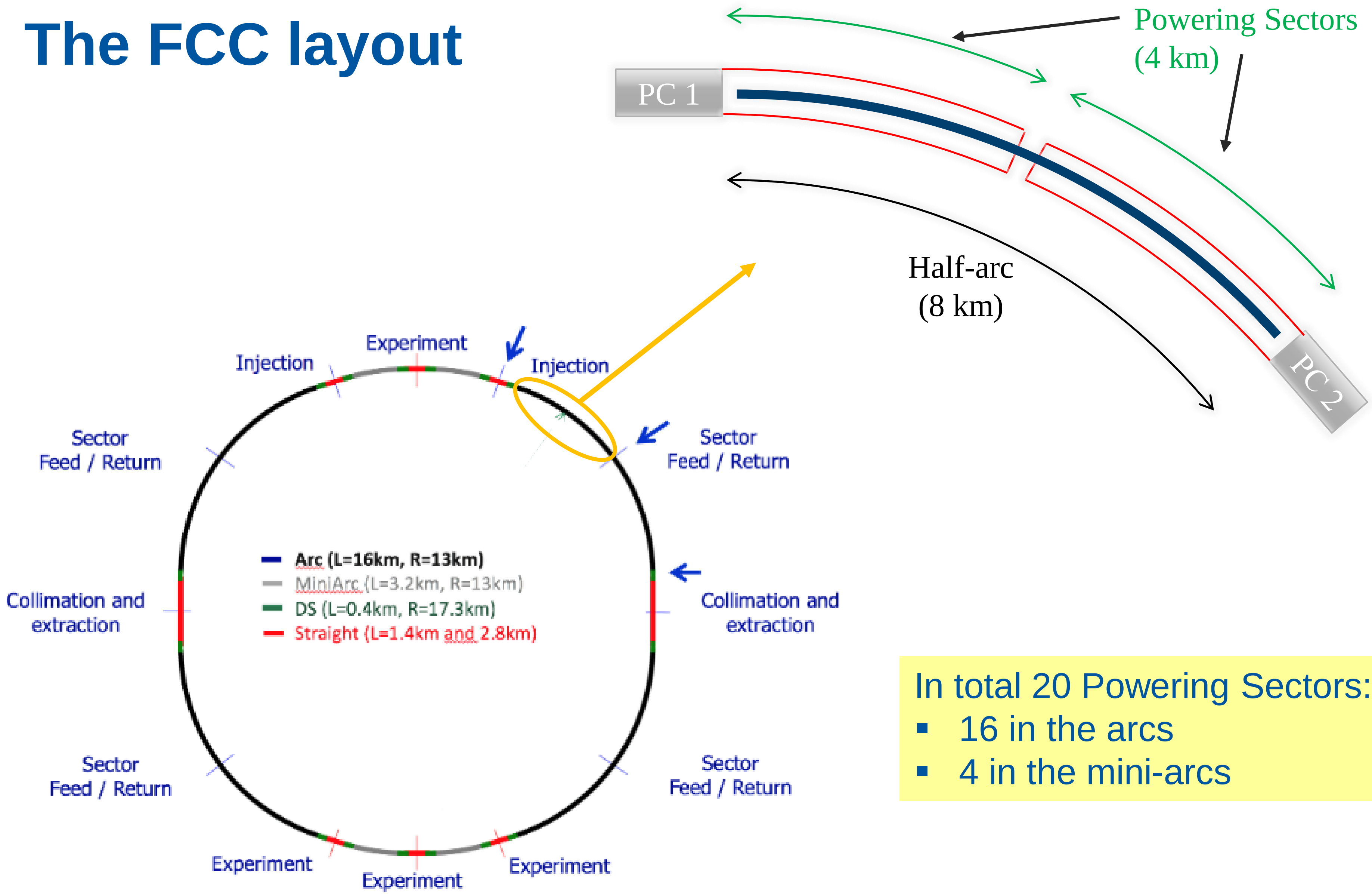
For a circuit, one would like to reduce:

- **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
- **τ_{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

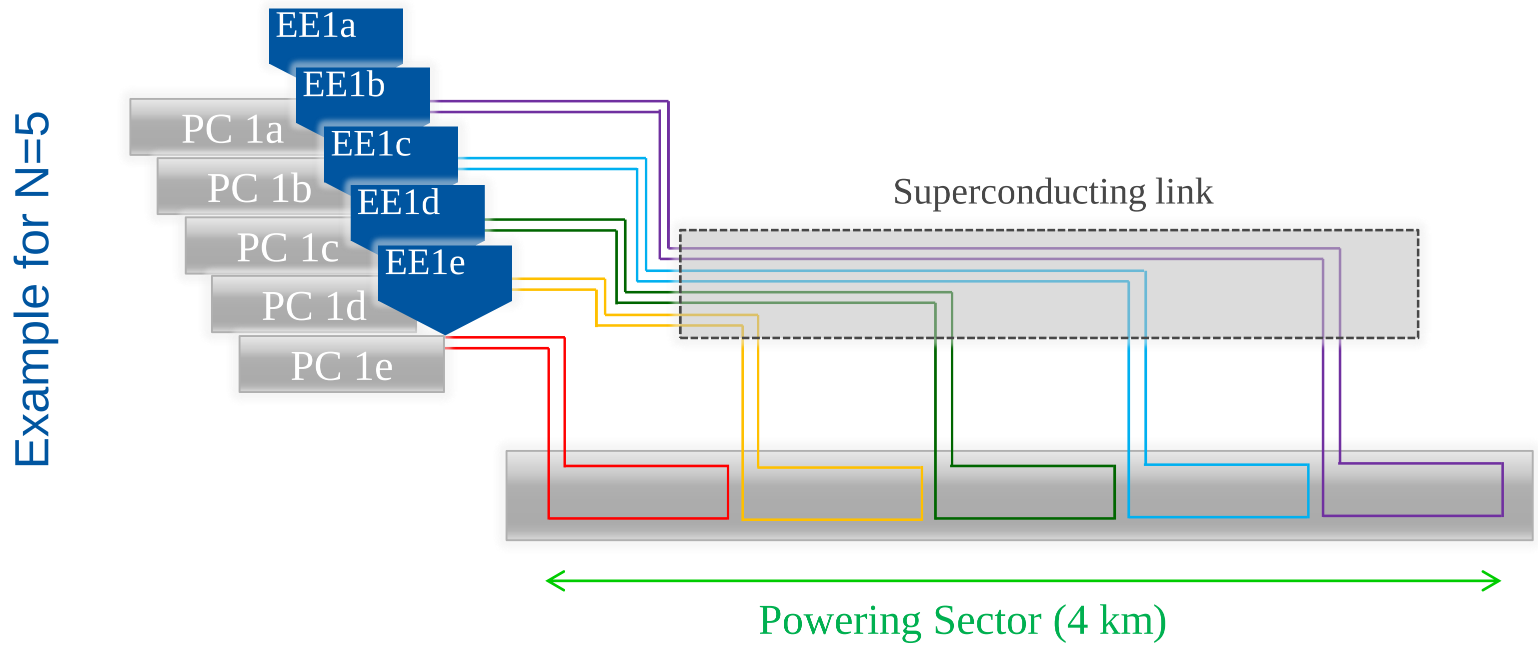


In total 20 Powering Sectors:

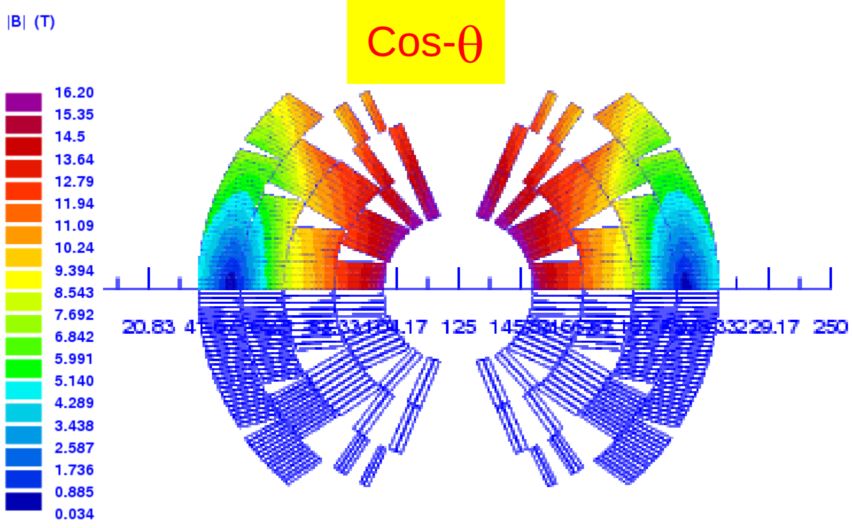
- 16 in the arcs
- 4 in the mini-arcs

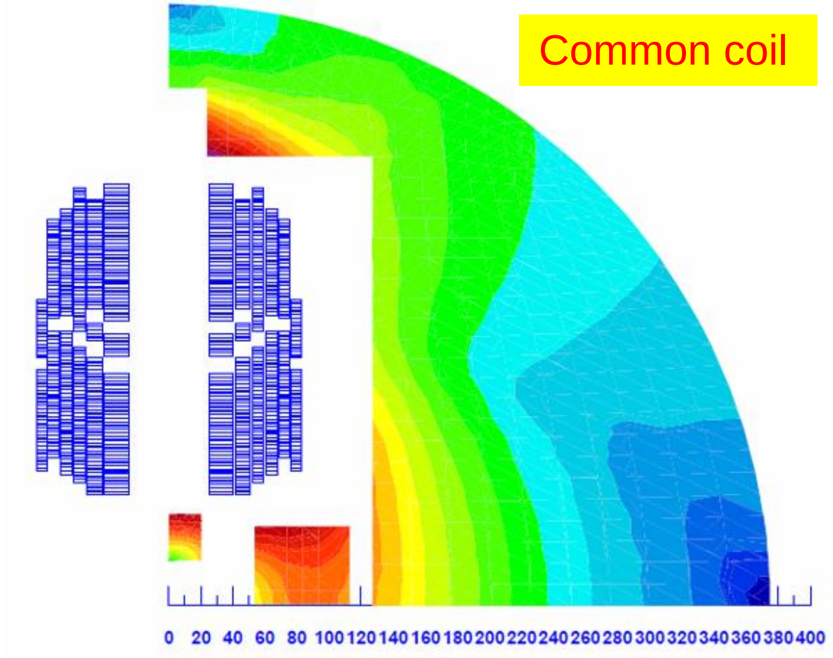
Strategy for circuit configuration

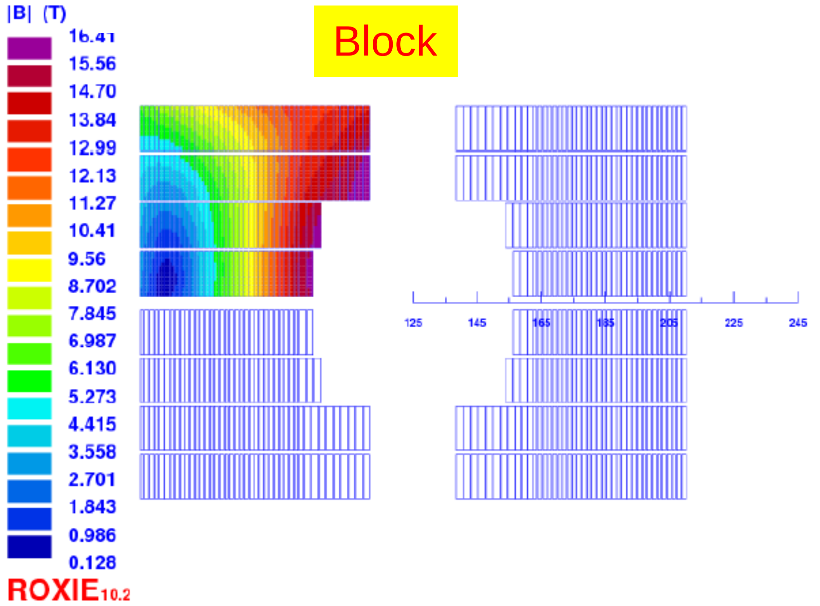
1. Locate power converters and EE systems in the access points.
2. Subdivide each Powering Sector in N circuits $\Rightarrow$ 20N circuits for the entire machine
3. Power both apertures of the dipoles in series, independently from the quads.
4. Power the circuits via a superconducting link.
5. Use one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

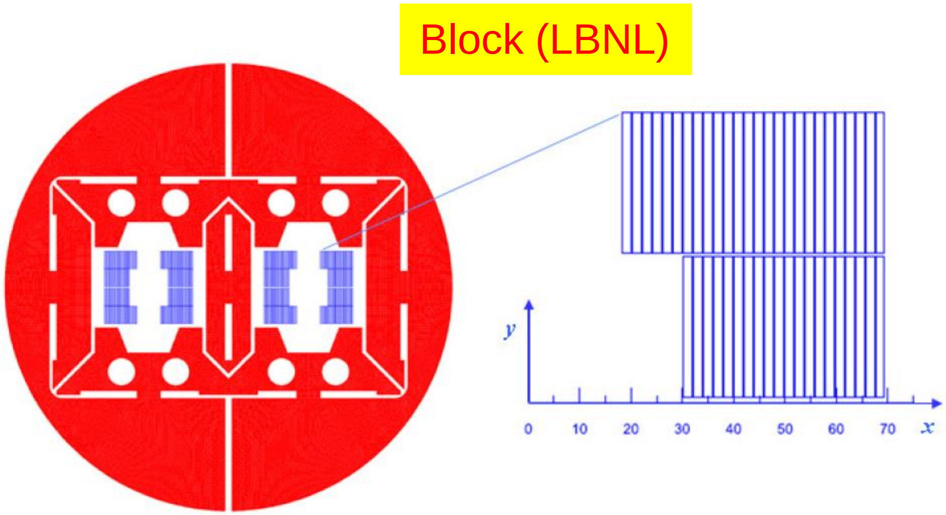


FCC magnet designs









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
τ_{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

Stored energy vs. Cost and Availability

Two remarks:

1. Assuming 200 GJ (about 40 MJ/magnet) and a ramp time of 20 min, requires an ***average*** power consumption during ramping of 170 MW (+losses due to converter efficiency and warm busbars). Increasing the stored energy has a huge cost! Reducing the ramp time has a large impact on availability. (Ramping up/down in the LHC takes a few hrs per day)

2. Cryo recovery after a LHC dipole quench (7 MJ/magnet) takes about 10 hours. Any further increase in stored energy for the FCC will increase the cost for the cryogenic system or increase down-time of the machine.

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
$V_{Q,max}$	~2x 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
τ_{circ}	2x smaller
A_{busbar}	√2x 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, τ_{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_{PC})
Ramp time (t_{ramp})

Circuit protection

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

Layouts for the EuroCirCol Cos-θ 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
τ_{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

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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
τ_{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
τ_{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
τ_{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-θ*** and ***block*** designs have clear advantages as compared to the ***common-coil*** design. But recent design of common coil with aux. coils is much better.
- 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, τ_{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. Another advantage is ***shorter unit lengths***, hence increasing the production yield of the conductor.

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

Final remarks

- 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.

- Large τ_{circ} in combination with large magnet stored energy will result in significant magnet-to-magnet quench propagation, hence very long cryogenic recovery. Thermal magnet-to-magnet propagation and possibilities to cryogenically decouple the magnets should be studied. This might have an impact on the spacing between dipoles (hence integrated field).

- The tunnel layout should foresee space for an additional cryo link to power the circuits.

- Connection from the link to the circuits should be studied, as this might also affect the spacing between the dipoles.