FUTURE
CIRCULAR
COLLIDER

FCC Week 2022
30 May 2022 to 3 June 2022
Université Sorbonne, Paris

POWER CONVERTERS R&D
–
FROM DC DISTRIBUTION TO ENERGY STORAGE SYSTEMS

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J. Bauche, CERN Magnet Group
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J.-P. Burnet, CERN Acc. Deputy Systems Dept. Head

Outline

FCC-ee Power Converter DRAFT layout

Evaluating DC Distribution

FCC-hh powering specificities

Conclusion

FCC-EE POWER CONVERTER DRAFT LAYOUT

FCCee power converters DRAFT layout

A first attempt

- The Power Converter Group at CERN will start optimizing the powering layout at the end of this year
- However, a draft, non-optimal baseline is needed to provide starting point numbers for losses and volumes to other working groups

→ Decided to propose first draft layout based on our group’s expertise's

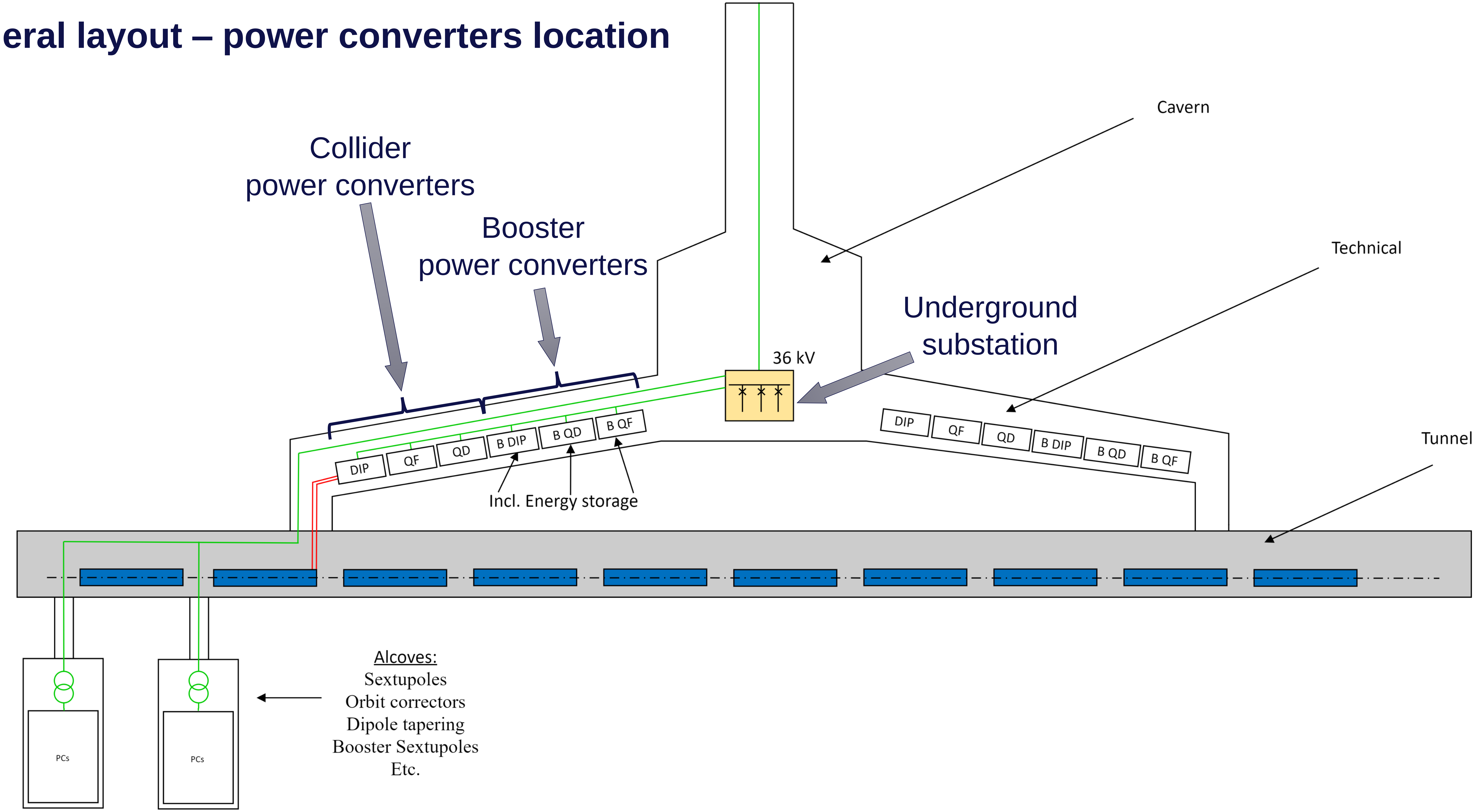
DISCLAIMER

In the following slides, numbers are draft/preliminary!

First non-optimized attempt

FCCee power converters DRAFT layout

General layout – power converters location



Alcoves:
Sextupoles
Orbit correctors
Dipole tapering
Booster Sextupoles
Etc.

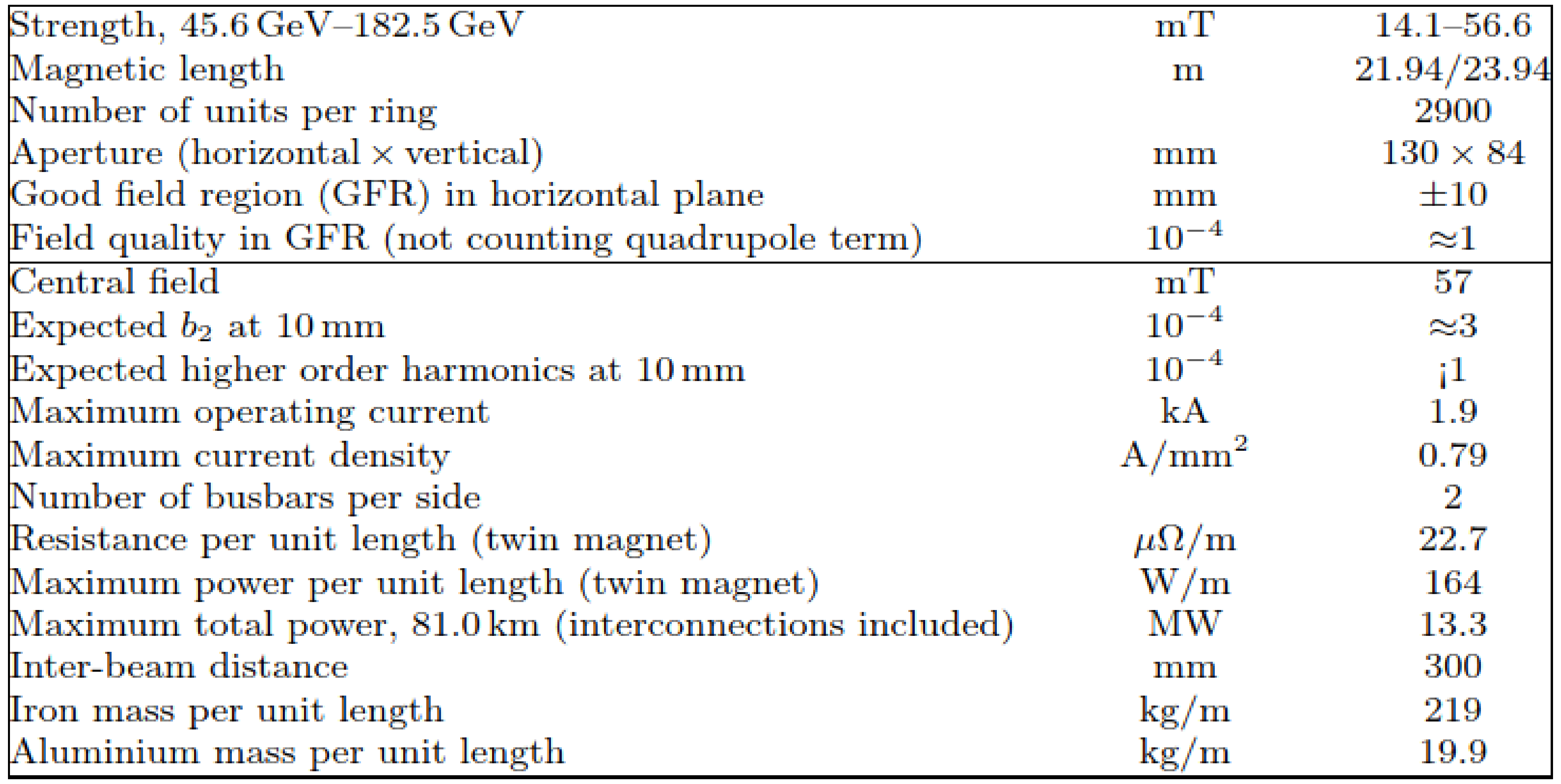
FCCee power converters DRAFT layout

Collider’s Dipoles – Underground service gallery

	Value	Unit
Converters/circuits number per power sector	2	-
Resistance per circuit	50	mΩ
Current per circuit (1 turn magnet)	3.8	kA
Voltage per circuit	189	V
Nominal power	717	kW
Converter dimensioning power (250V, 3.8 kA)	950	kW
Converter footprint requirement (1 unit)	**~45**	**m²**
Converter’s losses	10	%
Converter losses in water	**~85**	**kW**
Converter losses in air	**~10**	**kW**
DC cable distance per circuit (4 x 400 mm²/ pole)	50	m
DC cable losses per circuit	**~18.8**	**kW**

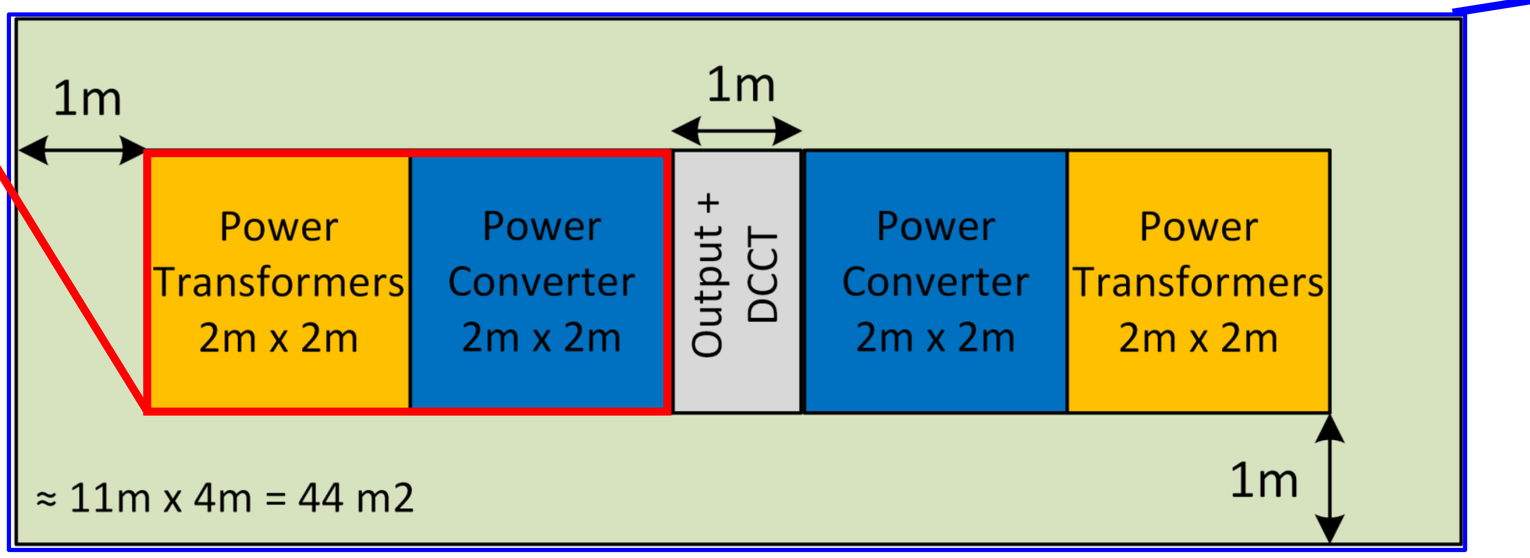
Draft numbers!

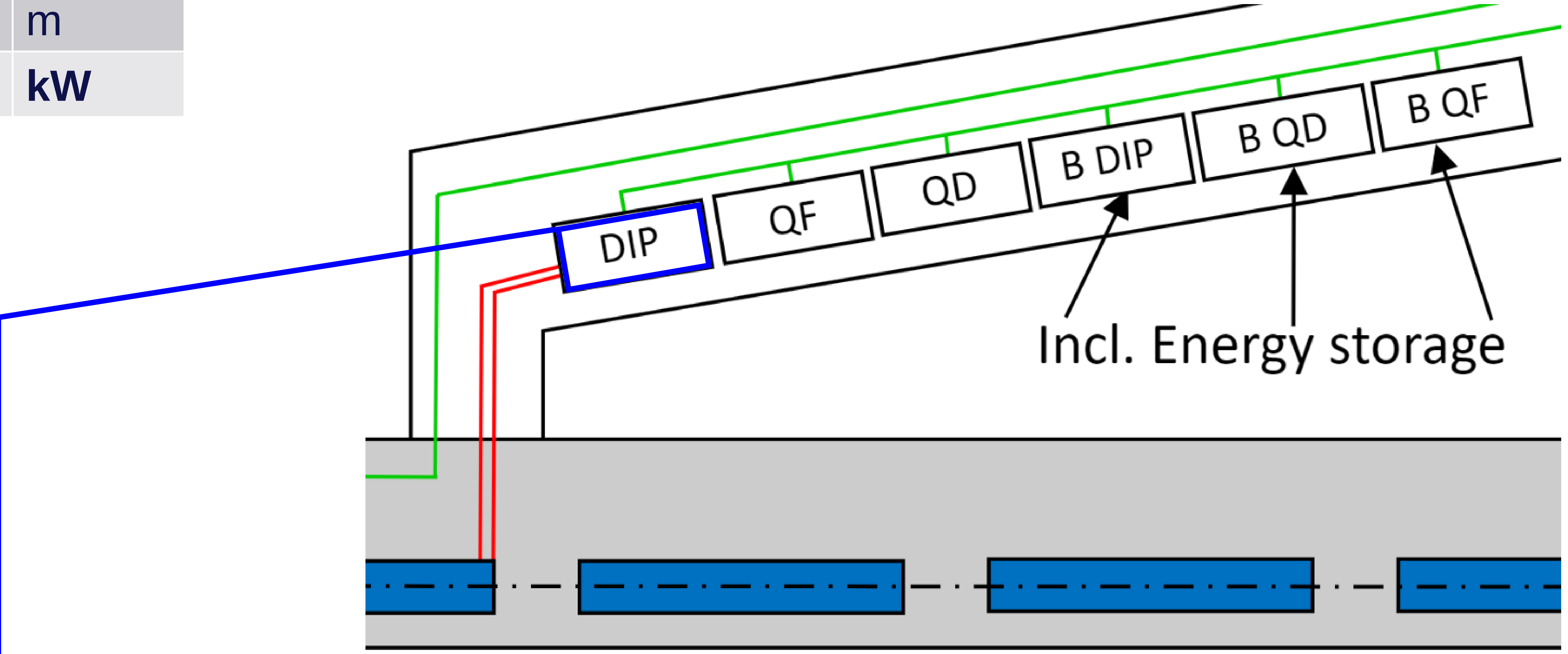
Dipole magnet specifications from CDR



Strength, 45.6 GeV–182.5 GeV	mT	14.1–56.6
Magnetic length	m	21.94/23.94
Number of units per ring		2900
Aperture (horizontal × vertical)	mm	130 × 84
Good field region (GFR) in horizontal plane	mm	±10
Field quality in GFR (not counting quadrupole term)	10^{-4}	≈1
Central field	mT	57
Expected b_2 at 10 mm	10^{-4}	≈3
Expected higher order harmonics at 10 mm	10^{-4}	¡1
Maximum operating current	kA	1.9
Maximum current density	A/mm²	0.79
Number of busbars per side		2
Resistance per unit length (twin magnet)	μΩ/m	22.7
Maximum power per unit length (twin magnet)	W/m	164
Maximum total power, 81.0 km (interconnections included)	MW	13.3
Inter-beam distance	mm	300
Iron mass per unit length	kg/m	219
Aluminium mass per unit length	kg/m	19.9

Estimated converter footprint





FCCee power converters DRAFT layout

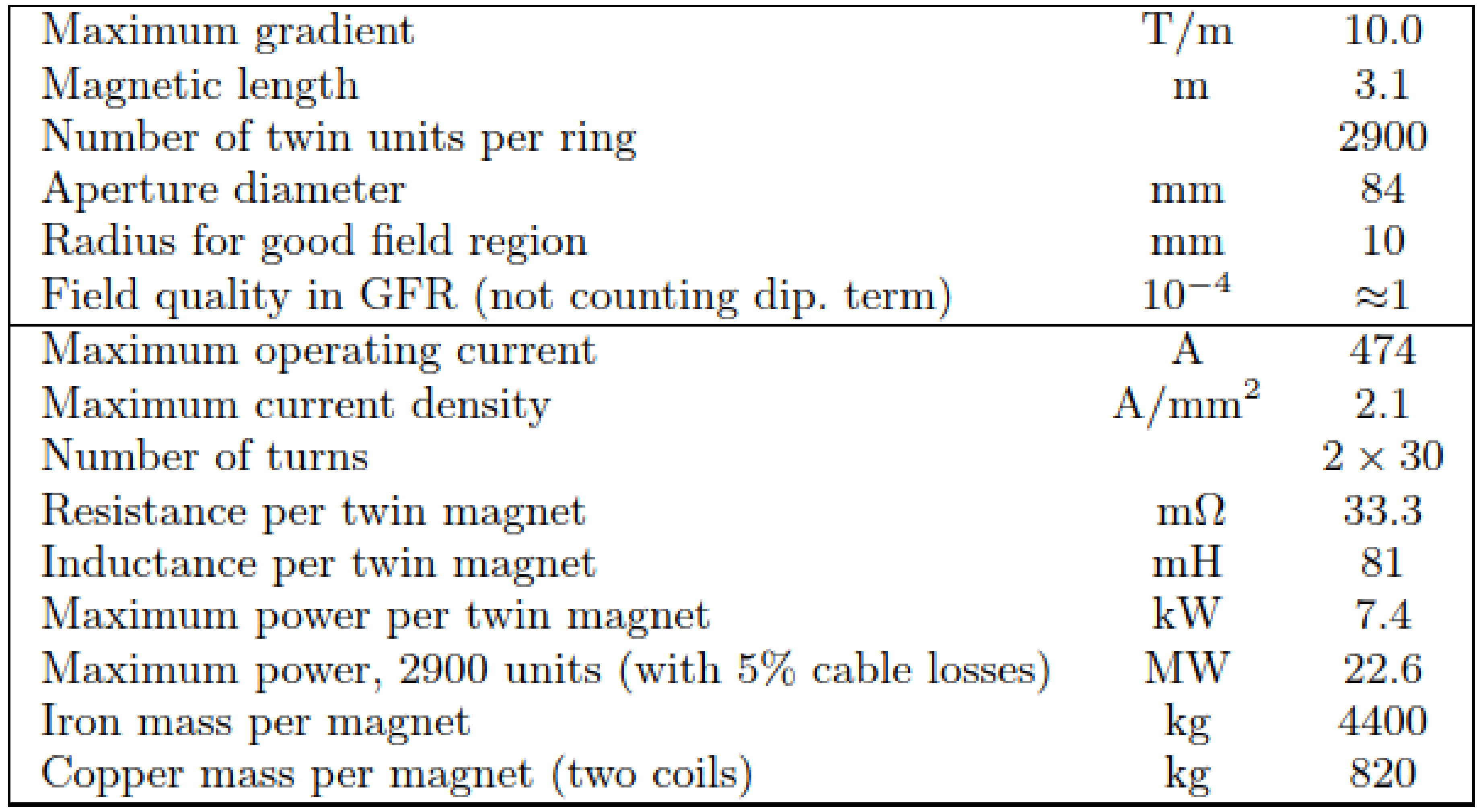
Collider's Quadrupoles – Underground service gallery

	Value	Unit
Converters/circuits number per power sector	4	-
Resistance per circuit	~3	Ω
Current per circuit (1 turn magnet)	474	A
Voltage per circuit	1430	V
Nominal power	680	kW
Converter dimensioning power (1500V, 500A)	750	kW
Converter footprint requirement (1 unit)	**~105**	**m^2**
Converter's losses	10	%
Converter losses in water	**~68**	**kW**
Converter losses in air	**~7**	**kW**
DC cable distance per circuit (2 x 150 mm^2/ pole) ⚠	11500	m
DC cable losses per circuit	**~178**	**kW**

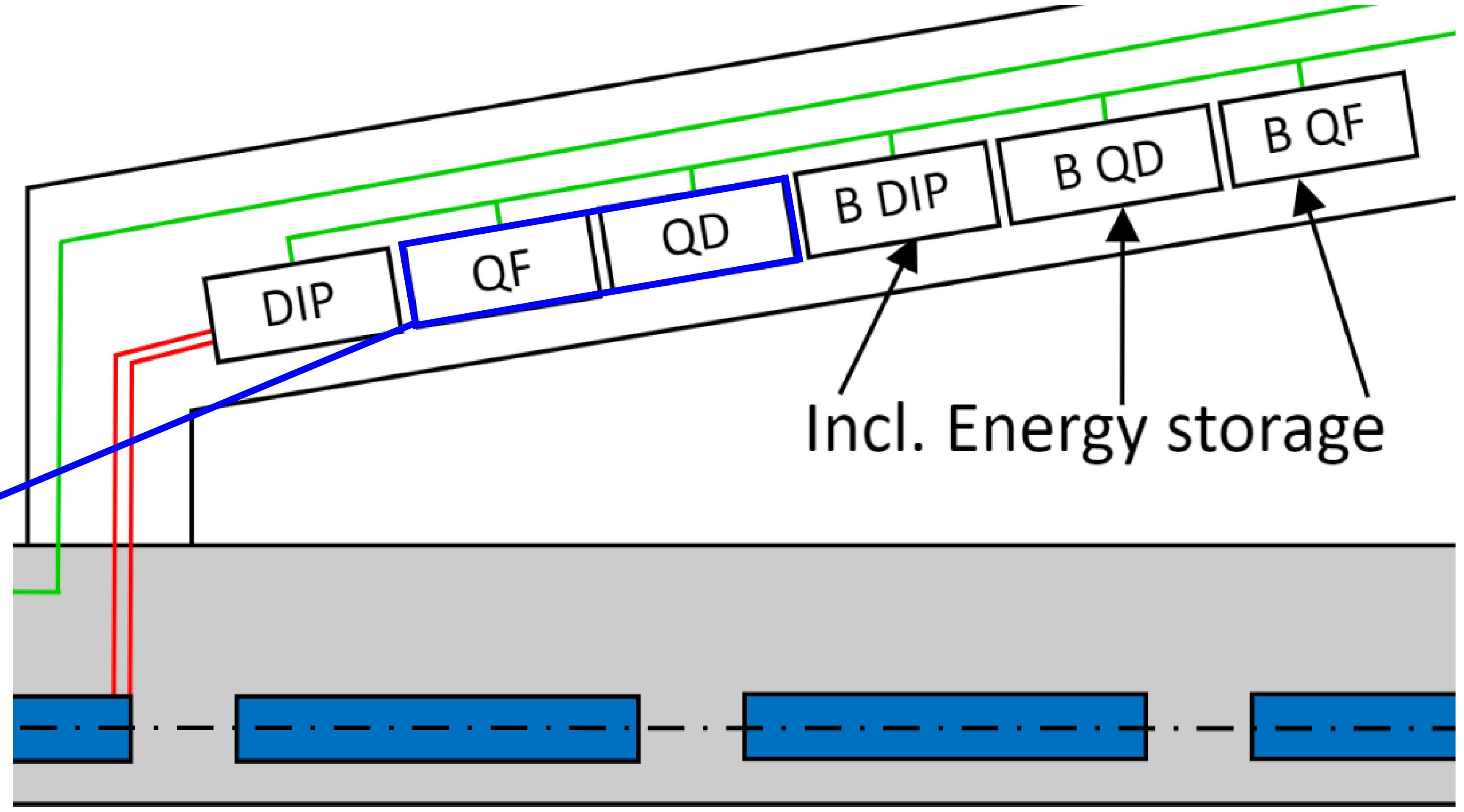
Draft numbers!

NOTE: Cable resistance not considered for the power converter dimensioning as optimization with magnet design is required

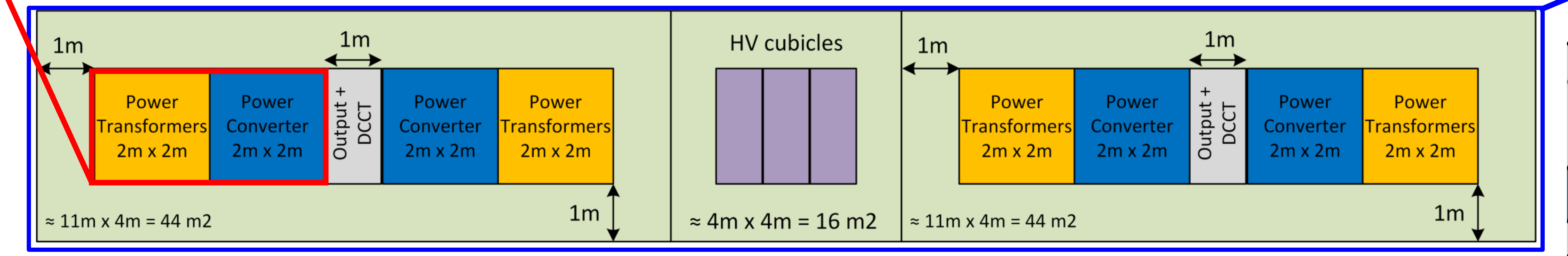
Quadrupole magnet specifications from CDR



Maximum gradient	T/m	10.0
Magnetic length	m	3.1
Number of twin units per ring		2900
Aperture diameter	mm	84
Radius for good field region	mm	10
Field quality in GFR (not counting dip. term)	10^{-4}	≈1
Maximum operating current	A	474
Maximum current density	A/mm^2	2.1
Number of turns		2 × 30
Resistance per twin magnet	mΩ	33.3
Inductance per twin magnet	mH	81
Maximum power per twin magnet	kW	7.4
Maximum power, 2900 units (with 5% cable losses)	MW	22.6
Iron mass per magnet	kg	4400
Copper mass per magnet (two coils)	kg	820



Estimated converter footprint



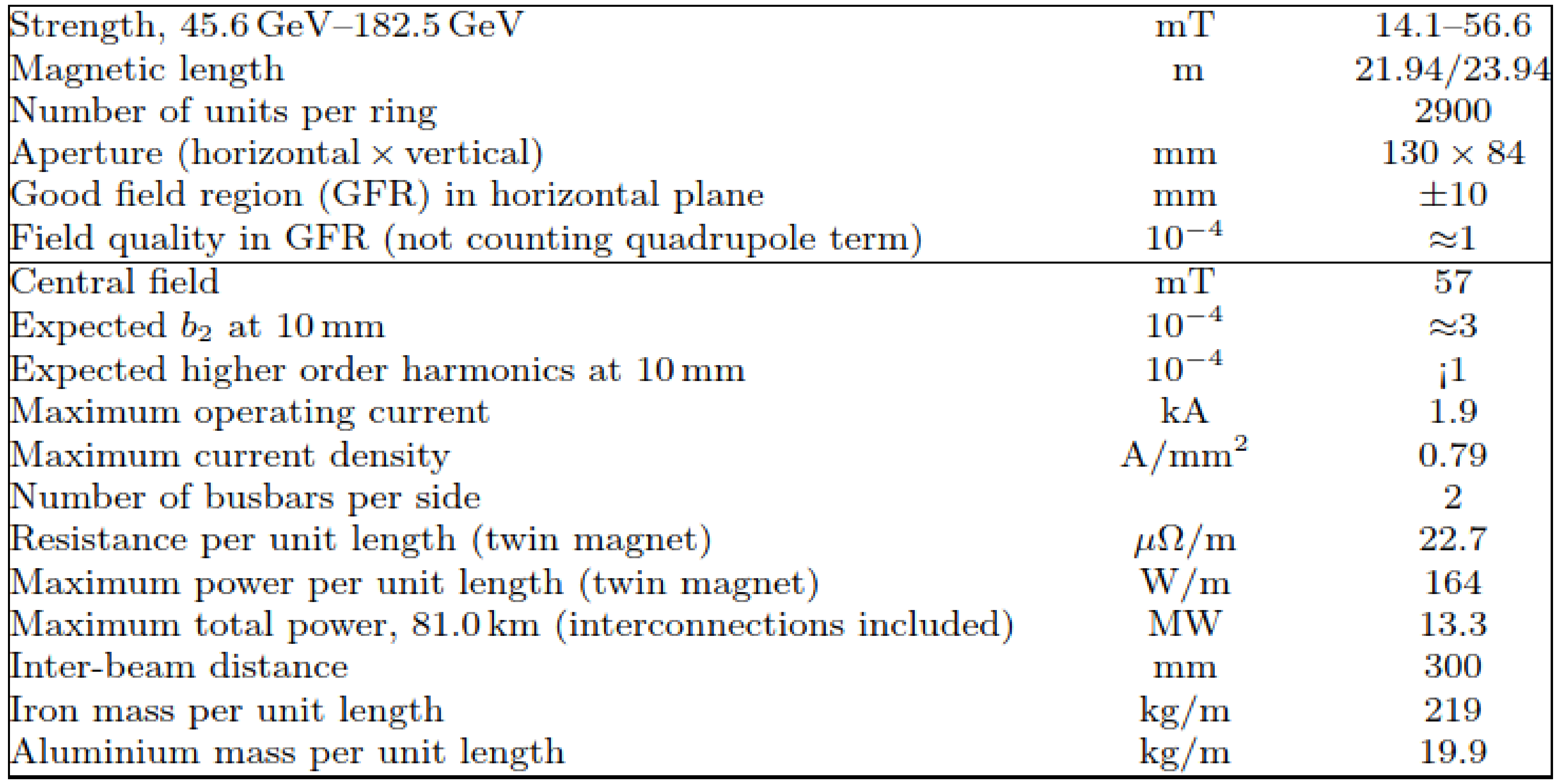
FCCee power converters DRAFT layout

Booster’s Dipoles – Underground service gallery

	Value	Unit
Converters/circuits number per power sector	2	-
Resistance per circuit	50	mΩ
Inductance per circuit	~160	mH
Current per circuit (1 turn magnet)	3.8	kA
Voltage per circuit	378	V
Nominal maximum power (selected converter: 400V, 3.8kA)	1436	kW
Magnet’s average consumption	260	kW
Converter footprint requirement (1 unit)	**~55**	**m²**
Converter’s losses	10	%
Converter losses in water	**~23**	**kW**
Converter losses in air	**~3**	**kW**
DC cable distance per circuit (4 x 400 mm²/ pole)	50	m
DC cable losses per circuit	**~10**	**kW**
Estimated energy storage (valid for Z and tt)	**~1**	**MJ**

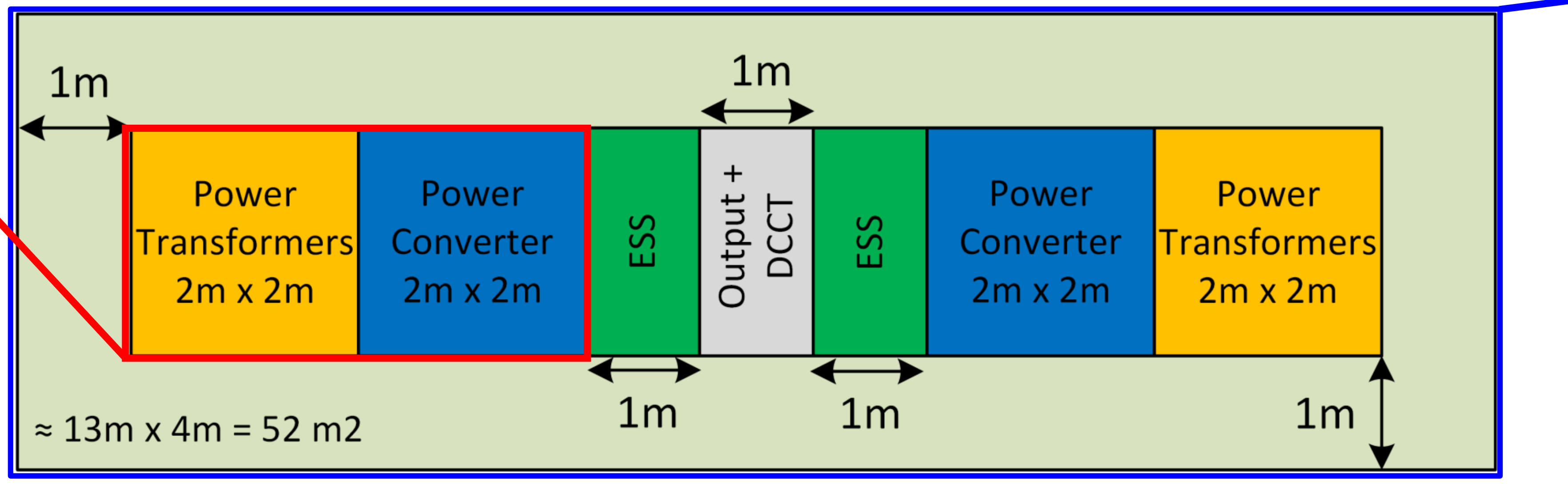
Draft numbers!

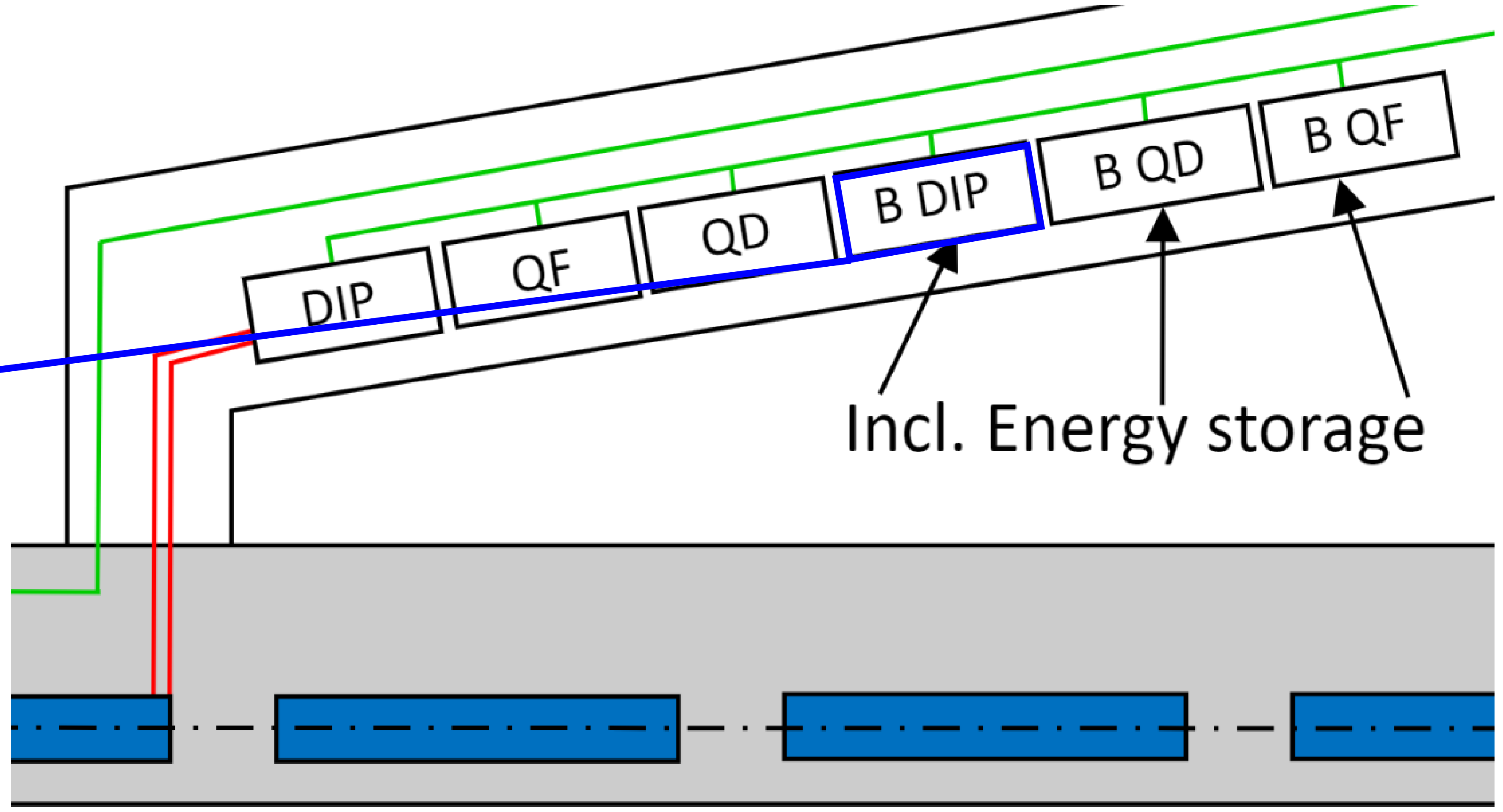
Dipole magnet specifications from CDR



Strength, 45.6 GeV–182.5 GeV	mT	14.1–56.6
Magnetic length	m	21.94/23.94
Number of units per ring		2900
Aperture (horizontal × vertical)	mm	130 × 84
Good field region (GFR) in horizontal plane	mm	±10
Field quality in GFR (not counting quadrupole term)	10^{-4}	≈1
Central field	mT	57
Expected b_2 at 10 mm	10^{-4}	≈3
Expected higher order harmonics at 10 mm	10^{-4}	¡1
Maximum operating current	kA	1.9
Maximum current density	A/mm²	0.79
Number of busbars per side		2
Resistance per unit length (twin magnet)	µΩ/m	22.7
Maximum power per unit length (twin magnet)	W/m	164
Maximum total power, 81.0 km (interconnections included)	MW	13.3
Inter-beam distance	mm	300
Iron mass per unit length	kg/m	219
Aluminium mass per unit length	kg/m	19.9

Estimated converter footprint





FCCee power converters DRAFT layout

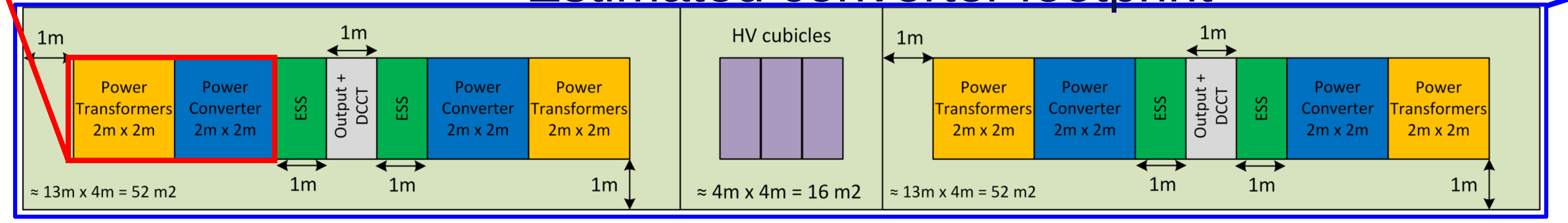
Booster's Quadrupoles – Underground service gallery

	Value	Unit
Converters/circuits number per power sector	4	-
Resistance per circuit	~3	Ω
Inductance per circuit	3,67	H
Current per circuit (1 turn magnet)	474	A
Voltage per circuit	1716	V
Nominal maximum power (selected converter: 2000V, 500A)	814	kW
Magnet's average consumption	242	kW
Converter footprint requirement (1 unit)	**~125**	**m²**
Converter's losses	10	%
Converter losses in water	**~21**	**kW**
Converter losses in air	**~3**	**kW**
DC cable distance per circuit (2 x 150 mm²/ pole)	11500	m
DC cable losses per circuit	**~64**	**kW**
Estimated energy storage (covers up to ttbar)	~1	MJ

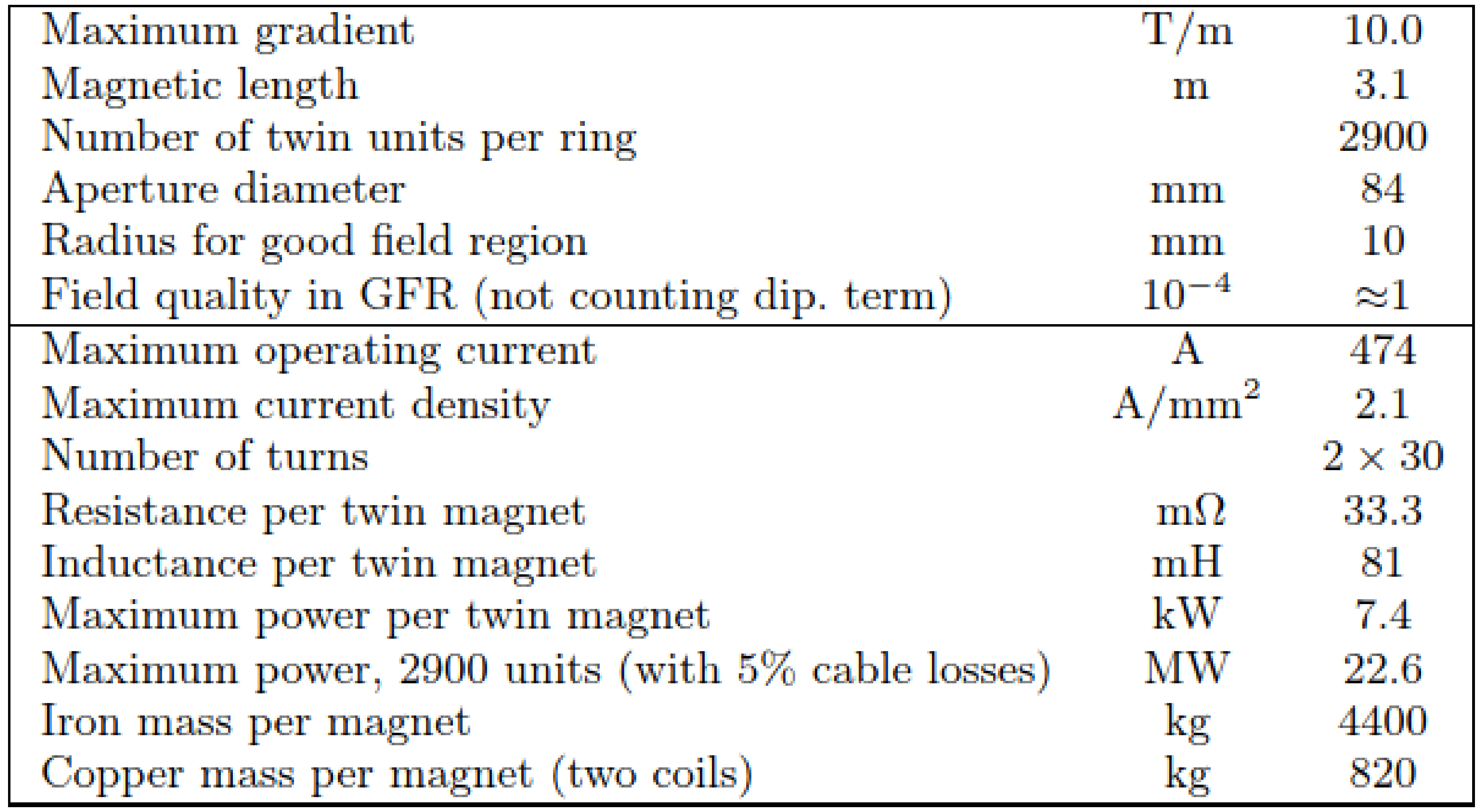
Draft numbers!

NOTE: Cable resistance not considered for the power converter dimensioning as optimization with magnet design is required

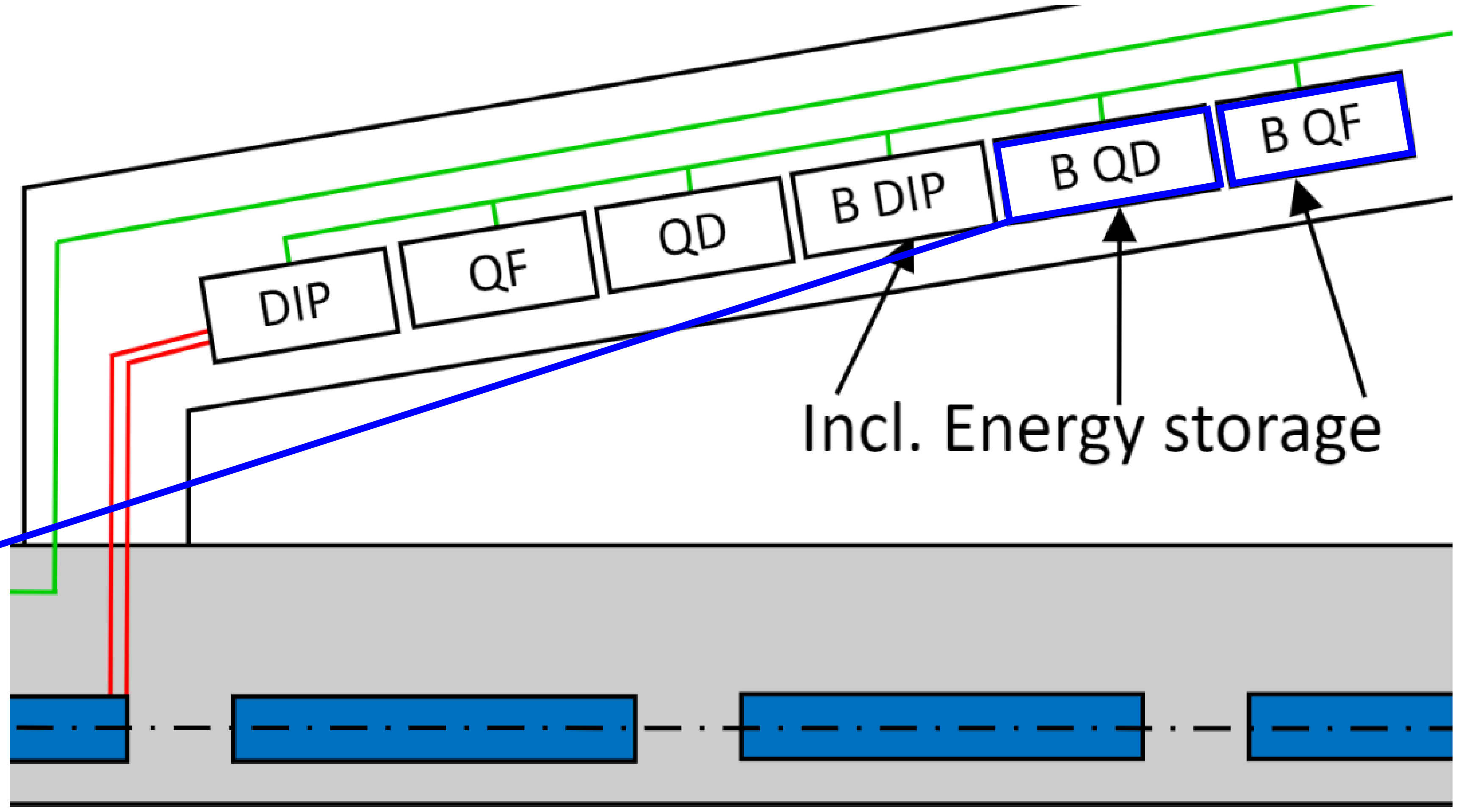
Estimated converter footprint



Quadrupole magnet specifications from CDR



Maximum gradient	T/m	10.0
Magnetic length	m	3.1
Number of twin units per ring		2900
Aperture diameter	mm	84
Radius for good field region	mm	10
Field quality in GFR (not counting dip. term)	10^{-4}	≈1
Maximum operating current	A	474
Maximum current density	A/mm²	2.1
Number of turns		2 × 30
Resistance per twin magnet	mΩ	33.3
Inductance per twin magnet	mH	81
Maximum power per twin magnet	kW	7.4
Maximum power, 2900 units (with 5% cable losses)	MW	22.6
Iron mass per magnet	kg	4400
Copper mass per magnet (two coils)	kg	820



FCCee power converters DRAFT layout

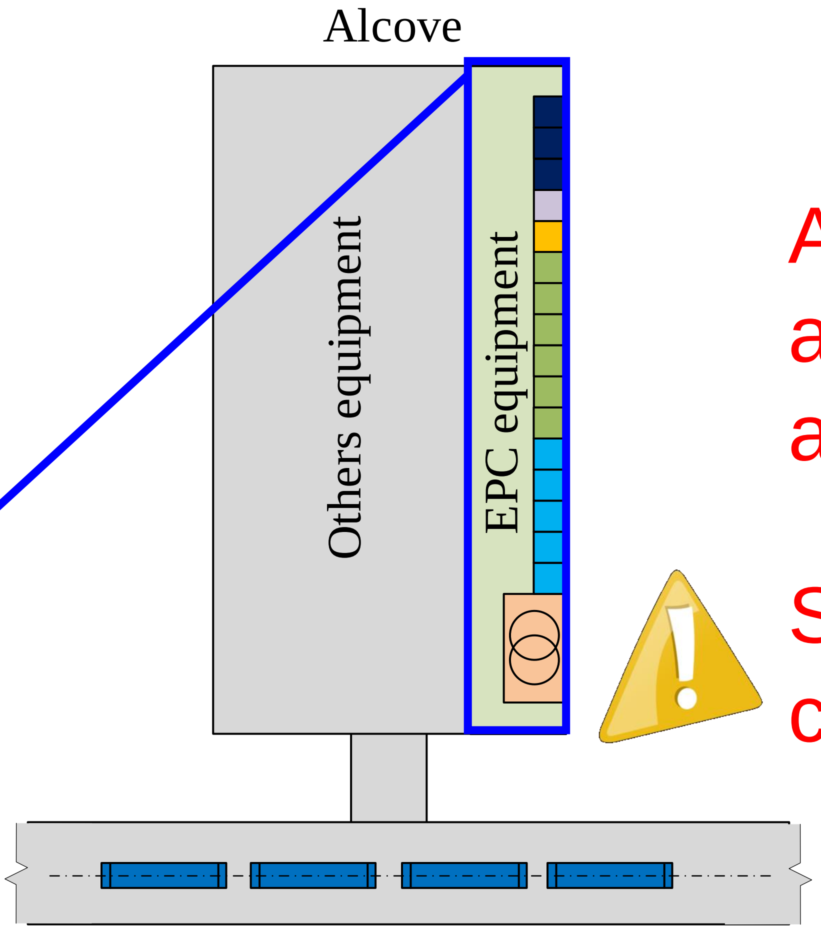
Collider's Sextupoles – Alcoves

	Value	Unit
Converters/circuits number per power sector	73	-
Resistance per circuit	1	Ω
Current per circuit (1 turn magnet)	200	A
Voltage per circuit	176	V
Nominal power	35.2	kW
Converter dimensioning power (200V, 200 A)	40	kW
Converter footprint requirement (1 unit)	**~1,5**	**m^2**
Converter's losses	10	%
Converter losses in water	**~3.6**	**kW**
Converter losses in air	**~0.4**	**kW**
DC cable distance per circuit (2 x 120 mm^2/ pole)	~250	m
DC cable losses per circuit	**~3,2**	**kW**

Draft numbers!

Sextupole magnet specifications from CDR

Maximum strength, B''	T/m^2	807.0
Magnetic length	m	1.4
Number of units per ring		$208\times4 = 832$ (Z, W) $292 \times 8 = 2336$ (H, $t\bar{t}$)
Number of families per ring		208 (Z, W) 292 (H, $t\bar{t}$)
Aperture diameter	mm	76
Radius for good field region (GFR)	mm	10
Field quality in GFR	10^{-4}	≈1
Ampere turns	A	6270
Current density	A/mm^2	7.8
Maximum power per single magnet at 182.5 GeV	kW	15.5
Average power per single magnet at 182.5 GeV	kW	4.4
Total power at 182.5 GeV (4672 units)	MW	20.5



All based on a first arbitrary assumption of 1 alcove every 400m

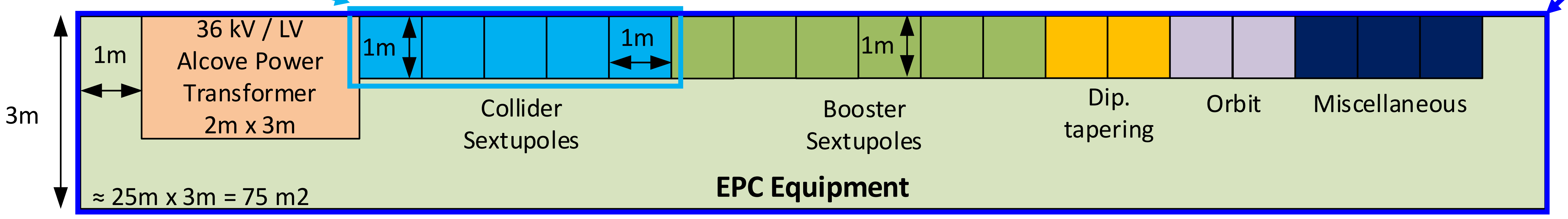
Space required for power converters only!


1.5 racks/converter

3 power converters

≈ 4.5 – 5 racks

Estimated converter footprint



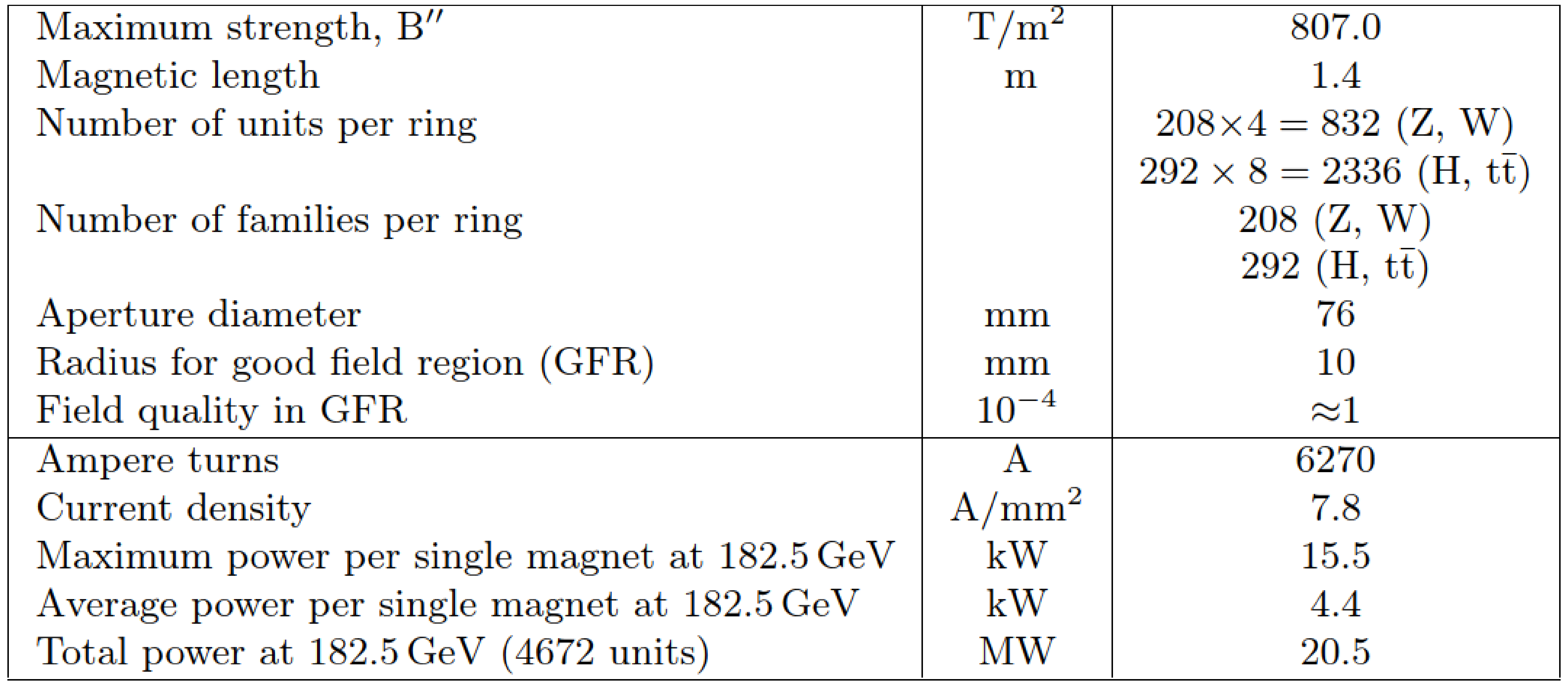
FCCee power converters DRAFT layout

Booster's Sextupoles – Alcoves

	Value	Unit
Converters/circuits number per power sector	37	-
Resistance per circuit (292 circuits of 8 magnets)	1	Ω
Inductance per circuit (292 circuits of 8 magnets)	128	mH
Current per circuit	200	A
Voltage per circuit	215	V
Nominal maximal power (selected converter: 250V, 200A)	43	kW
Magnet's average consumption	14.4	kW
Converter footprint requirement (1 unit)	**~2**	**m^2**
Converter's losses	10	%
Converter losses in water	**~1.2**	**kW**
Converter losses in air	**~0.2**	**kW**
DC cable distance per circuit (2 x 120 mm^2/ pole)	~250	m
DC cable losses per circuit	**~3,2**	**kW**

Draft numbers!

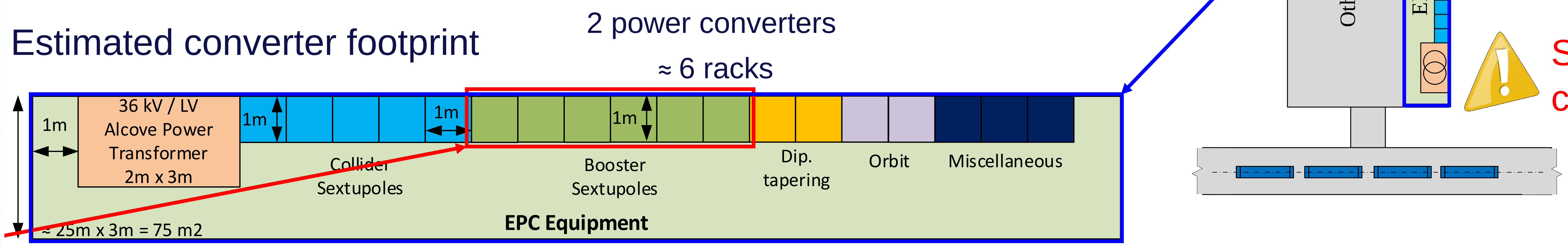
Sextupole magnet specifications from CDR



Maximum strength, B''	T/m^2	807.0
Magnetic length	m	1.4
Number of units per ring		$208\times4 = 832$ (Z, W) $292 \times 8 = 2336$ (H, $t\bar{t}$)
Number of families per ring		208 (Z, W) 292 (H, $t\bar{t}$)
Aperture diameter	mm	76
Radius for good field region (GFR)	mm	10
Field quality in GFR	10^{-4}	≈1
Ampere turns	A	6270
Current density	A/mm^2	7.8
Maximum power per single magnet at 182.5 GeV	kW	15.5
Average power per single magnet at 182.5 GeV	kW	4.4
Total power at 182.5 GeV (4672 units)	MW	20.5

Including energy storage

Estimated converter footprint



All based on a first arbitrary assumption of 1 alcove every 400m

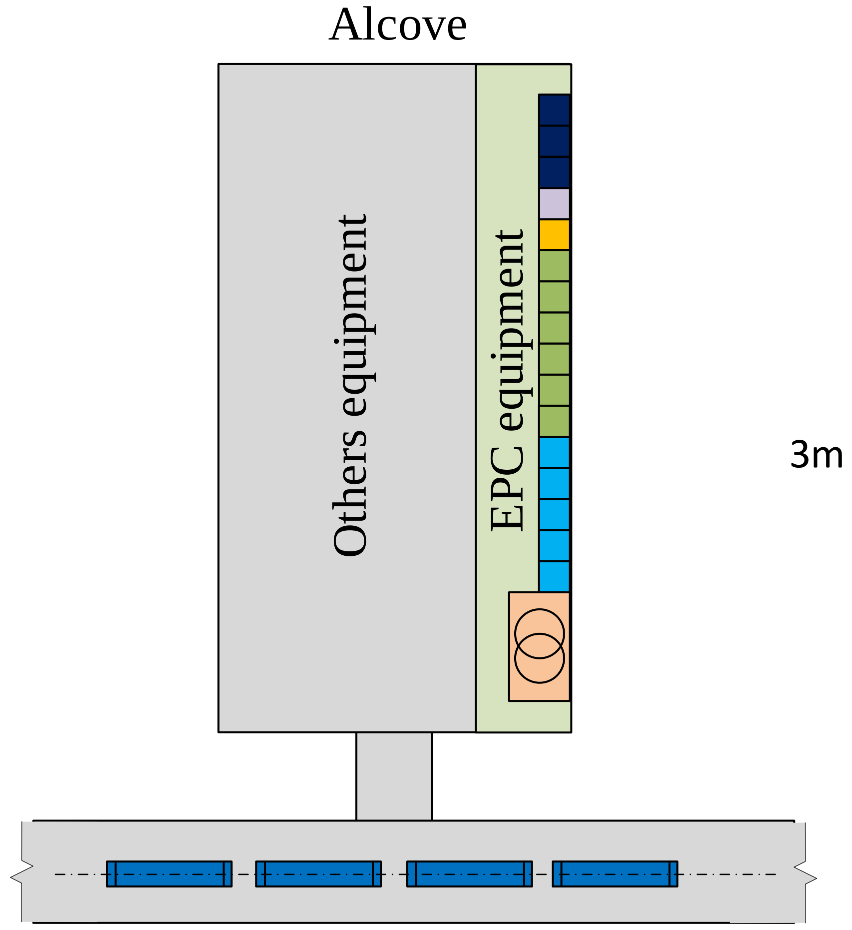
Space required for power converters only!

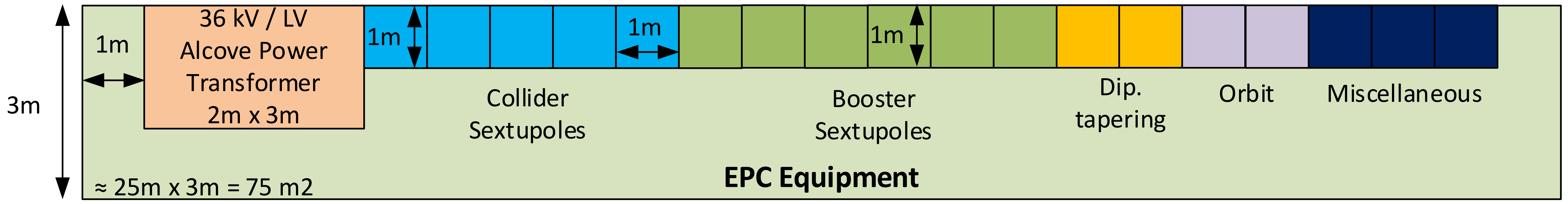
Summary of required space

Draft numbers!

Alcoves:

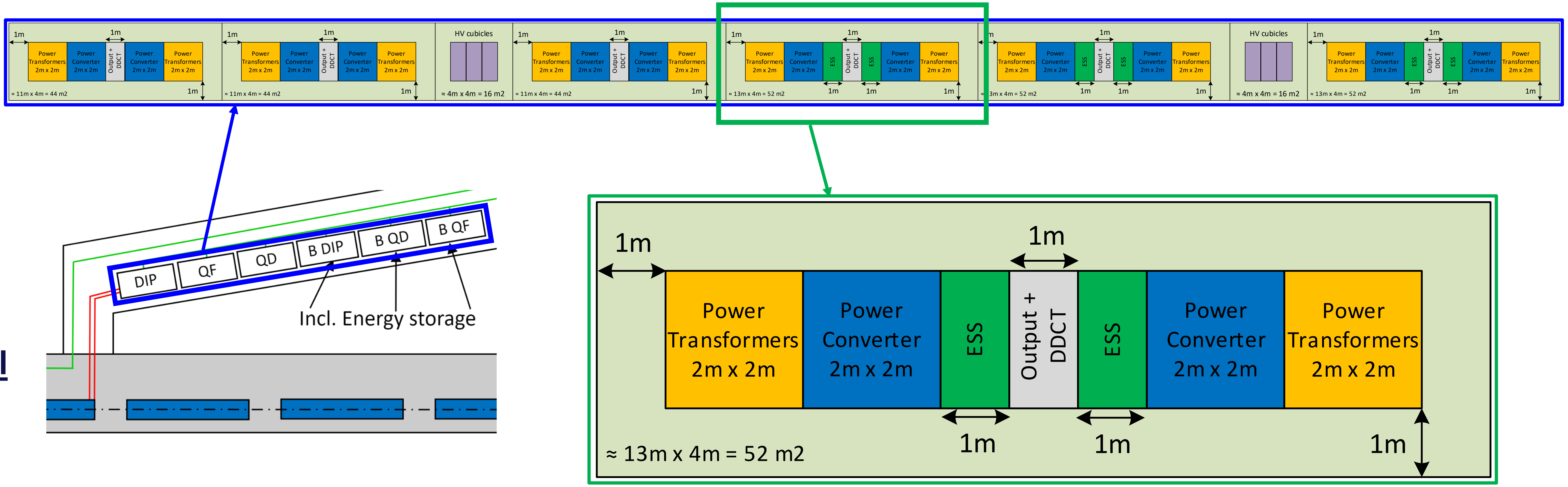
- ☐ 75m2/alcove are required only for Power Conv. equipment
- ☐ 18000 m2 required in total in alcoves for whole ring





Underground Technical galleries:

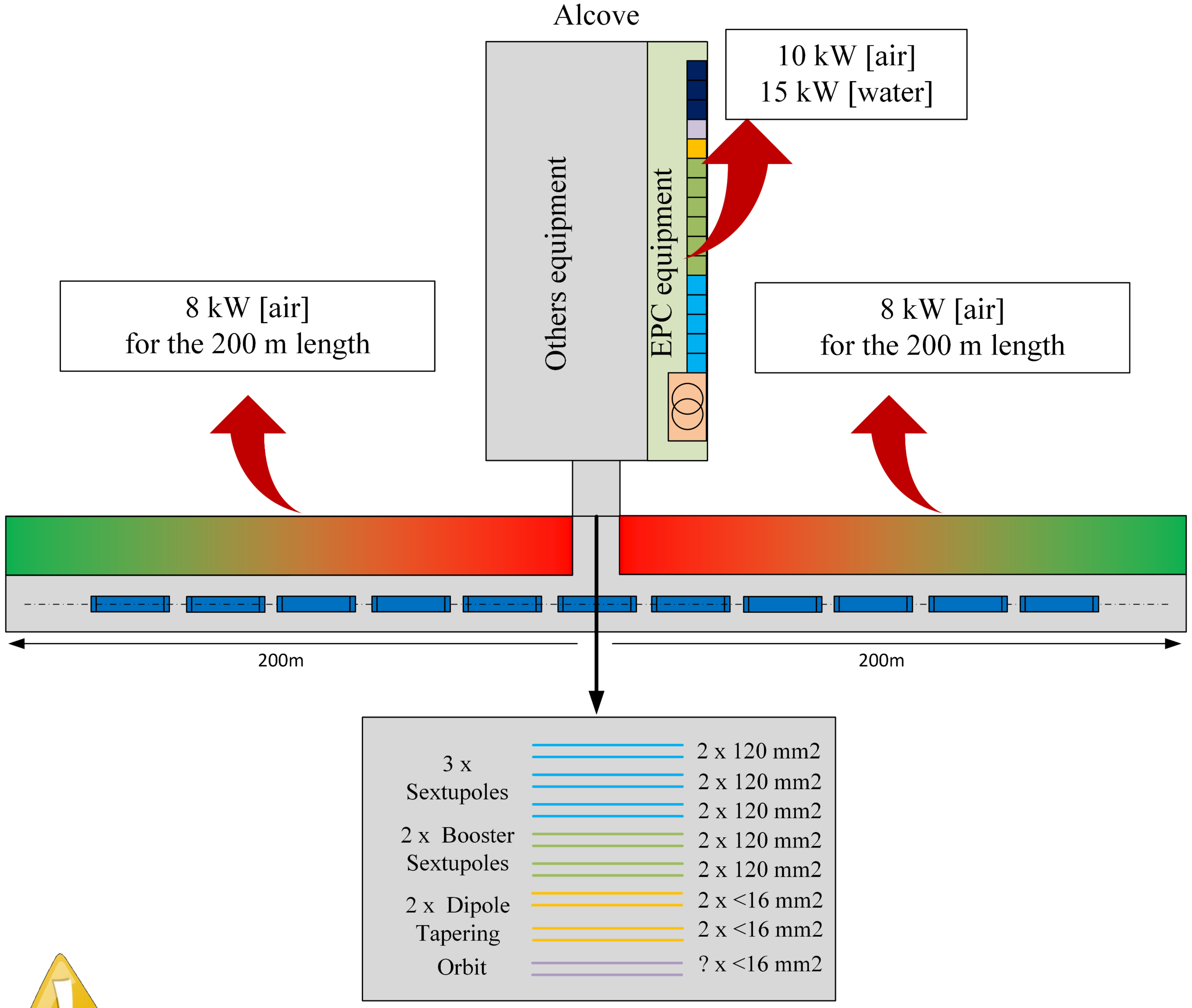
- ☐ 660m2/power sector are required only for Power Conv. equipment
- ☐ 5280 m2 required in total for the whole ring



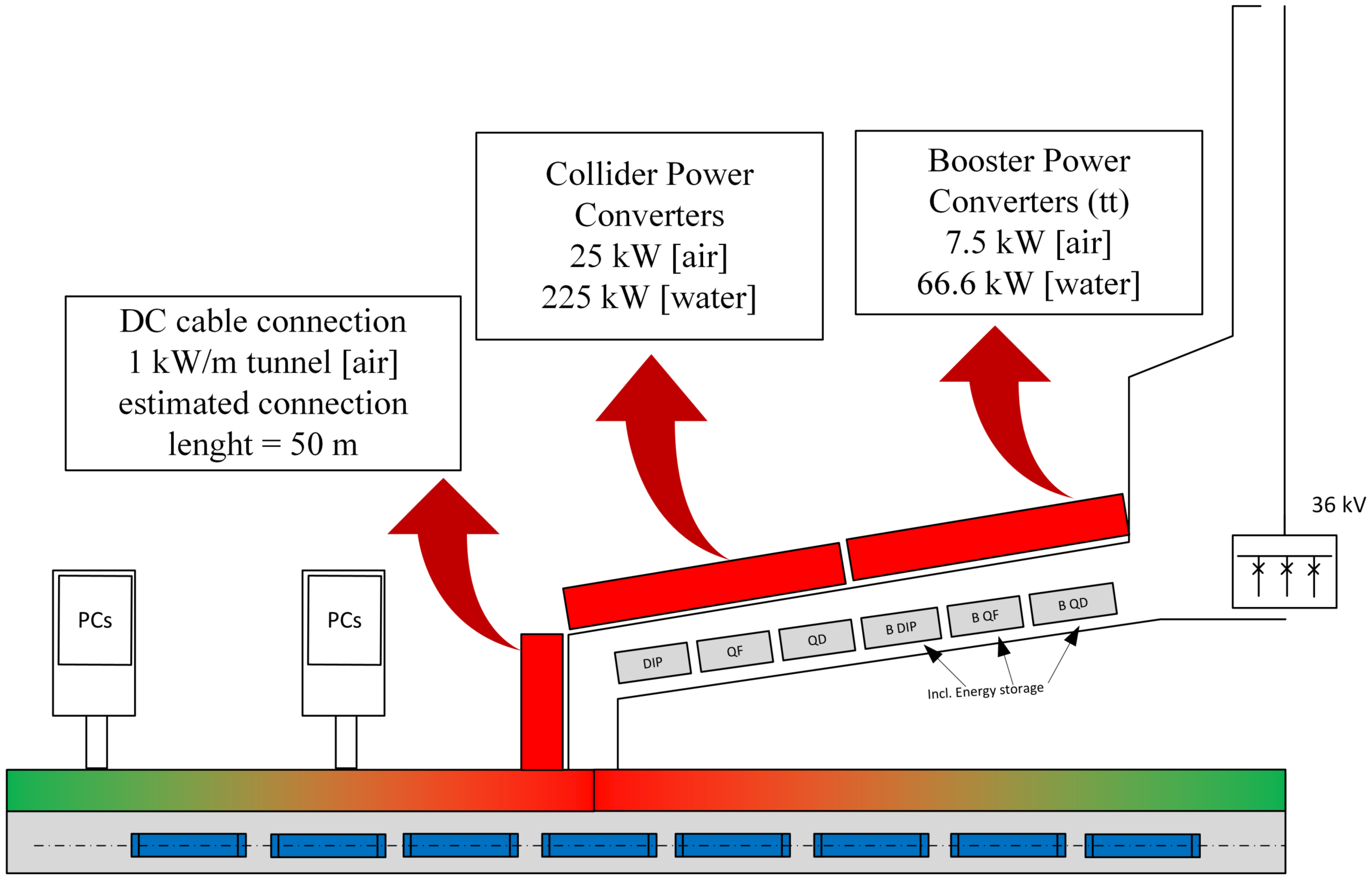
Simplified heat maps for thermal losses

Draft numbers!

Alcoves



Underground technical galleries



This does not include magnet losses, only converters and DC cables

Summary of power consumption and losses

Estimated power converters consumption

Power converter	Power consumption / circuit (kW)	Nb Circuits / Access point	Total consumption / access point (MW)
Collider Dipoles	830	2	1.662
Collider Quadrupoles	930	4	3.72
Collider Sextupoles	42.4	73	3.1
Booster Dipoles	296	2	0.592
Booster Quadrupoles	330	4	1.32
Booster Sextupoles	18.3	37	0.677
		TOTAL	9.4

Summary

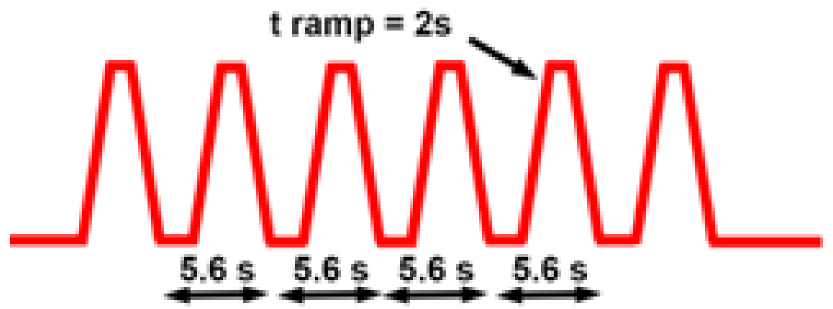
Circuit		Power requirement (MW)	Total (MW)
Collider	Dipoles	13.3	68
	Quadrupoles	29.8	
	Sextupoles	24.8	
Booster	Dipoles	4.7	20.7
	Quadrupoles	10.6	
	Sextupoles	5.4	
		All circuits	88.7

…from which DC cable losses

DC cable connection	DC Cable losses / Power converter (kW)	Nb Converters / Access point	Total DC cable losses / Access point (kW)
Collider Dipoles (4 x 400 mm^2/ pole)	18.8	2	37.6
Collider Quadrupoles (2 x 150 mm^2/ pole)	175	4	700
Collider Sextupoles	3.2	73	234
Booster Dipoles (4 x 400 mm^2/ pole)	10	2	20
Booster Quadrupoles (2 x 150 mm^2/ pole)	64	4	256
Booster Sextupoles	2,5	37	93
		TOTAL	1340

Considering CDR top-up injection cycle

tt Mode Operation



Note on these numbers:

- All this is draft and consider some arbitrary choices
- This includes only the 3 magnet's families for which we have a draft spec – <u>many converters/circuits missing!</u>

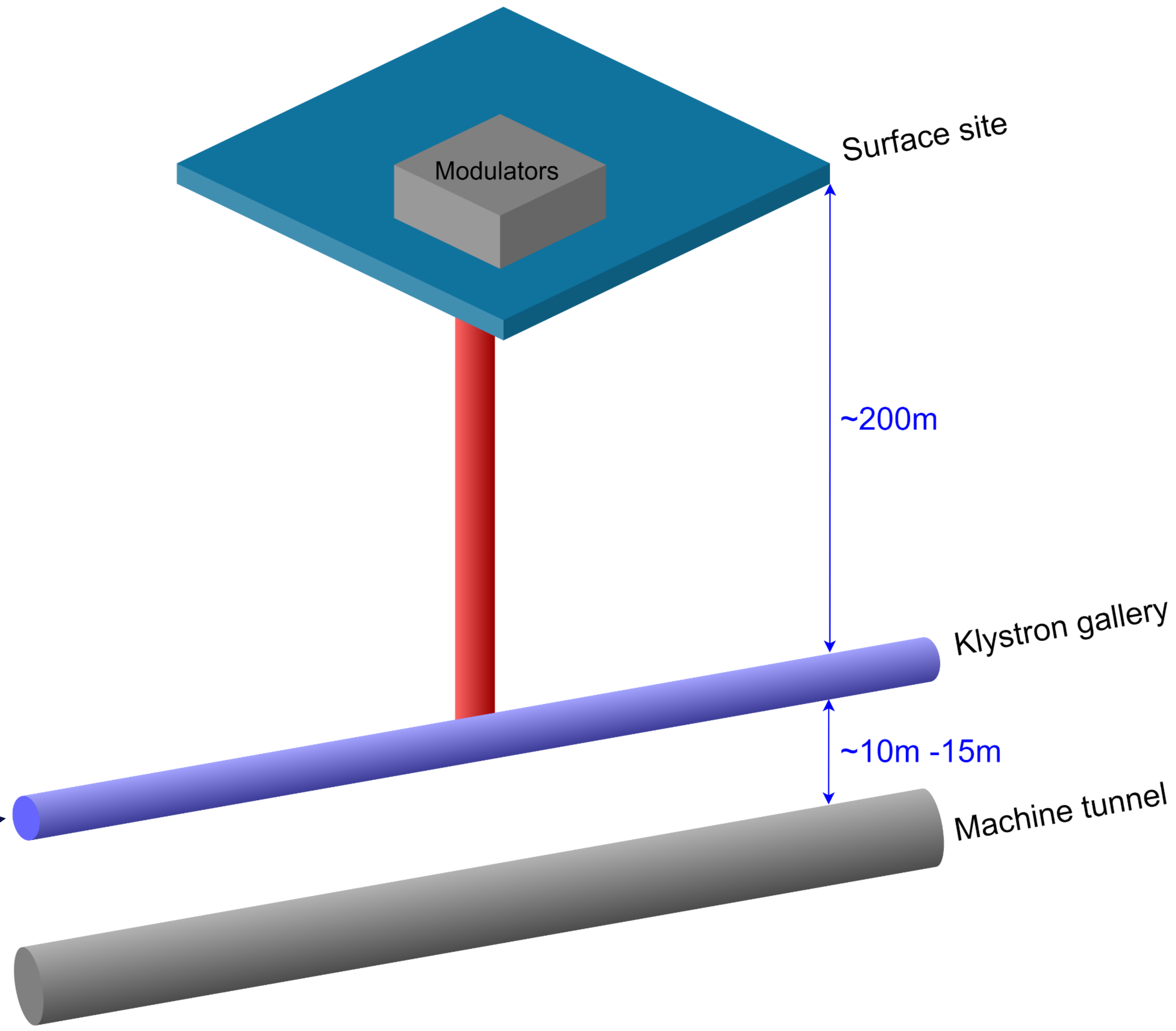
FCCee power converters DRAFT layout

RF Powering

- 50 MW synchrotron radiation loss per beam (collider only)
  - ~150MW electrical power (with high efficiency klystrons)
  - ~15 MW losses
- Modulators in pseudo DC (or CW) mode (or very slow cycling mode)
  - No need to install them near klystrons
  - Installation on surface possible
- High Voltage cables
  - length ~140 m to 250 m
  - Present roughly 100 pF/m → some energy stored!

Protection devices would be needed in klystron gallery to protect klystrons in case of arcing

- Still to be checked if cost effective to install modulator on surface…



EVALUATING DC DISTRIBUTION

Advantages of DC systems over AC

A DC system can transmit more power (for equal current and voltages) **on two cores than the AC using three cores**

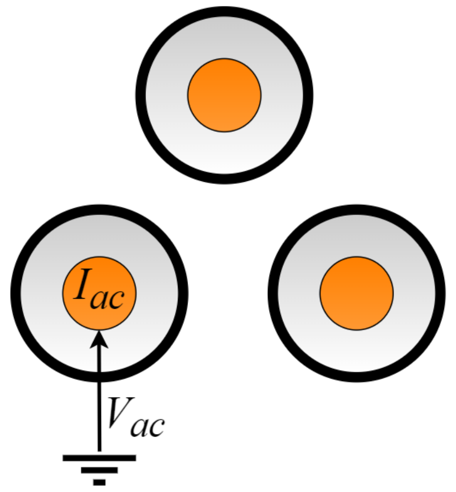
$$\frac{P_{DC}}{P_{AC}} = \frac{\frac{2}{\sqrt{3}}\sqrt{2}V_{DC}I_{DC}}{3V_{AC}I_{AC}} \approx 0.95$$

lower transmission losses, less copper required

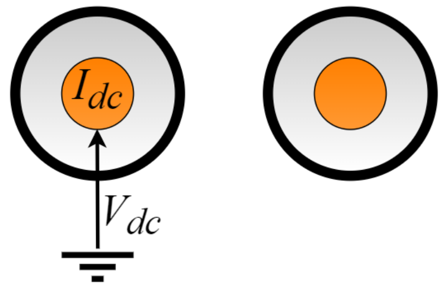
increased power transfer capacity, no need of compensating equipment

Lower voltage drops due to inductive effects

AC three phase system



DC system



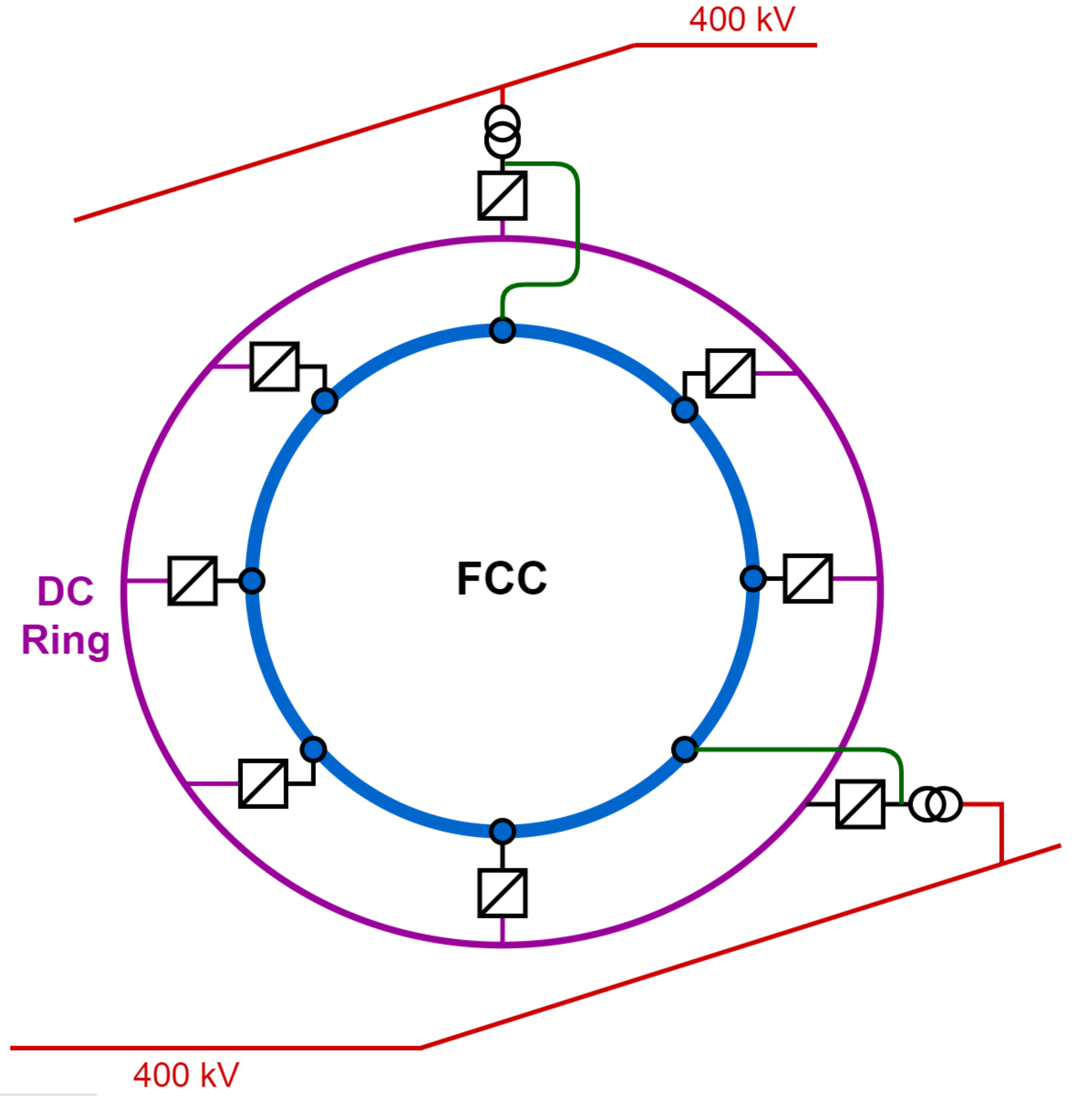
Many loads require somewhere a DC voltage:

- Power converters for magnet supply
- Uninterruptible power supplies
- Computing infrastructure and data centers
- Detector equipment
- …

DC networks for the FCC: scope

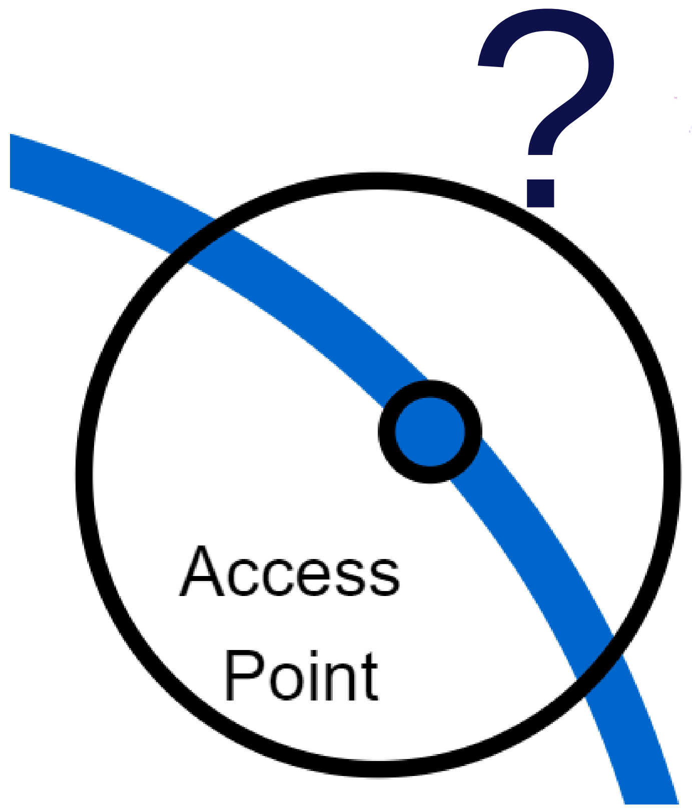
Level of readiness – Voltage Level

HVDC
Transmission
1MV – 50 kV



Transmission over 90-100 km

MVDC
Distribution
50kV – 10 kV

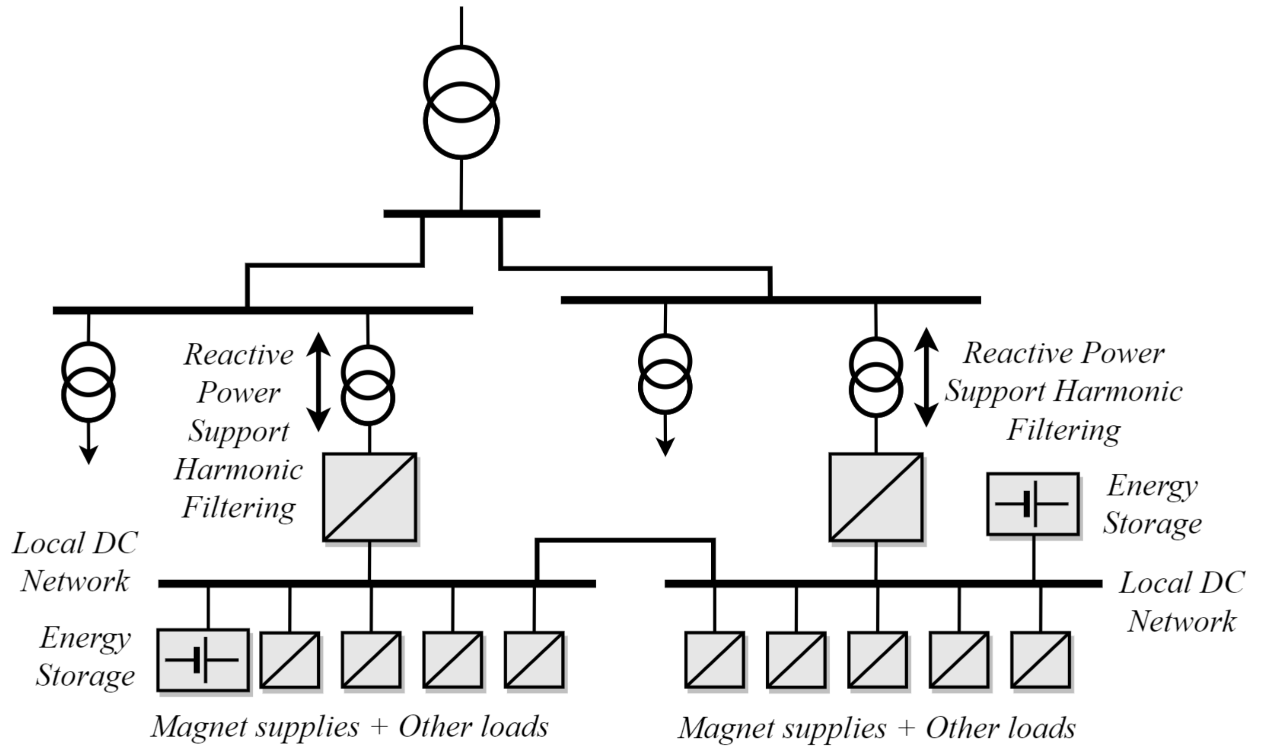


A cost-effective solution not found

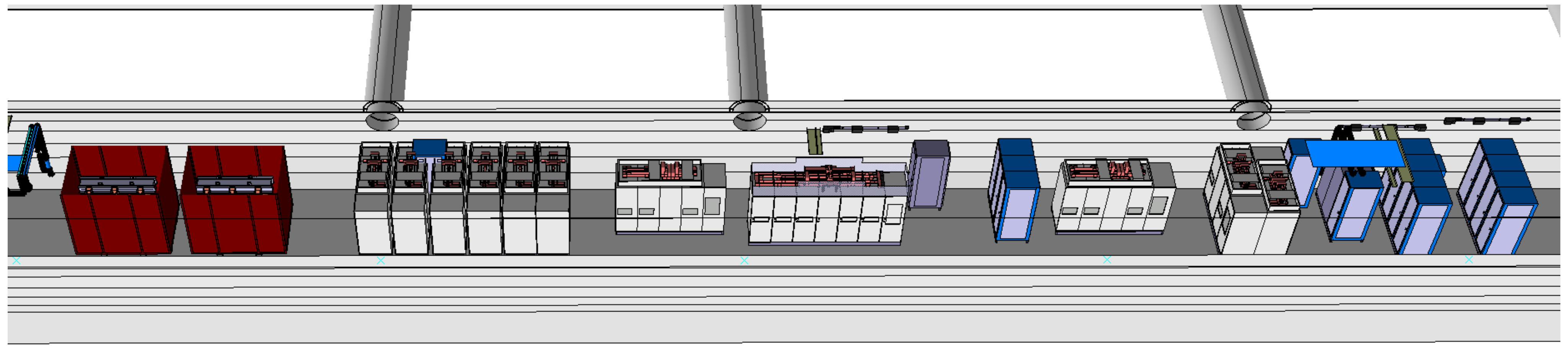
HV-LV conversion difficult

MVDC applications
10 kV – 1.5 kV

LV Distribution
1.5kV– 12V



Case study being analysed to supply one of LHC points via DC distribution



HVDC Transmission for the FCC

Build a **DC transmission ring** along the FCC circumference

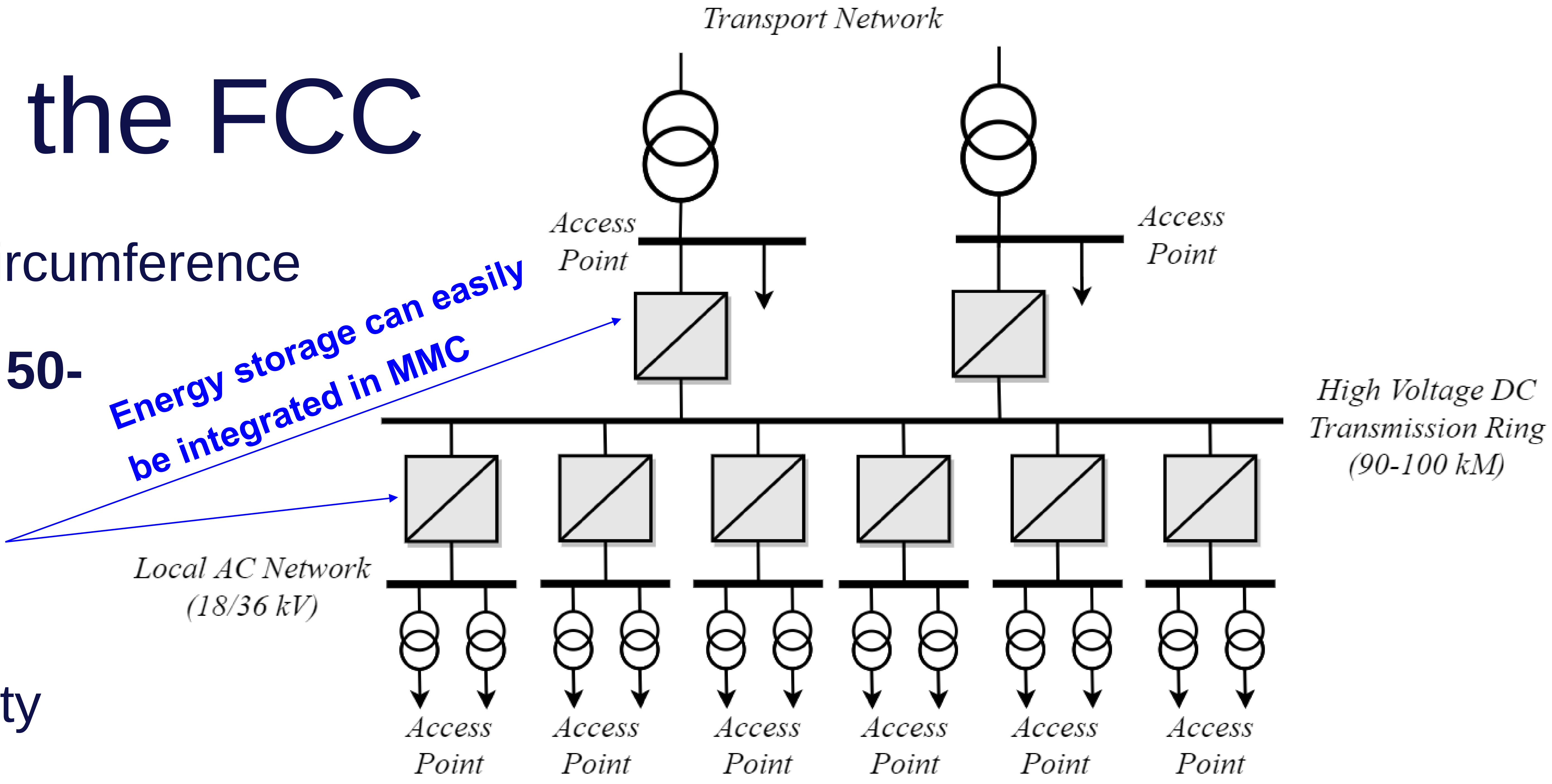
This network would operate at a **DC voltage of 50-150 kV** (depending on power demand)

These voltage levels can be easily achieved by using **Modular Multilevel Converters (MMC)**

The DC link decouples the grids regarding quality issues: **SVCs are not required**

Other features:
- Better **control of power flows**
- Better immunity to networks **Voltage Dips**
- **Modular design – high availability**
- **BUT:** protection systems still requiring R&D

Economical feasibility needs to be further developed
- **Savings in cable and reactive power compensation**
- **However slightly higher CAPEX and OPEX of converters**

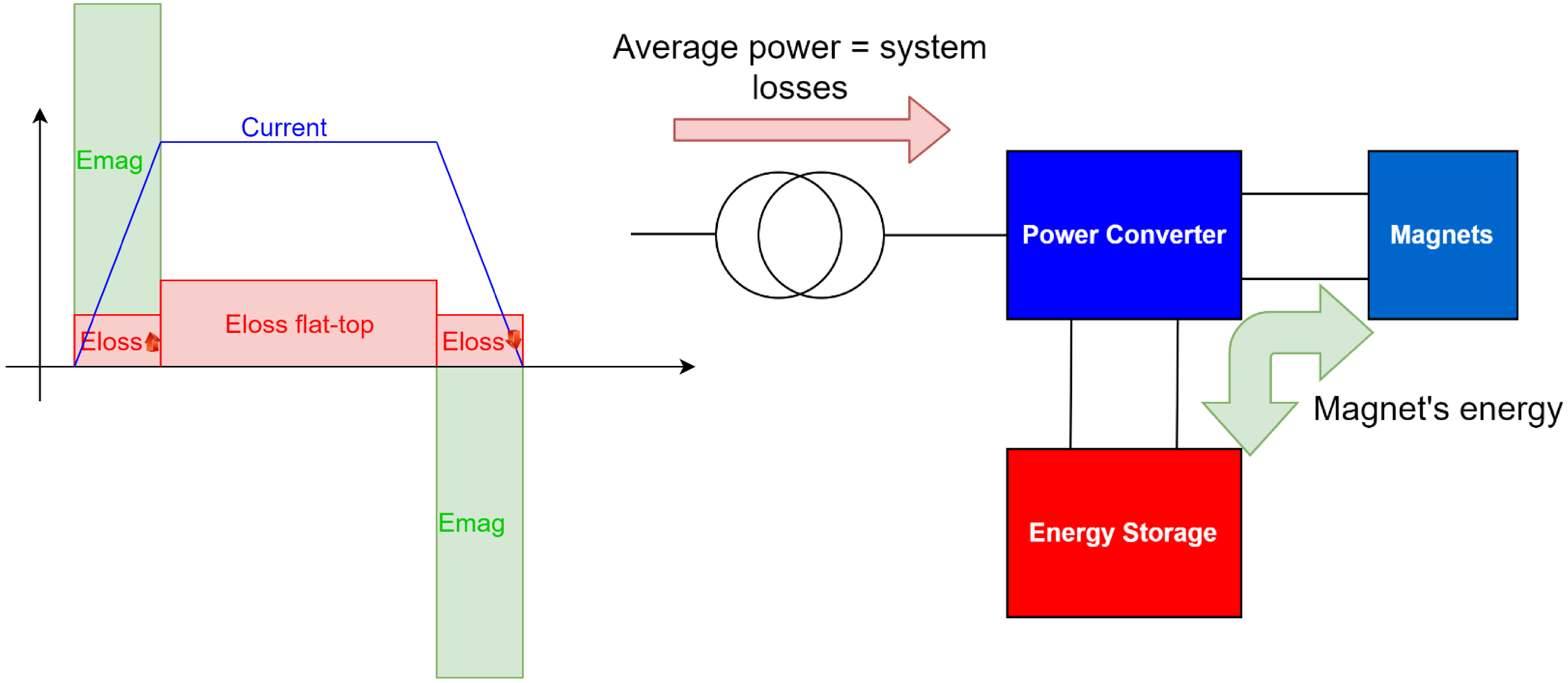


FCC-HH POWERING SPECIFICITIES

FCChh magnet powering specificities

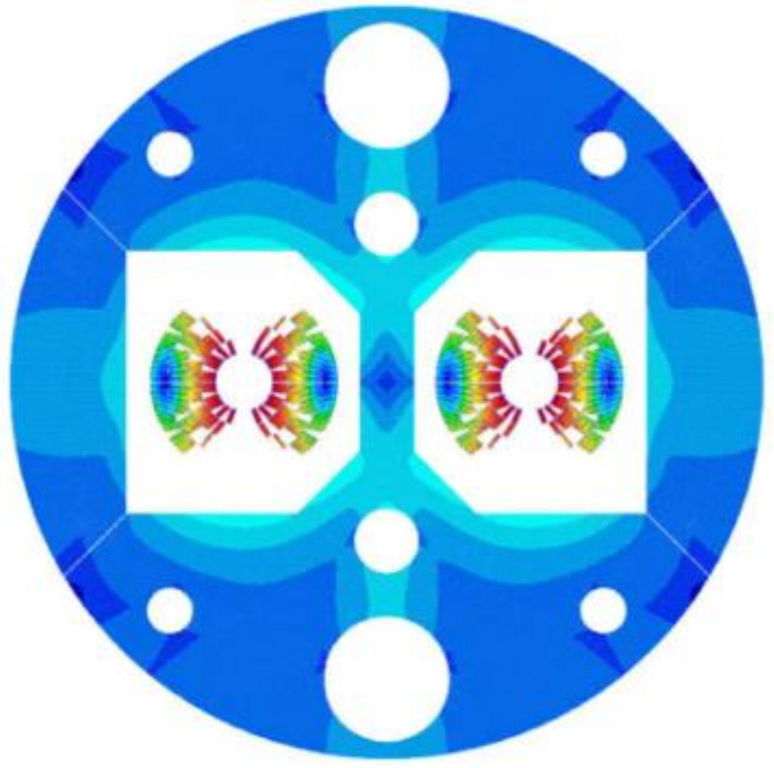
A different machines to power…

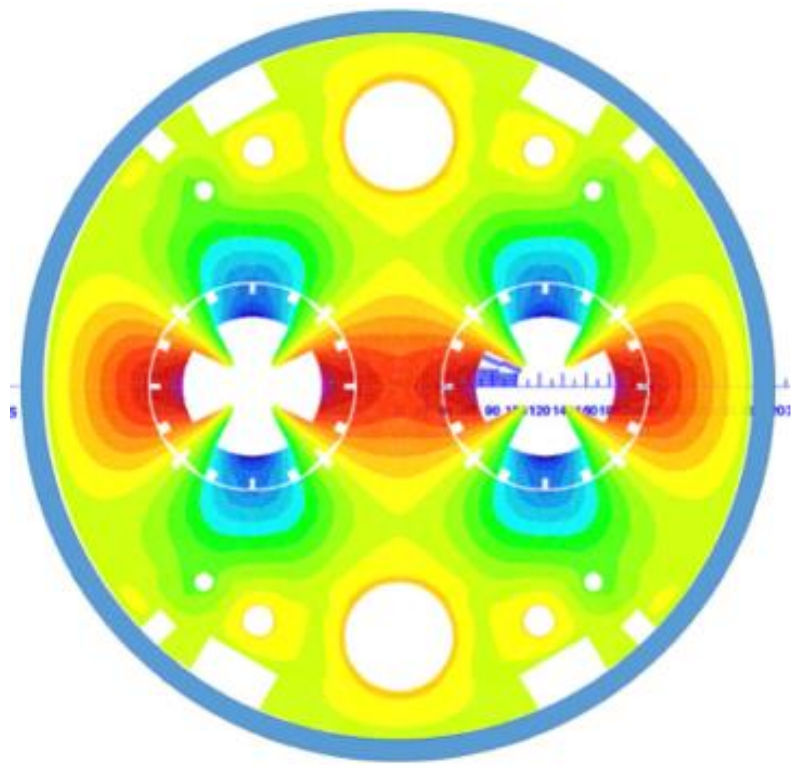
- From an “*RF machine*” to a “*superconducting and cycling magnet machine*”
  - Need to deal with higher currents and big distances…
  - Need for energy storage for peak power shaving into the network



Main magnet specs form CDR:

	Main dipoles	Main quadrupoles
Number of units	4668	744
Operating current	11.4 kA	22.5 kA
Inductance	570 mH	14.4 mH
Total stored energy	**174 GJ**	**2.7 GJ**
Peak power	290 MW	4.5 MW


Main dipoles


Main quadrupoles

175 GJ…

90 TGV at 360 km/h

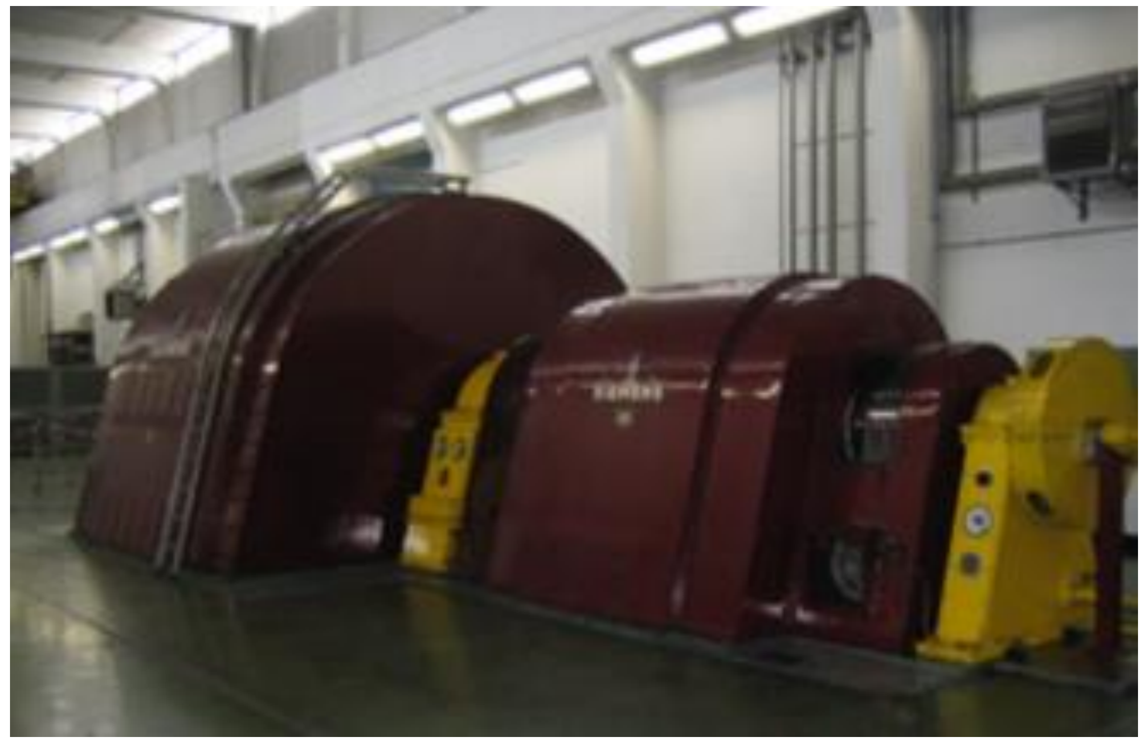
3.2 minutes production of a nuclear reactor

“Charles de Gaulle” lifted 410 m overseas

38 tons of TNT

10 min production / 16 min pumping
of the “Dixence” hydroelectric facility

880 fully charged electrical vehicles

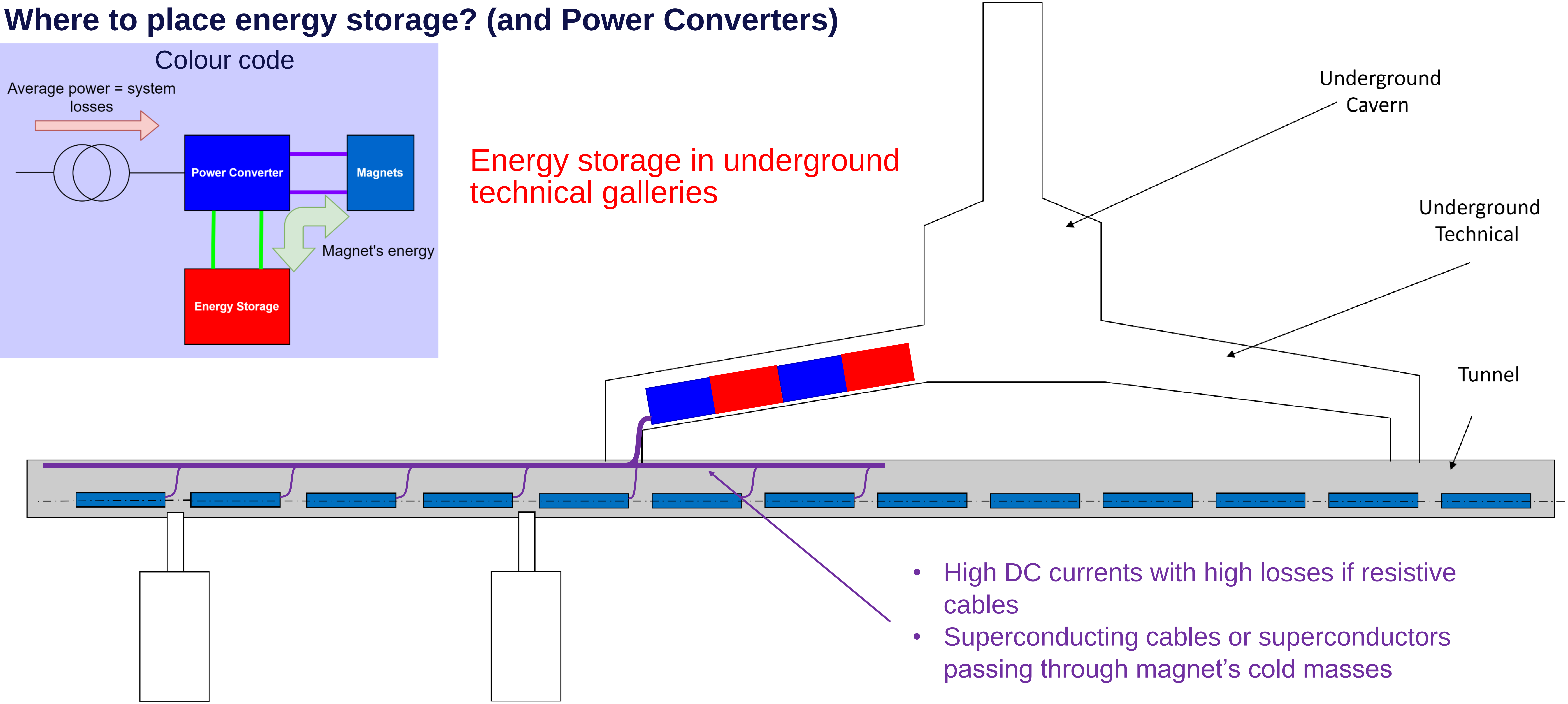


875 PS rotating machines

5’000 CHF
(0.1 CHF/kWh)

FCChh magnet powering specificities

Where to place energy storage? (and Power Converters)

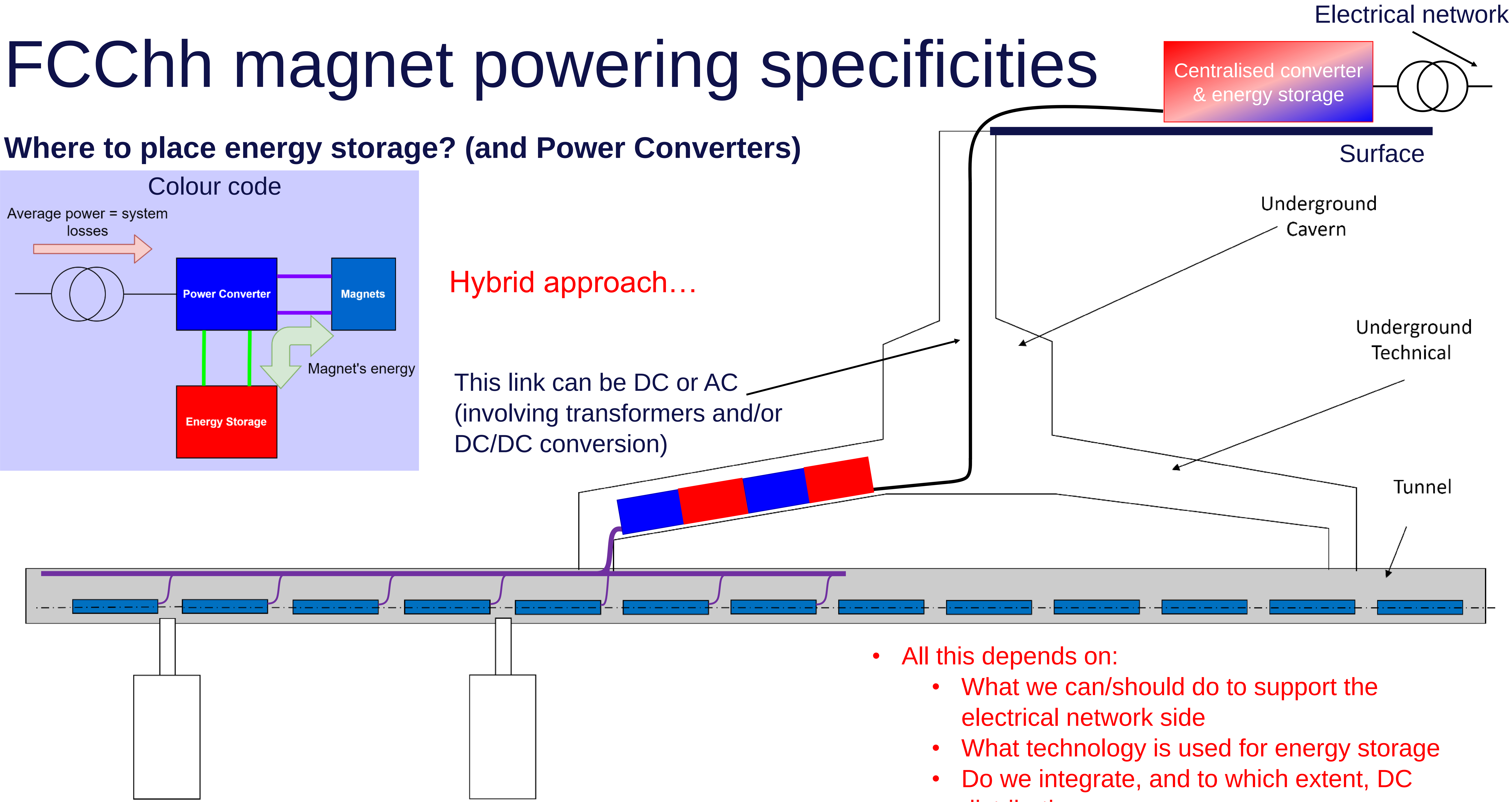


Energy storage in underground technical galleries

- High DC currents with high losses if resistive cables
- Superconducting cables or superconductors passing through magnet's cold masses

FCChh magnet powering specificities

Where to place energy storage? (and Power Converters)



Hybrid approach…

This link can be DC or AC (involving transformers and/or DC/DC conversion)

- All this depends on:
  - What we can/should do to support the electrical network side
  - What technology is used for energy storage
  - Do we integrate, and to which extent, DC distribution

FCChh magnet powering specificities

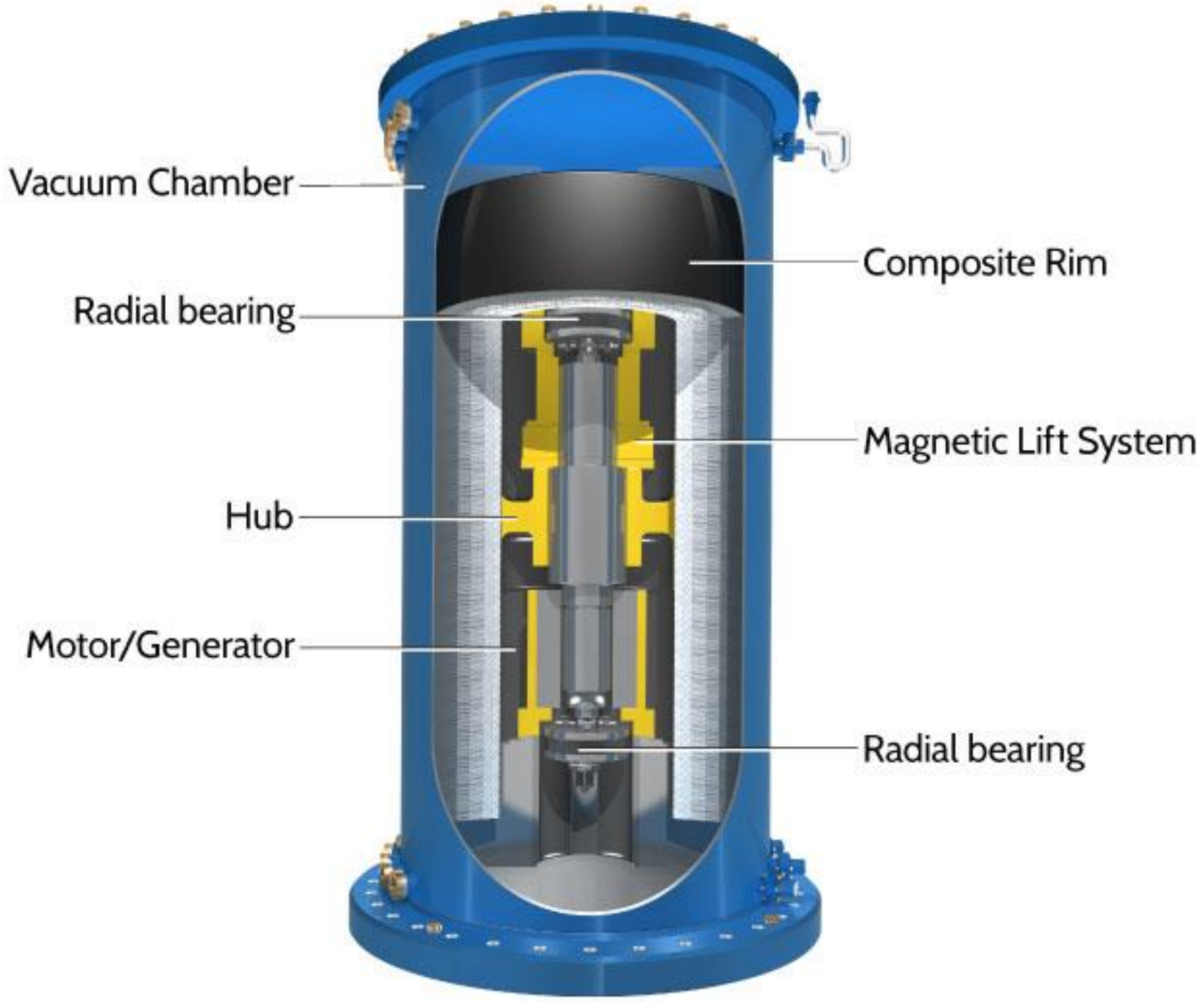
How big the energy storage? Depends on Technology! Few ones we evaluated so far…

Several technologies evaluated

Capacitors

- Energy/power ratio too low
- Too voluminous

Flywheels



- Energy/power ratio too low
- Too voluminous
- No maintenance / chemicals
- Room for improvements in the next 20 - 40 years (SC mag. levitation & bearings)

Supercapacitors

- Energy/power still too low
- We would need
  - 18980 m3
  - 14220 Tons

Today batteries seem the only viable solution!

FCChh magnet powering specificities

How big the energy storage? Depends on Technology! Few ones we evaluated so far…

Chemical storage – Batteries – LTO (Lithium-Titanate-Oxide)

The ratio Energy / power of the LTO batteries (280 J/W) is not far from the main dipoles (600 J/W) requirement.
The storage is sized to the required energy, which provides almost twice the required power.
The oversizing in power allows to reduce the cells temperature and increases the lifetime.

The system can be charged/discharged at 7C/7C within the 20% to 80% State of charge range.

- **Total volume: 760 m^3** → **95 m^3 in each access point → ~50m^2**
- Total weight: 1450 Tons
- **Expected lifetime with 1600 cycles / year: 22 years**
- Calendar life at 25°C: 25 years
- No emission of hydrogen in case of failure.

24 V / 70 Ah
(3.4 MJ from 20% to 80%)
LTO module

Batteries technology and recycling evolves rapidly, pushed by a demanding market (EV, photovoltaic) and shall be fully reassessed at the time of procurement.

FCChh magnet powering specificities

Only a conceptual idea

Thinking a bit out of the box…

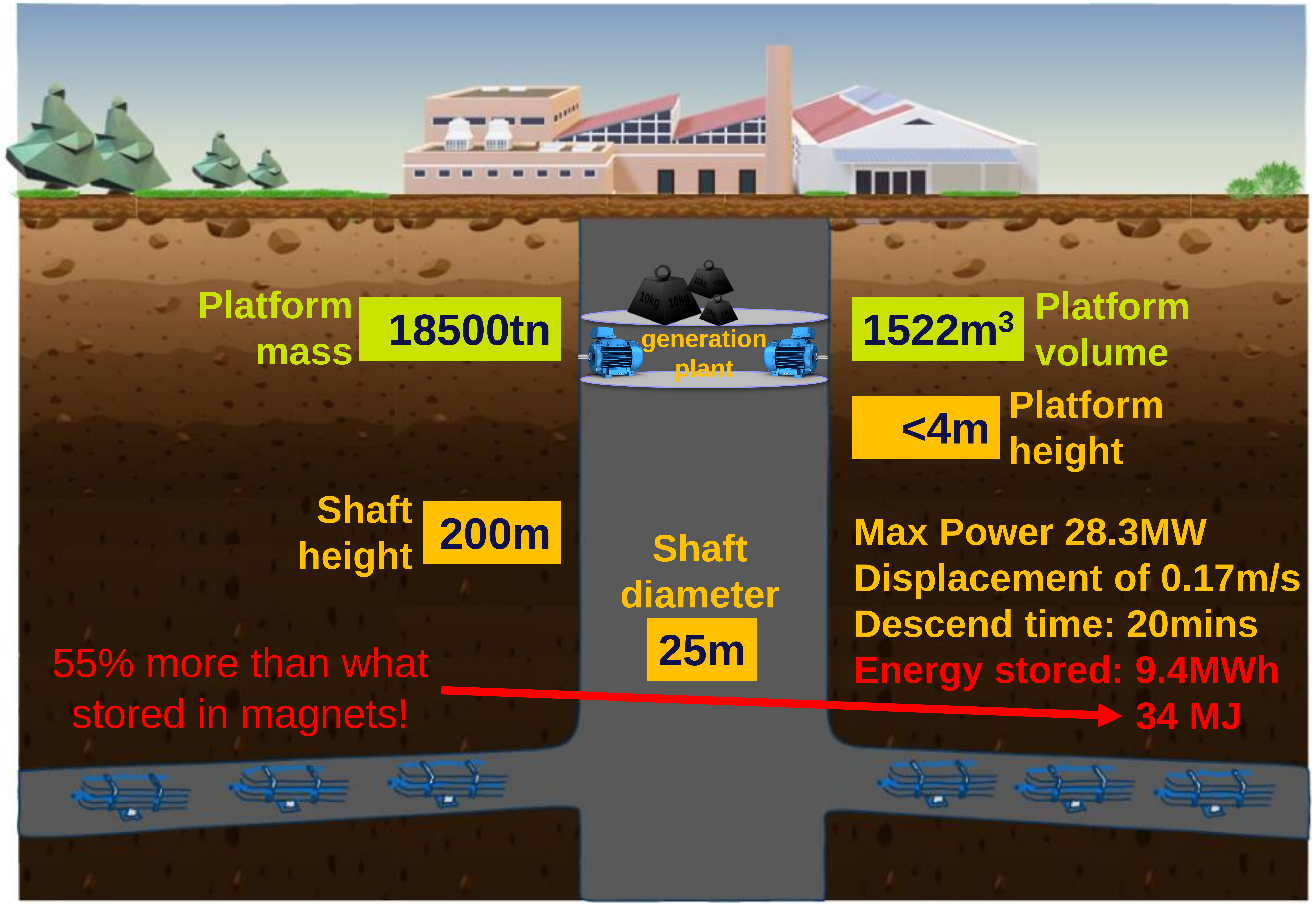
An example of a centralized energy storage system – Gravitational

- Well established/durable technology (e.g. pumped hydro)
- Utilisation of access shaft volume
- Technology leadership in Europe

Type	Max cycles/lifetime	Energy Density (wh/liter)
Pumped hydro	30-60 yrs	0.2-2
Compressed air	20-40 yrs	2-6
Li-ion battery	10-10,000	200-400
Lead acid	6-40yrs	50-80
Hydrogen	5-30yrs	600
Gravitational (lead mass)	30-60 yrs	6.2
Gravitational (molasse mass)	30-60 yrs	1.6

Re-use of excavated materials (molasses-granite) of 7300m3/point

Only a principle scheme– several layouts possible



Platform mass **18500tn**

1522m^3 Platform volume

<4m Platform height

Shaft height **200m**

Shaft diameter **25m**

Max Power 28.3MW
Displacement of 0.17m/s
Descend time: 20mins
Energy stored: 9.4MWh

55% more than what stored in magnets! → 34 MJ

FCChh magnet powering specificities

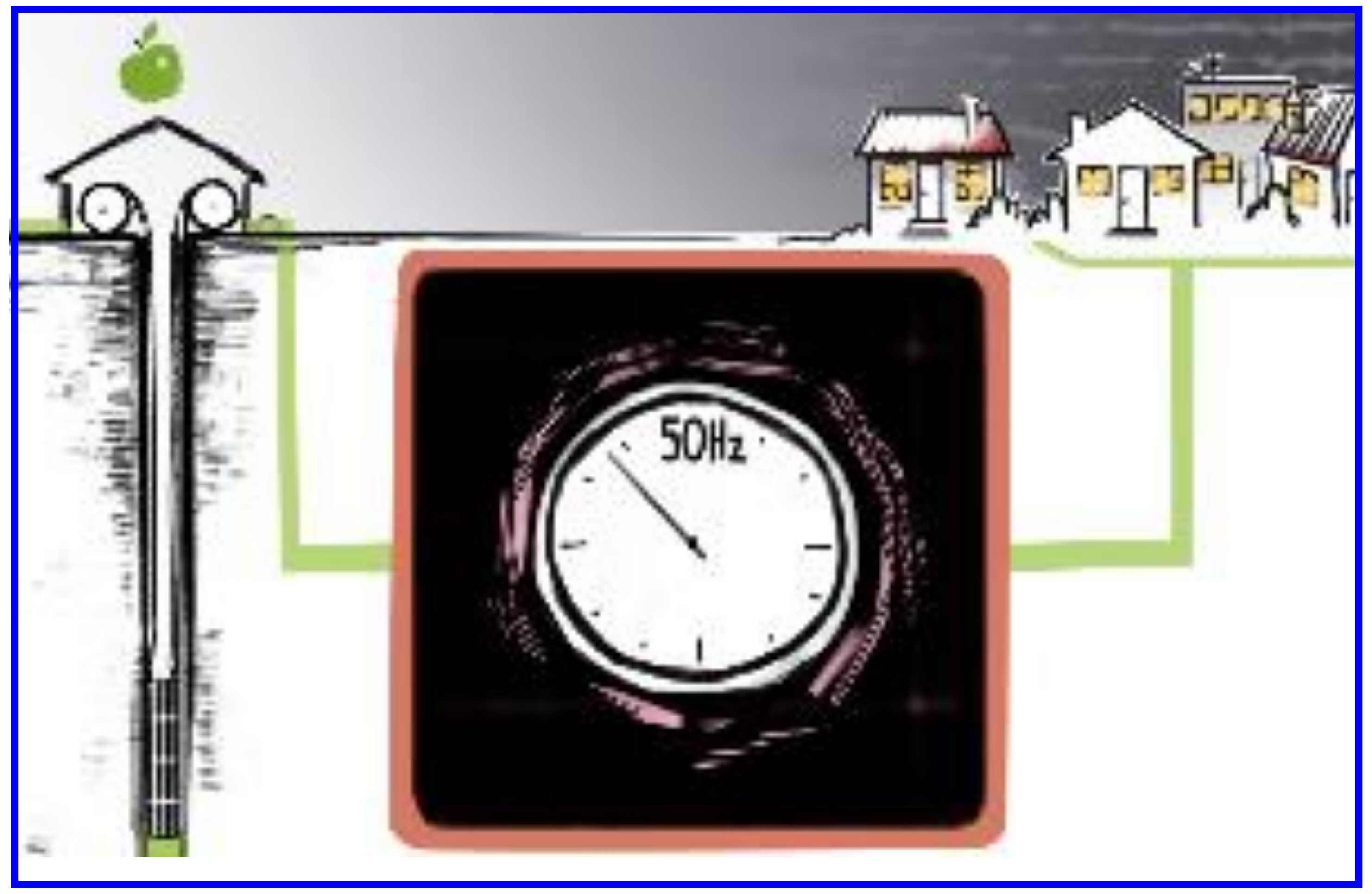
Only a conceptual idea

Thinking a bit out of the box…

An example of a centralized energy storage system – Gravitational

Centralised energy storage can be used to better integrate renewables on surface sites! (e.g. solar)

Gravitricity, Scotland, UK
12000tn up to 300m depth



New Energy Let'Go, Hamburg Germany
Heavy piston lifting by pumping water in reservoir

Energy Vault, CH, Ticino
Joule storing Jenga

CONCLUSION

Conclusion and R&D to come

- FCCee powering does not present huge challenges – Its powering can be done with power converters in use, or in development at CERN
- FCCee and FCChh powering need an integrated optimal design approach to maximize energy saving and investment cost
- FCChh needs to integrate a huge amount of energy storage. Centralized vs. decentralized storage need to be addressed considering electrical network support capabilities interests from RTE. With external support, evaluation of technological trends, and long-term commodity outlook, for energy storage & savings
- Need to develop reliability & availability models for power conv. controls and its infrastructure & energy storage. These models will be integrated into the optimal design tool considering MTBF (FEMA) prediction, Fault Tree Analyses, and FCC operational availability predictions
- In the framework of the energy management WG, we need to evaluate solutions to produce (or regenerate) energy by exploiting the FCC infrastructure

Thank you
for your attention.