



Architecture of powering and protection systems for high field circuits

same material as in Challenges and limitations of a 100 km magnet string (talk on Wdn)

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FCC week 2015

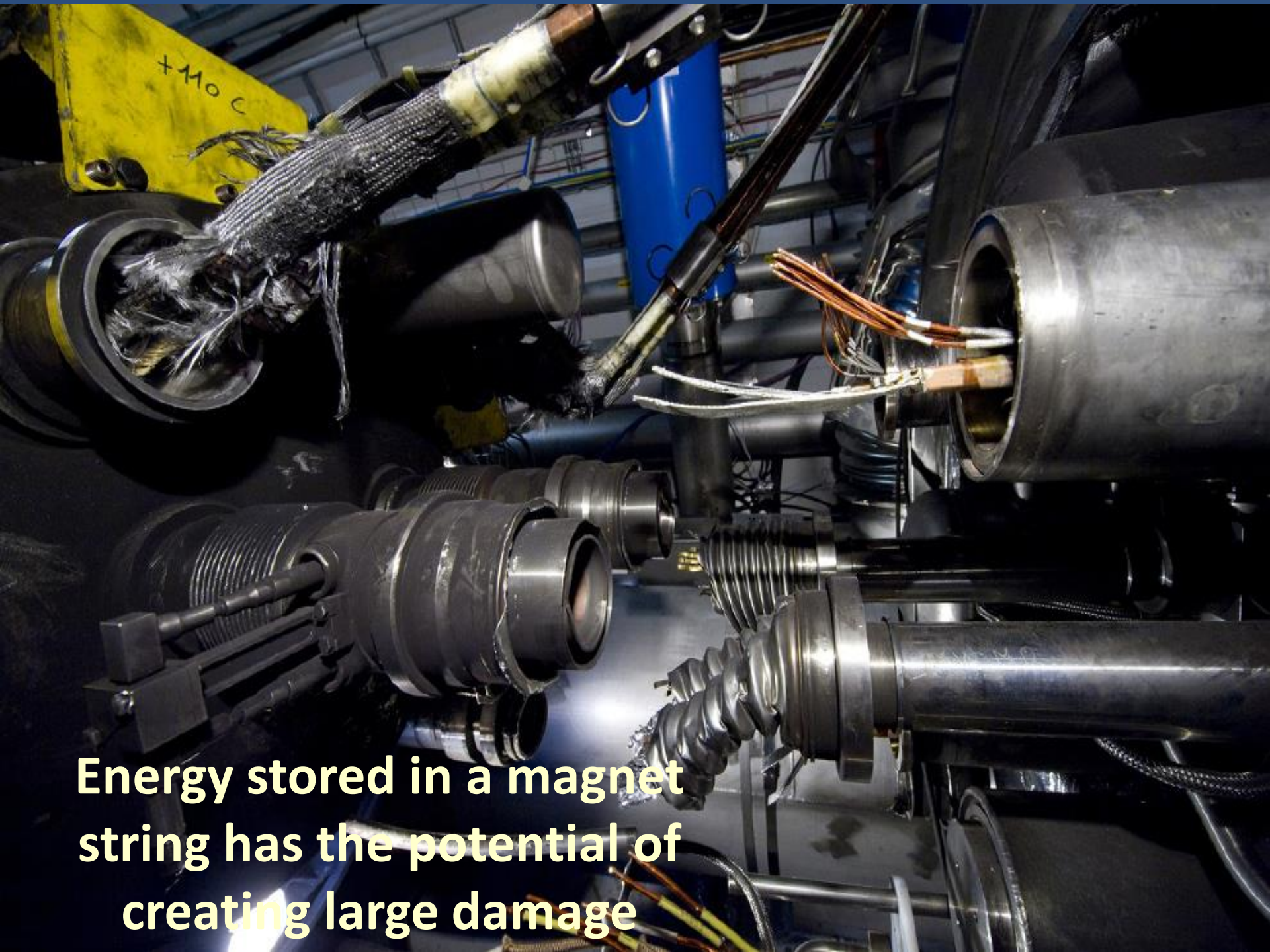
Stored energy in dipole magnets about 160 GJ

- 16 times higher than LHC, equivalent to nine A380 (560 t) at nominal speed (900 km/h)
- Magnet energy can melt 200 tons of copper

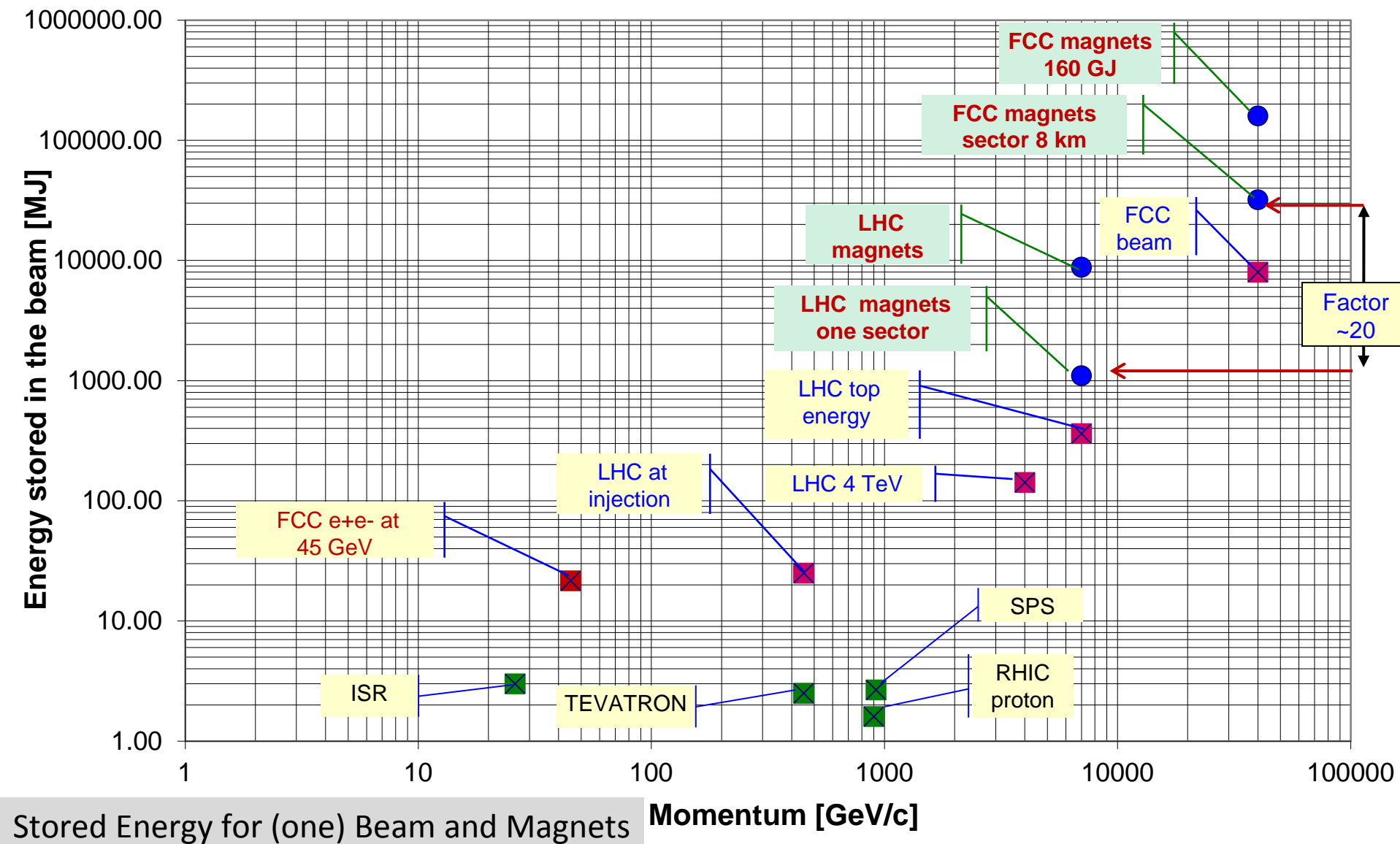


- Protection of individual magnets

Protection of electrical circuits to be addressed early on!



Energy stored in a magnet string has the potential of creating large damage



The part of the energy in the magnet system inside the coil is given by (scaling from LHC):

$$E_{\text{magnets}} \sim \frac{4 \times \text{Length} \times R^2 \times \pi \times B^2}{\mu_0}$$

Length \sim 80 km

Radius vacuum chamber $R = 25$ mm

$B = 16$ T

$\mu_0 =$ permeability

$E_{\text{magnets}} \sim 130$ GJ

The exact calculation uses the magnet inductance See later

Elements attached to the circuit

- Magnets
 - Power converters
 - Warm bus-bars (..might be water cooled)
 - Cold bus-bars
 - Possibly superconducting links
 - Interconnections
 - Warm-to-cold transitions (current leads)
 - Instrumentation (monitoring and protection)
 - Quench heaters and power supplies
 - High-current switches
 - Resistors for energy extraction
 - Interlocks
- +cryogenics, vacuum, ...

- Stored energy in LHC dipole magnets: 9.2 GJ
 - All other circuits contribute with less than 10% of total energy

- Magnet

- Spl
- No
- (10

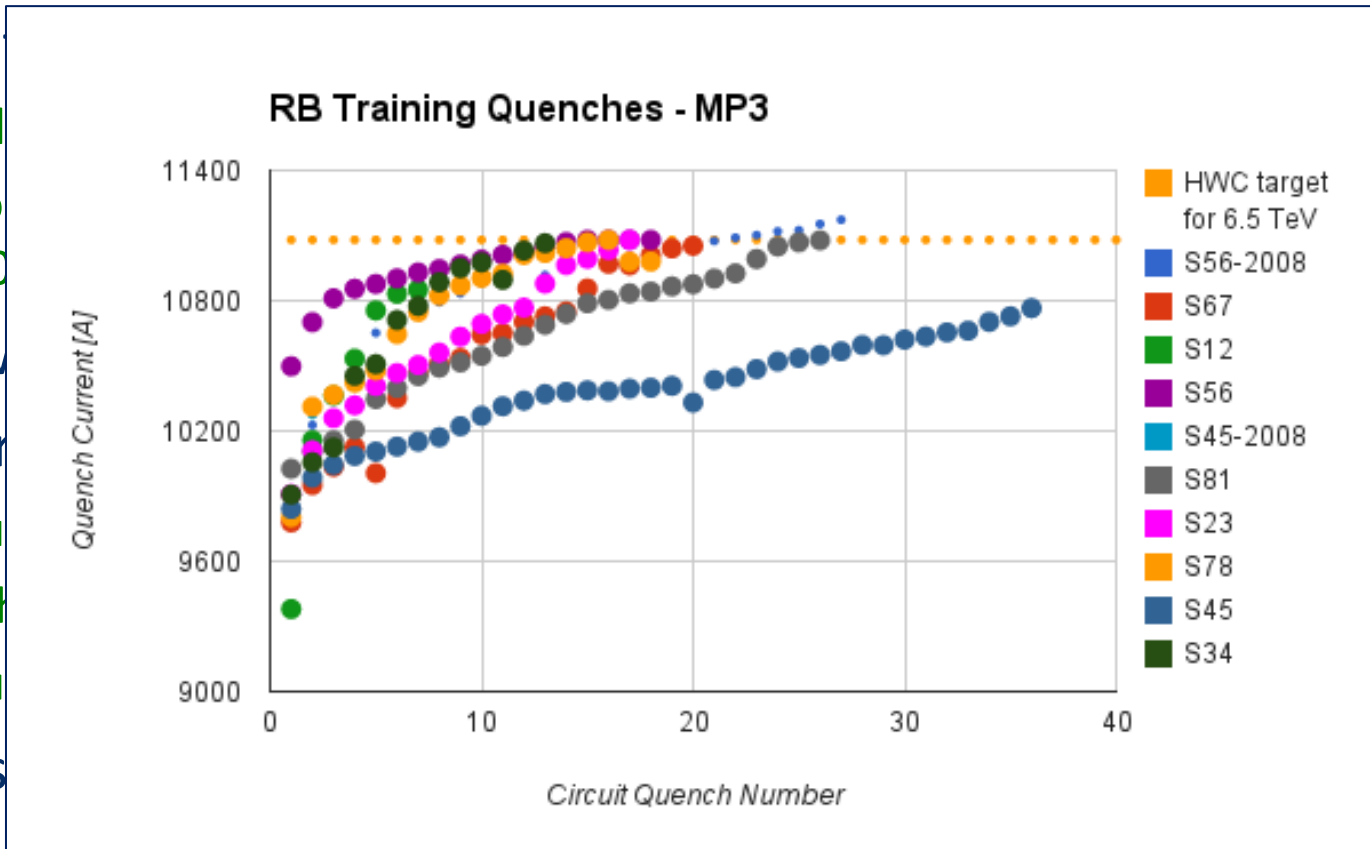
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- Decrease time constant: less quench propagation, diodes and bus-bars simpler

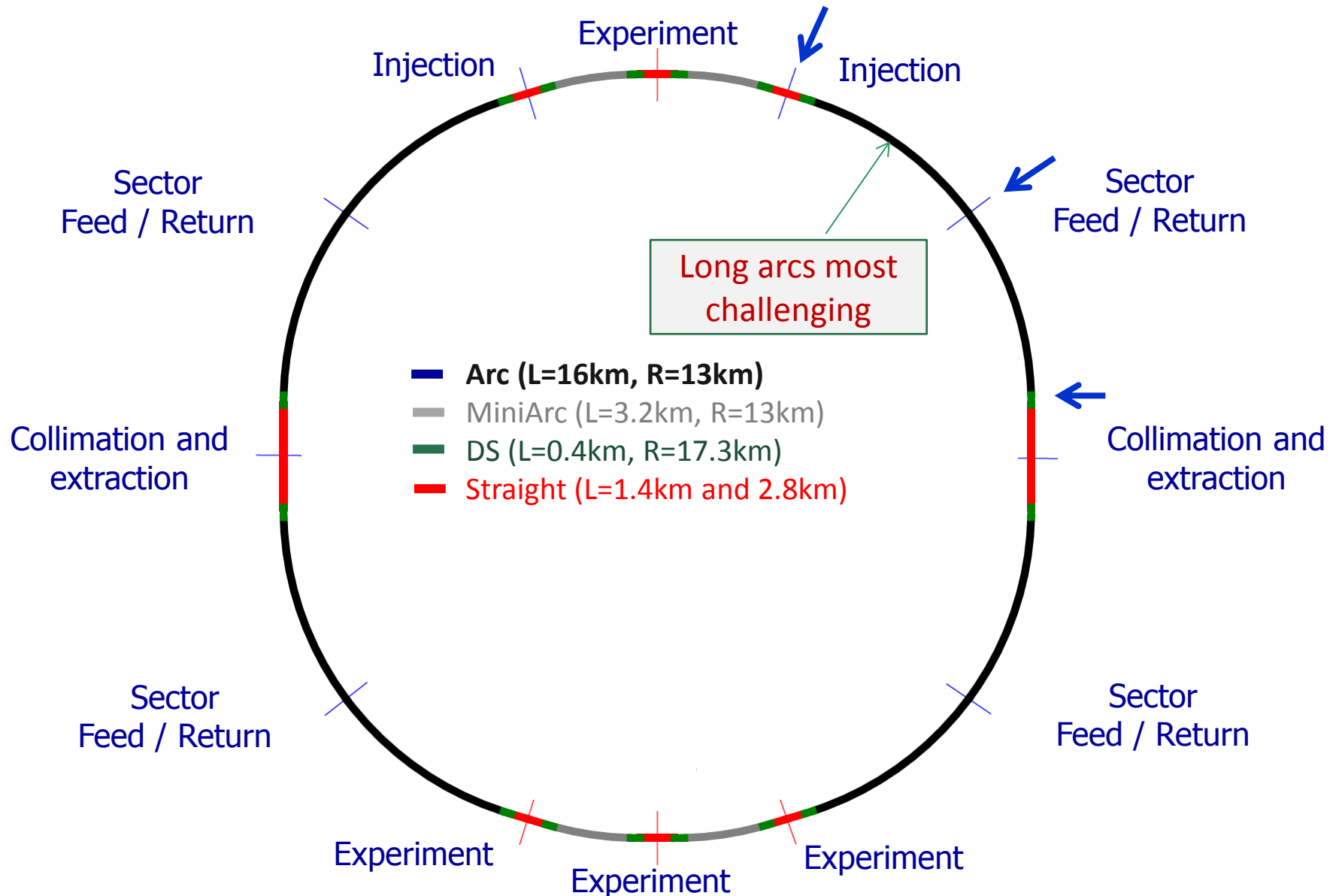


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Alignment **Shaft Tools**

Choose alignment option

Tunnel depth at centre: 286mASL

Gradient Parameters

Azimuth (°): -15

Slope Angle x-x(%): .3

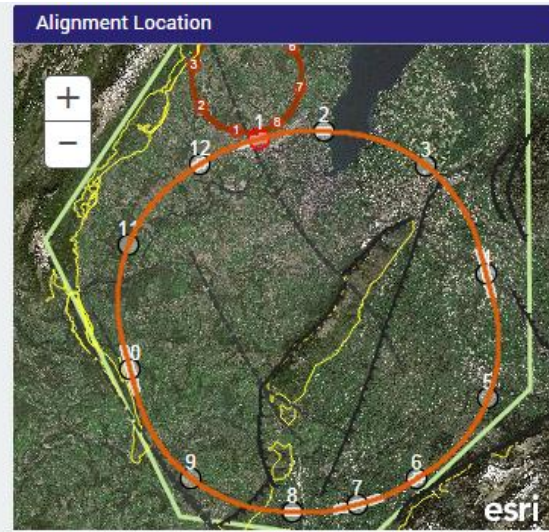
Slope Angle y-y(%): 0

CALCULATE

Alignment centre

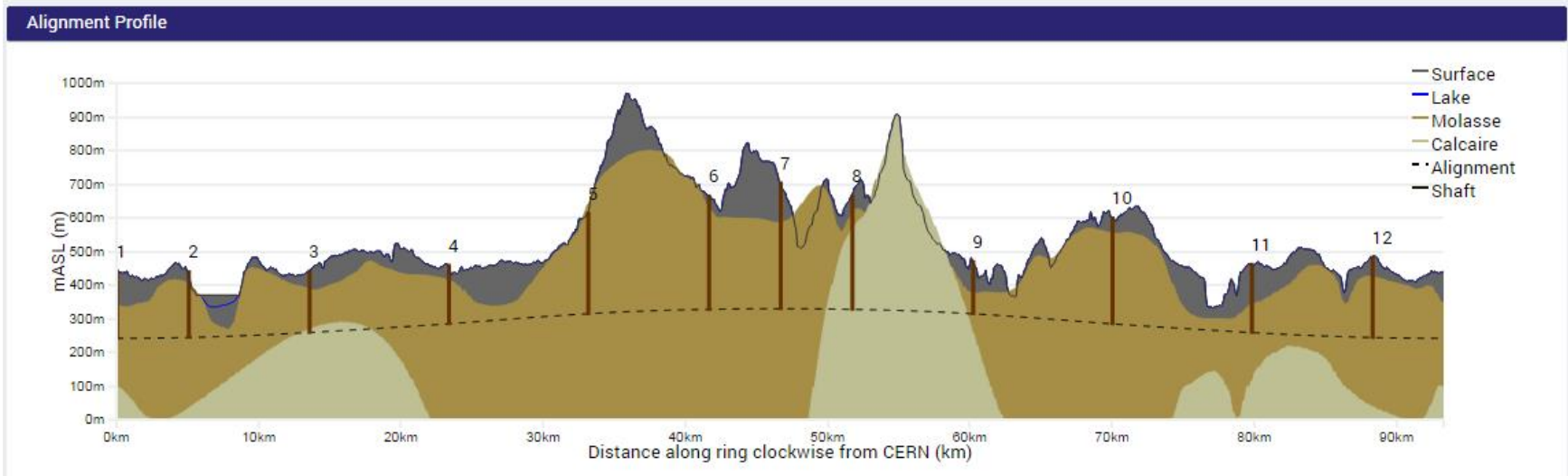
X: 2498923 Y: 1106695

LHC Intersection	IP 1	IP 2
Angle	1°	-1°
Depth	542m	542m



Geology Intersected by Shafts **Shaft Depths**

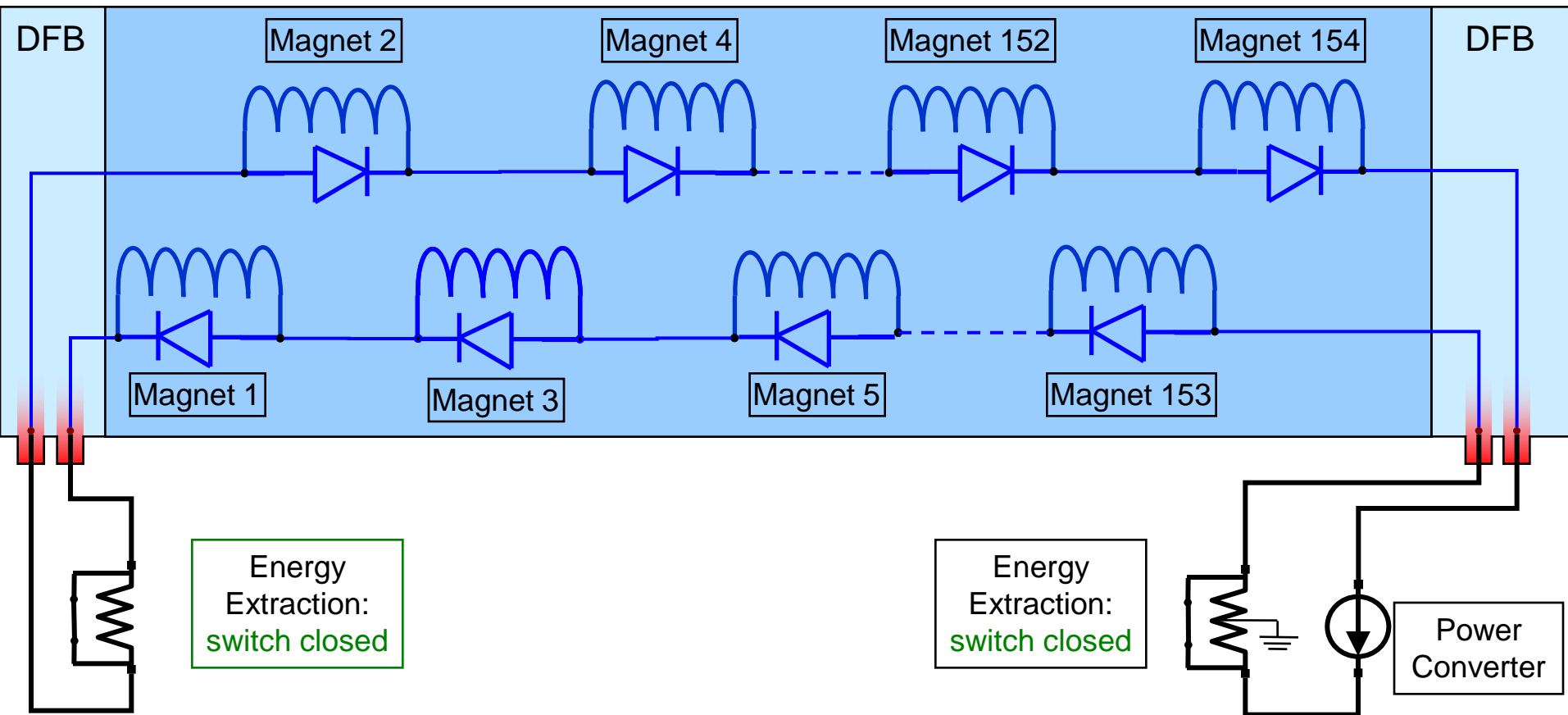
Shaft	Shaft Depth (m)				Geology (m)		
	Actual	Min	Mean	Max	Moraine	Molasse	Calcaire
1	200	195	197	200	92	108	0
2	196	143	181	211	34	162	0
3	183	175	184	194	53	121	9
4	174	146	166	178	44	130	0
5	299	286	311	350	0	325	0
6	336	325	339	350	35	302	0
7	374	349	377	412	119	256	0
8	337	318	341	366	44	56	237
9	155	131	145	167	94	61	0
10	315	305	320	336	46	269	0
11	203	199	202	204	122	81	0
12	239	229	238	243	58	181	0
Total	3014	2801	3001	3211	741	2052	247



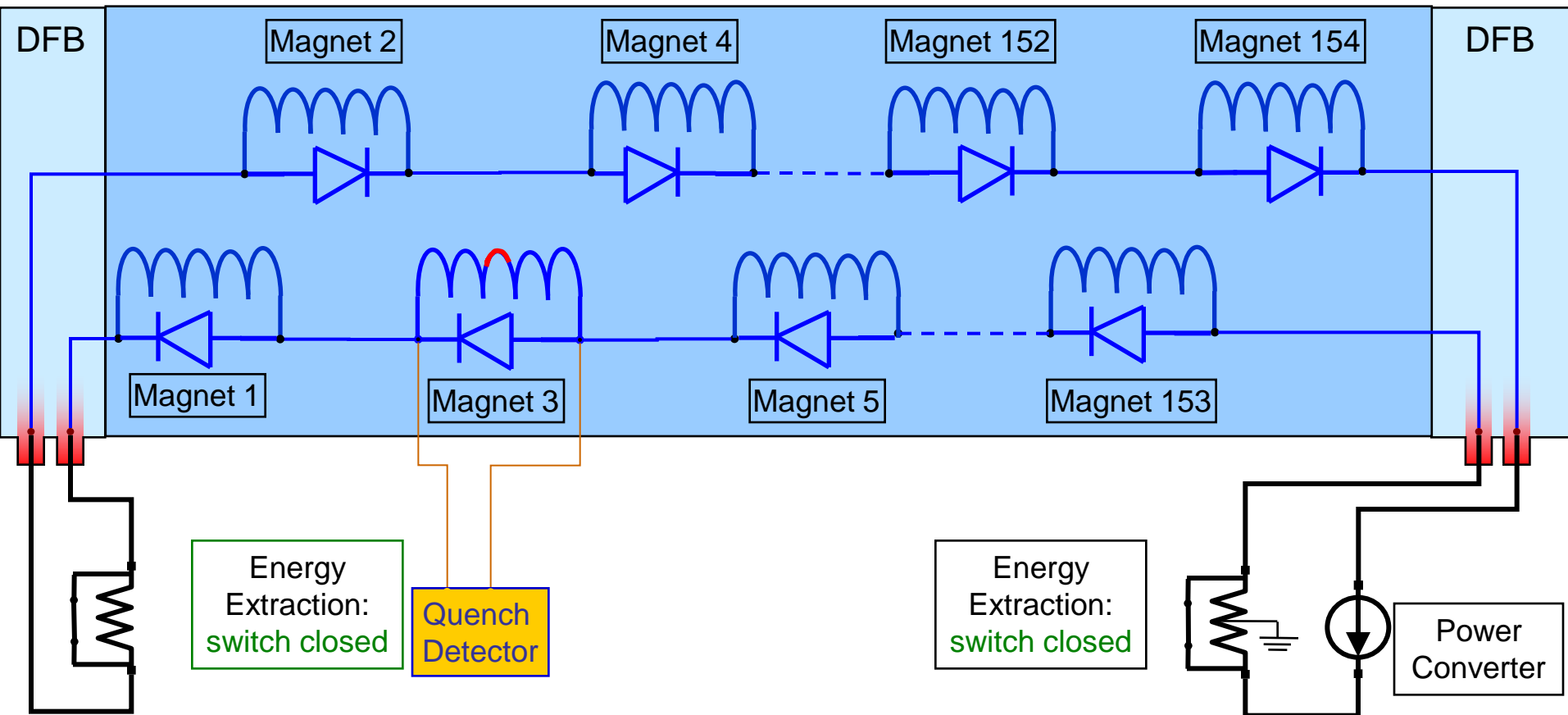
Difficult to imagine more access points

J. Osborne & C. Cook

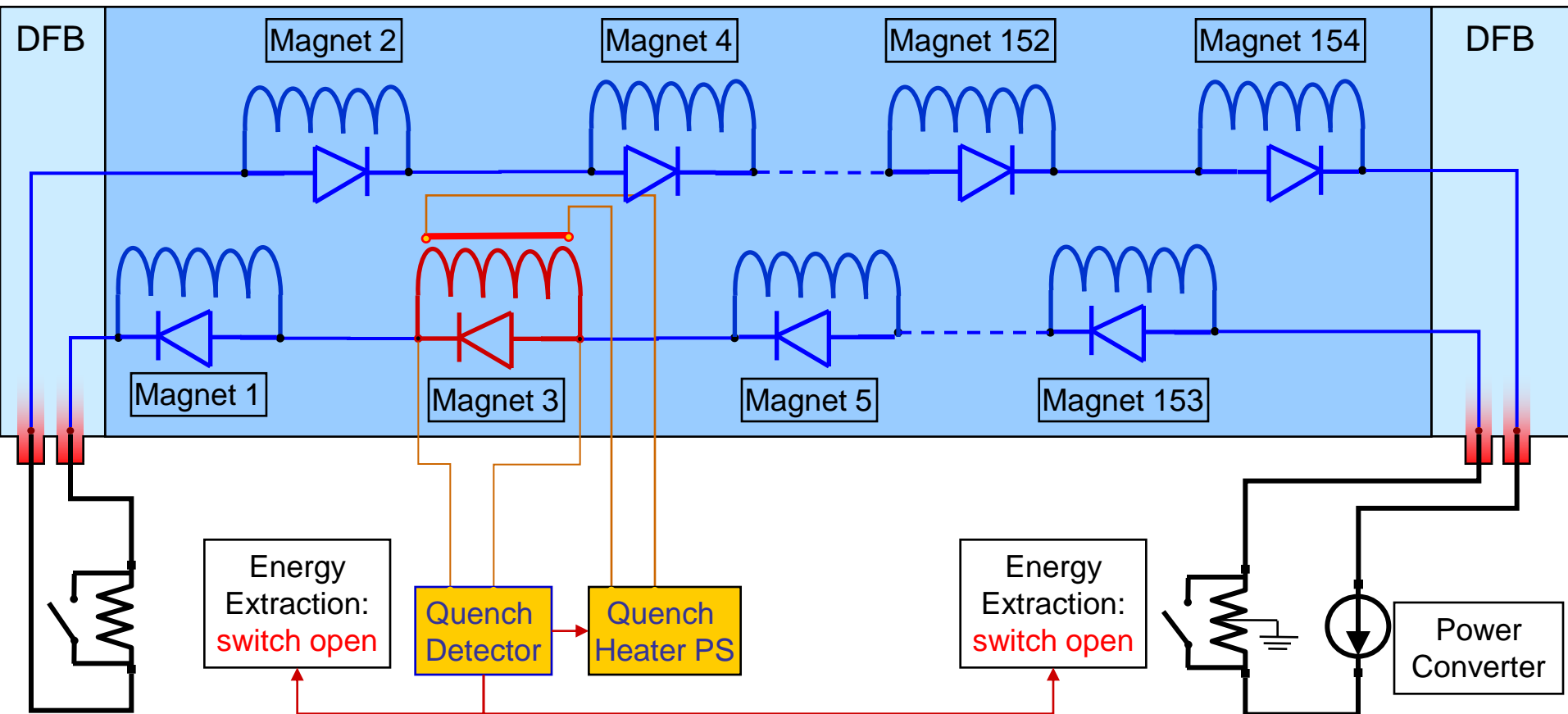
- Time for energy **ramp** is about **20-30 min** (Energy from the grid)
- Time for regular discharge is about **the same** (Energy back to the grid)



- **Quench in one magnet:** Resistance and voltage drop across quenched zone
- **Quench is detected:** Voltage across magnet exceeds 100 mV



- Quench heaters **warm up magnet** : energy deposited inside magnet (~ 200 ms)
- **Diode** in parallel **becomes conducting**: current in magnet string through diode
- **Resistance** is **switched into circuit**: **energy** of 153 magnets is **dissipated** into **resistance** (time constant of 100 s for main dipole magnets)



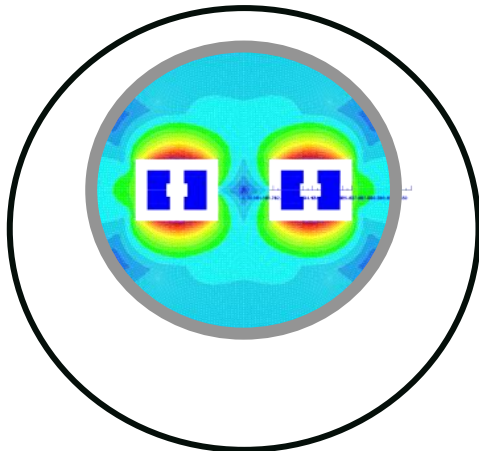
- To be considered: **Inductance** of a magnet string
- **Ramping** magnets needs energy => power converters need to provide electrical power
- **Discharge** after a quench in a given time => voltage

Start with scaling from LHC parameters

- Consider magnet strings of 8 km – one dipole circuit
- Assume magnet lengths as for LHC
- Assume field of 16 T
- Use three versions of magnet parameters (inductance, current)
 - Preliminary magnet parameters that were available (three options, D.Schoerling) are assumed
- Assume filling factor slightly better than LHC (length of field / length of sector)
- Calculate number of dipoles in a sector and circuit parameters
- Assume time for ramping the energy
- Calculate Voltage and Power required for ramp
- Assume time for discharge, e.g. after a quench
- Calculate discharge voltage during discharge with two (or more) energy extraction systems

Some parametric studies

- Split 16 km sector in two 8 km long powering sectors
- Length of a powering sector 8 km
- Consider dipole magnets



Design by D. Schoerling

	LHC	FCC option 1
	MB – cos(θ) @ 1.9 K	MB – block @ 1.9 K
Magnetic Length [m]	14.343	14.343
Mechanical Length [m]	15.000	15.000
Magnets in one sector	154	474
Total number of magnets	1232	4500
Current at top energy [kA]	11.80	16.26
Field at top energy [T]	8.330	16.0
Inductance [H/m]	0.0075	0.0190
Inductance [H] per magnet	0.108	0.273
Energy in one magnet [MJ]	7.52	36.03
Inductance in one sector [H]	16.6	129.2
Energy in one sector [MJ]	1157.9	17079.4
Energy in accelerator [MJ]	9263.4	162112.8

	LHC	FCC option 1	FCC option 1	FCC option 1
Voltage in ramp [V]	163.5	1750.7	2040.0	3391.5
Max power for ramping [MW]	1.93	28.47	45.90	29.00
Ramp time [min]	20	20	20	20
Max power for ramp all machine [MW]	15.4	270.2	435.7	275.2

- In one powering sector: 474 dipoles
- Ramping time of 20 min is assumed
- High voltage during ramping (magnets and all associated instrumentation must cope with it)
- Very high power to be provided by power converters during ramping

- Option 1 as LHC: Discharge time of 100 s, two energy extraction systems, one at each end of the string

	LHC	FCC option 1	FCC option 1	FCC option 1
Discharge time [s]	100	100	100	100
Number of EE systems	2	2	2	2
Total resistance required for discharge [Ohm]	0.166	1.292	1.088	4.760
Total Voltage across resistance [V]	1962.6	21007.9	24480.0	40698.0
dI/dt at the start of discharge [A/s]	118.0	162.6	225.0	85.5
Voltage for discharge [V] - 2 EE systems	981.3	10504.0	12240.0	20349.0

- Option 2 as LHC: Discharge time of 20 s, two energy extraction systems, one at each end of the string

	LHC	FCC option 1	FCC option 1	FCC option 1
Discharge time [s]	100	20	20	20
Number of EE systems	2	2	2	2
Total resistance required for discharge [Ohm]	0.166	6.460	5.440	23.800
Total Voltage across resistance [V]	1962.6	105039.6	122400.0	203490.0
dI/dt at the start of discharge [A/s]	118.0	813.0	1125.0	427.5
Voltage for discharge [V] - 2 EE systems	981.3	52519.8	61200.0	101745.0

- Option 3 : Discharge time of 20 s, many energy extraction systems (in this example 100)
- Option 4: Increased time constant (40 s = 50 EE systems)

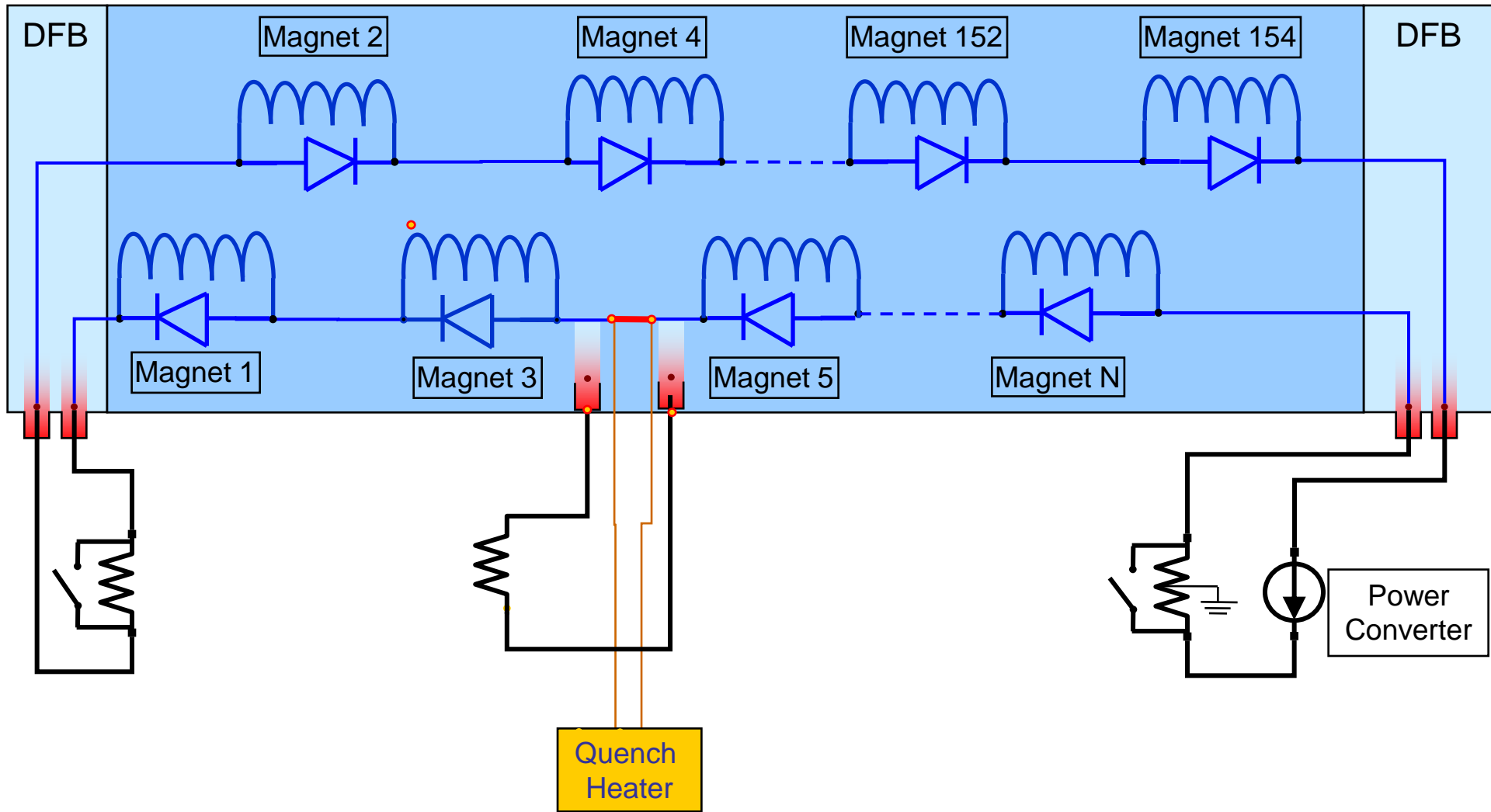
	LHC	FCC option 1	FCC option 1	FCC option 1
Discharge time [s]	100	20	20	20
Number of EE systems	2	100	100	100
Total resistance required for discharge [Ohm]	0.166	6.460	5.440	23.800
Total Voltage across resistance [V]	1962.6	105039.6	122400.0	203490.0
dI/dt at the start of discharge [A/s]	118.0	813.0	1125.0	427.5
Voltage for discharge [V] - 2 EE systems	981.3	1050.4	1224.0	2034.9
	LHC	FCC option 1	FCC option 1	FCC option 1
Discharge time [s]	100	40	40	40
Number of EE systems	2	50	50	50
Total resistance required for discharge [Ohm]	0.166	3.230	2.720	11.900
Total Voltage across resistance [V]	1962.6	52519.8	61200.0	101745.0
dI/dt at the start of discharge [A/s]	118.0	406.5	562.5	213.8
Voltage for discharge [V] - 2 EE systems	981.3	1050.4	1224.0	2034.9

- Option 5: increase time constant from 100 s to 360 s to reduce voltage

	LHC	FCC option 1	FCC option 1	FCC option 1
Discharge time [s]	100	360	360	360
Number of EE systems	2	2	2	2
Total resistance required for discharge [Ohm]	0.166	0.359	0.302	1.322
Total Voltage across resistance [V]	1962.6	5835.5	6800.0	11305.0
dIdt at the start of discharge [A/s]	118.0	45.2	62.5	23.8
Voltage for discharge [V] - 2 EE systems	981.3	2917.8	3400.0	5652.5

These values are approximate, and depend on several parameters, but will not change by more than, say, some 10%

- Best to have shorter powering sectors... civil engineering?
- Reduction of ramp rate reduces power... but 20 min is already long
- Powering each dipole aperture separately (gain a factor of 2, more bus-bars required)
- Fast extraction of energy by many energy extraction points
 - Limited by maximum current decay that is permitted without quenching magnets (possibly 1000 A/s)
 - Assume maximum voltage of about 1 kV
- Alternative to mechanical switches as in LHC: are superconducting switches possible?
 - Stretch of sc cable heated by a quench heater, becomes conducting
 - In parallel, resistor outside the cryostat with lower resistance
- Can we consider cold resistors?



One example

- Needs current leads that carry current during time for extraction
- Assuming voltage across extraction resistor of 1 kV
- The value of one resistor is 62.5 mOhm
- Assuming a time constant of 20 s, 100 of such resistors are required
- Assuming a time constant of 20 s and a current of 16 kA, a busbar of about 120 mm² is required to connect an extraction resistor
- Acceptable for cryogenic system?
- Volume of dump resistors to be considered

Providing the power

Energy in the FCC Magnets: 600 Teslas



Is there a way to store and recuperate the energy of the magnets using batteries?

As for LHC: lot of electronics in the tunnel ??

- FCC: Quench detection system requires several 10000 electronics cards and ~20000 quench heater power supplies
- Power supplies for orbit corrector magnets
- Beam loss monitors and their front-end electronics
- Equipment for vacuum control
- Equipment for cryogenics control

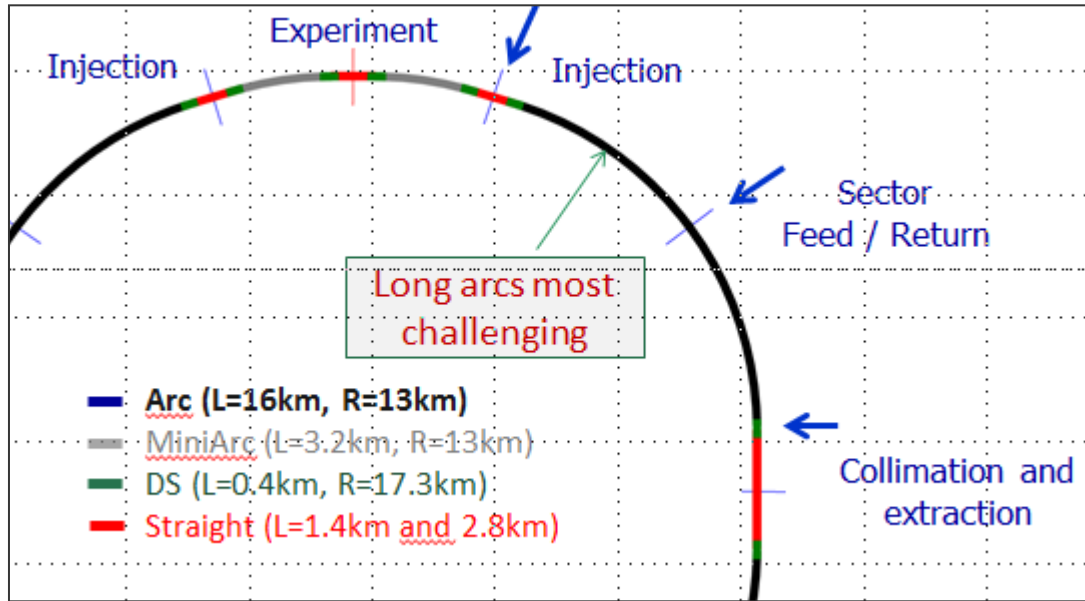
Radiation, limitation in design, long access time, safety of personnel in tunnel imposes restrictions, ...

As little electronics as possible in the tunnel

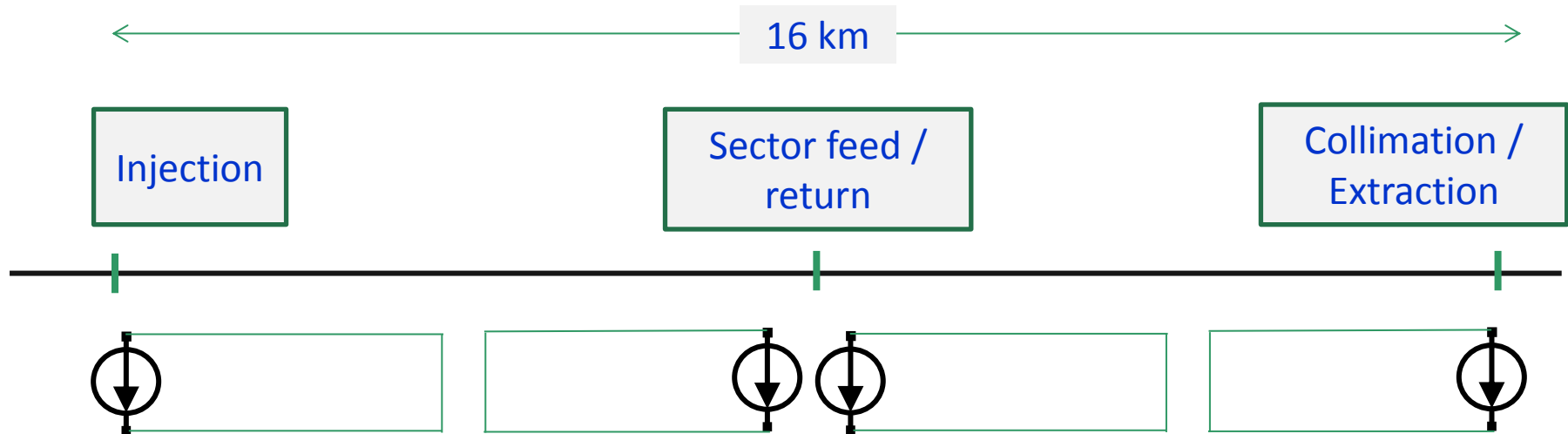
- Excellent experience with powering of many circuits via long cold bus-bars (all 600 A circuits) in so-called N-line and other lines
- Orbit corrector magnet supplied by sc cables in the cold
 - Powering of orbit power converters via type of “N-line”
- Quench heater power supplies / CLIQ system: can the High Voltage provided by a central HV supply and distributed to the magnets?
 - Local switches still required
- Minimum complexity of front end electronics: communication from service computers to front-end electronics in tunnel will be critical -> R&D required (also for HL-LHC)
 - Excellent experience with signal transmission via optical fibres
 - Experiments are thinking about wireless communication
- What to do with electronics for vacuum and cryogenics?

- Availability: as far as possible, redundant systems should be used
- Availability: no single failure in an electronics component or in a cable connection should lead to a beam dump
- For protection systems: 2oo3 voting to be considered (quench detection system, interlocks, beam loss monitors)
- For other system, redundancy / hot spares
 - To be designed such that beam survives switching to hot spare
 - Monitoring of failed unit required
 - Repair during maintenance period
- Longer sectors: longer intervention time, magnet training takes longer in case it is required

Reducing length of powering sector to 4 km ?



For the long arcs, this would result in 16 powering sector, each with 4 km length, ramp voltage in the order of 1 kV



- Is it possible to reduce the length of a magnet string?
 - Reduction by a factor of 2 by powering an 8 km long sector from both sides?
 - Further reduction?
- What ramp time should we consider?
- What voltage for the magnets is acceptable?
- Are sc switches possible?
- What about the load of current leads (e.g. 120 mm²) to the cryogenics system?

- Magnets with a field of 16 T magnet are very challenging
- The FCC powering and protection system to safely power a string with such magnets is similarly challenging
- Simple scaling from LHC will result in a system that is too expensive, and cannot be efficiently operated
- Shorter powering sectors are preferred
- For the system to ensure safe and efficient powering of the magnets, new ideas and R&D on new technologies is required!

MICHIGAN STATE UNIVERSITY

Lessons Learned [MJS] Mike Syphers
Tuesday

- Modularity in the optics design and layout was VERY important; “saved the day” several times
- A certain amount of “free space” in the arcs will be very important — diagnostics, collimators, other?
 - ▶ avoid MANY km of solid cryostat

To many colleagues who were involved in LHC powering over the years

Special thanks to....

- Arjan Verweij
- Luca Bottura
- Daniel Schoerling