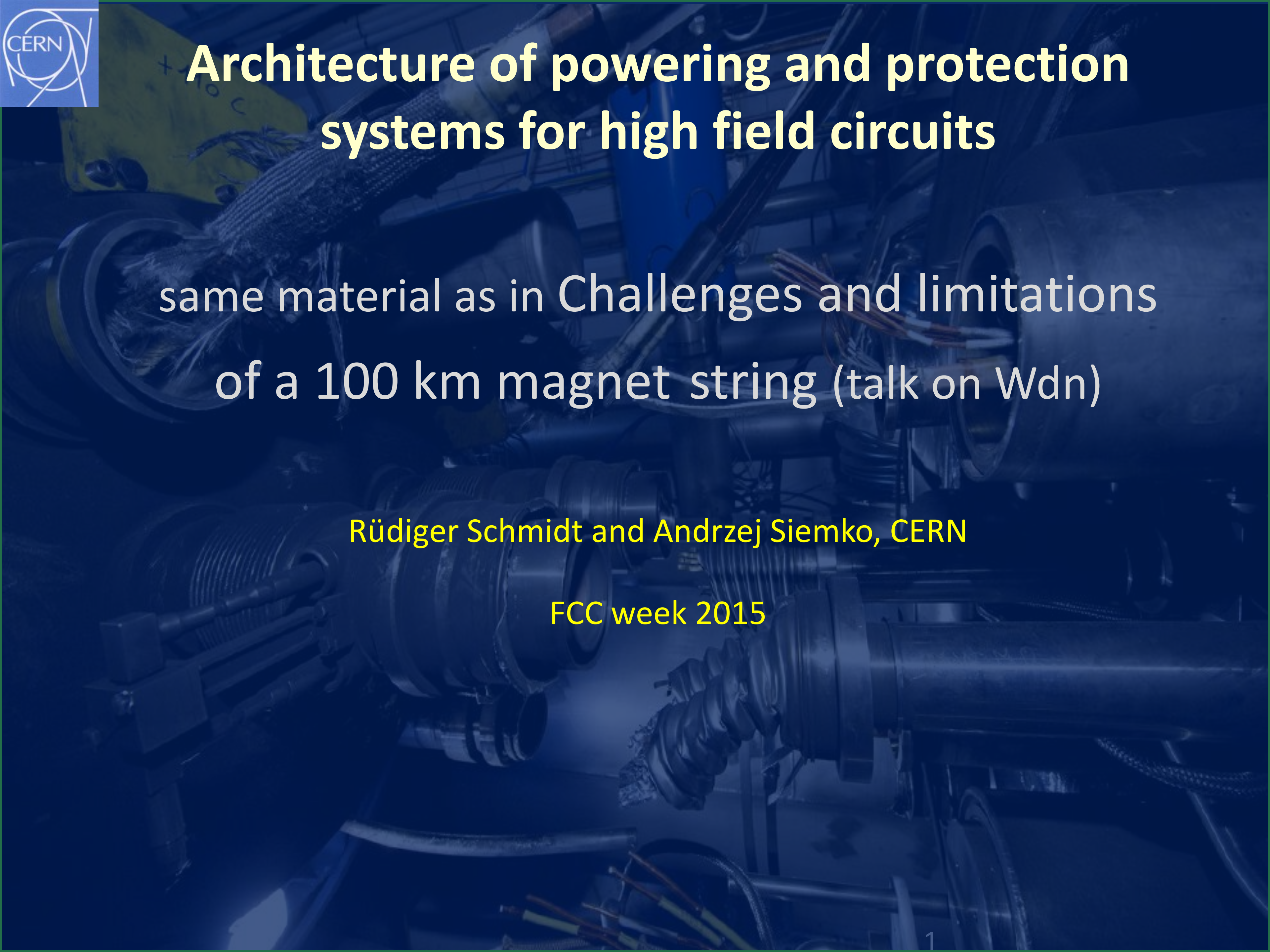


Architecture of powering and protection systems for high field circuits

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

Rüdiger Schmidt and Andrzej Siemko, CERN

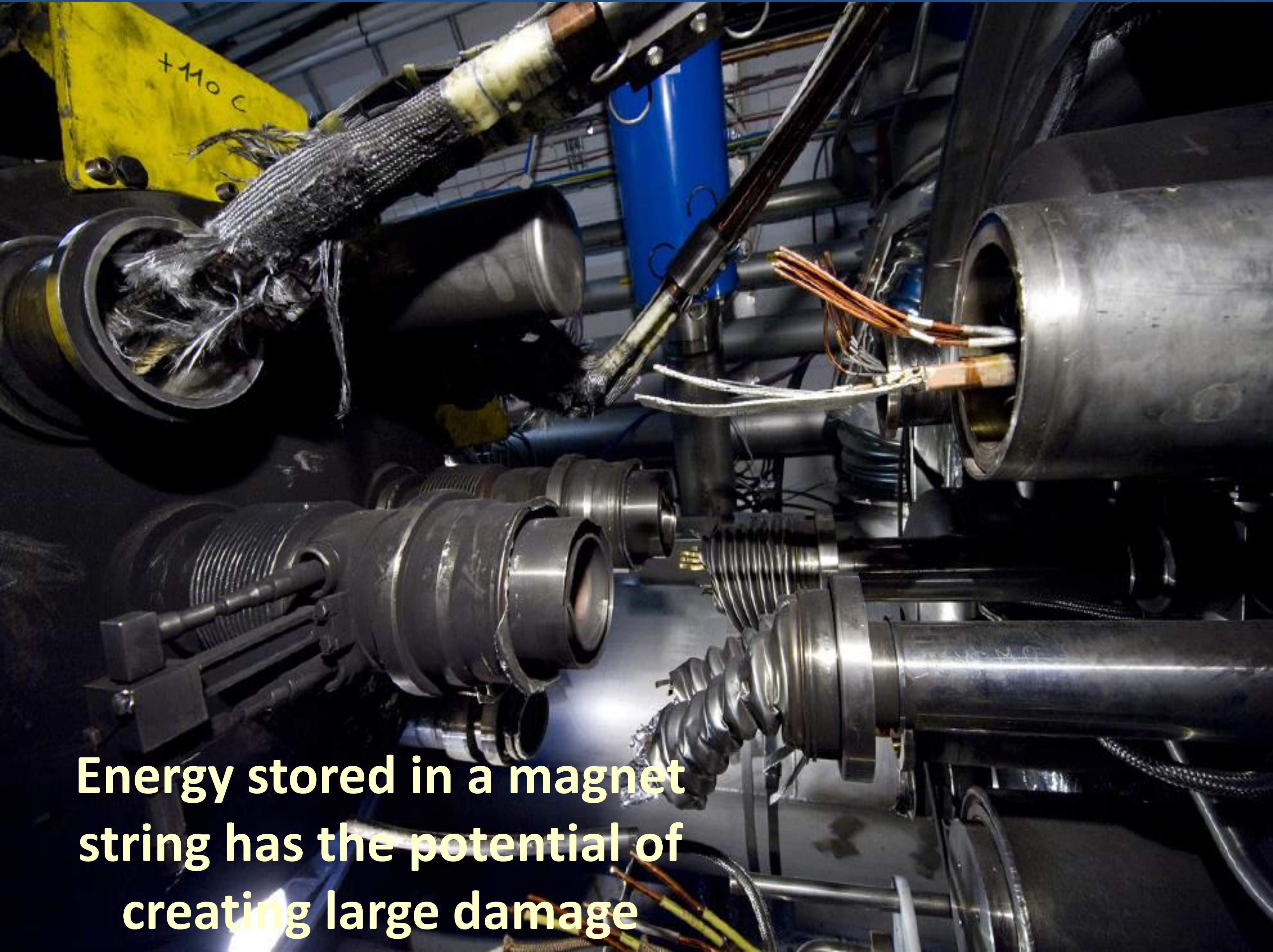
FCC week 2015

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

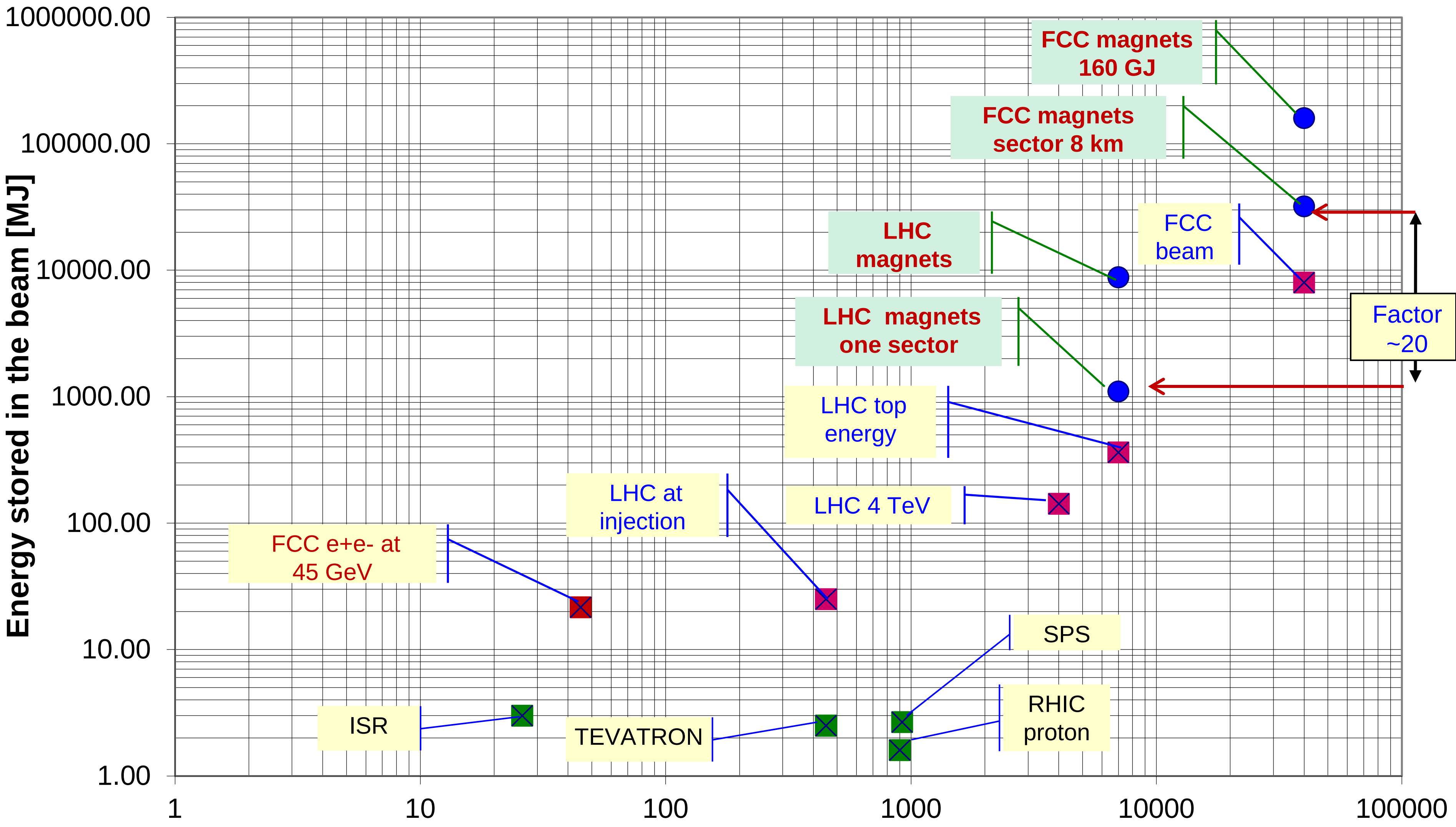
- Protection of individual magnets

Protection of electrical circuits to be addressed early on!



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

Energy versus momentum



Stored Energy for (one) Beam and Magnets

Momentum [GeV/c]

Energy stored in superconducting magnets

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

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

$\mathrm{Length} \sim 80\ \mathrm{km}$

$\mathrm{Radius\ vacuum\ chamber\ R} = 25\ \mathrm{mm}$

$\mathrm{B} \ = 16\ \mathrm{T}$

$\mu_0 = \mathrm{permeability}$

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

The exact calculation uses the magnet inductance …. See later

Electrical circuit for superconducting magnets

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, …

Some lessons from LHC

- Stored energy in LHC dipole magnets: 9.2 GJ
  - All other circuits contribute with less than 10% of total energy
- Magne
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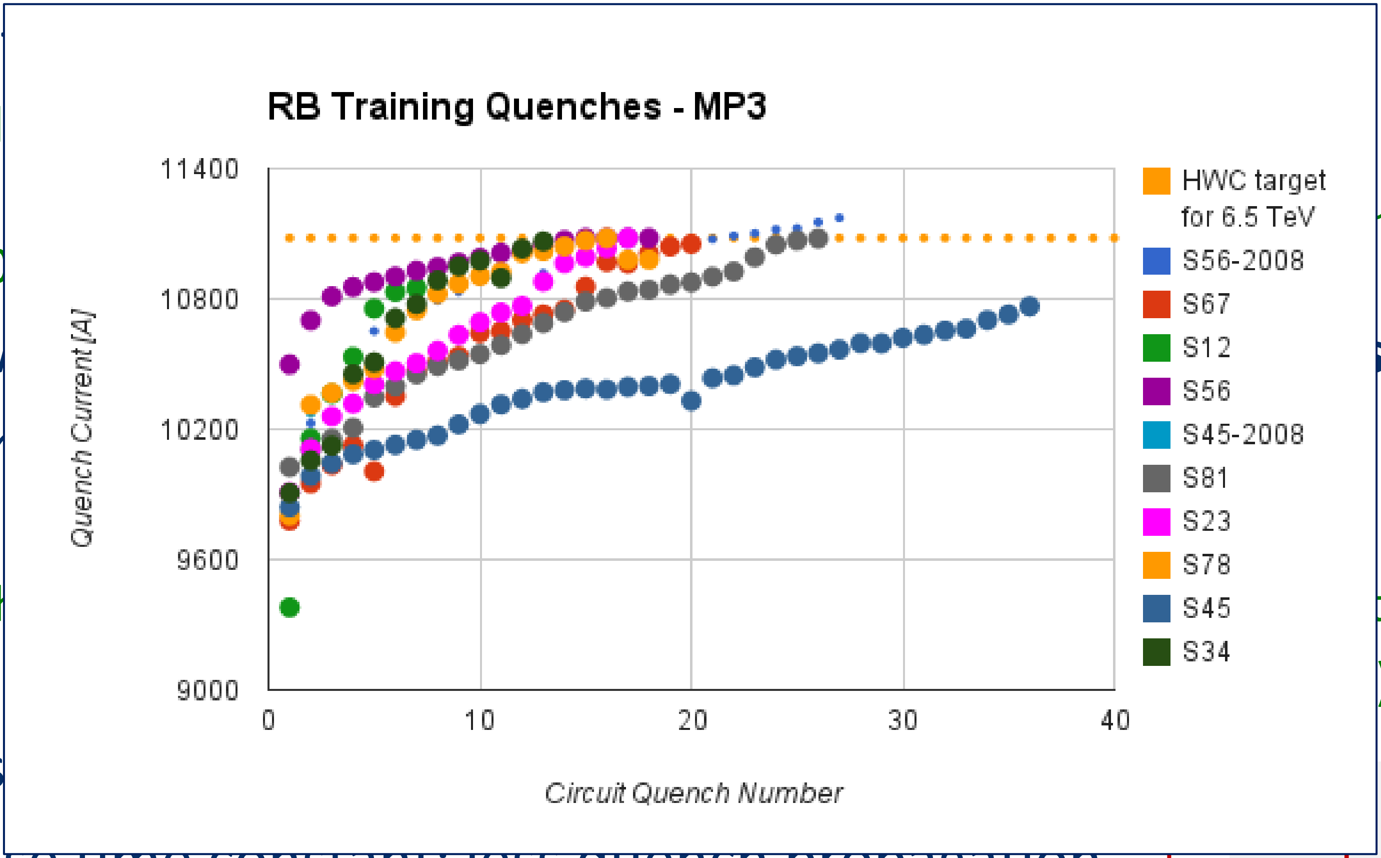
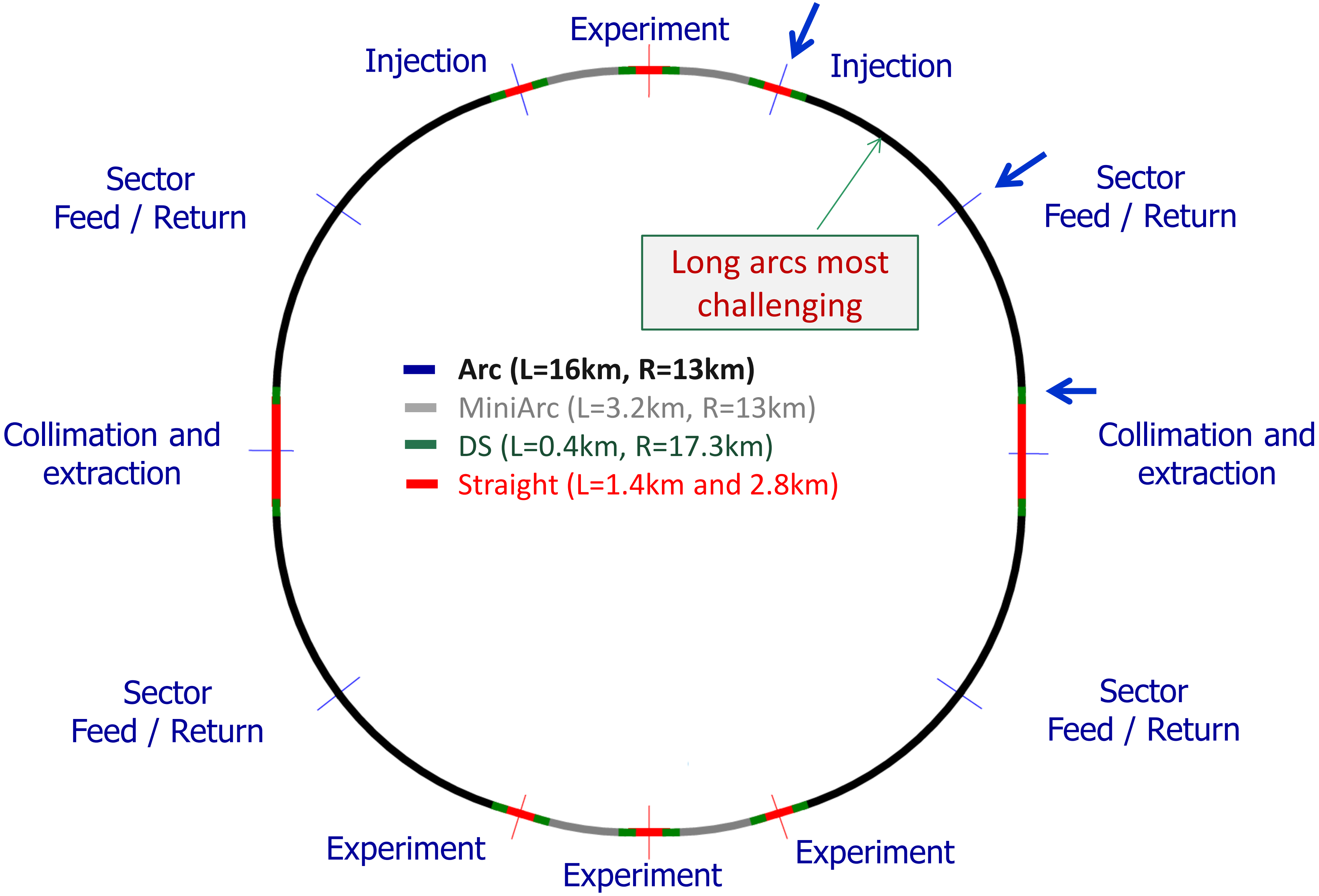
- Decrease time constant: less quench propagation, diodes and bus-bars simpler



s more studies

Layout of FCC-hh – defines options

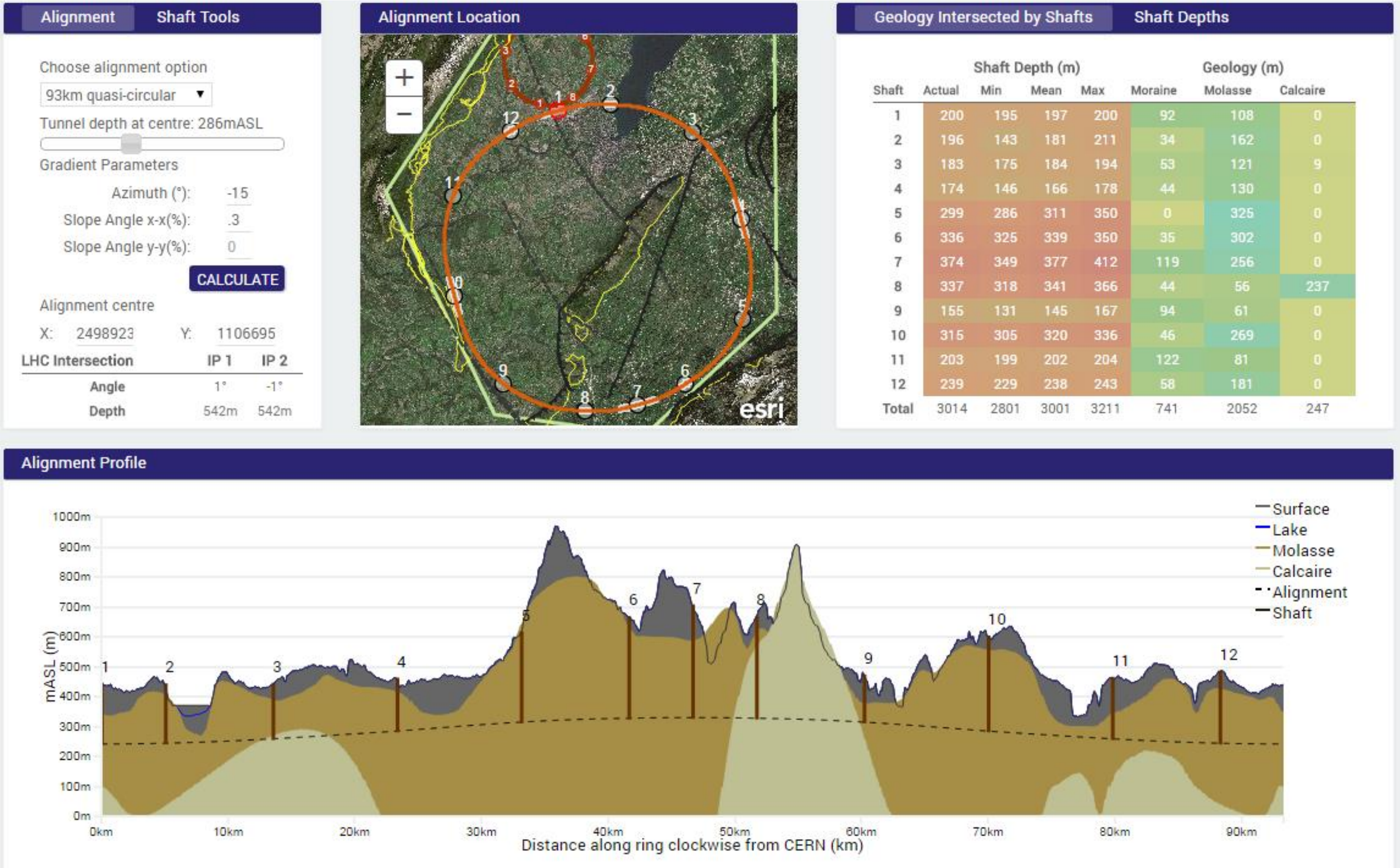


Long arcs most challenging

- 🟦 **Arc (L=16km, R=13km)**
- ⬜ MiniArc (L=3.2km, R=13km)
- 🟩 DS (L=0.4km, R=17.3km)
- 🟥 Straight (L=1.4km and 2.8km)

Siting study 93 km perimeter

PRELIMINARY



Choose alignment option

93km quasi-circular ▼

Tunnel depth at centre: 286mASL

Gradient Parameters

Azimuth (°): -15

Slope Angle x-x(%): .3

Slope Angle y-y(%): 0

Alignment centre

X: 2498923 Y: 1106695

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

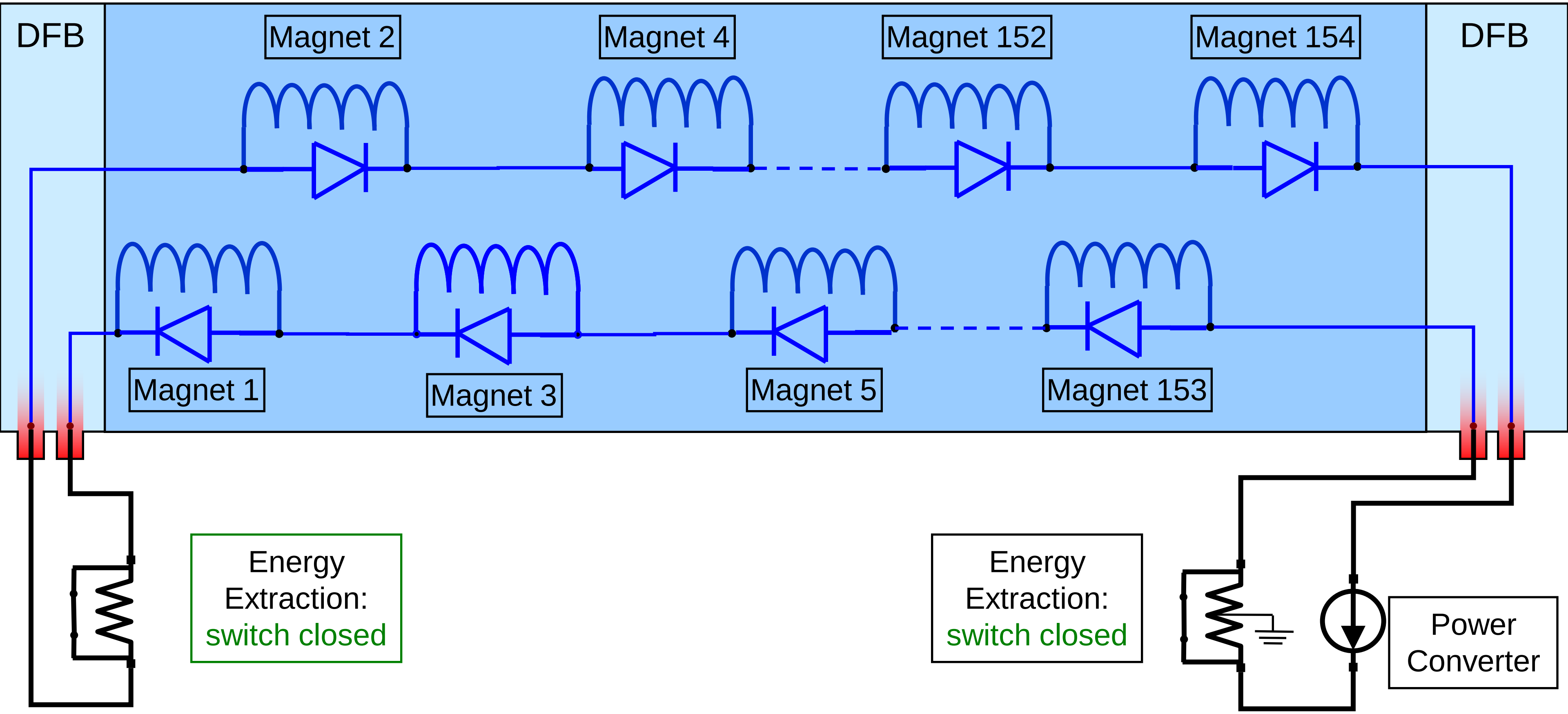
	Shaft Depth (m)				Geology (m)		
Shaft	Actual	Min	Mean	Max	Moraine	Molasse	Calcaire
1	200	195	197	200	92	108	0
2	196	143	181	211	34	162	0
3	183	175	184	194	53	121	9
4	174	146	166	178	44	130	0
5	299	286	311	350	0	325	0
6	336	325	339	350	35	302	0
7	374	349	377	412	119	256	0
8	337	318	341	366	44	56	237
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

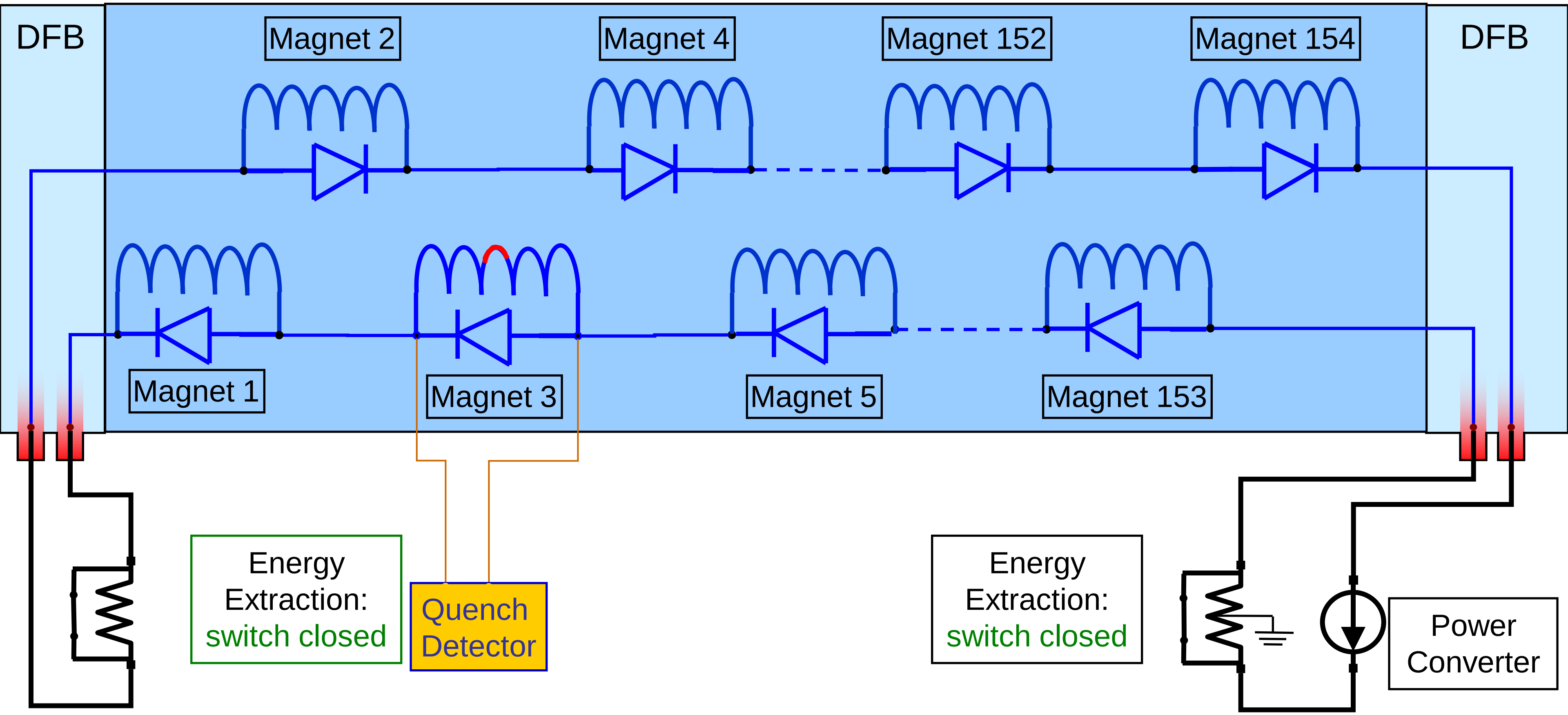
Powering and Protection of LHC dipole string

- 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)



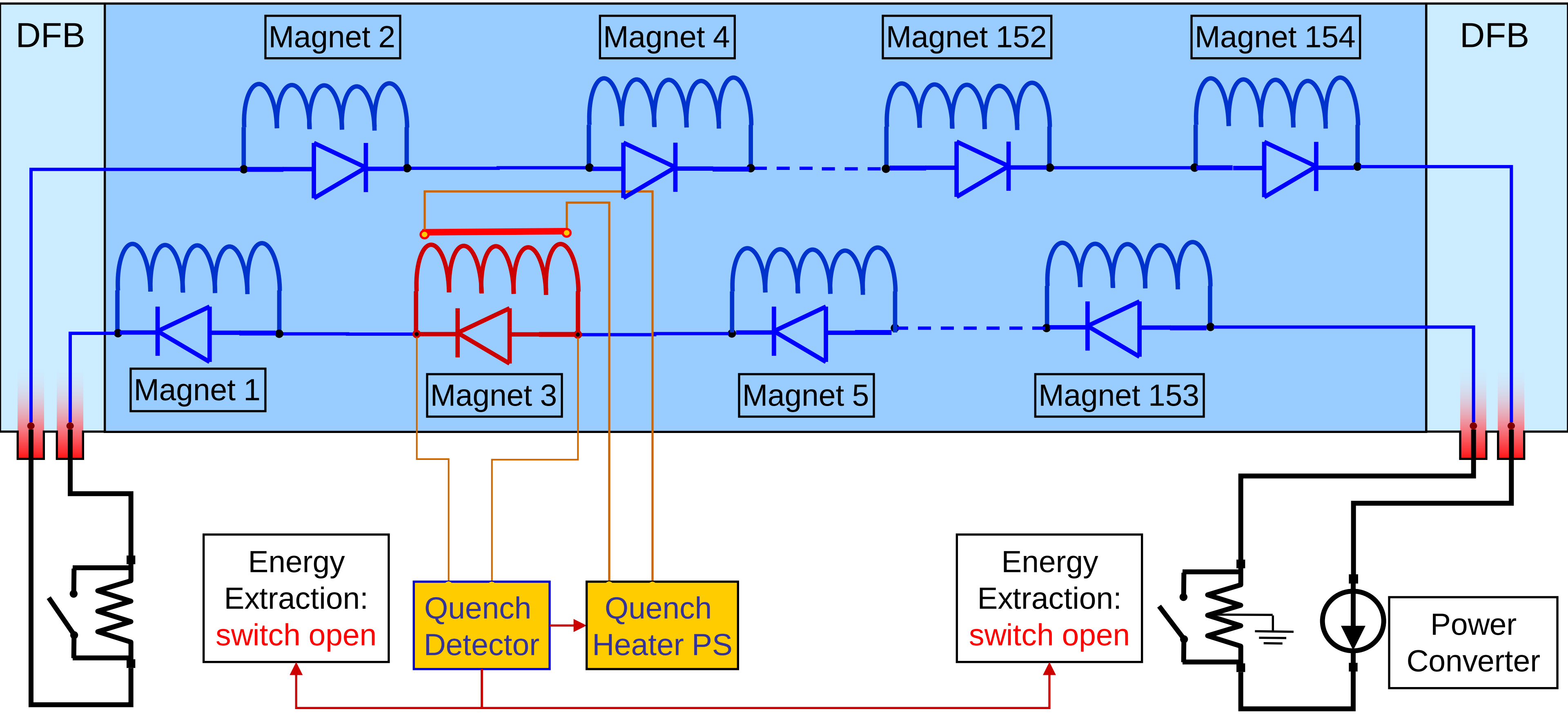
Powering and Protection of LHC dipole string

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



Powering and Protection of LHC dipole string

- 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)



Magnet String in FCC

- 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

FCC magnet string: dipoles

- 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

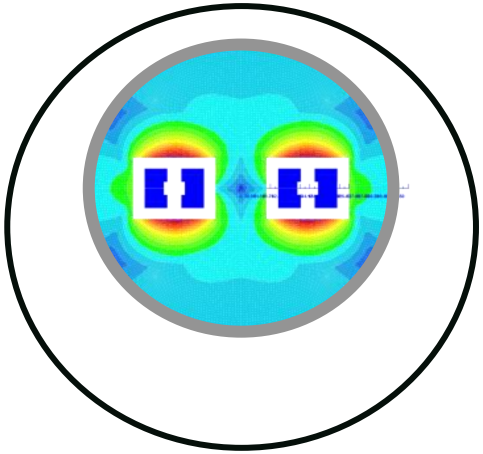
FCC magnet string: dipoles

Some parametric studies

Circuit parameter

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

	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



Design by D. Schoerling

Ramping the dipole string

	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

Discharge of the dipole string

- 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
dIdt 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
dIdt 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

Discharge of the dipole string

- 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
dIdt 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
dIdt 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

Discharge of the dipole string

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

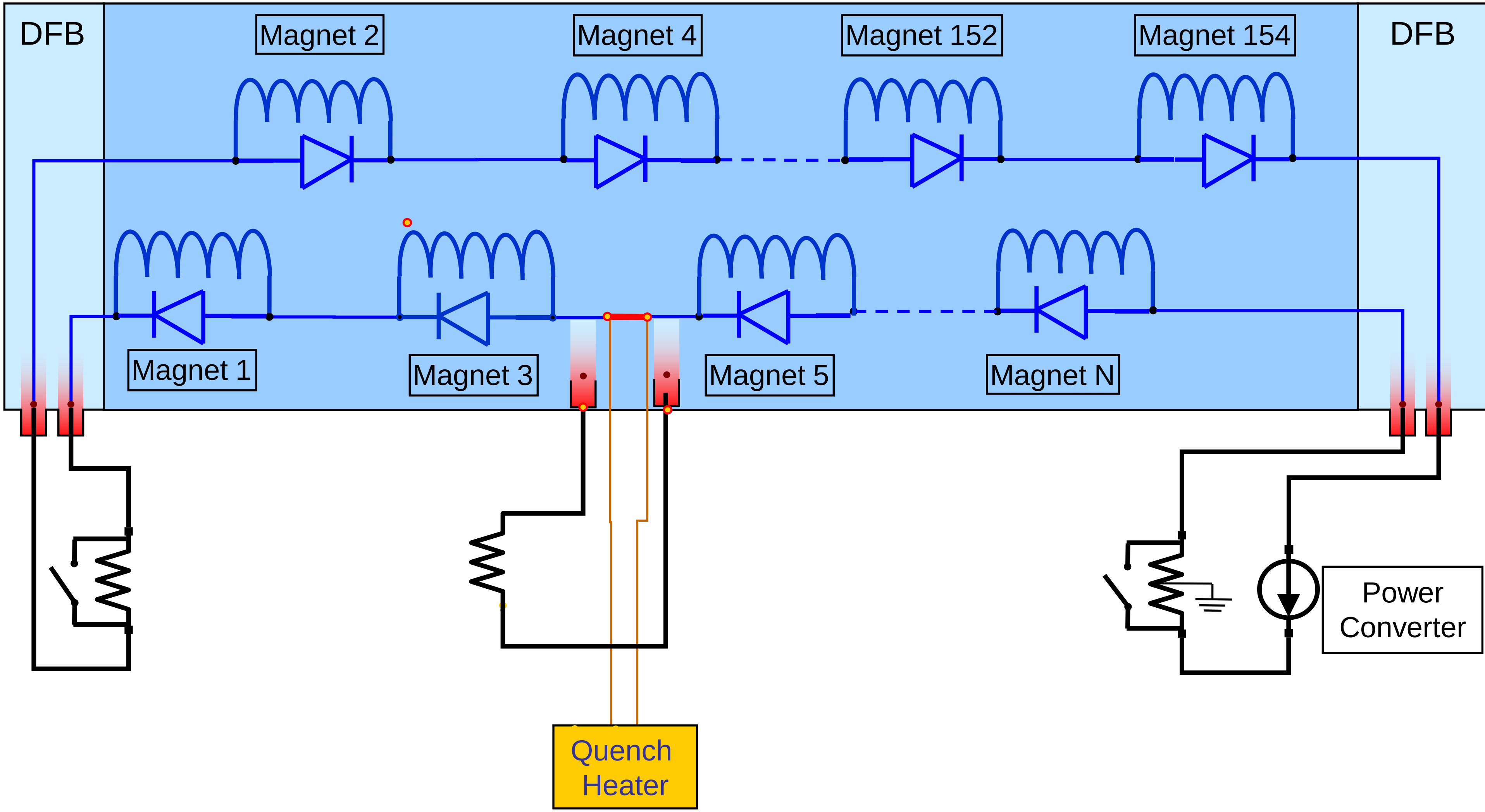
	LHC	**FCC option 1**	**FCC option 1**	**FCC option 1**
Discharge time [s]	100	360	360	360
Number of EE systems	2	2	2	2
Total resistance required for discharge [Ohm]	0.166	0.359	0.302	1.322
Total Voltage across resistance [V]	1962.6	5835.5	6800.0	11305.0
dIdt at the start of discharge [A/s]	118.0	45.2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

Some parameters to be explored….

- 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?

Powering and Protection of LHC dipole string



A long magnet string to be discharged…

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 bus-bar 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

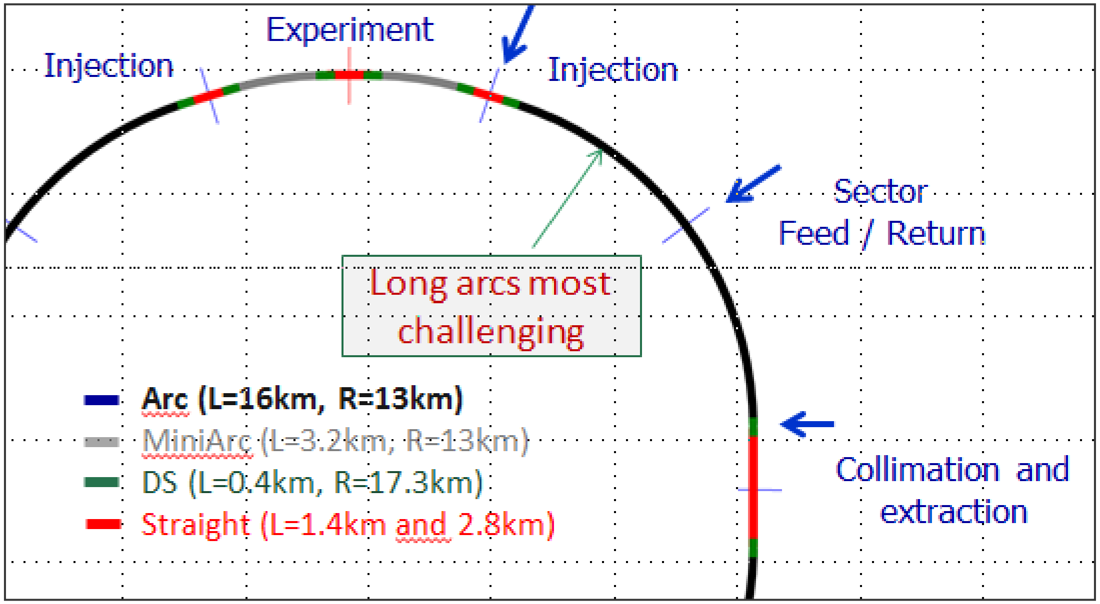
Ideas to be looked at

- 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?

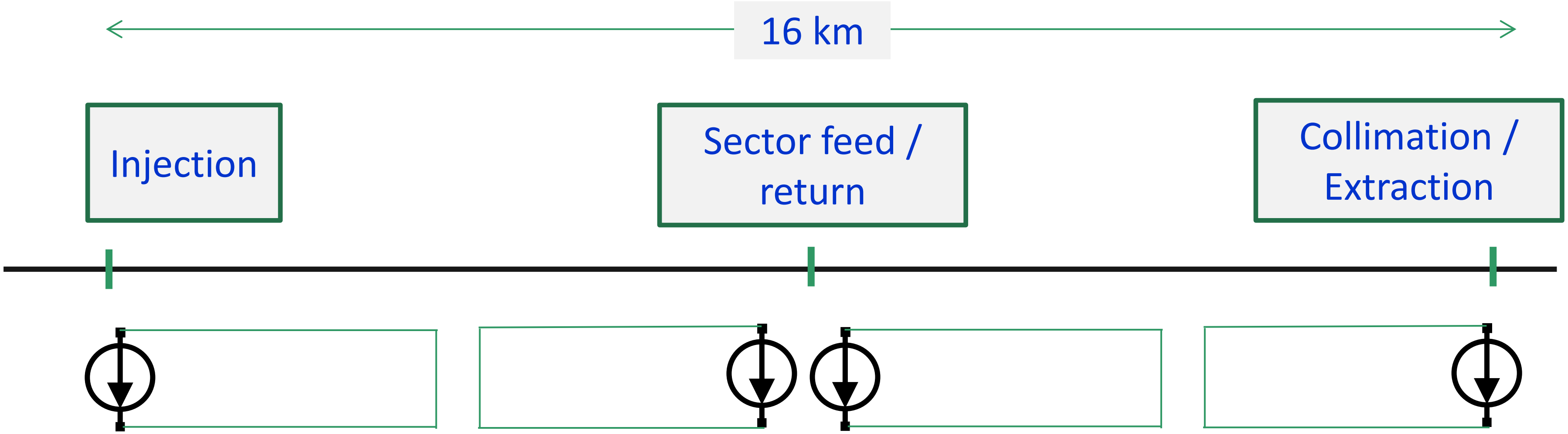
Availability

- 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

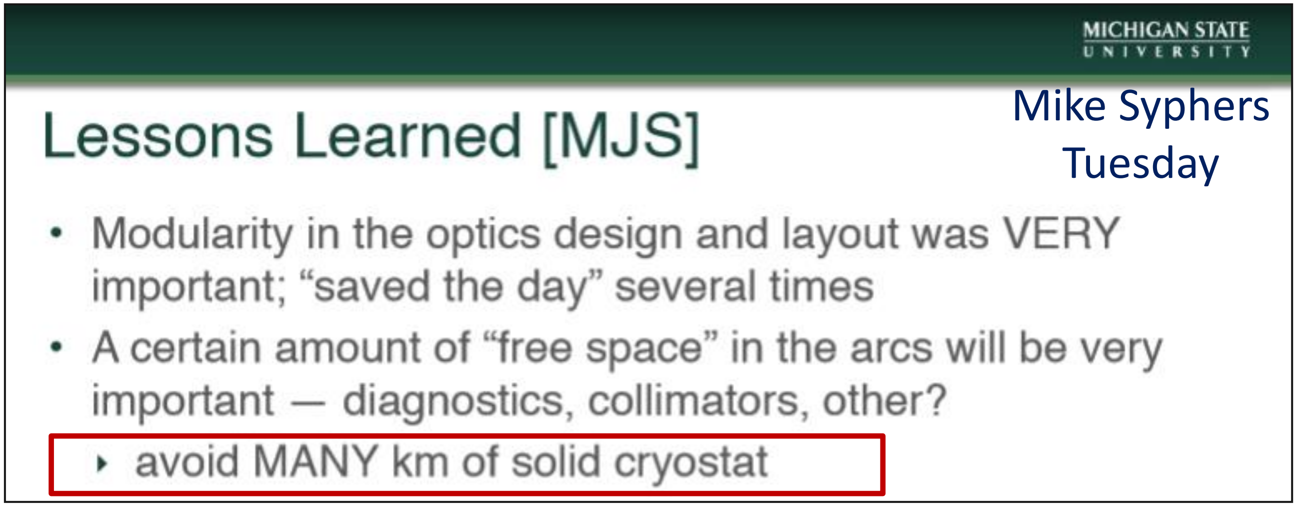


Some questions

- 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?

Conclusion

- 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!



Mike Syphers
Tuesday

Lessons Learned [MJS]

- 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

Acknowledgment

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

Special thanks to….

- Arjan Verweij
- Luca Bottura
- Daniel Schoerling