FUTURE CIRCULAR COLLIDER

POWERING STRATEGY - FOCUS ON MAIN DIPOLE MAGNETS

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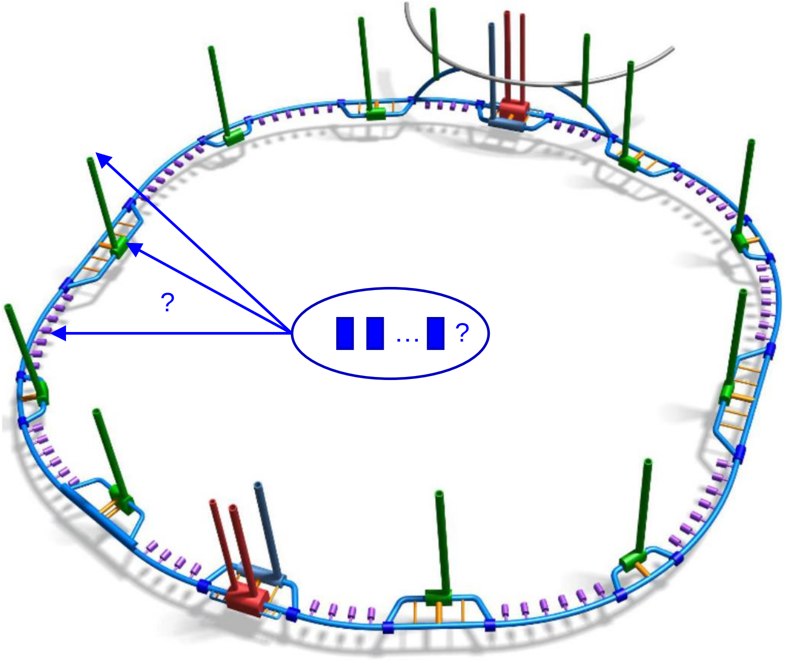
Table of content

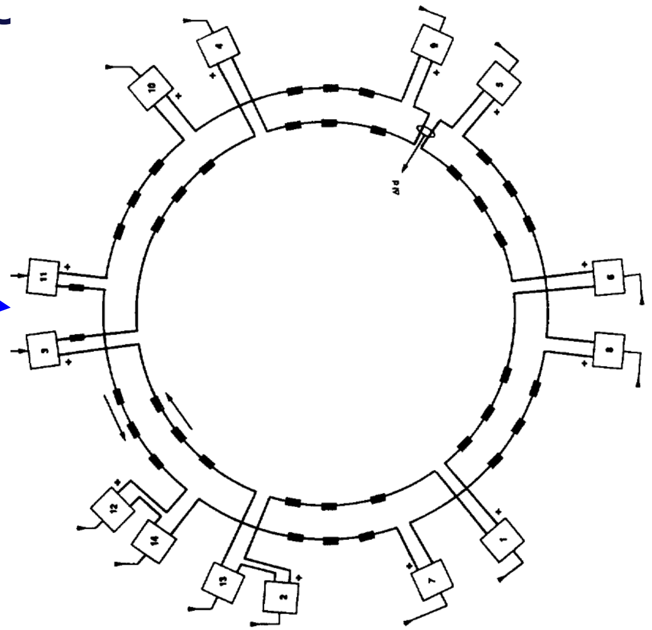
FCC-ee main converters number selection

Basic questions for main converters

- Converters in series or separated circuits?
- One or more converters per sector?
- Converters installed on surface (@ access point level) or alcoves, or service caverns?
- Considerations:
  - Cables can be costly & “lossy”
  - Location considering operation
  - Volume costs on surface or in alcove

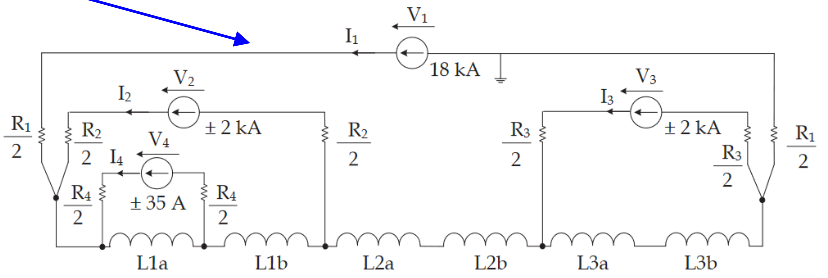


Main converters number selection



Possible circuits configurations

- Series connections? (as SPS @ CERN)
  - No real need as today good precision with separate circuits
  - Controls more laborious
  - Allow centralizing if magnet voltage insulation is low (< 1kV)
- Electrical trimming circuits / tapering? (e.g. inner triplet in LHC)
  - For tapering

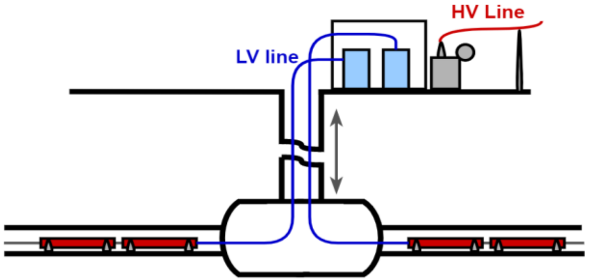


Powering baseline:
- Separated circuits for the mains
- Direct trims for tapering

Main Power converters location and number

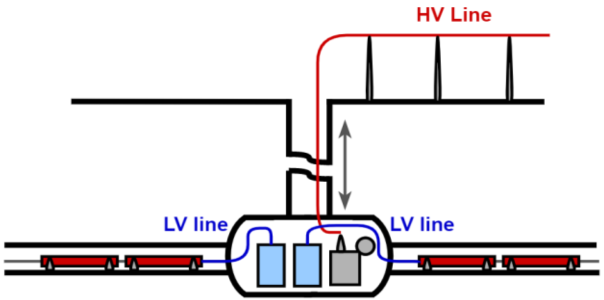
Converters on surface

- Reduced space requirements in tunnel ↑
- Easier and more efficient maintenance ↑
- Higher cost & transmission losses on low voltage line ↓



Converters in Service Gallery

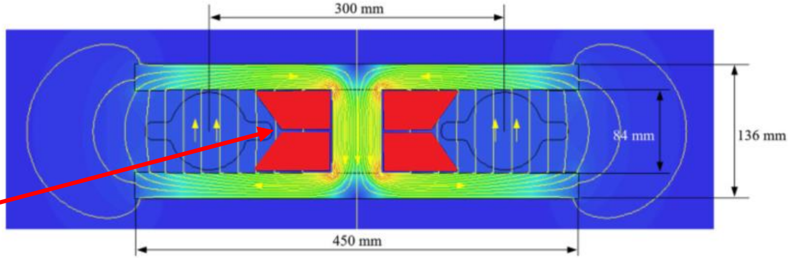
- More space requirements in tunnel ↓
- More difficult maintenance and longer access ↓
- Lower cable cost and losses ↑



Main Dipoles turns number

Number of magnets' turns

Winging turns number



- This choice greatly influences magnet & converters designs
- Turns number adapts voltage & current – to be evaluated against switches technology & topologies of power electronics converters
- A simple global model was prepared for the following analysis
- Considered baseline specs

Parameter	value	units
Ring perimeter	95000	m
Magnetic dipole length	81000	m
Ring average depth	300	m
Resistance per unit length / turn	1.14E-05	Ohm/m
Inductance per unit length /turn	7.25E-06	H
Maximum current density	7.90E+05	A/m2
Nominal current 1 turn	3800	A
Magnet length (average)	23	m
Copper resistivity	1.70E-08	
Price for copper	7.00E+00	Eur/kg
Price for aluminium	3.00E-01	Eur/kg
Density aluminium	2.71E+03	kg/m3
Density copper	8.94E+03	kg/m3

Main Dipoles turns number

12 sectors / 12 conv. / converter on surface

Turns Number	Voltage	current	Conv. power	Total power
1	350 V	3.8 kA	1.32 MW	15.9 MW
2	670 V	1.9 kA	1.26 MW	15.2 MW
3	980 V	1.3 kA	1.24 MW	14.9 MW
4	1300 V	0.95 kA	1.23 MW	14.8 MW

12 sectors / **24 conv.** / converter on surface

Turns Number	Voltage	current	Conv. power	Total power
1	200 V	3.8 kA	770 kW	18.4 MW
2	370 V	1.9 kA	710 kW	17 MW
3	550 V	1.3 kA	690 kW	16.6 MW
4	720 V	0.95 kA	680 kW	16.3 MW

12 sectors / 12 conv. / **converter in service caverns**

Turns Number	Voltage	current	Conv. power	Total power
1	290 V	3.8 kA	1.11 MW	13.3 MW
2	580 V	1.9 kA		
3	870 V	1.3 kA		
4	1160 V	0.95 kA		

12 sectors / **6 conv.** / converter on surface

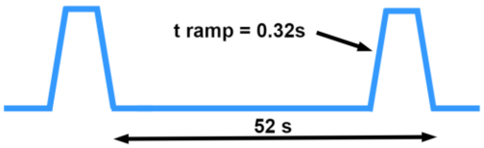
Turns Number	Voltage	current	Conv. power	Total power
1	640 V	3.8 kA	2.4 MW	14.6 MW
2	1250 V	1.9 kA	2.37 MW	14.2 MW

Magnet's windings voltage insulation limitations & limits for converter complexity/cost/volume

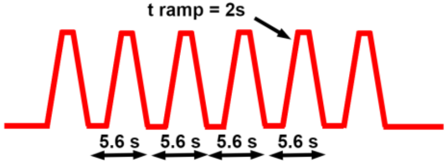
A word on the booster powering

Top Up Injection Cycles

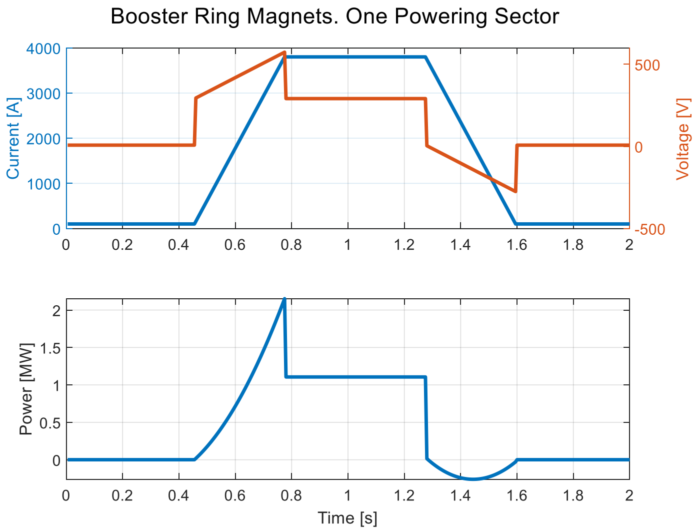
- Z Mode Operation



- tt Mode Operation



- Z Mode Operation: <u>Highest peak power</u>
- tt Mode Operation: <u>Highest average power</u>



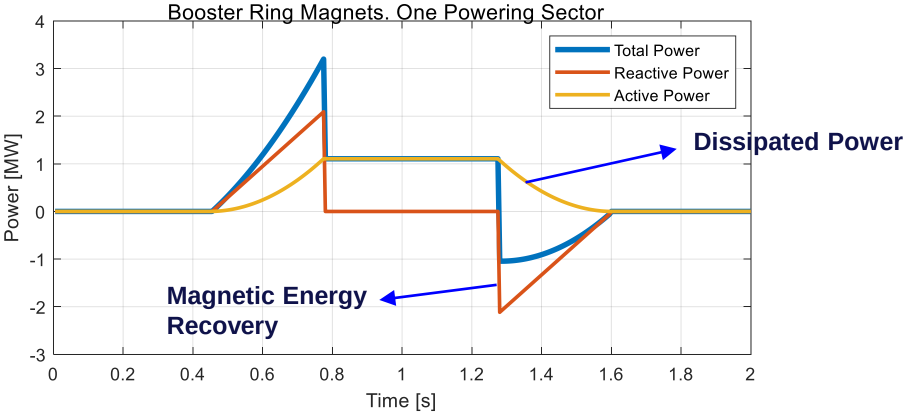
Case: Booster ring divided in <u>12 PS</u>

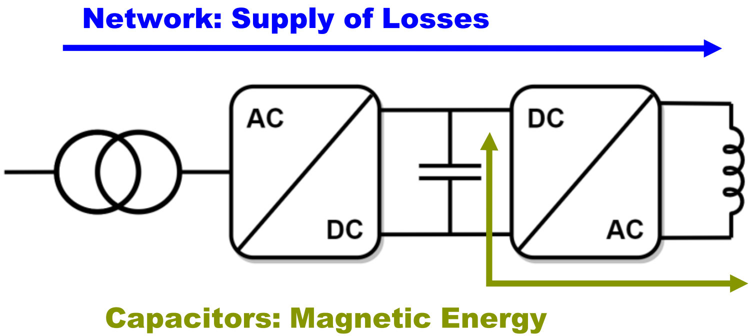
- **Booster magnets, cycle shape and currents unknown →** Main collider magnets as the baseline (1 turn but single aperture)
- Worst case for converter dimensioning → *FCCee-Z* mode. **Ramp-up time = 0.32s → Upeak ≈ 450V @ 3.8 kA**
- Maximum instantaneous power (12 PS) **≈ 21 MW (Z option)**
- Maximum average power (12 PS) **≈ 3.6 MW (tt option) @3.8kA**

[1] S. Ogur, K.Oide and others “Bunch Schedules for the FCC-ee Pre-Injector”

A word on the booster powering

- **Energy Recovery is widely used at CERN**
- **Advantages:**
  - Peak power shaving → **Reduced electrical infrastructure**
  - Lower losses → **Higher efficiency**
  - **Reduced impact on power network**





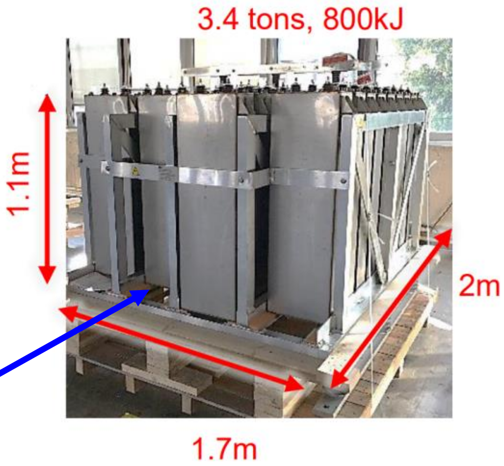
- **Booster Ring**

Stored Energy (1 *circuit*).

$$E = \frac{1}{2} L I^2 \approx 350\ kJ$$

- **POPS (Power for PS)**

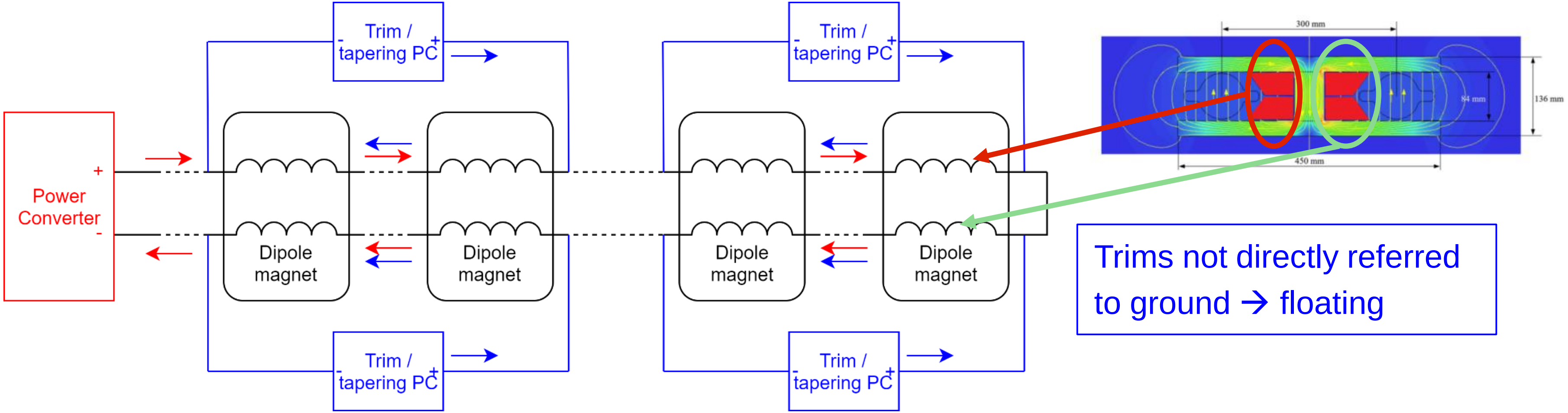
$$E = \frac{1}{2} L I^2 \approx 12\ MJ$$



Dipole tapering

Trim solution

- Possible to have trim power converters - 2 x 30 per sector – 720 units total
- Very small power (preliminary 22 A) “ very small voltage → not an issue
- Installation in alcoves
- A compromise should be studied to evaluate loosing one trim per beam per sector and global tapering still acceptable



Trims not directly referred to ground → floating

Future R&D activities

- FCC-ee R&D efforts oriented toward optimizing costs and maximising operability – no showstoppers
- RF powering not addressed yet – R&D efforts also oriented into optimising cost and operability
- FCC-hh much more challenging in terms of technology requirements – big energy amounts to be stored
- A big chunk of the powering R&D for finding synergies between FCC-ee & FCC-hh to reduce cost

Summary

- Number of main dipole circuits should be between 6 and 12
- Preference to locate main converters on surface - associated costs are marginal – operation/availability will greatly benefit form this choice!
- Generally collider magnets powering representing a marginal cost for the project
- Smaller correctors (such as tapering trims) probably in alcoves + service galleries
- Magnets with 1 turn are acceptable – benefits from magnets widely larger that drawbacks from power converters
- Booster powering needs energy storage systems to reduce overall costs - probably installed in service galleries – converters will be bigger than collider ones due to cycling
- Tapering can be relatively easily addressed via direct trimming converters

Thank you for your attention.