Power Converters for GSI and FAIR Magnets

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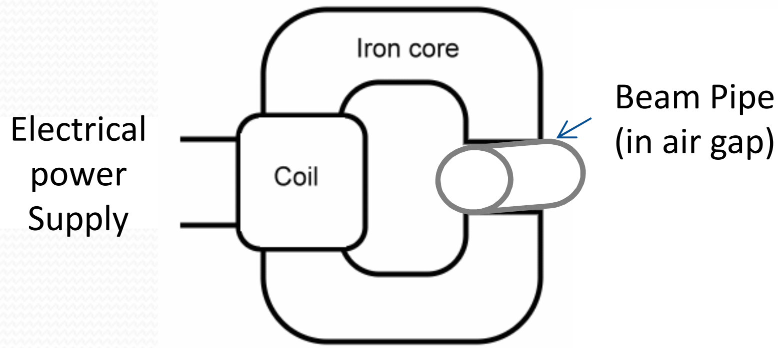
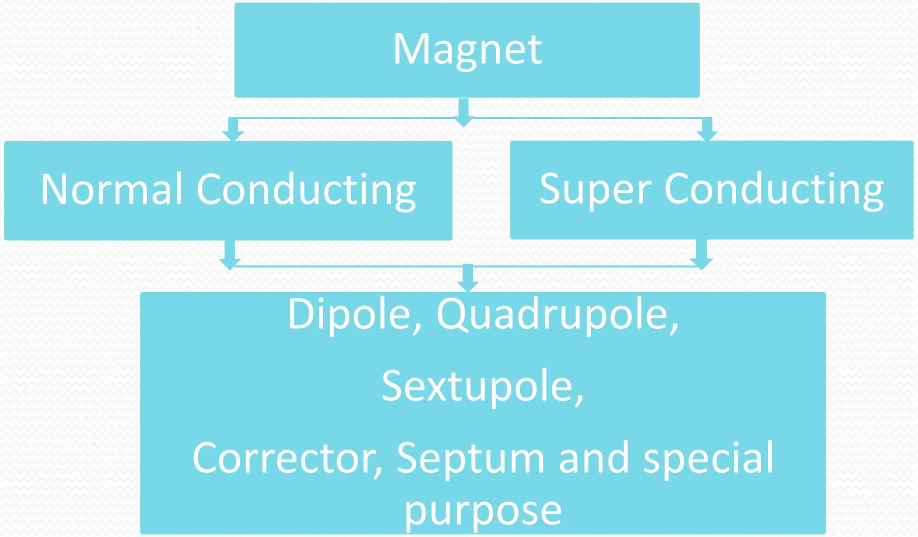
Particle Accelerator

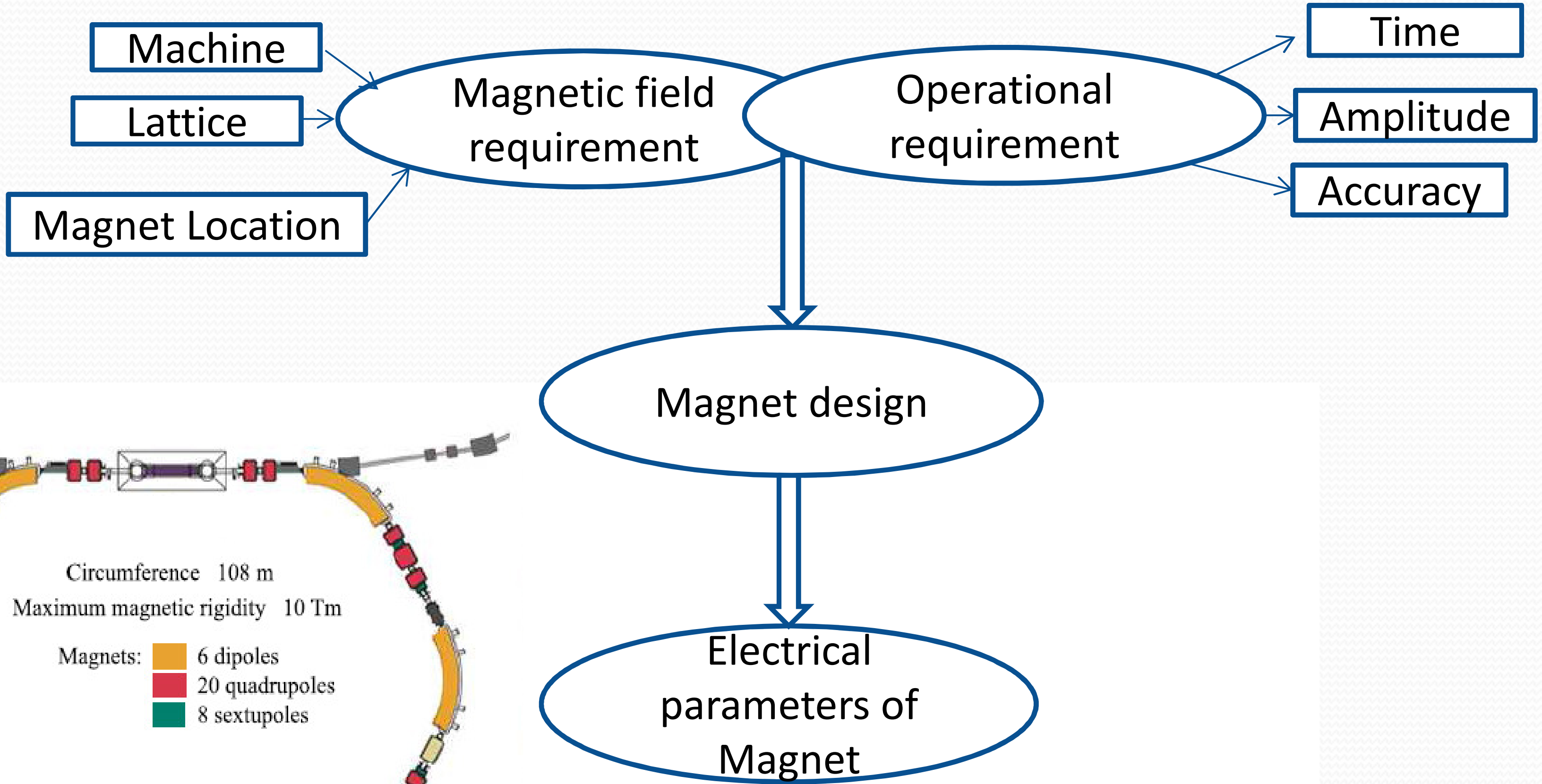
Electromagnets are there in

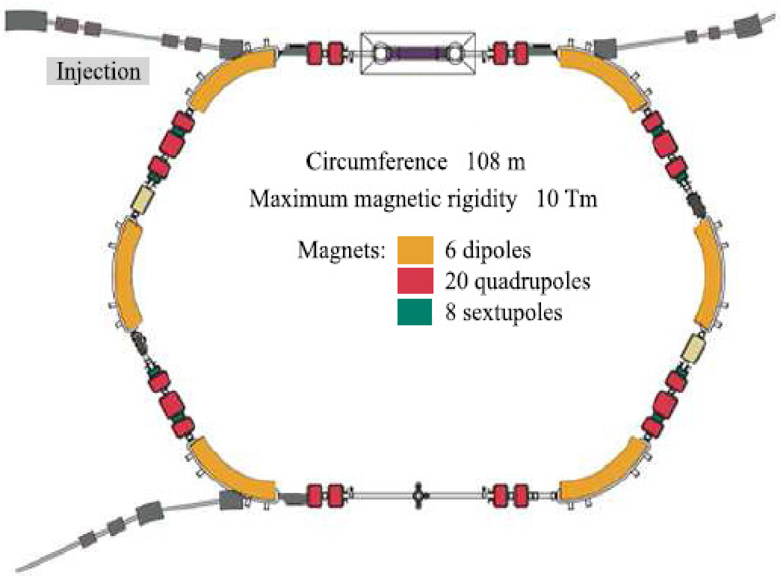
- Collider
- Light/Neutron/Ion Sources
- Linear or Open Structures
- Circular or Closed Structures





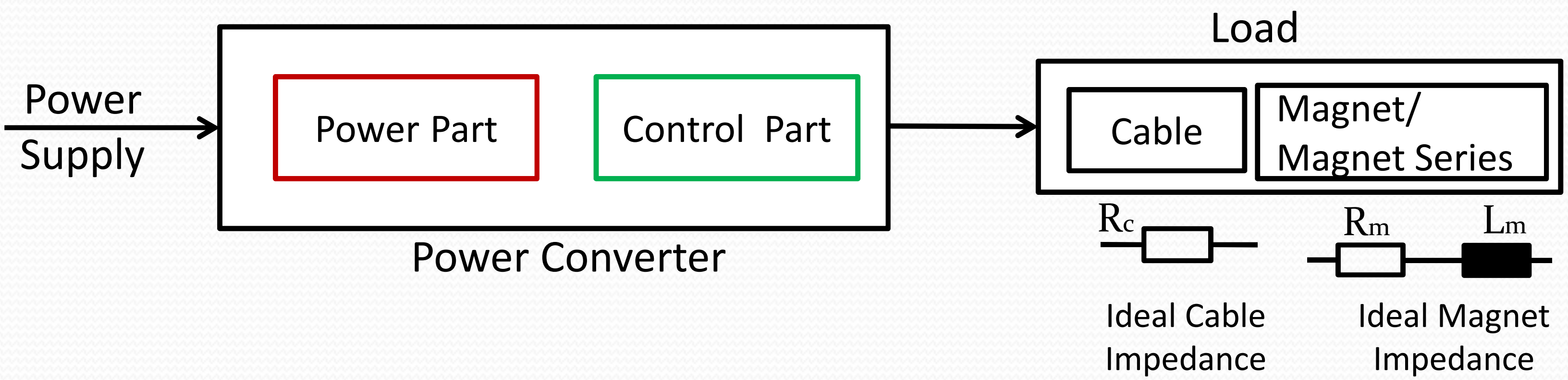
Magnetic Field Requirements





Power Converter: with Magnet as Load

Power Converter (PC): process and control the flow of electrical energy and supply the voltage and current in the form suitable to the load.



Magnet parameters considered for PC design:

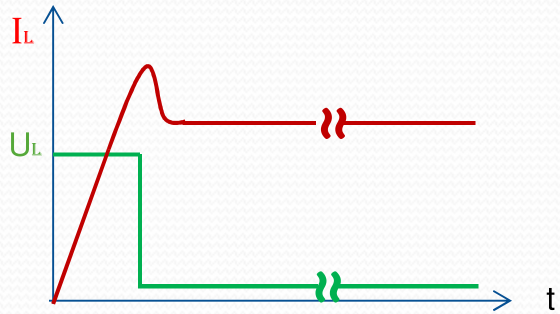
- Inductance
- Resistance
- Current rating
- Operational Requirement (di/dt, Cycle pattern, cycle frequency)
- Accuracy etc.

Magnetic Field/Current Requirements

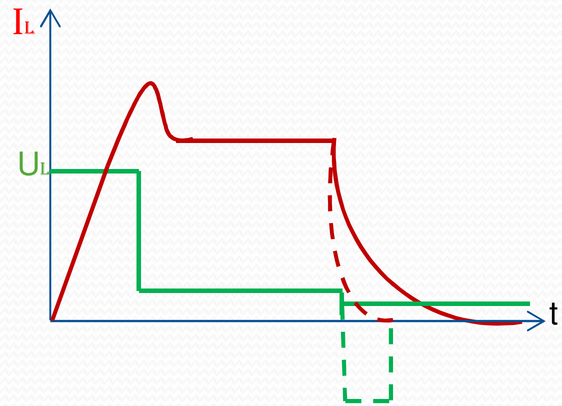
Voltage across the magnet, $U_L = L_m \frac{di}{dt} + i(R_m + R_c\ )$

Operational requirement, Example:

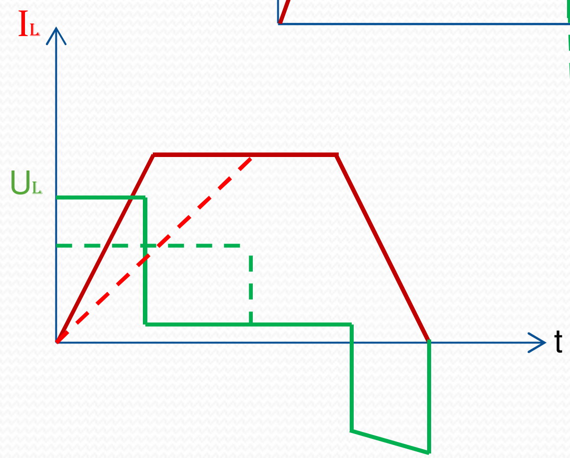
1. DC- constant current



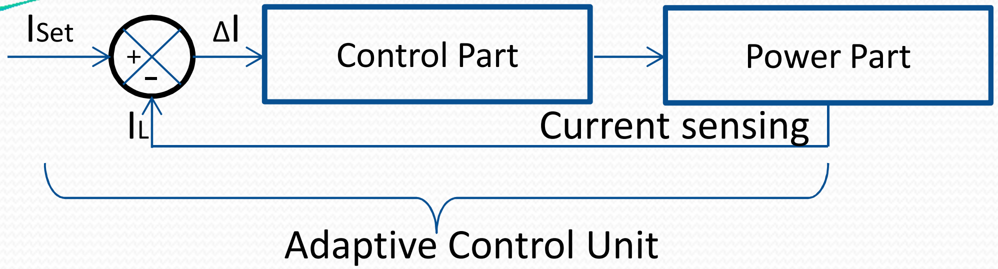
2. Pulsed- defined current for fixed duration

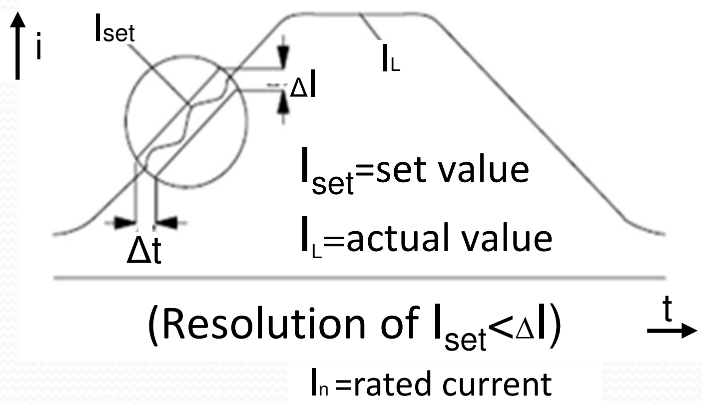


3. Ramped- rate of current ramping matters



Power Converter Accuracy



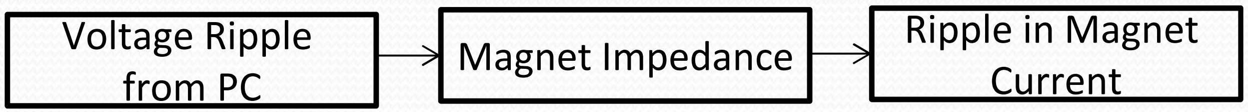


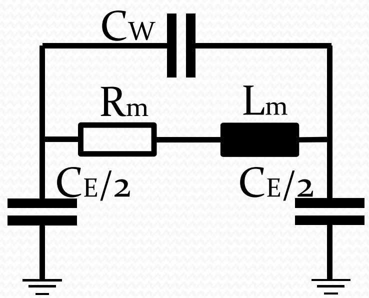
Current:

Accuracy- $I_{set} - I_L = \Delta I$ are altogether defined by

Total deviation, relative def., $= \frac{\Delta I}{I_L}$; abs def. $= \frac{\Delta I}{I_n}$

Ripple- Noise in I_L depends on switching frequency, magnet impedance and PC voltage ripple,





Stability- Long term drift in I_L at fixed load due to ageing, variations in temperature, humidity and grid voltage

Reproducibility of I_L : for same I_{set} at different time

PC Design Requirements

The design requirement:

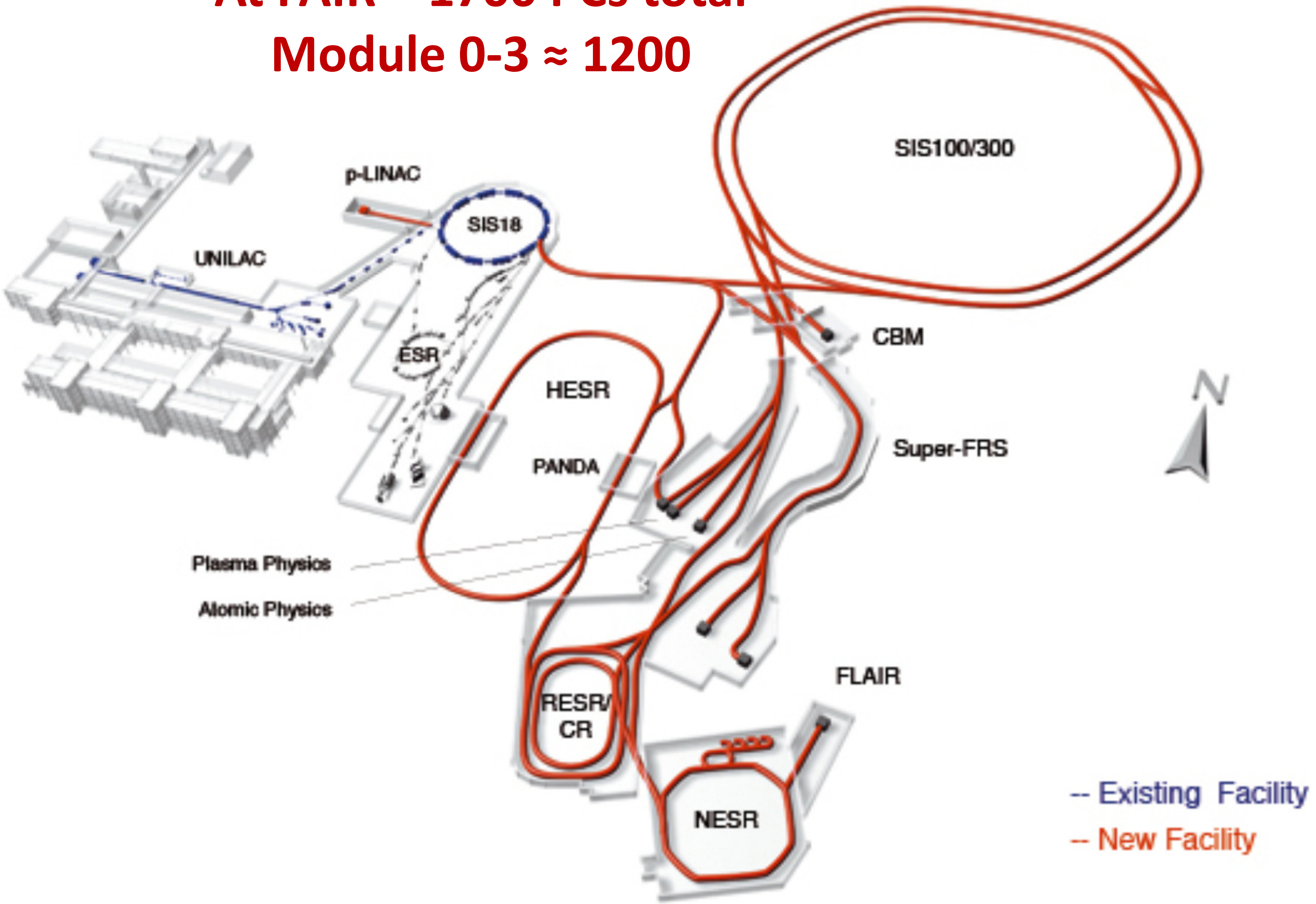
- Meet Specifications
- Reliable and
- Simple Circuit Structure
- Cost Effective

GSI and FAIR: Accelerator and Storage Rings/ NC and SC Magnets

At GSI ≈ 900 PCs

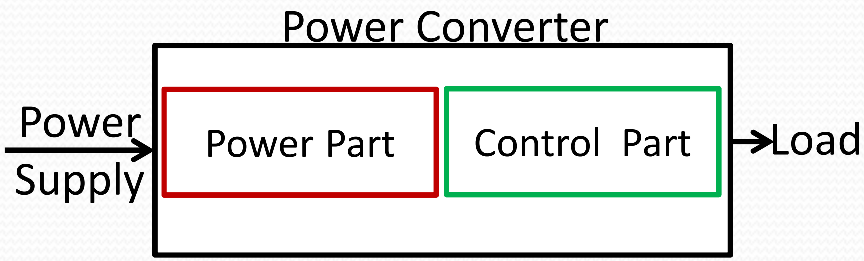
At FAIR ≈ 1700 PCs total

Module 0-3 ≈ 1200



Outline

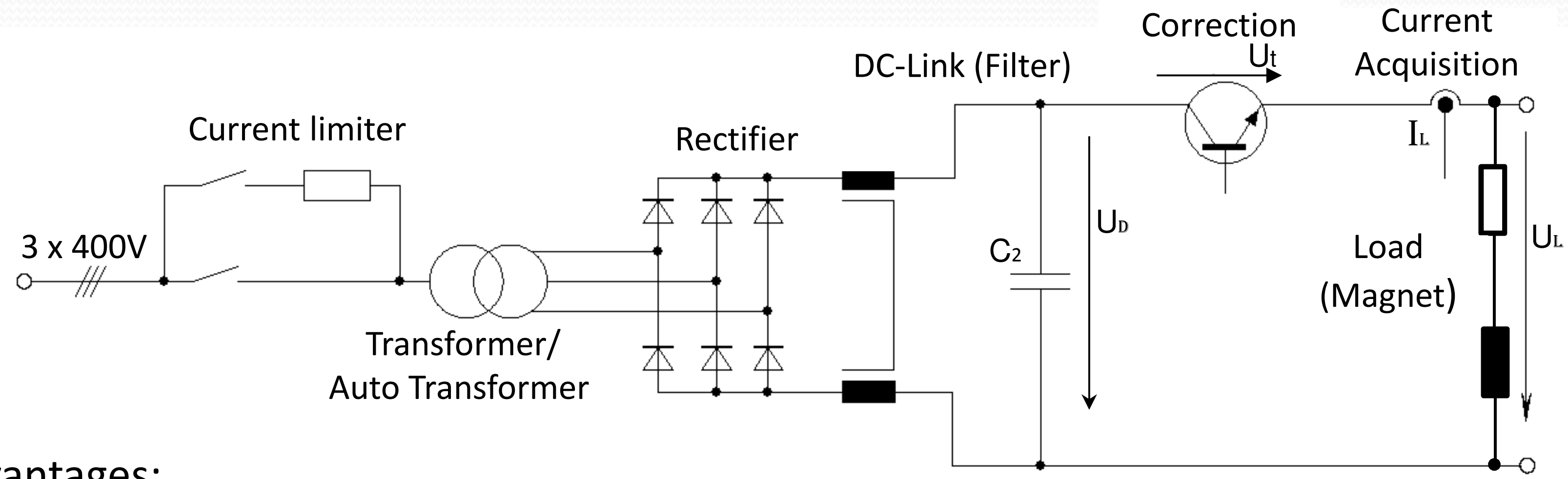
- Different Circuit Configurations/Topologies for PC
  - Linear Controlled
  - Switch Mode SM-1, SM-2 and SM-4
  - SCR (Silicon Controlled Rectifier)
  - Special Types
  - PC with Quench Protection
- Supporting Infrastructure
  - Power Supply System: Power grid
  - PC Control and Protection
  - Cooling: Air and Water
  - Power Cables
  - Building: PC size and General Installation
- Miscellenous



PC Topologies: Linear Controlled Type

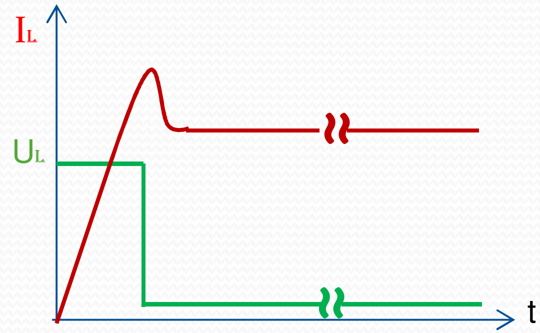
Total ≈30% of PC

Machine / PC Type	UNILAC	SIS	ESR	HEST	Test Bench	Sum	Special feature
Linear Controlled	178	10	58	16	1	263	10 to 400 A



Advantages:

- Good dynamics to reduce current ripple
- Low filter expences
- Low noise spectrum



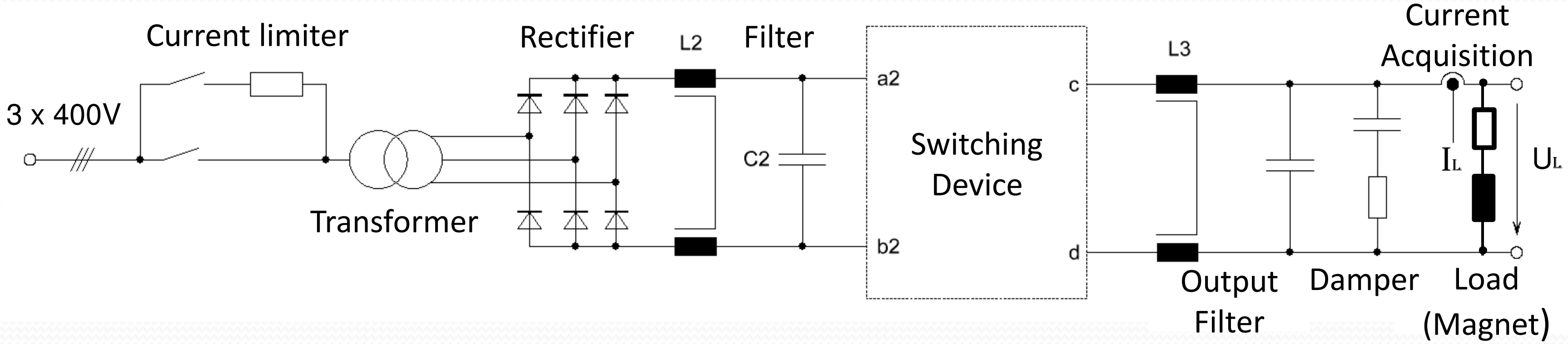
Disadvantages:

- High losses
- Only suitable for dc operation (with auto transformer to reduce losses)

PC Topologies: Switch Mode (SM) Concept

Total ≈60% of PC

Machine / PC Type	UNILAC	SIS	ESR	HEST	Test Bench	Sum	Special feature
Switch Mode	229	62	32	238	1	562	up to 6 kA



Advantages:

- Good dynamics (depends on output filter)
- Lower losses
- Moderate filter span

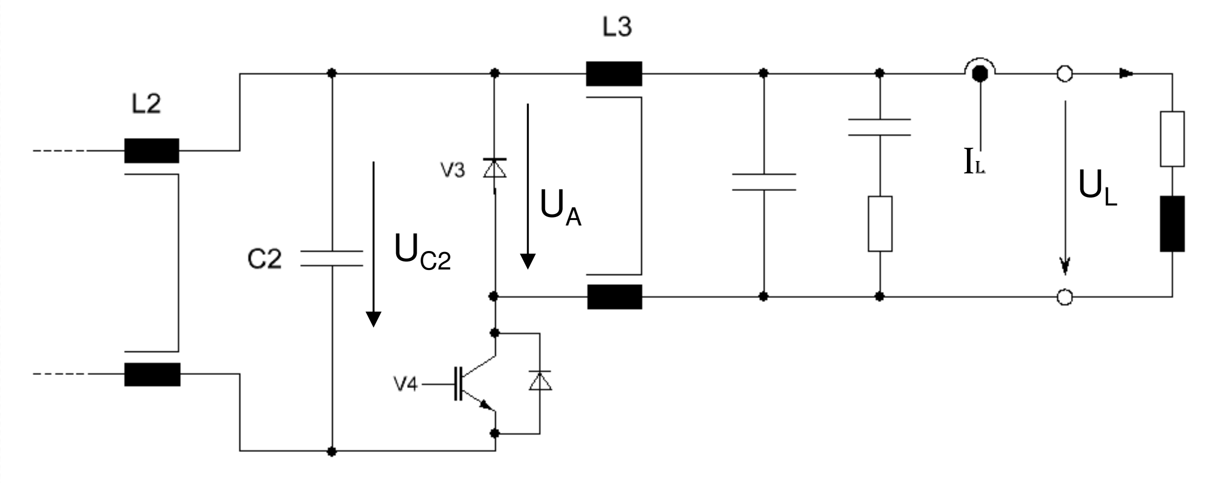
Disadvantage:

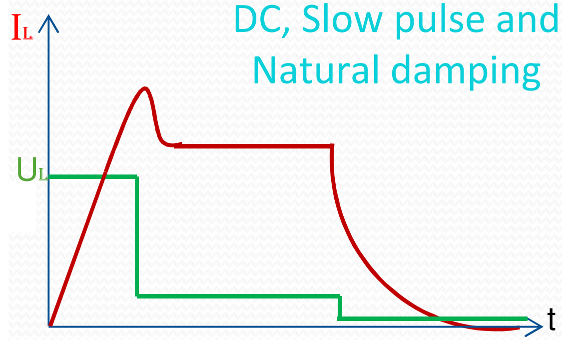
- measures have to be taken to reduce the noise spectrum of U_L

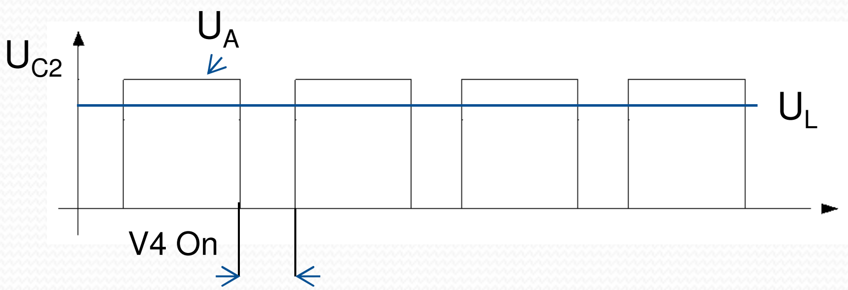
Most of the PC at GSI and FAIR are of this type

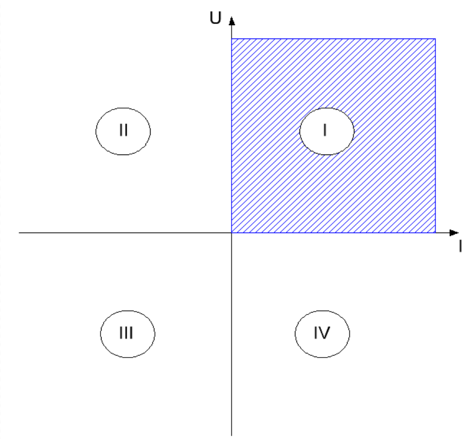
PC Topologies: SM-1; Chopper Circuit; 1-Quadrant

Example: HEST Dipoles
DC, Slow pulse and
Natural damping







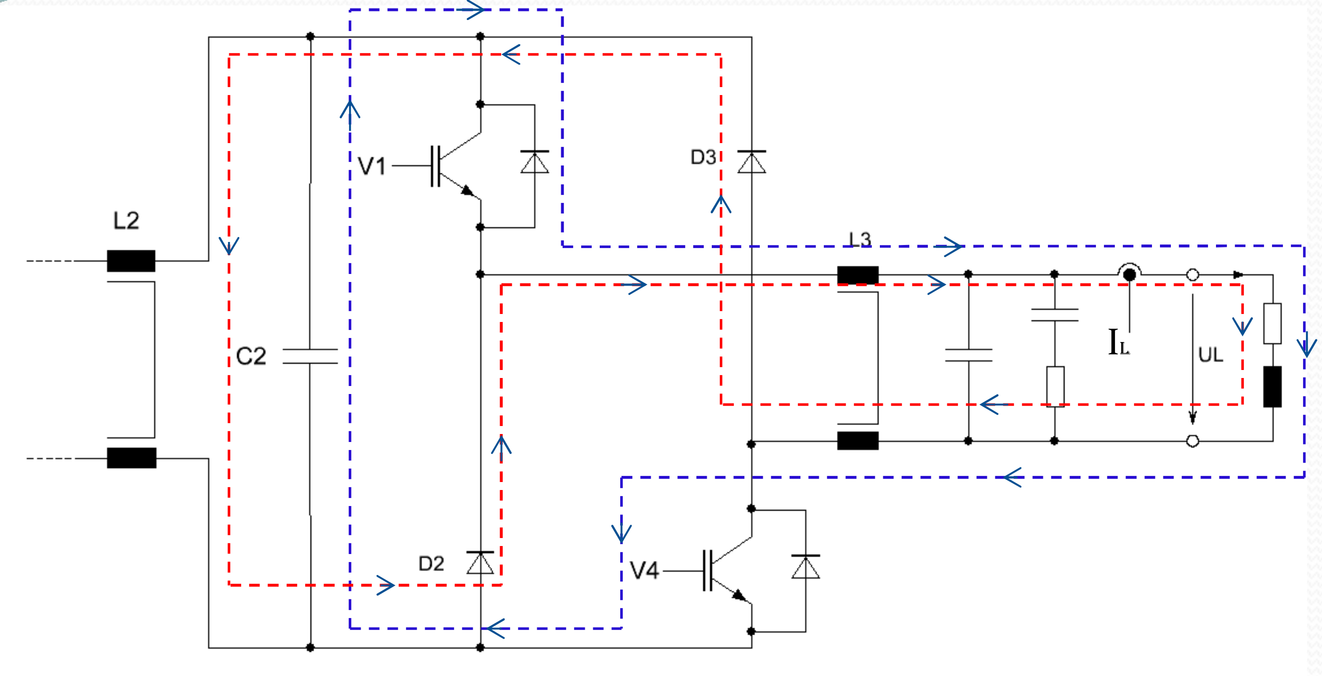


By varying the turn-on time of V4, mean value of U_L and hence of I_L are set/controlled

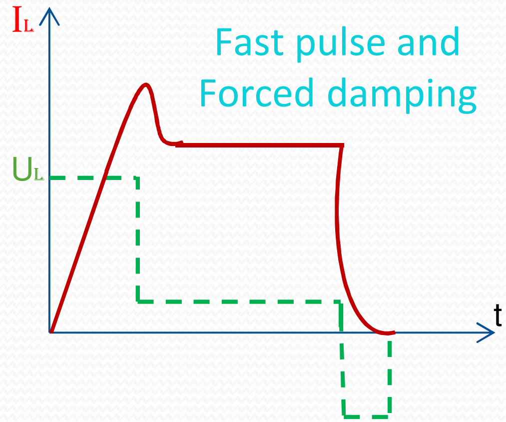
Only positive output voltage and current are possible (Single quadrant)

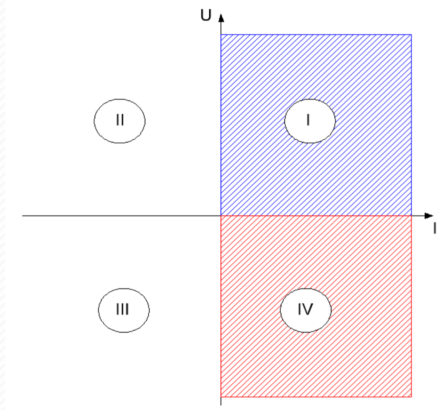
Standard switching frequency : 20 kHz

PC Topologies: SM-2; Half bridge with Energy Recovery



Example: UNILAC





Set value of U_L and I_L achieved by alternate switching of V1 and V4

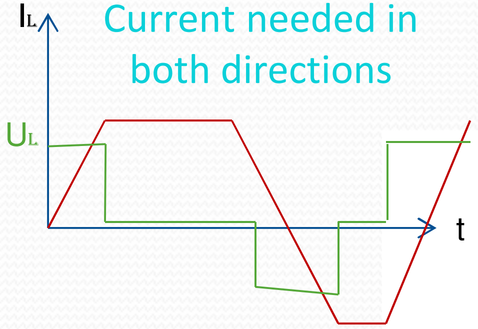
It halves the switching loss (half switching frequency per transistor)

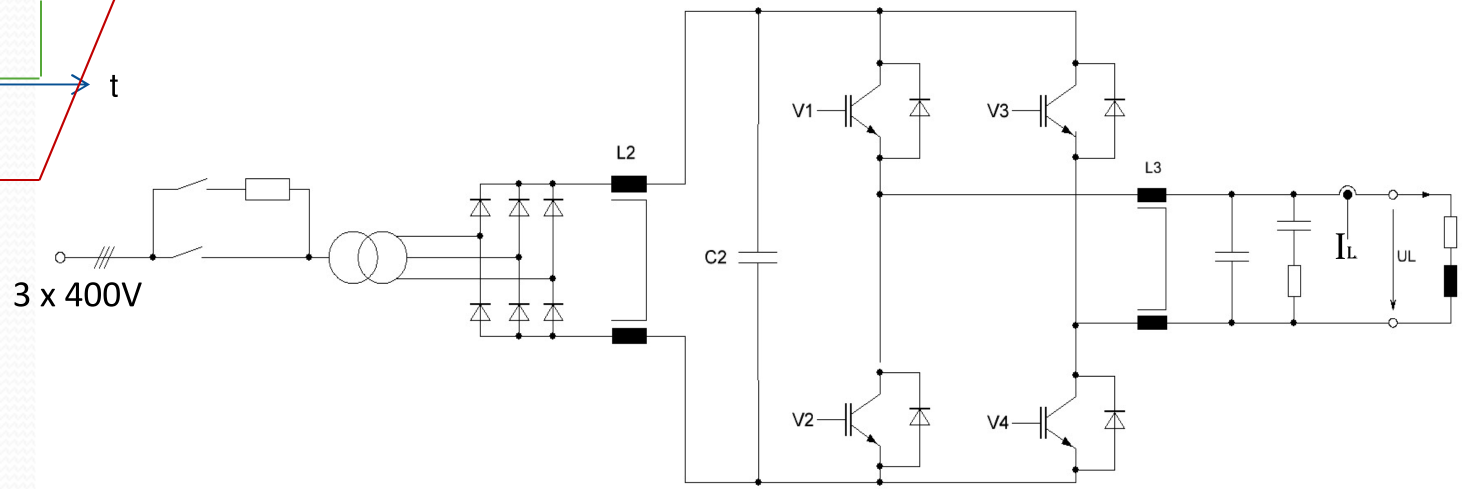
Only positive I_L but positive and negative U_L (1. und 4. quadrant)

V1 and V4 On ⇒ $+U_L$; D2 D3 On ⇒ $-U_L$ and energy fed back to dc-link

PC Topologies: SM-4; Full Bridge PC; Bipolar & Energy Recovery

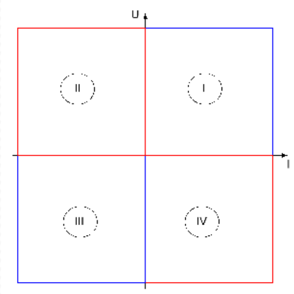
Example: SIS Steerers





By alternate switching of pairs V1, V4 and V2, V3 follows the set value of U_L and I_L

It halves the switching loss (half switching frequency per transistor)



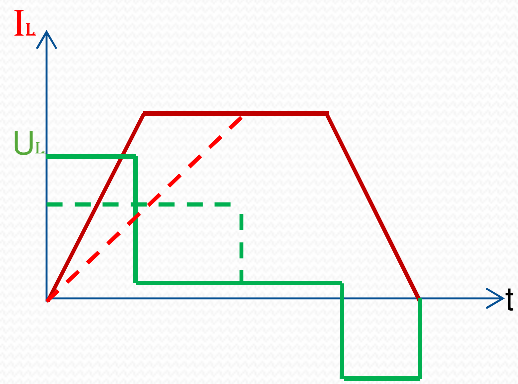
Positive and negative I_L and U_L (all 4 quadrants)

I_L pos: V1 and V4 On, + U_L; D2 D3 On, - U_L and energy fed back to dc-link

I_L neg: D1 and D4 On, + U_L and energy fed back to dc-link ; V2, V3 On - U_L

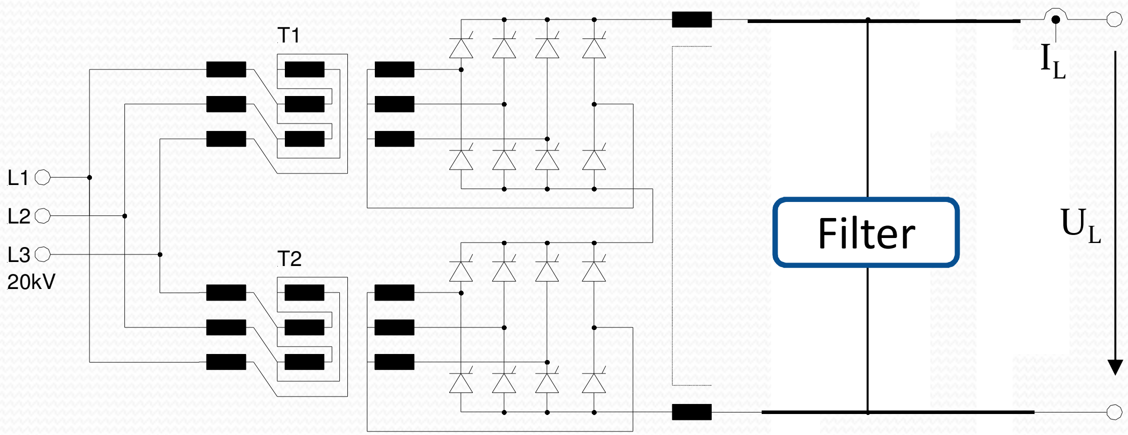
PC Topologies: SCR Large Power, high currents and Energy Recovery

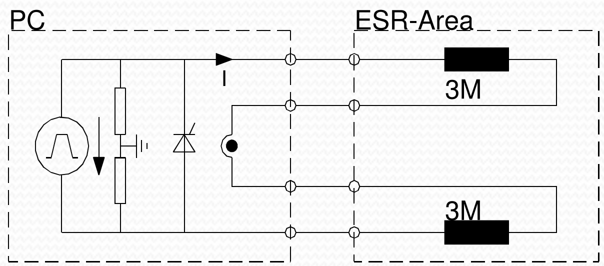
Machine / PC Type	UNILAC	SIS	ESR	Test Bench	Sum	Special feature
SCR	3	6	11	4	24	up to 20 kA



•SIS, ESR: Dipole, Quadrupole and extraction septum

• For very large power, connected to the 20kV level





In this PC unit:

- Large power , high currents
- Energy recovery to grid
- High reactive power, high harmonics (therefore in SIS/ESR converters have dedicated grid).

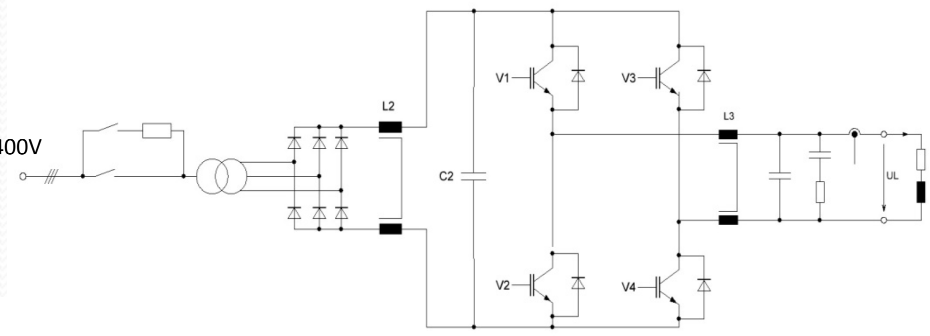
With Active filter:

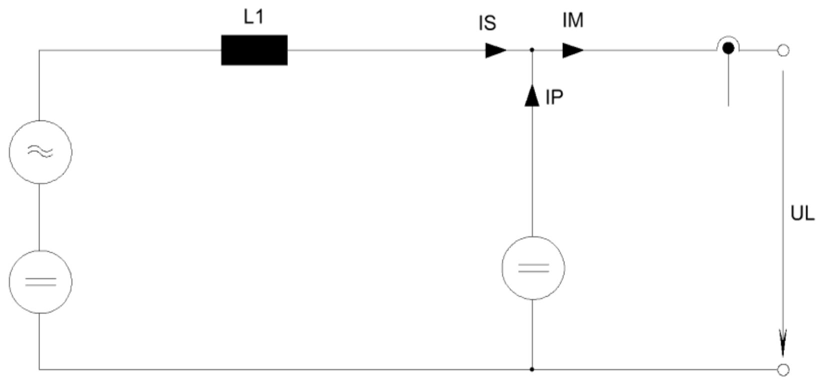
- Low Current ripple and good current dynamics
- Complex circuit/control

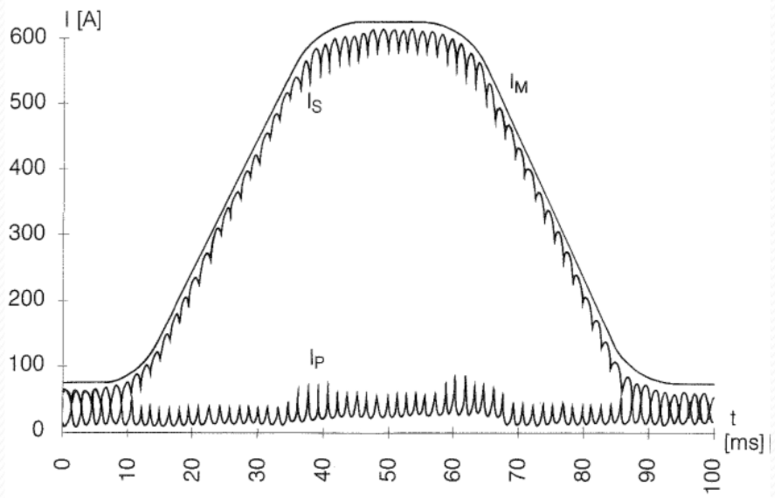
With Passive filter:

- High filter size, poor dynamics

PE Principle







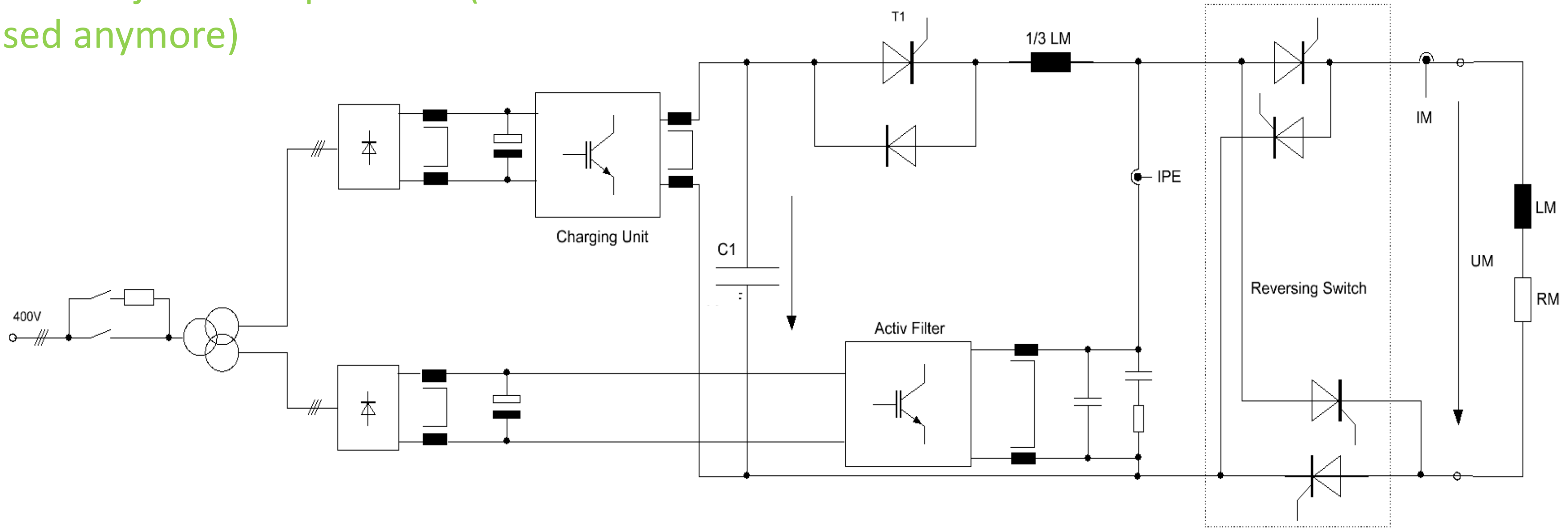
PE current is unipolar.

PE contribiute to the load current (30-60A) and keeps the ripples in rectifier current within the limit

PC Topologies: Special Type; PSM Linear Controlled and SM-4

GSI: Reinjection Septum SIS (not used anymore)

Proposed: CR Extraction Septum

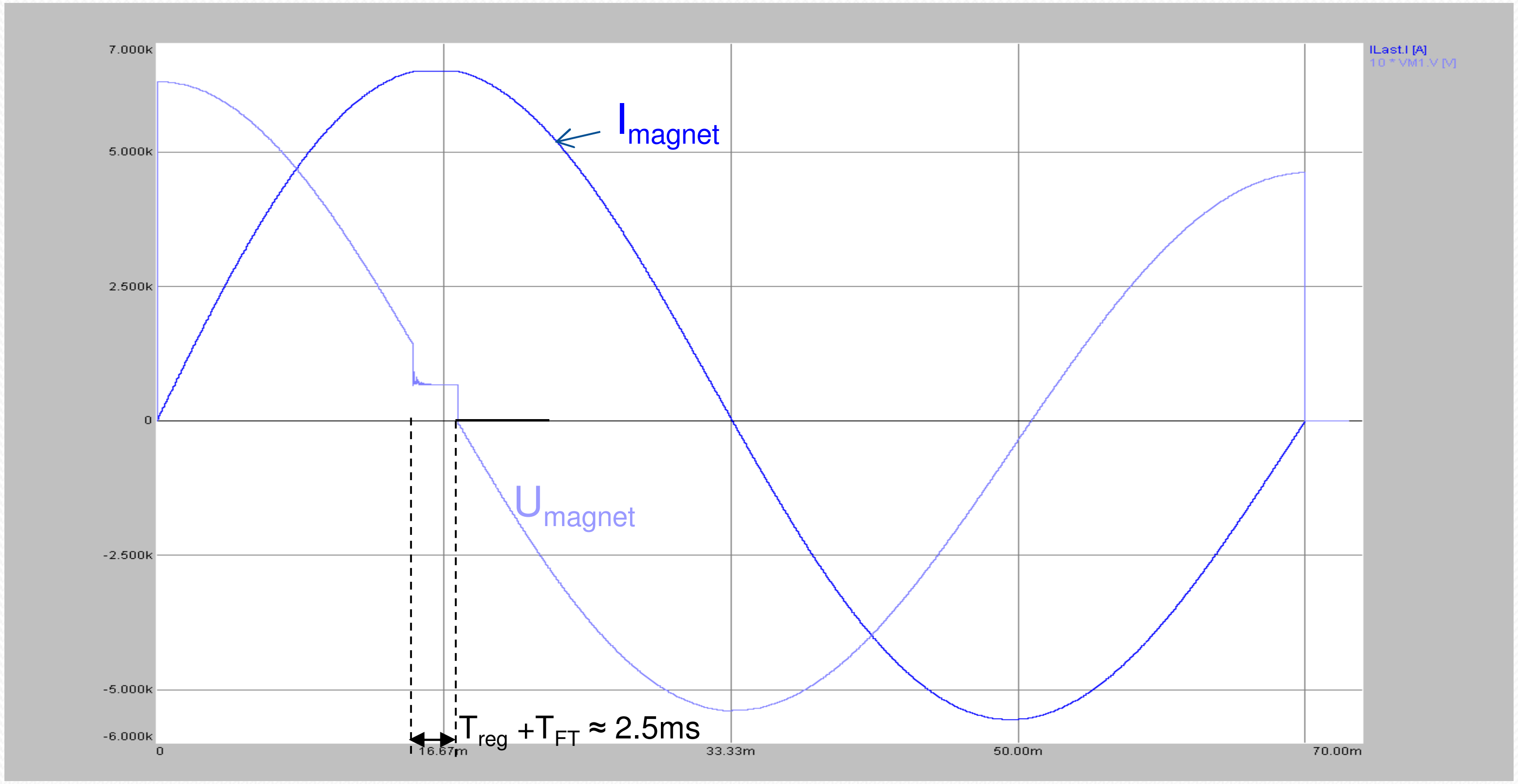


Charging Unit : controls the voltage of the main storage capacitor C_1

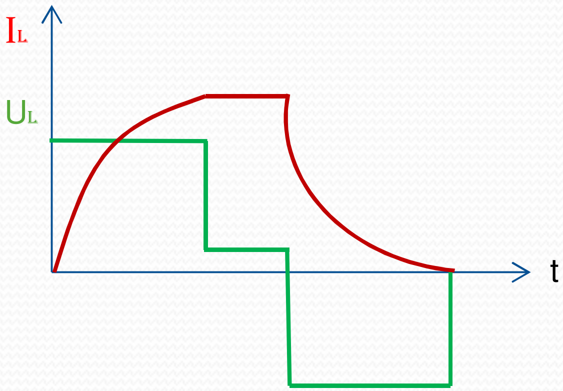
Active Filter: controls the current during flat top (cutting the sine wave at Imax)

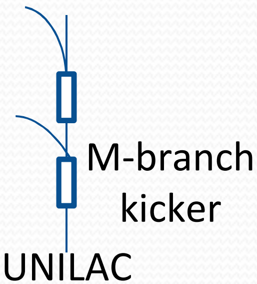
Reversing Switch: for polarity change of the power converter

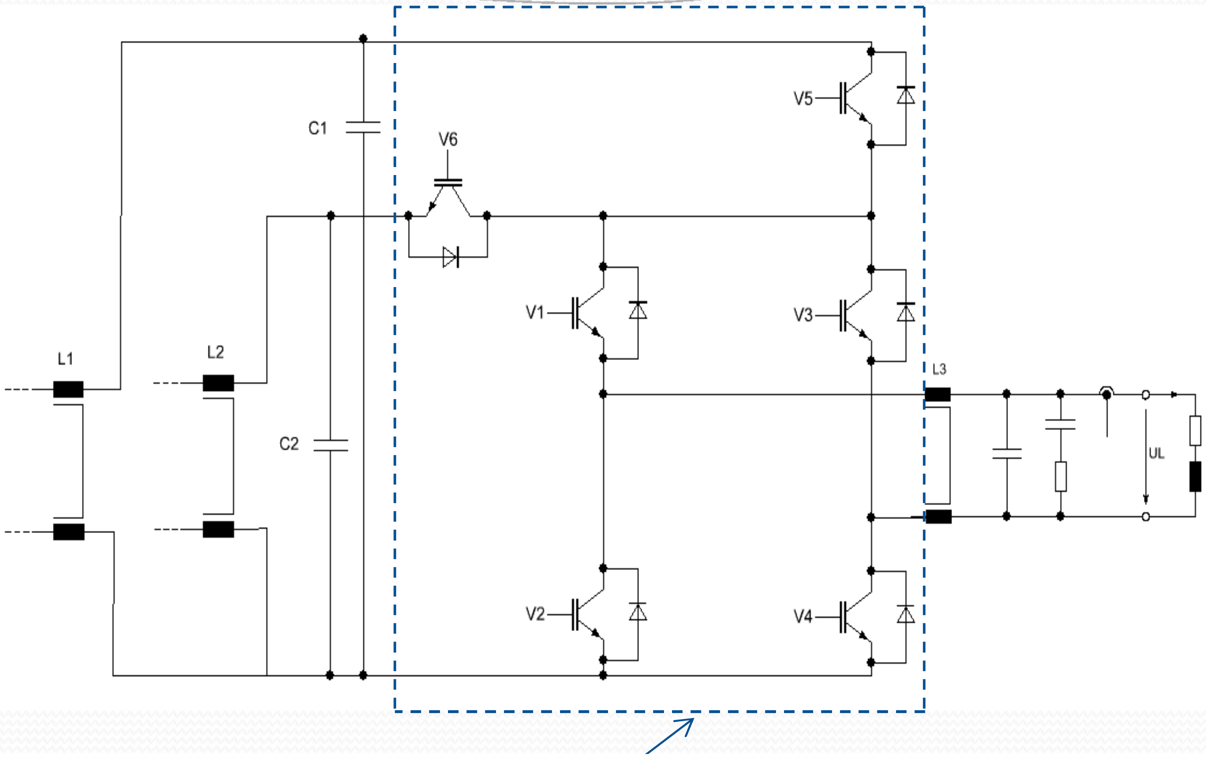
Fast Ramping



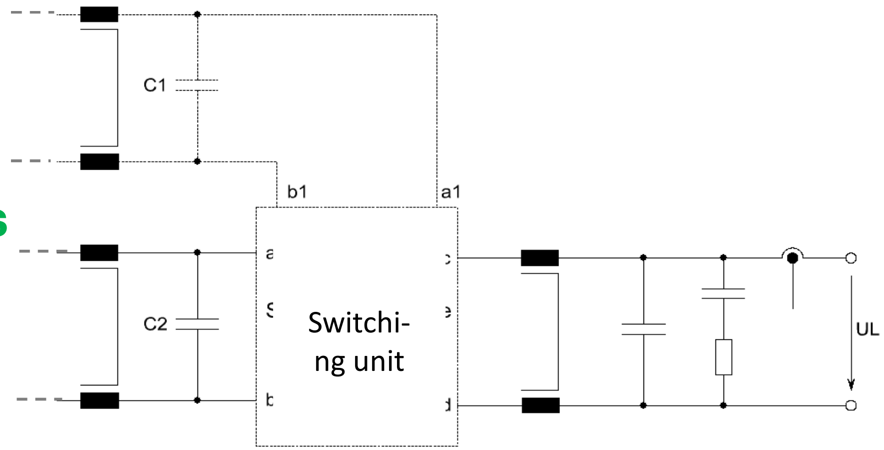
$$L_m \frac{di}{dt} + iR > (5\ to 10)iR$$



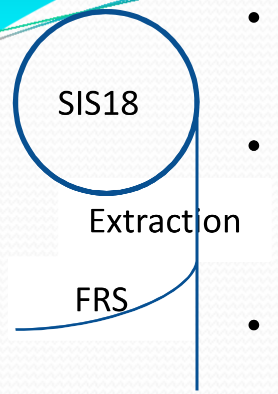




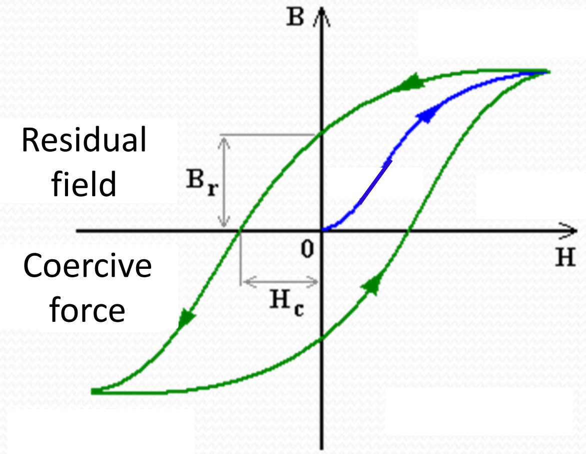
Switching unit controls the current pulse lengths

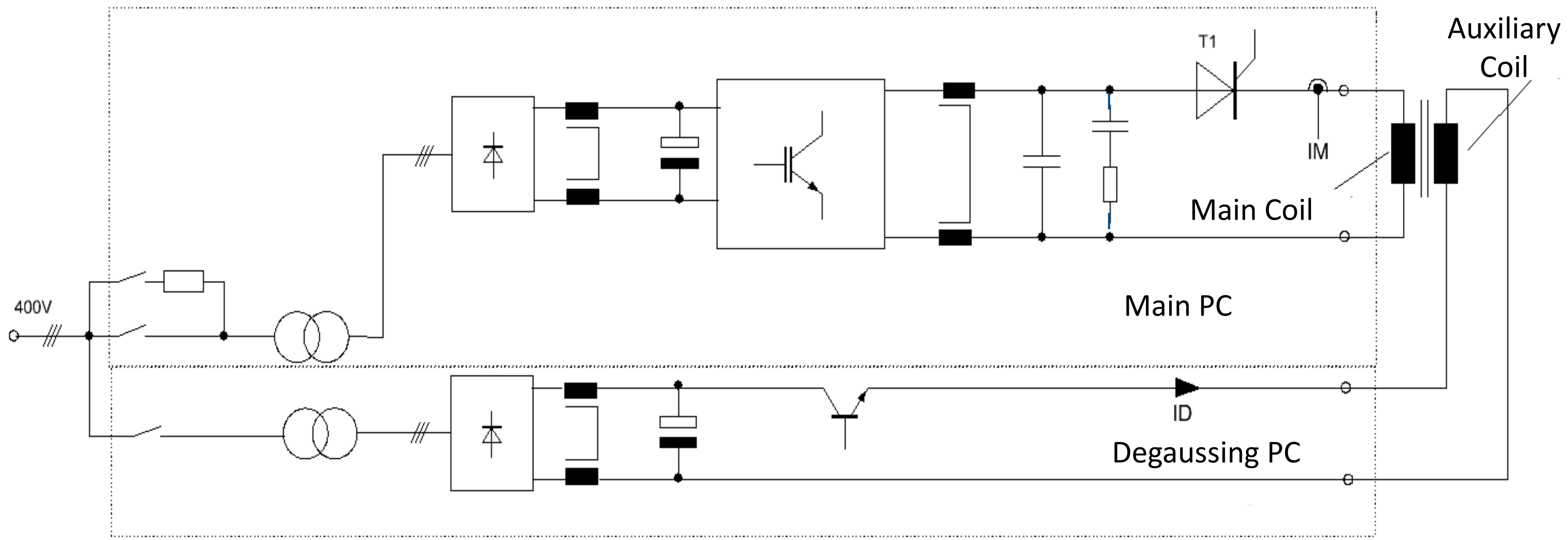


PC Topologies: Linear Controlled + SM Zero Field Control



- A hall sensor is used to measure the field in the magnet.
- To assure the magnetic field to be zero, an additional PC is used to nullify the residual field in main PC.
- To avoid the influence of main PC on degaussing PC, before activating the degaussing, the main PC to be switched-off (by switching off T1).



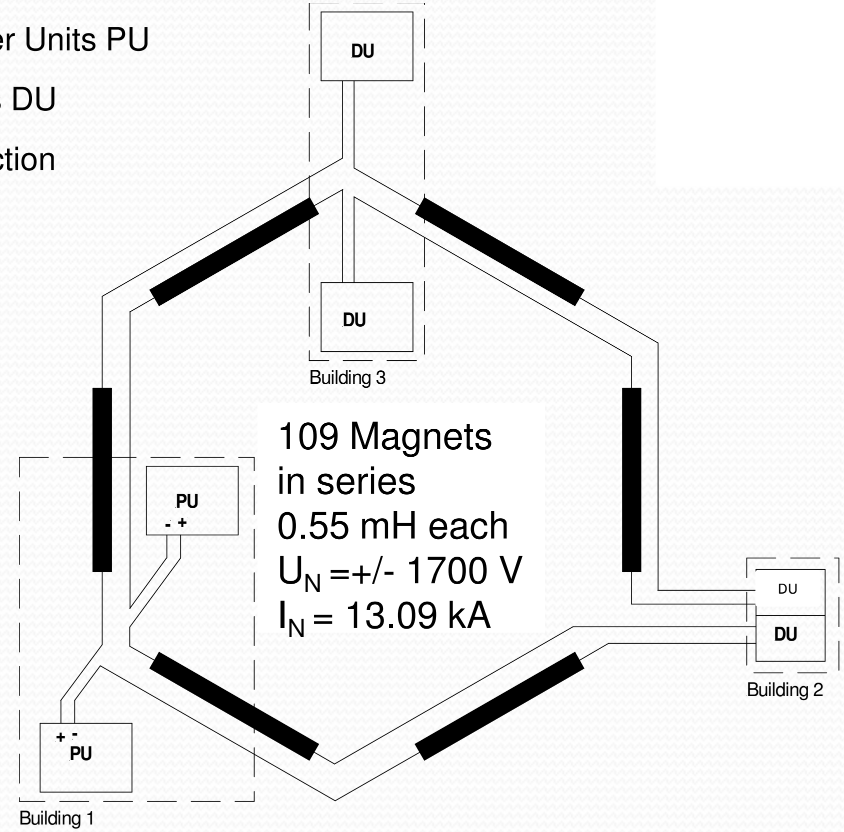


PC Topologies: Example of a Proposed SC Magnet PCs in SIS 100

System of Power Units PU

and Dump Units DU

in series connection



SC Magnet PC XI: SCR/ SM with Quench Protection Unit

Main Components of a Power Unit (PU):

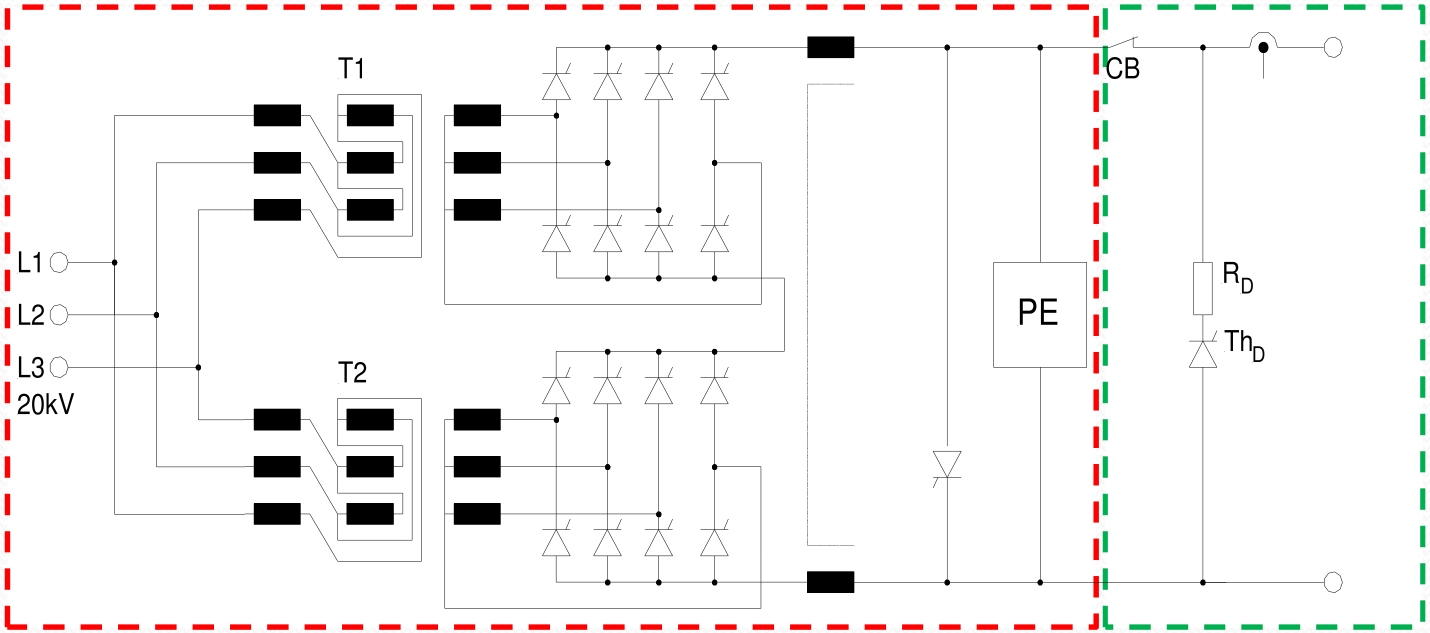
-20 kV transformer

-12 pulse SCR with controlled freewheeling thyristors

-Smoothing inductance

-Active filter (PE)

-Quench protection circuit (Dump Unit, DU and thyristors)



SC Magnet PC XI: SCR/ SM with Quench Protection Unit

Under quench, circuit breaker contacts open

Energy from the magnets is absorbed by the dump resistor units

Main Components of a Dump Unit:

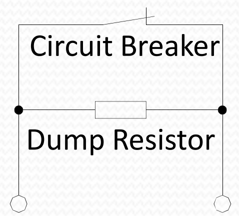
- Circuit Breaker

  Electronic switches 1ms>

  Commercial mechanical switches 15-20 ms

- Dump Resistor

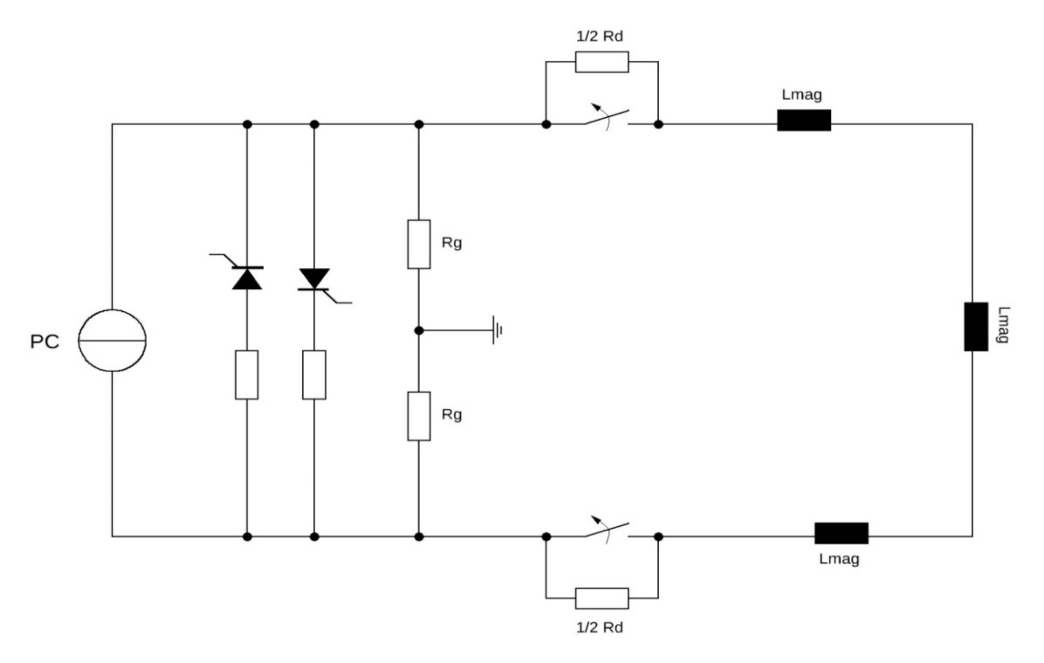
Dump Unit



PC Topologies: Example of Proposed SC Magnet PCs in SFRS

Proposed Layout of SFRS Dipole Power Converter

Energy from the magnets is absorbed by the dump resistor units



Power Converters at GSI

PC Type	Machine						
	UNILAC	SIS18	ESR	HEST	Test Bench	Sum	Special feature
Linear Controlled	178	10	58	16	1	263	10 to 400 A
Switch Mode	229	62	32	238	1	562	up to 6 kA (ESR injection)
SCR	3	6	11		4	24	up to 20 kA
Special type Bumpers, fast quads	2	5	1			8	up to 5 kA bumper
Sum	412	83	102	254	6	857	

Additional 30 HV PCs up to 300 kV!

With Current level 10 A to 20 kA ; Voltage level few V to 300 kV

At GSI, all together≈ 900 PCs

Outline

- Different Circuit Configurations/Topologies for PC
  - Linear Controlled
  - Switch Mode SM-1, SM-2 and SM-4
  - SCR (Silicon Controlled Rectifier)
  - Special Types
  - PC with Quench Protection
- Supporting Infrastructure
  - Power Supply System: Power grid
  - PC Control and Protection
  - Cooling: Air and Water
  - Power Cables
  - Building: PC size and General Installation
- Costing and Miscelleneous

Power Range

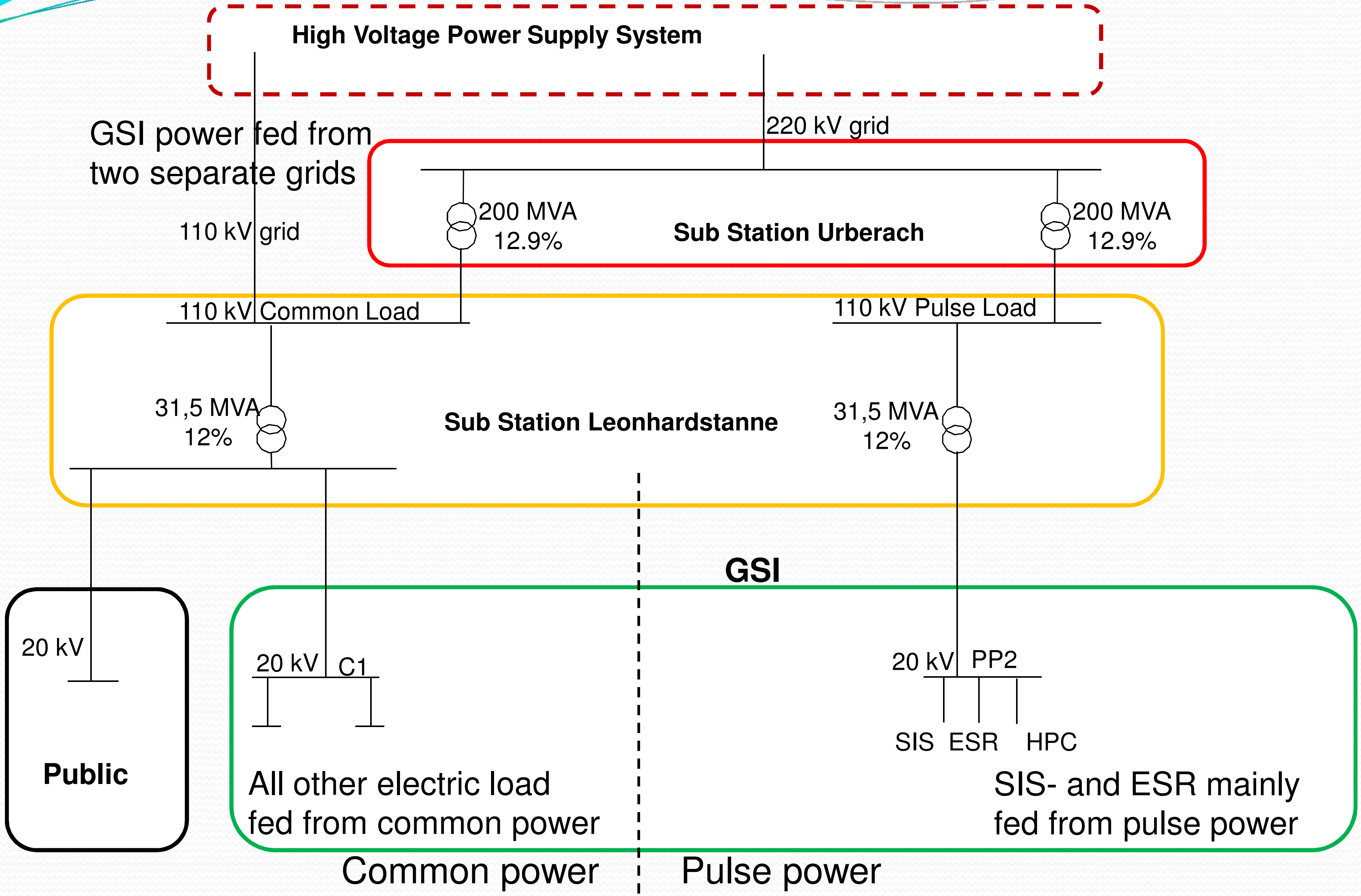
High Voltage Supply
in MW-Range

Power Converters
in kW-Range

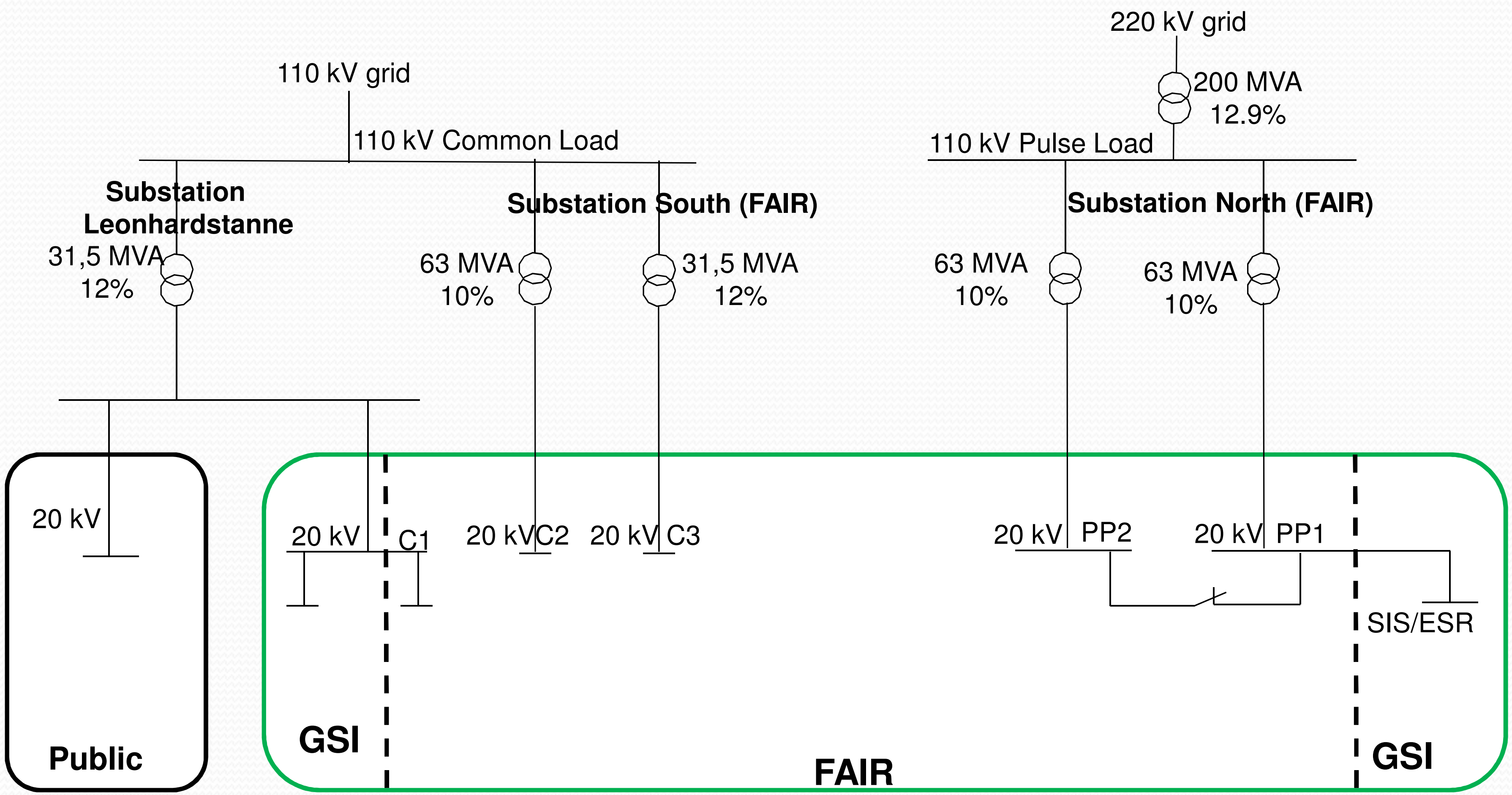
Controls
in W-Range

Power Supply System

Power Supply System for GSI: Until 2015



Power Supply System for FAIR: Connecting FAIR to Grid



Power Converters in FAIR

Sub Station	C1	C2 and C3	PP1 and PP2
Leonhardstanne	31.5 MVA		(31.5 MVA)
North (GSI+FAIR)			2*63 MVA SIS18, SIS100, HEBT and HPC
South (FAIR)		63 MVA and 31.5 MVA (All storage rings, cryo-plant and Infrastructure)	

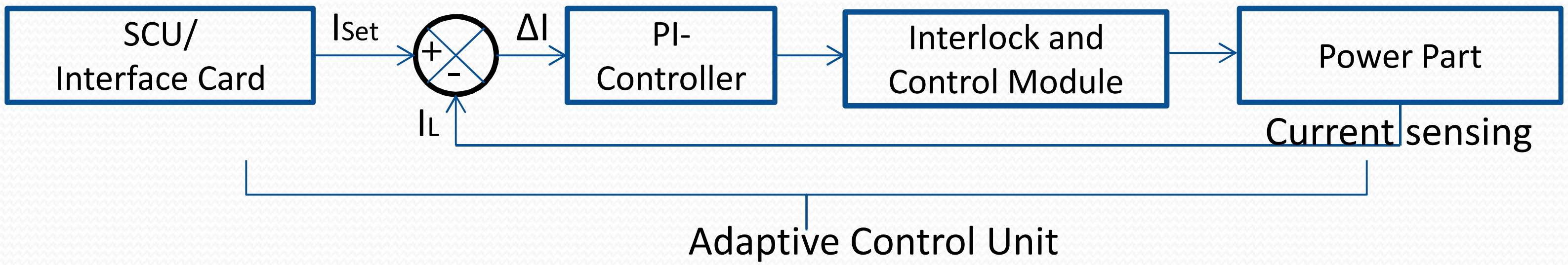
- SIS18 38 MVA (50 MW); SIS100 30 MVA (25 MW); HEBT 17 MVA and HPC 12 MVA

  Total: 63 MVA
- Installed power is double to keep the voltage drop to app 5%
- Cryo-plant has double redundancy from Substation north and south

Monitor, Control and Protection of PC

Control part of PC:

1. Controls the current I_L



2. An interlock is activated, in case of over current, under voltage, water flow/temperature, load temperature, PC temperature, quench etc. and protect it by switching it off

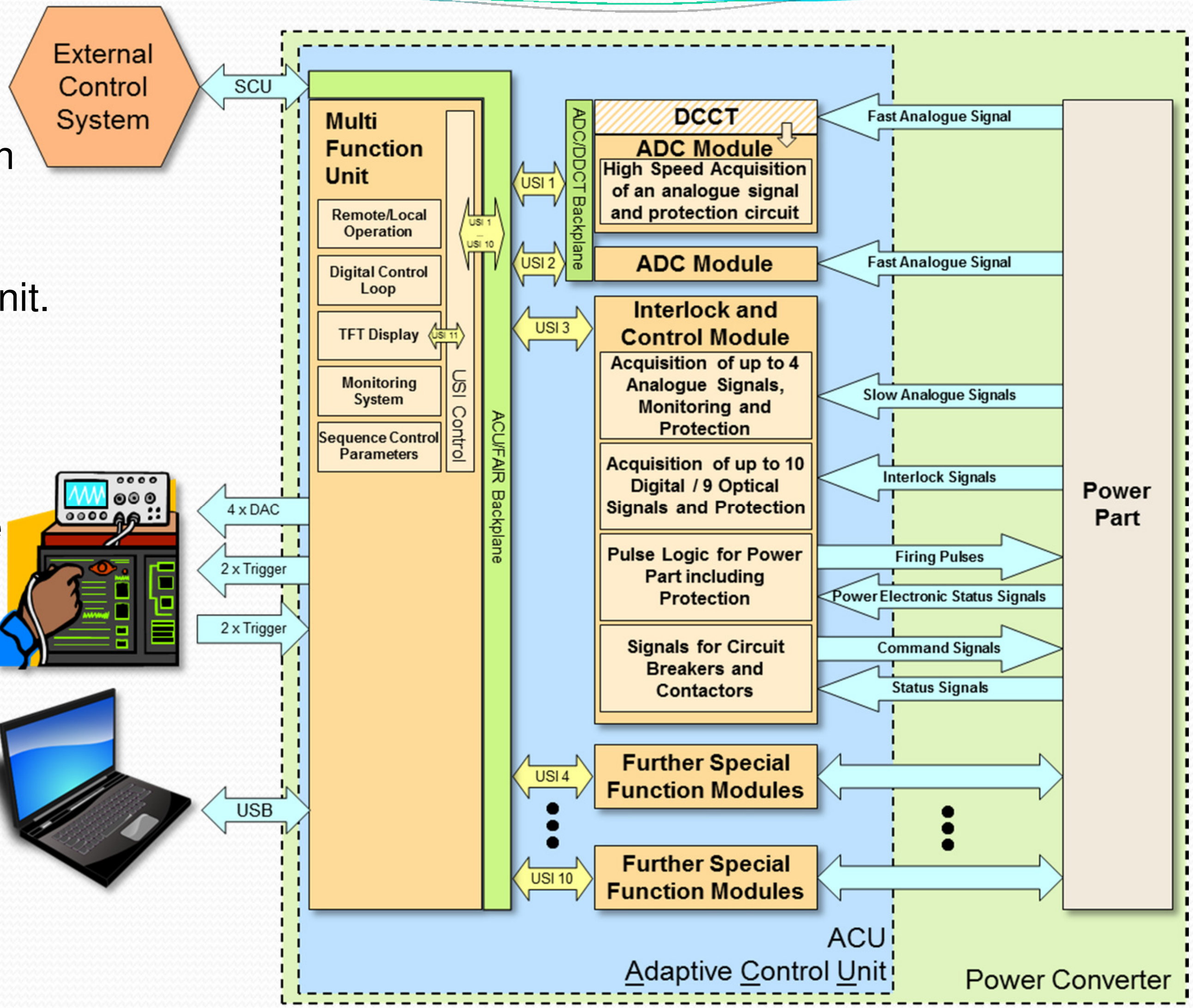
3. Monitors and display the key parameters like I_L,U_L,U_D, water flow etc.

Adaptive Control Unit (ACU)

- ACU is an interface between power converter and FAIR Central Accelerator Control System, Scalable Control Unit.

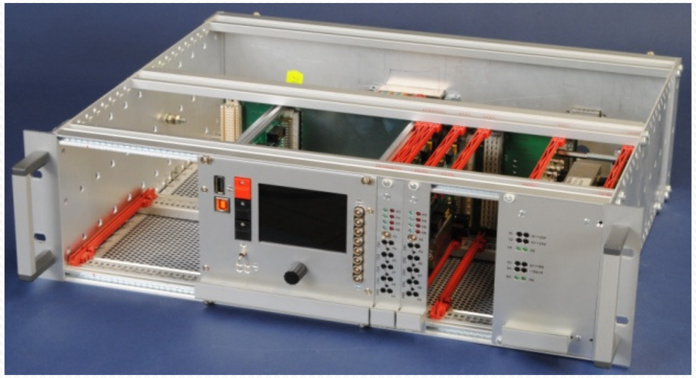
Main Components:

- Multi-Function Unit (MFU)
- InterLock & Control Module (ILC module)
- Analog to Digital Converter (ADC module)

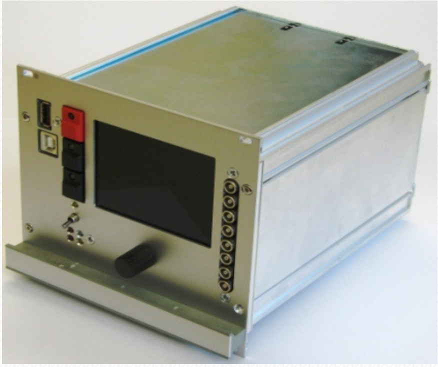


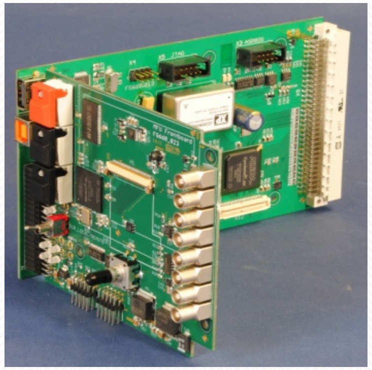
Hardware of ACU System

19" basic unit

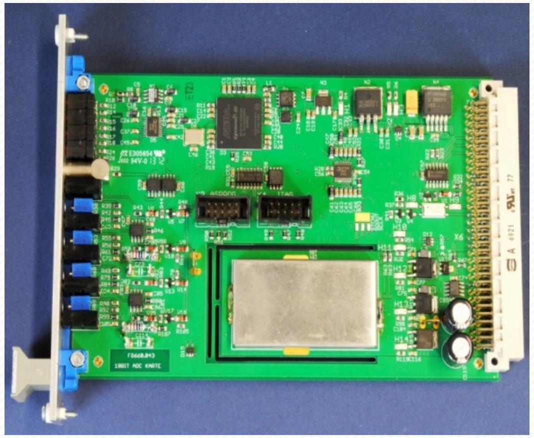


Multi-Function-Unit (MFU):

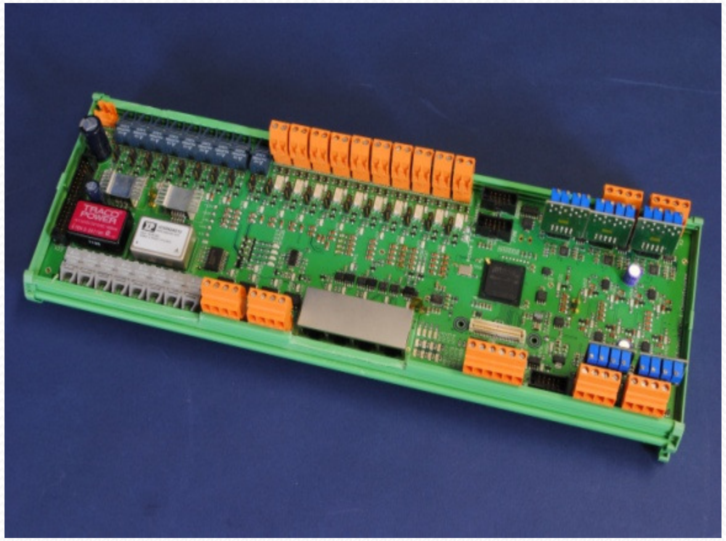




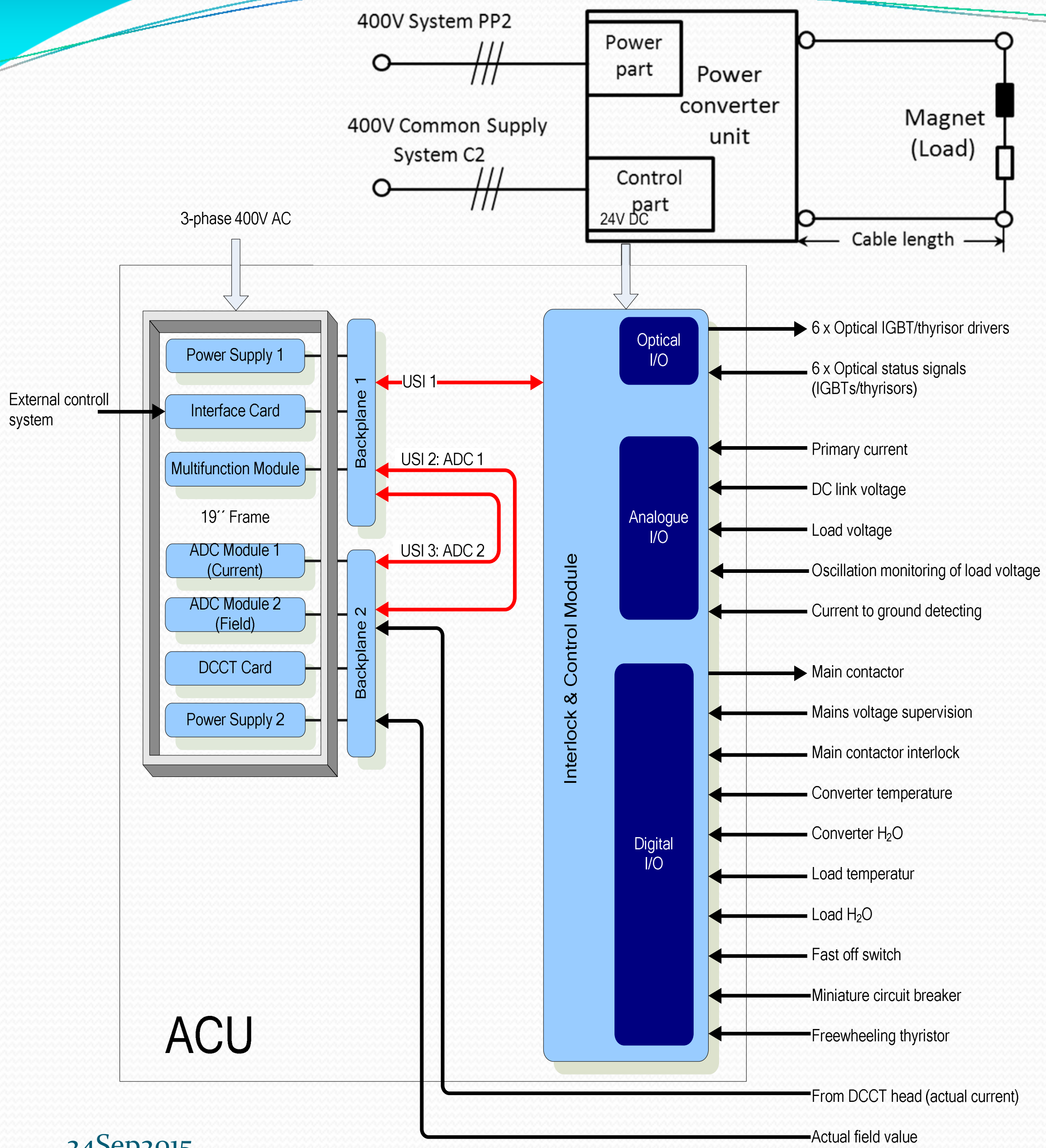
18 bit- ADC-Module (ADC)

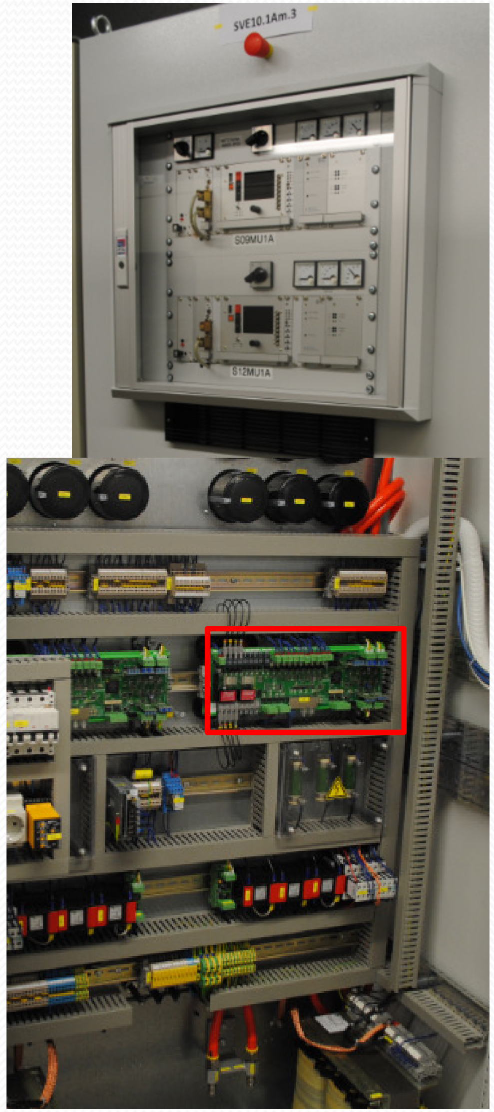


Interlock & Control-Module (ILCM)



Typical ACU Application: for a Standard PC at GSI/FAIR



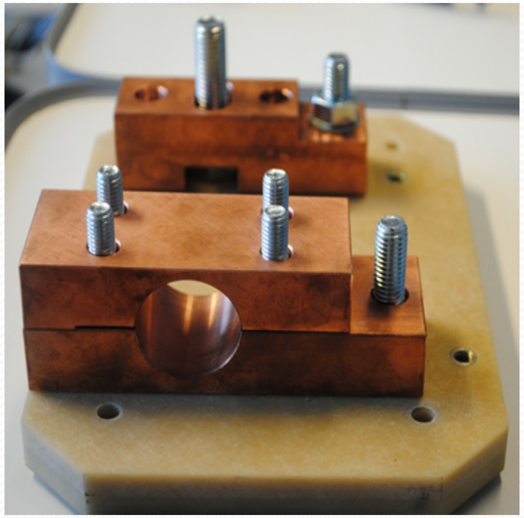


DCCT Examples

Load Cable and Connection: Coaxial Cable

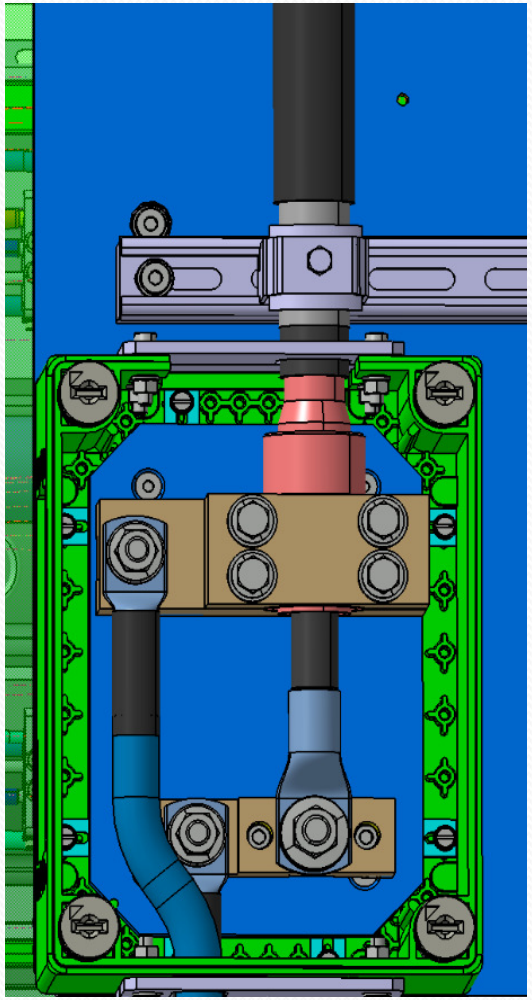
C/s of Co-axial cable

Copper bushing fixed over the outer conductors

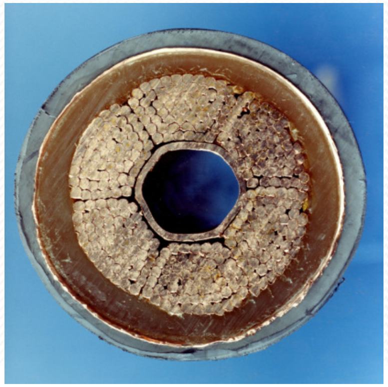


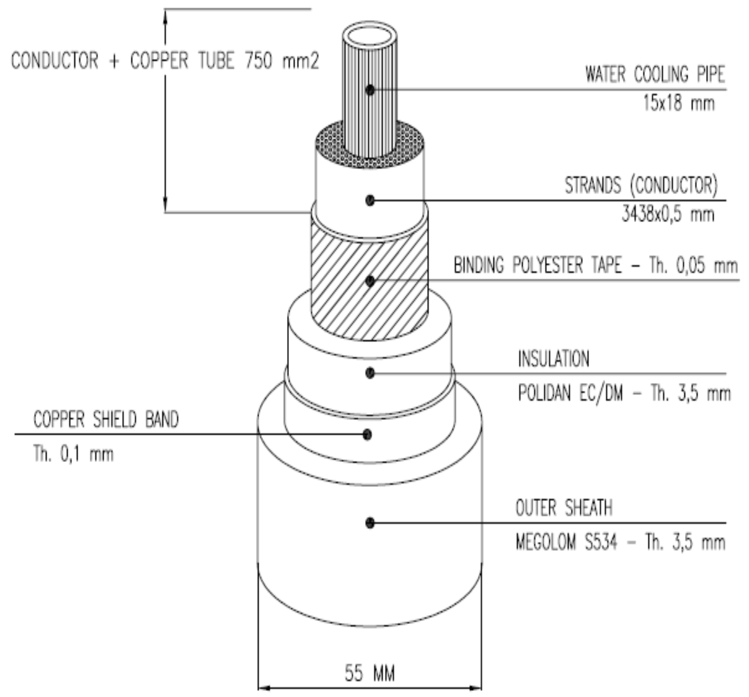
Copper connectors

Example of a cable connection



Load Cable and Connection: Water Cooled Cable





C/s of water-cooled cable

An example of water-cooled cable connection

Cooling Circuit: Air and Water Cooling

Environmental conditions ⟵ | ⟶ **In Power Supply**

Air Cooling:

Ambient temperature	18°C...28°C
Relative humidity	max. 80%

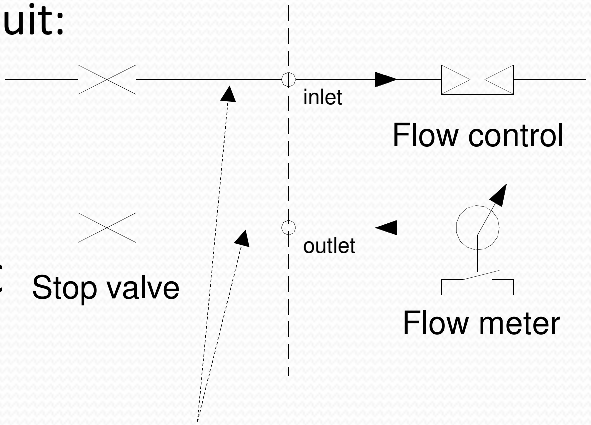
Fans are included in case of air cooling.

Air losses have to be specified.

Water Cooling:

Data of desalinated water circuit:

Max. pressure	13 bar
Peak pressure	15 bar
Inlet temperature	25±2 °C
Difference pressure	10 bar
Conductivity	< 1 µS/cm



Water flow q in l/min is adjusted as per the requirement of PC.

q should be independent of fluctuations in pressure difference.

Outlet temperature limit 55 °C.

Allowed materials: copper and stainless-steel.

Building: Considerations from PC Point-of-View

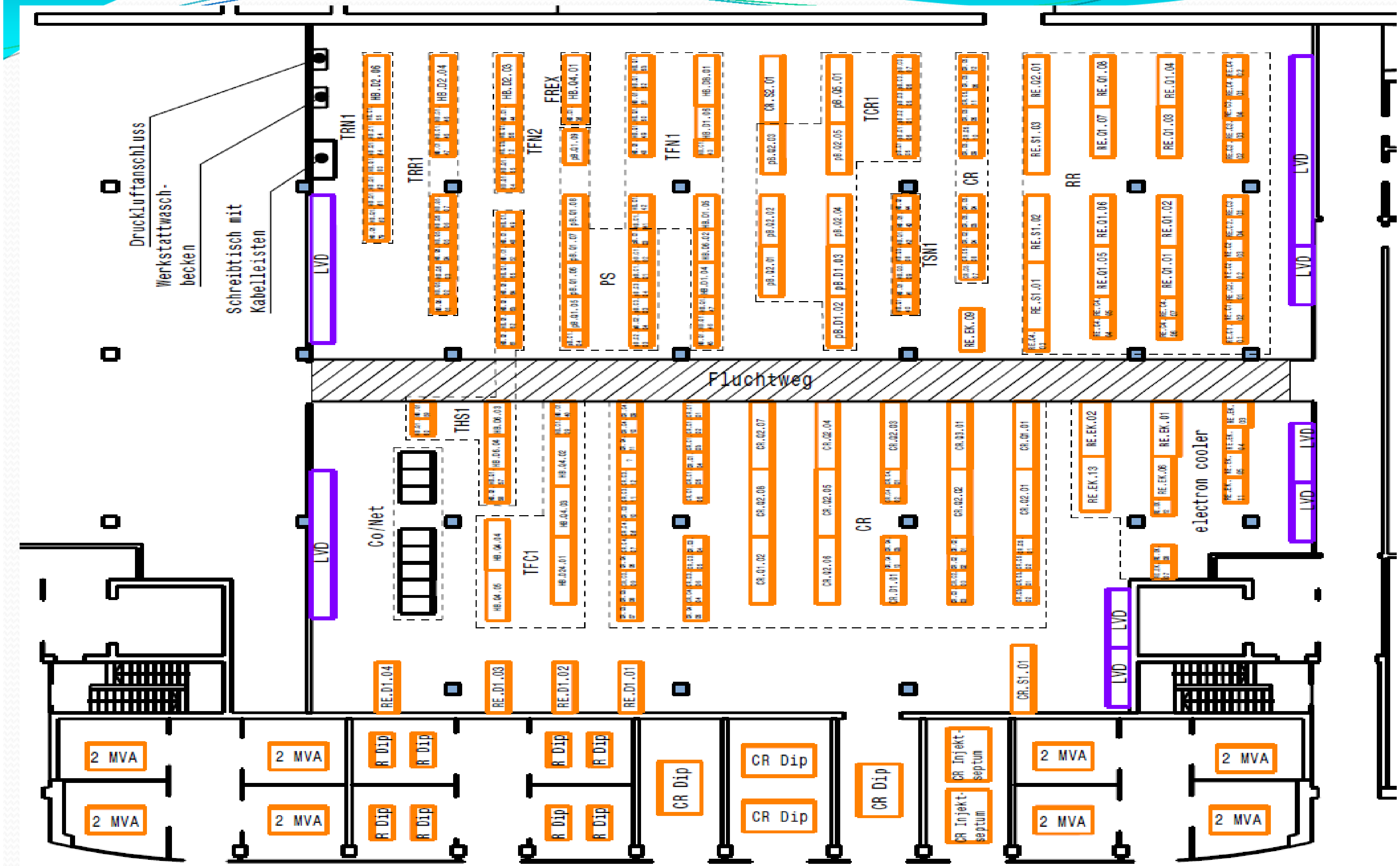
Power Supply Considerations:

- Cabinet size, weight and Height
- Floor space

General Installation Considerations:

- False floor; typical height 0.5m, local peak load 5000 N; distributed load 30 kN/m²
- Optimized current cabling (length, losses and cable tray arrangement)
- Keep air losses low
- Separate rooms with metallic false floor for 20 kV Transformers and inductors

Building: Considerations from PC Point-of-View



Costing: Power and Control Parts

- Power Part: Transformer, Switches, Input and output filter, Damping circuit etc. placed in a cabinet (Contractor)
- Control Part: ACU and DCCT (GSI in-kind)
- Cables (FAIR/ in-kind ?)
- Cable connectors (FAIR)

SIS18 Dipole Upgrade

GE is working on this project since December 2012

New 20 kVSwitch-Gear System

New power grid filter, delivered in mid of 2013

SIS18 Dipole Upgrade

Final SAT expected till December 2017

Power Transformers

New power-cable laying and connection in June 2015

Smoothening Reactors

My Sincere Acknowledgements to:

Mr. Welker, Mr. Ramakers, Mr. Trumm,
and to All my colleagues in LOEP

For their Guidance and Contribution

Thanks for Your Attention!