Technology
Department

ELENA Project Review

Power Converters

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15th October 2013

Technology Department

Overview of Power Converters for ELENA

Around 400kVA Installed Power
All power derived from 400V Network

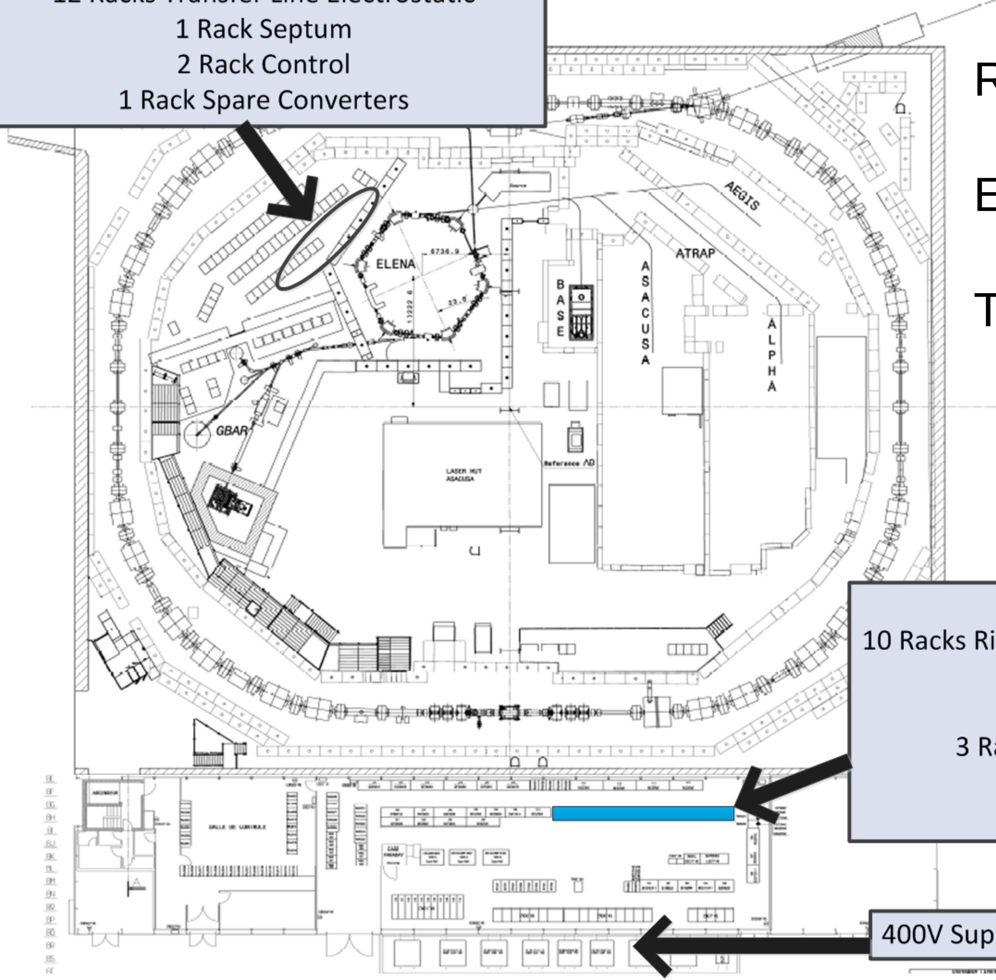
Ring: 26 Magnetic Circuits

Electron Cooler: 11 Circuits

Transfer Lines: 12 Magnetic Circuits
184 Electrostatic Circuits

Total: 233 Circuits

16 Racks
12 Racks Transfer Line Electrostatic
1 Rack Septum
2 Rack Control
1 Rack Spare Converters

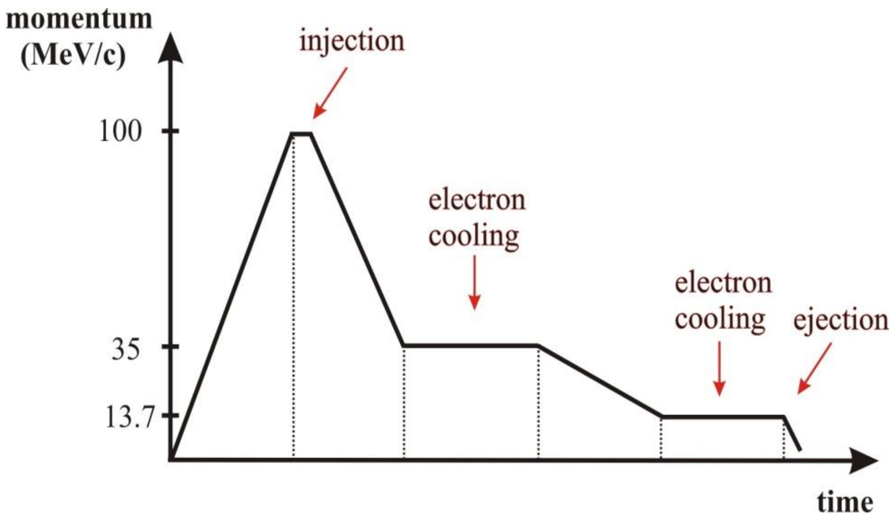


19 Racks
10 Racks Ring and Magnetic Transfer line Converters
3 Racks Electron Cooler
1 Rack Control
3 Racks Spare Main Dipole Converter
2 Rack Various Spares

400V Supply Transformers (EN/EL)

Cycling Magnetic Circuits

- Magnetic Elements in the ring will follow a varying current or field reference.
- Uncertainty of 500ppm, ***referred to instantaneous requested current/field***, must be respected at all energy levels
- All circuits require relatively small voltages at lowest energy level



Expected duration up to 30s

Maximum ramp time of 1s has been assumed for dimensioning of ring power converters

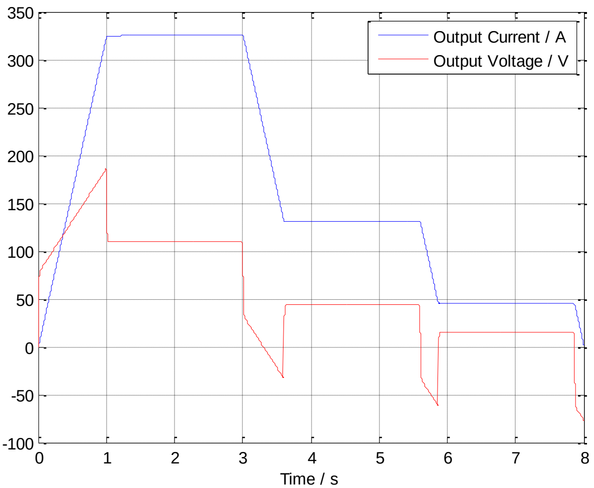
ELENA Ring: Overview of Circuits

Magnet Type	Number of Circuits	Number of Magnets in series per circuit	Total Circuit Resistance / mΩ	Total Circuit Inductance / mΩ	Flat-top Current / A	Minimum Current / A	Maximum Voltage / V	Power Converter Model and Accuracy Class	Nominal Voltage / V	Nominal Current / A	Uncertainty (one year) / mA	Minimum Relative Uncertainty
Bending PXMBHEKCWP	1	7	337	238	326	44.662	188	AUXPS_Type 2 50ppm	450	400	30	$6.72x10^{-4}$
Quadrupole PXMQNLGNAP	3	4	479	146	37	5.100	23.1	CANCUN_50 100ppm	30	50	5	$9.86x10^{-4}$
Sextupole PXMXNADNAP	2	2	187	10	21	2.900	4.1	CANCUN_50 100ppm	30	50	5	$1.74x10^{-3}$
H/V Corrector PXMCCAYWAP	16	1	100	4	40	5.500	4.2	CANCUN_50 100ppm	30	50	5	$9.12x10^{-4}$
Skew Quadrupole PXMXNADNAP	2	1	100	0.013	33	4.500	3.7	CANCUN_50 100ppm	30	50	5	$1.11x10^{-4}$
Comp. Solenoid PXMLNAFNAC	2	1	TBD	TBD	TBD	TBD	TBD	CANCUN_50 100ppm	30	50	5	TBD

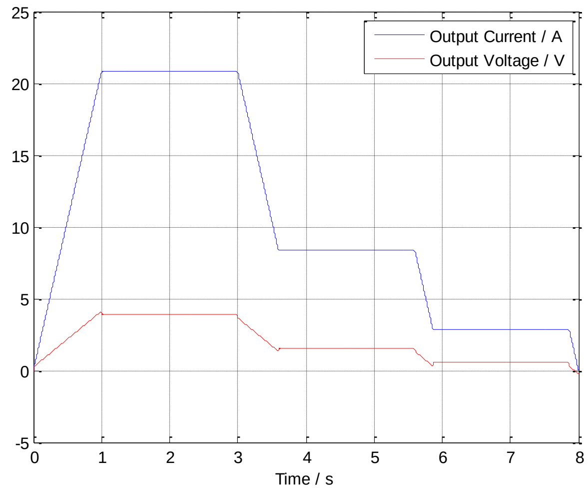
Notes: Total circuit impedances include cables which have been estimated based on conductor material, length and cross section <2A/mm^{2}. Minimum current assumes 0.137 x max flat-top current.

Cycling Magnetic Circuits: V/I Waveforms

Main Dipoles

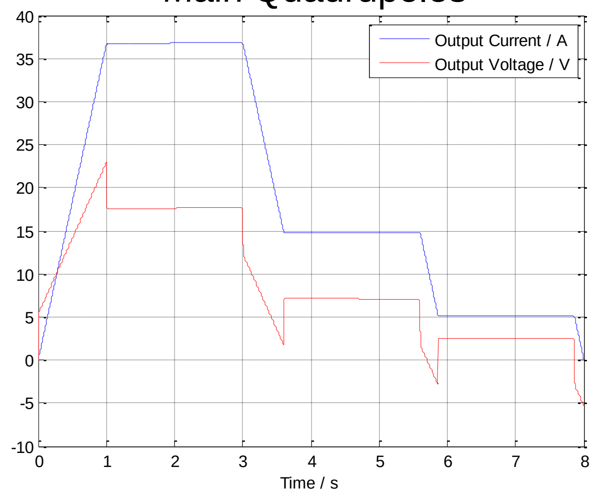


Sextupole

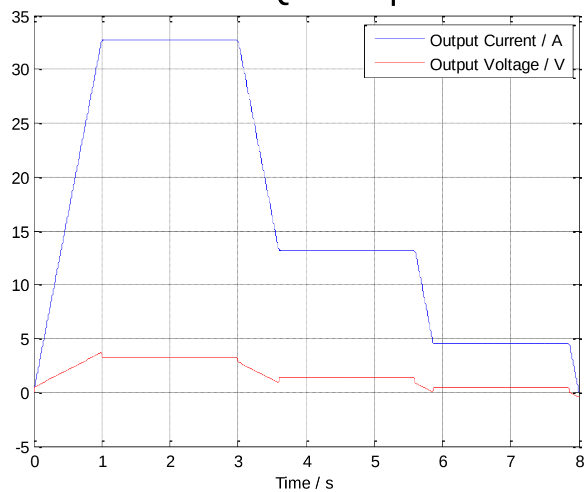


- Compensation Solenoid Awaiting magnet parameters
- All converters are 4 quadrant. Can provide negative voltage if necessary and have no problem operating near 0V which is a strong requirement for these circuits.
- Degaussing waveforms is possible for all magnets

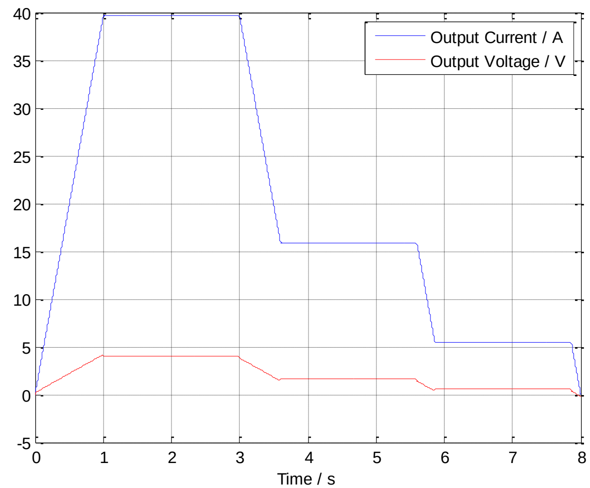
Main Quadrupoles



Skew Quadrupole



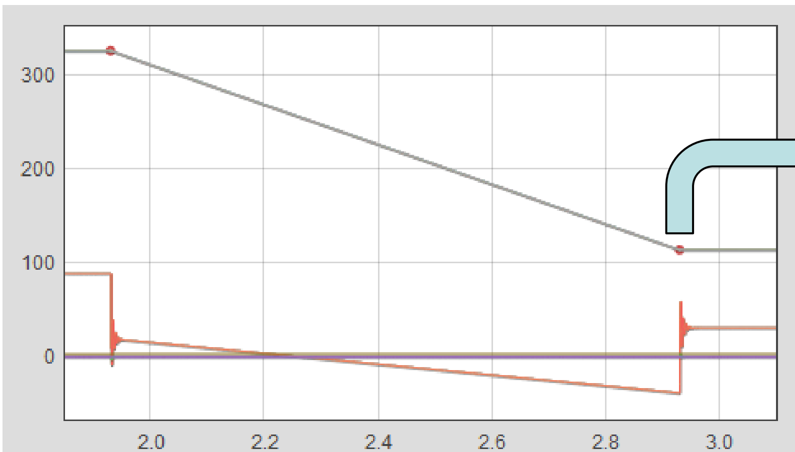
HV Corrector

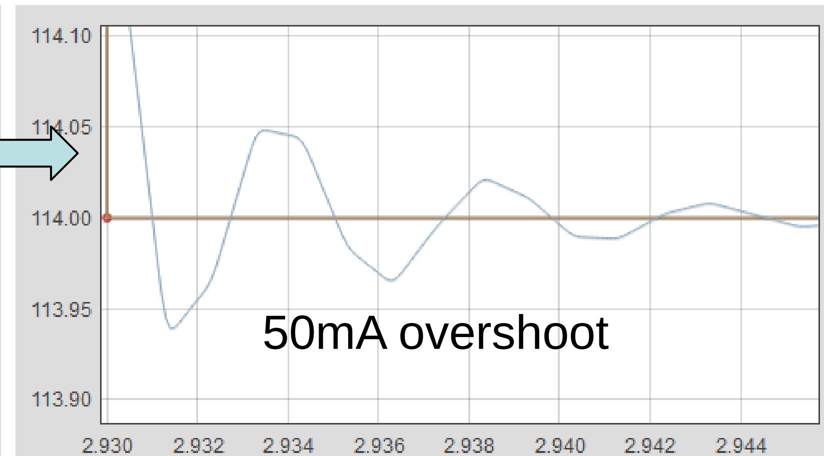


Dynamic Performance using Function Generator Controller

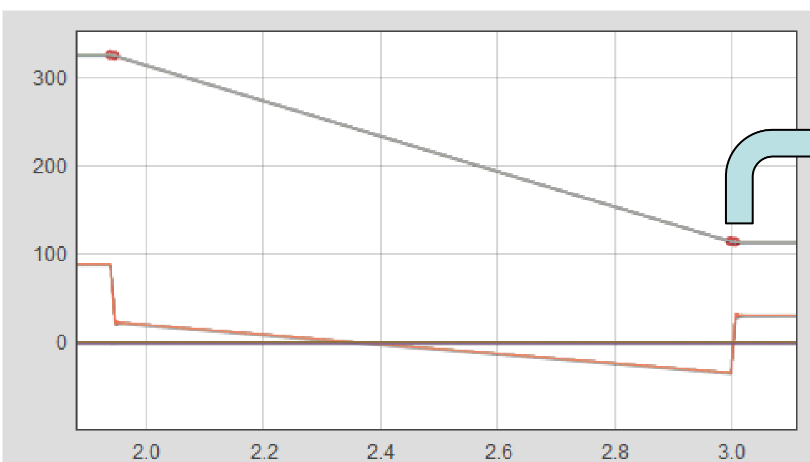
Looking at the transition between first and second plateaux for the main dipole:

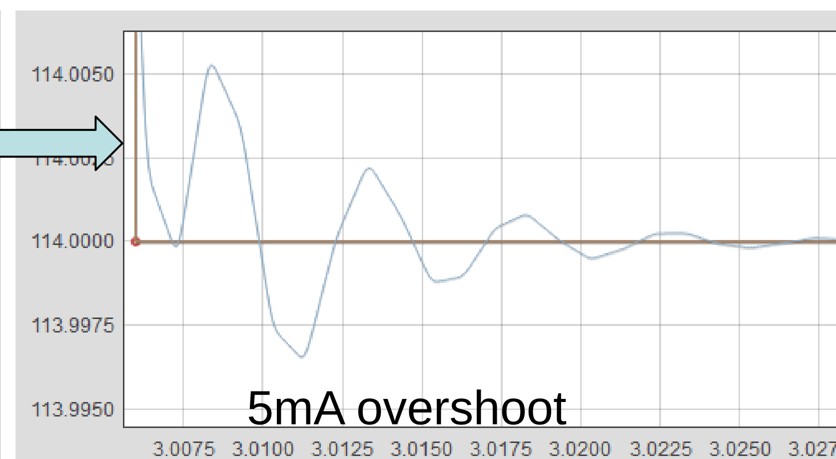
Table of points





PPPL Function





10us resolution of point placement is available for a 100s cycle

Transfer Line: Overview of Magnetic Circuits

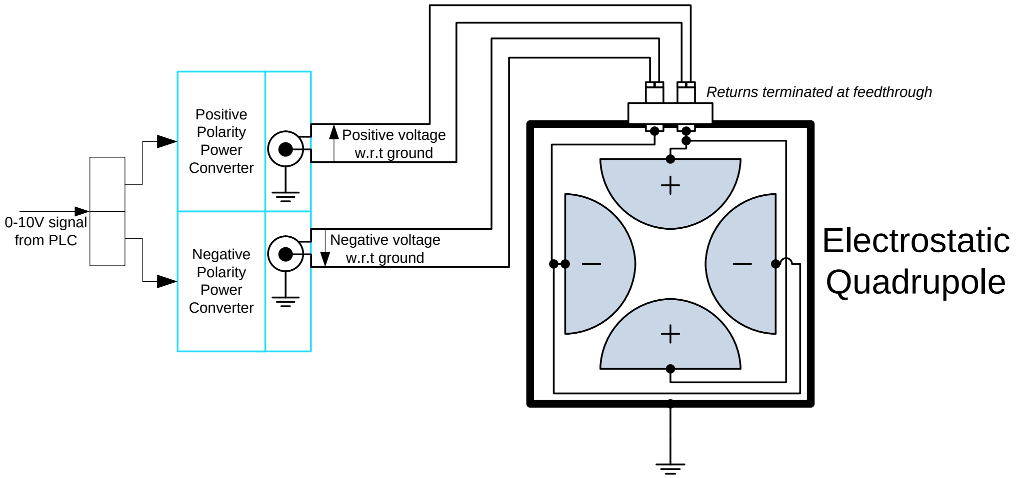
Magnet Type	Number of Circuits	Number of Magnets in series per circuit	Total Circuit Resistance / mΩ	Total Circuit Inductance / mΩ	Flat-top Current / A	Flat Top Steady-State Voltage / V	Power Converter Model	Nominal Voltage / V	Nominal Current / A	Uncertainty (one year) / mA	Flat-top Current Relative Uncertainty	Polarity Reversal
Bending PXMBHCBCWP	1	2	108	68	285	30.8	2 x COBALT 1000ppm	50	400	400	1.4×10^{-3}	NO
Quadrupole PXMQNLGNAP	3	1	177	36	37	6.5	CANCUN_50 100ppm	30	50	5	1.35×10^{-4}	YES
Quadrupole PXMQNAFNWP	1	1	65	3	200	12.9	COBALT 1000ppm	30	200	5	1.00×10^{-3}	NO
H/V Corrector PXMCCAYWAP	6	1	107	4	40	4.3	CANCUN_50 100ppm	30	50	5	1.25×10^{-4}	YES
Septum	1	1	9	0.42	950	9.1	*Commercial*	15	1200	TBD	TBD	No

- Possible to ramp all magnets to full current. Bending magnet is limited to approximately 1.5s

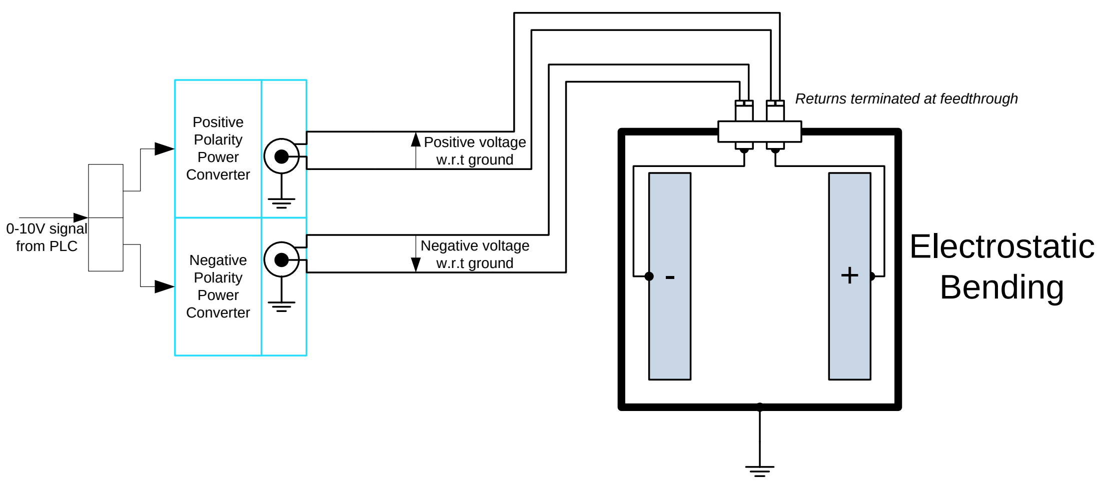
Electron Cooler: Overview of Circuits

Rep.	Function	Oper. Voltage / V	Oper. Current / A	Quantity	Model	Input Voltage / V	Output Voltage / V	Output Current / A	Quadrants	Control
1	Cathode	-350	-0.001	1	Commercial	230	-500	-0.001	1	FGC3 / PLC
2	Grid	±120	±0.001	1	Commercial	230	±500	±0.001	2	FGC3 / PLC
3	Repeller	-300	-0.001	1	Commercial	230	-500	-0.02	1	FGC3 / PLC
4	Collector	-250	-0.01	1	Commercial	230	-500	0.02	1	FGC3 / PLC
5	Filament	16	12	1	Commercial	230	35	24	1	FGC3 / PLC
6	Expansion Solenoid	18.8	152	1	CERN COBALT	400	50	200	1	FGC3
7	Gun/Collector Solenoid	1.4	45	1	CERN COBALT	400	50	200	1	FGC3
8	Drift Solenoid	3.15	45	1	CERN COBALT	400	50	200	1	FGC3
9	Toroïd	TBD	TBD	1	CERN COBALT	400	50	200	1	FGC3
10	Electron Beam steerer		10	10	CERN CANCUN 20	400	75	20	4	FGC3
11	Field correction coil		10	4	CERN CANCUN 20	400	75	20	4	FGC3

Electrostatic Elements: Powering Strategy

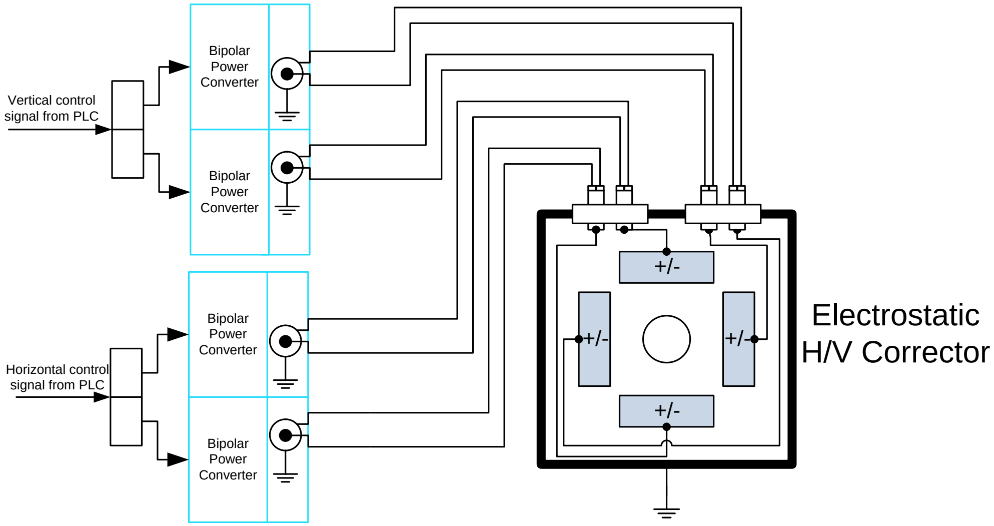


Bending and Quadrupole elements are powered using two back-to-back unipolar power supplies, polarity reversal is only possible with the addition of a polarity switch



Electrodes are always powered with a positive and negative power supply: **Neither electrode is at ground potential**

Electrostatic Elements: Powering Strategy



H/V Correctors powered using two back-to-back biploar power supplies; polarity reversal is inherently possible.

Electrodes are always powered with a positive and negative power supply: **Neither electrode is at ground potential**

Electrostatic Elements: Overview of Circuits

- 197 elements and 184 circuits; some elements will be powered in parallel from the same power converter.
- Differential Voltage range of 250V to 70kV. Achievable using commercial HV Cassette type power supplies.
- Controlled using a PLC

Setting Resolution	**$1x10^{-4}$**
Residual Ripple	< $1x10^{-4}$ pk-pk + 50mV pk-pk
Stability (8h constant conditions)	<$1x10^{-4}$

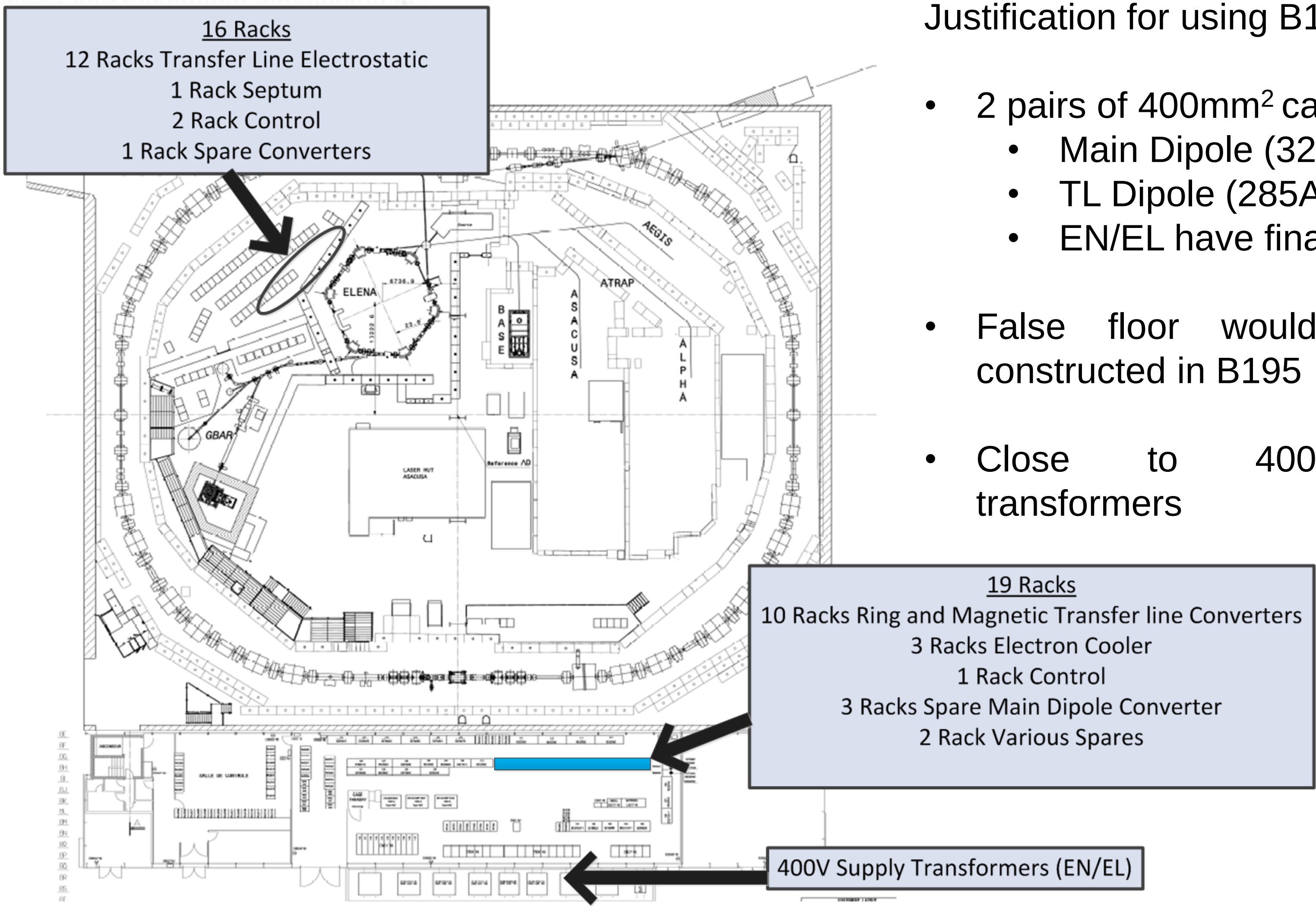
Element Type	Number of Circuits
Matching Quadrupole	74
Bending	12
Defocusing Quad	8
Focusing Quad	7
Corrector	82
Total	184

Zone	Number of Circuits	Number of Polarity Reversal Units	Number of Racks
LNE00	18	8	1
LNE01	28	0	2
LNE02	18	0	1
LNE03	13	0	<1
LNE04	12	0	<1
LNE05	13	0	1
LNE06	24	0	2
LNE07	27	0	2
LNE50	17	0	1
LNS	8	8	<1
LNI	6	4	<1
Totals	184	20	13

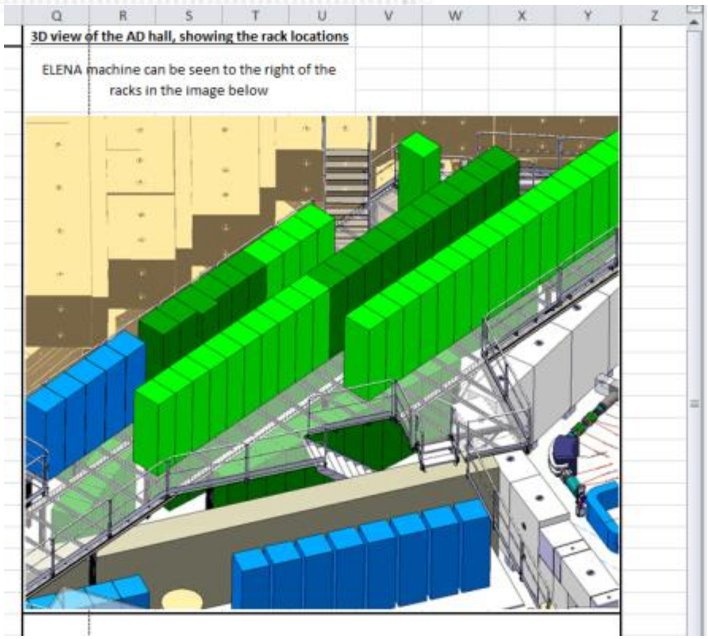
Installation Overview

Justification for using B193_R-407:

- 2 pairs of 400mm^2 cables available.
  - Main Dipole (326A)
  - TL Dipole (285A)
  - EN/EL have final say
- False floor would need to be constructed in B195
- Close to 400V distribution transformers



ELENA Ring (LNR): Installation Overview



AD Upper Floor

B193_R-407

Technology Department

B193_R-407 Electrical Requirements: AC Side

Cabinet	Application	Number of Racks	Number of DC Outputs	Models	Required Phases	Input Voltage / V	Input Current Full Load/ A	Power Full Load / VA
A	Operation	1	2	3 x COBALT	3PN+E	400	60	41569
B	Operation	1	6	6 x CANCUN_50	3PN+E	400	17	11432
C	Operation	3	1	1 x CERN_AuxPS_Type2	3P+E	400	286	198000
D	Operation	1	6	6 x CANCUN_50	3PN+E	400	17	11432
E	Operation	1	6	6 x CANCUN_50	3PN+E	400	17	11432
F	Operation	1	6	6 x CANCUN_50	3PN+E	400	17	11432
G	Operation	1	5	6 x CANCUN_50	3PN+E	400	14	9526
H	Operation	1	5	6 x CANCUN_50	3PN+E	400	14	9526
I	Operation	1	5	5 x HCE 35 -650	3PN+E	400	9	6163
J	Operation	1	3	3 x COBALT	3PN+E	400	60	41569
K	Operation	1	3	1 x COBALT, 2x CANCUN 30	3PN+E	400	26	17667
L	Spare	3	0	1 x CERN_AuxPS_Type2	3P+E	400.00	286	0
M	Spare	1	0	4 x CANCUN_50	3PN+E	400	17	0
N	Spare	1	0	1 x CANCUN_50; 1 x CANCUN 20; 1 x SM 35-45 1 x SM15400	3PN+E	400	x	X
O	Control	1	0	FGC Gateway, Ethernet Switch, Pulse Injector	3PN+E	400		~2000
							Total Power	375kVA

15 Feeders, 19 Racks

B193_R-407 Electrical Requirements: DC Side

			Circuit 1		Circuit 2		Circuit 3		Circuit 4		Circuit 5		Circuit 6	
Cabinet	Application	Number of DC Outputs	Output Voltage / V	Output Current / A	Output Voltage / V	Output Current / A	Output Voltage / V	Output Current / A	Output Voltage / V	Output Current / A	Output Voltage / V	Output Current / A	Output Voltage / V	Output Current / A
A	Operation	2	50	200	50	200	x	x	x	x	x	x	x	x
B	Operation	6	30	50	30	50	30	50	30	50	30	50	30	50
C	Operation	1	450	400	x	x	x	x	x	x	x	x	x	x
D	Operation	6	30	50	30	50	30	50	30	50	30	50	30	50
E	Operation	6	30	50	30	50	30	50	30	50	30	50	30	50
F	Operation	6	30	50	30	50	30	50	30	50	30	50	30	50
G	Operation	5	30	50	30	50	30	50	30	50	30	50	30	50
H	Operation	5	30	50	30	50	30	50	30	50	30	50	30	50
I	Operation	5	650	0	x	x	x	x	x	x	x	x	x	x
J	Operation	3	50	200	x	x	x	x	x	x	x	x	x	x
K	Operation	3	50	200	75	30	75	30	x	x	x	x	x	x
L	Spare	0	x	x	x	x	x	x	x	x	x	x	x	x
M	Spare	0	x	x	x	x	x	x	x	x	x	x	x	x
N	Spare	0	x	x	x	x	x	x	x	x	x	x	x	x
O	Control	0	x	x	x	x	x	x	x	x	x	x	x	x

AD Upper Floor Electrical Requirements: AC Side

Cabinet	Application	Number of Racks	Number of DC Outputs (up to)	Models	Required Phases	Input Voltage / V	Power Full Load / VA
A	ES Operation	1	18	Commercial	3PN+E	400	<2000
B	ES Operation	1	18	Commercial	3PN+E	400	<2000
D	ES Operation	1	18	Commercial	3PN+E	400	<2000
E	ES Operation	1	18	Commercial	3PN+E	400	<2000
F	ES Operation	1	18	Commercial	3PN+E	400	<2000
G	ES Operation	1	18	Commercial	3PN+E	400	<2000
H	ES Operation	1	18	Commercial	3PN+E	400	<2000
I	ES Operation	1	18	Commercial	3PN+E	400	<2000
J	ES Operation	1	18	Commercial	3PN+E	400	<2000
K	ES Operation	1	18	Commercial	3PN+E	400	<2000
L	ES Operation	1	18	Commercial	3PN+E	400	<2000
M	ES Operation	1	18	Commercial	3PN+E	400	<2000
N	SEP Operation	1	3	Commercial	3PN+E	400	<2000
O	Control	1	0	PLC	3PN+E	400	<2000
P	Control	1	0	FGC Gateway, Ethernet Switch, Pulse Injector	3PN+E	400	<2000
Q	Spares	1	0	Commercial	3PN+E	400	0

16 Feeders, 16 Racks

AD Upper Floor Electrical Requirements: DC Side

184 Electrostatic Circuits!
Circuit voltages and polarity reversal options to be finalized

EPC will specify cables and connectors and request a job for the placement by EN/EL.

Septum converter rated 1200A. Magnet designed for 1150A.

- Latest operational requirement is 950A.
- Assuming copper cables of 800mm^2 (2x 400mm^2):
- 8.7V is required in steady state
- 9.1V is required for 1 second ramp
- 3 x 15V 400A converters connected in parallel is proposed
- Current sharing is active
- **Voltage drop of cables is very significant as resistance of the septum is only 8mΩ.**

Cooling and Ventilation

Only the ring dipole power converter is water cooled.

The expected power to the cooling circuit is <10kW.

<10degC temperature rise inlet to outlet

Total max pressure drop of circuit = 3.5bar

In B193_R-407 total losses to air of the order of 40kW -> will be able to provide a more accurate figure. This is also strongly a function of the cycle definition.

List of Power Converters

Designation	Manufacturer	Model	Operation Quantity	Spare Quantity	Output Voltage / V	Output Current / A
1	CERN	CERN_AuxPS_TYPE2	1	1	450	400
2	CERN	COBALT	7	1	50	200
3	CERN	CANCUN_50	34	5	30	50
4	*Commercial*	*Commercial*	1	1	15	1,200
5	CERN	CANCUN_20	2	1	75	20
6	*Commercial*	*Commercial*	77	7	7000	0.002
7	*Commercial*	*Commercial*	12	2	2500	0.005
8	*Commercial*	*Commercial*	13	2	70000	0.000
9	*Commercial*	*Commercial*	81	8	1300	0.010
10	*Commercial*	*Commercial*	4	1	650	0.050
11	*Commercial*	*Commercial*	1	1	35	45
		Totals	**233**	**30**		

Conclusions

- Still to define:
  - Compensation Solenoid Power Converter (Working on base of CANCUN_50)

- Still to confirm:
  - Polarity Reversal Requirements of Electrostatic Elements
  - Electron Cooler requirements

- Documentation to upload to EDMS
  - Work Package Descriptions
  - Data for EN/EL: AC, DC and control cabling requirements

- **Circuits must be finalised** by the end of November to ensure that EPC can respect foreseen install date of June 2015.

Overview of Project Plan

2013	2014	2015	2016
Technical Design Report Work Package Descriptions end of year	*Market Surveys* and *Call for Tenders* where necessary Procurement and Manufacture of Power Converters Systems	Install Power Converters 01/06 – 30/10	ELENA Commissioning 01/04-01/07

BACKUP – Normal Quadrupole Magnet Characteristics

Parameter	Value	Unit	Remark
Type	Racetrack		
Cooling	Air-cooled		The maximum allowed j_{rms} shall therefore be respected
Conductor cross section	6.3 x 4	mm × mm	Without insulation, IEC 60317-02
Interturn insulation thickness	0.1	mm	Enamelled copper wire
Ground insulation thickness	3	mm	
Edge rounding radius	1	mm	
Number of turns	6 × 11 = 66		
Distance between coil and yoke	3	mm	
Nominal current density j	1.52	A/mm^2	
Resistance @ 20 ° C	0.103	Ω	For four coils
Inductance	36.4	mH	For four coils
Conductor length per coil	~ 36.3	m	= 66 × (2.75 × yoke length)
Weight per coil	~ 13	kg	

Parameter	Value	Unit	Remark
Nominal current I_{max}	37	A	
Rise time	≥1	s	

BACKUP – Skew Quad Magnet Characteristics

Parameter	Value	Unit	Remark
Type	Racetrack		
Cooling	Air-cooled		
Conductor material	Copper		
Conductor dimensions	6.3 x 4	mm x mm	IEC 60317-0-2, dimensions given without insulation
Conductor insulation	0.1	mm	Enamel
Coil windings	4 x 11 = 44		
Coil cross-section	71.5 x 16.8	mm x mm	= (11 x 6.3 + conductor insulation) x (4 x 4 + conductor insulation); used in simulations
Bending radius	8	mm	= 2 x conductor thickness
Resistance at 20˚C	33	mΩ	For four coils in series
Inductance	10.3	mH	For four coils in series
Coil mass	~ 2.5	kg	

Parameter	Value	Unit	Remark
Current	33.0	A	
Current density	1.36	A/mm²	
Voltage	1.1	V	At steady operation
Voltage during ramp to I_{nom} in 1 s	1.4	V	
Power dissipation	35.6	W	At steady operation

BACKUP – H/V Corrector Magnet Characteristics

Parameter	Value	Unit	Remark
Type	Racetrack		
Cooling	Air-cooled		
Conductor material	Copper		
Conductor dimensions	8 x 4.5	mm x mm	Following IEC60317-0-2
Cross section of conductor	35.14	mm^2	
Insulation	0.1	mm	Enamelled copper wire
Coil windings	3 x 7 + 2 x 6 x 4 = 69		The coil is divided in a “main coil” and two “compensation coils” (see Figure 2)
Coil cross-section	14.1 x 57.4 + 2 x 28.2 x 32.8	mm x mm	Does not include 2 mm ground insulation
Bending radius	12	mm	
Resistance at 20˚C	33.3	mΩ	For two coils in series per plane
Inductance	3.9	mH	Per plane
Coil mass	15	kg	Weight per coil; Estimate

Parameter	Value	Unit	Remark
Magnet	MCR		
Current	40	A	

BACKUP – Sextupole Magnet Characteristics

Parameter	Value	Unit	Remark
Type	Racetrack		
Cooling	Air-cooled		
Conductor material	Copper		
Conductor dimensions	2.5 x 7.1	mm x mm	Table 2, IEC 60317-0-2
Cross section of conductor	17.20	mm^2	
Insulation	0.1	mm	
Coil windings	6 x 4 = 24		
Average turn length	400	mm	Estimate
Coil cross-section	14.8 x 47.8	mm x mm	Includes 2 mm ground insulation
Bending radius	10	mm	= 4 x cable thickness
Resistance at 20˚C	60	mΩ	For six coils in series per magnet
Inductance	5	mH	Per magnet
Coil mass	2	kg	Estimate

Parameter	Value	Unit	Remark
Magnet	MXR		
Current	21	A	
Current density	1.2	A/mm^2	
Voltage	1.3	V	At steady operation
Maximum voltage during	1.4	V	

BACKUP – TL Dipole Magnet Characteristics

Parameter	Value	Unit	Remark
Type	Racetrack		
Cooling	Water-cooled		
Conductor material	Copper		
Conductor dimensions	10 x 10	mm x mm	Luvata Nr. 8139
Hole diameter of conductor	5.7	mm	
Cross section of conductor	73.6	mm^2	
Insulation	0.5	mm	
Coil windings	8 x 8 = 64		
Coil cross-section	94 x 94	mm x mm	Includes 3 mm ground insulation
Bending radius	20	mm	= 3.5 x hole diameter
Resistance at 20˚C	47	mΩ	For two coils in series per magnet
Inductance	32	mH	Per magnet
Coil mass	70	kg	Estimate

Parameter	Value	Unit	Remark
Magnet	MBL		
Current	285	A	
Current density	3.9	A/mm^2	
Voltage	13.4	V	At steady operation
Maximum voltage during	18	V	

Table from DS 07/08/2013

Element type	Label	Short label	Total number of magnets	Resistance in mOhm	Inductance in mH	Current in A at maximum field
Bending Magnet, Horizontal	PXMBHEKCWP	MBR	8	47	34	326
Quadrupole, Normal	PXMQNLGNAP	MQR	13	103	36	37
Sextupole, Normal	PXMXNADNAP	MXR	5	60	6	21
Quadrupole, Skew	PXMQSABNAP	MQS	3	33	10	33
Corrector H+V*	PXMCCAYWAP	MCR	9	32	4	45
Solenoid	PXMLNAFNAC	MLR	3	TBD	TBD	TBD
TL Bending magnet	PXMBHCBCWP	MBL	3	47	32	285

Example DCCT data

2.1 Measurement Characteristics	
Nominal Output Voltage	10V
Nominal current	600A
Output polarity	Bipolar (no discontinuity at zero)
Stability	< 2 ppm over 30 minutes
Unipolar linearity	< 10 ppm (for both polarities)
Gain	+10 V at + 600A - 10V at - 600A
Gain: adjustment and resolution	Adjustable to 0 ppm error, Resolution 0.2 ppm, Range ± 200 ppm
Gain: initial error	< 50 ppm
Gain: drift	< 5 ppm/24h, < 10 ppm/month, <30 ppm/year
Gain: temperature coefficient	< 2 ppm/K
Positive-Negative gain error	< 5ppm
Output offset: adjustment and resolution	Adjustable to 0 ppm error, Resolution 0.2 ppm Range ± 100 ppm
Output offset: initial error	< 5 ppm
Output offset: drift	< 3 ppm/24h, < 5 ppm/month, <10 ppm/year
Output offset: temperature coefficient	< 1 ppm/K
CMRR	>80 dB @ DC to 100 Hz
Bandwidth of output signal	15 kHz
Rms value of output noise related to V_{out}	10Hz …100Hz < 2 ppm^{PP} 100 Hz …10 kHz < 10 ppm^{PP} > 10 kHz < 30 ppm^{PP}