

PAUL SCHERRER INSTITUT 	Projekt / Project SLS-2
Titel / Title Power Supplies for SLS-2	Dokument Nummer / Document Identification SLS2-RB93-001-1
Autor(en) / Author(s) Beat Ronner	Datum / Datee 17.8.2017

Annex to SLS-2 Conceptual Design Report

Summary

This annex is a more detailed version of the power supply chapter of the SLS2-CDR. It contains background information about the calculated numbers and chosen solutions.

The key issues and challenges can be summarized as follows:

A comparison between the SLS and SLS2 storage ring shows two main differences that bring challenges on the power supply side:

- The beam emittance becomes much smaller, and with this also the tolerances of the corrector power supplies.
The noise-RMS requirement for the current of the SLS2 corrector power supplies is at the border of what can be reached.
- The number of needed power supplies becomes much higher.
The effort needed to develop the needed control boards as well as new converter designs exceeds the capacity of the power electronics section, such that parts of the development work will have to be given externally.

1 Tables

1.1 Table of contents

1	Tables	2
1.1	Table of contents	2
1.2	Used abbreviations	2
2	Information base	3
3	Power supplies for SLS2 storage ring	3
3.1	Technical base for new power supplies / new developments	3
3.2	New magnets & power supplies for the SLS2 storage ring	3
3.3	Power supply topologies	7
3.4	Performance requirements	11
3.5	Required power supply features	12
4	Existing SLS power supplies: Reuse or replace?	13
4.1	Overview	13
4.2	PS replacement in plant parts that stay unchanged with SLS2	14
4.3	Experiments	15
5	Tables	Error! Bookmark not defined.

1.2 Used abbreviations

1Q	1-quadrant (positive voltage, positive current)
4Q	4-quadrant (positive and negative voltage, positive and negative current)
DCCT	DC current transducer
IGBT	Insulated gate bipolar transistor (power semiconductor)
PS	Power supply
pu	per unit
XLPS	Extra large power supply

2 Information base

For this annex, the following information base was used:

- Holy list (magnets), status May 2017
<http://ados.web.psi.ch/SLS2/Notes/SLS2-SA84-003.xlsx>
- SLS PS list for replacement of existing PS
\\fs01\9320\Betrieb_Unterhalt\Anlagen\SLS\SLS PS-Liste .xls

3 Power supplies for SLS2 storage ring

3.1 Technical base for new power supplies / new developments

The existing power supply designs are a good base also for SLS2. However, this base needs to be complemented with new developments where no good fit exists.

For the correctors, power supplies with < 10 A are needed with a very high precision. In today's PSI power supplies, high-precision current measurements are done with DCCTs. They are especially for small power supplies rather costly (CHF 500.--/pcs), and also are DCCTs only available down to 10 A. Therefore, tests are currently done with shunt-based current measurements. The plan is to develop a very compact, PCB-based converter card including a high precision shunt current measurement and controller for small power supplies.

The controller card used in SwissFEL's power supplies is built with FPGA & DSP originating from ca. 2005. These components will be outdated at start of SLS2 operation. Therefore, also the development of a new universal controller card is planned as replacement of today's DPC controller card.

Additional to above developments, also existing converter designs have to be enhanced / optimized for use in SLS2:

- The 50 A SwissFEL converter needs to be adapted & optimized. For use in 1Q-applications, it needs to be built more compact.
- New variants for large power supplies (XLPS design) have to be designed for the SLS2 dipoles
- The XLPS design will also be adapted to serve as PS for the superconducting dipoles

All above developments will consume a major part of the available man-power in the power electronics section and even exceed the capacity, so that substantial work will have to be given externally.

The costs for this external work are not included in this report; it cannot be estimated before the scope is clearer and a more detailed work planning has been done.

3.2 New magnets & power supplies for the SLS2 storage ring

To supply all the magnets in the SLS2 lattice, different power-supply circuits are needed. The following table shows the number of magnets of each type, as well as the interconnections.

Magnet type	Winding	Current [A]	Stationary magnet voltage [V]	1Q / 4Q	Rise time 0 -> iMax [s]	Est. $L \cdot di/dt$ [V]	Est. Voltage drop cabling	Min. needed PS-Voltage [V]	Magnets	# circuits	Magnets in series	Selected PS type	Comment
VB-BN-VB	Main	420	15	1Q	n.a.		13	868	57	1	57	B	
	Corr1	5	10	4Q	n.a.		8	18	57	57	1	A	
	Corr2	5	10	4Q	n.a.		8	18	57	57	1	A	
AN, ANS	Main	200	15	1Q	n.a.		15	915	120	2	60	D	
	Corr	5	10	4Q	n.a.		8	18	114	114	1	A	
BS	Main	400	0	1Q	10	30	3	33	3	3	1	S	Supraconducting, L=0.7 H From magnet point of view, ramping up current needs >=2h
VBS	Main	400	15	1Q	n.a.		2.5	32.5	6	3	2	J	Still to design, rating is rough guess
	Corr	5	10	4Q	n.a.		8	18	6	6	1	A	
ANS	Main			1Q	n.a.			0	0	0	0	D	Bei AN abgedeckt
	Corr	5	10	4Q	n.a.		8	18	6	6	1	A	
½ BN-VBM	Main	420	7.5	1Q	n.a.		13	193	24	1	24	C	
	Corr1	5	10	4Q	n.a.		8	18	24	24	1	A	
	Corr2	5	10	4Q	n.a.		8	18	24	24	1	A	
ANM	Main	200	15	1Q	n.a.		15	375	24	1	24	E	
	Corr	5	10	4Q	n.a.		8	18	24	24	1	A	
QA		5	10	4Q	n.a.		8	18	72	72	1	A	As quad-windings on octupoles
QC		50	24	1Q	n.a.		2.5	26.5	96	96	1	F	l=150 mm
SR		50	9.5	1Q	n.a.		2.5	12	288	288	1	G	Variant with individual PS for each SR
SR		150	8	1Q	n.a.		17	113	288	24	12	H	Variant with SR 24 groups of 12
OC	Main	50	0.5	4Q	n.a.		16	28	144	6	24	I	
	Skew-Quad	5	10	4Q	n.a.		8	18	144	144	1	A	
CH		5	10	4Q	25 ms	2.4	8	20.4	120	120	1	A	di/dt: Mail from Michael, 20.03.2017 L=12 mH (L=74mH for design with 80 mT field, downscaled to 32 mT)
CV		5	10	4Q	25 ms	14.8	8	32.8	120	120	1	A	
CHU		5	10	4Q	n.a.		8	18	8	8	1	A	Correction before / after undulators horizontal Assumed 4 new Undulators
CVU		5	10	4Q	n.a.		8	18	8	8	1	A	Correction before / after undulators horizontal Assumed 4 new Undulators
CHEF		5	10	4Q	n.a.		8	18	4	4	1	A	Correction before / after undulators horizontal Assumed 4 new Undulators
CVEF		5	10	4Q	n.a.		8	18	4	4	1	A	Correction before / after undulators horizontal Assumed 4 new Undulators
Total										1217			

Table 1: Magnets in SLS2 storage ring lattice

Notes:

- Correctors for the undulators:
According to discussion in April 2017, a total of 14 undulators (10 existing + 4 new) were assumed. The existing undulators keep also the existing power supplies. Later, a max. extension to 3 more undulators is possible

The interconnections between the magnets and power supplies are visualized in the following figure:

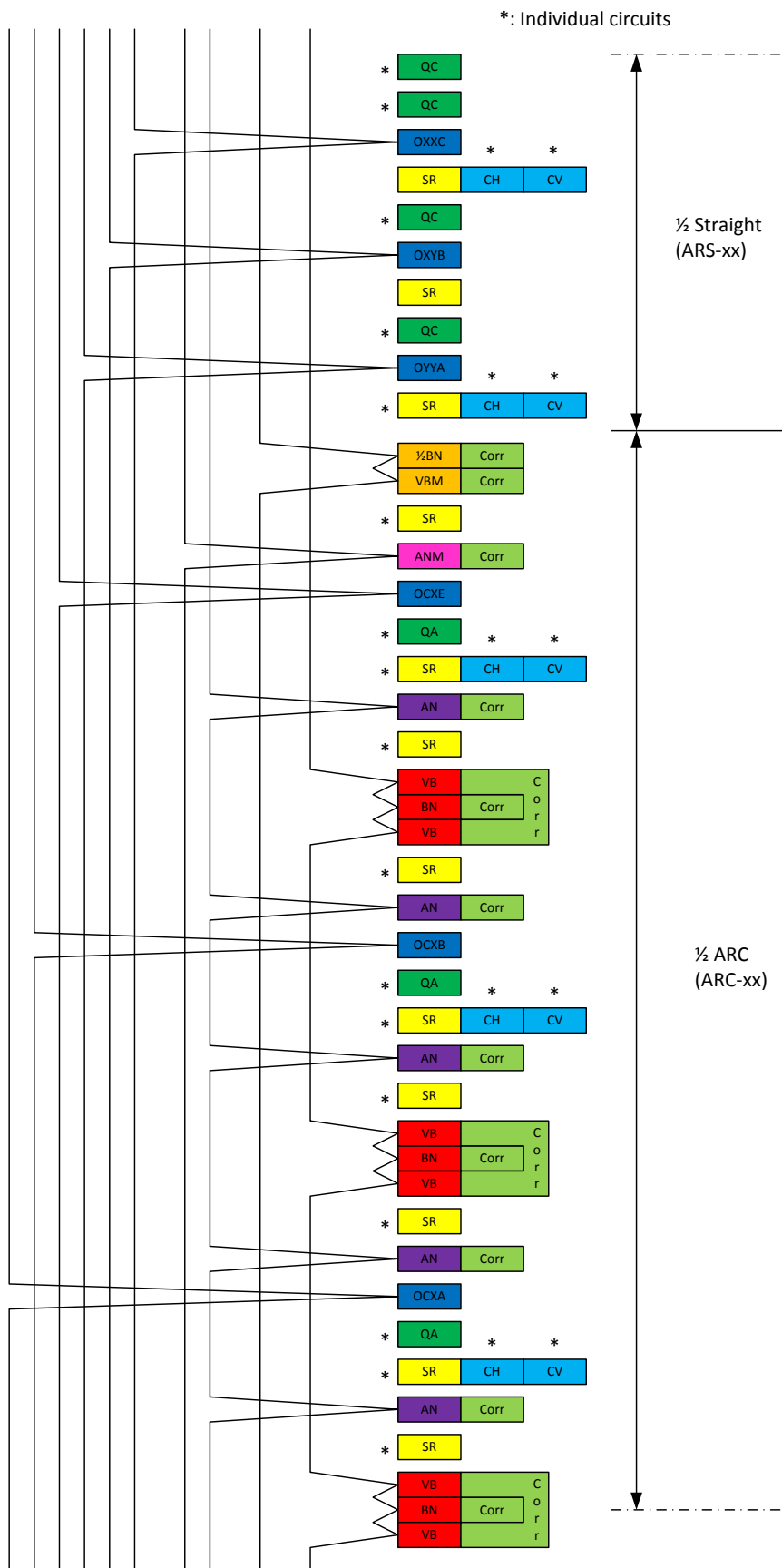


Figure 1: Lattice with power supply interconnections

3.2.1 Space & costs

From above magnet table, the number of needed power supplies as well as the needed space & costs can be estimated based on price- and volume information of today's power supplies.

PS- Type	Current max [A]	Voltage max [V]	1Q 4Q	# PS	Costs PS [CHF]	Space / PS	Unit Space	Space /PS [m^2]	Costs for SLS2 [kCHF]	Space for SLS2	Unit Space	Space for SLS2 [m^2]	Comment
A	5	24	4Q	792	1'900	0.042	Rack 900 x 610 x 2300	0.023	1'505	33	Rack 900 x 610 x 2300	18.1	
B	420	900	1Q	1	190'000	1	Cabinet 1200 x 2540 x 2300	3.0	190	1	Cabinet 1200 x 2540 x 2300	3.0	Evt. possible to use power part of existing SLS dipol PS
C	420	200	1Q	1	75'000	1	Cabinet 1200 x 1500 x 2300	1.8	75	1	Cabinet 1200 x 1500 x 2300	1.8	
D	200	950	1Q	2	105'000	1	Cabinet 1200 x 2000 x 2300	2.4	210	2	Cabinet 1200 x 2000 x 2300	4.8	
E	200	380	1Q	1	75'000	1	Cabinet 1200 x 1500 x 2300	1.8	75	1	Cabinet 1200 x 1500 x 2300	1.8	
F	50	50	4Q	96	7'600	0.2	Rack 900 x 610 x 2300	0.110	730	19.2	Rack 900 x 610 x 2300	10.5	Today's converter is 4Q. 1Q would be sufficient
G	50	20	4Q	288	6'600	0.2	Rack 900 x 610 x 2300	0.110	1'901	57.6	Rack 900 x 610 x 2300	31.6	Today's converter is 4Q. 1Q would be sufficient
I	50	50	4Q	6	7'600	0.2	Rack 900 x 610 x 2300	0.110	46	1.2	Rack 900 x 610 x 2300	0.7	4Q needed
J	400	40	4Q	3	55'000	1	Cabinet 1200 x 1500 x 2300	0.549	165	3	Cabinet 1200 x 1500 x 2300	1.6	
S	400	40	2Q	3	60'000	1	Cabinet 1200 x 1500 x 2300	1.8	180	3	Cabinet 1200 x 1500 x 2300	5.4	Superconducting
Subtotal				1193					5'076			79.434	
Addition for prototypes, inflation / uncertainty 15%									761				
Total									5'837 kCHF			79.434	

Table 2: Power supplies for SLS2

Notes:

- The indicated costs cover material & external work for the power supplies, but no PSI man-hours
- Rack space means pure rack space, i.e. no space for opening doors & passing between racks is included
- As comparison: SLS power supplies use ca. 80m² rack space, whereof ca. 50m² for the power supplies of the ring.

One of the main cost- and space contributors in above table are the type G power supplies for the sextupoles. In above Table 2, individual power supplies for each sextupole were assumed. If the sextupoles are connected in groups, costs and needed space become considerably smaller: The following table shows a comparison of the variants:

- Individual PS for each sextupole

- Sextupoles connected in 24 groups, each group 12 sextupoles in series

Variant	Costs for SLS2 [kCHF]	Space for SLS2 [m ²]
Individual PS for each sextupole	1'901	31.6
Sextupoles in groups	600	13.2

Table 3: Cost comparison: Sextupoles with individual power supplies vs. in groups:

A second major cost- and space contributor are the big number of small Type A power supplies used in correctors, correction windings of dipoles as well as quad- and skew quad windings on octupoles. A proud number of almost 800 of these power supplies are needed.

3.3 Power supply topologies

For the SLS2 power supply power part, the same basic concept as for SwissFEL or SLS is used. The basic structure is the same for all power supplies:

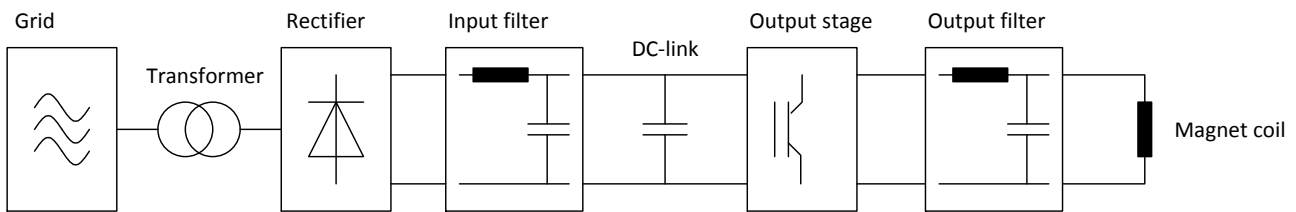


Figure 2: Power supply structure with diode rectifier

- The power supply is fed from the 400 V / 50 Hz grid via a transformer
- The voltage is then rectified
- An input filter smoothens the DC-link voltage
- The DC-link is the intermediate energy storage, decoupling load side from grid side
- The output stage adjusts the load voltage and thus the load current.
- The output filter smoothens the load voltage

For higher power, the rectifier is built up with a diode bridge. For smaller power ranges, transformer and diode rectifier are replaced by a commercially available DC supply device.

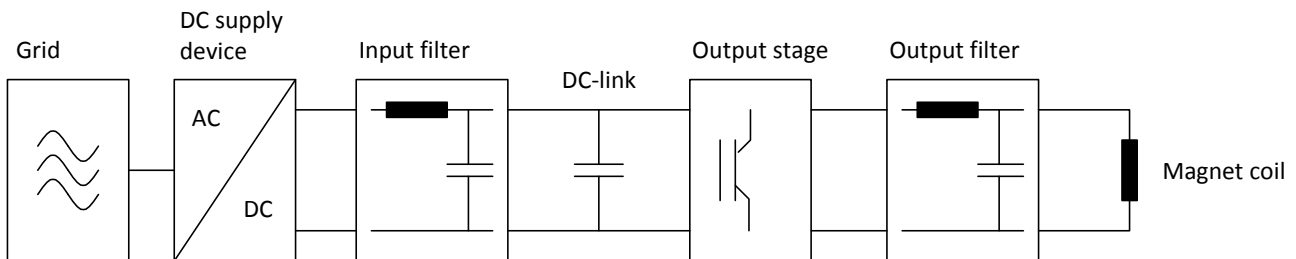


Figure 3: Power supply structure DC supply device

The output stage for 1-quadrant power supplies is built as follows:

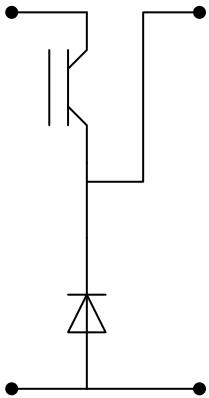


Figure 4: 1Q output stage

For bipolar power supplies, the output stage is 4 quadrant:

4Q-Output stage

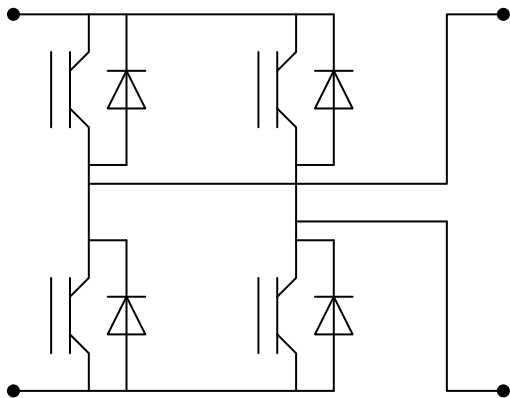


Figure 5: 4Q output-stage

For the different voltage and current ratings, a set of converter designs is available already today, and will be completed with new converter designs for SLS2.

For very high voltages, output stages can be connected in series, and for high current, a parallel connection of up to 3 output stages can be used.

3.3.1 Specialties for power supplies for superconducting magnets

For superconducting magnets, some specialties have to be taken into account:

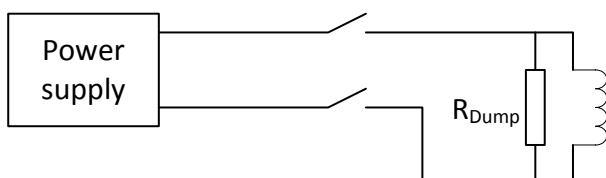


Figure 6: Power supply with dump resistor and quench breakers

In case of a quench (partial loss of superconductivity), the magnet needs to be demagnetized as fast as possible.

This is done by disconnecting the power supply from the magnet via quench breakers. The magnet current flows then into a dump resistor, which dissipates the energy and brings the current to zero.

Natural demagnetization of the superconducting coil would last several 10 min .. h. If a faster ramp-down of the current is needed, the power supply needs to be 2-quadrant, meaning +/- voltage (and only + current). With negative voltage, the current can be reduced a lot faster.

Negative voltage with positive current means energy flowing back into the power supply. This energy needs either to be fed back into the grid or dissipated in the power supply. 4 quadrant grid side converters are state of the art, but have never been built in the power electronics section at PSI. Since time and resources are scarce, and because of the low number of superconducting power supplies, the energy will be dissipated in the power supply via a braking chopper unit.

Since the superconducting magnets are dipoles that are typically run at constant current, and are not demagnetized very often, this is also reasonable from energy-waste point of view.

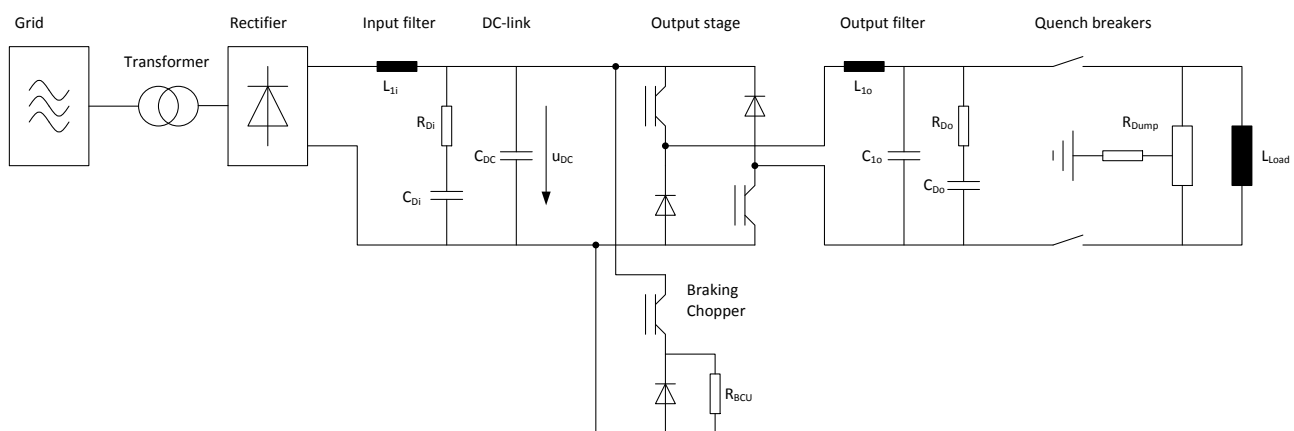
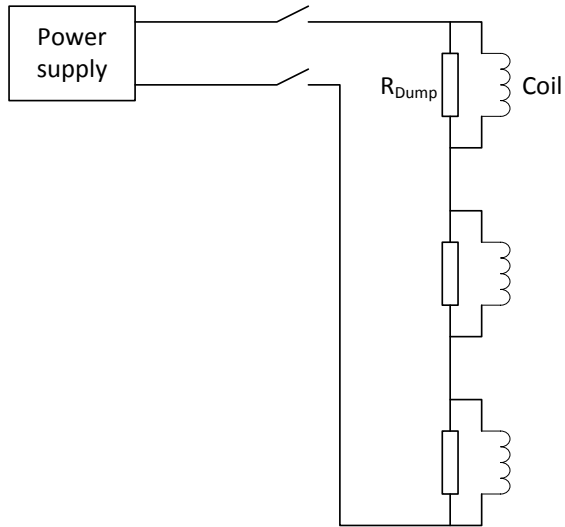


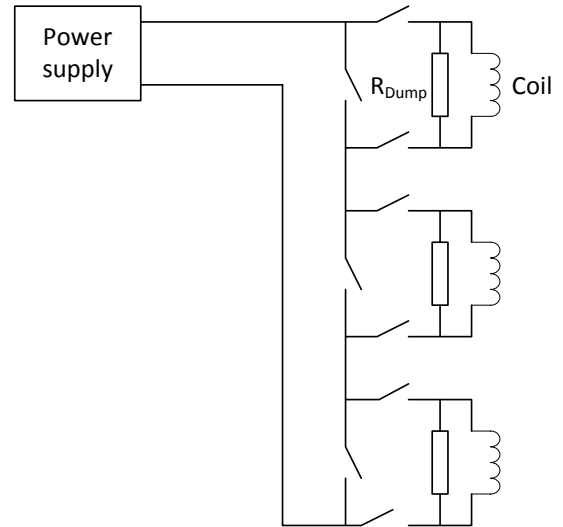
Figure 7: Power supply topology for superconducting magnet.

One aspect was whether the 3 planned superconducting magnets shall be fed by one common power supply or individual power supplies.

Considering the quench case, the connections between one common power supply, the magnets and the quench breakers would have to look as follows:



- + Simple
- Also non-faulty coils see high voltage and potential in case of quench of another coil



- + Non-faulty coils see neither high voltage nor potential in case of quench of another coil
- + Non-faulty coils could even still be operated
- Too many breakers (reliability)

Figure 8: Variant comparison for one power supply for several superconducting magnets

The right variant is much too complicated and needs too many breakers. The left variant would be rather simple, but would result in high voltages / potentials also on the healthy magnet coils. Also, quite long cables between the magnets would be needed.

The concept is thus to foresee individual power supplies for each superconducting magnet (as shown in Figure 7)

3.4 Performance requirements

The requirements for the SLS2 power supplies are:

Magnet type	PS bandwidth ($i_{\text{Ref}} \rightarrow i_{\text{Act}}$) [Hz]	Max. current ripple / noise [ppm pu RMS]	Long term current stability [ppm pu] ¹⁾	Ref resolution [ppm pu] ²⁾	Absolute current error [ppm pu] ³⁾
Dipoles	n.a.	15	15	15	100
CH, CV	>500 Hz	5	n.a.	30	1000
4-poles	> 5 Hz	100	15 ⁴⁾	15	100
6-poles	n.a.	100	100	15	100
8-poles	n.a.	100	100	15	100

Table 4: Performance requirements for the SLS2 power supplies

pu means based on nominal current of the magnet.

¹⁾ After Power-Supply operation time (“warmup”) at operation point > ½ h.

²⁾ Smallest step that the power supply can follow. Base are specifications from SLS-Handbook

³⁾ Max. (stationary) deviation between current reference and actual current. (Offset error, linear error, etc.

⁴⁾ Acc. to discussion with Michael Böge, March 13th 2017

Remark for magnets that have correction windings:

Above requirements are for total weighted current based on the nominal current of the main winding. The tolerances for the correction windings are thus much more relaxed, since they typically correct the magnet flux only by 1-2%, which means that their tolerances can be 50-100 x larger.

3.4.1 Critical requirements

Of above-named requirements, the one for current ripple / noise of the corrector power supplies is a critical one: Required are noise / RMS of 5 ppm of the magnet nominal current.

The parameters that influence the noise / ripple on the magnet currents are:

- Noise on the current measurement
- AD-converter resolution
- Power supply modulator resolution
- Power supply switching ripple (given by switching frequency and output filter)
- Load impedance

Measurements with existing PS at SwissFEL (QFD-corrector) show:

- With PS-on-board ADC (standard precision): 6-7 ppm (based on $I_{\text{Nom}}=10$ A)
- With high-precision AD-card: 3.6 – 4.7 ppm

With today’s PS, this would mean that a dedicated high-precision AD-card would be needed for every PS, which would increase the needed space especially for small PS (1 PCB-card for power part, + 1 PCB-card for AD-card).

The resulting high costs and space consumption is one of the main motivations of the planned new development of a tailored solution for small power supplies.

The SwissFEL measurements are for a QFD-corrector with a relatively high inductance. With other magnets with lower inductance (or better said time constant $\tau=L/R$), the measured ripple was up to 120 ppm.

Whether the required 5 ppm for ripple / noise can be reached depends thus on:

- Magnet
- Performance of the new to be developed controller card

→ Note that there is a risk this requirement can only be fulfilled with higher cost and needed space.

3.5 Required power supply features

3.5.1 Waveforms

To do analysis of the beam for better tuning, “wobbling” will probably be used for SLS2. For this, a periodic addition would be done to the current reference. This is done on several PS at the same time (but with no hard-real-time synchronization), with different frequencies.

The effect of this can then be seen in different places of the beamline. Since the frequencies are different, the effect of one power supply to a given location can be identified.

For this, it is required to run pre-saved waveforms on the power supplies.

Requirements:

1. Resolution up to PWM-frequency (higher not needed, but also not possibly because of modulator)
2. One fundamental period of frequencies of few 10 Hz can be stored.

4 Existing SLS power supplies: Reuse or replace?

4.1 Overview

While the storage ring of SLS is completely replaced for SLS2, booster, linac and parts of the experiments are kept in operation for SLS2. SLS went into operation in 2000, SLS2 will go into operation around 2025. This means that the components taken over from SLS will be over 25 years old already at start of operation and are supposed to operate for another 25 years.

A replacement program for power supplies (and supposedly for other components as well) has to be worked out, including time planning and financing. This is not part of this report and needs to be addressed separately.

Below table gives an overview over the number of different power supply types in the different SLS sections. An indication is given, which power supplies can be taken over / kept in operation also for SLS2, and which power supplies should be replaced.

SLS section	#	PS type	I_{DC} [A]	U_{DC} [V]	Polarity	Comment
Storage ring Equipment replaced by SLS2 equipment	1	2	500	880	1Q	
	4	3	120	75	1Q	
	24	5	140	35	1Q	
	3	6	120	240	1Q	
	2	7	120	130	1Q	
	153	8	120	30	1Q	
	157	16	7	24	4Q	
	1	27	500	200	1Q	
	3	33	150	90	4Q	
	50	36	10	24	4Q	
	1	13a	40	40	4Q	
Transition booster – storage ring	3	9	120	60	1Q	Replace, scope of replacement program
Not yet clear what will be built new with SLS2 and what stays as in SLS. Assumed that these PS stay the same for SLS2	7	10	120	15	1Q	Replace, scope of replacement program
	4	16	7	24	4Q	Replace, scope of replacement program
Booster	1	1	600	290	2QV	Replace either during construction of SLS2 or during a (longer) shutdown soon after
	2	4	90	45	2QV	Not yet clear, but not so relevant since only 2 pcs.
	1	13	40	24	4Q	Keep in operation
	2	14	6	110	4Q	Keep in operation
	1	15	5	60	4Q	Keep in operation
	108	16	7	24	4Q	Replace, scope of replacement program
Transition Linac – Booster	1	11	120	15	1Q	Replace, scope of replacement program
	6	12	120	15	1Q, pole switch	Replace, scope of replacement program

SLS section	#	PS type	I_{DC} [A]	U_{DC} [V]	Polarity	Comment
	7	16	7	24	4Q	Replace, scope of replacement program
Linac	1	9	120	60	1Q	Replace, scope of replacement program
	4	12	120	15	1Q, pole switch	Replace, scope of replacement program
	6	16	7	24	4Q	Replace, scope of replacement program
Experiments	51	16	7	24	4Q	Replace, scope of replacement program
	37	19	10	24	4Q	Keep in operation
	6	67	150	65	4Q	Relatively new Keep in operation

Table 5: Overview power supply types in existing SLS (before SLS2)

4.2 PS replacement in plant parts that stay unchanged with SLS2

The analysis of how fit the existing SLS power supplies are for operation after 2025 has given the following results (see also Table 5):

Power supplies that should be replaced:

- Power supply type 1 (booster bend)
This PS has problems with temperature cycles. IGBTs are already now periodically changed.
→ This PS needs to be replaced as part of the replacement program.
This is quite a big power supply with a complicated control. Exchange and recommissioning of this power supply will thus use more time than for a “normal” power supply and does not fit into a regular 1-month shutdown. This would speak in favor of replacing it during conversion SLS → SLS2.
However, this time period is already tightly packed with work for all involved parties because of the SLS2 reconstruction, such that also replacing the booster bend in this time period is not realistic. Ideal would be an extended shutdown (≈3 months) after commissioning of SLS2
- Power supplies type 9..12
Problematic of parallel diodes (negative temperature coefficient, meaning a diode that gets a little hotter will get more current and with that get even hotter).
Since ca. 2015 increased failures. Should be changed after SLS2 commissioning, as part of the replacement program
- Power supplies type 16
Already rather old. Should be changed after SLS2 commissioning in several stages as part of the replacement program.

Power supplies that can be kept in operation:

- Power supplies type 19
(4Q corrector power supplies)
Power supplies are still in good shape. Keep in operation
- Power supplies type 13, 14, 15
Only very few units. If possible not having to develop new power supplies for so few units. Since enough spare parts are available:
Try to keep in operation.

4.3 Experiments

For concept and cost estimation for power supplies, it is assumed that:

- The power supplies (correctors) of the undulators, which are taken over to SLS2 from SLS, can also be taken over.
- New undulators will be equipped with new power supplies
- According to Figure 9, 7 there will be maximally 7 new undulators.
It was assumed that at start of SLS2, 4 of these will be installed.

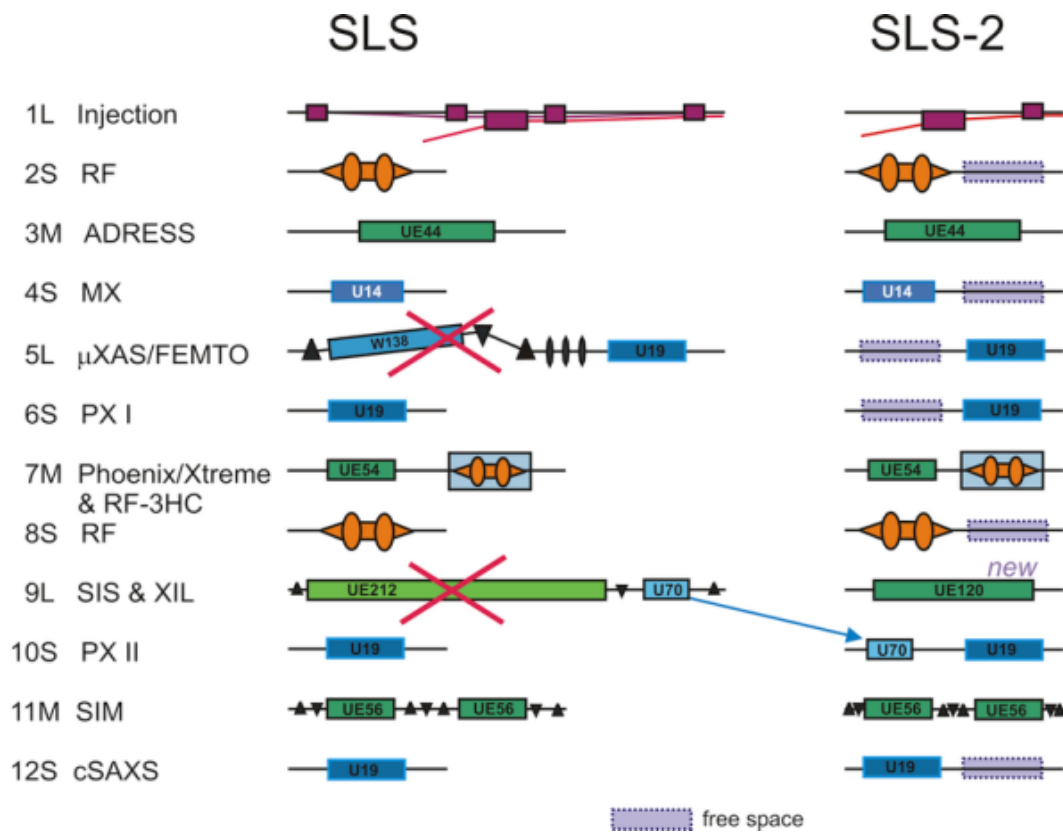


Figure 9: SLS2 straights