9. Power Supplies

9.1 Introduction

In this chapter, booster and storage ring power supplies will be discussed. Although, the magnets of the old booster are intended to be used for SESAME, the modifications that have been made in the design of the new booster, implies the use of some new power supplies. The extraction energy and the repetition rate of the BESSY I booster were 800MeV and 10Hz respectively and because of the high repetition rate, *White*[1] *Circuits* were being used for the old machine. A so-called White circuit is a combination of one AC and one DC power supply in which the AC output is superimposed on the DC part. The resultant current is then used to increase the energy of the particles from the injection level up to the extraction level. The main change in the design of the new booster compared to the old one is the decrease of the repetition frequency to 1Hz. As a result, the White circuits of the old machine cannot be used for SESAME and *Ramping Power Supplies* should replace them. The output current of a ramping power supply, however, moves linearly from the injection level to the extraction level and vice versa. For the SESAME, this process repeats some hundred times until the storage ring is filled with enough current, which is up to 300-400 mA. The ramping power supplies of the SESAME booster should be able of supplying both positive and negative output voltages in order to create the required ramping current waveform through the magnets. For the big power supplies of the booster, one possibility is to use the *B-6 bridge* configuration with the *thyristor* switches. As another alternative, one can use *SMPS's*[2] which generally have better performance compared to the thyristor bridges. But, a SMPS is more expensive than a thyristor bridge of the same size.

In the SESAME storage ring, the energy of the particles increases from 0.8 GeV to 2 GeV. The output currents of the storage ring power supplies, which are proportional to the instantaneous energy, increase from 40% to 100% of the nominal value in a few minutes. For the storage ring power supplies, *Chopper Circuits (Buck Converters)* could also be used. A Buck converter is a one-quadrant power supply, operated at a frequency around *20kHz*, which is used to decrease the level of an unregulated input DC voltage to a regulated DC output voltage. A *Diode Rectifier* supplies the required input power of the Buck converter. The switching devices of the Buck converters, are *Power BJT*[3]*'s*, *COOLMOS's* or *IGBT*[4]*'s*.

In the next two subsections, booster and storage ring power supplies will be discussed. The rest of the chapter discusses total power of the machine, disturbances to the mains, power supplies upgrade, connection of the magnets and location of the power supplies.

9.2 Booster Power Supplies

Three separate ramping power supplies are used to supply the ramping currents of the dipoles, focusing and defocusing quadrupoles of the SESAME booster. All the dipole magnets of the booster will be connected in series. This guarantees that all the dipoles will be supplied with same current. The same is true for the focusing and defocusing quadrupoles. The reference currents of these power supplies, which are in tight synchronization, are set by the control system at each time instant. The time sequence of one ramping period is as follows: 1) current stays at the injection level for some milliseconds. 2) It ramps up linearly to the extraction level in some hundred milliseconds. 3) It stays at the extraction level for some milliseconds. 4) It linearly decreases again to the injection level in another some hundred milliseconds. The whole process takes 1 second that corresponds to the 1 Hz repetition frequency of the booster. The pre-estimated ramping intervals of

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[1] - M.G.White et al. (1956)
[2] - Switched-Mode Power Supply
[3] - Bipolar Junction Transistor
[4] - Insulated Gate Bipolar Transistor

Table (9.1) were assumed for the *Matlab* simulations. The current and voltage and the resultant active and reactive power waveforms are shown in Figure (9.1).

Table 9.1: Estimated values of the ramping time intervals

Booster	Time interval	Unit
Flat bottom	50	mSec
Positive ramp	450	mSec
Flat top	50	mSec
Negative ramp	450	mSec
Sum	1000	mSec

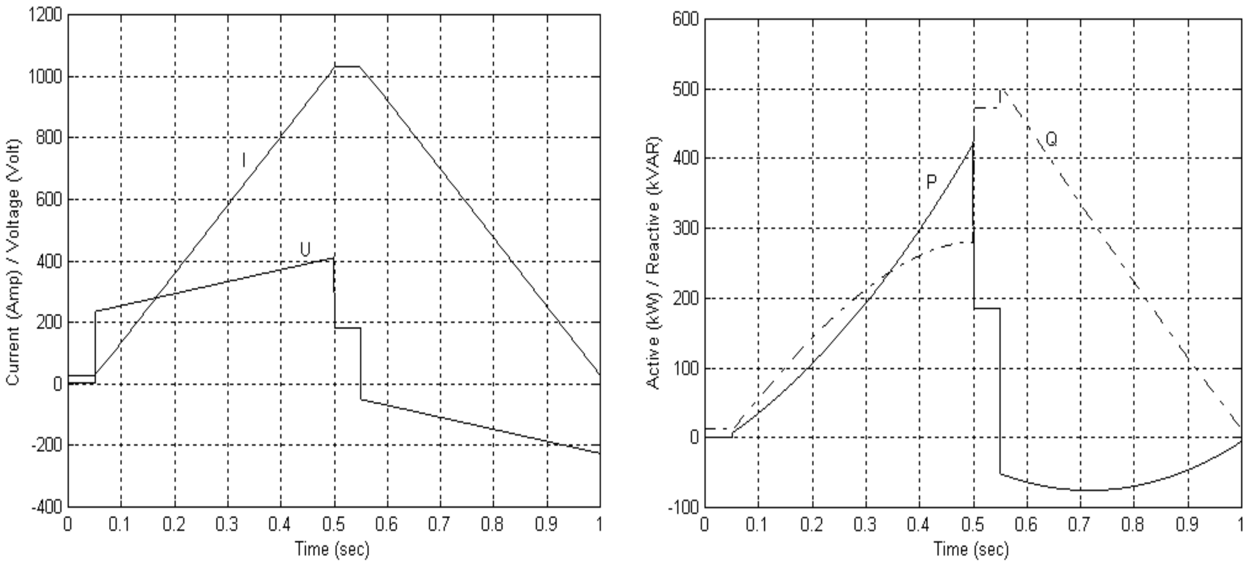

Figure 9.1: The left figure shows the current and voltage while the right one shows the active and reactive power waveforms of the booster dipoles. 16 diploes are connected in series. Total inductance=103 mH, Total resistance=175mOhm. Active and reactive power waveforms have been calculated for the B-6 configuration.

The same calculations have been done for the focusing and defocusing quadrupoles and the results are shown in Figures (9.2) and (9.3). As can be seen in the figures, for the three families of the magnets, three bipolar power supplies are required. The negative voltage is needed to decrease the magnet current down to the injection level. For the booster power supplies, the B-6 configuration could be used. It may also be possible to use SMPS's with the same amount of output power. SMPS's are in general more efficient, produce less reactive power and have smaller size compared to the thyristor bridges. On the other hand, modern power switches, like the IGBT's are usually used in the SMPS's. But, they are 2-3 times more expensive than the thyristor bridges.

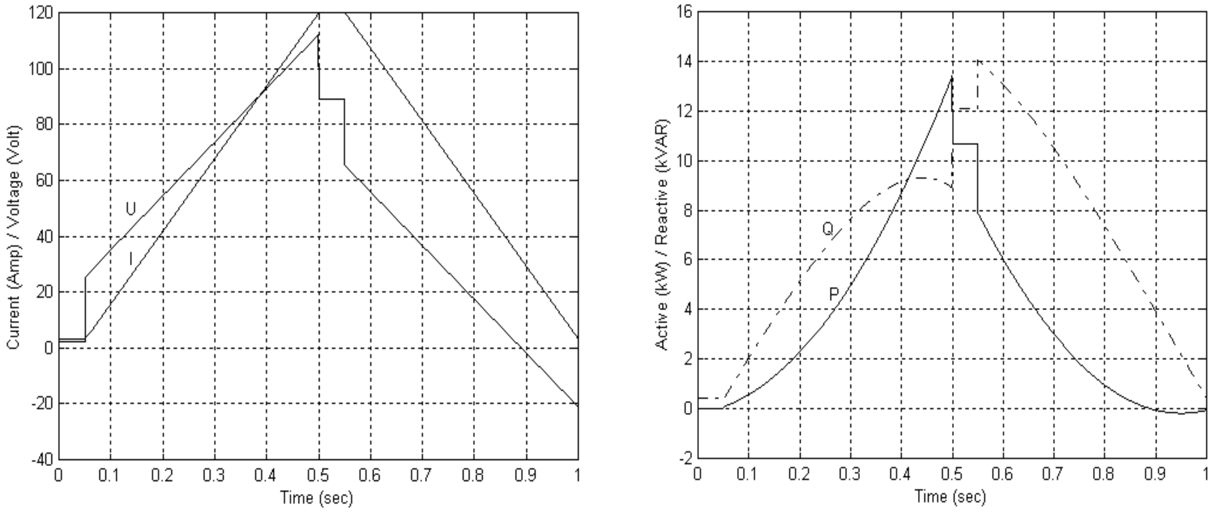

Figure 9.2: The left figure shows the current and voltage while the right one shows the active and reactive power waveforms of the booster focusing quadrupoles. 16 QF's are connected in series. Total inductance=89 mH, Total resistance=740mOhm. Active and reactive power waveforms have been calculated for the B-6 configuration.

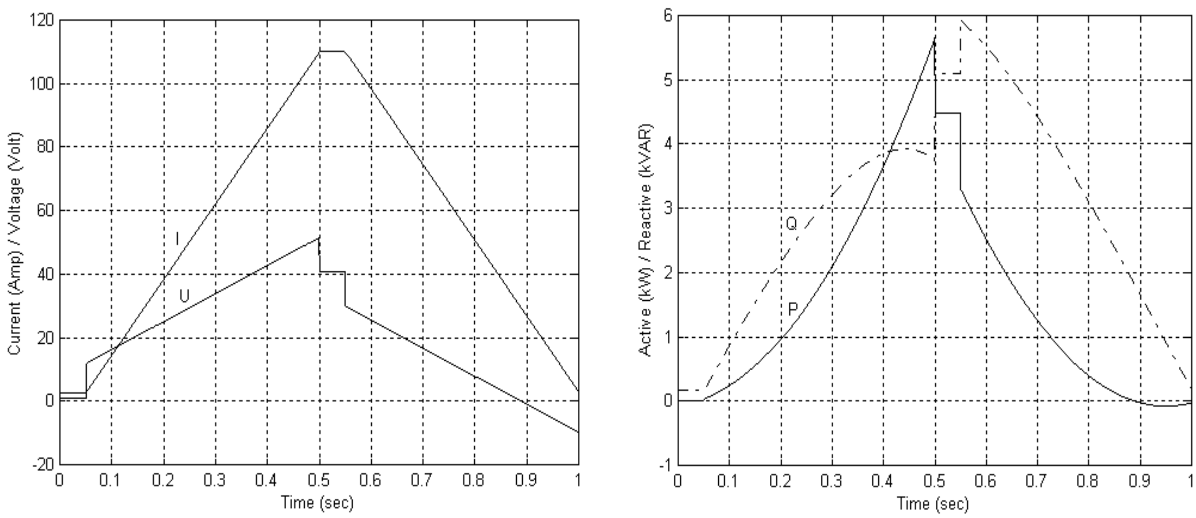

Figure 9.3: The left figure shows the current and voltage while the right one shows the active and reactive power waveforms of the booster defocusing quadrupoles. 6 QF's are connected in series. Total inductance=45 mH, Total resistance=370mOhm. Active and reactive power waveforms have been calculated for the B-6 configuration.

The electrical specifications of the booster magnets and the calculated power values are summarized in Table (9.2). The maximum output currents and output voltages of the power supplies were assumed to be *20%* higher than the "Optics" requirements.

Table 9.2: SESAME booster power supplies

800 Mev	Dipole	QF	QD	Unit	Sum
Total inductance	103	89	45	mH	
Total resistance at 40 deg C	175	740	370	mOhm	
Time constant	0.6	0.12	0.12	Sec	
Number of circuits	1	1	1		
Number of magnets per circuit	12	12	6		
Inductance per magnet	8.6	7.4	7.5	mH	
Resistance per magnet	14.6	61.7	61.7	mOhm	
Extraction current	1030	120	110	A	
Injection current	25.8	3	2.8	A	
Maximum voltage (optic)	410.1	111.9	51.4	V	
Minimum voltage (optic)	-225.3	-20.9	-9.7	V	
Maximum power (optic)	422.4	13.4	5.7	kW	
Drop on cable	2.8	2.6	2.4	V	
Power loss on cable	2864.4	38.9	32.7	W	2936
Maximum current (PS)	1236	144	132	A	
Maximum positive voltage (PS)	492.1	134.3	61.7	V	
Maximum negative voltage (PS)	-270.4	-25.1	-11.6	V	
Overall stability (PS)	100	100	100	ppm	
Active power (PS)	425.3	13.4	5.7	kW	444.4
Estimated power loss on PS	74.9	2.4	1	kW	78.3
Active power (Line)	500.2	15.8	6.7	kW	522.7
Reactive power (Line)	597	16.6	6.6	kVAR	620.2
Aparent power (Line)	601	19	8	kVA	628
Installed Power	608.2	19.3	8.1	kW	635.6
Transformer	766.3	24.3	10.2	kVA	**800.8**

9.3 Storage Ring Power Supplies

For the storage ring, DC power supplies are required to be used for the different families of the magnets. Besides, some small size power supplies are needed to energize the correction magnet coils. The output currents of the DC power supplies, which are proportional to the instantaneous energy of the particles, increase from 40% to 100% of the nominal value in a few minutes. The main factor in choosing the rise time, is the time constant of the magnets. The biggest time constant of the storage ring magnets, which corresponds to the dipole magnets, is 2 seconds approximately. A series of Matlab simulations have also been done to simulate the current, voltage, active and reactive power of the storage ring power supplies and the results are shown in Figures (9.4) to (9.6). The estimated time intervals of the storage ring are shown in Table (9.3). The lower limits of the time intervals were assumed for the simulations.

Table 9.3: Assumed storage ring time intervals

Storage ring	Time interval	Unit
Flat bottom	30-120	Sec
Positive ramp	60-120	Sec
Flat top	1-20	Hours
Negative ramp	30-180	Sec

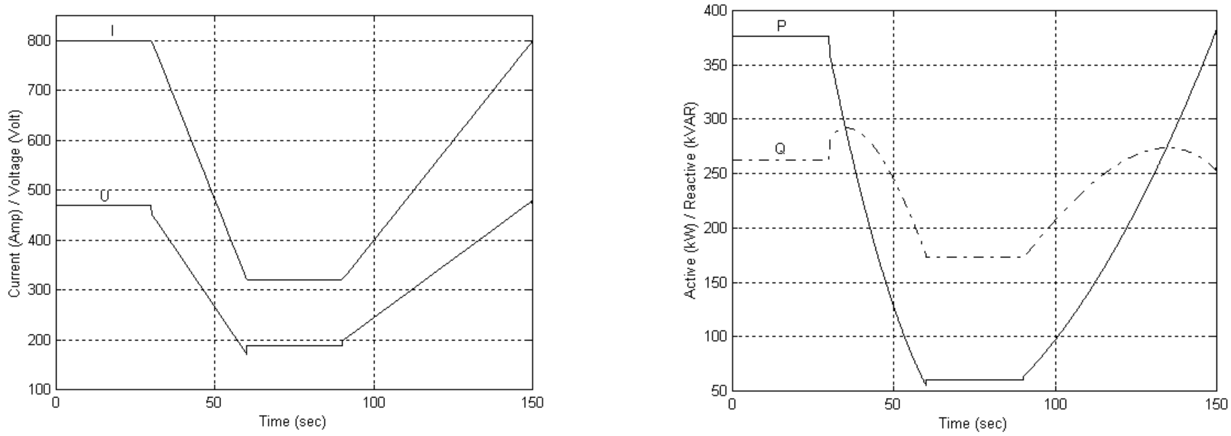

Figure 9.4: The left figure shows the current and voltage while the right one shows the active and reactive power waveforms of the storage ring dipoles. 16 diploes are connected in series in each circuit. Total inductance per circuit=1096 mH, total resistance per circuit=587 mOhm. Active and reactive power waveforms have been calculated for the B-6 configuration.

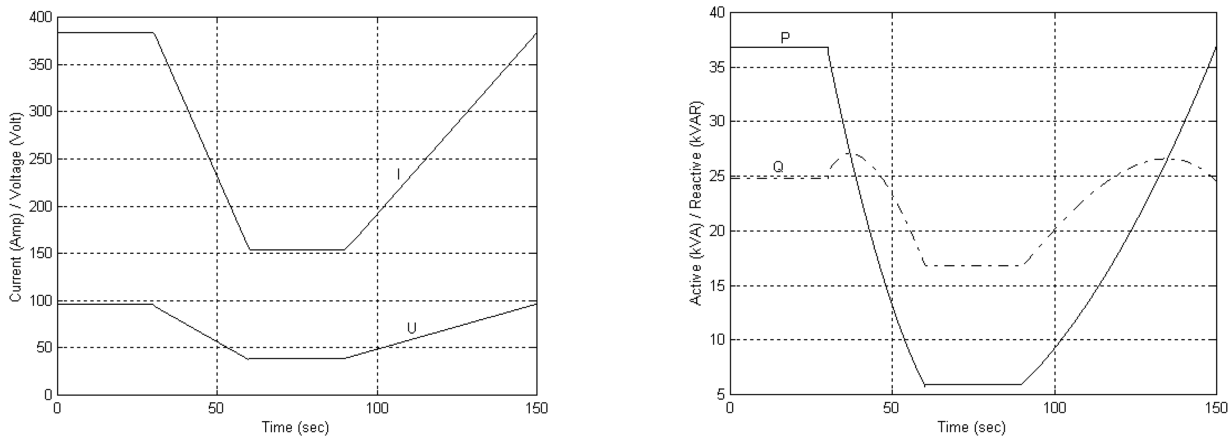

Figure 9.5: The left figure shows the current and voltage while the right one shows the active and reactive power waveforms of the storage ring quadrupoles. 16 quadrupoles are connected in series in each circuit. Total inductance per circuit=123 mH, total resistance per circuit=250 mOhm. Active and reactive power waveforms have been calculated for the B-6 configuration.

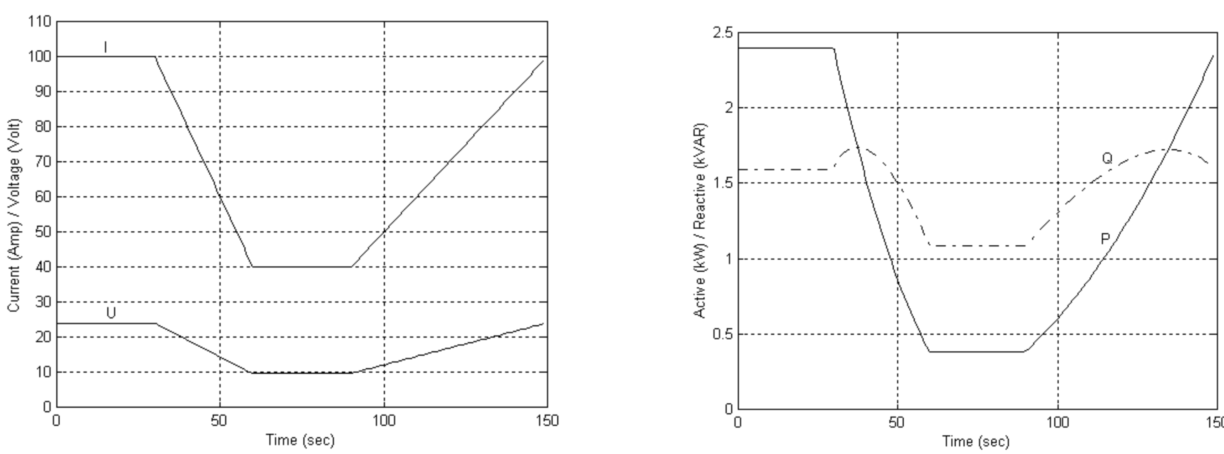

Figure 9.6: The left figure shows the current and voltage while the right one shows the active and reactive power waveforms of the storage ring sextupoles. 16 sextupoles are connected in series in each circuit. Total inductance per circuit=64 mH, total resistance per circuit=240 mOhm. Active and reactive power waveforms have been calculated for the B-6 configuration.

As can be seen in the figures, positive voltage values are required both to increase and to decrease the current of the storage ring magnets. This verifies the use of unipolar power supplies for the storage ring magnets.

The electrical specifications of the storage ring magnets and the calculated power values have been summarized in Table (9.4):

Table 9.4: SESAME storage ring power supplies

2Gev	Dipole	Quad.	Sext.	Corr - Hor	Corr - Ver	Unit	Sum
Total inductance (per circuit)	1096	123.2	64	2000	700	mH	
Total resistance (per circuit)	587.2	249.6	240	14000	20300	mOhm	
Time constant	1.9	0.5	0.3	0.14	0.03	Sec	
Number of circuits	1	3	4	32	12		
Number of magnets per circuit	16	16	16	1	1		
Inductance per magnet	68.5	7.7	4	2000	700	mH	
Resistance per magnet	36.7	15.6	15	14000	20300	mOhm	
Temprature rise	15	15	15			Deg C	
Final current (optic)	800	384	100	1	2	A	
Initial current (optic)	320	153.6	40				
Maximum voltage (optic)	478.5	96.2	24.1	15.4	50	V	
Maximum power (optic)	382.8	36.9	2.4	0	0.1	kW	504.3
Drop on cable	10	9.6	3.6			V	
Power loss on cable	8	3.7	0.4			kW	20.7
Maximum current (PS)	960	460.8	120	1.2	2.4	A	
Maximum voltage (PS)	574.2	115.4	28.9	18.5	60	V	
Overall stability (PS)	100	100	1000	1000	1000	ppm	
Active power (PS)	390.8	40.6	2.8			kW	523.8
Estimated power loss on PS	68.8	7.1	0.5			kW	92.1
Active power (Line)	459.6	47.7	3.3			kW	615.9
Reactive power (Line)	345	35	2.3			kVAR	459.2
Aparent power (Line)	546	57	4			kVA	733
Installed Power	551.2	53.2	3.5	0.022	0.144	kW	727.2
Transformer	694.5	67	4.4	0.028	0.181	kVA	**916.2**

9.4 Installed Power of the Machine

The estimated aparent power of the different parts of the SESAME are shown in Table (9.5).

Table 9.5: Total installed power of the machine

	Injection	Run
Booster	800 kVA	100 kVA
Storage Ring	400 kVA	900 kVA
RF	20 kVA	800 kVA
Infrastructure and Experiments	400 kVA	400 kVA
Microtron and Transfer Lines	100 kVA	20 kVA
Sum	**1.7MVA**	**2.2MVA**

As can be seen in the table, the total installed power of the machine is more than $2MVA$. The real power consumption of the machine, however, might be smaller than this value since the power supplies don't work necessarily with their maximum output. A *400V* step-down transformer is then required to supply power to the machine. The transformer, can either be provided by the power company or it may be part of the SESAME power supply system. In both cases, a safety guard around *50%* should be taken into account for the upgrade of SESAME. A *3 MVA* transformer, has already been proposed to be used for the whole machine. In this manner, around *1 MVA* will be reserved to be used in the future. As an alternative, one can use a *630 kVA* transformer for the infrastructure and experiments and supply the booster, storage ring and RF through some other transformers.

9.5 Disturbances to the Mains

As can be seen in Table the (9.2), the power variation of the booster synchrotron is about *600kVA*. These variations will then be reflected to the low-voltage grid and in case they exceed the acceptable threshold, the ramping profile may be seen as flicker of the electric lamps. The maximum disturbance that consumers are allowed to produce is defined in the grid specifications for each country. For example, this value is 3% in Germany according to the *VDE 0838* standard. For the range of flickering frequencies (up to *25 Hz*), this ratio is even lower. The maximum allowed power variation could then be calculated using this ratio and the short-circuit power of the grid. For the SESAME, the allowed disturbance threshold at the machine site should be taken into account to be sure that the power variation of the booster is acceptable. Otherwise, *VAR*[1] compensation circuits should be used to decrease the voltage variation down to the allowed level.

9.6 Power Supplies Upgrade

A variety of power supplies from the old BESSY I will be available to be used for SESAME. The specifications of these power supplies are shown in Table (9.6). The first part of the table is related to the power supplies of the microtron and the injection line from the microtron to the booster. The next parts give the specifications of the booster White circuits and the DC power supplies of the storage ring respectively.

In order to decrease the cost, maximum attention should be paid to use as much components as possible from the old machine. Nevertheless, buying some new power supplies will be mandatory. One example is the booster dipoles power supply, which will be about two times bigger than the biggest power supply of the old machine.

9.6.1 Collaboration with Yerphi[2]

Since one purpose of the SESAME project is to transfer the knowledge and technology of the accelerators to the Middle East countries, it is preferred –whenever possible- not to buy the required power supplies from the European companies but to let these components be built in the developing countries. In this way, the cost of upgrading decreases as well. On the other hand, it is required to use the knowledge and experience of the European synchrotron facilities and especially DESY in the design and development of the new power supplies and the electronics. In order to move with the above-mentioned strategy, it has been proposed to order the power supplies upgrading to the Yerphi in Armenia. Yerphi power supplies are also being used at DESY. Figure (9.7) shows one of these power supplies, which is being used at the HERA ring.

[1] - Volt Ampere Reactive
[2] - **Yer**evan **Ph**ysics **I**nstitute

Table 9.6: Power supplies of the BESSY I

Power supply	Qty	Nominal Voltage	Nominal Current	Output Power	Estimatet Input Power	Cost of PS	Actual Current in % of Nominal Current	Stability	Company	Type	Year
Unit		Volt	Amp	kW	kW	1000Euro		ppm			
Power Supplies of the Microtron and Injection Line form Microtron to the Booster											
Mic T-Coils	4	30	1,5	0,05	0,09	1.4		100	GMS	bipolar	1991
Mic-Sy I-Line Steerer	8	30	1,5	0,05	0,09	1.4		100	GMS	bipolar	1991
Mic-Sy I-Line Quads	4	70	20	1,40	2,80			1000	Delta	unipolar	1990
White Circuits and Steerer Power Supplies of the Booster											
Sy Steerer	12	30	1,5	0,05	0,09			100	GMS	bipolar	1991
DQAB neu BI	2	160	60	10	12	13	65	1000	TeT	AC	1992
FQAB Neu BI	2	120	80	10	12	12	80	1000	TeT	AC	1993
FQDB Neu BI	2	120	80	10	12	17	75	100	FuG	unipolar	1993
DQDB	1	120	80	10	12		65	100	SCX	unipolar	
MDAB Neu BI (peak)	2	340	550	187	243		75	100	Foeldi	AC	1986 and 1990
MDDB Neu BI	1	160	600	96	125	34	90	10	Jäger	unipolar	1995
Power Supplies of the Transfer Line and the Storage Ring											
TF-Quads	13	20	50	1	2	4		100	Hein	unipolar	1990
Steerer	12	25	20	1	1	3		1000	Foeldi	unipolar	1980
DIPPT	1	25	1025	26	33		75	10	Foeldi	unipolar	1980
DIPPR BI	1	305	900	275	357	61	85	10	Foeldi	unipolar	1980
DIPPR (Cosy) Spare	1	305	900	275	357	61	85	10	Foeldi	unipolar	1986
Q1T WLS	1	30	1100	33	43	20	75	100	Foeldi	unipolar	1993
Q5T WLS	1	47	1100	52	67	28	85	10	Foeldi	unipolar	1993
Q2T WLS	1	38	1400	53	69	28	80	10	Foeldi	unipolar	1993
QUAPPS BI	4	52	1025	53	69	31	40 - 80	10	Foeldi	unipolar	1980
S1 WLS	1	83	400	33	43	18	80	100	Dan	unipolar	1993
S2 WLS	1	63	300	19	25	17	45	100	Dan	unipolar	1993
Steerer SR	36	20	10	0,2	0,4			1000	Foeldi	unipolar umschaltbar	1980

In order to be sure that the power supplies will be made in the proper way, there should be collaboration among the DESY power supplies group, Yerphi and the SESAME power supplies group in the design, development and manufacture phases. The preliminary talks of the collaboration have already been made and the next steps will be taken in the coming months.

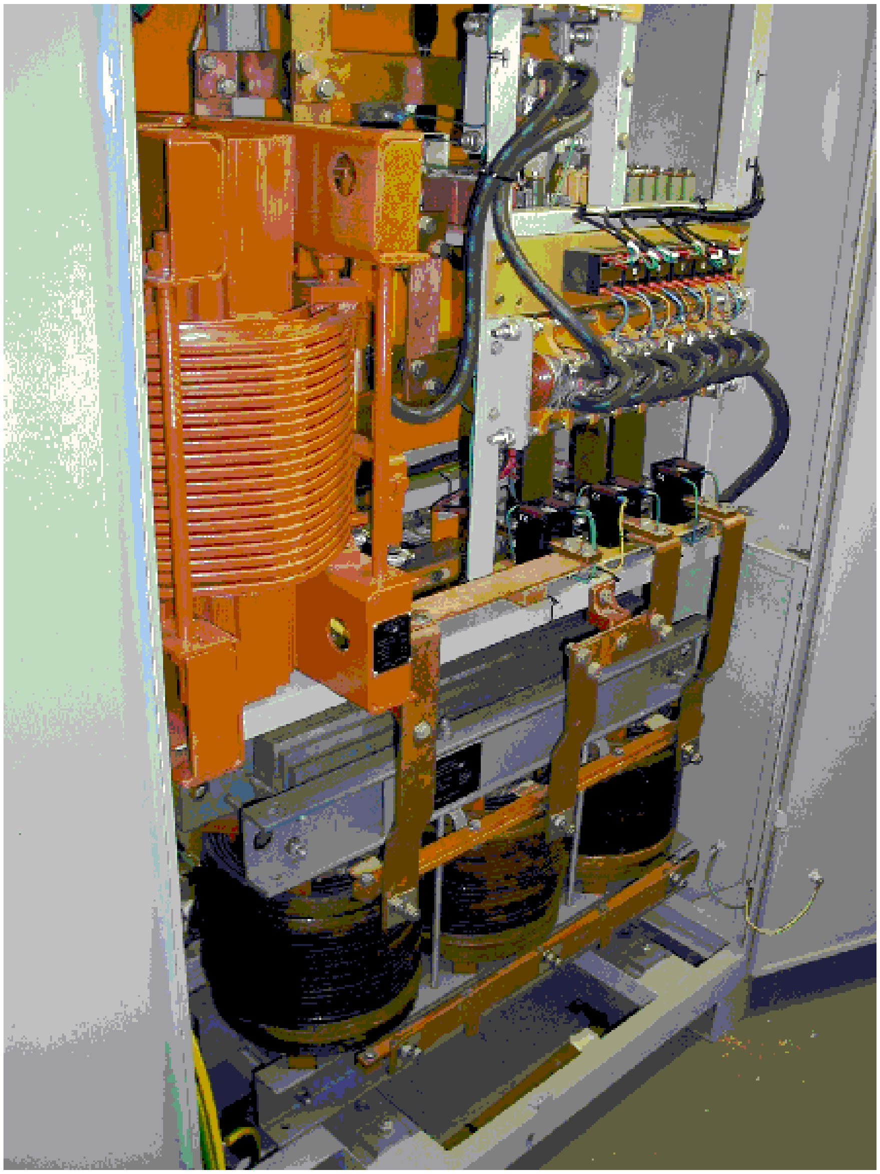

Figure 9.7 : A 500A/100V power supply made by Yerphi which is working at DESY (HERA ring). The transformer, choke, thyristors and the water cooling pipes are shown in the picture.

9.7 Connections of the Magnets

Building current loops around the booster and storage ring results undesirable vertical magnetic fields. In order to eliminate the fields, magnets should be connected in such a way that current moves in both clockwise and counterclockwise directions. The SESAME magnets have been numbered, starting from the injection points while moving in the counterclockwise direction. Figures (9.8a) to (9.8.h) show the connection of the different families of the booster and storage ring magnets. As can be seen in Table (9.7), the total current is zero, which results no vertical magnetic field.

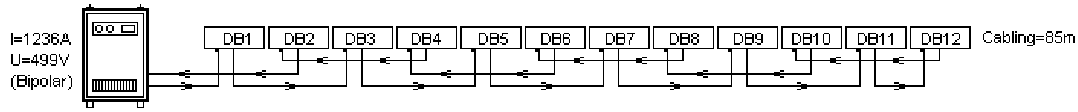

Figure 9.8a: Connection of the booster dipoles

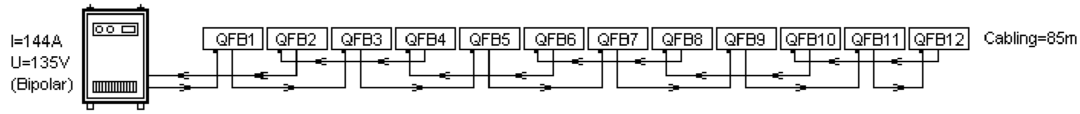

Figure 9.8b: Connection of the booster focusing quadrupoles

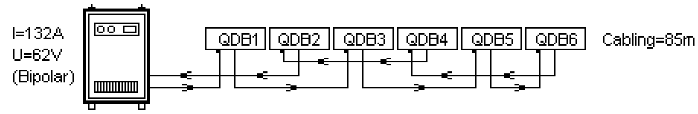

Figure 9.8c: Connection of the booster defocusing quadrupoles

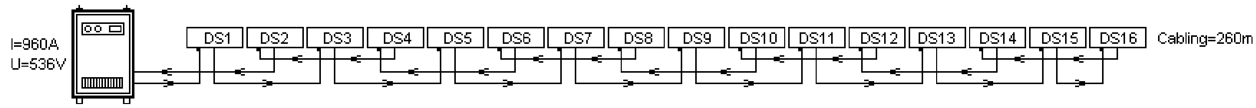

Figure 9.8d: Connection of the storage ring dipoles

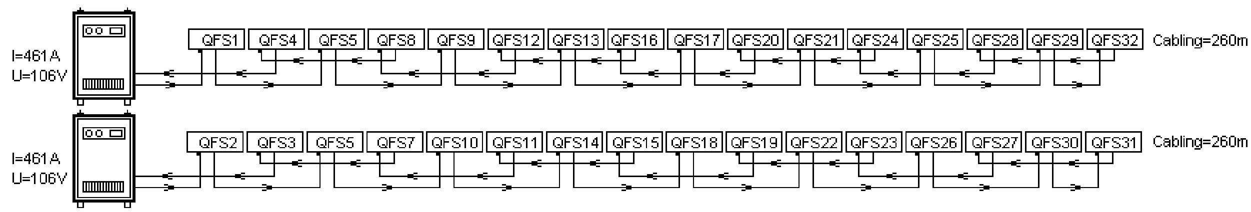

Figure 9.8e: Connection of the storage ring focusing quadrupoles. The two power supplies have different output currents. Therefore, field compensation should be done for each family separately.

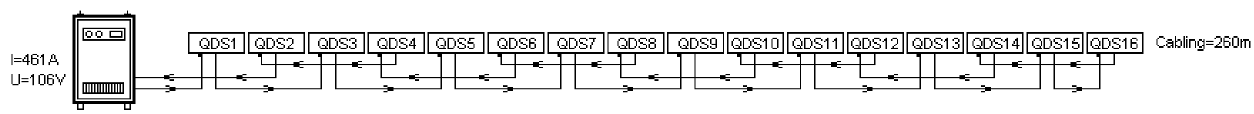

Figure 9.8f: Connection of the storage ring defocusing quadrupoles

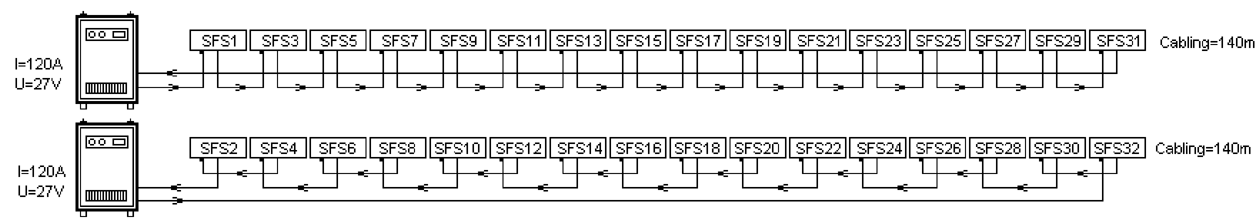

Figure 9.8g: Connection of the storage ring focusing sextupoles. The output currents of the two power supplies are the same. Thus, total field is zero.

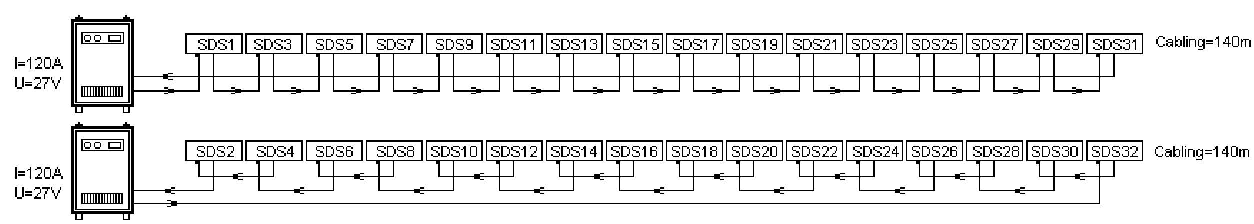

Figure 9.8h: Connection of the storage ring defocusing sextupoles. The output currents of the two power supplies are the same. Thus, total field is zero.

Table 9.7: Clockwise and counterclockwise currents around the booster and storage ring

	Booster			Storage Ring							
	Dipoles	QF's	QD's	Dipoles	QF1's	QF2's	QD's	SF1's	SF2's	SD1's	SD2's
Clockwise Current (Amp)	26-1030	3-120	3-110	320-800	154-384	154-384	154-384	0	40-100	0	40-100
Counterclockwise Current (Amp)	26-1030	3-120	3-110	320-800	154-384	154-384	154-384	40-100	0	40-100	0
Sum	0	0	0	0	0	0	0	0		0	
										Total Sum:	0 Amp

9.8 Location of the Power Supplies

The area inside the ring will be used for the power supplies; see Figure (9.9). This area will accommodate the booster and storage ring power supplies and the distribution boards. The main transformers will be located out of the building. The MV[1] power switches and the circuit breakers will be installed in the technical building which is separate from the main building. The available area inside the ring should be used efficiently so that there will be enough room for all the components.

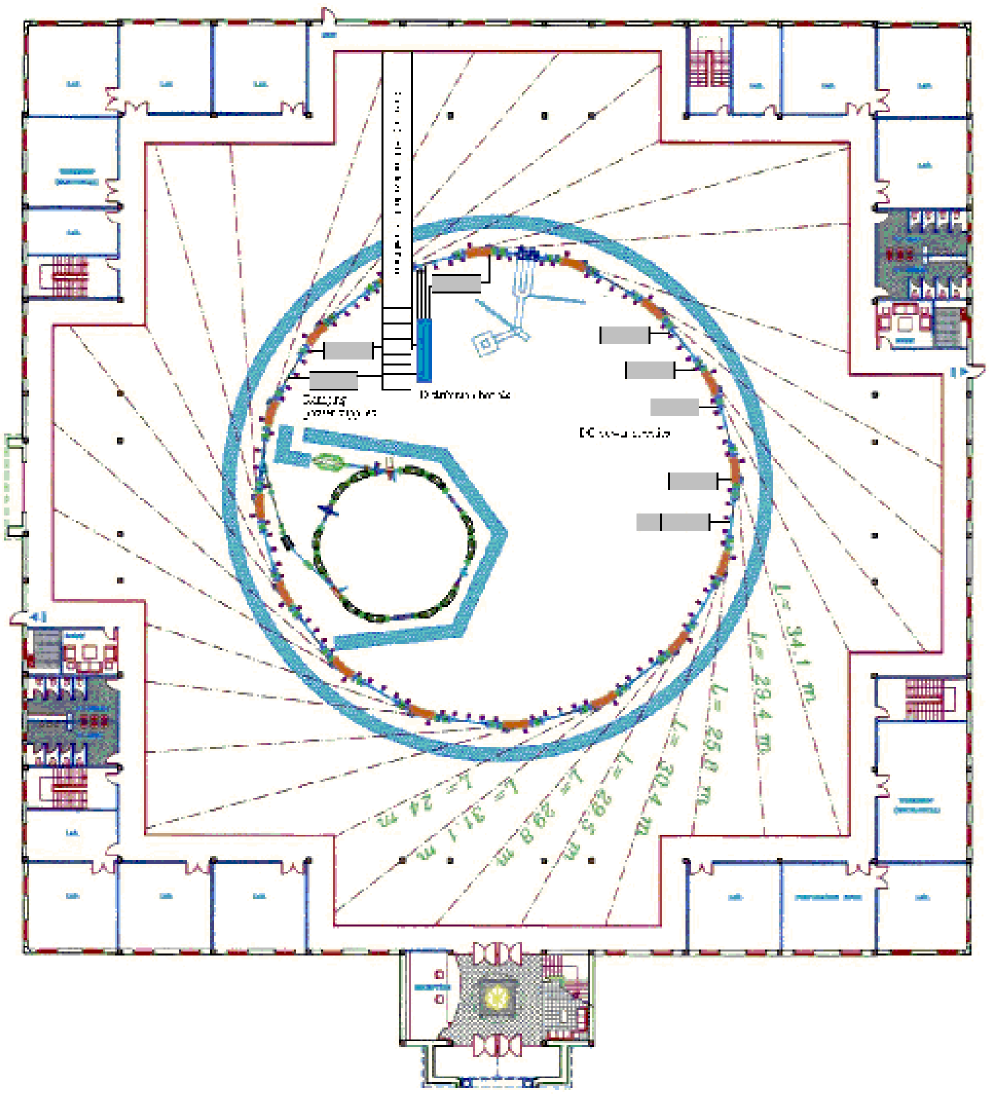

Figure 9.9: Location of the power supplies

[1] - Medium Voltage

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[2] D. Einfeld, "*First Draft Version of a Conception Design*", March (2002)

[3] H. J. Eckoldt, N. Heidbrook, *"Power Supplies for TESLA Modulators"*, TESLA report, 2000-36, (2000)