Chapter 3

UPGRADING OF BESSY I

3.1 Introduction

BESSY I is disassembled, very well packed, shipped from Berlin and has already been arrived in Jordan. The design of the building is finished, a call for tender process has taken place and the contract for the erection of the building will be signed soon. With the space in the experimental hall and the requirement of the users to have a length of the beam lines up to at least 30 m, the circumference of the storage ring can have a maximum value of 125m. The first proposal for an upgrading of BESSY I to energy of 1 GeV for the SESAME project is documented in the so-called “Green Book“, issued October 1999 [1]. From 1999 until now a lot of workshops concerning the scientific case at SESAME have been held and there exists a better understanding of what is needed in the “Middle East Region”. According to the report of H. Winick and the JSPS – Workshop in Amman [2], the number of x-ray beamlines should be increased and also one should try to increase the performance of the machine to smaller emittances and longer straight sections. This has to be done within the existing budget boundaries. The second proposal for the upgrading of BESSY has been work out in 2001 and 2002 and is described in the so-called “White Book”[3]. According to the proposal of the evaluation panel of the European Union and the outcome of the JSPS-Workshop photon energies up to 12 keV should be reached with undulators. This is only possible with higher energies and according to the above-mentioned restrictions the maximum energy of SESAME is 2.5 GeV. In the following chapter the background of the upgrading will be described.

3.2 Performance of a Synchrotron Light Source

The performance of a synchrotron light source is given by three factors:

- The spectral range covered by the synchrotron radiation (see chapter 2).
- The brilliance of the emitted light and,
- The number of experimental stations.

3.2.1 Spectral Range of the Synchrotron Radiation

The spectral range of the synchrotron radiation emitted from an electron beam in the bending magnets and wigglers is given by the critical photon energy (ε_{critic}), which is proportional to the square of the electron beam energy and proportional to the magnetic flux of devices. That one of the undulators is also proportional to the square of the energy and inversely proportional to the period length. In order to reach the 20 keV range, it was foreseen in the “Green Book” to run the machine at 1 GeV and make the installation of up to three super conducting wigglers (7.5 Tesla). This leads to a critical photon energy of 5 keV. The useable spectrum is extending to roughly four times the critical photon energy, hence to 20 keV.

The 20 keV range can also be covered with a 2 GeV beam and a magnetic flux density of 1.88 Tesla. The present technology allows construction of permanent magnet wigglers with flux density of 2.25 Tesla. A 2 GeV beam deflected in such a wiggler would cover a spectral range of up to 24 keV. This is the philosophy of the “White Book”. The radiation from the bending magnet (“Green Book” Design, 1 GeV and 1.87 Tesla) covers a range up to 5 keV. That one of a 2 GeV beam (“White Book-Design”) deflected in a bending with 1.5 Tesla covers a range up to 16 keV. A 2.4 GeV beam deflected in a 1.4 T bending magnet covers a spectral range of up to

24 keV. Because the spectrum range goes with the square of the energy it would be very worthwhile increasing it.

But this process is limited, because the emittance (see next paragraph) is proportional to the square of the energy and this decreases the brilliance.

3.2.2 Brilliance of the Radiation

The brilliance is the figure of merit for the classification of the synchrotron radiation. At a synchrotron light source, the radiation with the highest brilliance comes from the undulators or wigglers. At a 2 GeV machine the required 20 keV photons can only be delivered from wigglers (see chapter 2), hence SESAME will be a wiggler-dominated machine. The brilliance of a wiggler is given by Bessel functions, the energy of the beam, number of wiggler periods, current and the inverse of the cross section of the beam. The cross section of the beam is proportional to the emittance of the machine and the betatron functions. In general the emittance goes with the third power of the bending magnet deflection angle and with the square of the energy. In order to get a high brilliance of the wiggler radiation, the emittance of the machine and the betatron functions at the location of the wigglers should be small. Synchrotron light sources dominated by undulators or wigglers and with a small emittance (smaller than 15 to 20 nmrad) are called 3^{rd} generation light sources. In order to increase the brilliance of the radiation in an upgrading process of BESSY I one should try to decrease the emittance of the machine. The upgrading of BESSY I should be directed to get for SESAME a 3^{rd} generation light source.

3.2.3 Number of Experimental Stations

The number of experimental stations is given in general by the space in the experimental hall. In a 3^{rd} generation light source the number of experimental stations is proportional to the number of available straight section for the installation of insertion devices (undulator and wigglers) and with a lower priority the number of bending magnets. In order to qualify this point one uses the percentage of the circumference that can be used for the installation of insertion devices. Furthermore as indicated in section 2.2 the length of insertion device sections should be long for increasing the brilliance. In an upgrading process of BESSY I one should try to increase the number and length of the straight sections.

3.3 Upgrading Versions of BESSY I

3.3.1 Green Book (GB) Proposal for Upgrading SESAME to 1GeV

With the “Green Book (GB)” proposal [1], the energy of the BESSY I would be increased from 0.8 to 1 GeV by changing the magnetic flux in the bending magnets from 1.5 to 1.87 Tesla. Decreasing the gap and modifying the pole profile of the bending magnet can do this. To reach the required photon spectrum, up to three 7.5 Tesla super conducting wigglers can be installed. To increase the number of straight sections the lattice has been changed from the TBA- to a DBA- optic [4], which results in a 6-fold symmetry (increasing the useable straights by a factor 2) (see figure (3.1) and (3.2)). To avoid the influence of the high field wiggler to the beam and to increase the brilliance of the radiation a so-called “mini beta section” has to be introduced at the position of the wigglers. For the introduction of the “mini-beta-section” four more quadrupoles are needed within the straight section, as shown in figure (3.3) and (3.4). The circumference of the machine will increase from 64 to roughly 100 m. The parameters of BESSY I, the upgraded GB-1-version without and with a mini beta section (GB-2) are given in table (3.1). The number of the existing magnets and the power supplies of BESSY I are compiled in table (3.2).

Noticeable are the increase of the emittance and the reduction of the length of the straights by the introducing of the mini beta section. Also from the cross section of the beam (area of the spot size) GB-2 can't compete with BESSY I. The emittance depends upon the number of wigglers, according to the additional damping.

For the version GB-1 all magnetic elements of BESSY I can be used and 8 additional sextupoles with a length of 0.15 m are required. For the version GB-2 the 12 bending magnets have to be modified, furthermore 8 additional quadrupoles and 8 sextupoles are needed.

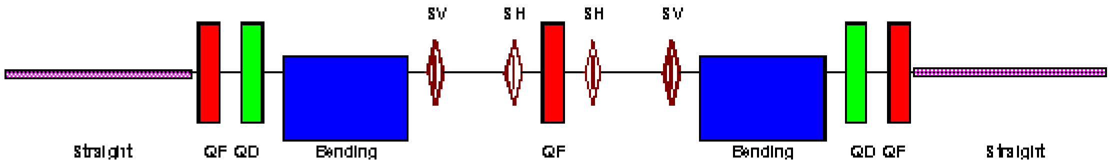

Figure 3.1: Arrangements of magnets within the unit cell of the version GB-1.

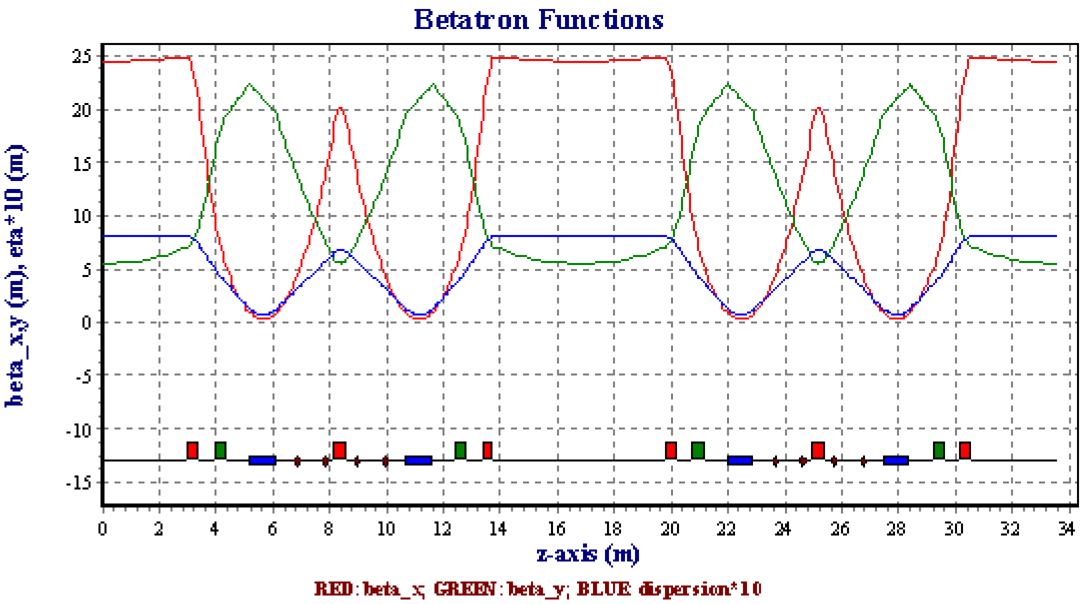

Figure 3.2: Machine functions within two unit cells of the version GB-1.

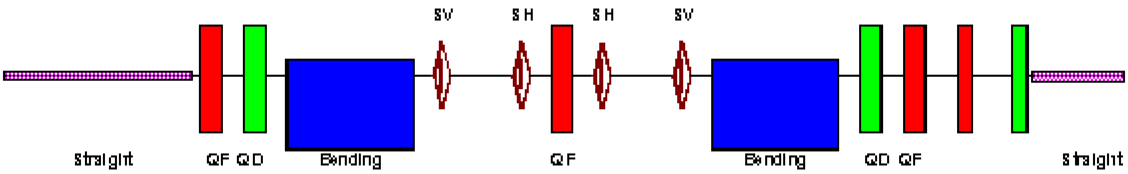

Figure 3.3: Arrangements of magnets within the unit cell of the version GB-2.

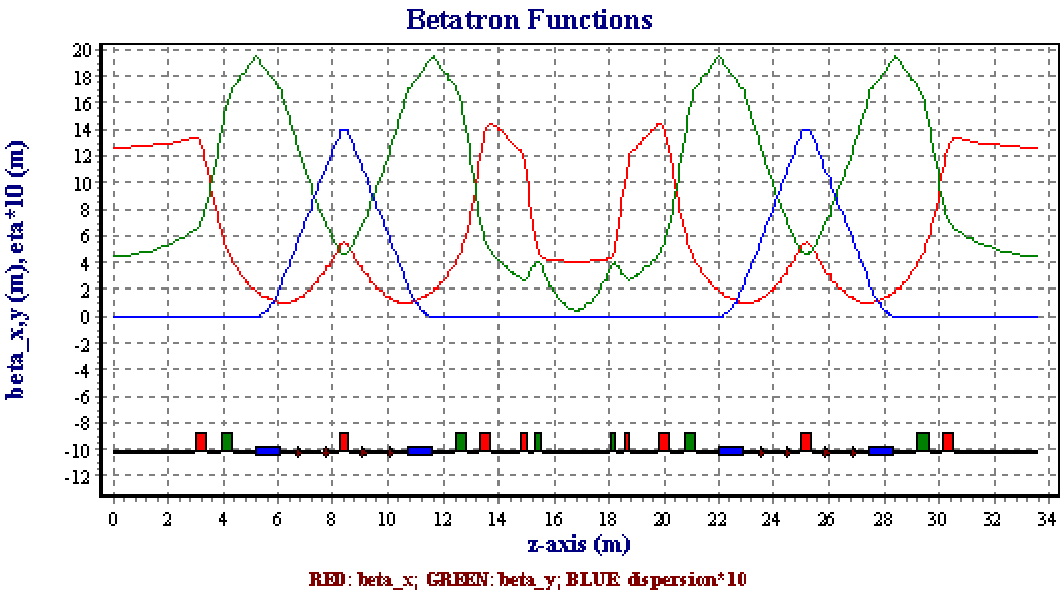

Figure 3.4: Machine functions within two unit cells of the version GB-2.

Table 3.1: Main parameters of BESSY I, the "Green Book Proposal" without (GB-1) and with a mini beta section (GB-2).

Parameter		BESSY I	GB-1	GB-2
Energy	(GeV)	0.8	0.8	1.0
Emittance	(nmrad)	56.8	7.85	50 – 107
Number of straights		4	6	6
Useable wiggler straights and length	(m)	2 / 2.60	4 / 4.80	3 / 2.00
Useable undulator straights and length	(m)			1 / 4.80
Circumference	(m)	64.0	100.8	100.8
Σ Length of straights/circumference	(%)	8.1	22.9	10.7
Beam size (σ_x, bending / wiggler)	(mm)	0.138/0.341	0.063/0.607	0.375/0.644
Beam size (σ_y, bending / wiggler)	(mm)	0.050/0.023	0.057/0.029	0.209/0.030
Beam size area ($2*\pi*\sigma_x*\sigma_y$)				
Bending magnet	(mm^2)	0.044	0.023	0.493
Wiggler / Undulator	(mm^2)	0.049	0.111	0.121/0.619
Critical photon energy				
Bending magnet	(keV)	0.64	0.64	1.24
Wiggler(2.25Tesla)	(keV)	0.96	0.96	1.50
Undulator	(keV)			
Wavelength shifter (7.5Tesla)	(keV)	3.0	3.0	5.0

3.3.2 White-Book Proposal (WB) for upgrading SESAME to 2 GeV

The energy of an accelerator is given by the integral of the magnetic flux around the ring. For the increase of the energy from 1 GeV to 2 GeV longer magnets must be installed. The easiest way is to keep the foreseen DBA-lattice in the GB-design and change the 12 bending magnets of BESSY I with a deflection radius of 1.779 m by new ones with a radius of 4.4474 m (the corresponding magnetic flux is 1.5 Tesla). In this case one needs 12 new bending magnets and 8 new sextupoles.

The emittance of the electron beam is proportional to the third power of the deflection angle of the bending magnets. Going from the 6-fold symmetry to 8 fold would decrease the emittance by a factor 2.4 and would increase the number of useable straight sections from 4 to 6. This design would be similar to ANKA.

Table 3.2: Characteristic data of the BESSY I magnets and power supplies. In the column "Number" the first figure gives the number of power supplies and the second the number of magnets.

Power Supply	Number	Data	Data(mm)	Voltage(V)	Current(A)	Power(kW)
Bending magnet	1 / 12	1,5 T	60 gap	305	900	275.0
Quadrupole Q0	4 / 28	11.5 T/m	100 bore	52	1025	213.0
Quadrupole Q1	1 / 4	11.5 T/m	100 bore	30	1100	33
Quadrupole Q2	1 / 4	14,5 T/m	100 bore	38	1400	53.2
Sextupole Sh	1 / 8	557 T/m^2	120 bore	83	400	33.2
Sextupole Sv	1 / 4	418 T/m^2	120 bore	63	300	18.9
Corrector magnets	20			20	10	4.0

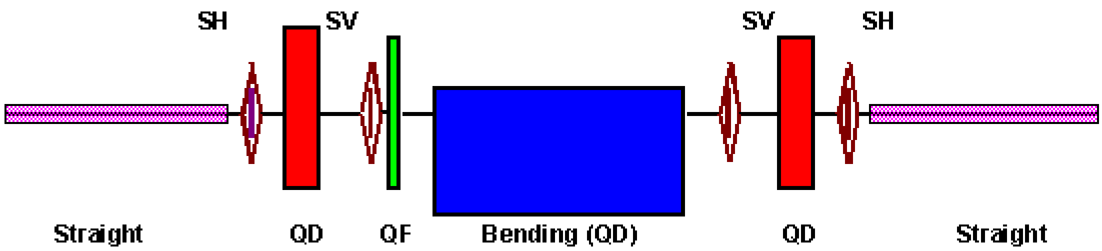

Figure 3.5: Arrangements of magnets for the half cell of TME-structure. Within the "White Book" the TME structure is proposed for the upgrading of SESAME to 2 GeV.

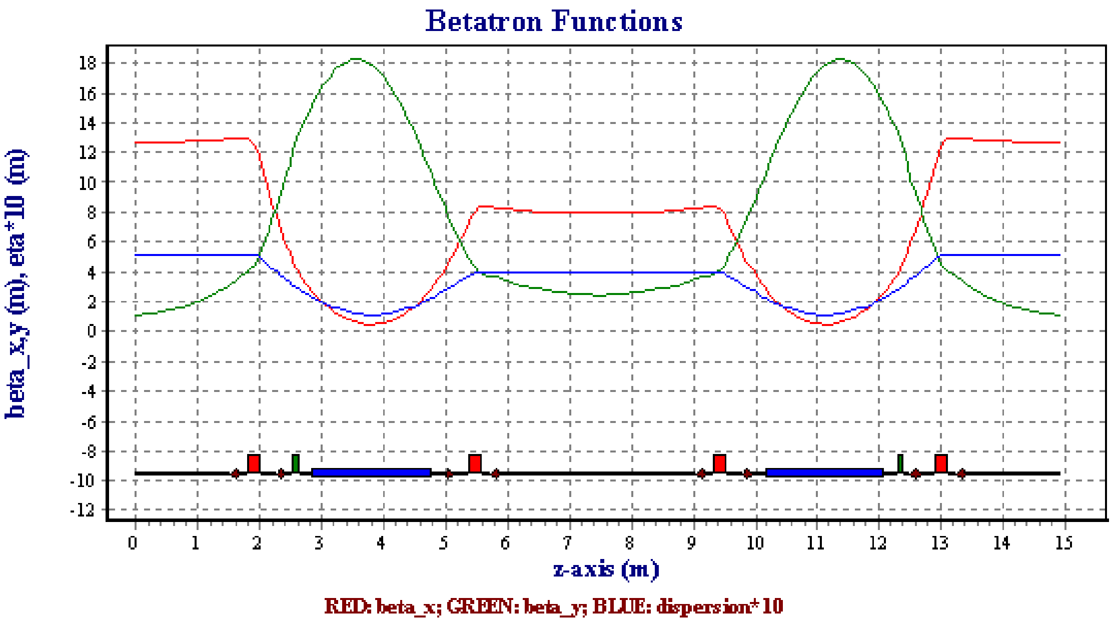

Figure 3.6: Machine functions within the unit cells of the White Book Design.

Table 3.3: Main parameters of White-Book Design with an upgrading to 2 GeV.

Parameter		WB
Energy	(GeV)	2.0
Emittance	(nmrad)	18.7
Number of straights		16
Useable wiggler straights and length	(m)	8 / 2.43
Useable undulator straights and length	(m)	6 / 1.80
Circumference	(m)	120.0
ΣLength of straights / circumference	(%)	35.7
Beam size (σ_x, bending / wiggler)	(mm)	0.167/0.613
Beam size (σ_y, bending / wiggler)	(mm)	0.078/0.032
Beam size area ($2*\pi*\sigma_x*\sigma_y$)		
Bending magnet	(mm^2)	0.082
Wiggler/ Undulator	(mm^2)	0.123/0.092
Critical photon energy		
Bending magnet	(keV)	3.60
Wiggler (2.25Tesla)	(keV)	6.00
Undulator	(keV)	
Wavelength shifter (7.5Tesla)	(keV)	20.0

Introducing combined magnets, for example gradient bending magnets, can reduce the number of magnets in an accelerator. In the past a lot of synchrotron light sources have been designed with gradient bending magnets (ALS, ELETTRA, CLS, SPEAR3 etc.). This design has further the advantage that the emittance will be reduced. The emittance can more reduced by changing the lattice from the DBA-structure to the TME-structure (Theoretical Minimum Emittance), which gives the smallest emittance in a storage ring. The arrangements of magnets for a TME-structure are given in figure (3.5) and the machine functions in figure (3.6). The parameters of these versions are summarized in table (3.3). Within the TME-structure the whole vertical focusing will be performed by the gradient in the bending magnet. In order to change the focusing in the vertical direction the quadrupole QF is introduced.

3.3.3 Yellow-Book Proposal (YB) for Upgrading SESAME to 2.5 GeV

According to the history of SESAME, the space of the building is fixed since 2001. With the requirement of the users, to have beam lines with a length of roughly 30 m, the maximum circumference of the storage ring is 125 meter. Furthermore the users are asking also for a special length of the straight sections, which should not be smaller as 3 meters. This value is already reached in the WB-design. The “White Book Design” with energy of 2 GeV has, according to table (3.3) a circumference of 120 meter. Hence for the upgrading to 2.5 GeV only 5 meters exist. By reducing the number of magnets, for example by eliminating the quadrupole Qf in figure (3.5) and (3.6), further space could be available. But this procedure is only possible, if there exist a possibility to change the vertical focusing in the machine. This can be done with the “Pole Face Winding” technique, which will be explained in detail in chapter 6. The lattice for the proposed upgrade of SESAME to 2.5 GeV is given in figure (3.7) and (3.8) and the parameters are compiled in table (3.4).

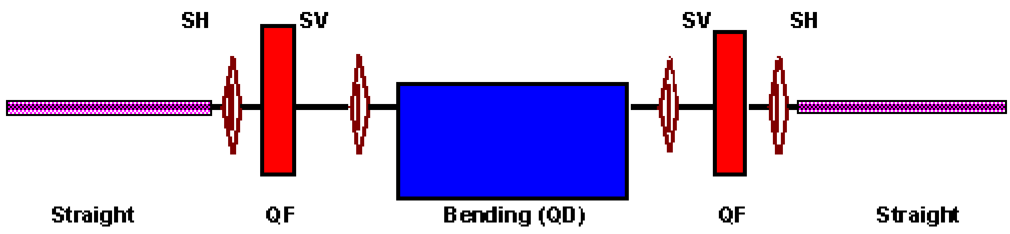

Figure 3.7: Arrangements of magnets for the proposed upgrade of SESAME to 2.5GeV.

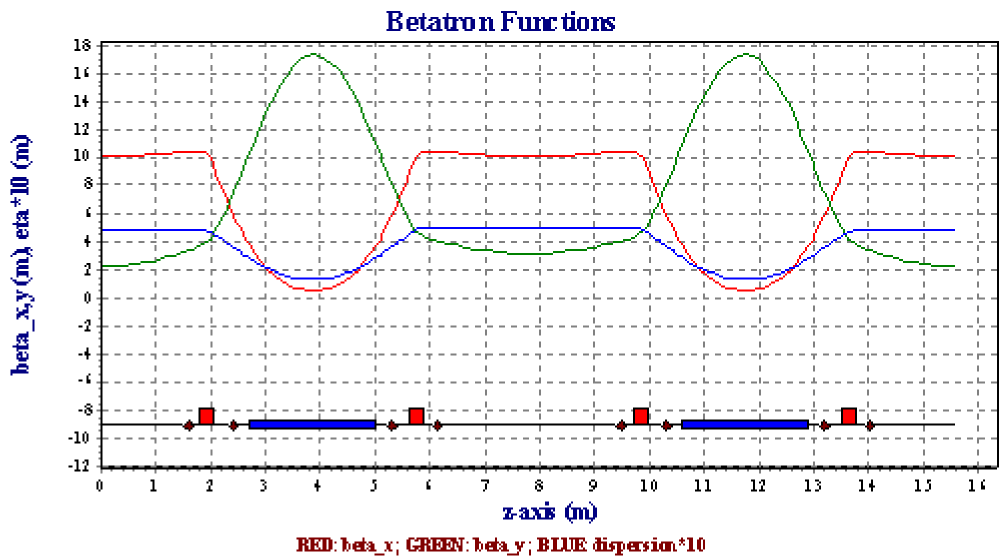

Figure 3.8: Machine functions within the unit cells of the White Book Design.

Table 3.4: Main parameters of Yellow-Book Design with an upgrading to 2.5 GeV.

Parameter		YB
Energy	(GeV)	2.5
Emittance	(nmrad)	24.9
Number of straights		16
Useable wiggler straights and length	(m)	8 / 2.40
Useable undulator straights and length	(m)	6 / 2.20
Circumference	(m)	124.8
ΣLength of straights / circumference	(%)	39.7
Beam size (σ_x, bending / wiggler)	(mm)	0.187/0.730
Beam size (σ_y, bending / wiggler)	(mm)	0.068/0.022
Beam size area ($2*\pi*\sigma_x*\sigma_y$)		
Bending magnet	(mm^2)	0.080
Wiggler/ Undulator	(mm^2)	0.100
Critical photon energy		
Bending magnet	(keV)	5.82
Wiggler (2.25Tesla)	(keV)	9.35
Wavelength shifter (7.5Tesla)	(keV)	31.2

3.4 Comparison of the Different Versions

3.4.1 Magnets

For the different upgrading versions the needed magnets are summarized in table (3.5). To upgrade the storage ring to 1 GeV (version: GB 2) the bending magnets have to be modified in order to reach a field of 1.87 Tesla. Furthermore 8 quadrupoles and 8 sextupoles are needed. For this version a DBA lattice is foreseen and the symmetry of the machine is 6 fold.

Table 3.5: Number of magnet elements needed for the different upgrading versions for SESAME. The lengths of the elements are given in brackets.
***) This is a combined quadrupole / sextupole magnet**

Version	Bendings	Quadrupoles	Sextupoles	New bends	New quads	New sextup.
BESSY I	12	32 (0.44) 4 (0.25)	16 (0.25)			
Green Book 1	12	30 (0.44)	16 (0.25) 8 (0.15)			8 (0.15)
Green Book 2	12	30 (0.44) 12 (0.25)	16 (0.25) 8 (0.15)	12 modified	8 (0.25)	8 (0.15)
White Book	16	32 (0.23)	24 (0.15) 16 (0.20)*)	16	32 (0.23)	24 (0.15) 11 (0.20)*)
Yellow Book	16	32 (0.265)	64 (0.14)	16	32 (0.265)	64 (0.14)

The version "White Book" needs 16 new bending magnets, 32 quadrupoles with a length of 23 cm, 24 sextupoles with a length of 0.15 (m), and 16 to 32 combined sextupole / quadrupole magnets. The version "Yellow Book" needs 16 new bending magnets, 32 quadrupoles with a length of 26.5 cm, and 64 sextupole magnets.

Table 3.6: Main parameters of the different synchrotron light sources

Source	Energy	Emitt.	In. Len.	Angle	Circumf.	Percent.	Nor. Emitt	Factor 1	Factor 2	Factor 3
	(GeV)	nmrad	(m)	(rad)	(m)	(%)	**)			
BESSY I	0.8	55.2	13.07	0.524	64	20.4	599.5	6.7	4.3	0.06
Green Book 1	0.8	7.7	36	0.524	100.8	35.7	83.6	602.4	385.5	5.11
Green Book 2	1	50	25.35	0.524	100.8	25.1	347.5	10.1	10.1	0.21
MAX II	1.5	9	31.4	0.3142	90	34.9	129.0	430.7	969.1	2.10
ALS	1.9	5.6	81	0.1745	196.8	41.2	291.9	1312.5	4738.0	0.48
BESSY II	1.9	6.4	89	0.1963	240	37.1	234.4	905.4	3268.3	0.68
White Book	2	16.5	48.8	0.3927	120	40.7	68.1	149.4	597.5	8.77
ELETTRA	2	7	74.78	0.2618	258	29.0	97.5	591.5	2366.1	3.05
INDUS II	2	44	36.48	0.3927	172	21.2	181.6	11.0	43.8	0.64
Yellow Book	2.5	24	49.5	0.3927	124.8	39.7	63.4	68.9	430.4	9.86
NSLS	2.5	44	36	0.3927	170	21.2	116.2	10.9	68.4	1.57
ANKA	2.5	88	31.34	0.3927	110.8	28.3	232.5	3.7	22.8	0.52
LLS	2.5	8.76	87.6	0.1745	252	34.8	263.8	453.0	2831.2	0.50
SLS	2.4	5	63	0.244	288	21.9	59.8	875.0	5040.0	6.13
Boom	3	6.88	76.72	0.2244	216	35.5	67.7	750.4	6753.4	7.76
CLS	2.9	18.2	62.4	0.2618	170.4	36.6	120.6	110.6	929.8	2.52
SOLEIL	2.75	3.72	159.6	0.1963	354	45.1	65.0	3257.9	24638.2	10.66
DIAMOND	3	2.74	218.2	0.1309	561.6	38.9	135.7	5175.2	46576.7	2.11

****) = nm*rad/((E^2)*(Angle^3)**

Factor 1 = 1000*(Percent.) /{[(Emitt)^2]}
Factor 2 = 1000*(Percent.)*(E^2) /{[(Emitt)^2]}
Factor 3 = 1000*(Percent.) /{[(Norm Emitt)^2]}

3.4.2 Performance of the Different Upgrading Versions

If building a synchrotron light source, the most determined factor is the available budget. With the budget, the building and the circumference of the machine is fixed. The energy is given by the scientific case. Now it is the work of the accelerator physicist to build a good machine, which meets the requirement of the users and gives a small emittance with a large number of long straight sections. The main parameters of different synchrotron light sources are compiled in table (3.6). The parameters are:

- Energy in GeV.
- Emittance in nm*rad.
- Overall length of insertion devices in meter.
- Angle of the bending magnets in rad.
- Circumference of the machine in meter.
- Percentage of the circumference, which is available for insertion devices.
- Normalized emittance in nm*rad / [(Energy^2)*(Angle^3)].
- Factor 1 = 1000*Percentage / (Emittance^2).
- Factor 2 = 1000*Percentage * (Energy^2) / (Emittance^2).
- Factor 3 = 1000*Percentage / [(Normalized emittance)^2].

The green boxes mark the upgraded versions for SESAME.

For state of the art machines, between 37 and 45 % of the circumference can be used for the installation of insertion devices. This is also fulfilled for the White - and the Yellow Book Design. The emittance of the machine is proportional to the square of the energy and the third power of the bending magnet deflection angle. The so-called normalized emittance, as defined above, gives an expression how optimized the design of the machine is. According to table (3.6) the smallest normalized emittance has the Swiss Light Source with a value of 59.8, followed by the “Yellow-Book-Design” and SOLEIL. Also the White-Book-Design has with 68.1 a pretty nice value.

The brilliance, which can be reached at the different machines are given by the factor 1. It is clear, that the machines with the smallest emittance, like DIAMOND, SOLEIL, ALS, SLS, etc have the largest value. SESAME belongs to the class of MAX II, NSLS, Indus II, ANKA, etc. Also for the factor 1 SESAME has a good value. If for this expression the normalized emittance is used instead the emittance (factor 3) then the SESSAME has values, which can compete with the best synchrotron light sources of the world.

References

[1] “SESAME, A Proposal for Synchrotron Radiation Source in the Middle East”, October 1999, UNESCO-Office, Amman.

[2] “JSPS, Asian Science Seminar, Synchrotron Radiation Science”, October 19-28, 2002, AL SALT, JORDAN.

[3] “Conceptual Design for the Upgrading of SESAME to 2 GeV”, July 2002, Amman, UNESCO-Office. See also the SESAME website: http://www.sesame.org.jo/ .

[4] A.Ropert, “Lattices and emittances”, CAS-CERN Accelerator School, CERN 98-04.