Chapter 11

INJECTOR

11.1 Introduction

Within a storage ring currents of some hundred mA are stored. This current produces the synchrotron radiation delivered via the optical elements to the investigated samples. Each storage ring of a synchrotron light source needs an injector because it is not possible to produce in one accelerator high currents and bring them up to energies of several GeV. So the acceleration has to be made in steps.

First the electrons will be produced in a gun, with a current of some hundreds of mA and injected into the pre accelerator (Linac or microtron), which delivers a beam of 10 to 100 mA.

Second the pre-accelerator delivers the beam to the booster synchrotron, which accelerates the beam up to hundreds of MeV or some GeV in 100 or 1000 ms. The current within the synchrotrons is some 10s of mA.

Third, the booster synchrotron delivers the beam to the storage ring. According to the ratios of the circumferences from the booster synchrotron and storage ring the beam in the last accelerator is per shot some mA. The beam within the storage ring will be accumulated until the desired beam current is reached. In order to get a current in the storage ring of 400 mA at least 400 to 600 shots from the synchrotron are needed. This procedure takes some minutes. The beam energy is then ramped to the desired final beam energy.

The particles must be successively delivered from one accelerator to the next one. The specifications of the various accelerators are very different, i.e. each machine has its own equilibrium emittances and machine functions; therefore it is necessary to match them appropriately so that an optimal beam transfer can occur. For SESAME the transfer line between the pre-injector and the booster synchrotron will be the same as at BESSY I but a new transfer line from the booster to the storage ring is needed. It must be designed based on the existing elements of the old transfer line.

The successive injections are designed to take place in the horizontal plane. In order to save space the whole injector is inside the storage ring. The slow injection system from the pre-injector to the booster as well as the slow extraction system from the booster will not change compared to what it was at BESSYI. For injection to the storage ring a design based on a fast injection system is needed for high accumulation efficiency. On the other hand because SESAME will be a compact storage ring, a 2.5 GeV machine with 125 meters circumference, there isn’t any long enough straight section to put all the injection elements. Therefore, other possibilities have been studied; for instance an injection scheme consisting of 4 kickers distributed in three successive high beta sections.

In the following sections, first the specifications of the microtron and the booster synchrotron are introduced, then the transfer line to the storage ring and finally the injection elements and injection scheme to the storage ring are discussed.

11.2 Microtron

The preinjector of BESSY I was a 22 MeV classical microtron figure (11.1). The characteristics of this microtron are listed in table (11.1).

To get experience in the operation of the microtron and perform some refurbishment and upgrading, a reinstallation of the microtron in 2003 is planned. A future upgrade of the injection system would entail replacing the 22 MeV microtron by a 53 MeV or 100 MeV racetrack microtron.

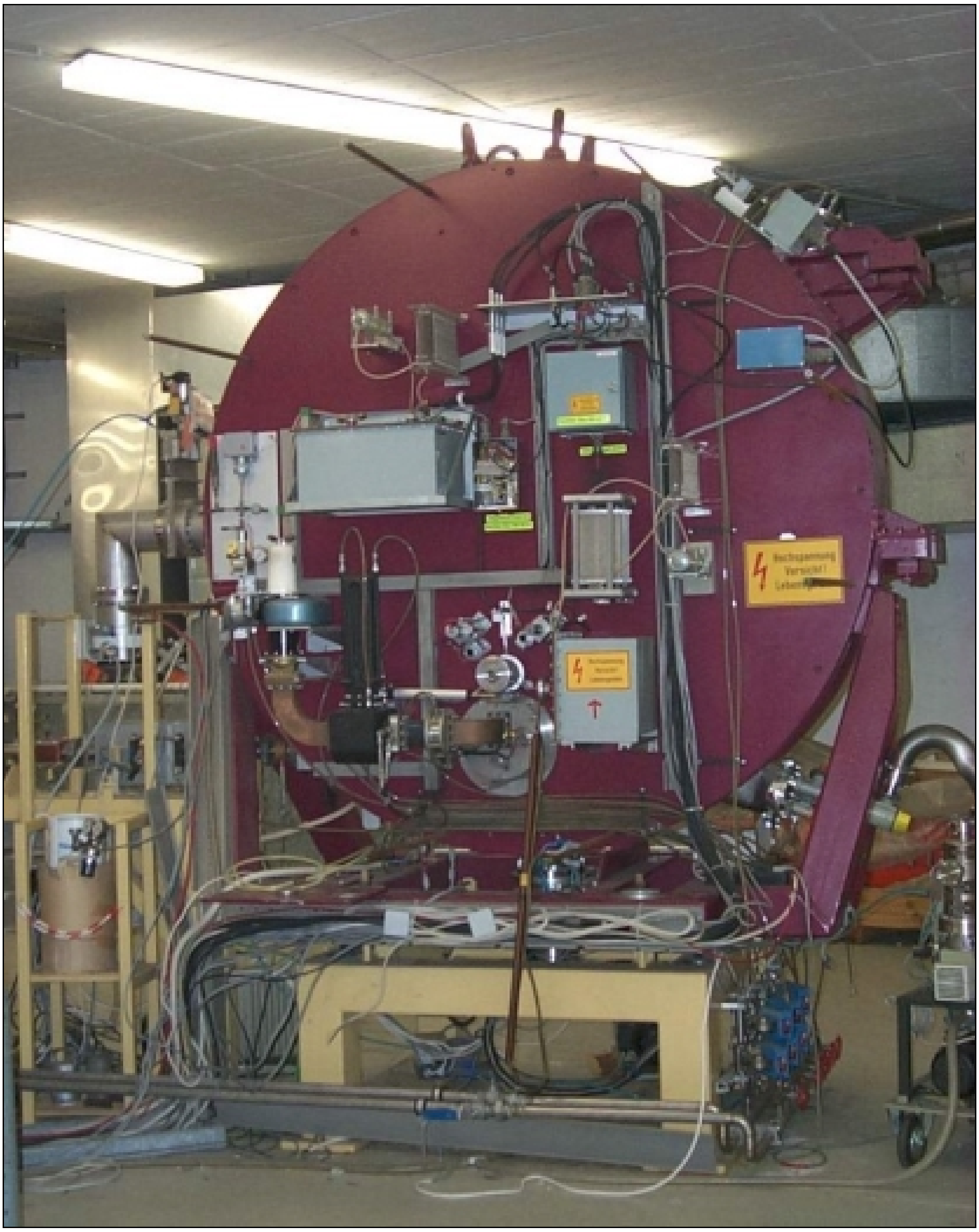

Figure 11.1: Microtron of BESSY I during disassembly.

Table 11.1: Characteristics of the microtron.

Extractable energy , *MeV*	22.5
Energy gain per turn , *keV*	535
Energy spread (FWHM), *keV*	35
Magnetic field , *T*	0.112
Magnet diameter , *m*	2.22
Pole piece diameter , *m*	1.8
Gap height , *m*	0.11
Magnet width , *m*	0.45
Microwave frequency , *GHz*	3.0
Microwave peak power , *MW*	2
Pulse duration , *μs*	4
Pulse repetition rate , *Hz*	≤ 250
Working vacuum , *mbar*	10^{-6}
Pulse current , *mA*	15
Vertical emittance , *mm-mrad*	≤ 8
Horizontal emittance , mm-mrad	≤ 3

11.3 Booster Synchrotron

The booster synchrotron [11.1] has a six fold symmetry with a substructure according to table (11.2), see figure (11.2). A picture of the booster synchrotron during the disassembly is shown in figure (11.3).

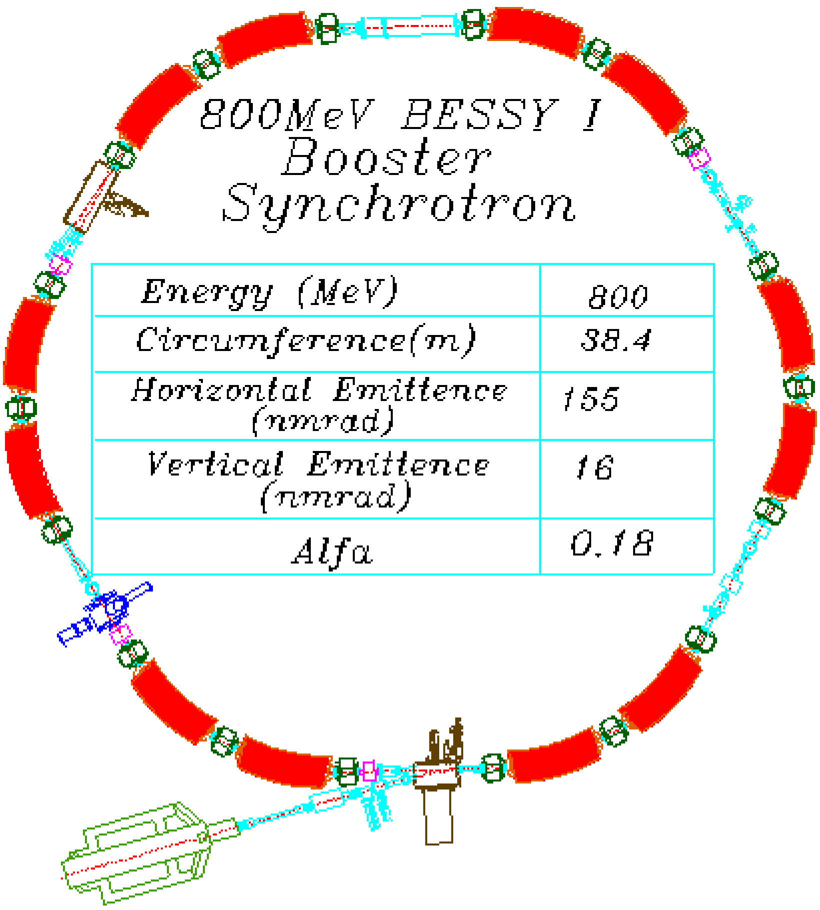

Figure 11.2: Layout of the booster synchrotron and the microtron.

The unit cell and the main optical functions are shown in figure (11.4). The characteristics of the booster are listed in table (11.3). There will be a different way of powering magnets;

instead of White circuits of the BESSY I a DC power supplies with 1Hz repetition rate will be used. Currents up to 15 mA have already been reached at BESSY I. With even 50% injection efficiency, which is well below what we expect to have for SESAME, this means less than three minutes for the filling time of the storage ring. In table (11.2) the lattice of the booster is listed.

Table 11.2: Lattice of booster synchrotron, the super periodicity is six.

Name code	Element	Length, *(m)*	ρ,*(m)*	*k*,*(m*$^{-2}$*)*	*s*,*(m)*
1	D1	1.025			1.025
2	QF	0.25		1.69	1.275
3	D2	0.21			1.485
4	rB	1.398	2.67		2.883
5	D2	0.21			3.093
6	QD	0.25		-1.53	3.343
7	D2	0.21			3.553
8	rB	1.398	2.67		4.951
9	D2	0.21			5.161
10	QF	0.25		1.69	5.411
11	D1	1.025			6.436

Table 11. 3: Characteristics of the booster.

Maximum energy , *MeV*	800
Injection energy , *MeV*	20
Circumference , *m*	38.58
Super periodicity	6
Number of bending magnets	12
Number of focusing quadrupoles	12
Number of defocusing quadrupoles	6
Repetition rate , *Hz*	1
Horizontal tune , Q_x	2.22
Vertical tune , Q_y	1.31
Momentum compaction factor α	0.18
Harmonic number	64
RF-frequency , *MHz*	500
RF-output power , *kW*	2
Cavity shunt impedance , *M*Ω	3
Current @maximum energy , *mA*	7
Vertical emittance , mm-mrad	0.016
Horizontal emittance , mm-mrad	0.155

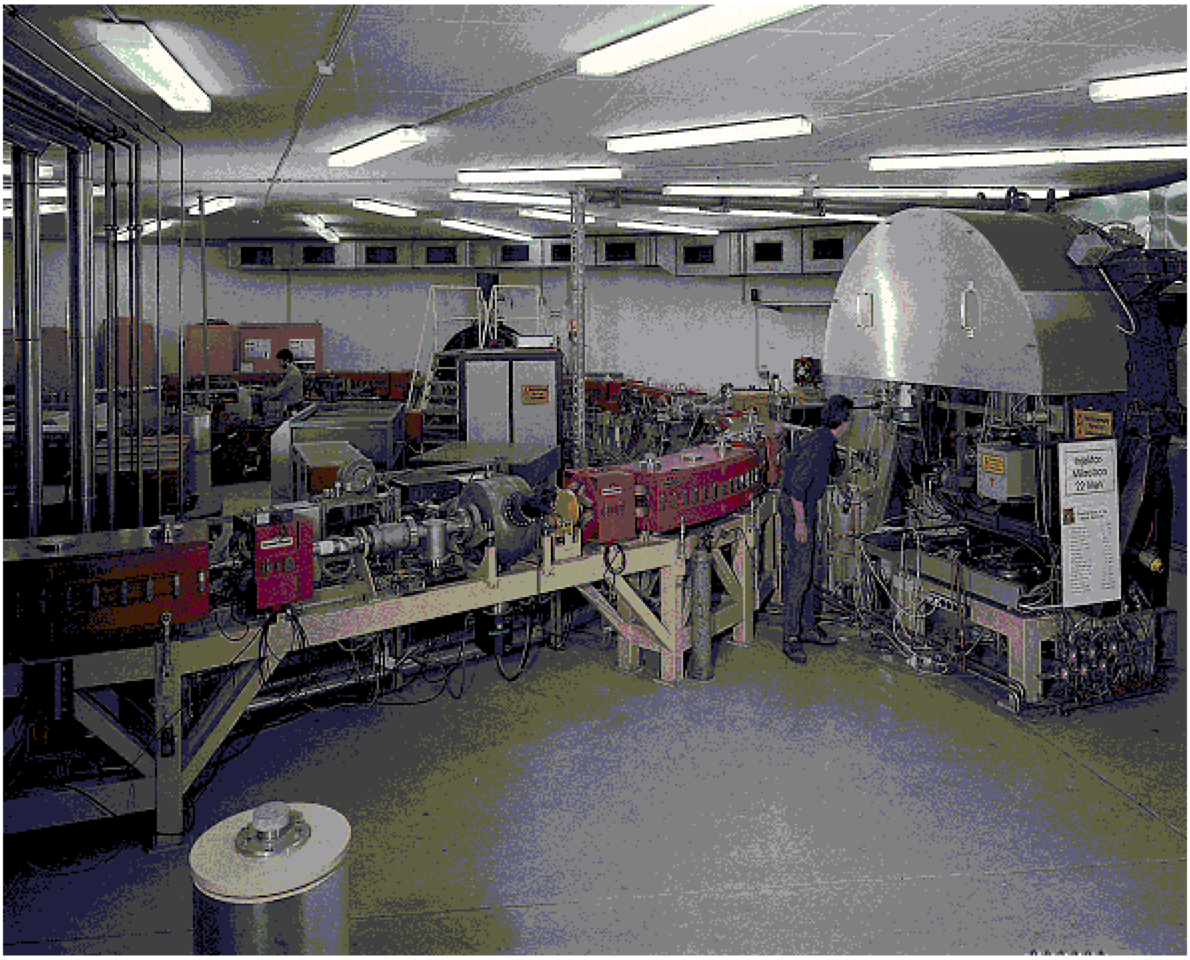

Figure 11.3: Booster Synchrotron during dismantling of BESSYI.

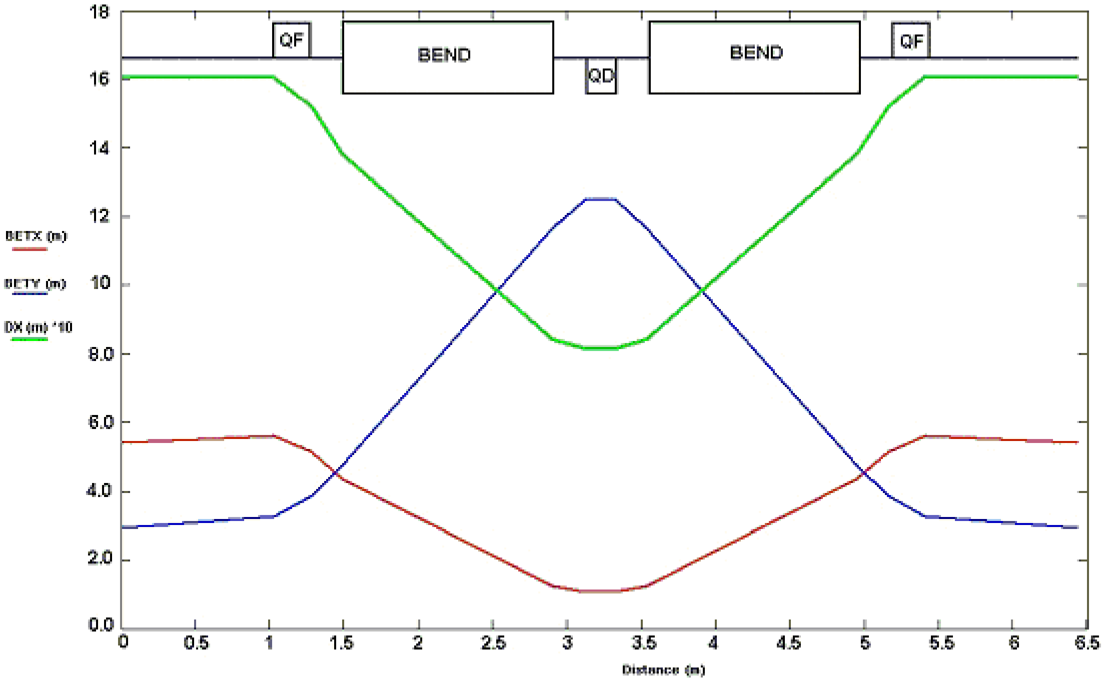

Figure 11.4: Beta functions and Horizontal Dispersion function versus position in one cell of the booster synchrotron consisting of two bending magnets and three quadrupoles.

11.4 Transfer Line

11.4.1 Lattice of the Transfer Line

The transfer line of BESSYI can not any longer be used because of the reasons: 1.The storage rings are totally different; 2. The location of the injector in reference to the storage ring has changed 3. While at BESSY I a vertical injection was used, it is now foreseen to inject horizontally. Therefore a new transfer line for SESAME has to be built using existing elements of old transfer line of BESSY I. Table (11.4) shows the availability of required elements for new design. Figure (11.5) shows some pictures of old transfer line of BESSYI and its elements during its running period.

Table 11.4: Elements of the transfer line and their status.

Element	Number	Status
Quadrupoles and their power supplies	6	Available from BESSYI
Steerers and their power supplies	12	Available from BESSYI
Main bending magnet	1	Available from BESSYI
Small bending magnet	1	Available from BESSYI
Extraction septum	1	Available from BESSYI
Injection Septum	1	Not available from BESSYI

Values of the optical functions at the two ends of transfer line are listed in table (11.5). The starting point is the straight section of booster just before extraction septum and the end is just after the injection septum to the storage ring. This defines what hereafter we call full match.

In the vicinity of the storage ring there are many geometrical limitations coming from the convention of putting the injector inside the storage ring. Calculation of transfer line has been made for latest 2.5 GeV energy upgrade, see also table (11.7).

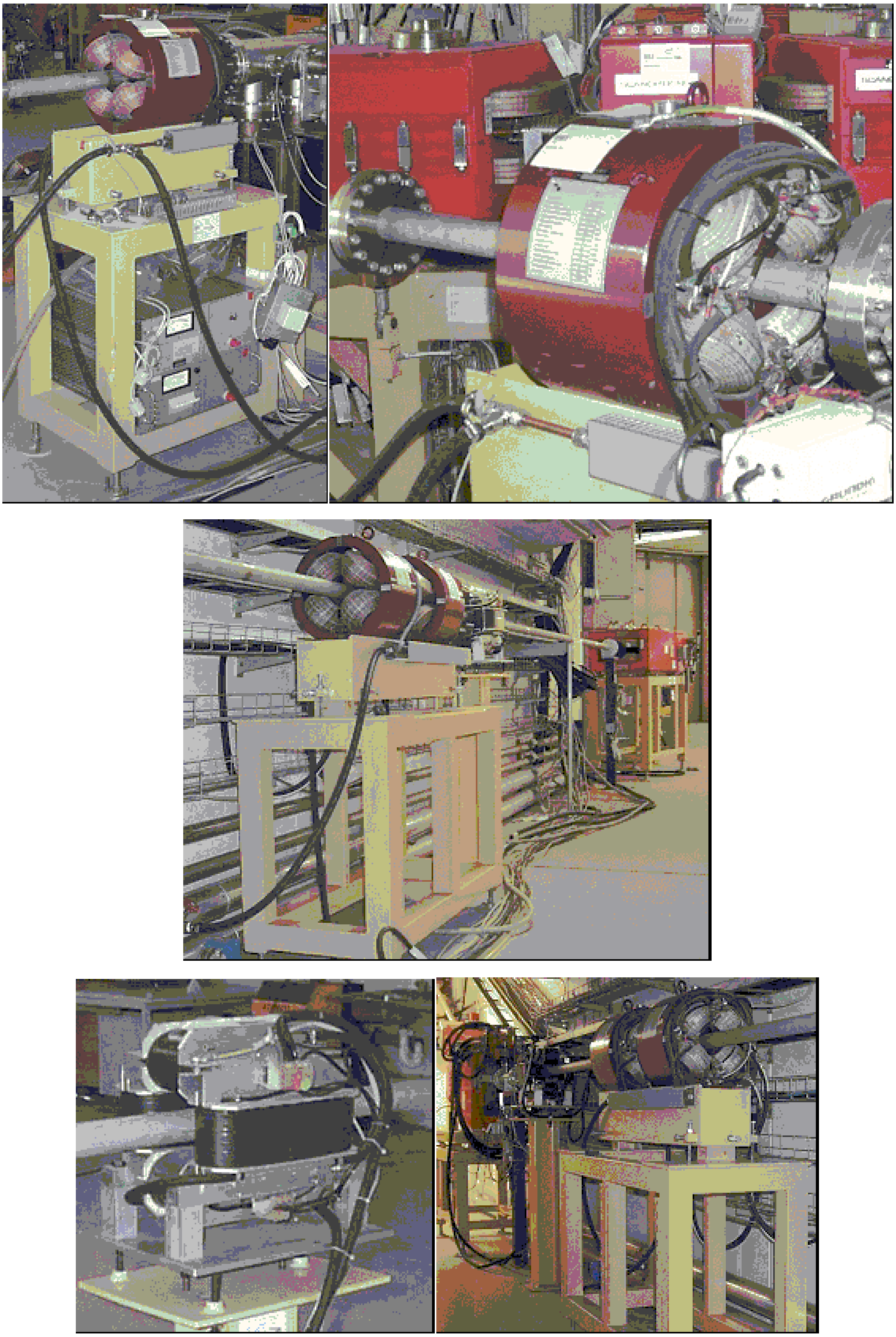

Figure 11.5: Some elements of transfer line of BESSYI. They all will be used for new transfer line.

Table 11.5: Full matching conditions.

Optical functions	Booster synchrotron (before Extraction septum)	SESAME (after injection septum)
BETAX (m)	5.421	10.915
BETAY (m)	2.914	1.818
ALFX	0.0	-0.036
ALFY	0.0	-0.231
DX (m)	1.605	0.538
DPX	0.0	0.0

The matching of the optics was performed using Matching module of MAD. Figure (11.6) shows the machine functions for a fully matched transfer line. The cross section (σ_x ,σ_y) of the beam in the transfer line are shown in figure (11.7).

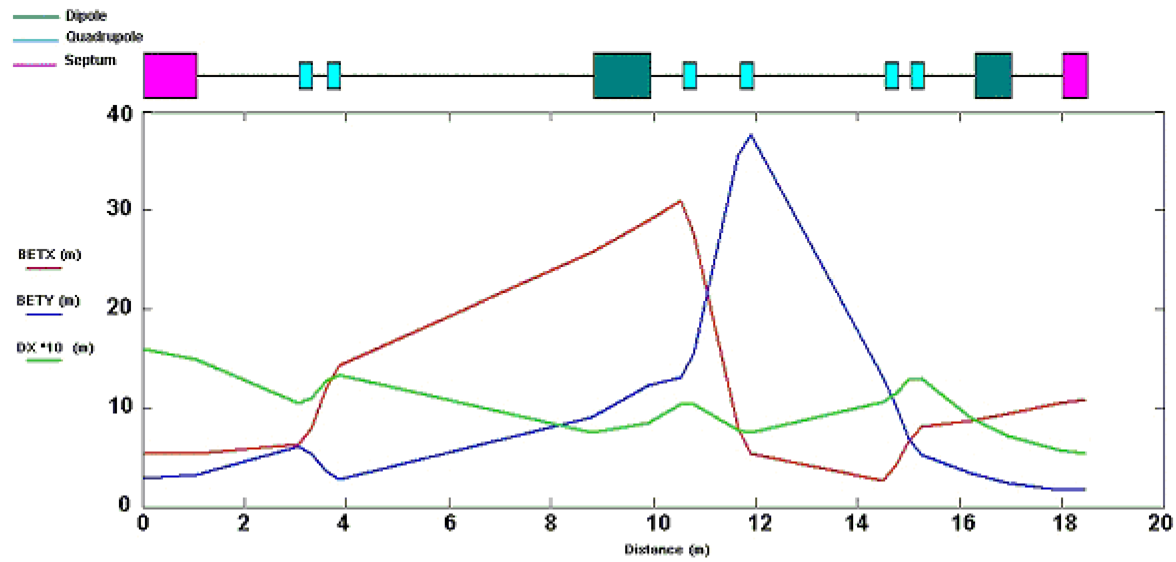

Figure 11.6: Main optical functions versus position in the transfer line for full matching.

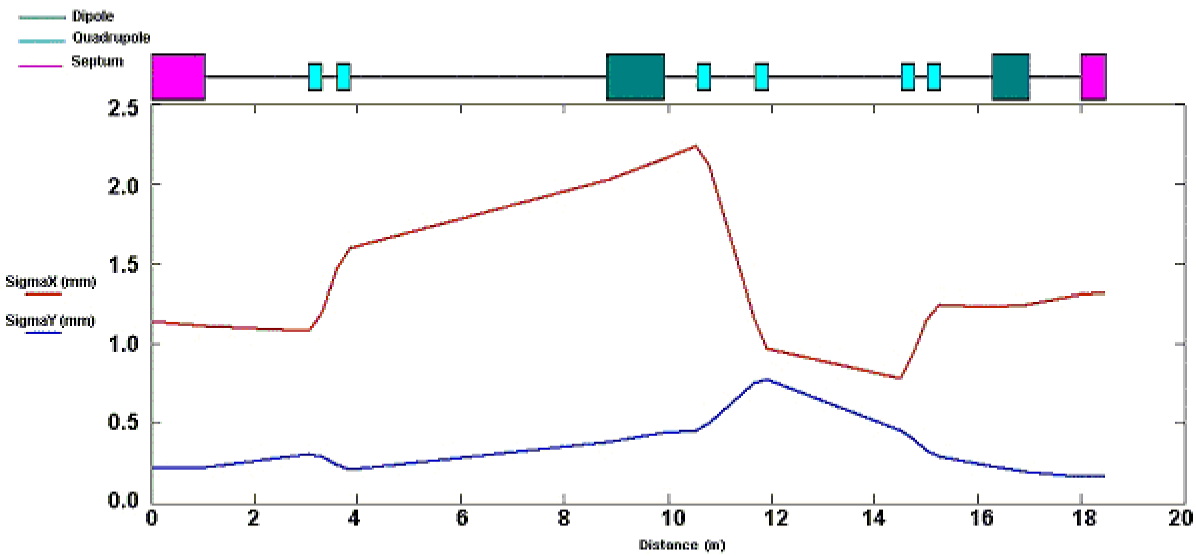

Figure 11.7: Horizontal and Vertical beam half width, and its variation in the transfer line for full match.

In table (11.6) the lattice of the transfer line is listed. Table (11.7) contains the storage ring lattice in the calculations of this chapter. In figure (11.8) the layout of the transfer line with the elements of the injection straight section is shown.

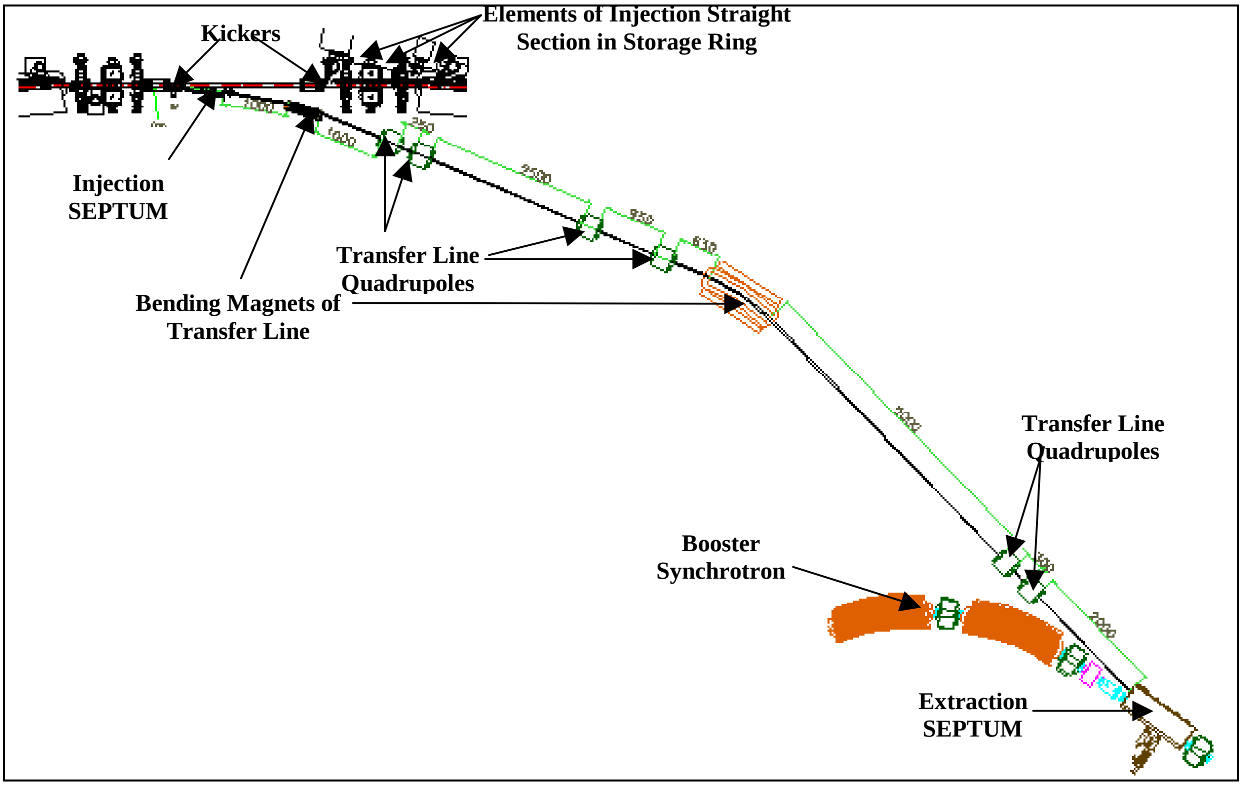

Figure 11.8: The transfer line and its elements and their arrangement with respect to the booster and the storage ring.

Table 11.6: Lattice of the transfer line, quads setting are for full matching.

Name code	Element	Length, (*m*)	ρ, (*m*)	k, (m^{-1})	s, (*m*)
1	Sep-ej	1.035	5.93		1.035
2	D1	1.999			3.034
3	Q1	0.25		-3.142	3.284
4	D2	0.3			3.584
5	Q2	0.25		2.1954	3.834
6	D3	4.944			8.779
7	rB1	1.95	2.6698		9.882
8	D4	0.63			10.512
9	Q3	0.25		2.2438	10.762
10	D5	0.875			11.638
11	Q4	0.25		-2.1565	11.888
12	D6	2.581			14.469
13	Q5	0.25		-1.5574	14.719
14	D7	0.249			14.968
15	Q6	0.25		2.892	15.218
16	D8	1			16.218
17	rB2	0.6985	2.668		16.919
18	D9	1			17.919
19	Sep-in	0.503	2.882		18.422

Table 11.7: One half-super period of the storage ring, the super periodicity is eight.

Name code	Element	Length, (m)	ρ, (m)	k, (m^{-1})	m,(m^{-1})	s, (m)
1	D1	1.505				1.505
2	S1	0.14			18.38816	1.645
3	D2	0.155				1.8
4	Q1	0.285		2.03801		2.085
5	D3	0.255				2.34
6	S2	0.14			-25.8388	2.48
7	D4	0.205				2.685
8	Bend	2.3391155	5.95651	-0.3636		5.024
9	D5	0.205				5.229
10	S3	0.14			-25.1926	5.369
11	D6	0.255				5.624
12	Q2	0.285		2.02928		5.909
13	D7	0.155				6.064
14	S4	0.14			17.89482	6.204
15	D8	1.596				7.8

The beam optics of the transfer line have been checked for a variety of mismatches; table (11.8) shows the results of these calculations. In each column there are some settings for quadrupoles that could result in the desired set of optical values measured at the end of transfer line. In this table the first column shows the values for the full matching according to table (11.5). Beta mismatches are studied in the next eight columns, here the bolded pink numbers show the values which are obtained for dispersion, not necessarily desired, but they are acceptable. The last two columns are the results for dispersion mismatching. Dispersion prime set to zero in all the calculations for both ends of transfer line. This transfer line could make any reasonable setting. All k-values of the quadrupoles are between –4 and 3 1/m^2, the extremes are bolded red numbers, and we know that g-factor of quadrupoles of BESSYI is >12 T/m and the energy of particles in transfer line is 800 MeV. Therefore, any value between –4.4 and 4.4 for k-value of quadrupoles is allowed. Also except than some extreme cases the maximum and minimum values of the beta functions are acceptable.

Table 11.8: Flexibility checks for the transfer line.

$Q1[K1]$	**-3.142**	-3.141	-3.66	-3.49	-3.07	**-3.9**	-3.25	-3.38	-3.26	-3.22	-3.28
$Q2[K1]$	**2.1954**	2.195	2.33	2.56	2.33	2.64	1.954	1.89	1.76	2.11	2.13
$Q3[K1]$	**2.2438**	2.263	2.05	2.29	2.25	1.88	2.24	2.13	2.17	2.1	2.5
$Q4[K1]$	**-2.1565**	-2.176	-2.1	-2.29	-2.22	-2.07	-2.16	-1.99	-2.12	-2.2	-2.38
$Q5[K1]$	**-1.5574**	-1.1185	-1.18	-1.21	-1.03	-1.09	-1.08	-1.21	-1.23	-1.07	-1.12
$Q6[K1]$	**2.892**	2.67	2.214	**2.98**	2.85	2.27	2.21	2.05	2.02	2.22	2.94
$\beta_X(m)$ $\beta_Y(m)$ D_X	**10.915** **1.818** **0.538**	10.915 3.636 **0.435**	10.915 0.909 **1.08**	5.46 1.82 **0.33**	5.46 3.64 **0.38**	5.46 0.909 **1.12**	21.8 1.82 **0.673**	21.8 3.64 **1**	21.8 0.909 **1.1**	10.92 1.82 1	10.92 1.82 0
$\beta_{X,\max}$	**31**	31	42	21	21	29	54	68	73	40	42
$\beta_{X,\min}$	**2.7**	3	0.8	3	3.3	1.55	1.3	0.42	0.41	0.77	5.2
$\beta_{Y,\max}$	**37.7**	38	68	50	32	75	51	64	58	42	52
$\beta_{Y,\min}$	**1.818**	2.8	0.909	1.64	2.92	0.909	1.82	2.4	0.909	1.35	1.7

11.4.2 Instrumentation of the Transfer Line

For instrumentation of this transfer line some elements are foreseen; table (11.9).

Table 11.9: Instrumentation of the transfer line.

Element	Number
F.C.T	1
Scraper	1
Screen monitors	3

11.5 Injection to the Storage Ring

For the injection process kickers and a septum, both named as injection elements, are needed. The kickers (normally three or four are needed) perform the required closed orbit deviation for capture of the beam and the septum brings the beam close to the vacuum chamber. As mentioned in 11.1, the injection elements should be distributed over several successive straight sections, like what has been implemented at ANKA [2] and MAXII [3]. At SESAME, four kickers instead of three will be used. This is because of two points, first it will make the possibility to have more smooth orbit nearby the SEPTUM and secondly for a definite orbit deviation the necessary strength for each one of kickers will be reduced. The required fast magnets and their specifications are listed in tables (11.10) and (11.11). A typical orbit bump by means of four kickers is shown in figure (11.9), the layout of the injection straight is shown in figure (11.10).

Table 11.10: Elements required for injection to the storage ring.

Injection elements	**Number**	**Length,** *(cm)*	**Pulse width, half sinusoidal** (μ *sec)*	**Strength** (*mrad*)
Kicker	4	22.5	3	~2
Septum	1	50.3	250	175

Table 11.11: ANKA base design for kickers.

Energy, *MeV*	800	
Kicker length, *m*	0.225	
Kicker strength (max), *mrad*	1.875	
Magnetic flux density, *mT*	25	
Magnetic field inside ferrite, *mT*	125	
Pulse length, μ sec	3	
Pulse shape	Half sinusoidal	
Number of turns	1	2
Current, *A*	900	450
Inductance of kicker, μH	0.6	2.48
Inductance of cable, μH	0.1	0.1
Total inductance, μH	0.7	2.58
Capacity of charg. capa. μF	1.3	0.36
Charging voltage, *kV*	0.66	1.2

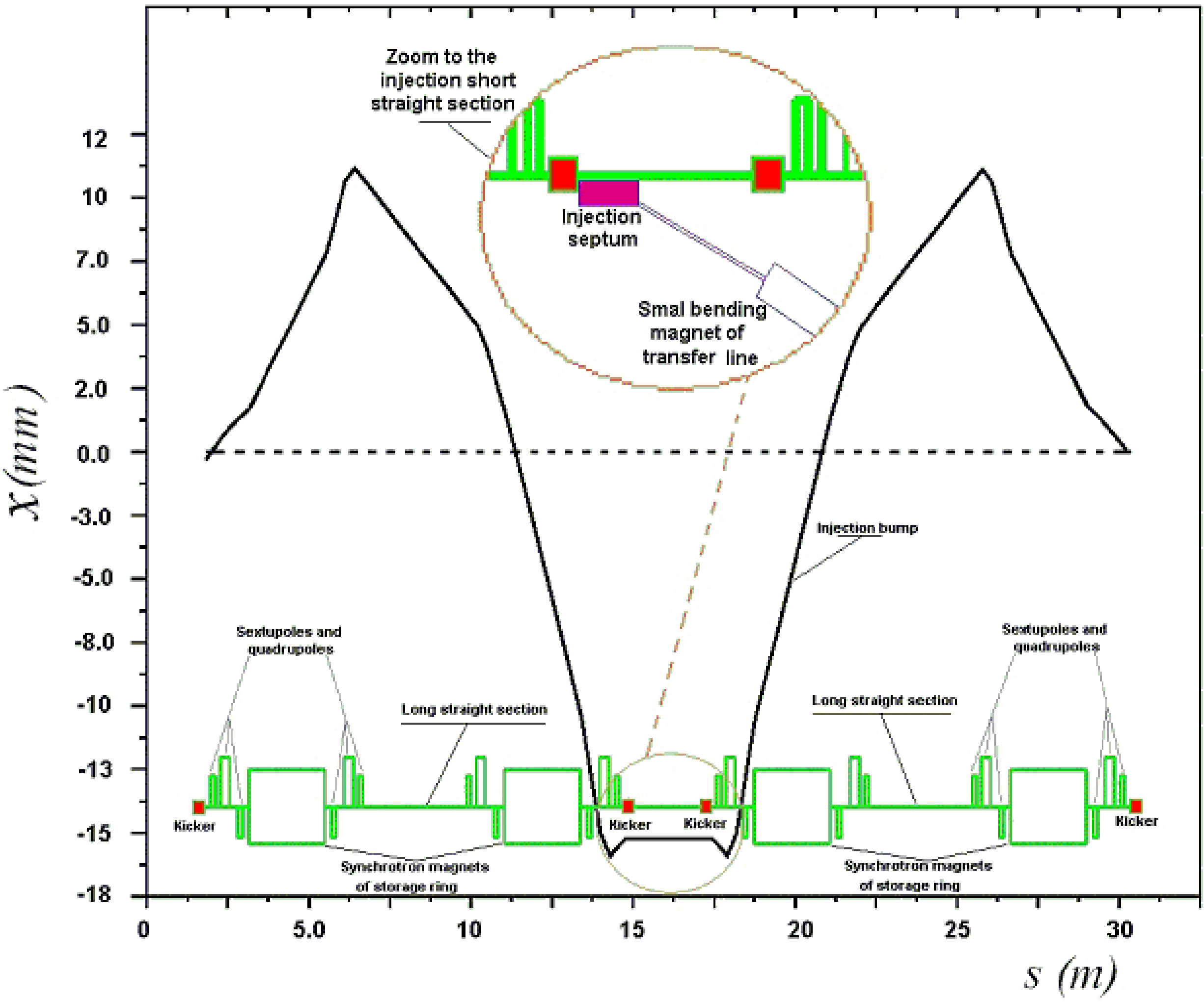

Figure 11.9: Layout of the injection region of SESAME showing also the orbi bump by means of four kickers.

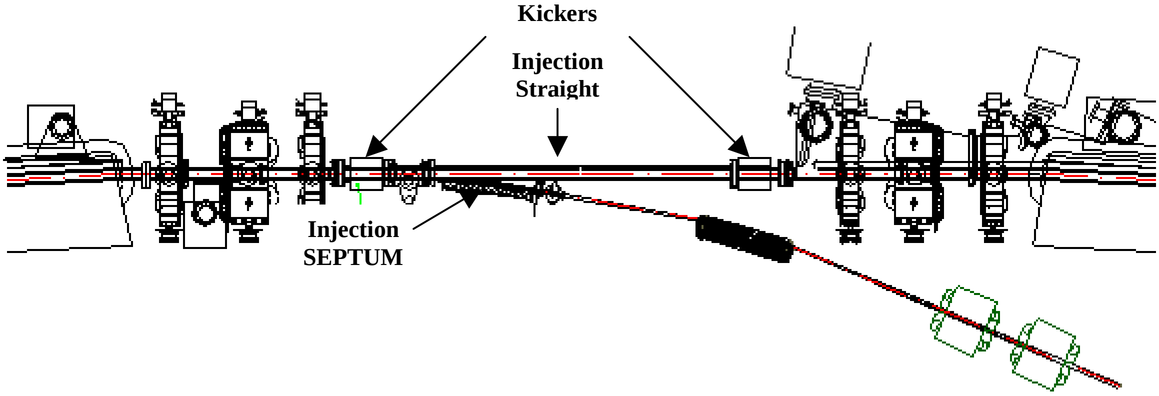

Figure 11.10: the layout of the injection straight.

11.5.1 Optimization of the Placement of the Kickers

In order to make a closed orbit bump by four kickers there is a set of equations for strengths of kickers, but even after applying them one has to take into account the effect of the sextupoles and then it becomes more clear that the best way to deal with this problem is by a numerical method. The kicker strengths are in general dependent on the deviation from reference orbit at the location of the SEPTUM, the phase advances, the values of optical functions and the choice of symmetric or asymmetric bump.

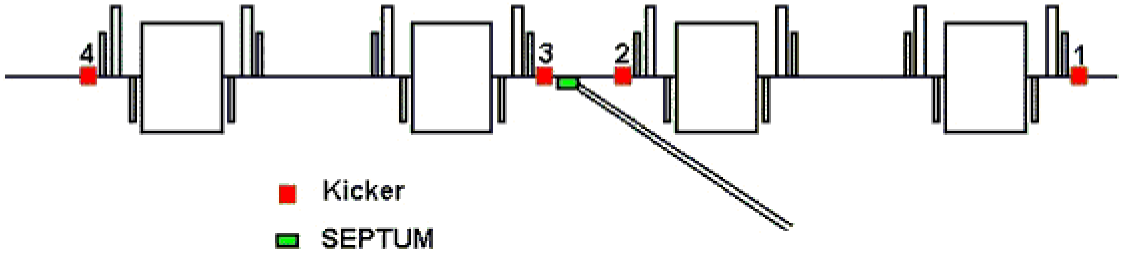

Figure 11.11: Three high beta sections of the storage ring with two low beta sections in between. Kickers are placed in high beta sections

11.5.2 Injection Efficiency Studies and Simulation of Injection Process

In this part of the study a simulation has been done which takes into account fast elements like kickers and any reasonable distribution of particles. The phases between the kicker's activating pulses can be set and the nonlinear effect (sextupoles) on bump closure also has been taken into account. First particles distribution is introduced into the transfer line and then resultant of this tracking delivered to injection process simulator. In this simulation one can inject at crest of activating pulse of kickers as well as on latter turns.

The circumference of the SESAME storage ring is $416\,n\sec$ (in time domain). The kicker pulse waveforms are similar to ANKA, with a pulse width of 3μsec and half-sinusoidal variation. With these characteristics and injecting at the crest of the pulse, in addition to the main kicks, the orbit will experience three weaker series of kicks. The values of the tunes have their own role. Also geometrical limits should be taken into account, especially the cross section of the vacuum chamber at the place of the SEPTUM. The best setting for the kickers strength is respectively 1.76, -1.28, -1.28 and 1.76 (mrad) for kickers 1, 2, 3 and 4.The shape of orbit bump was shown in figure (11.9). The fractional part of horizontal tune is nearly 0.2 and the acceptance of the machine can accommodate all the particles during action of kickers. The injected particles will face totally 4 series of kicks, and they will survive to all conditions. In figure (11.12) the results of tracking with active kickers for 3μsec is shown. As mentioned before they are injected at the crest of activating pulse. A total of 1000 particles distributed with an assumed Gaussian distribution in $2.86\sigma_x$ and $2.86\sigma_{x,}$ major and semi major radius are considered to be extracted from booster. They are tracked throughout transfer line and the resulting distribution is marked as 0 in figure (11.12). Right after injection they will face kickers 3, 4, 1, 2 of figure (11.11) respectively. Then after this turn they will go to position 1 of figure (11.12). Now by facing next complete chains of kicks they will go to position 2 and 3 of figure (11.12) and for the forth time after kicker 4 when they arrive to position of kicker 1 the kickers are off. This tracking should be continued for some turns with the kickers off. Only in this case the survival of particles will be insured. Figure (11.13) shows the result of tracking for some turns after the action of kickers.

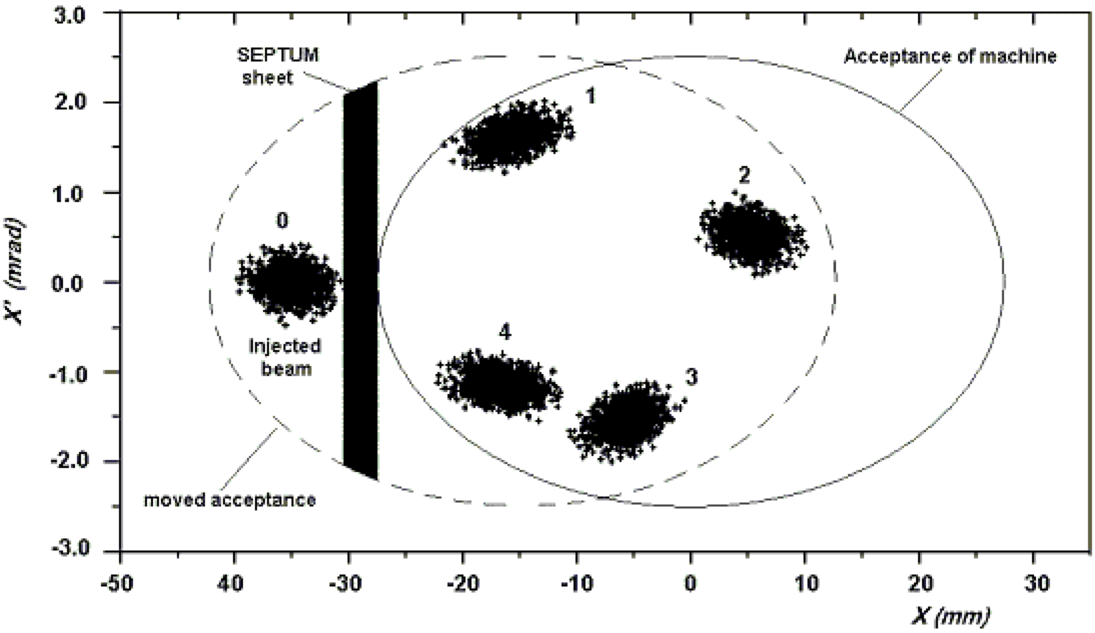

Figure 11.12: Injected beam and its movement in phase space at the injection point during the action of kickers.

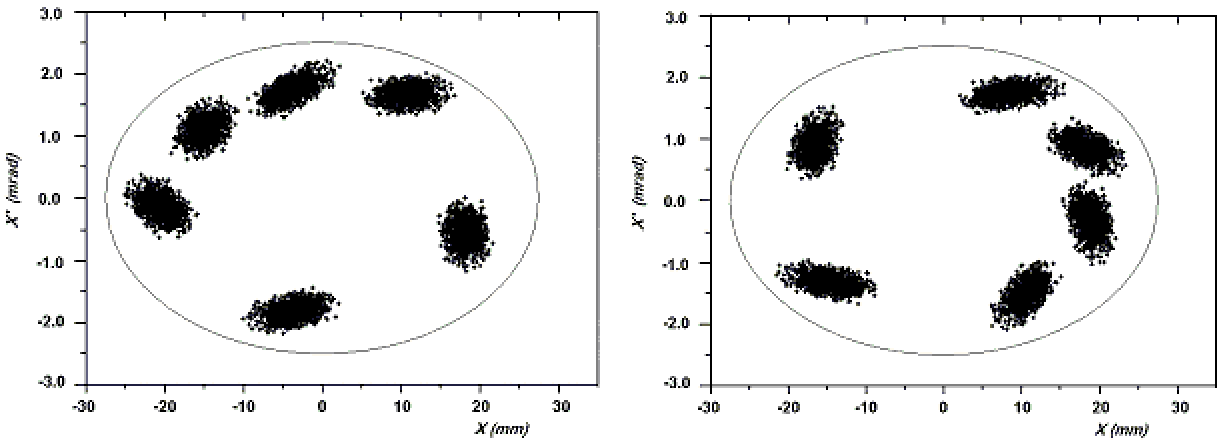

Figure 11.13: The particles of Figure (11.12) are survived in the physical aperture of the machine (kickers off)

According to the results of tracking, the position and the angle acceptances are large enough to accommodate all injected particles. Therefore, with characters of kickers according to table (11.11) and mentioned setting acceptable injection efficiency is expected, near *%100*.

Reference

[1] G. V. Egan-Krieger, D. Einfeld, W.- D. Klotz, H. Lehr, R. Maier, G. Mulhaupt, R. Richter and E. Weihreter, *"PERFORMANCE OF THE 800 MeV INJECTOR FOR THE BESSY I STORAGE RING"*.

[2] D. Einfeld, S. Hermle, E. Huttle, R. Rossmanith, R. Walther, "*THE INJECTION SCHEME FOR THE ANKA STORAGE RING*".

[3] Greg LeBlanc and Lars-Johan Lindgren, "*The Injection Scheme for the New 1.5 GeV Storage Ring, MAX-II"*.