Chapter 8

RADIO FREQUENCY SYSTEM

8.1 Introduction

In an electron storage ring the electrons lose energy by emitting synchrotron radiation when they are deflected in a magnetic field. It is the task of the RF system to restore this energy loss. In the storage ring SESAME and in a booster, where the electrons are accelerated up to the nominal energy of the storage ring, the RF system must also provide the power to accelerate the beam. Given that the revolution frequency of the electrons in a storage ring is in the radio frequency (RF) range, it is self evident that the energy restoration must also take place in this range. Thus, an RF system with enough power to achieve this purpose must be provided. In addition, the RF system has the function to provide stability to the beam and a large energy acceptance to get a long lifetime. As the length of the electron bunch depends on the characteristics of the RF voltage, one finds that the pulse length and the repetition rate of the emitted SL also depend on the RF frequency.

The transfer of power to the electrons is done by a high frequency electromagnetic field inside the cavities. At SESAME powers between 200 and 500 kW have to be transferred to the cavities. This field is generated in the klystron and transferred to the cavities through the wave guide system. A picture of RF-system of ANKA, where one klystron is feeding two cavities, is shown in Figure (8.1). A schematic overview of the whole RF-system is given in figure (8.2)

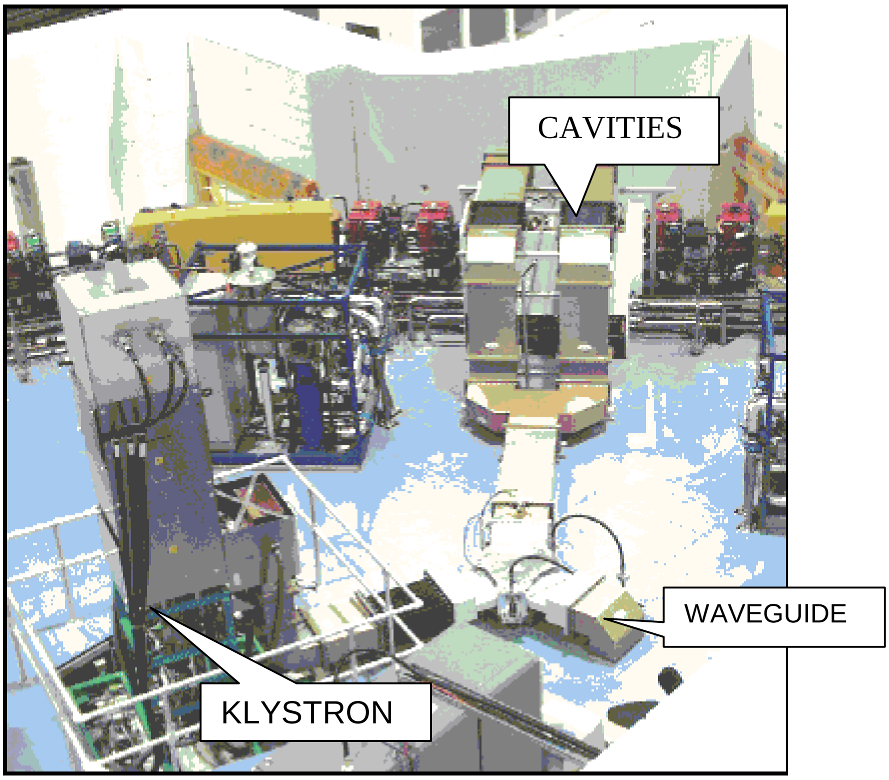

Figure 8.1: RF system of the ANKA storage ring. 250 kW microwave power is produced in the klystron. The power passes a circulator, which protects the klystron from the reflected power, split into two arms by a Magic T and coupled into two cavities.

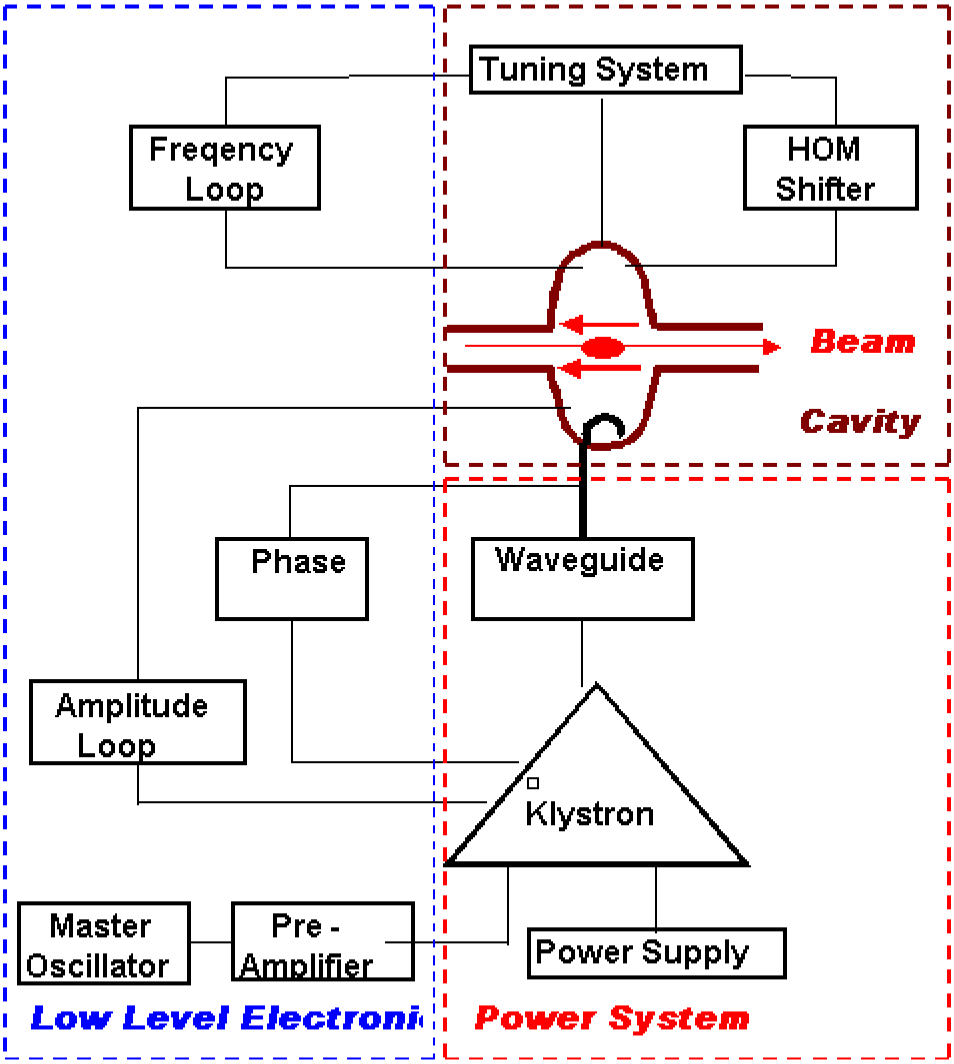

Figure 8.2: A schematic layout of the RF system for a synchrotron light source. The main groups of the system are the cavities, the power system and the low level electronics.

8.2 Components of the RF-System

8.2.1 Cavities

A cavity is a resonant structure, a metallic empty volume. Inside it, an electromagnetic field resonates at certain given frequencies that are determined by the geometry of the structure. The cavities have a cylindrical geometry, are made of high conductivity copper and they have some holes to allow the electrons to enter and exit the cavities in its way around the accelerator, to feed the RF power into the cavity, to install pick up coils for diagnostics and to install a vacuum pump. In figure (8.2) we can see one of the cavities of ANKA

One of the cavities of ANKA is shown in figure (8.2).

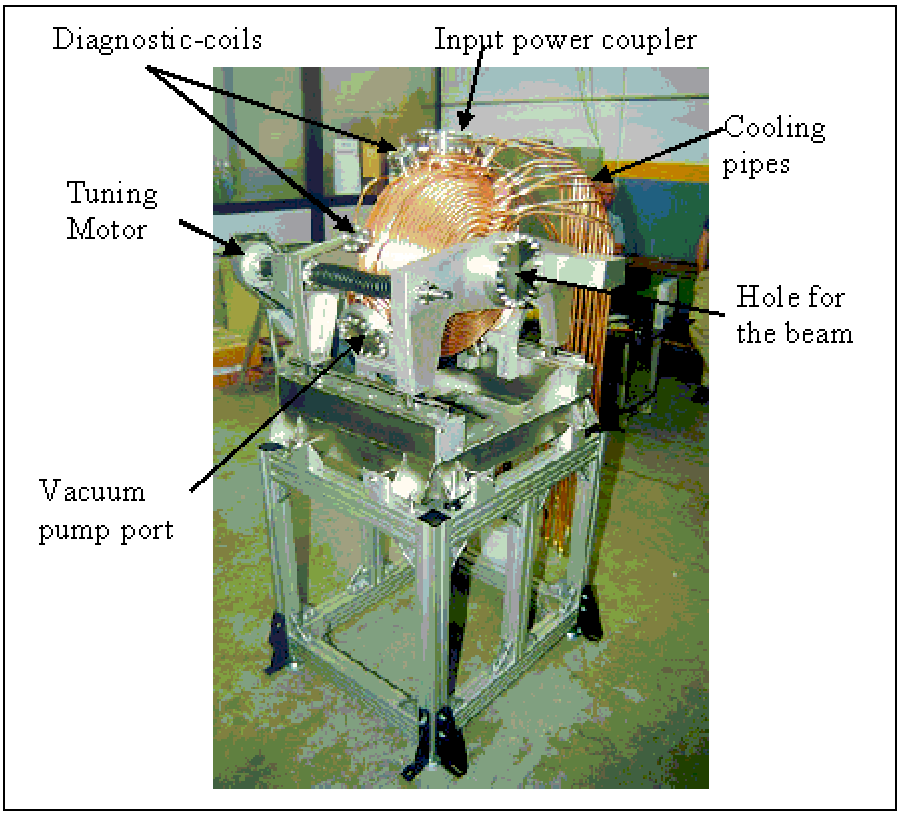

Figure 8.3: Cavity and their parts.

The fundamental mode of the cavity is a frequency of 499.567 MHz for reaching exactly a wavelength of 0.6 meter. The characteristics of the cavity are given by the shunt-impedance R_S and the quality factor Q (see table (8.1)). The acceleration of the beam happens with the fundamental mode.

Table 8.1: Fundamental mode parameters.

Frequency	MHz	499,7
Quality factor, Q		39000
Shunt impedance R_s	MΩ	3.4
Max. cavity voltage	kV	630
Max. cavity power	kW	60
Max coupler power	kW	120

Furthermore the cavities also have higher order modes, that reacts with the beam too and lead to the so called multi bunch instabilities. A well established method to cope with the multi bunch instabilities is the fine tuning of the high order modes of the cavities by accurate temperature regulation of the cavities. The ELETTRA cavities are optimal for this kind of operation and are in use in several labs around the world (ELETTRA; SLS; ANKA; INDUS; LNS) with great performance. For this reason we have chosen this kind of cavity for SESAME.A typical set of Longitudinal (TM) and Dipolar (TE) HOMs for this kind of cavity are given in table (8.2).

Table 8.2. High Order Modes.

Longitudinal HOMs			
Modes	**f [MHz]**	**R/Q [Ω]**	**Q**
L0	499.70		
L1	947.16	28.2	42381
L2	1057.96	1.1	36111
L3	1420.24	5.1	25763
L4	1512.24	4.7	26751
L5	1607.17	10.0	19550
L6	1874.88	0.5	16241
L7	1947.06	1.6	27342
L9	2122.36	7.9	30932

Dipolar HOMs			
Modes	**f [MHz]**	**R/Q [Ω]**	**Q**
D1	742.44	4.6	45125
D2	746.02	15.8	25000
D3	1113.12	13.0	37799
D4	1220.34	0.1	64201
D5	1241.79	4.5	7018
D6	1303.82	0.2	46042
D7	1559.50	0.0	33712
D9	1709.90	1.6	17522
D10	1715.25	0.5	43668

8.2.2 Klystron

A klystron is a high power RF amplifier with an amplification factor of about 10.000 times (a gain of 40 dB). It is driven by a 25 W solid state amplifier, that in turn has to be driven by a signal generator, which creates the 500 MHz primary signal.

In the gun of the klystron a high electron DC current is produced (50 kV, 8 A). This current is velocity modulated in the first cavity, which is exited by the driving power. After some drift the electron beam is grouped in pulses, then it enters three intermediate cavities that enhance the pulses, i.e. make them shorter and shorter. This pulsed stream induces a high field in the last cavity, out of which the high power is decoupled. An electromagnetic coil in all the length of the klystron (about 4 m) maintains the electrons focused in a tiny beam.

More than half of the DC power is transferred into microwave power. The remaining is dumped in a collector. Overall 400 kW of DC power is transformed to 250 kW of RF power, giving klystron efficiency about 60%.

The main parameters of the high voltage PS are given in the table (8.3).

Table 8.3: HVPS parameters.

Voltage	kV	52
Current	A	9
Stability	%	0.1
Ripple	%	0.4

8.2.3 Wave Guide System

The wave guide system connects the klystron to the cavities and is the path for the RF power. The power out of the klystron is passing a circulator, which is a three port wave guide system that isolates the klystron from the cavities. Any reflected power from the cavities is dumped in a water load installed in one of the ports. The power is then split into two by a Magic Tee (equally in amplitude and in phase) and transferred to the two cavities.

Bi-directional couplers are used to monitor forward and reflected power in the line. There are four: one after the klystron, one after the circulator and two before the two cavities. Phase shifter, in one arm going to one cavity adjusts the phase between the two cavities.

Two water loads, one in the third arm of the circulator and the other one in the fourth arm of the magic tee dissipate any reflected power. Transitions, bends and straight sections complete the line. All the components will be able to cope with the full power, 250 kW.

8.2.4 Low Level Electronics

Each one of the RF units has to be controlled with a complete low level system with which to adjust the frequency, amplitude and phase of the RF signal in the cavity. This is achieved with the so called tuning, amplitude and phase loops.

With the frequency loop, the cavity is maintained on resonance with respect to the master oscillator frequency. In fact it is slightly set out of resonance to get a higher stability. An amplitude loop for each RF plant is used to maintain the voltage in the cavities at the required value. The phase loop is used to keep the phase between the plants constant.

8.2.5 Principle of Operation

The cavity is connected over the wave guide system with the RF-amplifier, which feeds the high frequency power Pgen from the amplifier into the cavity (see figure (8.4)). This RF-power builds up an electric field, which accelerates the beam. The electron bunch within the cavity has a fixed relationship to the electric filed, given by the synchronous phase Phi(o). At the phase Phi(o) the electron is in average getting back the energy losses according to the emission of synchrotron light.

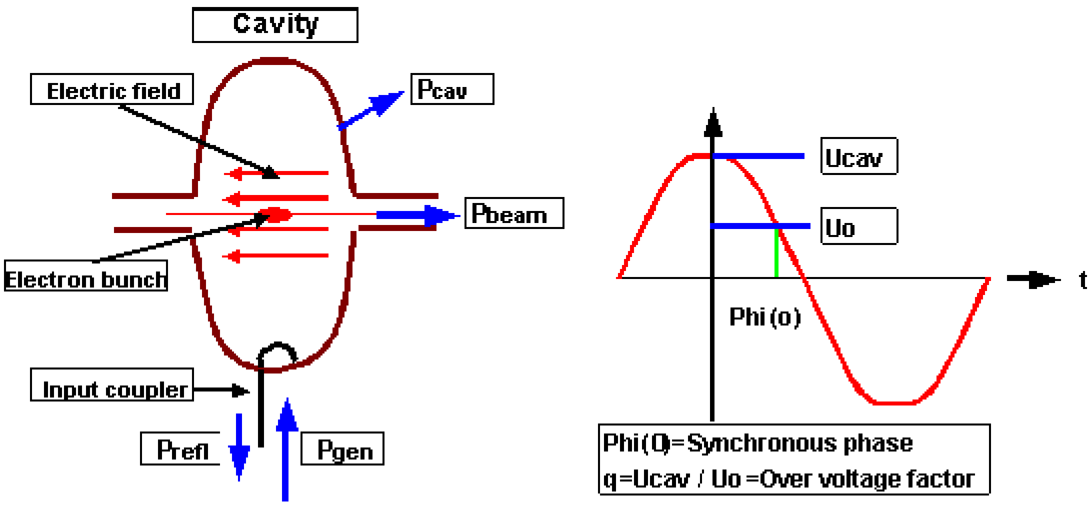

Figure 8.4: Schematic drawings for the explanations of used expressions for the RF system

The phase Phi(o) has to be at the falling slope of the electromagnetic field as shown in figure (8.4). The circumference of the accelerator must be an integer number multiplied with the wavelength of the RF-system. For SESAME it is intended to use a 500 MHZ system with an wavelength of exactly 0.6 meter. The inter number is called harmonic number.

According to the conversation of power the power, of the generator is equal to the beam-, cavity-, and reflected power:

$$P_{gen} = P_{cav} + P_{beam} + P_{refl} \tag{8.1}$$

$$P_{cav} = U_{cav}^{2} /(2R_{s}) \tag{8.2}$$

$$P_{beam} = I \cdot U_{o} \tag{8.3}$$

R_s is the shunt impedance of the cavity, I is the current of the stored electrons in the accelerator and U_o are the energy losses according to the synchrotron radiation by travelling through the bending magnets, wigglers and undulators or other insertion devices. These losses are given in equation (8.4) and (8.5).

$$U_{0,bend} = 88.5keV \cdot (E[GeV])^{4} / \rho[m] \tag{8.4}$$

$$U_{0,wigg} = 0.633keV \cdot L[m] \cdot (E[GeV])^{2} \cdot (B_{m}[T])^{2} \tag{8.5}$$

Where:

E : energy of the electrons
ρ : deflection radius in the dipole
I : electron current
B_m: peak field
L : length of insertion device

The reflected power is zero, if the coupling factor of the input coupler has a value of:

$$\beta_{opt} = 1 + (P_{beam} / Pcav) \tag{8.6}$$

Due to the fact that more than one cavity will be installed in such a machine, it is necessary to adjust the phase of the microwave inside each cavity in order that all of them act coherently accelerating the beam. The phase between the cavities is determined by the path length of the electron orbit between them, taking into account that the velocity of the electrons is the velocity of light.

8.3 RF System Parameters

8.3.1 Parameters of the stored Beam

The parameters of the stored beam like: bunch length, synchrotron frequency and energy acceptance are a function of the main parameters of the storage ring, which are summarized in the table (8.4).

Table 8.4: RF main parameters of SESAME.

Nominal energy, E_0	[GeV]	2.0	2.5
Circumference, C	[m]	124.8	124.8
Revolution frequency, f_0	[MHz]	2.402	2.402
RF frequency, f_{RF}	[MHz]	499.654	499,654
Harmonic number, h		208	208
Momentum compaction factor, α		0.00932	0.00932
Natural Emittance, ε	[nm rad]	15.5	24.3
Energy spread, σ_E		$0.92\ 10^{-3}$	$1.14\ 10^{-3}$

The parameters of the RF-system are determined by the power loss according to the synchrotron radiation and the required lifetime of the beam. With an average pressure of 2 nTorr and an energy acceptance of 1.2 % the so called gas life time and the Touschek life time are within the same order of 6 to 8 hours. The Touschek lifetime is affected by the energy acceptance of the machine which is determined by the energy acceptance ε_{HF} and the bunch length σ_l of the stored electron beam. For example by increasing the over voltage factor from 1.2 % to 1.5 % the lifetime would increase by a factor 2. This means the over voltage factor must be as high as possible. Both factors as well as the synchrotron frequency and the longitudinal tune value are determined by the over voltage factor q. The dependency is given in the following Equations (8.7) to (8.13) and the Figures (8.5) and (8.6).

$$U_0 = V_{cav} \cdot \sin(\Phi_s) = \frac{1}{q} \cdot V_{cav} \tag{8.7}$$

$$\varepsilon_{rf} = \sqrt{k_1 \cdot F(q)} \tag{8.8}$$

$$k_1 = \frac{U_0}{\pi \alpha h E_0} \tag{8.9}$$

$$F(q) = 2\left[\sqrt{q^2 - 1} - \arccos(1/q)\right] \tag{8.10}$$

$$k_2 = \frac{\alpha h}{\sqrt{2}} \cdot \sqrt{k_1} \tag{8.11}$$

$$\nu_s = k_2 \cdot \sqrt{q \cos(\Phi_s)} \tag{8.12}$$

$$\sigma_l = \frac{\alpha \sigma_E C}{2\pi} \cdot \frac{1}{\nu_s} \tag{8.13}$$

Where:

- U_0: Energy loss per turn
- Φ_s: Synchronous phase
- q : Over voltage factor
- α: Momentum compaction factor
- h: Harmonic number
- σ_E: Relative energy spread of the beam
- ν_l: Longitudinal tune value
- C: Circumference of the machine

The energy acceptance of SESAME as a function of the over voltage factor is given in the Figure (8.5).

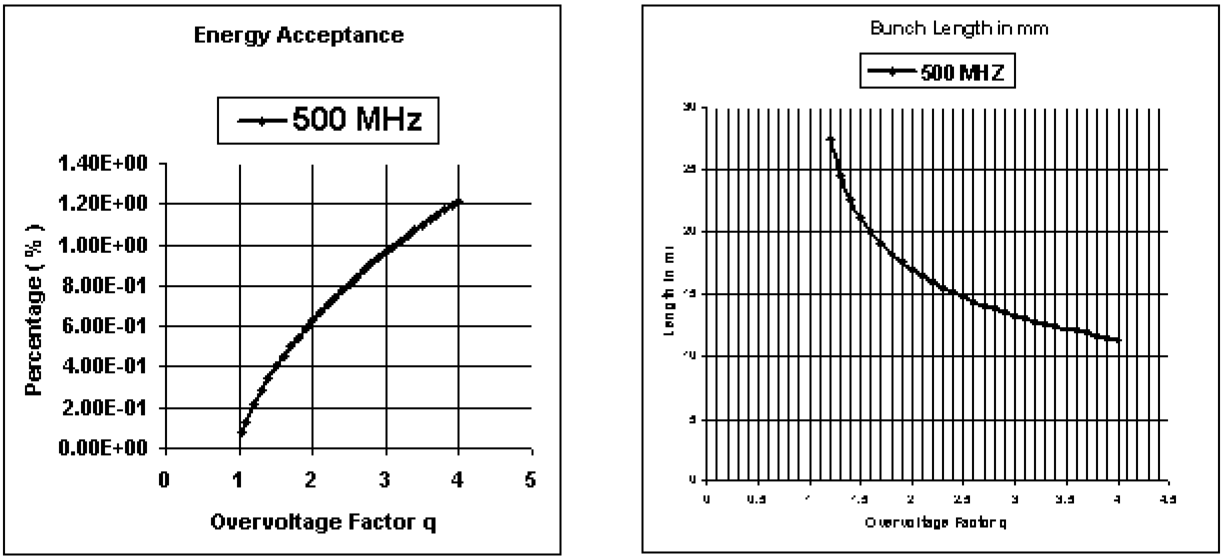

Figure 8.5: The RF-energy acceptance and the bunch length of SESAME as a function of the over voltage factor for an energy of 2 GeV

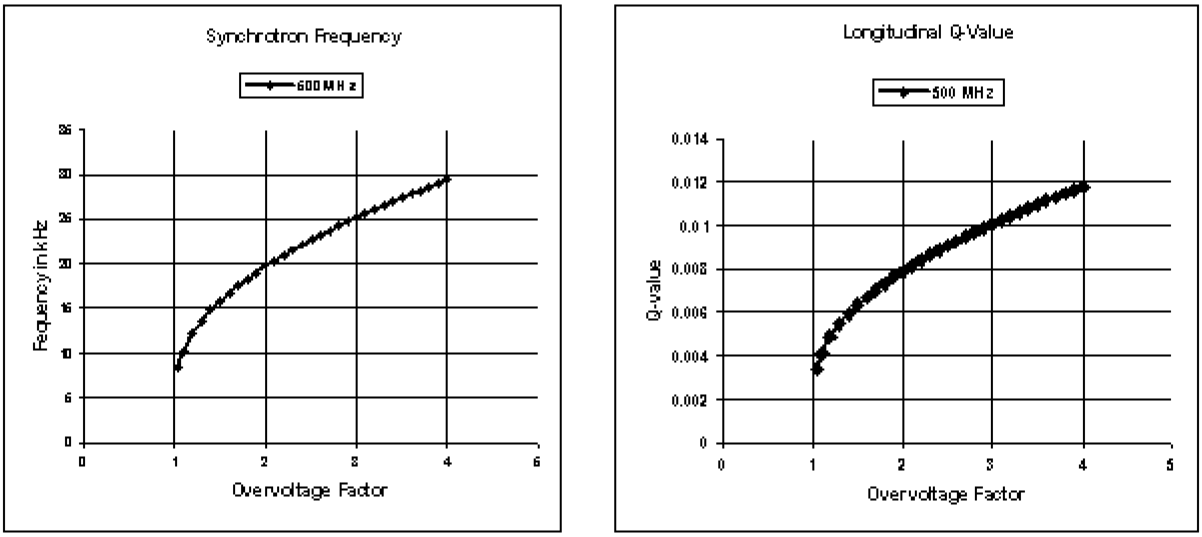

Figure 8.6: Synchrotron frequency and longitudinal working point of SESAME as a function of the over voltage factor for an energy of 2 GeV.

The energy acceptance of the machine is given by the closed orbit deviations introduced by energy changes:

$$X_{(\delta E/E)} = \eta \cdot (\delta E / E) \tag{8.14}$$

With a maximum deviation of 22.5 mm and a dispersion function of 0.5 meter, the highest energy acceptance is according to equation (8.14) is 4 %. With an energy acceptance of 1.2 % the Toushek life time is in the same order as the gas life time for an average pressure of 2 nTorr. To optimise the lifetime the average pressure should be smaller than 1 nTorr, which leads to gas life times of 30 hours and the lifetime in the storage ring would be Touschek limited. Hence the RF-system should provide a high cavity voltage instead of storing a large current. For the first layout of the RF-system it is assumed to get an over voltage factor between 4 to 5.

8.3.2 Parameters of the Power System

The power loss of the electrons circulating in a storage ring depends on the type of dipole magnets and the number, type of insertion devices installed, and the required life time. The synchrotron radiation losses and the needed power due to insertion devices (IDs) have been estimated for 2 and and 2.5 GeV, for different number of wigglers and different number of cavities. For all this calculations the over voltage factor was fixed to 4 in order to get an sufficient energy acceptance. The wiggler has a maximum field of 2.5 Tesla, a period length of 120 mm and a length of 2.4 meter. The results are compiled in the tables (8.5) and (8.6). The intention is to install in the storage ring sets of two cavities, as given in figure (8.7).

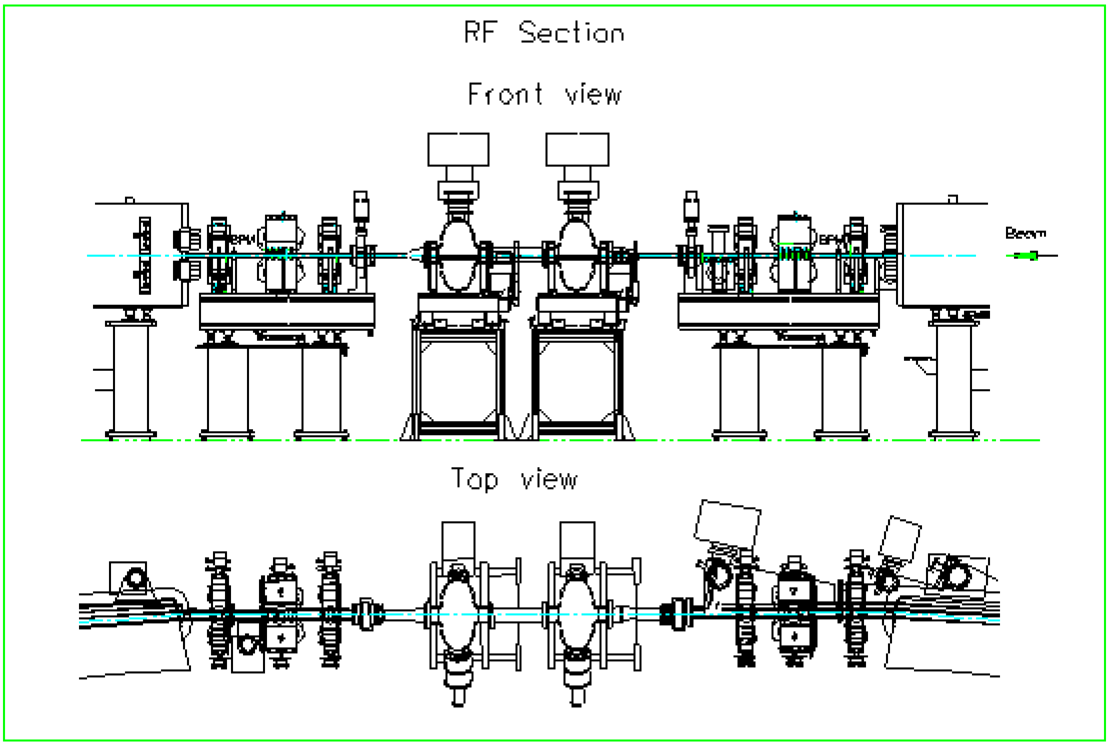

Figure 8.7: Arrangement of 2 cavities in the long straight section of SESAME.

At the beginning SESAME will start with energy of 2 GeV. The limits of the cavities are given by (see table (8.1)) : U_{cav} = 630 kV, P_{cav} = 60 kW and P_{input} = 120 kW. This limits are reached according to table (8.5) with 2 wigglers and a stored beam of 400 mA. The energy loss per turn (U_0) reaches with 4 wigglers a value of 390 keV. With an over voltage factor of 4 and two cavities the required cavity voltage is 780 keV, what is out of the specifications of the cavity. Hence the installation of 4 wigglers at energy of 2 GeV requires 4 cavities. According to table (8.5) it is possible to run SESAME up to 2.2 GeV with a current of 300 mA and the installation of 6 wigglers.

The corresponding calculations for an energy of 2.5 GeV are compiled in table (8.6). With 4 cavities it is only possible to run the machine without any wigglers. Already the installation of 2 wigglers at 2.5 GeV exceeds the maximum available voltage in the 4 cavities. With 6 cavities it is possible to operate 6 wigglers with a current of up to 350 mA.

Table 8.5: Voltages and power for the RF-system of SESAME for energy of 2 GeV.

Energy	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0		2.2	GeV
Beam current	2000	4000	2000	4000	1650	2000	4000	4000		3000	mA
Numb . of wigglers	0	0	2	2	4	4	4	6		6	
Energy loss	2380	2380	3137	3137	3900	3900	3900	4660		6240	keV/turn
Numb . of cavities	2	2	2	2	2	4	4	4		4	
Cavity voltage	4850	4770	6314	6320	7790	3980	3950	4680		6330	kV
Cavity power	347	335	586	588	983	233	229	322		590	kW
Beam power / cavity	238	475	314	627	321	195	390	466		468	kW
Total power / cavity	585	810	900	1215	1215	428	619	788		1058	kW
Total r.f.-power	1170	1620	1800	2430	2430	1710	2480	3152		4232	kW
Amplifier power	1300	1800	2000	2700	2700	1900	2750	3500		4700	kW

Table 8.6: Voltages and power for the RF-system of SESAME for an energy of 2.5 GeV.

Energy	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	GeV
Beam current	200.0	400.0	200.0	200.0	400.0	200.0	400.0	350.0	mA
Numb. of wigglers	0	0	2	2	2	4	4	6	
Energy loss	580.0	580.0	700.0	700.0	700.0	818.0	818.0	937.0	keV/turn
Numb. of cavities	4	4	4	6	6	6	6	6	
Cavity voltage	581.0	583.0	705.0	468.0	468.0	547.0	545.0	627.0	kV
Cavity power	50.0	50.0	73.0	32.2	32.2	44.0	43.7	57.9	kW
Beam power / cavity	29.0	58.0	35.0	23.3	46.6	27.3	54.5	54.6	kW
Total power / cavity	79.0	108.0	105.8	55.5	78.8	71.3	98.2	112.5	kW
Total r.f.-power	315.0	432.0	432.0	333.0	472.8	427.8	589.2	675.0	kW
Amplifier power	350.0	480.0	480.0	370.0	525.0	475.0	655.0	750.0	kW

The RF-system at SESAME will be build up in the following steps:

1. Installation of 2 cavities with a power of up to 250 kW in order to operate SESAME at 2 GeV with 2 wigglers. A schematic layout of this "RF-unit" is given in figure (8.8)
2. Installation of an other RF-unit with a power of up to 250 kW. Overall a RF-power of up to 500 kW is now available. It is possible to run SESAME at 2.2 GeV with up to 6 wigglers and a current of 300 mA.
3. Installation of an other RF-unit with a power of up to 250 kW. Overall a RF-power of up to 750 kW is now available. It is possible to run SESAME at 2.5 GeV with up to 6 wigglers and a current of 350 mA.

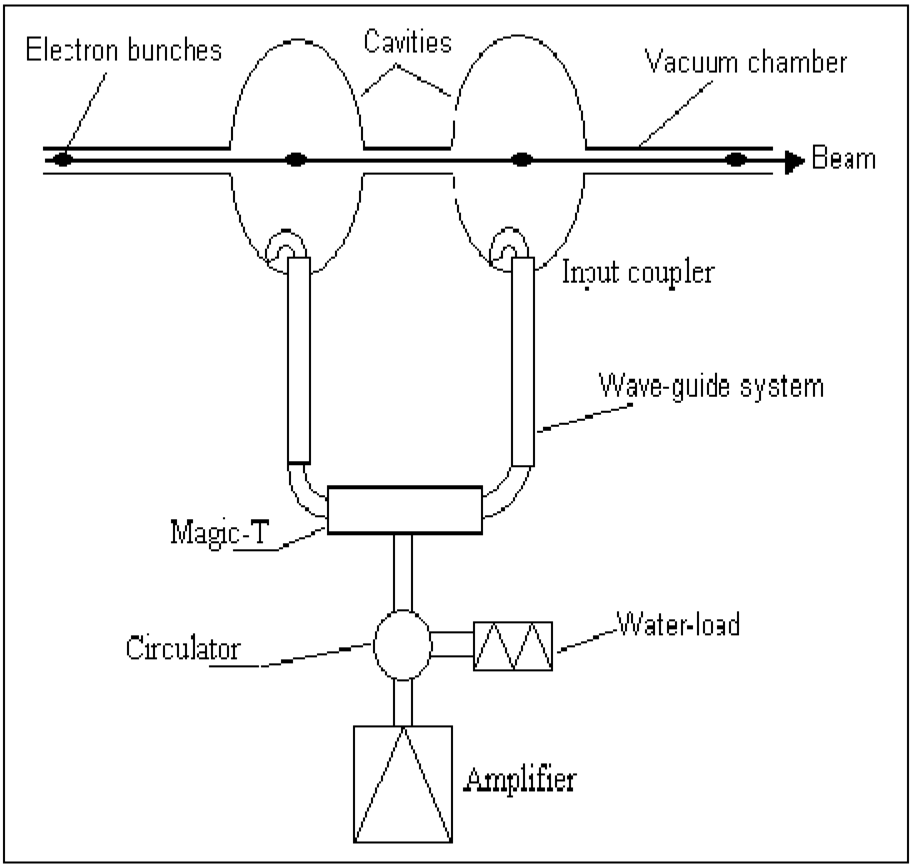

Figure 8.8: RF-power assembly layout at the first stage with 2 cavities and an power of the amplifier of up to 250 kW in order to operate SESAME at an energy of 2 GeV with 2 wigglers or 2.5 GeV without any wigglers. This is the "RF-unit" of SESAME

8.4 Low Level Electronics

Each one of the RF units has to be controlled with a complete low-level system with which to adjust the frequency, amplitude and phase of the RF signal in the cavity. This is achieved with the so-called tuning, amplitude and phase loops.

8.4.1 Amplitude Loop

The amplitude loop controls the voltage of the two cavities counteracting the beam loading effect at any beam current. In order to have a stable beam, the amplitude of the RF voltage must be maintained within 1% of the set value. The amplitude loop is used to achieve this stability by regulation of the power from the generator via a variable attenuator in the low power part, as shown in figure (8.9):

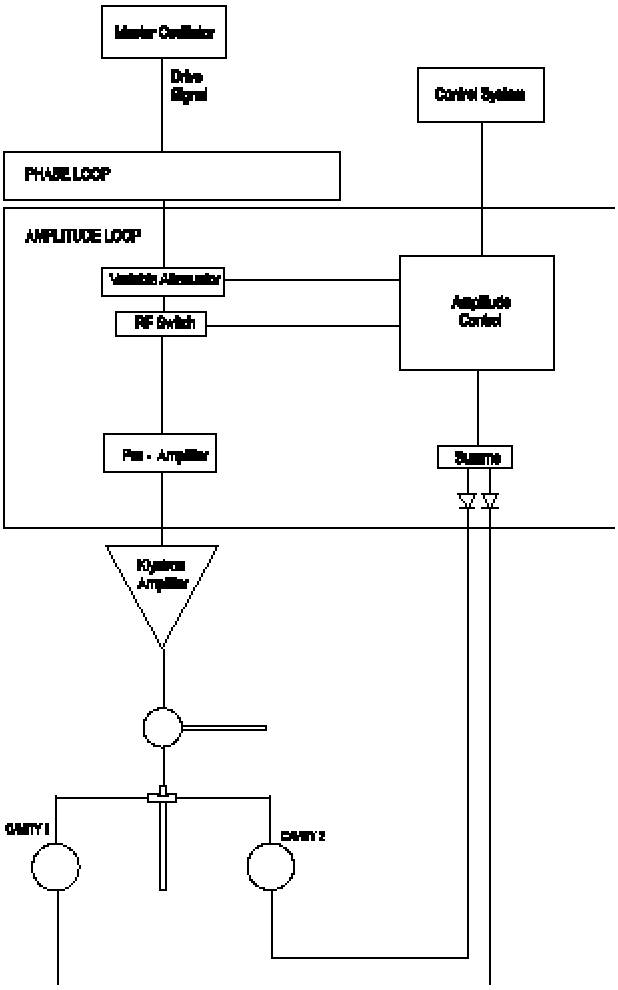

Figure 8.9: Amplitude loop scheme.

8.4.2 Phase Loop

With regards to the phase, as there are more than one unit, it is necessary that the power transmitted to the beam by each cavity pair acts coherently. Therefore, the power arriving to each cavity pair must have the correct phase relative to that arriving at the others. Naturally, this value depends on the exact position of the cavities around the machine. The setting of the appropriate phases is achieved with a mechanical phase shifter.

In all circumstances the input power must have phase stability better than 0.5 degrees. This stability is ensured with the aid of a phase loop, which compensates phase changes induced by the components placed between the mechanical phase shifter and the cavity (eg. the klystron, the circulator, the electronics, etc) with an electronic phase shifter. See figure (8.10).

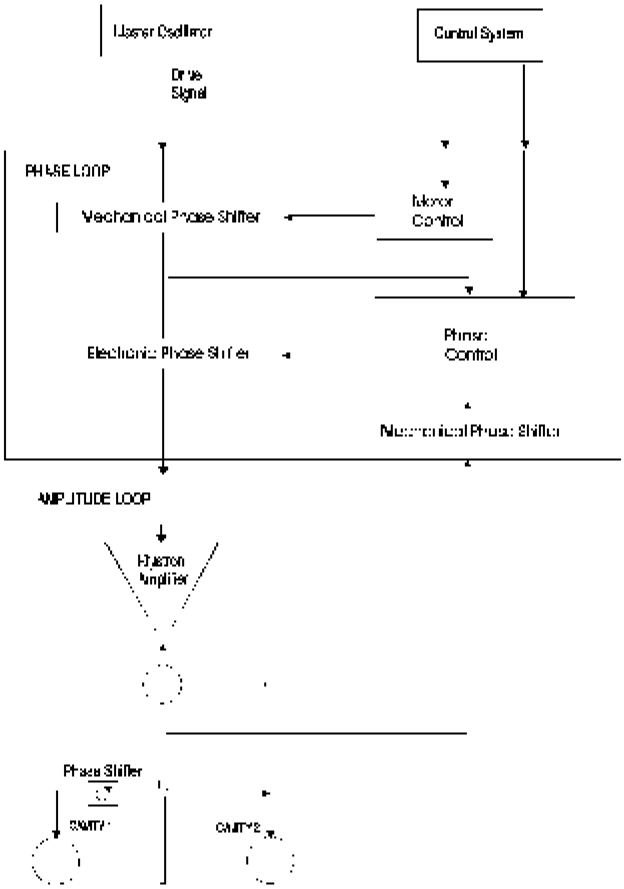

Figure 8.10: Phase loop scheme.

The phase between the two cavities of the same unit are geometrically fixed by the mechanical arrangement, but it can be fine adjusted by a waveguide phase shifter.

8.4.3 Tuning Loop

With regards to the frequency, the reference is given by a high precision 500 MHz signal generator, which in all likelihood constitutes the clock for the entire machine. The pre-amplifier providing the reference signal to the klystron is driven by this clock signal. However, because the resonant frequency of the cavity depends on its geometry, it will change by dilatation due to temperature changes or by deformation due to differential pressures. Thus, to maintain the cavity tuned to the reference frequency, it is necessary to install a tuner in the cavity, which is controlled by a so called frequency loop, figure (8.11).

The beam loading on the RF cavity depends on the average beam intensity, which decays during a fill because of the losses due to the finite lifetime. Compensation for this change in the beam loading is also achieved with the frequency loop. Finally, the frequency loop, in conjunction with the phase loop described above, is also used to compensate for the sudden changes in beam loading which occur during injection.

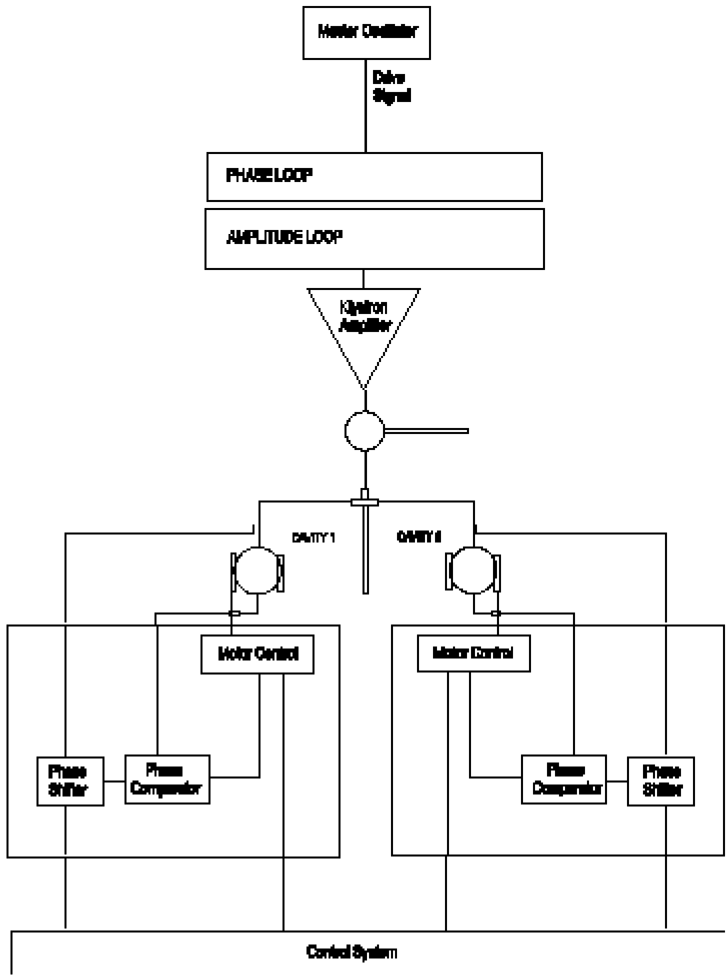

Figure 8.11: Tuning loop scheme.