8. Radiofrequency 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, that is, to provide long lifetimes by means of a large enough energy acceptance. 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. This field is generated in the klystron and transferred to the cavities through the wave guide system. A picture of the system at ANKA is shown in Figure (8.1).

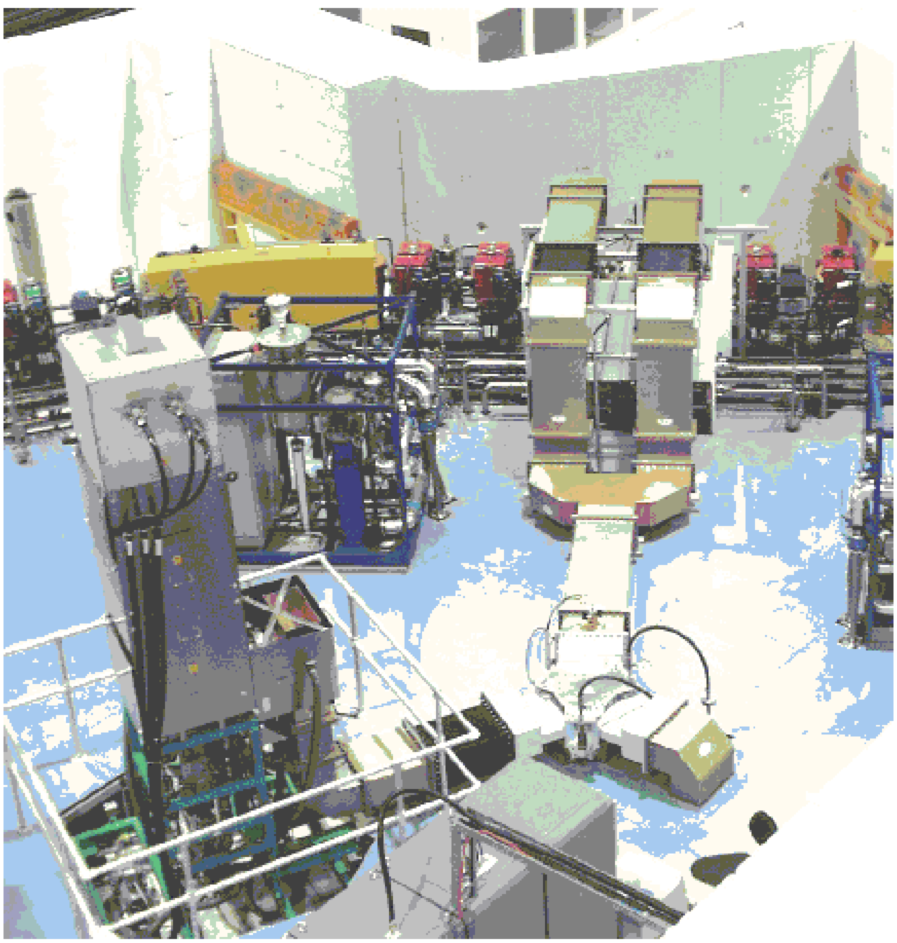

Figure 8.1: RF system of the ANKA storage ring. 250 kW microwave power is produced in the klystron. The power passes a circulator, which protects the klystron from the reflected power, split into two arms by a Magic T and coupled into two cavities.

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.

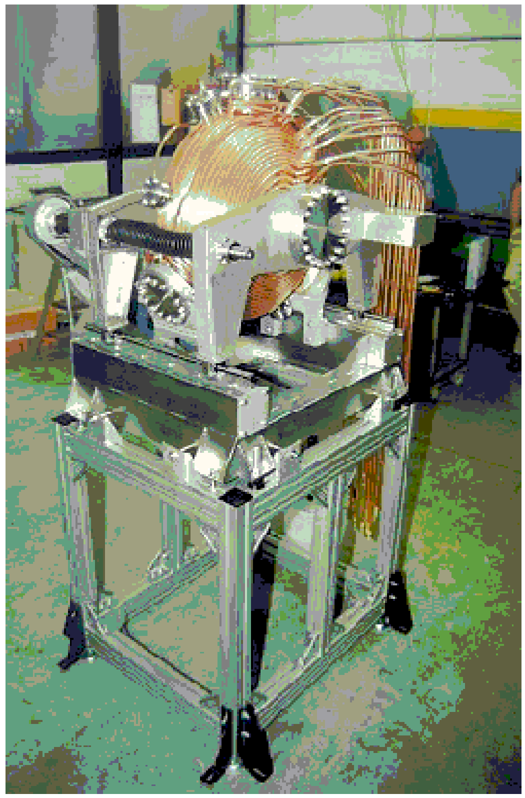

Figure 8.2: Cavity and their parts

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.

Fundamental mode: The main parameters of the fundamental mode of the cavity are given in Table (8.1).

Table 8.1: Fundamental mode parameters

Frequency	**[MHz]**	**499,7**
Quality factor, Q		40000
Shunt impedance R_s	$[M\Omega]$	3.4

High order modes: 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 Waveguide System

The waveguide 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 electrons circulating in an storage ring or booster receive acceleration when they cross the cavities. The acceleration is given by the electromagnetic field stored in the cavities.

For this acceleration to become effective the structure of the beam should fit with the frequency of the electromagnetic field inside the cavities, i.e. the beam should be bunched in pulses, the distance between the pulses should be the same as the wavelength of the electromagnetic field. For SESAME, as for most of the existing accelerator, this is in the range of the microwave: 500 MHz frequency or 0.6 m wavelength.

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. See Figure (8.3).

In addition, to provide stability to the beam, the bunched pulses should see the falling slope of the electromagnetic field. So, if the minimum required voltage is given by:

$$Uo[kV] = P[kW] / I[A] \qquad (8.1)$$

Where P is the power lost by the electrons and I the current of the electron beam (see next paragraph), the required voltage in the cavities should be a factor q higher, this factor is know as over voltage factor:

$$V_{cav}[kV] = qUo[kV] \qquad (8.2)$$

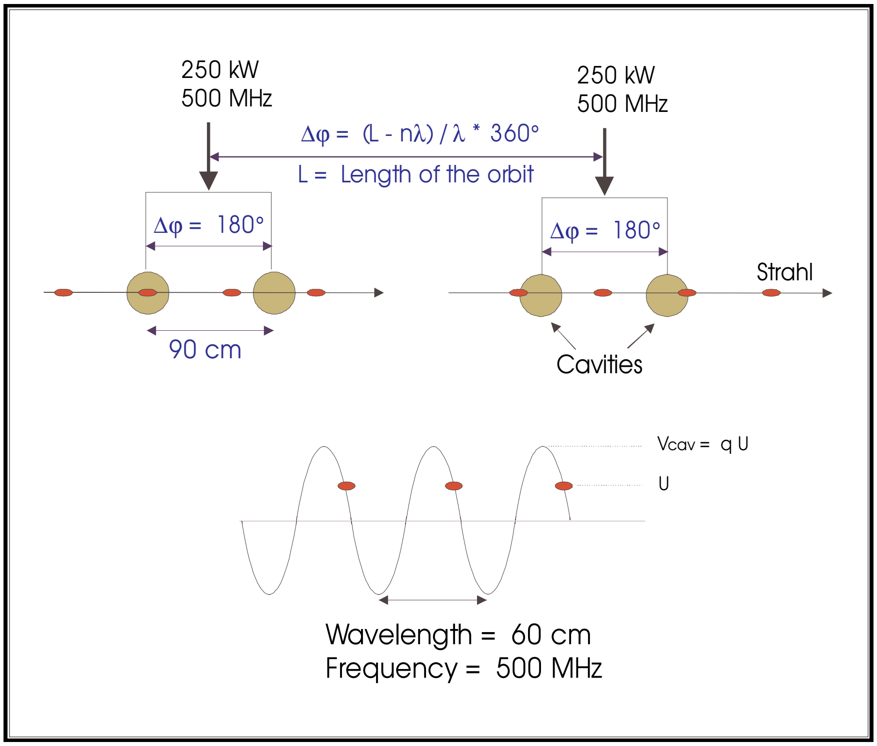

Figure 8.3: In a storage ring particles coming in pulses are accelerated by microwaves fed into cavities. The distance between the pulses must be equal to the wavelength of the microwave. The phase in the cavities must be adjusted.

The value for q is usually around 2 to 4.

The power loss of the electrons circulating in a storage ring depends on the type of dipole magnets and the number and type of insertion devices installed. It is calculated by the Equations (8.3) and (8.4) respectively for dipoles and insertion devices.

$$P_{bend}[kW] = U_{0,bend}[kV] I[A] = 88.5 (E[GeV])^4 I[A] / r[m] \qquad (8.3)$$

$$P_{wigg}[kW] = U_{0,wigg}[kV] I[A] = 0.6331 [m] I[A] (E[GeV])^2 (B_m[T])^2 \qquad (8.4)$$

where:

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

The dissipated power in the cavities is given by the formula:

$$P_{cav}[W] = V_{cav}[kV]^2 / (2R[M\Omega]) \qquad (8.5)$$

where V_{cav} is the peak voltage and R is the cavity shunt impedance which is equal to 3.4 MΩ.

8.3 RF System Parameters

The main parameters of the storage ring, which determine the layout of the RF-system are given in the Table (8.4).

Table 8.4: RF main parameters of SESAME

Nominal energy, E_0	**[GeV]**	**2.0**
Circumference, C	[m]	120.0
Revolution frequency, f_0	[MHz]	2.5
RF frequency, f_{RF}	[MHz]	499,974
Harmonic number, h		200
Momentum compaction factor, α		0.0082
Natural Emittance, ε	[nm rad]	16.9
Energy spread, σ_E		$0.9\ 10^{-3}$

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 life time 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 (8.6) to (8.12) and the Figures (8.4) and (8.5).

$$U_0 = V_{cav} \cdot \sin(\Phi_s) = \frac{1}{q} \cdot V_{cav} \tag{8.6}$$

$$\varepsilon_{rf} = \sqrt{k_1 \cdot F(q)} \tag{8.7}$$

$$k_1 = \frac{U_0}{\pi \alpha h E_0} \tag{8.8}$$

$$F(q) = 2\left[\sqrt{q^2 - 1} - \arccos(1/q)\right] \tag{8.9}$$

$$k_2 = \frac{\alpha h}{\sqrt{2}} \cdot \sqrt{k_1} \tag{8.10}$$

$$\nu_s = k_2 \cdot \sqrt{q \cos(\Phi_s)} \tag{8.11}$$

$$\sigma_l = \frac{\alpha \sigma_E C}{2\pi} \cdot \frac{1}{\nu_s} \tag{8.12}$$

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 (8.4).

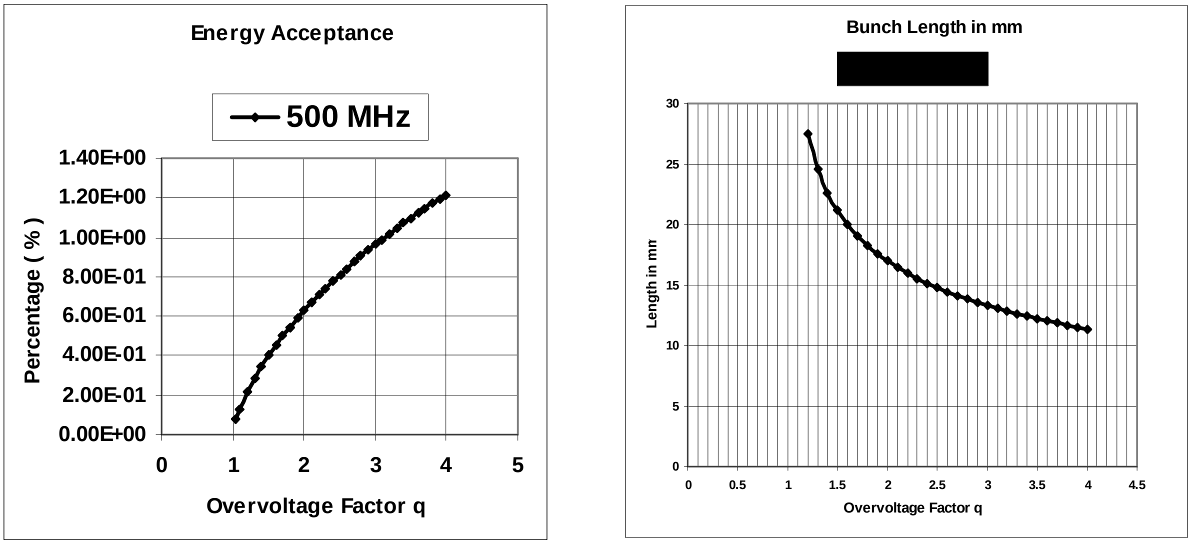

Figure 8.4: The RF-energy acceptance and the bunch length of SESAME as a function of the over voltage factor

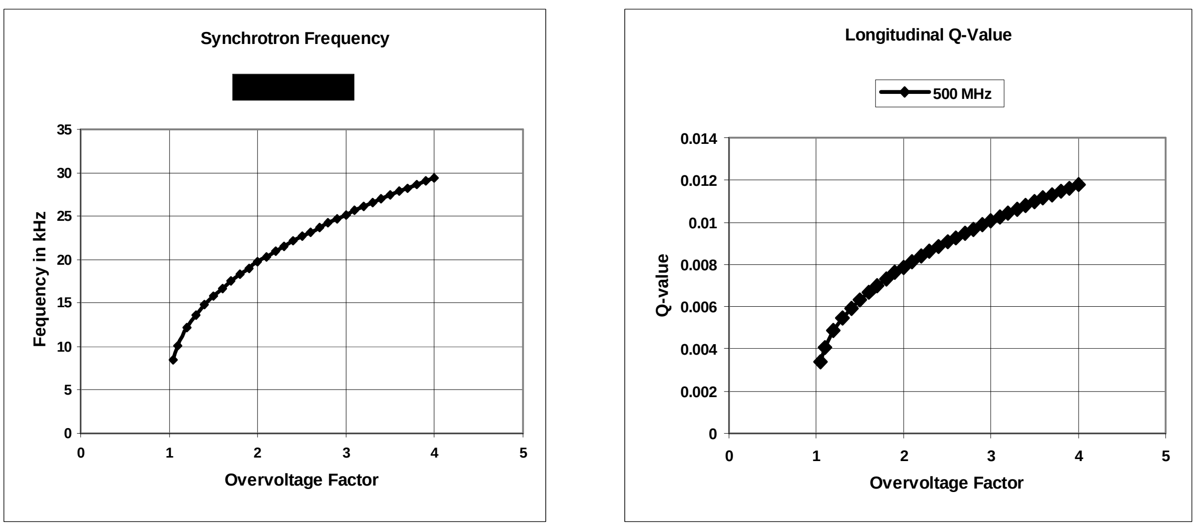

Figure 8.5: Synchrotron frequency and longitudinal working point of SESAME as a function of the over voltage factor

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

$$X_{(\delta E/E)} = \eta \cdot (\delta E / E) \qquad (8.13)$$

With a maximum deviation of 22.5 mm and a dispersion function of 0.5 meter, the highest energy acceptance 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 optimize 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.

Table 8.5: Voltages and power for the RF-system

		0 IDs	2 IDs	4IDs	8 IDs
Losses in bending magnets	[keV/turn]	286.5	286.5	286.5	286.5
Losses in Ids	[keV/turn]	0.0	53.2	106.4	212.8
Total loss	[keV/turn]	286.5	339.7	392.9	499.3
Beam current	[mA]	400	300	200	400
Beam power	[kW]	171.9	152.9	117.9	249.7
Overvoltage factor		4	4	4	4
Total cavity voltage	KV	1146	1359	1572	1997
2 Cavities					
Cavity voltage	KV	573	680	786	
Disssipated power per cavity	KW	48.3	66.0	90.0	
Beam power per cavity	KW	57.3	51.0	39.3	
Total power per cavity	KW	105.6	117.0	129.3	
4 Cavities					
Cavity voltage	KV			393	500
Dissipated power per cavity	KW			22.7	36.8
Beam power per cavity	KW			19.6	50
Total power per cavity	KW			42.3	86.8

The power loss of the electrons circulating in a storage ring depends on the type of dipole magnets and the number and type of insertion devices installed. The synchrotron radiation losses and the needed power due to insertion devices (IDs) have been estimated for four cases: 600 mA @ 0 IDs, 450 mA @ 2 IDs, 300 mA @ 4 IDs and 500mA and 8 IDs. The total loss and therefore the required RF power are given in the Table (8.5).

With a 250 kW klystron and feeding two cavities the maximum power coupled into the cavities is roughly 112.5 kW including 10% losses in the wave guide system. According to Table (8.4) it is possible to store with one 250 kW RF-system a current of 400 mA without any insertion devices and a current of 300 mA with 2 times 2.25 wigglers as insertion devices. This would be the first setting of the RF-system, see Figure (8.5).

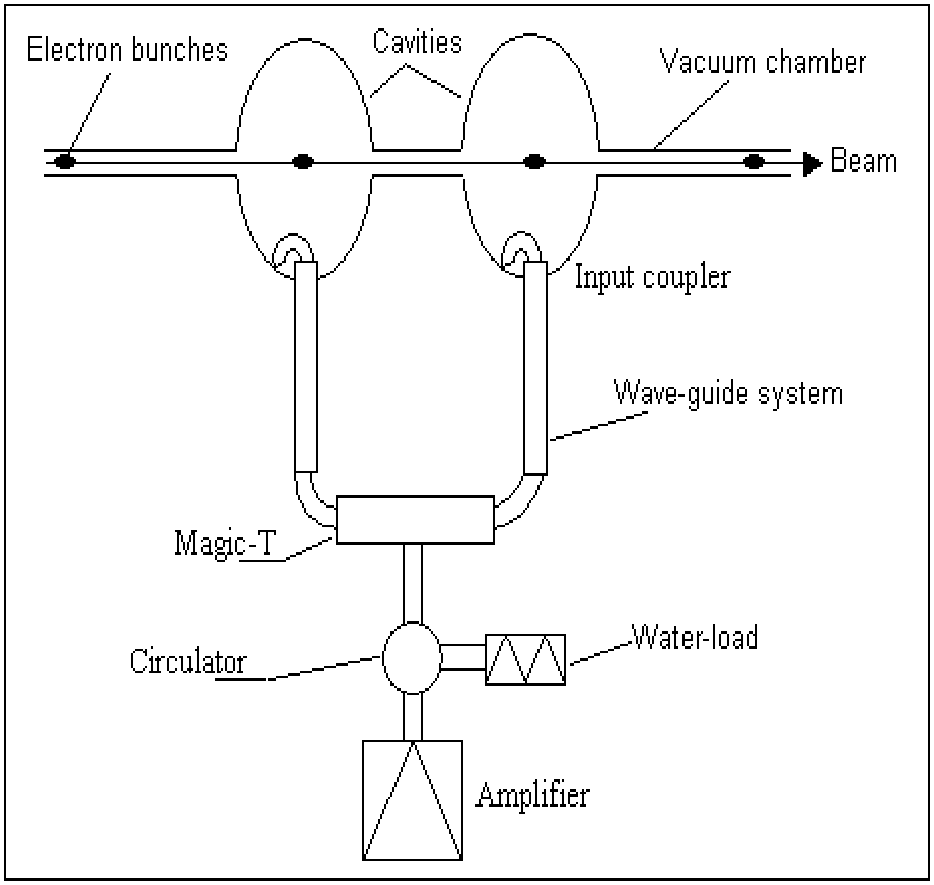

Figure 8.6: RF-power assembly layout at the first stage

With 4 insertion devices the maximum current would be 100 mA with an acceptable life time or 200 mA with a reduced life time.

With the introduction of more than two wigglers one has to upgrade the RF-system by another 250kW station. In this case the current or the lifetime can be increased according to the requirements of the user.

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 (8.7):

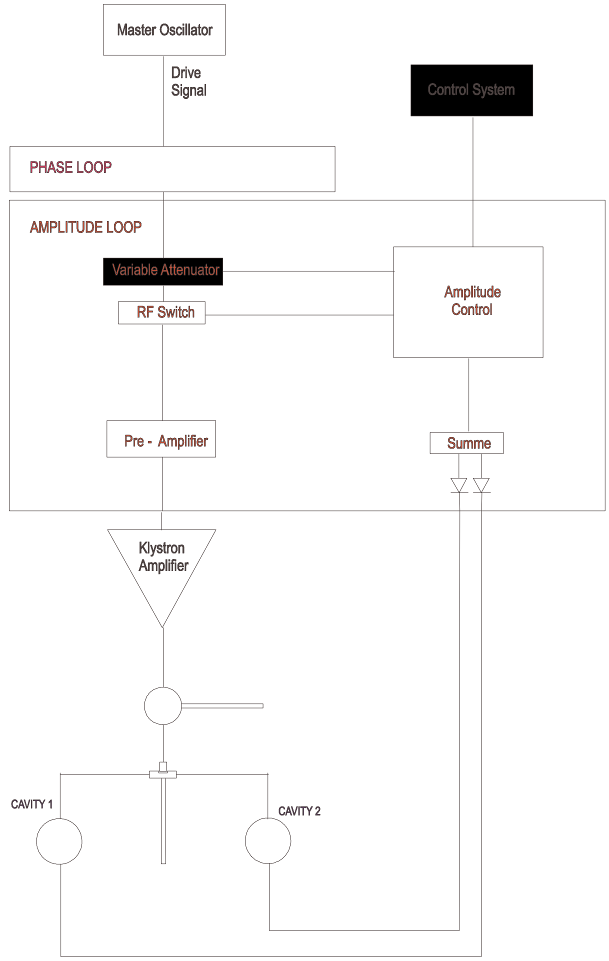

Figure 8.7: Amplitude loop scheme

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 (8.8).

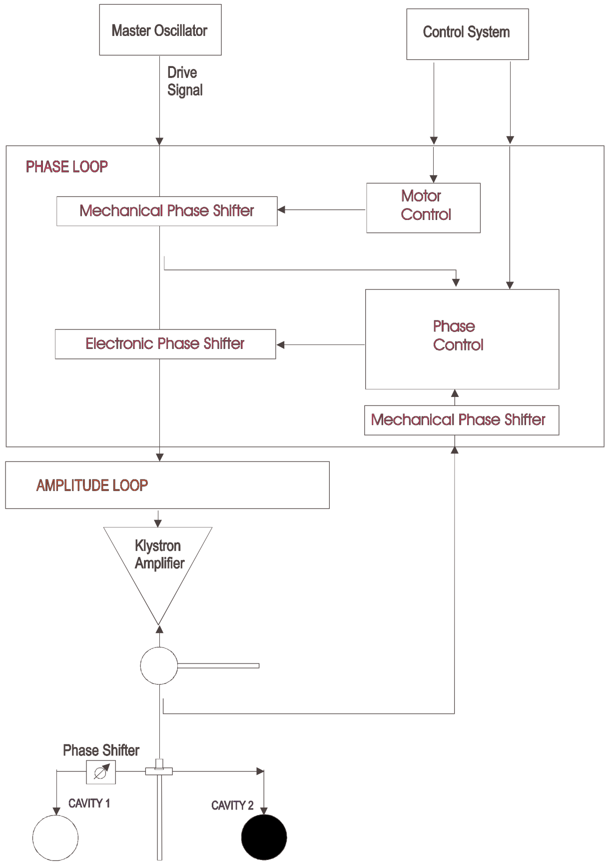

Figure 8.8: Phase loop scheme

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 (8.9).

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.

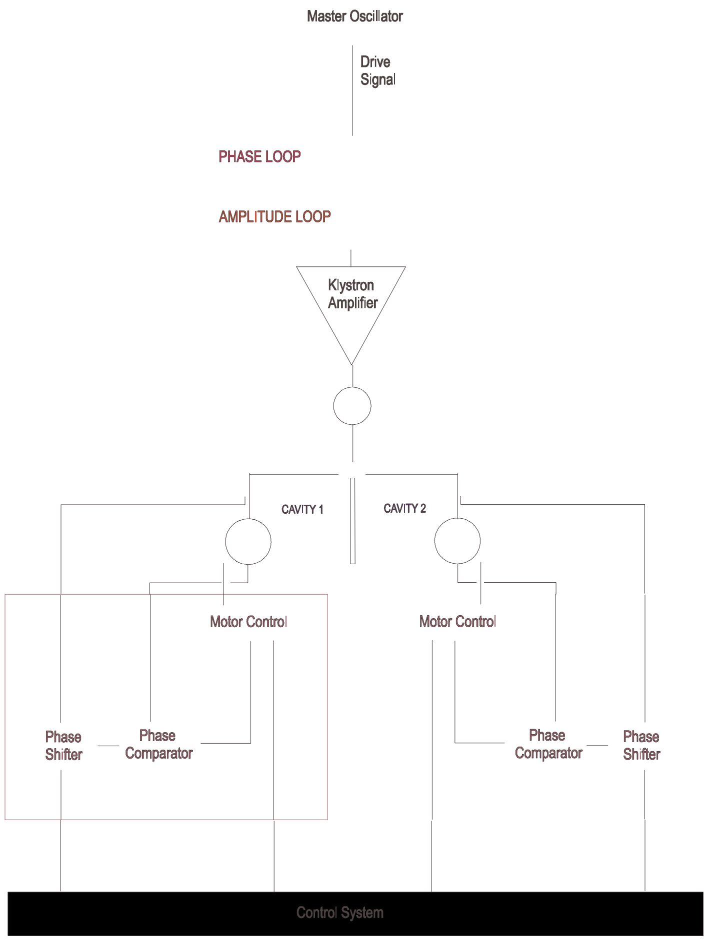

Figure 8.9: Tuning loop scheme