3.3 Radio-Frequency System

As the electrons go around in the storage ring they radiate energy in the form of synchrotron radiation at bends and insertion devices. In addition, particles lose energy due to their interaction with surrounding vacuum chamber walls of finite conductivity and changes in the chamber geometry. This energy needs to be restored to the electrons so that they can maintain a steady orbit in the storage ring. The purpose of the RF system is to provide sufficient accelerating voltage to make up for these energy losses. The voltage of the RF system should have enough high acceptances for stable particle energy oscillations thus providing a long beam lifetime.

The energy loss of a single particle to synchrotron radiation per turn in the storage ring is given by

$$U_0[KeV] = 88.5\frac{E^4[GeV]}{\rho[m]} \tag{3.3.1}$$

where E is the electron energy, and ρ is the bend radius. For 3 GeV operation, the energy loss of the electrons per turn in the CANDLE storage ring is U_0 = 0.97 MeV. This defines the minimum required voltage in the RF cavities if the beam is to remain in equilibrium orbit. However, because the radiation is emitted in discrete quanta, the particles undergo longitudinal (synchrotron) oscillations. Other factors, which contribute to longitudinal instabilities of the electrons, are Coulomb collisions, and collisions with residual gas as explained in section 3.5, Beam Lifetime. To compensate for these effects and to achieve phase stability of longitudinal oscillations, the total peak voltage V_{RF} provided by the cavities needs to be greater than U_0. The ratio of maximum possible electron energy gain per turn (when the electron is on the crest of the RF wave) eV_{RF} to the energy loss per turn U_0 is known as the over-voltage factor. The over-voltage factor should be more than 2 to maintain good beam lifetime. Fig.3.3.1 shows the particle trajectories in the longitudinal phase space of CANDLE when the total RF voltage of the ring is 3.3 MV. The equilibrium synchronous phase ϕ_s is defined as the phase of the electron beam with respect to the RF accelerating wave when the energy gain by the particle (eV_{RF} sin ϕ_s) is equal to the energy lost to synchrotron radiation (U_0) per turn, meaning the synchronous phase should be chosen such that $U_0 = eV_{RF}$ sin ϕ_s. The convention used for phase is that $\phi_s = 0$ at the zero crossing and the rise of the RF voltage. The stable boarding separatrix in the figure defines the energy acceptance of the stored particles that is at the level of 2.4%.

The power transferred from the RF to the electron beam is given by $P_b(kW) = U_0 I_b$, where I_b is the circulating current in Amps. In addition there is also the power dissipated in the cavity walls given by

$$P_{wall} = \frac{V_{RF}^2}{2n_c R_{sh}} \tag{3.3.2}$$

where n_c is the number of cavities, R_{sh} is the shunt impedance of a single cavity. Thus, the total power to be replenished is $P = P_b + P_{wall}$. The storage ring will have 6 RF cavities for replenishing the electron beam energy losses.

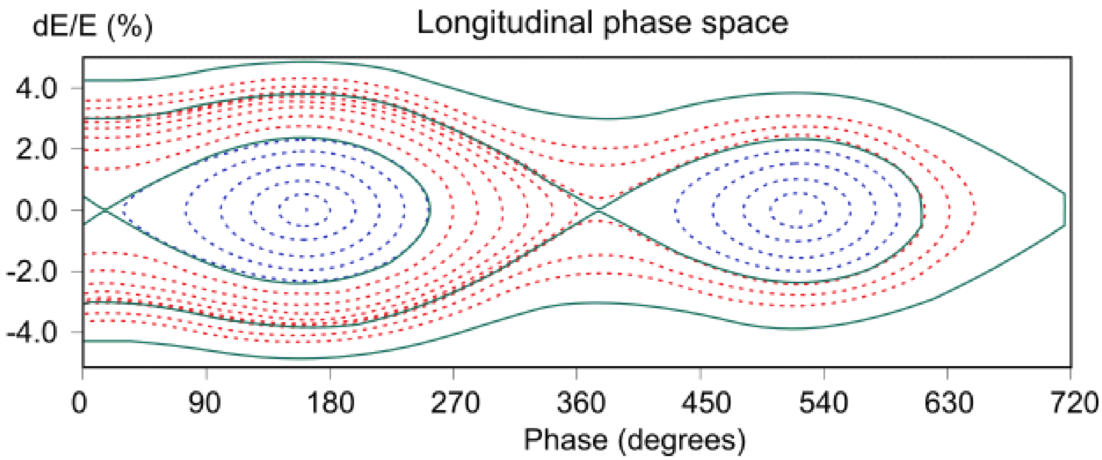

Fig. 3.3.1 The energy separatrix and unstable trajectories in longitudinal phase plane. Green: separatrix, red: unstable and blue stable trajectories.

3.3.1 Cavities

The ring RF cavities are operated at frequency of 499.654 MHz so as to be integer sub-harmonic of the 3 GHz S-band injector Linac. The ring circumference of 216m gives the harmonic number h=360 (number of RF periods per ring) with the convenient decomposition of (360= $2^3 \cdot 3^2 \cdot 5$) which allows the possibility of the ring operation with many different bunch patterns. In the multibunch mode, from the available 360 RF buckets, the beam will be stored in 282 contiguous RF buckets with a 78 bucket ion-clearing gap to prevent ion trapping by the electric potential of the beam.

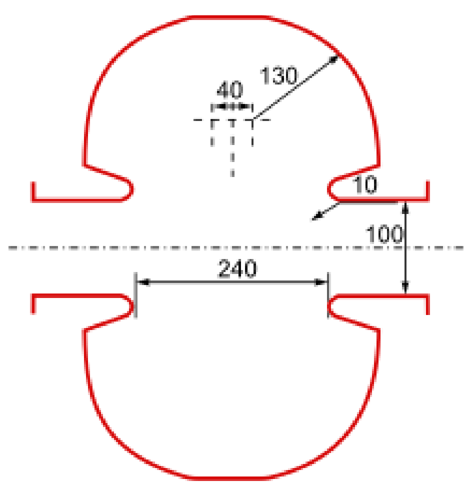

Fig. 3.3.2 Longitudinal section of the ELETTRA type cavity.

As a starting point we have assumed similar RF cavities as are used in ELETTRA [1], the Italian synchrotron light source in Trieste, that was successfully adopted for the Swiss Light Source (SLS) [2] and ANKA [3]. These are conventional room temperature cavities and use well-proven technology. The cavity shape schematically is shown in Fig.3.3.2.
The RF system of CANDLE will consist of six single-cell 500 MHz cavities, located in three straight sections. Each two cavities are powered with one 300 kW CW klystron amplifier. The cavities are made out of normal conducting, OFHC copper, purity 99.99%. The nominal axis length of the cavity is 480 mm. This length can be adjusted for tuning

purpose by a few millimeters. The internal diameter of the cavity is 526 mm. The inside profile of the cavity section is made up of quarters of ellipse (Fig. 3.3.2). Table 3.3.1 lists the single cavity parameters.

Table 3.3.1 Storage ring single cavity parameters (ELLETRA Type).

Resonant frequency f_{RF} (MHz)	499.654
Max Power from Klystron P_{kl} (kW)	180
Effective length (m)	0.9
Shunt impedance R_{sh} (MΩ)	3.4
Quality factor, Q_0	40000
Peak RF voltage V_{RF} (kV)	650
Power dissipation at Peak voltage, P_{wall} (kW)	62

To identify any possible beam cavity interaction, so called Coupled Bunch Instability, the full characterization of the High Order Modes (HOM) spectrum is required. The cavity characterization includes the frequency f, quality factor Q, longitudinal $R_{\|}$ and transverse $R_{\perp}$ shunt impedance, R/Q and the identification of the HOM. Table 3.3.2 presents the cavity characterizations for 6 first longitudinal and transverse HOM measured for the ANKA cavities [3]. The listed modes resonate below the cut off frequency of the beam pipe and are therefore trapped within the cavity.

Table 3.3.2 Cavity HOM modes characteristics.

Longitudinal HOM's					Transverse HOM's				
	f_r MHz	R/Q Ω	Q	R_{II} kΩ		f_r MHz	R/Q Ω	Q	$R_{\perp}$ MΩ/m
L1	950	28.9	37000	1070.0	T1	743	4.7	41400	3.0
L2	1057	0.7	40200	28.1	T2	746	15.8	41800	10.3
L3	1421	5.0	33300	166.5	T3	1114	13.0	34100	10.3
L4	1514	4.9	27700	135.7	T4	1220	0.1	40000	0.1
L5	1600	9.0	21000	189.0	T5	1242	4.5	24500	2.9
L6	1876	0.3	31000	9.3	T6	1304	0.3	30700	0.3

3.3.2 RF Power Requirements

With the maximum number of insertion devices in place, the total energy that has to be restored to the electron beam per turn in the ring is the sum of the energy losses in the bends, wigglers and undulators, plus the miscellaneous energy losses in the vacuum chamber. In the first stage of machine operation we hope to commission two bends, one undulator, one wiggler1 and wiggler2 beam lines. The number of beam lines from insertion devices will be further increased in accordance with the establishment of the user groups. To estimate the RF requirements in the case of machine operation with complete installation of all insertion devices (in total 12) we assume five undulators, three wigglers of type 1 and four wigglers of type 2. Table 3.3.3 shows the RF requirements in the storage ring for 3 GeV energy and 350 mA circulating current.

Table 3.3.3 Storage Ring RF System Requirements.

Parameters	Without ID	Initial Stage	Final Stage
Number of wigglers (type 1)	-	1	3
Number of wigglers (type 2)	-	1	4
Number of undulators	-	1	5
Energy loss in bends U_0 (MeV)	0.97	0.97	0.97
Energy loss in ID's U_{ID} (MeV)	-	0.1	0.415
Energy loss per turn (MeV)	0.97	1.07	1.39
Number of cavities	6	6	6
Total voltage V_{RF} (MV)	3.3	3.3	3.4
Energy acceptance (%)	2.38	2.26	2.02
Overvoltage factor	3.4	3.08	2.45
Synchronous RF phase ϕ_s (deg.)	162.9	161.06	155.90
Synchrotron tune Q_s	0.01099	0.0108	0.0104
Total shunt impedance n_cR_s (MΩ)	20.4(6x3.4)	20.4	20.4
Power loss in cav. walls P_W (kW)	267 (6x44.5)	267	283(6x47)
RF-to beam power P_{beam} (kW)	340 (6x57)	374(6x62)	486(6x81)
Miscellaneous losses P_m (kW)	50	50	60
Total RF power needed (kW)	660 (6x110)	690(6x115)	830(6x14)

The total RF voltage for the operation of the machine is at the level of 3.3 MV providing the energy acceptance of RF system better than 2%. The total power that goes to beam at 350 mA stored current is 430 kW without ID, 474 kW at the first stage and 486 kW at the stage of fully populated normal conducting insertion devices.

To achieve zero reflected power in cavities with full beam loading, the RF system should fulfill the following conditions:

a. the reactive component of the beam current should be canceled by properly detuning the cavity so that the beam-loaded cavity is seen as a pure resistance;
b. this equivalent resistance is matched to the RF source impedance by the correct setting of the coupling factor.

The detuning Δf_m and the coupling factor β_m satisfying the conditions a) and b) are given by

$$\Delta f_m = \frac{f_{RF}}{2Q_0}\frac{P_b}{P_W}\cot\phi_s, \qquad \beta_m = 1 + \frac{P_b}{P_W} \quad , \tag{3.3.3}$$

where Q_0 is the unloaded cavity quality factor, and ϕ_s is the synchronous phase. Table 3.3.4 shows the possible operating conditions for each of the single cavities for 3 GeV beam energy and 350 mA of stored current.

Table 3.3.4 Single cavity operating conditions.

Stage	Number of cav.	V_{RF} (MV)	ϕ_s (deg.)	P_W (kW)	P_b (kW)	β_m	Δf_m (kHz)
Without ID	6	3.3	162.9	44.5	57	2.28	25.96
Initial stage	6	3.3	161.1	44.5	62	2.39	25.4
Final stage	6	3.4	155.9	47.2	81	2.71	23.98

The input coupler must be capable of feeding into the cavity a CW RF power of at least 150 kW (forward) and also to handle the full reflection. It is intended to be similar to those operating in ELETTRA, which are of the coaxial type, terminated by a coupling loop. The coupling coefficient β_m shall be adjustable within a range of 1 to 3.5 in order to match different beam loading conditions.

The RF requirements as well as the beam parameters are in strong dependence of the beam energy. Fig. 3.3.3 (a-d) shows the energy loss per turn (a), the energy acceptance (b), the bunch length (c) and horizontal radiation damping time (c) when the beam energy is scan within the range 2.5-3.2 GeV.

For the energy of 2.5 GeV the energy loss per turn is only 470 keV and the beam can be maintained with only 2 cavities in operation with the total voltage of 1.3 MV. The energy acceptance is still acceptable 1.55%, although the Touschek lifetime is reduced to 7.3 hours, which results on the total lifetime of 5.6 hours.

For the energy of 3.2 GeV the total voltage of 3.3 MV with 6 cavities is maintaining the replenishment of the energy lost per turn of 1.25 MeV with the energy acceptance of the 2.1 %. The Touschek lifetime increase to 49 hours, while the bremsstrahlung lead to lifetime reduction to 39 hours. However, an integrated beam lifetime is still at the level of 18.5 hours. With 3.2 GeV beam energy the bunch length is increasing to 7.5 mm, while the horizontal radiation damping time is reduced to 2.8 msec providing an improved beam injection process from the booster.

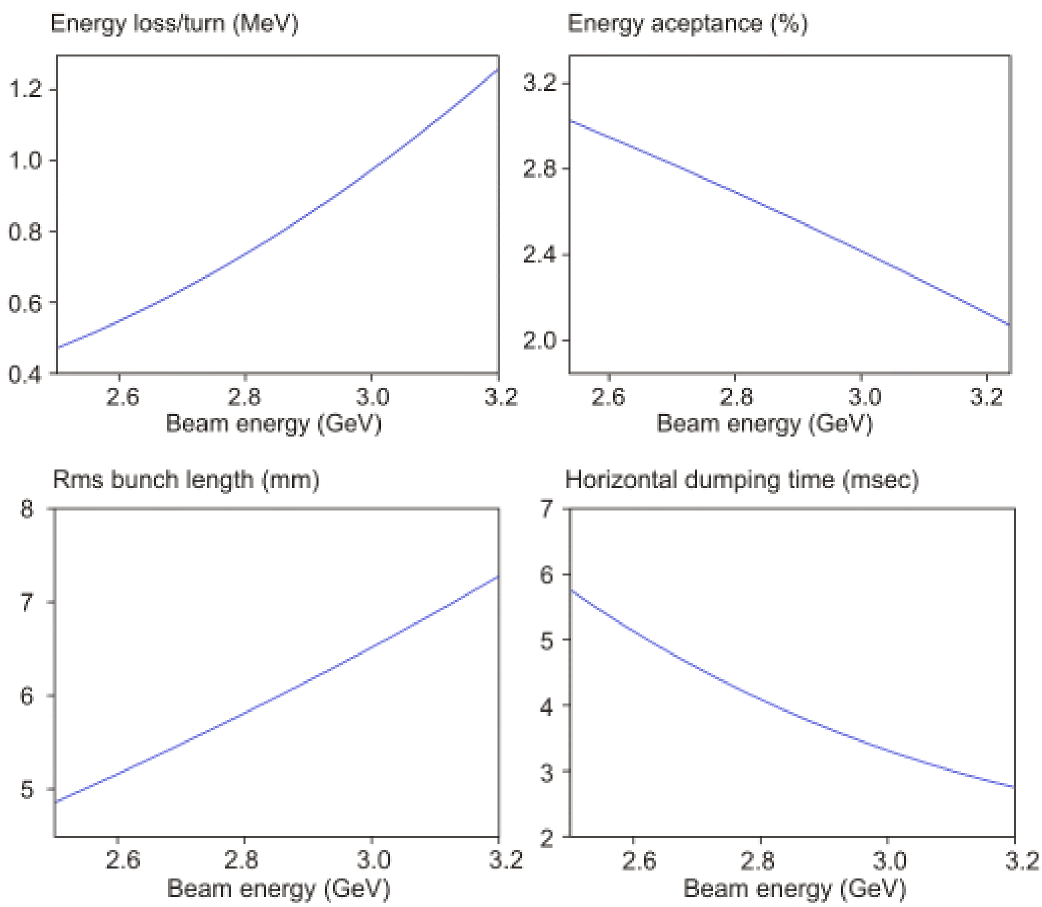

Fig. 3.3.3 Energy loss per turn (a), energy acceptance (b), rms bunch length (c) and horizontal damping time (d) versus beam energy.

3.3.3 RF Operation and Low Level Electronics

The CANDLE storage ring RF power source includes three stations based on CW klystrons capable of providing 300 kW power each. Each individual klystron supplies two RF cavities. The total available power of 900kW is sufficient then to serve the storage of 3 GeV energy, 350 mA current electron beam in the case of the fully populated insertion devices in the ring. The power transmission line connecting the klystrons to the cavities will be composed of commercially available WR –1800 waveguide. The block-diagram of the RF stations system is shown in Fig. 3.3.4. The system includes a 500 MHz master-oscillator and preamplifier; stable reference signal line; variable beam loading compensation; fundamental frequency tuning loop; amplitude regulation loop; phase regulation loop; RF signal measurements tools.

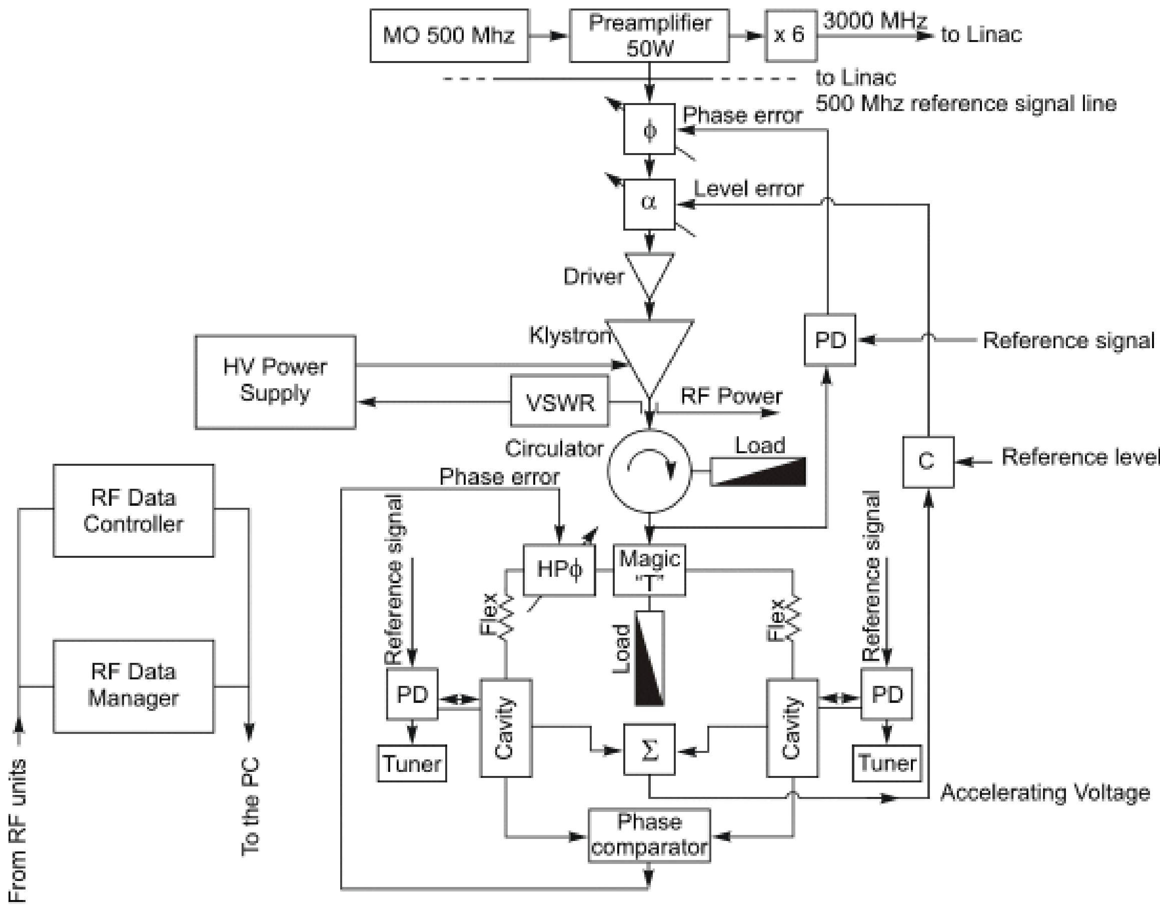

Fig. 3.3.4 Block-Diagram of the Klystron-Cavities supply system. ϕ- Phase shifter, α- Input power regulator, PD- Phase detector, C- Comparator, CHPϕ - Cavity high power phase, HPϕ- High power phase shifter, Σ- Summator.

As a 500 MHz Master-Oscillator (MO) we are planning to utilize a synthesized oscillator, which is both high stable and easy controllable. The output signal of the MO is amplified by a solid state 50 W preamplifier and is fed through a phase shifter (ϕ) and regulator of

RF input level (α). The input RF phase shifter and amplitude regulator are computer-controlled. The accelerating voltage's level and phase of cavities are compared with reference signals and adjusted by the noted units. The high-power phase shifters (HPϕ) are included to tune the relative phase between the cavities. The common phase on the output of klystron must be adjusted by means of the phase-shifter located before the driver. The bandwidth of the control loops must be adjusted to be less than synchrotron oscillation frequency of the beam in the storage ring. Those parameters will be measured and controlled by a hard-wired interlock chain. The system will provide the fast monitoring and control of the klystron window sparks and gun arcs.

The frequency regulation loop has a tuning range of ± 200 kHz, which corresponds to a change in the cavity length of ± 0.2 mm (within the limit of elastic deformation). This allows maintaining the cavity temperature variation of about $\pm 20^{o}$C with a sufficient budget for the compensation of the strongest beam loading effect on the frequency detuning which is around 25 kHz (Table). The maximum tuning speed of 1 kHz/s is fast enough for injecting the full beam in less than 30 s. In addition, the sensitivity of the loop is adjustable within the range of ± 0.1- 1 kHz and will be experimentally optimized to avoid an extra use of the tuner.

The amplitude regulation loop has 3 dB bandwidth and is adjustable up to 5 kHz. It regulates the cavity accelerating voltage better than 1% by controlling the drive power.

The phase loop compensates for the phase changes up to $\pm 30^{o}$ in amplification chain with variable power. It also has a 3 dB bandwidth adjustable up to 5 kHz and must ensure a phase stability of $\pm 0.5^{o}$.

*RF Cooling***.** The tasks of RF Cooling Subsystem (see Fig. 3.3.5) are**:**

- To carry away the power dissipated in the cavities walls
- To keep the working temperature of the cavities;
- To carry away the power dissipated in the Circulator and "Magic T" loads;
- To cool the Klystron.
- To cool the Klystron Power Supply;

RF cavities cooling system will be based on the heat exchange between two water circuits: the primary circuit connected to the CANDLE external water plant and the secondary one, which represents a closed water circuit connected to the cooling pipes of cavities.

The main task of this cooling station is to extract the RF power dissipated in the cavities walls. The cooling rack must allow a tight regulation of the cavity external surface temperature in a wide temperature range, in order to make possible the cure of Coupled Bunch Instabilities via temperature tuning.

The secondary water flux must always keep constant in any operating condition. Precise cavity temperature regulation is obtained by regulating the flux of the primary cooling water through a heat exchanger. The temperature of the cavity walls will be measured by a thermode. The initial heating of the secondary circuit water will be possible by means of a heating resistances bank installed in the thermal bath. The preliminary cooling parameters are listed in Table 3.3.5.

Table 3.3.5 Parameter list of cavity cooling system.

Water Flow	250 l/min
Input Water Temperature and Stability	30-70°C ±0.1°C
Water condition	Demineralised (deionized), Conductance of 1 μS/cm
Cavity Temperature Range and Stability	40-70°C±0.05°C
Handled Power	60 kW

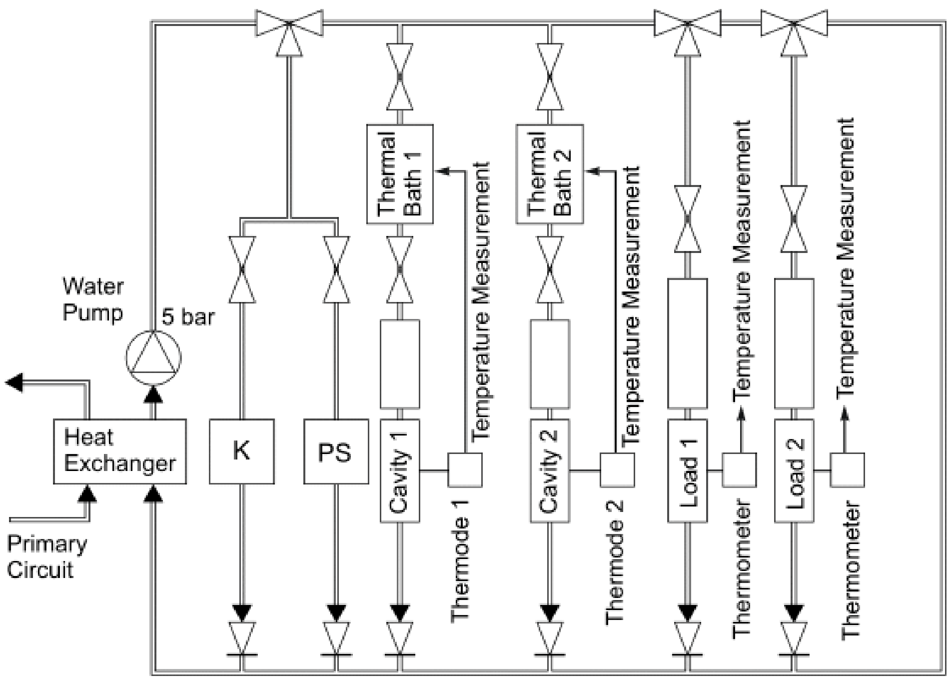

Fig.3.3.5 Storage Ring's RF Station's Cooling Circuit (for a pair of cavities): K – klystron, PS – Power Supply, FM – Flowmeter.

The cooling water must be the demineralised (deionized) with a conductance of 1 μS/cm. The needed water flow will be more exactly defined later on. Because the working temperature of the cavities can be differ for each of the cavities, we are planning to have an independent temperature control unit for each cavity to achieve the required stability.

3.3.4 HOM Damped Cavity

The RF cavity described before although quite conventional and operating at relatively conservative performance levels should be capable of achieving the CANDLE nominal requirements. However, taking into account that the new High Order Mode damped normal conducting cavity at 500 MHz for 3rd generation light sources is under development at BESSY [4], the cavity option for the CANDLE source can be improved to avoid multi-bunch instabilities. The fully tested HOM damped cavity will be available in 2003 [5].
The cavity is cylindrically shaped with the beam pipe diameter of 74 mm. The wavequides have a cutoff frequency of 650 MHz that is sufficiently below the frequency of the first dangerous HOM, but sufficiently above the fundamental mode to avoid strong coupling.

Fig. 3.3.6 presents the three dimensional view of the cylindrically symmetric HOM damped cavity and the longitudinal cross section of the cavity. The main parameters of the cavity are given in Table 3.3.6.

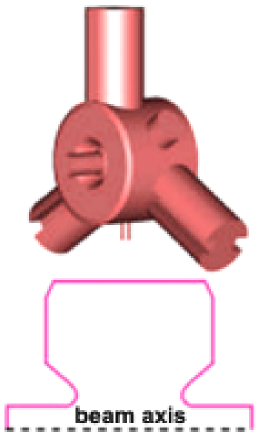

Table 3.3.6 HOM damped CS cavity parameters.

Frequency (MHz)	500
Effective insertion length (m)	0.7
Impedance (MΩ)	4.5
Peak voltage (kV)	617
Thermal power capability (kW)	100

Fig. 3.3.6 The HOM damped cavity shape (CS).

The relevance of a given cavity impedance spectrum for the excitation of multibunch instabilities in a storage ring is best described by the threshold impedance Z^{thresh}, which can be obtained by equating the radiation damping time with the respective multibunch instability rise time. The longitudinal and transverse threshold impedances are given by

$$Z_{\|}^{thresh} = \frac{2EQ_s}{N_c f_{\|,HOM} I_b \alpha \tau_s} \; ; \qquad Z_{x,y}^{thresh} = \frac{2E}{N_c f_{rev} I_b \beta_{x,y} \tau_{x,y}} \qquad (3.3.4)$$

where E is the electron energy, I_b is the average current, N_c is the number of cavities, Q_s is synchrotron tune, $f_{\|,HOM}$ longitudinal HOM frequency, f_{rev} is the revolution frequency, $\tau_{x,y,s}$ damping times, $\beta_{x,y}$ beta function at the cavity, α is the momentum compaction factor. Fig. 3.3.7 presents the longitudinal and transverse threshold impedances for CANDLE and SLS storage ring and the HOM impedance of CS cavity .

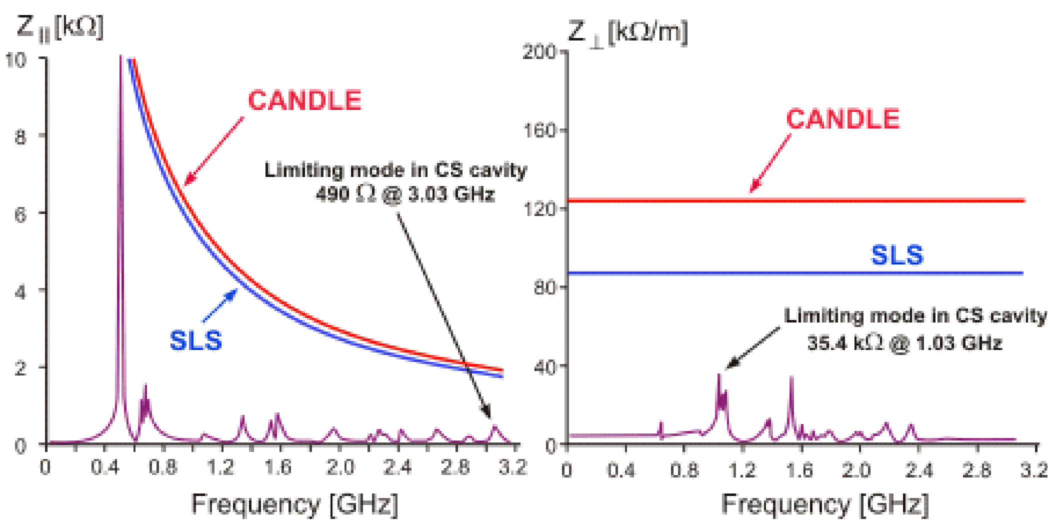

Fig.3.3.7 Longitudinal (left) and transverse (right) threshold impedances for CANDLE and SLS storage rings together with impedance spectra of the cylindrical HOM damped cavity.

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