352.2 MHz RF SYSTEM FOR THE ESRF

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Abstract

For the ESRF a 352.2 MHz RF system using 1 MW-CW klystrons and five-cell LEP type cavities has been adopted. In the storage ring (SR), two klystrons will feed a total of four cavities in order to provide the maximum required accelerating voltage of 8.9 MV. In the injector synchrotron (SY), two cavities fed by one klystron in a cycling mode at 10 Hz will give the maximum needed accelerating voltage of 7.3 MV. In multibunch operation of the SR, coupled bunch oscillations will be driven by the higher order modes (HOMs) of the cavities, and may limit the maximum beam current to about 60 mA. Spare ports will allow to install HOM dampers on the cavities in order to raise the instability thresholds above the design current of 100 mA. In addition, active feed back systems may be implemented.

1 Introduction

The European Synchrotron Radiation Facility (ESRF) is constructing a 6 GeV **storage ring (SR)** at Grenoble. A linear preinjector will supply 200 MeV electrons (2nd stage: 400 MeV positrons), which will then be accelerated to 6 GeV in a full energy booster **synchrotron (SY)**. The SY will be the injector for the SR and operate in a cycling mode at 10 Hz. Accelerating cavities powered by adequate RF transmitters will be needed for acceleration in the SY and for compensation of particle energy loss in the SY and SR. Since the goal is to operate the first beam lines as early as 1993, it has been decided to use a 352.2 MHz RF system, which will strongly rely on the already existing CERN design for the LEP ring.

2 RF parameters

2.1 Voltage requirements

For the SR, the energy loss per particle and per turn U_0 is due to synchrotron radiation in the dipoles (4.75 MeV) and in the insertion devices (1.5 MeV for a standard set). For the single-bunch mode, with 10 mA in only one bunch, additionnal parasitic losses of 0.3 MeV have been predicted [1]. At full energy (6 GeV), U_0 amounts to 5.22 MeV in the injector SY [2]. These values appear also in table 1, where the main RF parameters for the ESRF are summarized. The overvoltage factor q gives the bucket size that is necessary to reach a theoretical quantum beam lifetime of more than 100 hours for the SR and 1 minute for the SY [1,2]. V_c is the resulting minimum accelerating voltage that must be provided by the RF system.

In table 1, three working points are considered for the SR with respect to the beam current I_b: the already mentionned single and multibunch modes of operation with design values of 10 mA and 100 mA, respectively, and a maximum figure of 200 mA, which might correspond to a further ESRF improvement and which must not be limited by the RF system. The last column gives the corresponding parameters for the SY when the particles are at 6 GeV. Besides the required minimum accelerating voltage V_c, the RF system has to provide the beam power P_b.

2.2 RF system design

The 352.2 MHz LEP cavity is composed of five cells coupled to each other through slots. The cells are shaped to optimize the shunt impedance using nose cones: R_s = 53.6 Linac-MΩ from measurement [3]. The mean rated cavity power dissipation being 125 kW, one obtains a maximum accelerating voltage of 2.59 MV per cavity, so that four cavities are needed to meet the SR voltage requirements. Two 6 m long straight sections with low beta functions will each house one pair of cavities.

For the SY which is cycled at 10 Hz, the average power dissipated in the cavity is less than 30 % of the peak value [2]. Thus, there will be only two cavities in the SY, providing 3.65 MV each at the peak of the booster cycle (a peak voltage of 4 MV per cavity has been reached at LEP/CERN [4]).

Table 1: RF parameters

ITEM	SR singleb.	SR multib. (design)	*SR multib. (max.)*	SY (at 6 GeV)
Uo/e	6.55 MV	6.25 MV	"	5.22 MV
q	1.36	1.38	"	1.4
Vc	8.9 MV	8.6 MV	"	7.3 MV
Ib	10 mA	100 mA	*200 mA*	10 mA
Pb = Ib Uo/e	66 kW	625 kW	*1250 kW*	52 kW
klystrons	2	2	"	1
cavities	4	4	"	2
Vc/cavity	2.23 MV	2.15 MV	"	3.65 MV
Pc = Vc Vc/Rs	370 kW	345 kW	"	497 kW
Pg (klystron)	0.48 MW	1.07 MW	*1.75 MW*	0.60 MW
P/window	55 kW	121 kW	*200 kW*	137 kW
ß = 1+Pb/Pc	-	2.8 -> 3	*4.6*	1.1

The third part of table 1 gives the overall figures for 4 cavities in the SR and 2 cavities in the SY, respectively. At nominal current, due to the high beam loading, the power flow into one cavity (242 kW for the SR and 274 kW for the SY) is nearly twice the figure of LEP. There, 113 kW are nominally fed through a single vacuum ceramic window, each window being tested at 140 kW [4]. Thus, as a major ESRF modification of the LEP cavity, the power will be coupled through **two windows per cavity**: the couplers will be arranged on diametrically opposite locations in the central cell. It can be shown that each coupler must then only couple with half the β value given in table 1.

Table 1 shows that twice the nominal beam current would require as much as 200 kW to be coupled through one window. But a CERN experiment in which a window withstood 180 kW gives hope that one could work at such high powers later [2,4].

The power, which has to be delivered by the klystrons is

$$P_g = P_c + P_b + P_r + 10\ \%\ \text{waveguide losses.}$$

In table 1 it has been assumed that the reflected power is $P_r = 0$. This corresponds to the case where the coupling factor β between the waveguide system and the accelerating mode (defined as $\beta = Q_o/Q_{ext}$) is adjusted according to $\beta = 1+P_b/P_c$.

The klystrons, which have been developed for LEP, have a maximum nominal output power of 1 MW per unit at 352.2 MHz. Although 1 MW is nearly enough to sustain 100 mA in the SR, it has been decided to provide one klystron for each pair of cavities. This gives the possibility to work with the individual klystrons at lower power levels where they are more stable and the operation will be more reliable. Moreover, the availability of 2 MW RF power represents a good margin to go to higher beam currents or, as will be discussed in the next chapter, to install, later, cavities with a lower shunt impedance. However, the waveguide system will also allow to feed all the four cavities with only one klystron.

The coupling coefficient will be adjusted to **β=3**, which gives an optimum working point at 110 mA, slightly above the SR design current. A tuner servo loop will be used to suppress the reactive power in the beam loaded cavity: this will minimize the needed RF power and meet Robinsons stability criterion [5]. Below 110 mA, mismatch will lead to reflected power and thus, for single-bunch operation, $P_r \approx 100$kW must be added to P_g in table 1.

Above 110 mA, in order to compensate the reactive part of the beam loading, P_c must be higher than the minimum necessary for the required beam lifetime; assuming that a vacuum window withstands 190 kW, the beam current will be limited to 160 mA by the maximum cavity dissipation of 125 kW rather than by the available RF power. Without insertion device, U_o is lower by 24 %, so that 24 % higher currents will correspond to the same beam loading P_g.

3 Higher order modes (HOMs)

3.1 HOM measurements

In multibunch operation, coupled bunch oscillations, driven by the HOMs of the cavities, will limit the maximum beam current. Instability thresholds at 105 mA for longitudinal and 63 mA for transverse oscillations were predicted from computations, based on the HOM impedances calculated with the URMEL code for a single cell [2]. These figures were based on one optimistic and one pessimistic assumption. The optimistic one was that the HOM resonances of different cells are sufficiently far apart, so that their effects do not add. The pessimistic one was that the interaction of a single cell mode with a multibunch oscillation mode was exactly resonant [2].

In reality, due to the coupling slots, the cavity supports passbands of coupled HOMs. These HOMs may have either lower or higher impedances than the corresponding single cell modes. This is due to either destructive or constructive interference with the particle beam. In order to make more realistic instability predictions, the complete HOM spectrum of a LEP cavity has been investigated experimentally up to 1 GHz [3]. The impedances have been measured by applying the usual perturbation technique, and the multibunch instability thresholds I_{th} have been scaled in inverse proportion to the impedances. It was now assumed that only one of the 4 SR cavities interacts with one bunch oscillation mode.

A lot of the observed HOM properties may be explained by the azimuthal asymmetries of the cavity and by the difference in diameters between the 5 coupled cells:

a) The dipole modes have fixed orientations, which are mostly turned by nearly ±45° with respect to the horizontal plane. This causes a reduction of the transverse impedances which split into a horizontal and a vertical component.

b) The lower order dipole passbands consist of 5 coupled modes with one orientation and 5 decoupled modes with the orthogonal orientation.

c) At higher frequencies, complicated intercell and intracell coupling schemes between single cell modes of different types and different azimuthal orders lead to large passbands containing more than 5 or 10 modes. The measurements showed that this coupling between high impedance and low impedance mode fields gives overall lower impedances.

d) The measured unloaded quality factors were in general lower than the URMEL predictions.

In table 2, the single cell calculations and the cavity measurements are listed for the HOMs with the highest impedances in the frequency range up to 1 GHz. The impedance is given by the loss independent R/Q times the quality factor Q_0. The monopole modes couple with synchrotron oscillations via their longitudinal impedance expressed in linac-Ω, and the dipole modes couple with betatron oscillations via their transverse impedance, which is given in linac-Ω per meter offset from the beam axis.

The highest ratio between the thresholds predicted for a single cell calculation and a five cell measurement is 1.73 for the 1st monopole passband. This ratio is only 1.1 and 1.2 for the 4th monopole and the 2nd dipole passbands, respectively. For the 3rd dipole passband, the five-cell LEP cavity gives even higher thresholds than one single cell. The lowest threshold predicted for the total cavity is 57 mA and thus only slightly lower than the minimum single cell prediction of 63 mA.

The last column in table 2 gives the field distribution among the cells: the letters "0","i" or "I" symbolize a low, medium or high field in the corresponding cell. The considered mode of the 4th monopole passband, for example, is a trapped mode having field mainly in cell 5.

3.2 Multibunch instability cures for the ESRF

There are principally three possible ways to raise the multibunch instability thresholds:

a) Using a cavity with lower HOM impedances: a significant improvement would require a new cavity design and development, which would not fit the time schedule of the ESRF. However, a 2nd generation cavity could be considered as a long term alternative. There is enough reserve of RF power in the foreseen installation to work with a cavity that may have a lower accelerating mode impedance.

b) HOM couplers and dampers: will be the object of a medium term research and development activity. For this, 35 mm spare ports will be available on each cell, to allow later the individual damping of even dangerous single cell HOMs. However, the measurements showed that it will be possible to damp most of the HOMs with couplers at horizontal positions on cells 2 and 4.

c) Active feedback systems: have been shown to be feasible for the ESRF [6]. They could be applied if passive damping is not sufficient.

4 Conclusion

The RF system for the ESRF will use three 1 MW klystrons at 352.2 MHz, which will each feed two LEP cavities. It is expected that the HOMs of the four SR cavities will drive multibunch oscillations and limit the beam current to half the design value of 100 mA. Passive and active HOM damping should allow to raise the instability thresholds above the design current.

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Table 2: Highest HOM impedances and lowest instability thresholds

	URMEL calculation (1 cell)				MEASUREMENT (5 coupled cells)				
Mode	f	R/Q	Q_0	I-threshold	f	R/Q	Q_0	I-threshold	Field-distr.
1st monopole	506.9 MHz	64.3 Ω	40 600	107 mA	500.24 MHz	150 Ω	30 000	62 mA	iiIii
4th monopole	920.4 MHz	36.6 Ω	40 700	105 mA	908.40 MHz	45 Ω	36 000	97 mA	0000I
2nd dipole	613.8 MHz	527.4 Ω/m	70 800	66 mA	619.86 MHz	718 Ω/m (hor)	60 000	57 mA	II0II
3rd dipole	761.7 MHz	695.8 Ω/m	55 800	63 mA	717.81 MHz	577 Ω/m (hor.)	30 000	141 mA	0III0
					762.38 MHz	562 Ω/m (vert.)	40 000	108 mA	000iI