RF system for high luminosity e^+ e^- circular colliders

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Summary

The RF system for the first stage (L=10^{33} cm^{-2} s^{-1}) of the proposed B-Meson factory in the CERN ISR tunnel (BFI) is described. Computed and measured results are presented. Alternatives for upgrading the initial system towards a L=10^{34} cm^{-2} s^{-1} machine are also discussed.

1. Introduction

The BFI [1] is one of many projects actually under study around the world [2] all which propose high luminosity e^+e^- colliders for heavy flavor particle physics. A common characteristic of these machines is that they require, simultaneously, intense beams and short bunches. A high RF voltage is necessary for the focusing of short bunches. In order to generate this voltage with a reasonable amount of power and length of accelerating structure, the RF cavities must present a high fundamental impedance. Also, concurrently, their higher order mode (HOM) impedances, in the presence of the intense circulating current, must be acceptable from the point of view of the beam stability and parasitic energy losses. These goals require an optimization of the cavity shape, a strong attenuation of the HOM resonances and the use of a limited number of cells.

The feasibility study of the BFI [1] has been based on the following general strategy: work out an asymmetric machine (3.5 GeV on 8 GeV) for an initial luminosity of 10^{33} cm^{-2} s^{-1} while choosing the major components (vacuum chamber, magnets) which have the potential of handling a luminosity of 10^{34} cm^{-2} s^{-1}; in addition, the possibility of conversion to a symmetric machine (5.3 GeV on 5.3 GeV) is also considered in the initial design.

2. Design considerations

The task of the RF system may be divided into two parts.

1. It must provide the longitudinal focusing, which, for a given lattice, gives the desired RMS bunch length, σ_s. Thus, the required accelerating voltage is $V_{acc} \simeq$ const α E^3 / f_{RF} σ_s^2 (α: momentum compaction factor, E: beam energy, f_{RF}: RF frequency). This leads to a power dissipation per cavity of $P_{dis}^{1cav} = V_{acc}^2 / 2\, n_{cav}^2\, R_s$ (n_{cav}: number of cavities, R_s: cavity shunt impedance).

2. It must compensate the total power lost by the beam. P_{beam}, the power delivered to the beam is the sum of two components: the synchroton radiation power, P_{rad} = const E^4 I_{beam}, and the HOM power, $P_{HOM} = P_{HOM}^{ch} + n_{cav}\, P_{HOM}^{1cav}$;
   $P_{HOM}^{ch} = k_{HOM}^{ch}\ (\sigma_s)\ T_{rev}\ I_{beam}^2\ /\ n_b$ (vacuum chamber),
   $P_{HOM}^{1cav} = k_{HOM}^{1cav}\ (\sigma_s)\ T_{rev}\ I_{beam}^2\ /\ n_b$ (RF cavities);
   I_{beam}: average beam current, T_{rev}: revolution period, n_b: number of bunches, k_{HOM}^{ch} and k_{HOM}^{1cav}: vacuum chamber and cavity loss factors.

The total RF power requirement is then $P_{tot}^{RF} = n_{cav}\ P_{dis}^{1cav} + P_{beam}$.
The main design constraints for the RF system are the following:

- *available space in the ring allocated for the RF cavities;*
- *compatibility with the existing injection system* (longitudinal acceptance);
- *technical limitations concerning the RF cavities and their associated equipment* (achievable accelerating field, power dissipation in the cavity walls, input and HOM coupler power)
- *total RF power requirements;*
- *tolerable parasitic impedances for the beam stability.*

3. The RF system of the first stage L=10^{33} cm^{-2} s^{-1} machine [1], [3]

The RF requirements for the first stage BFI are compatible with the use of normal conducting (n.c.) cavities. Considerations regarding bucket length, space and power requirements as well as the availability of commercial RF sources, lead us to choose 500 MHz as the fundamental RF frequency. Single cell type cavities are selected in order to facilitate both the attenuation of the parasitic resonances (minimum number of cells, lower density of modes and, therefore, easier optimization of the damping system) and the coupling of high power into each cell. A cavity shape characterized by a smooth gap region and a large pipe diameter is proposed instead of the conventional "nose cone shape". It allows to achieve higher accelerating gradient (lower E_{max}/E_{acc} ratio, more uniform power distribution along the cavity walls, surface easier to cool externally), at the expense of a relatively low increase in total power consumption; in addition, it presents lower transverse parasitic impedances and propagation cutoff frequency. In order to efficiently attenuate the high Q parasitic resonances, passive HOM dampers consisting of inductively coupled external loads are provided on each cavity. A full size model cavity has been designed and built according to these general guidelines [4], [5]. Its shape is represented in figure 1 and its computed characteristics are listed in tables 1 and 2.

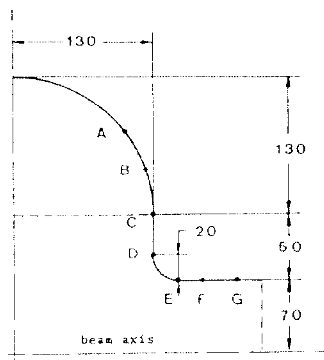

Figure 1: Shape of the RF cavity (a quadrant)

f_r $[MHz]$	500.
R/Q $[el.\Omega]$	73.
Q_o	50000.
$R_s[M\Omega]$	3.65
E_{max}/E_{acc}	2.1
$k_{HOM}^{1cav}[V/pC]$	0.125
Cutoff freq. [GHz]	1.3 (D) 1.6 (M)

Table 1: The main characteristics of the RF cavity.

Frequency [MHz]		Q_o	R/Q [Ω or Ω/m]	R_o=R/Q . Q_o [kΩ or kΩ/m]
(M)	863.	47000	30.	1400.
	1071.	70000	0.1	7.
	1366.	60000	1.6	94.
	1370.	68000	7.	475.
	1590.	72000	1.2	8.5
(D)	675.	51000	61.	3100.
	749.	58000	172.	10000.
	1023.	43000	300.	13000.
	1113.	48000	90.	4300.
	1175.	87000	6.	500.
	1259.	51000	33.	1700.

Table 2: HOM characteristics (unloaded) of the RF cavity; impedances in Ω for monopole (M) and Ω/m for dipole (D) modes.

The low power measurements of the frequency, Q and R/Q (perturbation method) for the different cavity modes show good agreement between experimental and computed results. The HOM loaded Q factors were also measured while the cavity was equipped with 2 HOM dampers as described in figure 2. The results are listed in table 3.

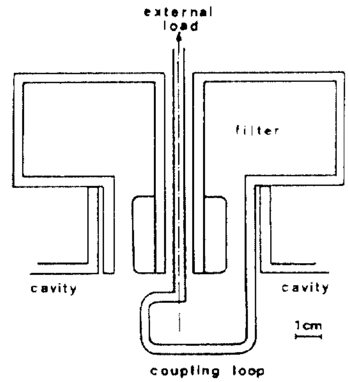

Figure 2: Section of the coaxial HOM damper

	f [MHz]	Q_L
(M)	865.	350.
	1058.	250.
	1370.	<100.
	1375.	<100.
	1585.	1500.
(D)	674.	250.
	745.	2000.
	1024.	2000.
	1107.	5000.
	1170.	1200.
	1259.	<100.

Table 3: Measured HOM loaded Q[†]

Each HOM damper (actually made from brass) produced a loading of the fundamental mode of about 4 %. A factor of 2 less is expected from copper versions of the damper. Further improvements of the fundamental - to - HOM loading ratio are expected from more iterations and optimization of the coupling loop shape. The possibility of damping the HOM with dampers installed on the beam pipe will also be investigated.

The parameters of the RF system for the first stage BFI using the described cavities are listed in table 4.

Machine 1	ring 1 (e^+)	ring 2 (e^-)
Energy, E [GeV]	3.5	8.
Mom. comp. factor, α $[10^{-3}]$	8.6	
Energy spread, δ_E/E $[10^{-4}]$	5.2	8.5
Total beam current, I_{beam} [A]	1.28	0.56
Number of bunches, n_b	80	
Radiation loss per turn, U_o [MeV]	0.31	5.6
RMS bunch length, σ_s [mm]	20.	
RF frequency, f_{RF} [MHz]	497.9	
Harmonic number, h	1600	
Accelerating voltage, V_{acc} [MV]	2.	13.
Number of cavities, n_{cav} (n.c.)	4	20
Accelerating gradient, E_{acc} [MV/m]	1.6	2.2
Fund. dissip. per cav., P^{1cav}_{dis} [kW]	35.	60.
Cav. HOM loss factor, k^{cav}_{HOM} [V/pC]	0.125	
HOM losses per cav., P^{1cav}_{HOM} [kW]	8.2	1.6
Vac. ch. loss factor, k^{ch}_{HOM} [V/pC]	2.15	
Vac. ch. HOM losses, P^{ch}_{HOM} [kW]	140.	30.
Beam power, P_{beam} [MW]	0.57	3.2
Input power per cav., P^{1cav}_{input} [kW]	175.	220.
Total RF power, P^{RF}_{tot} [MW]	0.70	4.4
Number of 1 MW, n_{klyst}	1	5

Table 4: Parameter list for the reference L = 10^{33} cm^{-2} s^{-1} asymmetric BFI.
The loss factor of the vacuum chamber is estimated from values measured in the CESR ring at Cornell [13]; for symmetric machines the contribution of separators is included.

†Cavity equipped with 2 HOM dampers at location AB as defined in figure 1 and azimuthally at 90° with respect to each other.

The use of 6 units, each consisting of a 1 MW klystron powering 4 cavities, leads to performance levels comparable to those of already operating systems.

In the high energy ring, the dissipation per cavity reaches 60 kW, about twice the power dissipated in one cell of the PETRA RF system [6]. This extra factor in total dissipation per cell can be handled since the shape of our selected cavity is more favorable to cooling. The corresponding maximum E-field at the cavitity surface, about 5 MV/m, is lower than that currently observed in the PETRA cavities. The amount of power to be fed into the cavity through the input coupler is 220 kW. This level of performance has already been realized at other laboratories (CESR 500 MHz system [7], for example). If this becomes a critical issue, the installation of 2 input couplers per cavity is a possible alternative.

In the low energy ring, the higher beam current leads to a HOM power deposited per cavity of about 8.5 kW. Distributed into four HOM couplers, this is still a tolerable power level to handle using conventional coaxial HOM couplers.

According to the expected loaded HOM impedances, a complementary active system is required in order to insure the suppression of the coupled bunch instability [8], [9]. The single bunch stability condition is theoretically satisfied in both rings [1], [10].

Conversion of this machine to a L = 10^{33} cm^{-2} s^{-1} symmetric collider (5.3 GeV on 5.3 GeV) would not present any serious problem from the point of view of the RF system; the general conditions would be quite similar to those of the corresponding asymmetric case (table 5).

Machine 2		$V_{acc}[MV]$	15.
		n_{cav} (n.c.)	24
E [GeV]	5.3	$E_{acc}[MV/m]$	2.1
α $[10^{-3}]$	17.	$P^{1cav}_{dis}[kW]$	57.
δ_E/E $[10^{-4}]$	5.6	P^{1cav}_{HOM} [kW]	4.
I_{beam} [A]	0.56	P^{ch}_{HOM} [kW]	95.
n_b	48	$P_{beam}[MW]$	0.8
U_o [MeV]	1.1	$P^{1cav}_{input}[kW]$	90.
σ_s [mm]	13.3	$P^{RF}_{tot}[MW]$	2.2
		n_{klyst}	3

Table 5: Parameter list for a L = 10^{33} cm^{-2} s^{-1} symmetric BFI (one ring).

4. Possible alternatives for upgrading the RF system towards a L = 10^{34} cm^{-2} s^{-1} machine

Several options are envisaged to upgrade the initial machine towards the "ultimate" luminosity (flat beams, round beams, crab crossing) [1]. Each option presents quite different RF requirements [3]. R&D in the first stage machine should point out the most critical limitations in each area. Parallel development and tests on both superconducting (s.c.) and n.c. equipment will determine their relative performance (maximum achievable accelerating field, ability to feed high power into the cavities, damping of the parasitic resonances, handling of the HOM power, ...). This experimental program should permit us to better define the requirements and guidelines with which to follow for upgrading the RF system. The envisageable alternatives are the following:

- increase the number of n.c. cavities (a n.c. system might still remain attractive if the required voltage is lower than 50 MV);
- replace the n.c. system by a s.c. one;
- combine n.c. and s.c. cavities (in the same ring) for realizing a "separate function system" - n.c. system used for the compensation of the beam energy losses, s.c. one for providing the focusing.

Different examples of $L = 10^{34}$ cm^{-2} s^{-1} machines are presented in table 6. In each ring, a maximum of 64 cavities can be installed in the 16 half cell straight sections reserved for the RF. The use of s.c. cavities is therefore unavoidable in the 8 GeV ring of machine 3 (asymmetric flat beams). In its 3.5 GeV ring, a n.c. system fits within the available space; however, the required number of cavities leads to a critical value of the broad band impedance driving single bunch instabilities; the situation is largely improved by the use of a s.c. system [1], [10]. Machines 4 (asymmetric round beams) and 5 (symmetric crab crossing) are both fully realizable with n.c. cavities.

Hybrid n.c. / s.c. system

In a combined n.c. / s.c. system, both system may contribute to the compensation of the beam energy losses as well as to the longitudinal focusing of the bunches. Examples are given in table 6. Another possibility is to limit the role of the s.c. system to a pure focusing task by setting its synchronous phase to 180° (no acceleration). In this latter scheme, the s.c. system might be operated in a completely idle mode (i.e. no external RF source). The RF power required for the compensation of the beam energy losses would be entirely provided by the n.c. system. A proper detuning, Δf, of the s.c. cavities should permit use of the beam induced voltage as the focusing voltage. In steady-state regime, it will be given by: $V_{foc} \simeq (R/Q)\, I_{beam}\, (\Delta f/f)^{-1}$. The transient behaviour and stability of such a system remain to be studied in detail. A small amount of extra power from the n.c. system should be sufficient to damp the phase oscillations produced by the s.c. system during the transient build up of its voltage.

In the examples of table 6, the frequency of both n.c. and s.c. systems is assumed to be 500 MHz. A higher harmonic (1.5 GHz, for example) could be chosen for the s.c. system. At higher frequency, for the same focusing strength, a lower voltage is required and one would profit from a higher achievable E-field in the s.c. cavities [11]. However, the use of a higher frequency involves a reduction of the longitudinal acceptance. This would require the injection of shorter bunches or maintaining the voltage of the s.c. system at a low level during the whole injection process.

The present state of the art HOM damping systems for s.c. cavities [12] are not effective enough for our application. Power handling capability and attenuation efficiency must be improved by nearly two orders of magnitude. This involves serious technical difficulties associated with the cryogenic environment. The shielding of the s.c. cavities from the synchrotron radiations is another subject which has to be investigated. Long term studies and development are required to solve these problems and prove the feasibility of a s.c. system capable of satisfying the BFI requirements.

Machine 3	n.c.	s.c.		n.c./s.c.*	n.c./s.c.**
	3.5 GeV	3.5 GeV	8 GeV	8 GeV	8 GeV
n_{cav}	40	8	64	12 / 40	32 / 40
V_{acc} [MV]	20.	20.	119.	5.5 / 113.5	10. / 110.
E_{acc} [MV/m]	1.7	8.5	6.3	1.5 / 9.4	1. / 9.1
P_{dis}^{1cav} [kW]	37.	-	-	30. / -	14. / -
P_{HOM}^{1cav} [kW]	35.	35.	6.5	6.5 / 6.5	6.5 / 6.5
P_{beam} [MW]	2.5	1.5	6.8	2.3 / 4.4	6.8 / 0.
P_{input}^{1cav} [kW]	100.	180.	110.	220. / 110.	230. / 0.
P_{tot}^{RF} [MW]	4.	1.5	6.8	2.6 / 4.4	7.3 / 0.
n_{klyst}	5	2	8	3 / 5	8 / 0

Machine 4	n.c.		s.c.	n.c./s.c.*	n.c./s.c.**
	3.5 GeV	8 GeV	8 GeV	8 GeV	8 GeV
n_{cav}	8	44	36	32 / 4	36 / 4
V_{acc} [MV]	3.5	20.5	20.5	9. / 12.	9.5 / 11.
E_{acc} [MV/m]	1.5	1.5	1.9	0.9 / 9.6	0.9 / 8.8
P_{dis}^{1cav} [kW]	27.	30.	-	11. / -	11. / -
P_{HOM}^{1cav} [kW]	23.	4.5	4.5	4.5 / 4.5	4.5 / 4.5
P_{beam} [MW]	1.3	8.4	8.3	7.4 / .95	8.3 / 0.
P_{input}^{1cav} [kW]	195.	220.	230.	240. / 235.	240. / 0.
P_{tot}^{RF} [MW]	1.6	9.7	8.3	7.7 / 0.95	8.7 / 0.
n_{klyst}	2	11	9	8 / 1	9 / 0

Machine 5	n.c.	s.c.	n.c./s.c.*	n.c./s.c. **
n_{cav}	24	16	12 / 4	16 / 4
V_{acc} [MV]	17.1	17.1	4.9 / 12.2	5. / 12.1
E_{acc} [MV/m]	2.4	3.5	1.35 / 10.	1.05 / 10.
P_{dis}^{1cav} [kW]	72.5	-	24. / -	15. / -
P_{HOM}^{1cav} [kW]	10.	10.	10. / 10.	10. / 10.
P_{beam} [MW]	3.5	3.4	2.5 / 0.9	3.4 / 0.
P_{input}^{1cav} [kW]	217.	215.	235. / 225.	230 / 0.
P_{tot}^{RF} [MW]	5.2	3.4	2.8 / 0.9	3.65 / 0.
n_{klyst}	6	4	3 / 1	4 / 0

Table 6: Examples of RF systems for $L = 10^{34}$ cm^{-2} s^{-1} machines

- 3 asymmetric flat beams (n_{bunch} = 320, σ_s = 4.8 mm, E = 3.5 GeV x 8 GeV, I_{beam} = 2.56 A x 1.12 A)
- 4 asymmetric round beams (n_{bunch} = 320, σ_s = 12. mm, E = 3.5 GeV x 8 GeV, I_{beam} = 3.3 A x 1.45 A)
- 5 symmetric crab crossing (n_{bunch} = 800, σ_s = 8. mm, E = 5.3 GeV, I_{beam} = 2.8 A)
- *(**) hybrid nc/sc system with (without) external RF source for the s.c. system.

5. Conclusions

The RF requirements for the initial $L = 10^{33}$ cm^{-2} s^{-1} machine can be achieved with a reasonable number of n.c. cavities and power. For the upgrade of the initial machine towards the "ultimate" luminosity ($L = 10^{34}$ cm^{-2} s^{-1}), various options are envisaged, each corresponding to quite different RF requirements. Use of s.c. cavities may be advantageous and even unavoidable in certain versions. A development program is necessary to prove the feasibility of a s.c. system in such a hostile environment.

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