RF Issues for High Intensity Factories

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Abstract

This paper presents a brief report on the RF issues concerning high-luminosity electron-positron colliders, referred to as "factories", such as phi, tau-charm, and B factories. In order to realize the high luminosity required for such factories, heavy demands are placed on the RF system. This paper discusses the requirements for the RF system, approaches to the challenging tasks, and the R&D status at each factory.

1 INTRODUCTION

The "factories" are high-luminosity e^+e^- colliders which provide a high-rate production of some particular particles for very precise experiments. The design luminosity ranges from 10^{33} to 10^{34} cm^{-2}sec^{-1}, which is nearly two orders of magnitude higher than that of the ever existing e^+e^- colliders. After extensive efforts for feasibilities study and conceptual designs, several factories started construction.

The Frascati phi factory, DAΦNE [1], is in a final stage of construction. KEKB [2] and PEP II [3] are asymmetric energy B-factories, which are under construction, and will be commisioned in a couple of years. The CESR upgrade to Phase III [4] will increase its luminosity to a level comparable to the asymmetric B factories. As for tau-charm factories, there have been several studies and proposals, including CERN-Spain [5], JINR (Dubna) [6], ITEP (Moscow) [7], and IHEP (Beijing) [8]. This paper mainly discusses the RF issues concerning these e^+e^- factories. The CERN high-luminosity proton-proton collider, LHC [9], will be installed in the LEP tunnel. This paper also refers to the LHC RF system, since it is in some respects similar to the factory RF system.

Table 1 shows RF-related machine parameters for the factories. The strategy to achieve their luminosity goals is common to many factory designs: (1) high beam current of several amperes with many bunches, (2) short bunch length and small β^* at the interaction point, and (3) a double ring collider in most cases. In order to realize these conditions, many challenging tasks are placed on the RF system. Most of the challenges concerning the RF systems result from extremely heavy beam-loading.

2 HOM DAMPING

HOM impedance A very high beam current can cause strong coupled-bunch instabilities. The growth rate of any coupled-bunch instability must be smaller than the damping rate, or at least smaller than the level where the instability can be suppressed by a bunch-by-bunch feedback system or other methods. The higher-order mode (HOM) impedance must be sufficiently reduced to typically below 1 kΩ per cavity for any monopole modes, and a few kΩ/m for dipole modes. The Q-values should be reduced to typically below 100, which is nearly two orders of magnitude lower than those achieved with antenna-type HOM couplers.

Damped structure Several types of heavily damped cavity structures have been proposed and studied around the world. This report does not review all of them, but discusses only those which have and are being developed for the factories.

The methods for extracting energy from the cavity can be classified as follows: (1) by using widely opened beam pipes; (2) by using wave guides, the cut-off frequencies of which are above the fundamental mode, but below the lowest HOM; and (3) by using a coaxial or radial line with a notch filter which rejects the operating mode.

The first scheme allows for a simple structure, and is favorable for superconducting (SC) cavities. It is used for the KEKB [10] and CESR-B [11] single-cell SC cavities. Inside the beam pipe HOM absorbers are attached. In order to damp the lowest frequency dipole modes, one beam pipe is further enlarged (KEKB cavity), or a fluted beam pipe [12] is adopted (CESR-B cavity). The second method is used in many normal-conducting (NC) damped cavities, including PEP II [13] and DAΦNE [14]. The third scheme was originally independently proposed for linear colliders [15] and for a crab cavity [16]. This method is currently being considered for the KEKB NC cavity [17]. For damping scheme 2 or 3, additional dampers may be needed to absorb high-frequency waves that are coupled-out via the beam pipes. They are being considered for the DAΦNE and KEKB NC cavities.

The damping properties have been studied using computer codes and measurements. The agreement is usually good, and sufficient damping has been obtained with these damping schemes.

HOM absorber The beam-induced power going to the HOM absorbers amounts up to 10 kW per cavity. The HOM absorber is required to have the following properties: wide band, low-reflection, handling 1 — 10 kW, working in vacuum at a low outgas rate.

The DAΦNE cavity uses a broadband waveguide to coaxial transition, so that the HOM power is dissipated in the air

Table 1: RF-related parameters for the e^+e^- factories, together with the LHC

Factory	DAΦNE	BTCF †	KEKB		PEP II		CESR-III	LHC
Physics	phi	tau-charm	B (asymmetric)		B (asymmetric)		B	p-p col.
No. of Rings	2	2	2		2		1	2
Particle	e^+, e^-	e^+, e^-	e^+	e^-	e^+	e^-	e^+ and e^-	p, p
Beam energy (GeV)	0.51	2.0	3.5	8.0	3.1	9.0	5.3	7 TeV
Circumference (m)	97.69	384	3016		2199		768	26659
Revolution freq (kHz)	3069	780	99.4		136.3		390	11.2
Luminosity (10^{33} /cm^{2}s)	0.53	1	10		3		1	10
Total current / ring (A)	1.4 (∼5)	0.57	2.6	1.1	2.25	1.0	0.5 + 0.5	0.53
No. of Bunches	30 (120)	29	∼5000		1658		45	2800
Particles/bunch (10^{10})	9.0	16.0	3.3	1.4	6.0	2.8	17.8	10.5
Momentum compaction	0.0058	0.027	$1 \sim 2 \cdot 10^{-4}$		0.0012	0.0024	0.0114	$2.9 \cdot 10^{-4}$
Energy damping (msec)	17.8	15.5	43/23	23	30	18.3		12.5 hours
Bunch length (cm)	3.0	1.0	0.4		1.0	1.15	1.7	7.5
β_x^* (m)	4.5	0.5	0.33		0.5	0.67	1.0	
β_y^* (m)	0.045	0.01	0.01		0.015	0.02	0.018	
Crossing angle (mrad)	±12.5	0	±11.0		0		± ∼2	
RF frequency (MHz)	368.3	500	508.9		476		500	400.8
RF voltage (MV)	0.26	6.8	9.4	16.2	5.1	14.0	7.2	16
Synchrotron tune	0.0078	0.093	0.02	0.02	0.033	0.045		0.0019
Rad. loss power (MW)		0.095	4.0	3.8	1.62	3.58		
Parasitic loss (MW)		∼0.1	0.57	0.14				
Total beam power (MW)	0.03(0.08)	∼0.2	4.5	4.0	1.85	3.73		0.26†††
Cavity type	NC	SC	NC or SC††		NC	NC	SC	SC
No. of Cavities	1	3	20††	10††	6	20	4	8
R/Q (Ω/cav.)††††			15	93	230	230	89	89
Q_0	30000		130000	$\sim 10^9$	30000	30000	$\sim 10^9$	
Q_L	5000		36000	50000	6522	6522	2×10^5	
Coupling β	5		2.7	-	3.6	3.6	-	
Voltage / cav. (MV)	0.26	2.2	0.47	1.6	0.85	0.70	1.8	2.0
Input power / cav. (kW)			355	∼400	413	256	325	176
Wall loss / cav. (kW)	19	-	130	-	103	70	-	-
No. of Cav. / klystron	1	1	2	1	2	4	1	2 or 1
No. of Klystrons	1	3	10	10	3	5	4	4 or 8
Klystron power (kW)			760	∼400	859	1067	325	
First collision	∼1996		∼1998		∼1998		∼1998	

† — Machine parameters for other tau-charm factories are similar. The Beijing tau-charm factory, BTCF, has four phases: standard, small crossing angle, monochrometer, and polarized beam collision. The standard phase is shown here.
†† — The NC case for LER (e^+) and the SC case for HER (e^-) are presented below for KEKB, although no decision has yet been made.
††† — The power necessary to ramp the energy from 450 GeV to 7 TeV in 20 minutes.
†††† — $R/Q = V^2/PQ = V^2/\omega U$.

via a ceramic feedthrough [18]. The CESR-B and KEKB SC cavities use a ferrite material, bonded by brazing (CESR-B) or by the hot isostatic press HIP method (KEKB) to the beam pipes. The absorbers have been tested up to 15 kW in the air [19] and 7 kW in vacuum [20]. The PEP II cavity uses an Al-N ceramic, and the KEKB NC uses a SiC ceramic for the load. The absorbers have been tested up to 3 kW in vacuum [21], [22].

3 INSTABILITY DRIVEN BY THE ACCELERATING MODE

Growth rate In a large-circumference ring, the accelerating mode itself can cause strong longitudinal coupled-bunch instabilities with a coupled-bunch mode of -1, -2, and so on. The growth rate can be very high due to the high impedance of the accelerating mode. A key issue for the B-factory RF system is how to avoid this instability, whereas this is no problem for the phi and tau-charm factories.

In storage rings, the resonant frequency of the cavities should be detuned toward the lower side in order to compensate for the reactive component of the beam loading. Without this detuning, a large amount of RF power is reflected from the cavity, and extra power is required. The detuning frequency (Δf) is given by

$$\Delta f = \frac{I \sin \phi_s}{2V_c} \times \left(\frac{R}{Q}\right) f = \frac{P_b \tan \phi_s}{4\pi U}, \qquad (1)$$

where f is the RF frequency, I the beam current, ϕ_s the synchronous phase, V_c the cavity voltage, P_b the power to the beam, and U the stored energy in the cavity. If a high beam current is stored in a large storage ring, such as B-factories, Δf can be comparable to, or even exceed the revolution frequency. The coupling impedance at the upper synchrotron sideband of the revolution harmonic frequencies becomes significantly high. The growth time can be on the order of 10 — 100 μsec, which is much faster than the radiation damping time.

High stored energy The strategy to conquer this instability is completely different between the KEKB and PEP II factories. At KEKB, Δf is reduced by increasing the stored energy of the cavities, as shown in Eq. 1. There are two possible ways in this direction. The use of a SC cavity is a straightforward solution, since it can be operated at a high accelerating voltage. Another solution is to use the accelerator resonantly-coupled with an energy storage (ARES) NC cavity system [23]. The ARES is a three-cavity system where an accelerating cavity is resonantly coupled with an energy-storage cavity operating in a high-Q mode via a coupling cavity in between. This system increases the total stored energy by an order of magnitude, while the cavity dissipation power is kept at a reasonable level. By using the SC and/or the ARES, the growth rate becomes smaller than the radiation-damping rate in KEKB [2].

Feedbacks The other way to avoid this instability, that the PEP II proceeds, is by using a combination of feedback loops: a direct loop, a comb filter loop, and a bunch-by-bunch feedback system [24]. Since the bandwidth of the direct loop is restricted by the total group delay, a short klystron group dalay and/or a phase equalizer are required. The comb filter loop provides an additional reduction over a narrow band about each upper synchrotron sideband. Together, these two loops bring growth rates down from a few microseconds to several milliseconds. Test measurements and simulation work have shown that the driving impedance can be reduced from 760 kΩ to 10 kΩ [25].

4 HIGH-POWER HANDLING

A high beam current requires a large amount of power to be transfered to the beam: on the order of MW for the B-factories and several hundred kW for the phi and tau-charm factories. On the other hand, the required RF voltage is typically 5 - 20 MV or less. The voltage is much lower than that of colliders at the energy frontiers, although it is relatively high compared to the radiation loss so as to provide a short bunch length. In addition, in view of reducing the total impedance in the ring, it is desired to have the smallest number of cavities as possible. As a result, each cavity should provide several hundred kW to the beam, which is much higher than that at the energy-frontier colliders. The RF power-handling capability of each cavity system should be improved to a large extent.

The availability of high-power sources and other high-power components has mainly lead to choosing RF frequency of 350 — 500 MHz. One MW-class of CW klystrons, circulators, and dummy loads are already available, or are being developed at these frequencies.

The most challenging part in this regard are RF input couplers for cavities. Intensive R&D is in progress, and recent test results encourage us. The input coupler for the KEKB SC cavities is a coaxial type, the same as that had been used for the TRISTAN SC cavities, but with a small modification. Two couplers, back-to-back assembled in a test bench and evacuated, have been tested up to an 850 kW throughput power [26]. The input coupler for PEP II uses a disk window in a waveguide. Two windows have been tested up to a 500 kW throughput power [21].

Because of the complicated structure required for HOM damping, the wall dissipation at the NC cavities can be concentrated on a particular location: for example, around the contact region between the HOM waveguide and the cavity. Careful studies concerning thermal-stress analyses and cooling system design have been conducted. High-power tests have been carried out in recent years: up to 150 kW for the KEKB NC cavity, 120 kW for the PEP II cavity [21], and 26 kW for the DAΦNE cavity, all which are well beyond the nominal operating points.

While these test results are successful, it should be noted that yield rate in mass production, and system reliability in a long-term operation are still issues for the factories.

5 CONTROL ISSUES

Among the many functions of low-level RF control system, we discuss here several points which are characteristic of high-intensity factories.

5.1 Phase control

The RF phase should be controlled with an accuracy of typically one degree. In a double ring collider a phase error of one ring relative to the other gives rise to a displacement of the colliding point. For those factories with a short bunch length and small β^*, even a small phase error reduces the lunimosity, due to the hourglass effect.

Another reason is that a phase error in one cavity among two or more in the ring causes extra input power to that cavity due to heavy beam loading. For example, if the phase of one KEKB SC cavity is different from the others by one degree, an extra power of 30 kW is fed to that cavity to keep the cavity voltage constant.

We can take advantage of the heavy beam-loading by measuring the input power and controlling a low-level phase shifter so that the power to each cavity is balanced.

5.2 Bunch gap transient

In order to avoid ion-trapping in the electron ring, a bunch gap will be introduced at KEKB and PEP II. The bunch gap, however, modulates the longitudinal bunch position. It changes the colliding point bunch-by-bunch, and can reduce the luminosity. The 5% gap in PEP II changes the bunch phase by 10 degrees, which corresponds to 17 mm, which is larger than the bunch length.

The LHC beam also has bunch gaps. Although the displacement of the colliding point in LHC is negligible compared to the bunch length, the phase modulation causes capture losses during injection.

The phase modulation ($\Delta\phi$) is approximately given by [27]

$$\Delta\phi = \frac{\omega}{2V_c}\frac{R}{Q} \times I\Delta t = \frac{P_b \Delta t}{2\cos\phi_s U}, \qquad (2)$$

where Δt is the length of the gap. Again, it is inversely proportional to the stored energy: a high stored energy is beneficial to reduce the phase modulation.

The displacement of the colliding point can be reduced by introducing a corresponding gap in the positron ring, so that it makes a similar phase modulation. The compensation gap reduces the relative displacement to below 0.5 degree in KEKB, which is acceptable [28]. In addition to the compensation gap, the same input coupling factor was set for both rings in PEP II. The relatively large phase modulation is then reduced to an acceptable level [29]. At LHC, the generator power will be modulated so as to suppress the phase modulation at injection [9].

5.3 Robinson stability

The ratio of the beam-induced voltage on resonance (V_{br}) to the cavity voltage (V_c), $Y = V_{br}/V_c$, reflects the beam-loading effect on the RF system. For the factories we should operate in the region $Y = 2 \sim 5$, where a small margin exists for the stability criterion. Without a sufficient margin, the system can be unstable, due to a transient effect or cross talk between the amplitude control loop and phase lock loop [30].

The system must be operated stably under the heavy beam loading. An appropriate choice of the parameters, such as the loaded-Q value and/or the tuning angle, can relax the stability margin to some extent. The stability margin can be further increased by a direct RF feedback loop, which reduces the coupling impedance seen by the beam [31].

5.4 Trip occasion

In order to protect the cavities, klystrons, and other high power components on the occasion of abnormal operating conditions, the klystron station should be switched off by interlocks. In some factories with relatively small number of klystrons, any klystron trip will result in dumping the beam. In other factories, one might want to keep the beam, even if one (or more) station trips. In this case, followings are necessary: (1) each station should provide additional power to make up for the tripped one; (2) the tripped cavities should be immediately detuned to a safe frequency (without this, a beam power of several hundred kW is induced); and (3) a recovery procedure should be established to switch on the tripped station under the circulating beam, after the cause of trip is solved.

6 CRAB RF SYSTEM

For factories with finite angle crossing, it is a critical issue whether the luminosity and/or beam lifetime are degraded by beam-beam effects. The crab-crossing [32], [33] is considered to be a viable fall-back solution to the potential problems encountered with the finite angle crossing for KEKB.

The requirements for the crab cavity are: (1) to provide a high transverse deflecting voltage; and (2) to be a damped cavity. In addition to HOMs, there are lower-order parasitic modes to be damped: the fundamental TM010 mode and unwanted polarization of the crabbing mode.

A superconducting squashed-crab cavity operating in the TM110 mode was developed under the KEK-Cornell collaboration [16]. By using a coaxial beam pipe together with an extremely polarized cell (“squashed” cell), all monopole and dipole parasitic modes are damped, including the fundamental TM010 mode and the unwanted polarization of the TM110 mode. The crabbing mode, the frequency of which is below the cut-off of the dipole mode in the coaxial beam pipe, is trapped in the cavity. A notch filter is attached at the coaxial beam pipe to reject any TEM-coupled components of the crabbing mode caused by some asymmetry due to machining errors or misalignment.

The R&D efforts are being continued at KEK, aiming at fabricating full-scale niobium cavities.

7 BEAM TESTS

CESR beam test The prototype SC cavity for CESR III was tested in CESR in 1994. The total required voltage of 7.5 MV was provided by CESR NRF cavities (6 MV) and the SC cavity (1.5 MV). The maximum stored current was 220 mA (in 27 bunches), the limitation of which was not due to the SC cavity, but due to heating of the ring components. The maximum power transfered to the beam was 155 kW. Up to 2 kW HOM power was absorbed by the ferrite absorbers [34].

LHC cavity test in SPS A prototype SC cavity was tested in SPS with a proton beam. It was operated at 1 MV and the peak current was 100 mA. The limitation was due to the power source (tetrode amplifier) [35].

KEKB cavity test in TRISTAN-AR Beam tests of the KEKB SC cavity and the ARES NC cavity are progressing at TRISTAN-AR. The first part of the test, aimed at storing 100 mA, ended successfully. The accelerating voltage was provided by the SC, or the ARES alone. The SC cavity stored a 110 mA single bunch beam, providing 2.3 MV. The limitation of current was not due to the SC cavity performance. The SC cavity also stored a 60 mA beam continuously for 10 hours without any trip at 2.0 MV. The accelerating cavity of the ARES stored a 110 mA two-bunch beam, providing 0.5 MV. Although in the begining the SC cavity performance was degraded due to too a bad vacuum pressure during a ring-conditioning operation, it was completely recovered after warming-up to 70 K in order to degass adsorbed gas on the surface.

In June, all of the existing APS NC cavities, which have been used for user runs, will be removed, so that the stored current can be increased up to 500 mA. The full ARES (with the storage cavity) system will be installed during the summer shut down in order to be tested this autumn.

8 SUMMARY

The main challenging tasks for the factory RF systems to realize the required high luminosity include: (1) development of heavily HOM-damped cavities, (2) a cure for the coupled-bunch instability driven by the accelerating mode (in B factories), (3) high-power handling capability, (4) accurate phase control and cure for the bunch gap transient, and (5) carefully designed low-level control system. Effective approaches to these challenges have been identified at each factory and R&D activities have been intensively persued. Successful results in simulation studies, high-power bench tests, and beam tests have proven the design validity and system reliability. The next step is to commission and operate the systems in the factories.

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