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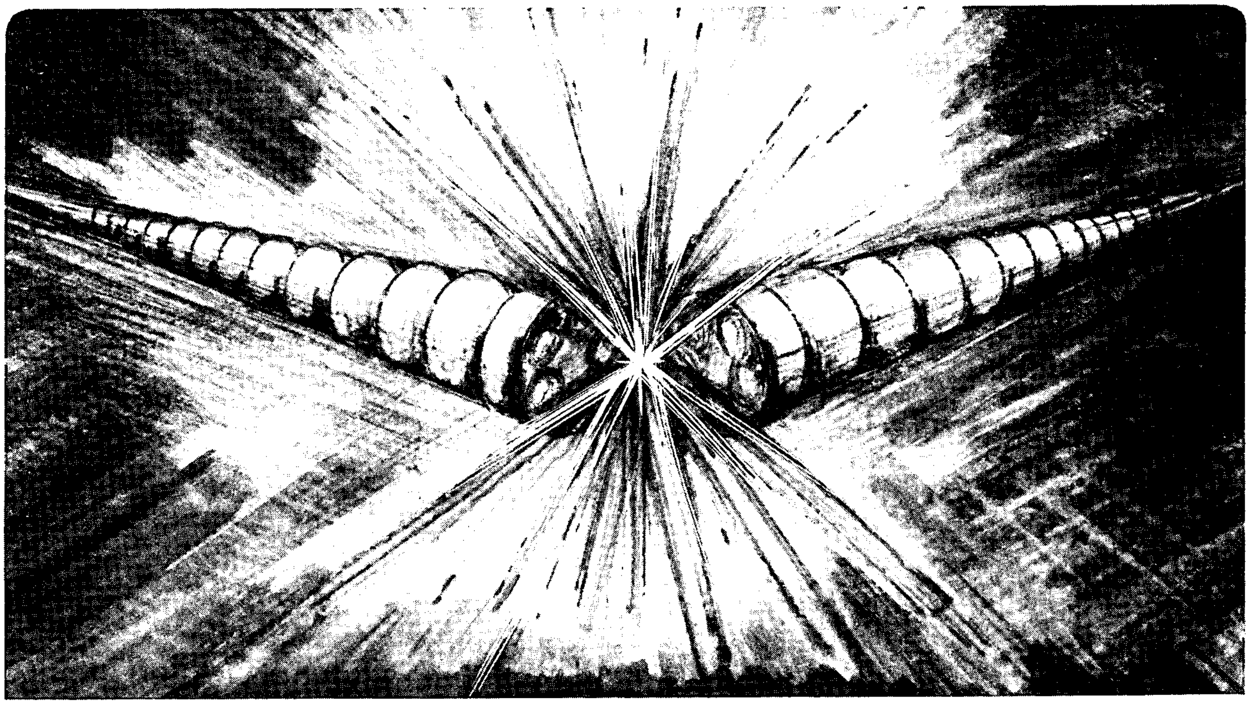

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B Factory RF System Design Issues*

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B Factory RF System Design Issues†

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ABSTRACT

We discuss the issues of relevance to the design of a B factory RF system. First, the general parameter regime is outlined, and the reasons behind certain commonly made choices are indicated. This regime involves high beam currents, and many relatively short bunches. Next, the physics difficulties associated with coupled-bunch instabilities are described briefly. We then describe in general terms the alternative approaches taken by various B factory designers, the motivation for these choices, and the technical issues raised by them. Technical solutions have been proposed for both the room-temperature and the superconducting RF scenarios, and considerable R&D is being carried out worldwide to confirm and optimize these solutions.

1. INTRODUCTION

In recent years, a number of groups have carried out in-depth studies aimed at the design of an asymmetric B factory collider. Such a collider requires two independent rings, operating at different beam energies, with a common interaction region (IR). To carry out experiments that probe the origins of CP violation in the B meson system, an asymmetric B factory must deliver very high luminosity, a typical design goal being $\mathscr{L} = 3\times10^{33}$ cm^{-2} s^{-1}. Reaching this luminosity requires very high beam currents and large numbers of short bunches, and thus places severe demands upon the collider RF systems. It is important to note that the actual "figure of merit" for a B factory is the *integrated* luminosity, which means that a high premium must be placed on reliability of the RF system. Designs based on either conventional room-temperature (RT) or superconducting (SC) RF technology have been studied by various groups. Here we describe the two alternative approaches and the technical issues that must be dealt with for each of them to operate reliably in the B factory parameter regime.

2. PARAMETER REGIME

For equal beam sizes at the interaction point (IP), and equal beam-beam tune shifts for both beams in both transverse planes ($\xi_{1x} = \xi_{1y} = \xi_{2x} = \xi_{2y} = \xi$), the luminosity can be written as [1]

$$\mathscr{L} = 2.17\times10^{34}\,\xi(1+r)\left(\frac{I\cdot E}{\beta_y^*}\right)_{1,2}\ [\mathrm{cm^{-2}s^{-1}}] \qquad (1)$$

where $r = \sigma_y^*/\sigma_x^*$ is the beam aspect ratio, I is the total beam current, E is the beam energy in GeV, and β_y^* is the vertical beta function at the IP in cm.

In practice, the limitation from the beam-beam interaction is expected to restrict the maximum beam-beam tune shift to $\xi \approx 0.03$–0.05, and this is the range that has been adopted by most B factory designers [1–6]. Because there is no present experience with an asymmetric e^+e^- collider, some caution is warranted, and it has generally been considered prudent to base the collider design on a value of $\xi = 0.03$. With this choice, attaining the design luminosity requires that the quantity $(I\cdot E/\beta_y^*)$ in Eq. (1) be 4.6. For a typical β_y^* value of 1.5 cm and $E = 8$ GeV, a beam current of $I \approx 1$ A results for the high-energy ring (HER). In the low-energy ring (LER), a higher beam current of $I \approx 2$ A is needed at $E = 3.5$ GeV.

For the parameters above, we see that the luminosity determines the *total* beam current but does not constrain the number of bunches (or, equivalently, the bunch separation distance, s_B). The number of bunches to be used depends on details of the collider design and the separation scheme selected. For a given beam-beam tune shift, having fewer bunches means a larger beam emittance is needed, and this parameter is ultimately

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limited by the magnet apertures deemed cost effective. In the various B factory designs, the bunch separation distance lies in the range of 0.6–4.2 m, with corresponding numbers of bunches ranging from a few hundred to a few thousand. As will be discussed below, however, the coupled-bunch beam instabilities that must be handled are sensitive mainly to the total beam current, and not to the number of bunches.

To avoid degradation of the luminosity due to the "hourglass effect," it is important that the rms bunch length be less than the smallest beta value at the IP ($\sigma_\ell \leq \beta_y^*$). This means that a typical bunch length of 1 cm is needed. For a given lattice, the bunch length scales with RF parameters as

$$\sigma_\ell \propto \left(V_{\mathrm{RF}} f_{\mathrm{RF}}\right)^{-1/2} \tag{2}$$

Although both voltage and frequency are in principle free parameters, the commercial availability of high-power (≈1 MW) klystrons at 500 MHz has led all B factory designers to opt for this choice. At this frequency, the voltage required for the various B factory designs ranges from 7–35 MV to produce bunches with a length of about 1 cm. It is worth noting that, all else being equal, a bunch length of 0.5 cm requires an RF voltage four times higher than for a 1-cm bunch.

The other important requirement for the RF system is to replenish the beam power lost due to synchrotron radiation. The required power (in kW) is given by

$$P_{\mathrm{SR}} = \frac{88.5E^4 I}{\rho} \tag{3}$$

where ρ is the bending radius of the dipoles and the other symbols were defined previously. A typical bending radius for the HER of a B factory is $\rho \approx$ 100 m, in which case the required power is in the range of 3–5 MW at a beam current of 1 A. Published RF parameters for the high-energy rings of various projects are given in Table 1. Because each project makes different assumptions about the beam-beam tune shift, and hence the required beam current to reach a given luminosity, comparisons must be made carefully. Note that some rings require mainly voltage (KEK), some rings power (PEP-II), and some rings both (CESR-B).

Table 1. Required RF Parameters for B Factory HER.

Project	$\mathcal{L}$ (10^{33})	V_{RF} (MV)	f_{RF} (MHz)	σ_ℓ (cm)	P_{SR} (MW)
BFI	1	13	498	2	3.1
CESR-B	3	35	500	1	4.5
DESY	3	17	500	1	2.4
INP	5	7	500	0.8	1.9
KEK	2	48	508	0.5	0.9
PEP-II	3	19	476	1	5.3

3. THE PROBLEM

The difficulty with the high beam currents required for a B factory is associated with coupled-bunch instabilities. The high beam current gives rise to strong wakefields in the RF cavities. Because the higher-order modes (HOMs) of the cavities have high Q, these wakefields are still present during the passage of subsequent bunches and so the motions of all bunches become coupled [7]. The effects of the cavities on the beam are quantified in terms of the HOM impedances:

$$R = n_{\mathrm{cell}}\left(\frac{R_s}{Q}\right)Q \tag{4}$$

The instability growth rates are proportional to the real part of the complex impedance sampled by the beam. For stable operation of the collider rings, it is necessary to reduce the instability growth rates below the radiation damping rate. If this cannot be accomplished, a feedback system can be used to control the remaining instability growth (limited, of course, by the capabilities of a practical feedback system).

There are several approaches to reducing the HOM impedance seen by the beam:

- reduce the number of RF cells
- reduce R_s/Q
- reduce Q
- all of the above

The particular choices made depend on the collider parameters and the RF technology being used.

As can be seen in Fig. 1, it is generally impractical to avoid the HOM impedance in the B factory parameter regime (large ring circumference, short bunches). The beam samples the impedance at harmonics of the revolution frequency (vertical lines in Fig. 1), with a strength that is weighted by the power spectrum of the beam

$$h(\omega) \propto \exp\left[-\left(\frac{\omega\sigma_\ell}{c}\right)^2\right] \tag{5}$$

Thus, short bunches can see impedance up to quite high frequencies, e.g., a 1-cm bunch corresponds to a frequency of $f \approx 5$ GHz. For typical B factory rings, the rotation frequency is $f_0 \approx 0.1$–0.4 MHz, so an HOM at $f = 1$ GHz must have $Q \geq 10^4$ to have a chance to fully avoid the beam harmonics.

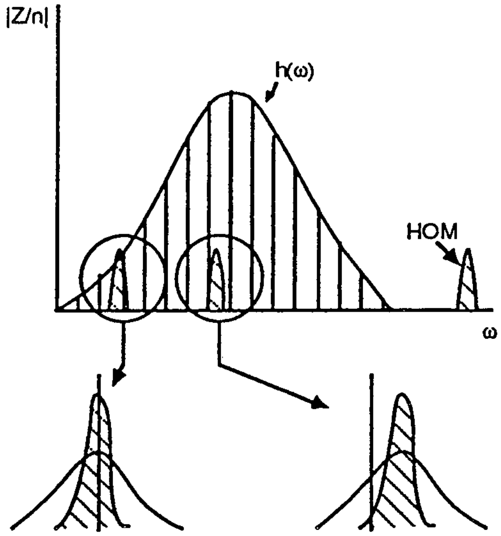

Fig. 1. Schematic diagram of impedance sampled by coupled bunches.

4. APPROACHES AND ISSUES RAISED

It is obvious that reducing the number of RF cells is advantageous from a cost standpoint. There are two issues that determine the minimum number of cells that can be used:

- limitations on achievable gradient
- limitations on input power

How few cells can be used in a particular design depends on the RF technology employed, and also on whether the parameters are limited by the gradient or the input power. In the latter case, the number of cells that must be used is about the same for either room-temperature or superconducting technology. This is because the high beam current in a B factory leads to an RF system that is heavily beam loaded—about two-thirds of the RF power goes into the beam even in the case of a room-temperature RF system. If the input power limitation for both technologies is similar, the required number of cells will not be too different.

For a room-temperature RF system, reducing the number of cells leads to high gradients and thus to high power dissipated in the cavity walls. The wall power is given by

$$P_{\text{wall}} = \frac{V_{\text{cell}}^2}{2R} \tag{6}$$

For a voltage per cell of 1 MV and a shunt impedance of $R = 5$ MΩ, $P_{\text{wall}} = 100$ kW. The PEP-II cavity design [1] calls for a dissipated power of 150 kW per cell. To put this value in context, we note that the RF cavities for the Advanced Light Source (ALS) at LBL have been tested (without beam) to a power level of 60 kW/cell. The temperature and stress effects of the high dissipated power are straightforward to calculate with three-dimensional finite-element codes. Still, it is prudent to test a high-power model cavity.

A second issue associated with using a minimum number of RF cells is that the power through the cavity input window becomes very high. For both room-temperature and superconducting cavities the aim is to provide a window capable of transmitting about 500 kW. In either case, but especially for a superconducting system, the consequences of a window failure are very severe and must be avoided in order to maintain the "factory-like" operational reliability needed to produce the desired integrated luminosity. It is worth noting here that proper designs for high-power tuners and couplers are also challenging, especially in terms of reliability.

Reducing the R/Q of the HOMs is easier with superconducting than with room-temperature cavities. This is because the quantity R/Q is mainly a geometrical parameter, and shape changes are needed to reduce it. In practice, such shape changes (illustrated in Fig. 2, taken from Ref. 5) tend to lower the

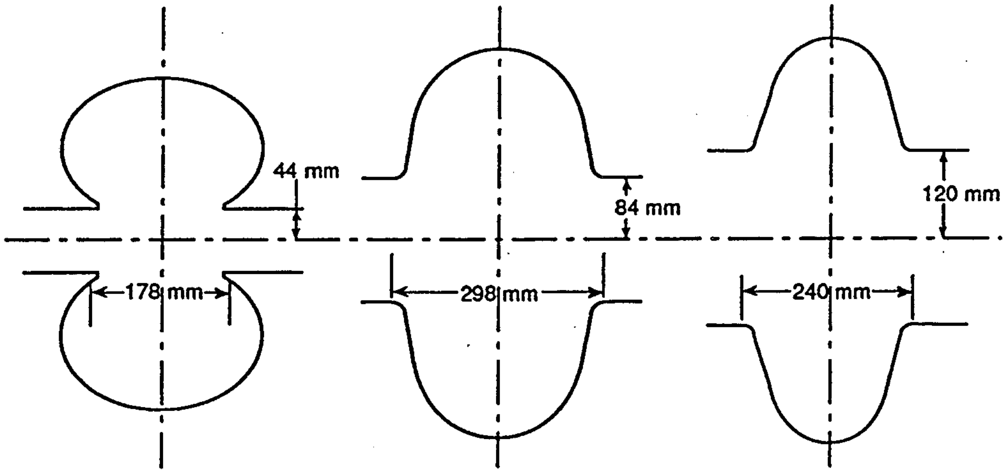

Fig. 2. Schematic cavity shapes for RT (left), standard SC (center), and B factory SC (right) cases, from Ref. 5.

fundamental shunt impedance unacceptably for a room-temperature system. Superconducting cavities for a B factory use a large bore tube to permit the unwanted HOMs to "leak out" into the beam pipe where they can be damped. For a particular HOM, it is also possible to make a judicious choice of cavity length that gives a favorable transit-time factor. As suggested by Fig. 2, the large aperture of the B factory SC cavity also helps in reducing the impedance of transverse HOMs.

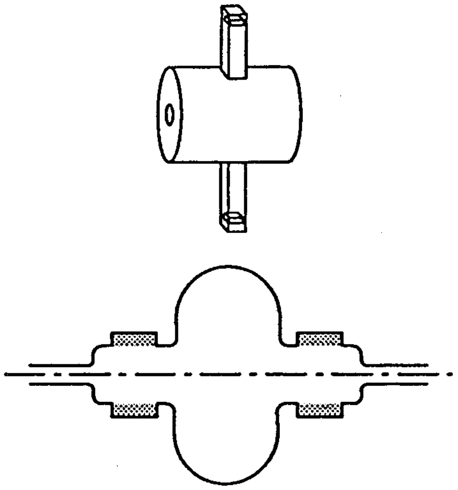

Fig. 3. Illustration of RT (top) and SC (bottom) cavity damping approaches.

For either RT or SC RF, the main game is to damp the HOMs. Present designs based on single- or two-cell cavities aim for damping the HOMs to $Q \approx 50$. A similar damping concept (illustrated in Fig. 3, from Ref. 2) is used with either RF technology, though the details differ somewhat. In both cases, the damping loads must be broadband, and must be capable of dissipating on the order of 10 kW of HOM power.

In the room-temperature RF case, the damping is accomplished by attaching waveguides, having damping loads at their ends, to the cavity body. The waveguide dimensions are chosen such that the cavity fundamental mode is below cut-off, and thus does not propagate to the loads. The waveguides must be located such that they couple to all dangerous HOMs. Typically, the proper location for the waveguides is determined from three-dimensional electromagnetic codes, and verified experimentally with model cavities.

The same damping technique is not directly applicable in the superconducting case, because penetrations in the cavity body must be avoided. Thus, a variant of the above approach is employed in which the beam tube aperture is enlarged sufficiently that all modes above the fundamental are not trapped in the cavity. The damping loads in this case are rings that are located in the beam chamber.

In the room-temperature approach, as exemplified in Fig. 4 for the PEP-II design, the main problems associated with the damping scheme are that the thermal loads at the waveguide penetrations can be difficult to cool. Furthermore, there is a concern about the possibility of multipactoring in the waveguides.

In the superconducting approach, as illustrated in Fig. 5 for the CESR-B design, the damping loads (ferrites) are visible to the beam and may get warm. The open

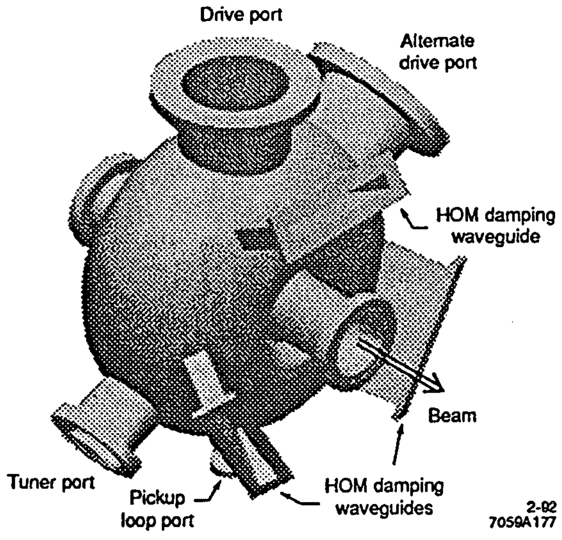

Fig. 4. RT cavity design (low-power model) for PEP-II, from Ref. 1.

geometry means that the heat source is directly visible to the cryogenic surfaces and could lead to quenching. It will also be important to understand the resistive wall effects of the damping material (which requires that the electromagnetic properties of the material be known at low frequencies, near $f_0/2$). Because ferrites are potentially dusty materials, it is important that the load be produced in such a way that dust cannot migrate into the cavity.

There are a few other issues that arise in the design of a B factory RF system. For superconducting cavities, the operational experience at TRISTAN [8] is that the cavities closest to the arcs are most prone to quenching. Thus, the sensitivity of high-gradient superconducting cavities to synchrotron radiation under *operating* conditions must be assessed. Similarly, the present experience [9] with superconducting RF in operating accelerators is that the operating gradient is only about half that reached in tests without beam. It is not entirely clear what causes the degradation. The key point is to understand how to arrive at a prudent design gradient for a B factory superconducting cavity in the absence of a high-current test facility.

Especially for a room-temperature B factory RF system (and to a lesser extent for a superconducting system as well), beam-loading compensation requires significant detuning of the cavity fundamental. The detuned fundamental mode can then strongly drive coupled-bunch modes near $m = 0$ unstable. Because of the high impedance of the fundamental mode, special feedback systems operating on the cavity are needed to deal with this situation. Among other things, it is necessary to have "extra" klystron power available for feedback purposes. A description of this issue can be found in the talk by Pedersen at this Conference [10]. Because the spacing between rotation harmonics increases as the ring circumference decreases, a large ring is more sensitive to this effect than a smaller one.

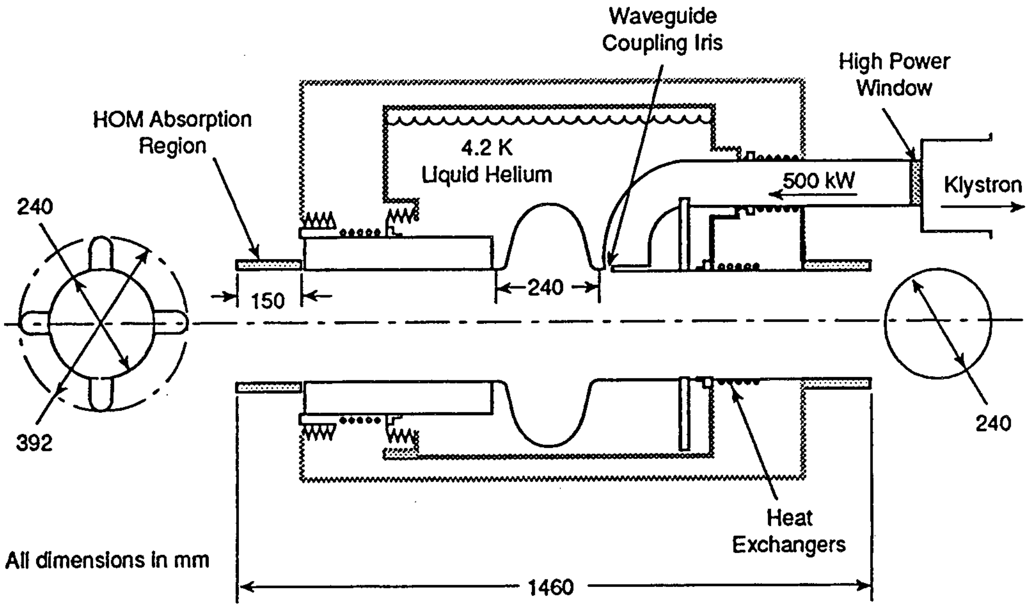

Fig. 5. B factory SC RF cavity, taken from Ref. 5.

5. CONCLUSIONS

It is clear that the B factory parameter regime (high beam current, short bunches, high input power, stringent HOM damping) offers considerable challenge for RF system design. Solutions to the various issues have been worked out for both room-temperature and superconducting RF systems, and R&D activities to confirm and optimize design choices are under way at many laboratories worldwide. It is important to recognize from the outset that operational reliability is crucial to the successful performance of a B factory. Thus, it is paramount to avoid getting "too close to the edge" in the design of the RF system.

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