

PRELIMINARY ESTIMATE OF THE B-FACTORY IMPEDANCE*

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ABSTRACT

A preliminary impedance budget for the B-factory is given. The appendix summarizes the possible designs of bellows.

INTRODUCTION

The impedance is one of the main parameters of a B-factory. An accurate estimate of the impedance is hardly possible without bench measurements, and, especially, on the present step of the machine design. On the other hand, it is now or never if we are to influence the design of the machine to minimize its impedance.

This note gives a preliminary estimate of the impedance. It summarizes the information which I have collected from numerous discussions with B. Bartella, M. Calderon, A. Hutton, G. Lambertson, P. Morton, A. Lisin, J. L. Pellegrin, H. Weidner, P. Wilson, M. Zisman and others on different aspects of the problem.

The PEP experience can be taken as a basis. To describe the beam loss J. N. Weaver^{1,2} introduces the loss resistance Z_r related to the beam power loss P in the higher order RF modes (HOMs):

$$P = I_{av}^2 Z_r = eN_B k_l I_{av}, \quad Z_r = k_l / (n_B f_{rev}).$$

Here k_l is the loss parameter k_l (the energy loss per electron in eV in a bunch with a charge of one coulomb), N_B is the number of particles per bunch, n_B is number of bunches in a beam, $I_{av} = n_B e N_B f_{rev}$ is the average beam current, and $f_{rev} = c / (2\pi R)$ is the revolution frequency.

The PEP RF cavities give the main contribution to Z_r : $Z_{RF} = 58.7 \text{ M}\Omega$. The rest gives $Z_{vac} = 24.5 \text{ M}\Omega$. With the PEP parameters $n_B = 6$, $f_{rev} = 136.6 \text{ kHz}$, Z_{vac} corresponds to $k_l = 20 \text{ V/pC}$.

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Criteria of stability of coherent motion usually uses the low-frequency limit of the longitudinal impedance $Z(n)/n$, where n is the harmonic number $n = \omega/\omega_{rev}$. This quantity can be estimated from the result of the numeric code TBCI which gives the loss parameter k_l . To obtain Z/n from k_l we use a relation between the loss parameter of a Gaussian bunch with rms length σ and the longitudinal impedance $Z(k)$:

$$k_l = 4 \int_0^{\infty} dk \left(\frac{Z(k)}{Z_0} \right) e^{-k^2 \sigma^2}, \quad k = \omega/c.$$

Consider the model frequency dependence:

$$\frac{Z(k)}{kR} = \begin{cases} \frac{Z(n)}{n}, & \text{if } \omega < \omega_{cut}; \\ \frac{Z(n)}{n} \left(\frac{\omega_{cut}}{\omega} \right)^{3/2}, & \text{otherwise.} \end{cases}$$

Here the cutoff frequency is related to the beam pipe aperture $\omega_{cut} \simeq c/a$. The model gives the relation:

$$\left(\frac{Z(n)}{n} \right) = 60.0 \frac{a}{R} \sqrt{\frac{a\sigma}{(cm)^2}} \frac{k_l}{V/pC} [\Omega].$$

(Notice that for a step and a taper, where loss is dominated by the high frequency contribution, impedance is frequency independent above cutoff. In this case

$$\frac{Z(n)}{n} = \frac{Z_0}{2\sqrt{\pi}} \frac{\sigma^2}{R} k_l.$$

However, for the preliminary estimates we use the model described above for all elements, hopefully, without large errors for B-factory parameters.)

For PEP $R = 350$ m, $a = 5$ cm, $\sigma = 2.3$ cm. Then $k_l = 20$ V/pC due to the PEP vacuum chamber that corresponds to $Z(n)/n = 0.58 \Omega$. (For $\sigma = 1$ cm 1.0 V/pC that corresponds to $Z(n)/n = 0.019 \Omega$). We believe that the vacuum chamber of the B-factory can be also designed with such an impedance. That would be sufficient because bunch current in the B-factory is almost an order of magnitude lower than that of PEP.

IMPEDANCE GENERATING ELEMENTS

The RF cavities will be one of the main sources of the impedance of the B-factory. The PEP RF cavities have the loss factor 1.05 V/pC/cavity . Ten such cavities would give $k_l = 10.5 \text{ V/pC}$ that corresponds to $Z(n)/n = 0.29 \Omega$. This number should be compared with the contributions of other elements of the vacuum chamber to give a rough estimate for the contribution of the RF cavities to the impedance of the B-factory.

The B-factory comprises 12 half superperiods. Each of them consists of 7 normal 60° , 15.2 m FODO cells (one cell without sextupoles); 2 cells in the dispersion suppressor; and 3 cells in a straight section. The cells in a straight section and one of the cells in the dispersion suppressor do not have dipoles. For simplicity we consider all cells to be identical albeit maybe with a different number of dipoles. A normal cell contains 2 bends, 2 quads, and 2 correctors with sextupoles. The impedance generating elements in a cell are: 1 bellows, 2 lumped vacuum ports, 1 BPM, 5 flanges, and slots of the perforated wall for distributed pumps in bends and quadrupoles. One clearing electrode will be installed for each half of the betatron wavelength, 48 total. Straight sections will have a round 10 cm pipe while the vacuum chamber in the arcs has PEP hexagonal shape 6 cm high and 10 cm wide. That requires 12 tapers per ring between arcs and straight sections. There will be 14 valves per ring (a valve per half a superperiod and 2 valves in the interaction region (IR)). Feedback kickers and pickups give additional impedance, as do masking tapers and 2 crotches in the IR. Some elements (e.g., abort system), certainly, will be added later. All impedance generating elements per 1/12 of the ring (i.e., 12 cells of an arc and a straight section) are summarized in Table 1.

Table 1. Impedance generating elements in 1/12 of the ring

Flanges	60
BPM	12
Vacuum ports	24
Bellows	12
Clearing electrodes	4
Valve	1
Taper	1
Slots of the distributed pumps	$3 \cdot 10^4$

Impedance generating elements of a feedback system, injection system, collimators and IR should be added to the table.

MODELING OF THE IMPEDANCE GENERATING ELEMENTS

The bunch rms length $\sigma = 1$ cm is used for the estimates.

• A Flange

For the impedance estimate, a flange can be considered as a groove in the wall and be modeled as a tiny pillbox cavity with the inner and outer radii $a = 3$ cm, $b = a + 0.1$ cm, and the gap 0.25 mm. TBCI gives the loss factor for such a cavity $k_l = 2.46 \cdot 10^{-5}$ V/pC. The total contribution of the flanges is $k_l = 0.018$ V/pC/ring or negligibly small $Z(n)/n = 3.5 \cdot 10^{-4} \Omega$.

• A BPM

The 4-button design of the BPM from DESY is available. Unfortunately, there are no data on the impedance or losses for the device. The contribution of BPMs to the PEP impedance is negligibly small, below the accuracy of the measurements. We assume that it is true also in our case.

• A Vacuum Port

A vacuum port is shielded with a perforated screen. There are two possible designs of the screen: one is a honeycomb structure with 60 1.1 cm diameter holes, and another is a slot structure with 10 longitudinal slots 14 cm \times 0.2 cm. The second design is preferable.

For the estimate we use M. Sands' formula³ for the loss of N_h holes with a radius $r \ll \sigma$:

$$k_l = 7.15 \cdot 10^{-3} \left(\frac{r^6}{a^2 \sigma^5} \right) g N_h .$$

(Note that 1 V/pC = 1.11 cm⁻¹). Here a is the beam pipe radius, and $g = \sigma/l$ is the coherence factor depending on the average distance l between holes, $g \geq 1$. A similar formula for a long slot is unknown, but a narrow long slot is probably equivalent to 2 holes separated by the length of the slot. That gives $k_l = 5.1 \cdot 10^{-9}$ V/pC per one port for the slot design. The loss for the honeycomb design is by a factor of 4 larger. In both cases the total loss is negligibly small. For comparison, the loss of 300 PEP shielded pumps gives $k_l < 0.9$ V/pC.

• A Perforated Wall

The slots of the distributed pumps may be considered in the same way as slots of the lumped pumps. The perforation has 2 rows of 9 \times 0.2 cm slots. There are 10 slots per meter (M. Calderon), and $N_h = 3 \cdot 10^4$ slots per ring (assuming that 2/3 of the ring has distributed pumps). The total loss factor $k_l = 1.7 \cdot 10^{-5}$ V/pC/ring is negligibly small again.

The walls in the quads will have perforation on the top and bottom sides. The impedance is still negligibly small.

• A Feedback System

A stripline loop kicker for the feedback system is described elsewhere.⁴ The low frequency reactive impedance of 4 kickers and pickups of the feedback system is estimated to be $Z(n)/n = 0.05 \Omega$. That corresponds to $k_l = 2.51 \text{ V/pC/ring}$.

• Clearing Electrodes

Electrodes for extraction of trapped ions should provide voltage large in comparison with the average field 1.1 kV/cm of the beam. (A flat beam with the horizontal average $\beta_x = 25 \text{ m}$, $N_B = 4.15 \cdot 10^{10}$, and $\epsilon_x = 46 \text{ nm}$ is assumed here. The result for LER is about the same). The impedance of the clearing electrodes may be substantially reduced using RF filters and high resistivity coating of the surface.⁵ In this design $Z(n)/n = 0.0015 \Omega$ has been achieved in the frequency range up to 1 GHz per button-like electrode with OD 32 mm . 48 clearing electrodes of this type would give $Z(n)/n = 0.072 \Omega/\text{ring}$ what corresponds to 3.8 V/pC/ring . However, the scaling of this result to shorter bunches is not obvious. The coated electrode may be considered as a hole and losses may be estimated using M. Sands' formula provided that the radius of the electrode is small compared with the bunch length. For a button-like electrode for which $r = \sigma = 1 \text{ cm}$ we get $Z(n)/n = 0.01 \Omega/\text{ring}$. However, the energy loss scales as r^6 and extrapolation of the Sands' formula to $r = \sigma$ may be invalid. The measurements of the beam impedance of a button electrode by A. Jacob and G. Lambertson⁶ give as larger value: 0.05Ω at 500 MHz , and indicate resonances with peak values up to 2.5Ω in the frequency range up to 2.5 GHz . We assume the EPA result⁵ for the estimate keeping in mind that it may be improved by scaling down the size of the electrodes.

• A Taper

The loss factors of 12 tapers connecting arcs and straight sections has been estimated with TBCI. The parameters used in the simulation are: the taper angle 0.1 rad (half of the ratio σ/a), $\sigma = 1 \text{ cm}$, beam pipe radii 5 and 10 cm . The cylindrical symmetry is assumed what overestimates the loss. The loss factors of a "taper-in" is $k_l = -0.315 \text{ V/pC}$, and that of a "taper-out" is $k_l = 0.467 \text{ V/pC}$. Although the gain and the loss of tapers are almost canceled, their contributions to the impedance should be considered independently because of the large distance between tapers. That gives $Z(n)/n = 0.09 \Omega/\text{ring}$. This result is considered an overestimate and has to be checked with MAFIA to understand the effect of the asymmetry.

• An Interaction Region

The IR ($\pm 2 \text{ m}$ around the interaction point) contains a number of mask tapers with very small total loss $k_l = 0.06 \text{ V/pC}$. That corresponds to $Z(n)/n = 0.0015 \Omega$ and is negligibly small.

Two crotches farther away from the IP may be considered as steps with the ratio of radii equal two. That gives a δ -functional kick to a particle and the loss $k_l = 2 \ln(2)/(\sigma\sqrt{2}) = 0.7 \text{ V/pC}$. The low frequency impedance $Z(n)/n = 0.013 \Omega$ is very small.

• Bellows Shields

Today there is a common belief that bellows have to be shielded. Bellows are a challenge for a designer. We compared several possible designs (see discussions in the Appendix). For an overall estimate of the machine impedance I choose one of them (tapered sliding contact on the outer side of the beam pipe) leaving the final choice open. Such bellows are simple and reliable with rather small loss $k_l = 4.52 \cdot 10^{-3}$ V/pC. One hundred and forty-four bellows of this type give $k_l = 0.65$ V/pC/ring, or $Z(n)/n = 0.012 \Omega/\text{ring}$.

• Valve

The PEP valves will be probably used for the B-factory. The loss of a valve is¹ $k_l = 0.006$ V/pC. For $\sigma = 1$ cm bunches that gives $Z(n)/n = 2.0 \cdot 10^{-4} \Omega$, or $Z(n)/n = 2.0 \cdot 10^{-3} \Omega/\text{ring}$.

CONCLUSION

The summary of the main contributions to low-frequency parameter $Z(n)/n$ (in *Ohms*) is given in the Table 2.

Table 2. The impedance budget

Bellows	0.012
Clearing electrodes	0.072
Taper	0.09
Feedback system	0.050
Interaction region	<u>0.015</u>
Total	0.26

With the contingency¹ $Z(n)/n = 0.06 \Omega$ for the injection system and collimators the total impedance $Z(n)/n = 0.35 \Omega$ seems to be achievable. Although more accurate estimate and experimental measurements are necessary it is more important to realize where are the main sources of the impedance and to make reasonable efforts to minimize their contribution with proper design.

REFERENCES

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2. R. L. Warnock and P. Morton, "Coherent Synchrotron Radiation in a Toroidal Chamber," SLAC-PUB-456, March 1988.
3. R. L. Warnock, "Shielded Coherent Synchrotron Radiation and Its Effect on Very Short Bunches," SLAC-PUB-5375, November 1990.
4. A. A. Sokolov and I. M. Ternov, "Synchrotron Radiation," Nauka, Moskwa, 1966, p. 39, Eq. (5.2) (in Russian).

APPENDIX: DESIGN OF THE BELLOWS

The 100°C temperature expansion of the 15 m copper beam pipe (the coefficient of the linear expansion $1.4 \cdot 10^{-5}/^{\circ}\text{C}$) produces the length excursion 2.1 cm. Misalignment errors are smaller than that. A specific feature of a B factory, is the necessity to take care of the synchrotron radiation power deposited in the bellows (100 W/cm). If the heating of the bellows is excessive the masking of bellows may be used with a tiny cylindrically symmetric taper on the upstream inner surface of the beam pipe. The height of the mask is defined by the angle of the synchrotron radiation ($1/\gamma$) and is of the order of $25 \mu\text{m}$. Such a mask is, probably, transparent to the heat flow. The taper angle, say 0.1 rad, should be small compared with σ/a .

Several designs of bellows are considered.

• Sliding Contact on the Outer Side

This design is reliable and simple: a sliding contact on the outer side of the beam pipe is enforced by a circular spring. The required gap is of the order of the temperature excursion. The 2" gap can be shielded from inside with a $25 \mu\text{m}$ high mask. The main drawback of the design is relatively large cavity formed by the sliding contact and the 5 mm thick beam pipe walls. The loss of such a cavity ($\sigma = 1 \text{ cm}$, $a = 5 \text{ cm}$, $b = 5.5 \text{ cm}$, $g = 2''$) is relatively large: $k_l = 0.0146 \text{ V/pC}$, giving $k_l = 2.1 \text{ V/pC/ring}$. The design may be improved by cutting the beam pipes not laterally but at small angle (0.1 rad) to the axis, so that the resulting cavity is tapered, see Fig. 1. Two-inch-long tapers on each side reduce the loss by factor 3 giving $k_l = 4.5 \cdot 10^{-3} \text{ V/pC/bellow}$, or $k_l = 0.65 \text{ V/pC/ring}$ for 144 bellows.

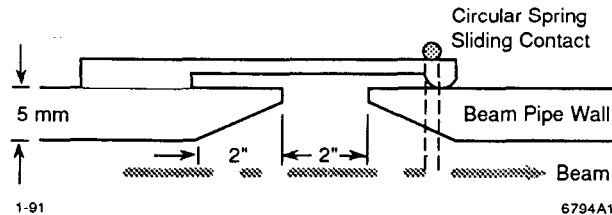


Fig. 1. The screen with an outer sliding contact. Only the part enclosed in the bellow is shown.

• Sliding Contact on the Inner Side

Another possible design is a spring contact on the inner wall (M. Calderon), see Fig. 2. Downstream pipe is cut at the angle to the axis making with a spring a symmetric taper, which is shorter than in the first design. The loss of a taper (angle 0.1, $a = 5 \text{ cm}$, $b - a = 0.4 \text{ mm}$, $\sigma = 1 \text{ cm}$) is $k_l = 2.9 \cdot 10^{-3}$, i.e., smaller than in the first design. However, the spring inside the vacuum chamber is less reliable and more susceptible to synchrotron radiation.

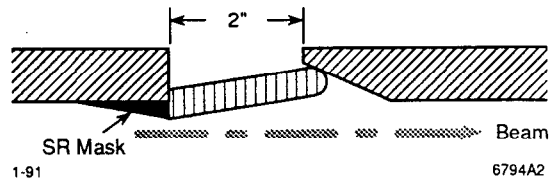


Fig. 2. The screen with the sliding contact on the inside surface. The black triangle is the synchrotron radiation mask.

• Interleaved Pipes

The longitudinal cuts can be made in both pipes making fingers uniformly distributed on the pipe surface. When pipes are hot, the fingers close the gap leaving maybe only small slots, see Fig. 3. Slots become larger if the pipes are cold. G. Lambertson noticed that if slots are narrow it is not necessary to screen such bellows. The loss of the bellows with 3 mm wide fingers and 1 mm slot in between may be estimated by M. Sands' formula considering two slots as a pair of holes with 2 mm radius. It gives $k_l = 10^{-5} \text{ V/pC/bellow}$ but the loss increases rapidly with the width of the fingers. The main drawbacks of the design are that the narrow fingers are fragile, and the tolerance on the lateral misalignments is tough. The usual problem of sliding contacts in vacuum is worsened here due to the large number of them.

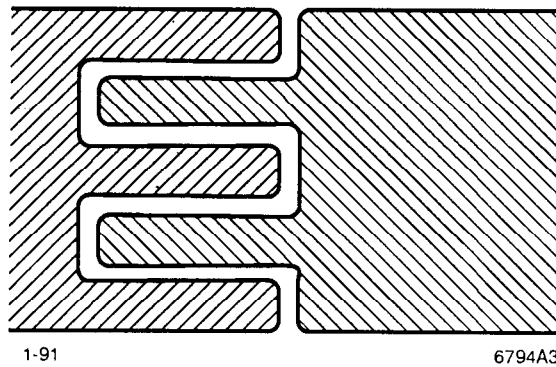


Fig. 3. Fingers cut in the beam pipe wall.

• Wire Braiding

Bellows may be made as wire braiding (similar to that used for shielding of RF cables) welded to both pipes. The wire braiding forms a smooth taper. The impedance may be very small. The main disadvantage here is that very little is known about performance of such a design; in particular, about the abrasion of the wires, which can deteriorate in vacuum.

• Chinese Lantern

This design is very attractive not having sliding contacts. It has been used in the BEP ring in INP, Novosibirsk. It looks like a thin cylinder welded to both pipes with narrow longitudinal cuts. The cuts allow lateral bulging and, as a result, make possible longitudinal excursions. Ideally, the cold bellow is almost flat giving practically zero impedance. The impedance of bulged bellows can be estimated as the impedance of two tapers. Slots give negligible contribution provided that they are narrow compared with the bunch length. The main problem of the design is the geometric constraints. The thermal excursion Δl , the sagitta of the bulged out bellows h , the bellows length L , and the bulging angle θ with the axis are related:

$$h = \sqrt{\frac{3}{8}L\Delta l}, \quad \theta = \sqrt{6\Delta l/L}.$$

The restriction on the angle $\theta < \theta_{max}$ means that the length L should be rather large. For $\theta_{max} = 60^\circ$ the length $L > 6\Delta l$, i.e., $L > 6''$ to allow $\Delta l = 1''$. The alignment tolerance means some bulging of the bellows even in the cold vacuum system. For a 6''-long bellow the alignment tolerance $\Delta l = 5.0$ mm gives $h = 3\Delta l = 1.5$ cm. That has to be doubled to allow tolerances of both signs. A taper with the length $L = 6''$ and $h = 1.5$ cm (and $a = 5$ cm, $\sigma = 1$ cm) has the loss $k_l = 0.104$ V/pC which seems to be too large.