Summary Report of the Impedance and Instability Subgroup

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Table 1 shows a comparison between the BTCF and a few high performance electron storage rings which are either recently constructed or presently under construction. The parameters compared are those relevant to the collective effects. A quick glance of the comparison leads to the following observations:

- BTCF requirements are as demanding as those others in Table 1.
- A closer inspection shows that, relative to those other storage rings in Table 1, the single bunch intensity specified for BTCF tends to be higher, while the bunch spacing tends to be longer. This suggests that the single bunch instability effects are relatively more severe while the coupled-bunch instability effects are less severe. This observation, as will be detailed in this report, is indeed what we found.

Table 1. Comparison between BTCF and other high performance storage rings.

	BTCF standard	BTCF crossing angle	BTCF monochromator	PEP II LER	KEKB LER	DAΦNE	ALS
beam current (mA)	570	570	210	2140	2600	5200	400
particles per bunch (10^{10})	14	5.7	5.3	5.9	3.3	8.9	3.1
bunch spacing (m)	12	4.8	12	1.3	0.6	0.8	0.6

1. Impedance Catalog and Budget

An impedance survey and budget has been made in Ref.1. This survey has considered the leading sources of impedance including

- RF cavities
- resistive wall
- interaction region and the beryllium pipe around the interaction point
- Y-junctions
- electrostatic separators

- masks and collimators
- beam position monitors
- bellows
- feedback kickers
- pumping slots

For each item, an estimate has been made on the longitudinal impedance, and a total impedance has been obtained by adding up the contributions from the individual components.

Recognizing the importance of an impedance budget which is as complete and accurate as possible, it is suggested that

(a) the impedance budget be extended to include

- space charge (Laslett effect with image currents)
- injection ports
- instrumentation devices other than beam position monitors
- clearing electrodes (if needed)
- abort system
- injection kicker.

(b) One needs to exercise extra care when performing numerical calculations of the wake fields and the impedances because these calculations tend to be subtle and error prone. A set of checking procedures should be established to be applied to each component impedance obtained.

(c) It is critical to establish an impedance "policing" effort when entering the engineering design stage of BTCF. Designers of vacuum chamber components are to recognize that an innocent looking discontinuity (e.g. a 1 mm step) contributes a significant amount of impedance, and must be avoided whenever possible.

2. Interaction Region, Electrostatic Separators, Beryllium Pipe, and Y-junctions

Figure 1 is a sketch of the interaction region, where the beryllium pipe, the electrostatic separators and the Y-junctions are located. One also notes that the vacuum chamber cross-section in this region varies in such a way that several cavities of various sizes and shapes are formed.

As the multiple bunches of the two beams traverse this region, they generate microwaves. One result of these microwaves is to heat up the vacuum chamber environment. With the high beam intensities of the BTCF, this microwave heating is a concern. In particular, the beryllium pipe is close to sensitive silicon detectors and can not tolerate much of the microwave heating — the tolerance for the PEP II case is set to be 200 watts.[2] At the beryllium pipe, microwaves come from two sources:

(a) microwaves trapped by the berrylium pipe "cavity" (See Fig.1). It is estimated for PEP II that this contributes about 60 watts of microwave power.

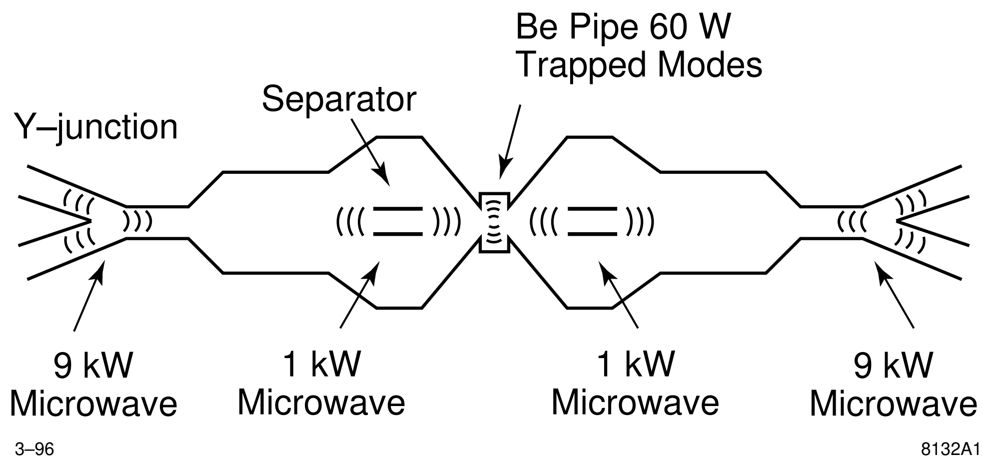

Fig. 1. A sketch of the interaction region.

(b) microwaves generated at the Y-junctions or the separators, and propagated to the beryllium pipe along the vaccum chamber. The microwave power is estimated for BTCF to be about 9 kW for each Y-junction and 1 kW for each separator.[3] With a total of 20 kW microwave power bouncing around, it is necessary to protect the beryllium pipe carefully. One should install microwave absorbers to absorb the microwave power from the Y-junctions. It would be more difficult to deal with the microwave power from the separators because there is no space to install absorbers. It is therefore suggested that the separator plates be shaped with tapered ends and tapered thickness, as sketched in Fig.2. The tapering would minimize the microwave generation at the separators, but it would compromise the effective length of the separators, thus requiring higher electrostatic voltage. One could also consider installing some higher order mode dampers inside the separator housing, perhaps behind the plates, provided this can be done without triggering premature voltage sparkings.

The various cavity structures in the IR are potentially a rich source of trapped modes, which can cause coupled-bunch instabilities and should be evaluated. Trapped modes in general are discussed in the next section.

In addition to heating and trapped modes, the microwaves can also cause single-bunch instabilities. This is not expected to be a severe problem and in any case has been considered in the overall impedance budget.

3. Trapped Modes

As mentioned, trapped modes can cause microwave heating, as well as coupled-bunch instabilities, and should be examined for each vacuum chamber component in the impedance budget. Other than the IR, trapped modes can occur in

- beam position monitors[4]
- interior of RF cavities[5]

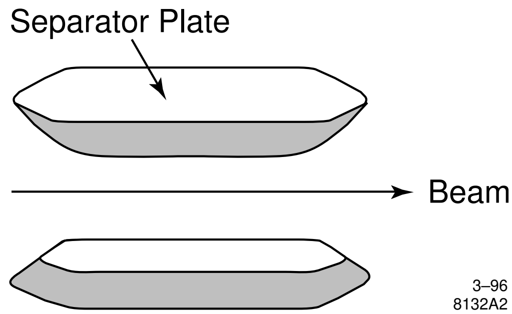

Fig. 2. Tapered electrostatic separator.

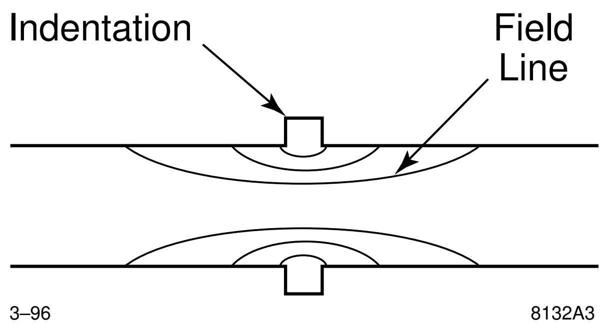

Fig. 3. A trapped mode.

- pumping slots
- bellows.

In general, a trapped mode can occur when there is a small indentation of the vacuum chamber, as sketched in Fig.3. Configurations involving small indentations should be avoided as much as possible. For example, PEP II has designed the pumping slots and the bellows to avoid possible trapped modes.[6] Their designs are as sketched in Fig.4. Designs of Fig.4(a) and 4(c) are avoided, while designs 4(b) and 4(d) are adopted for PEP II. In Fig.4(b), the trapped modes are "squeezed out" of existence.

It should be mentioned here that the design of beam position monitors is to optimize the various requirements including:

- signal sensitivity
- broad band impedance
- avoiding trapped modes
- limit of power in the cable.

4. Microwave Instability

The broad band impedance estimated in the impedance budget has[3]

$$\frac{Z}{n} = 0.23\ \Omega$$

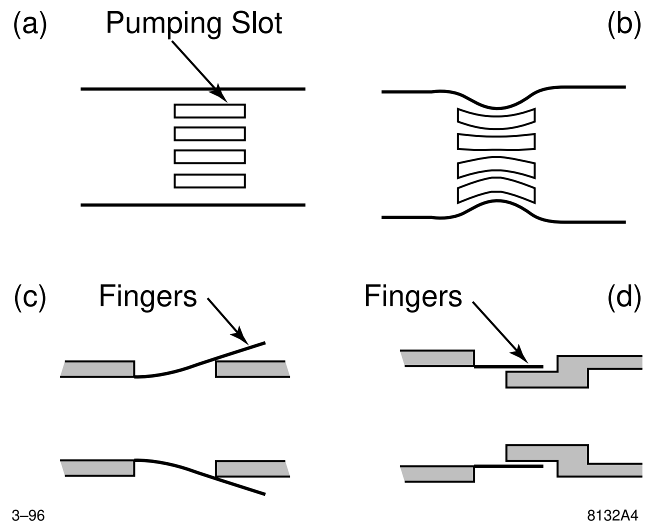

Fig. 4. (a) and (b) are possible designs of pumping slots. (c) and (d) are possible designs of bellows. (a) and (c) may trap modes and are to be avoided. (b) and (d) avoid mode trapping.

The Boussard-Keil-Schnell criterion for microwave instability predicts for the present design an instability threshold of

$$\frac{Z}{n} = 0.42\ \Omega$$

Although there is apparently a safety margin, this safety margin is very necessary because

- the theory may not be very accurate,
- the impedance estimates may not be very accurate, and
- not all impedance sources have been included.

It would not be prudent to consider reducing this safety margin at the present stage of the BTCF design.

However, there may exist a need to reduce this safety margin in order to help the beam-beam problem in the present BTCF design. This is because the beam-beam effect in the present BTCF design[7] is unusually strong due to synchro-betatron resonances. Such resonances are known to cause beam lifetime problems in the past and should be avoided.[8] It may then be necessary to reduce the strength of these beam-beam driven synchro-betatron resonances. There is therefore a pressure to

- lower the synchrotron tune ν_s from the present design value of 0.09, perhaps by a factor > 2, and to
- reduce the bunch length σ_z so that $\sigma_z < \beta^*$.

One way to accomplish this is to reduce the momentum compaction factor α_p (keeping $\alpha_p > 0$). But a small α_p would erode the safety margin against microwave instability.

The choice of the basic parameters ν_s, σ_z/β^*, and α_p must take into consideration of optimizing both the beam-beam and the microwave problems. This is a strategic issue that needs an early attention. It also affects the choice of the optimal beam

Table 2. Comparison of a few KEKB and BTCF parameters.

	BTCF	KEKB
α_p	0.027	0.0002
σ_z (cm)	1	0.4
β^* (cm)	1	1
ν_s	0.09	0.013

emittances, and Touschek lifetime considerations. A comparison of these parameters with the KEKB design is shown in Table 2. As one can see, the designs of BTCF and KEKB are in very different ball parks. Although this is not to say the KEKB ball park is necessarily better, it does indicate a need to carefully evaluate these parameter choices.

Although not a feasibility issue, single bunch instability considerations are a serious concern for the BTCF. It should be mentioned that some work on transverse single-bunch instabilities, such as mode coupling instability, was performed in Ref.1, but was not addressed during this workshop.[9]

5. Bunch Lengthening

The BTCF tolerance on bunch lengthening is low because the rms bunch length σ_z is already made equal to β^* and any increase would enhance those beam-beam induced synchro-betatron resonances mentioned earlier. If any change is to be made, one should try to make σ_z shorter.

Bunch lengthening has two contributions: one from potential-well distortion and one from longitudinal microwave instability. Assuming the broad band longitudinal impedance is as budgeted (with $Z/n = 0.23\ \Omega$), a simulation shows that the potential well distortion contributes to about 10% of bunch lengthening, while the beam is not lengthened due to microwave instability because the beam intensity is below the instability threshold.[10] These simulation results are consistent with the analytical estimates but are nonetheless preliminary because

- The wake fields used in this simulation are obtained using a test bunch with $\sigma_z = 1$ cm. It is suggested that a test bunch with $\sigma_z = 1$ mm be used so that high frequency contents of the wake fields are kept in the simulation.

- The wake fields of individual components must be calculated carefully with checking procedures.

However, bunch lengthening effects are most likely weak in the BTCF provided the impedance is within budget.

In case it becomes necessary to control the bunch lengthening due to potential well distortion, one may consider adopting a lattice with $\alpha_p < 0$.[11] For that reason, it may be useful to study this alternative further, for example, by confirming the theory and simulation with the recent SUPERACO experiments, and then apply to a specific BTCF lattice.

6. Coupled Bunch Instabilities

Due to the relatively large bunch spacing, the coupled-bunch instabilities in the BTCF are less demanding than those in the B-factories.

The transverse resistive wall instability growth time is estimated to be about 3 ms for the case when the vacuum chamber consists of 70% aluminum and 30% stainless steel.[3] This can easily be handled by a narrow-band feedback system. Although the resistive wall mainly causes a transverse instability, it is suggested that the longitudinal resistive wall instability should also be examined for the BTCF.[6]

As mentioned earlier, trapped modes in various vacuum chamber components require investigation and avoided whenever possible to minimize coupled-bunch instabilities.

It has been pointed out that long range wake fields can also cause single-bunch instabilities for PEP II.[12] The net result is a reduction of the instability growth times, and possibly rendering high order modes unstable. Such high order modes are not damped by feedback systems. An examination of this effect is suggested for the BTCF.

It was stated that the coupled-bunch instabilities due to higher order modes of the RF cavities have growth rates less than the radiation damping rates and therefore are not a problem for the BTCF.[13] Feedback systems, however, are still recommended because

- Transverse feedback systems are needed for other purposes such as to control the resistive wall instability, the ion instability, the photo-electron instability, and effects due to trapped modes.

- Longitudinal feedback would be needed to deal with trapped modes. The longitudinal feedback, although required to be wide-band, can be accomplished by a relatively simple design.[5]

7. Microwave Power

Microwave power is a concern not only in the IR. There is approximately 100 W/m of microwave power generated in the rest of the storage ring as well. How to prevent this power from depositing onto sensitive devices (e.g. BPMs, bellows, vacuum pumps, etc) is a new issue facing all accelerators of the factory class. The physics of microwave heating is well known, but the magnitude of the problem is much pronounced in the factories, and this issue is being elevated to the level of basic design considerations. The KEKB design, for example, considers installing microwave absorbers along the circumference.[8]

A higly conducting vacuum chamber pipe helps resistive wall instability, but hurts

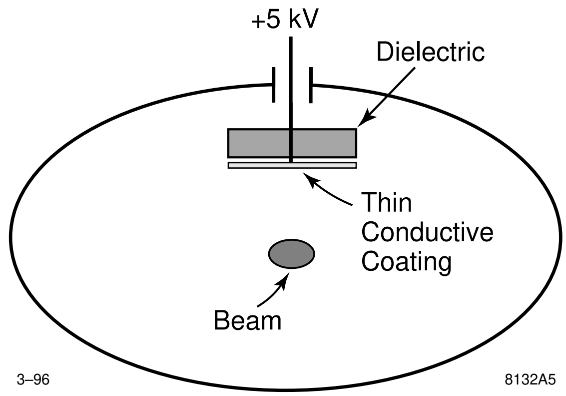

Fig. 5. DAΦNE design of ion clearing electrode.

the absorption of microwave power. The use of stainless steel (instead of aluminum or copper) pipe in the straight sections helps somewhat the reduction of microwave power, and is a preferred choice, even though the microwave absorption by the stainless steel wall is far from sufficient to avoid the problem completely. Sensitive devices must be designed carefully in such a way that the impinging microwaves are reflected back into the vacuum chamber.

8. Ions

There are two ion effects to be considered. A "conventional" ion effect considers the possibility that ions are trapped by the circulating electron beam. This effect can be prevented by introducing a gap in the electron bunch train. A preliminary study indicates that a large 30% gap in the electron bunch train would avoid ion trapping in 80% of the ring, and the ions trapped in the remaining 20% of the ring would cause a tune shift of 0.008 in the electron beam.[14] This result requires further confirmation because the analysis uses a theory which has not yet been fully established and it should be used with caution.

If the above estimate is reconfirmed, it has the consequence that, if untreated, the present specification of a 10% gap would not be acceptable and that ion trapping can only be avoided by sacrificing substantially on luminosity. If so, one might have to consider introducing clearing electrodes. Then there is a question of how to design electrodes with minimal impedance. One such interesting design has been adopted in DAΦNE,[15] and is sketched in Fig.5. The high voltage is supplied through a feed-through. The electrode consists of a dielectric which is coated with a very thin layer of a conducting material (a glass-metallic compound) with high resistivity. The thickness of the conducting material (25 microns) is much thinner than the skin depth at the bunch spectrum frequency. This design does not have trapped modes, and the impedance seen by the beam is basically that due to the feed-through.

In addition to the conventional ion trapping issue, there is also the issue of transient ion instability which has been a serious concern for the two B-factories presently under construction.[16] This instability has a "characteristic growth time" τ in the limit of small oscillation amplitudes. A comparison of the values of τ for three factories is given in Table 3. These τ values are obtained by computer simulations (they are consistent with theoretical predictions). The first column gives the values of τ calculated ignoring the oscillation frequency spread of the ions. This frequency spread has a big effect on τ as shown by the second column of Table 3. Ion frequency spread has not yet been included in the simulations for BTCF.

As can be seen from Table 3, the transient ion instability is much weaker in BTCF than in the B-factories. This is mainly due to the facts that[17]

- the BTCF beam has a large beam emittance, and
- there are much fewer number of bunches in the electron bunch train.

Table 3. Estimates of the characteristic growth time of transient ion instability.

	without ion oscillation frequency spread	with ion oscillation frequency spread
KEKB	0.04 ms	0.5 ms
PEP II	0.007 ms	0.5 ms
BTCF standard	1.6 ms	?
BTCF monochromator	0.2 ms	?

It should be emphasized that the transient ion instability (as well as the photo-electron instability to be discussed in the next section) have not been observed in actual accelerators before. To this extent, these effects are feasibility issues for the two B-factories. The present best theoretical efforts indicate that these instabilities are indeed serious problems for the B-factories, but are within the capacity of their feedback systems. However, the uncertainty remains, and the same uncertainty also applies to BTCF. The only thing we can say confidently presently is that these effects should be much weaker in BTCF than in the B-factories.

An experiment is planned to test the transient ion instability at the TRISTAN Accumulator Ring in 1996 and an experiment has been proposed at the PLS, Korea in 1997. BTCF team has been participating in these important activities.

Transverse feedback systems are needed to deal with the transient ion instability. It is conceivable that the feedback system may not need to be very extensive for BTCF. This is because

(a) The instability is not too strong, at least compared with the B-factories. The band-width required is also not as wide due to the larger bunch spacing.

(b) Althought the "characteristic growth time" τ may be short, it does not necessarily mean an excessively powerful feedback kicker because

- the instability growth behaves like $\sim e^{\sqrt{t/\tau}}$ instead of exponentially like $\sim e^{t/\tau}$, and

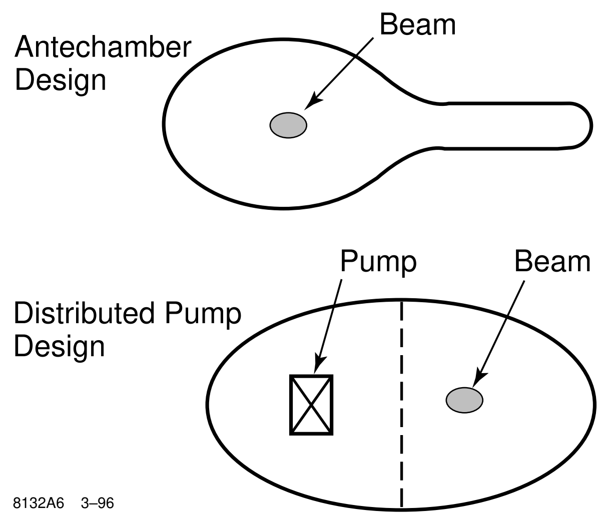

Fig. 6. Two vacuum chamber design options: (a) antechamber or (b) distributed pumping.

- the growth saturates when the oscillation amplitude approaches the level $\sim 1\sigma$, where σ is the transverse beam size.[6] This means the feedback system does not need to act on big oscillation amplitudes, and thus the power required is correspondingly less.

9. Photo-electron Instability

This is another instability effect which has not been observed before but is affecting the design of the B-factories.[18,19] Although the effect is expected to be weaker for the BTCF, it is advisable that the same caution be exercised. At present, the simulation program from KEK has been implemented, but has yet to be applied to the BTCF configuration. In the mean time, the simulation program is being upgraded at KEK.[8]

A collaboration has been established between KEK and IHEP to carry out an experiment using BEPC in 1996 to test the photo-electron instability effect.

There are two vacuum chamber design options considered for BTCF.[1] One is with an antechamber, and can be made by aluminum extrusion. Another is with distributed ion pump. These two options are illustrated in Fig.6. It is recommended that the antechamber configuration be adopted for BTCF. There are several advantages (and not many disadvantages):

- Without the pumping slots, the antechamber configuration has a smaller impedance.

- It much reduces the threat from photo-electron instability.

- ALS provides an existing operating experience.

- The advantage of antechamber configuration is more pronounced with smaller rings, due to the geometric layout.[4]

- The distributed pumps are a potential source of dust particles.

For these reasons, the antechamber design is recommended for BTCF.

It should be mentioned that the dust particles is another topic to be evaluated for the BTCF, although our subgroup did not address this issue sufficiently due to lack of time. In contrast with the transient ion and photo-electron instabilities, the existence of dust particles and its influence on accelerator operations have been established experimentally. In addition to the distributed pumps, another potential source of dust particles is the bellows with sliding fingers.[6]

10. Touschek Lifetime

The Touschek lifetime has been calculated to be 8 hrs. for the standard lattice of BTCF.[1] This is quite acceptable. It should be mentioned that if the beam emittance is to be reduced to optimize other considerations[20] (e.g. to reduce the apertures of the IR quadrupoles), the Touschek lifetime must be re-evaluated because it depends sensitively on the beam emittance.

The monochromator scheme requires a small beam emittance. Assuming the momentum aperture remains the same as in the standard scheme, then the Touschek lifetime would be reduced to the level less than 1 hr. This is a serious limitation and at present should be considered a feasibility issue as far as the monochromator scheme is concerned. A round of parameters optimization is called for to resolve this issue.

11. Summary

Our subgroup discussed several technical issues facing the BTCF. Most of these are R&D issues to be performed before a construction start. The two uncertainties facing the B-factories and the BTCF alike, namely the transient ion instability and the photo-electron instability are much weaker in the BTCF. Another uncertainty concerns the monochromator scheme, for which a round of parameters optimization is called for.

The R&D issues can be collected into a long list. Our discussions are by no means exhaustive, but are listed below as a summary of this report:

- Impedance policing is to be established.
- Single bunch instability is marginally acceptable.
- Beam-beam effects is to be considered together with microwave instability to optimize the overall design.
- Microwave power is a new issue which needs attention.
- Trapped modes need attention.
- Aluminum antechamber vaccum chamber design is recommended.
- Electrostatic separators need to be designed to minimize the microwave power generation.
- Dust particles need attention.

The long list of R&D issues reminds us of the fact that factories are demanding accelerators. It is a wise strategy for BTCF to follow what has already been considered in the B-factory designs. The two B-factories, however, are not expected to achieve their respective luminosity goals immediately. There will be many new operational and technical issues exposed by the initial operations of these pioneering accelerators. It is conceivable that the timing is such that BTCF is to be constructed after the commissioning stage of the two B-factories. In that case, one can benefit greatly from their operational experiences.

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