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Bunch Timing Aspects for the ILC

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1. Introduction

During the past decade several proposals for linear electron positron colliders were launched, based on different accelerator technologies [1,2,3]. In 2004 it was decided to use the superconducting technology for the global project ILC (International Linear Collider) [4].
The ILC accelerator complex consists of two high energy LINACs for particle acceleration from 5GeV to 250GeV or more, a beam delivery system BDS to prepare the high energy beams for collision and separate the spent beams, two damping rings for preparation of low emittance beams at 5GeV and an injector system for the electrons. The positrons will be produced using the high energy electron beam for synchrotron light generation via an undulator and a conversion target. Figure 1 shows a non scaled schematic view of this accelerator complex.

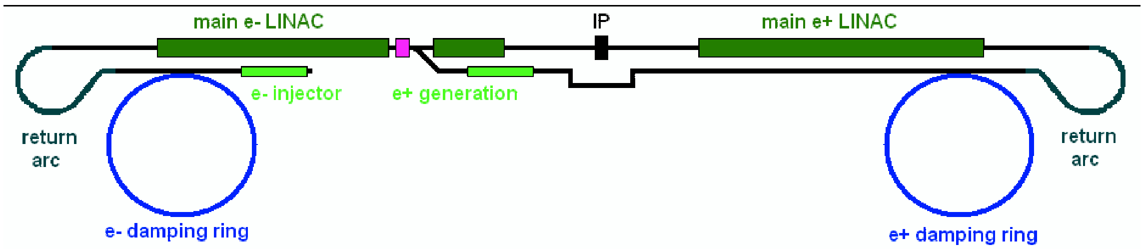

Figure 1: the ILC accelerator complex

Since the LINAC RF has to be pulsed the luminosity will be achieved by collisions of bunchtrains. It is planned to use 5 RF pulses of about 1ms duration per second and about 3000 equally spaced bunches, resulting in a bunch crossing time at the interaction point IP of about 300ns.
Global constrains for these parameters are defined by the luminosity requirement, the DC to beam power conversion efficiency and the beam separation after collision.
The bunch structure for each LINAC must be delivered by the corresponding damping ring. Since the timing flexibility in circular accelerators is more stringent than in LINACs the damping rings define the bunch timing of the ILC.
For TESLA some aspects of the bunch timing were discussed [5, 6] and will be updated here, some restrictions and some optimized sets of parameters will be presented.

2. Compression

For the design parameters one bunch train will be 1ms or about 300km long. To avoid damping rings of such extreme sizes all bunches of one bunchtrain have to be stored in the damping ring with a strongly reduced bunch to bunch distance. The bucket[1] distance in the damping ring t(DR) is given by
t(DR) = t(L) / k,

[1] Here one "bucket" is defined as one possible place for a bunch of particles. The bucket distance has to be a multiple of the (shorter) RF bucket distance.

with k (integer number) as the compression factor. The bunch train for the LINAC is created by single bunch ejections with a bucket feed k. This k indicates also the number of damping ring revolutions needed for a complete ejection cycle.

The bucket distance in the damping ring t(DR) has to be a multiple of the RF bucket distance t_{RF}(DR)

$t(DR) = i\ t_{RF}(DR)$,

with i as an integer number.

Also the bucket distance in the LINAC t(L) has to be a multiple of the RF bucket distance t_{RF}(L)

$t(L) = j\ t_{RF}(L)$,

with j as an integer number.

As a consequence the compression factor k has to be chosen as

$k = t(L) / t(DR) = j\ t_{RF}(L). / i\ t_{RF}(DR) = j\ f_{RF}(DR). / i\ f_{RF}(L)$.

An easy relation between the RF frequency of the damping ring f_{RF}(DR) and the RF frequency of the LINAC f_{RF}(L) allows some more flexibility in the compression factor k.

3. Damping ring ejection

For the generation of the LINAC bunchtrain (equally spaced bunches without gaps) a sequence of single bunch ejections is necessary, where always filled buckets have to be met. With an arbitrary number of buckets N_B and an arbitrary compression factor k this is not necessarily fulfilled[2]. Some restrictions have to be satisfied. There are a few different solutions:

a) Allow different bunch distances in the LINAC; use a constant kicker feed k for one revolution and adjust the bucket feed per revolution with one different kicker feed[3]. In this case the initial postulation of equally spaced bunches in LINAC is violated.

b) Avoid common dividers of the number of buckets N_B and the kicker feed k. There are two general possibilities to achieve this: choose the number of buckets N_B or the kicker feed k as a prime number[4]. (This is not mandatory but a general solution.)

c) Use a fixed bucket feed per revolution of exactly one bucket (+ or -) and a bucket number restricted to[5]

   $N_B = p\ k +/- 1$

   with p as integer number.

In the latter cases the number of bunches N_B and the compression factor k must be well chosen.

4. Flexibility

Once the damping ring circumference C is fixed, the possibilities for different bunch numbers are defined. The circumference C of any circular accelerator (for particles with the speed of light c) has to be a multiple of the RF wavelength λ_{RF}(DR)

$C = h\ \lambda_{RF}(DR) = h\ c / f_{RF}(DR)$,

with h as the "harmonic number", giving the number of RF buckets.

With the assumption of equally spaced buckets (not mandatory in general, but reasonable) the number of buckets N_B is given by

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[2] Example: N_B=100, k=10 => after one revolution an already ejected bucket is met.

[3] Example: N_B =100, nine times k=10 and one k=9 and so on

[4] Example: N_B =101 and arbitrary k, e.g. k=10, or arbitrary N_B, e.g. N_B =100, and k=11

[5] Example: N_B =101, p=10, k=10 or p=5, k=20 …

$N_B = h / i$.

Changes in the number of bunches N:

During operation it could become necessary or desirable to change the number of bunches N. It would be trivial simply to omit a certain number of bunches[6], but it is also possible to change the number of buckets, as long as the harmonic number h stays constant. A highly dividable harmonic number h allows a high flexibility in bucket number changes; e.g. an exact doubling of the initial number of buckets N_B is possible, if the initial divider i is dividable by 2.

The real flexibility for changes depends on the ejection scheme:

a) With allowed jumps in the bunch distance there are no further restrictions; the necessary jumps will appear at different positions in the bunchtrain, depending on the number of buckets.
b) If the number of buckets N_B is chosen as a prime number, by definition it's impossible to divide it or to multiply it with another prime number as result. In this case N_B is fixed.
   If the kicker feed k is chosen as a prime number there are no further restrictions.
c) With a bucket number restricted to fulfill $N_B = p\ k +/- 1$ it is nearly impossible to change it without changing the harmonic number h and thus the circumference.

Changes in the compression factor / kicker feed k:

Once the damping ring circumference C and the damping ring RF frequency f_{RF}(DR) are fixed, in general it is possible to vary the bunch distance in the LINAC t(L), the bunchtrain length T(L)and the necessary RF pulse length T_{RF} by changing the compression factor k.

$t(L) = k\ t(DR)$

$T_{RF} = (N_B - 1)\ t(L) = (N_B - 1)\ k\ t(DR)$

Due to the different restrictions for the compression factor k the resulting flexibility for the three ejection schemes is different:

a) With allowed steps in the kicker feed, k can be changed, as long as an adjusting k step per revolution is applied.
b) With N_B as prime number the compression factor k can be changed arbitrarily; in the other case k is restricted to stay a prime number
c) With a constant number of buckets $N_B = p\ k +/- 1$ changes in k must be compensated by corresponding changes in p. A good choice of N_B can allow a good flexibility.

5. Different damping ring circumferences for e^+ and e^-

Up to now consideration has been focused on a single damping ring. In the ILC scheme two rings are coupled via the main LINACs and the beam delivery system. One essential requirement is that the collisions must always take place at the same longitudinal position (namely at the IP inside the detector). This requires an absolutely equal bunch structure of both (e^+ and e^-) bunchtrains. The bunch distances in the electron LINAC $t(L)_{e+}$ and the positron LINAC $t(L)_{e-}$ must be the same:

$t(L)_{e-} = t(L)_{e+}$

$k_{e-}\ t(DR)_{e-} = k_{e+}\ t(DR)_{e+}$

$i_{e-}\ k_{e-}\ t_{RF}(DR)_{e-} = i_{e+}\ k_{e+}\ t_{RF}(DR)_{e+}$

If the bucket number N_B of both rings should be the same[7], a difference in the RF bucket distance t_{RF}(DR) (different RF frequencies for the two rings) or the factor i would result in a different circumference C, but must be compensated by the corresponding kicker feed k. (A difference in the RF frequencies of the LINACs f(L) would not affect this relation, but would

[6] Consequences of missing bunches will be discussed below.

[7] Consequences of missing bunches will be discussed below.

give additional restrictions for the kicker feeds.) This is only possible for the ejection scheme with fixed kicker feed per revolution:

a) With allowed steps in the LINAC bunch distance in general the kicker feed k is a free parameter, but since the position/time of the required step depends on the circumference, it is impossible to create equal bunchtrains with different circumferences. The circumferences of both rings must be the same.
b) With a prime bucket number differences in i are not possible, but a different circumference due to a different RF frequency could be compensated by the compression factor k, as long as it stays an integer. By definition there is no flexibility for the bucket number itself.
   With prime compression factors k it's impossible to achieve equal bunch distances in the LINAC, different circumferences are impossible.
c) With fixed bucket feeds per revolution and bucket number restricted to $N_B = p\ k$ +/- 1 differences in i or $t_{RF}(DR)$ could be compensated by corresponding differences in k and p:
   $i_{e-} = x\ i_{e+}$, $k_{e-} = i_{e+} / x$, $p_{e-} = x\ p_{e+}$ => $N_{Be-} = N_{Be+}$, $C_{e-} = x\ C_{e+}$
   Different circumferences are possible.

6. Gaps in the LINAC bunch train

It may be necessary to generate well directed gaps (a sequence of missing bunches) within the bunchtrains. These can be produced by omitting bunches in the damping rings. In general a string of missing bunches in a bunchtrain would transform to a corresponding number of single missing damping ring bunches with a distance of k. With gap sizes larger than N_B / k another staggered sequence of missing bunches would be necessary; the offset is given by the ejection bucket feed per revolution.
If this bucket feed per revolution is equal to one (see ejection scheme c) the damping ring bunch pattern would contain a series of p gaps.
A special case would be a number of missing bunches at the beginning or the end of the bunchtrain, resulting in a decreased train length.

7. Gaps in the damping ring bunch pattern

On the other hand it may be necessary to have artificial gaps in the damping ring bunch pattern. One single sequence of contiguous empty buckets in the damping ring would transform to single missing bunches in the LINAC bunchtrain with a distance of N_B / k. With a gap size larger than k small sequences of missing bunches would appear in the bunchtrain.
With an ejection bucket feed per revolution equal to one a series of p equidistant gaps would create one single gap in the LINAC bunchtrain, which could be placed at the beginning or end of the bunchtrain.
Applications for gaps in the damping ring bunch pattern:
In- and ejection:
Both in- and ejection kicker pulses have to affect only one single bunch. Thus the effective rise time and the effective fall time of the kicker pulses must fit in the time between the bunch to be in- or ejected and the neighboring bunch. If all buckets are filled and all bunches are equally spaced both the rise and fall time must be smaller than the bucket distance t(DR), as shown in figure 2.

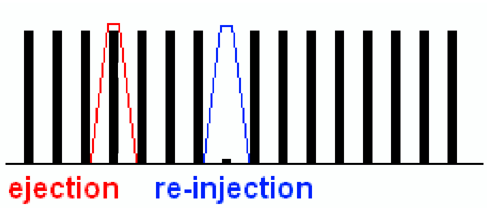

Figure 2: damping ring bunch structure and symmetric kicker pulses

The pulse shape may perhaps be asymmetric, e.g. the rise time could be significantly shorter than the fall time (including ripple). In this case it would be useful to have a certain gap after each bunch to be in- or ejected at the expense of some missing bunches. Exactly this could be realized with the ejection scheme with fixed ejection bucket feed per revolution.
With $N_B = p\,k - 1$ it is possible to provide gaps before and with $N_B = p\,k + 1$ after the ejected bunch. Since also the re-injection pulses will need enough space, it will be impossible to refill exactly the same bucket. The gap size must be chosen to be greater than the sum of the dominating part of the in- and ejection pulse length as shown in figure 3.

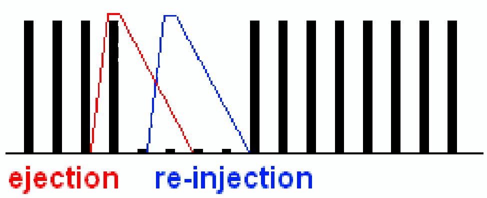

Figure 3: damping ring bunch structure with gaps and asymmetric kicker pulses

For a given number of bunches N and a given bunch distance in the LINAC t(L) the compression factor k and thus the number of gaps depends on the circumference C. For damping rings with large circumferences and a consequently larger bucket distance t(DR) this gap solution becomes less attractive since a large number of buckets has to be unused. For rings with small circumferences and very small bucket distances this technique could be used to ensure enough space for the kicker pulses.
Clearing:
It may be necessary to operate the damping rings with special significant gaps (one or more) of empty buckets to avoid multibunch instabilities. The needs for these gaps will be independent of parameters like ejection kicker feed. The ejection scheme with fixed bucket feed per revolution allows gaps without creation of missing single bunches in the bunchtrain, but only with a large number of small gaps. One single clearing gap would transform to missing bunches in the bunchtrain.

8. First conclusion and proposal

If constant bunch crossing times at the IP are required only the ejection scheme with prime kicker feeds k allows bucket number and bucket distance changes during operation. For a high flexibility the harmonic number h has to be highly divisible. At the same time it's possible to vary the bunch crossing time and the RF pulse length by changing k to other prime numbers. With a fixed ejection bucket feed per revolution equal to one the bucket number is fixed, but for several reasons a number of equally spaced gaps can be provided.

Using prime kicker feeds one can find some harmonic numbers (and thus circumferences) which ensure for some k's an ejection bucket feed per revolution equal to one, allowing also gaps. Such circumferences would provide the best flexibility for the beam operation[8].

Examples:	C = 6614m,	f(DR) = 650MHz,	h = 14340
	C = 8451m,	f(DR) = 433MHz,	h = 12216
	C = 10516m,	f(DR) = 650MHz,	h = 22800
	C = 12785m,	f(DR) = 650MHz,	h = 27720
	C = 14916m,	f(DR) = 650MHz,	h = 32340

9. Re-injection

After ejection of one damping ring bunch this bucket has to be refilled for the next cycle (the next bunchtrain). With a time independent particle source this re-injection can be done at anytime after ejection, e.g. after the ejection of all bunches or immediately after the ejection of one bunch. But for a meaningful operation the bucket to be refilled has to be emptied before. (In general also a refill with a certain offset (in multiples of the RF bucket distance) is imaginable, but all technical systems including the kickers have to deal with this staggered mode and effective reduced bunch spacing.)
For the ILC it is foreseen to generate the positrons using the high energy electron beam. In this case the timing of the positron "injector" is given by the electron bunchtrain structure and timing. At the same time the arrival time of the generated positron bunches at the damping ring injection position must fit to the damping ring bunch pattern. This results in a coupling between the timing needs and the ILC geometry, since the positron arrival time can only be influenced by changing the path length between the generation point and the damping ring injection. Unfortunately, due to the mostly linear geometry of the linear collider complex, this path length geometry is nearly preassigned as shown in figure 4.

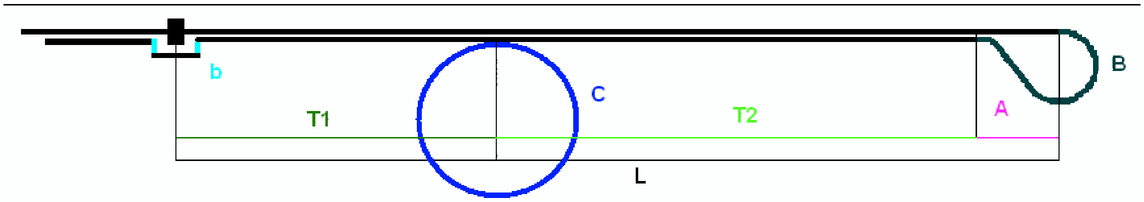

Figure 4: geometry of the positron part of the linear collider

- C = circumference of the damping ring
- L = distance between the IP and the beginning of the linear tunnel (BDS, LINAC, BC…)
- T1 = distance between the IP and the damping ring
- T2 = distance between the damping ring and the beginning of the 180° return arc
- B = path length of the 180° return arc
- A = linear tunnel length between both 180° return arc ends
- b = *additional* path length for the IP bypass line, artificial detours somewhere in the positron transport line or other reasons (e.g. also for taking into account the small effect of positron velocity differing from c just after generation)

[8] Allowed changes in the damping ring bunch patters could be applied from one bunchtrain to the next, simply be changing the injector triggers.

Assuming that the newly generated positrons have the speed of light and are transported in parallel to the remaining part of the electron LINAC (and BDS), the new positron bunches appear as "reflected" at the IP (every colliding positron bunch meets its corresponding new positron bunch, generated by its collision-partner electron bunch, just at the IP).

If a damping ring bunch pattern should be "self reproducing" (even one single ejected bunch is refilled), an ejected bucket must be refilled by its partner electron bunch. For a single ejected bunch and an initially completely filled ring there is exactly one empty bucket which must be met for re-injection In this case the overall path length of the transported colliding and new positron bunch must fit to a multiple of damping ring revolutions:
$n\,C = T2 + B + L + b + T1$,
assuming the damping ring in- and ejection at the same position. With
$L = T1 + T2 + A$
the linear tunnel length is strictly given by
$L = (n\,C - (B - A) - b) / 2$.
Since the additional path length b and the detour path length due to the 180° return arc (B-A) are small in comparison to the damping ring circumference C the linear tunnel length L has to be approximately a multiple of half the DR circumference.
This relation is true for all stages of the linear collider, also for possible energy upgrades with longer LINAC's and also for solutions with more than one single IP at different longitudinal positions[9]. The exact ILC geometry can be "adjusted" with the return arc geometry and with artificial detours.
Both the damping ring position between positron generation and return arc and the damping ring geometry have no influence on this relation, as long as the in- and ejection position are connected linearly and parallel to the LINAC (e.g. "dog bone" shaped damping rings). More generally the double length of the linear tunnel plus all detours (deviation from the linear path) in the positron transport line from generation to the LINAC injection has to fit to a multiple of the damping ring circumference[10].

Also for a non self reproducing scheme an empty bucket has to be met. In case of the design operation with regular bunchtrains of equidistant bunches in the LINAC some empty buckets with the distance $d = c\,t(L)$ are available for re-injection. The number of empty buckets depends on the overall positron path length (about $2\,L / d$). One possibility is to extend the presented path length relation for the self reproducing scheme by adding multiples m of this bunch distance d:
$L = (n\,C + m\,d - (B - A) - b) / 2$,
relaxing the geometry restriction to the order of magnitude of the bunch distance d[11].
Alternatively one may assume a combined in- and ejection kicker system[12] and an immediate re-injection into the just ejected (and thus by definition emptied) bucket. Here the overall path length of the transported colliding and new positron bunch must be a multiple of the bunch distance in the LINAC d:
$2\,L + (B - A) + b = m^{*}\,d$.

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[9] The path length difference of a second IP with a different longitudinal position can be compensated with an additional artificial detour, used only during the operation of this IP. Another possibility would be an IP distance of exactly one bunch distance in the LINAC t(L), which would thus be frozen and would restrict the freedom in choosing operation parameters.
[10] See appendix
[11] For the design parameters this length is about 100m.
[12] Maybe interesting also for another reason: compensation of kicker pulse imperfections with two synchronously fired kicker systems (one for ejection and one for injection) and 180° betatron phase advance.

In this very special case[13] the damping ring circumference is arbitrary.
Since the bunch distance d appears in both equations, it will be defined by the chosen geometry and will not be open for changes, unless m d or m^* d remains constant. The relaxed geometry restrictions reduce the operation flexibility in changing the bucket distance t(L) and thus the RF pulse length T(L) and the compression factor k.

Also, for an ejection scheme with flexible gaps to suit kicker pulse, the unavoidable path length difference between ejected and re-injected bucket e = l c t(DR) must be taken into account for the geometry:

$L = (n\,C + m\,d + e - (B - A) - b) / 2$

or

$2\,L + (B - A) + b = m^*\,d + e.$

Once the damping ring circumference and all path lengths are fixed, this distance e would also be fixed, allowing no further changes.

In general all geometry constraints could be compensated by adding artificial (and possibly variable) path length into the positron transport line. Unfortunately the order of magnitude could be up to half the damping ring circumference (several km) for the self reproducing scheme.
Nevertheless a small path length adjustment option in the positron path is necessary, because of the coupled RF phases[14] and the need for a phase adjustment tool at the positron damping ring injection.
An extended path length adjustment possibility allowing changes in the time between ejection and injection kicker pulses as shown in figure 3 would be reasonable.

10. Conclusions

To ensure some flexibility in choosing beam operation parameters such as number of bunches, distance of bunches in the damping rings and the LINACs and RF pulse length, the circumference and RF frequency of the damping rings must be well chosen. For the best flexibility both damping rings should have the same circumference and RF frequency. An accurate design could allow additional flexibility by permitting equidistant gaps in the damping ring bunch pattern.
With an undulator based positron source, the re-injection timing for the positron damping ring is defined, resulting in stringent geometry restrictions for the overall ILC layout. Only if the geometry allows the refill of one damping ring bunch by its collision partner, the damping ring fills can be “self reproducing”, which would be essential for single bunch ejection.

References

[1] TESLA Technical Design Report, DESY 2001-011, ECFA 2001-209, TESLA-Report 2001-23, TESLA-FEL 2001-05

[2] 2001 Report on the Next Linear Collider, FERMILAB-Conf-01/075-E, LBNL-PUB-47935, SLAC-R-571, UCRL-ID-144077

[13] There are much more empty buckets available, but with a time difference to the just ejected bucket shorter than t(L).

[14] The RF phase of both main LINACs defines the exact collision point, the RF phase of the damping rings must fit to the corresponding LINAC, and the phase of the incoming positrons at the damping ring injection is given by the electron LINAC phase and the transport path length.

[3] I. Wilson, "The Compact Linear Collider CLIC", Phys.Rept. 403-404: 365-378, 2004
[4] Executive Summary of the International Technology Recommendation Panel, http://www.interactions.org/pdf/ITRPexec.pdf
[5] W. Kriens, "Basic Timing Reqirements for TESLA", DESY-TESLA-2001-10
[6] H. Ehrlichmann, "Damping Ring and Linac Length", presentation at the DESY LC meeting, 02/2002

Appendix

The "dog bone" geometry with integrated usage of one dog bone bending section as the 180° return arc, shown in figure 5, is also covered by the given equation. (This geometry was proposed for TESLA.)

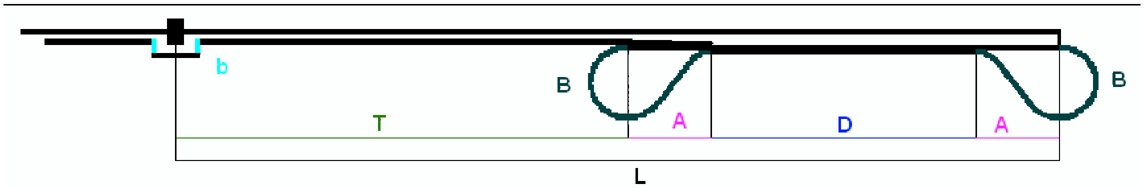

Figure 5: geometry of the positron part of the linear collider with a dog bone shaped damping ring

C	= circumference of the damping ring = 2 (A+ B + D)
L	= distance between the IP and the beginning of the linear tunnel (BDS, LINAC, BC…) = T + A + D + A
T	= distance between the IP and the damping ring
D	= linear sections of the damping ring, parallel to the LINAC
B	= path length of the 180° return arc
A	= linear tunnel length between both 180° return arc ends
b	= *additional* path length as above

Again the overall pass length of the transported colliding and new positron bunch must fit to a multiple of damping ring revolutions:
n C = L + b + T + A + D + B,
resulting again in:
L = (n C – (B – A) – b) / 2.

Another possibility would be a layout with damping ring in- and ejection not connected via a linear path in parallel to the LINAC. Two examples are shown in figures 6 and 7, allowing some coupling between the electron and positron injectors and damping rings.

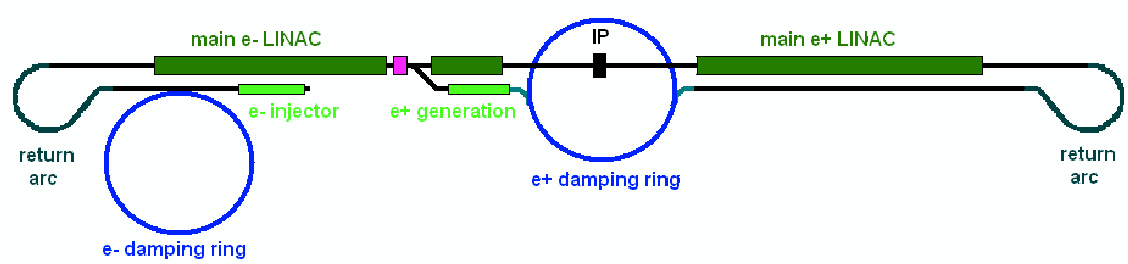

Figure 6: ILC geometry with positron damping ring around the IP

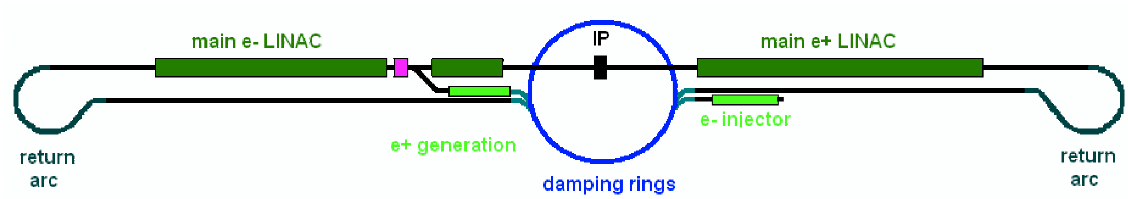

Figure 7: ILC geometry with both damping rings around the IP

For such cases a generalized scheme for the path length treatment is shown in figure 8.

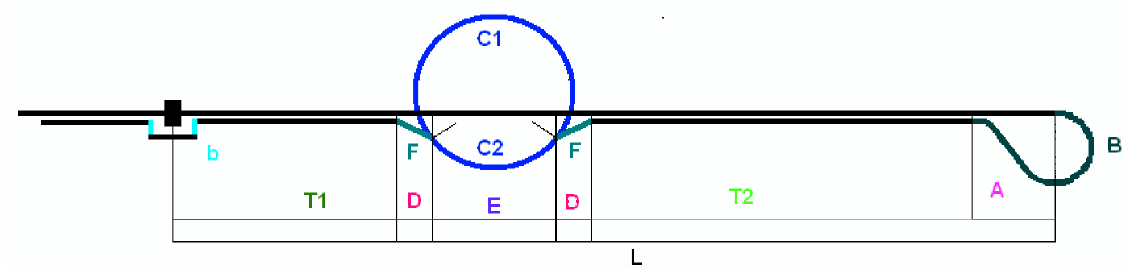

Figure 8: geometry of the positron part of the linear collider with damping ring in- and ejection at different positions along the ring

C1 = path length along the damping ring circumference between ejection and injection
C2 = path length along the damping ring circumference between injection and ejection
C = damping ring circumference = C1 + C2
E = linear tunnel length between injection position and ejection position
F = path length of the injection and ejection arcs
D = projection of the in- and ejection arcs onto the linear tunnel length
T1 = distance between the IP and the injection arc
T2 = distance between the ejection arc and the 180° return arc
B = path length of the 180° return arc
A = linear tunnel length between both 180° return arc ends
L = distance between the IP and the beginning of the linear tunnel (BDS, LINAC, BC…) = T1 + D + E + D + T2 + A
b = *additional* path length as above

As above the overall path length of the transported colliding and new positron bunch must fit to a multiple of damping ring revolutions, following the notation of figure 8:

$n\,C = F + T2 + B + L + b + T1 + F + C2$

or

$L = (n\,C - (B - A) - b - 2\,(F - D) - (C2 - E)) / 2$

This shows that for re-injection into the original bucket the double length of the linear tunnel plus all detours (deviation from the linear path) in the positron transport line from generation to the LINAC injection has to fit to a multiple of the damping ring circumference. For re-injection into other buckets this equation can again be extended by the corresponding bucket feeds d and/or e.