Recommendations for ILC Configuration Satisfying Timing Constraints

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Abstract

We discuss timing issues for the ILC in the context of the present baseline configuration. Timing constraints affect the lengths of a number of beamlines (including the damping rings circumference, and the location of the second interaction region). We make recommendations for the ILC layout to ensure a significant amount of operational flexibility.

0. Charge for the Task Force on ILC Timing Constraints

"The task force will assess options for satisfying the timing constraints on the operation of the ILC, and make recommendations for a specific timing solution for the baseline configuration.

In particular, the task force will consider issues associated with the need to provide flexibility in the bunch charge, bunch spacing in the linac and the number of bunches per pulse. The timing issues have a potential impact on various configuration and design parameters, including:

- the damping rings' circumference and RF frequency;
- the fill patterns in the damping rings (e.g. presence of ion-clearing gaps);
- the lengths of the beamlines connecting the damping rings with the sources (particularly the positron source) and with the main linacs;
- the longitudinal separation of the two interaction points;
- the locations of the damping rings within the accelerator complex.

The task force will work with the leaders of the Area Systems and Global Systems groups to evaluate the options for satisfying the timing constraints, in terms of the implications for, and impact on, the different systems.

The task force will recommend a specific timing solution for the design to be documented in the Reference Design Report, detailing precise system locations and beamline lengths where appropriate. Where possible, alternatives will also be specified. Technical issues associated with performance of specific components (e.g. low-level RF controls, and synchronization of RF systems) are beyond the scope of the task force, and recommendations on such issues will not be made.

The recommendations will be summarized in a report to be presented to the GDE no later than March 9, 2006."

1. Introduction

In the past the timing constraints for TESLA and ILC have considered under general conditions [1,2]. Many of the key parameters involved in the timing constraints have already been specified in the baseline configuration [3]; these include the damping rings' circumference and RF frequency. In this report, we consider possible solutions for the timing of the ILC, subject to boundary conditions drawn from the baseline configuration [3]. Our objective is to identify solutions that provide good flexibility for dealing with unexpected limitations in the performance of particular components or subsystems (e.g. the damping ring injection/extraction kickers, or the damping ring fast feedback systems), and make specific recommendations for the machine geometry to allow these solutions to be realized. The boundary conditions specified by the baseline configuration impose strong constraints on the possible solutions, and the solution providing maximum flexibility depends on the boundary conditions and other assumptions. Our discussion should not therefore be regarded as the final word on this issue: as the machine design develops and assumptions about operational conditions change, the timing solution may need to be reconsidered.

The Task Force did not reach a consensus on the optimum configuration. Our "recommendations" therefore simply consist of a description of a limited number of options that satisfy some of the requirements to different degrees, together with some discussion of the issues that will need to be considered when making a choice between the options.

2. Boundary Conditions

The baseline configuration for the ILC specifies a large number of system parameters that will affect the options for satisfying the timing constraints. Briefly, some of the key specifications are:

- The damping rings' circumference is approximately 6 km. This was decided after a thorough set of studies comparing options ranging from 3 km to 17 km, considering beam dynamics issues (acceptance, space-charge, electron cloud and ion effects etc.) and the performance of technical subsystems (kickers, damping wigglers etc.) [4].
- The damping rings' RF frequency is 650 MHz. This is a simple harmonic of the main linac RF, which should make synchronization between the different RF systems more robust. 650 MHz RF frequency also has the advantage over the alternative 500 MHz RF frequency, that for a given circumference, the damping rings have a higher harmonic number, allowing a lower bunch charge (desirable from point of view of issues at the interaction point) for a given average current.
- The maximum linac average beam current is 9.5 mA. This is a working assumption for the design of the main linac RF systems.
- The beam pulse length is approximately 1 ms. This is a working assumption based on the design of the main linac RF systems, but is not a "hard" constraint; we assume an upper limit of 1.2 ms. The linac RF pulse length is longer than the

beam pulse length by the fill time of the cavities (about 500 ns). A linac RF pulse length exceeding 1.4 ms would likely make the RF more difficult [5].

- The minimum bunch separation should be 3.08 ns (2 damping ring RF buckets) to allow for the kicker/rise and fall time. This is based on an estimate of the minimum achievable rise and fall time, based on recent experiments. For a given stripline length L, there is a lower limit on the rise/fall time equal to $2L/c$. Assuming striplines of length roughly 30 cm, this lower limit is 2 ns.
- The maximum kicker repetition rate during an extraction cycle is 6 MHz. This is a likely upper limit based on present tests of fast, high-power pulsers (e.g. at KEK-ATF) and is itself a challenging goal.
- Fills with longer bunch spacings (e.g. 3 or 4 damping ring RF buckets) are desirable, to allow for kicker rise/fall times that may be longer than 3 ns, or to mitigate electron cloud effects (which are sensitive to bunch spacing).
- Injection and extraction should proceed from the ends of the bunch trains in the damping rings; this has the potential to relax the fall-time specification on the kickers (which is more difficult to achieve than the rise time) since bunches affected by any residual pulse will be newly injected (i.e. not damped) bunches.
- Gaps of at least 40 ns should appear in the damping rings' fill approximately every 50 bunches, for ion clearing. This is based on expectations from recent simulation studies of fast ion instability.
- The number of particles per bunch should not exceed 2.2×10^{10}, and the layout should be capable of accommodating fills with bunch charge as low as 1×10^{10}. This requirement is based on effects at the interaction region. Larger bunch charges may also impact the performance of the damping rings, through effects such as the electron cloud instability, fast ion instability, microwave instability and intrabeam scattering.
- The total number of particles in a bunch train should be at least 5.6×10^{13}, to achieve the required luminosity.
- The layout should have flexibility in providing collisions at two interaction points with some longitudinal separation, as specified in the baseline configuration. If two of the possible linac bunch spacings are in a simple ratio to each other, this may be achieved by careful selection of the longitudinal separation. Greater flexibility may be provided by the use of delay lines or simply by allowing gaps (occasional missing bunches) in the linac bunch trains. Delay lines may be introduced between (one of) the damping rings and the IP, or between the positron source and the positron damping rings.

We consider options for the timing configuration satisfying boundary conditions, shown in Table 1, based on the present baseline configuration.

Table 1: Boundary conditions on timing configuration options.

Damping ring circumference	~ 6 km
Damping ring RF frequency	650 MHz
Maximum average linac beam current	9.5 mA
Minimum linac beam pulse length	0.9 ms
Maximum linac beam pulse length	1.2 ms
Minimum damping ring bunch separation	3 ns
Maximum kicker repetition rate	6 MHz
Minimum length of gaps for ion clearing	38 ns
Maximum number of particles per bunch	2.2×10^{10}
Fixed total number of particles per linac bunch train	5.6×10^{13}

3. Damping Ring Circumference and Fill Patterns

3.1 Linac Bunch Train Without Gaps

We consider first the case where there are no gaps allowed in the bunch trains in the main linacs, i.e. each bunch train consists of a sequence of bunches with exactly the same distance between bunches (there are no missing bunches). In this case, bunches are arranged in minitrains in the damping rings, with gaps between minitrains to allow for ion clearing. It may be arranged that extraction proceeds uniformly from the rear of each minitrain, so that as each bunch is extracted, the bunches immediately following are recently injected, undamped bunches. Thus, we avoid following an extracted bunch with damped bunches, which may be susceptible to increased jitter if the fall time of the extraction kicker is longer than expected.

We use the following notation to describe the fill patterns in the damping rings:

- h is the harmonic number of the damping ring.
- N_b is the maximum number of bunches per linac bunch train (the maximum number of bunches stored in the damping rings during a damping cycle). Generally, the upper limit on N_b is set by the specified bunch spacing and the minimum gaps required for ion clearing. The total number of bunches can always be reduced by omitting bunches at the head or tail of the linac bunch train. For a fixed total number of particles per linac bunch train, the charge per bunch is increased if N_b is reduced, so the lower limit on N_b is set by the maximum charge per bunch or the maximum average current in the linacs.
- N_0 is the number of particles per bunch, in units of 10^{10}. Note that this is chosen to give a total charge per linac bunch train of 5.6×10^{13} particles.
- t_{beam} is the linac beam pulse length in ms.
- n_b is the minimum separation between bunches in the damping rings, in damping ring RF buckets. Thus, the bunch spacing in the damping rings is t_{DR} (sec) = n_b /650×10^6.
- k_b is the time between injection/extraction kicker pulses, in damping ring RF buckets. Thus, the bunch spacing in the linac is t_{linac} (sec) = $k_b/650\times10^6$. The maximum kicker repetition rate of 6 MHz sets a minimum value for k_b of 108.

- i is the greatest common divisor of the harmonic number h and the kicker timing parameter k_b. This indicates the number of "used" buckets, in the sense that the exact same bunch time structure could be achieved if the RF frequency were divided by a factor i.
- p, f_2, g_2, f_1 and g_1 specify the fill pattern, which may be described as follows (see Fig. 1). At the "rear" of the fill, there are n_b empty buckets, followed by f_1 bunches (spaced by n_b RF buckets), followed by g_1 empty buckets. In the case $f_2 = g_2 = 0$, the pattern of f_1 bunches followed by g_1 empty buckets is repeated $(p–1)$ times, so that the total number of bunches is $p \times f_1$. If the fill is such that $f_2 \neq 0$ (and $g_2 \neq 0$), the repeated part of the pattern consists of f_2 bunches (spaced by n_b buckets), followed by g_2 empty buckets, followed by f_1 bunches (spaced again by n_b buckets), followed by g_1 empty buckets: in this case, the total number of bunches is $f_1 + p \times (f_1 + f_2)$.

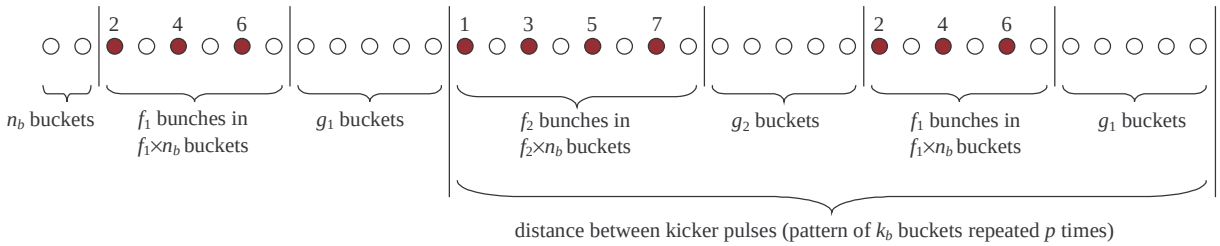

Fig. 1. Example of fill pattern in a damping ring.

As an example of this notation, consider Fig. 1. Filled circles represent filled buckets; empty circles represent empty buckets. In this example (not satisfying the boundary conditions!), the parameters have the following values:

$$\begin{aligned} h &= 37 \\ n_b &= 2 \\ i &= 1 \\ k_b &= 24 \\ p &= 1 \\ f_1 &= 3 \\ g_1 &= 5 \\ f_2 &= 4 \\ g_2 &= 5 \end{aligned}$$

The bunches should be considered as moving to the right; extraction starts on turn 1 with the bunch labeled "1", and continues on subsequent turns with bunches labeled by the turn number. A regular train is produced in the linac if the following conditions are satisfied:

$$\left.\begin{aligned} h &= pk_b + n_b \\ g_2 &= 0 \end{aligned}\right\} \qquad f_2 = 0 \tag{1}$$

or:

$$\left.\begin{aligned} h &= (p+1)k_b - f_1 n_b - g_1 \\ g_2 &= (f_1 - f_2 + 1)n_b + g_1 \end{aligned}\right\} \qquad f_2 \neq 0 \text{ and } f_2 \neq f_1 \tag{2}$$

The parameter i gives the number of "used" buckets and is an indicator of operational flexibility. For example, the highest frequency at which the feedback system will need to operate is given by f_{RF}/i; having options with a range of larger values of i may provide better opportunities for dealing with performance limitations in the feedback systems. We note that modern feedback systems can achieve very good performance; for example, the feedback systems in DAΦNE work well with 2.7 ns bunch spacing, providing a damping time of approximately 15 turns.

With the boundary conditions given in Table 1, and a requirement for no gaps in the trains in the linacs, the fill patterns in the damping rings are highly constrained. Some possibilities are given in Table 2; note that we use a fixed charge per pulse of 5.6×10^{13} particles, so that all the fill patterns shown produce the same nominal luminosity.

Table 2: Example fill patterns for four damping ring circumferences, assuming the boundary conditions of Table 1, no gaps in the linac bunch train, and fixed total charge per pulse of 5.6×10^{13} particles. The beam pulse length (t_beam) is given in ms; the number of particles per bunch, N_0, is in units of 10^{10}, and the average current is given in mA.

h = 14044: 9 patterns

Nb	N0	I_avg	t_beam	i	nb	kb	p	f2	g2	f1	g1
5546	1.01	8.8	1.02	1	2	119	118	0	0	47	25
5474	1.02	9.0	0.99	2	2	118	119	0	0	46	26
4152	1.35	7.6	1.19	2	2	186	75	28	38	27	38
3493	1.60	8.1	1.10	1	3	205	68	26	26	25	26
3120	1.79	8.0	1.12	2	4	234	60	0	0	52	26
3055	1.83	8.8	1.02	4	4	216	65	0	0	47	28
2970	1.89	7.6	1.19	4	4	260	54	0	0	55	40
2860	1.96	7.6	1.19	2	4	270	52	0	0	55	50
2677	2.09	9.2	0.97	4	4	236	59	23	28	22	28

h = 14340: 6 patterns

Nb	N0	I_avg	t_beam	i	nb	kb	p	f2	g2	f1	g1
5778	0.97	7.5	1.19	2	2	134	107	0	0	54	26
4050	1.38	8.1	1.10	3	3	177	81	0	0	50	27
3267	1.71	7.5	1.19	3	3	237	60	27	39	27	36
3136	1.79	8.3	1.08	4	4	224	64	0	0	49	28
3024	1.85	7.5	1.19	4	4	256	56	0	0	54	40
2835	1.98	7.7	1.17	4	4	268	53	27	28	26	28

h = 14502: 5 patterns

Nb	N0	I_avg	t_beam	i	nb	kb	p	f2	g2	f1	g1
5800	0.97	8.0	1.12	1	2	125	116	0	0	50	25
5625	1.00	8.9	1.00	2	2	116	125	0	0	45	26
5300	1.06	7.6	1.18	1	2	145	100	0	0	53	39
4131	1.36	7.9	1.14	1	3	179	81	0	0	51	26
2812	1.99	8.9	1.00	2	4	232	62	23	26	22	26

h = 14516: 5 patterns

Nb	N0	I_avg	t_beam	i	nb	kb	p	f2	g2	f1	g1
5782	0.97	8.2	1.09	1	2	123	118	0	0	49	25
5658	0.99	8.7	1.03	2	2	118	123	0	0	46	26
4346	1.29	7.6	1.18	1	2	177	82	0	0	53	71
3646	1.54	7.9	1.14	1	3	203	71	26	25	25	25
2767	2.02	8.9	1.00	4	4	236	61	23	28	22	28

The case with h = 14340 is of particular interest, because it provides good flexibility in terms of allowing three values of i greater than 1; the other cases have limited flexibility

in this respect. All the cases shown provide flexibility of bunch spacings at the two IRs without the need for delay lines, with the possibilities shown in Table 3. We note that the case h = 14516 provides slightly better flexibility for the second IR, without delay lines (three possible modes, rather than two for the other cases). See Section 4 for further discussion.

Table 3: Flexibility in positioning of second IR with particular damping ring circumferences, assuming no gaps allowed in the linac bunch train. Δs_{IR} is the longitudinal separation between the two interaction regions. Possible separations up to 200 m are shown.

h	Δs_{IR} (λ_{DR})	Δs_{IR} (m)	possible k_b values	particles per bunch (10^{10})
14044	118	54.42	118, 236	1.02, 2.09
	236	108.85		
	354	163.27		
14340	134	61.80	134, 268	0.97, 1.98
	268	123.61		
	402	185.41		
14502	116	53.50	116, 232	1.00, 1.99
	232	107.00		
	348	160.50		
14516	118	54.42	118, 236	0.99, 2.02
	236	108.85		
	354	163.27	118, 177, 236	0.99, 1.29, 2.02

3.2 Allowing Gaps in Linac Bunch Train

Allowing gaps (i.e. occasional missing bunches) in the bunch train in the main linacs increases the range of possibilities for the fill patterns in the damping rings. In general, fill patterns can be constructed by filling every ith RF bucket in the damping ring, and selecting a kicker interval k_b such that k_b/i is prime and *not* a factor of h/i. Some examples with k_b/i = 53, and again satisfying the boundary conditions shown in Table 1, are given in Table 4. There is again a fixed charge per pulse of 5.6×10^{13} particles. We use the same notation as in Section 3.1, except that now p is the number of minitrains, $p = N_b/f_1$. Note also that $f_2 = g_2 = 0$. The gap between minitrains is (g_1+1) damping ring RF buckets, or roughly 38 ns for all the cases shown in Table 4.

Table 4: Example fill patterns for two damping ring circumferences, assuming that gaps (missing bunches) are allowed in the linac bunch train, and fixed total charge per pulse of 5.6×10^{13} particles. The beam pulse length (t_beam) is given in ms, and the average current in the linac (I_ave) is given in mA. Examples with a fixed value of k_b/i = 53 are shown.

h=14340

Nb	N0	I_ave	t_beam	i	nb	kb/i	kb	p	f1	g1/i
5824	0.96	9.45	1.17	2	2	53	106	112	52	12
3885	1.44	9.44	1.17	3	3	53	159	111	35	8
2912	1.92	9.45	1.17	4	4	53	212	112	26	6
2565	2.18	8.58	1.17	5	5	53	265	57	45	5

h=14516

5850	0.96	9.40	1.18	2	2	53	106	117	50	12
2925	1.91	9.40	1.18	4	4	53	212	117	25	6

The bunch pattern in the linac is not given explicitly, but in general, one will expect the proportion of missing bunches to be roughly $1 - if_1p/h$, or generally around 20%.

To allow flexibility in the bunch spacing at a second IP, the longitudinal separation between the IP's must be chosen carefully. Some possibilities up to 200 m separation, corresponding to the fill patterns in Table 4, are shown in Table 5.

Table 5: Flexibility in positioning of second IR with particular values of k_b, assuming gaps are allowed in the linac bunch train, and there are no delay lines. Δs_{IR} is the longitudinal separation between the two interaction regions. Possible separations up to 200 m are shown.

Δs_{IR} (λ_{DR})	Δs_{IR} (m)	possible k_b values
106	48.89	106, 212
159	73.33	106, 159
212	97.78	106, 212
318	146.67	106, 159, 212
414	195.56	106, 212

Note that the case with h = 14340 allows good flexibility in i (= 2,3,4,5). The case with h = 14516 is more limited (i = 2 or 4 only).

For schemes of this type, extraction and re-injection does not occur consistently from the rear of a minitrain. This means that the bunch immediately following an extracted bunch is often a damped bunch awaiting extraction; if the kicker fall time is longer than expected, then tails in the kicker pulse may affect the stability of these bunches.

We note that with a longitudinal separation of 146.67 m between the IR's, three of the values of k_b from Table 4 are allowed at the second IR, corresponding to i = 2, 3 and 4. This implies a little greater flexibility with h =14340 than with h = 14516.

4. Linac and Transport Line Lengths

Since the positrons are generated by the high-energy electron beam, the arrival time of the positrons at the damping ring injection point is given by the electron beam timing and the positron transport path length. For re-injection into the positron damping ring, each new positron bunch has to arrive at an empty RF bucket. In the case of bunch patterns without gaps and possible single bunch ejection (which may be important during commissioning or re-commissioning after MPS events) only one bucket is available. In case of fill patterns with gaps (or operation with always complete extraction cycles) there are more possibilities. Here, bunch patterns could be reproduced with a certain bucket shift after one complete extraction cycle. But the greatest operation flexibility is achieved if the machine layout is such as to provide a "self-reproducing" fill, where each damping ring bucket is refilled by its electron collision partner bunch. Such a scheme sets strong constraints on the ILC geometry.

4.1 Self-Reproducing Fills and the First Interaction Region

Let us consider first the case of one interaction region. A schematic layout with the significant beamline lengths is shown in Fig. 2.

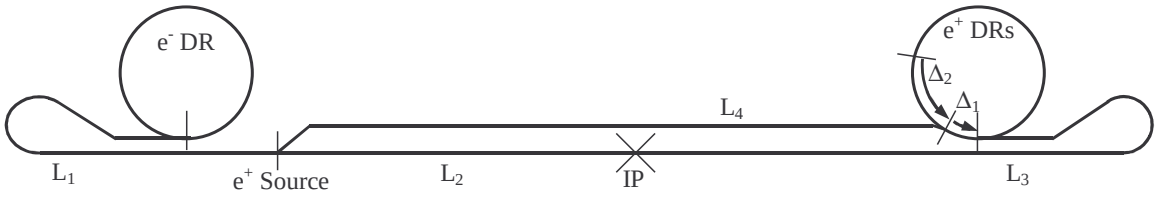

Fig. 2: Schematic layout with significant beamline lengths and one IR.

The lengths of various beamline sections are defined as follows:

- L_1 is the distance from the electron damping ring extraction point, to the positron production target.
- L_2 is the distance from the positron production target to the IP.
- L_3 is the distance from the positron damping ring extraction point, to the IP.
- L_4 is the distance from the positron production target to the positron damping ring injection point.
- Δ_1 is the distance from the injection kicker to the extraction kicker in the positron damping ring.
- Δ_2 is the distance that a bunch in the positron damping ring travels in the time between the extraction of the electron bunch with which it will collide, and the arrival of the positron bunch at the positron damping ring *injection* kicker.

The distance Δ_2 can be changed simply by adjusting the kicker timings: all other lengths are fixed in construction.

To ensure collisions at the IP:

$$L_1 + L_2 = \Delta_2 + \Delta_1 + L_3 \tag{3}$$

We want the fill to be "self-reproducing" (i.e. each newly created positron bunch replaces the positron bunch that collides with the electron bunch that creates the new positron bunch). The condition for this is:

$$L_1 + L_4 = \Delta_2 + nC \tag{4}$$

where C is the damping ring circumference and n is an integer.

Eliminating Δ_2 (which is the only variable after the machine is constructed) between (3) and (4):

$$L_4 + \Delta_1 + L_3 = L_2 + nC \tag{5}$$

Assuming L_2, Δ_1 and C are fixed early in the design, the constraint (5) can be satisfied by adjusting (at the design stage) L_3+L_4. We note that in this case, the position of the positron damping ring along the main linac is arbitrary; it may be adjusted simply by increasing (reducing) L_3, and reducing (increasing) L_4 by an equal amount.

4.2 Second Interaction Region

Now let us consider the second interaction region; we assume there are no delay lines, and the lengths of all beamlines (except for Δ_2) are fixed as before. A schematic for this situation is shown in Fig. 3.

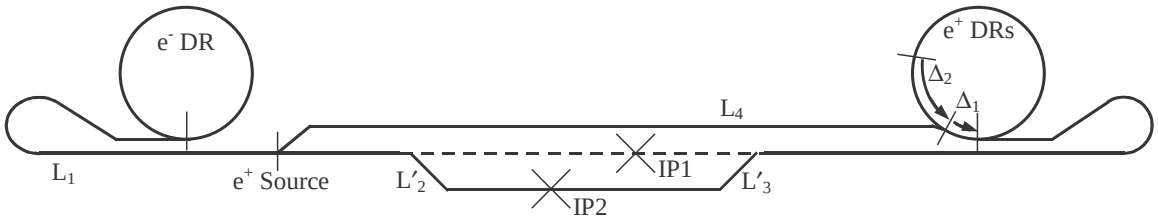

Fig. 3: Schematic layout with second IR.

To allow a second IP with longitudinal separation from the first, we must relax the constraint (2) that leads to "self-reproducing" fills; in other words, each electron bunch no longer collides with the positron bunch that is replaced in the damping ring by a positron bunch that the electron bunch creates.

The second IP must have a longitudinal displacement that satisfies:

$$\Delta L_3 = \Delta L_2 + r\lambda \cdot \mathrm{LCM}(L_{\mathrm{sep}}) \tag{6}$$

where

$$\Delta L_3 = L_3' - L_3 \tag{7a}$$
$$\Delta L_2 = L_2' - L_2 \tag{7b}$$

λ is the linac RF wavelength, L_{sep} is the set of possible bunch separations in the linac (in linac RF wavelengths), r is an integer, and LCM() is the least common multiple. If we make the approximations:

$$\Delta L_3 \approx -\Delta L_2 \tag{8}$$

and

$$\Delta s_{\mathrm{IR}} \approx \Delta L_3 \tag{9}$$

where Δs_{IR} is the physical longitudinal separation of the IRs (in meters), then we can write:

$$\Delta s_{IR} \approx \tfrac{1}{2} r\lambda \cdot \mathrm{LCM}(L_{sep}) \tag{10}$$

Note that while Eqn. (10) is an approximation, Eqn. (6) is an exact condition.

For example:

$$L_{sep} = \{236,354,472\} \tag{11}$$

Then $\mathrm{LCM}(L_{sep}) = 1416$, and:

$$\Delta s_{IR} \approx \tfrac{1}{2}\lambda \cdot \mathrm{LCM}(L_{sep}) = 163.27 \text{ m} \tag{12}$$

If delay lines are used, then there can be greater flexibility in the longitudinal separation of the two interaction regions.

4.3 Fills that are Not Self-Reproducing

Allowing fills that are not self-reproducing according to the conditions in Section 4.1 will ease the geometry constraints. In this case, the main constraints arise from the need for the newly-produced positron bunches to arrive at the positron damping ring coincident with an empty RF bucket. This leads to the main disadvantage of such a scheme, which is that the "guarantee" of available empty buckets provided in the self-reproducing scheme is lost. In particular, there may be situations where empty buckets are only guaranteed if a complete (or near-complete) bunch train is extracted from the damping ring; partial extractions of just a small number of bunches may not be possible.

A further issue is that in general, the fill pattern in the positron damping ring is "shifted" after refilling, with respect to the positions of bunches before extraction. However, it will be possible in principle to refill the electron ring to produce an equivalent shift; the relative positions of bunches in the electron and positron damping rings will thus be kept in step with each other.

In general, if each positron bunch extracted from the damping ring is replaced by a new bunch m buckets later, then Eqn. (5) becomes:

$$L_4 + \Delta_1 + L_3 = L_2 + nC + m\lambda_{DR} \tag{13}$$

Let us consider the conditions that apply to m. First, we wish to preserve the value of i during the extraction/injection process. This means that we require that m is exactly divisible by i, or in other words:

$$m \bmod i = 0 \tag{14}$$

Secondly, if we require that the first newly arriving bunch goes into one of the gaps in the damping ring fill, then we must have:

$$m \bmod k_b \le g_1 \tag{15}$$

This must be satisfied for all values of k_b that we wish to use. Eqn. (15) is a generally sufficient condition for new bunches arriving at the positron damping ring always to arrive at an empty bucket (assuming that all the damped bunches in the damping ring are being continuously extracted). However, it is not a strictly necessary condition, and there are other alternatives. For example, the first newly arriving bunch can go into an empty bucket left by one of the already extracted bunches. The bunches in the ring make n turns between the extraction of the first bunch and the arrival of the first new bunch. In the case where $f_2 = g_2 = 0$, this means that n bunches from the tail of each minitrain have been extracted, leaving gaps that are available to be filled. The condition for the newly arriving bunch to fill one of these gaps in this case is:

$$m \bmod k_b > k_b - n \times n_b \tag{16}$$

If flexibility is required in the linac bunch spacing (i.e. it is desired that several different values of k_b be allowed), then the conditions for newly arriving bunches always to fill empty buckets place strong constraints on the beamline lengths in ILC. For example, with $h = 14340$, there are no solutions (other than those with $m < 40$, which are not very helpful) for all six of the fill patterns shown in Table 2. However, if we take only the fill patterns with $k_b = 134$, 224, 237 and 268, then there are now six interesting solutions to Eqn. (14) and either Eqn. (15) or (16); these are shown in Table 6.

Table 6: Values of m for non-self reproducing fills, to ensure new positron bunches arriving at empty buckets in the damping ring, for $h = 14340$. Only fills with $k_b = 134$, 224, 237 and 268 are allowed

4032	8064	12336
4044	8316	12348

In the case with $h = 14516$, there is a larger number of solutions, for all five fill patterns shown in Table 2. The possible values of m are shown in Table 7.

Table 7: Values of m for non-self reproducing fills, to ensure new positron bunches arriving at empty buckets in the damping ring, for $h = 14516$.

2844	5904	8736	11572
2848	5908	8740	11576
2852	5912	8744	

We should also comment that for the schemes that are not self-reproducing, bunches are generally injected into the gaps between bunch trains in the damping rings, and situations can therefore arise where bunches are injected only short distances before damped bunches awaiting extraction. This is undesirable, because if the fall-time of the injection kicker is longer than expected, then the stability of the damped bunches may be affected.

If the fill in the damping ring is such that gaps appear in the linac bunch train, then the situation may be different. We have not considered this case explicitly.

5. Summary

5.1 Damping Rings Circumference

We consider that the choice should be made between two cases, namely h = 14340 and h = 14516. For a given total charge per train of 5.6×10^{13} particles, and no gaps in the bunch train in the linac, both these cases allow a range of bunch charges between approximately 1×10^{10} and 2×10^{10}, depending on the number of bunches. With the highest bunch charge (or smallest number of bunches), the bunch spacing in the damping rings in each case is 6.15 ns; there are also ion-clearing gaps of 40 ns occurring regularly in the fill.

Briefly, the advantages and disadvantages of each case may be stated as follows:

h = 14340

Advantage:

- Allows regular fills with i = 2,3,4,5,6… providing better flexibility in case of problems with the feedback systems.

Disadvantage:

- Without delay lines or gaps in the linac bunch train, there is slightly less flexibility in bunch spacing/bunch charge at the second IR than the case with h = 14516 (two fill patterns allowed, compared to three for h = 14516). We assume the position of the second IR is chosen carefully.

h = 14516

Advantage:

- Provides a little more flexibility in providing (three) different bunch charges/bunch spacings at a second IR without the need for delay lines or gaps in the linac bunch train, compared to the case with h = 14340 (two different bunch charges). We assume the position of the second IR is chosen carefully.

Disadvantage:

- Lower flexibility in fill patterns than h = 14340 case: i = 1,2,4 only.

Delay lines will increase flexibility, but will also add cost and operational complexity (for example, the need for tuning for low-emittance transport).

Schemes based on allowing gaps in the bunch train in the linac have the potential drawback that extraction does not happen uniformly from the rear of a bunch minitrain in the damping rings; this means that damped bunches awaiting extraction may be susceptible to increased jitter if the kicker fall time is longer than expected.

5.2 Linac and Transport Line Lengths

Maximum operational flexibility is provided if the lengths of the linacs and transport lines should be designed to allow "self-reproducing" fills. This may be achieved by designing beamline lengths to satisfy Equation (5). The precise lengths of the beamlines will depend on optics designs and other aspects; as the designs of the beamlines develop, attention should be paid to designing lengths that satisfy the condition for self-reproducing fills. We note that the requirement for self-reproducing fills leads to geometry constraints only in the case that the positron source uses high-energy electrons from the main linac (as in the baseline configuration).

As an example, we consider the lengths of the beamlines as estimated in January 2006 [6]. The relevant lengths are shown in Table 8. Note that the length L_4 is estimated based on the geometry, as indicated in Fig. 2, using a radius for the turn-around in the RTML (ring to main linac) of 27 m. Also, we take the start of the section with length L_2 to be the start of the beamline ELTU, which transports the electron beam from the main linac to the positron production undulator; this is valid if we take L_4 to start from the same point, since it simply implies adding equal lengths to L_2 and L_4, which appear on opposite sides of the equation we shall use, Eqn. (5).

Table 8: Estimated lengths of beamlines, from BCD Beamline Descriptions [6].

Section	Beamline units	Beamline unit lengths	Total section length
L_2	ELTU, EUND, EUTL	850 m	7843 m
	ELIN2	4620 m	
	EBDS	2373 m	
L_3	PRTML	2500 m	16073 m
	PLIN1	11200 m	
	PBDS	2373 m	
L_4		22133 m	22133 m
Δ_1		49 m	49 m

Using a damping ring circumference C = 6614 m (corresponding to h = 14340), we find from Eqn. (5) that $n \approx 4.6$. However, to satisfy the self-reproducing condition, n needs to be an integer. There are four possible solutions:

1. modify the damping ring circumference to satisfy Eqn. (5);
2. drop the requirement for self-reproducing fills;
3. add a delay line of 2646 m to the positron transport line (increase L_4 by 2646 m), or increase the positron RTML by 2646 m (increase L_3 by 2646 m) – in practice, one would likely add 1323 m to the linac tunnel, thereby increasing both L_3 and L_4 by 1323 m each, or a total of 2646 m;
4. modify the layout [2] to shift the center of the positron damping ring: for example, in the case that the center of the damping ring is close to the linac tunnel, and injection and extraction happen on opposite sides of the damping ring, a length of $(\pi\text{-}2)R \approx 1200$ m to the distance $L_4 + \Delta_1 + L_3$, where R is the radius of the damping ring.

Solution 1 will severely limit the flexibility of operation; it is not easy to find circumferences that provide good flexibility, and we strongly advise against choosing this solution. Solution 2 is a possibility, and we discuss this further, below. Solution 3, although increasing the total beamline length by a significant amount and therefore adding some cost, will ensure that the maximum operational flexibility is retained. (Solution 3 also provides some safety margin for the gradient in the positron linac). By modifying the layout (Solution 4) in different ways, up to one damping ring circumference may be added to the total path length $L_4 + \Delta_1 + L_3$. It is also possible, of course, to combine solutions 3 and 4.

Let us consider in more detail the second solution listed above, namely that we drop the requirement for self-reproducing fills. In that case, we need to consider Eqn. (13), with the constraints on m given by Eqn. (14) and either Eqn. (15) or Eqn. (16). For h = 14340, we can retain four different fill patterns in the damping ring (k_b = 134, 224, 237 and 268) with six different values of m. In the case n = 4 and m = 8316, then Eqn. (13) is satisfied if a length of 120 m is added to L_2 (or 120 m is subtracted from the total of L_3 and L_4), compared to the value shown in Table 8.

Choosing the other option that we considered above for the damping ring circumference (C = 6695 m, or h = 14516) makes a small difference. If a self-reproducing fill scheme is required, then the required combined increase in length of L_3 and L_4 is 3013 m (an extra 1507 m of tunnel). If a self-reproducing scheme is not required, then we can choose m = 8736, and Eqn. (13) can be satisfied by adding a length of 397 m to the total of L_3 and L_4 (an extra 199 m of tunnel), or subtracting 397 m from L_2.

In summary, requiring a geometry that provides self-reproducing fills will provide maximum operational flexibility. However, this may require the addition of a significant (maybe 1.5 km) extra length of tunnel. At the sacrifice of some flexibility, the geometry may be arranged so as to provide a fill scheme that is not self-reproducing, in which case the required changes in tunnel length are only of the order of 100 – 200 m.

5.3 Longitudinal Separation of Interaction Regions

Assuming some set of common bunch spacings in the linac for the two interaction regions, then the lengths of the beamlines feeding bunches to the second interaction region must be chosen to satisfy Eq. (6).

If a damping ring circumference with h =14340 is chosen, and gaps in the linac bunch train are allowed, then a longitudinal separation of 146.67 m (see Table 5) between the IR's allows for at least three different bunch charges/bunch separations at the second IR, without the need for delay lines. If gaps in the linac bunch train are not allowed, then a separation of the IR's from Table 3 should be chosen; only two bunch charges/bunch separations are allowed.

If a damping ring circumference with h = 14516 is chosen, then a longitudinal separation of IP's of 163.27 m allows for three different bunch charges/bunch separations at the second IP (and five at the first IP), without the need for gaps in the linac bunch train.

6. Final Remarks and Recommendations

The Task Force was not able to reach a consensus on recommendations for the configuration in terms of the timing schemes. While there was agreement on the need to find a solution that provided the maximum flexibility, there were different opinions on how this should be interpreted, and, in particular, how strictly (or even whether) the boundary conditions from the Baseline Configuration should be applied. Below, we summarize some of options that we considered, together with some of the issues that need to be considered when making a choice between them. The comments made in connection with the options and issues should not be interpreted as indicating a general agreement among the members of the Task Force in favor of one option or another.

To provide the ability to work around unforeseen problems, it is essential that the configuration of the ILC be chosen to allow great flexibility in operating parameters. The timing schemes are directly related to important parameters such as the bunch charge and bunch spacing in the linac. Since the possible timing schemes are strongly constrained by the layout, the machine must be designed to allow as much flexibility as possible in the timing schemes that can be achieved in operation.

The flexibility of a given layout depends on the assumptions that are made for operational limitations, such as: the maximum RF pulse length in the linac; the length of ion-clearing gaps required in the damping rings; the maximum possible repetition rate of the damping ring injection/extraction kickers etc. An optimization assuming freedom in all these parameters was beyond the scope of this Task Force; instead, in this report we assumed fixed limits set by the Baseline Configuration, and looked for solutions providing flexibility within those bounds. As the ILC design evolves, the boundary conditions are likely to change, and the configuration providing maximum flexibility in timing schemes will need to be re-examined.

However, for the Baseline Configuration and the Reference Design Report, choices for the damping rings circumference and lengths of various beamlines do need to be made. On the basis of timing flexibility, we feel that the choice for the damping rings circumference should be made between harmonic numbers 14340 and 14516. These allow six and five bunch charges/bunch spacings respectively at the first IP, with the number of particles per bunch varying from 1×10^{10} to 2×10^{10} for a fixed number of 5.6×10^{10} total particles per pulse. For a single IP, or if two timing schemes for the second IP are thought sufficient, then the harmonic number 14340 is probably the better choice, because it allows greater flexibility in the fill harmonic (since 14340 is divisible by 2, 3, 4, 5, 6…). Damping rings with harmonic number 14340 do allow for three bunch charges/bunch spacings at the second IP if gaps are allowed in the linac bunch train; however, this is not attractive since it means extracting bunches from the middle of minitrains in the damping ring. In this case, the stability of damped bunches may be

adversely affected by a slow fall of the injection/extraction kickers pulse. Choosing the harmonic number 14516 for the damping rings allows for three possible bunch charges/bunch spacings at the second IP, while extracting and injecting uniformly from the rear of each minitrain in the damping rings.

The location of the second IP must be chosen carefully to satisfy basic timing requirements, and to take advantage of any potential flexibility in bunch charge/bunch spacing at the second IP. Delay lines are an option that will generally increase the flexibility for any given geometry; these should be studied in more detail, and the benefits and technical issues more thoroughly understood.

Irrespective of the damping rings circumference, the optimal layout of the ILC from point of view of timing flexibility is one that allows "self-reproducing fills." However, this places strong constraints on the geometry that must be satisfied by adding approximately 1.3 km of tunnel (2.6 km of beamline) to the presently estimated lengths. As an alternative, timing schemes are possible in which the fills are not self-reproducing. This relaxes the geometry constraints, which can now likely be met with changes in length of order 100 – 200 m; however, there is significant loss of flexibility, because of the need to ensure that bunches from the undulator-based positron source arrive at empty buckets in the positron damping ring. Depending on the harmonic number chosen for the damping rings, some of the fill patterns may be no longer possible. There are also potential additional complications arising from the fact that if the fill is not self-reproducing, then the fill pattern "shifts" around the ring as the result of an extraction/injection cycle.

We emphasize once again that whatever configuration is chosen, the flexibility in timing schemes depends on a wide range of parameters. As work on the design progresses, the whole configuration should be continually re-examined, to ensure that flexibility is not being lost by changes made to the design, and to take advantage of opportunities for design choices that may improve operational flexibility. The comments in this report should be viewed as applying to the Baseline Configuration as it stands at present; work should continue on optimizing the overall design for maximum flexibility.

References

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