Timing Constraints on ILC

Presented at the Annual Meeting of Accelerator Society of Japan

M.Kuriki, K.Kubo (KEK), E.Ehrichmann (DESY), S.Guiducci (INFN-LNF),
A.Wolski (Cockcroft Inst.)

Timing Constraints on ILC

M. Kuriki*, K. Kubo, KEK, Tsukuba, Ibaraki, Japan
H. Ehrlichmann, DESY, Hamburg, Germany
S. Guiducci, INFN-LNF, Frascati, Italy
and A. Wolski, Cockcroft Institute, Warrington, Cheshire, UK

Abstract

ILC(International Linear Collider) is a future project of the high energy physics as a partnership among the world countries. The baseline design of ILC, which has been developed by ILC-GDE(Global Design Effort) in 2005, has various constraints on the beam handling and layout due to the inter-system dependencies. We discuss these constraints and possible solutions.

INTRODUCTION

ILC (International Linear Collider) is aiming at electron-positron collisions at 1 TeV center of mass energy. Because ILC is based on the super-conducting accelerator, a long pulse of 1ms with 10mA average beam current must be implemented. The all bunches in one pulse-train has to be stored in DR, because the damping time is much longer than the pulse duration, 1 ms. The bunch spacing has to be compressed and expanded in the injection and extraction respectively for a reasonable circumference of DR. This complex injection/extraction scheme makes constraints not only on the bunch spacing in DR and linac, but also the fill pattern in DR.

Other aspects of the timing in ILC is coming from the e+ generation. In the current baseline design of ILC[1], e+ is generated from the high energy gammas produced by the undulator radiation with the e- beam before the collision. The new e+ beam is then born during the collision and can be conflict with the un-extracted e+ bunches in DR. Compton based e+ production[2], which is an alternative method of ILC, gives constraints on DR circumference (harmonic number) and extraction and injection scheme.

Objective of this article is to discuss the constraints of ILC system, which was originally considered for TESLA project[3] and initiated by H. Ehrlichmann for ILC[4], and identify possible solutions that provide good flexibility for dealing with unexpected limitations in the performance of particular components or subsystems.

DR FILL PATTERN

The bunch spacings in linac and DR has to be an integer of the linac and DR RF periods respectively. The baseline configuration is 1.3GHz for linac and 650MHz for DR, which are in a simple harmonic relation[6]. The bunch is handled independently with a fast kicker, which has 3ns rise/fall time[5]. Table 1 defines parameters for the following discussions. C_{DR} is DR circumference. As general conditions for the parameters, i must be a divisor of h, i.e.

Table 1: Parameter definitions.

name	definition
DR RF period	t_{DRRF}
Bunch spacing in DR	$t_{DR} = it_{DRRF}$
Linac RF period	t_{LNCRF}
Bunch spacing in Linac	$t_{LNC} = jt_{LNCRF}$
DR harmonic number	$h = C_{DR}/(ct_{DRRF})$
Harmonic relation	$k = t_{LNC}/t_{DR}$
Possible number of bunches in DR	$N_B = h/i$

$h/i \in \mathrm{N}$, where N means the natural number class, and bunch spacing in Linac has to be an integer of that in DR, $j/k \in \mathrm{N}$.

Uniform solution

There are two kinds of solutions for DR fill pattern and extraction/injection scheme. One is Uniform solution, in which the bunch spacing in linac is uniform. In that case, the following propositions have to be true

$$\{\exists p,\ k,\ e \in \mathrm{N} | N_B = pk \pm e\} \quad (1)$$

$$\left\{\forall m \in \mathrm{N}, 2 \leq m \leq e \left| \neg\left(\frac{N_B}{m} \in \mathrm{N} \wedge \frac{e}{m} \in \mathrm{N}\right)\right.\right\} \quad (2)$$

where p and e mean number of mini-trains in DR fill pattern and number of remainder bunch position when all mini-trains are filled. Fig. 1 shows an example of fill patterns. Prop (2) means that N_B and e has no common divisors. It
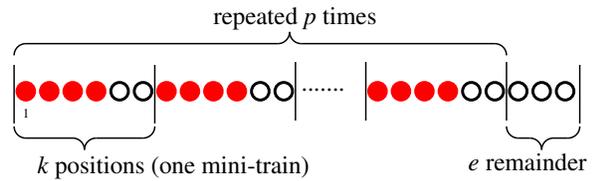
repeated p times

k positions (one mini-train) e remainder

Figure 1: An example of fill pattern. Solid and open circles are the filled and vacant positions , respectively.

can be understood by considering an example, which violates Prop. (2); N_B=100, p = 12, k=8, and e=4. Let us assume that extraction starts first with at the bucket position 1 and continues to the positive direction. The extracted bunch train labeled by the bucket position is :

$$1, 9, 17, \cdots, 89, 97, 5, 13, \cdots, 93, 1, \cdots, \quad (3)$$

where the extraction is back to the initial position after two turns. At that time, only 25 of 100 bunches are extracted

and other 75 bunches are never extracted. If the parameters are : N_B=100, p = 11, k=9, and e=1, which satisfy Prop. (2), extraction sequence is

$$1, 10, 19, \cdots, 91, 100, 9, 18, \cdots, 99, 8, \cdots\cdots, 92, 1, \tag{4}$$

where the extraction is back to the first position after 10 turns, when all bunches has been extracted. In case of Prop. (1) and (2) are satisfied, all bunches are already extracted whenever the extraction is back to the first position.

This is similar to considerations for the Weyl's billiard; when a ball is shot into an angle of a rational number in a billiard table, the ball will return to the original position in some period. In case of the irrational number, the ball will never return to the original position and the orbit covers everywhere in the table.

In Uniform solution, the bunch fill pattern does not have any exact periods, because N_B and e do not have any common divisors. In the second example shown in (4), the bunch fill pattern has roughly 11 periods, but the period is not exact due to the remainder, e. Once h is fixed, Uniform solution has a limited flexibility because the parameters p, k, and e must satisfy Prop. (1) and (2).

Step Solution

The second solution is Step solution. The condition for Step solution is expressed as

$$\{\exists p, \ k \in \mathrm{N} | N_B = pk\}. \tag{5}$$

Please remember the first example, (3), which does not satisfy the condition of Uniform solution. The extraction is back to the first position after two turns. If we move to the position 2 instead of the position 1 by stepping one bunch spacing in DR, it_{DRRF}, the bunch extraction can be continued without hitting any vacant buckets. This is Step solution. All bunches are extracted by making a step whenever we hit a vacant bucket. Due to the step, the bunch spacing in linac, jt_{LNCRF} is varied periodically to be $jt_{LNCRF} \pm it_{DRRF}$.

In the step solution, the bunch fill pattern has exact super-periods determined by parameter p. In addition, with a fixed N_B, a wide flexibility changing parameters k and p exists comparing to Uniform solution.

Boundary conditions and solutions

In addition to the general considerations for the DR pattern, there are several boundary conditions coming from the real accelerator system as follows:

- The damping ring's circumference is approximately 6 km. This was decided after a through set of studies considering beam dynamics issues.

- The maximum linac average beam current is 9.5 mA.

- The beam pulse length, $T_{pulse} = N_B t_{LNC}$, is approximately 1 ms.

Table 2: Examples of Uniform solution for DR fill patterns. Units for N_0, I_{avg}, and T_{pls} are 10^{10} particles, mA, and ms respectively.

h	N_f	N_0	I_{avg}	T_{pls}	i	p	k	e
14340	4601	1.22	9.5	0.95	2	107	67	1
	3484	1.61	9.5	0.95	3	81	59	1
	2752	2.03	9.5	0.95	4	64	56	1
14516	5289	1.06	9.3	0.96	2	123	59	1
	3074	1.82	9.3	0.96	1	71	203	103
	2644	2.12	9.3	0.96	4	61	59	30

Table 3: Examples of Step solution for DR fill patterns. Units for N_0, I_{avg}, and T_{pls} are 10^{10} particles, mA, and ms respectively.

h	N_f	N_0	I_{avg}	T_{pls}	i	p	k
14400	5040	1.10	9.63	0.93	2	120	60
	4032	1.39	9.63	0.93	3	96	50
	2688	2.08	9.63	0.93	3	64	75
	2520	2.20	9.63	0.93	3	60	80

- The minimum bunch separation should be 3.08ns (two damping ring RF periods) to allow for the kicker/rise and fall time.

- The maximum kicker reputation is 6 MHz, which is a likely upper limit based on present tests[5].

- Gaps of at least 40 ns should appear in the DR's fill approximately every 50 bunches, for ion cleaning. 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 1.0×10^{10}. This claim is based on effects at the interaction region.

- The total number of particles in a train should be at least 5.6×10^{13}, to achieve the required luminosity.

Examples of Uniform solution are given in Table 2. Those solutions with h=14340 and 14516 have 6.6 and 6.7 km circumferences, respectively. In this table, N_f is bunch number actually filled, N_0 is number of particles in a bunch, and I_{avg} is average beam current. An interesting point is that e is almost half of k for the last two solutions. In these cases, separation of mini-trains (k) is actually half ($\sim k/2$) and number of mini-trains (p) is double ($\sim 2p$), because the extractin position is shifted by roughly half of k value every DR revolution.

Examples of Step solution are given in Table 3 with C=6.6 km. The definition and units of the parameters are same in Table 2. Those solutions have exact periodic pattern, e.g. 10, 15, 32, etc. This characteristic is usable for the positron production based on the Compton scheme as described later.

CONSTRAINTS FROM THE POSITRON PRODUCTIONS

Self-reproduction Condition

E+ beam is generated by e- beam before the collision by passing the undulator. Gamma ray is converted into e+ beam in a conversion target and transported into e+ injector linac. The self-reproduction condition, in which the e- generates the new e+, who is the collision partner in the next pulse. Assuming this self-reproduction, the generated e+ can be accepted by DR with any DR fill patterns, because the corresponding e+ bunch is already extracted. The path length for the round trip from and to the e+ DR has to be an integer of DR circumference.
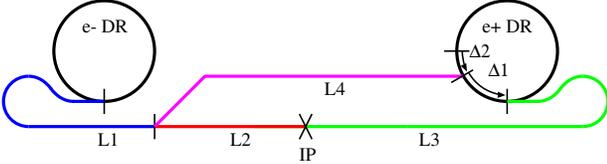

Figure 2: A schematic layout with the significant beam line length.

A schematic layout is shown in Fig. 2. e+ production target is at the junction of three sections, L_1, L_2, and L_4. Δ_1 is the distance from the injection kicker to the extraction kicker in the positron DR. Δ_2 is the distance that a bunch in the positron DR 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 DR injection kicker. Δ_2 can be changed simply by adjusting the kicker timings; all other lengths are fixed in construction.

To ensure collisions at the IP:

$$L_1 + L_2 = \Delta_1 + \Delta_2 + L_3. \qquad (6)$$

For the self-reproducing, the condition is:

$$L_1 + L_4 = \Delta_2 + nC, \qquad (7)$$

where C is the DR circumference and n is an integer. Eliminating Δ_2:

$$L_4 + \Delta_1 + L_3 = L_2 + nC. \qquad (8)$$

Assuming L_2, Δ_1, and C are fixed early in the design, the constraint 8 can be satisfied by adjusting (at the design stage) $L_3 + L_4$. We note that the position of the positron DR along the main linac is arbitrary; it may be adjusted simply by increasing L_3, and reducing L_4 by equal amount, and vice versa.

Longitudinal separation of two interaction points

In the current baseline design of ILC[1], two interaction points with a longitudinal separation is assumed. The longitudinal separation should be an integer of a half of the linac bunch spacing for collisions. It is desirable allowing several fill patterns and it could be implemented when possible bunch spacings are in a simple ratio to each other. Greater flexibility is provided by the use of delay lines, which is now a part of the baseline design.

Super-period in DR Fill Pattern

In Compton e+ production scheme, gammas, which will be converted into e+, are produced by Compton scattering between laser and e- beam.

Laser is operated in a mode-locked with 325 MHz, stored, and stacked in an optical cavity, in which the laser power is enhanced by the stacking. The laser burst wave shuttles back and forth in the optical cavity with 325 MHz. Electron bunches are stored in CR with 3.08 ns bunch spacing to ensure the synchronous Compton scattering every 325 MHz cycle.

Because CR has circumference exactly 1/10 smaller than that of DR in the current design and positron bunches generated in a period corresponding to 10 turns of CR, will be filled into DR, the bunch fill pattern in CR must be repeated 10 times in DR. At this moment, some remainder is allowed, i.e. DR pattern can be $10 \times (CR\ bunch\ pattern) +\ some\ extra\ buckets$. However, because the e+ intensity from one Compton scattering is 1/100 less than the requested, this process is repeated 10 times, so that positron bunches are stacked into a same bucket 10 times. After some cooling period, this process is repeated 10 times to achieve the full intensity.

Because the bunch fill patterns in CR and DR have to be synchronized to each other over many turns, DR harmonic number, h, and the DR bunch fill pattern must have exactly 10 super-periods. Because this can be implemented only with Step solution and not with Uniform solution, only Step solution is possible when the e+ generation with the Compton scheme is employed.

SUMMARY

Constraints of ILC system for the DR fill pattern, injection/extraction scheme, and the layout were discussed. We have confirmed that various solutions exist, providing different flexibilities. The final solution should be obtained as a result of a system-wide optimization by considering technical detail of each components.

REFERENCES

[1] ILC Baseline Configuration Document (February 2006). http://www.linearcollider.org/wiki/doku.php?id=bcd:bcd_home

[2] S. Araki et al. "Compton based ILC positron source", KEK-Preprint, (September 2005).

[3] W. Kriens, Basic timing requirements for TESLA, TESLA 2001-10 (2001).

[4] H. Ehrlichmann, Bunch timing aspects for ILC presented in ILC-GDE meeting at Frascati, Italy (December 2005).

[5] T. Naito et al., Annual meeting of PASJ, 21P056, (August 2005)

[6] A. Wolski, J. Gao, S. Guiducci (eds.), Configuration studies and recommendations for the ILC damping rings , LBNL-59449 (February 2006).