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Injection Issues of Electron-Positron Storage Rings*

John T. Seeman

Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309 USA

ABSTRACT

The general issues of injection into e^+e^- colliders are discussed using results from several storage rings. Observations from these colliders indicate that the starting conditions and duration of each fill are often different. Consequently, it is shown that the optimum storage time is expected to be about twice as long as that expected from simple-uniform filling cycles. Injection parameters for several proposed B-Factories are listed. Finally, the concept of continuous filling (injection transparent collisions) is explored which suggests that a factor of 4.5 to 6 increase in integrated luminosity may be achievable.

1. INTRODUCTION

The goals for the injection process of a B-Factory are to:

- (a) maximize the average luminosity,
- (b) minimize component / detector damage,
- (c) provide rapid fills from a no current state,
- (d) provide careful filling for 'topping off',
- (e) be very reproducible,
- (f) be able to upgrade to continuous filling,
- (g) be easy to operate,
- (h) and have a minimum cost.

These goals are difficult to achieve simultaneously (if not separately) and often compromises must be made.

2. OPTIMUM STORAGE TIME USING A STEADY STATE MODEL

In a steady state filling cycle the collider has a peak luminosity of L_0, an exponential luminosity decay time of τ, a filling time of T_f, and a storage time for collisions of T_s. The identical fills repeat cycle after cycle. The integrated luminosity is given by [1,2]

$$\int_0^{T_s+T_f} L\,dt = \int_0^{T_s} L_0\, e^{-t/\tau}\,dt \qquad [1]$$

The maximum average luminosity is produced when T_s satisfies

$$(T_s + T_f) / \tau = e^{T_s/\tau} - 1 \qquad [2]$$

giving

$$< L >_{max} = L_0\, e^{-T_s/\tau} \qquad [3]$$

Plots of the optimum storage time for filling times of 0.1, 1.0, and 5.0 hours are shown in Figures 1, 2, and 3, respectively. Optimum storage times range from 30 minutes to several hours depending on the luminosity lifetime. The filling cycles in an actual collider vary more than the steady state situation described above, which can be seen schematically in Figure 4. These varying injection cycles are investigated below for various present day colliders, leading to a calculation for a more practical optimized case.

3. PRESENT COLLIDER OBSERVATIONS

Observations of injection and collision cycles for several colliders (CESR, LEP, PEP, and TRISTAN) under recent operation lead to a more realistic model. Several observed injection cycles over a period of a day are shown in Figures 5, 6, 7, and 8 for CESR [3], LEP [4], PEP [5], and TRISTAN [6]. The injection times range from several minutes to several hours in these examples. Not only does the injection time vary, but the maximum luminosity after a fill changes by up to 30%.

The distributions of injection times for CESR [7], PEP [5], and TRISTAN [8] are shown in Figures 9, 10, and 11, respectively. For a given collider, the filling times have approximately a binomial distribution with the mean fill time being 0.5 to 3 times the minimum time. Distributions of the initial luminosity immediately after the start of a fill are shown in Figures 12 and 13 for CESR and PEP. The mean starting luminosity is about 80 to 90 % of the maximum.

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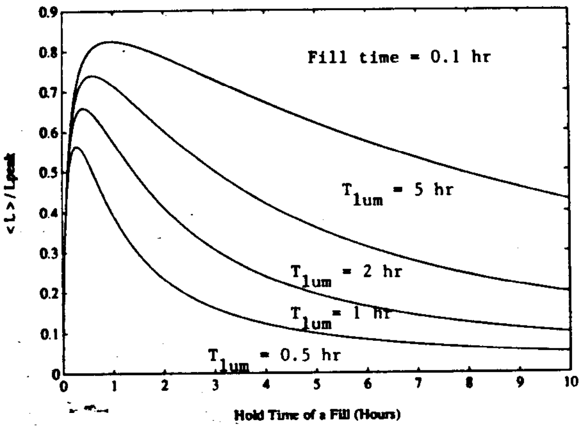

Figure 1 Fractional average luminosity versus storage time for a fill time of 6 minutes.

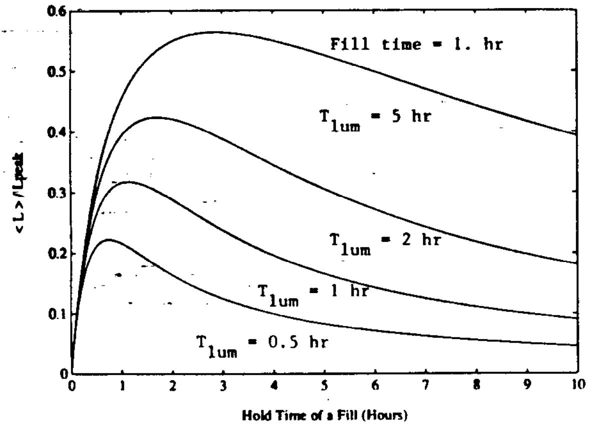

Figure 2 Fractional average luminosity versus storage time for a fill time of 60 minutes.

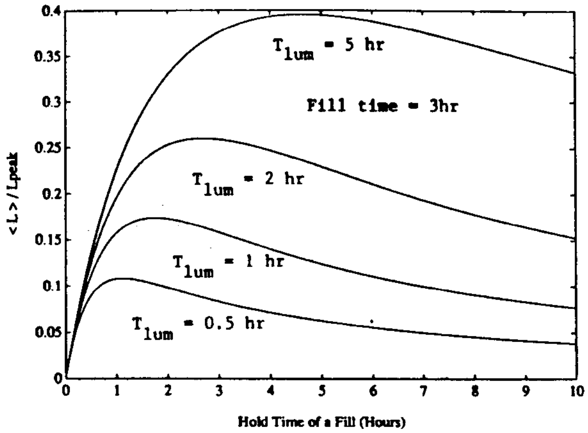

Figure 3 Fractional average luminosity versus storage time for a fill time of 5 hours.

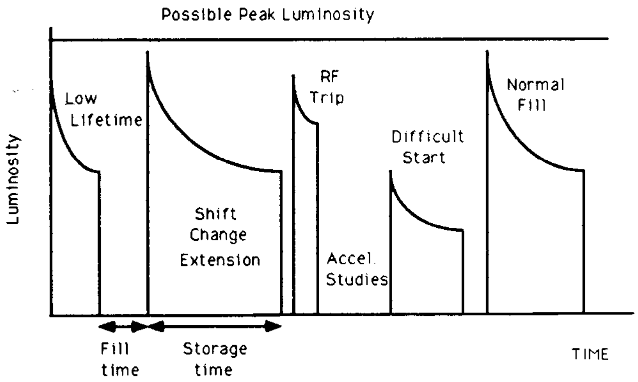

Figure 4 Schematic representation of actual filling cycles of a storage ring.

4. EFFECT OF FILL TIME AND INITIAL LUMINOSITY DISTRIBUTIONS ON OPTIMUM FILL TIME

A simulation of 100 fills was made to calculate the effects of varying filling times and initial luminosity on the optimum storage time for a collider. In the simulation the luminosity is assumed to decay exponentially with a lifetime of 60 minutes and the minimum filling time is 6 minutes. The initial luminosity and filling time distributions used in the simulation are similar to those observed in the rings discussed above (Figures 9-13) and are shown in Figures 14 and 15. The luminosity was averaged over the 100 fills while the storage time was varied. The results are shown in Figure 16. An ideal curve as calculated from Section 2 assuming identical 6 minute fills and identical peak luminosities is also shown. The conclusions are that the average luminosity decreases by about a factor of two with these added complications and that the optimum storage time also increases by about a factor of two.

5. INJECTION TIME CALCULATIONS

The time required for injection is calculated in general and then applied to several proposed B Factories.

5.1 Injection from Zero Current

A rapid injection rate is important when the beam current is lost for some reason. Several such reasons for injection from no stored charge are (1) RF dumps, (2) accelerator physics studies, (3) ring magnet standardization cycles, [4] errors during energy ramping of the rings, or [5] beam aborts for average power losses.

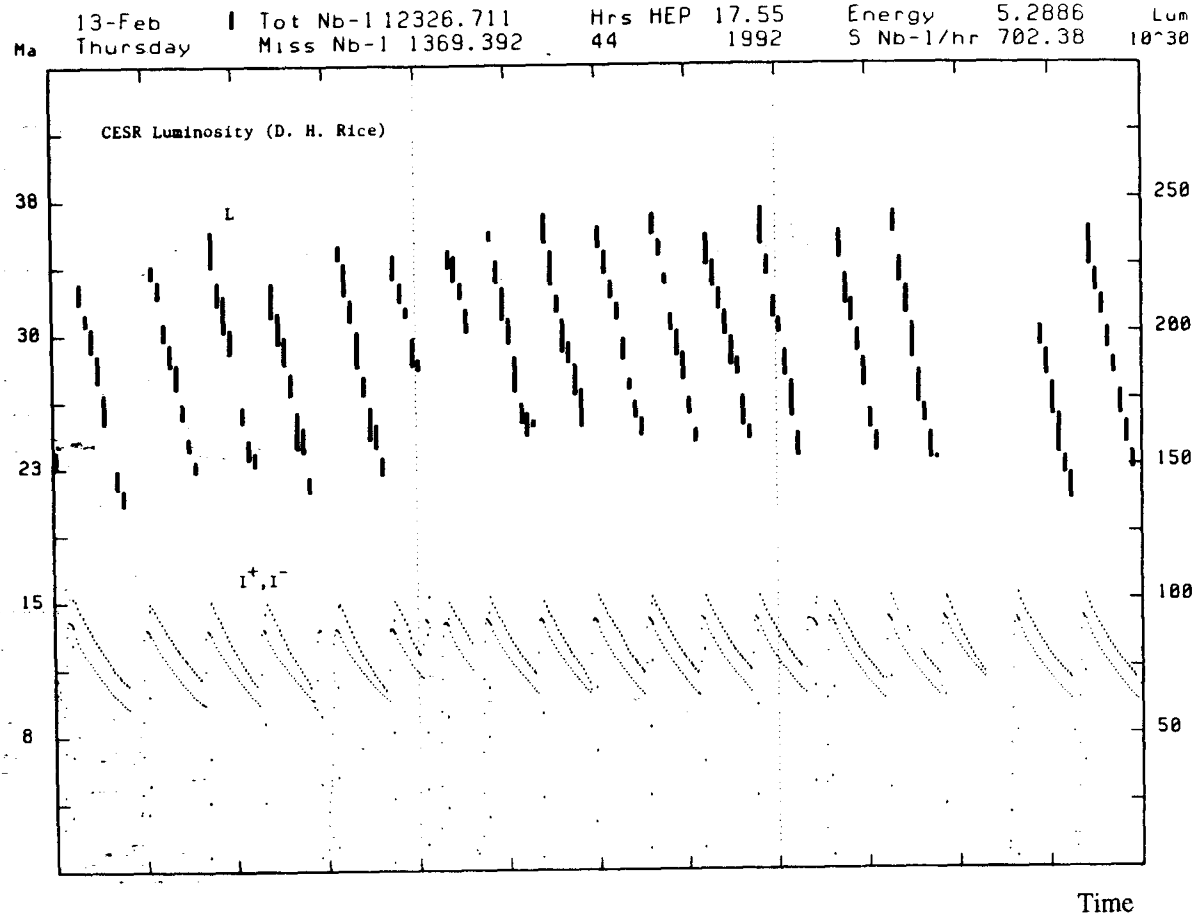

Figure 5 CESR injection and collisions for 24 hours from D. Rice.

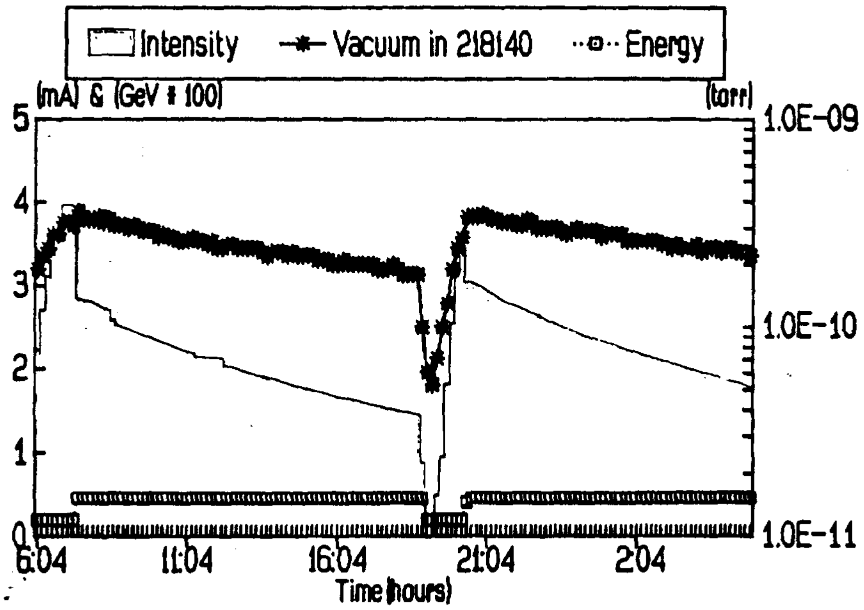

Figure 6 LEP injection and currents for 24 hours from V. Hatton.

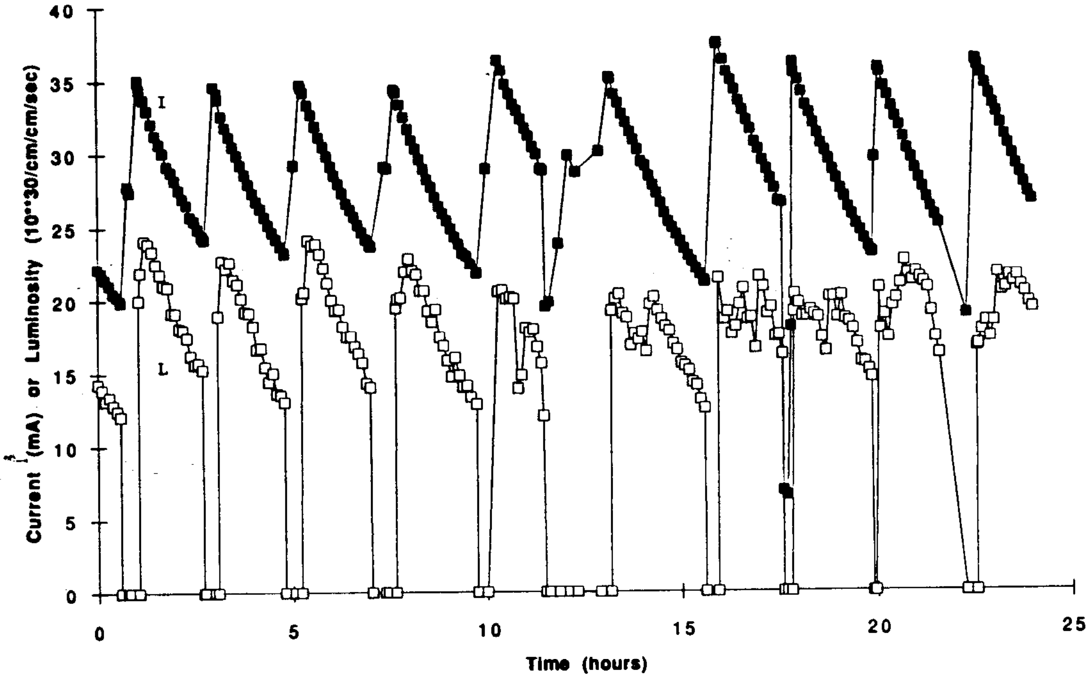

Figure 7 PEP beam current and luminosity for 24 hours (May 1985).

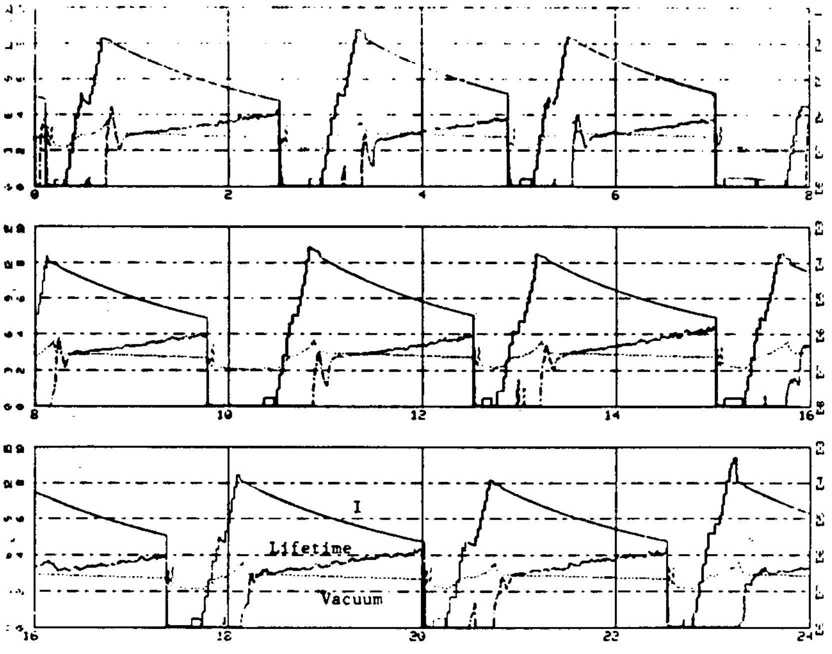

Figure 8 TRISTAN current, lifetime, and vacuum pressure for 24 hours from M. Yoshioka.

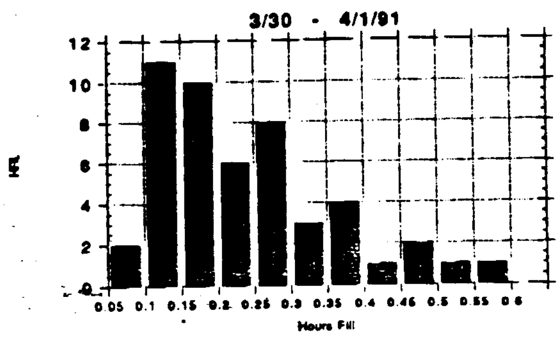

Figure 9 CESR fill time distribution from D. Rice.

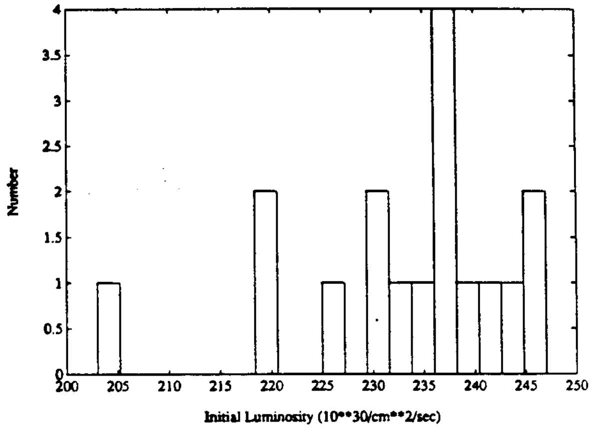

Figure 12 Initial luminosity distribution of CESR from D. Rice (Feb. 13, 1992).

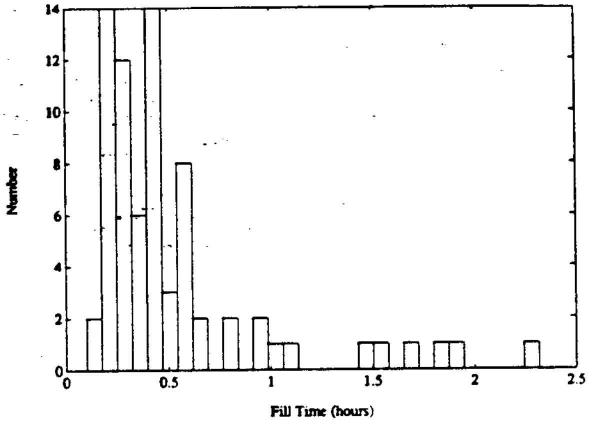

Figure 10 PEP fill time distribution (May 9-18, 1985).

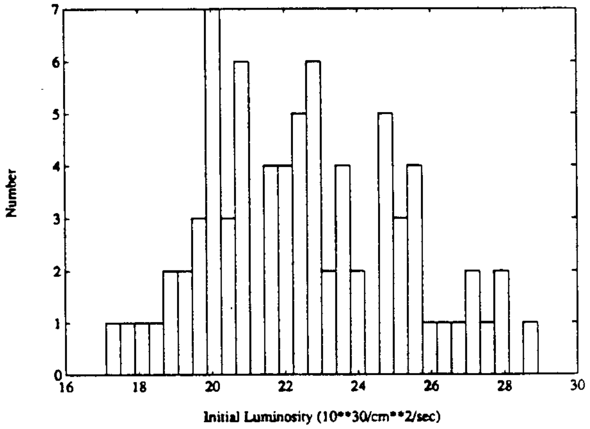

Figure 13 Initial luminosity distribution of PEP (May 9-18, 1985).

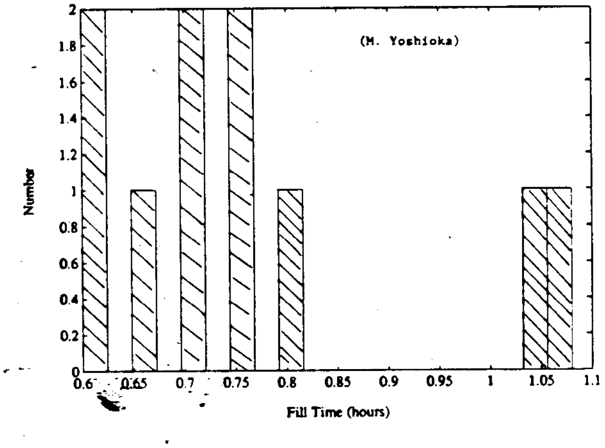

Figure 11 TRISTAN fill time distribution from M. Yoshioka.

The parameters which determine the injection time are:

K = number of potential bunches in the ring*.
N = number of particles in one ring bunch.
f = injection cycles per second.
k = number of injected bunches per cycle.
n = number of particles per injected bunch.
T_f = filling time.
g = fraction of ring not in the ion-clearing gap.
η = efficiency of capture for injected particles.
α = survival fraction for stored particles per injection cycle from injection bumps and septa walls.

* The actual number of bunches in the ring = g K.

If we assume a) that $\alpha = 1$, b) that all K bunches are filled except the bunches in the ion gap, and c) that there are no fluctuations from pulse to pulse, then to completely charge the ring the number of injected particles must equal the required number of stored particles.

$$g K N = \eta k n f T_f \qquad (4)$$

or

$$T_f = g K N / \eta k n f. \qquad (5)$$

The filling time must be added, of course, for both rings. However, if there are losses in the ring ($\alpha < 1$), then the injection time calculation is more complicated.

$$d(g K N)/dt = f(-[1-\alpha] g K N + \eta n k) \qquad (6)$$

Injection stops when the injection rate equals the ring loss rate.

$$[1-\alpha] g K N = \eta k n \qquad (7)$$

This situation has been seen many times in actual storage rings and the key is to provide an injection rate sufficiently high to easily reach the desired current [9].

The total injection time depends not only on the particle filling times for the two rings but also the magnetic standardization time (if needed), the time to turn off the physics detector to prepare for injection, the time to restore the detector after injection, and the time to reduce the backgrounds during collisions to acceptable levels.

5.2 Injection in Top-Off Mode

Most future colliders will operate in a 'top-off' mode where the beam current is not dumped after a fill but is only replenished to full charge during filling. For example, this mode of operation is evident in the CESR data in Figure 5 and the PEP data in Figure 7. During this mode of operation no magnetic standardization is done, no energy ramping is done, the detector turn-off and turn-on times are very short, and the injected bunch charge is carefully monitored and controlled. Furthermore, a method must be developed to remove (or not inject into) the beam bunches which are located in the ion gap. Two potential methods are (1) to remove (kick out) these bunches before injection or (2) to remove these bunch once in the ring by transverse deflections or RF manipulations. Once mastered, the 'top-off' injection mode saves considerable time and strongly increases the average luminosity.

5.3 Injection Parameters for Several B Factories

The injection times for both beams of several proposed B-Factories have been calculated using the nomenclature in Sector 4.1 and their respective accelerator parameters [1,10,11,12]. A summary is shown in Table 1. The resulting calculated filling times in most cases are well below an hour. The required hardware changes needed to provide these filling rates vary considerably among the listed cases.

6. ADVANTAGES OF CONTINUOUS FILLING

The average luminosity of a B Factory can be increased significantly if injection is performed every few minutes or continuously using every acceleration cycle. The goal is to reduce the observed filling time as seen by the physics detector to near zero while similarly reducing the other associated times (e.g. detector preparation, energy ramping, or standardization). Such rapid injection probably means that the detector must remain operational during injection implying that it must be more radiation hard and more insensitive to lost particle backgrounds. The gain in average luminosity is significant and comes from three effects. The first is that the average luminosity is always near the peak luminosity and is not allowed to decay. The second is that as far as the accelerator operators are concerned the collider looks like a "DC" accelerator allowing an improved operational consistency. Thirdly, if the injector is reasonably powerful, the loss rate of the stored beam at injection can be raised leading to an increased stored charge and a higher luminosity. The details are given in Section 6.1.

In order to allow continuous injection, several improvements are needed to colliders in general. The physics detector must be made more robust against particle loss or shielded such that it does not know that injection is even occurring. Such a situation may be called "injection transparent collisions." Injection transparent collisions probably require that the injected beam be collimated so that no particles entering the collider will be subsequently lost either longitudinally or transversely during the injection process. Furthermore, very fine bunch-by-bunch control of the individual bunch charges is required to maintain the bunch intensities (to a percent or so) to avoid deleterious beam-beam effects. Finally, the ring orbit bumps which bring the stored beam near the injection septa allowing the injected beam to remain inside the ring aperture will likely need a larger amplitude. This increased bump amplitude, undoubtedly, will deposit more beam power near the septa.

Table 1 INJECTION PARAMETERS OF SEVERAL PROPOSED B FACTORIES

Parameter	CESR +	CESR -	DESY +	DESY -	KEK +	KEK -	SLAC +	SLAC -
K	164	164	640	640	432	432	1746	1746
N (x 10^{10})	8.4	19.2	8.2	5.3	3.3	1.4	5.9	4.1
f	60	60	12.5$^{\&}$	12.5$^{\&}$	50	50	60	60
k	30	30	$1^{\&}$	$1^{\&}$	$20^{\$}$	$20^{\$}$	1	1
n (x 10^{10})	0.006	0.08	0.4	0.3	0.015	~0.1	1.0	1.0
g	1.0	1.0	1.0	1.0	1.0	1.0	0.95	0.95
η (%)#	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
α	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
T (minutes)*	4.2	0.7	35.	30.	3.2	0.2	5.4	3.8

\# An efficiency of 50% was assumed for each injection system. $ Number of micro-structures in the beam.

* Time for filling each ring starting from zero current. & The PETRA injection system was assumed.

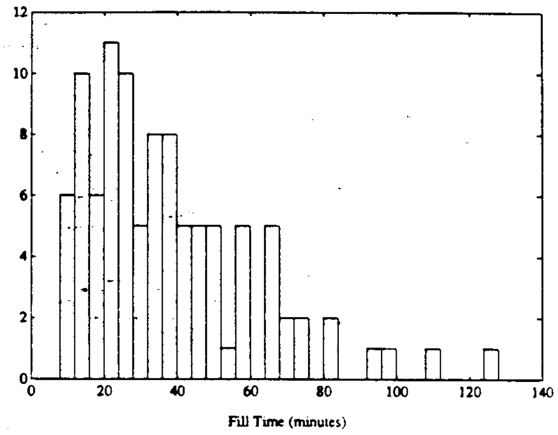

Figure 14 Fill time distribution in the simulation.

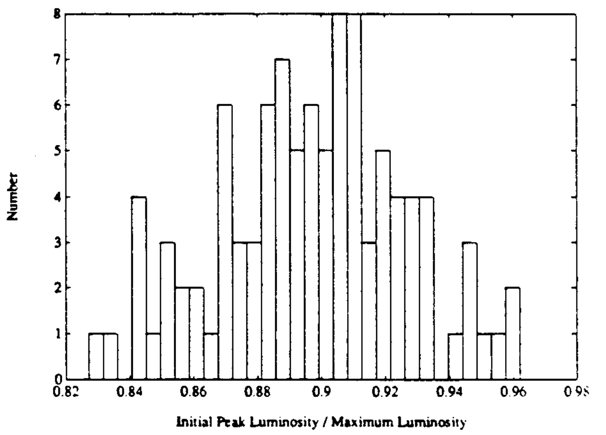

Figure 15 Initial luminosity distribution in the simulation.

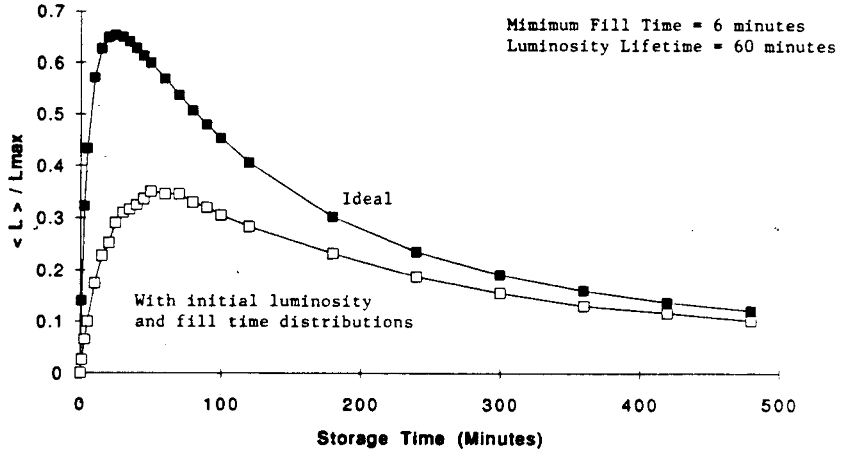

Figure 16 Simulated average luminosity with and without filling time and initial luminosity variations.

6.1 Luminosity Increase from Continuous Injection

If the beam current is replenished every few minutes so that no net loss in beam charge occurs, then the average luminosity is equal to the maximum luminosity. As seen in Figure 16 this would increase the average luminosity according to the ideal case by about 50%.

Since the filling process is now continuous the accelerator operators deal with a continuous process instead of a transient event and thus can improve on the fill to fill variations which normally occur. From Figure 16 the removal of the fluctuations from fill to fill increases the average luminosity by about 100%.

Finally, the luminosity in a collider increases as the square of the current until the beam-beam tune shift saturates. Thereafter, the luminosity and the vertical beam size increase linearly with current [13]. In the saturated situation the addition of more current to increase the luminosity reduces the beam lifetime as particles travel closer to the aperture. A plot of the measured reduction of the beam lifetime with luminosity is shown in Figure 17 from CESR, SPEAR, and TRISTAN [6] data. The exponential decrease in lifetime with beam size (proportional to luminosity) is expected [14]. Therefore, it is clear that if continuous injection could support a significant reduction in the beam lifetime then a substantial increase in luminosity could be realized. In an example below using PEP II with a modified SLC injection system, a luminosity gain of about 1.5 to 2 is shown to be possible with an aggressive continuous injection scheme.

In summary, using the factors discussed above, continuous injection has the potential to increase the collider's average luminosity by a factor of 4.5 to 6 (= 1.5 x 2. x [1.5 to 2.0]), which may prove important when the luminosity goal of 10^{34} /cm^2/sec is in sight.

6.2 A Continuous Filling Example for PEP II

In this example the bunch spacing in PEP II is modified to allow multiple bunch injection on a single accelerator pulse as constrained by a possible configuration of the SLC linac and damping ring. With this scheme a batch of 17 bunches per cycle are injected into a ring at 40 Hz. Each PEP II bunch in both rings can be replenished every 2.1 seconds allowing a beam life time of 4.2 minutes. This example is an extreme illustration of what might be done. Much work remains to be done if this scheme is to be made a viable approach.

This example has 17 bunches spaced by the normal 4.2 nsec followed by a no charge gap where 4 bunches would have been. This gap is used for the rise and fall times of the injection bumps in each ring. This configuration is shown in Figure 18. Given the 2200 m circumference of PEP II, 83 batches of 17 bunches can be accumulated. The total number of bunches in PEP II per ring is then 1411 (15% lower than the present design). Each 17 bunch train covers 67 nsec and can be reasonably injected and extracted from the SLC damping rings and accelerated in the linac. The orbit bumps needed for injection into PEP II are also shown

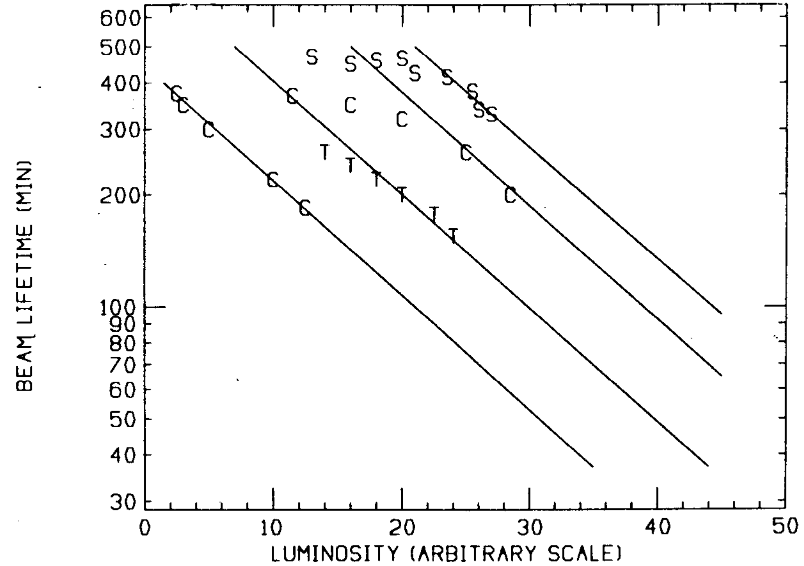

Figure 17 Beam lifetime versus luminosity after the beam-beam tune shift has saturated. At low luminosity the lifetime is dominated by the vacuum and becomes a constant. (C = CESR, S = SPEAR, T = TRISTAN)

in Figure 18. These orbit bumps only affect one batch of 17 bunches at a time for a single turn or injection cycle.

Each injected bunch has 2 x 10^9 particles. The injection rate is 40 Hz in each ring. The damping ring total charge is 17 x 2 x 10^9 = 3.4 x 10^{10}, which is well below present operational levels (down by a factor of 2).

The amplitude of the PEP II orbit bump is to be chosen to force 1 x 10^9 particles in each of the 17 affected stored bunches to be lost every cycle on the injection septum. This heavy cut allows the injected bunches to be about 4 transverse beam sigma from the stored beam core. The injected bunches then have an unobstructed passage through the physics detectors. The heat loading on the septa from the lost particles is likely to be large and must be investigated.

With every injection cycle each affected stored bunch looses 1 x 10^9 particles on the septum and gains 2 x 10^9 particles through injection. Thus, the net gain of charge per cycle can be used to compensate a sharply reduced beam-beam lifetime from a higher charge (1.2 x 10^{11}) and corresponding higher luminosity per bunch (x2). An effective minimum beam-beam lifetime τ can be calculated.

$$\tau = N \Delta t / n \qquad [8]$$

Using N = 1.2 x 10^{11}, $\Delta\tau$ = 2.1 sec, and n = 10^9, a beam-beam lifetime of about 4.2 minutes can be supported. Therefore, from Figure 17 an increase in luminosity on the order of two can be expected.

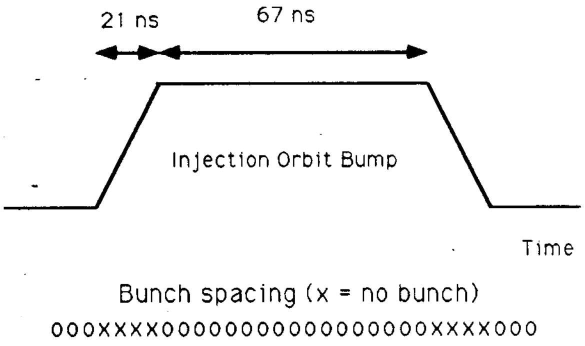

Figure 18. Ring orbit bumps and bunch spacing for a PEP II continuous injection example.

7. CONCLUSIONS

Injection is a necessary but troublesome detail for a B Factory. Several suggestions have resulted from reviewing present collider history and from several new operational possibilities.

a) Short filling times are important.
b) Full energy injection is best.
c) Reproducibility is vital.
d) Continuous injection is very attractive though may be difficult and requires a philosophical design change.
g) Physics detectors more insensitive to injection are needed.

8. REFERENCES

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