TOP UP INJECTION AT PEP-II AND APPLICATIONS TO A CIRCULAR e+e- HIGGS FACTORY*

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Abstract

The PEP-II B-Factory at SLAC (3.1 GeV e+ x 9.0 GeV e-) operated from 1999 to 2008, delivering luminosity to the BaBar experiment. The design luminosity was reached after one and a half years of operation. PEP-II surpassed by four times its design luminosity reaching 1.21 x 10^{36} cm^{-2} s^{-1}. It also set stored beam current records of 2.1 A e- and 3.2 A e+ in about 1732 bunches.

Top-off injection, or continuous injection, was developed in PEP-II using the linac injector to allow constant luminosity with the BaBar detector being fully operational during injection. The electron beam top-off was developed initially as its lifetime was the shortest and thus made the luminosity nearly constant. Second, the positron beam top-off was developed making the luminosity fully constant. Either electrons or positron could be injection up to 30 Hz if needed, deciding pulse-by-pulse which beam (bunch) was needed. Technical details of PEP-II top-off will be discussed. The implications for top-off into a circular Higgs factory are also presented. For this article top-up injection, top-off injection, trickle injection, and continuous injection mean the same thing [1-9].

The SLAC linac as built for the SLC was used for the injector of PEP-II with up to 30 Hz of either positrons or electron injected into the two rings. The injections for top-up typically were about 3 to 10 Hz for HER and 5 to 15 Hz for LER in steady state operations.

Table 1: PEP-II Collision Parameters

Parameter	Units	Design	April 2008 Best	Gain Factor over Design
I+	mA	2140	3210	x 1.50
I-	mA	750	2070	x 2.76
Number bunches		1658	1732	x 1.04
β_y*	mm	15-25	9-10	x 2.0
Bunch length	mm	15	11-12	x 1.4
ξ_y		0.03	0.05 to 0.06	x 2.0
Luminosity	10^{34} /cm^2/s	0.3	1.2	x 4.0
Int lumin per day	pb^{-1}	130	911	x 7.0

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PEP-II PARAMETERS

In PEP-II the Low Energy Ring (LER) was mounted 0.89 m above the High Energy Ring (HER) in the 2.2 km tunnel as shown in Figure 1. To bring the beams into collision at the single IP, LER was bent down 0.89 m to the HER level and then with horizontal deviations for both rings are made to collide. Since both rings had the same circumference, each bunch in one ring only collides with one bunch in the other ring.

The high beam currents were supported large RF systems consisting of 1.2 MW klystrons at 476 MHz and high power cavities with HOM absorbing loads. Each cavity had three HOM loads each with the capability of 10 kW. At the peak currents the HER cavities received 285 kW and the LER cavities 372 kW. The average klystron power was 1.01 MW. An overhead of about 20% in power was needed to allow the longitudinal bunch-by-bunch RF feedback systems to be stable.

Figure 1: PEP-II tunnel with LER above the HER.

TECHNICAL ITEMS FOR TOP-UP

There are seven technical items that need to be accomplished to achieve successful top-up injection. 1) Each bunch charge in real time must be measured and determined when it needs to be refilled. 2) In the ring and injector, a timing signal is produced to generate a bunch so to deliver it after all the transport gymnastics (gun, linac, damping rings, transport lines) to the needed particular bunch (bucket) in the ring. 3) The linac bunch or bunches need to be injected into the collider with very low losses. 4) The injected beam backgrounds in the

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particle physics detector need to be measured. 5) Cures for the injection backgrounds need to be found using gating and collimation. 6) Methods to monitor relevant backgrounds need to be developed for the accelerator operators to tune on in real time to keep top-up operating efficiently. 7) Trigger masking for the detector physics need to be developed by taking accelerator turns and azimuthal variations into account.

PEP-II TOP-UP INJECTION

The parameters for PEP-II top-up injection are listed here.

Energy = 3.5 x 9 GeV.
Ring circumference = 2200 m.
One collision point (IR) at luminosity = 1.2 x 10^{34}.
Full energy injection from the linac and damping rings.
Number of bunches = 1732 per ring.
Beam currents = 2.1 A x 3.2 A.
Particles = 1.0/1.5 x 10^{14} / beam (HER/LER).
Lifetimes:
Vacuum = ~10 hours
Touschek = ~3 hours (LER)
Luminosity = ~1 hour
Lost particles per second = 4.2 x 10^{10} / second.
Top-up injection = one bunch per linac pulse.
Injection rate: ~3-15 Hz (30 Hz max).
Particles per injection: 3 to 9 x 10^9 per pulse.
There are several discrete injection quanta.
Bunch injection controller: picked the lowest bunch.
Injection efficiency = ~ 80%, but can be as high as 95%.
Injection kicker pulse length = 0.4 microsecond.
Ring path length = 7.3 microsecond.

The resulting luminosity 24 hour plots of top-up injection before and after are shown in Figure 2 and 3.

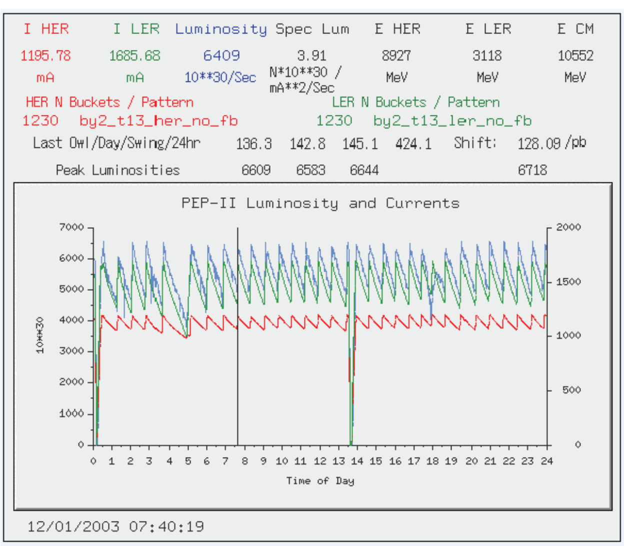

Figure 2: PEP-II collisions for 24 hours before top-up injection with HER beam current (red), LER beam current (green), and luminosity (blue). Fills every 45 minutes.

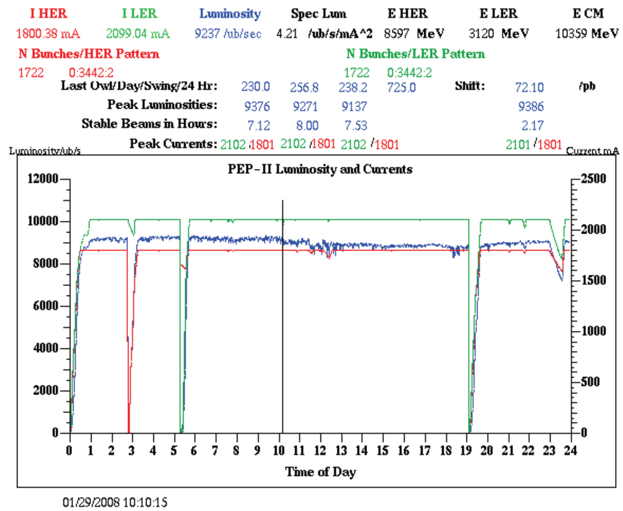

Figure 3: PEP-II collisions for 24 hours after top-up injection with HER beam current (red), LER beam current (green), and luminosity (blue). The luminosity varied somewhat with time due to changing orbits day to night which resulted in changing lattice functions at the IR and around the rings.

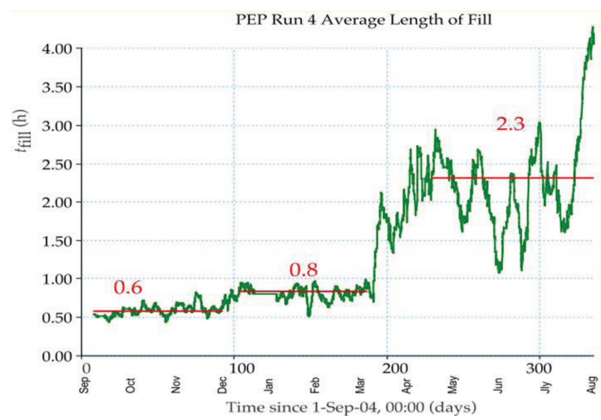

Figure 4: Increase in fill duration for PEP-II collisions after one ring trickle (HER only, center) and two ring trickle (adding LER, right).

After, PEP-II had 35% increased integrated luminosity achieved and the run length was greatly increased as shown in Figure 4. In Figure 5 are shown the time allocations during operating PEP-II of different activities corresponding to BaBar data taking, PEP-II machine development, tuning and filling, unscheduled off and scheduled off averaged over a long time period. The time for integrating luminosity increased by 35% and the time for filling and tuning reduced by 50% after trickle injection.

The injected beam particles were collimated carefully before injection to reduce the particles that would be lost later after injecting into the ring. Also, internal to the rings the injected beam transverse and energy tails were

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carefully controlled and collimated as best possible but without reducing the stored beam lifetimes.

BABAR MASKING AND VETO

BaBar trigger masking included masking all of ring for a few tens of turns, followed by a small part of the ring turn for a longer time of about 0.9-1.3 msec. The plots of BaBar backgrounds and masking are shown in detail

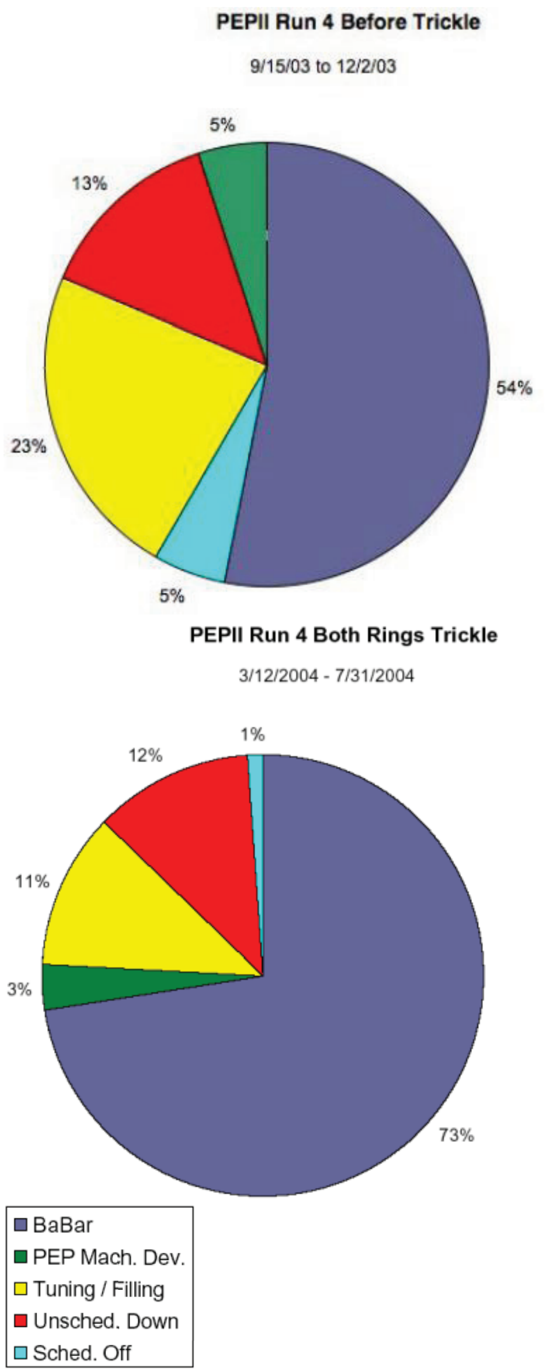

Figure 5: Time accounting in PEP-II operation before (upper) and after trickle (top-up) injection (lower) was implimented. The improvement was 35% in BaBar physics data taking and reduded by 2 in filling time.

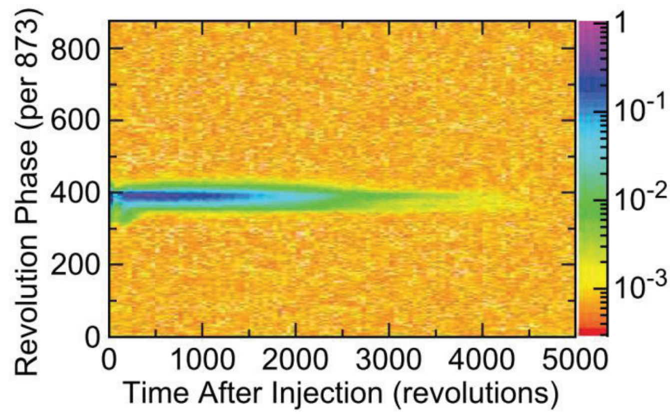

Figure 6: The injection background signal in BaBar as a function of time (left to right) and the azimuthal position around the ring (i.e. bunch number) (vertical). Only the time near the injected bunch makes long term backgrounds.

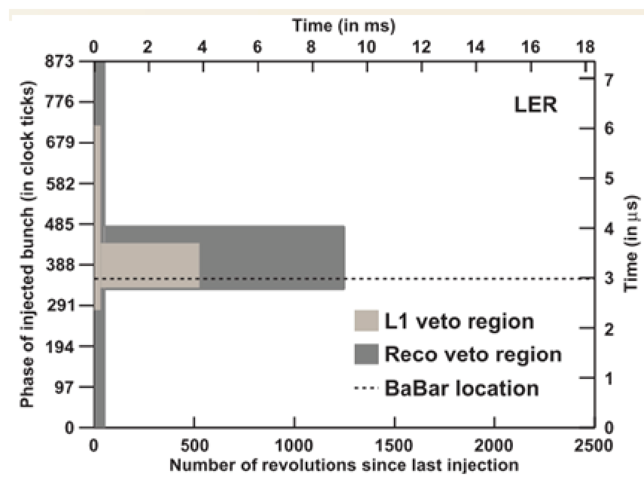

Figure 7: The BaBar trigger vetoes associated with the background signals in Figure 6.

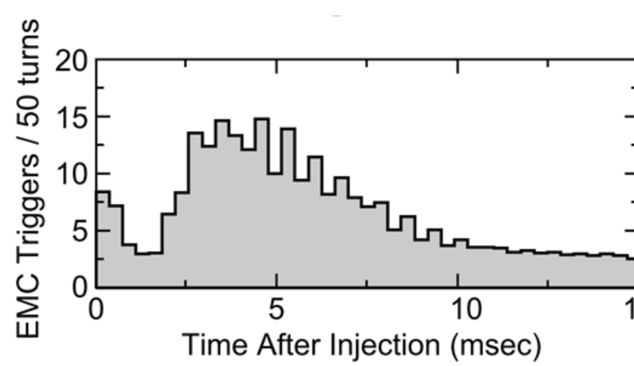

Figure 8: The total injection background signal as a function of time after injection.

in Figures 6,7,8,and 9. Note the long term backgrounds are only in time with the injected bunch and not all around the ring. The needed trigger vetoes only mask the

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event triggers near the injected bunch. The vetoes for HER injection are different than LER injection as the backgrounds have slightly different time structures. The vetoes only last for up to about 2000 turns and were shorter for LER injection.

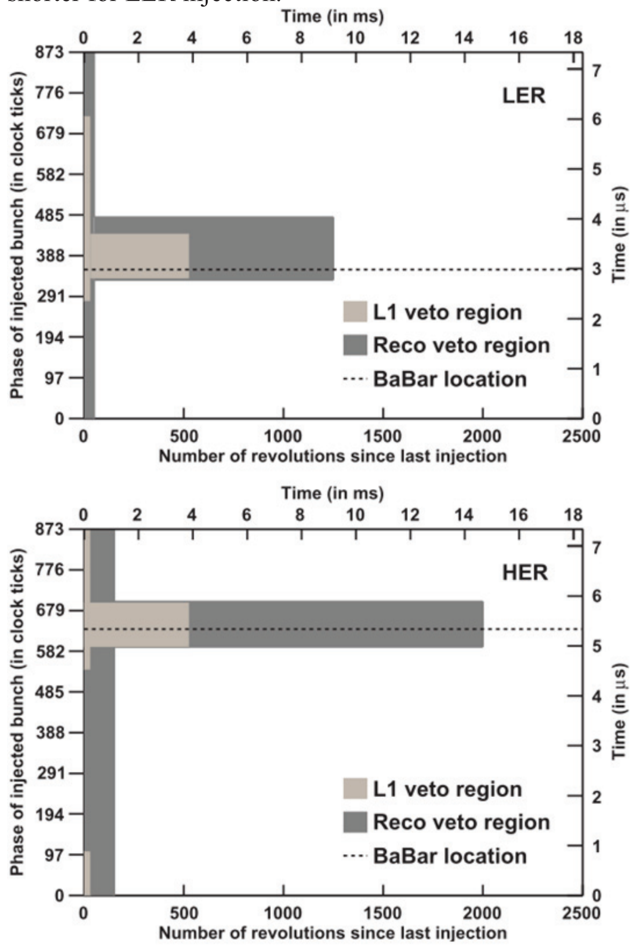

Figure 9: Veto masks in BaBar for LER injection (above) and HER injection (below).

HIGG FACTORY TOP-UP INJECTION

The parameters assumed for e+e- Higgs factory at the injection septum are listed here.

β_x at injection septum (stored) = ~200m
β_x at injection septum (injection) = ~30m
$\varepsilon_{xstored}$ (stored) =6 nm
ε_{xinj} (injected) =40 nm
$\sigma_{xstored}$ at septum (stored) = 1.1 mm
σ_{xinj} at septum (injected) = 1.1 mm
X_s = Septum blade thickness =~ 5 mm
X_c = septum clearance distance = $\sim 6\sigma_x$
Xinj < A_x
Xinj = 4σinj+X_s+Xc = ~16 mm
A_x = machine aperture > ~20 mm

The stored beam is bumped to near the septum with pulsed dipoles in the ring as shown in Figure 10. The duration of the pulse can be much less than a ring turn. The injected bunch enters via the septum and is captured in the main ring after the pulse bump is removed. The injected bunch then damps to the enter the stored bunch after several damping times.

The requirements for a Higgs Factory injector are similar to what has been done before in terms of particle numbers. The CEPC stores about 2 x10^{13} e+ per ring. The CEPC with 1 hour lifetime needs 1.25 x10^{13} e-/e+ per hour or ~3.5 x10^{9} e+ and e- per second at full energy. As examples, the CERN LEP injection complex delivered ~10^{11} e+ per second. Alternatively, the SLAC SLC injection complex delivered ~6 x 10^{12} e+ per second.

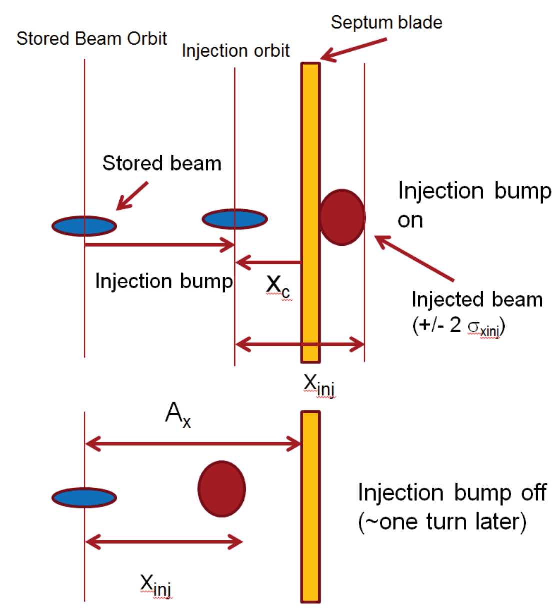

Figure 10: Schematic injection spacings at the injection septum showing the bumped stored bunch and the injected beam bunch. Horizontal injection is shown here, although vertical injection can be done as in PEP-II. Note the injected bunch can have different beta functions than the stored bunch to allow it to be closer to the septum.

SLOW RAMP INJECTOR

The slow injector (Figure 11) can be a ramped storage ring. The ramping rate can be small going from low to high energy in a few minutes. The field quality in the ring have to be good to allow the stored and ramped beam to have good lifetimes. The CERN LEP ring is a good example. Parameters of a ramped storage ring for a Higgs Factory:

Top-up injection = 50 bunches / pulse / beam.
Slow ramp due to magnet laminations.
Injection rate: Once every 4 minutes.
Particles per ring injection: 8.4 x 10^{11} / pulse.
Particles per injected bunch: 1.7 x 10^{10} / pulse.
Bunch injection controller: Fill all bunches at once.
Need to tailor (charge) each bunch separately.

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Ring path length = 182 microsecond.
Injection kicker pulse length = 182 microsecond.
Kickers = 13 stronger than PEP-II but long flat top.
Luminosity varies from 100% to 74% over 8 minutes with 4 minutes injection cycles per ring.

As an example: CERN LEP: 26.7 km with a ramping speed of 0.5 GeV/sec. Thus, 120 GeV needs 4 minutes.

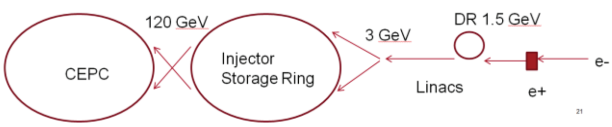

Figure 11: Slow ramped injector for a Higgs Factory.

FAST RAMP INJECTOR

The injector (Figure 12) can be a rapidly cycling synchrotron similar to the 60 Hz cycling Cornell synchrotron (12 GeV) except 10 times longer but with the same magnets. Some parameters for a rapid cycling Higgs Factory injection are:

Fast Cycling Synchrotron with laminated dipoles and quadrupoles
Top-up injection = 50 bunch / pulse.
Cycle rate = 3 Hz.
Injection rate: 1 Hz e+, 1 Hz e-, 1 Hz e- to make e+.
Particles per injection: 4 x 10^9 / pulse over 50 bunches with 90% injection efficiency.
Produces 8 x 10^7 /bunch which means low instability effects and RF feedback.
Easy positron source at 120 GeV e-.
Bunch injection controller: Tailor the charge of each bunch as needed
Magnet laminations same as AC transformers.
Injection kicker pulse length = 183 microseconds (= 53 km)
Kickers = 13 stronger than PEP-II but 7 times slower.
Ring path length = 183 microseconds (53 km).
The luminosity stays within 0.12% of the peak.

An example is the Cornell synchrotron of 768 m with a biased sine wave-magnet excitation. It ramps from 0.2 GeV to 12 GeV in 8.3 msec at 60 Hz. The ramping cycle does not affect the CESR storage ring operation just 1.5 m away.

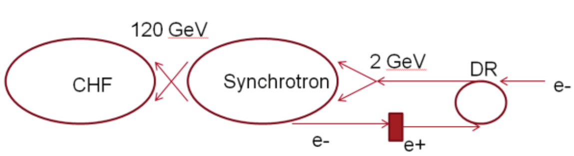

Figure 12: Fast cycling synchrotron injector for a Higgs Factory.

DETECTOR MASKING FOR HIGGS

The physics detectors for CEPC need to the mask the injection bunches. The masking will depend on the type of injector.

For the slow ramped storage ring injector the detector must mask all of ring for about 10 microseconds every 4 minutes but the luminosity is only constant to ~16%.

For the synchrotron injector the detector must mask only part of the ring for about 10 microsecond at 1 Hz but the injected bunches and injection charge are 200 times smaller and luminosity is constant to 0.1%. Thus, the fast cycling synchrotron is far superior.

There is a pressing need to make an initial complete scale design of a full energy 1 Hz synchrotron injector.

CONCLUSIONS

There is no doubt that top-up injection will work for a Circular Higgs Factory as done at PEP-II and KEKB. A full energy injector is needed because of beam lifetimes which are on the order of 10 minutes. A synchrotron injector will work the best if it is fast cycling and will have enough capacity to be more than is needed (60 Hz). A ramped storage ring is barely adequate (4 min) but will likely be marginally satisfactory. Also, a slowly ramped storage ring injector doesn't make the luminosity constant enough. The detectors will need to mask out the buckets with damping injected bunches during data taking. Both the accelerator and detector designs must work together to make this top-up injection successful.

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