TOP-UP INJECTION FOR A FUTURE ELECTRON-POSITRON COLLIDER*

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Abstract

Top-up injection was developed in PEP-II and KEKB both using a linac injector to allow nearly constant luminosity with the BaBar and Belle detectors, respectively, being fully operational in data taking mode during injection [1-13]. This note will cover injection parameters, injection hardware, detector background masking, background detection, and top-up injection commissioning. For this paper top-up injection, continuous injection, trickle injection and trickle charging all refer to the same injection technique.

The positron beam top-off in PEP-II (Figure 1) was first developed in fall 2005. The positron beam lifetime (3 GeV) was the shortest and thus made the luminosity much more constant after top-up injection. Second, the electron beam top-off (9 GeV) was developed making the luminosity fully constant in spring 2006. For PEP-II either electrons or positron could be injection up to 30 Hz each if needed, deciding pulse-by-pulse which beam (i.e. bunch) was desired. The typical injection rate for each beam was a few Hz.

Top-up injection for KEKB (Figure 2) for both electrons and positrons was developed in winter 2005. Which beam was injected was determined by the configuration of the linac and transport lines at the moment. The switching time between injected beams was a about a minute.

REQUIRED INJECTION PARAMETERS FOR A CIRCULAR $e^+ e^-$ FACTORY

Future e+e- colliders such as CEPC or FCCee will store about 2 to 6 $x10^{13}$ e- and e+ per beam at the Higgs beam energy. The lifetime is expected to be about 0.5 hr lifetime, thus, needing about 3 to 7 $x10^{13}$ e- and e+ per hour or about 0.5 to 2 $x10^{10}$ e+ and e- per second at full energy (75% capture). These rates compare well with previous particle generation rates such as those CERN delivered from the LEP injection complex ~10^{11} e+ per second and SLAC delivered from the SLC injection complex ~6 x 10^{12} e+ per second.

The requirements for top-up injection involve all aspects of injection and detector operation: One must measure each bunch's charge in real time and determine when it needs refilling. In the injector, the accelerator will initiate a bunch generation to deliver it to the needed particular bunch (bucket) in the ring. Then one must inject the bunch(es) into the collider with very low losses. Then one determines the injected beam backgrounds in the particle physics detector and find cures using collimation and steering. Next, one develops methods to monitor relevant backgrounds in real time for accelerator operators to tune on. Finally, one develops trigger masking for the detector physics data taking with trigger vetoes by the number of turns and within azimuthal locations within the ring.

Figure 1: PEP-II tunnel with LER above the HER with injection in the vertical plane.

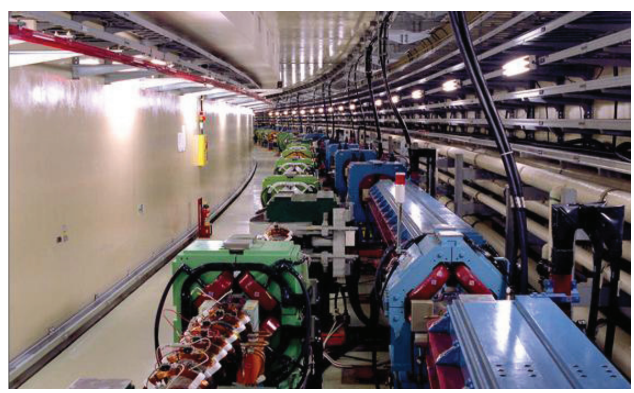

Figure 2: KEKB tunnel with LER and HER side-by-side with injection in the horizontal plane.

Top-up injection into each ring can be provided by stacking into an existing bunch as in PEP-II and KEKB (Figure 3) or by full bunch charge exchange (Figure 4). Most rings use the stacking method but some newer light sources are using charge exchange as the stored dynamic aperture is small making the injection aceptance small.

Listed here are typical lattice parameters at the injection septum for the stacking of bunches in the ring.

β_x at injection septum (stored) = ~200m
β_x at injection septum (injection) = ~30m

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$\varepsilon_{xstored}$ (stored) =9.4 nm
ε_{xinj} (injected) =50 nm
$\sigma_{xstored}$ at septum (stored) = 1.4 mm
σ_{xinj} at septum (injected) = 1.2 mm
X_s = Septum blade thickness =~ 5 mm
X_c = septum clearance distance = ~$6\sigma_x$
Xinj < A_x
Xinj = 4 σinj+X_s+Xc = ~18 mm
A_x = machine aperture > ~20 mm

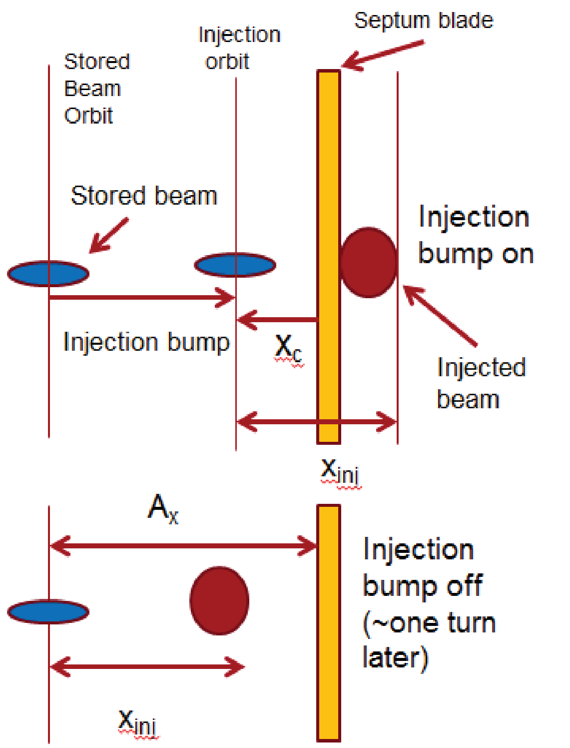

Figure 3: Injection transverse phase space for bunch stacking shown for the horizontal plane but vertical will work as well.

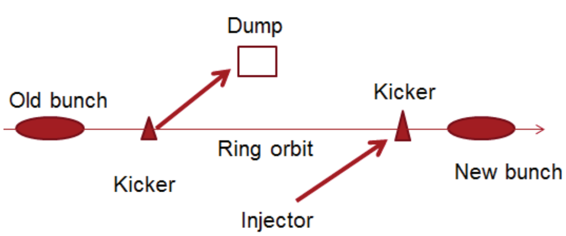

Figure 4: On-axis injection with bunch charge exchange.

PEP-II/BaBar TOP-UP INJECTION

Typical PEP-II stored beam parameters are listed here and shown in Figure 5 and in Table 1. The PEP-II interaction region is shown in Figure 6.

Energy = 3.5 x 9 GeV
Circumference = 2200 m
One collision point (IR) at luminosity = 1.2 x 10^{34}
Full energy injection from linac and damping rings
Number of bunches = 1732 / ring
Beam currents = 2.1 A x 3.2 A
Particles = 1.0 to 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 / pulse, either e+ or e-
Injection rate: ~3-15 Hz (30 Hz max)
Particles per injection: 3 to 9 x 10^9 / pulse, selectable
Bunch injection controller: pick the lowest charged bunch
Injection efficiency = 50 to 90%
Injection kicker pulse length = 0.4 microsecond
Ring path length = 7.3 microsecond

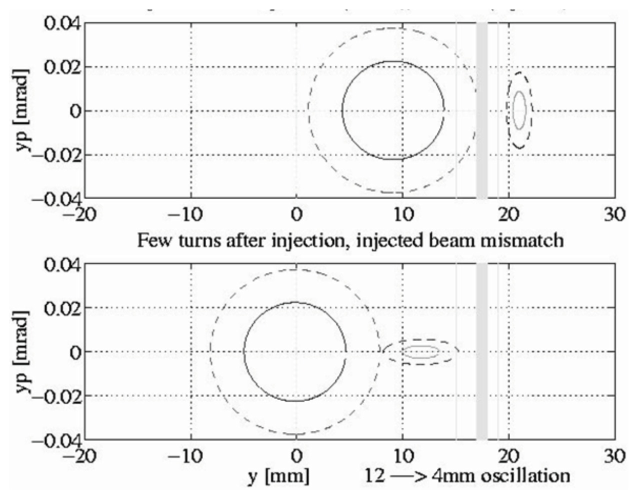

Figure 5: PEP-II injection aperture in the vertical plane with the vertical stored emittance of 3 nm and injected 0.57 nm. The grey area is the 2 mm septum blade.

Table 1: Additional PEP-II Injection Parameters

Parameter	e^+	e^-
Energy (GeV)	3.1 GeV	9 GeV
1-σ Emittance (x/y)	6.6/0.8 nmr	2.3/0.3 nmr
FWHM energy spread	0.7%	0.7%
Energy acceptance	0.7%	0.7%
1-σ pulse length	1 mm	1 mm

For PEP-II injection the first goal is to set a low injection loss rare to make injection efficient and reduce background in BaBar. The second is the stored beam trajectory (orbit) should not oscillate due to a missmatched injection kicker to avoid luminosity dips and potential abort triggers. There are many issues for the lattice and injection kickers to be considered to make these two goals optimal.

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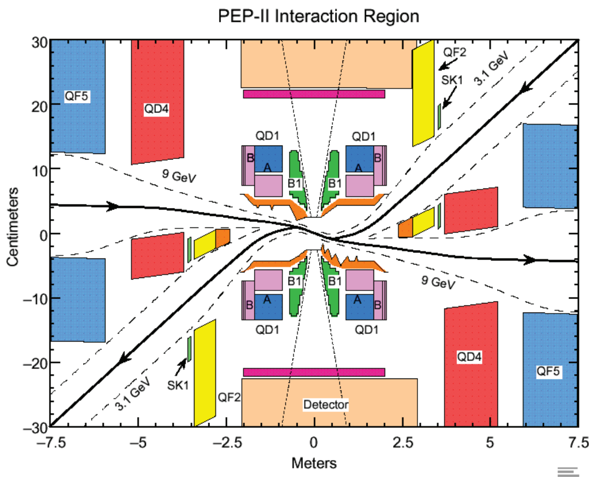

Figure 6: PEP-II interaction region where particle losses affect BaBar's data collection but can be reduced by collimation and trajectory adjustments.

For the lattice constraints, we needed to inject inside the dynamic aperture of both rings of PEP-II, the betatron phase advance between the kickers needed to be adjusted to 180 degrees, the local dispersion of the injection bump was adjusted to acceptable levels after overall ring errors, and the non-linearity of the magnetic field of the septum magnet (steel and blade) corrected or compensated.

For the injection kicker magnets, we needed to adjust the kicker magnet amplitudes to be matched, the kicker timing pulses synchronized, the kicker reflections reduced to acceptable levels or were cancelled, made sure the excitation does not cause aborts, the kicker amplitude not too large and within capabilities of the HV pulser, and the horizontal oscillation due to magnet rolls or coupling fields were within bounds.

During actual top-up injection for PEP-II the charge could be set to about 5 levels but were typically set only to the "smallest quanta" day to day. The maximum top-up injection rate was about 3 per second during set up and collisions. Not all bunches have the same charge loss due to beam-beam and other lifetime effects as shown in Figure 7. The controller to determine which bunch to inject into next is shown in Figure 8. An example of the injection quanta variations with time is shown in Figure 9. With top-up injection the "pseudo beam lifetime" appears to be infinite. However, the real lifetime was calculated using the DCCT-based beam lifetime of bunches that are not being injected into. When the beam currents were very low, for example filling from scratch, the injection rate was set to maximum to reduce the overall time to fill each ring, meaning we avoided "trickling from scratch".

Continuous (trickle charge) (top-up) injection was planned for from the design phase of PEP-II. The LER was accomplished first in 2005 with BaBar taking data. The HER continuous injection was six months later. See Figure 12 before and Figure 13 after top-up. A 40% increase in average integrated luminosity was achieved. The effect of top-up injection was seen immediately with the average length of a fill as shown in Figure 10.

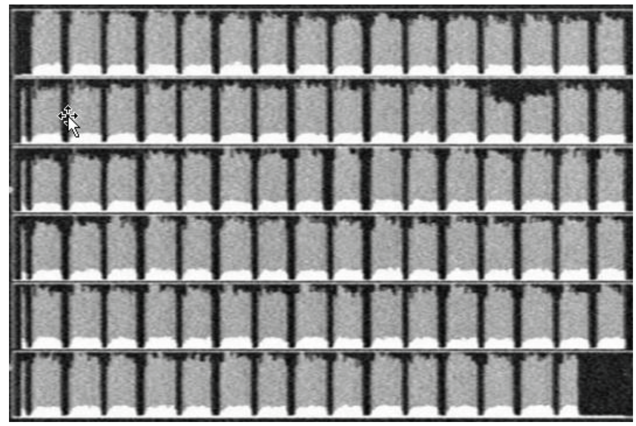

Figure 7: Wrap-around bunch charge plot of the stored bunches in PEP-II with bunch trains in a by-2 bunch pattern with 95 trains of 14-15 bunches in 18 potential bunch locations with 3-4 missing bunches per gap for e+ cloud suppression (~2004) and a long gap at the end for potential ions in the electron beam.

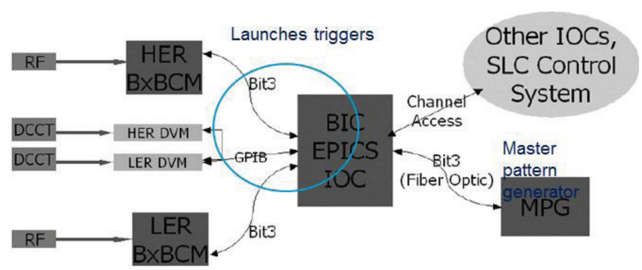

Figure 8: Bunch injection controller BIC that arranged for a bunch to be generated in the injection chain to be delivered to the correct bunch in LER or HER.

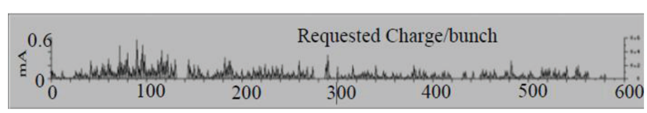

Figure 9: LER injection requests for the first 1/6 of LER versus bunch number. Different bunches have different beam-beam lifetimes and thus injection rates and charge "quanta".

There were several improvements to PEP-II injection that made BaBar backgrounds much better. These improvements took several months to achieve. First, we reduced the rms energy (and phase) jitter of the beam from the damping ring. This allowed the injected beam to fit into the ring energy aperture better, as shown in Figure 11. Second, the bunch charge per bunch was stabilized from the electron gun as shown in Figure 12 allowing fewer injections per ring bunch.

The improvement from top-up injection in the PEP-II integrated luminosity per day is shown in Figure 13 with the corresponding parameters shown in Table 2. Typical

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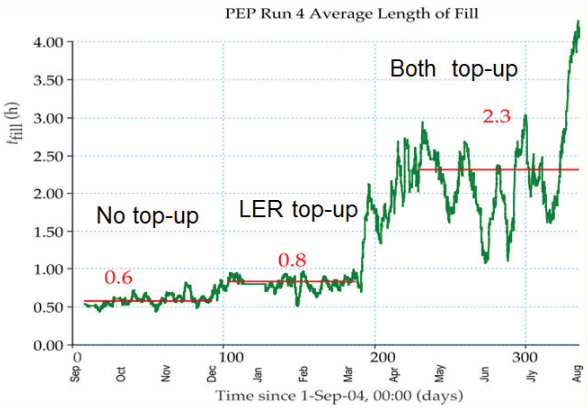

Figure 10: Improvement of PEP-II fill length with LER and then LER+HER top-up injection, giving about x4 gain.

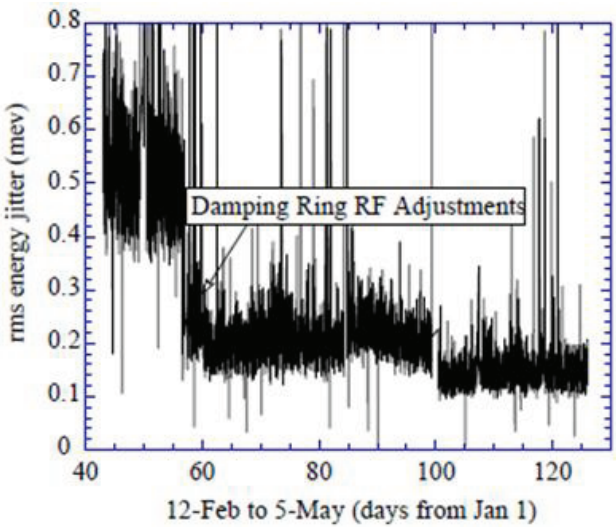

Figure 11: RMS energy jitter reduction into PEP-II to help top-up backgrounds by adjustments to the Damping Ring RF system.

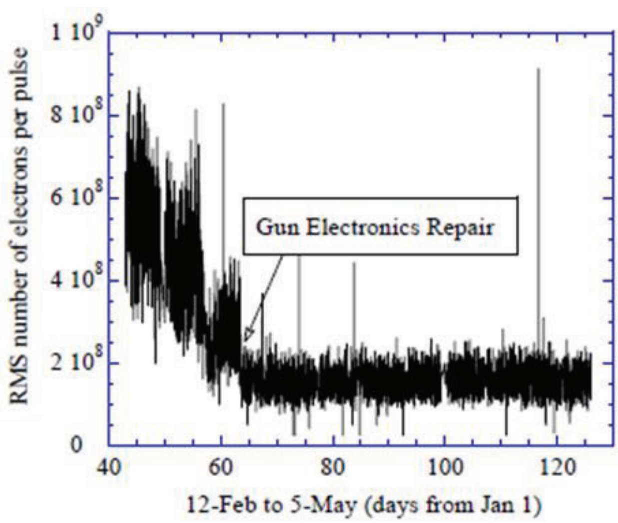

Figure 12: With a repair of the linac electron gun electronics the rms jitter of injected bunches was reduced.

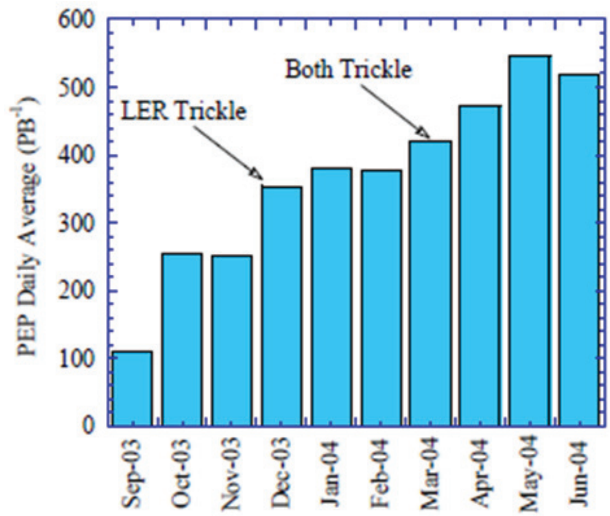

Figure 13: PEP-II integrated luminosity per day increased with top-up injection, first with LER then both rings.

Table 2: PEP-II Top-up Mode Operating Summary

	Top-up	LER trickle	Both trickle
Lum. lifetime	364	560	N/a
Avg./peak ratio	72%	86%	99…100%
Top-ups/shift	10	6	n/a
Gain (expected)	0	15%	29%
Gain (delivery)	0	35%	50%

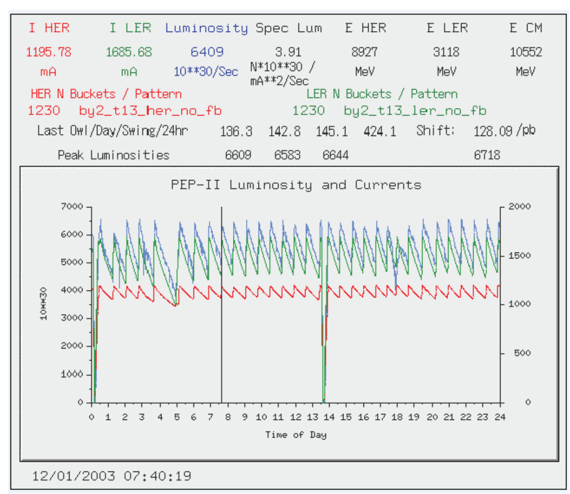

Figure 14: Luminosity and beam currents for 24 hours showing the fill-coast mode of PEP-II in early years.

plots of the daily luminosity and currents before and after top-up injection are shown in Figure 14 and 15, with the improvement in PEP-II efficiencies shown in Figure 16.

KEKB/BELLE TOP-UP INJECTION

The e+/e- linac at KEK provides injected beams to four rings (KEKB LER, KEKB HER, Photon Factory and Accumulator Ring). In the original scheme, a transport

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line and linac switch was needed every time the injector mode for the different rings changed. All accelerator

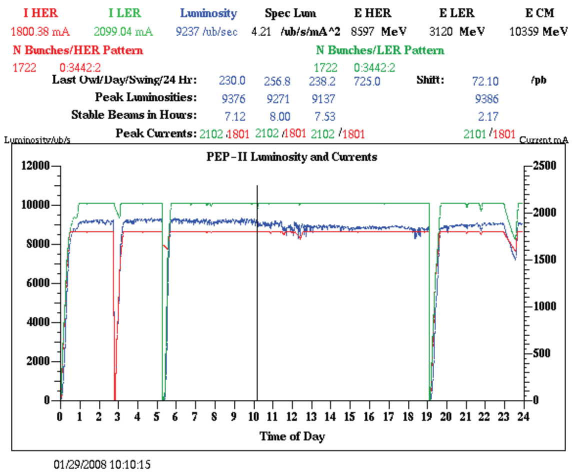

Figure 15: Luminosity with top-up injection for both PEP-II beams.

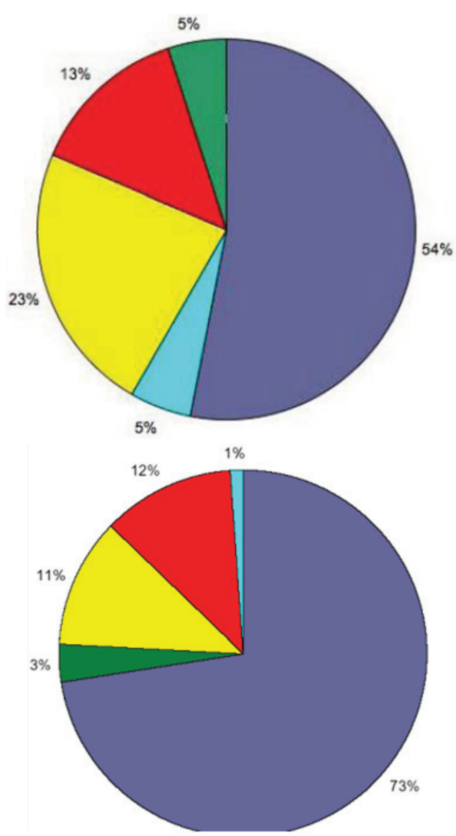

Figure 16: PEP-II run time improvement with no-top-up above and with top-up below. Blue is BaBar data taking, green PEP-II development, yellow tuning and filling, red unscheduled down, and ligth blue scheduled off.

parameters had to be reloaded, since the beam energies of these rings are different. The switching time was more than 30 seconds. The Linac Group at KEK have been shortening the switching time over many years which took considerable effort. In April 2009, they finally succeeded in making the pulse-to-pulse switching injection to the three rings (KEKB LER, KEKB HER and PF), which is much faster switching than originally planned. Because of this injection scheme, the accelerator parameter scans at KEKB have become much faster with constant beam currents stored in the rings and it has become possible to find better beam-beam machine parameters than before. Another motivation of the introduction of fast switching of the injector mode is related to the beam lifetime issue. They could explore machine parameter space which had not been accessed to due to short beam lifetime before and that they could find better parameter sets which achieved a higher luminosity. This kind of improved machine parameters is expected as well in the new accelerator SuperKEKB.

In the top-up injection scheme, the KEKB beams were injected at 10 Hz versus 50Hz in the conventional scheme. After each beam injection, data taking is vetoed for 3.5 msec, which means that the detector dead time is about 3.5% coming from this veto. In the case of KEKB, the electron and positron beams cannot be injected simultaneously. The early mode of injection (electron or positron) was switched every 5 minutes. The top-up injection scheme was realized with preparations and trial-and-errors for more than one year. Several serious problems had to be overcome. One was the malfunction of pre-amplifiers of the TOF detector and frequent DAQ (data acquisition) errors of Belle under high beam background conditions. To solve the problem with the pre-amplifiers, Belle modified them so that the circuits could accept a higher noise level. The DAQ problems were overcome by upgrading the DAQ system during the summer shutdown in 2003. On the other hand, efforts were made to decrease the detector backgrounds during beam operations, which was done mainly by optimizing accelerator parameters. The luminosity and beam lifetime were trade-offs which had to be managed. The typical injection parameters for KEKB are shown in Figure Table 3. The filling cycle for KEKB is shown in Figure 17 before and after top-up injection with a clear improvement in luminosity and average luminosity. The daily luminosity plots for KEKB showing luminosity and beam currents before and after top-up are shown in Figures 18 and 19 with the specific luminosity constant to about 5 % with top-up.

The side-by-side comparison of injection parameters are shown in Table 4 with similar results. However, there some differences. PEP-II injected vertically and KEKB horizontally. PEP-II had shorter beam lifetimes due to reduced number of particles due to the shorter circumference. BaBar had slightly reduced dead time compared with Belle. KEKB had longer fills on average than PEP-II as PEP-II had higher beam currents in the RF systems, thus resulting in increased aborts. Collimation efforts gave somewhat better results in KEKB over PEP-II.

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Table 3: KEKB Injection Parameters

Beam mode	KEKB HER	KEKB LER
Beam energy	8 GeV e-	3.5 GeV e+
Number of bunch	2	2
Bunch charge	1 nC	1 nC (primary e-
Maximum beam repetition	50 Hz	50 Hz
Injection per day	> 250	> 500

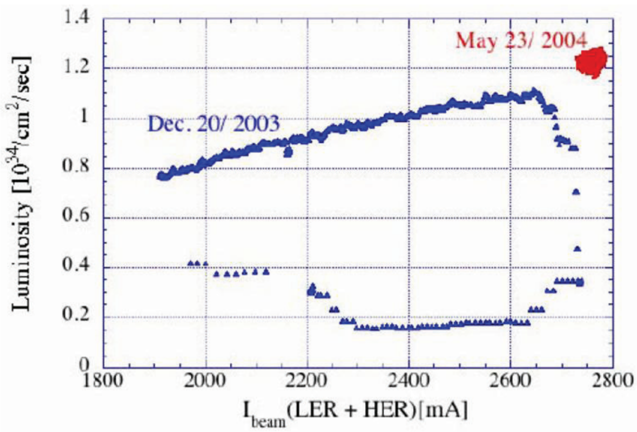

Figure 17: Luminosity during a KEKB fill cycle without top-up injection in blue and the luminosity with top-up in red (small concentracted area.).

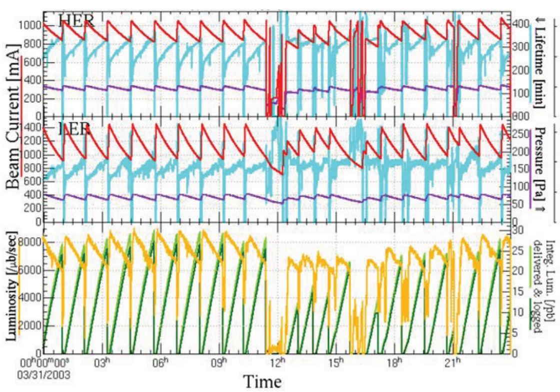

Figure 18: KEKB luminosity versus time over 24 hours before top-up injection.

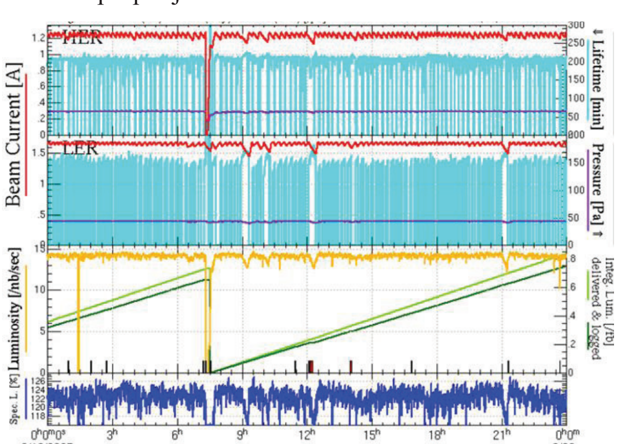

Figure 19: KEKB luminosity in operation after top-up.

Table 4: Summary of KEKB and PEP-II Top-up Injection Parameters

Parameter	KEKB	PEP-II
Injection plane	horiz.	vertic.
Beam lifetime	250/200 m	400/60 m
Gain	30%	30…50%
Detector gate	3.5 ms	15 ms/0.9 μs
Deadtime due to gating	3.5%*	1.8%*
Average length of fill	6…8 h	2.5…4 h
Background reduction by collimation	> 2	≈ 1.5
most important collimation	vertic.	horiz.
Background monitoring	Injection-gated from detector	dto.
Injection control	reduce rate	reduce rate and charge

DETECTOR BACKGROUND MASKING IN BaBar

The backgrounds in BaBar and Belle from top-up injection were dealt with several approaches. The background signals provided to PEP-II by the BaBar detector were gated on immediate injected pulses. The systematic improvements of the e- beam resulted from steady upgrades of the linac injected beams; for example, the systematic reduction of the distance of the injected beam from the closed orbit near the septum reduced backgrounds. The stabilization of the injected beam trajectories through feedback helped. The injection kickers were investigated to make sure the "closed injection bunch" was indeed closed and tuned to the optimum.

There were several improvements that Babar made to improve data collection with top-up. These included smoothing out the trickle-algorithm in Bunch Injection Controller BIC and Master Pattern Generator MPG, avoiding data stoppage including cleaning up BIC-MPG communication. The EPICS bar-chart display showing rate of injection per bunch was updated. There was a desire to display the total injection rate overall. A hardware real-time injection indicator (pulsed LED or counter) was constructed. The accelerator needed to make sure the injection (LER and HER) feedbacks did not stop if too many small quanta were used for a given period from BPM mis-readings. The BIC needed to stabilize the setup of the bunch quanta (intensity, energy). BaBar needed to update its interlocks with time as several were bypassed early on. Finally, BaBar needed to speed up the refresh of injection-trigger histograms.

Several of the injected beam signals are made to be shown in real time as shown in Figure 20. In Figures 21-24 are shown BaBar trigger data indicating real time background signals. Many of the triggers show up around the time of a quarter turn in a synchrotron oscillation in either the LER or HER indicating energy or bunch phase injection errors. Figure 25 shows the masking of the BaBar triggers showing only a partial turn has to be vetoed after a short complete veto. The BaBar trigger includes masking all of ring a few tens of turns and then mask only the injected bunch area. The inhibited area is 600 nsec by 10 msec per 7.33 microseconds times the injection rate which gives about 1% loss at 10 Hz injection rate. The backgrounds increased slowly as a fill progressed. The period from 0 to 240 seconds involved a large quanta injected into HER and LER at 15 Hz each.

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The period from 240 to 320 seconds uses small charge quanta injection into HER. The period from 240 to 410 seconds includes 30Hz injection into LER. Finally, the trigger veto provides injection quality feedback to the accelerator operators, identifies possible configuration loss periods, the resetting of the electronic front ends, and then stops data collection when the configuration is being reset.

Likewise, the detectors for FCCee/CEPC will need to mask injection bunches. 1) For a ramped "Storage Ring" style injector (with injection once every 5 minutes), the detector must mask the entire ring for about 10 milliseconds every 5 minutes at injection meaning large injected charge and many bunches (from 50-100) will be entering the ring. The expected integrated luminosity loss will be around 10%. 2) For a ramped "Main Injector" style injector (with injection one every ten seconds or so), the detector must mask the entire ring for about10 milliseconds every 10 seconds indicating small injected charges and many bunches (from 50 to 100). Here the integrated luminosity loss should be around few %. 3) For a rapid "synchrotron injector" RCS (with injections a few per second), the detector must mask about 1/80 of ring for about 10 milliseconds at 0.1 Hz indicting small injected bunch charges but few bunches (from1 to 3). Here the integrated luminosity loss will be much less than 1%.

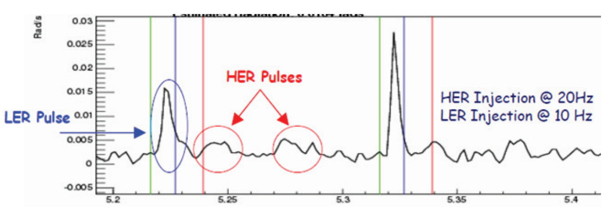

Figure 20: BaBar noise sampling in real time (sec) with HER and LER injections.

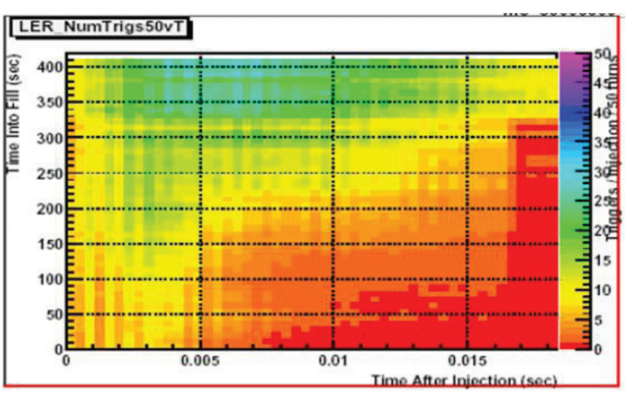

Figure 21:BaBar backgrounds from PEP-II LER injection versus time and time after injection. Red is very low backgrounds.

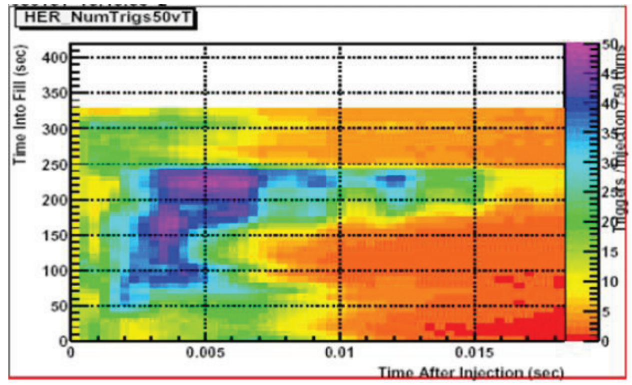

Figure 22: BaBar backgrounds from HER versus time and time after injection. Red is very low backgrounds. The peak backgrounds occur after about 4 msec related to injection energy errors.

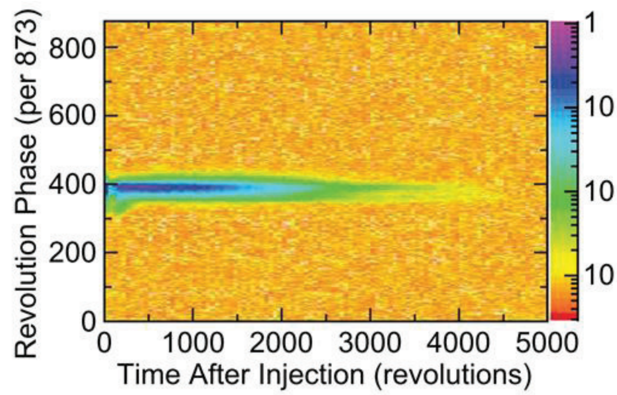

Figure 23: BaBar triggers versus time and bunch number within a turn.

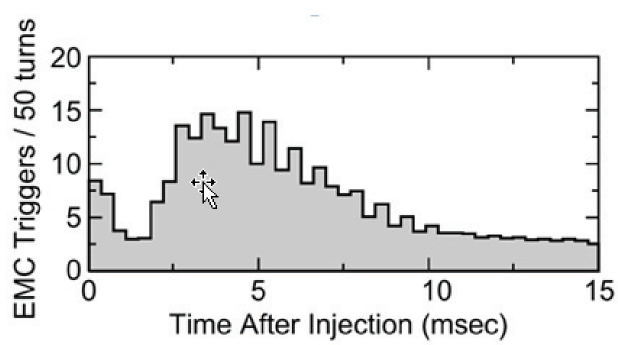

Figure 24: BaBar calorimeter triggers verus time after injection.

TOP-UP INJECTION COMMISSIONING

The commissioning of top-up injection required many shifts and hardware and software improvements prior to actual full time use. After full time use, the tuning for optimum backgrounds took a long period and in some sense is a continuous-ongoing action. Certain radiation detectors can only be used during very high backgrounds including the radiation diodes, vertex tracker signals, and crystal detectors. The injection trigger counters counted the electro-magnetic calorimeter EMC triggers (the most

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sensitive BaBar detector component) after every injection pulse and made a histogram of triggers versus time. The EPICS variables with integral counts were shown. Also, an FFT of the background was used to show the effect of accelerator changes with beam-energy deviations as a time display. Everything was normalized to the injection rate. The drift chamber DCH current was good for monitoring the average backgrounds and was not too fast for it could show an assessment of injection spikes. The L3 trigger rate had a similar behavior to the DCH current.

Overall, real time signals from the detector are crucial for making top-up injection function well and for tuning up top-up injection.

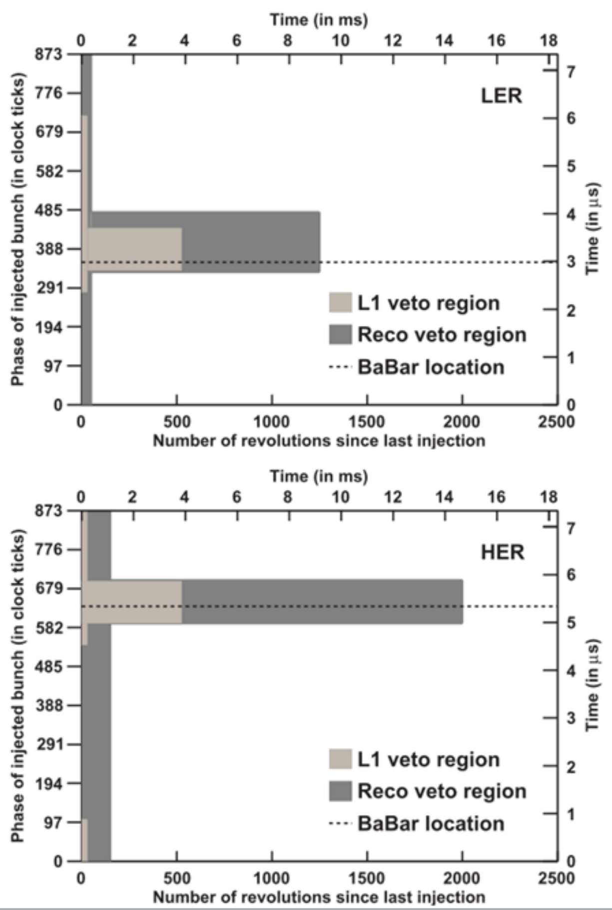

Figure 25: BaBar trigger masking versus time after injection and time in a turn relative to the injected bunch.

CONCLUSIONS

Top-up injection will work and should work well for a future circular e+e-factory. A full energy injector is needed because of the short beam lifetime.

The detectors will need to mask out the buckets being injected into during the damping times of the injected bunches during data taking but not for the whole circumference of the ring (only the injected bunch region).

A single bunch injection controller needs to be worked out in detail for both the accelerator and the detector.

Finally, commissioning can be complicated as many issues both on the accelerator and detector sides arise mainly with detector backgrounds and masking and have to be worked out in parallel with common purpose.

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