Studies of Bunch Trains in LEP

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Abstract

With the quest for higher luminosities over the coming years, one option under consideration is to operate LEP with four or eight equidistant bunch trains instead of four or eight single bunches in each beam. Each bunch train consists of a few bunches with a bunch spacing of a few tens of metres. The bunch trains collide at a horizontal crossing angle of about 1 mrad. The criteria for the choice of bunch spacing, crossing in the horizontal or vertical plane, and the crossing angle are presented. First results of machine experiments with bunch trains are discussed. The most important problems found are the parasitic encounters of the bunch trains near the interaction points, synchrotron radiation background from the off-centred beams in the quadrupoles nearest to the interaction points, and bunch current limitations due to higher-order mode losses in the super-conducting RF cavities. Possible ways around these problems are outlined.

1 INTRODUCTION

The transverse mode coupling instability severely limits the bunch current in LEP at values $I \approx 0.5$ mA [1]. One way of raising the luminosity L is to increase the number of bunches k. Because of the storage cavities of the Cu RF cavities in LEP and the requirement of the LEP experiments, the pretzel scheme [2] is limited at $k = 8$. Bunch trains, proposed for CESR at Cornell University and being implemented [3], are one way of achieving $k > 8$ in LEP.

1.1 Design Criteria

The two beams are separated at the parasitic collision points on either side of the interaction points IP by a horizontal crossing angle α at the IP. Because the criterion for the crossing angle $\alpha < \sigma_x/\sigma_s$ due to synchro-betatron resonances [4] is only met in the horizontal plane; α is a compromise between the above criterion and conditions on the ratio of beam separation and beam radius $|x|/\sigma_x > 4.2$ and the separated beam-beam tune shifts $|\xi_x|$, $|\xi_y| < 0.0028$, obtained by fits to measured CESR data.

1.2 Parameters

For the tests in 1993, the original proposal [5] was adapted in several ways. The number of bunches in the bunch trains was limited to $k = 3$ bunches, resulting in a length of the train $l \leq 54.476$ m, short enough for vertical separation in the odd pits. The bunch spacing chosen, $s \geq 32\lambda_{\mathrm{RF}} \approx 27.238$ m, respects the bunch spacing requirement of the beam observation system, and allows the read out of the positions of the first bunch in a train.

1.3 LEP Configuration for Bunch Train Studies

The LEP bunch train configuration [6] was derived from the 1993 standard configuration, and allows one to excite the horizontal crossing angle in the even pits with the pretzel separators. It has the same tunes Q_x and Q_y and the same phase advances $\mu_x = \pi/2$ and $\mu_y = \pi/3$ in the arcs. The phase advances in the even straight sections are changed such that the pretzel separators excite the horizontal crossing angle, and are compensated by opposite changes in the odd straight sections. Hence, a few critical collimator phases which are in conflict with separator phases, are simply wrong, and lead to off-momentum lepton background in the LEP experiments, and particularly in the LEP luminosity monitors. Several skew quadrupoles are not strong enough to compensate the solenoids because they also are at unfortunate phases. The dynamic aperture of the bunch train configuration is almost as good as that of the standard configuration.

2 MACHINE DEVELOPMENT

Four machine development sessions are discussed below, the fifth is discussed in Section 3.

2.1 Accumulation of Bunch Trains in one Beam

Four e^+ trains of three bunches each were accumulated with a bunch spacing of 32 λ_{RF}, by first filling the first bunch of each train for some SPS cycles, then filling the second bunch, and finally filling the third bunch, and then repeating the process a few times. The bunch current equaliser was used to limit the bunch train current at each stage, and in fact finally restricted the currents to a software limit of 1 mA. A total circulating current of 3.6 mA was reached in this way without difficulty. Four trains of three bunches were ramped to 45 GeV.

At 20 GeV the first bunch of a train was stable, while the second and third bunches show progressively more vertical blow-up. The lifetime of the first bunch remained good, while that of the second and third bunches fell to 8 and 2 hours, respectively, as the current increased. Ramping to 45 GeV caused beam loss from bunches 2 and 3, while the current in bunch 1 did not change. Bunches 1 and 2 oscillated at the same synchrotron tune, while that of bunch 3 was different.

2.2 *Optics for Collisions with Crossing Angle*

New optics, G21R20 through G05R46H, with tune and orbit corrections used during normal operations were loaded into the machine. With all separators off, four e^+ bunches were injected and accumulated without problems.

With vertical separators ZL on, two beams of four bunches were accumulated at 20 GeV, limited to 100 μA/bunch by the equaliser. A full crossing angle of 1 mrad was excited. At this point the radiation level in ALEPH, the only one monitored, went up from zero to around 5 rad/hour. The beams were ramped with constant crossing angle, with up to 100 rad/hour in ALEPH before it fell to zero at about 30 GeV in the ramp. The beams were brought into collision with a horizontal crossing angle of 1 mrad. The two experiments who tried to turn on, L3 and ALEPH, could not because of very high background.

2.3 *Trains in two Beams with Crossing Angle*

With the G21R20 optics, 4 e^+ bunches and 4 e^- bunches were accumulated. When turning on the crossing angle $\alpha = 1$ mrad, radiation levels rose in the experiments. Attempts to correct the coupling made the beams flatter but caused even higher radiation, and coupling compensation was abandoned.

e^+ bunches 2 and 4, and e^- bunches 1 and 3, which interact in the even IPs, were accumulated. Attempts to inject into leading and trailing bunches, both for e^+ and e^-, suffered from lifetime problems. It was not clear whether the problems came from single beam or two beam effects. With $\alpha = 0.5$ mrad, lifetimes were markedly better. With $\alpha = 0$, it was still possible to accumulate at some level.

2.4 *Trains in two Beams without Angle*

The G21R20 optics was used without exciting a crossing angle. We accumulated 4 trains of 3 e^+ bunches up to 0.5 mA per train. The bunch spacing was 35 λ_{RF} with the central bunch at the nominal bucket setting. We dumped the beam and repeated the procedure for e^-. Then with the e^- trains circulating, we unsuccessfully attempted to inject e^+ bunches 2 and 4 into the central bucket. The lifetime of two of the circulating e^- trains was reduced in this attempt.

We accumulated trains 2 and 4 of e^+ bunches. With these circulating it was not possible to accumulate e^- bunches 1 and 3 into the nominal bucket position.

We tried various combinations of e^+ and e^- bunches, and concluded that the intermediate collision point at 35/2 λ_{RF} from the IP were the cause of the problem. Filling only the extreme bunches in a train, spaced by 70 λ_{RF}, allowed accumulation without serious difficulty.

3 BEAM INDUCED BACKGROUND

Simulations predict a 400 fold increase of the synchrotron radiation (SR) photon background level at the LEP detectors with crossing bunch trains. This is substantially higher than can be tolerated by the detectors. The separated beams pass the straight section quadrupoles off-axis and radiate more and harder SR photons. As the radiated photon fans from off-axis locations have larger angles with respect to the beam axis, many more photons strike the vacuum system in the vicinity of the IP and can be scattered into the experiment. To test this prediction, the SR photon background was measured as function of the angle of an asymmetric horizontal orbit bump through the IP's [7]. This bump however is much shorter than the separator bump required for bunch trains.

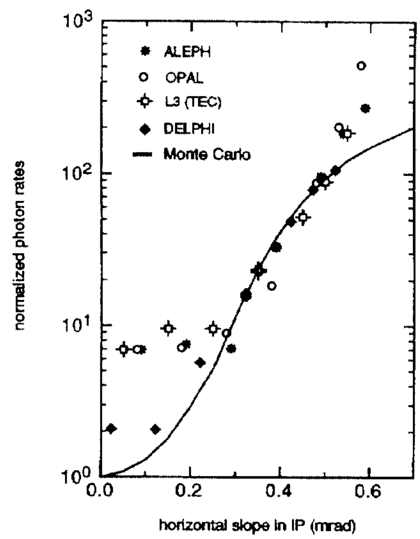

Figure 1: Normalised background rates vs. slope of the asymmetric orbit bump

A steep increase of the photon background rate with increasing slope is seen in all four LEP experiments (Fig. 1). To compare photon rates from different detectors with each other and with Monte Carlo (MC) predictions, all rates have been adjusted at 0.5 mrad and are then normalised for a predicted rate of 1 at zero angle. Relative photon rates from the four detectors agree well over the complete angular range, apart from DELPHI, where smaller rates are seen for slopes below 0.2 mrad. Good agreement between data and MC simulations of the machine development (MD) situation [8] is obtained for angles between 0.2 mrad and 0.5 mrad. For larger slopes the MC modelling of the orbit is no longer sufficient and too low rates are predicted. For slopes below 0.2 mrad measured photon rates stay about constant. This is due to an additional photon contribution, not obtained in the model, and independent of the orbit through the straight section. It was found in a later MD to be due to photons radiated from arc dipoles. The good agreement found between the relative increase of measured and predicted photon rates under MD conditions gives sufficient confidence in the MC predictions for crossing bunch trains. Therefore, one must expect a factor of about 400 increase of the SR photon background for 1 mrad crossing bunch trains compared to normal physics conditions. However, the quoted maximum tolerable increase in photon rates is normalised to 1992 physics conditions, which were 8 to 10 times higher than the MC rate at zero crossing angle during the MD. Therefore the missing factor above tolerable levels is only 4 to 5 for a total beam current of 3 mA. As bunch trains aim for much higher currents, missing factors of well above 10 would have to be coped with.

4 HIGHER-MODE LOSSES

The super-conducting (s.c.) RF cavities being installed for the LEP 2 programme are equipped with higher-order mode (HOM) couplers which can extract a few hundred watts of RF power, enough for four or eight equidistant bunches in each beam. The damping due to the HOM-couplers is too small to damp the HOM between bunches in a train. One cannot exclude by design that any arbitrary bunch spacing s is an exact multiple of the wavelength λ of a HOM. In that case one must add the HOM fields of the bunches in a train in phase, instead of simply adding their power. Similarly, the bunch trains in the e^+ and e^- beams pass through the s.c. cavities too close in time for damping between them. The damping due to the HOM couplers of the s.c. cavities is strong enough to damp the HOM between bunch trains in the same beam. Therefore, one may add the power of bunch trains in the same beam.

The superposition of the HOM fields from the bunches in a train is described by the beam loading enhancement factor B for a mode with frequency $f_{\rm HOM}$, given by:

$$B = \frac{1}{k}\left[\frac{\sin(f_{\rm HOM}ks\pi/c)}{\sin(f_{\rm HOM}s\pi/c)}\right]^2$$

and normalised such that $B = 1$ means addition of power. The maximum value, $B = k$, implies addition of the fields in phase; $B < 1$ (partial) cancellation. For $k = 3$ and the dominant accelerating mode at 639 MHz, B is small for many values of s; $s = 32\lambda_{\rm RF}$ is an unfortunately choice, and $s = 35\lambda_{\rm RF}$ is a good one.

Fig. 2 shows B against the resonant frequency $f_{\rm HOM}$ for the favourable bunch spacing $s = 35\lambda_{\rm RF}$ and $k = 3$; B remains small enough over a range of about 6 MHz in $f_{\rm HOM}$. Hence, there is enough room for variations of $f_{\rm HOM}$, caused by mechanical tolerances on the cavities.

The results of measurements of the HOM power $P_{\rm HOM}$ on 8 cavities at $s = 32\lambda_{\rm RF}$ are shown in Tab. 1; $P_{\rm HOM}$ fluctuates more between cavities with bunch trains than with single bunches, exactly what is expected when the phases of a higher-order mode vary because of small frequency variations from cavity to cavity.

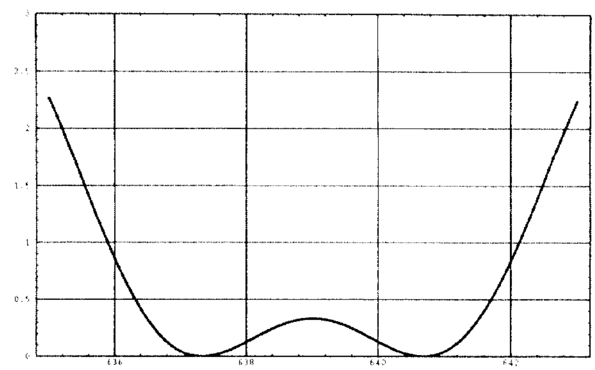

Figure 2: Beam loading enhancement factor B versus the HOM frequency $f_{\rm HOM}$ for $s = 35\lambda_{\rm RF}$ and $k = 3$

Table 1: Measurements of the HOM power $P_{\rm HOM}$ for 4 equidistant bunches and 4 equidistant bunch trains with $k = 3$ and $s = 32\lambda_{\rm RF}$ at bunch current I.

I	Cavity							
mA	1	2	3	4	13	14	15	16
4×0.5	6.1	5.6	7.4	4.3	6.7	5.9	4.1	6.2
12×0.3	2.1	4.4	12.8	3.0	5.1	7.7	5.0	8.1
12×0.3	2.0	4.1	10.9	2.8	4.0	7.7	4.8	8.1

5 CONCLUSIONS

Assembling bunch trains in LEP is straightforward for one beam, more difficult for two beams. The transverse stability and lifetime at 20 GeV depend on the bunch current and are less good for later bunches in a train. Bunch trains for LEP with a horizontal crossing angle increase the synchrotron radiation background in the LEP experiments by about two orders of magnitude. This radiation is caused by the offsets of the beams in the quadrupoles close to the IP. No method has been found to shield the experiments. Technical problems, associated with the compensation of the solenoidal fields in the LEP detectors, injection oscillations, and collimation of background due to off-momentum leptons, could be overcome in principle. Today, however, a different bunch train scheme [9] looks more promising. It uses a much longer bunch spacing in the trains and vertical separation, and avoids the crossing angle by starting the separation beyond the quadrupoles next to the IP.

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