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Complicated Bunch Pattern in PEP-II *

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Abstract

PEP-II, the asymmetric B-Factory at SLAC, has delivered a luminosity of $3.1 \cdot 10^{33}$ cm^{-2} s^{-1}. This was achieved with 692 bunches in a basic "by-3" bunch pattern. Many gaps in the bunch train were necessary to suppress a blow-up of the positron beam due to an electron cloud instability (ECI). The actual pattern had 10 bunches in a row (every third bucket), then 6 bunches missing. This 48-bucket long pattern was repeated till the last bucket (3320) before the ion clearing gap. The Low Energy Ring (LER) required an additional modification of the first bunch after each of the gaps. With a smaller spot size due to less ECI blow-up, the charge in these bunches was reduced by 10-20% to avoid kicking out the corresponding High Energy Ring (HER) bunches. A readout error of the charge along the whole train was counteracted with a 20% charge variation in the input. The reasons and developments of these and more complicated bunch patterns are discussed.

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PEP-II, the asymmetric B-Factory at SLAC, has delivered a luminosity of $3.1 \cdot 10^{33}$ cm^{-2} s^{-1}. This was achieved with 692 bunches in a basic "by-3" bunch pattern. Many gaps in the bunch train were necessary to suppress a blow-up of the positron beam due to an electron cloud instability (ECI). The actual pattern had 10 bunches in a row (every third bucket), then 6 bunches missing. This 48-bucket long pattern was repeated till the last bucket (3320) before the ion clearing gap. The Low Energy Ring (LER) required an additional modification of the first bunch after each of the gaps. With a smaller spot size due to less ECI blow-up, the charge in these bunches was reduced by 10-20% to avoid kicking out the corresponding High Energy Ring (HER) bunches. A readout error of the charge along the whole train was counteracted with a 20% charge variation in the input. The reasons and developments of these and more complicated bunch patterns are discussed.

1 PATTERN RECOGNITION

The maximum number of RF buckets in PEP-II is 3492. With an abort (or ion clearing) gap of 171 buckets (or about 5%) 3321 buckets are left to be filled with bunches. Filling every other bucket in a train (or a "by-2" pattern) results close to the design number of 1658, namely 1661 filled buckets. Other straight patterns will have a certain maximum allowed number of bunches (Tab. 1).

Pattern	by-1	by-2	by-3	by-4	by-5	by-6
# n_b	3321	1661	1106	831	665	553

Table 1: Maximum number of bunches per pattern.

A basic pattern might need some adjustments to get the highest luminosity for a certain total current. By reducing the number of filled buckets each bunch gets more current till the beam-beam limit is reached. A typical example was a basic by-4 pattern with 9 bunches in a row followed by 3 empty spaces in a so-called micro-gap:

|…|…|…|…|…|…|…|…|…|…_…_…_… and so on.

The input for this pattern would look like this: 0:3320:4[=1];36:3320:48=0;40:3320:48=0;44:3320:48=0. This can be further varied by alternating bunch trains of 9 and 10; or by introducing mini-gaps which consist of a whole bunch train missing at 1/3 and 2/3 of the fill, which help to balance the effect of the ion clearing gap.

The intensity of each bunch can also be adjusted. This was necessary for the LER ring (positrons), which sees some blow-up from the electron cloud around it. The first bunch of each train is reduced to 80 or 90% to avoid kicking out the first HER bunches (e.g.: 0:3320:48=0.8). The front of the whole fill needs a slow ramp up for the positrons, e.g.: 0=0.7; 0:160:4=R would give a ramp from 70% to 100% over 160 buckets with every 4th bucket filled. All these different patterns were derived from setups and measurements, which are discussed next.

2 ELECTRON CLOUD

It was found early in November of 1999 that the luminosity at around 10^{33} cm^{-2} s^{-1} didn't scale with the number of bunches [1]. Besides the beam-beam force there had to be another mechanism to blow up the beam. Electrons in the LER ring, multiplied by multipacting, are believed to be the culprit for a positron beam blow-up. A solenoid field of about 5 mT, introduced in one out of six straights of the ring, to suppress the electron multipacting helped to reduce the beam blow-up and increased the luminosity. But there was still a luminosity reduction along a bunch train as illustrated in Fig. 1.

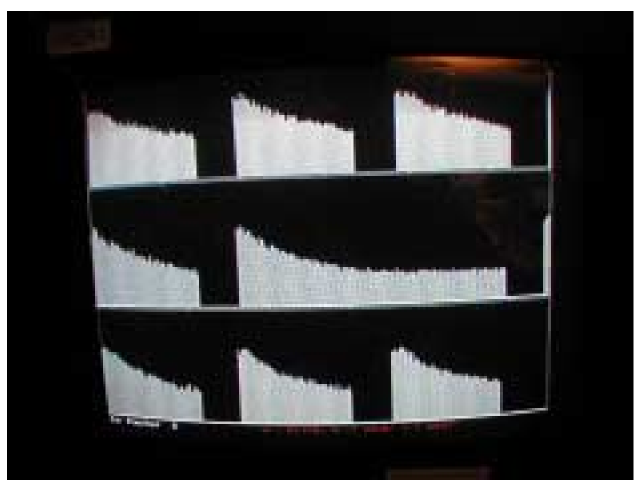

Fig. 1: Bunch-by-bunch luminosity versus position over the whole train. Large gaps nearly the size of the abort gap (at the end) clear the electron cloud, which slowly builds up again over about 10% of the whole train. The first bunches of the mini-trains have a high luminosity, which drops all the way to 40% at the end of the longer train.

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2.1 Optimum Gap Length

The gaps between the bunch trains in Fig. 1 seem to clear the electron cloud in the LER ring. We tried to investigate what the optimal duration of the gap is. The “basic” bunch pattern was by-4 with every fourth bunch missing: |…|…|…_…|…|…|…_… . Besides this one missing bunch we made gaps of 4, 9, 17 and 25 missing bunches in the middle of the train and additionally we had the 32 missing bunches of the abort gap. After this abort gap the luminosity is flat for about 12 mini-trains (36 bunches). Then within the next 12 mini-trains the train develops a structure of about 100% luminosity in the first and third bunch, while the second bunch is only at 80%. This ratio of 80/100 stays constant, but slowly (over 300 bunches) drops to 60%/75% in the middle of the whole train where the additional gap is. Depending on the size of the gap the luminosity jumps back to 75 to 100% (Tab. 2). From these results we decided to build short trains of 9 bunches (by-4) followed by a gap of 3 bunches missing. We ran most of 2000 and 2001 close to this pattern.

Gap size [#n_{miss}]	Luminosity after gap [%]	Degradation time [#n_{bunch}]
32	100	54
25	95	42
17	90	36
9	85	30
4	80	18
1	75	1
0	60/75	-

Table 2: Luminosity after a gap in the train.

2.2 Electron Cloud Oscillations

There are two time constants to this luminosity reduction that depend on the number of buckets. There is a slow time constant which seems to be responsible for the accumulation of electrons near the positron beam. They hang around and don’t disturb the beam size (see [1], Fig. 5) or with more current (and buckets) they have a small effect on the beam size. There is also a fast effect from one bunch to the next. It seems that the electron cloud makes fast oscillations: The first positron bunch passes through nearly unaffected, attracting the electrons to the center of the beam pipe. The second bunch (in the by-4 pattern) sees a big concentration of electrons and blows up by 20%. The third bunch has again a weaker electron cloud concentration and therefore more luminosity (Fig. 2). Then the oscillation seems to wash out. More theoretical discussion about the ECI can be found elsewhere [2].

In a basic by-3 pattern the second bunch comes earlier accelerating the electron cloud further to the center where it passes through before the third bunch arrives, avoiding most of the cloud. This by-3 pattern delivered about 10-12% more luminosity and gave us a record of $3.1 \cdot 10^{33}$ cm^{-2} s^{-1}, unfortunately it creates more higher order mode power and therefore heating in the kicker system of the longitudinal feedback.

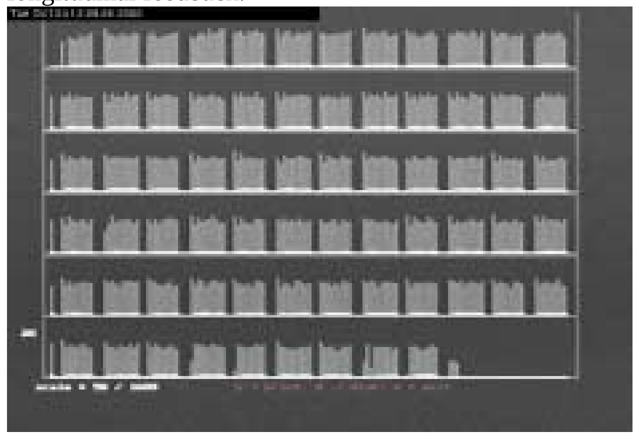

Fig. 2: Luminosity of a by-4 bunch pattern with trains of 9 and 10 (alternating). The first and third bunch show some 5-10% more luminosity than the second bunch after a small gap. Four HER buckets near the end (lower row) are blown up and deliver much less luminosity.

3 PATTERN IRREGULARITIES

Irregularities in the bunch pattern can also be used as a diagnostic to find other problems in the instrumentation and setup used to fill the rings.

3.1 Flat Current Distribution

The Bunch Intensity Control (BIC) software fills the bunches equally or according to the desired ratios. The signal derived from a fast bunch-by-bunch BPM button is sensitive to a phase shift along the bunch train, which resulted in an uneven fill giving about 20% more current in the last part of the train. This was first observed in the separate current information of the RF system, but not associated with filling issues. We finally noticed that a few buckets at the tail end of the HER beam started to get kicked out indicating a problem (Fig. 2). It was temporarily fixed by producing a continuous ramp down from 100 to 80% (Fig. 3). This effect was less with two mini-gaps, which reduced the one big phase transient from the ion clearing gap into three manageable smaller ones.

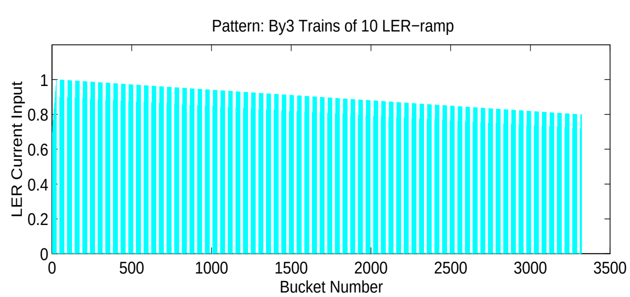

Fig. 3: Input for the LER current pattern with ramps. The pattern: “By-3 trains of 10 LER-ramp” has a ramp up over the first mini train and a ramp down to counteract

otherwise unequal filling. The first bunch of a mini train is 10% lower than its neighbors.

3.2 Longitudinal Offset Oscillations

Recently we have found that the parked cavities of one of the three RF stations in the LER ring make a significant phase oscillation of 3º peak-to-peak along the bunch train. There are about three oscillations giving a longitudinal offset at the interaction point. This was actually confirmed by the BaBar detector, where the reconstructed vertices come from different parts in *z* depending on the position within the bunch train [3]. Unfortunately the lifetime for the LER was worse in the first, third and fifth part out of six, while there were some HER buckets kicked out in the second, fourth and last part out of six. This behavior might be a hint that the beam waists of the two beams are not exactly at the same position in *z*. If one beam bunch moves in one direction due to a phase offset it might get to a real waist, while the other beam bunch moves further away from its waist.

4 SUPPORTING MEASUREMENTS

Besides the bunch-by-bunch luminosity monitor, other devises have shown effects of the different bunch patterns.

4.1 Integrating Measurements

By changing the bunch pattern and then looking at the result of a measurement, which integrates over the whole bunch train, the advantages of different patterns can be distinguished. For instance, the overall luminosity was better with a complicated by-4 pattern with micro- and mini-gaps than a straight by-5 pattern with exactly the same number of bunches.

Other diagnostics are the vacuum pump readings in the straight sections, which increase when the electron cloud starts to take off. But they also show that for a further beam current increase the pump reading actually goes through a maximum and then decreases indicating an oscillatory local behavior. The synchrotron light monitor shows the integrated spot size of all bunches. It starts to increase at about 1500 mA for a single, non-colliding beam (Fig.4).

4.2 Bunch-by-Bunch Measurements

After the success of the bunch-by-bunch luminosity monitor, different displays were upgraded to show bunch-by-bunch information. A very useful one it the bunch-by-bunch current monitor from the BIC. It shows clearly "dropping" buckets in the HER, and also the already mentioned lifetime reductions of the LER beam in the 1st, 3rd, 5th part out of six. By examining the first part more precisely it becomes obvious that over each little train of now 20 bunches the lifetime increases creating a saw-tooth pattern at the end of a 50 min coast down.

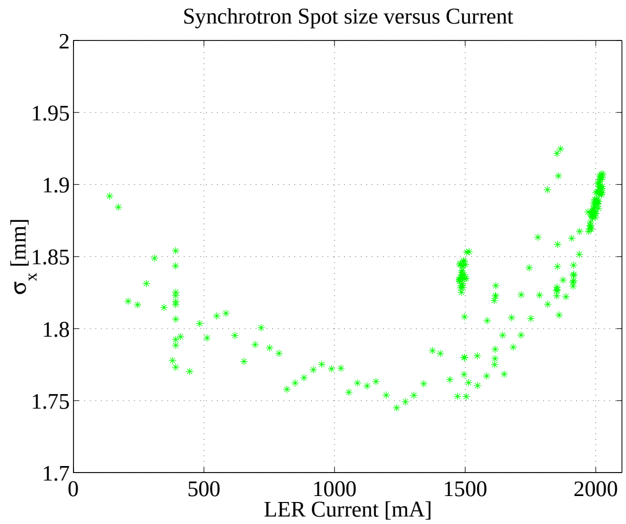

Fig. 4: LER single ring synchrotron spot size in *x*. The spot size is nearly constant (slowly decreasing) till about 1500 mA, then the measurement shows an increase by 15% till 2000 mA. The darker spots are longer periods of stored beam, with probably different tunes at 1500 mA. Similar curves were taken in a by-2 and by-3 pattern. A 50% increase to about 2.6 mm during collisions is due to the combination of the beam-beam effects and the electron cloud effects.

5 SUMMARY

Each little bucket space has more unique features than we ever expected to know. Starting from the ion clearing gap the symmetry is broken, creating phase changes, tune changes, different densities in the electron cloud and other variations along the bunch train. Complicated bunch patterns try to counteract some of these effects.

6 REFERENCES

[1] F.-J. Decker et al., "Towards Achieving the Design Number of Bunches in PEP-II", EPAC'00, Vienna, June 2000.

[2] F. Zimmermann's web page: http://wwwslap.cern.ch/collective/electron-cloud/

[3] M. Sokoloff, J. Boyd, J. Albert, private communication.