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More Results on Tune and Chromaticity Splits in Bunch Trains

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Abstract

Changes in tunes and chromaticities are caused by the head-on and parasitic beam-beam collisions when LEP is operated with bunch trains. Two LEP configurations are considered, (i) L05P46 with bunch train collisions near pits 4 and 8 during the tests in November and December 1994, and (ii) M05P46 with collisions between four bunch trains in each beam foreseen for 1995. Contrary to an earlier calculation I now calculate tunes and chromaticities with the MAD command EMIT instead of TWISS, and include the energy sawtooth. The differences in tunes and chromaticities between the two calculations are rather small. I show that the splits in tunes and chromaticities between bunches are caused by the β-beating due to the head-on beam-beam collisions. Differences between the vertical emittances of the bunches in a train are caused by the different patterns of the collision points. These emittances are due to the fact that the parasitic beam-beam collisions cause vertical orbit offsets all around LEP which are larger in the M05P46 than the L05P46 configuration.

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1 Introduction

This note is a follow-up to my recent note on tune and chromaticity splits in bunch trains [1]. I take this opportunity to correct two mistakes in that note. On page 3, the bunch current should be $I = 0.5$ mA. On page 6, just above the table, the chromaticity splits should read $\delta Q'_x \approx 1.2$ and $\delta Q'_y \approx 3.3$. J. Jowett suggested that I verify the tunes and chromaticities, obtained with TWISS commands, by using the EMIT command with quantum excitation, radiation damping, and energy sawtooth. The new tables can be found below. Section 2 gives the results for tune and chromaticity splits in the LEP configuration L05P46 used in November and December 1994, while Section 3 gives the results for the LEP configuration M05P46 which will be used in 1995. Section 4 contains a discussion of the vertical emittance and its causes, Section 5 discusses β-beating further, and Section 6 the vertical offsets at the even pits. Section 7 contains my conclusions.

2 Tune and Chromaticity Split for L05P46 in 1994

For the bunch train tests in November and December 1994, bunch train bumps were only installed and bunch train collisions occurred only near Pits 4 and 8. The MAD data and results for this case are stored on the hp system in my directory `LEP/L05P46/27Feb95` in files whose names start with `feb27b`.

The data set largely resembles the data set used earlier. However, the following point should be noted: The EMIT command updates the horizontal and vertical emittance attributes in the BEAM command. In order to prevent these changes to be propagated into the BEAMBEAM elements, I define emittances EPSX and EPSY by numbers, and use them in the BEAMBEAM commands. The bunch train bumps shown in Fig. 1 of [1] still apply to this case.

Table 1: Horizontal and vertical tunes, Q_x and Q_y, and horizontal and vertical chromaticities, Q'_x and Q'_y for various collision patterns in the L05P46 configuration during the 1994 tests computed with TWISS commands [1]

Collision pattern	Q_x	Q_y	Q'_x	Q'_y
Single beam	90.289232	76.194238	1.002426	0.996986
IPs 4 and 8	90.372094	76.257129	−1.406906	−1.368651
Even IPs	90.436430	76.306284	−2.404394	−2.835564
A-D in Pits 4 and 8	90.380113	76.234205	−0.985616	2.655608
B-E in Pits 4 and 8	90.386000	76.254552	−0.969160	0.115623
C-F in Pits 4 and 8	90.386000	76.254553	−0.969374	0.114423
D-G in Pits 4 and 8	90.380117	76.234218	−0.985686	2.648789

I still label the collision points in the neighbourhood of the pits from A to

G, where D coincides with the head-on collision point IP. Collision points A to C are to the left of the IP, while collision points E to G are to the right of the IP. I study the same cases as before. In all calculations, I continue to assume the following beam parameters: Energy $E = 45.6$ GeV, horizontal emittance $\epsilon_x = 30$ nm, vertical emittance $\epsilon_x = 1.2$ nm, bunch population $N = 2.78 \times 10^{11}$, corresponding to a bunch current $I = 0.5$ mA. The results of the simulation are shown in Tab. 1 for the earlier calculation using TWISS, and in Tab. 2 for the new calculation with EMIT, in order to facilitate the comparison. The tunes agree to the third decimal place, while the chromaticities differ by $\delta Q' \approx 0.1$ at most

Table 2: Fractional part of the horizontal and vertical tunes, Q_x and Q_y, and horizontal and vertical chromaticities, Q'_x and Q'_y for various collision patterns in the L05P46 configuration during the 1994 tests computed with the EMIT command

Collision pattern	Q_x	Q_y	Q'_x	Q'_y
Single beam	.28942440	.19509278	0.99692	0.98980
IPs 4 and 8	.37206650	.25754883	−1.38546	−1.41304
Even IPs	.43645521	.30731986	−2.39830	−2.84542
A-D in Pits 4 and 8	.38006948	.23475080	−0.96404	2.56484
B-E in Pits 4 and 8	.38593317	.25505107	−0.95078	0.04272
C-F in Pits 4 and 8	.38594456	.25505594	−0.95110	0.03170
D-G in Pits 4 and 8	.38009781	.23498894	−0.97060	2.59666

3 Tune and Chromaticity Split for M05P46 in 1995

In 1995, it is foreseen to operate LEP in the M05P46 configuration with four trains of four bunches each in each beam. This configuration is being developed by A. Verdier and C. Zhang [5]. The bunch trains collide in seven collision points in the neighbourhood of all eight pits. The collisions at collision point D in the even pits are head-on. All other collisions are parasitic. The bunch train bumps are as shown in Fig. 2 of [1]. I study the same cases as before.

The MAD data and results are in my directory `LEP95/M05P46/27Feb95` on the hp system in files whose names start with `feb27a`. The results of this calculation are summarized in Tab. 3 for the earlier calculation using TWISS, and in Tab. 4 for the new calculation using EMIT. In the first four rows, i.e. with no or head-on collisions only, the results for the tunes agree to three decimal digits, and the differences in the chromaticities are about $\delta Q' \approx 0.1$. In the last four rows with parasitic collisions, the vertical tunes differ by at most $\delta Q \approx 0.07$, which is a lot. The chromaticities differ by at most $\delta Q' \approx 0.5$. The largest difference occurs when collision points A or G are active, i.e. for the leading and trailing bunch in a train.

Table 3: Horizontal and vertical tunes, Q_x and Q_y, and horizontal and vertical chromaticities, Q'_x and Q'_y for various collision patterns in the M05P46 configuration foreseen for 1995, computed with the TWISS command. The difference of Q_y between TWISS and EMIT is rather large in the A-D case.

Collision pattern	Q_x	Q_y	Q'_x	Q'_y
Single beam	90.272850	76.173615	1.010405	1.058820
IPs 4 and 8	90.355181	76.229763	0.400643	0.352277
Even IPs	90.418826	76.273876	1.291204	−0.519814
All 8 IPs	90.419863	76.268732	1.294495	−0.242769
A-D	90.462647	76.218996	2.939993	−2.176752
B-E	90.472609	76.226441	1.755024	1.177981
C-F	90.472536	76.226085	1.749458	1.287474
D-G	90.462436	76.218840	2.890707	−2.020521

Table 4: Fractional parts of the horizontal and vertical tunes, Q_x and Q_y, and horizontal and vertical chromaticities, Q'_x and Q'_y for various collision patterns in the M05P46 configuration foreseen for 1995, computed with the EMIT command

Collision pattern	Q_x	Q_y	Q'_x	Q'_y
Single beam	.27314878	.17420847	0.99072	1.08240
IPs 4 and 8	.35531650	.23002790	0.39636	0.36580
Even IPs	.41894393	.27473035	1.27754	−0.43412
All 8 IPs	.41998301	.26968280	1.28034	−0.18820
A-D	.46315251	.22630671	3.03032	−2.66650
B-E	.47270065	.22959539	1.74620	1.10704
C-F	.47226805	.22442704	1.72768	1.55890
D-G	.46132684	.21551974	2.70728	−1.82950

4 Vertical Emittance and Dispersion

A computation of the horizontal and vertical equilibrium emittances, ϵ_x and ϵ_y, is a by-product of the EMIT command. The surprising results are summarized in Tab. 5. In the 1994 configuration L05P46, the vertical emittance is always much smaller than the value assumed in my calculations $\epsilon_y = 1.2$ nm. In the 1995 configuration M05P46, the vertical emittance ϵ_y remain small as long as the collision points A and G are not active. If this is the case, ϵ_y becomes comparable or larger than the assumed value.

Table 5: Horizontal and vertical emittances, ϵ_x and ϵ_y in nm, computed with the EMIT command, and average vertical dispersion $\overline{D}_y$ in m, computed with the TWISS command, for various collision patterns used in 1994 and foreseen for 1995. In the L05P46 configuration the parasitic collision points are active only near Pits 4 and 8.

Configuration	L05P46			M05P46		
Collision pattern	ϵ_x/nm	ϵ_y/nm	$\overline{D}_y$/m	ϵ_x/nm	ϵ_y/nm	$\overline{D}_y$/m
Single beam	35.26893	0.01620	0.0162	35.33820	0.05851	0.0279
IPs 4 and 8	30.48924	0.00295	0.0082	30.42098	0.02720	0.0222
Even IPs	28.38949	0.00259	0.0082	28.20515	0.05161	0.0275
All 8 IPs				28.22209	0.05902	0.0289
A-D	30.85771	0.00500	0.0100	28.90912	1.49502	0.1381
B-E	31.10070	0.00292	0.0079	28.97846	0.15747	0.0546
C-F	31.08921	0.00288	0.0080	29.01382	0.12397	0.0527
D-G	30.78399	0.00495	0.0103	28.61682	1.17583	0.1357

The reasons for the increase in the vertical emittance ϵ_y become clear by looking at the columns with the average vertical dispersion $\overline{D}_y$ in Tab. 5. In the 1994 configuration L05P46, $\overline{D}_y$ is small in all cases, while in the 1995 configuration M05P46 $\overline{D}_y$ increases when the collision points A or G are active. A small value of $\overline{D}_y$ in the case of a single beam with the bunch train bumps excited is a design feature of this configuration [5]. This feature is destroyed by the beam-beam collisions in points A and G. Figs. 1 and 2 show D_y for collisions in points A-D and B-E, respectively.

I thought that the extra vertical dispersion was caused by the beam-beam kicks. To estimate their contributions analytically, I start from the integral representation of D_y:

$$D_y(s) = \frac{\sqrt{\beta_y(s)}}{2\sin\pi Q_y}\int_s^{s+C}\frac{\sqrt{\beta_y(\sigma)}}{\rho_y(\sigma)}\cos[\mu_y(\sigma)-\mu_y(s)-\pi Q_y]\mathrm{d}\sigma \tag{1}$$

Here the symbols have their usual meaning, C is the circumference, and ρ_y is the vertical bending radius of the elements whose contribution to D_y is to be calculated. Profiting from the fact that the beam-beam collisions are short, and that the ratio $\mathrm{d}\sigma/\rho_y(\sigma) = \Delta y'$, i.e. the beam-beam kick, the integral can be replaced by a sum over all beam-beam kicks:

$$D_y(s) = \frac{\sqrt{\beta_y(s)}}{2\sin\pi Q_y}\sum_i\sqrt{\beta_{yi}}\Delta y'_i\cos[|\mu_{yi}-\mu_y(s)|-\pi Q_y] \tag{2}$$

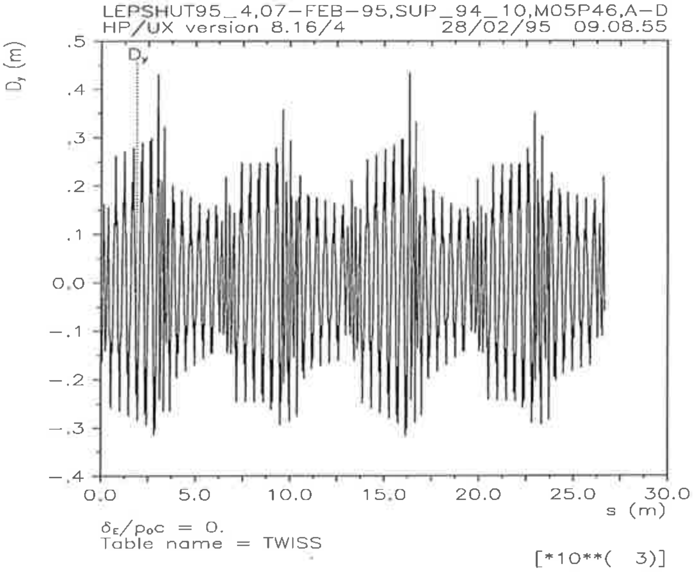

Figure 1: Vertical dispersion D_y in the M05P46 configuration with beam-beam collisions in points A-D. Pit 1 is at the left.

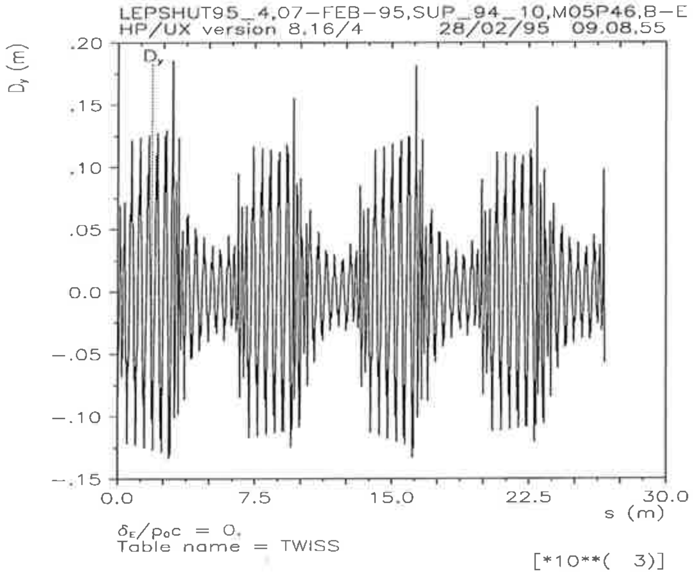

Figure 2: Vertical dispersion D_y in the M05P46 configuration with beam-beam collisions in points B-E. Pit 1 is at the left.

Apart from small changes in the notation, this expression is identical to the equation for the vertical orbit distortion y due to the beam-beam kicks [6] used in the `ORBIT7` program [7]. Hence, the contributions of the beam-beam kicks to D_y are the same as their contributions to the orbit offsets. Figs. 3 and 4 show the vertical orbit offsets for the L05P46 and M05P46 configurations, respectively. Although the vertical orbit offsets are larger in the M05P46 configuration, their values do not explain the observed values of D_y with parasitic beam-beam kicks. Therefore, the high values of D_y must have other causes, i.e. the orbit offsets in the arcs. A good configuration for bunch trains should avoid the accumulation of vertical orbit offsets in the arcs due to the parasitic beam-beam kicks.

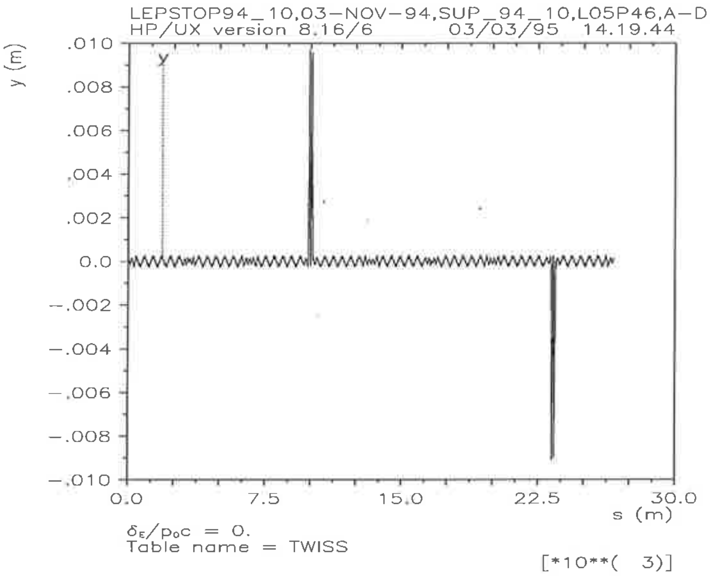

Figure 3: Vertical orbit offsets y in the L05P46 configuration with beam-beam collisions in points A-D of Pits 4 and 8. Pit 1 is at the left.

5 Further Discussion of β-Beating

The discussion of β-beating given earlier was rather brief and difficult to understand. I therefore repeat it now. My argument was that the head-on collisions in the even pits cause β-beating [4], and affect the tunes and the chromaticities in different amounts for different patterns of collision points. I thought for a while that it ought to be simple to remove the β-beating, and hence the splits of the tunes and chromaticities, by rematching the low-β insertions. So far, I have not managed to find a satisfactory match. In a discussion with J.-P. Koutchouk, I realized that removing the head-on collisions should remove the

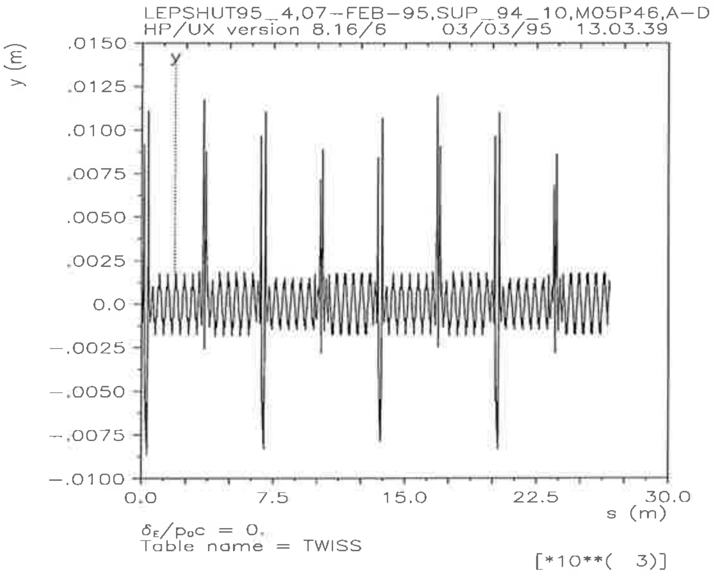

Figure 4: Vertical orbit offsets y in the M05P46 configuration with beam-beam collisions in points A-D of all pits. Pit 1 is at the left.

β-beating, and hence the splits of the tunes and chromaticities, if my argument is correct. This calculation is easy, and I did it with the TWISS command in the `LEP95/M05P46/24Feb95` directory in filenames starting with `feb24g`. Its results are summarized in Tab. 6. The first two rows demonstrate that the odd IPs have a small effect on both tunes and chromaticities, as expected. The last four rows should be compared to the last four rows of Tab. 3. The difference in the horizontal chromaticity between pairs of collision points is now $\delta Q'_x < 1$, somewhat smaller than before, while the difference in vertical chromaticity is dramatically reduced to $\delta Q'_y \approx 0.6$. A comparison of the vertical β-beating in the two cases is shown in Figs. 5 and 6. The β-beating caused by the head-on beam-beam collisions is impressive.

6 Effects of Vertical Miscrossings

When I observed the vertical emittances described in Section 4, I was very surprised. I also noticed rather large vertical bam-beam kicks y' at the even IPs, where the two beams are supposed to collide head-on. The vertical offsets at the even pits, caused by the beam-beam kicks at the parasitic collision points all around LEP are well known [6], and minimizing them is one of the design criteria for the M05P46 configuration [5]. In my MAD simulations, the BEAMBEAM elements get vertical offsets YMA which are the opposite of the orbit offsets which

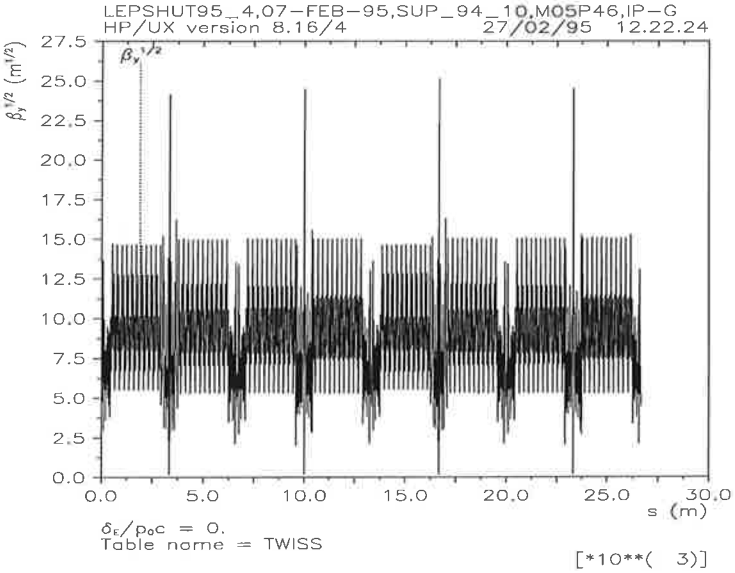

Figure 5: Vertical orbit function $\sqrt{\beta_y}$ in the M05P46 configuration with beam-beam collisions in points D-G, i.e. with head-on collisions in the even pits. Pit 1 is at the left.

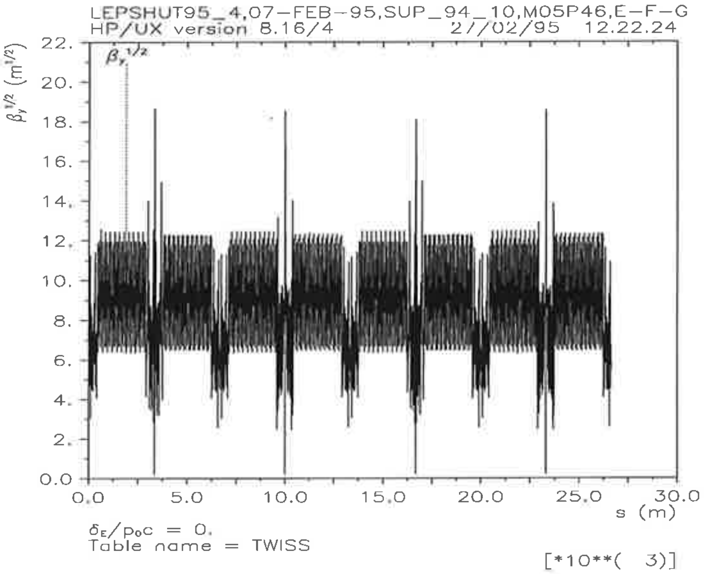

Figure 6: Vertical orbit function $\sqrt{\beta_y}$ in the M05P46 configuration with beam-beam collisions in points E-G, i.e. without head-on collisions in the even pits. Pit 1 is at the left.

Table 6: Horizontal and vertical tunes, Q_x and Q_y, and horizontal and vertical chromaticities, Q'_x and Q'_y for various collision patterns in the M05P46 configuration foreseen for 1995, computed with the TWISS command, without head-on collisions in the even pits.

Collision pattern	Q_x	Q_y	Q'_x	Q'_y
Single beam	90.272850	76.173615	1.010405	1.058820
IPs 1+3+5+7	90.273632	76.172664	1.009236	1.101944
A+B+C	90.308919	76.141341	2.107793	−0.899111
B+C+E	90.315841	76.150543	1.123764	−0.278732
C+E+F	90.315817	76.150641	1.119343	−0.272204
E+F+G	90.308780	76.141609	2.076274	−0.855907

I calculate with the vertical separation bumps in the absence of the beam-beam collisions. It is impossible to do this calculation self-consistently without manual iteration, also bearing in mind the vertical vernier adjustments included in the `ORBIT7` program [7]. An example of the results for the orbit offsets y and the vertical slopes $y'_\pm$ before and after the beam-beam kicks in the even pits is shown in Tab. 7. The vertical slopes y' are different for different bunches in the trains, and reach about ±0.75 mrad, the beam-beam kicks reach about 50 μrad. The consequences of these miscrossings should be studied further. Their effect on the offsets y and the vertical dispersion D_y is rather small because they are multiplied by $\sqrt{\beta_y}$.

Table 7: Vertical offsets y in μm and vertical slopes y' in mrad before and after the beam-beam collisions in the even pits for the M05P46 configuration.

IP	IP2			IP4		
CP	y/μm	y'_-/mrad	y'_+/mrad	y/μm	y'_-/mrad	y'_+/mrad
A-D	6.531	.683503	.636899	3.213	.774354	.749368
B-E	6.930	.298088	.249291	1.009	.290928	.282874
C-F	8.430	−.239708	−.295756	−0.012	−.255806	−.255713
D-G	10.273	−.594900	−.657892	1.181	−.698192	−.707604

IP	IP6			IP8		
CP	y/μm	y'_-/mrad	y'_+/mrad	y/μm	y'_-/mrad	y'_+/mrad
A-D	6.134	.678347	.633966	2.628	.771165	.750586
B-E	6.729	.295436	.247687	0.653	.285279	.280072
C-F	8.873	−.235629	−.293591	0.331	−.260996	−.263639
D-G	10.950	−.589120	−.654243	1.756	−.701496	−.715397

7 Conclusions

I compared the changes in tunes and chromaticities which are caused by the head-on and parasitic beam-beam collisions when LEP is operated with bunch trains by using the TWISS and EMIT commands in MAD. I considered two LEP configurations, (i) L05P46 with bunch train collisions near pits 4 and 8 during the tests in November and December 1994, and (ii) M05P46 with collisions between four bunch trains in each beam foreseen for 1995. I found that the differences in tunes and chromaticities between the two commands are rather small, and in any case smaller than the differences between different bunches in the bunch trains. I demonstrated that these changes are caused, at least to a large extent, by the β-beating due to the focusing action of the head-on beam-beam collisions. I also computed the horizontal and vertical emittances for the various patterns of beam-beam collisions. I find that the vertical emittance is largest when the out-most parasitic collisions points A or G are active. I believe that the vertical emittance in these cases is caused by the vertical orbit offsets in the arcs due to the parasitic beam-beam kicks which are larger in the M05P46 configuration than in the L05P46 configuration used last year. I also find that different bunches travel through the even pits at vertical slopes which vary between ±1 mrad.

References

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[3] C. Bovet et al., CERN SL/94-95 (AP) (1994).

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[6] E. Keil, CERN SL/94-76 (AP) (1994).

[7] E. Keil, SL Note 95-07 (AP) (1995).