Presentation 1

More Bunches with Pretzel

By J.M. Jowett

1.1 Introduction

LEP has run successfully for almost a whole year with the 8-bunch pretzel scheme. The luminosity has been substantially higher than could be obtained with 4 bunches and flat orbits. The basic hardware installation of the scheme that is now in place allows a number of other numbers and arrangements of bunches which may provide still higher luminosity. In this talk, I shall present some of the options which are available and could be considered for the 1995 run of LEP.

Schemes with up to 36 evenly-spaced bunches were considered in the original design of the LEP pretzel scheme [1, 2]. An 8-bunch version of the scheme, using separators recuperated from the SPS, was proposed in late 1990 [3] and has now become the normal operational mode of LEP. The main reason for limiting the present scheme to 8 bunches was the need to use the copper RF system: the beating of stored energy between the accelerating and storage cavities provides the maximum accelerating voltage only 8 times per revolution period. When enough super-conducting RF cavities become available, this restriction will be removed. On the other hand, there are some possibilities for increasing the number of bunches by placing them in positions close to the maximums of the effective accelerating voltage, as in the proposal for a 9th monitoring bunch [4, 5].

1.2 Pretzel schemes with evenly-spaced bunches

In [2], it was shown that pretzel schemes with $k_b \in \{8, 10, 12, 18, 24, 36\}$ evenly spaced bunches are feasible with 90° phase advance per cell in the horizontal plane[1]. Some aspects of the pretzel schemes presented in that report require review in the light of what we now know about the 8-bunch scheme.

A pretzel scheme with $k_b > 8$ evenly spaced bunches cannot be realised until we have at least 350 MV available from the super-conducting RF system, enough to allow operation at 45 GeV without help from the copper system. This will certainly not be the case in 1994 but might be in 1995.

1.2.1 Bunch encounters

As can be seen from, e.g., Figure 1.1, a scheme with $k_b = 18$ has no encounters in mid-arc and encounters at other places occur with a separation reduced by 0–30% compared with the separation

[1] Although these studies were done using a 90°/90° optics which is now rather out of date, the conclusions remain essentially valid

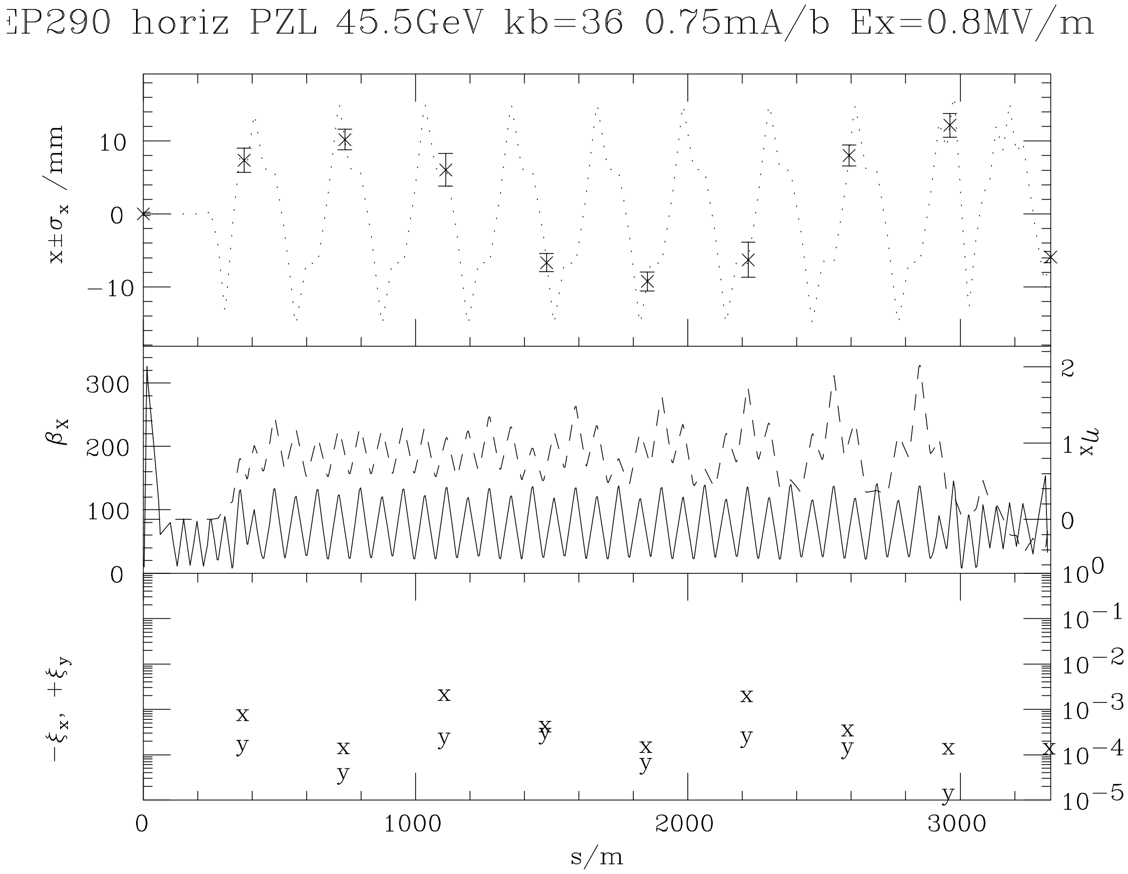

Figure 1.1: Beam-beam parameters in a pretzel scheme with $k_b = 36$, reproduced from Figure 4 of [2]. The top frame of this plot shows the pretzel orbit of one beam in an octant of LEP; the IP is on the left. The "error bars" at the encounter points indicate the horizontal RMS beam size. The second frame shows β_x (full line) and the dispersion D_x (dashed line) which is not properly matched here. The bottom frame shows the values of the parasitic beam-beam strength parameters at each of the parasitic crossings. Since $\xi_x^{(j)}$ is negative for $x/\sigma_x \gtrsim 2$, we have plotted $-\xi_x^{(j)}$ on the log scale with $\xi_y^{(j)}$.
To see the beam-beam encounters for a scheme with $k_b = 18$, just look at every second encounter starting from the one at the IP ($s = 0$) on the left of the plot.

in mid-arc. This is not necessarily a disadvantage since the dispersion is similarly reduced and we know that some of the bad effects from the mid-arc encounters are due to dispersion [6, 7].

Another point worth bearing in mind is that schemes in which k_b is not divisible by 4 (e.g. $k_b = 10$ or 18) do not require the vertical separation bumps at the odd IPs.

Evenly-spaced pretzel schemes for $k_b \geq 8$ can continue to be used at LEP2 energies. If high enough bunch currents can be stored, and if the emittance can be reduced by changes of the damping partition, then it is unlikely that more than 8 bunches will be required [8]. A pretzel scheme at LEP2 with $k_b > 8$ would have to forgo use of the copper RF system with the storage cavities.

1.2.2 Hardware Requirements and Cost Estimate Update

In [2], it was assumed that new horizontal separators would be built from scratch for the pretzel scheme, implying a substantial cost and delay for their construction. Meanwhile, the separators recuperated from the SPS have been installed and found to be adequate, eliminating both these barriers to the realisation of a many-bunch pretzel scheme. Table 1.1 is a quick attempt to update the cost estimate in Table 10 of [2], taking this and some other items into account.

Item	8-bunch pretzel	18–36-bunch pretzel	
		Min. cost	Max. cost
	(MSF)	(MSF)	(MSF)
Electrostatic separators	0	0	0.0
Upgrade to HOM couplers		0	2.0
BOM system	0	0	10.0
Other beam instrumentation	0	0.5	2.0
LPI e^+ production increase		2.5	2.5
LEP injection kickers		0.1	0.2
Contingency		0	1.0
Total	0	1??	16??
Previous Total [2]	10.5	18.4	33.9

Table 1.1: Very rough attempt at an update of the previous cost-estimate for a many-bunch pretzel scheme [2]. It is stressed that this is partly guesswork on the part of the speaker and most of the hardware groups concerned were not consulted in the preparation of this talk. The point is just to show that it would now be much cheaper to modify LEP for such a many-bunch scheme. The "Min." estimate is certainly optimistic and the "Max." probably pessimistic.

The largest remaining item for a full pretzel scheme is the BOM system. When a bunch-bunch encounter takes place too close to a narrow-band pickup, that pickup can be put out of action for orbit measurements. In the present 8-bunch scheme, 2 pickups are lost around each mid-arc point but the consequences for normal orbit correction are not serious. Orbit correction is most important in the straight sections and pretzel scheme, by construction, *never creates any additional encounters in the straight sections*. Adding more bunches removes pickups only in the arcs. More detailed study is required to determine the point at which this becomes unacceptable for purposes of orbit correction.

1.3 A 16-bunch pretzel for 1995

In this section, I shall present a new scheme for increasing luminosity, closely related to the present pretzel scheme. The reasons for proposing this scheme (from the machine point of view) are:

1. It could be used during a period (possibly the 1995 run) in which LEP still has to be rely mainly on the copper RF system.

2. It requires only minimal modifications to the present scheme (reversal of pretzel polarity and a small modification of the injection kickers which could all be done by the start of 1995).

3. After running with this scheme, it is easy to revert to an evenly-spaced pretzel scheme for LEP2 or any future period when higher luminosity at the Z might be required. (In this sense it is compatible with LEP2).

It must be stressed that, if enough super-conducting RF is available in 1995, then there is no reason whatever to adopt this scheme (unless the experiments happen to like the bunch-spacings that come with it). It is intended only as a stop-gap measure for higher luminosity at the Z as a prelude to LEP2 with an 8-bunch pretzel scheme.

1.3.1 Bunch spacings with the copper RF system

The bunch spacings that are possible with the copper RF system were considered in the context of the 9th bunch scheme in [5][2]. The storage cavities cause a beating of the peak RF voltage at $8f_0$ so that any bunch in a bucket at a position s_9 relative to one of the ordinary 8 bunches will experience a reduced RF voltage

$$\frac{\hat{V}}{\hat{V}_{\mathrm{max}}} = \cos\left(16\pi s_9/C\right) \tag{1.1}$$

and synchrotron tune

$$\frac{Q_s}{Q_{s\mathrm{max}}} = \sqrt{\frac{\hat{V}}{\hat{V}_{\mathrm{max}}}\sqrt{\frac{1-\left(U_0/\hat{V}\right)^2}{1-\left(U_0/\hat{V}_{\mathrm{max}}\right)^2}}}. \tag{1.2}$$

Clearly if the copper RF system must be used then we want to place bunches in buckets as close as possible to the usual 8 which experience the maximum peak voltage. However we also want to ensure that any additional beam-beam encounters occur inside the pretzels.

Figure 1.2 shows the parasitic beam-beam tune-shifts as a function of distance from an IP through one octant while Figure 1.3 shows the *combination* of tune-shifts seen in one octant by a 9th bunch. As explained in more detail in [5], the tune-shifts on this plot are the sum of 4 different encounters of the 9th bunch with the other 8.

You may by now be asking why I am bringing up the 9th bunch scheme again in this talk. It turns out that it can lead us to a new 16 bunch scheme in which neither the usual 8 buckets, nor the nearby 9th bunch buckets are filled but, instead, a bunch is placed in a bucket at a distance $s_9/2$ on either side of them. This can be seen from Figure 1.4 which shows the torus obtained by taking the product of the LEP circumference and a revolution time. The encounters in this scheme occur at exactly the same places as in the 9th bunch scheme—but there are more of them of course.

[2] Some minor corrections to that note were made in a presentation to the SL Performance Committee on 6/10/93.

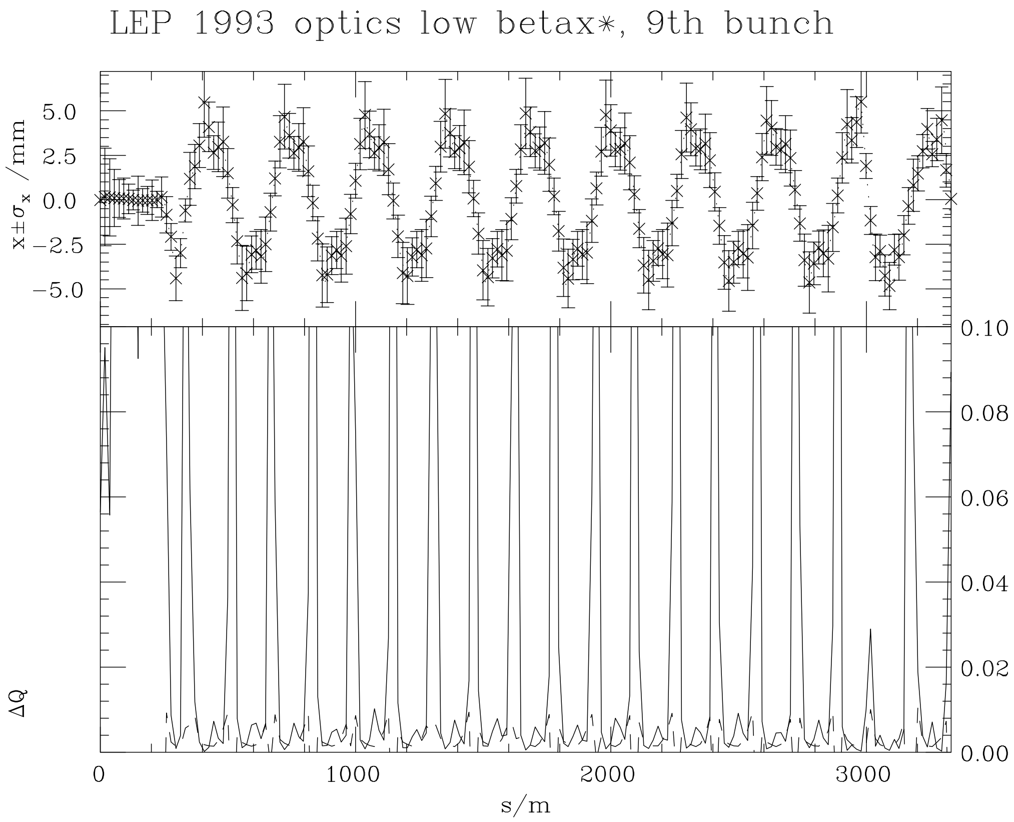

Figure 1.2: The upper part of the plot shows the pretzel orbit with error bars representing the RMS beam sizes $\sigma_x = \sqrt{\epsilon_x \beta_x + D_x^2 \sigma_\epsilon^2}$ at each encounter of the many bunch pretzel scheme described in the text. In the lower part, the solid line joins the points representing the vertical parasitic beam-beam tune-shifts and the Parasitic beam-beam tune-shifts for collisions occurring at many places over one octant of LEP. (Figure reproduced from [5].)

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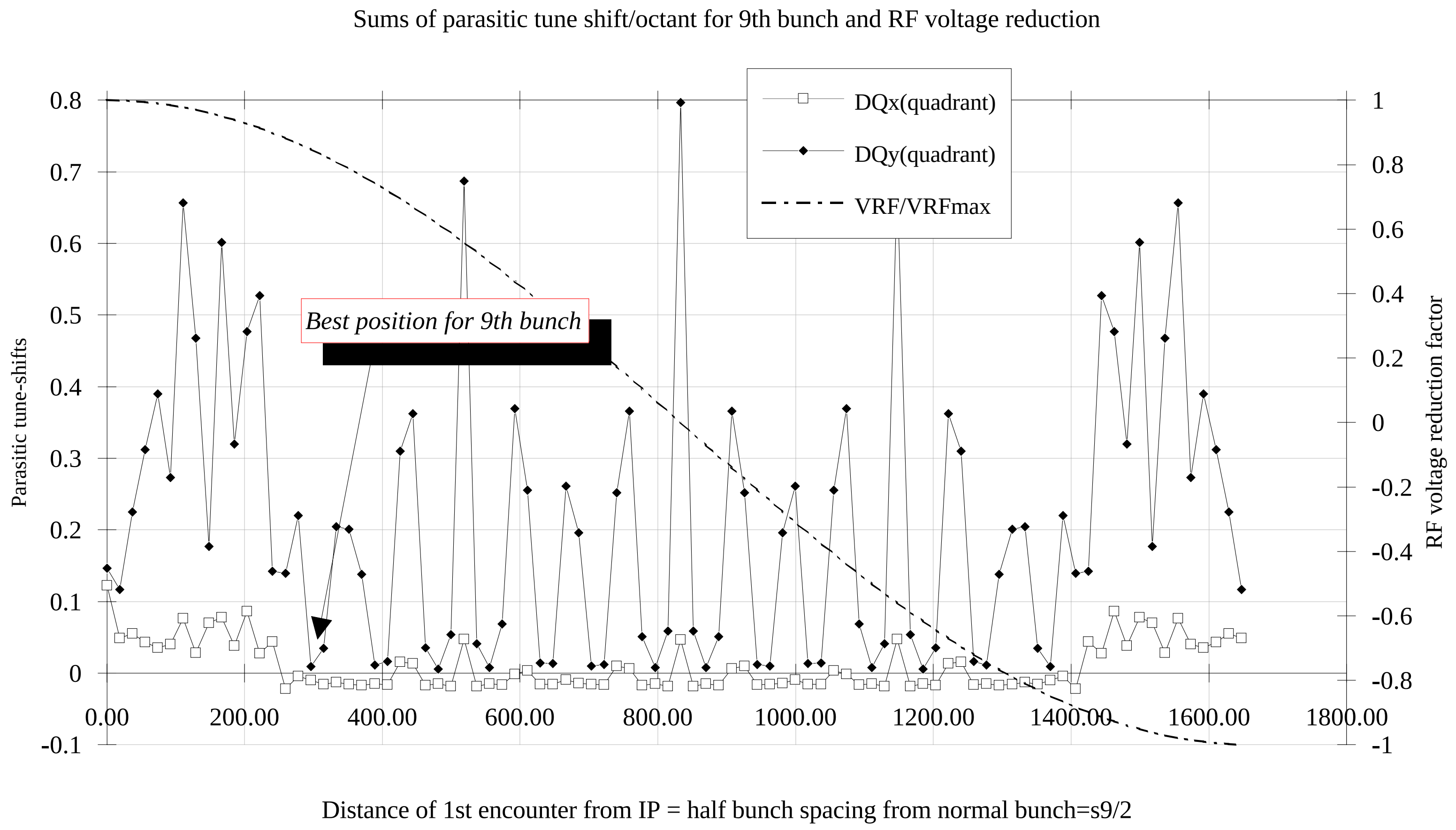

Figure 1.3: See text in Section 1.3.1 for explanation. (Figure reproduced from [5].)

In this scheme, all bunches have the same synchrotron tune Q_s given by Eq. 1.2 but with s_9 reduced by a factor of 2. The possible values of s_9, now the separation between two bunches in a train, can be read off from Figure 1.3. There are a few bunch spacings allowed, the smallest being the same 600 m used in the 9th bunch scheme but there are at least two more around 800 m and 1000 m, corresponding to spacings in time of around 2, 2.7 and 3.6 μs.

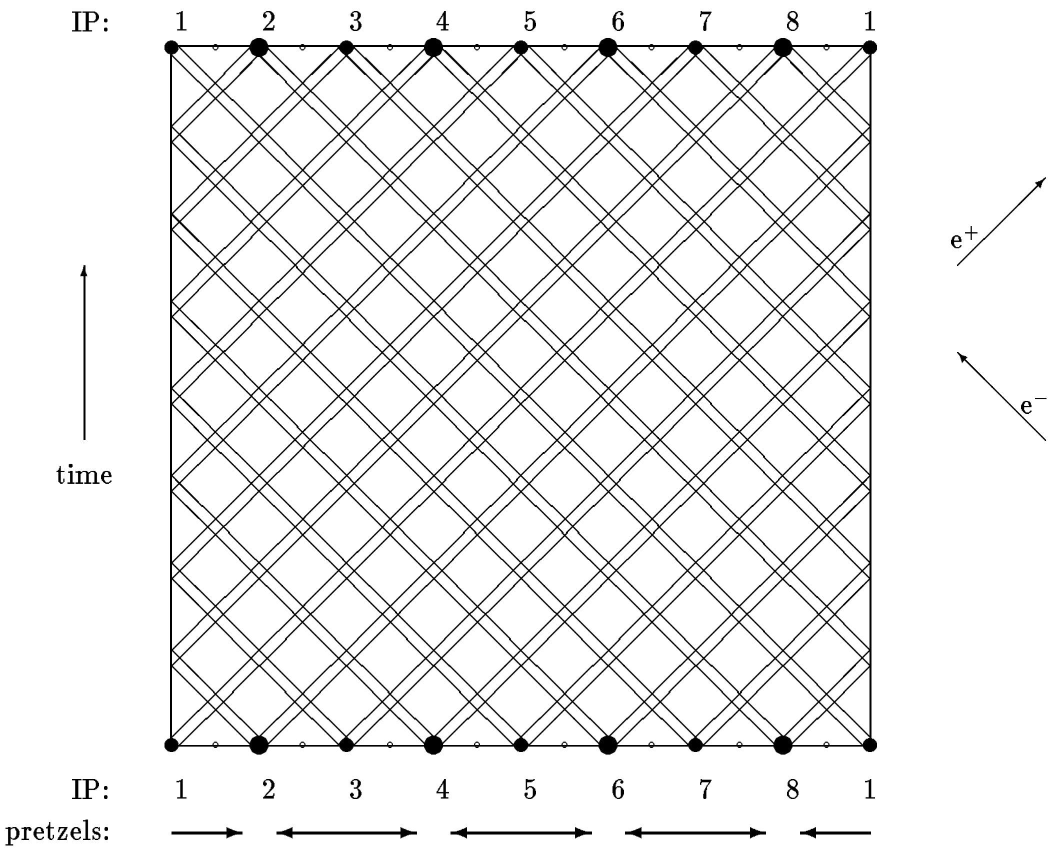

Figure 1.4: Space-time torus showing bunch encounters in the 2×8 bunch pretzel scheme.

The separation and beam-beam tune-shifts at encounters, as computed by WIGWAM are shown in Figures 1.5–1.8 for both an injection and physics configuration. The combinatorics of encounters are a little more complicated than in the case of evenly-spaced pretzel schemes. Now not every bunch has an encounter at every azimuth where another bunch might.

At best one could hope for a further factor of 2 in luminosity compared with what can be achieved with an 8 bunch scheme.

1.3.2 Injection kickers

The hardware implications for this scheme follow from injection considerations [9]. It is possible to inject a second family of 8 bunches after the first is filled using present hardware (implying that some MD on this scheme would be possible in 1994). However to reach the highest intensities, it

WIGWAM output for 16 bunch scheme, 704 bucket spacing
G05P46HV2 optics, 45.6 GeV, V(ZX)=120 kV, one quadrant

Encounter	s	ebucket	pbucket	X/mm	X/sigx	xi_x	xi_y	|xi_x|	|xi_y|
IP2=0	298.839	351	351	9.49	18	-0.00304	0.00154	0.00304	0.00154
1	3631.197	351	351	6.98	13	-0.00535	0.00192	0.00535	0.00192
IP3=2	3332.359	7477	351	0.0874	0.29	0.883	2.26	0.883	2.26
3	0	7477	351	0.0165	0.19	1.01	0.637	1.01	0.637
QF49.R2=4	1665.754	3562	351	9.78	6.4	-0.00466	0.00116	0.00466	0.00116
5	4998.109	3562	351	10.1	6.7	-0.0039	0.00179	0.0039	0.00179
6	1965.444	4266	351	6.2	5.4	-0.00652	0.00637	0.00652	0.00637
7	5297.801	4266	351	8.06	7.2	-0.00332	0.0042	0.00332	0.0042
8	3332.359	351	7477	0.0874	0.29	0.883	2.26	0.883	2.26
9	0	351	7477	0.0165	0.19	1.01	0.637	1.01	0.637
10	6365.875	7477	7477	9.68	18	-0.00295	0.00157	0.00295	0.00157
11	3033.516	7477	7477	6.77	13	-0.00656	0.00244	0.00656	0.00244
12	4699.27	3562	7477	6.37	5.8	-0.00526	0.00673	0.00526	0.00673
13	1366.91	3562	7477	7.9	7	-0.00369	0.00418	0.00369	0.00418
14	4998.961	4266	7477	10	6.7	-0.00393	0.00181	0.00393	0.00181
15	1666.602	4266	7477	9.83	6.5	-0.00462	0.00115	0.00462	0.00115
16	1665.754	351	3562	9.78	6.4	-0.00466	0.00116	0.00466	0.00116
17	4998.109	351	3562	10.1	6.7	-0.0039	0.00179	0.0039	0.00179
18	4699.27	7477	3562	6.37	5.8	-0.00526	0.00673	0.00526	0.00673
19	1366.91	7477	3562	7.9	7	-0.00369	0.00418	0.00369	0.00418
20	3032.668	3562	3562	6.79	13	-0.0067	0.00235	0.0067	0.00235
21	6365.023	3562	3562	9.9	18	-0.00294	0.00147	0.00294	0.00147
22	3332.359	4266	3562	0.0874	0.29	0.883	2.26	0.883	2.26
23	0	4266	3562	0.0165	0.19	1.01	0.637	1.01	0.637
24	1965.444	351	4266	6.2	5.4	-0.00652	0.00637	0.00652	0.00637
25	5297.801	351	4266	8.06	7.2	-0.00332	0.0042	0.00332	0.0042
26	4998.961	7477	4266	10	6.7	-0.00393	0.00181	0.00393	0.00181
27	1666.602	7477	4266	9.83	6.5	-0.00462	0.00115	0.00462	0.00115
28	3332.359	3562	4266	0.0874	0.29	0.883	2.26	0.883	2.26
29	0	3562	4266	0.0165	0.19	1.01	0.637	1.01	0.637
30	3632.05	4266	4266	7	13	-0.00546	0.00187	0.00546	0.00187
31	299.691	4266	4266	9.7	18	-0.00302	0.00142	0.00302	0.00142

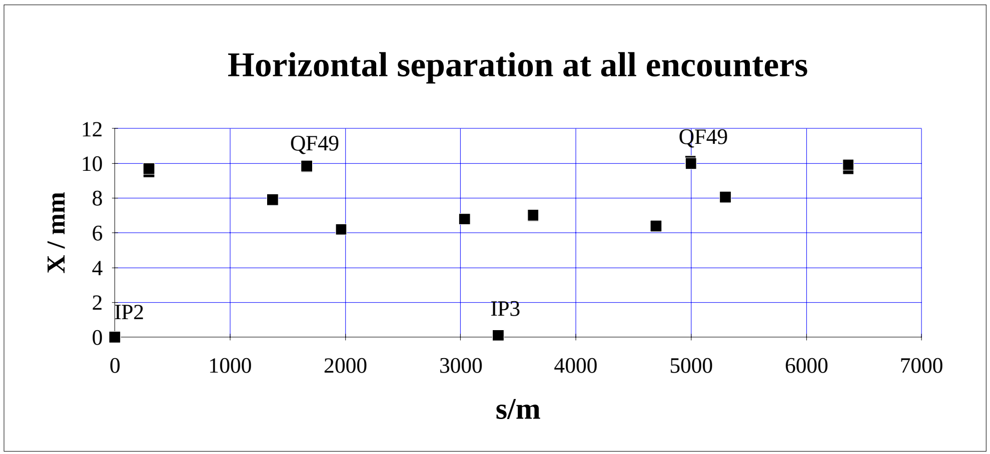

Figure 1.5: Parameters associated with all beam-beam encounters in the 2×8 bunch pretzel scheme at injection energy. Encounters are shown between pairs of bunches according to their bucket numbers.

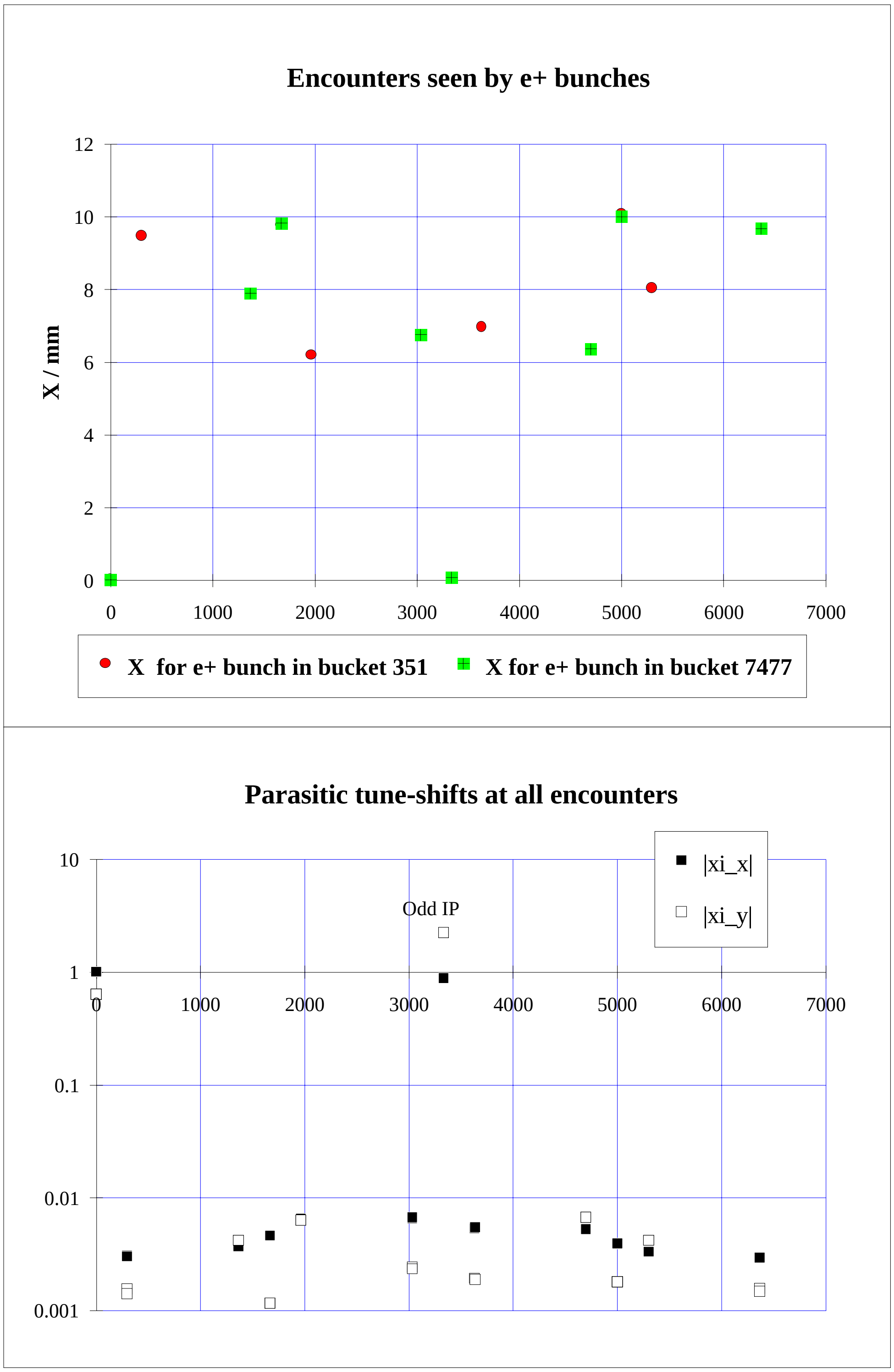

Figure 1.6: Further parameters associated with beam-beam encounters in the 2×8 bunch pretzel scheme at injection energy.

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WIGWAM output for 16 bunch scheme, 704 bucket spacing G05P46HV2 optics, 45.6 GeV, V(ZX)=120 kV, one quadrant

Encounter	s	ebucket	pbucket	X/mm	X/sigx	xi_x	xi_y		
0	298.839	351	351	9.49	18	-0.00304	0.00154	0.00304	0.00154
1	3631.197	351	351	6.98	13	-0.00535	0.00192	0.00535	0.00192
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7	5297.801	4266	351	8.06	7.2	-0.00332	0.0042	0.00332	0.0042
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9	0	351	7477	0.0165	0.19	1.01	0.637	1.01	0.637
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20	3032.668	3562	3562	6.79	13	-0.0067	0.00235	0.0067	0.00235
21	6365.023	3562	3562	9.9	18	-0.00294	0.00147	0.00294	0.00147
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30	3632.05	4266	4266	7	13	-0.00546	0.00187	0.00546	0.00187
31	299.691	4266	4266	9.7	18	-0.00302	0.00142	0.00302	0.00142

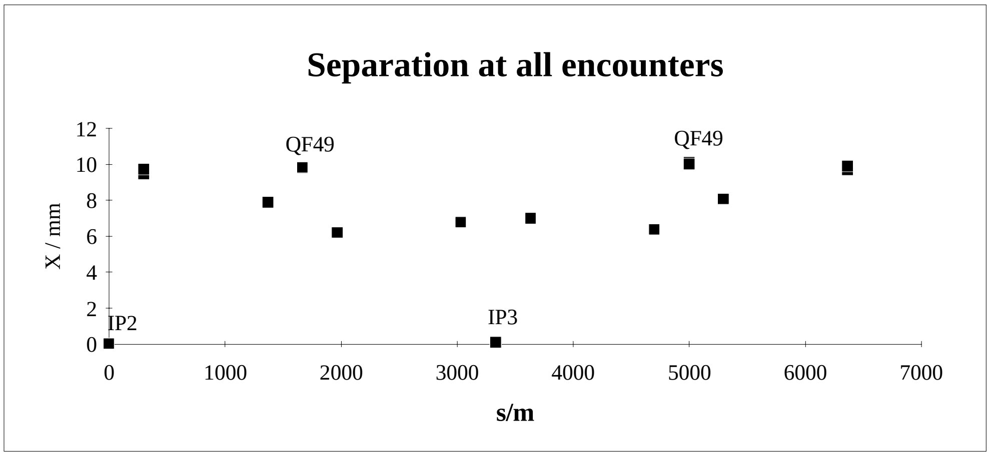

Figure 1.7: Parameters associated with all beam-beam encounters in the 2×8 bunch pretzel scheme at Z-energy. Encounters are shown between pairs of bunches according to their bucket numbers.

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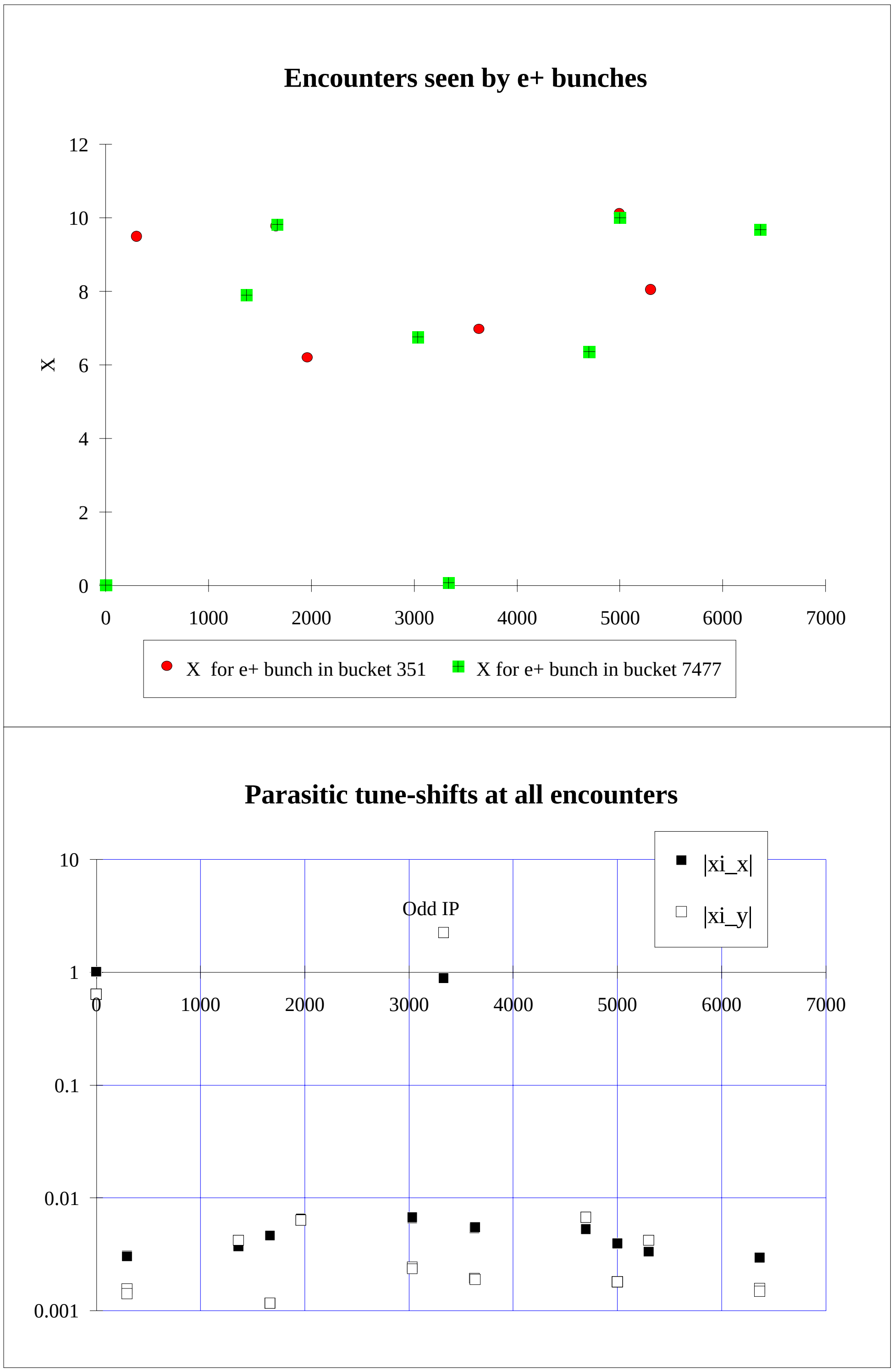

Figure 1.8: Further parameters associated with beam-beam encounters in the 2×8 bunch pretzel scheme at Z-energy.

will almost certainly be necessary to fill the buckets alternately, keeping the intensities as equal as possible. This cannot be done because the injection kicker would kick out certain bunches.

Fortunately a low-cost technical solution [9] is available (a cost estimate was included in Table 1.1) and could be implemented in about 6 months from the go-ahead of the project (i.e., we could have it for 1995). Adding a pulse transformer to the injection kickers would allow a long kicker pulse and permit many kinds of multi-bunch injection (including *all schemes discussed in this talk*). It would also be trivial to revert to the present type of pulse.

Using this solution would, however, necessitate a reversal of the pretzel polarity to avoid bringing the injected beam too close to the septum. This, in turn, could be done at modest cost (only manpower) by turning the pretzel separator tanks around (to maintain the polarity favourable to minimise sparking). This would require a few weeks work in the tunnel including the opening of the vacuum [10] and could only be done in the winter shutdown. Unfortunately, the present separator polarity would have to be restored for pretzel operation of LEP2 to ensure that the pretzel separation would combine constructively with the separation due to the energy sawtooth [3]. This rules the scheme out, as such, for LEP2 but we have seen that it would be easy to revert to an evenly-spaced scheme.

1.3.3 Beam instrumentation

Items like the Beam Current Transformer (BCT) would be adaptable to schemes with $k_b > 8$; it is just a question of modifying software. Again the main item of instrumentation requiring consideration is the Beam Orbit Measurement (BOM) system. From a first analysis that I have just done, it appears that, besides the pickups `PU.QD48.Ln` and `PU.QD48.Rn` which are already disabled by the mid-arc encounters, pickups `PU.QL12.[LR]n`, `PU.QS14.[LR]n`, `PU.QD40.[LR]n`, `PU.QD42.[LR]n` would also go. It is also possible that `PU.QL14.[LR]n` and `PU.QS12.[LR]n` will also go. In any case, at least 448 out of our original 512 pickups will remain!

1.4 Low-cost Pretzel Future for LEP

If we decide to persist with the pretzel scheme to maximise the luminosity of LEP at each stage, then the future would go as follows (an alternative course is given in *italics*):

1994: continue with 8 bunches, working to improve intensities and luminosity,

1995: Increase the number of bunches by running with super-conducting RF at the Z energy, upgrading at least the injection kickers. *(If the copper RF has to be used, make the same kicker upgrade, reverse pretzel polarity and use the* 2×8 *bunch pretzel scheme.)*

1996 onwards: *(Restore pretzel polarity if necessary.)* LEP2 operation at 90 GeV with pretzel option of 8, 10, 12, ... evenly spaced bunches, depending on RF power available and the current per bunch.

Combined with an increase of J_x (in the rather likely eventuality that the dynamic aperture at LEP2 is insufficient to run with the natural emittance [8, 11]), a many-bunch scheme with reduced emittance might be the only way to obtain an acceptable luminosity at LEP2.

A Z-factory LEP with many bunches remains an option, albeit a very demanding one, for some far-distant future, should it ever be required.

1.5 Conclusions

- Pretzel schemes with 8, 10, 12, 18, 24 or 36 evenly spaced bunches remain options for future higher luminosity running at the Z. They are basically compatible with LEP2 although it is clear that the RF power limit (and some beam-dynamics aspects) means that only the lower bunch numbers will be of interest.

- Considered as an option for future higher luminosity running and for LEP2, pretzel schemes have the advantages that little if any, new hardware is required, considerable experience has already been gained, their limitations are known and there is hope to overcome them by improvements to the machine. We should recall that, at CESR, the luminosity gains from the transition to pretzel operation took time to come.

- Like any scheme for more than 4 bunches, pretzel schemes create new beam-beam encounters with the consequent loss of some narrow-band pickups. However those narrow-band pickups which are disabled are located only in the arcs—by its basic construction, the pretzel scheme allows no encounters in the straight sections of the machine and the BOM system maintains its total integrity in this, the most critical part of the machine.

- A new pretzel scheme with 8 long trains of 2 bunches has been proposed as a stop-gap measure for a period in which there is not yet enough superconducting RF to run at the Z. The transition to this scheme and the reversion to an evenly-spaced pretzel scheme for LEP2 require minimal modifications to the machine.

On the other hand, the disadvantages of a pretzel scheme must be mentioned:

- The single-bunch intensity limits are still less than for 4 bunches.

- Maximising luminosity in physics conditions is more difficult than with 4 bunches.

Finally, I would like to remark that the present pretzel scheme is good practice for LEP2. Many of the differences between electrons and positrons due to the separation of the orbits are similar to effects that one can expect to arise from the energy-sawtoothing at LEP2. Similar problems will arise in maximising luminosity at LEP2.

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[5] J.M. Jowett, "Where to Put a 9th Bunch in LEP", SL-MD Note 101 (1993).

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[7] J.M. Jowett, "Horizontally separated encounters in the middle of the arcs", this workshop.

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[10] W. Kalbreier, private communication.

[11] J.M. Jowett, "Dynamic Aperture for LEP: Physics and Calculations", this workshop.