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A Study of RF Effects on Bunch Trains in the 1995 Running

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Abstract

This note describes an analysis of the possible energy shifts implied by the disagreement between calculated and measured LEP parameters within the context of the 1995 RF model. The "Standard" RF model for 1995 is compared with a version which has been modified to reproduce the distribution of bunch collision points seen by the LEP experiments, and possible changes in energy are calculated. Estimates of the range of energy shifts are consistent with the systematic errors assigned to the RF corrections for the Summer 1996 conferences. New errors, based on a more detailed analysis, are assigned for the possible effects of bunch train modelling uncertainties. They are: 0.8, 0.6, 0.1, and 0.6 MeV for IPs 2, 4, 6, and 8, respectively. To be conservative, the values are assumed 100% correlated between IPs and energy points for the 1995 running.

1 Introduction

This note describes an analysis of the possible energy shifts implied by the disagreement between calculated and measured LEP parameters within the context of the 1995 RF model. As was noted in the complete description of the 1995 RF analysis[1], several discrepancies exist between the predictions of the "standard" RF model outlined in that text and the experimental data. Most notable of these was a large difference between the predicted and measured values of the positions along the beam axis (z coordinate) of the collision points of the three bunchlet families a, b, and c. This is shown graphically in Figure 1, reproduced from the original 1995 RF note[1]. The shifts in the collision points can *not* be reproduced even with drastic changes to the parameters of the RF model. The rest of this note procedes under the hypothesis that the standard acceleration processes that occur in the RF system cannot be responsible for these shifts, and that another yet-to-be-understood beam-cavity interaction is the source. Further details will be given below.

Other discrepant details of the RF data come from the Q_s measurements. Comparisons of the difference in Q_s between bunchlet families and between electrons and positrons of the same family reveal differences that cannot be explained by simple modifications of the RF model. An example of this is shown in Figure 2, where the difference in Q_s between electrons and positrons and the difference in Q_s between bunchlet a and bunchlet c are shown as a function of time, comparing calculated values and those measured in LEP. At this time, there is no physical explanation for these effects; the leading candidates will be discussed in the conclusions of this note.

The rest of this note presents an empirically modified version of the "standard" 1995 RF model which reproduces as best as possible the Q_s and z positions of the collision points. As alluded to above, this version of the RF model operates under the following assumptions:

- Something other than the longitudinal accelerating field provided by the RF system is causing the collision point shifts and the changes in Q_s, *i.e.*, the standard simulations of beam-loading and phasing of cavities are still valid
- The measured Q_s values do not suffer from any pathological problems and can be taken as correct
- The perturbations to the "standard" RF model are small enough to be treated linearly.

2 The Modified RF Model

Modifications to the RF model based on the above assumptions take a simple form. Shifts in the collisions positions can be directly related to differences in the stable phase angle ϕ_s between the electron and positron beams. In the course of typical LEP running, these arise from cavity misalignment effects, which shift the stable phases of the two beams in opposite directions, forcing a vertex shift. The actual formula relating the two is

$$\Delta\phi_s = 4\pi\Delta z \cdot \frac{f_1 + f_2}{2c} \tag{1}$$

where f_1 and f_2 are the two frequencies of the CU RF system, and Δz is in meters. Numerically, this reduces to

$$\Delta\phi_s = \Delta z \times 14.765 \tag{2}$$

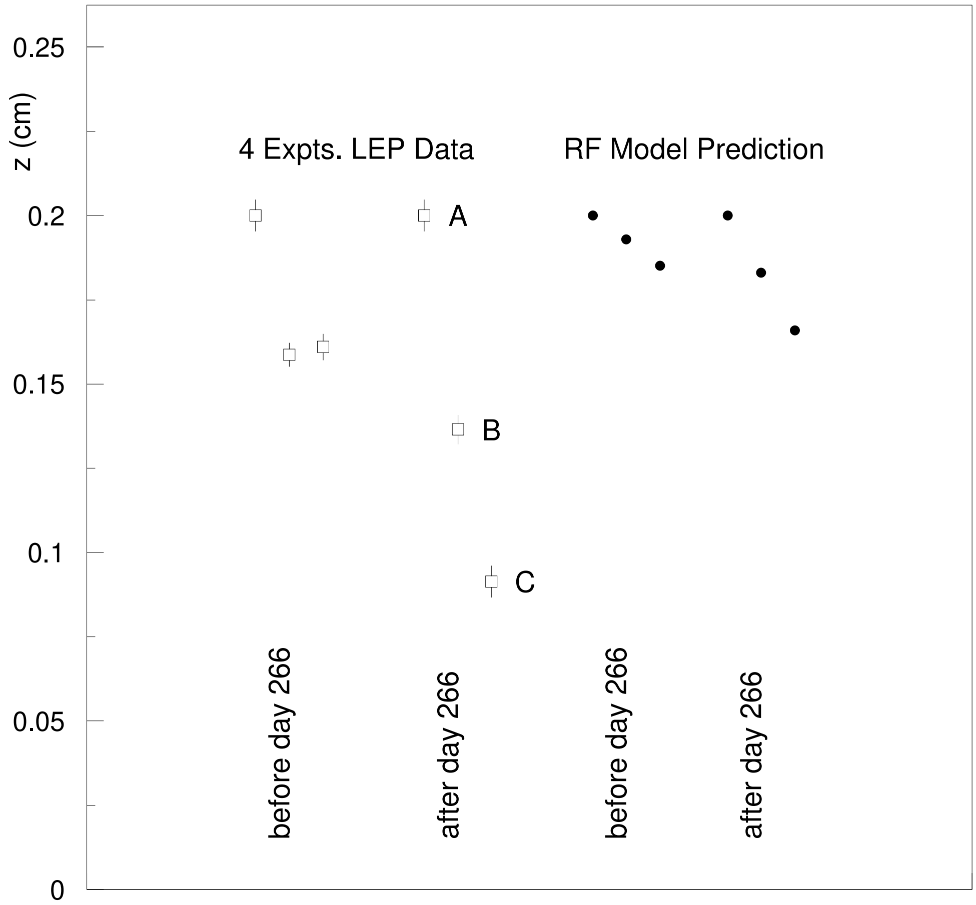

Figure 1: A comparison of the measurements and predictions of the average z position of the collision points of the three bunchlets, labelled "A", "B", and "C". The predictions of the RF model are also shown for the default "weak" beamloading model. The data are broken into two periods during the Scan, one before the SC RF was dominant (before day 266) and one after.

where here the 14.765 has units of meters^{-1}. If we assume that the shifts in z are a manifestation of some external interaction, then it is a simple matter to reproduce the observed Δz distribution within the RF system. This is done by calculating a shift in stable phase for each record in the RF database so that the predicted bunchlet collision positions exactly match what was seen by the experiments at that time. In the context of the RF model, the effect of the unknown external interaction is to *force* the bunchlets to sit at a different stable phase angle than what we would have naively calculated otherwise. The systematic error estimates on the Summer 1996 energy files for bunch train effects were derived from a model such as this. As will be seen below, a more detailed analysis of this model's predictions lends added confidence that the preliminary errors are more or less correct, even if the model does not quite reproduce the observed distributions.

To begin, we show in figure 3 the raw output of the model in terms of vertex positions,

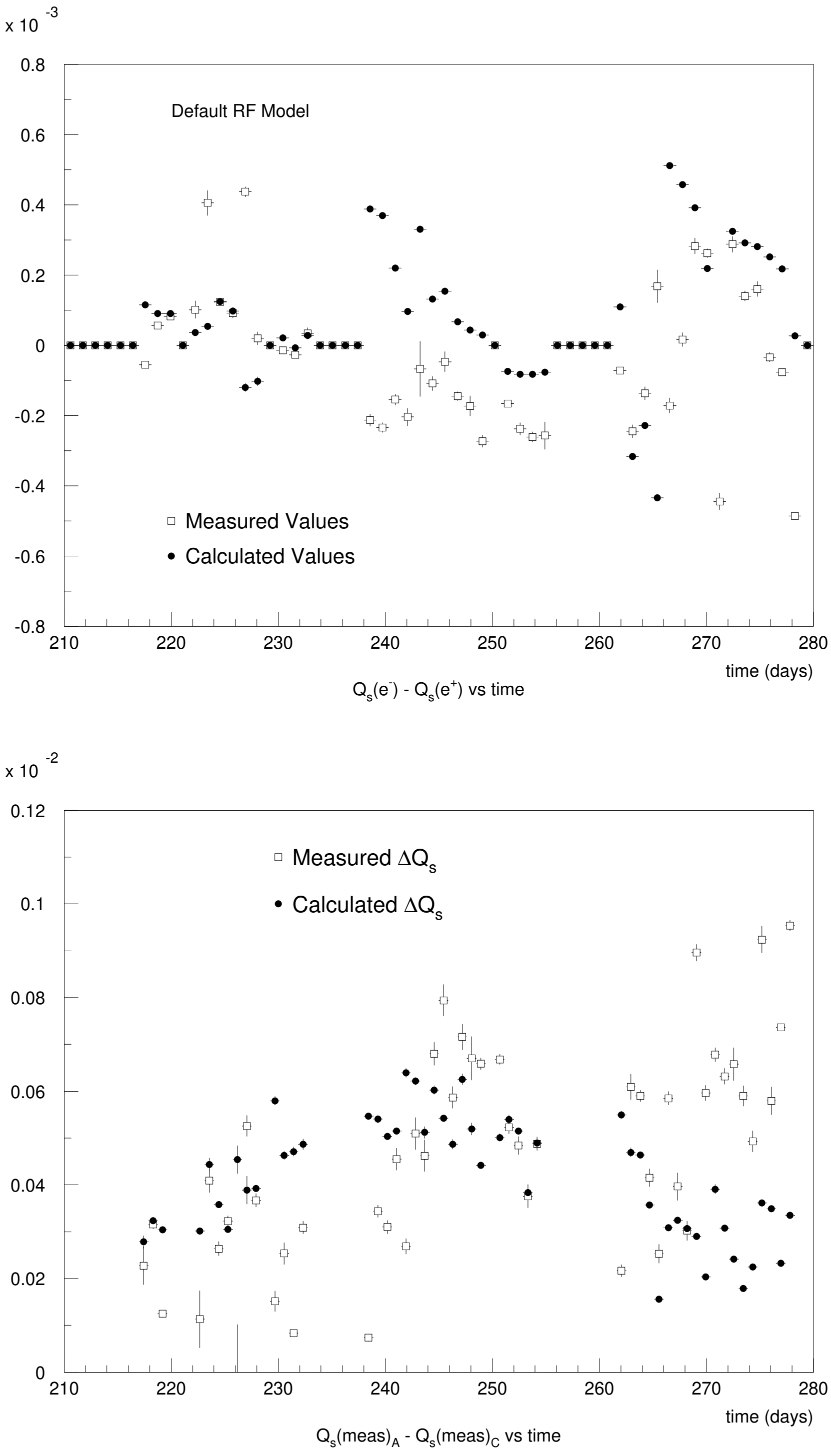

Figure 2: A comparison of the measurements and predictions of the difference between the average electron and positron Q_s (top) and the the difference between the average Q_s for bunchlet a and that for bunchlet c (bottom). These are shown for the "default" 1995 RF model. Note the large discrepancies after day 266 in the bottom plot.

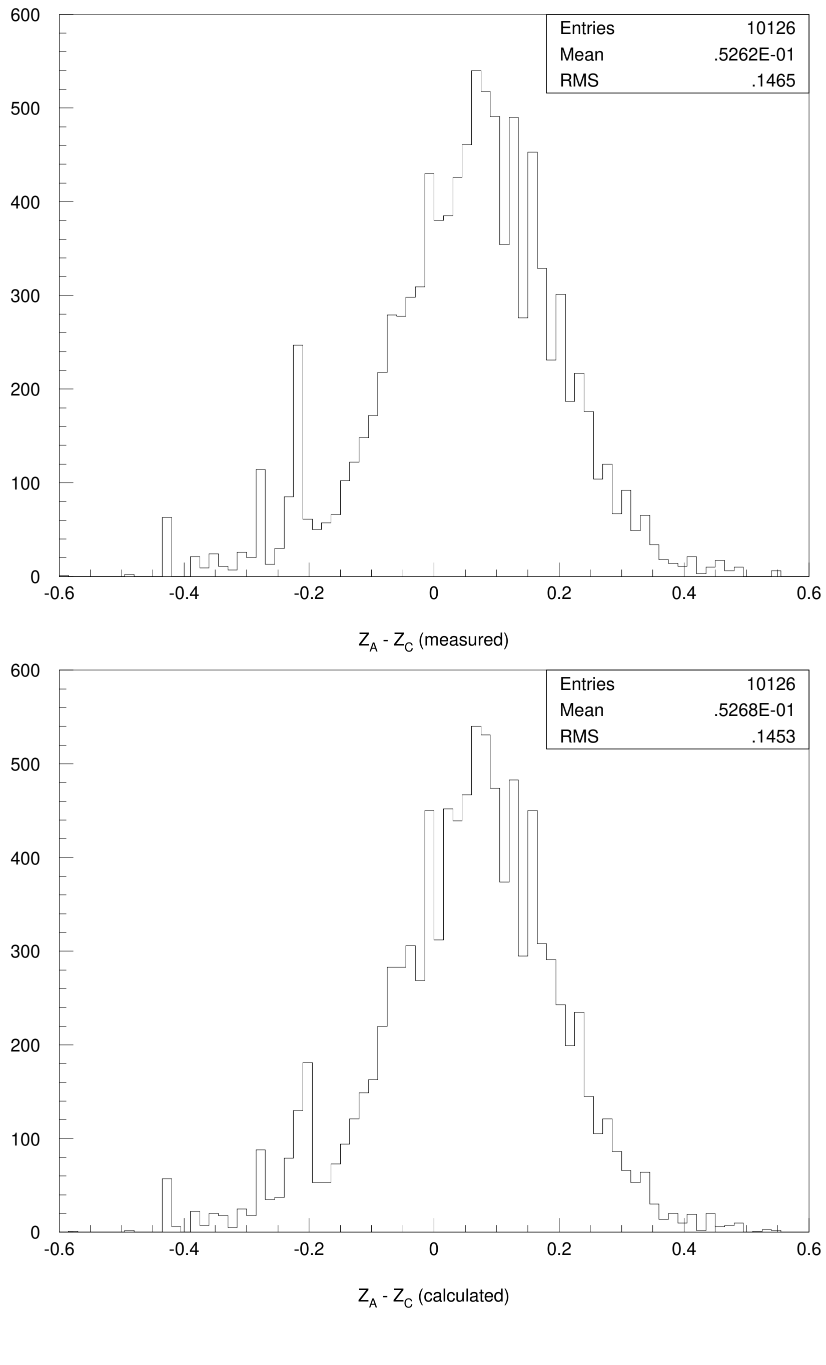

Figure 3: A comparison of the measurements (top) and predictions (bottom) of the difference in z position of the collision points of bunchlets a and c for the modified RF model.

Table 1: The mean difference between the calculated and measured Q_s values for the default 1995 RF model and data, and the modified model ($\Delta\phi$) and the data, for the period after day 266. All differences are in units of $\times 10^{-4}$. The rms of the difference is also given in each case. For a comparison, the same differences are given for the time before day 266 in Table 2.

	Default $\langle \Delta Q_s \rangle$	rms	$\Delta\phi$ $\langle \Delta Q_s \rangle$	rms
$Q_s^a(\text{calc}) - Q_s^a(\text{meas})$	-3.8	8.8	-2.1	9.0
$Q_s^b(\text{calc}) - Q_s^b(\text{meas})$	-3.1	8.8	-1.0	9.0
$Q_s^c(\text{calc}) - Q_s^c(\text{meas})$	0.2	8.4	2.9	8.7

compared with what is measured in the data. Here, the electron ϕ_s has been changed to obtain the predicted values. The agreement is nearly perfect. Using this as a starting point, we can now begin to investigate the consequences of these unexplained phase shifts on the energy of the beams.

3 Q_s, Q_s, and more Q_s

The Q_s spectra of the individual bunches contain a tremendous amount of information about the local environment of each family. Before trying to guess the effects of these phase shifts on the beam energy, it's worth looking to see if the phase shifts also reproduce the Q_s spectra. If this is the case, our confidence in the validity of this model increases.

Let us concentrate on the "problem period" near the end of the Scan, where the RF configuration consisted mostly of SC cavities. Technically, this period "starts" 266 days into 1995, with fill 3019. Values for the other two-thirds of the running will be given as well, but not discussed at length (the modelling problems for the early running are much less severe.).

Table 1 gives values for the difference between the calculated and measured Q_s for each bunchlet, for the "standard" RF model and the phase-shifted ($\Delta\phi$) model under discussion. In this case, the agreement is slightly better for the modified RF model. An overall shift of the average value of Q_s due to cavity phase errors or voltage scale errors does very little to change the energy, however, so these differences are not too significant[1].

What cannot be easily gleaned from this table, however, is a comparison of the spread in Q_s between the three bunches. Given that the measured spread in vertex positions is telling us that the bunches are really sitting at different ϕ_s values from those calculated, it is important to see if the modified model can reproduce these distributions better than our default model. Even an improvement in agreement would tell us that the new model moves in the right direction. Table 3 contains the differences in the average Q_s values for pairs of bunches in the default model and the phase-shifted model, as well as in the data. It can

[1] Just to put this in numbers, a shift in the mean Q_s (caused by changing the overall voltage calibration constant by 2%.) of 9.5×10^{-4} causes shifts of 0.24 MeV at IP2, –0.02 MeV at IP4, 0.04 MeV at IP6, and 0.02 MeV at IP8 for this running period. For this instance, this is exactly what is expected, since

$$Q_s^i \propto \sqrt{-\sum \frac{dE^i}{d\phi_s^i}}\ , \tag{3}$$

where E^i is the energy gain at cavity i. In this case, since E^i is changed directly by 2%, Q_s should change by $\sqrt{2}\%$ of its average value of 0.06444, or 9.1×10^4.

Table 2: The same quantities shown in Table 1, but for the running time before day 266. All differences are in units of $\times 10^{-4}$.

	Default $\langle \Delta Q_s \rangle$	rms	$\Delta\phi$ $\langle \Delta Q_s \rangle$	rms
$Q_s^a(\text{calc}) - Q_s^a(\text{meas})$	0.9	8.0	0.1	8.5
$Q_s^b(\text{calc}) - Q_s^b(\text{meas})$	0.2	8.0	-0.2	8.6
$Q_s^c(\text{calc}) - Q_s^c(\text{meas})$	0.6	8.1	0.2	9.5

Table 3: The inter-bunchlet difference between the mean (average of e^+ and e^-) Q_s values for the default 1995 RF model, the modified model ($\Delta\phi$) and the data, for the period after day 266. All differences are in units of $\times 10^{-4}$. The rms of the difference is also given in each case.

	Default $\langle \Delta Q_s \rangle$	rms	$\Delta\phi$ $\langle \Delta Q_s \rangle$	rms	Data $\langle \Delta Q_s \rangle$	rms
$Q_s^a - Q_s^b$	1.1	0.5	0.7	2.0	1.7	2.7
$Q_s^a - Q_s^c$	2.9	1.1	1.9	2.0	6.6	4.8

easily be seen that the phase-shifted model doesn't put forth a better description of the data; neither model can reproduce the spread in Q_s seen in the data. One can also see the effects of adding the shifts in ϕ_s to the RF model on the rms of the Q_s differences, which does make the distributions look more similar to those from the data.

From these results, it would seem that shifting the phases to match the observed collision positions is not a complete model of the bunchlet spacing. For the RF system to move the bunchlets in z, however, the only free parameter is the phase difference between the two bunchlets in the counterrotating beams. Whatever mechanism is behind these discrepancies seems to behave in almost an opposite manner to what comes out of the RF model. The data would prefer a small difference in Q_s between electrons and positrons, but large phase differences so that the collision points shift. Unfortunately, large phase differences in the RF model produce large differences in Q_s... To match the Q_s spread, on the other hand, requires phase differences much larger than what are needed to reproduce the collision position shifts.

In the absence of a more complete model, however, the shifted model provides us with a means of estimating the energy shifts generated by moving around the stable phase angle of the beams, since it allows us to calculated the necessary first derivatives of the corrections. We turn to this technique in the next section to present different scenarios of bunchlet behaviour.

4 Energy Shifts Arising from Varying ϕ_s

Table 4 gives the calculated corrections to the average center-of-mass energy due to the RF system for the "default" model and the phase-shifted model. One of the unexpected results of this study is that changing the stable phase ϕ_s has a much more drastic effect (a factor of ~ 10) on the RF corrections to E_{CM} than does moving Q_s around with cavity phase errors, *etc.* Table 5 gives the coefficients $\Delta E_{CM}/\Delta Q_s$ for a model where ϕ_s is changed to correct Q_s and/or z discrepancies.

Another quantity one can form is the relative shift in bunchlet energies for a relative

Table 4: The corrections to the center-of-mass energy from the RF model for the default 1995 model (top) and the phase-shifted model (bottom). The corrections are given for each IP and each bunchlet, as well as an average correction. (As above, this is for days after 266.)

	ΔE_{CM} IP2	ΔE_{CM} IP4	ΔE_{CM} IP6	ΔE_{CM} IP8
Default Model:				
ΔE^a_{CM}	9.17	-0.85	1.60	0.75
ΔE^b_{CM}	9.37	-0.91	1.67	0.81
ΔE^c_{CM}	9.53	-0.98	1.74	0.87
ΔE^{ave}_{CM}	9.36	-0.91	1.67	0.81
$\Delta\phi$ Model:				
ΔE^a_{CM}	9.49	-1.12	1.51	1.02
ΔE^b_{CM}	10.07	-1.49	1.55	1.33
ΔE^c_{CM}	10.95	-1.82	1.60	1.71
ΔE^{ave}_{CM}	10.10	-1.46	1.55	1.36

Table 5: The slopes of the corrections to the center-of-mass energy *vs.* Q_s from the default RF model in a modified simulation which relies on shifts of the stable phase for agreement with collision point or Q_s data. The values are derived from a comparison of the $\Delta\phi$-shifted model with one having no shifts. The Q_s used in this calculation is the mean Q_s for the bunchlet (average of e^+ and e^-). The data used are from days after day 266.

	IP2	IP4	IP6	IP8
$\Delta E^a_{CM}/\Delta Q^a_s$	11334	-8666	-2000	8666
$\Delta E^b_{CM}/\Delta Q^b_s$	9466	-6932	-1332	6800
$\Delta E^c_{CM}/\Delta Q^c_s$	9460	-6922	-308	6846

change in Q_s, which gives an idea of the effects of increasing the spread in bunchlet Q_s by moving ϕ_s. This is derived from a comparison of a "non-shifted" model compared with the $\Delta\phi$ model, and the results are shown in Table 6. The values are similar to those obtained for the shifts in absolute E_{CM}.

Using these slopes and the various differences in Q_s shown in Tables 1 - 3 we can make several estimates of the potential size of shifts in the mean E_{CM} due to unmodelled bunch

Table 6: The slopes of the difference in corrections to the center-of-mass energy *vs.* the difference in Q_s between two bunchlets. The Q_s used in this calculation is the mean Q_s for the bunchlet (average of e^+ and e^-). The data used are from days after day 266.

	IP2	IP4	IP6	IP8
$\Delta E^{a-b}_{CM}/\Delta Q^{a-b}_s$	9250	-6500	-1000	6250
$\Delta E^{a-c}_{CM}/\Delta Q^{a-c}_s$	8900	-5700	-500	5600

Table 7: The additional shifts in the corrections to the center-of-mass energy which arise if the entire discrepancy between model and data in the Q_s spectra is attributed to shifts in ϕ_s. The corrections are given for each IP and each bunchlet, as well as an average correction. (As above, this is for days after 266.)

	ΔE_{CM} IP2	ΔE_{CM} IP4	ΔE_{CM} IP6	ΔE_{CM} IP8
ΔE^a_{CM}	-4.31	3.29	0.76	-3.29
ΔE^b_{CM}	-2.93	2.15	0.41	-2.11
ΔE^c_{CM}	0.19	-0.14	-0.01	0.14
ΔE^{ave}_{CM}	-2.35	1.77	0.39	-1.75

Table 8: The additional shifts in the corrections to the center-of-mass energy which arise if the entire discrepancy between model and data in the Q_s spectra is attributed to shifts in ϕ_s. In this case, the average difference in Q_s between data and model has been adjusted to zero. The corrections are given for each IP and each bunchlet, as well as an average correction. (As above, this is for days after 266.)

	ΔE_{CM} IP2	ΔE_{CM} IP4	ΔE_{CM} IP6	ΔE_{CM} IP8
ΔE^a_{CM}	-1.81	1.39	0.32	-1.39
ΔE^b_{CM}	0.85	0.62	0.12	-0.61
ΔE^c_{CM}	2.27	-1.66	-0.07	1.64
ΔE^{ave}_{CM}	0.43	0.12	0.12	-0.12

train effects. The simplest and most extreme case is to assume that all differences in Q_s between the default model and the data are due solely to unexplained shifts in the stable phase angle. Invoking this assumption and converting the differences between the default model and the data show in Table 1 directly into energy shifts using the values in Table 5 gives the (large!) corrections shown in Table 7. Note that this method ignores the fact that the calculated shifts in z will be too large compared to those seen by the LEP experiments.

A few comments should be made on these results. They only apply to the last third of the scan running, so any error resulting from this effect is only a third as large. The first two thirds of the scan would only need to be shifted by something like the correction calculated for bunchlet c if the values in Table 2 are used. Note also that the shifts for IP4 and IP8 are completely anticorrelated, which will reduce the total error. The effects are much smaller at IP6 because there is no CU RF on at IP6 during this period; changes in ϕ_s have a much smaller effect when they occur on the well-aligned SC cavities. Also, the difference in average Q_s between model and data after day 266 is non-zero. Shifting the average Q_s by another means without changing the beam energies very much is also possible, so that the true size of the effect probably lies between the shifts in Table 7 and those given in Table 8, where the average Q_s value between data and model have been adjusted to be the same. Here, there are still large shifts in the bunchlet corrections, but the average correction is small (and still needs to be divided by three to get the size of the effect correct).

Another way of estimating the size of the effects is to look at the interbunchlet shifts in Q_s, converting them into energy shifts using the values from Table 3 and Table 6. This

Table 9: The additional shifts in the corrections to the center-of-mass energy which arise if the entire difference between model and data in the bunchlet Q_s is attributed to shifts in ϕ_s. The corrections are given for each IP and each pair of bunchlets, as well as an average correction. The average shift is computed assuming that bunchlet a acquires no shift in energy. (As above, this is for days after 266.)

	ΔE_{CM} IP2	ΔE_{CM} IP4	ΔE_{CM} IP6	ΔE_{CM} IP8
ΔE_{CM}^{a-b}	0.55	−0.39	−0.06	0.38
ΔE_{CM}^{a-c}	3.29	−2.11	−0.19	2.07
ΔE_{CM}^{ave}	1.28	−0.83	−0.08	0.82

sidesteps the issue of the disagreement in average Q_s values, because all that is considered is the difference in Q_s between the two bunchlets. Table 9 gives the shifts in the relative energies of the bunchlets following this prescription, and an average shift in E_{CM} assuming, conservatively, that bunchlet a doesn't move.

Qualitatively, these results are similar to those obtained in Table 7: the shifts (and hence the errors) at IP4 and IP8 are anticorrelated, and the effect at IP6 is small. Again, the errors would be obtained by dividing these results by three.

Since we have no way of knowing *a priori* which of these prescriptions is correct, I propose adopting the most conservative estimate, with the appropriate division by three, to get the errors on the RF corrections to E_{CM} for the 1995 Scan running. This leads to errors of 0.8, 0.6, 0.1, and −0.6 MeV for IPs 2, 4, 6, and 8 respectively. In this model, the corrections and the corresponding errors are, by the nature of the LEP geometry, completely anti-correlated between IP4 and IP8. Since the underlying mechanisms for producing the vertex and Q_s shifts are completely unknown, claiming that the effects at IP4 and IP8 exactly cancel seems unjustified. Because of this, the 0.6 MeV should be taken as correlated, rather than uncorrelated, between IP4 and IP8, and the IP2 and IP6 errors should also be taken as correlated. These errors and correlations apply equally to all energy points for 1995.

As supporting evidence, measurement of the energy difference between bunchlets a and c, made with resonant depolarisation, have a mean value of −0.06 MeV, with an rms of 0.33 MeV. These were done in dedicated fills, so they are not representative of the RF configuration during the end of the Scan running. They do, however, put an independent limit on the size of the effects, as already argued in the 1995 analysis note[1]. It is encouraging that the estimates agree on the possible magnitude of the errors.

5 Summary and Conclusions

We have presented a detailed, though far from complete, analysis of the potential effects of the mismodelling of bunch trains in the 1995 RF model. A model that reproduces the measured z collision positions of the bunchlets by separately shifting the RF stable phase of the bunchlets can imply large shifts in the collison energies at the four LEP IPs. Because of the large misalignments of the CU cavities, *any* model of the RF system that accomodates differences between the modelled and measured quantities by changing ϕ_s will have large shifts in E_{CM}. Unfortunately, merely reproducing the collision point shifts does not reduce the discrepancy in the Q_s spectra, which implies that there is some other mechanism at work.

The most conservative estimate, then, of errors on the RF model arising from uncertainties in the bunch train modelling is to assume that the Q_s discrepancies arise from phase shifts, and to use the corresponding changes in the corrections to E_{CM} as the errors.

As far as potential sources of the underlying mechanism, only one candidate exists. Because of the bunch train bumps, the beams pass through the RF cavities off-axis, which can excite higher-order-modes which effect trailing bunches. Studies of these effects, mostly concerned with transverse beam-beam breakup[2] have been performed in LEP. They could, however, be resposible for some of the orbit shifts, since different closed orbits for individual bunches in a train is one of the effects. The potential effects on Q_s are unknown. In principle, these effects could somehow be included in the RF model. Unfortunately, the parameters responsible for these interbunch wakes are rather ill-determined for inclusion into an analytic model, especially since we are interested in the average behaviour of a large number of idiosyncratic, relatively (for the 1995 running) unstable cavities. Since the above modified RF model, if not correct, at least allows the calculation of potential energy shifts in an unambiguous way, we shall take this as an estimate of the uncertainties due to bunch train modelling and leave the studies of interbunch wakes for later experiments, if necessary.

References

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[2] B. Zotter, 'Beam Break-Up Instability in Bunch Trains', SL Note 95-86;
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