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Preliminary RF Corrections to the LEP Energy for the '95 Scan

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Abstract

This note describes the analysis resulting in corrections to the center-of-mass energy (E_{CM}) at the four LEP IPs due to the interaction of the LEP beams with the RF system and other LEP components, prepared for the release of preliminary energies for 1995 for the Summer Conferences.

1 Introduction

This note describes the analysis resulting in corrections to the center-of-mass energy (E_{CM}) at the four LEP IPs due to the interaction of the LEP beams with the RF system and other LEP components, prepared for the release of preliminary energies for 1995 for the Summer Conferences.

As in past years [1, 2, 3], the modelling of the corrections due to RF effects at each of the IPs is carried out by the iterative calculation of the stable RF phase angle ϕ_s incorporating all of the known energy losses and gains of the beams as they travel around the machine. In the past, the measured value of the synchrotron tune Q_s was compared to the value calculated from the model, and modifications were made to the model in order to achieve better agreement between the two Q_s values. In addition, longitudinal shifts of the collision point in the IPs could also be traced to changes in the RF configuration, and hence could be predicted from the model. A comparison of these predicted and measured shifts provides another way of cross-checking the model's validity.

In addition to these standard features, the 1995 RF Energy Corrections model contains several new modifications. For the first time, a "complete" RF database exists for all of the off-peak fills. Thanks to the heroic effort of two of the authors (G.W. and K.Y.), virtually all of the data missing from the official LEP logging during the '95 scan has been recovered from alternate logging or extrapolated from the surrounding logged values. This means that we have recorded a complete set of data from which to calculate the RF corrections and compare model predictions approximately every 5 minutes during the '95 scan. This gives us the possibility for very detailed cross-checks of the model predictions, as well as enhanced diagnostic to discern those times within the scan that something is "wrong" with the RF. This data has been interfaced with a series of user routines that allow access to the RF data as well as such quantities as the NMR dipole fields, resonant depolarization energy results, vernier scan results, *etc.* This structure has proven to be a powerful analytic tool in deriving the final energy corrections for the '95 scan. In addition, a second feature has been introduced to describe the bunch train running which was used during the scan. Essentially, the entire RF model has been made three times as complicated such that ϕ_s is calculated separately for each bunchlet in the bunch train. A new cross-check, the actual shape of the energy-gain "sawtooth" as measured in the beam orbit (known as R_{BOM}) which is sensitive to phase errors in the RF system, has also been implemented.

After a brief description of the available data in the new database (and how to access it), the rest of this note proceeds through each point of the RF energy correction analysis.

2 The Database and How to Access it

All of the relevant information to be used in calculating the RF corrections to E_{CM} as well as a growing amount of non-RF-related LEP energy data can be found in a database structure located on the CERN `/afs` system under

`/afs/cern.ch/delphi/tasks/scan95` .

Here, there is source code for processing the `.sql` files that are extracted from the LEP logging, as well as a set of pre-processed, patched, and corrected data representing our best current knowledge of the logged data. There also exist utilities for synchronizing any given set of quantities that are present in the database which will interpolate the requisite records to match the time structure of a specific data set. For further information regarding access to the data, prospective users are asked to contact one of the authors of this note.

3 Available Data

In order to calculate the corrected E_{CM} at each IP, four sets of data are required: the voltages present on all of the used and unused RF cavities in LEP, the currents of each individual bunchlet, the currents in the emittance wigglers, and the cavity alignment and phasing data from the LEP RF group. In addition, we must know whether or not the longitudinal stability feedback is active. Cross-checks of the model predictions require the measured value of Q_s for each of the bunchlets and the value of R_{BOM} derived from the measured BOM data. The longitudinal positions of the interaction points of the three bunchlets over time are also necessary; this data has been provided by each of the four LEP experiments and has been incorporated into the database structure. The quality of each of these data sources (for off-peak fills only) will be discussed in the sections below.

3.1 RF Voltages

A "complete" set of RF voltages has been provided from a combination of the standard LEP Logging Database, and the Private Logging Database of the RF group, which comes from files stored on the control workstations residing in the LEP tunnel for each unit. In the following discussion, the LEP Logging Database will be referred to as "Standard" logging, while the other source is called "Alternative" logging. The Alternative logging was only used to patch large holes in the available data when the logging database was down. None of these sources was 100% reliable during the 1995 scan period; fortunately many of their breakdowns were non-overlapping so that a more or less complete dataset could be derived with only a small need for interpolation. The procedure to create this dataset was as follows[4]:

- Whenever an RF record appears (Standard or Alternative), write it out
- If there is no record after a period of 5 minutes, write an RF record using values interpolated from the previous records.

  All records contain non-zero values; missing values for individual units are interpolated using the existing information.
- Provide a "goodness" word with each record which gives the quality of the information therein (*i.e.*, are there interpolated values, and have they been interpolated over a large gap in time.).

As a quality check, voltage measurements within 1 minute of each other from the standard logging and alternate logging were compared. Typical RMS differences between these voltages are of order 1.2 MV. The mean of the differences is tiny, of order 0.01 MV. This "measurement error" will be considered in the systematic errors of the voltage calibration determination.

To get some idea of the gaps missing in the standard RF logging and what has been recovered[4] from the alternate logging sources, see Table 1. Table 2 gives the same figures, but allowing an extrapolation over 15 minutes ($\sim$ 3 records) to fill in the gaps. Note that the final file available for calculating the RF corrections has *all* of the "lost" data replaced by interpolated values without regard to the length of time over which it was necessary to extrapolate. These values can be used with suitable errors determined from comparisons of the model predictions to Q_s and R_{BOM} data.

Table 1: Fractions of the RF Voltages that have been obtained from existing records in the Standard or Alternate logging given for records, units within a record, and overall. No interpolation has been allowed. Of the existing entire records, 82% come from the Standard logging, 28% from Alternate logging.

	Entire Records	Individual Units	Total
Existing Records	98.6%	73%	72%
"lost"	1.4%	27%	28%

Table 2: Fractions of the RF Voltages that have been recovered from existing records in the Standard or Alternate logging given for records, units within a record, and overall, with interpolation up to 15 minutes allowed.

	Entire Records	Individual Units	Total
Existing Records	99.6%	94%	94%
"lost"	0.4%	6%	6%

3.2 Bunchlet Currents

In contrast to the RF voltages, bunchlet currents tend to be more stable, and thus interpolation of values is more easily trusted. This is also helped by the fact that the currents only *decrease* during a fill. Since changes in the beam-loading effects in the RF cavities due to different bunchlet currents are relatively small compared to the overall corrections due to RF misalignment, errors in the bunchlet currents have a relatively small impact on the total error on the correction to E_{CM}. That said, we have carefully reconstructed the bunchlet current information by interpolating missing records and removing the so-called "stuck" values where the value logged does not change for long periods of time due to some other type of database error. Table 3 summarizes the quality of the logging.

3.3 Emittance Wiggler Currents

Comments similar to those made above in reference to the bunchlet currents also apply to the importance and logging reliability of the emittance wiggler currents. These have also been carefully reconstructed from the available information in the same manner. In the case

Table 3: Fractions of the bunchlet currents that have been obtained from existing records in the Standard logging. All failures including "stuck" values have been labelled as Bad or missing .

	Entire Records
Existing Records	92.4%
Bad or missing	7.6%

of the wiggler currents, it is possible to use the logged wiggler current *Setting* value, since this has been shown to be identically equal to the read back value when the comparison can be made. It is estimated that we have a reliable knowledge of the wiggler status 99% of the time during the scan.

3.4 RF Alignment and Phase Information

For the 1995 scan, the previous "RF Effect" has been modified by the addition of a number of superconducting (SC) RF cavities, each of which possesses its own misalignment and phasing errors. As the voltages on these cavities tend to be much larger than those on their copper counterparts, the errors due to imprecise knowledge of the correct phases and positions could become large.* Fortunately, the logged values of the forward and reflected klystron power can be used to recognize large phase errors on the SC cavities.

We turn first to the alignment issues. We have been assured [5] that copper RF cavities have not been touched since 1991, so we have used the previous misalignments[1, 2] and their errors in the calculations. For the SC RF, multiple measurements of the alignment error were made over the course of the run[6]. The RMS changes between the various measurements is of order 0.4 mm, which can be taken as the alignment uncertainty for the SC cavities†. The placement of the individual SC RF modules is also included in the RF model. Recent measurement suggest that there may be some bias to the alignment measurements. This additional error will be assesed below.

The history of various changes in the phasing of the RF was obtained from the RF group logbook. This information has been digested and compared with that from E. Peschardt[6] to get some idea of the phase drifts in the SC cavities. The behaviour of the unit phases over the Scan has been included in the RF model in a manner consistent with the observed Q_s and R_{BOM}values, as is described below. In addition, the data presented by E. Peschardt[6] contains measured voltage errors on the SC cavities which have typical values of 3-4%, but with potentially non-negligible variation over repeated measurements. These are also considered as a source of systematic error.

3.5 Measured Q_s Values

One of the most powerful constraints on the predictions of the RF model is the comparison of the calculated *vs.* measured value of the synchrotron tune Q_s. In the RF model, Q_s is calculated from the expression

$$Q_s^i = \sqrt{-\frac{h_f \alpha_c}{2\pi E_{beam}} \sum \frac{dE^i}{d\phi_s^i}} \ . \qquad (1)$$

Here, h_f is the LEP harmonic number (31324), α_c is the momentum compaction factor for the $90^\circ/60^\circ$ lattice, and $dE^i/d\phi_s^i$ is the gradient of the bunchlet energy with respect to the stable phase angle for that bunchlet, which is the part actually calculated in the model. The measured values of Q_s with which this calculation can be compared have also been obtained from the LEP logging database and from various private logging. Missing values and records have been filled in by interpolating between the previous and subsequent 10 valid measurements

*More precise measurement and control of these quantities may become a critical issue for the LEP2 running if an E_{CM} energy error of 15 MeV is to be achieved.

†This may be inflated to take into account the uncertainty on the alignment of those cavities without reliable (or repeated) measurements.

Table 4: Fractions of the Q_s values that have been obtained from all existing records given for records, values within an existing record, and overall.

	Entire Records	Individual Values	Total
Existing Records/Values	92.4%	90.9%	83.3%
"bad" or "missing"	7.6%	9.1%	16.7%

within a fill. A quality word is attached to each record noting how many individual values were interpolated, and how many interpolations include data from more than 10 minutes away from the record in question. Also, those values where the beam longitudinal oscillation frequency approaches a harmonic of the line frequency were "smoothed" by removing values close to the 750 Hz resonance. Any Q_s value of 0.0666 or 0.0665 was replaced by an interpolated value in the same manner as missing records; the quality word attached to these makes no distinction between "smoothed" and "missing", *i.e.*, all of the "stuck" values are considered as bad. With the replacement values, there now exist Q_s records at a frequency of about one every 1.5 minutes. Table 4 gives a summary of the quality of Q_s logging.

3.6 Beam Orbit Information: the Sawtooth

From an analysis of the available BOM data, J. Wenninger has provided a set of values which allow us to monitor the behaviour of the energy sawtooth in LEP. The values in the database are the difference between the mean horizontal positions of the electron and positron beams (Δ^{+-}) at both sides of each IP ("Left" and "Right"), and these are entered approximately every 5 minutes. Typically, 4 BOM pickups are used in calculating the average position. From these values, the RF phase-sensitive quantity R_{BOM} can be formed:

$$R_{BOM} = \frac{|\Delta^{+-}_{L3\ Left}| + |\Delta^{+-}_{L3\ Right}|}{|\Delta^{+-}_{OPAL\ Left}| + |\Delta^{+-}_{OPAL\ Right}|}\ . \qquad (2)$$

Based on the modelled energy loss and the known lattice dispersion, this quantity can also be calculated in the RF model. Comparison with the measured values will determine whether or not the RF phases of the cavities input to the model are correct.

4 Calculation of the RF Correction to E_{CM}

This section gives an overview of the course the analysis of the RF corrections to E_{CM}.

4.1 Arriving at the Final Model

As a starting point, the RF model code has been updated to include the following information:

- The full set of voltages for each of the SC RF half units, which was only present in the standard logging for some fraction of the run.
- The best known cavity alignment values and voltage calibrations[6]. These are summarized in Table 5.

- The known phase errors and phase changes that existed/took place over the course of the scan.
- A "Weak" beam loading model for the unused cavities in which the bunchlets deposit energy equivalent to the measured induced voltage on the cavity but there is no interaction with the stored energy in the cavity.

Table 5: The measured misalignments and voltage calibrations for the SC cavities used in the 1995 scan, given with the dates of each measurement. Measurements deemed unreliable by the RF Group have been dropped from consideration in this table. The comments "1 module" or "2 modules" refer to whether the alignment and phasing was measured for the half- or full-unit. The voltage calibrations for those measurements marked with a * are incorrect; the alignment values for these cases should be valid. A negative aligment means that the units are too close to the IP which is used as a reference for the measurement, in this case, IP6.

RF Unit	Voltage Correction (%)	Misalignment (cm)	Date of Measm't.	Comments
233.2	−10.70	−0.30	19/07/95	2 modules
	−8.27	−0.29	31/10/95	
273.1	−5.77	−0.10	30/04/95	1 module
	−3.53	−0.00	19/07/95	
273.2	8.00	0.16	19/07/95	1 module
633.1	−4.20	−0.36	08/05/95	2 modules
	−3.84	−0.26	19/07/95	
	−3.32	−0.36	31/10/95	
633.2	3.46	−0.45	08/06/95	2 modules
	3.26	−0.48	19/07/95	
	4.68	−0.50	31/10/95	
673.1	−8.24	0.00	30/04/95	1 module*
	4.26	0.15	19/07/95	2 modules
	7.68	0.24	31/10/95	
673.2	0.51	0.33	30/04/95	1 module*
	9.62	0.16	19/07/95	2 modules
	9.93	0.22	28/09/95	2 modules
	11.32	0.11	31/10/95	

Following this, the measured value of R_{BOM} is used to check that the RF phasing in the model is correct and any discrepancies are removed once they are understood. Any correction applied to the phasing of RF units must improve the agreement between calculated and measured Q_s. In the absence of other phasing information, the agreement between calculated and measured Q_s values is the final arbitrator when more than one correction is possible. The effects of varying the corrections within some "reasonable" bounds of Q_s agreement are considered as a systematic error.

4.2 Results of "Tuning" the RF Model

Using the procedure described above, the measured and inferred variations of the phases of the RF units as a function of time have been included in the model. The results of the tuning are shown in Figures 1 and 2, where the calculated and measured values of Q_s are shown, and in Figures 3, which compare the calculated and measured values for R_{BOM}. Figures 4 and 5 give the numerical details of the comparison between the measured and calculated quantities. Note that the calculated values are computed with an overall scaling factor of 2% applied to the measured RF voltages. This is necessary to set the mean difference between calculated and measured Q_s to be essentially zero. The full range of this correction is taken as a systematic error and will be discussed below.

The tuned model represented in Figures 1 to 5 shall be considered from this point on to be the *default* RF model for the 1995 scan. Unless further revision is necessary (*i.e.*, we learn something more about parasitic bunch collisions, path length differences, or beamloading), the final corrections for 1995 come from this model. Known discrepancies will be considered below in the discussion of systematic errors. Table 6 shows the RF corrections for each IP and each energy point. Table 7 gives the average bunchlet-specific corrections for each IP. Since the CU RF was on at IP 2 most of the time, IP 2 sees the largest bunchlet-to-bunchlet variation due to the natural spread in bunchlet energies caused by their relative positions on the voltage "envelope" of the CU cavities.

Table 6: The corrections (in MeV) to E_{CM} for each LEP IP and each off-peak point for the 1995 Scan default RF model.

LEP IP	$\Delta E_{CM}(\mathrm{P}--2)$	$\Delta E_{CM}(\mathrm{P}+2)$
2	14.70	14.69
4	0.81	1.29
6	4.31	4.54
8	−0.88	−1.38

Table 7: The average corrections (in MeV) to E_{CM} for each LEP IP for each bunchlet in the 1995 Scan default RF model.

LEP IP	$\Delta E_{CM}(a)$	$\Delta E_{CM}(b)$	$\Delta E_{CM}(c)$
2	14.30	14.72	15.07
4	1.08	1.06	1.05
6	4.30	4.45	4.56
8	−1.16	−1.15	−1.13

5 Residual Discrepancies and Systematic Errors

5.1 Vertex Positions

Other, detailed cross-checks of the RF model predictions against experimental data can be made. At the time of this writing, a comparison between experimental results and the RF model predictions for the average position of the luminous region in z (along the beam axis) and the collision points of the individual bunchlets shows large deficiencies in the model. This section will present a discussion of the available evidence and then try to assign a systematic error to the energies from this disagreement.

5.1.1 Average Vertex Positions

Figure 6 presents an overview of the current situation with regard to the average vertex position in z. In this view, the agreement between the measured average vertex position from the four LEP experiments and the predictions of the RF model seems quite good, even over sizeable variations in position. Except for several short transients, this is generally true. The data for the LEP 1.5 running later in the year also agrees to better than 0.2 mm on average. However, a closer inspection of the end of the Scan period reveals a residual discrepancy of approximately 1 mm between the model and data, as shown in Figure 7. If this 1 mm shift over these few days of running were all that is observed, there would be little cause for alarm, and this would be considered a relatively small effect. Given the history of the discrepancy, however, which started out as a large and very worrisome shift of almost 5 mm, some caution must be taken in the interpretation. There are several facts which should be stated here:

- Within the RF system, the only way a shift in the collision position of the two beams can arise is if the two beams sit at different stable phase angles ϕ_s. This can occur, for example, when the voltage on a misaligned cavity changes. In general, anything within the RF system that effects the energy gain of the beams differently depending on whether they are entering or leaving an IP with RF units can cause a shift in the collision point.
- At this time during the scan, the SC modules were tuned to move the resonance frequency of the cavities closer to the RF frequency. This was in order to reduce the effects of the ponderomotive mechanical oscillations of the cavities.
- Once the cavities were re-tuned, a number of them were run at maximum gradient. This was the first time during the scan that this was attempted, and it resulted in a very asymmetric RF distribution, with most of the RF being supplied by the SC units at IP6.

As will also be seen below, changes in the details of the interaction between the circulating beams and the RF cavities can have large effects on the position and relative motion of the collision point(s). This can be seen graphically in Figure 8, where the experimental beam positions are compared with the default, so-called "weak" beam loading model and one with a "stronger" interaction between the beams and the unused CU cavities‡. Note that, due

‡The "strong" beamloading model assumes that the induced voltage left by each preceding bunch decelerates the following bunchlets. This is equivalent to assuming that all of the voltage deposited by each bunchlet is at exactly the RF frequency, and that the induced voltage rotates exactly 180° in phase during the 87 RF

to the change in RF configuration during this period, it is only during this portion of the Scan that the difference between "weak" and "strong" beam loading is apparent; the two models provide equivalent descriptions of the data elsewhere. Since it is clear that the strong beamloading model shows a dependence on beam current that is not seen in the data, it will be dropped from consideration as a valid alternate model and will be used later only as an example.

After careful examination of the RF model, it was found that only two "physical" effects could be responsible for large vertex shifts and yet leave the other predictions of the model consistent with all other data. These are:

- extra systematic misalignment of the SC cavities not seen in the alignment measurements (A shift of approximately 0.5 cm of all cavities towards the IP is required.)
- a non-zero arc length difference between the path IP2-IP4-IP6 and IP2-IP8-IP6, defined as $\Delta\ell_{26}$, (A path length difference of 0.85 cm would be required.).

Taking these points in turn: the alignment measurements are done using a pair of symmetrically placed CU cavities, typically at IP6. Two symmetrically placed CU cavities are used so that their relative misalignments cancel. The Q_s is maximized for each of the two beams (at $E_{beam} = 22$ GeV and low bunch currents) to guarantee that the two cavities are in phase with each other, and then the relative phase of the cavity to be measured is recorded for the two beams. Any difference in the optimum phase between the two beams can be directly converted into an alignment error. During the 1996 startup, alignment measurements were checked by using CU cavities at IP2 to check for any possible bias from using the IP6 cavities as a reference. These actually show a difference in the two alignment measurements of 0.25 cm for the one cavity that was cross checked. This will be taken as the uncertainty on the alignments of the SC cavities, but is too small to explain the observed effect. The arc length difference $\Delta\ell_{26}$ is also directly checked in the process of verifying the alignment procedure; the discrepancy of 0.25 cm in the one cavity that was checked directly translates into a measured $\Delta\ell_{26} = 0.5$ cm. This is in contradiction to the alignment data of Table 5, since the cavities at IP2 are in fact measured using CU cavities at IP6. The fact that there is no net shift of the cavities at IP2 clockwise or counterclockwise around the ring suggests that the arc length difference is very small. In addition, since the measured cavity misalignments are included in the RF model, the effects of this should be properly simulated. The full 0.5 cm will be taken as the possible systematic shift $\Delta\ell_{26}$ in calculating the systematic errors. This is almost the correct size to explain the discrepancy in vertex position, but, given the contradictory nature of the measurements, further LEP MD time will be necessary to obtain a self-consistent answer.

We can also postulate that something external is causing the extra vertex motion, and to calculate the effect of having one of the beams sit at a slightly different ϕ_s. Using the stable phases calculated from the RF model for the fills in question, the energy shifts are 0.7 MeV at Peak−2 and 0.8 MeV at Peak+2 for all IPs. Using the OPAL integrated luminosity, these fills represent 1.6 pb^{-1} at Peak−2 and 1.0 pb^{-1} at Peak+2, so the overall effect on the entire Scan would be to induce net shifts of 0.14 MeV and 0.1 MeV at Peak−2 and Peak+2, respectively. For the time being, these are taken as systematic errors due to this residual discrepancy, and the other possibilities raised by the alignment checks are considered as independent errors.

periods between bunchlets. As such, this can be considered a "worst case" beamloading model for the unused cavities. Note that it naturally produces an asymmetry between the energy gains for incoming and outgoing beams.

This error is common to all experiments, and should be treated as 50% correlated between Peak−2 and Peak+2 to be conservative.

5.1.2 Bunchlet Vertex Positions

A summary of the model/data agreement on the position of the bunchlet vertices can be seen in Figure 9. Two striking features of the data are easily visible:

- The bunches do not sit "symmetrically" in stable phase. Bunchlet b is on average closer to c than to a, most obviously so for the beginning portion of the Scan.
- The spacing in z between a and c is much larger that that predicted by the RF model.

These two features imply that neither the average stable phase for each bunchlet nor the stable phase differences between the two beams are being properly modelled. To understand this statement, further elaboration on what actually *is* modelled is probably useful.

In the RF model, there exists a natural mechanism for producing shifts in the stable phases between bunchlets, which is due to the fact the the voltage envelope on the CU cavities cannot be at maximum as each of the bunchlets passes. Rather, it reaches its peak while bunchlet b is at the IP. If there is CU RF operating on only one side of an IP, then bunchlet a of the electron beam and bunchlet c of the positron beam receive roughly the same energy. Electron bunchlet c and positron bunchlet a also receive roughly the same energy, but it will be different in magnitude to the previous case. This then would induce a symmetric spread in z of the collision positions between the three bunchlets, as seen in the RF model predictions of Figure 9. If the CU cavities are operated in symmetric pairs around each IP, however, then the envelope effect would essentially cancel and each of the bunchlets would collide at the same position in z. The RF was never this symmetric in 1995, so we always have some spread in the collision positions. In the default RF model, this is the only mechanism for producing a spread in the bunchlet z positions. When, during the early periods of the Scan, it was noticed that the bunchlet spacing seemed to be much larger than that predicted by the model, the "strong" beamloading model was introduced in an attempt to improve the model/data agreement. Even this model, which, as shown above, is inconsistent with the vertex data, cannot reproduce the observed bunchlet spacing. This is true even with the energy loss due to beamloading and hence the effect on the bunchlet spacing is multiplied by two over what could be expected from the induced voltages on the cavities. From this result, it can be assumed that the bunchlet spacing cannot be modelled by the RF model given our current understanding of the available parameters.

Some other facts should be injected into the discussion:

- There is evidence that the $a - c$ spacing is current dependent.
- The bunchlet spacing does depend on the RF configuration in a stronger way than that shown in Figure 9. Fill-to-fill variation is seen.
- The average difference in the energy of bunchlet a and c measured by resonant depolarization at IP1 is −0.1 MeV, with an rms of 0.3 MeV.

The current-dependence of the bunchlet spacing is consistent with either a beamloading effect from the RF or some sort of path length shift induced by the parasitic bunchlet- bunchlet near-collisions, whose magnitude should also be current-dependent. Sufficient analysis on the many possible parameters of this complicated system has not been done to separate or even understand the effects of RF configuration and current. The fact that the energy difference between the bunchlets has been measured does, however, place a constraint on the maximum possible effects at IP4 and IP8. Taking the rms as the full allowed range of the $a - c$ energy difference, this translates into a maximum possible difference in E_{CM} of 0.8 MeV between bunchlets a and c. Since only average energies are given, this would amount to a 0.4 MeV uncertainty at IP4 and IP8, assuming b sits on average half way between a and c. This error should be taken as 50% correlated between Peak−2 and Peak+2, and correlated between experiments. At IP2 and IP6, estimating the possible energy shifts is more difficult, since it is possible that large effects could be induced locally by the RF which would be invisible outside of that specific IP. As of yet, there is no evidence for these local effects, although we cannot exclude them with our present knowledge of the situation.

Assuming that the RF system cannot be responsible for the bunchlet shifts (*i.e.*, some external constraint forces them to sit at different stable phase angles ϕ_s), we can "simulate" the effects of the longitudinal shifts in the following manner. For each RF record in the dataset, the difference in z position between the RF model prediction and the LEP average beam position is calculated for each bunchlet. This is converted into a difference in stable phase angle $\Delta\phi_s$, which is then input back into the RF model as a constraint on the simulation. The energies at each IP are then calculated for the appropriate RF configuration at a stable phase $\phi_s + \Delta\phi_s$. The bunchlets are then allowed to have energies different from the average energy in the LEP arcs, and the corresponding shifts in E_{CM} are calculated at each IP. The results of this simulation do show differences in E_{CM} of $\sim$ 0.3 MeV at IP4 and IP8, which are certainly consistent with the constraints derived above. At IP2 and IP6, shifts of up to 0.6 MeV are seen. We take the largest variation (which occurs at IP2) as the error in this case. This should have the same correlation as the error at IP4 and IP8.

5.2 Other Systematic Errors

In this section we turn to the more familiar errors which were evaluated with great care for the 1993 Scan. We begin here with those quantities related to the quality of agreement between the data and the RF model.

As mentioned above, the voltages obtained from the database must be scaled upwards by an overall factor of 2% in order to obtain good agreement between the measured and calculated Q_s. In the 1993 analysis, half of the normalization factor was taken as the error. In 1995, however, the rms of the difference between the measured and calculated Q_s is nearly twice as large. This is due mainly to the instability of the RF configuration during the Scan. The consequence of this is that neither the total RF voltage in LEP nor the phasing of the cavities are necessarily accurately logged or predictable for some fraction of the running. To cover the full spread of possibilities in the voltage description, we choose to take the full normalization correction as the error. This results in errors of 0.4 and 0.1 MeV at IP2 and IP6, respectively, and much smaller errors at IP4 and IP8. As this sets the overall scale, it should be 100% correlated between Peak−2 and Peak+2, and correlated between IP2 and IP6.

The quantity R_{BOM} provides a rather stringent constraint on the possible phase errors between IP2 and IP6 and within the RF at each IP. To estimate the quality of the RF model's description of the phasing of the RF, the error for the measurement of each of the quantities Δ^{+-} in Equation 2 is taken to be 20μm[7], and the corresponding error on R_{BOM} is calculated for each entry. The distribution $[R_{BOM}(\text{calc}) - R_{BOM}(\text{meas})]/\sigma(R_{BOM})$ has a width of approximately 2.1, which implies that R_{BOM} and hence the phasing of the machine is only tuned to a level of approximately twice the available resolution of 0.03. The implications of this can be studied by shifting the relative RF phase between IP2 and IP6 in a way to move R_{BOM} by 0.06 on average. The largest effect is caused by changing the phases on only the CU cavities, and this is taken as the potential error due to misphasing. The size of the effect is 0.1 MeV at IP2, 0.04 MeV at IP6, and negligible at IP4 and IP8, and is correlated between IP2 and IP6. This should be taken as 50% correlated between energy points to be conservative.

The difference between the Q_s measured for electrons and positrons is 0.00004, which is consistent with there being no large residual phase errors on the CU cavities. This difference in the RF model output, however, is 0.0001. An overall uncertainty of 0.2 MeV is added for all experiments to account for possible differences in energy due to this effect. This should be 50% correlated between Peak–2 and Peak+2, and anticorrelated between IP4 and IP8.

A comparison of the RF model and the data has been carried out for the fills at Peak–2, Peak, and Peak+2 separately. The difference in the agreement between measured and calculated Q_s at Peak–2 and Peak+2 is 0.00007, which is negligible in terms of a possible energy difference. For fills on the Peak, the agreement between calculated and measured Q_s, –0.00049 is slightly larger than the fills off-Peak. This is almost certainly due to the benign neglect the Peak fills have received in the cleaning and patching process described above, as well as the fact that the RF phases in these fills have not been optimized. This discrepancy corresponds to an additional ~ 0.2 MeV error on the Peak energies, so it is entirely negligible.

In addition to the errors arising from the procedures discussed above, there are errors due to uncertainties on the following quantities[2]:

- RF cavity positions (0.4 MeV in IP2 and IP6 in '93 for the CU cavities). For 1995, we have estimated the effects of the cavity misaligments for the CU and SC cavities independently, and add the results to obtain the total error. The uncertainty on the CU alignment is taken to be ± 1 mm, where the most conservative estimate of the effect is to assume that the total uncertainty on the difference in cavity positions is 2 mm, moving the cavities coherently towards or away from the IP to calculate the effect. This leads to a shift of 0.6 MeV at IP2 and 0.2 MeV at IP6. As mentioned above, recent measurements suggest that the SC cavity alignments could be uncertain by 2.5 mm. [§] With the largest possible relative displacement of the cavities taken in the same manner, this leads to a shift of 0.2 MeV at IP2 and 1.7 MeV at IP6. The total error for these two sources is then 0.8 MeV at IP2 and 1.9 MeV at IP6, uncorrelated between the two. As the source of this error is geometric, it is 100% correlated between energy points.

- The lengths of the LEP arcs (1.0 MeV (anticorrelated) in IP4 and IP8 in '93). Since the recent measurements give the same estimate for the possible uncertainty in $\Delta\ell_{26}$ as was used in 1993, the errors are the same. The correlation between energy points is 100%, again, due to the geometric nature of the effect.

- momentum compaction factor α_c (0.1 MeV (correlated) in IP2 and IP6 in '93) This is also the same as 1993. A 100% correlation between energy points should be taken.

The errors from interpolating to recover the missing values can be estimated by comparing the agreement in the measured and calculated Q_s values for all those records which have had

[§]Note that the energy error due to misalignment actually *does* scale as E^4_{beam} and will result in large errors at LEP2 ($\sim$ 20 MeV) if the situation does not improve.

to be extrapolated to fill in gaps in the records. Approximately one-third of all the records used in the analysis have at least one extrapolated value! The difference in agreement of Q_s is $-.0006$, which results in an energy shift of ~ 0.3 MeV. Taking one-third of this leaves another overall uncertainty of 0.1 MeV to be added. This error is common to all experiments, and should be given a 50% correlation between energy points.

The errors and their correlations are summarized in Table 8

Table 8: A summary of the systematic errors for the preliminary 1995 analysis of the RF corrections. Those errors common to all experiments are given first, and should be assumed to be 100% correlated IP to IP. The additional errors for the individual IPs and their correlations are given below.

Common Errors				
Error		ΔE_{CM} (MeV)	P $\pm$ 2 Corr.	Comments
Mean $\langle z \rangle$ shift		0.1	100%	
Bunchlet $\langle z \rangle$ shifts	IP4, 8	0.4	50%	
	IP2, 6	0.6	50%	
$Q_s(e^-) - Q_s(e^+)$		0.2	50%	IP4 and IP8 anticorr.
Missing data		0.1	50%	
IP-Specific Errors				
Error		ΔE_{CM} (MeV)	P $\pm$ 2 Corr.	Comments
$\Delta \ell_{26}$	IP4, 8	1.0	100%	IP4 and IP8 anticorr.
Voltage scale	IP2	0.4	100%	
	IP6	0.1	100%	IP2 and IP6 corr.
RF misphasing	IP2	0.1	50%	
	IP6	~ 0	-	
RF misalignment	IP2	0.8	100%	
	IP6	1.9	100%	uncorrelated
$\Delta \alpha_c$	IP2	0.1	100%	
	IP6	0.1	100%	IP2 and IP6 corr.

6 Summary and Conclusion

We have presented a preliminary analysis of the IP-specific corrections to the center-of-mass energies due to the RF system for the 1995 Scan. For IP2, IP4, and IP8, the errors on the individual experiments' energy scale due to the RF are approximately 1 MeV. The corrections at IP6 currently have an uncertainty of 2 MeV, due essentially to the uncertainty in the alignment of the SC cavities. The overall LEP error for the summer conferences, excluding the contribution for IP6, is 0.6 MeV per experiment when all of the correlations are properly taken into account. Improvements in the analysis are forthcoming: future LEP MD time will be needed to understand possible biases in the RF alignment measurements, which have to be sorted out for LEP2. In addition, a full simulation of the bunchlet-bunchlet interactions, including RF effects, is being constructed. This should, if it is consistent with other aspects of the RF model, allow a greater understanding of the currently unexplainable bunchlet collision positions.

References

[1] G. Quast, "Present Understanding of RF Effects", Memo to Energy Working Group 93-2, April 6, 1993, and references therein.

[2] G. Quast, "Uncertainties on the Energy Correction due to RF Effects in 1993", Memo to Energy Working Group 93-??, December 20, 1993, and references therein.

[3] For 1994: John Yamartino and G. Quast, private communication.

[4] G. Wilkinson, "RF Patching/Cleaning Status", presentation to the LEP Energy Working Group, Oct. 24, 1995.

[5] E. Peschardt, private communication.

[6] E. Peschardt, "SC Phase Adjustments 1995", Presentation to the LEP Energy Working Group, Oct. 13, 1995.

[7] Jörg Wenninger, private communication.

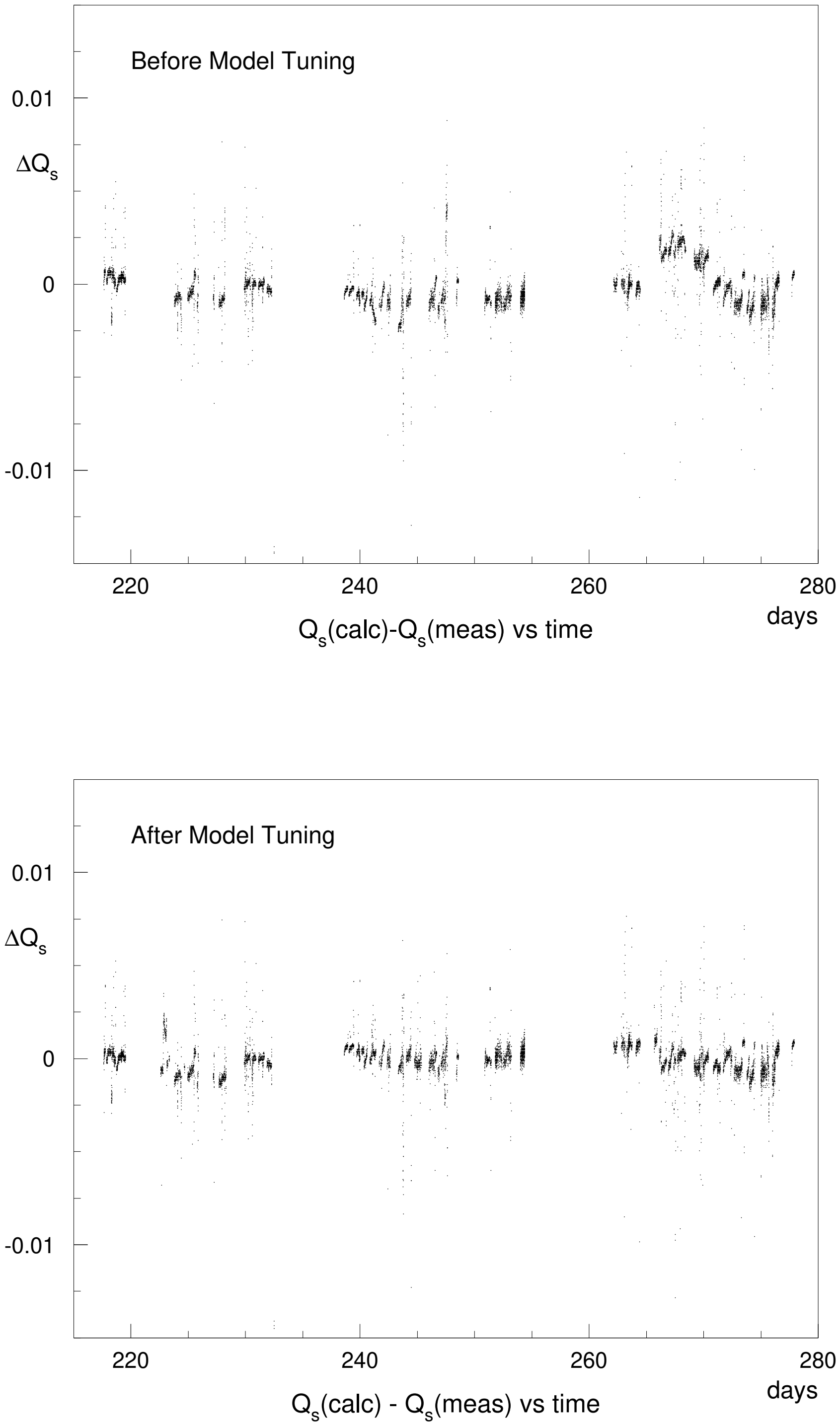
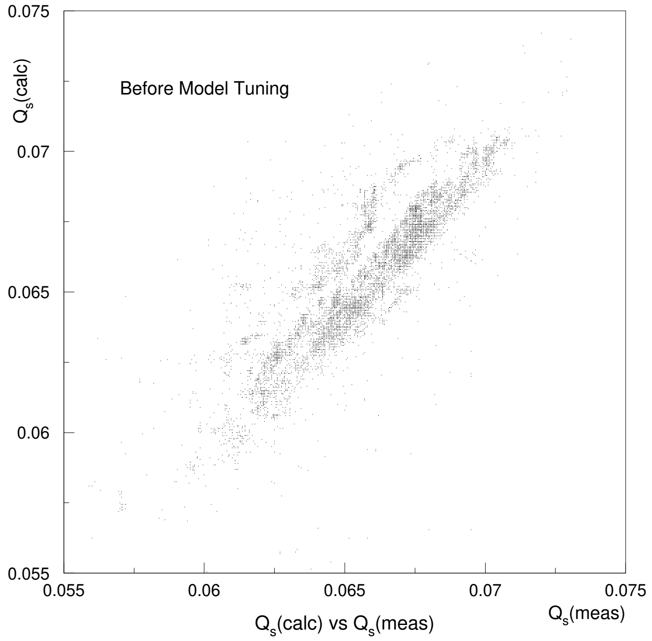


Figure 1: The difference between the measured value of Q_s and that calculated from the RF model over the whole '95 scan before and after the tuning of the RF model. The large difference around day 266 in the untuned case is caused by a $\sim 45^\circ$ mis-phasing of SC cavity 633-2.



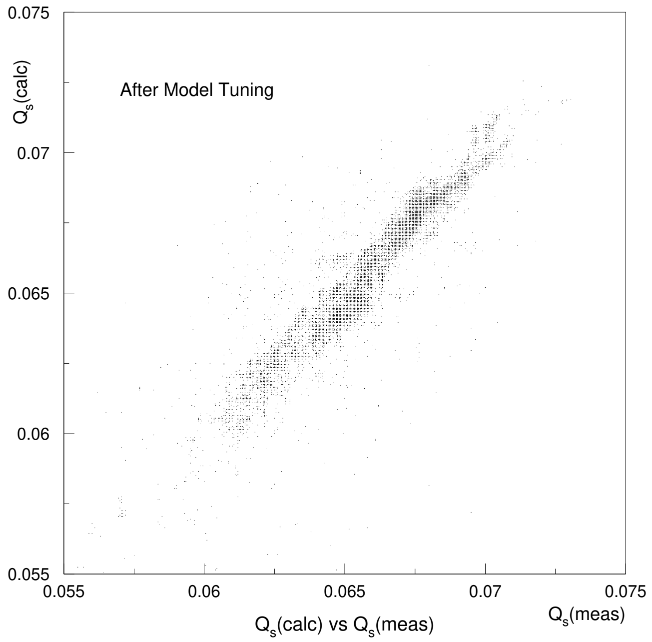


Figure 2: The measured value of Q_s plotted against that calculated from the RF model over the whole '95 scan before and after the tuning of the RF model. Note that the agreement between the model and the data is significantly better after tuning.

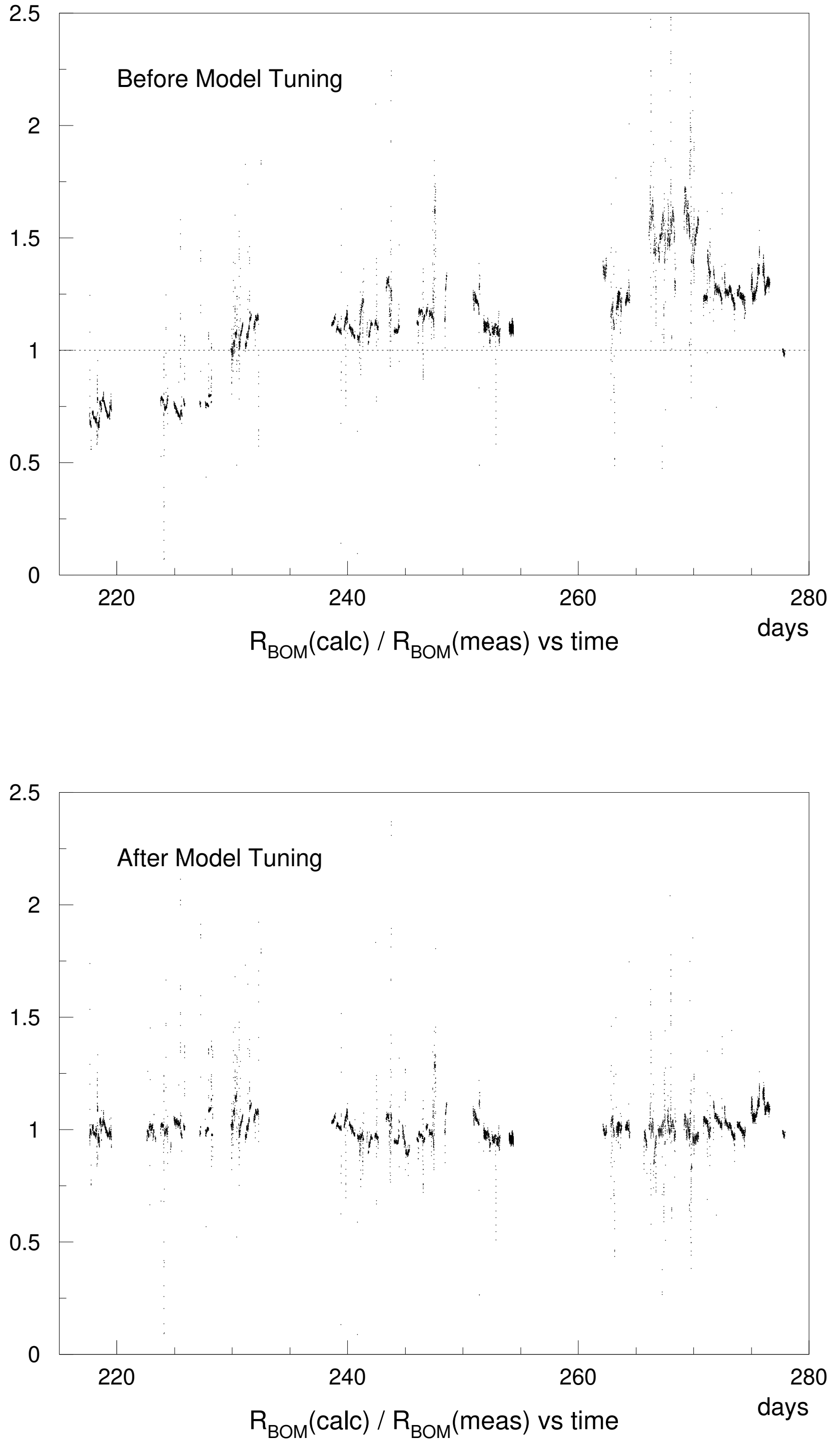


Figure 3: The ratio of the measured value of R_{BOM} and that calculated from the RF model over the whole '95 scan, before and after the tuning of the RF model. The evolution of phasing errors in the RF system can be seen. The large jump around day 220 is due to a phase correction of 8° between IPs 2 and 6. The excursions around day 265 are due to a $\sim 45°$ mis-phasing of SC cavity 633-2.

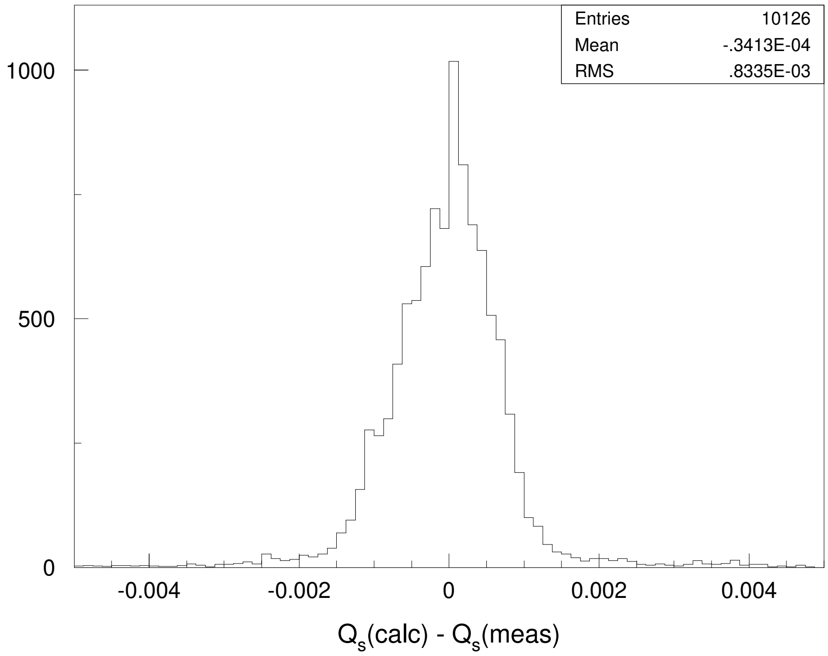


Figure 4: The difference between the measured value of Q_s and that calculated from the RF model. The mean of this distribution is -0.00034, and the RMS is 0.0008. The corresponding values for the '93 scan after RF model tuning were 0.0001 and 0.0004.

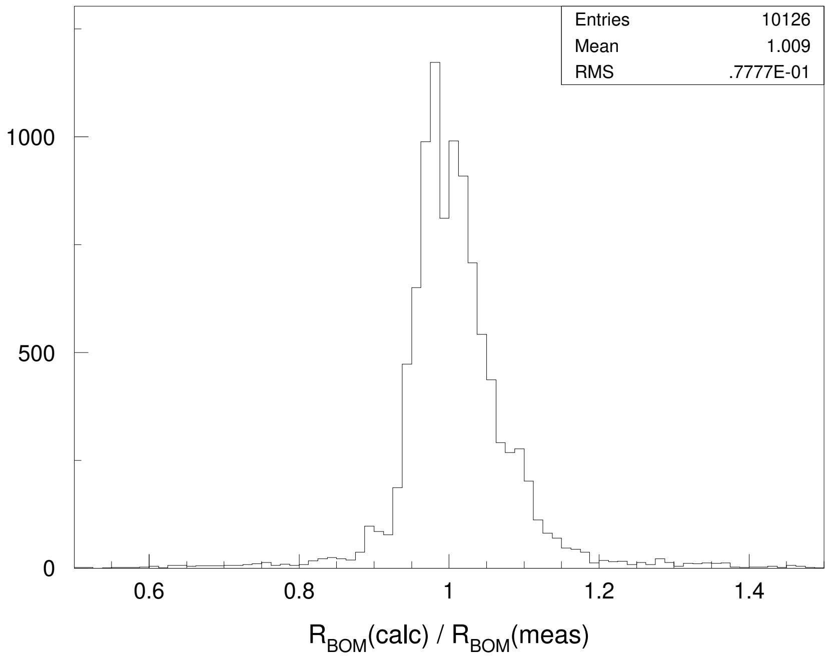


Figure 5: The ratio between the measured value of $R_{BOM}$and that calculated from the RF model. The mean of this distribution is 1.009, and the RMS is 0.077.

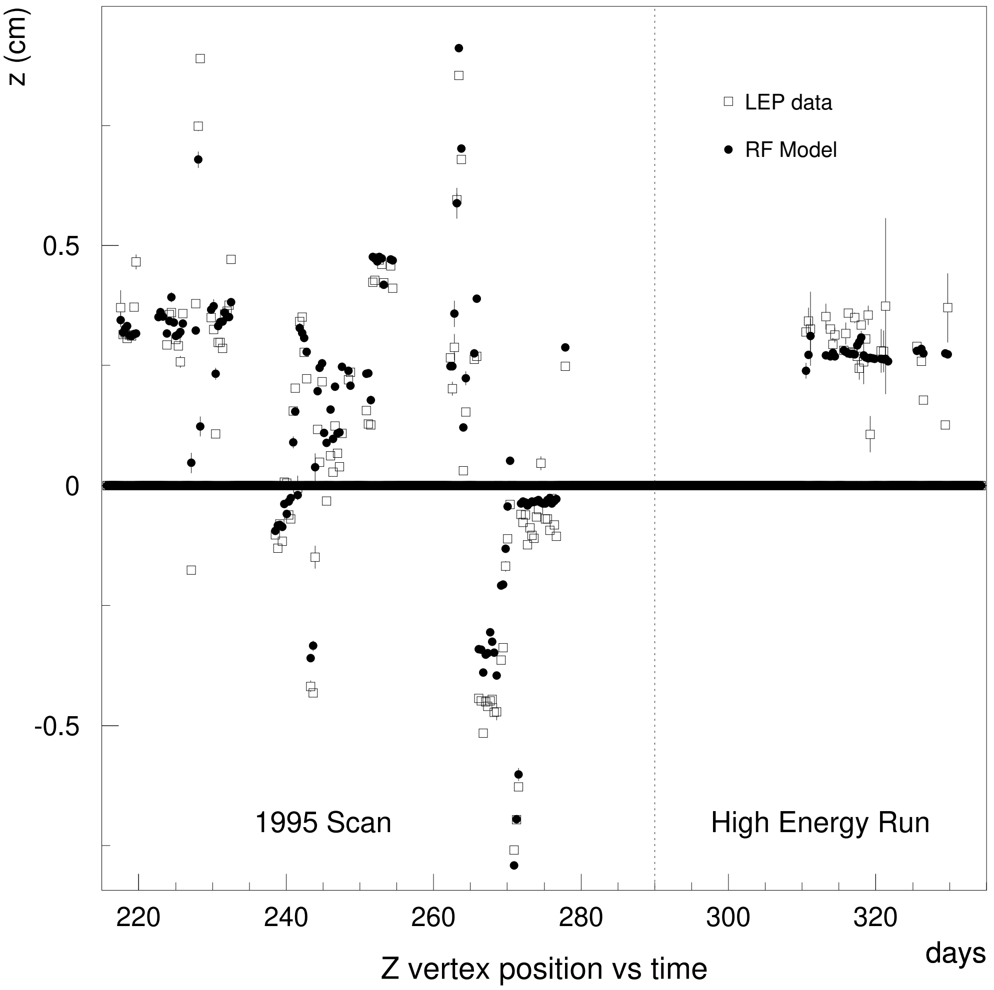


Figure 6: A comparison of the measurements and predictions of the average z position of the interaction vertex for all of the 1995 running, including LEP 1.5. The squares represent the mean of the four LEP experiments' best determination of the interaction point z at the time of each RF record. The filled dots are the predictions of the RF model. In general, the agreement is quite good. The problem region is from day 266 to day 270.

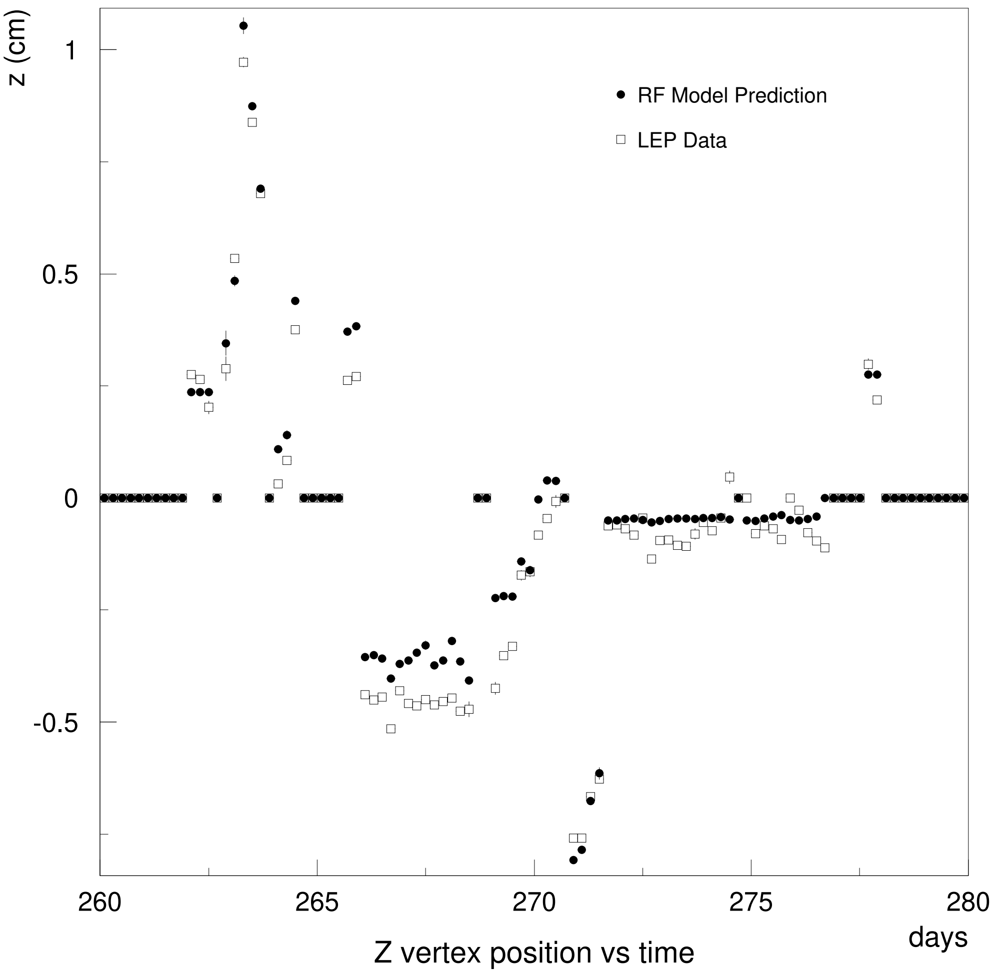


Figure 7: A comparison of the measurements and predictions of the average z position of the interaction vertex at the end of the Scan period. The squares represent the mean of the four LEP experiments' best determination of the interaction point z at the time of each RF record. The residual discrepancy between the model predictions and the data can easily be seen.

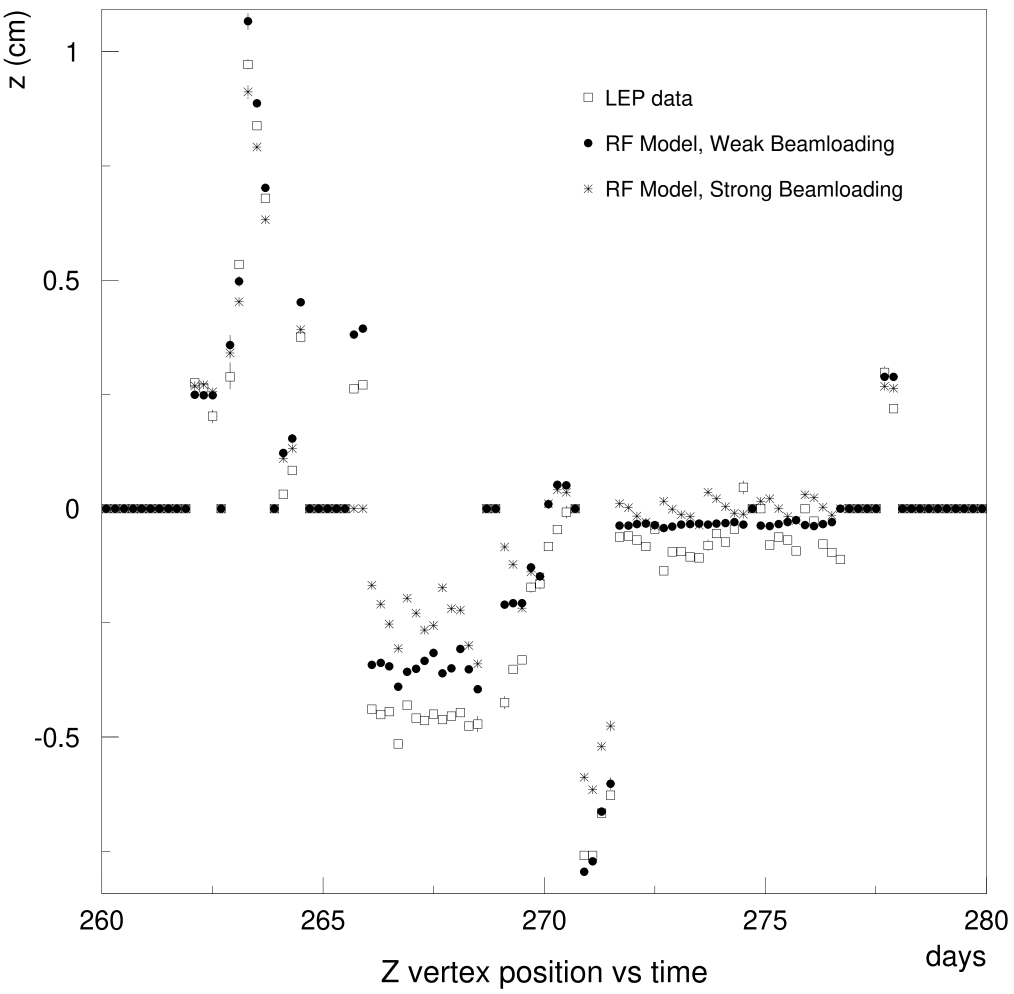


Figure 8: A comparison of the measurements and predictions of the average z position of the interaction vertex at the end of the Scan period. Two predictions of the RF model are shown, one with the default "weak" beamloading, one with a "strong" beamloading model. See text for a description of the models.

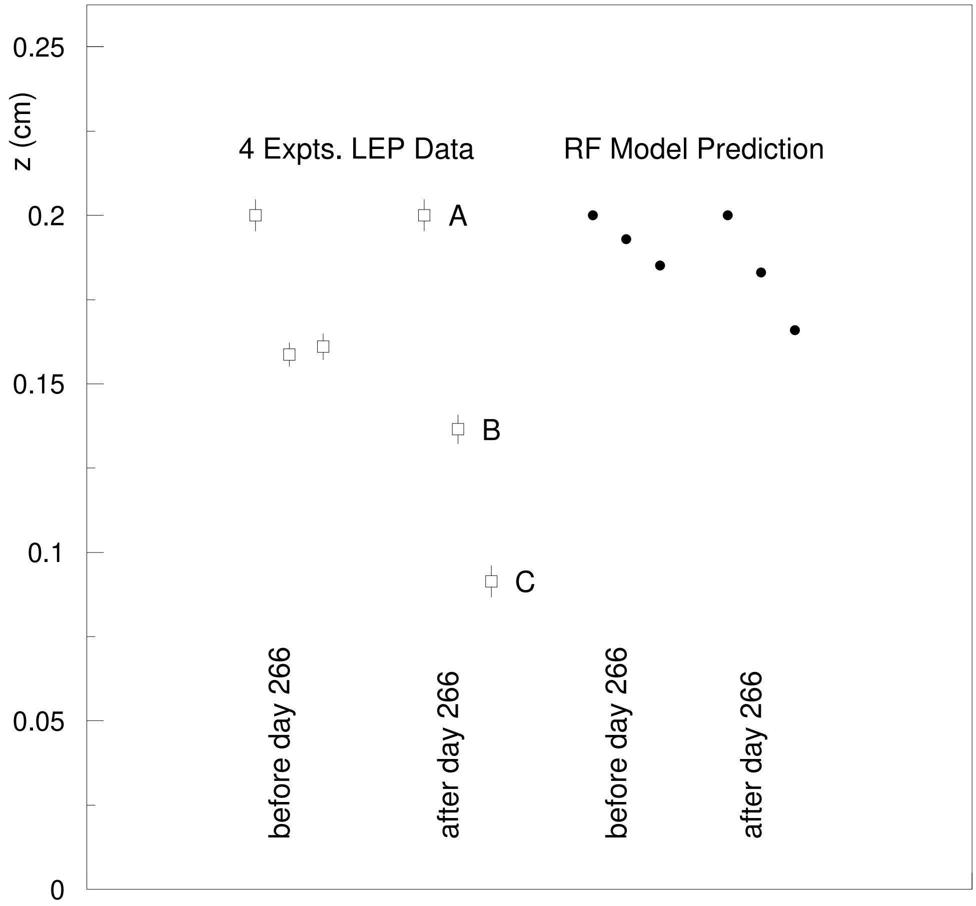


Figure 9: A comparison of the measurements and predictions of the average z position of the collision points of the three bunchlets, labelled "A", "B", and "C". The predictions of the RF model are also shown for the default "weak" beamloading model. The data are broken into two periods during the Scan, one before the SC RF was dominant (before day 266) and one after.