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RF Corrections to the LEP Energy for the '94 Running

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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 during the 1994 LEP running.

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. This is an analysis of the 1994 running, including the running with substantial voltage on the newly-installed Superconducting (SC) cavities. The analysis has been completed for all fills up to Fill 2435, *i.e.*, the bunch-train test running at the end of the year has been excluded. This note documents the final analysis of the 1994 RF corrections, and is intended as the source of all systematic error determinations on the RF corrections for this period.

As in past years [1, 2], 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. The measured value of the synchrotron tune Q_s is compared to the value calculated from the model, and modifications are 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 can 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. A complete description of the analysis technique can be found in the note describing the 1995 corrections[3].

2 Available Data

The necessary inputs to the RF model, namely the wiggler currents, the beam currents, and the RF voltages, have been obtained from the standard LEP database sources. The voltages on the SC cavities were taken from the RF group logbook for those cases early in the running (Fills 2167, 2168, (2334, 2374, 2375, and 2376)) where cavity 273.1 was running at 10 (20) MV, and from the RF group private logging for the running in week 41 where cavity 673.1 was run at many different voltages.

3 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}.

3.1 Arriving at the Final Model

The 1994 RF model is slightly more primitive than its 1995 and LEP2 counterparts. In particular, the following effects are not included:

- there is no attempt to calculate beam loading effects in the SC cavities
- there is no model for energy loss in unused cavities
- no attempt has been made to correct the model for potential time-dependent mis-phasing of the RF cavities (No large corrections seemed necessary.)
- the alignment data of the SC cavities has not been incorporated (Their measured mis-alignments are smaller than 1mm.)

As will be seen shortly, the systematic errors on the energy corrections are sufficiently small, so the neglect of the above effects can be justified, as least *a posteriori.*

3.2 Results of "Tuning" the RF Model

The results of the "tuning"[1] are shown in Figures 1 and 2, where the calculated and measured values of Q_s are shown. As can be seen in these figures, there is a small amount of the running during which the calculated and measured Q_s do not agree. This is probably due to tripped cavities where either the voltage or the Q_s was not updated in the database at the same time as the other quantity. The overall effect on the systematic errors due to this mis-modelling is negligible.

Figure 3 gives 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 1.5% 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 3 shall be considered from this point on to be the *final* RF model for the 1994 scan. Known discrepancies will be considered below in the discussion of systematic errors. Table 1 shows the RF corrections for each IP. Figure 4 shows the complete set of corrections to E_{CM} for each IP, computed for each valid RF database record.

Table 1: The corrections (in MeV) to E_{CM} for each LEP IP for the 1994 RF model.

LEP IP	ΔE_{CM}(Peak)
2	19.06
4	−0.20
6	18.93
8	0.03

4 Systematic Errors

In this section we turn to the systematic errors arising from effects which are not represented correctly in the RF model or effects from uncertainties in the model input parameters. We begin here with those quantities related to the quality of agreement between the data and the RF model.

4.1 Errors from Data and Model Disagreement

As mentioned above, the voltages obtained from the database must be scaled upwards by an overall factor of 1.5% 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 1994 the rms of the difference between the measured and calculated Q_s is about 50% larger. This is due mainly to the lack of detailed phase information in the RF model. The consequence of

[1] In this case, the only "tuning" that has been done is to adjust the assumed voltages for the SC cavities when they are taken from the RF logbook to make the calculated and measured Q_s agree.

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, as was done for the 1995 analysis. This results in errors of 0.4 MeV at IP2 and IP6 and much smaller errors (< 0.1 MeV) at IP4 and IP8. This error is correlated between IP2 and IP6.

To estimate the error on the corrections due to improperly modelled phasing errors, the relative phase of the cavities in IP2 and IP6 is shifted by 5 degrees, the same amount as used in the 1993 analysis. Without more stringent constraints of the misphasing, this value of 5 degrees is the estimate of how much different the relative phase of IP2 and IP6 could be without effecting the quality of LEP running. The size of the energy shifts caused by this phase change is 0.5 MeV at IP2 and IP6 and negligible at IP4 and IP8, and is anti-correlated between IP2 and IP6.

The difference between the Q_s measured for electrons and positrons is 0.0001, which is consistent with there being no large residual phase errors on the CU cavities. This difference in the RF model output is is 0.00005, which is consistent. Therefore, no additional uncertainty needs to be introduced for this effect.

There is a small ($2 \times 10^{-7}/\mu$A) dependence of the difference in calculated and measured Q_s as a function of (single) beam current. This is much smaller than the effect seen in 1993, where a 0.2 MeV error was added to IP2 and IP6, assuming that the current dependence is due to a mis-modelling of higher-order-mode losses. Since the effect is much smaller in 1994, this additional error will be neglected.

4.2 Errors from Model Input Parameters

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). In 1994, we have estimated the effects of the cavity misalignments 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 0.4 MeV at IP2 and 0.4 MeV at IP6. New measurements[4] of the SC cavity alignment also give an uncertainty in the position of the cavities of order 1 mm. Since the SC cavities were only on for a small fraction of the time, however, the overall change in E_{CM} induced by this uncertainty is negligible. The total error for these two sources is just that given for the CU alignment, and is uncorrelated between IP2 and IP6.

- The lengths of the LEP arcs (1.0 MeV (anti-correlated) in IP4 and IP8 in '93). The same recent measurements of cavity alignment show the measured $\Delta\ell_{26}$ to be zero. Since the reproducibility of this alignment method is of order 1 mm, this should be taken as the uncertainty on the value of zero. This reduces the completely anti-correlated error from this effect at IP4 and IP8 to 0.1 MeV.

- momentum compaction factor α_c (0.1 MeV (correlated) in IP2 and IP6 in '93) This is the same as 1993.

In addition, the points raised in the introduction of this note need to be addressed. As was discussed above, the effects of alignment uncertaities or misphasing are small. The other points concerning modelling of the SC cavities are estimated as follows:

- To quantify the effects of energy loss in unused SC cavities, we calculated the change in E_{CM} when we add to the simulation an energy loss proportional to the beam current which is similar to what was observed for the CU cavities in 1995 (5 MeV for a bunch current of 350 μA; the recorded energy loss in the SC cavities was smaller.). The changes were negligible.

- The effects of beam loading were estimated by changing the accelerating voltage provided by the SC depending on whether the bunch was entering or leaving the IP, so that outgoing bunches see 4% less voltage than incoming. This effect is approximately ten times larger than what would be expected from beamloading in the SC cavities. The changes were again negligible.

The errors from missing values is conservatively taken to be twice as large as was assumed in 1993, which results in 0.2 MeV for IP2 and IP6. No attempt has been made to quantify this; the stability of the RF system in the two years was similar, and the RF configuration itself was essentially identical except for the small addition of two SC cavities whose operation affected a small fraction of the total luminosity. This error is correlated between IP2 and IP6.

The errors and their correlations are summarized in Table 2

Table 2: A summary of the systematic errors for the 1994 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)	Comments
Missing data		0.2	
IP-Specific Errors			
Error		ΔE_{CM} (MeV)	Comments
$\Delta\ell_{26}$	IP4, 8	0.1	IP4 and IP8 anticorr.
Voltage scale	IP2, 6	0.4	IP2 and IP6 corr.
RF misphasing	IP2, 6	0.5	IP2 and IP6 anticorr.
RF misalignment	IP2, 6	0.4	
$\Delta\alpha_c$	IP2, 6	0.1	IP2 and IP6 corr.

4.3 Cross Checks of the RF Model

4.3.1 Average Vertex Positions

Figure 5 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 OPAL experiment and the predictions of the RF model seems quite good, even over sizeable variations in position. No large residual discrepancies are seen, so no systematic error is assigned from a disagreement between data and model from unexplained vertex shifts.

5 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 1994 running. For IP2 and IP6, the errors on the individual experiments' energy scale due to the RF are approximately 0.8 MeV, with equal contributions to the error from uncertainties in RF phasing, cavity alignment, and the overall voltage scale. Thanks to the recent detailed verification of the alignment uncertainties for the SC cavities, the error on the energy scale due to the RF at IP4 and IP8 has been reduced to just 0.1 MeV. Due to the small number of SC cavities and the fact that they were only run for a limited time during 1994, the details of their function can more or less be ignored as long as the accelerating voltage they provide is known to a reasonable precision. This work puts the 1994 RF analysis on equal footing with that of the 1993 and 1995 work in terms of the quantitative treatment of errors, and should allow us to combine the results from the three years more easily.

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] M.D. Hildreth, G. Duckeck, G. Quast, G. Wilkinson, K. Yip, 'Preliminary RF Corrections to the LEP Energy for the 1995 Scan', LEP Energy Group/96-02.

[4] M.D. Hildreth, 'Report on SC Alignment Checks', Presentation to the LEP Energy Working Group, October 25, 1996.

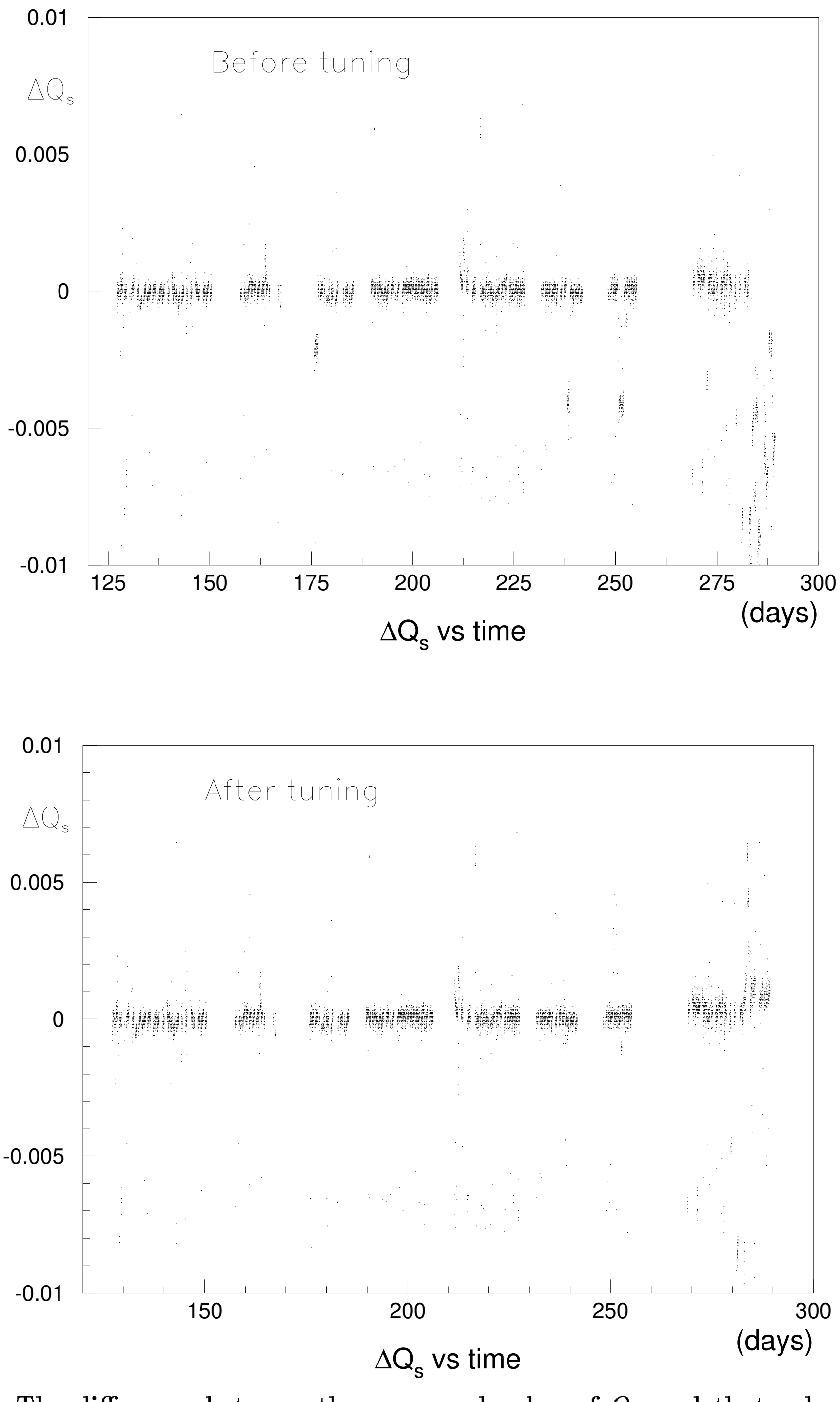

Figure 1: The difference between the measured value of Q_s and that calculated from the RF model over the 1994 running before and after the tuning of the RF model. The large differences in the untuned case are caused by the lack of logging of the SC cavity voltages in the standard LEP logging. These were added from alternate sources to achieve the "tuned" case.

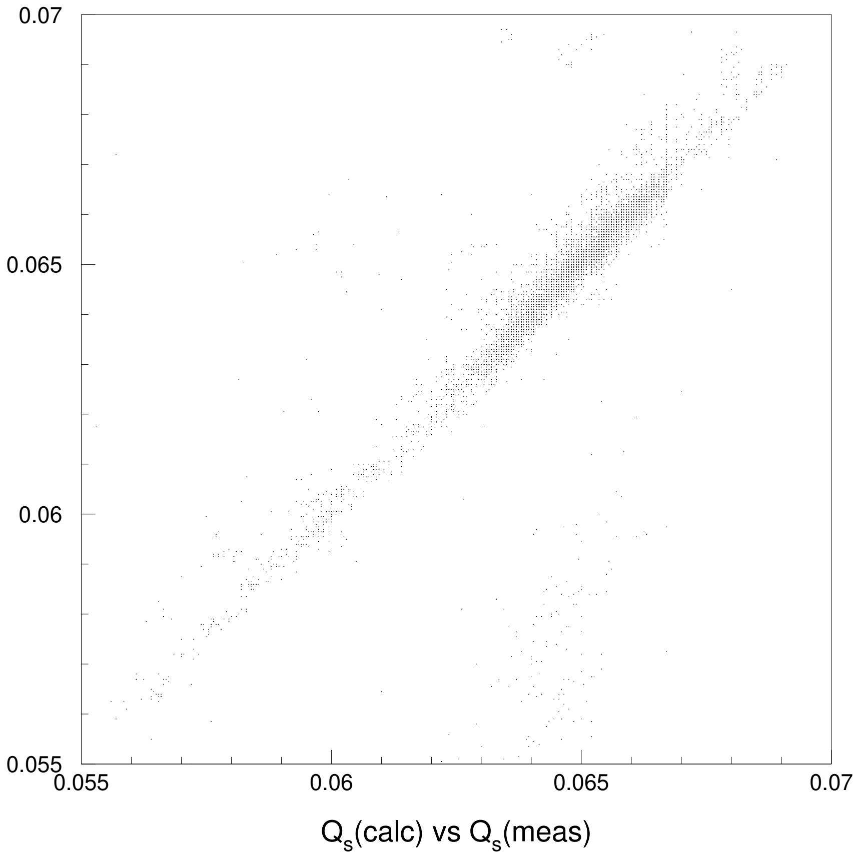

Figure 2: The measured value of Q_s plotted against that calculated from the RF model for the 1994 running after the tuning of the RF model. Note that the agreement between the model and the data is good, except for a small cluster of off-axis points.

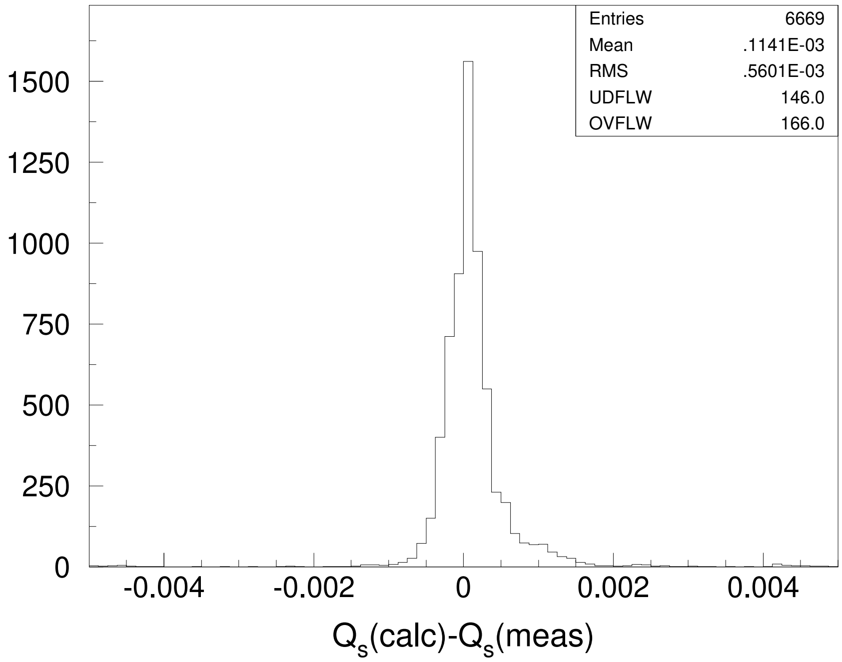

Figure 3: The difference between the measured value of Q_s and that calculated from the RF model. The mean of this distribution is -0.0001, and the RMS is 0.0006. The corresponding values for the '93 scan after RF model tuning were 0.0001 and 0.0004.

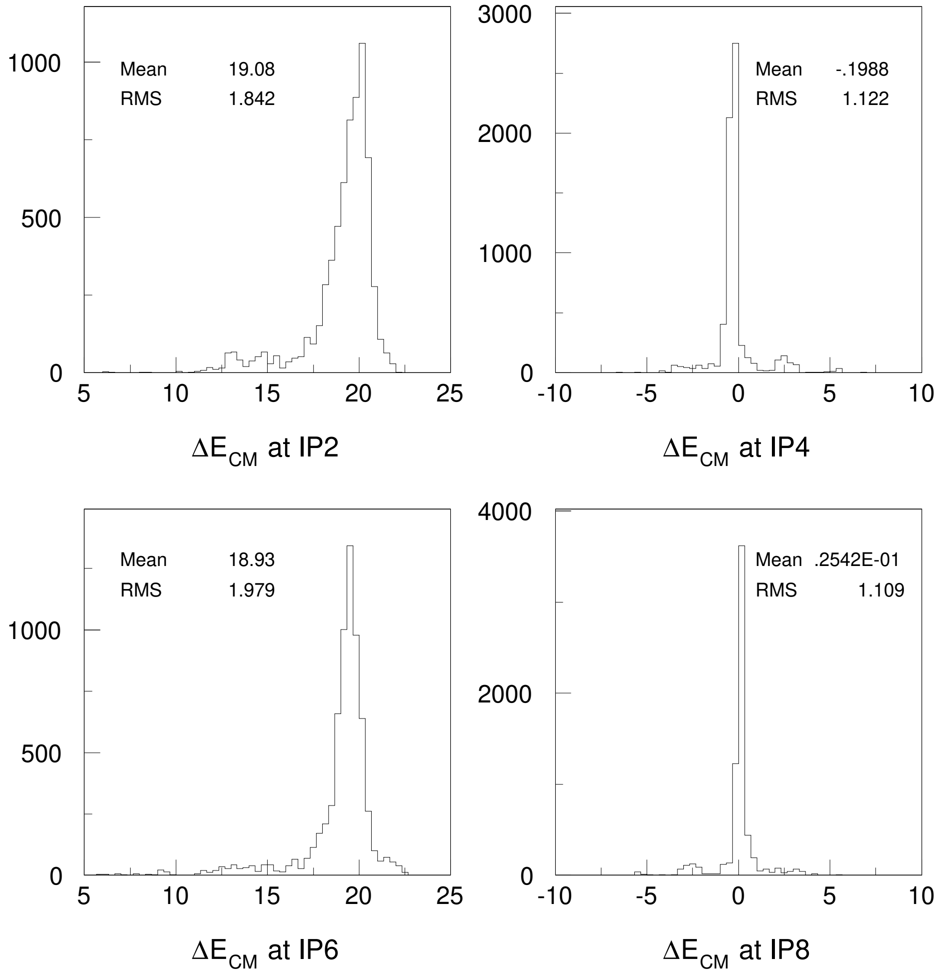

Figure 4: The corrections to E_{CM} at each LEP IP. There is one entry in each of these plots for each valid RF record from the database. The "shoulders" on the corrections for IP4 and IP8 at approximately ± 2.5 MeV are the result of an RF unit trip.

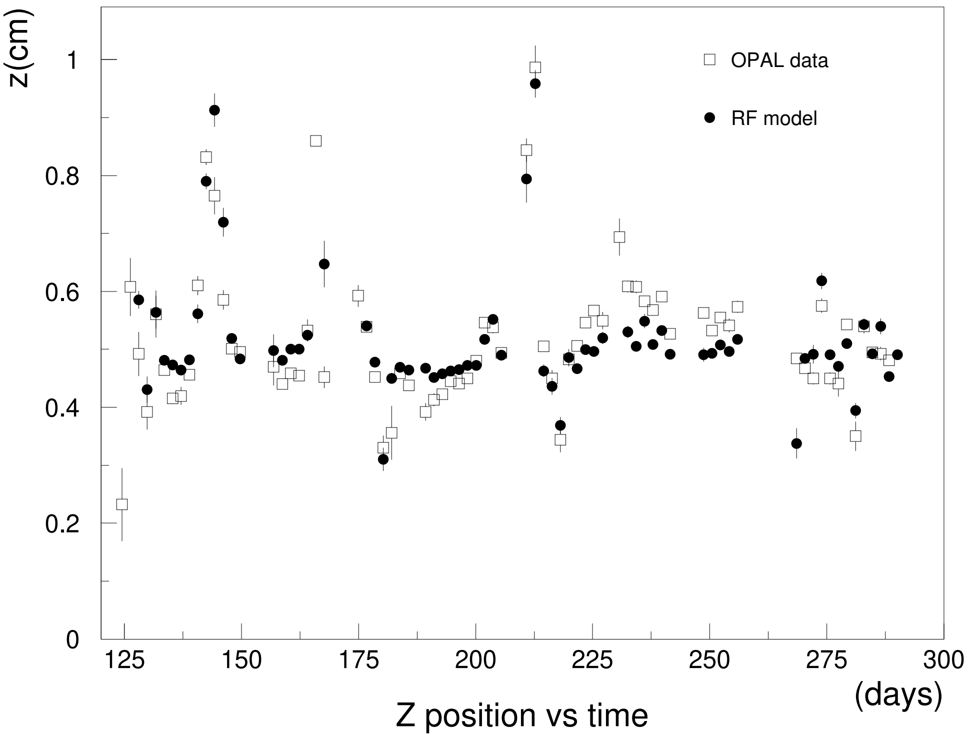

Figure 5: A comparison of the measurements and predictions of the average z position of the interaction vertex for all of the 1994 running. The squares represent the OPAL experiment's best determination of the interaction point z at the time of each RF record. The filled dots are the predictions of the RF model. In general, the agreement is quite good.