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A Systematic Check of SC Cavity Alignment Using LEP Beams

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Abstract

During the commissioning period preceding the 172 GeV running of LEP in 1996, an extensive series of measurements of the positions of the superconducting (SC) RF cavities were made. The alignment method, various cross checks of the measured positions, and the current understanding of the results are presented. A procedure for evaluating the uncertainty on RF corrections to the center of mass energy is described.

1 Introduction

This note describes a series of measurements performed during the 1996 LEP running to clarify the question of the exact positions of the SC RF cavities and the error on these positions. This study was motivated by some preliminary measurements made during the startup in June of 1996 [1] which showed a discrepancy of 2.5 mm in the position of one SC cavity depending on whether CU RF units at IP2 or IP6 were used as a reference point (the alignment measurement technique will be described below). Taken at face value, this potential uncertainty was used to calculate a systematic error on the RF corrections to the center of mass energy (E_{CM}) for each IP, resulting in a 1.7 MeV error at IP6 from this effect[2] for the 1995 Energy Scan analysis. Allowing the uncertainty on E_{CM} from this effect to remain at such a large level is unacceptable, both for the Z^0 lineshape results and for LEP 2 running, where the size of this error scales as the the applied voltage.

In October 1996, during the startup for the 172 GeV running, a set of measurements were performed to establish the validity of the one alignment cross-check performed in June. The presentation of the measurement results and a discussion of their impact on the Energy analyses is the subject of this note.

2 The RF Cavity Alignment Technique

Since the SC RF cavities reside deep inside cryostats, their exact positions during LEP running conditions (at 4.5 K) cannot be determined by standard optical survey methods. Instead, one can use the LEP beams for a beam-based alignment, which results in a positional uncertainty of order 1 mm, barring any systematic effects. The principle of beam-based alignment is straight-forward:

1. At injection energy, very low-current beams of electrons and positrons are made to circulate in LEP. (Low bunch current minimises the effects of beam loading on the measurements).

2. Cavities somewhere in LEP (typically, symmetric pairs of CU cavities at IP2 or IP6; they are chosen symmetrically on either side of the IP so that their misalignments cancel.) are chosen as reference points, and their RF power keeps the beams in circulation.

3. The phase of the cavity to be surveyed is stepped over a wide range ($\pm 100^\circ$ or so), and the value of Q_s is measured at each step for each beam.

4. If the cavity is not aligned relative to the center of the reference cavities, the maximum value of Q_s as a function of phase will not be at the same tuning angle for the two beams. See the description of Figure 1. The difference in phase angle between the two maxima can easily be converted into an alignment offset using the RF wavelength of approximately 85 cm.

Several effects can compromise the precision of these measurements, the most important of which is noise on the Q-meter used to measure Q_s of the two beams. If, for some reason, the Q_s spectrum is very unstable or has many frequency components, the Q-meter may not "lock" properly on the desired beam, or it may read the same for both beams.

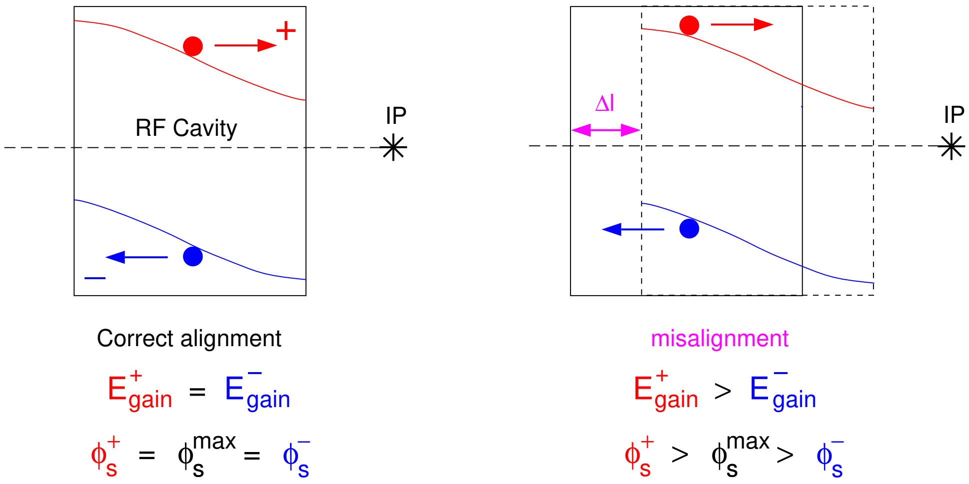

Figure 1: A schematic representation of a "properly aligned" RF cavity (left) and a "misaligned" cavity (right). In a perfect LEP, the counter-rotating beams would each gain the same amount of energy from each RF cavity, and would thus sit at the same stable phase ϕ_s. In the case of the misaligned cavity, displaced *away* from the IP, the incoming beam gains more energy than in the perfect case because it arrives "early", while the outgoing beam gains less energy because it arrives "late". Since $Q_s \propto \sqrt{dE/d\phi_s}$, each of the beams has moved away from the point of maximum slope (ϕ_s^{max}) on the RF envelope, but in opposite directions. If we define $\Delta\ell > 0$ if the cavity is *too far* from the IP, then $\Delta\ell = [(\phi_s^+ - \phi_s^{max}) - (\phi_s^- - \phi_s^{max})]/2 \times \lambda_{RF}$. Note that the sign of $\Delta\ell$ given by this expression depends on whether the positron beam is entering or leaving the IP; it is correct for the situation in the figure.

This instability can also be caused by a lower-than-desirable RF voltage, which may have been the case for some of the measurements discussed here. In any case, this may render some of the measurements invalid. The implications of this will be discussed below.

3 Cross-Checks of RF Cavity Alignment

Since the installation of SC cavities in LEP, their positions have been measured many times in the manner described above, using CU cavities at IP6 as a reference. (For an overview of the RF cavity positions in LEP, see Figure 2.) The cross check of alignment performed in June 1996 used CU cavities at IP2 (232 and 272) as a reference for the first time, and resulted in a discrepancy of 2.5 mm in the measured cavity position of the half-unit 233-2 when compared with the measurements using reference CU cavities at IP6.

In October 1996, an attempt was made to cross-check the positions of as many SC cavities as possible, using (except for one measurement) CU cavities 232 and 272 at IP2 as a reference. These CU units were run with the klystron powering the storage cavity, K2, turned *off*, so that they operated at the RF frequency f_{RF} for which they had been positioned initially. This was to remove any potential systematic bias arising from using badly misaligned CU cavities as a reference, even if they were chosen in such a way that their misalignments should cancel. Unfortunately, it also resulted in the total available power, and hence the maximum attainable Q_s, was lower than is typical for making the alignment measurements. This may have affected the quality of some of the measurements, as will be discussed below.

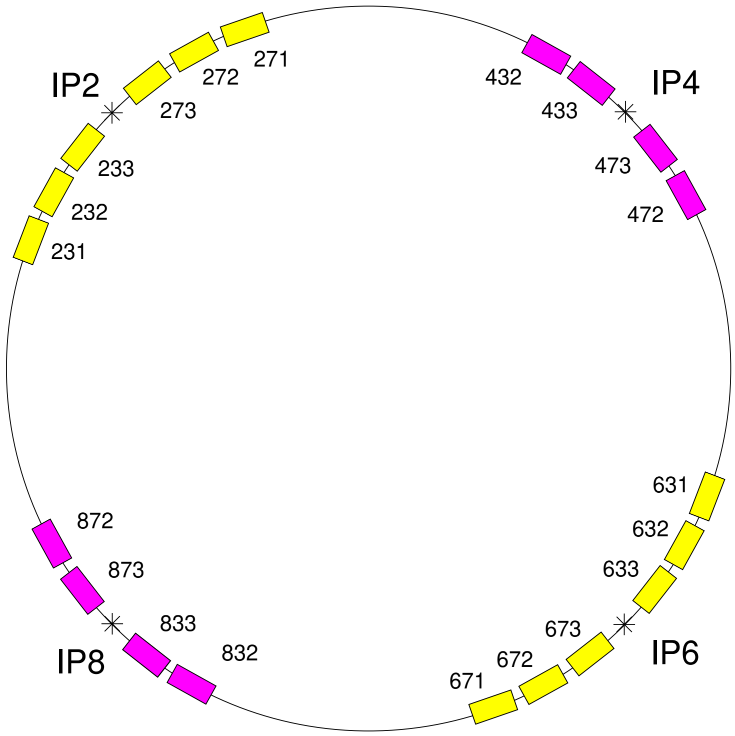

Figure 2: The location of RF cavities in LEP for the 1996 running.

The first set of measurements made were a cross-check of the relative positions of the CU cavities at IP2 and IP6. In this case, units 632 and 672 were used to check the position of 272, all running with klystron K2 off. The Q_s values for each of the beams at each tuning angle were identical, meaning that within the precision of this measurement, the CU cavities are *aligned* with respect to f_{RF}. This is as clean a measurement of the path length difference between IP2 and IP6 as has been obtained, with the one caveat discussed below. Turning on K2 on unit 272 resulted in the data shown in Figure 3, which shows clearly the effects of the $\sim$ 2 cm effective misalignment of the CU cavities. Both the sign and magnitude of this effect are as predicted from the relation between the two different klystron operating frequencies.

One effect which can also be seen from the measurements is that, due to either the low Q_s values used or other instrumental effects/noise, the measured value of Q_s "locks" to be that of one beam or another when the magnitude of Q_s is nearly the same for both beams. It is clear from the figure that the measured value of Q_s for the positron beam at a tuning angle of 320° should be substantially higher than that observed, which is identical to the Q_s of the electron beam. Since the Q_s maxima are well separated, this has little effect on the alignment results in this particular case. In the case of the measured zero misalignment of the CU cavities relative to f_{RF}, small misalignments could be hidden by this effect. Since misalignments as small as 0.05 cm were measured on the SC cavities

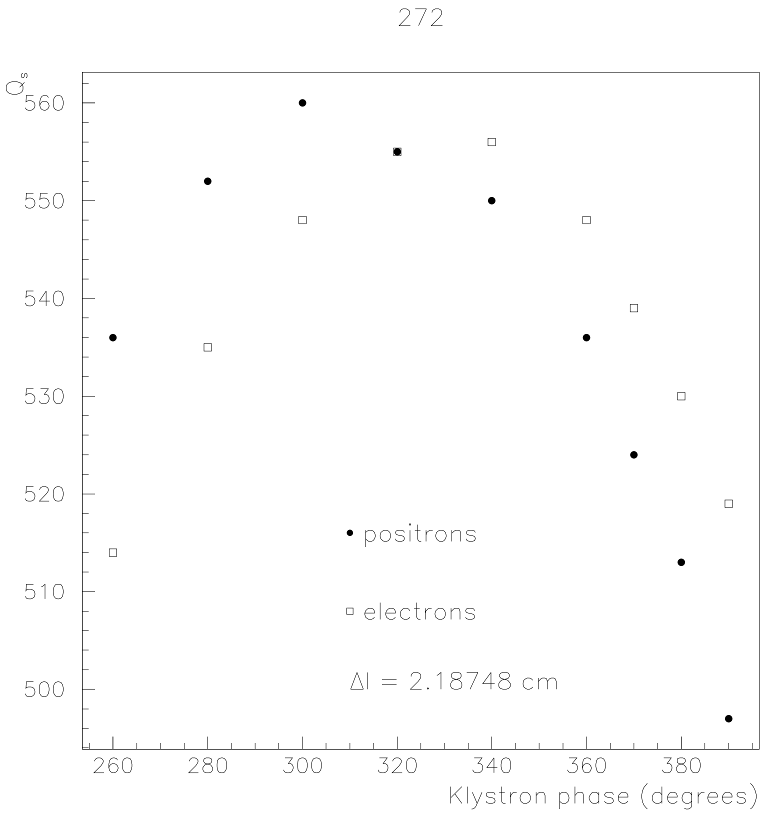

Figure 3: Measured values of Q_s for each beam as a function of klystron tuning angle on CU unit 272 when the klystron powering the storage cavity is operating. The different positions of the maximum Q_s for each beam is converted into the measured misalignment $\Delta\ell = 2.2$ cm.

using this technique, it is unlikely that a large misalignment could have been masked by this effect.

The next series of measurements checked the positions of as many of the SC units as possible, using the CU cavities at IP2 as a reference. The results of these measurements are given in Table 1, along with the positions measured previously using IP6 reference cavities, and the differences. Those measurements denoted with a question mark "(?)" are particularly badly effected by the Q_s locking problem and thus have some larger uncertainty associated with their values. One of these, for cavity 832-2, is shown in Figure 4.

4 Cross-Checks of Cross-Checks

To clarify the potential effects of noise in the Q_s spectrum and the extent to which the "sticking" of Q_s values biases the results, several SC units were remeasured with the K2 klystron on, at higher Q_s values. The results of one of these tests is shown in Figure 5, where it can be seen that virtually identical results were obtained for the alignment

unit	$\Delta\ell$ using IP6	$\Delta\ell$ using IP2	$\Delta(\Delta\ell)$
233-1	1.21	1.25	0.04
233-2	-0.25	-0.44	-0.19
633-1	-0.35	-0.11(?)	0.24(?)
633-2	-0.49	-0.82	0.33
673-1	0.17	0.00	-0.17
673-2	0.17	0.35	0.18
432-1	-0.61	-0.78	-0.17
432-2	-0.51	-0.77	-0.26
433-1	-0.68	-1.06	-0.38
433-2	-0.41	-0.33	0.08
472-1	-0.56	-0.11(?)	0.45(?)
472-2	-0.13	0.02(?)	0.15(?)
832-1	-0.75	-0.95	-0.18
832-2	-0.45	-0.23(?)	0.22(?)
833-1	-0.45	-1.02	-0.57
872-1	-0.24	0.05	0.24
872-2	-0.57	-0.39	-0.18
873-1	-0.01	0.00	0.01
873-2	-1.43	-1.30	0.13

Table 1: The misalignments ($\Delta\ell$, in cm) of a number of SC cavities. Those values which have used IP6 as a reference are the average of a number of different measurements (up to 5 per cavity). Those using IP2 are new measurements made in 1996. The new measurements of unit 233-2 performed in October were identical to those of June. Measurements labelled with a question mark (?) are described in the text.

measurements. The other remeasured cavity positions were consistent with those obtained with K2 off to better than 0.05 cm, which suggests that, for those cavities with sufficient numbers of non-identical Q_s values, the original measurements are useful.

5 Comments on Results

A comparison of the alignment measurements made with IP2 and IP6 used as a reference reveals some interesting structure. The overall mean shift (using only the "non-questionable" measurements) between the IP6 and IP2 measurements is $-.09$ cm, with an rms of 0.24 cm. The distribution is very broad. If the data set is broken down into those cavities to the left (the 30's) or right (the 70's) of each IP (see Figure 2), it can be seen that these two subsets of data each cluster at larger positive or negative values, with a much reduced rms. These distributions are shown in Figure 6. It seems that, for some reason, the shifts measured on different sides of each IP are, in fact, different. At present, there is no known explanation for this effect. Hopefully, further tests can be performed in the 1997 startup to clarify the different systematics associated with alignment measurements.

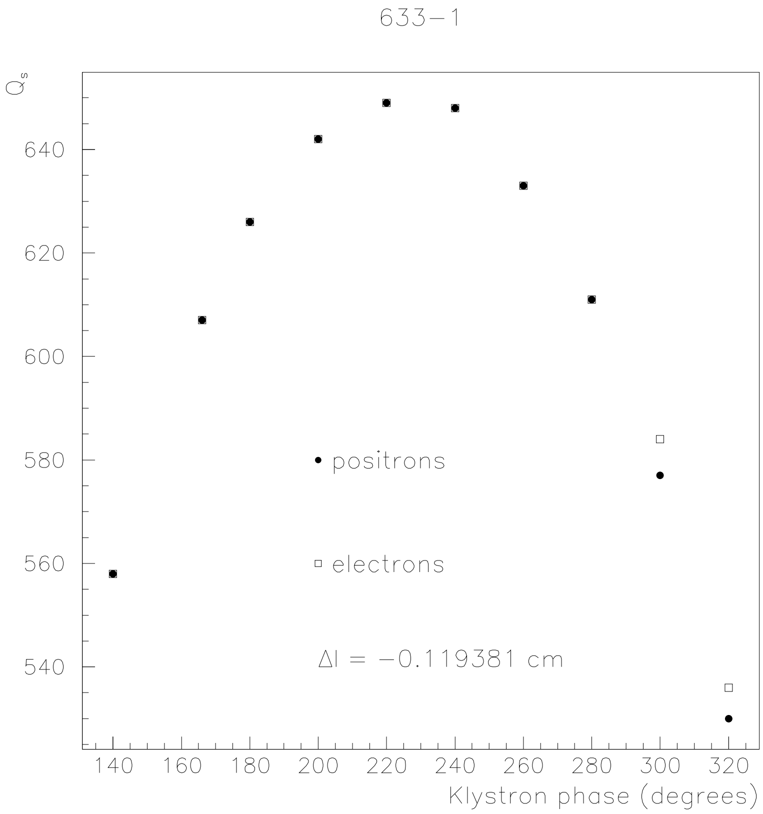

Figure 4: Measured values of Q_s for each beam as a function of klystron tuning angle on SC unit 633-1. The last two points at 300° and 320° suggest that the two curves really aren't identical, but all of the other points have "stuck" together.

6 A Suggestion for Estimating the Alignment Systematic Error

Since *a priori* there is no reason to believe that the misalignments referenced to IP2 are less valid than those referenced to IP6, both sets of measurements should be treated on an equal footing. For the results generated to date using the RF model, the IP6 numbers have been used for the central values, mainly because they are the result of numerous repeated measurements whose scatter can be used as some estimate of the reproducibility of the technique. To evaluate the systematic error arising from an uncertainty in the cavity positions, the RF corrections to E_{CM} have been reevaluated using the IP2 positions *plus* an additional 1 mm shift in the direction of $\Delta\ell_{IP6} - \Delta\ell_{IP2}$, *i.e.*, the cavities are moved 1 mm beyond the shift between IP6 and IP2. This takes into account the 1 mm scatter seen on the both the repeated IP6 measurements and the uncertainty on the mean shift between IP2 and IP6.

Note that this implies that the uncertainty in path length difference between IP2 and IP6 depending on whether the beams are travelling via IP4 or IP8 has been measured to be essentially zero, with a 1 mm error, not 1 cm as was previously used in the RF analysis

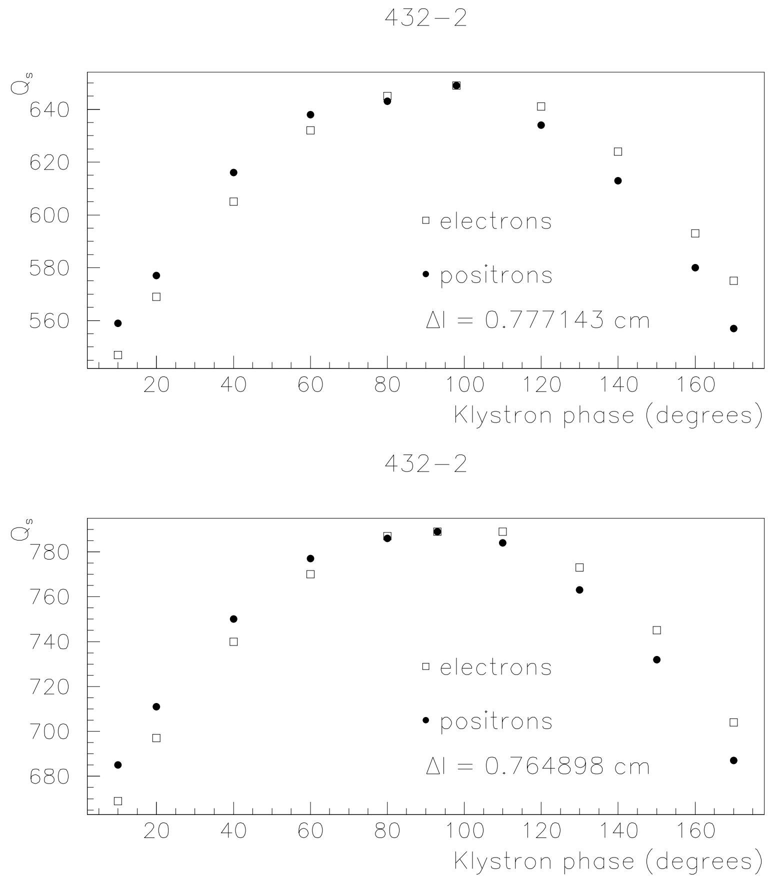

Figure 5: Measured values of Q_s for each beam as a function of klystron tuning angle on SC unit 432-2 taken with klystron K2 on the reference CU cavities off (top) and on (bottom). No significant difference in the measured misalignment is observed.

for 1993 and the the preliminary 1995 results.

When computed using this prescription, the error on the RF corrections for the 1995 Scan due to the uncertainty in SC cavity misalignment is reduced to 0.1 MeV for IP2 and 0.5 MeV for IP6, a much more "comfortable" set of values. The errors for the LEP2 running of 1996 are 3 MeV due to this same effect. Although this seems small, more understanding is needed to be sure that there are no additional problems with the alignment constants.

7 Conclusions

In 1996, substantial progress was made in understanding the systematics of measuring the positions of the SC cavities in LEP. This note presents the most thorough study of the alignment procedure performed to date, and provides us with enough data to reduce several of the systematic errors in the RF Model analysis. A more detailed understanding,

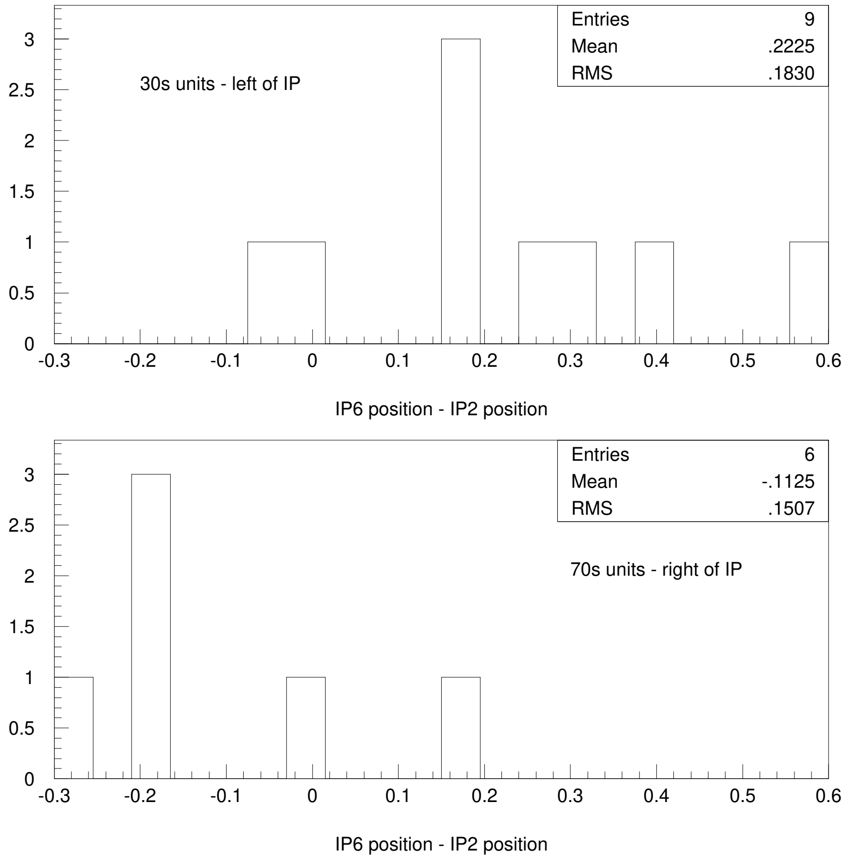

Figure 6: The difference between the misalignments measured using IP6 or IP2 as a reference, for those cavities to the left of each IP (top) and to the right of each IP (bottom). These two sets of cavities seem to have systematically different behaviour.

especially of the differences between the left and right sides of the IP, is desirable, however, to insure that we really are not missing some large effects. Hopefully, some additional tests can be performed during the 1997 startup which will clarify these matters.

8 Acknowledgments

I would like to thank Günter Geschonke and especially Ernst Peschardt for allowing me to perform these measurements during the phasing of the RF system for the 172 GeV running, and for their generosity in spending the time to answer my incessant questions about sign conventions, RF hardware, and other things like, "just how do you measure this, anyway?"

References

[1] E. Peschardt, "Phasing of the RF System", presentation to the LEP Energy Working Group, 5 July, 1996.

[2] 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.