Memo to LEP Energy Working Group

Status Report on RF Corrections for the '95 Scan

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1 Introduction

This note attempts to describe the current efforts to obtain 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.

As in past years [1, 2, 3], the modelling of the corrections 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 beam as it travels 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 should give us the possibility for very detailed cross-checks of the model predictions, as well as enhanced diagnostic capablitity 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 will 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 should prove 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 four times as complicated such that

ϕ_s is calculated separately for each bunchlet in the bunch train. Detailed tuning of the individual bunchlet interactions with the unused copper RF cavities will be necessary to reproduce the distribution of longitudinal collision point offsets seen by the four experiments. 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 and discusses its status.

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 the our best current knowledge of these quantities. 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*. 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. In addition, the longitudinal positions of the interaction points of the three bunchlets over time will be necessary†. The quality of each of these data sources (for off-peak fills only) will be discussed in the sections below.

*In addition, we must know whether or not the longitudinal bunch stability feedback is active. At this point, it is not clear how large an effect this uncertainty is, since apparently there is no way (except looking at the data) to tell whether it is on or off.

†This quantity must be provided by the four (or at least two) of the experiments and does not come from any of the LEP databases. Presently, files of the mean collision points along the beam direction for the three bunchlets are available in a useable form from Aleph and Opal and need only be incorporated into the existing database structure.

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%

3.1 RF Voltages

A "complete" set of RF voltages has been provided from a combination of the standard LEP Logging Database, the Private Logging Database of the RF group, and the Frontend logging of each of the units from its control workstation. In the following discussion, the LEP Logging Database will be referred to as "Standard" logging, while the other two sources are called "Alternative" logging. The Frontend logging was only used to patch large holes in the available data when the other two logging databases were 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. This "measurement error" will have to 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 correction 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 predicitions to Q_s and R_{BOM} data.

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%

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%

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 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 readback 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 couterparts, the errors due to imprecise knowledge of the correct phases and positions could become large.‡

We turn first to the alignment issues. We have been assured [5] that there is no way for the alignment of the copper RF cavities to have changed, so we will use 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 error for the SC cavities§. The placement of the individual SC RF modules will be put into the RF model.

The history of various changes in the phasing of the RF was obtained from the RF group logbook. This information needs to be properly digested and compared with that from E. Peschardt[6] to get some idea of the phase drifts in the SC cavities. When this is complete, the changes in phase of the various cavities as a function of time will be added to the RF model. At that time, we can begin to asess how large an error needs to be assigned to the SC RF phases. In addition, the data presented by E. Peschardt[6] contains measured voltage errors on the SC cavities which have typical values of 3-4%. Since in past years the overall error on the RF voltage scale was $\pm 1.0\%$, this may have to be reevaluated in light of the present data.

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

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

Here, h_f is the LEP harmonic number (31324), α_c is the momentum compaction factor for the 60° 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 within a fill. A quality word is attatched 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,

‡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 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%

those values where the longitudinal beam oscillation frequency approaches a harmonic of the beam revolution 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 attatched 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:

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

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.

3.7 Other (non RF-related) Data

Also currently included in the database are many quantities unrelated to the RF energy corrections but vital for the calculation of the overall E_{CM}. These include: 1) The "smoothed" values of the NMRs – these have been produced by averaging the logged values (updated every 30 seconds) over 15 minutes and have had the spurious beginning-of-fill bend modulations during "Physics" mode removed; 2) The NMR values as logged in the standard LEP database. 3) the complete set of magnet temperatures; 4) the raw and processed (tide-corrected) set of Resonant Depolarization Energies – raw and processed values for each subcalibration and the average are included; 5) X_{BOM}, the average of the difference of the electron and positron beam positions in the LEP arcs, one measurement per fill. It is envisaged that other quantities relevant to the calculation of the LEP energy will be added as they become available/well-understood.

4 Steps Towards an RF Correction to E_{CM}

This section gives an overview of the course the analysis of the RF corrections to E_{CM} will take during the coming weeks/months. As complete a list of possible of the task to be accomplished will be presented; of course, if there are surprises, new cross-checks and other analyses will have to be added.

4.1 Arriving at the Final Model

As a starting point, the RF model code must be updated to include the following information:

- We now have the full set of voltages for each of the SC RF half units, which was only present for some fraction of the run. The code had been changed to compensate for this, and so this correction must be removed.
- The best known cavity alignment values and voltage calibrations[6].
- The known phase errors and phase changes that existed/took place over the course of the scan.

Following this, the measured value of R_{BOM} can be used to check that the RF phasing in the model is correct and any discrepancies can be removed once they are understood.

Once the phase information is more or less correct, an overall voltage scaling factor (and its error) can be determined by making the average calculated and measured Q_s values agree.

At this stage, detailed consideration of the small-scale structure predicted by the model can begin. One cross-check that must be done is to compare the predictions of the model for the shifts in longitudinal vertex position to those measured by the experiments. Presently, no choice of parameters related to the higher-order-mode (HOM) losses in the unused cavities can reproduce the vertex position distributions seen in the experimental data. This will almost certainly require another look at the model of energy loss/gain in the unused cavities. Some iteration on the above steps will probably be required.

4.2 Systematic Errors

Any discrepancy between the measured and calculated values for Q_s, R_{BOM}, and the vertex shifts must somehow be converted into systematic errors. At this point, it is not at all clear a) how to do this, and b) what the size of the errors will be. For completeness, we show in Figures 1, 2, and 3 the comparison of the measured and calculated values of Q_s and R_{BOM} at this stage of the analysis, *i.e.*, before anything has been done. The errors from interpolating to recover the missing values will also be necessary. 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 IPs 2 and 6 in '93)
- The lengths of the LEP arcs (1.0 MeV (anticorrelated) in IPs 4 and 8 in '93)
- momentum compaction factor (0.1 MeV (correlated) in IPs 2 and 6 in '93)

Each of these requires running the RF model several times with different parameter sets in order to determine the size of the errors and the correlation between the different IPs.

5 Conclusion

In this memo we have attempted to present as detailed a picture of the status of the RF energy-correction analysis as is currently possible. As can be seen from reading this document, virtually all of the work up until this point has gone into arriving at a complete dataset which can be used for the analysis, and the tools with which to do this. Now the energy analysis can actually begin! As can also be seen, there is a nontrivial amount of work remaining to produce actual RF corrections to the LEP center-of-mass energy. This procedure will likely take at least a month, if not more. Barring any unforseen circumstances, we should certainly have the analysis finished in time for the 1996 Summer Conferences

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.

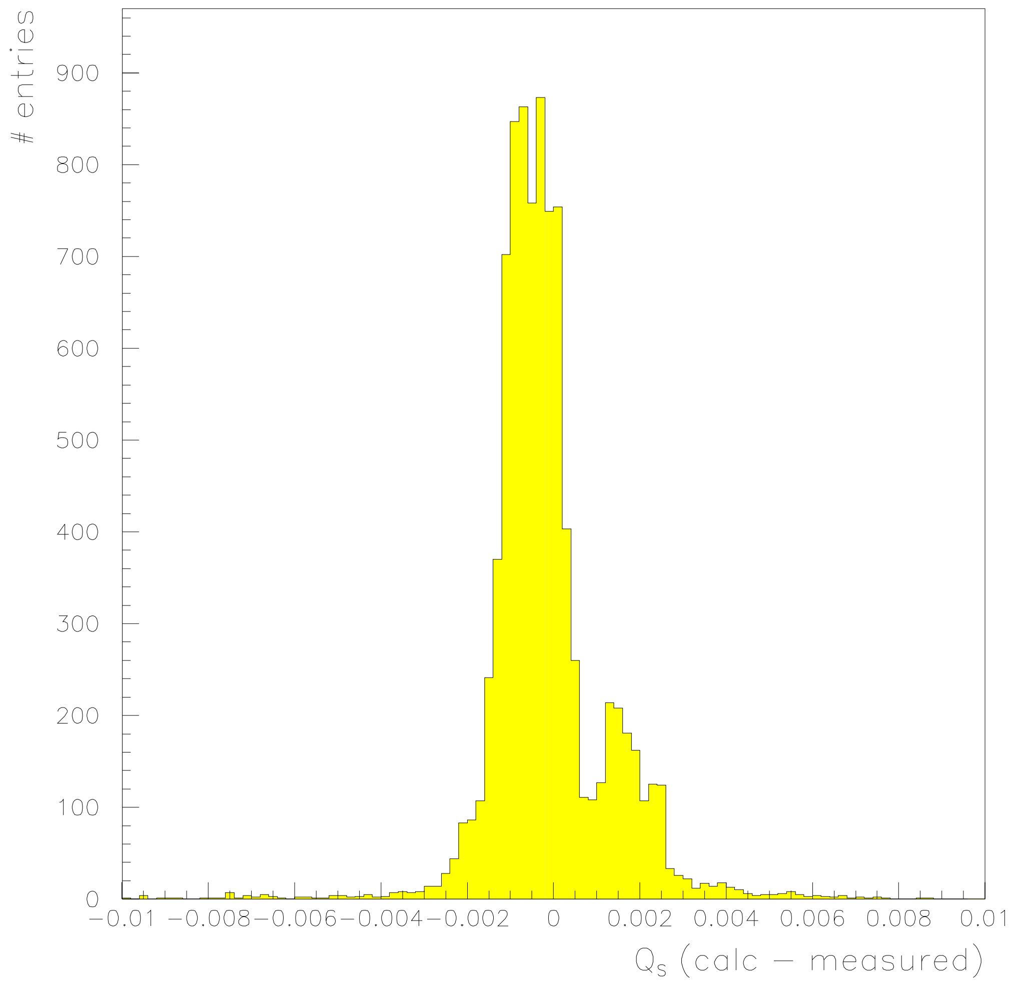

Figure 1: The difference between the measured value of Q_s and that calculated from the RF model. The mean of this distribution is -0.00015, and the RMS is 0.0013. The corresponding values for the '93 scan after RF model tuning were 0.0001 and 0.0004.

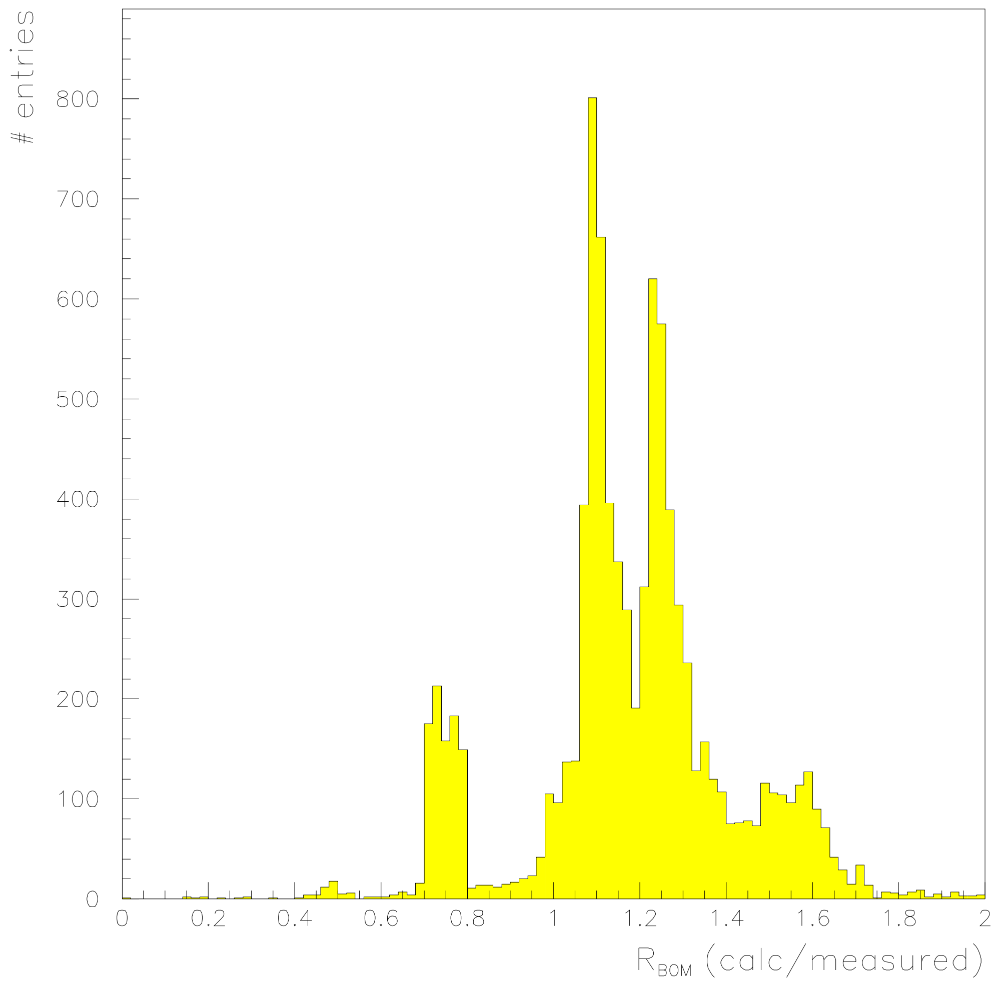

Figure 2: The ratio of the measured value of R_{BOM} and that calculated from the RF model. The difference from 1 is an indication of phase errors in the RF system.

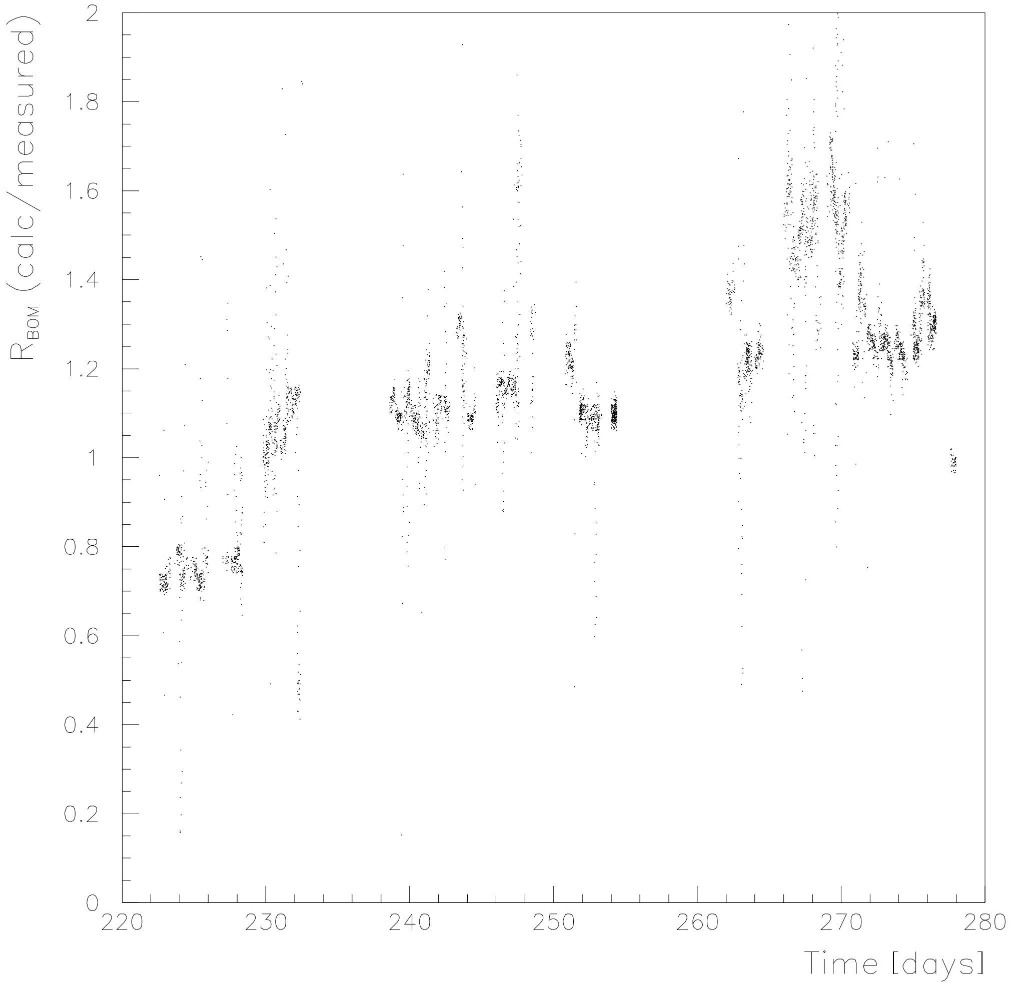

Figure 3: The ratio of the measured value of R_{BOM} and that calculated from the RF model over the whole '95 scan. The evolution of phasing errors in the RF system can be seen. The large jump around day 220 is due to a phase correction of 8° between IPs 2 and 6. The excursions around day 265 are due to modifications of the SC cavities and the extensive high-power use of SC RF.