RE-ALIGNMENT: IT IS THE TUNNEL FLOOR WHICH MOVES, ISN'T IT?*

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It is shown that on the months to years time scale, accelerator tunnels built in compacted geological strata exhibit a movement of the floor systematic (unidirectional) in each point. Attempts to characterize the movement through one global number (a <rms> deviation) based on a random model are conceptionally wrong and can only lead to erroneous design decisions for future accelerators. In the extrapolation limit, differences are especially pronounced for differential movements in the case of short (days) time spans, and for accumulated movements in the case of long (years) time spans.

The work described here evolved while I was on sabbatical leave in the Accelerator Physics group of the SPS/LEP division at CERN during the 1991/92 running period. I was fascinated to learn that reducing the LEP <rms> orbit of a new fill to a level suited for collisions with good luminosity and low background, a task which should have taken no longer than 15 minutes, took the astonishing time of more than two hours. This took valuable time, comprising the highest luminosity, away from the colliding physics program. Furthermore, in the end, only a modest level of vertical <rms> deviation, typically between 0.6 to 0.9 mm, could be achieved. This was a level not understandable from either the (1) experience of the previous year nor from (2) reasonable assumptions about how the physical alignment of LEP, a tunnel completely bored underground in compacted stone, could have changed in the intervening time. Worse, as the months went by, the situation seemed to deteriorate rapidly.

Naturally, among other possibilities, misalignment due to long-term tunnel floor movements quickly became suspect. In looking at the experimental evidence I followed what I call the *Fischer Principle*: "Every Ground Motion has a Definite Explanation" (rain, drought, summer, winter, cracks in the floor, a cut, a hill, an earthquake fault...). No evidence was found of a fundamental physics law which could explain the more than 15 years of ground motion data covered in the investigation. Nor was it necessary for analysis. Horizontal and vertical movements have generally been found to be about equal in magnitude because the geological forces inside of mountains involved are such that gravity does not play a major role. The following investigation focuses on vertical movements, more important for classical storage rings. It deals only with motions in the months to years region and does not addres the wide and important field of vibrations with time scales of 1 sec or less. Nevertheless, one can rightfully extrapolate the type of motion investigated, which is characterized by a resulting yearly change in <rms> of 0.15 mm/year, to the low end of validity: one day or some such similar time.
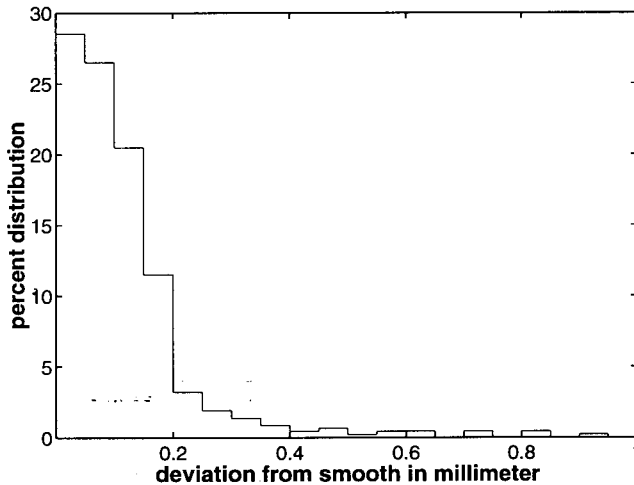
To explain the conceptual difficulties in understanding the root cause(s) of LEP's difficulties, a little historical digression is in order. Since its invention in 1953 by Courant and Snyder [Courant 1958], strong focusing has been the basis for much of the improvement in performance of accelerators and storage rings. There are concurrent increased demands on alignment tolerances, but over the years it was recognized that absolute positioning of magnetic elements is not essential, that mainly relative (element to element) smoothness is important, thus greatly easing the task on hand. How exactly smoothness is defined we will not discuss here; let's for now assume the concept is self-understood (smoothness may mean quite different things in different context, see e.g., the discussion of smoothing concepts in [Ruland 1991]). In the context of smoothing, the alignment <rms> deviation from an ideal or smooth reference orbit became an important parameter for machine physicists. Accelerator simulations were designed to investigate what <rms>, independent of source, would be sufficient for satisfactory operation. No particular effort was made to understand the root causes for the movements underlying <rms> deviations. In the course of these accelerator studies, often an artificial cutoff on the misalignment distribution of 3 sigma (or even less, as in the case of LEP) was arbitrarily imposed without any basis that such an achievement might even be possible from the actual experi-

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ence of surveying theory and practice.[1]

In principle, it is possible with enough beam position measuring devices (BPM's) and a corresponding number of correctors, to center the beam in each quadrupole, that is to reduce the "operational" <rms> orbit deviation, and thus "smooth" the machine operationally. In practice it was found that the luminosity in storage rings depended mainly on the physical alignment of quadrupoles and did improve dramatically after each re-alignment.

The concept of smoothness has led to the development of many wonderful techniques to achieve it, e.g., the non-parametrical principal curve analysis [Friedsam 1989], and other, less exotic and more parametrical least square fit based methods (splines and polynomials to name a few), and more recently beam based alignment. This new dogma (*smoothness*) has led to many successes like the principal curve based alignment of the Stanford Linear Collider (SLC) arcs [Pitthan 1987] or the beam based alignment of the Stanford Linear Accelerator itself [Adolphson 1989], where without either, SLC would not work. But these were successes achieved without paying attention to the actual absolute movements of tunnel floors and/or the machine elements attached to it.

Figure 1 Histogram of horizontal adjustments required during the installation of 300 alternate gradient magnets in the SLC South Arc. Outliers are found up to 9 standard deviations.

Because by their very nature, smoothing methods produce deviations (from the thus defined mean) which are more or less Gaussian (normal) distributed. That is, **seemingly** they are the result of a random underlying process (the movement). This paper will show, for the first time, that on the time scale of months to years in **actuality** many accelerator tunnels do not move in a random but rather in a systematic way, probably due to persistent geological forces, and that exact and simple mathematical prescription can distinguish between random and systematic movement.

Proponents of the random model [Baklakov 1991] have complained that each accelerator builder claims that his or her tunnel is special. Such statements miss the whole point. It is not only each tunnel which, due to geological uniqueness, is particular, it is each point in each tunnel which is special because of its history. For example, for PEP (used as an example below) one needs to know which part is built on fill (where it sinks), where and when synchrotron light beam lines were built, where and when the SLC Collider hall was excavated, and so on. All these historical actions were the cause for distinct, identifiable movements of certain areas in PEP. For LEP, which does not use monuments at all because the alignment method uses a more modern concept of smoothing, one has to know in addition which magnets were adjusted, taken out for repair and replaced, and such similar happenings. For the measurements used in this paper all such contaminated data have been carefully corrected or excluded, respectively.

It was observed that there were strange outliers in many alignment distributions, but these were generally attributed to human error in the positioning process, a prevalent assumption which probably was wrong. Figure 1 shows an example from the alignment of the South Arc of the Stanford Linear Collider. While close to 90% (2 standard deviations) of the 300 elements are within 0.2 mm, there are outliers up to 1 mm (9 sigma!), clearly not a Gaussian distribution, and definitively not one which
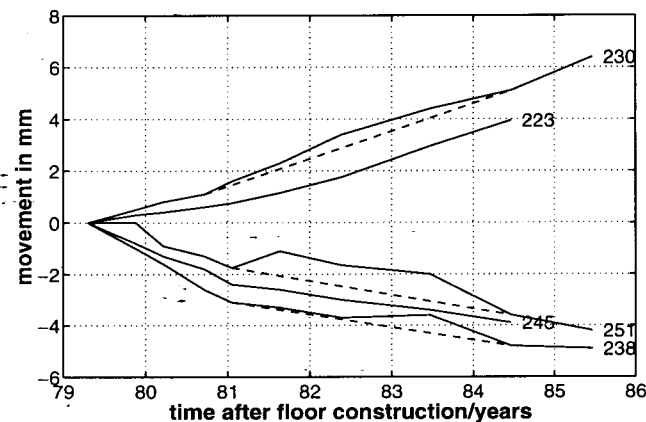
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[1] The choice of 2.4 sigma as cut-off for LEP, e.g., was predicated on the failure of simulation programs to find valid solutions for larger values. With higher cuts on <rms> from random numbers the orbit in the simulations sometimes was unstable or the machine was anti-damped [Keil 1992].

would justify a cut-off at 3 sigma or less, but one which is quite typical for actual misalignments found in the field if enough time has elapsed since the last alignment (see, e.g., Figure 5 below).

Because of the validating successes of smoothing techniques for machine element positioning, not much effort has been expended in recent years on investigating long-range tunnel movements in both the space and time domain. But the absolute movements still do matter, be it only to estimate in the design phase what (1) the maximum travel of the adjustment system should be or (2) how often an accelerator or a beam line has to be-realigned. In view of the strong cost implications of these two points alone, it is not quite rational that there never has been a systematic look into the global experience with tunnel floor movements in different accelerator laboratories.

Figure 2 Accumulated maximum vertical movements of PEP monuments, independent of location, with distance as parameter.

The oldest published local long-term study is the SLAC LINAC Fresnel lens laser alignment data collected by the late Gerhard E. (Gerry) Fischer (for his data, see [Fischer 92]). In a sense, these data are too good for they are too easily understood.

The LINAC is straight, thus lending itself to the use of a laser alignment system. Furthermore, the SLAC LINAC tunnel is not a bored tunnel; it was built with a cut-and-cover technique designed to minimize the earthwork needed. Consequently, the movements of the LINAC housing were easy to interpret following the *Fischer Principle*: it sank where built on fill, rebounded in the cuts, slid sideways on the hills, and jumped along a fault line during the 1989 Loma Prieta Earthquake. Thus, not much can be learned from the SLAC LINAC for the problems of the movements of a bored tunnel.

Figure 3 Accumulated movement of some PEP vertical monuments during the same time span as Figure 2. The local rise in curves above the dashed lines are believed to be due to the unusually heavy rainfall in the winters of 1981 and 1982. Data for monument 223 and 245 breaks off because of construction activity in the vicinity, as outlined in the text.
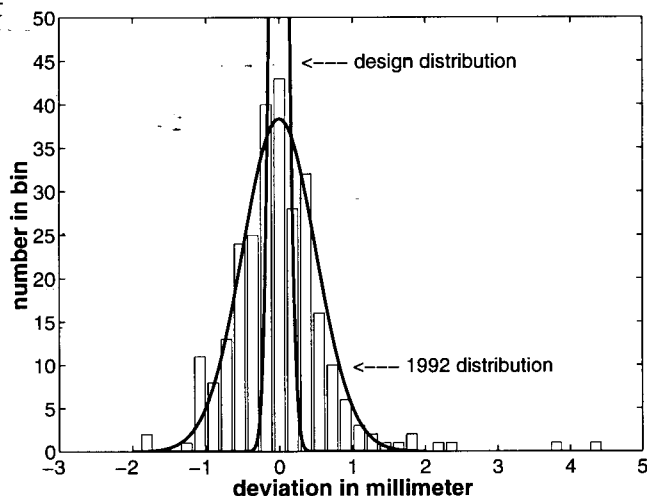
PEP at SLAC is more instructive. Originally collected in preparation for the construction of SLC, the data in Figure 2 shows an updated representation of the data from the hydrostatic level system of PEP [Linker 1982].

The observed movements of up to over 12 mm in 6 years, and the assumption that the SLC tunnel floor would move similarly, had great impact on the tolerances eventually adopted for the SLC arc alignment: they were made larger, or at least efforts by the machine physicists to design the machine to magnet-to-magnet tolerances below 0.1 mm for next neighbor accuracy were rejected.

Even more startling is Figure 3, gleaned from the same set of data: it shows that the tunnel moves in a systematic, as opposed to random, fashion. That is, once a particular piece of tunnel moved in one direction, it never seemed to reverse the direction of movement. But Figure 3 also shows other important truths: (1) even for underground structures the seasonal changes and inclement weather have a short-term effect superimposed over the long-term trend and (2) the upward movement seems to be larger and more sustained than the settling motions, albeit slower in starting.
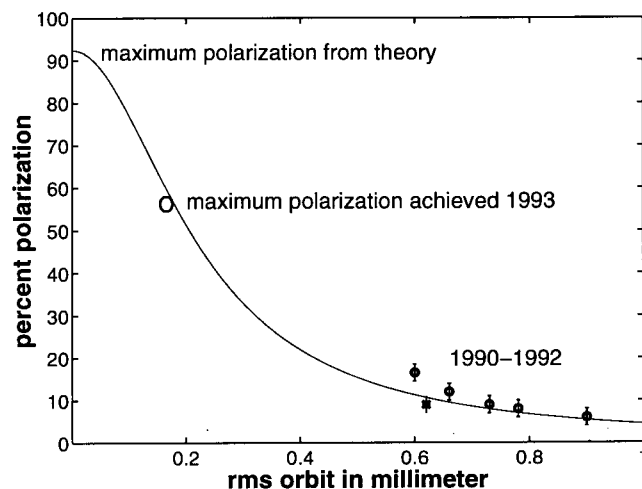
A closer look at existing long-term data from CERN [Quesnel 1988] and SLAC shows that indeed the measured movements of accelerator tunnels built in compacted geological strata (i.e., not sand like at DESY) are far from random. To the contrary, most points in a tunnel move in one direction only. More important, this is the more pronounced the bigger the rate of movement is; that is, the higher the impact on machine operation.

The effort to understand possible causes of the large <rms> orbit deviations in LEP and the operational difficulties to reduce those in a timely manner at each fill, led at first to the discovery that the axis' of beam orbit measuring devices were different from that assumed in the machine control software (but not different from what certain experts knew). Later it was found that the accrued misalignment of the machine was much worse than assumed. The first topic has been documented [Pitthan 1992] and in the meantime has led to novel efforts to determine the relation of the center of a BPM to the center of a quadrupole next to it after installation (*K modulation*, [Schmidt 1994]). Here we will deal with the second topic. We will show, mathematically without ambiguity, that the individual movements in the LEP tunnel are predominantly systematic (unidirectional) and not random in nature and thus explain the rapid degradation of the physical alignment of LEP between 1991 and 1993. There are lessons to be learned for the maintenance alignment, as contrasted to the installation alignment, of LHC and other future large accelerators.

Figure 4   LEP Polarization as a function of operational <rms> orbit deviation. circles 91/92, square 90/91. The precise shape of the theoretical curve depends on the machine imperfections and has been matched to the points.

In order to understand the machine physics background, one must recall that in the early 90's an effort was made at LEP to explore the possibility of running with polarization. Simulations had shown that good polarization (let's say > 15%) could only be achieved if the <rms> orbit deviation in the operating machine could be brought below 0.6 mm. The desired design value was 0.3 mm. Part of the plan was to increase the basic polarization with various methods of harmonic spin matching [Assmann 1994], but to get there, some minimum amount of polarization had to first be established.
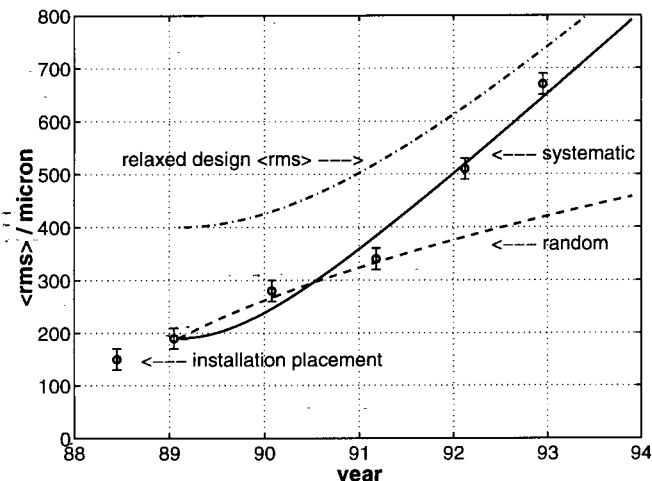
Figure 5   Comparison between the vertical design distribution (<rms>=0.1mm), validated by control surveys in 1989, and the experimentally found distribution of 267 quadrupoles distributed over all of LEP in 1992 (<rms>=0.52 mm). Positive (up) outliers are found up to 9 standard deviations.

The right lower side of Figure 4 shows that the <rms> orbit in 1992 did not reach the <rms> goal and that with the <rms> the polarization was poor and seemed to get worse with time. Since no global re-alignment was performed in 1992, the maximum polarization LEP reached in the 1992/1993 running cycle was 8%.

To save money, and because the luminosity in the previous running cycle had been good, the regular global survey and re-alignment had been skipped since the installation. Fortunately, there were data available to investigate the situation. The vertical movement in six critical or suspect areas, namely

4

the four experimental straights, the arcs under the Jura Mountain, and the injection area in Point 1, comprising just over half of all quadrupoles in LEP, had been monitored [Hublin 1992]. Figure 5 shows the statistical summary of these data. As in Figure 1, outliers up to 9 standard deviations are visible. As will become clear, it is not sufficient to focus on the one statistical number alone (the <rms> deviation). To tell the whole story one must examine how individual misalignments come about.

Except for the isolated outliers the <rms> deviations in the 6 different parts of LEP surveyed are in agreement with each other. They all group between 0.5 and 0.6 mm, indicating that whatever the process is which makes the tunnel floor move, it is not dissimilar in the different geological strata of LEP.
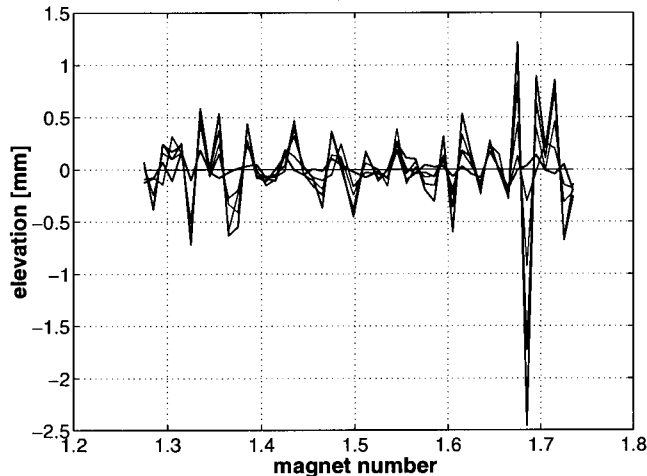

Figure 6   The movement of 48 Quadrupoles in Point 1 of LEP between 1989 and 1993. The elements were placed there in 1988; a control survey was done in 1989. The data shown have a second order polynomial subtracted.

As outlined above, the focus in accelerator survey and alignment in recent years has been on smoothness. Good data on global movements are hard to come by. Therefore, in the following discussion the results for Point 1 will be taken as representative for all of LEP. Point 1, the injection straight, was chosen because it was the most extensively surveyed area of LEP; data were available for every year starting with 1989; no additional construction which would corrupt the data had taken place after installation. Also, the components had been placed there only 8 months before the first control survey.

The usual problem of datum definition and smoothing fits had to be addressed. It was found that the type of fit had great impact on the amount of movement found. In other words, the smoothing routine eliminated deformations which had to be regarded as real. This effect was, as one would expect, especially pronounced at both ends of the survey (toward magnet numbers 1.25 and 1.75). After applying polynomial fits up to fourth order it was decided to limit polynomial fits to second order and evaluate the data in two alternate ways:

Method 1:. A second order polynomial was fitted to the leveling results and subtracted. All calculations were performed on the modified data. They are plotted in Figure 6. It was felt that the measurements were of very high quality in a homogeneous environment (e.g., the straight of Point 1 does not contain an experimental hall with its inherent temperature gradients) and that systematic deformations requiring polynomials of higher order should be negligible. For a straight line fit (not shown) a pitch between 0.2 and 0.4 microradian was found for the 5 sets of data, well within the estimated systematic error of the instrument.

Figure 7 The <rms> deviation of 48 quadrupoles (data of Figure 6) in the straight section of Point 1 vs. time. The curves show the expected development of <rms> if all points in the tunnel would move systematic (unidirectional) or truly random, respectively. Also shown is a curve for a relaxed design criteria of <rms>=0.4 mm instead of the actual design value 0.1 mm in the case of systematic movement. The error bars are the estimated systematic errors;; the statistical error on the <rms> alone would be in the micron region.

The <rms> values were calculated with Method 1 for each survey and plotted vs. time in Figure 7, together with curves for random and for systematic movement of the tunnel floor. If each point would

move truly randomly the misalignment would grow with the usual form proportional to the square root of time (lower dashed curve). In the systematic case (solid curve in the middle), in contrast, the apparent <rms> deviation will grow linearly with time. It is quite evident that the data are consistent only with a predominantly systematic movement.

Figure 8 The movement of 47 Quadrupoles in Point 1 of LEP. Similar to Figure 6, except that the movements were related to the next neighbor quadrupoles as described in the text.

Two obvious differences between the two types of movement can be pointed out: (1) Since the movement is built upon an existing finite <rms> from the installation placement, the rate of change in the <rms> description for very short time spans (days to months) is finite for the random case, but zero for the systematic curve. This has important potential consequences for the operational day-to-day, possibly mechanical remote, alignment for future colliders. (2) For large time spans (years) the curves diverge when the systematic case enters the linear regime. This has consequences for the long-term (let's say yearly) maintenance alignment for future colliders.

For the latter case it is apparent from Figure 7 that for LEP the projected <rms> deviation for end-1993 is nearly twice what one might expect under the assumption of a truly random movement of the tunnel floor and the magnets attached to it. It must be emphasized that the main result, namely the clear favoring of systematic over random movement, is independent of the order of polynomial used (up to fourth order were investigated, but it was felt that the higher orders were reducing the amplitude of true tunnel movements, see above).

Method 2: For each magnet the average deviation to the next neighbors was determined. All calculations are performed on this "new" (more precisely: the original) set of elevation differences. This method has the advantage of eliminating all model dependencies as well as to be most representative of the actual method of measuring elevations (directly from magnet to magnet). Treating the data this way also allows them to be regarded as a set of measurements independent of each other, which makes the statistical treatment cleaner (not that it matters for the conclusions of systematic vs. random movements). For Method 2 the data are shown in Figure 8.

In Figure 9 <rms> deviations were calculated and theoretical curves plotted, similar to Figure 7. It is not surprising that in the case of the "next neighbor deviation" the <rms> values are smaller than with Method 1. In fact, the January 1989 control survey, 8 months after installation, yields a <rms> value of only 0.09 mm. But as in the case of the straight line data, Figure 9 shows that the degradation of alignment points clearly toward systematic tunnel movements, such that the <rms> in 1993 was already 0.55 mm.

How can this information be used profitably? Sur-
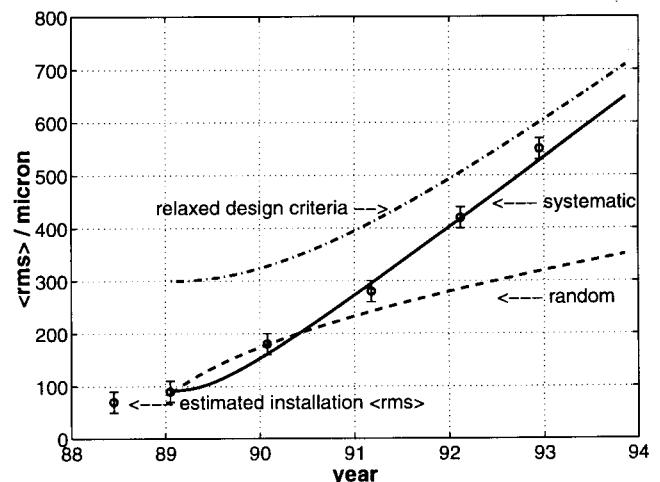
Figure 9 The <rms> deviation of 47 quadrupoles in the straight section of Point 1 vs. time, similar to Figure 7, but evaluated with Method 2. The curves show the expected development of <rms> if all points in the tunnel would move systematic (unidirectional) or truly random. Also shown is a curve for a relaxed design criteria of <rms>=0.3 mm instead of the actual design value 0.1 mm.

6

veying and aligning a machine of LEP's size is a costly enterprise. But even more costly is to loose operating beam time by running a machine which is not optimally aligned. Since the movement of the floor can be anticipated based on the history of the movements, it will be shown that the positioning can be biased in a way to ensure that within reasonable limits the <rms> quadrupole (or any other) deviation gets better with time [*Running With The Wind*,[1] CERN Courier **34,4** (1994) p.19]. The time span after it reaches a minimum in <rms> only depends on the magnitude of the <rms> error one is willing to suffer at start-up. But this has as a requirement that the alignment tolerances are set rationally from the outset. It is clear that the original design tolerance for LEP (0.1 mm) was unnecessarily tight. Otherwise the machine could not have produced good luminosity even with <rms> orbit deviation approaching 1 mm.
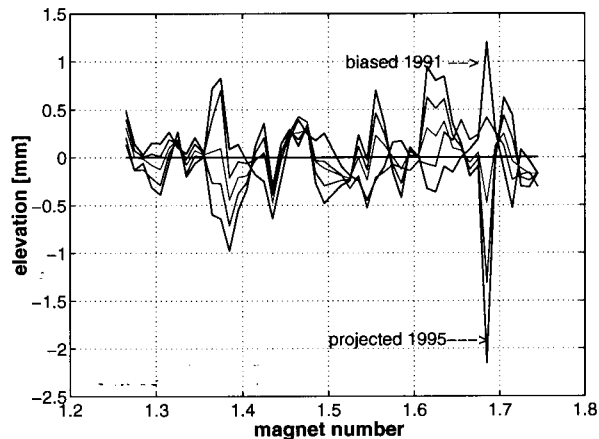
Figure 10 The Gedankenexperiment of *Running With The Wind.* using Method 2. By choosing the initial <rms> value wisely the "integrated" closed orbit deviation over an alignment cycle can be minimized and the number of re-alignments can be reduced.

actual survey data, shows that the measured <rms> for Method 1 will go down (in this Gedanken experiment, at least) to 0.20 mm in 1993. After that we have no data, but presumably the <rms> would grow again and reach a value of 0.5 mm for the misalignment <rms> as late as 1995. Figure 11 shown the <rms> analysis analogue to Figures 7 and 9. The fitted minimum <rms> reached in 1993, 0.21 mm, is very close to the starting <rms> value of 1989, 0.19 mm. The difference between the two is indicative of the random content of the movement, or any non-linearity in its systematic time dependence. In any case, both contributions must be small, below the 10% level, judging from the data.

With this concept the time averaged <rms> would have been kept below 0.4 mm, while deferring re-alignment, for 4 years. The time span of no global re-alignment can be extended by two methods: (1) tolerating a higher initial <rms> and/or (2) aligning

So let's assume that an <rms> tolerance of 0.4 mm as defined with Method 1 would be tolerable. Then, from Figure 7 we know that in 1991 the <rms> value was 0.36 mm, below that value. Figure 10 shows the result from the following Gedanken experiment: in 1991 we place all quadrupoles in locations off-set from the smooth beam line by amounts opposite to what they would move in the next 2 years assuming the movement between 1989 and 1991 continues linearly. The new locations correspond to the difference between the 1989 and the 1991 locations, to a <rms> of 0.34 mm (this is lower than the 1991 <rms>, see Figure 7). Since the movements are unidirectional, two years later the machine should again be in good alignment. Indeed, Figure 10, using the
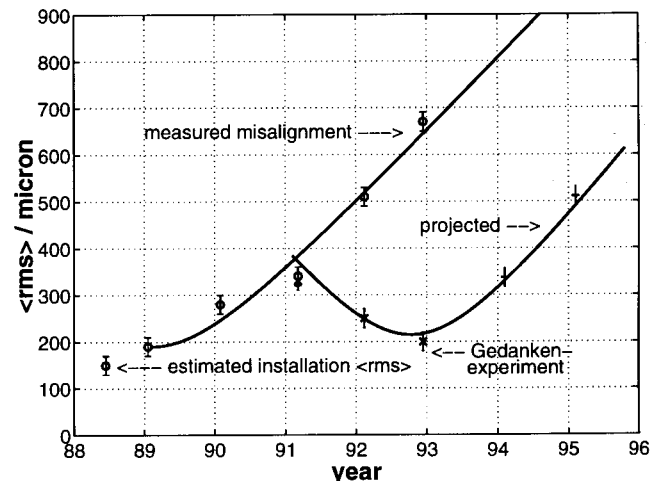
Figure 11 The <rms> of 48 quadrupoles in the straight of Point 1 of LEP in the Gedanken experiment performed in 1991 as described in the text. For 92 and 93 (December of 1992) the calculations are based on actual survey data (x's) and show that biased alignment *(Running With The Wind)* would have worked well. The data beyond 1993 (+'s) use a linear extrapolation of the 91->93 movement, but the initial positioning derived from the 89->91 data.

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[1] The coinage of this expression is probably due to John Poole of CERN's SL division
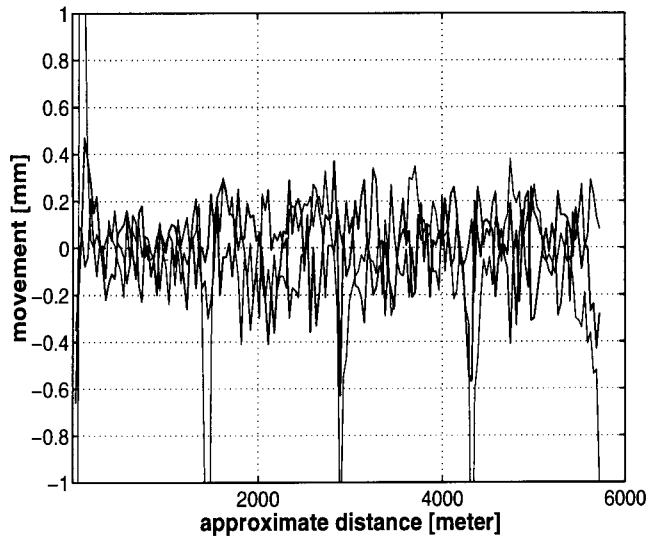
Figure 12 Movement of HERA wall monuments over a 20 month period. The four large movements are due to the loading of the experimental halls. Otherwise no systematic ground motion can be recognized. Also, the <rms> values are rather constant (between 0.16 and 0.18 mm).

the outliers from time to time.

Could the method of the Gedanken experiment be used in the installation of accelerator elements? Probably yes, since the tunnel can be surveyed long before placement of the elements and the final smoothing phase of alignment. The movements of the floor at the magnet locations can be monitored and magnet placement can be biased to take the known floor movements into account. Instinctively, engineers responsible for alignment want to line up the elements along an ideal (or at least smooth) orbit, but we know now there is a predictable time dependency of the smoothness; we should use it for better results by biasing the position of critical machine elements as described above.

All outliers in Figure 5 could be identified. Without exception they were due to particularly rapid floor movements and not to human error. Outliers can be damped with preventive survey and biased positioning before installation. While their number is not large and, therefore, their impact can be eliminated with a relatively small effort, they do have a large impact on the <rms> and consequently on operation. A good example is element 1.685 in Figures 6, 8, and 10 which could have been easily kept at small deviations, thus minimizing its considerable contribution to the overall <rms>. With this approach reality might actually be made to agree with the <rms> cut-offs in simulations [Keil 1992].

Is the unidirectionality of floor movements as found in LEP (and PEP, the SPS, ...) a universal law? Definitely not (again following the *Fischer Principle*). A good example is HERA at DESY. It is build in sand; there are no preferred geological movements. Consequently, the survey history of the monuments in the tunnel walls show only random movement. Figure 12, when compared to the LEP Figures 6 and 8, qualitatively shows this to be true.

So, in the end, what makes the tunnels move? It is believed mostly the geology of the site: details of the water flow, soil type, fault lines. Simple things like that. No tunnel floor can be built strong enough to resist the motion of the mountains. One good final example is the case of TT20 in a SPS transfer tunnel (Figure 13). There are several different explanations how this movement comes about. Some point to certain errors in the construction layout, which funnels water to this location. Others blame only the geology. In the end it does not matter. TT20 moves, year-in, year-out, in one direction.

ACKNOWLEDGMENTS Many people have contributed to the data and thoughts expressed here. My deepest gratitude goes to the late Gerry Fischer, who used an innocuous remark of mine about the difficulties the SLC arcs surely had to face in the alignment, to recruit me for the task. If I had

Figure 13 Accumulated movement of element TT20 in a SPS transfer tunnel.

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