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Measurements of Magnet Motions at the FFTB with the Wire Alignment System

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Introduction

The Final Focus Test Beam (FFTB) is a prototype final focus system for a future linear collider. An international collaboration consisting of members from Budker Institute (Novosibirsk), DESY (Hamburg), Fermilab (Chicago), KEK (Tsukuba), LAL (Orsay), MPI (Munich) and. SLAC (Stanford) has designed and built the beam line in a straight-ahead tunnel at the end of the SLAC linac.

The goal of the experiment is to achieve a spot size of 1.0 µm × 0.06 µm, to develop methods and techniques to tune and measure this small spot size and to show the operational feasibility of the techniques involved. Beside tight mechanical and electrical tolerances, extensively usage of beam-based alignment techniques and third order geometric and chromatic correction schemes are the basic tools to decrease the spot size.

In order to increase the long term stability of the set-up, the positions of the quadrupole and sextupole magnets are monitored with a wire alignment system: Two wires are stretched along all magnets in a straight beam line section. A harmonic rf-signal of 100 MHz is coupled to the wire. High resolution pick-up monitors attached to the magnet centers by means of tooling frames monitor continuously the motion of the magnets with respect to the wires, thus providing the data for a slow feed-back system.

The wire alignment system (WAS) was developed by DESY group MKI [1] based on previous works of group MEA [2]. The data acquisition is based on a PC-network with separate database, programs for data acquisition, data analysis and presentation, and a link to the SLAC control system.

The Wire Alignment System

The wire alignment system consists of 4 sections and 5 fix points called Wire Terminators (WT). The terminators are located near horizontal bending magnets which are necessary for the generation of dispersion.

The map of Fig. 1 gives a schematic overview of the four sections. Magnet numbers, related names, as well as the magnet positions and temperature sensor names are listed in Tab.1.

Each magnet carries two tooling frames with three Wire Position Monitors (WPM) as shown in Fig. 2. The wire monitors work in principle like Beam Position Monitors. The tooling frame is made from invar and is attached to the magnet split planes to serve as precise reference to the magnet center.

The three monitors allow to determine both transverse motions of the magnet and the rotation about both transverse and the longitudinal axis. The mover system can correct only the roll angle of the magnets, thus one tooling frame with two monitors would be sufficient, however, the tooling frames are also used as fiducial points for the conventional magnet alignment and hence two frames have been necessary.

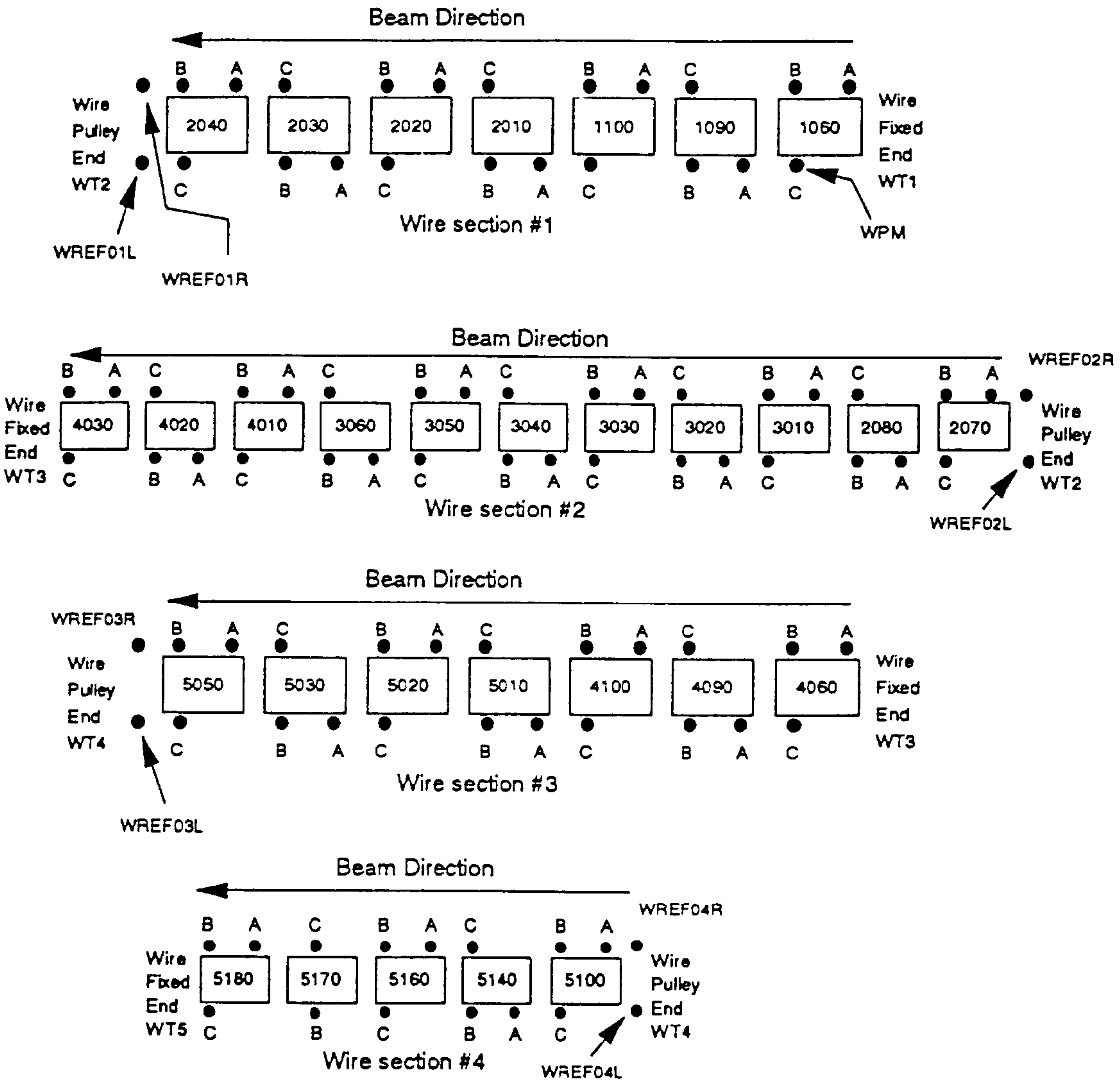

Fig. 1 Schematic layout of the wire alignment system. Each pulley has a reference WPM mounted next to it (e.g. WREF01L). This WPM tracks motions of the wire which occur when the pulleys ride up and down on their bearings.

In order to deduce the motion of the magnet center from the wire readings straight lines are fitted to the horizontal and vertical readings of those monitors which are located at one side of one magnet. The slopes of these lines are used to correct the readings for the longitudinal position with respect to the middle of the magnet.

This correction has in general only a small effect and is neglected in case of a failure of one monitor.

The corrected values $\Delta x_L, \Delta y_L$ and $\Delta x_R, \Delta y_R$ are used to calculate the motion of the magnet center. (The index L and R refer to the left and right wire, respectively.) :

$$\Delta y = \frac{\Delta y_R + \Delta y_L}{2}$$

Magnet name	Magnet number	Magnet position (ft)	Wire Monitor name	Temperature Sensor name
Wire Terminator 1				
QA2	1060	585.5	WM1060AX,CY	TSQ1060L,R
QM3A	1090	614.4	WM1090AX,CY	TSQ1090L,R
QN3A	1100	632.0	WM1100AX,CY	TSQ1100L,R
SF1A	2010	633.8		
QN3B	2020	635.7	WM2020AX,CY	
QN2A	2030	654.9	WM2030AX,CY	TSQ2030L,R
QN1	2040	676.8	WM2040AX,CY	TSQ2040L,R
Wire Terminator 2				
QN2B	2070	698.6	WM2070AX,CY	TSQ2070L,R
QN3C	2080	717.9	WM2080AX,CY	TSQ2080L,R
SF1B	3010	719.7	WM3010AX,CY	
QT1	3020	721.5	WM3020AX,CY	
QT2A	3030	732.6	WM3030AX,CY	TSQ3030L,R
QT2B	3040	734.8	WM3040AX,CY	TSQ3040L,R
QT3	3050	758.9	WM3050AX,CY	TSQ3050L,R
QT4	3060	783.8	WM3060AX,CY	
SD1A	4010	785.6	WM4010AX,CY	TSS4010L,R
QM3B	4020	787.4	WM4020AX,CY	
QM1A	4030	806.7	WM4030AX,CY	TSQ4030L,R
Wire Terminator 3				
QM2	4060	828.5	WM4060AX,CY	TSQ4060L,R
QM1B	4090	850.4	WM4090AX,CY	TSQ4090L,R
QM3C	4100	869.6	WM4100AX,CY	
SD1B	5010	871.4	WM5010AX,CY	TSS5010L,R
QM3D	5020	873.3	WM5020AX,CY	
QM1C	5030	903.5	WM5030AX,CY	TSQ5030L,R
QC5	5050	915.1	WM5050AX,CY	TSQ5050L,R
Wire Terminator 4				
QC4	5100	957.3	WM5100AX,CY	TSQ5100L,R
QC3	5140	993.0	WM5140AX,CY	TSQ5140L,R
QC2	5160	1013.0	WM5160AX,CY	TJQ5160L,R
QX1	5170	1019.9	WM5170BX,CY	TJQ5170L,R
QC1	5180	1022.7	WM5180AX,CY	TJQ5180L,R
Wire Terminator 5				

Tab. 1 List of device names and positions

$$\Delta\varphi = \frac{\Delta y_R - \Delta y_L}{D_x}$$

$$\Delta x = \frac{\Delta x_R + \Delta x_L}{2} - D_z \cdot \Delta\varphi$$

D_x = horizontal distance between left and right wire ~ 0.33m

D_z = vertical distance from the wire to the horizontal magnet split plane ~0.20m

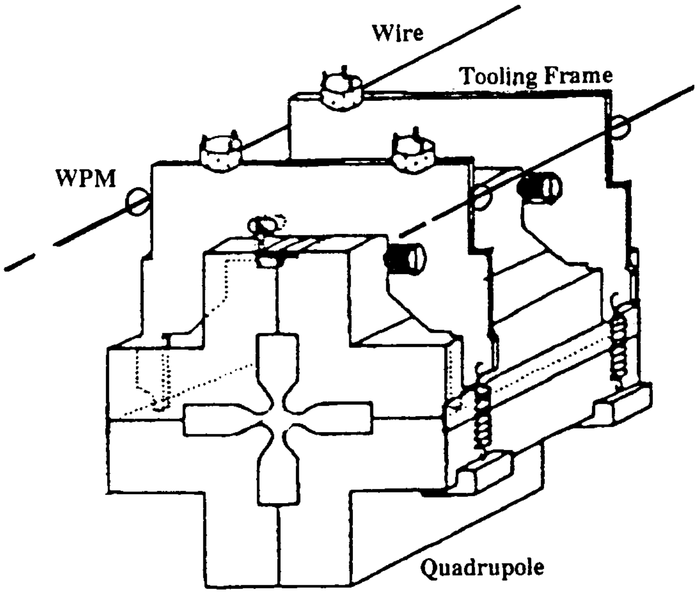

Fig. 2 Quadrupole magnet with tooling frames attached to the magnet split planes, Wire Position Monitors (WPM) and reference marks for the magnet alignment.

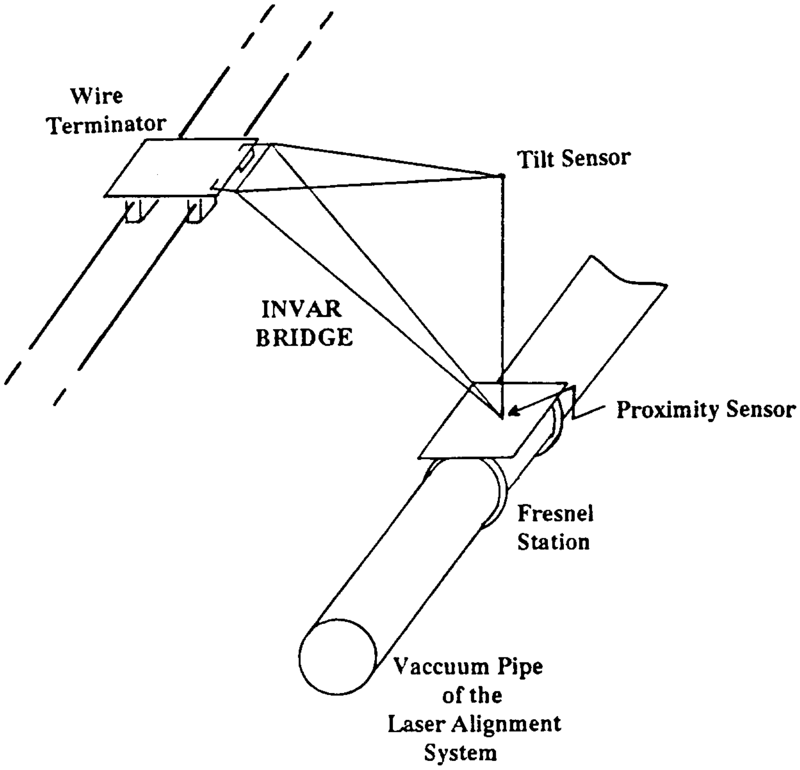

Fig. 3 Invar bridge for the measurement of the wire terminator motion with respect to the laser alignment system.

D_z depends on the sag of the wire and was determined by rotating some magnets in each section and fitting a parabola to the data for the rest of the magnets.

A harmonic rf-signal of 100 MHz is used as generating signal to give a strong coupling of the wire signal to the antennas in the wire monitor. The detected signal is then mixed with a 50 kHz signal which can easily be digitized with a 16 Bit ADC. Hence the resolution of the monitors is about 100 nm over a range of ± 1.5 mm.

The wires are stretched between two terminators. The wire tension is provided by a heavy mass (~35 kg) and transmitted over a low friction pulley to maintain constancy of force. A reference monitor, attached to the pulley casing, is used to detect motions of the pulley on its bearing.

The FFTB is build up in a straight-ahead tunnel at the end of the SLAC linac which is well insulated from the outside by a sand cover of several meters thickness. Only the last part of the beam line extends into a new extension building with no insulation. WT4 is the last element of the wire alignment system that is located in the old tunnel, WT5 and magnets in between are in the extension building. This configuration increases the sensitivity of the magnet positions in the downstream end of the beam line to thermal variations of the outside temperature.

Terminators 1, 2 and 5 are – like the magnets – based on solid blocks made out of a quartz epoxy called ANOCAST©.

Terminators 3 and 4 are based on a triangular steel support, mounted to the tunnel wall.

In order to keep track of the terminator motion, SLAC has developed a mechanical bridge system to measure the motion of terminators 3, 4 and 5 with respect to a laser alignment system that is used as general reference line for the SLAC linac. While the motion of the bridges are permanently detected with proximity and tilt sensors, the laser alignment system is not working continuously. The fresnel stations of the laser alignment system are less sensitive to thermal motions since they are build up directly onto the floor. Measurements with the wire alignment system and the laser alignment system indicate, however, that especially the downstream end of the FFTB line including WT5 and the fresnel station of the laser alignment system move with a night-day variation of up to some 10μm horizontally and 35μm vertically.

A schematic layout of the bridge system is shown in Fig.3.

The motion of wire terminator 1 and 2 will be corrected only for temperature correlated motions.

Error Sources and Correction Schemes

The sag of a stretched wire follows a hyperbolic cosine function that can be approximated by a parabola. (For typical FFTB values the difference between the hyperbolic cosine and a parabola is smaller than 10^{-9} m.)

Since the end points (wire terminators) are in general not in a horizontal line, the center of the parabola is shifted by Δs (see Fig. 4 for comparison). Hence, the wire sag is given by:

$$y(s) = \frac{(s-\Delta s)^2}{2 \cdot a} - y_0$$

with $$a = \frac{F \cdot g}{2 \cdot A}$$

F = tension of the stretched wire
g = gravitational constant
ρ = density of the wire material
A = cross sectional area of the wire

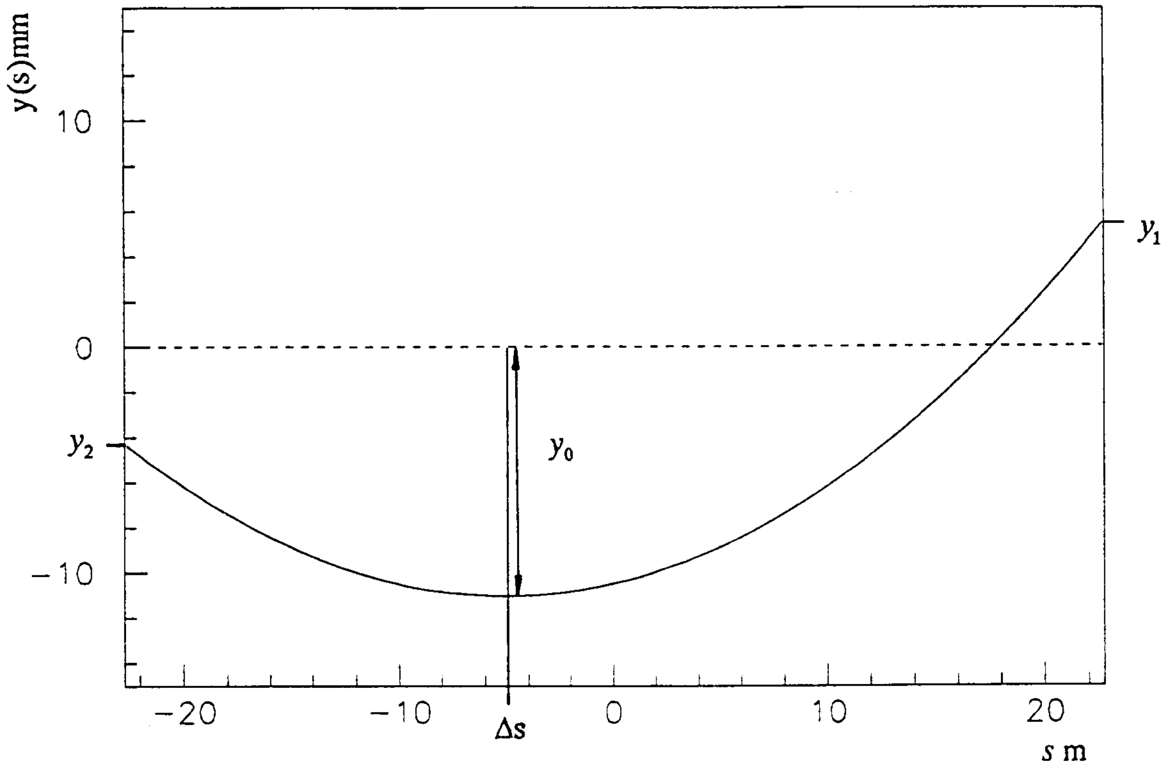

Fig. 4 Curvature of a stretched wire and notation of sag parameters.

Denoting the total length of the wire with L and with $y(L/2) = 0$ and $\Delta s = 0$ one finds:

$$y_0 = \frac{(L/2)^2}{2 \cdot a}$$

and thus $$\Delta s = \frac{(y_1 - y_2)a}{L}$$ (see Fig. 4).

The tension of the wire is provided by a heavy mass, hence the wire sag depends on the temperature only due to the change of the wire density per unit length. ~~We find~~:

$$y_0(\Delta T) = y_0(1 + \alpha \Delta T)$$

or for the change of the sag:

$$\Delta y_0(\Delta T) = y_0 \alpha \Delta T$$

with $\alpha \cong 10^{-5}$ K^{-1} and $y_0 \cong 20 * 10^{-3}$ m the maximum change of the wire sag in the middle of the wire section is 0.2 µm/K.

Laboratory observations indicate that due to a small friction in the pulley a hysteresis may occur in case of large, rapid temperature variations. So far we have no indications that the same effect occurs in the tunnel where the temperature varies more smoothly.

Another, more severe, error source is introduced by motions of the wire terminators. In principle these motions could be detected by means of 'overlapping wires'. This possibility has not been realised at the FFTB yet. Instead, the motion of 3 of the 5 terminators is detected with mechanical bridges equipped with proximity sensors and tilt sensors (see Fig. 3).

The measurement is done with respect to a fresnel station of the SLAC laser alignment system, which serves as general base line for the SLAC linac and the FFTB.

The purpose of the wire alignment system is not an absolute measurement of the magnet positions but to observe the relative motion of the magnets with respect to their positions defined by the beam-based alignment.

Hence, if the wire terminators move in the vertical direction or if the sag of the wire changes, the monitor readings follow a function, given by:

$$\Delta y(s) = \frac{(s-\Delta s)^2}{2\cdot a} - y_0 - \frac{(s-\Delta s')^2}{2\cdot a'} + y_0'$$
$$= s^2\left(\frac{1}{2a} - \frac{1}{2a'}\right) - s\left(\frac{\Delta s}{a} - \frac{\Delta s'}{a'}\right) + const.$$

symbols with a prime indicate the reading to a reference time

with $\Delta s = \frac{(y_1 - y_2)a}{L}$:

$$\Delta y(s) = s^2\left(\tfrac{1}{2a} - \tfrac{1}{2a'}\right) - \tfrac{s}{L}\left(y_1 - y_2 - (y_1' - y_2')\right) + const. \qquad (1)$$

The motion of the terminators leads to a linear correction of the wire readings.
Beside the possibility of an external measurement of the terminator motion, an estimate of this effect can be based on a least square fit to the monitor readings, thereby getting also information about a change of the wire sag.
Since we have two wires in each section, we can minimise

$$(\bar{y}_{Li} - y_{L(s)})\cdot(\bar{y}_{Ri} - y_{R(s)})\,\Big|_{s=i}$$

$\bar{y}_{L,R_i}$ = monitor reading on the left (right) wire at position i

$y_{L,R(s)}$ = fit function for the left (right) wire at position s=i

instead of $(\bar{y}_i - y_{(s)})^2$ for each wire separate.

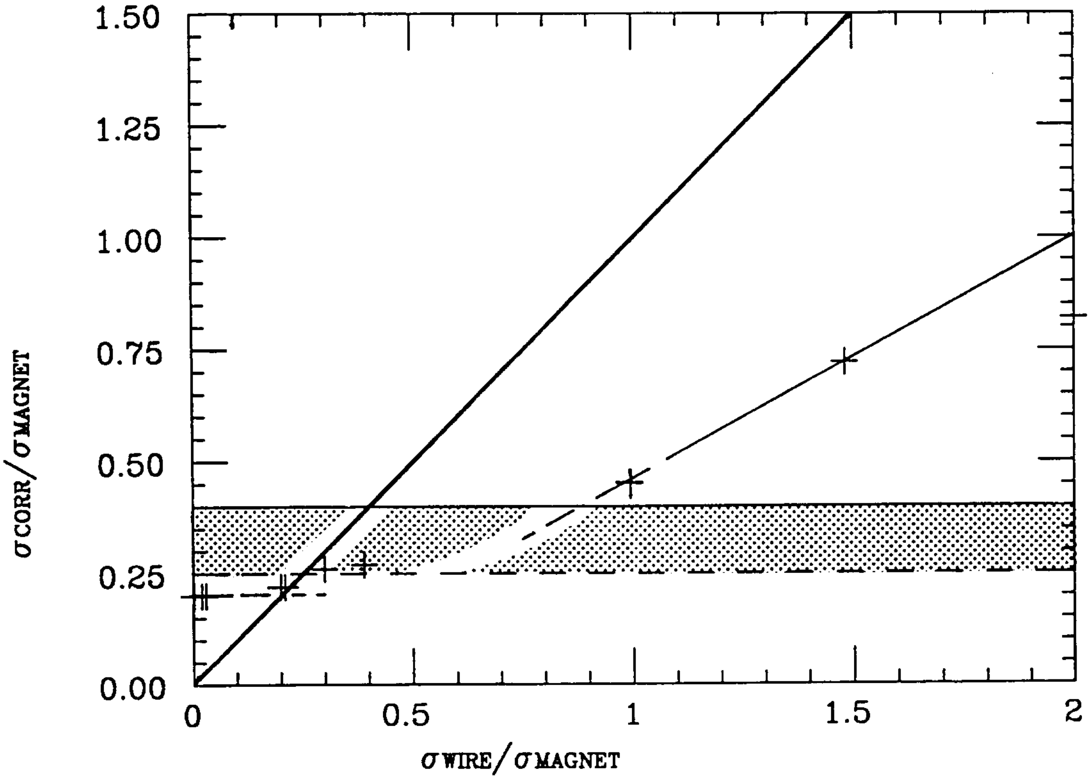

Fig. 5 Effect of errors due to terminator motions or wire sag variations with and without fitting algorithm. For details see text.

More details about the fit function are given in the appendix.

Fig. 5 shows results for a simulation based on this fitting algorithm for wire section 2 of the FFTB line.

Section 2 is 39m long and extends over 11 magnets which are not equally distributed along the wire. 8 of the magnets form 3 groups of 2 and 3 magnets, respectively, so that the typical distance between the magnets is about 6m. The magnet groups will in reality move more like a single magnet since each group is build up on a single anocast stand. In the simulation they are, however, treated as totally independent objects.

It is convenient to express the simulation result in terms of rms values over the magnet and wire displacements at the positions of the magnets in the section, respectively. An rms wire displacement of 1μm corresponds to a relative motion of the wire terminators of ~3μm or a change of the sag at the center of the wire of a similar amount. The magnets are displaced randomly with a gaussian distribution. The plotted results show average values for a large number of different random magnet settings.

The abzissa of Fig. 5 shows the ratio of the rms wire displacement to the rms magnet displacement. The ordinate of Fig. 5 shows the ratio of the rms magnet displacement after correction to the rms displacement before correction. Here correction means that the corrected magnet position is given by the difference of the initial displacement and of the displacement as calculated with the fit algorithm. So if the fit algorithm would work perfectly $\sigma_{corr}/\sigma_{Magnet}$ would be zero.

The bold diagonal refers to the result if no fitting algorithm is used i.e. $\sigma_{corr} = \sigma_{wire}$.

If the fitting algorithm is applied, $\sigma_{corr}/\sigma_{Magnet}$ is on the average 0.4, i.e. on the average only 40% of the magnet motions are corrected, independent of the motion of the wire.

This number is reduced to 25% if the motion of the wire terminators is assumed to be known. However, knowing the motion of the wire terminators reduces also typical values of $\sigma_{wire}/\sigma_{Magnet}$ since σ_{wire} is caused only by changes of the wire sag which is small.

By correcting only a fraction of the fitted wire displacement, a mixture of the results can be realised (crosses and light line in Fig. 5). In the plotted case only half of the fitted correction was applied.

These results indicate that due to the limited statistics (only 11 magnets in a line), the direct application of the fitting algorithm is useful only if $\sigma_{wire}/\sigma_{Magnet} > 0.4$.

If σ_{wire} is a smaller fraction of σ_{Magnet} the situation could be somewhat improved by correcting only a fraction of the fitting result. In any case typical values for the ratio $\sigma_{wire}/\sigma_{Magnet}$ would have to be determined to find the optimum correction scheme which is a difficult task.

If one assumes that the terminators move typically with the same amplitude as the magnets and if sag variations are negligible $\sigma_{wire}/\sigma_{Magnet}$ would be 0.3, i.e. the result could not be improved with the fit algorithm.

The fit algorithm has not yet been implemented into the data analysis to allow a simpler interpretation of the measurements.

It should be noted that correlated motions of the magnets which are introduced for example by temperature effects are treated as terminator motions by the fit algorithm if the wave length of the motion is of the order of the wire length.

In the next section the sensitivity of the beam to correlated magnet displacements will be discussed.

Sensitivity of the spot size on misalignments

Using the wire alignment system, the residual alignment errors introduced by the terminator motion or by a change of the wire sag are correlated errors in form of a straight line or a parabola. This is the case weather a fitting algorithm is used or not.

In order to investigate the effect of these correlated alignment errors on the spot size of the beam at the final focal point the program DIMAD and the standard FFTB optics deck has been used.

We consider the vertical case only.

Fig. 6 shows the effect of misaligning a single magnet of the beam line by 10µm. No optical corrections have been applied to the beam to compensate the misalignment. The nominal spot size is 60nm. The spot size is particularly sensitive to motions of the magnets in the -I transformation in the CCS Y section i.e. magnets SD1A, QM1A, QM2, QM1B and SD1B which are close to wire terminator 3. The other important contributions are generated by QM1C, QC5 and QC4 near terminator 4 and – to a smaller amount – by SF1A, QN2A, QN2B and SF1B in the CCS X section. These results differ somewhat from previous calculations [3] which might be due to a somewhat different optics.

Fig.7 shows the effect of a vertical misalignment of 50µm of the various terminators.

The spot size is particularly sensitive to motions of WT3 and WT4 which are close to the magnets mentioned above. The alignment tolerances for the terminators are hence relaxed only by a factor of ~5 compared to the magnet tolerances.

Fig. 7 also shows the effect of a change of the maximum wire sag by 50µm. Section 2 and 3 are most sensitive.

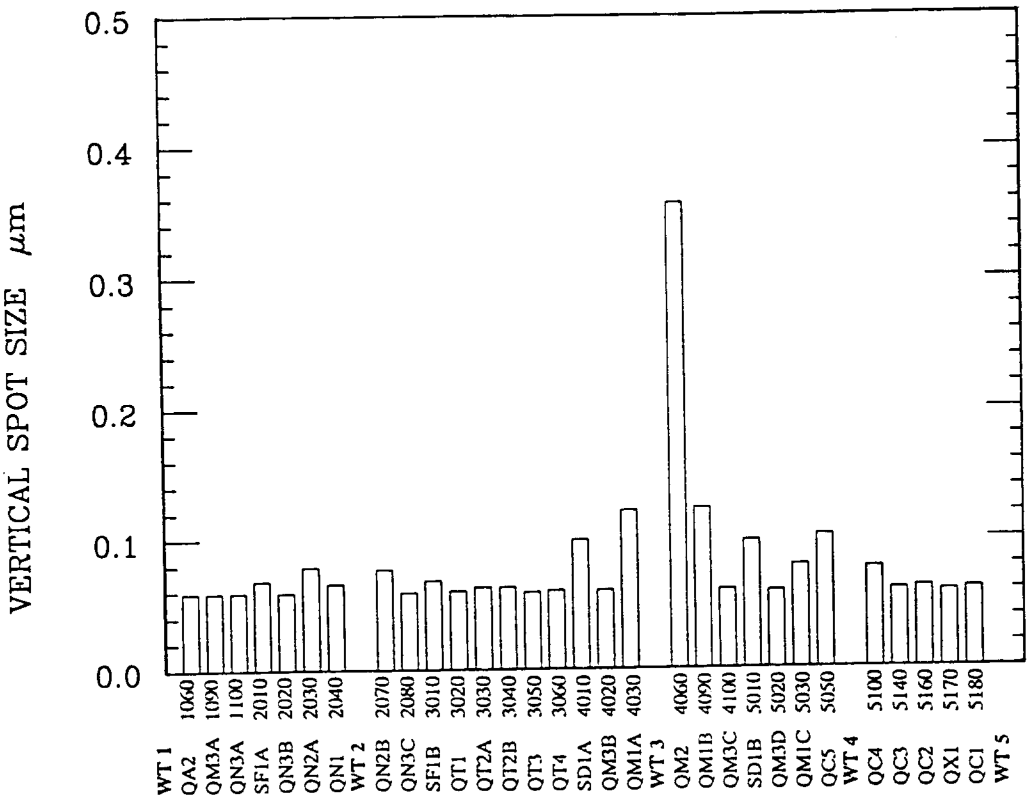

Fig. 6 Vertical spot size for a 10µm vertical misalignment of single magnets in the FFTB line. Nominal spot size: 60nm.

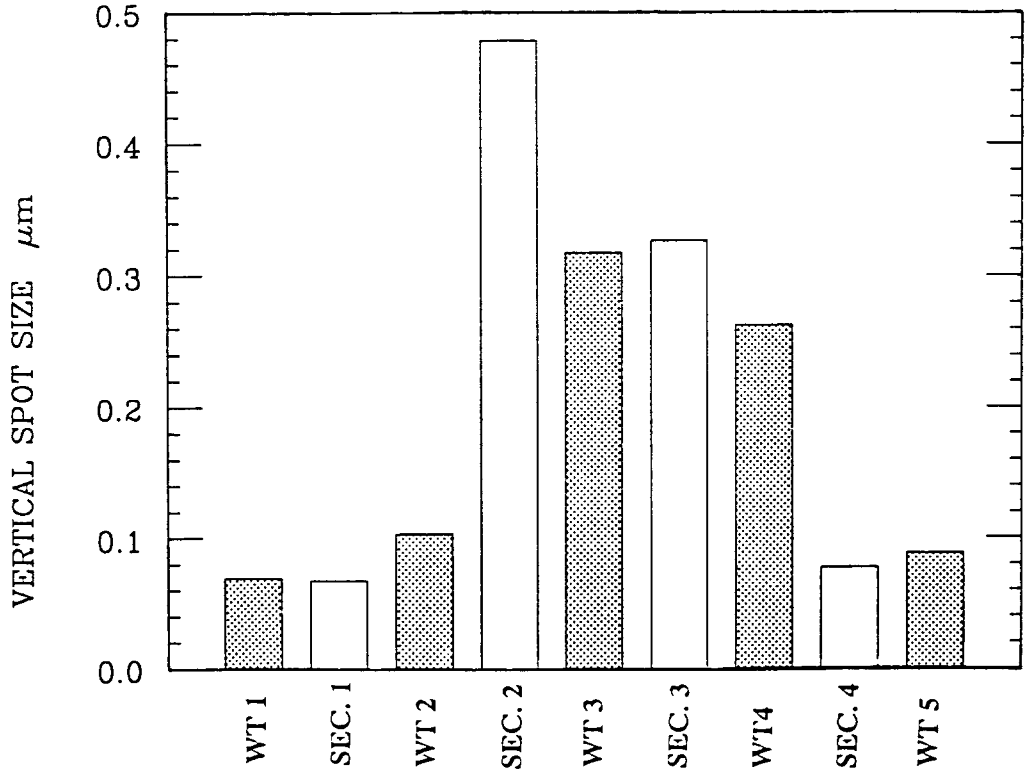

Fig. 7 Vertical spot size for a 50μm vertical misalignment of the wire terminators in the FFTB line (WT1-5) and a change of the maximum wire sag Δy_0 of 50μm (SEC.1-4). Nominal spot size: 60nm.

Thermal Effects

I Vertical motions of the magnets

Thermal effects are the most obvious reasons for magnet motions in the FFTB line.
Since the magnets are placed on solid blocks of anocast, the motions can be described simply by the thermal expansion coefficient of $12 \cdot 10^{-6}$ K^{-1} and the heights of the blocks ranging from 0.80m to 1.30m. In addition an aluminium support of 0.26m heights is placed between the anocast stand and the magnet. Assuming that the stand and the aluminium support have the same temperature we expect a vertical thermal expansion of 16 to 22 μm/K.
The magnet itself may have a different temperature due to the heating of the electrical currents. A temperature variation of the magnet leads to a vertical shift of the magnet center of 1.8μm/K.
Fig.8 shows a measurement of magnet QT3 (in the middle of section 2) extending over 14 days. The lines show:

1. The readings of the three wire position monitors WM3050AY, -BY and -CY. AY and BY are on the same wire while CY measures with respect to the opposite wire (see Fig. 1).
2. The temperature of the anocast stand (TSQ3050R) and the magnet (TSQ3050L).
3. The LVDT reading of the mover system.

At the sixth day the FFTB magnets were switched on for seven days leading to a temporary temperature increase of ~2.5K on the magnet stand and ~3.3K on the magnet. While the magnet reaches its temperature within roughly 10 hours, we observe a temperature increase of 2K within 24 hours followed by a slow drift of 0.1K per day at the anocast stand. A

temperature correlated motion of the magnets can be seen. (Note that the wire readings are negative when the magnets move up.)
Fig.9 shows the same measurement but here the wire readings have been corrected for:

- the motion of WT3
- the LVDT reading
- the thermal effects

While the reading of the monitors on the right wire (AY and BY) is reduced to ~10µm, the motion of the left wire is still about 25µm. This difference seems to be caused by a temperature correlated rotation of the triangular steel support of WT3.

II Horizontal motions of the magnets

Horizontal motions of the magnets are introduced due to the asymmetric construction of the mover system. The effect depends on the temperature of the magnet itself and on the temperature of the aluminium support plate. In the case that both temperatures change by the same amount the motion is about 1.5 µm/K. If the temperature change is different the effect can be up to 2.2 times larger. Even this is nearly negligible since the beam is not very sensitive to horizontal motions.

III Vertical motions of the Wire Terminators

The temperature correlated vertical motion of WT1 and WT2 can be easily predicted within ~10 µm from temperature measurements. Fig. 10 shows a measurement of the terminator temperature and a simultaneously taken laser interferometer measurement of the terminator motion. An expansion of ~16 µm/K can be estimated which fits well into theoretical predictions. The temperature sensor is placed in a hole of the anocast stand to measure the core temperature. Some delay of the terminator motion with respect to the measured temperature can nevertheless be observed.

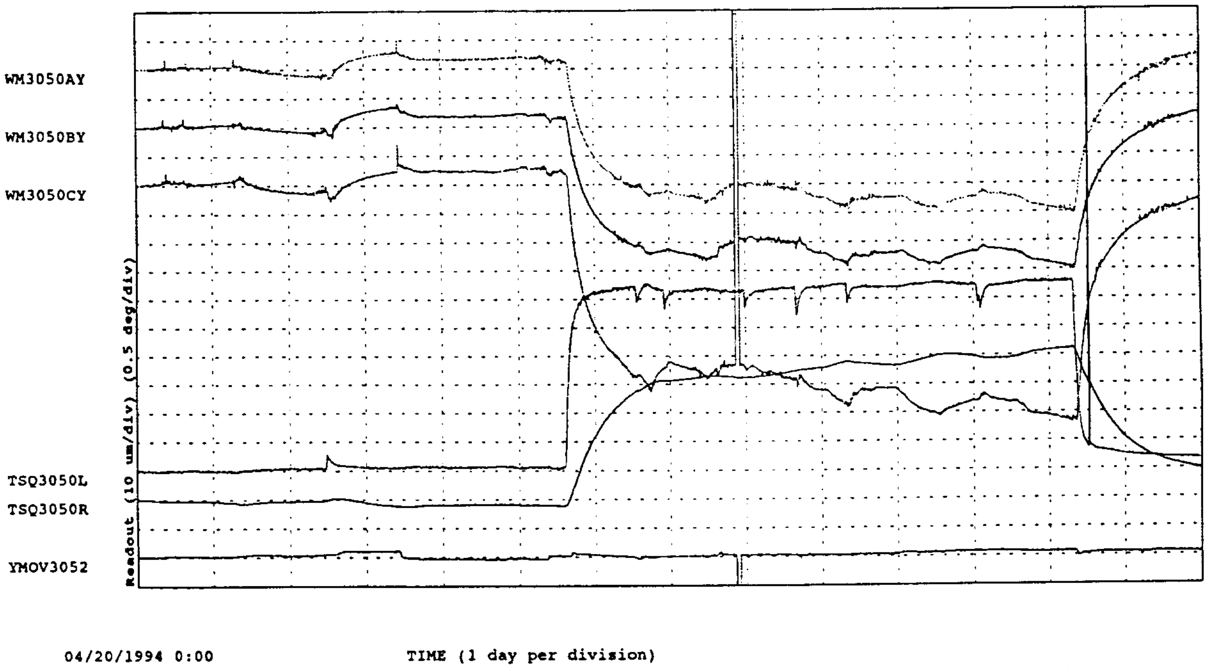

Fig. 8 Motions of Magnet QC3 3050 starting at 04/20/94 0:00. At the sixth day the magnets have been switched on for seven days.
WM3050AY -CY = vertical magnet readings
TSQ3050L = magnet temperature
TSQ3050R = temperature of the magnet stand
YMOV3052 = LVDT reading of the mover system

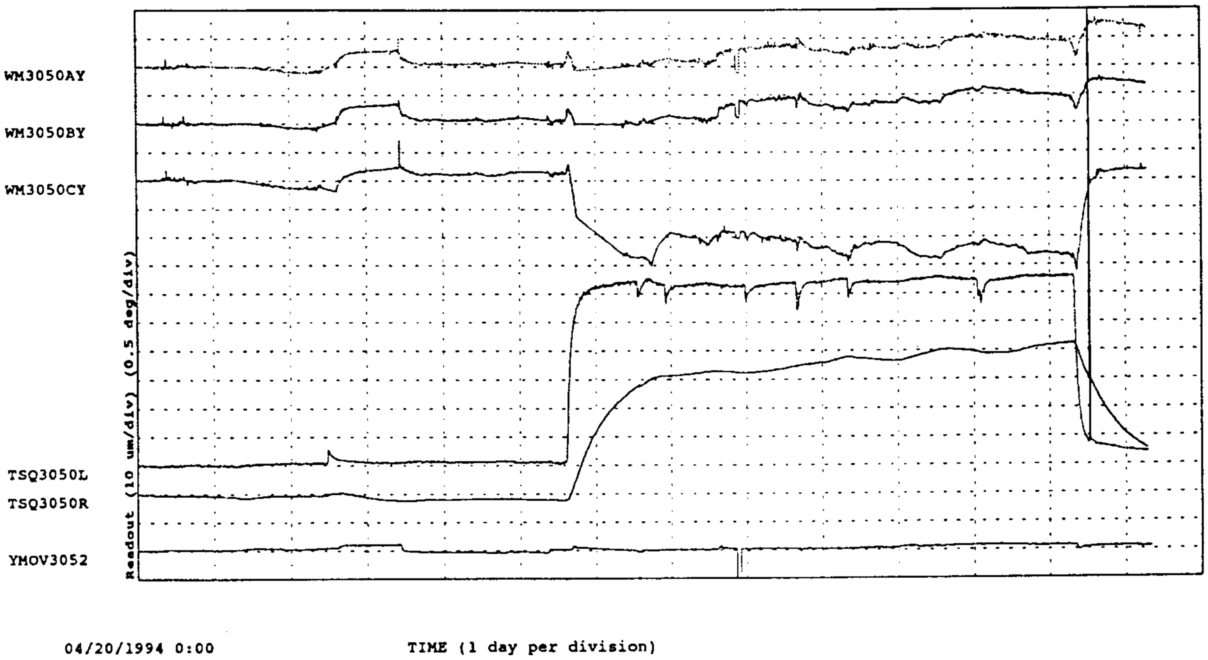

Fig. 9 Same as Fig. 8 but with correction of the wire readings for the motion of WT3, the LVDT reading of the mover system and temperature effects.

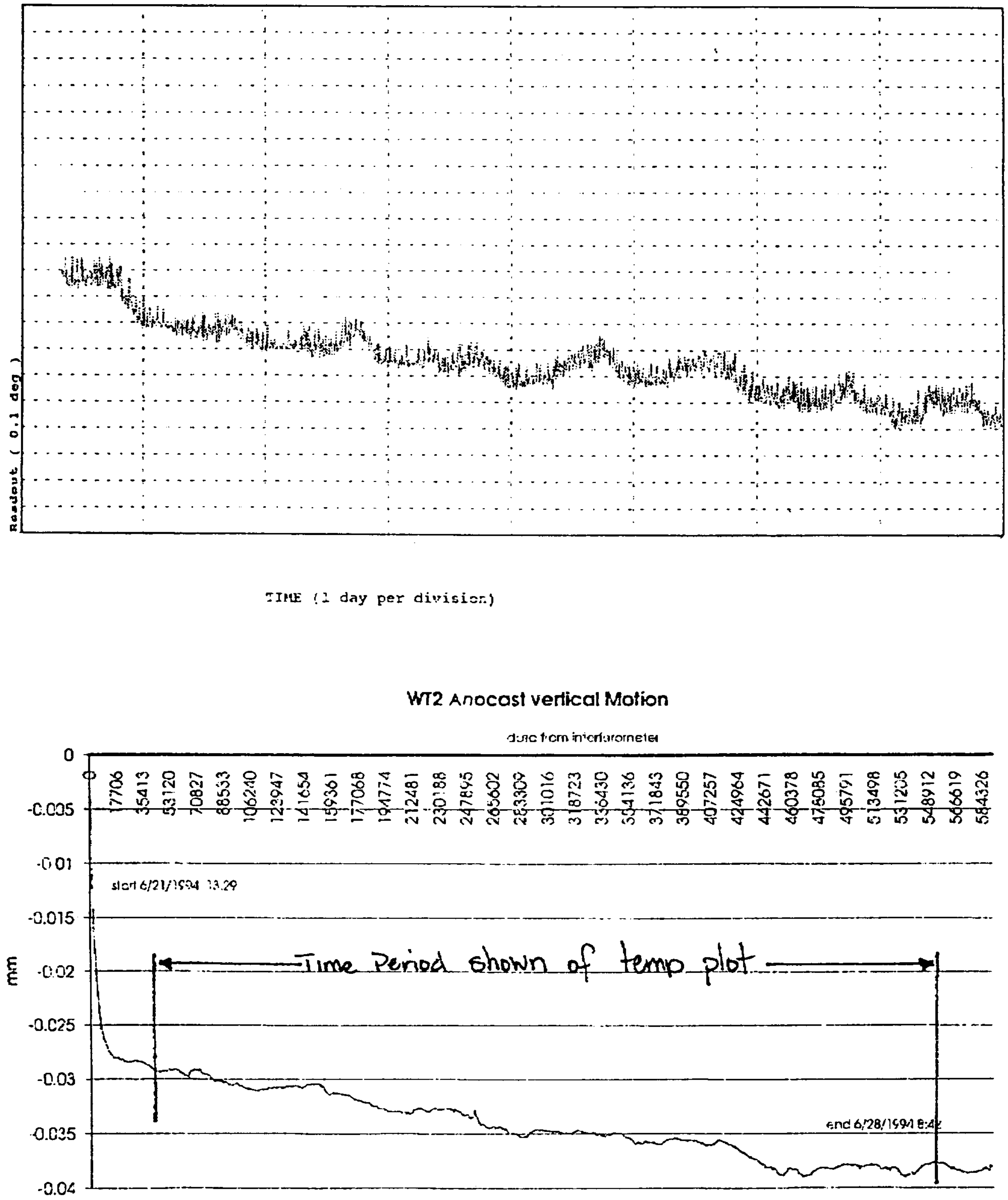

Fig. 10 Thermal expansion of wire terminator 2 (WT2). The upper graph shows the temperature of the anocast stand, while in the lower graph the read out of the laser interferometer attached to the stand is plotted. The temperature measurement is somewhat diluted due to electronic noise.

Measurements at the beam line

First measurements with the wire alignment system were taken during the second FFTB run in spring 1994.

The main goals of this run have been to commission the beam line, commission new kinds of spot size monitors and to tune the beam to a small spot size. At the end of the run a spot size of 1.5 × 0.075 μm has been achieved.

Due to the limited time with a small, sensitive spot size the wire alignment system has not been used for the beam line stabilisation so far.

The past run divides in FFTB run time (FFTB 'ON') of typically 5 to 7 days and intermediate SLC commissioning time (FFTB 'OFF') of also 5 to 7 days.

The temperature difference in the tunnel between FFTB 'ON' and FFTB 'OFF' was about 3 K. In addition a slow temperature increase over the whole run period of ~2 month was observed. During the tuning procedures the magnets have been moved and the currents have been changed. Hence the conditions in the tunnel have not been very stable and are not representative for what we might expect for a future Linear Collider.

In the following we will concentrate on measurements taken during the last week of run time, where the conditions have been most stable. These measurements are not necessarily representative for the past run, but show some effects which might be expected for a future Linear Collider.

I Vertical Motion

Fig. 11 shows a history plot of quadrupole QT1 (3020), starting at Wednesday the 11. of May and extending over 6 days to the 16. of May. The lines represent the vertical readings of the three wire monitors attached to the magnet (WM3020AY, -BY,-CY), a temperature monitor attached to the magnet stand (TSQ2080L) and the reading of the vertical LVDT of the mover system (YMOV3022). On Monday the magnet has been moved from its position for a short while, leading to the sharp peaks in the wire readings and the LVDT reading.

The temperature has been increased by roughly 0.7 degree during the period of 6 days and the magnet has moved up by ~30μm (the wire readings are inverse to the magnet motion). Assuming an equal temperature of the magnet stand, the magnet support (mover, etc.) and the magnet itself one would deduce a motion of only ~15μm.

The wire readings indicate a small night-day variation below ~3μm and an additional small stochastic signal during day time which, however, can not be seen on Saturday and Sunday. The source of the signal seems to be cultural noise.

Man-made motions are well known from vibration measurements. It is, however, interesting that we similar effects can be observed with the wire alignment system. Since each measured point shows an average of about 1 second, the system is not able to detect vibrations above ~1 Hz. Below 1 Hz the wave length of waves travelling through the ground is much longer than the wire section, so that the section should move as a whole.

The observed motion seems to have dissipative character, similar as predicted by the ATL law [4, 5] which, however, has not been related to cultural noise so far.

Fig. 12 shows the motion of magnet QM2 (4060) in the middle of the CCY section (channel names and dates equivalent to Fig. 10). QM2 is of special interest, since the spot size is most sensitive to the motion of this magnet. The motion of about 12μm in 6 days would lead to a spot size increase of above 400nm. However, the time scale of the motion is in general slow enough to re-tune the spot size within reasonable time steps.

In Fig. 13 the motion of magnet QC4 (5100) is plotted. The magnets of Fig. 11 and 12 are located in the old linac building which is well insulated with a sand cover while QC4 is the first magnet (downstream) in the new extension building which has no special insulation.

As one might expect, large periodic night-day fluctuations of ~35μm can be observed which, however, have no strong correlation to the temperature of the magnet stand.

In addition a slow drift of ~5μm per day correlated to a temperature increase of ~0.2 K per day can be found. This motion of ~25μm/ K is close to the theoretical value for a pure temperature variation of the magnet stand. (The reason for the steps in the readings of monitors -Ay and -By on Sunday and Monday is not fully understood.)

Fig. 14 shows the motion of QC1 (5180), the last magnet before the final focal point. The final doublet magnets, i.e. QC1 together with QX1 and QC2, are mounted on a special positioning table [6]. The night-day variations of the magnet position are below ~12μm. The temperature sensor is not connected directly to the quad table but to a nearby laser station of the laser alignment system.

The measurements on the magnets of section 4 indicate that the hole research yard including all magnets and wire terminator 5 moves up and down by ~35μm per day. Since wire terminator 4 is located in the old linac tunnel, while wire terminator 5 moves with the research yard the wire readings appear demagnified for the magnets closer to wire terminator 5. The distance of QC1 to wire terminator 5 is approximately one third of the distance to wire terminator 4, hence the reading is reduced by a factor of ~3.

II Horizontal Motion

The horizontal magnet motion is not as critical as the vertical since it has not such strong effects on the spot size.

Small horizontal motions are introduced due to the asymmetric construction of the mover system. (The horizontal fix point for thermal motions is not in the split plane of the magnet.) The observed motions are, however, larger than due to pure temperature variations of the magnet stand and the magnet, respectively. As in case of the vertical motion, the horizontal motions are largest in the extension building. Fig. 15 and 16 show examples for magnet QC3 (5140) and QC1 (5180), respectively.

The night-day variations are about ~30μm for QC3 and ~20μm for QC1. In addition a temperature correlated drift of ~20μm/ K can be observed which is a factor of 5 larger than expected.

III Wire Terminators and Bridges

Wire terminator 1,2 and 5 are based on an Anocast stand, similar to the magnet stands while terminator 3 and 4 are mounted to the tunnel wall. Large motions have been observed especially at the wall-mounted terminators 3 and 4 in the beginning of the run time in combination with large temperature fluctuations in the tunnel (FFTB 'ON' and FFTB 'OFF').

Fig. 17 shows the horizontal motion of all magnets after 24 hours of observation. The readings of the bridge system are not taken into account. The measurement was taken after switching the magnets on, hence the temperature in the tunnel increases by 1.0 – 1.5K within the 24 hours. Section 3 shows a clear offset. Fig. 18 shows the same measurement but includes the corrections of the bridge system. (In addition the sign of all readings has been reversed between both plots.) Now the motion of section 3 is reduced to ~15μm.

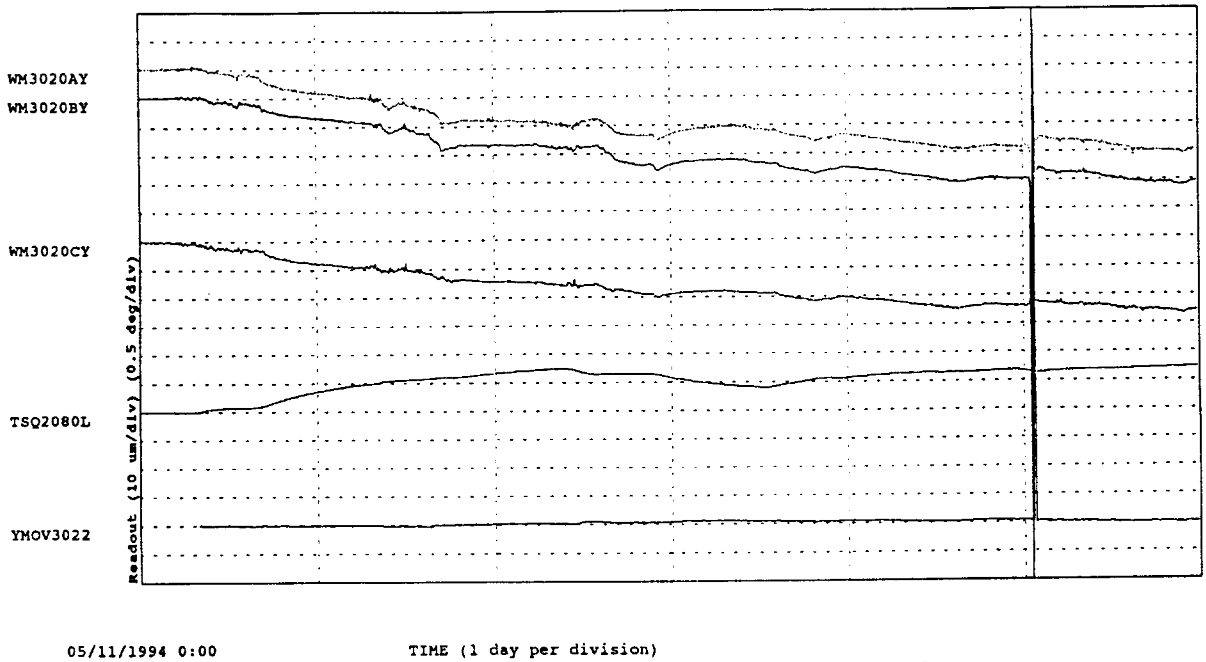

Fig. 11 History plot of magnet QT1 3020 starting Wednesday 11 of May.
WM3020AY, -CY = vertical wire reading
TSQ3020L = temperature of the magnet stand
YMOV3022 = LVDT reading of the mover system

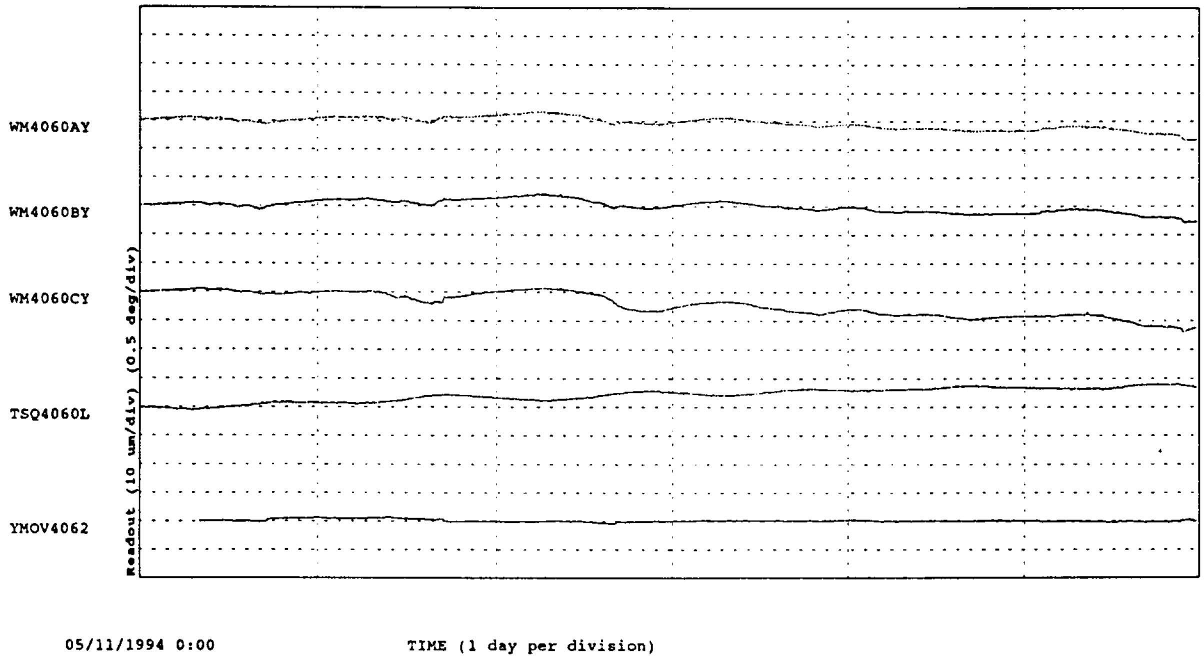

Fig. 12 History plot of magnet QM2 4060 starting Wednesday 11 of May.
WM4060AY, -CY = vertical wire reading
TSQ4060L = temperature of the magnet stand
YMOV4062 = LVDT reading of the mover system

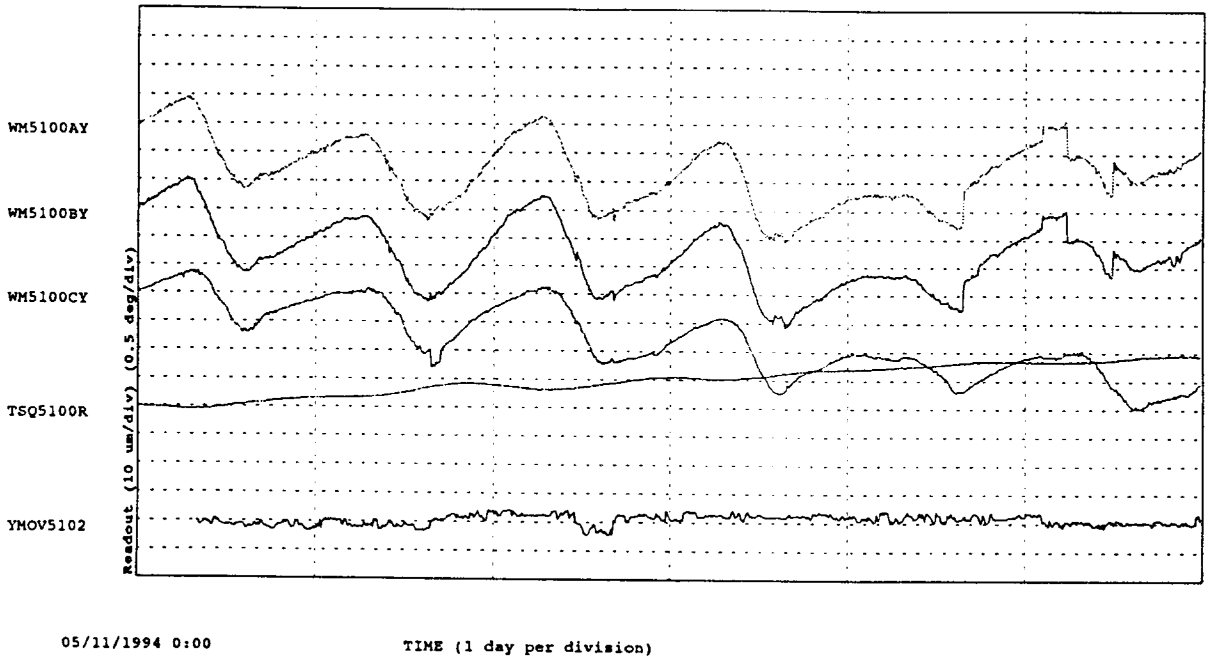

Fig. 13 History plot of magnet QC4 5100 starting Wednesday 11 of May.
WM5100AY, -CY = vertical wire reading
TSQ5100R = temperature of the magnet stand
YMOV5102 = LVDT reading of the mover system

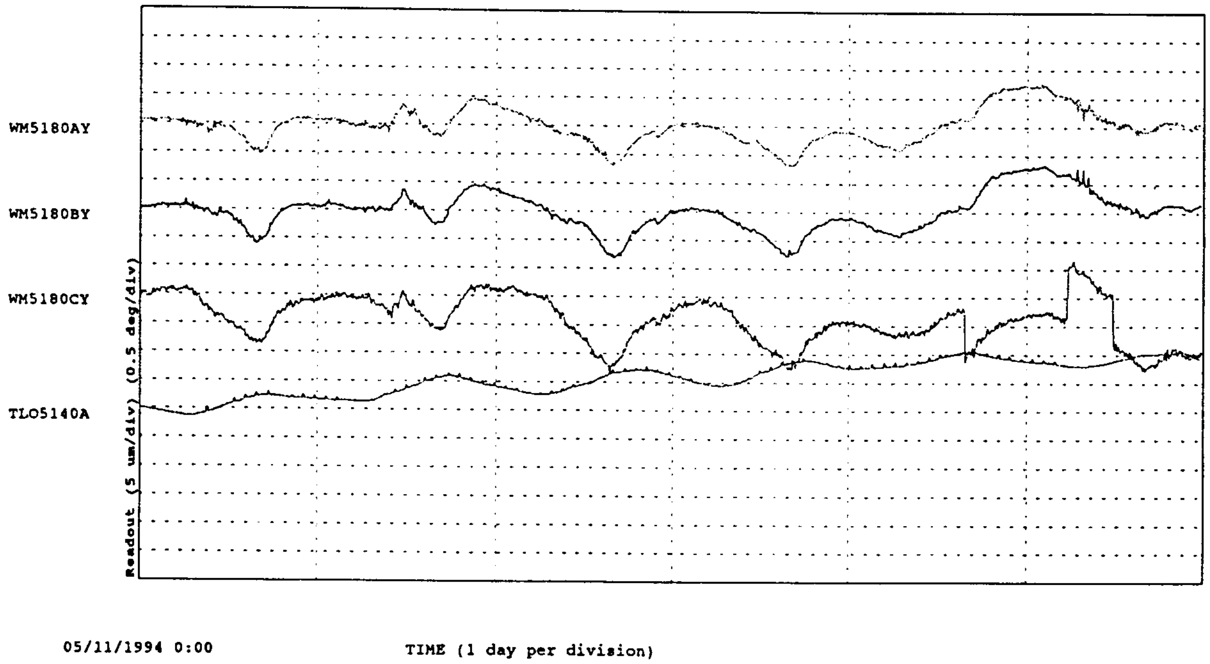

Fig. 14 History plot of magnet QC1 5180 starting Wednesday 11 of May.
WM5180AY, -CY = vertical wire reading
TLO5140A = temperature of the magnet stand

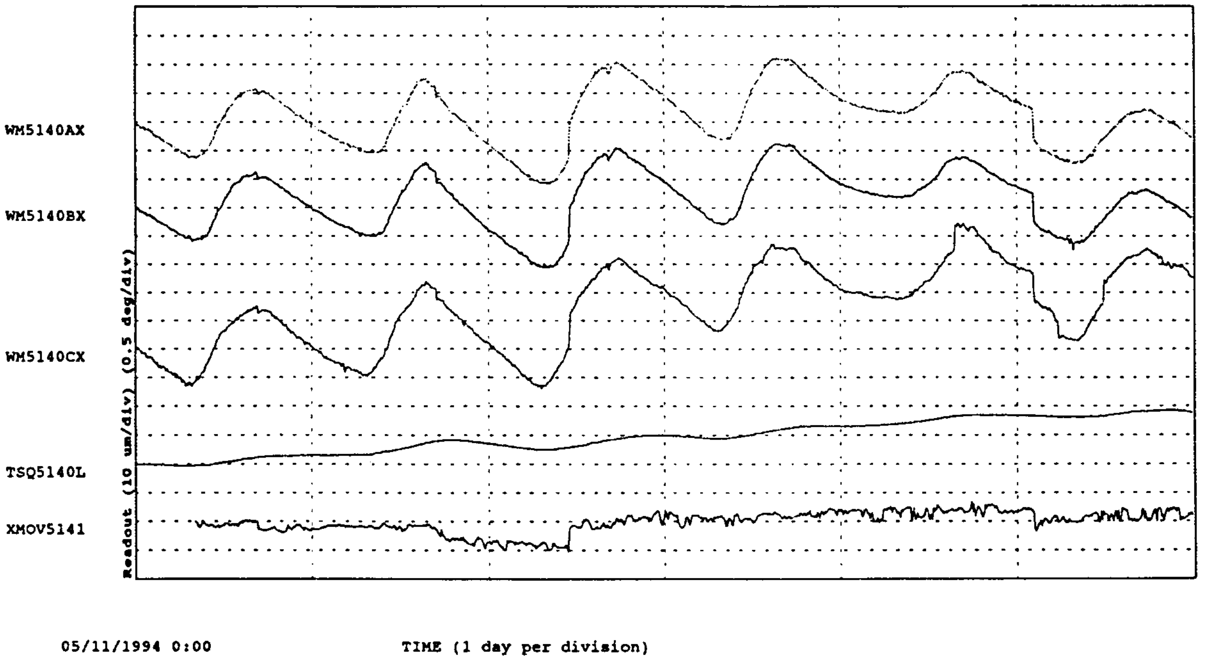

Fig. 15 History plot of magnet QC3 5140 starting Wednesday 11 of May.
WM5140AX, -CX = horizontal wire reading
TSQ5140L = temperature of the magnet stand
YMOV5141 = LVDT reading of the mover system

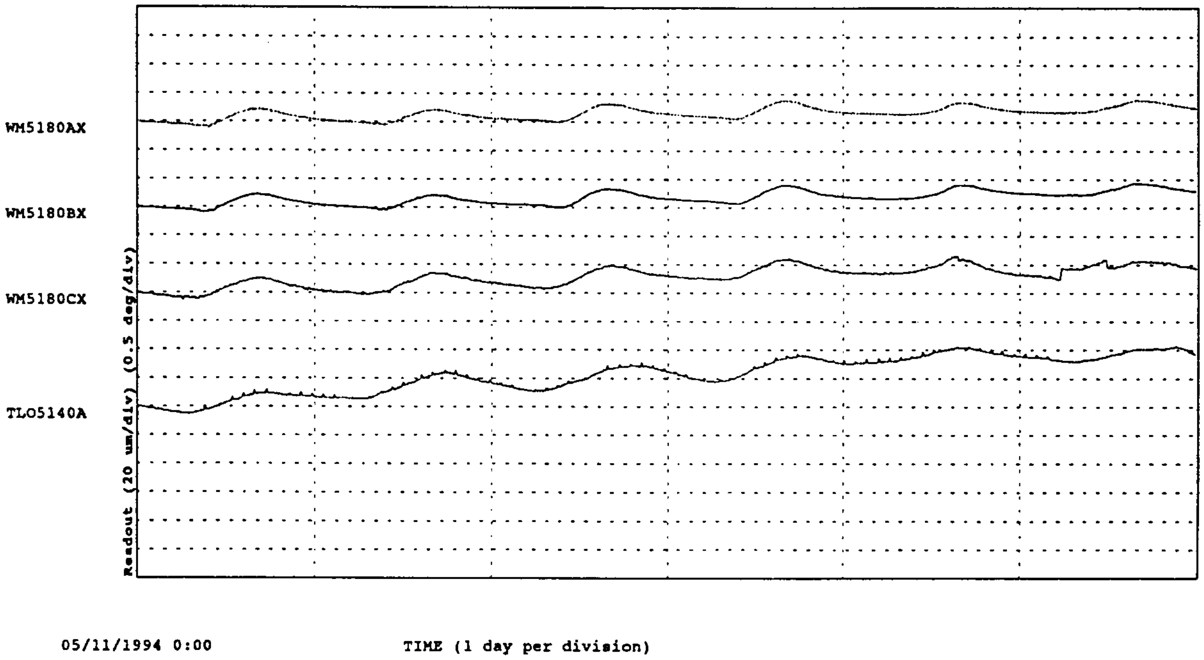

Fig. 16 History plot of magnet QC1 5180 starting Wednesday 11 of May.
WM5180AX, -CX = horizontal wire reading
TLO5140A = temperature of the magnet stand

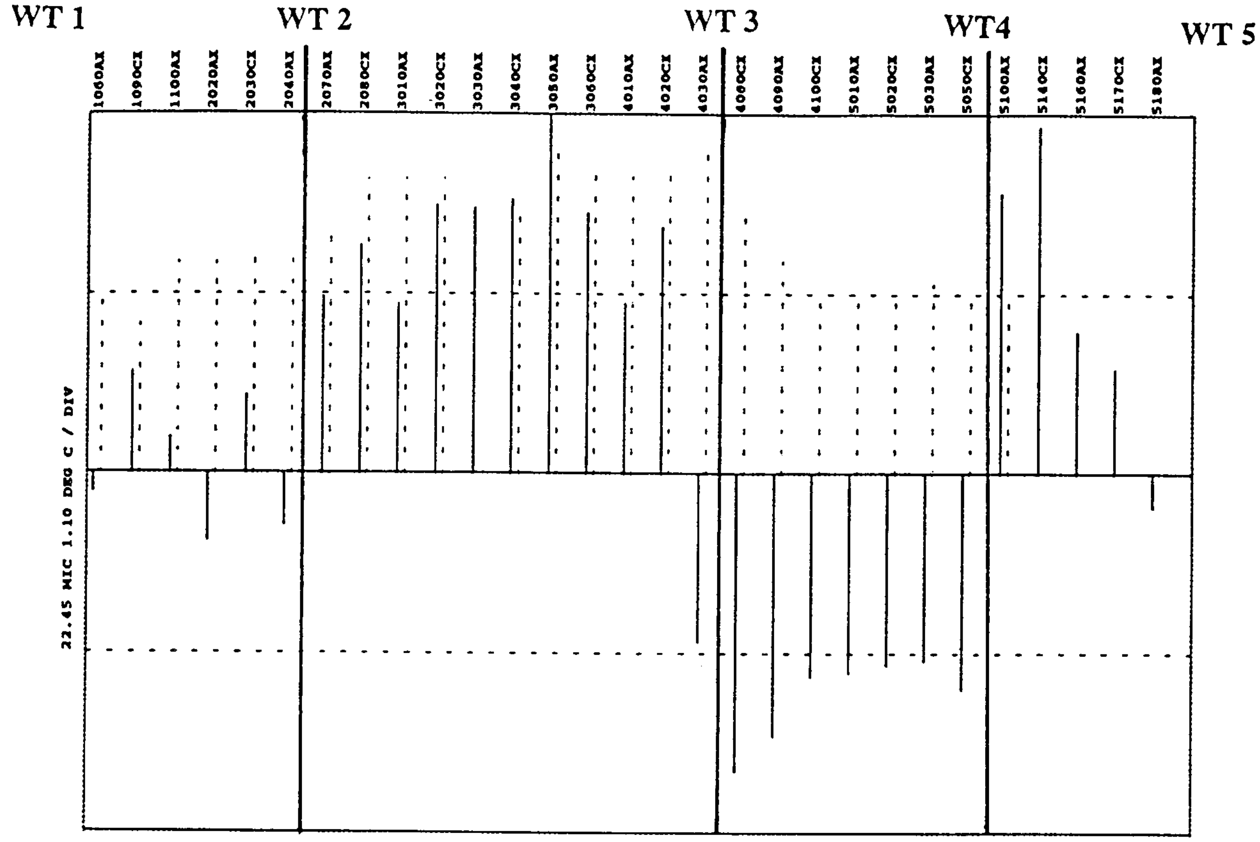

Fig. 17 Difference of horizontal magnet positions and temperatures over a period of 24 hours. Readings of the bridge system are not included. Solid lines: horizontal magnet motion, dotted lines: temperature readings.

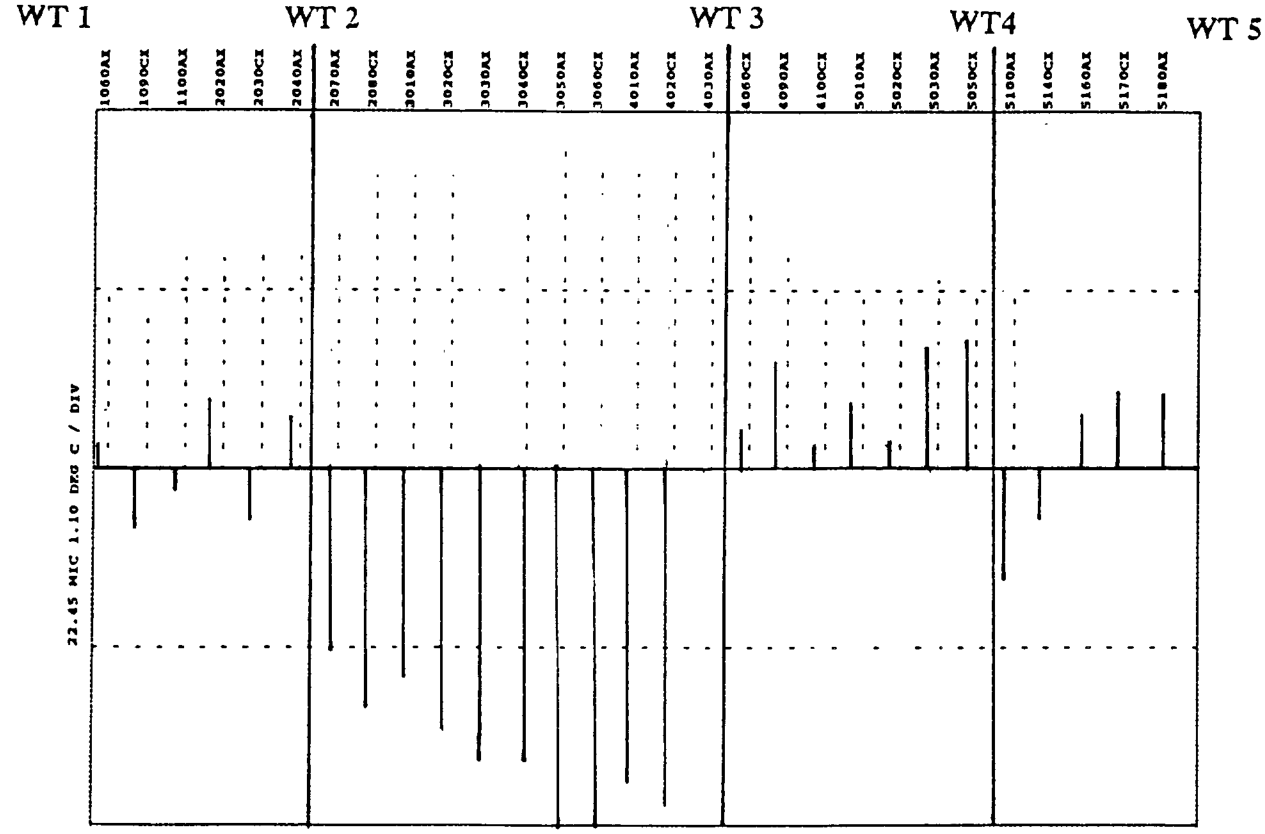

Fig. 18 Same as Fig. 17 but with corrected terminator motions and reversed sign of the displacement readings.

Conclusion

The wire alignment system has worked for extended periods of time without major problems. Motions of 30 magnets in a beam line of ~150m length have been measured with high resolution. Due to the limited time with a small, sensitive spot size the wire alignment system has not been used for the beam line stabilisation so far. Weak points of the system are the wire terminator motions which can be measured only with an external system in the FFTB. A future wire alignment system should be build with 'overlapping wires', so that the motions of the terminators can be continuously observed.

The magnet positions in the FFTB line are dominated by motions due to thermal expansion. A good qualitative understanding of the magnet motion in the up stream end of the tunnel can be based on temperature measurements and simple mechanical models. The down stream end of the beam line is located in the extension building. The motions are in general larger than in the up stream end of the tunnel. Simple mechanical models underestimate the motions due to temperature variations significantly. Measurements with the wire alignment system and with the laser alignment system indicate that the extension building moves as a whole with respect to the components in the old linac tunnel.

The final focus system of a future Linear Collider will be build up in a well insulated tunnel. In addition the run periods will be longer so that the temperature will be more stable. Motions due to thermal expansion may nevertheless play an important role. This motions are in general correlated over long distances. It has been shown, however, that also correlated misalignments can lead to a significant spot size increase.

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Appendix

Defining the fit function by:

$$y_{L(s)} = \alpha_L x_i^2 + \beta x_i + \gamma_L \Big|_{s=i}$$

$$y_{R(s)} = \alpha_R x_i^2 + \beta x_i + \gamma_R \Big|_{s=i}$$

the minimum of : $(\bar{y}_{Li} - y_{L(s)}) \cdot (\bar{y}_{Ri} - y_{R(s)}) \Big|_{s=i}$ is given by:

$$\alpha_L = \frac{B_R - 2D\beta}{E}$$

$$\alpha_R = \frac{B_L - 2D\beta}{E}$$

$$\beta = \frac{A \cdot E - (B_R + B_L)}{4(C \cdot E - D^2)}$$

$$\gamma_L = \frac{1}{n}\left[\langle \bar{y}_{Li} \rangle - \langle x_i^2 \rangle \alpha_L - 2\langle x_i \rangle \beta\right]$$

$$\gamma_R = \frac{1}{n}\left[\langle \bar{y}_{Ri} \rangle - \langle x_i^2 \rangle \alpha_R - 2\langle x_i \rangle \beta\right]$$

$$A = \langle x_i(\bar{y}_{Ri} + \bar{y}_{Li}) \rangle - \frac{\langle x_i \rangle (\langle \bar{y}_{Ri} \rangle + \langle \bar{y}_{Li} \rangle)}{n} \qquad C = \langle x_i^2 \rangle - \frac{\langle x_i \rangle^2}{n}$$

$$B_L = \langle x_i^2 \cdot \bar{y}_{Li} \rangle - \frac{\langle x_i^2 \rangle \langle \bar{y}_{Li} \rangle}{n} \qquad D = \langle x_i^3 \rangle - \frac{\langle x_i \rangle^3}{n}$$

$$B_R = \langle x_i^2 \cdot \bar{y}_{Ri} \rangle - \frac{\langle x_i^2 \rangle \langle \bar{y}_{Ri} \rangle}{n} \qquad E = \langle x_i^4 \rangle - \frac{\langle x_i \rangle^4}{n}$$

$\langle\ \rangle$ = sum over all measurements
n = total number of measurements

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