HIGH PRECISION SURVEY AND ALIGNEMENT OF LARGE LINEAR COLLIDERS
- VERTICAL ALIGNMENT -

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Abstract. Future linear colliders of 1 TeV energy like TESLA at DESY require new techniques of precise alignment. The planned 33km long accelerator facility will be established in a subterraneous tunnel, which follows an equipotential expanse. The required accuracy for the vertical alignment of the accelerator components is 0.2mm per 600m. To fulfill this demand, a HLS with a free surface ("half filled pipe") has been developed. For scanning the fluid surface ultrasonic measurement equipment is used. A new concept of “in-situ” calibration which eliminates drifts of the sensor as well as temperature effects is presented, supported by results of a HLS-test installation of up to 1 km in length. An accuracy estimation for the adjustment of the accelerator components is made.

Key words: linear collider, linear accelerator, vertical alignment, HLS, hydrostatic leveling system, free surface, half filled pipe, ultrasonic, in-situ calibration

1. INTRODUCTION

Particle physicists all over the world are demanding new research facilities with highest possible energies. To achieve maximum particle speed various linear accelerators are planned, e.g. TESLA at DESY. The demanded accuracy of the accelerator components of

$$\sigma_H = \mathbf{0.5mm\ (transversal)}$$
$$\sigma_V = \mathbf{0.2mm\ (vertical)}$$

over a range of 600m is a challenge for alignment and leveling.

For economic reasons there will be one base network in the tunnel, which is used to adjust the components of the different beamlines of TESLA. This base network is determined by a measuring train which acts semi-autonomous. A tacheometer on a separate car is then used to transfer the coordinates from the determined reference points to the components of the accelerator (Fig. 1).

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[1] Parts of this work were done while being employed at the Bauhaus-University Weimar

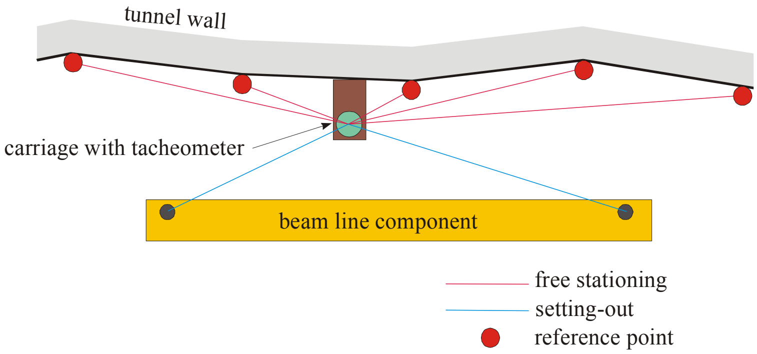

Fig. 1 measuring concept in the tunnel

This paper will focus on the leveling part of the base network survey. For alignment and the measuring train please refer to [1], for an overview of the measuring concept refer to [2], both also presented at IWAA 2002.

TESLA is designed to follow an equipotential expanse. This is mainly because of practical reasons, e.g. smaller coolant pumps, less deep buildings to access the middle of the tunnel, etc.. In this scenario all classic geodetic methods and instruments can be used, because they are always related to the gravity field, too (e.g. tachoemeters, levels, hydrostatic levels).

2. HYDROSTATIC LEVELLING SYSTEM (HLS)

2.1. Basic concept

The fluid in a HLS is normally not in motion ($v = 0$), so the Bernoulli equation is reduced to

$$p + \rho gz = const. \tag{2.1}$$

with p being the static pressure, and ρgz the gravity pressure (ρ density of the fluid, g gravity acceleration and z height above an arbitrary level). The surface of the fluid then is defined with the equilibrium condition

$$p_{air} = p_{fluid} \tag{2.2}$$

and, in a sealed system

$$p_{air} = p_{fluid} = const. \tag{2.3}$$

can be assumed. In this case the surface of the fluid follows an equipotential expanse.

Two different kinds of hydrostatic leveling systems are existing:

1. “Classic” HLS, consisting in a flexible or a rigid tube, filled with fluid, with at least two cylinders to read the water level, and (optional) another tube, which connects the gas parts of the cylinders.
2. Free surface HLS, consisting in an inelastic tube, half filled with fluid [12].

Classic HLS are well-known for a long time [4],[5], but they have a couple of disadvantages for high precision measurements. First, there is an influence of density and therefore temperature

[7], [6] of the vertical water column (Fig. 2). This is critical, because temperature differences of up to 40K are to be expected in the TESLA tunnel.

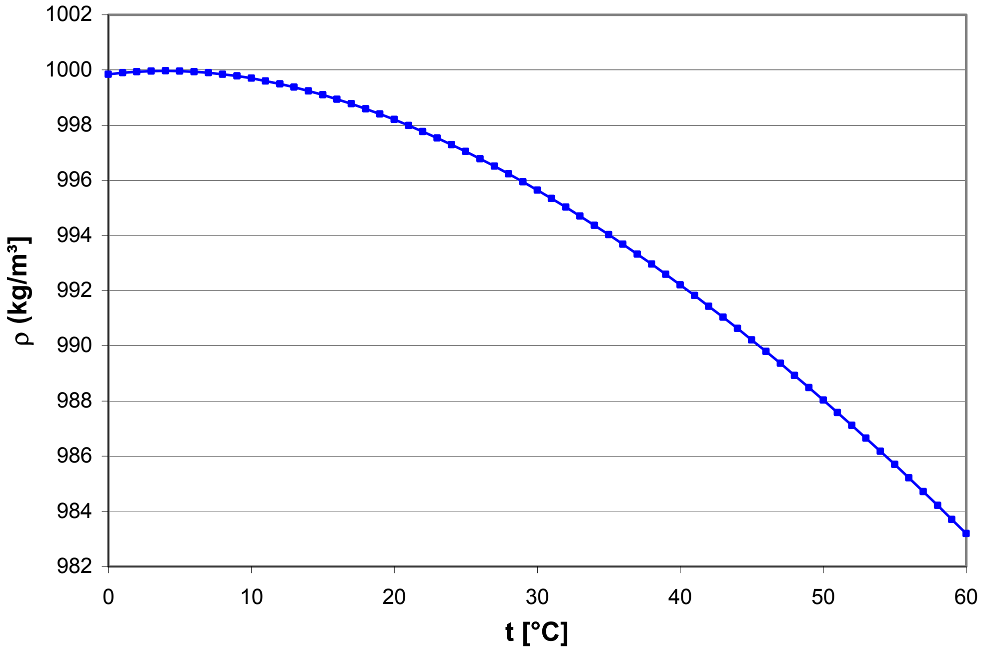

Fig. 2 density of water related to temperature

With a system optimized to small water columns and a working range of 20mm with 5 mm extra security, a minimal vertical water column of 25mm is possible. This results in an height error of 0.4 mm over a temperature range of 40K (Fig. 3). If the temperature is measured and corrected up to an accuracy of 1K the resulting error is about 0,01mm which is 5% of the demanded system accuracy and is acceptable. The problem remains that the temperature has to be registered at each measuring pot and that the use of a flexible tube for the water part of the system is not permitted, because of the desired small vertical columns.

As a second disadvantage of classic systems they need a separate air tube to keep the air pressure constant for the whole system (formula 2.3). This tube needs to be installed with a constant slope to prevent blocking with condensed fluid.

Free surface HLS eliminate these disadvantages. Because the vertical water columns are made zero, temperature and density variations in the system are no longer of effect to the surface of the fluid (disregarding the height change in the whole system). The tube is leveled and half filled with water, this means that there is no need for a separate air tube. For this free surface HLS it is indispensable that the tube is leveled correctly to prevent interruption of the water surface or blocking of the tube with water at any point.

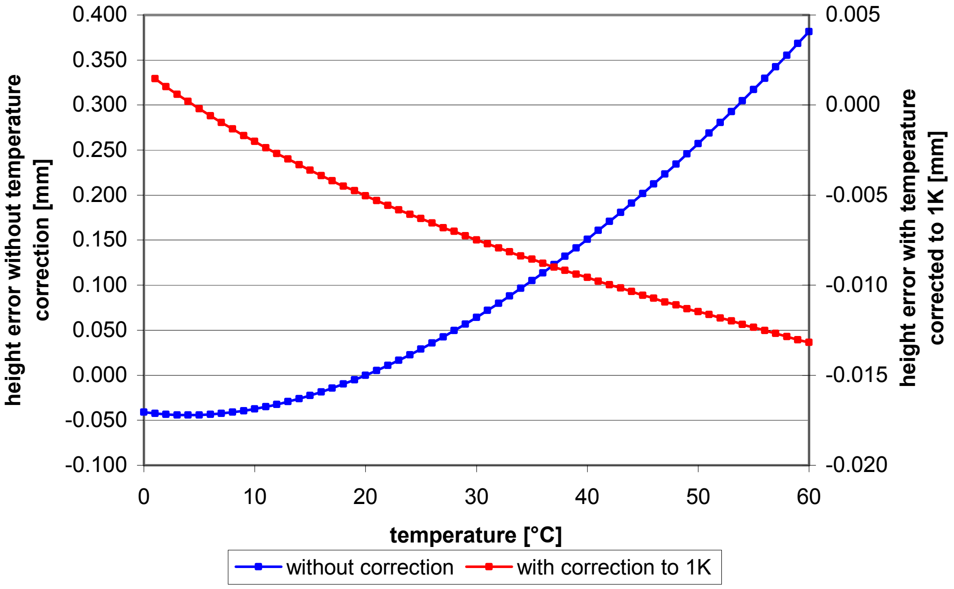

Fig. 3 height error of a 25 mm water column

2.2. Selection of sensors

At the measuring points the surface of the fluid must be referenced to a point outside the tube for further surveying. A wide variety of sensors could be used for this purpose, all with different advantages and disadvantages. Contact-free and unmovable sensors are to be preferred.

Laser-triangulation sensors for instance, give a very high accuracy when looking directly at the surface, but have problems to measure through the tube wall, even if it is transparent. If these sensors should be used, one has to be installed in each measuring pot, which means that about 1500 sensors at 5000€ each are needed.

Capacitive sensors on the other hand are cheap, because only the sensor head has to be installed in each pot, the electronic part could be moved from point to point. Unfortunately the measuring range is limited to a few millimeter, and drifts, temperature and humidity are critical for these sensors.

Ultrasonic sensors could be split in sensor head and electronic part, too. A sensor head has to be installed in each measuring pot, but they are low priced, about 100€ each. The more expensive (~5000€) electronic part could then be moved from sensor to sensor.

Because of cost-efficiency and the possibility of "in-situ" calibration (described later) an ultrasonic system USM25 Krautkramer [3] was chosen for use in the HLS. The measuring resolution of such a system is about 0.01 mm with a 10 MHz sensor (Fig. 4).

The ultrasonic system was calibrated against an incremental length gauge. The calibration revealed no differences between resolution and accuracy. A software improvement of the used firmware will improve the resolution to 3µm. Calibration with this improved resolution is still to be done.

The sound frequency of 10 MHz implies that the measurement must take place in the water part of the system, so the sensor head has to be placed at the bottom of the measuring pot. Sound velocity changes with the temperature of the medium (Fig. 5) and has a large effect on distance measurements (Fig. 6). Therefore a system was developed to eliminate this influence (sect. 2.3).

Fig. 4 ultrasonic measurement equipment, KRAUTKRAMER [3]

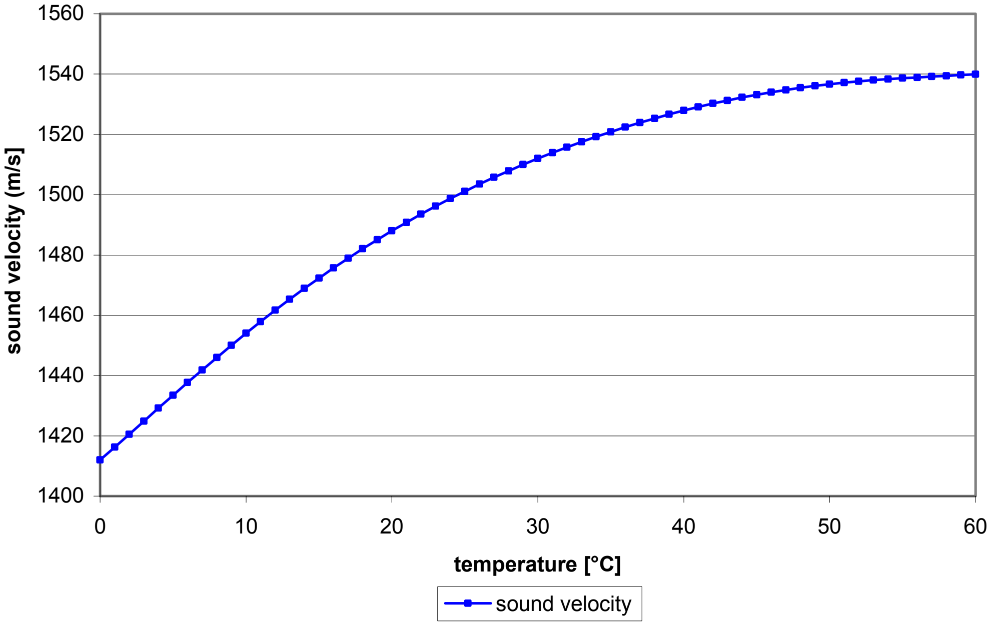

Fig. 5 sound velocity in water related to temperature

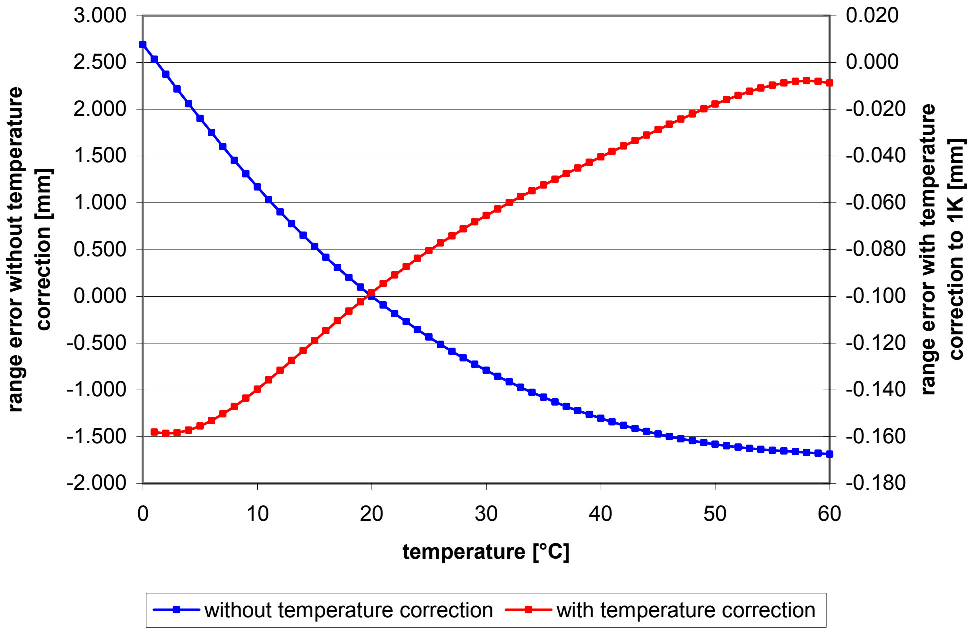

Fig. 6 range error of ultrasonic measurement related to temperature (distance = 25mm)

2.3. Concept of the measuring pot

An advantage of ultrasonic measurement is, that “in-situ” calibration is possible. The basic idea is not only to measure the desired range, but to measure additional “well-known” distances to do the calibration [11], [13].

Therefore a special measurement pot had been developed (Fig. 7), in which two reference distances D_1 and D_2 are calibrated and to be kept constant over time. The reference is made of invar, to achieve maximum temperature invariance and stainlessness. During a measurement, three distances R_1, R_2 and OF are registered quasi simultaneous. With this, it is possible to get an undisturbed result for H_P (formula 2.4), even if the measured distances are biased, for example by electrical drifting or changes in sonic speed.

$$H_P = H_W + D_2 - D_1 \frac{OF - R_1}{R_2 - R_1} \tag{2.4}$$

The position of the sensor head does not need to be fix. This is of importance in case of a defect, because it is possible to change the sensor head without a new calibration. To ensure the stability of the references a few random samples could be recalibrated from time to time.

The principle of in-situ calibration had been tested in a climatic cabin. While the raw distance OF shows variations of about 4 mm over a temperature range of 40 K, the corrected height H_P is nearly uninfluenced (Fig. 8). In fact the remaining errors are about 0.05 mm and are expected to be eliminated in the near future with an improved experimental setup.

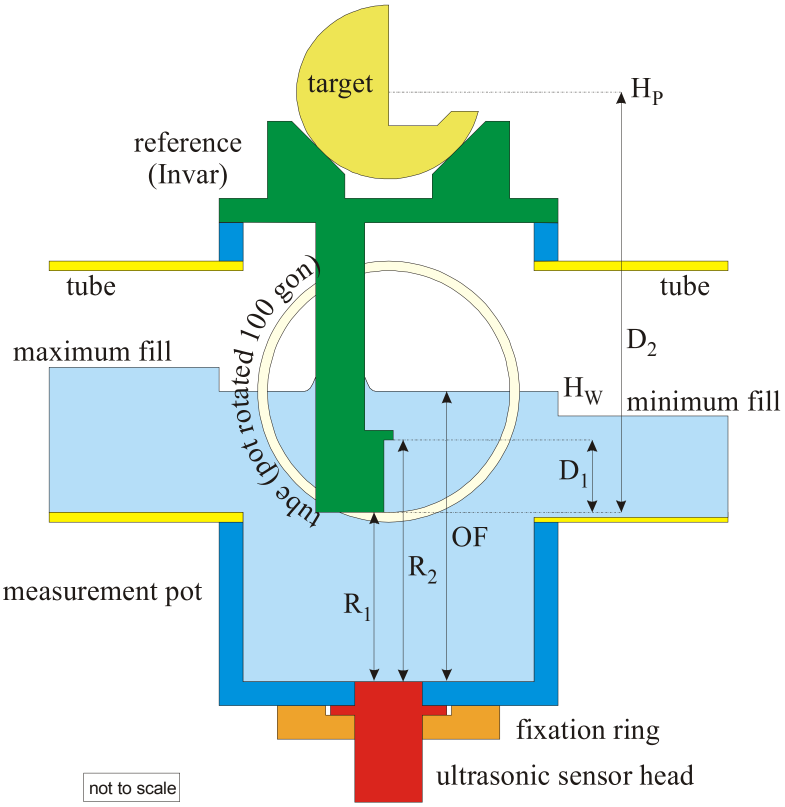

Fig. 7 measurement pot

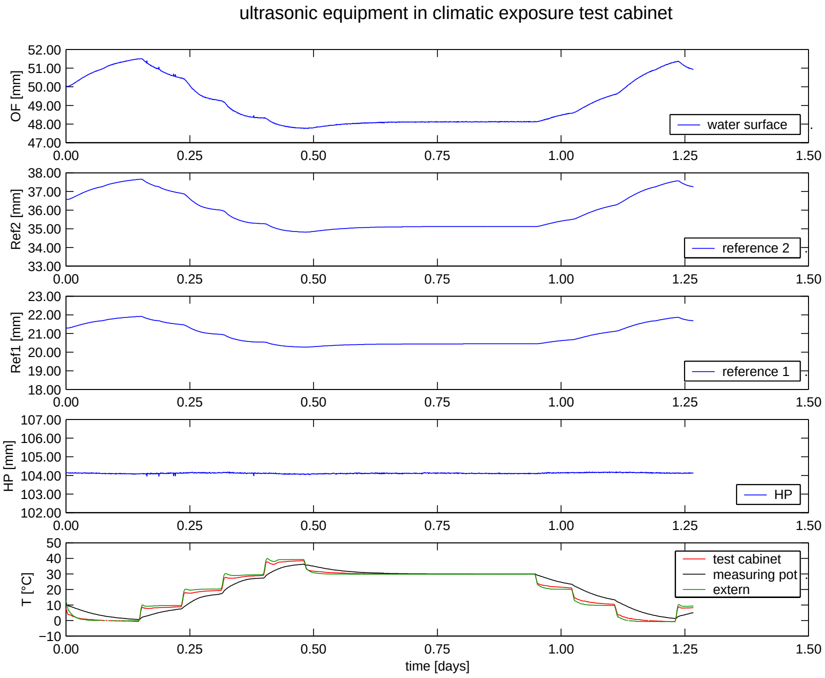

Fig. 8 ultrasonic equipment in climatic cabin

3. TEST FACILITY OF A FREE SURFACE HLS

To get experience with large free surface HLS a test facility was installed in a water adit near Katzhütte in the Thuringian Forest. There were two tubes installed: first, a 1 km copper tube with a diameter of 20 mm and afterwards a 300 m stainless steel tube with a diameter of 50 mm. Both systems were filled with water and tested concerning damping, surface wave propagation and influence of earth tides.

Damping was very strong in the 20 mm tube. After filling the tube with the appropriate amount of water, it took about three weeks to get a balanced surface (Fig. 9). Damping in the 50 mm tube was much weaker, it took only half an hour to get a balanced surface here. This effect is caused by surface tension which constricts the distribution of the water, this effect is more distinct in smaller tubes.

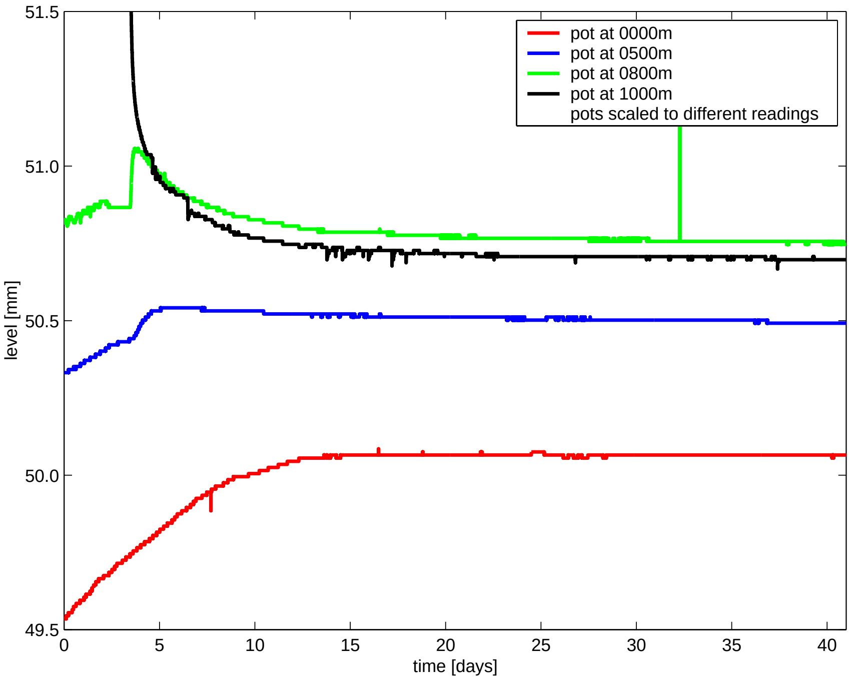

Fig. 9 leveling of water surface, tube diameter 20mm

The difference in damping could also be seen in the wave propagation tests. Wave damping was much stronger in the 20mm tube (Fig. 10 and Fig. 11).

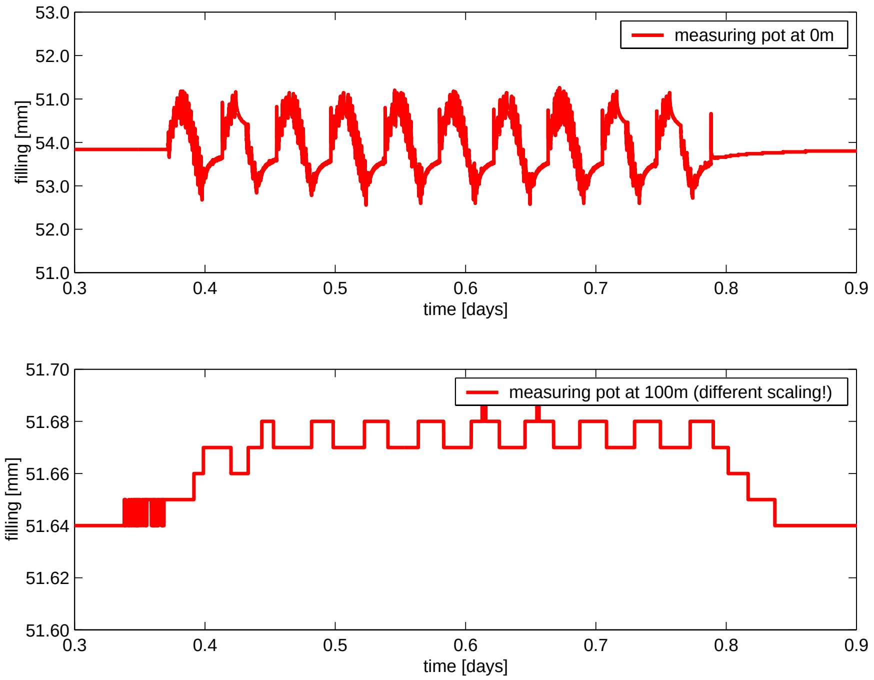

Fig. 10 surface wave propagation, tube diameter 20mm, amplitude 0.5mm, period 60min

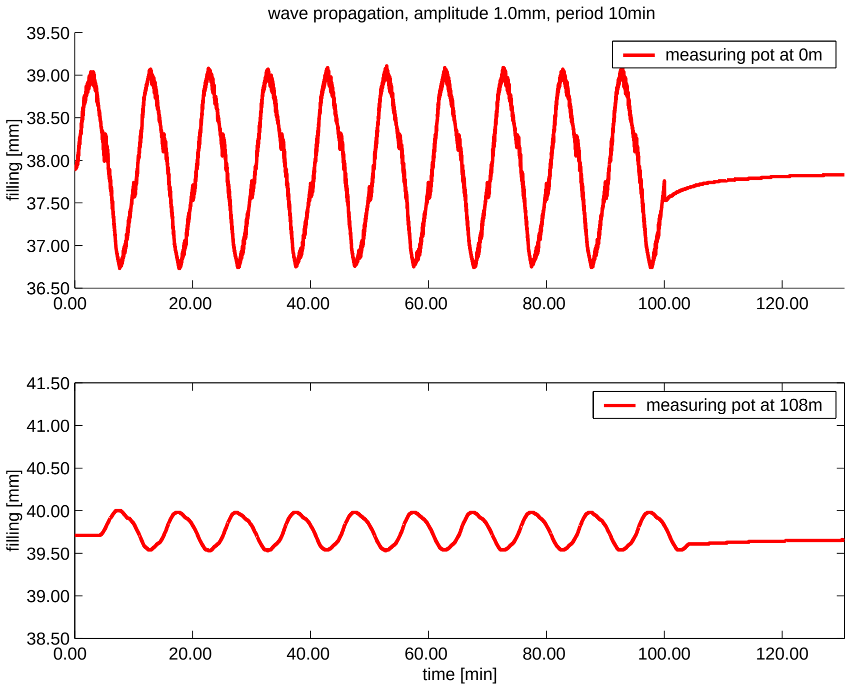

Fig. 11 surface wave propagation, tube diameter 50mm, amplitude 1.0mm, period 10min

Earth tides can be detected in the 50mm tube (Fig. 12). Due to strong damping they could not be seen in the 20mm tube. The various parts of the effect could be shown clearly in comparison with synthetic earth tides calculated from ETERNA [10], using fourier analysis (Fig. 13).

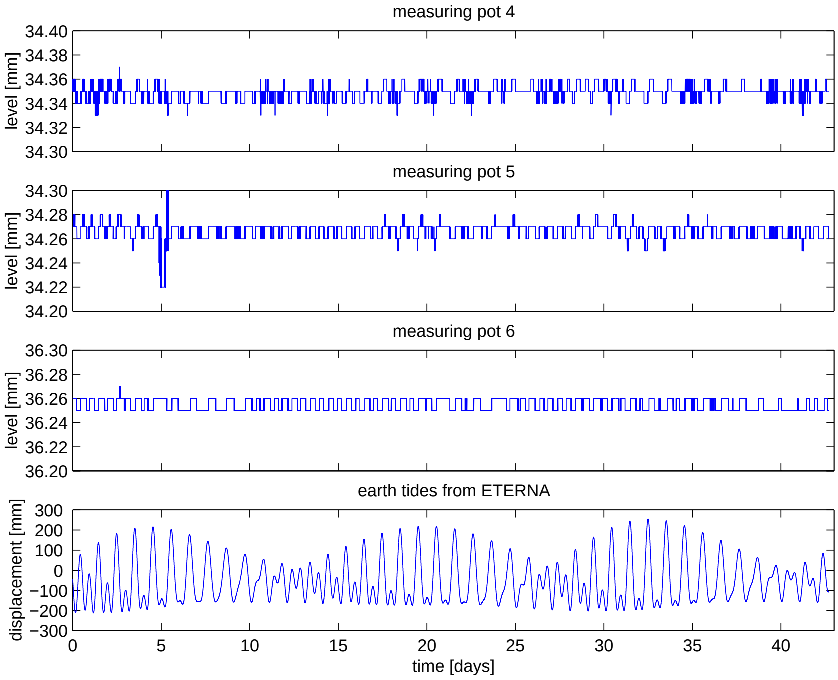

Fig. 12 earth tides in the 50mm tube

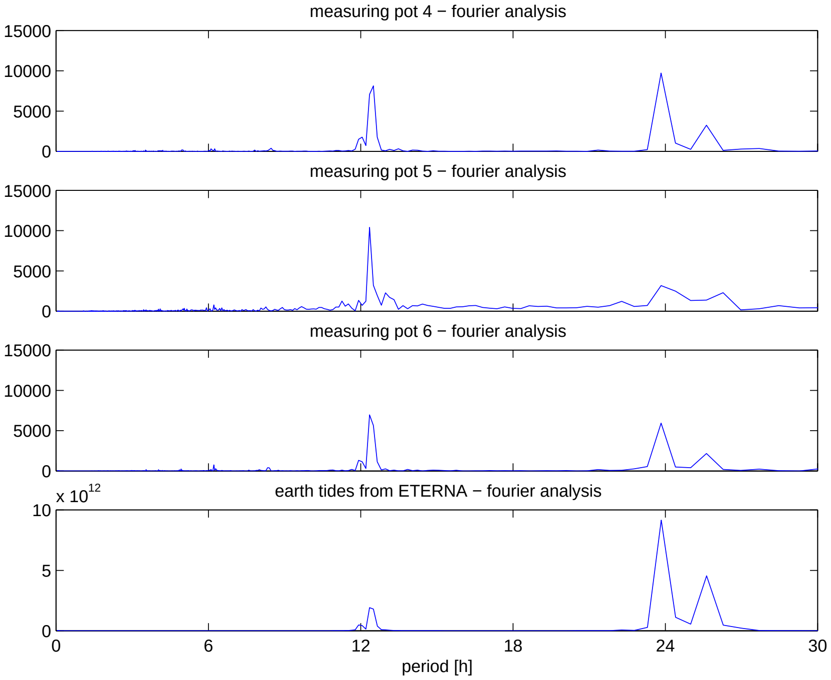

Fig. 13 Earth tides in the 50 mm tube, fourier analysis

4. ACCURACY

The desired vertical accuracy for the components of the accelerator is $\sigma_v \leq 0.2mm$. This accuracy must be split on the different parts of the measurement.
The water surface is an equipotential expanse per definition, so this represents an error free level, provided that there are no external forces disturbing the surface. This means, that the desired relative vertical accuracy can be seen as a vertical accuracy for the height difference between two arbitrary measuring pots.
The participating measurements are:

ΔH_M : distance measurement between the water surface and the target
ΔH_T : trigonometric measurement between target and component of the accelerator

Law of error propagation gives

$$\sigma_V{}^2 = 2\left(\sigma_M{}^2 + \sigma_T{}^2\right) \tag{4.1}$$

For the calculation of $\sigma_T{}^2$ a maximum target distance of 12m can be assumed. Also assuming that all zenith distances are about 100 gon this results in

$$\sigma_T{}^2 \approx 2\left(s\sigma_Z\right)^2 \tag{4.2}$$

with
σ_Z : standard deviation of a zenith distance
s : distance between tacheometer and target

With σ_Z set to 0.3 mgon

$$\sigma_T{}^2 \approx 0{,}0064\, mm^2 \tag{4.3}$$

The height difference between the water surface and the target is calculated by formula 2.4. The height of the water surface H_W is error free per definition (see above). The distances D_1 and D_2 are calibrated in the laboratory and have the standard deviations σ_{D1} and σ_{D2}. The ranges R_1, R_2 and OF are measured by the ultrasonic system. Because of the small distances it may be assumed that one standard deviation σ_{US} fits for all three ranges. Using the law of error propagation results in:

$$\sigma_M{}^2 = \left(1 + \frac{(\mathrm{OF} - \mathrm{R}_1)^2}{(\mathrm{R}_2 - \mathrm{R}_1)^2}\right)\sigma_{\mathrm{D}1}{}^2 + \left(2D_1{}^2\left(\frac{(R_2 - R_1)^2 + (OF - R_1)^2 - (OF - R_1)(R_2 - R_1)}{(R_2 - R_1)^4}\right)\right)\sigma_{US}{}^2 \tag{4.4}$$

replacing D_1 geometrically identical with (R_2-R_1)

$$\sigma_M{}^2 = \left(1 + \left(\frac{\mathrm{OF} - \mathrm{R}_1}{\mathrm{R}_2 - \mathrm{R}_1}\right)^2\right)\sigma_{\mathrm{D}1}{}^2 + \left(1 + \left(\frac{OF - R_1}{R_2 - R_1}\right)^2 + \left(1 - \frac{OF - R_1}{R_2 - R_1}\right)^2\right)\sigma_{US}{}^2 \tag{4.5}$$

To get a small variance $\sigma_M{}^2$ the distance (OF-R_1) should be small, the distance (R_2-R_1) should be large. All other geometric parameters, for instance the distances D_2 or R_1, are not of interest.

To keep the reference completely in the fluid the following restriction applies

$$(OF - R_1) - (R_2 - R_1) \geq 0 \tag{4.6}$$

From the view of error theory reference R_1 should be positioned near the sensor head, reference R_2 should be positioned near the surface of the fluid. Of course the variation of the surface and the geometry of the sound beam must be taken into account.

For the used pot the following parameters apply:

R_1 = 35 mm
R_2 = 50 mm
OF = 60 mm ± 5 mm (variation of the surface)

This results in

$$\sigma_M{}^2 = 5\sigma_{D1}{}^2 + 6\sigma_{R1}{}^2 \tag{4.7}$$

This shows, that $\sigma_{D1}{}^2$ and $\sigma_{R1}{}^2$ are of the same importance for the variance $\sigma_M{}^2$, so it is reasonable to have them measured with the same accuracy.
Introducing

$$\sigma_{D1} = \sigma_{D2} = 0{,}02 \text{ mm} \tag{4.8}$$

$$\sigma_{R1} = \sigma_{R2} = \sigma_{OF} = \sigma_{US} = 0{,}02 \text{ mm} \tag{4.9}$$

as the standard deviation for a calibrated distance, resp. for an ultrasonic measurement, one gets for the worst case (OF = 35mm)

$$\sigma_M{}^2 = 0{,}0044 \text{ mm}^2 \tag{4.10}$$

This gives for the overall variance

$$\sigma_V{}^2 = 0{,}0216 \text{ mm}^2 \tag{4.11}$$

and the standard deviation

$$\sigma_V = 0{,}15 \text{ mm} \tag{4.12}$$

The demanded accuracy of $\sigma_V \leq 0{,}2$ mm can be reached.
For the practical implementation of the measurement there would of course be more targets used for the trigonometric height transfer, so the variance $\sigma_T{}^2$ should be reached easily.

5. SUMMARY

It is shown that a free surface HLS is useable for the adjustment of next generation linear accelerators and has several advantages compared to “classic” HLS. Furthermore ultrasonic systems were qualified for the use in HLS and a method for in-situ calibration of ultrasonic sensors was developed. The mathematical model for the fluid surface and the effect of earth tides will be improved. Disturbances of the gravity field along the planned collider have to be considered in the future.

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