HLS online monitoring during beam assisted girder re-alignment at the accelerator SLS (Swiss Light Source)

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Key words: hydrostatic leveling system, synchrotron, vertical emittance, girder re-alignment, long-term monitoring.

SUMMARY

Synchrotron Light Sources can be described as ”Supermicroscopes”. In a synchrotron accelerated electrons are kept in a vacuum tube by means of electromagnetic fields mainly generated by dipole and quadrupole magnets. These magnets have to be aligned very precisely. Misalignments can be corrected by additional magnets with dipole fields, however a deviation from ideal trajectory of the electron-beam remains. A result of this deviation is a finite vertical beam size varying around the ring which is best described by a conserved physical quantity called vertical emittance. It depends quadratically on the beam size. In order to enable ultra-low emittances, the Swiss Light Source synchrotron (SLS) at the Paul Scherrer Institute (PSI, Switzerland) is trying to reduce the vertical emittance to very small values. To this end correction techniques need to be refined together with an improvement of the magnet alignment. Since the magnets are mounted on girders supporting several magnets the minimization of misalignments of these girders is of great importance for the reduction of the vertical emittance. At the SLS the re-alignment can be done with stored beam since the girder are remotely controlled. In 2011 the SLS was for the first time re-aligned since 2001 [1]. This re-alignment procedure is inherently dangerous since a movement of girders can potentially destroy accelerator components. Therefore it is of great importance that both, heave and pitch can be exactly monitored with the Hydrostatic Leveling System (HLS). The HLS records signals of 192 high-precision levelsensors. Initially it was developed to monitor the long-term underground stability of the SLS. The measuring system allows to compare the signals from the levelsensors distributed on a circle with a circumference of 300 m simultaneusly. The fast response of the HLS allows it to be used as an ”online” monitoring tool for re-alignment activities on all girders in the SLS.

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1. INTRODUCTION

The Swiss Light Source (SLS) at the Paul Scherrer Institut is a third-generation synchrotron light source. With an energy of 2.4 GeV, it provides photon beams of high brightness for research in materials science, biology and chemistry (Fig.1/2).

Fig. 1): Paul Scherrer Institut, Switzerland.

Fig. 2): Storage ring of the SLS.

One of the main aims of 3rd generation synchrotron light sources like the SLS and future damping rings is the minimization of the vertical beam emittance. This goal is accomplished by the careful correction of betatron coupling and spurious vertical dispersion to very small values. Furthermore light sources need a well defined control of the vertical emittance in order to vary the beam lifetime.

2. HOW SYNCHROTRON LIGHT IS PRODUCED

To gain Synchrotron Light, electrons have to be accelerated to near light speed, inside an electron accelerator. Magnetic fields there force the flying electrons into a circular orbit. The electrons react to this force with the emission of electromagnetic radiation, called **Synchrotron Light**.

To make an efficient Synchrotron Light Source one arranges many magnets into a storage ring, where the high energy electrons can circulate for hours. In a so-called undulator one has a periodic array of magnets with alternating polarity of the magnetic field. This forces the electrons into a slalom course. This in turn concentrates the synchrotron light into discrete wavelengths, a brilliant light beam. Contrary to X-rays, produced in a conventional X-ray tube, the intense synchrotron light beams are sharply focused like a laser beam.

The SLS accelerator facility consists of three major parts: a linac, a booster and a storage ring. The linac (short for linear accelerator) pre-accelerates electrons, which are produced in an electron source, to an intermediate energy of 100 MeV.

The booster (short for booster synchrotron), accelerates the electrons, coming from the linac, to the final energy of 2.4 GeV. After extraction from the booster the electrons are then injected into the storage ring. In the storage ring these high energy electrons circulate for hours, generating the desired synchrotron light, which in turn is used in several beam line facilities. An ultra-high vacuum inside the beam tube is necessary to avoid losses of the electrons due to collisions with air molecules. Storage ring and booster are housed in a tunnel with concrete shielding walls. Two layers of 40 cm thick concrete beams cover the tunnel and can be removed to give a crane access to the accelerator components, see figure 2. The linac is located in a separate tunnel.

3. HOW THE SYNCHROTRON LIGHT IS OPTIMIZED

The SLS was designed as a "state of the art" facility, producing synchrotron light of a very high quality. This required the installation of a large number of magnets - a total of 330 - to keep the electrons on their circular track, and the diameter of the electron beam as small as possible. Special care was taken for the performance of the high- vacuum system, to guarantee a long lifetime (in the order of 10 h) of the circulating beam, ensuring very small beam losses. The synchrotron light emitted by the electrons is very intensive, corresponding to an average power of 200 kW. This power has to be refurnished to the electrons by four RF transmitters, operating at a frequency of 500 MHz.

A sophisticated diagnostic system keeps the position of the electron beam constant to less than 1 micro-meter. This guarantees a very high stability of the photon beam on the samples to be examined.

Different types of magnets, dipoles (blue), quadrupoles (red) and sextupoles (yellow) are mounted on 48 girders (Fig.3). The girders have been produced within a horizontal and vertical accuracy of +/- 15 micro-meter (Fig.4).The girders have to be aligned very accurately, since the proper mechanical alignment is a prerequisite for the magnetical alignment and focusing of the beam. For that purpose each girder can be remotely adjusted by excenter motors (Fig.5a). The most important mechanical corrections (Fig.5b) are heave (v, or vertical level) and pitch (χ,or vertical angle, in direction of beam).

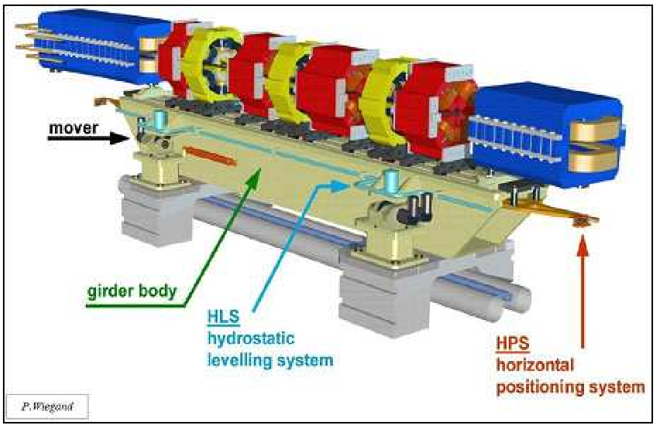

Fig. 3): Girder carrying the bending, focusing and dispering magnets. The girder body (grey) is mounted on four "legs" with overs which can move the girder in the vertical axis. This vertical movement is monitored by a HLS sensor at each mover.

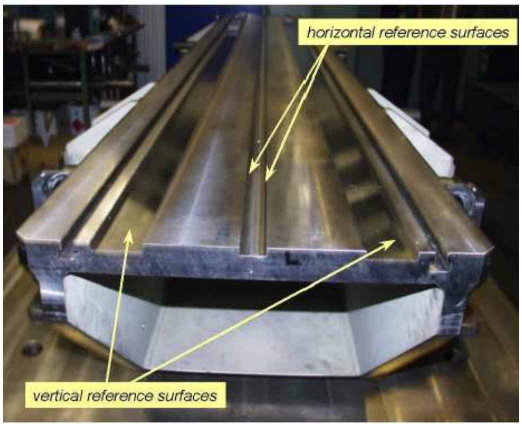

Fig. 4): The mounting surface of the girders is produced within an accuracy of +/- 15 micro-meter.

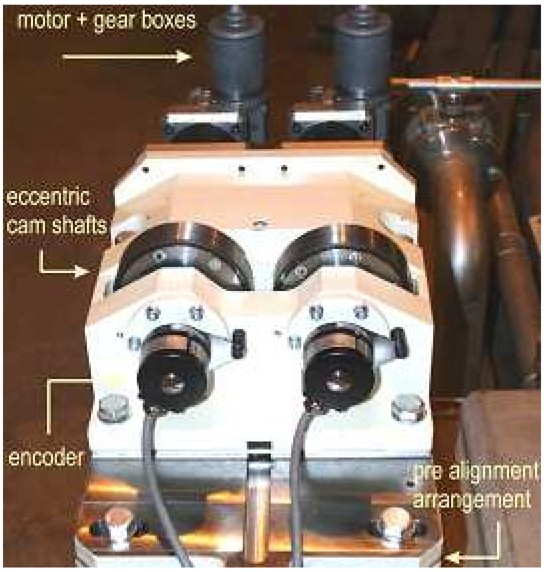

Fig. 5a): Excenter cam shafts with motor + gear boxes and encoders. Allows to move the girder with micro-meter precision in the vertical.

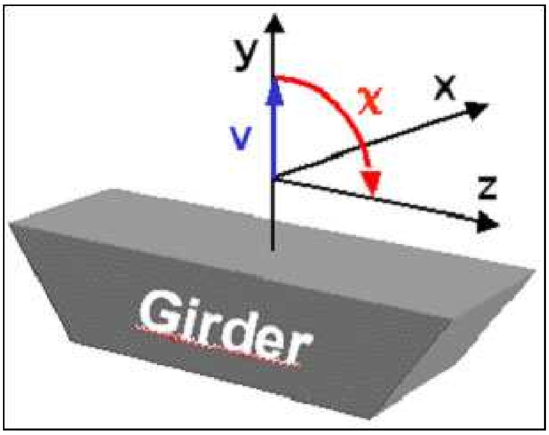

Fig. 5b): The most important corrections are heave (v) and pitch (χ)

In 2000 the girders were aligned by the mechanical alignment group using a laser-based alignment system (Lasertracker Leica LTD500). The first synchrotron light was produced just before Christmas 2000. Since that time the girders were not moved anymore. The electron beam could be kept in a plane orbit just by use of the forces of the electromagnets. The position of the beam is monitored locally by 73 beam positioning monitors. Figure 6 shows an image of the synchrotron light which was recorded before the alignment. The two light spots are vertically polarized synchrotron light, which ocurs when the electron beam is bended by a dipole magnet. Best scientific results are achieved when the light spots are small and sharp.

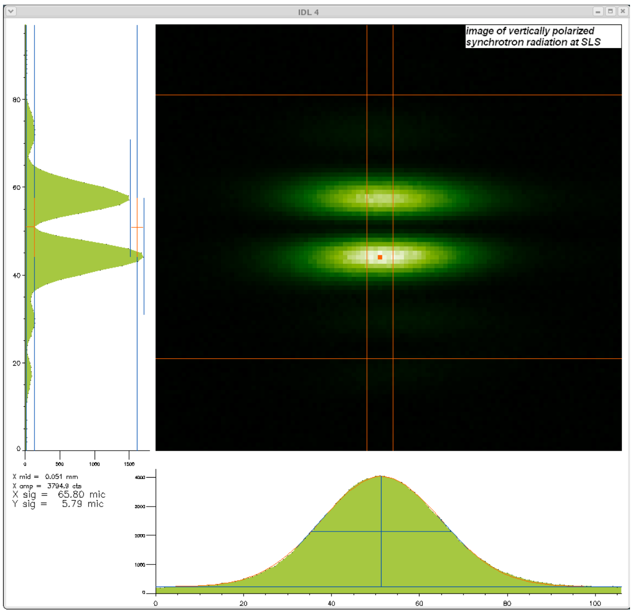

Fig. 6): Image of vertically polarized synchrotron radiation at SLS.

4. THE HYDROSTATIC LEVELLING SYSTEM (HLS) AT SLS

The hydrostatic levelling system (HLS) provides an absolute vertical reference for the SLS storage ring. The system monitors any relative and global vertical position change with a sub micro-meter resolution and within a working window of 14 mm. Capacitive proximity gauge based sensors are housed in stainless steel cylinders. The dimensions of the measuring device have been optimized for maximum sensitivity and minimum influence of thermal and vibrational effects. A total of 192 sensors are installed around the SLS storage ring (Fig.7a/b). They are connected by a stainless steel pipe, which is half filled with liquid. Four devices per girder are positioned exactly above the four movers, and the devices at all the 48 girders are connected to one singular liquid level. With such an arrangement, heave and pitch can be calculated from the vertical positions, and corrections executed by the girder mover system can be monitored with a high precision. For the most important corrections, heave and pitch, two sensors would be sufficient. With a third sensor the roll of the girder can be determined and the fourth sensor gives a redundance signal, which can be used for quality assurance.

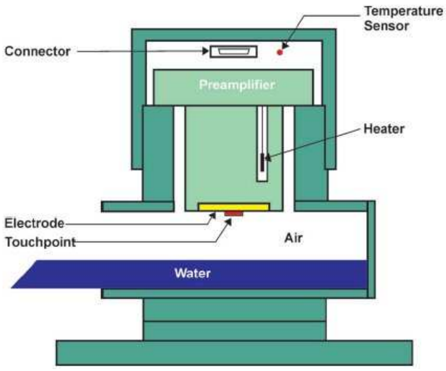

Fig. 7a): Level sensor mounted on the girder, and connected to the stainless steel piping system.

Fig. 7b): Cross section of a HLS device

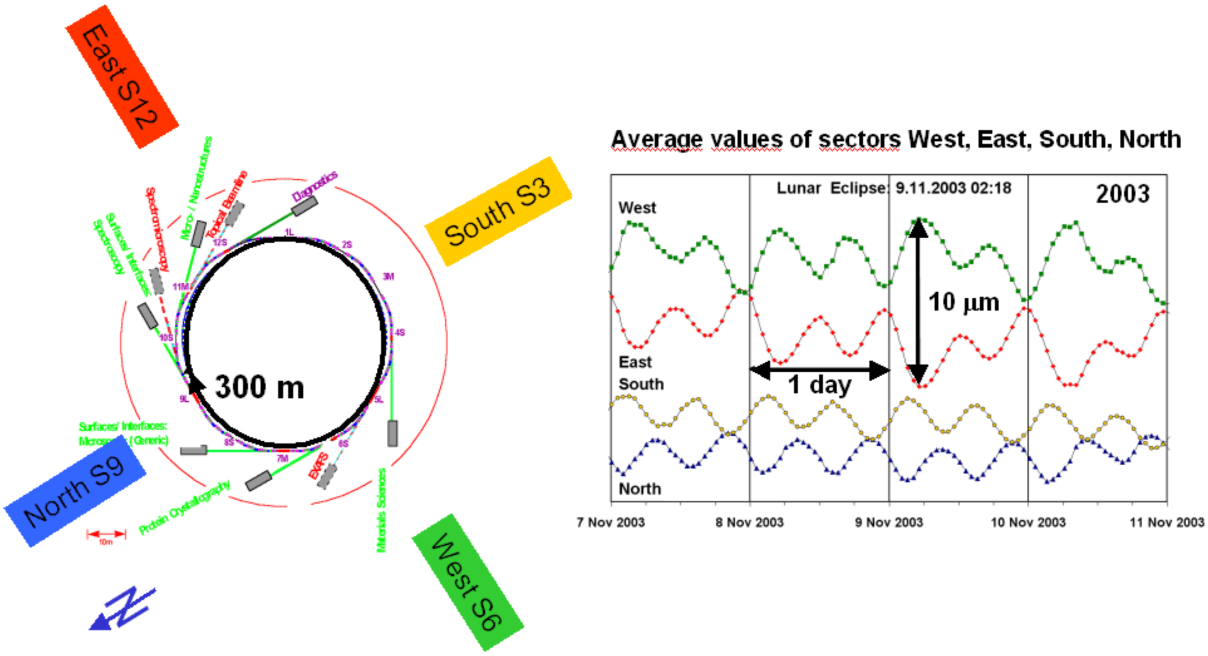

Fig. 8): A four day HLS data sample from the year 2003 with a time resolution of 1 hour. The influence of the Earth tides with 2 periods a day is clearly visible, demonstrating the power of the HLS as a highest-precision monitoring system. The largest difference between East and West on 9 November is a result of the eclipse of the moon.

A HLS data sample recorded at the SLS is shown in figure 8 [2,3]. The selected samples are hourly averages of the signals in the four main directions. The complementary up and down signals, twice every day, in North-South direction are ground deformations and gravitational tilt due to the moon. The signals in East-West direction show an additional daily component, which is the influence of the sun. This natural calibration signals can be used as a continuous quality control.

5. HLS REALTIME ALIGNMENT MONITORING

In April 2011 the re-alignment campaign was launched based on the 2010 survey data and involved the remotely controlled movement of all girders. Until the end of November all girders were successfully re-aligned.

Figure 9 summarize the necessary pitch (vertical angle) and heave (vertical position) changes for all girders. Since the suggested heave corrections exceed +0.6 mm a reference line (blue line) has been defined by the fit of a smooth function to the corrections. In fact it would be best to move the girders to the horizontal zero reference (green line), however, the re-alignment of the girders to the blue reference line does not effect the machine performance, since the electron beam is guided in a inclined instead of a horizontal orbit. Much more critical to the machine performance are misalignments in the orbit. Misalignments can be corrected using magnetic forces by sending electric currents through the electromagnets (orbit feedback). The better the magnets are mechanically aligned the less correction energy is needed and the brighter is the synchrotron light.

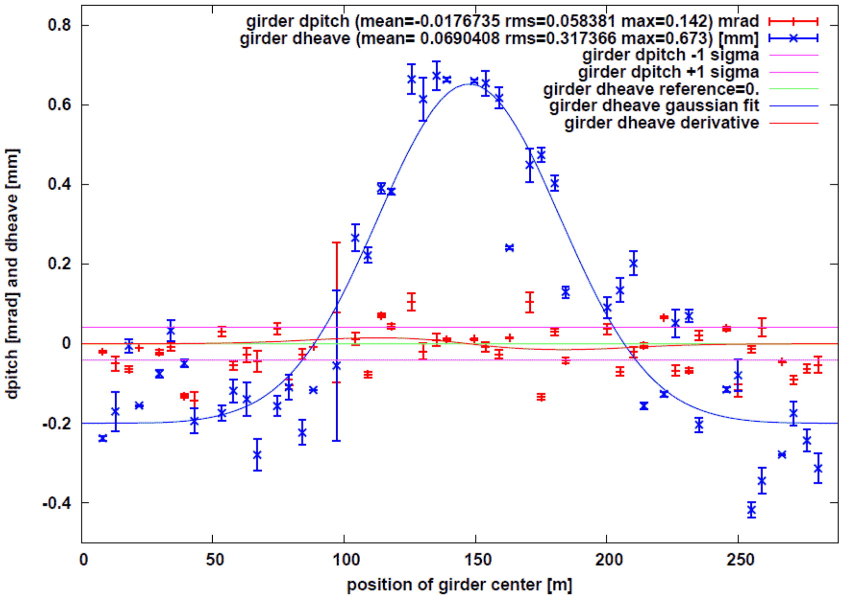

Fig. 9): Pitch (red + symbols) and heave changes (blue x symbols) for all girders based on the quadrupole misalignment survey data taken in 2010. The girders were aligned to a smooth non-zero reference line (blue solid line).

Figure 10 shows a graph used by the controls group for alignment control before and after mechanical re-alignment of a misaligned girder in sector 2. The pink line shows the best fit line for the centre of the quadrupled magnets (pink asterisk *). The centres of the magnets are not accessible. Since the magnets are mounted rigidly on stiff girders, the centre position can be calculated from accessible elements (green crosses +) on the girders. Between girders G06 and G07 a “train-link” (dashed circle) was re-established by moving G07. This was done remotely during normal operation of the synchrotron. According to the stored beam position and the measurements of the element-positions by the mechanical alignment group in 2010 a “heave” of 60 micro-meter and a “pitch” of 70 micro-radian was calculated for G07 (brown lines). During the following shutdown, when the elements were accessible again, the elements have carefully been measured again and confirmed the correct adjustments. The blue crosses (x) show the deviation of the individual errors from the fit.

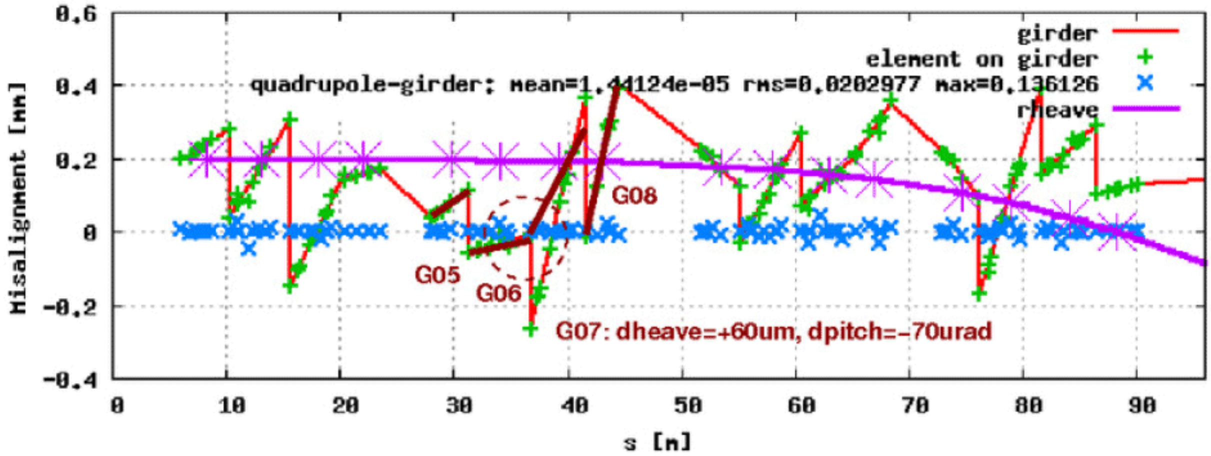

Fig. 10): Misalignments of the magnets (quadrupoles, +) in the sector 2. The red line is the corresponding girder fit for four girders (G05-08). The blue crosses (X) show the deviation of the individual errors from the fit.

The realignment was merely done with stored beam and running fast orbit feedback since the girders are remotely controlled [4] and the orbit effects of the proposed girder movements can be dynamically handled by the orbit correction system. This procedure allows a very precise control of the re-alignment process since the corrector variations within the feedback loop directly reflect the girder manipulations. Simultaneously the movement of the girders is also monitored by the independent hydrostatic levelling system (HLS) which confirms the vertical adjustment within a few micro-meter. After steady state conditions the HLS delivers very precise results. When large girder movements are performed the liquid flows from the higher to lower levels until is equilibrated again.

The analysis of the HLS data from 12 July 2011 confirms heave and pitch correction of girder G07. Figure 11 shows the pitch change by −70 micro-radian which is consistent with encoder read backs from the girder motors, the observed corrector change and the mechanical alignment group.

The girder re-alignment of 22 November 2011 was monitored online by the HLS remote desktop. The print screen (Figure 12a) shows all HLS sensors of sector 11 before the adjustment and the zoomed data after the adjustment steps in millimetres (Figure 12b). First, a small pitch of the first girder was performed. After 3 minutes the main adjustment step using heave and pitch was implemented. It was first time that the HLS signals were observed online during girder alignment. It showed a fast response-time of a few seconds to the alignments.

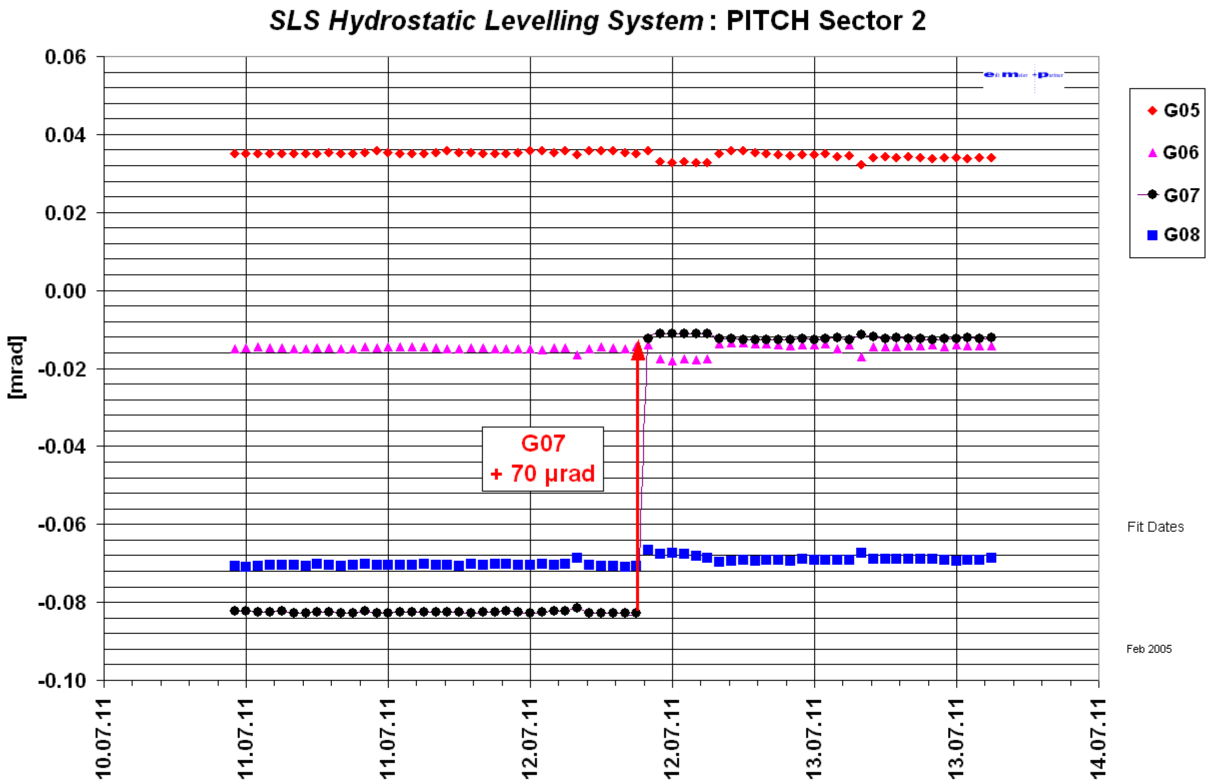

Fig. 11: HLS pitch record sector 2

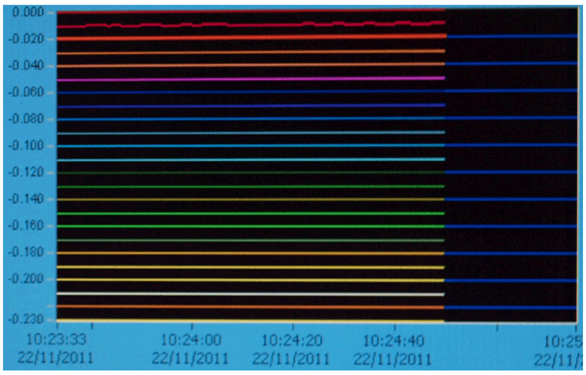

Fig. 12a): Normal HLS signals of sector 11 before re-alignment, one sample every two seconds. All the signals are stable below micro-meters.

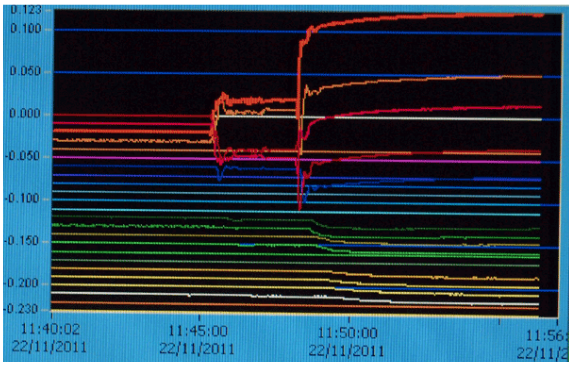

Fig. 12b): Online monitoring of the HLS signals during re-alignment. First a pitch was performed and a few minutes later a heave and pitch combined.

CONCLUSIONS and OUTLOOK

The HLS is initially built and used for long-term monitoring of the underground. In the present paper, the successful application of the HLS for the SLS beam alignment optimisation is demonstrated. Since all 192 detectors of the HLS system are connected over a single 300m long liquid tube, and since the system is operated continuously since 2003, the complete history of the girder displacements is stored in the HLS data, in sub-micro-meter precision. The alignment campaign in 2011 has shown that the HLS delivers also very fast and precise results which can be used during the alignment work in real-time. Based on the re-alignment, a world record emittance of 1 pm-rad [5] was achieved in December 2011.

In order to further improve the real-time performance of the HLS, the liquid dynamics can be calculated in the half filled liquid tube, and used to correct the online values towards a dynamic measuring tool. Liquid dynamics calculations will also give hints how to change the properties of the piping system and its liquid to maximize the damping of dynamically induced waves, to further improve the precision of level measurements with high temporal resolution.

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BIOGRAPHICAL NOTES

Edi Meier, is managing director of the engineering company Edi Meier + Partner AG, Winterthur, Switzerland. He studied Geophysics at ETH Zurich. Subsequently he worked as a manufacturer of seismic instruments (Streckeisen Switzerland) for six years and founded his own engineering company in 1987. Since 1995 the company is collaborating in research and development of new instruments with the Institute of Geodesy and Photogrammetry of ETH Zurich.

Michael Böge, is a senior accelerator physicist at the Paul Scherrer Institute (PSI), Villigen, Switzerland. He studied Physics at the Kiel and Hamburg University, Germany, where he got his PhD in 1994. After a fellowship at the European Organization for Nuclear Research CERN, Switzerland, he joined the Swiss Light Source Project at PSI.

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