The Ultrasonic Level Sensors for Precise Alignment of Particle Accelerators and Storage Rings

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1. INTRODUCTION

Tasks of slow ground motion studies and high accuracy alignment of large accelerator machine components are important now. In accordance with the program of collaboration between BINP, Russia, SLAC and FNAL, USA, the development of the Slow Ground Motion Measuring Systems and of their components is in progress. Development of the high-resolution hydrostatic Capacitance based [1] and Ultrasonic Level Sensor (ULS) is a part of this joint program. The principle of ultrasonic location with the measurement of delay between excited and returned deflected ultrasonic pulse is applied.

The Ultrasonic Level Sensors (ULS) type monitor is intended for vertical displacement measurements in the 5 mm displacement range with a resolution about 0,2µm. The monitors are oriented on operation with half filled tubes.

For the ULS we had accepted the next, widely used principles:

- To measure the hydrostatic level in communicating vessels;
- To use the water as a liquid media inside the vessels;
- To use stainless steel for the monitor body.

Each ULS vessel is equipped with a piezoelectric transducer, temperature sensor and electronics box. The electronics of the monitor has a built-in microcontroller to provide measurements, initial calculation of signals and calibrating tests. Two models had been developed: the **ULS-PR** with Panametric transducer and with ***RS-485*** interface and second one **ULS-KE** with Krautkraemer transducer and with ***PoE*** (Power – over – Ethernet) interface.

It is proposed that ULS-KE type of ULS will be used at LCLS in combination with capacitive Hydrostatic Level Sensors (SAS) in order to provide accurate measurement of alignment with possibility of absolute calibration.

This report describes these newly developed Ultrasonic Level Sensors (ULS), their principle of operation, design and some test results, obtained at BINP and SLAC test stands. (*)[1]

2. ULTRASONIC BASED METHOD OF LEVEL MEASUREMENTS

The ultrasonic hydro-location is well known and widely distributed method of distance measurements for many applications. One of precise methods was described by *Markus Schlösser, Andreas Herty* at their report presented four years ago at the 7th International Workshop on Accelerator Alignment [2]. Their idea is to locate not only the water surface in a vessel, but also two addition surfaces with calibrated distance between them (D1) and at the calibrated

(*) Work is supported by SLAC

distance to alignment reference target (D2), see Fig. 1. This idea had pushed us to develop the electronics and, as a result, all the Ultrasonic Level Sensor (ULS) module for the same purposes – to be a part of Hydrostatic Level Measurement System for precise measurement of the vertical displacements of some accelerator structures.

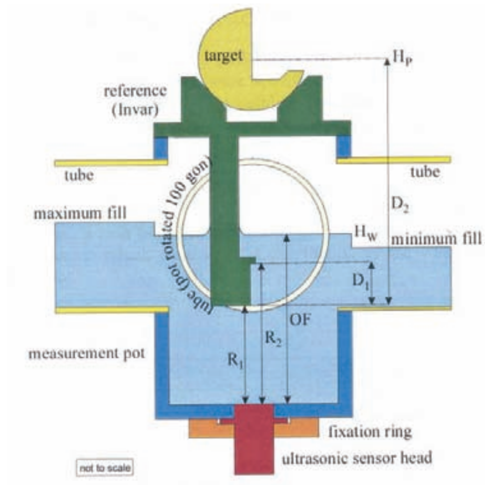

Fig.1 Principle of organizing the reference surfaces at the ULS

(Picture from the reference [3])

For our device we are going to use pulse-echo method for water level measurements. Pulse-echo ultrasonic measurements can determine the location of free water surface in a vessel or a reflective surface into the water by accurately measuring the time required for a short ultrasonic pulse, generated by a transducer (sensor head), to travel through a thickness of water, to reflect from the free water surface or from the reflective surface, and to be returned to the transducer. The two-way transit time measured is divided by two to account for the down-and-back travel path and multiplied by the velocity of sound in the test media. The result is expressed in the well-known relation:

$$D = V \cdot t / 2 .$$

Here D is the distance from the upper surface of transducer to the reflective surface or to free water surface, *v* is the velocity of sound waves in water, and *t* is the measured round-trip transit time.

For the ultrasonic measurements into water there are special transducers – immersion transducers. These transducers are designed to operate in a liquid environment. They usually have an impedance matching layer that helps to radiate more sound energy into the water and to receive reflected one. Immersion transducers can be equipped within a planner or focused lens. A focused transducer can improve sensitivity and axial resolution by concentrating the sound energy to a smaller area but, as opposed to this, the working range is reduced. Unfocused transducers may be used in applications where large working range is essential. The sound that irradiated from a piezoelectric transducer does not originate from a point, but instead originates from all the surface of the piezoelectric element. Round transducers are often referred to as piston source transducers because the sound field resembles a mass in front of the transducer. The sound field from a typical piezoelectric transducer is shown on Fig.2.

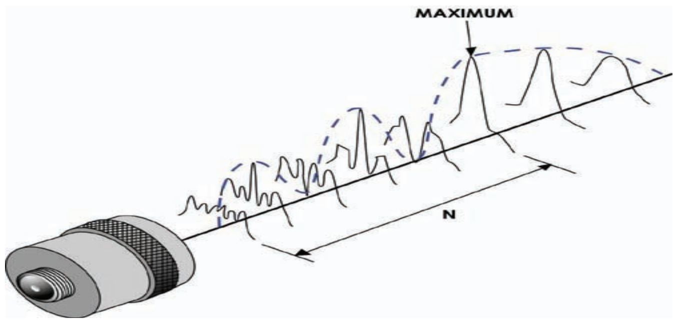

Fig.2 Sound field pictures of the typical piezoelectric transducer

Since the ultrasound originates from a number of points along the transducer face, the ultrasound intensity along the beam is affected by wave interference. These are sometimes also referred to as diffraction effects. There are extensive fluctuations near the source, known as the near field. These high and low pressure areas are generated because the crystal is not a point source of sound pressure, but rather a series of high and low pressure waves which are joined into a uniform front at the end of the near zone. Because of acoustic power variations within a near field, it can be extremely difficult to accurately measure locations of the reflective surfaces when they are positioned within this area. The ultrasonic beam is more uniform in the far field, where the beam spreads out in a pattern originating from the center of the transducer. The transition between these zones occurs at a distance ***N*** and is sometimes referred to as the "natural focus" of a flat (or unfocused) transducer. The near/far distance ***N*** is significant because amplitude variations that characterize the near field change to smoothly declining amplitude at this point. This area just beyond the near field is where the sound wave is well behaved and at its maximum strength. *Therefore, optimal measurement results will be obtained when reflective surfaces are close to **N** area, but farther it. This requirement determines the minimal distance from transducer to target surfaces.*

For a piston source transducer of diameter (*d*), central frequency of exciting signal (***f***), and sound propagation velocity (***V***) at a liquid medium, the equation below allows the estimation of the near/far field transition point:

$$N = f \cdot (d/2)^2 / V$$

As discussed above, circular shape transducers are often referred to as piston source transducers because the sound field resembles a cylindrical mass in front of the transducer. However, the energy in the beam does not remain in a cylinder, but instead spread out as it propagates through the material. The phenomenon is usually referred to as beam spread but is sometimes also called beam divergence or ultrasonic diffraction. Although beam spread must be considered when performing an ultrasonic inspection, it is important to note that in the far field, or Fraunhofer zone, the maximum sound pressure is always propagates along the acoustic axis (centerline) of the transducer. Therefore, the strongest reflection is likely to come from the area directly in front of the transducer. At the beginning of the far field, however, the beam strength is always greatest at the centerline of the beam and diminishes as it spreads outward (Fig.3). Beam spread angle is one of important parameters of the transducer, because beam spread lowers the amplitude of reflections since sound fields are less concentrated and, therefore, weaker. For a flat piston source transducer, an approximation of the beam shape may be calculated as a function of Diameter (*d*), frequency (***f***), and sound velocity (***V***) in water:

$$Sin(\alpha / 2) = 0.514 \cdot V / (d \cdot f) .$$

The digital coefficient in equation corresponds to -6dB intensity decreasing.

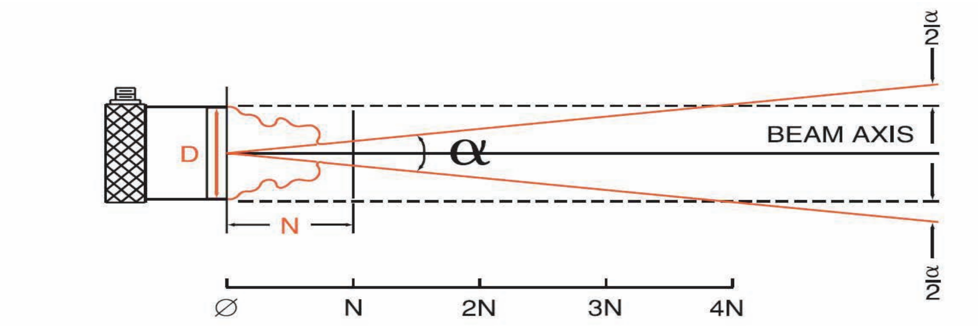

Fig.3 A simplified view of a sound beam for flat transducer

During selection of the transducer two important parameters were took into consideration: the near/far distance ***N*** and beam spread angle. The near/far distance is longer when using a high frequency transducer than for a low frequency one. As the diameter of the transducer increases the near/far distance rises under second power. Beam spread is greater when using a low frequency transducer than when using a high frequency one. As the diameter of the transducer increases the beam spread will be reduced.

As a result two types of immersion transducers were selected for developing of the ULS: V310-RU of Panametric Corp. [3] and H10 KB 3 of Krautkramer Corp.[4]. Some parameters of transducers are presented at the Table 1.

Table 1: Unfocused immersion transducer parameters

Parameter \ Transducer Type	Units	V310-RU (Panametric)	H10 KB 3 (Krautkraemer)
Central frequency	MHz	5.0	10.0
Bandwidth	%	>70	<40
Transducer diameter	mm	6.35	5.0
Beam spread angle (α/2)	Degree	1.365 (0.0243 rad)	0.884 (0.0154 rad)
near/far distance ***(N)***	mm	33.6	41.7

In our opinion, they are the best choice for ULS applications, where good axial or distance resolution is necessary. One of advantages of the Krautkraemer's transducer is that it has guaranty in long time (months) operation in immersion position. It was done two Sensors with Panametric transducer and five with Krautkraemer's. For the pulse-echo method it is very important to have wide bandwidth and, as a result, fast time – response. For example, typical time response of V310-RU transducer is presented on Fig.4.

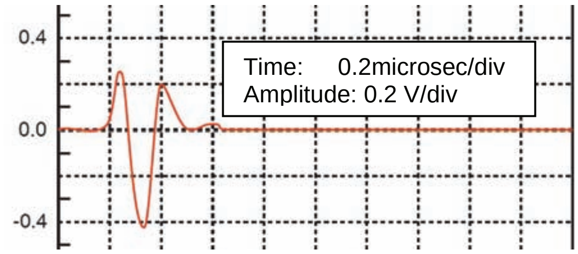

Fig.4 Typical time response of V310-RU transducer

3. ULTRASONIC SIGNALS AND ULS ELECTRONICS

As we can see from the sketch of Fig.1, main idea of organizing the precise water level variation measurements is to use the reference distances: one of them is the distance **D1** between two surfaces inside water of monitor; another one – the distance **D2** between one of this surfaces and geodesic reference probe positioned on the top of monitor outside of the vessel. These distances are well known due to possibility of special mechanical measurements at the stand outside the system and due to stable length of the monitor reference head, made of Invar.

For this configuration of the reference head the transducer is placed at the bottom of the vessel. It transmits into liquid media (water) the pulse with the time response shape similar to shape on Fig.4. Three reflected signals arrives the transducer with the delays, corresponding to the distances **R_1**, **R_2** and **OF** from the transducer to each surface (Fig.5). Transducer, being in a role of receiving ultrasonic antenna, accepts all these signals and transmits them to the amplifier and to the electronics module for signal processing. The looked for distance between geodesic reference point and water surface is: $H = D_2 - D_1 \cdot \frac{t_{of} - t_1}{t_2 - t_1}$.

The goal of ULS electronics is to measure time intervals with the accuracy as fine as possible and to calculate the resulting values.

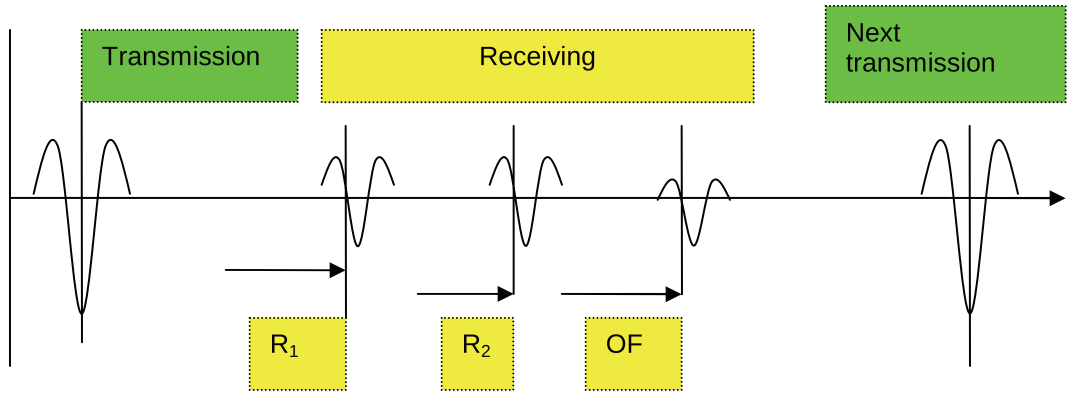

Fig.5 Time diagram of the transducer operation

In compliance with the mechanical design of the prototype ULS we should measure three distances: ***R1, R2*** and ***OF.*** The scale of distances and corresponding time intervals to be measured are presented at the Table 2.

Table 2: Reference distances and typical time intervals for measurements

Type	***R1***	$2t_1$	***R2***	$2t_2$	***OF***	$2t_{of}$	***dH***	***dt***
	mm	*μsec*	*mm*	*μsec*	*mm*	*μsec*	*mm*	*μsec*
ULS-PR	45	60.69	50	67.43	62	84.3	± 2.5	±1.7
ULS-KE	55	74.17	62.5	84.29	75	101.46	±2.5	±1.7

Table shows that we are going to have all reflective surfaces in far field zone between ***N*** and ***2N*** distances.

Time intervals are calculated for the velocity of sound in water equal to 1483m/sec at 20°C. They correspond to sound wave propagation from transducer to reflecting surfaces and back. The last value ***(dH)*** is the dynamic range of water level variation. For the displacement resolution about 0.2μm and accuracy about 5μm (for the displacement ± 2.5mm) we should have time domain resolution about ±140picosecond and accuracy about 3.4nanosecond. The signal repetition frequency at the ULS was chosen 100 Hz. To have possibility of comparing the results for different types of Sensors, we accepted the criteria that sensitivity (resolution) should be applied to the measurements with one second averaging time interval.

How to get the required parameters for time interval measurements? To solve the problem we had applied the next solutions:

- to have the transducers with as high as possible value of operating frequency. It means 5MHz and 10MHz;
- all (three) time intervals should be measured in parallel under one clock of "Start";
- Applying of the "zero level" comparator to fix the arrival time of the reflected pulse;
- Applying the Time-to-Digit converter of the TDC-GP1 type, with highest precision measurement function. Short list of TDC-GP1 parameters is presented below;
- Microprocessor based electronics for each Sensor to make necessary individual calibrations and processing with signals: storing of measurement results, calculation and averaging them.

The functional circuit diagram of ULS electronics is presented on the Fig.6. All the electronics is operated under the ***Flash microcontroller of MSC1211Y4*** Type of Texas Instruments Corp. The latter is controlled by the commands of Operator Board computer via RS-485 or PoE Interface. The MSC1211Y4 algorithm of autonomous operation is distributed inside its internal flash memory.

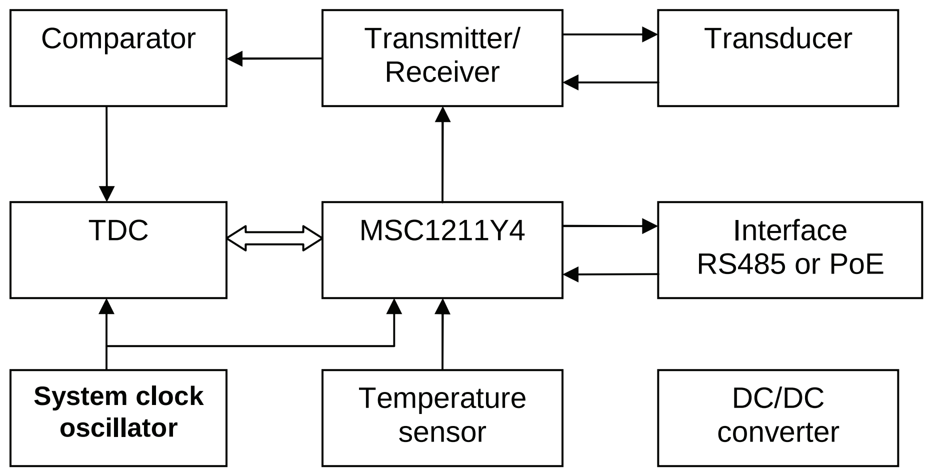

Fig.6 Functional circuit diagram of ULS electronics

Time-To-Digital Converter (TDC) is also one of central chips of the ULS electronics. We use the TDC-GP1 of ACAM Corp. [5]. The TDC-GP1 is a universal 2-channel Time-to-Digital Converter with a resolution of typically 125ps and a measurement range of maximum 200ms. Both channels have a common start input and measure up to FOUR independent STOPs. The various stops pulses can not only be calculated against the start pulse, but also each other. The time between two (up to eight) events is digitized with a dynamic range up to 29bit and a measurement rate up to 4 million measurements per second. There is no need for special printed board design as it would be necessary for highest frequency references. The TDC-GP1 is CMOS device and so it has a very low current consumption. The TDC-GP1 offers a standard 8-bit bus interface that allows using the TDC-GP1 as a simple peripheral circuit to the microcontroller. All inputs and outputs are CMOS compatible and allow including the TDC-GP1 directly into a digital environment. The built-in 16-Bit ALU is able to perform the arithmetic operations necessary for calibration immediately after the measurement and stores the result in eight 16-bit output registers. There are 8 control registers available to program the many different operation modes of the TDC-GP1. The TDC-GP1 is perfectly suited to any applications where time has to be measured with highest precision in a minimum of time at low current consumption.

The main features of TDC-GP1:

- 2 measuring channels with up to four independent stops and with a typical resolution of 250ps;
- Optional high resolution mode (Range 2) with one channel and typical resolution of 125ps; In this mode the result is the sum of different fine-count and coarse-count results (nonius method).
- 4-fold multi-hit capability per channel, double pulse resolution typ. 15ns, retriggerable;
- 2 measurement ranges => a: 2 ns -7.6 μs => b: 60 ns-200 ms;
- The 8 events of the two channels can arbitrarily be measured against one another;
- Variable edge sensitivity of the measuring inputs;

- Internal ALU for the calibration of the measurement result. A 24-Bit multiplication unit enables the results to be scaled;
- Wide range for the reference clock: 500 KHz - 35 MHz;
- Extremely low power consumption;
- 8-bit processor-interface.

In the mode of TDC operation “Measurement Range 2” only 1 channel is available with 4 possible STOPs in normal resolution (250 ps) and 3 possible STOPs in high resolution (125ps), but it is quite enough for our task. *In our case we have to measure three time intervals (three stops against one start).*

Some explanations about Comparator and it’s function. Comparator converts analogous signal of reflected oscillations into the digital “ON/OFF” form. To avoid the dependence of time measurements from reflected pulse amplitude we had applied the “zero level” comparator. It’s time diagram is presented at Fig.6. In Comparator the reflected analogous signal, looking like a short bunch of oscillations, enters to the gate. Gate has predicted time position, duration and raw comparator. All of this allows selecting, for example, ”*transition to the first positive pulse after first negative pulse with sufficiently large amplitude”*. This signal enters to comparator having zero reference level and sufficiently high gain. It’s output produce the STOP signal for TDC.

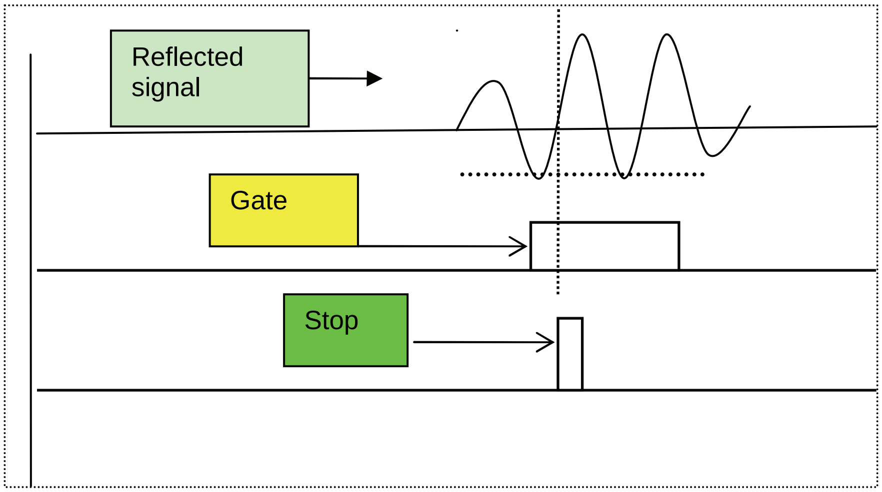

Fig.7 Time diagram of “zero level” comparator operation

The sequence of operations of the electronics of Sensor is: after power “***ON***” the Microcontroller begin fulfillment of program placed in its internal memory. At the command of computer (PC) the microcontroller makes measurement cycle. It forms start pulses for the Transmitter and TDC. The Transmitter generates electrical pulse for Transducer. The Receiver takes the reflected signals and sends them to the Comparator. The Comparator transforms analogous signals into digital pulses. TDC measures time intervals between the start pulse and the pulses coming from the Comparator. The work of the microcontroller and TDC is synchronized by System clock quartz oscillator. The Microcontroller gets digital codes of the measured time intervals from TDC and transforms them to the distance digital codes for the next transmission to PC computer. Number of cycles and clock frequency of PC is determined by system and size of the ULS memory.

The Microcontroller also can measure temperature of ULS vessel and accordingly temperature of water inside the vessel with help of temperature sensor and inboard ADC. Temperature measurement resolution is about 0.1^{o}C.

4. DATA ACQUISITION SYSTEM AND SOFTWARE

Data acquisition in Hydrostatic Level Measurement System is organized with the help of standard serial interface ***RS-485*** for ULS-PR or ***PoE*** for ULS-KE and standard system of commands ***Field Point F1001*,** developed by National Instruments Corporation. All interfaces are Plug and Play compatible and can work under Widows 2000/XP Operating System.

External electric circuit has galvanic isolation from all the other electronics of the ULS.

The Software will allow continuous processing of hydrostatic level and temperature. It will allow utilization of user-defined data treatment modules and transmitting of the raw data and results of the data processing via standard data exchange procedures. All needed adjustment and test procedures are included into the software kit.

All the power for the ULS electronics is supplied via DC/DC converter. The input voltage of the converter can be in range from 36V to 48V DC. Power consumption is about 3W for ULS-PR and about 4W for ULS-KE. Electronics Module with analogous and digital parts are presented on Fig.8.

Fig.8 ULS electronics Module

5. MECHANICAL DESIGN

Fig.9 presents the 3D scetch of both ULS versions. All dimensions are given in *mm*. All the body parts are done with stainless steel with the exception of part 1. It is done with invar for best temperature stability of linear size. The ULS-PR has two output pipes of 50mm in diameter, oriented into two opposite directions, but the ULS-KE has only one water connecting pipe. All the stainless parts are joined with welding technology. The Ultrasonic transducer is fixed on bottom side of body with the help of special adjusting device and screws. At this area the vessel has a cylindrical hole for temperature sensor and three special holes for fixing the vessel on the measurement surface.

Part 1 (reference body) is fixed on the top of the vessel with help of screws. It has one reference surface on the top and two reference surfaces immersed into water. The distance between last of them is equal to 5mm for ULS-PR and 7.5mm for the ULS-KE with high accuracy. These reference surfaces give possibility to calibrate water level measurements. The distance between upper reference surface and nominal water free surface (water fills the pipes exactly by half) is equal to 12.5mm. In reality several versions of the part 1 were designed and fabricated, scetch represents the versions. The most appropriate version will be selected later and usually it is a design subject of system as a whole. Reference distances of these prototypes are presented at the Table 2 of this report.

There are no any electronics inside body of the ULS. It is placed into separate box with allowed distance to transducer up to 2m. Distance can be increased up to 10m after some additional tuning and tests.

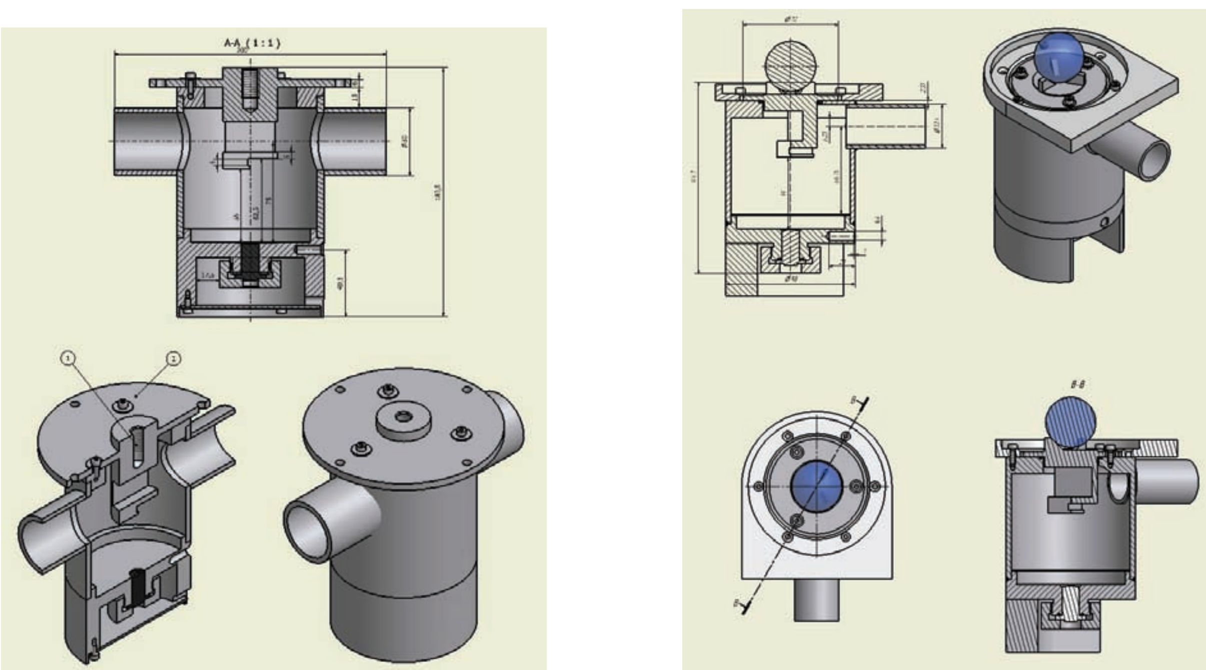

Fig. 9. ULS design modifications: with two water pipes *(left)* and one pipe *(right)*

6. TEST RESULTS

The tests were made at BINP and SLAC sites with using of two prototypes of ULS-PR and four prototypes of ULS-KE. Hydrostatic level system with half filled pipes was installed on the granite table (Fig.10). This system consists of three capacitive HLS sensors of SAS type and of two prototype ultrasonic sensors of ULS-PR type. The sensors were installed in one line alternated with each other. Distances between neighboring sensors are about half of meter.

Fig.10 General view of the test stand

For the ***test of the ULS sensitivity*** the Step test was fulfilled. For measurements two ULS-PR sensors were connected into Hydrostatic system. In the system the sensors were placed near each other on distance about half of meter and connected by transparent flexible pipe. It was small hole in the pipe. Through the hole the water drops with help of small were added. The rate of drops adding was approximately one per minute. Results of the Step test are presented at the Fig.11. Two upper graphs represent absolute water level data in sensors L4 and L0, and the third graph represents difference of water levels of these two sensors. All water level data are in µm and the time data are in minutes. Rate of ULS-PE internal averaging of signals is one second with clock frequency of measurements 100Hz.

One can see that the level step due to drop is about 0.5µm and peak – to – peak error (excluding the short time intervals near transient process produced by water drops) is about 0.3µm for each Sensor(0.5µm for both), that corresponds to r.m.s. value about 0.1µm for each ULS of this 15-minutes run.

Checking of the accuracy was made in displacement range up to 5mm. The method is: a valve on one of the deadlock ends of the HLS system pipe was opened when the absolute level into the sensor vessels were about low boundary of measurement range. Approximately during 1.5 hour the water flew in until the absolute level into the Sensor vessels became close to upper boundary of measurement range. The graphs of the absolute levels and level difference of two sensors are presented on Fig 12. Absolute level and level difference data are in µm, time data are in hours. As absolute level data of the sensors increase more then by 5mm, changes of level difference data are in range of 4µm only.

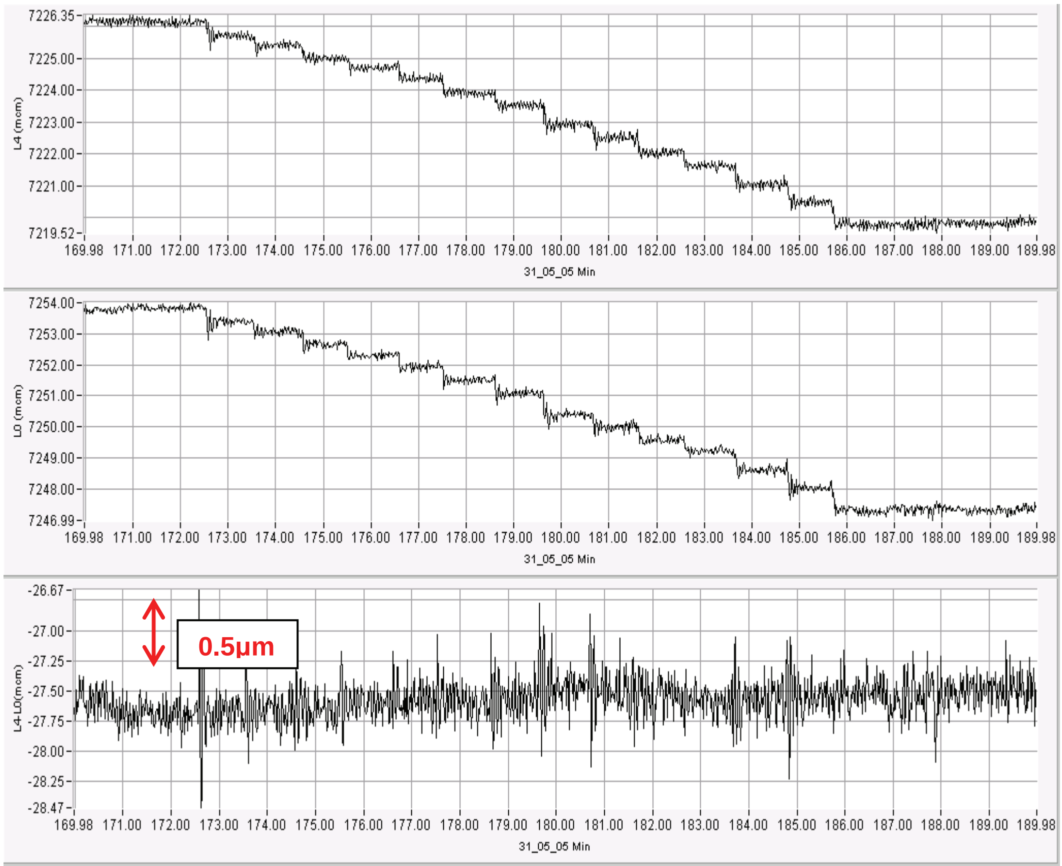

Fig.11 Sensitivity Step test of the ULS-PE

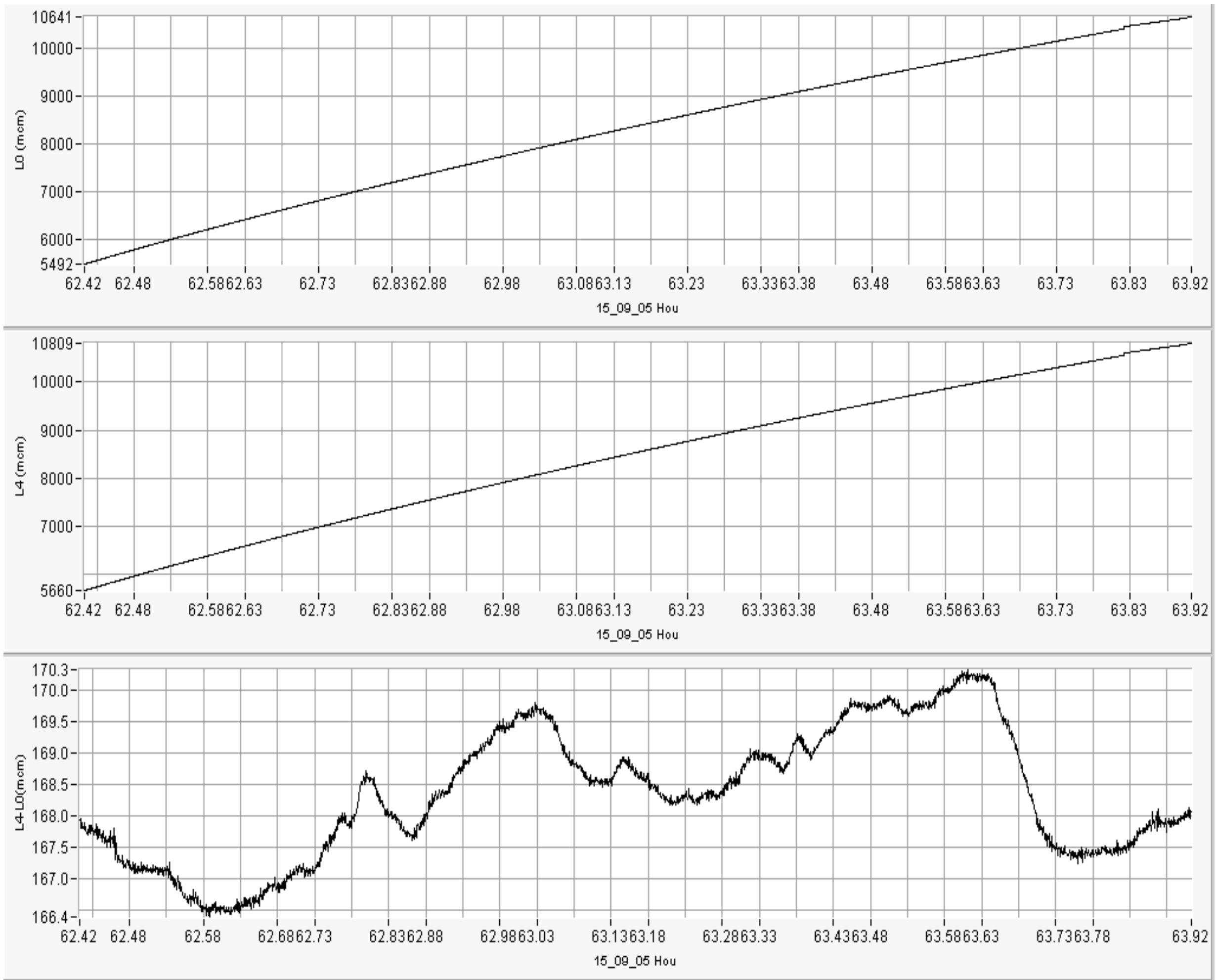

Fig. 12 ULS accuracy at the dynamic range

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