Charging of the test mass due to electric field of ESD and effect of charging on interaction of the test mass with ESD.

L.G. Prokhorov, K.V. Tokmakov, V.P. Mitrofanov

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Abstract

These notes are the addition to our paper "Space charge polarization in fused silica test masses of gravitational wave detector associated with the electrostatic drive" which has a LIGO document number P1000077-v3 and will be published in CQG. The notes present results of measurements of the charge accumulation on the suspended fused silica cylinder (pendulum) under the electric field of the ESD model. In order to promptly build up large charge on the cylinder end face we used the pumping down of the vacuum chamber with the pendulum while the high voltage to the ESD was left. The additional measurements have shown that in this case large charge is a result of electrical breakdown in rarefied air. We explored the interaction between the ESD and the pendulum measuring the variation of the pendulum natural frequency caused by this interaction.

Experimental setup

The key element of the setup is a quasi monolithic fused silica pendulum. It was fabricated and suspended about ten years ago in our laboratory. The pendulum is a 0.5 kg fused silica cylinder, 7 cm in length and 6.5 cm in diameter suspended by two fused silica fibers 25 cm in length and 200 μm in diameter (see Fig.1). We used the cylinder with two fused silica cones that were hydroxide-catalysis bonded to the surface of the optical flat polished along the length of the cylinder. The fused silica cylinder with the bonded cones was manufactured and provided to us by S. Rowan and J. Hough from the University of Glasgow. The fused silica suspension fibers were manufactured by P. Willems at Caltech. The fibers were welded to the cones by flame of a propane-oxygen welding torch.. Top ends of the suspension fibers were welded to a fused silica disk that was attached through an indium gasket to the cover of the vacuum chamber rigidly fastened to a concrete wall. The chamber was pumped down by turbomolecular pump to a pressure less than 10^{-7} Torr.

We used the free torsion oscillation of the cylinder in the measurements because the torsion mode of a bifilar pendulum has the high quality factor Q due to the pendulum damping dilution factor. The natural frequency of the torsion mode was found to be 1.14 Hz with the $Q \approx 6\times10^7$. The mode relaxation time τ^* of about 1.6×10^7 s allowed us to monitor charge sitting on the end face of the cylinder in the process of free decay of the pendulum torsion oscillation over several months (Phys. Lett. A 278 (2000) 25).

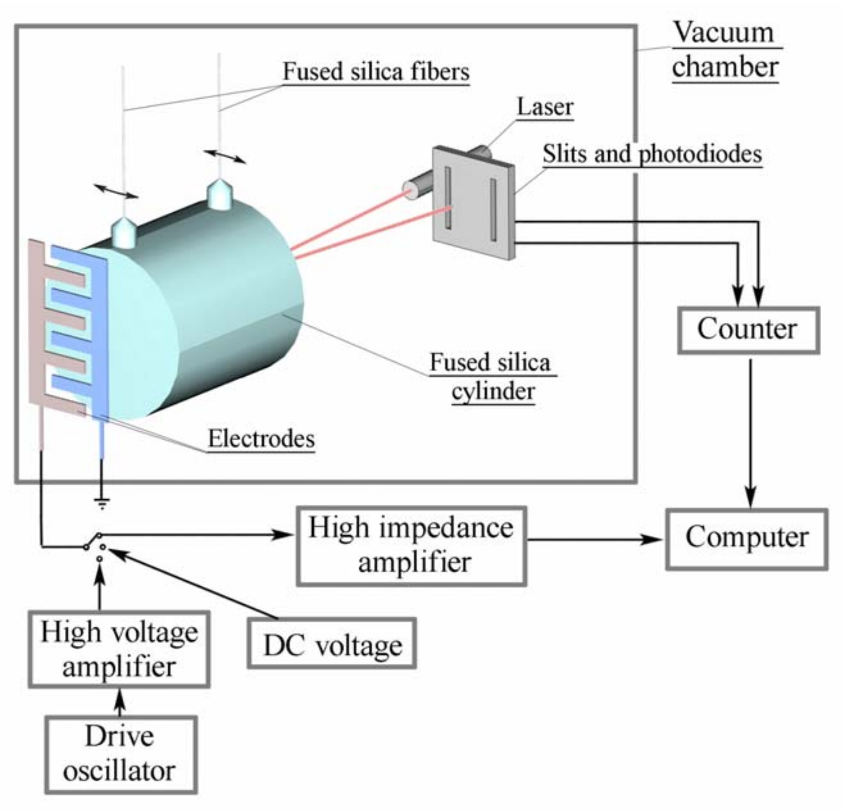

Fig. 1. Schematic layout of experimental setup #1

The amplitude of the torsion oscillation of the bifilar pendulum was monitored by the optical sensor that converted the amplitude into the time interval measured by a counter. The laser beam reflected from the other end face of the suspended cylinder was directed to the pair of 1 mm slits, with photodiodes placed behind them. Torsion oscillations of the pendulum resulted in a sequential pass of the light beam through the slits. The pulse signal was generated whose duration determined the pendulum amplitude. The Q factor was calculated from the measured decay time of free oscillations. This optical sensor was also used for measurements of the torsion oscillation frequency of the pendulum.

The ESD plate was mounted parallel to the end face of the suspended cylinder with a separating gap of ≈ 3 mm. It was the fused silica plate, 5 cm in length, 3 cm in width and 1 cm in thickness. Two sets of gold strips were sputter-deposited on the polished surface of this plate. Each strip had the width of 4 mm and was separated from the next one by the 3 mm gap. One set of the strips was grounded. The voltage was applied to the other set of the strips. The center of the ESD plate was displaced from the center of the cylinder by 1.5 cm to excite the torsion mode of the pendulum. The ESD could perform three following functions (operation modes):

1. The ESD was used to excite the torsion oscillation of the pendulum. The ac exciting voltage (100V) at the frequency of the torsion mode (approximately 1.14 Hz) was added to the dc bias (300V) and was applied to electrodes of the ESD. When the amplitude of the torsion motion was excited to the appropriate level of ~ 0.05 rad the exciting voltage was switched off and the oscillation of the pendulum were allowed to decay freely.

2. A bias voltage could be applied to the electrodes of the ESD during a long time producing the electrical polarization in the suspended fused silica cylinder.

3. The ESD was also used as the electrostatic probe to monitor electrical charges sitting on the end face of the suspended fused silica cylinder. In this case, the electrodes were connected to the high impedance operation amplifier AD 549. The oscillation of the charged cylinder induced the variation of the charge on the electrodes and AC voltage at the amplifier output. The amplitude of the AC voltage V_0 was proportional to the charge located on the cylinder against the electrodes and to the amplitude of the torsion oscillation of the cylinder. Since the amplitude was changing in the process of free oscillations we calculated a correction factor to reduce the output signal V_0 to the same pendulum amplitude. The other correction was done to regain the signal at the amplifier input. This sensor did not allow us to find the true magnitude and distribution of the charge on the cylinder end face. We could only estimate roughly this magnitude assuming definite distribution of the charge.

Results of measurements

1. The first group of measurements regarded to the behavior of charges located on the cylinder against the ESD in the case when a bias voltage of 1400 V was applied to the ESD during a long time. The measurements were carried out in vacuum (residual gas pressure was less than 10^{-7} Torr). Once a several days we switched off the ESD bias voltage and monitored the charge by the ESD connecting its electrodes to the high impedance amplifier. The switching off the high voltage applied to the electrodes before the switching the ESD to the sensor mode of operation produced the transient in the output signal of the sensor. We assume that this transient was associated with the remnant electrical polarization of isolators, which supported the high voltage conductors, e.g. vacuum electrical feedthroughs. To decrease an effect of the transient the charge measurements were carried out in hour after the switching off the high voltage.

The signal V_0 of the charge sensor as a function of time is shown in Fig. 2. In four days after a start of the measurements the bias voltage of 1400 V was applied to the ESD. Thereafter the signal V_0 began to increase approximately proportionally to time. The application of the bias voltage with the opposite sign decreased the signal V_0. Our previous measurements of the charge distribution on fused silica sample induced by the electric field of the ESD (LIGO-P1000077-v3) allowed us to assume that the signal of the sensor was caused by the charges accumulated on the end face of the silica cylinder against the electrodes of the ESD. The charge accumulation occurred slowly due to the very small electrical conductivity of fused silica.

In order to build up large charges on the cylinder we used the pumping down of the vacuum chamber with the pendulum while the high voltage to the ESD was left. The similar experiment was made at LASTI last year (LIGO-T0900435-v1). After this procedure the charge sensor has shown that large charges (with a density of the order of 10^9 electrons per cm^2) were built up on the cylinder end face.

2. Electrical charges sitting on the end face of the suspended fused silica cylinder interact with the electric field of the ESD and change the total force exerted on the cylinder. The interaction between the cylinder and the ESD was studied by measuring the change of the natural frequency of the pendulum torsion oscillation as a function of the bias voltage applied to the ESD. A bias voltage V_e applied to the ESD produces a torque $M_d = aV_e^2$ acting on the cylinder due to the interaction of polarized silica with the nonuniform electric field of the ESD (a is the constant of proportionality). If there are electrical charges on the end face of the cylinder they produce the additional torque $M_c = bV_e$ where b is the constant of proportionality depending on

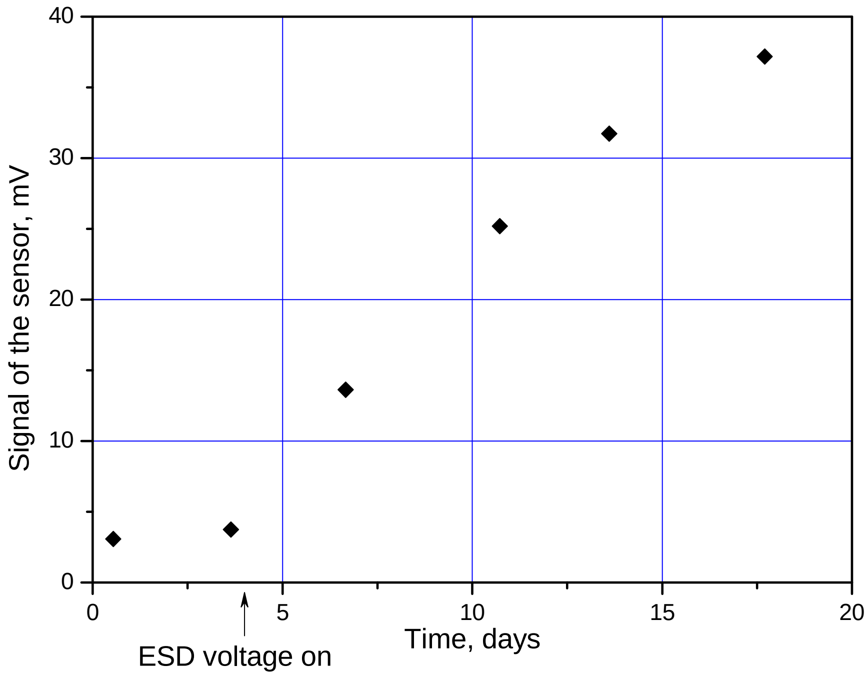

Fig. 2. Signal of the charge sensor vs. time (Bias voltage of 1400 V was applied to ESD four days later the start of the measurement)

the charge magnitude and distribution as well as on the separation gap between the ESD plate and the end face of the cylinder. Consequently, the field of the ESD introduces the (negative) torsion spring constant $K_e \approx d(M_{\mathrm{d}} + M_{\mathrm{c}})\ /d\theta$ (where θ is the angle of the torsion motion) in addition to the own pendulum torsion spring constant K . The ratio K_e/K can be found from the equation $K_e/K \approx 2\Delta f/f$ valid when $|\Delta f| << f$ where f is the natural frequency of the pendulum torsion mode and Δf is the change in this frequency caused by the ESD.

Fig. 3 shows the relative variation of the frequency of the pendulum free oscillation as a function of the dc bias voltage applied to the ESD. One can see that the curve describing this dependence is nonsymmetrical relatively the vertical axis. It is well approximated by the formula:

$$2\Delta f/f = 5.0 \times 10^{-6} + 8.0 \times 10^{-8}\, V - 1.1 \times 10^{-10}\, V^2$$

The second linear term in this formula indicate that the significant electrical charge was located on the end face of the fused silica cylinder. Unfortunately, these measurements did not allow us to calculate the charge distribution on the end face of the cylinder.

Additional measurements of charge distribution caused by the pumping down of the vacuum chamber while the high voltage to the ESD was left.

The schematic layout of the setup that was used for these measurements is show in Fig. 4. A polished Corning 7980 silica glass sample had a disk shape with a diameter

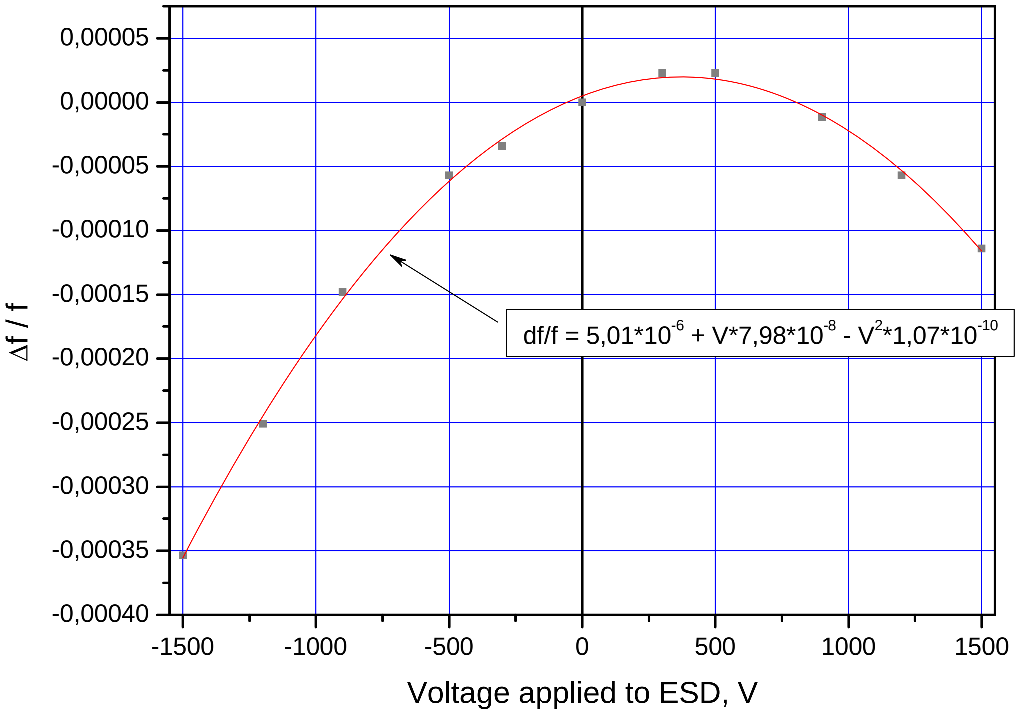

Fig. 3. Relative variation of the frequency of the pendulum free oscillation as a function of the dc bias voltage applied to the ESD

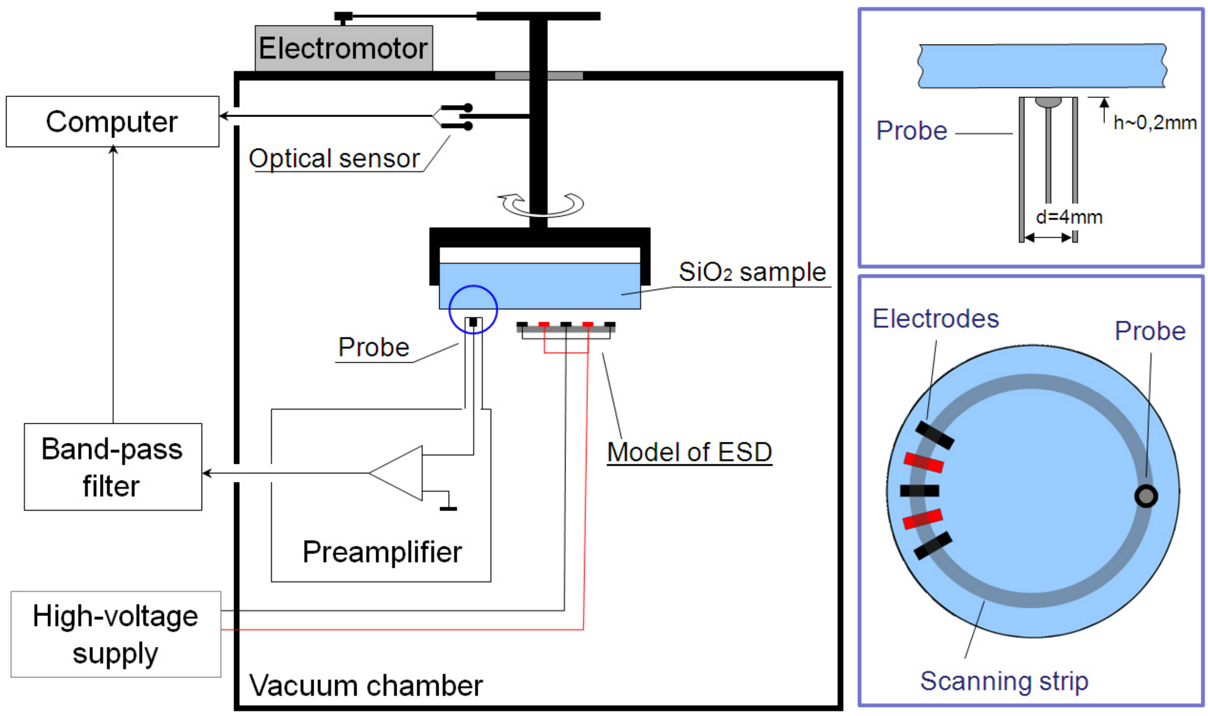

Fig. 4. Schematic layout of experimental setup #2

of 76 mm and a height of 25 mm. The sample was mounted on a turntable. A plate with the comb electrode pattern modeling the ESD was placed under the sample to induce the electric field in the sample. The electrode pattern consisted of five aluminum electrodes (length of 10 mm and width of 3 mm separated by a gap of 3 mm) placed on a teflon plate (see insert in Fig.4). A separation between the surface of the electrode pattern and the surface of the sample was about 1 mm. A differential polarizing voltage ΔV_{pol} was applied to the electrodes so that, for instance, - $\Delta V_{pol}/2$ was applied to the electrodes #1, #3 and #5 and + $\Delta V_{pol}/2$ was applied to the electrodes #2 and #4. The middle point of the voltage source was grounded.

We used a capacitive probe technique to measure the distribution of the accumulated electrical charges in the sample. A fixed capacitive probe was placed under the fused silica sample. A diameter of the sensitive plate of the probe (3 mm) was equal to the width of the electrode. When the sample rotated the charged area passed over the probe and the electrical charge was transformed to the output voltage of a high impedance amplifier connected to the probe. We monitored only spatially alternating components of the charge distribution located on the sample along the circular scanning strip. This resulted in some misrepresentation of the charge distribution but allowed us to reduce effects of the amplifier drift and environmental disturbances in long lasting measurements. Measurements were carried out in a vacuum chamber which was pumped down by means of turbomolecular pump. The sample was cleaned in an ultrasound bath with acetone and methanol before the measurements.

The voltage V_{probe} measured at the probe output presented as a function of the angular position on the sample represents the distribution of charge density on the sample along the scanning strip.

In Fig. 5 there are charge distributions obtained for two cases. The curve #1 shows the distribution of the charge which was formed on the sample after application of the polarizing voltage V_{pol} = 600 V during 28 days. The central peak of the distribution is against the electrode of the ESD with the applied positive potential. The central peak corresponded to the negative charge on the sample. The curve #2 shows the distribution of the charge which was formed on the sample during the pumping down of the vacuum chamber with the sample while the high voltage V_{pol} = 600 V to the ESD was left. In the second case the sample was turned so that the field of the ESD acts on the other place of the sample. In both cases the charges appeared against the electrodes of the ESD. In the second case the amplitude of the positive and negative charge densities was significantly larger. The charge pattern was obtained after several minutes of the pumping. The central peak corresponded to the positive charge on the sample.

The curve #2 in Fig. 6 shows the charge distribution on the sample before the next pumping down. It is the same distribution as is shown in Fig. 5. Some decrease of the amplitude was caused by decay of the charge when the sample was in air after venting of the chamber. The curve #3 shows the charge distribution on the sample after the next pumping down while the high voltage V_{pol} = 470 V to the ESD was left. One can see that the new charge peak pattern has appeared on the sample against new position of the ESD, while the previous charge peak pattern has disappeared.

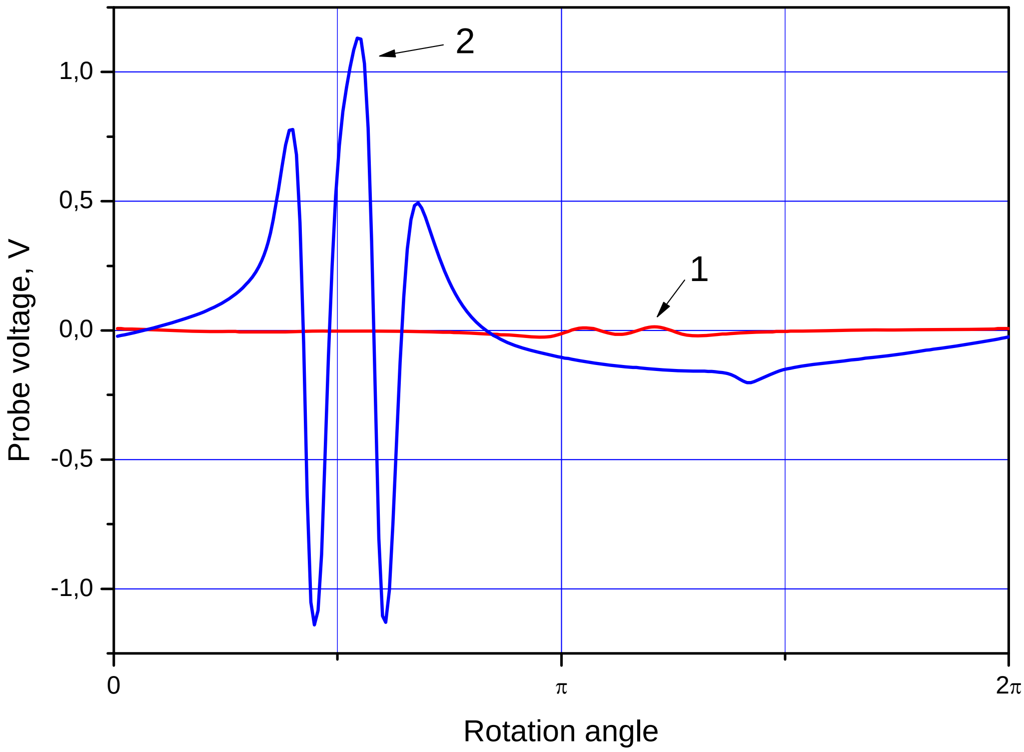

Fig. 5. Charge distributions

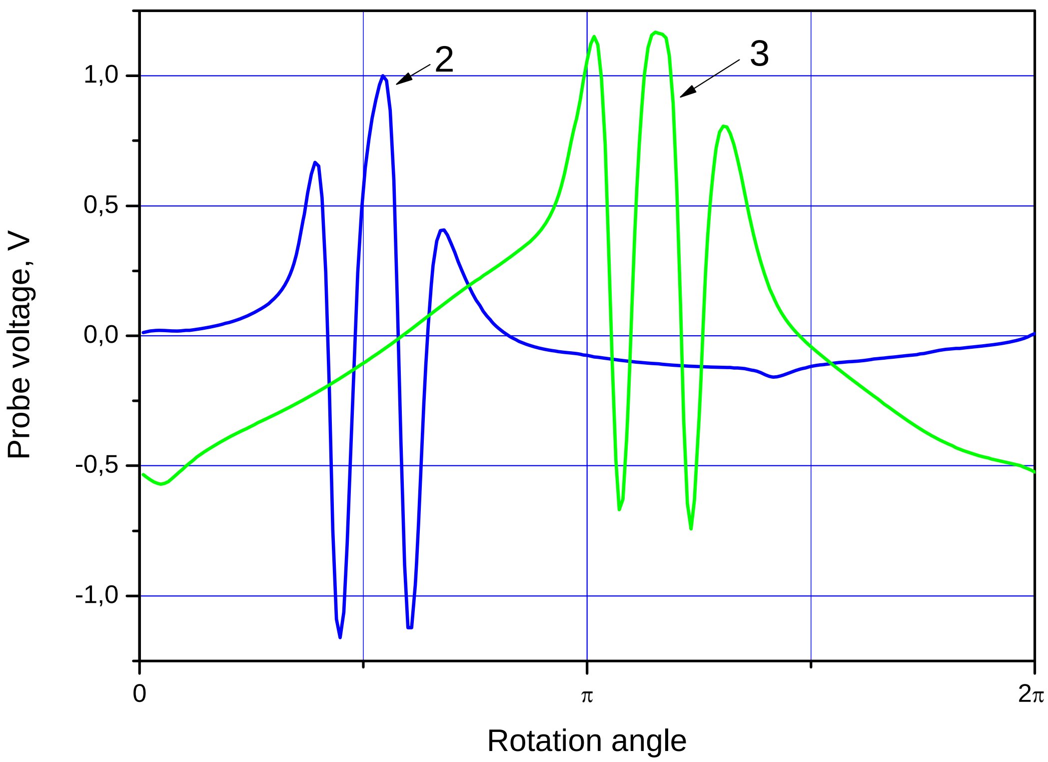

Fig. 6. Charge distributions

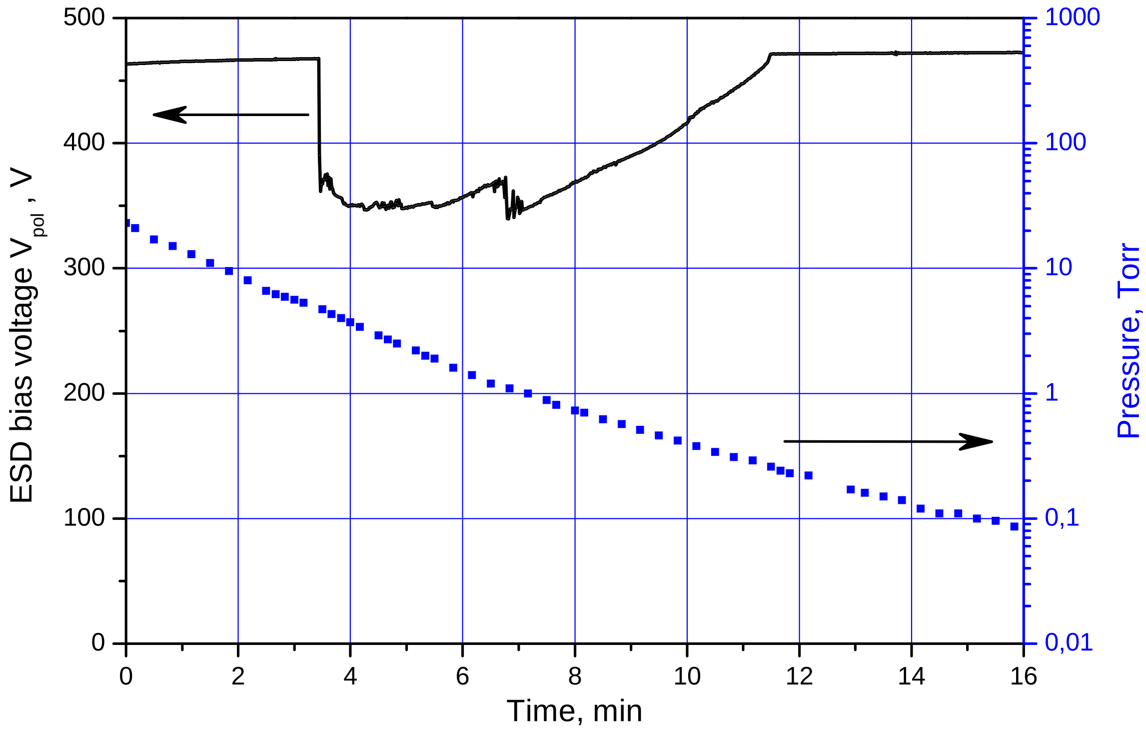

Fig 7. DC voltage on the electrodes of the ESD and the residual gas pressure measured in the process of pumping down of the chamber

To explain such a behavior we measured the dc voltage on the electrodes of the ESD in the process of pumping down of the chamber (see Fig.7). At the pressure of about 5 Torr the jump like reduction of the voltage occurred. This indicated about an electrical current which flowed between the electrodes of the ESD because we used the low power bias voltage source with a high internal resistance. Also the blue glow near the ESD was observed. At the pressure of about 0.3 Torr the ESD bias voltage returned to the initial magnitude and the glow deceased. When we reduced the ESD bias voltage down to 290 V there was no charging of the sample and reduction of the voltage on the electrodes in the process of pumping down of the chamber. All this indicated that an electrical breakdown occurred in the rarefied air when the chamber was pumped down. Reduction of the ESD bias voltage resulted in absence of the breakdown in accordance with Paschen's Low. Notice that the breakdown built up charges on a silica sample if the electrodes were close to the sample and charged ions deposited on the sample due to the field of the electrodes. The breakdown mitigated charges which were located on the sample far from the place where the breakdown occurred due to the field of these charges. The breakdown may be dangerous for the LIGO test masses because of the possible sputtering of the material of the ESD electrodes and their deposition on the test mass.

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