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LIGO-T060140-00-R 6/14/06

Development of a Tuning-Fork Chopper Kelvin Probe for Sensing Static Charge on LIGO Optics

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1 Introduction

There is growing concern over charge buildup on LIGO optics and the noise and other issues these charges present. Understanding and remedying the charging problem will require measuring the magnitude of these charges *in situ* and the time constant with which they fluctuate. This document describes the development of a Kelvin probe to perform these measurements, and details the probe's sensitivity and ways in which it can be further improved.

2 Charge on Optics

2.1 Problems Associated with Charging

The buildup of surface charge on LIGO optics as a potential noise source was identified at least as early as 1996 [1]. More recently, static charge has been suggested as a reason for the difficulty in controlling the LLO ITMY optic during S5, and possibly why the optic became wedged in its limit stops during May of 2006. Charging has also been suggested as a limiting noise source in the 40-100 Hz frequency band; this noise contribution disappeared at LLO after venting to correct the wedged ITMY [2].

Surface charge layers could interfere with the magnetic position control of the optics, as mentioned for ITMY above. Fluctuating electric fields from these charge layers could also introduce low frequency suspension noise. Static charges could also attract dust to the surface of an optic, reducing reflectance as well as the finesse of an optical cavity.

2.2 Sources of Charging

Charging of optics can occur during pumpdown of the interferometer, due to friction as dust scrapes across the surface of an optic [1]. Charge can also be deposited by contact with another material such as the earthquake stops [3]; this could be the mechanism by which ITMY is being charged. Another potential source is cosmic rays – Rai Weiss's 1996 note declares this effect as negligible, but a recent calculation by Braginsky and others [4] suggests that a cascade of energy from a cosmic ray striking a dense material could deposit excess electrons on an optic, and the AC Coulombic force created could mimic the waveform of a burst event. Mitrofanov *et al* [5] have observed jumps in the charge on an optic in vacuum of up to 10^8 e^-/cm^2, which may be attributable to cosmic rays.

2.3 Prior Measurements

Measurements by the Moscow State group have shown a substantial charging rate of $\sim 10^5$ e^-/cm^2/month [5]. Another study showed that the friction between dust and a charged optic could reduce the mechanical Q of the optic, but in a different geometry from the LIGO suspensions [6]. There are no current measurements, however, of the charging of optics in the actual LIGO interferometers during science running.

Another important and unmeasured quantity is the time constant for the fluctuation of electric fields produced by surface charge. We may find the fluctuating force power spectrum by assuming that these fluctuations are a Markov process with a single correlation time τ_0. The general derivation is given in Landau and Lifshitz [7]; for our situation the power spectrum is given by [1]:

$$F^2(f) \approx \frac{2\left\langle F^2\right\rangle}{\pi\tau_0\left(\frac{1}{\tau_0^2}+\left(2\pi f\right)^2\right)} \approx \frac{2\left\langle F^2\right\rangle}{\pi\tau_0\left(2\pi f\right)^2}$$

where τ_0 is the correlation time and $\langle F\rangle$ is the average Coulombic force. The second expression is for the case when τ_0 is large, which we expect for an insulating surface. Thus an understanding of the correlation time is necessary to estimate the expected direct, Gaussian noise contribution from surface charge.

Figure 1 shows an estimate of the noise contribution from charging, given a correlation time of one day and a total charge buildup of 3×10^{-12} Coulombs, along with the overall expected Advanced LIGO noise level. This implies that for shorter correlation times or greater charge densities, charging is a potentially limiting noise source in the 10-100 Hz frequency band.

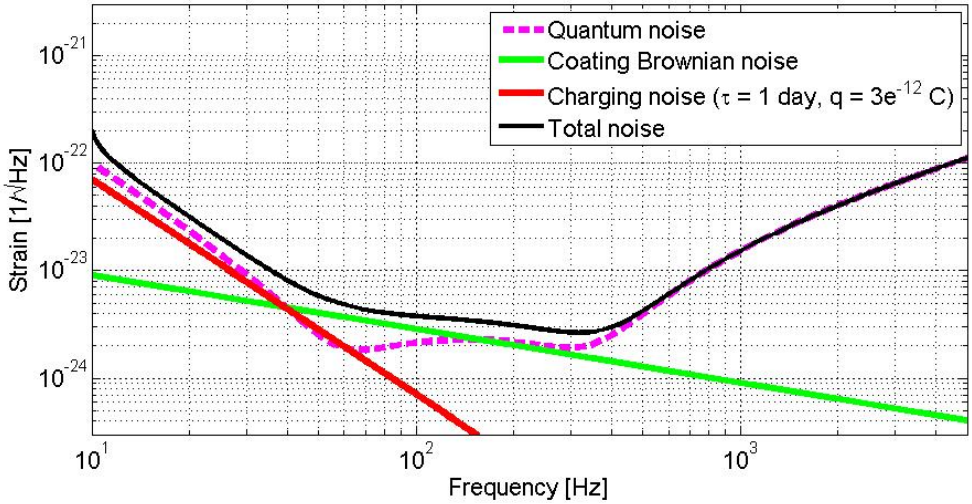

Figure 1: Estimated charging noise curve versus Advanced LIGO benchmark

A proposed remedy for optic charging comes from the LISA project [8]. Charge can be directly removed from the optic through illumination with UV light. This scheme, however, still requires some means of measuring the contact potential of the optic in order to control the level illumination and not “overcorrect” (remove too many electrons such that the optic is now positively charged).

3 The Kelvin Probe

3.1 Theory and Signal Modulation

One device for the measurement of surface charge is the Kelvin probe. The Kelvin probe is a capacitive device; a charge layer on the sample induces charge to flow to the surface of the probe. Measuring the voltage produced when this charge flows across a large resistance gives a signal linearly related to the magnitude of charge on the sample.

Of course, this is only a one-time effect. In order to produce a repeatable, measurable signal, the capacitance between probe and sample must be modulated. In most commercial probes this is accomplished by modulating the position of the probe tip, either with a PZT or voice coil. Such commercial probes can be very expensive, however; quotes from Besocke Delta Phi GmbH and www.kelvinprobe.com ranged from \$8,000 - \$12,000 for a vacuum-compatible probe.

Another possible means of modulation is to alternately occlude and expose the probe tip to the sample. This can be accomplished via the tuning-fork chopper from Boston Electronics shown in Figure 2. Current flows through the coil in the center, magnetically attracting and repelling the chopper blades, which opens and closes the aperture between. When the aperture is closed, the electric field lines from charge on the sample will terminate at the grounded chopper blades, and charge will flow away from the probe tip. The tuning fork chopper has the advantages of small size, vacuum compatibility, and low cost (\$850 with driver circuit). This document will detail the development of a Kelvin probe using this modulation method.

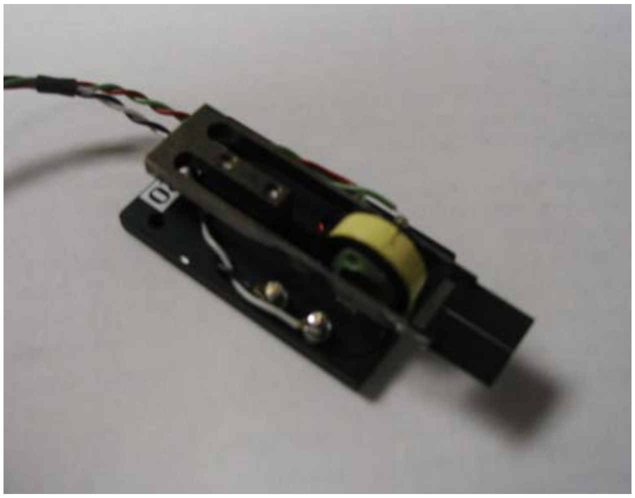

Figure 2: Tuning-fork chopper from Boston Electronics

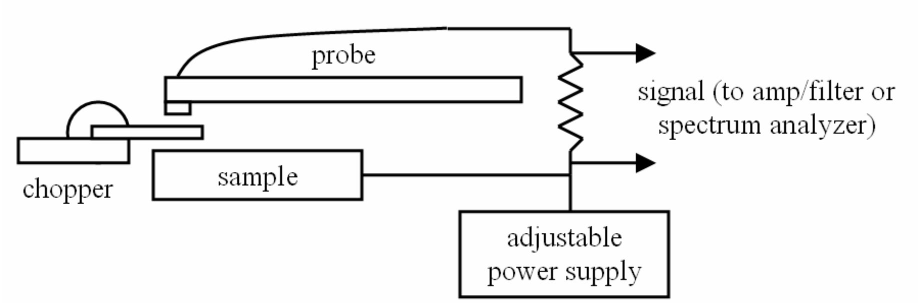

Figure 3: Circuit and physical layout for tuning-fork chopper Kelvin probe

3.2 Kelvin Probe Circuit

The physical layout and electronics associated with the tuning-fork chopper Kelvin probe are shown in Figure 3. The probe and sample are placed 1cm apart with the chopper blades in between. The probe signal is measured across 100 MΩ of resistance. In initial testing, the probe signal was read out by a SR780 network signal analyzer, set to measure the voltage at the chopping frequency of 504.5 Hz. Ultimately the goal is to use an Analog Devices AD549LH low-noise op-amp to amplify the signal for readout.

The sensitivity of the probe is measured in air in two ways. First, as shown in Figure 3, a known voltage is applied to a conducting sample in order to calibrate the probe. Second, charge is deposited on an insulating sample (in this case, a piece of plexiglass is rubbed with felt), with the goal of measuring how the charge varies with time.

3.3 Probe Prototypes

Our Kelvin probe has evolved through three geometries, as shown in Figure 4. The first probe consisted of a square copper tip element, 4 mm on a side, mounted on a piece of plexiglass. A copper grounding ring 2.5cm in diameter was added to prevent stray electric field lines from reaching the probe tip from the sides; the grounding ring was electrically isolated from the tip by another piece of plexiglass. This probe design was discarded because it was too large; the probe mechanically contacted the coil on the tuning-fork chopper with the tip more than a centimeter away from the chopper blades.

The second probe used a tongue-shaped geometry to allow the tip to be closer to the chopper and sample, which required the removal of the grounding ring. Initial measurements with this probe gave a signal on the order of tens of millivolts at 504.5 Hz even with no sample present, but which decreased with distance to the chopper. The conclusion was that the chopper coil was generating an oscillating electric field at the chopping frequency, which was being picked up by the probe.

The third probe reintroduced the grounding ring to minimize this noise source. To keep the probe small, the ring was made of a copper disk 13mm in diameter, with a 5mm diameter hole drilled through the center. The probe tip is now just the stripped end of 20 AWG copper wire. Pickup from the chopper coil was also reduced by enclosing all but the blades of the chopper in a grounded aluminum box, wrapping the probe and grounding ring leads in grounded aluminum foil, and electrically isolating the chopper power supply from the rest of the circuit. All of these improvements resulted in a noise peak of 0.12 +/- 0.01 mV at 504.5 Hz with no sample present.

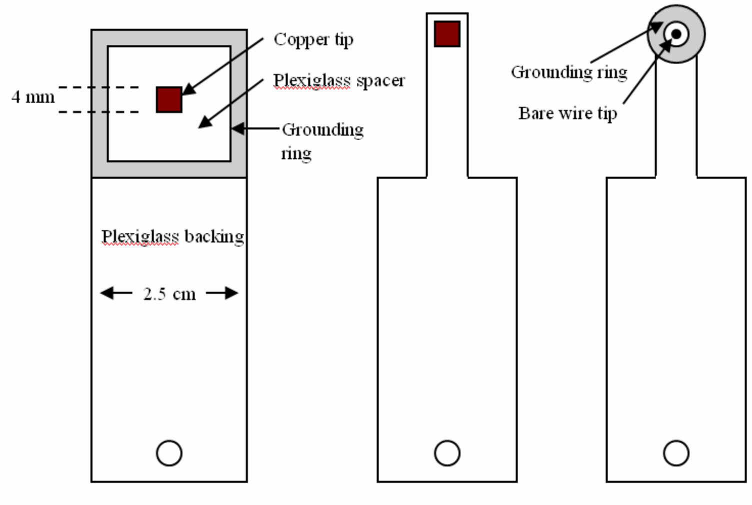

Figure 4: Probe prototypes, chronologically from left to right

4 Experimental Results

4.1 Calculated Sensitivity

Even with the noise peak minimized as much as possible, the third probe geometry is still not sensitive to changes of voltage on the conducting sample. It can, however, measure charge deposited on the insulating sample. A rough calibration is made by measuring the voltage on the insulating sample using a Surface DC Voltmeter from AlphaLab, Inc. We find that when the probe measures a signal of 1 mV at 6 mm from the sample, the voltmeter reads roughly 1500 V at a distance of 2.5 cm from the sample.

For a voltage V as measured by the surface voltmeter for a finite-sized insulating sample, the charge per unit area S in C/m^2 is given by [9]:

$$S = \frac{V\left(1+4\frac{L^2}{D^2}\right)}{2L\left(5.7\times10^{10}\right)}$$

where L is the distance from the voltmeter to the sample and D is the width of the sample (in our case, both are 2.5 cm). So for a reading of 1500V, $S = 2.6 \times 10^{-6}\ C/m^2 = 1.6 \times 10^9\ e^-/\text{cm}^2$. Since this corresponded to a probe signal of 1 mV, and the uncertainty in our measurements is 0.01 mV, then the sensitivity of our Kelvin probe is given by $1.6 \times 10^7\ e^-/\text{cm}^2$.

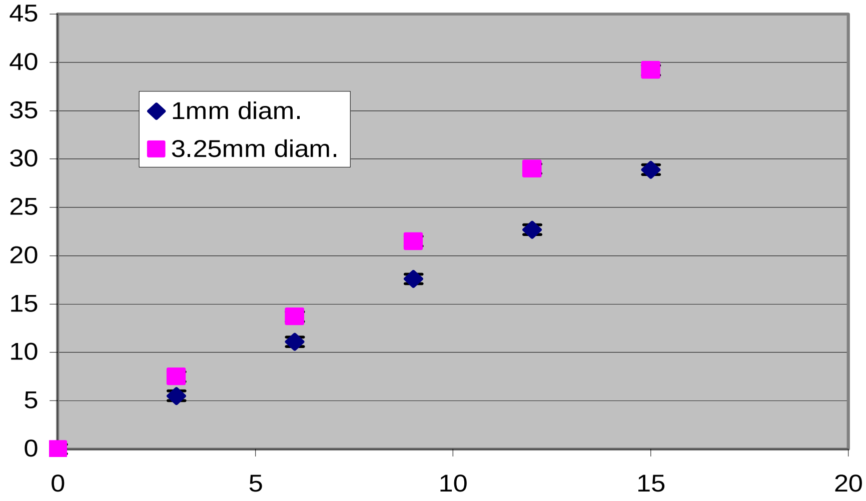

Figure 5: Response of rotary chopper probe to conducting sample with applied voltage

4.2 Sensitivity with Rotary Chopper

We then replaced the tuning-fork chopper with a rotary chopper (impractical for *in situ* LIGO optics measurements because it is not vacuum-compatible) to estimate the best possible sensitivity for a chopper-modulated Kelvin probe. With no sample present, there is negligible signal at the chopping frequency. The conducting sample is also clearly measurable; the probe signal versus sample voltage is shown in Figure 5. One set of data points represents the bare wire probe tip, with a diameter of 1.0 mm. For the second set of data points, a small quantity of solder was applied to the probe tip to broaden its diameter to 3.25 mm, resulting in a small improvement in signal. The probe-to-sample distance in both measurements in 6 mm.

The uncertainty in each measurement, due to fluctuation in the probe signal, is 0.5 μV. Using the conversion from the previous section, this corresponds to a sensitivity of 8×10^5 e^-/cm^2. Much of the signal fluctuation appeared to be due to roaming in the chopping frequency, which would change by as much as 2-3 Hz during a measurement. Use of a more constant chopper and the low-noise amplifier mentioned in section 3.2 would undoubtedly improve the sensitivity yet further.

4.3 Signal Versus Sample Distance

Figure 6 shows the behavior of the probe with rotary chopper for different distances to the conducting sample. The signal size shown is the difference between the signal at 15V applied to the sample, and the signal at 0V applied to the sample. At separations greater than 4 mm, the signal size closely follows an inverse square relationship with distance. Below 4 mm, the noise peak at zero applied voltage quickly grows to over 50 μV, or nearly 50% of the signal size.

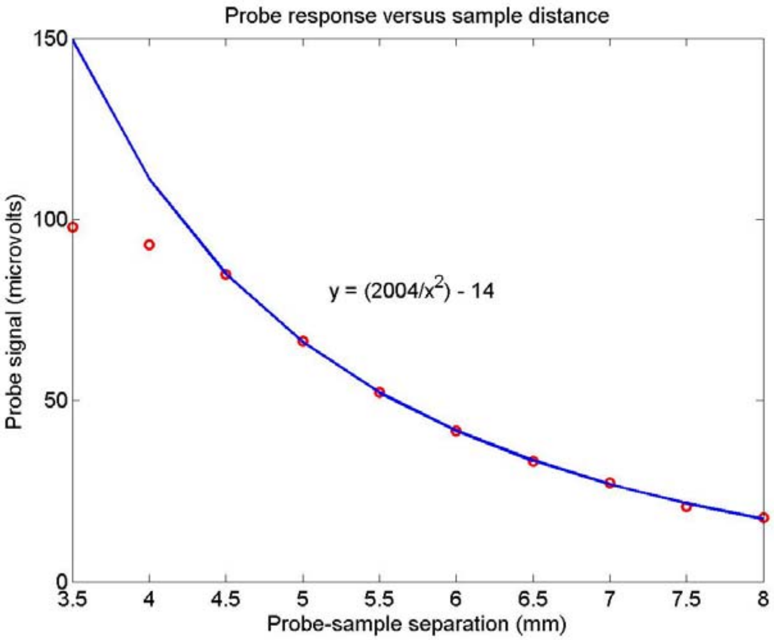

Figure 6: Probe signal as a function of distance from conducting sample

4.4 Charge Dissipation Over Time

Figure 7 shows two sets of measurements using the tuning-fork chopper, in which we measured the dissipation of charge in air from a piece of plexiglass that we charged by rubbing with felt. In each case the 0.12 +/- 0.01 mV noise peak has been subtracted from each data point before plotting; this fluctuation is the primary source of uncertainty in the measurement. There were two initial hypotheses for the dramatic change in decay constant: (a) changes in the weather, particularly humidity, or (b) differeng levels of contact between the plexiglass and the optical table magnets anchoring the sample in place.

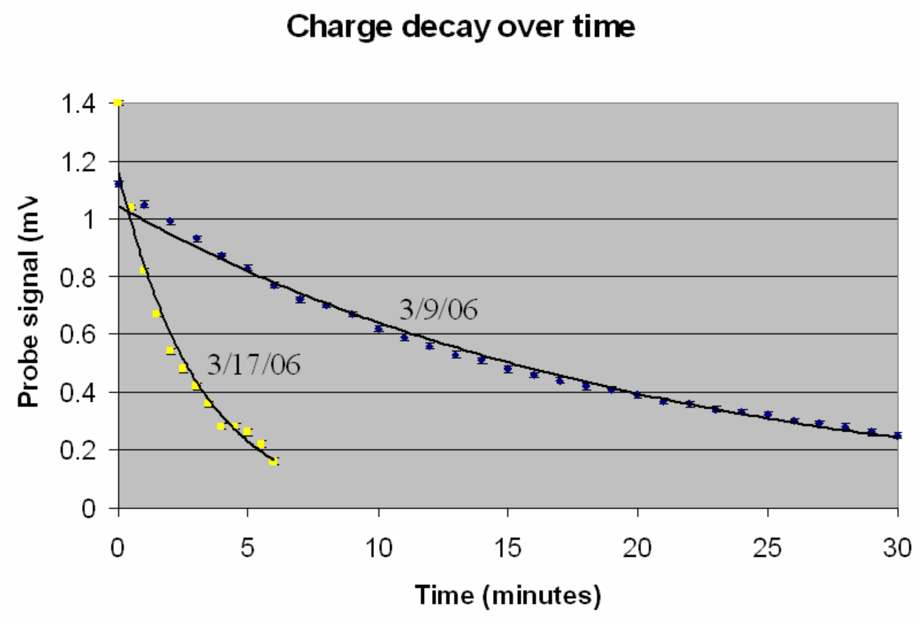

Figure 7: Charge vs. time for plexiglass sample measured with tuning-fork chopper probe

Three more decay measurements were made using the rotary chopper, as shown in Figure 8. The weather in the lab was monitored during these measurements, and consistently stayed in the following ranges: 74-76 degrees Fahrenheit, 1035-1036 millibars atmospheric pressure, and 63-69 percent relative humidity. The sample was also electrically isolated from the optical table magnets by wrapping its lower half in felt, secured in place with electrical tape. As can be seen in Figure 8, there is still a large difference in dissipation rate between the 6/9 measurement and the other two, for reasons unknown.

Another open question is what function describes the shape of these decays. As can be seen in Figure 8, an exponential fit works well only for the data of 6/7. The other two sets are better fit by a logarithmic decay, y = -(a ln x) + b; Figure 9 shows that when using a logarithmic scale for the x-axis, these two data sets are linear. We have also fit all three data sets with the sum of two exponentials with different decay constants, but there is no commonality between the constants from one fit to the next, and with so many degrees of freedom, the fit may not be meaningful.

An equation for the dissipation of charge from a dielectric in a vacuum is given by Davies [10]:

$$\frac{1}{\sigma}=\left(\frac{1}{\sigma_0}+\frac{1}{2ned}\right)\exp\left(\frac{4\pi ne\mu t}{\varepsilon}\right)-\frac{1}{2ned}$$

where σ is the surface charge density, σ_0 is the initial charge density, n is the density of intrinsic charge carriers in the material, d is the thickness of the dielectric, and μ is the electron mobility. If the number of charge carriers is small, the exponential term can be Taylor expanded as a polynomial in t. Figure 10 shows the reciprocal of the probe measurements, fit to a polynomial of degree 2 in time. While the fits appear to match well, from the above equation it should not be possible for the t^2 term to have a negative coefficient, as is the case for the data from 6/8.

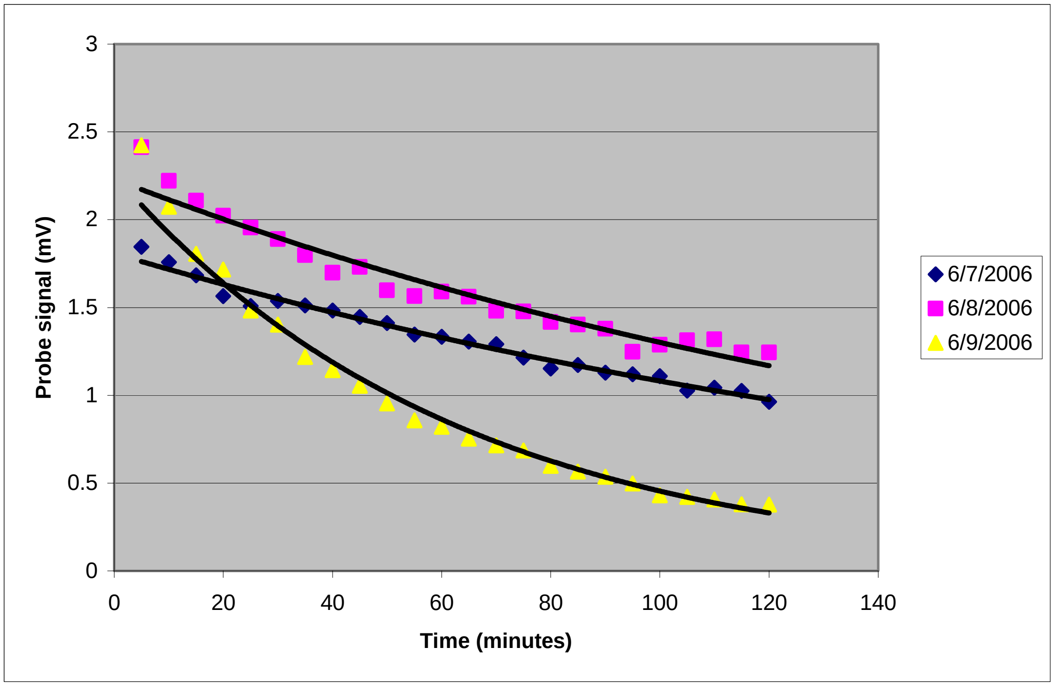

Figure 8: Charge dissipation data with rotary chopper and exponential fit

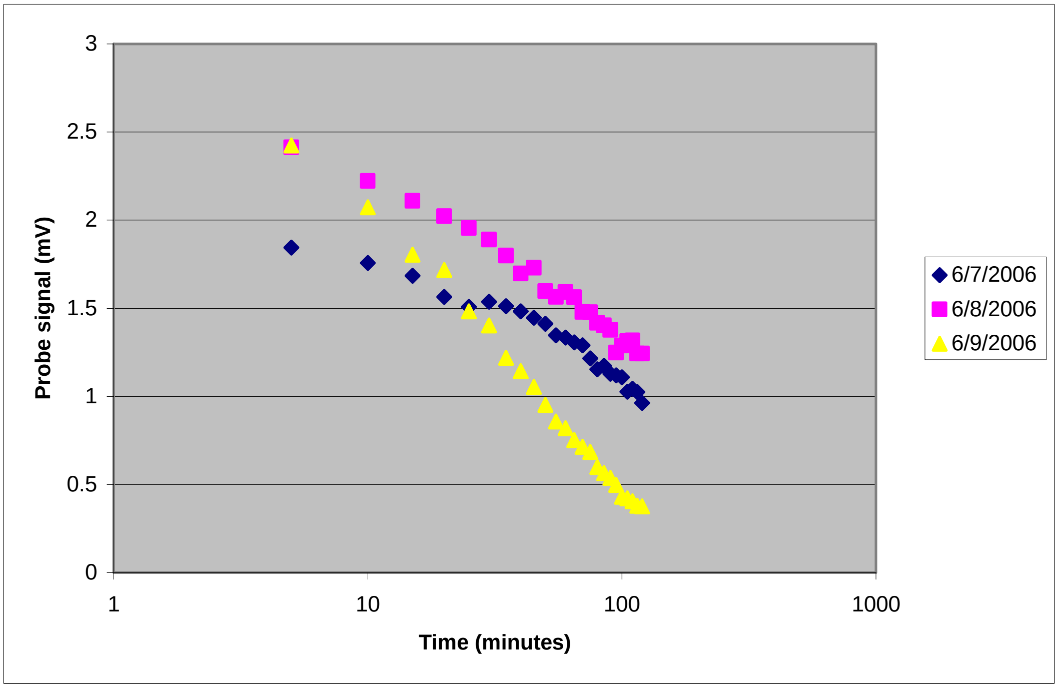

Figure 9: Charge dissipation data with rotary chopper, showing logarithmic decay shape

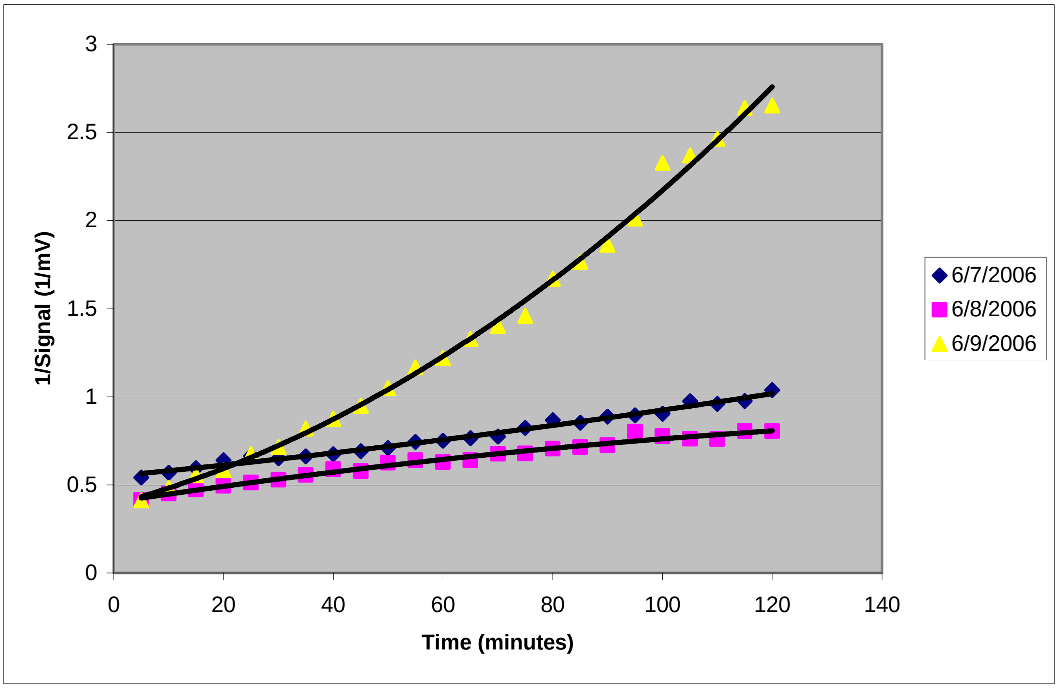

Figure 10: Reciprocal of probe signal versus time, with quadratic fit

5 Conclusion

We have developed a working, vacuum-compatible Kelvin probe modulated by a tuning-fork chopper, with a measured sensitivity of $1.6 \times 10^7\ e^-/\mathrm{cm}^2$. Substituting a rotary chopper has also shown that the method is capable of at least two more orders of magnitude of improvement in sensitivity. The limiting factor is currently pickup of fluctuating electric fields at the chopping frequency from the actuating coil on the tuning-fork chopper.

Further development work will involve (a) improving shielding around the tuning-fork chopper, (b) investigating other choppers that are vacuum-compatible and do not produce noise at the chopping frequency, and (c) moving the probe test setup to vacuum. A reference cavity chamber on loan from MIT to Trinity University has been designated for this final step; equipment still required to begin using the chamber includes roughing and turbopumps, a multipin instrument feedthrough, and a Pirani pressure gauge. The expected pressure in the chamber should be on the order of 10^{-5} torr. Once the chamber is commissioned, further testing will include:

- Remeasuring the sensitivity of the probe to a conducting sample
- Measuring the correlation time for charge dissipation from a dielectric material
- Repeating the correlation time measurement for small samples of LIGO optical materials (fused silica, sapphire), and coatings (silica/tantala, silica/titania-doped tantala, others under development).
- Using a remote-controlled translation stage to measure charging as a function of position

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