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-LIGO-
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of the LIGO Project.

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ABSTRACT

We report on our measurements of the quality factors of sapphire and fused silica masses of LIGO and Advanced LIGO test mass sizes. We are pleased to report that both materials have very low losses in large sample sizes.

EXPERIMENTAL METHOD

In all cases, the sample was a right circular cylinder with bevelled corners. The faces and circumference were mechanically polished, although the circumferential polish of the sapphires was poor. No sample had any coatings. We suspended all samples from a rigid steel clamping structure using single metal wire loops around their equators, and the wires were mechanically polished and greased with lard. The modes of the masses were excited using a comb electrostatic actuator on a plate near to and covering about half of one face of the sample. The deformation of the sample was measured by monitoring the change in polarization of a HeNe laser beam transmitted through the sample due to stress birefringence (the Syracuse technique). All experiments were done in a vacuum of about 10^{-5}-10^{-6} Torr.

RESULTS: SAPPHIRE

We measured two sapphires provided by Crystal Systems and polished by Insaco. They are 40kg Advanced LIGO prototypes, with 15.7cm radius and 13cm thickness, but with no wedge. As mentioned earlier, the circumferential polish was very poor, and viewed from the side the sapphires were translucent. One sapphire was very clear, with virtually no bubbles or inclusions within it. We refer to this as the ‘clear’ sapphire. The other was pink over half its volume, and there were a very large number of bubbles and inclusions visible throughout its volume. We refer to this as the ‘pink’ sapphire. Both sapphires had a small chip at one edge. Both had the a-axis pointing out the flat face.

We suspended the sapphires several times, using .020” stainless steel wire and .016” and .020” music wire. The type of wire did not seem to make a systematic difference in the results. The sapphires were always suspended with the c-axis horizontal.

All the data for the clear sapphire are presented in Figure 1, and all the data for the pink sapphire are presented in Figure 2. Both sapphires had a mode with Q greater than or equal to 200 million, and thus meet the requirements for Advanced LIGO.

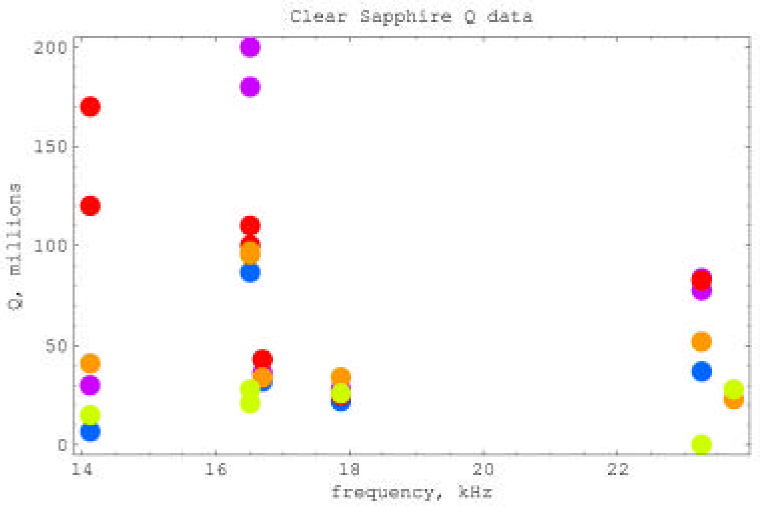

Figure 1: clear sapphire Q data. All points with the same color were measured using the same suspension.

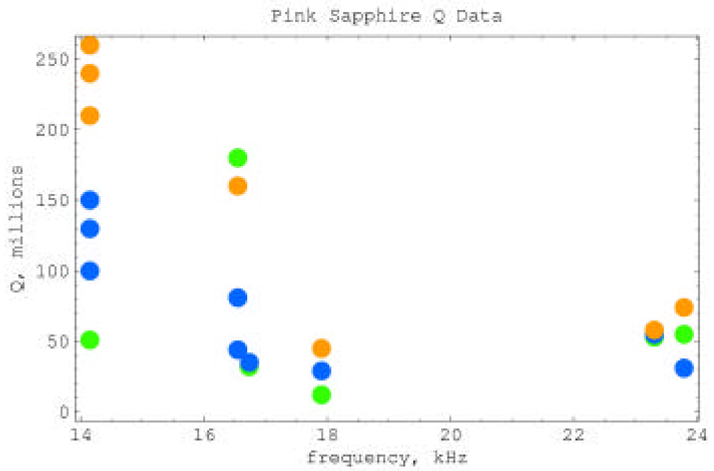

Figure 2: pink sapphire Q data. All points with the same color were measured using the same suspension.

The best Q's measured for the two sapphires vary over an order of magnitude from mode to mode, but this variation is similar for the two sapphires. This suggests that the variation is not random. One possibility is that the internal friction of sapphire is anisotropic, so that different modes will have different Qs to the extent that they exercise different parts of the stress tensor. However, the sapphire crystal has trigonal symmetry, and therefore has six independent elastic moduli; with data for only six modes we have little hope to constrain the anisotropy of the loss, especially in the presence of experimental uncertainty and extraneous loss mechanisms.

The most likely extraneous loss mechanism is the poor barrel polish. Good surface quality is generally a requirement for very high Q measurement. To test this possibility, we used a finite element model of the sapphires made by Dennis Coyne using I-DEAS. The mode frequencies it predicted for the sapphires were all within 2% of the measured mode frequencies, giving us confidence that it accurately modelled our masses. Using this model, he calculated the fraction of the oscillation energy that was localized within a small layer at the circumference of the sapphire for each mode. We then used the best data for each mode for each sapphire to fit a model that assumed that the loss was the sum of a bulk internal friction plus a surface damage friction contribution proportional to the circumferential energy fraction for that mode. Thus, the six Q's measured constrained a two parameter model. The best Q data plus the fit are presented for the clear sapphire in Figure 3 and the pink sapphire in Figure 4. The fits are quite good, especially for the pink sapphire. The error bars for the experimental data are 10% and are based on the repeatability of Q measurement for a given mode for a single suspension attempt. The error bars in the model are 20% based on Dennis Coyne's estimate.

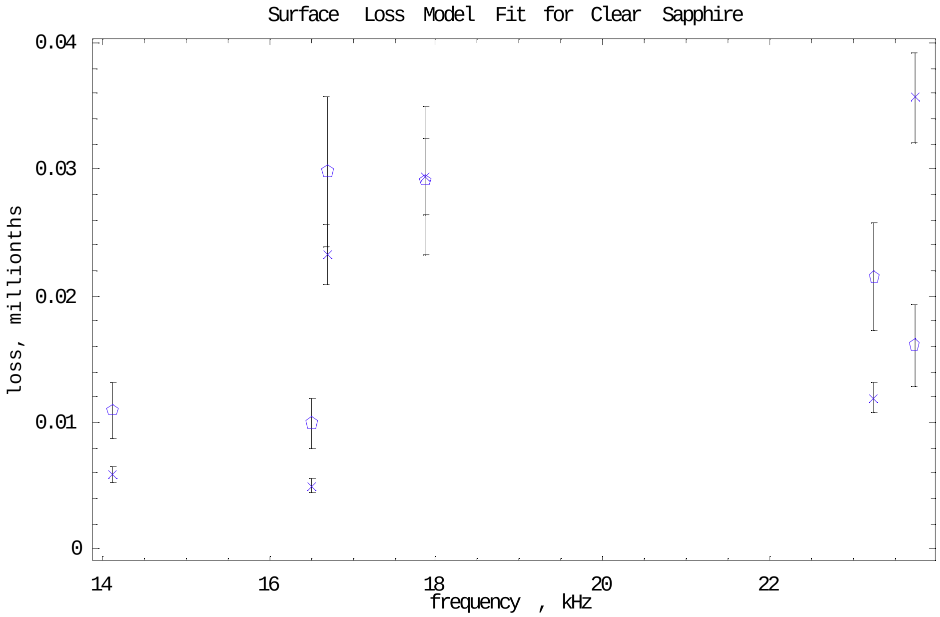

Figure 3: best losses for the clear sapphire plus the best fit of the surface loss model. The crosses are the data and the open circles are the model predictions.

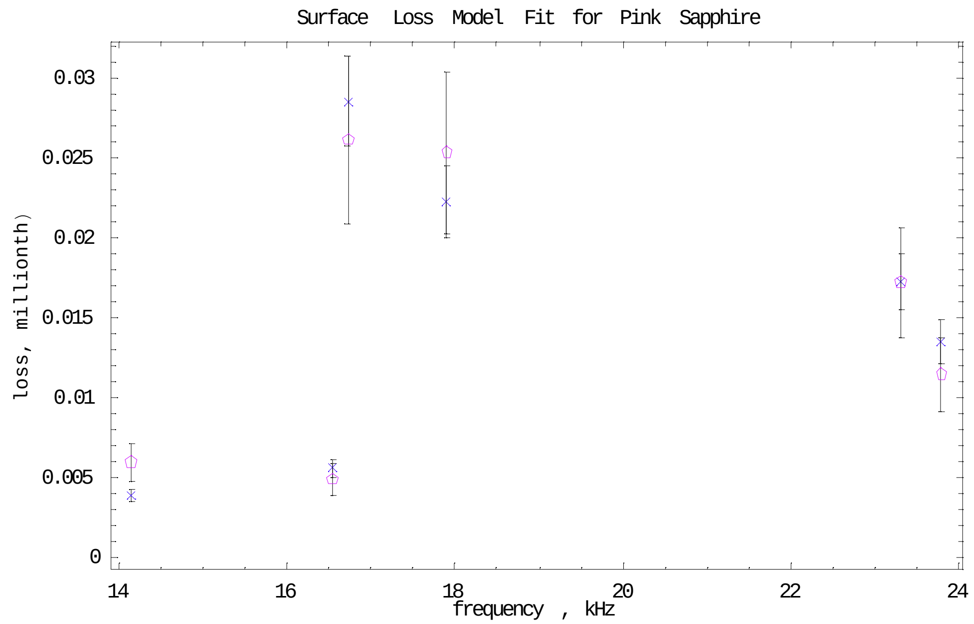

Figure 4: best losses for the pink sapphire plus the best fit of the surface loss model. Symbols are as in Figure 3.

The model is likely only an approximation to the true effect of the surface on the losses, because it assumes a uniformly poor polish on the circumference of the sapphires, while the actual polish is patchy. Nevertheless, the agreement between data and theory is so close that we recommend that these sapphires should be repolished before any additional measurements are made on them.

RESULTS: FUSED SILICA

We studied ITM11, a spare LIGO input test mass. It is manufactured from Suprasil 312 and polished by CSIRO to 2? microroughness, with 12.7cm radius and 10.8cm thickness, and no wedge. The polish on the barrel was very good, except for a few small alignment and identification markings.

We suspended this mass from .012” and .009” music wire, but the best results came with the thinner wire. We also tried .006” music wire, but it broke under the weight of the mass. Again, the wire was polished and then greased with lard.

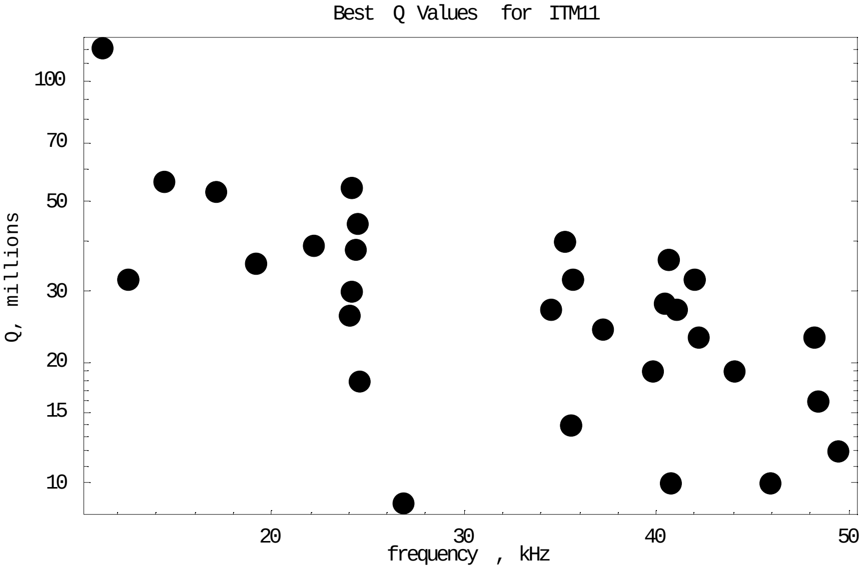

Figure 5: best measured Qs for the fused silica mass ITM11

The best Q's measured for each mode are plotted in figure 5. As can be seen, the Q's for this mass are substantially higher than have been measured for any other LIGO mass. In fact, the Q measured for the 11.202kHz mode, at 120 million, is the third highest measured in any sample of fused silica anywhere. This result is gratifying because it indicates that fused silica may indeed be competitive with sapphire for low thermal noise, as suggested by the recent results of Steve Penn and Sasha Ageyev, since such high Q has now been observed in a polished mass. However, this result is also puzzling, for several reasons. The Q's of LIGO masses have been measured several times in the past. There is nothing else remarkable about this one, so it is unclear why its Q is so much higher. There may be some value in testing other uncoated spares. Also, Q's this high in fused silica are generally achieved only after careful annealing, and often flame polishing, but this mass has not been subject to either treatment. It may be possible, as Gregg Harry has suggested, that the thermal history of this mass during its manufacture resembles a careful anneal, but we have no evidence to support this idea. It is interesting to note that the 'envelope' of highest Q values over the whole frequency band measured appears to overlap with and extend to lower frequency the trend of Q vs. frequency seen by Kenji Numata in annealed samples (43 million at ~32kHz) and links it to the record high Qs seen by Penn and Ageyev in an annealed, flame polished sample of 200 million at 383Hz and 170 million at 2829Hz. This trend is plotted in Figure 6.

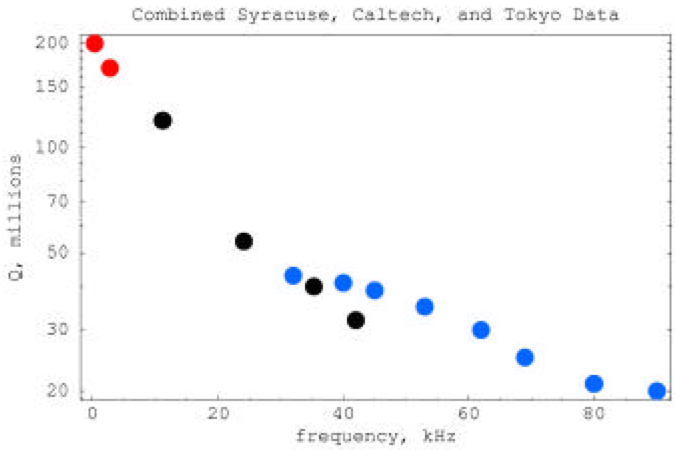

Figure 6: combined best data from Syracuse (red), Caltech (black), and Tokyo (blue) for Suprasil 312 fused silica. The Tokyo data was read off a plot and may be inaccurate at the 20-30% level.

This mass has also been modelled in I-DEAS by Dennis Coyne, although to date his model predicts modes only up to 22kHz, and the predicted mode density is too high to easily identify all measured frequencies with a model mode prediction. The highest Qs measured for all three masses, sapphire and fused silica alike, were for modes identified by his models to be the lowest order radial antisymmetric modes. These are modes for which the mass is compressed on one axis while stretching on the orthogonal axis, such as would happen if a gravitational wave passed through the mass along its axis. There are two such modes, offset from each other by 45°, and to lowest order they are degenerate. For the sapphire, this degeneracy is lifted by the anisotropy of the crystal; these modes lay at 14.14kHz and 16.53kHz. Because fused silica is isotropic, these two modes, at 11.202kHz, are nearly degenerate for the silica mass- they are split by only about 50mHz, and this splitting that does exist may be due to external influences such as the suspension wire (the splitting was not reproducible). It was often- though not always- impractical to excite only one of these modes at a time, and so the ringdown amplitude of the mass exhibited strong beating at times. However, the modulation depth of the beating decayed at the same rate as the overall amplitude, which meant that the two modes decayed with the same rate, and therefore had the same Q. About half the modes in the fused silica mass were doublets, and had this property.

Dennis Coyne's model also predicts modes for this mass at 7kHz and 9kHz. While they might be overly susceptible to suspension friction it seems worthwhile to find these modes and measure their Qs.