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Upper limits on mechanical loss due to surface polishing

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1 Introduction

The goal of this research activity was to determine if the polishing of silica substrate surfaces could affect the mechanical loss angle, and eventually contribute to thermal noise for Advanced LIGO.

For this reason we measured the quality factor of several fused silica disks with a diameter of 75 mm and a thickness of 1 mm. The dimensions are the standard ones used for the Coating Ringdown Measurement experiment [4, 1]. We tested the effect of the superpolishing process by vendor A and the ion-beam figuring process by vendor B. Three sets of samples were considered:

1. Four of our standard substrates, manufactured by vendor C, were re-polished by A. Note that our substrates have sharp edges, or in other words there are no bevels. Vendor A did not feel comfortable in repolishing to this shape, so they added bevels. To factor this difference out, two substrates were beveled but not polished, while two additional substrates were both beveled and polished on the main surfaces.
2. Vendor A also manufactured from the raw material four substrates to our specifications, including the bevel. With these samples we can test of there is an effect due to cutting and grinding.
3. Vendor B ion-beam-figured a total of eight samples: two of our standards substrates, with no additional polishing by A; four of our substrates that were polished at A; two of the substrates supplied by A.

For all the substrates above, we measured the quality factor before polishing when possible, and after polishing. All substrates were annealed at 900°C for 10 hours, and cleaned with First Contact when necessary (the samples back from vendor B were particularly dirty due to dust and other form of contamination).

We have to note that there is some variability in the substrate quality factors, even for the standard polishing provided by vendor C. We typically see quality factors as high as 10^8 at low frequency (1 kHz), but some substrates are lower. We have identified the reason to be due to small cracks and chips around the edges. The more the samples are manipulated, the higher the risk that the quality factors will degrade.

2 Superpolishing by vendor A

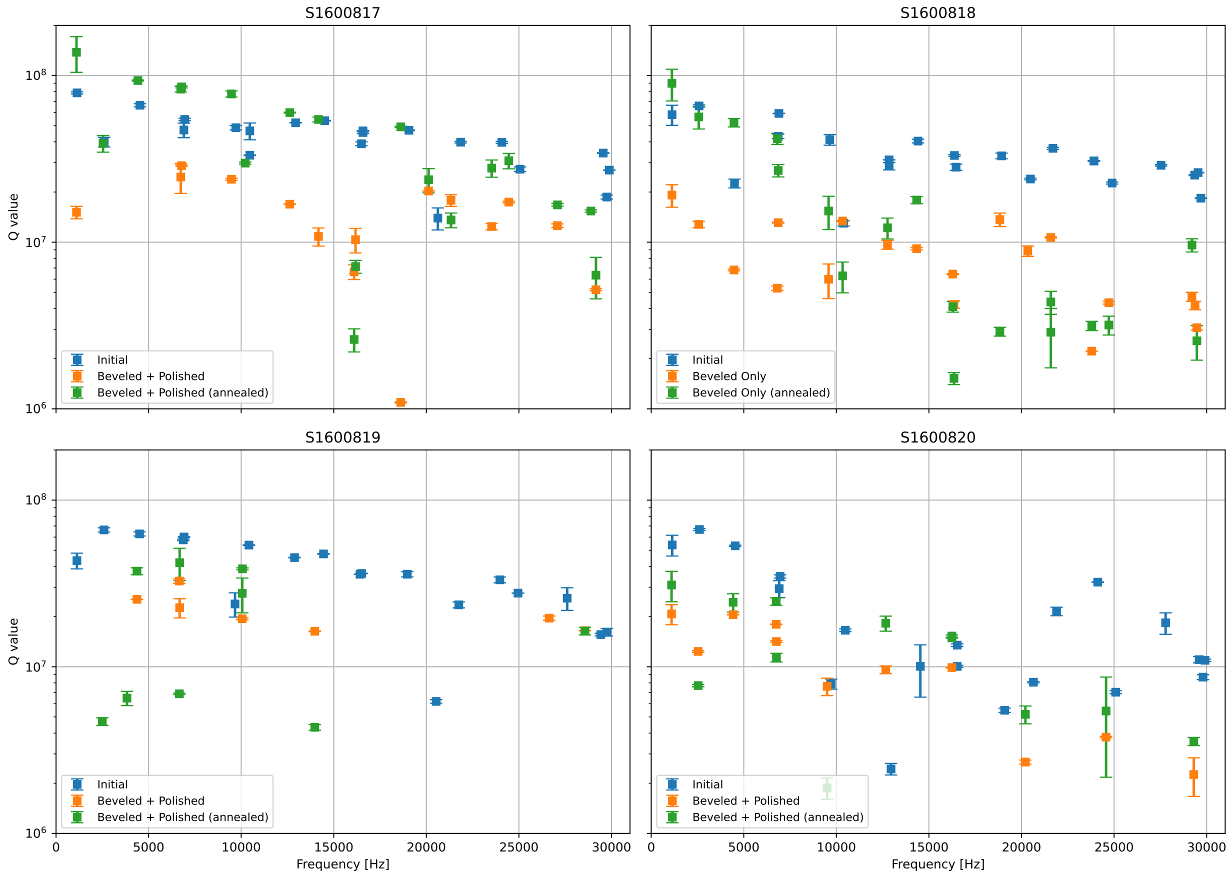

Figure 1: Measured quality factors of our standards substrates: blue after 900°C annealing and before any other process; orange after processing at vendor A (bevel and/or polish); green after subsequent annealing at 900°C. The polishing by vendor A reduces a bit the quality factors, but good values are recovered after annealing, indicating that the degradation was likely due to sample contamination. We have often observed that the quality factor of fused silica substrates degrades over time, probably due to water absorption from the air, and that high quality factors can be recovered with annealing.

3 Cut and polished from material by vendor A

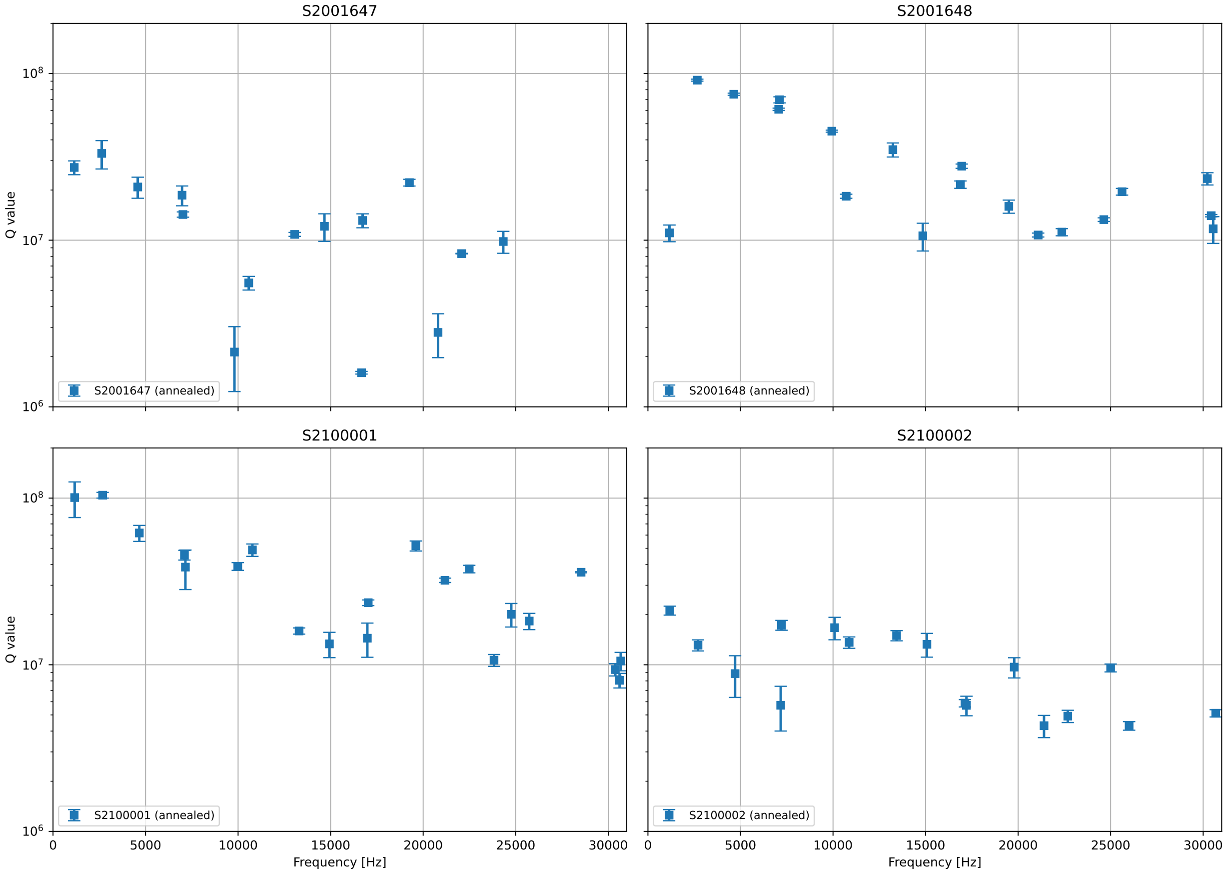

Figure 2: Measured quality factors of substrated manufactured and superpolished by vendor A, after 900°C annealing for 10 hours. The variability in the quality factor is not untypical, although a bit larger than what we normally see with substrates by vendor C. In any case the highest measured quality factors are in line with results from our standard samples.

4 Ion-beam figured by B

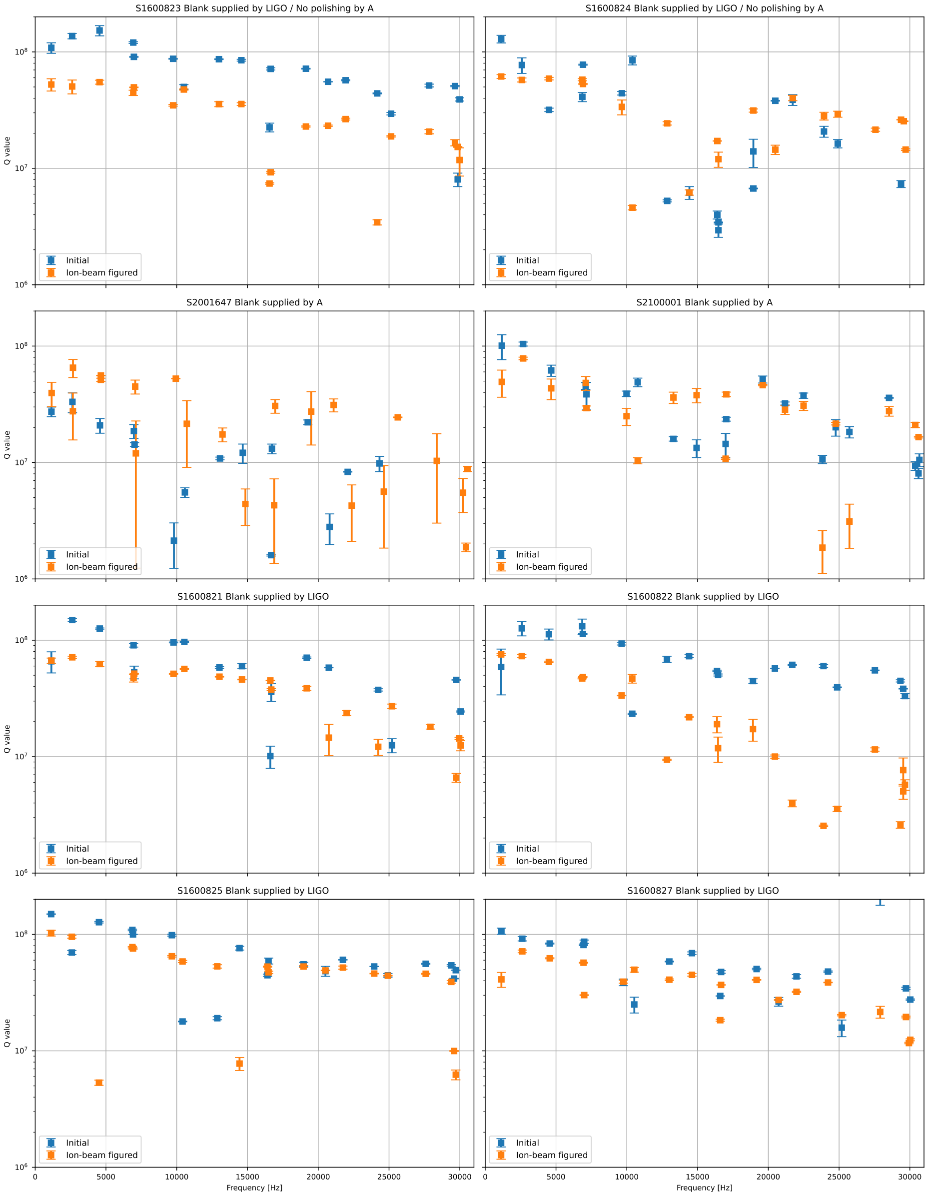

Figure 3: Measured quality factors of substrate ion-beam-figured by vendor B: blue is before any process but after the initial 900°C annealing for 10 hours; orange is after processing at vendor B and after an additional annealing at 900°C. In most cases there is a slight reduction in the quality factor.

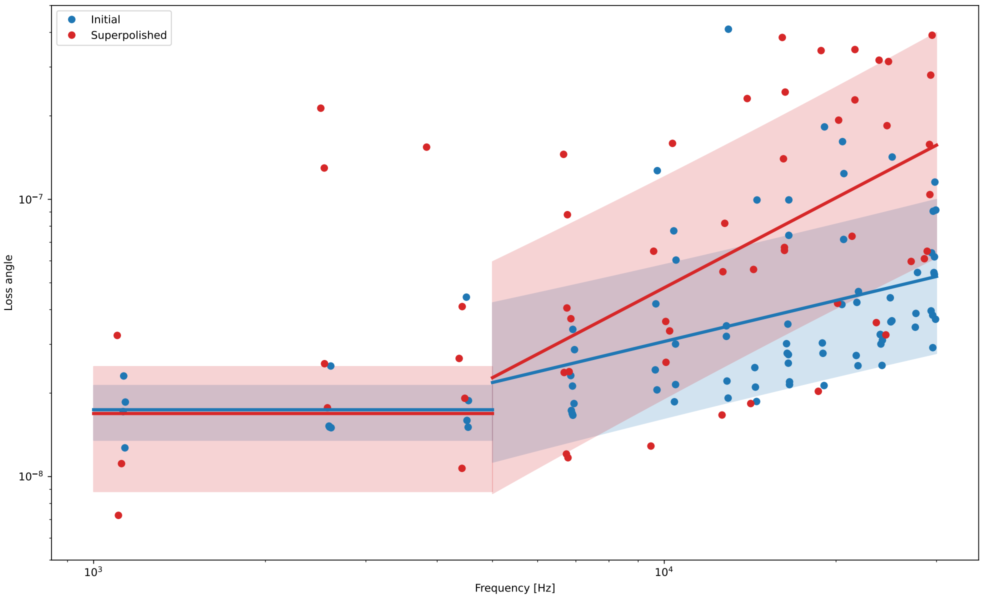

Figure 4: Comparison of frequency dependent loss angles for all LIGO-provided samples polished by vendor A. Blue points are before processing by vendor A, and red point after superpolishing by vendor A. The solid lines and shaded region show fits to the data, performed separately for frequencies below 5 kHz and for frequencies above 5 kHz.

5 Discussion

We can convert the measured quality factor into a bulk-equivalent loss angle by simply doing $\phi = 1/Q$. Figures 4 and 5 show the change in the loss angle versus frequency when the substrates are polished by vendor A or ion-beam-figured by vendor B. We collated all measurement into a single scatter plot. The frequency dependence of the loss angle show clearly two regimes: below about 5 kHz the loss is constant, while above 5 kHz it follows approximately a power law. In the two figures, the solid lines and shaded areas show fits to the two regimes, done independently from each other. A more proper fit should include both behaviors at the same time, to avoid the discontinuity around 5 kHz. For them moment being we are content of this fit, since the most important region for Advanced LIGO is below 5 kHz. We therefore take into account only the low frequency constant loss angle. The frequency dependency of the loss angle above 5 kHz might be related to surface losses as pointed out by Penn et al. in [2].

In the case of the superpolishing process by vendor A, we do not have evidence of excess low frequency losses, since

$$\begin{aligned} \phi_{\text{before}} &= (1.74 \pm 0.39) \times 10^{-8} \\ \phi_{\text{after}} &= (1.69 \pm 0.81) \times 10^{-8} \end{aligned}$$

In the case of ion-beam figuring by vendor B, there seems to be an excess of losses after processing:

$$\begin{aligned} \phi_{\text{before}} &= (0.99 \pm 0.33) \times 10^{-8} \\ \phi_{\text{after}} &= (1.56 \pm 0.35) \times 10^{-8} \end{aligned}$$

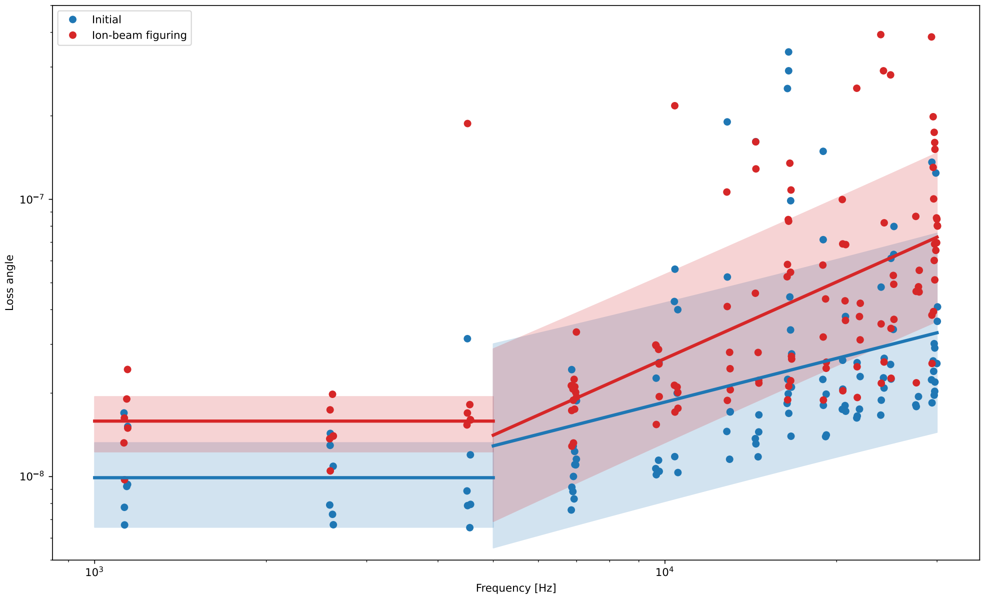

Figure 5: Comparison of frequency dependent loss angles for all LIGO-provided samples ion-beam figured by vendor B. Blue points are before processing by vendor B, and red point after ion-beam figuring by vendor B. The solid lines and shaded region show fits to the data, performed separately for frequencies below 5 kHz and for frequencies above 5 kHz.

However, the loss angle of the post-figuring substrates is still good, and at the same level of the samples polished by vendor A. It is worth noting also that the samples received back from vendor B were quite dirty, with contamination due to dust and unidentified halos. We cleaned those samples with First Contact before annealing and measuring them. The safest conclusion is therefore that the process by vendor B introduces excess surface losses at a level not larger than about $\delta\phi = 0.5 \times 10^{-8}$.

We can convert the loss angle of the sample to an estimate of the loss angle of the surface layer. If we assume the polishing adds a lossy layer at the surface with a thickness t, a Young's modulus Y and a loss angle ϕ, we have that the substrate excess loss angle due to the layer is with very good approximation

$$\delta\phi \simeq 3 \frac{Y t}{Y_{\mathrm{SUB}} t_{\mathrm{SUB}}} \phi \tag{1}$$

where Y_{SUB} and t_{SUB} are the Young's modulus and thickness of the substrate. We can therefore extract the quantity

$$Y t \phi = \frac{Y_{\mathrm{SUB}} t_{\mathrm{SUB}}}{3} \delta\phi \simeq 1.2 \times 10^{-10}\,\mathrm{GPa\,m} \tag{2}$$

We can further assume that the Young's modulus of the lossy layer is the same as the substrate and obtain a product of loss and thickness

$$t\phi \simeq 1.7 \times 10^{-12}\,\mathrm{m} \tag{3}$$

This quantity can be implemented directly in the simplified formula for Brownian noise [3]

$$S(f) = \frac{4 k_B T}{\pi^2 f} \frac{t\phi}{Y_{\mathrm{SUB}} w^2} \tag{4}$$

where k_B is the Boltzmann's constant, T is the temperature, w the beam radius. At 100 Hz, the upper limit $t\phi < 1.7 \times 10^{-12}$ corresponds to a Brownian noise level of about $3 \times 10^{-22}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$. This can be compared with the estimated level of Brownian noise from the coating, that is at the level of $10^{-20}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$. Therefore the effect of excess surface losses due to the polishing is likely negligible.

References

[1] G Vajente et al. A high throughput instrument to measure mechanical losses in thin film coatings Rev. Sci. Instrum., 88:073901, 2017.

[2] S. D. Penn et al., Frequency and surface dependence of the mechanical loss in fused silica Phys. Lett. A 352:3, 2006

[3] G. M. Harry et al., Thermal noise in interferometric gravitational wave detectors due to dielectric optical coatings. Class. Quantum Gravity 19 (5), 897. (2002)

[4] https://dcc.ligo.org/LIGO-D1600189/public