# Advanced LIGO Substrate Selection Recommendation

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Participants: Armandula, Billingsley, Black, Camp, Coyne, Crooks, Desalvo, Fejer, Finn, Fritschel, Harry, Hough, Kells, Numata, Penn, Reitze, Robertson, Route, Rowan, Saulson, Shoemaker (chair), Sneddon, Willems

*Executive Summary*

An LSC group with broad technical skills worked over a several-year period to coordinate and evaluate research in order to arrive at a recommendation for the choice of substrates for Advanced LIGO. This Summary is intended to communicate the principal criteria and to give the consensus view of the recommended path. A more complete working document is also available[1], with references to further resources.

The overview of our findings is as follows: The two substrates offer somewhat different astrophysical sensitivities, but with no net discriminant found there. While either material could probably be made to work, there are risks (known difficulties and concern due to lack of experience of unknown difficulties) for sapphire. The costs are similar, as are the baseline schedules, but with sapphire more likely to cause schedule difficulties due to the risks. The suspension designs for the two substrates are close enough that we can require a design which can be converted at a later date to accommodate a change in our information.

***Our recommendation is that we proceed with fused silica.***

While not exhaustively complete, the body of knowledge regarding properties of fused silica and sapphire is sufficient for this committee to recommend this change in the baseline test mass material from sapphire to fused silica. The timing of this decision is driven by the need for solidifying the suspension design. While unlikely, it is possible that further research will uncover new information of sufficient importance to cause a change in this recommendation. In that light we also recommend that the ongoing research programs by the LIGO Laboratory and LSC research groups in the properties of sapphire and fused silica be continued. This will enable us to fill in the 'knowledge gaps' about each of these materials essential to the successful construction of Advanced LIGO. It will also allow us to fall back (or forward) to sapphire should we discover in the near future that the performance of the Advanced LIGO detectors is improved by sapphire.

A point-by-point summary of the principal considerations follows.

[1] http://www.ligo.caltech.edu/docs/T/T020103-08.pdf (draft)

**1) Substrate and coating thermal noise, mechanical properties**

Sapphire: Thermoelastic noise in sapphire has been directly measured, and agrees well with theory, so we are confident in our prediction of a principal noise source for a sapphire-based instrument. We have measurements of the losses of relatively high-frequency modes of sapphire samples, including full-scale substrates, which suggest acceptable Brownian thermal noise; however, we are not sure how to extrapolate that to GW-band frequencies.

Silica: Extensive measurements of the mechanical Q of silica samples (including a 120 million Q at 11 kHz in an initial LIGO substrate) have allowed the development of a semi-empirical model of the loss in silica. This understanding is in agreement with measurements at much higher frequencies and with a molecular theory of the loss. The theory predicts lower mechanical loss at lower frequencies, which has been tested as low as 300 Hz.

Annealing to reduce the mechanical losses and thus the thermal noise, while promising for small samples of silica, is untested on full-scale substrates; however, the need for doing this is also unclear . It is expected that the thermal noise from silica substrates will still be sufficiently low even without annealing. Further research on annealing silica to improve its mechanical performance should be pursued.

Coatings are still in development, with no clear sign that one or the other substrate would be better. The best coating for reducing thermal noise on either silica or sapphire substrates is currently a silica/tantala coating with a titania dopant in the tantala. Further reduction of mechanical loss in tantala, or the discovery of another high index material with low mechanical loss, would be beneficial with either substrate. There are very limited data on coating mechanical loss on sapphire, partially due to unforeseen difficulties measuring Q's; however, there is no reason to believe coating mechanical loss will be different on different substrates.

Both substrates profit, perhaps almost equally, from Mesa beams (our best understanding at present is that coating thermal noise goes as 1/radius, and coating thermal noise is a significant contributor for sapphire at high frequencies, and dominant for silica at all frequencies). The theory and certainly practice of thermal noise from Mesa beams is still being researched, although it seems a promising technology for either substrate, and one which Advanced LIGO could adopt before or after the initial commissioning.

Excitation of test mass mechanical modes by light pressure is as yet an unknown; there appears to be some advantage for sapphire due to more widely spaced modes. The modal Q's of *in situ* mirrors of either material will probably be similar, being dominated by the coating and silicate bonded regions. This work is in progress.

**2) Substrate and coating optical properties**

At this time, thermal compensation has significant unknowns for both substrates; prototyping of thermal compensation is expected to give additional information in 2006. Experience and lack of crystalline properties favor fused silica, given the known material parameters. The spatial variation of absorption in sapphire is challenging for the compensator design and ultimate success.

Annealing has been shown to reduce optical absorption in small samples of sapphire. However, reducing optical absorption, and its spatial variation, in full-size pieces of sapphire to low enough levels to reduce or eliminate the need for thermal compensation has not been demonstrated. Again, we recommend continued pursuit of this approach.

Polishing is more difficult on sapphire; in particular, achieving good barrel polish is as yet unsolved. What quality of polish on the barrel is necessary for thermal noise and for optical purposes has not been completely determined.

Very few coatings have been deposited on sapphire to date. Initial efforts showed some problems; this could be due to a fundamental difficulty with coating sapphire, or just insufficient experience with the process. There is no clear signal that one or the other substrate is better for coatings in optical sense, but there was one example from SMA-Virgo of ‘an acceptable coating’ on sapphire. Some concerns about adhesion to sapphire also exist.

**3) Integration with Suspensions, rest of interferometer**

The smaller physical size of sapphire is an advantage, but not a defining or critical one.

The Sapphire-fused silica interface at the fiber attachment point is a potential source of noise due to releases of stored stress energy which comes about from the differential thermal expansion. This concern could limit our ability to clean the substrate through baking after the addition of the attachment points.

Suspensions will be made to be convertible to the other substrate to allow for the possibility that further research determines that there is a significant performance advantage for the other substrate material.

**4) Cost and schedule issues**

The baseline costs are similar; no differentiation between two materials is possible on this basis. We believe that both sapphire and fused silica can be fabricated for Advanced LIGO. However, the fabrication of sapphire entails more risk due to the relative lack of industrial experience.

There are concerns about throughput for Sapphire production given that there is less experience with growing, polishing, and coating large substrates. There is a single known credible vendor for sapphire, and two vendors for silica (although one is strongly preferred for performance).

There are greater risks for many of the steps of preparation of completed, installed, suspended test masses for Sapphire; many of these can be potentially traded against delays in the fabrication and integration of the instrument.

**5) Astrophysical reach**

For baseline sensitivity, fused silica is better at low frequency; sapphire is better at high frequencies. The improved performance of fused silica relative to our initial thinking is due to the discovery of significantly lower substrate mechanical loss; sapphire is dominated by the originally unappreciated thermoelastic noise.

With respect to sources, there were similar numbers of votes from astrophysicists for each frequency region. The committee could determine no strong sense among most of the astrophysicists that this is an important criterion given the baseline sensitivity.

**6) Incremental improvements**

A last point is that there appears to be more room for incremental improvements in the performance of a silica-based instrument. The thermoelastic noise largely ‘pins’ the performance of a sapphire instrument. However, continued improvements in coating thermal noise would yield a significant improvement (at the time of the initial installation, or through later installation of recoated spares) in a silica-based Advanced LIGO.