



KAMIOKA GRAVITATIONAL WAVE TELESCOPE

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KAGRA

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Strawman design

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This is an internal working note of the

***KAGRA* Large-scale Cryogenic Gravitational Wave Telescope Project.**

<http://gwcenter.icrr.u-tokyo.ac.jp/en//>

I made a strawman design of several items that need to be designed, and considerations that need to be refined, so that we can discuss the issues in detail and ask the right questions before proceeding to the mechanical design of these components of KAGRA.

This is only a conceptual design, no idea is firm, and many of the considerations that I made are discussible, or maybe even wrong.

Please read carefully, contribute your criticism, suggestions, evaluation of the assumptions that I have done.

We need contributions from seismic, vacuum, cryogenics, auxiliary optics and main interferometer design, and maybe others, to make a successful choice of design strategy.

I will take care to update the document with your own consideration until we will reach a consensus on all the engineering solutions to be adopted.

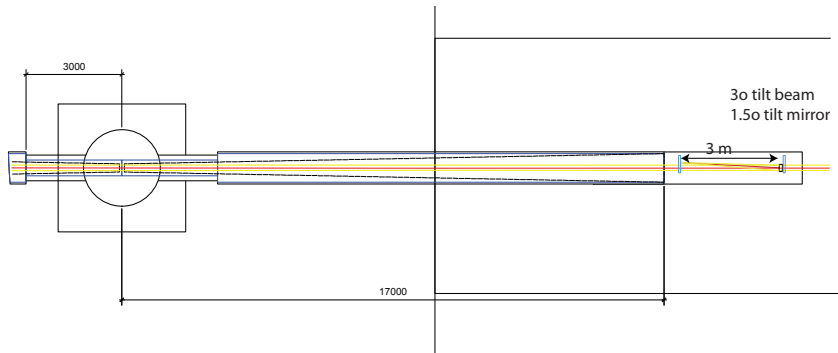
1 End telescope

KAGRA will need an end telescope. LIGO was forced to make a very short one, and this made it very complex and prohibitively expensive, mostly because of the requirement of parabolic offset mirrors.

Can we make a cheaper telescope with a smaller angle and spherical mirrors?

The first strawman design is about the end telescope.

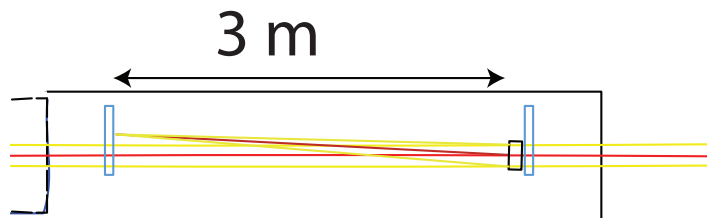
It has to sit after the cryogenic baffles and has to be suspended.



I assume a 220 mm primary beam to catch the entire transmitted beam, the same diameter of the main mirror (a smaller primary beam would make the problem easier). I also assume a 3 m long telescope. A 1.5° mirror tilt, 3° beam inclination is sufficient to shift the reflected, focused beam by more than 1 radius.

Is this a small enough angle, causing sufficiently small aberrations, to avoid the necessity of using offset parabolic mirrors?

3σ tilt beam 1.5σ tilt mirror

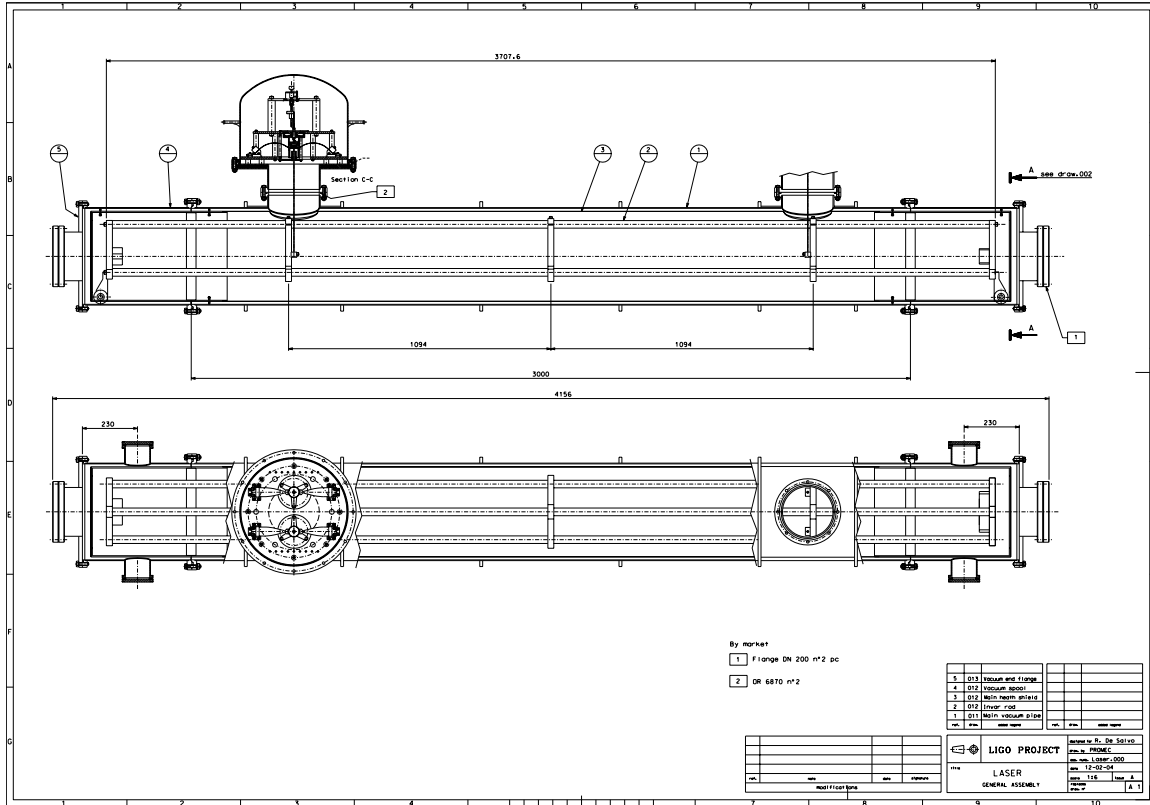


If yes, then we can simply modify the mesa beam interferometer geometry, simply widening its endplates.

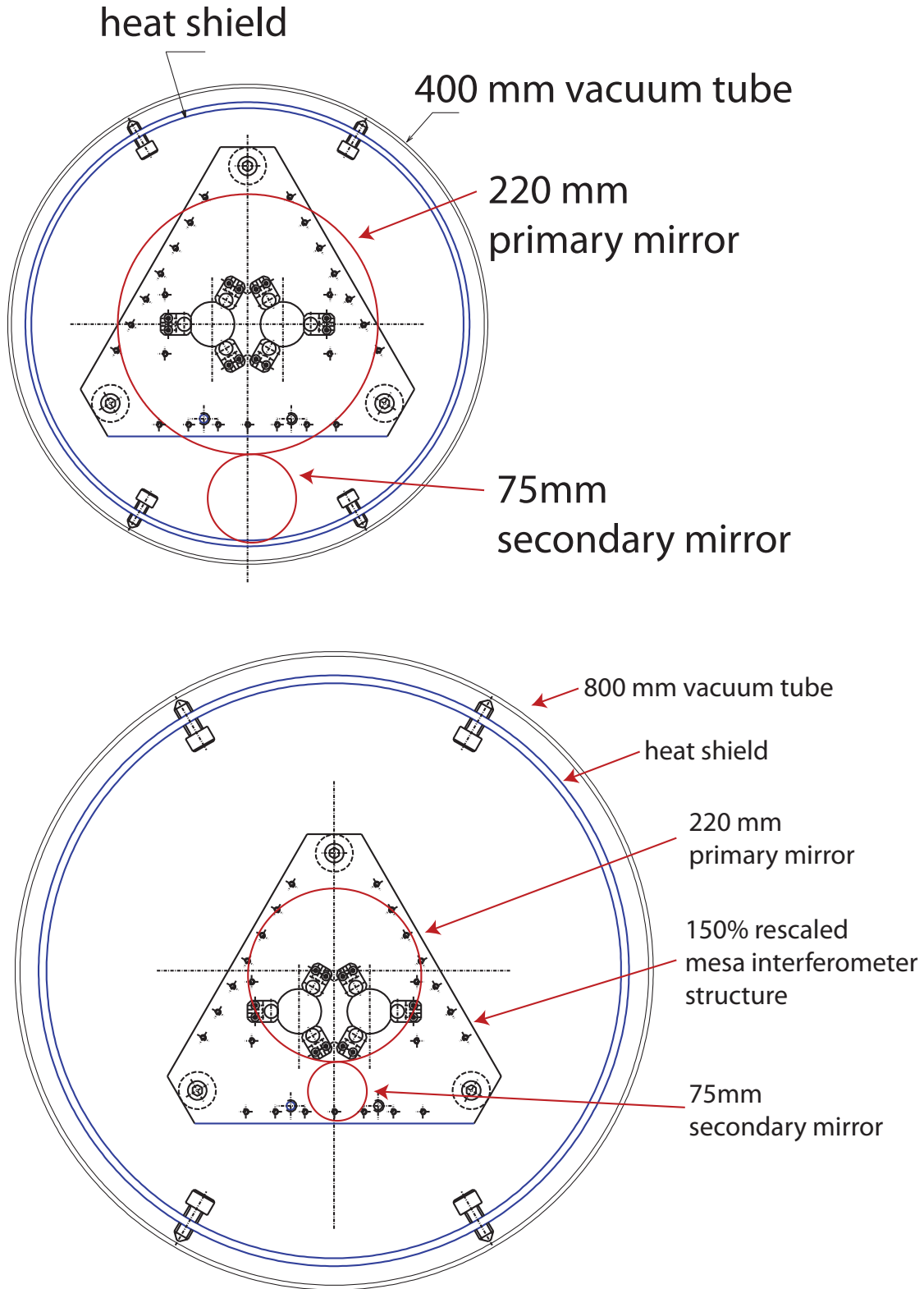
The general concept looks good. I will calculate the Guoy phase error using an off-axis spherical mirror telescope as a function of off-axis angle and report the results by e-mail next Thursday (4/26/12, PST). [MS]

The mesa beam interferometer design is a triangular structure built around three invar rods, each 3 m long, which would allow construction of the 3° tilt telescope described above. The structure of the mesa interferometer fits inside a 400 mm vacuum tube, is suspended by four small GAS filters, mounted in two mushroom tanks above the vacuum tube that also allow pitch and vertical alignment. A pure aluminum shroud inside the pipe guarantees a high level of thermal uniformity in the structure.

The structure of the mesa beam interferometer is too small to contain the KAGRA end telescope with a 220 mm primary mirror, however it only requires ~ 50% rescaling to do the job and would easily fit inside a standard KAGRA 80 mm vacuum tube.



The mesa beam structure was supported by two pairs of GAS blades. The end telescope would be suspended by two scaled GAS filters.



An attenuation of ~ 1000 above 10 Hz can be achieved.

Horizontal flexures can be added to the design for yaw alignment, if necessary.

2 Suspended Baffles and main mirror optical levers

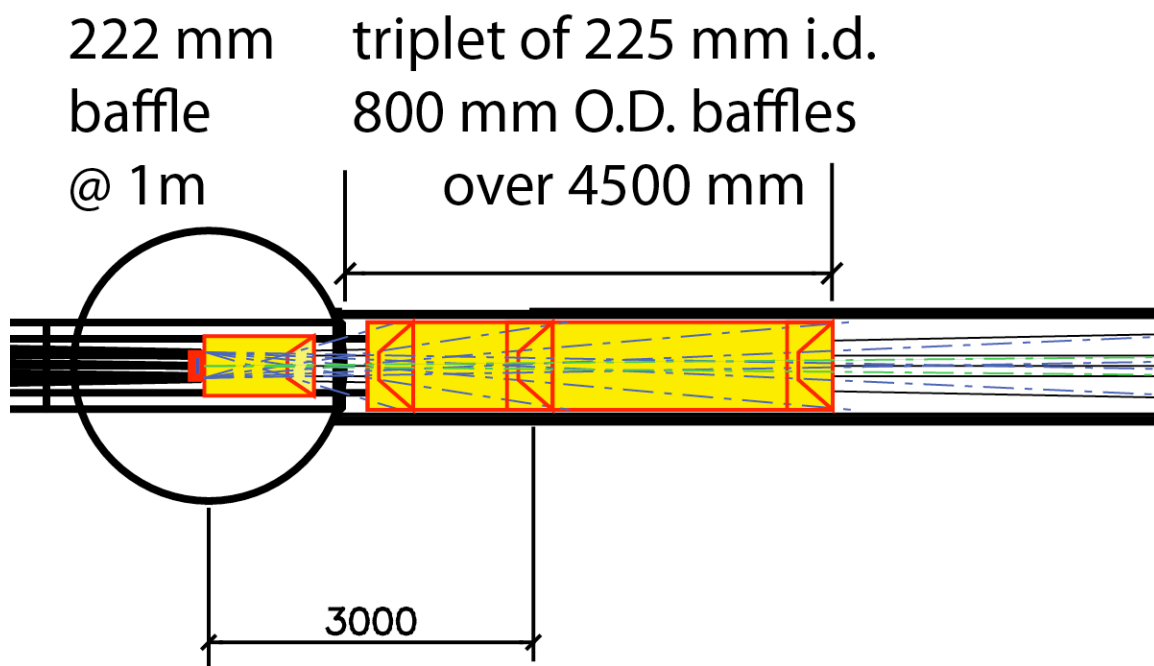
KAGRA will need suspended baffles to intercept scattered light in different locations.

No scattered light from the mirror should reach a non-seismic isolated surface in the vicinity of the mirrors, which includes the cryogenic pipe baffles.

A first cryogenic baffle, located inside the main cryostat, will need to be suspended just in front and around each test mass, to collect the very large angle scattering from the mirror and keep it from bouncing on the noisy cryostat and back on the mirror. This special baffle should have aperture just above the mirror diameter of 220 mm. We assume 222 mm aperture at about 1 m from the test mass.

The figure below, with the envelope of the wide angle scattered light shown in blue dashed lines, illustrates how, even with the 222 mm baffle enveloping the test mass, there is no way to keep scattered light from hitting the cryogenic baffles intended to shield the thermal heat, which therefore will have to be suspended and seismically isolated as well. **It is desirable that the cryogenic baffles be suspended; however, the scattered light calculations indicate that it may not be necessary.** [MS]

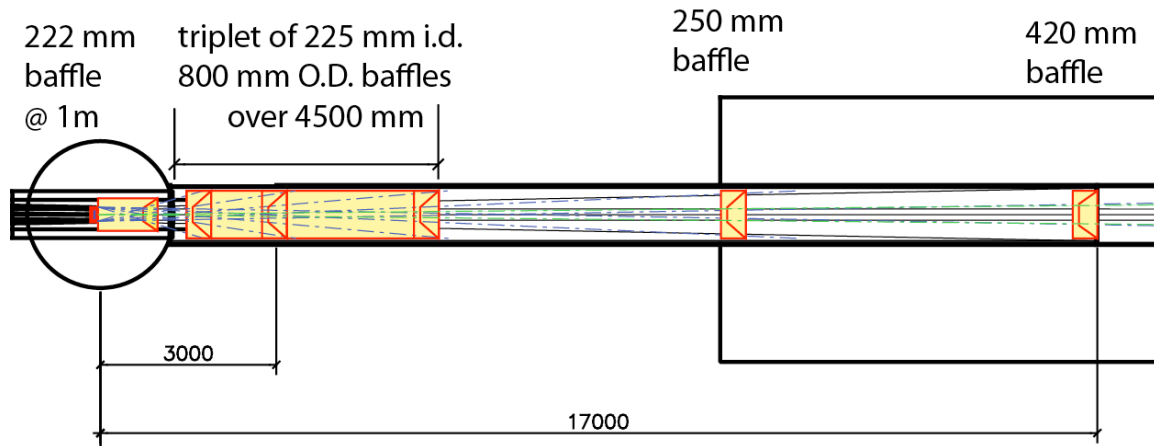
A minimal solution is to arrange a triplet of 225 mm baffles inside a 800 mm diameter pipe, 4500 mm long, suspended like the end telescope and cooled via soft aluminum fibers.



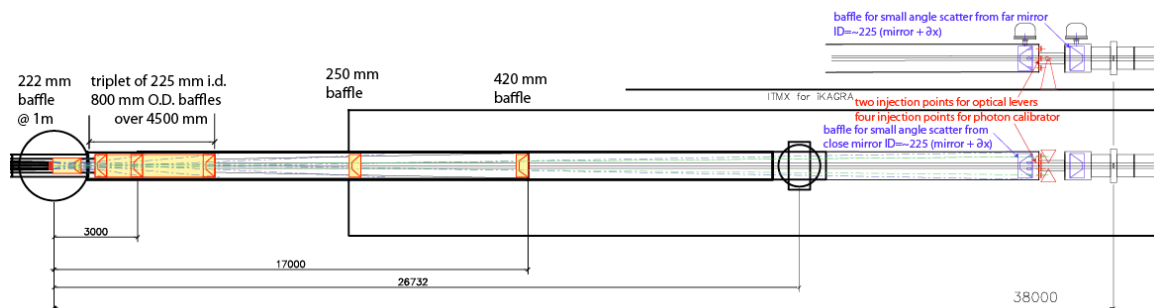
The triplet would be followed by two additional, individually-suspended baffles, also housed inside a 800 mm diameter pipe, located along the cryogenic pipe section. The triplet and the two independent baffles could be cooled at different temperatures. The wall of the thermal cryo baffle do not see the scattered light and do not need to be suspended. If additional thermal baffles have to

be added, they would also have to be suspended and isolated if they become illuminated by the scattered light.

The baffles would have 800 mm outer diameter, while the cryogenic tube would be 1000 mm diameter, to allow for 50 mm of superinsulation and 3-5 mm of aluminum pipe cold wall at ~900 mm diameter



The individual baffle closer to the test mass would have the same 225 mm aperture, but the last one would have to have a 420 mm aperture to allow the passage of optical ever and photon drive beams, illustrated as green dashed lines.



A double set of warm suspended baffles will be optimally located just before the pipe gate valves, which are located at 38 m from the test masses. The baffles should have apertures just larger than the cryogenic baffle aperture 222 mm. We assume 224 and 225 mm aperture for the warm baffles. We assume that this pair of baffles will be centered at ~ 35 m from the test masses.

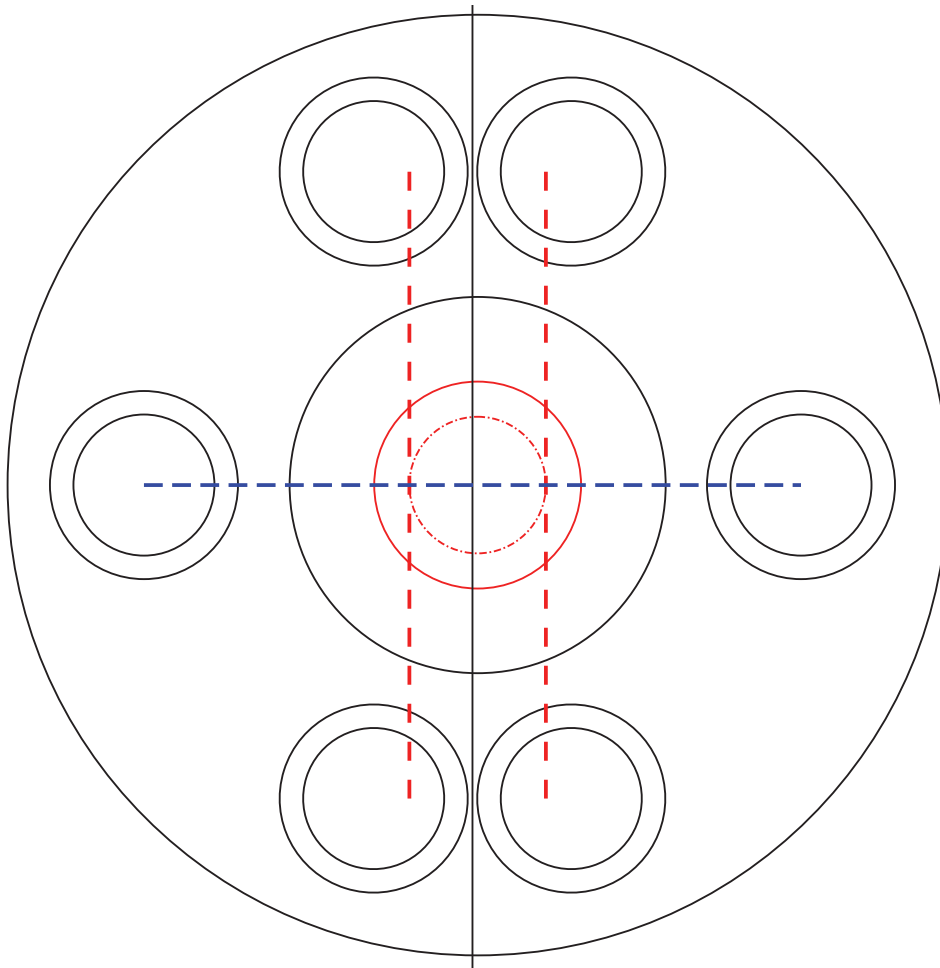
The baffle looking at the far mirror, 2962 m away, will collect most of the small angle scattered light from that mirror, and keep it from entering the cryostat. The baffle looking at the close mirror, ~34 m away, will collect the large angle scattering that is missed by the cryogenic baffle. **It is important to have this baffle to hide the corner if the viewport necked-down section is added to the design. [MS]** It will have small cutout openings to allow the passage of optical levers and photon calibrator beams. The cutout openings will have to be smaller than the viewport opening, to shade the vacuum pipe from the mirror.

All the suspended baffles will be suspended in a way similar to what foreseen for the end telescopes.

The 420 mm baffle only needs to be wider on the optical lever-photon drive side. On the back side it can be smaller to minimize the thermal load to the mirror.

Because very little light goes through the end test mass, on its back side the baffles can sit simply on the vacuum pipe, without suspensions. Seismic isolation is needed on the back side if the input test mass because the injection beam and the signal transit through there.

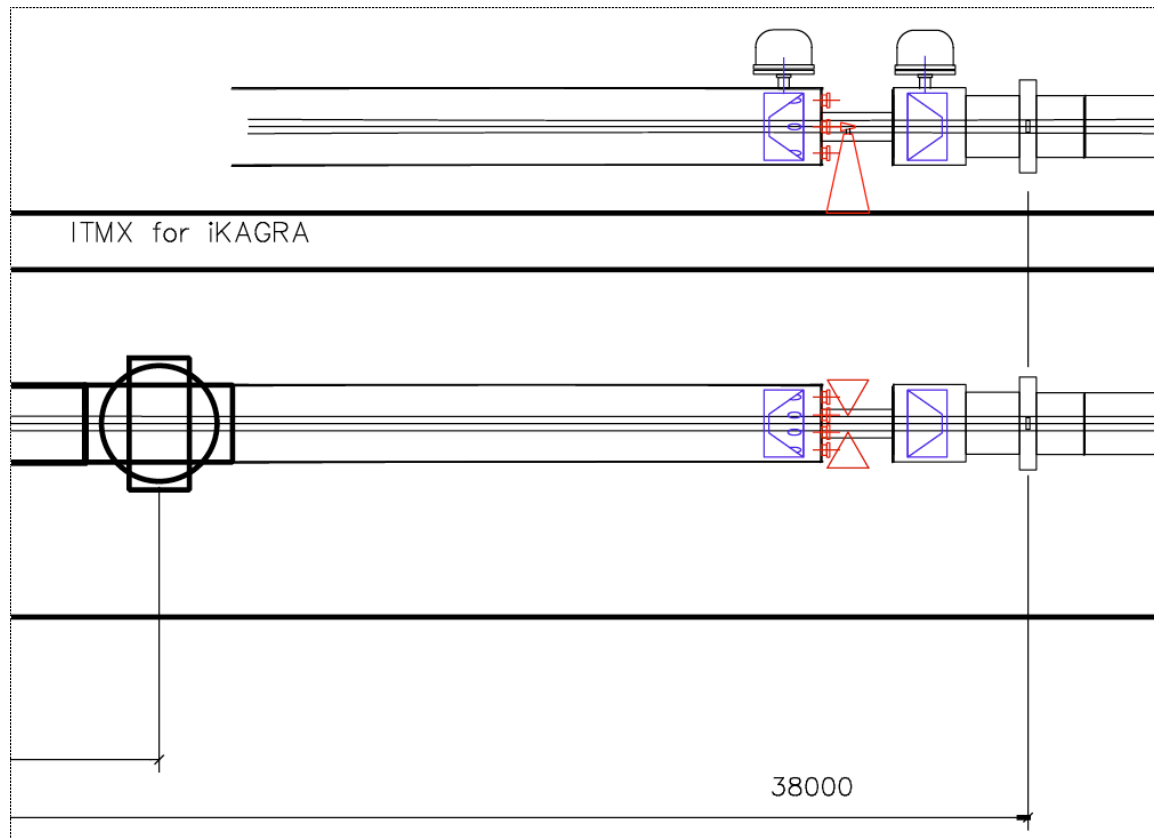
The optical lever pylons and photon calibrators should also be located at ~ 35 m from the test masses, sandwiched between the pair of baffles. The launching and collecting will be made from a beam-pipe restriction of 400 mm diameter with a set of six conflat 150 or conflat 200 viewports. The four viewports for the photon calibrators are in pairs with vertical separation between pairs. The two optical lever viewport have horizontal separation. The photon calibrator beams, shown in red-long dashes, hit the mirror (red-solid) on a 0.66 diameter circle (red-short dashes). **This the optimum percussion point for the beams to hit (according to Rick Savage), which minimizes the excitation of internal modes of the mirror.** [MS] The optical lever beam is shown in blue-long dashes.



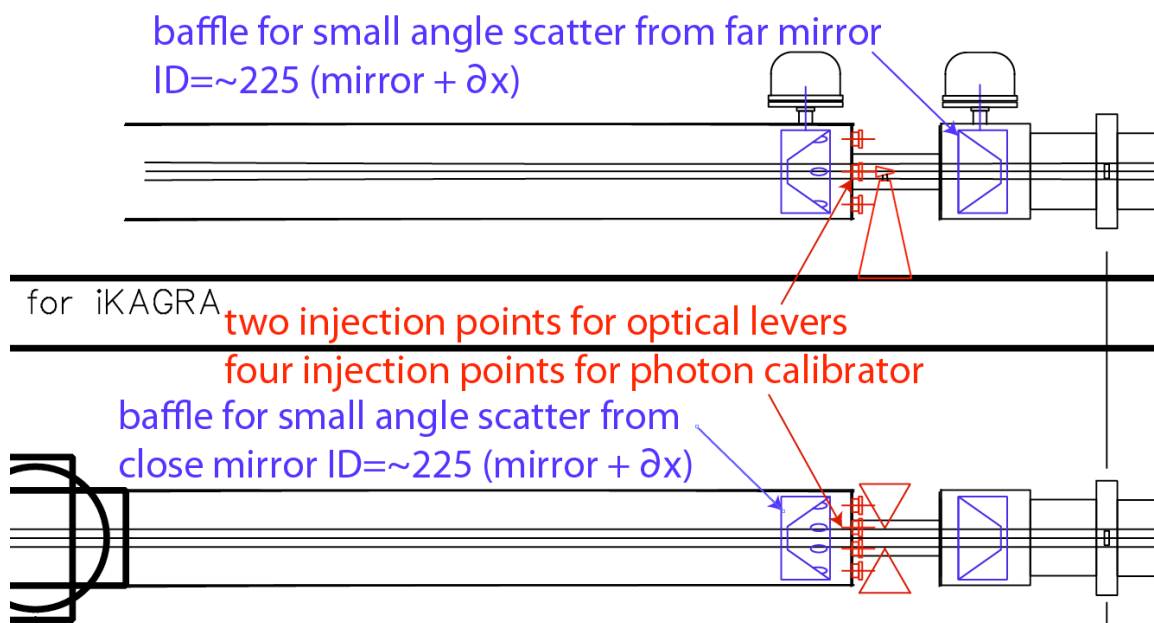
Putting the baffles close to the gate valve, as far away from the mirror as possible, minimizes the solid angle covered by the launching and retrieving optical lever and photon calibrator optics.

The large distance also minimizes the required openings of the cryogenic thermal radiation baffles, thus minimizing the mirror radiative thermal load.

In addition to this, the farthest one can position the last suspended baffle, the least number of baffles will be required in the vacuum pipe.



Suggested positioning of the warm suspended baffles and positioning scheme for the optical lever windows.



3 Beam baffles

Two possibilities can be considered for the beam line along the 3 km.

A minimal number of small aperture (250 mm) and suspended beam baffles, or a somewhat larger number of larger aperture (350 mm) baffles directly mounted on the beam tube inner surface.

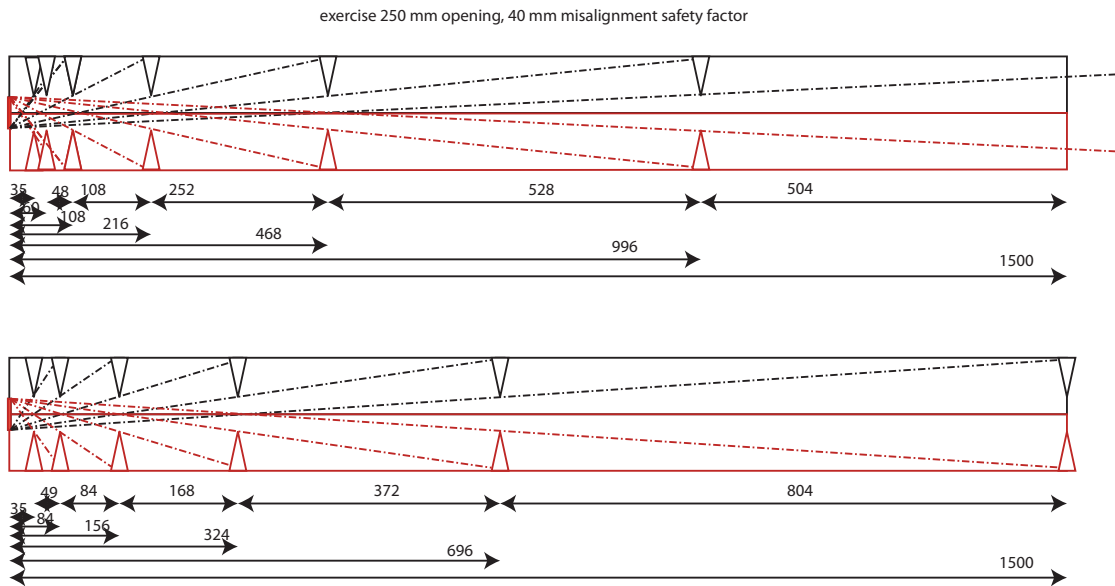
Note that the number of baffles should be minimized, not only for cost considerations, but also, and especially, because the edge scattering is much worse than the surface BRDF on the surface of electropolished and DLC coated baffles.

Note also that in the evaluation of the 350 mm aperture one needs to account for the nominal section to section ± 40 mm beam pipe alignment error. **The diffraction and scatter noise increases with $\sqrt{\text{of number of baffles}}$.** [MS]

The ideal separation between baffles is the one that shades the tube surface from the mirrors with a minimal number of baffles.

A transversal beam pipe positioning error of ± 40 mm must be accounted for.

The suspended beam baffle solution appears to be more complicated and expensive, even if it requires only 9 baffles per arm in addition to the gate valve one.



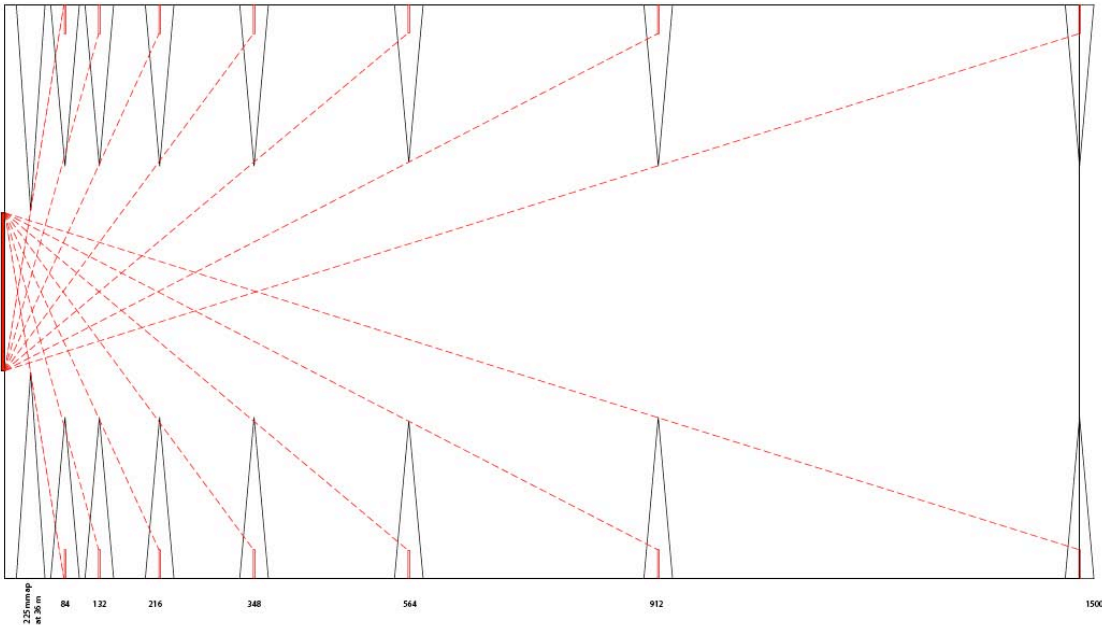
Fixed baffles can be used if the aperture is large enough that a sufficiently small amount of optical power can illuminate its edge and be scattered or diffracted back on a mirror.

Assuming that a 350 mm aperture baffle is sufficient to reduce the diffraction to acceptable levels, and that a baffle aperture alignment of the order of ~ 1 mm is achieved (which is easily achieved in both directions even if the pipe is misaligned), then 11 baffles are necessary.

Assuming a ± 40 mm alignment error, 13 baffles per arm are necessary, as illustrated below, 15 baffles if an additional safety margin is applied.

In all cases a positioning granularity of 12 m was assumed, to be able to mount the baffles near a flange.

Clearly the much cheaper fixed baffle option is to be chosen.



350 mm aperture baffle positioning along tube, assuming 40 mm misalignment.

The red marks take into account for the 40 mm alignment error of the beam pipe.

One may ask if by inserting 350 mm aperture baffles one limits the future potential of the KAGRA pipe, by impeding the use of larger mirrors when they would become available. This problem only presents itself for the mirrors close to the beam splitter because the interferometer will in any case be used in the negative G configuration (quasi-concentric rather than quasi-planar) because of the Seidle-Sigg instability. This means that 150 m the beam would be 10% smaller, an effect that becomes larger as wider mirrors and beam spots are implemented.

In addition the ± 40 mm alignment error is a “built-up” error, which means that it is much smaller near the mirrors, and the effective aperture of the baffles is 40 mm wider near the mirrors where it counts most.

The 350 mm aperture baffles therefore can accommodate substantially larger mirror without modifications.

Because the beam pipes are flanged and O-ring sealed, if much larger mirrors became available one can think of replacing the first several baffles.

4 Baffle shapes

There are four possible shapes of baffles:

1 The wedge in a box, with surface near the Brewster angle for maximized absorption and minimized BRDF scattering. It is useful only in the main cryostat, outside the circular confines of the beam pipe. It needs to be aligned with the beam polarization

2 The cone in a cylinder, it is the most used solution, and also the most expensive. Because its aperture lays in a plane perpendicular to the beamline, it is the most sensitive to coherent diffraction back to the mirrors, and definitely requires the shark teeth edge, unless it is suspended. It also uses multiple reflections to absorb the light and even if off-45° angle is chosen (45 deg should never be used because it becomes an effective retroreflector) [MS], a small BRDF is sufficient to send the light back where it came from, to the mirrors.

This geometry though is by far the most advantageous geometry wherever suspended and seismically isolated baffles are necessary inside the circular beam pipe confines.

3 Tilted flat baffle with ellipsoidal aperture, it is cheap because it is a simple metal sheet with no post cut machining or welding, but it has some of the same problems of the conical baffles, and is relatively difficult to mount snugly in a pipe. LIGO used the technique of mounting an expansion ring to the inside of the pipe, and then mounting the flat baffle with brackets to the firmly mounted ring. [MS]

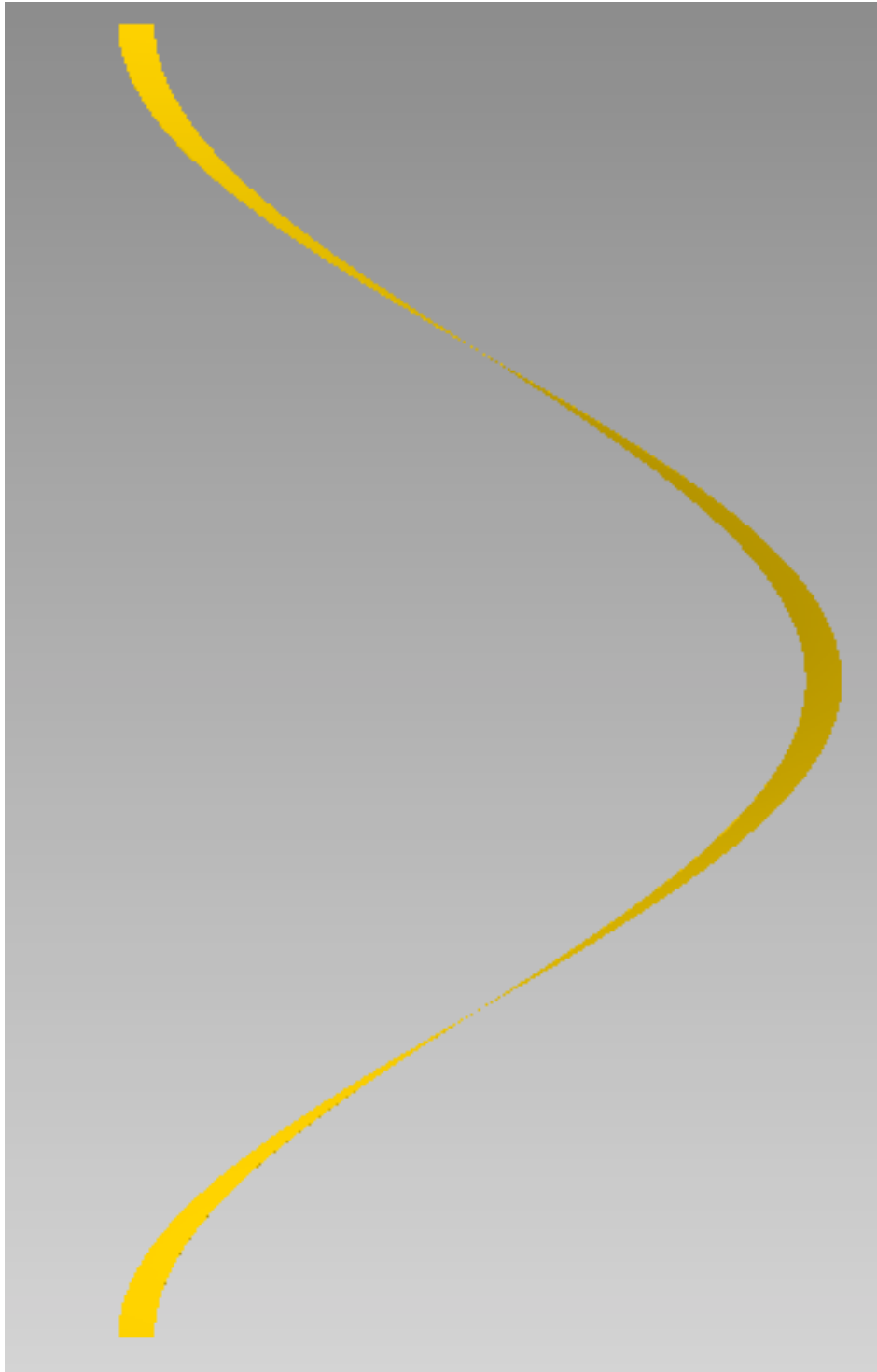
4 Spiral baffles, they are not used yet, but they are as cheap as the tilted flat baffles. cheap, there is no possibility that multiple reflections and BRDF scattering can send light back to the mirrors, when released they spring back into the beam tube, the aperture edge is far from the plane perpendicular to the beam line, and they lend itself to several shark teeth strategies.

This is a clever design; however, since the baffle is not directly attached to the beam tube, the vibration of the loose baffle may cause amplification of the beam tube seismic motion; an FEA analysis of a loosely spring-load attached baffle should be made to determine the internal vibration modes. [MS]

Because they are not used they are described in detail in the following.

To make a spiral baffle one starts from a ring of outer diameter larger than the beam pipe, then cut it in one point and lift one of the two edges to form a spiral. As one raises one edge with respect to the other, one increases the spiral pitch and the outer diameter containing the spiral shrinks.

One continues lifting until the cylinder containing the spiral is smaller than the pipe, then insert the spiral in the pipe.



The pitch is given by the formula:

$$\text{Pitch} = \pi \sqrt{(\text{OD}_{\text{ring}}^2 - \text{ID}_{\text{pipe}}^2)}$$

Where OD_{ring} is the Outer diameter of the ring and ID_{pipe} is the inner diameter of the pipe.

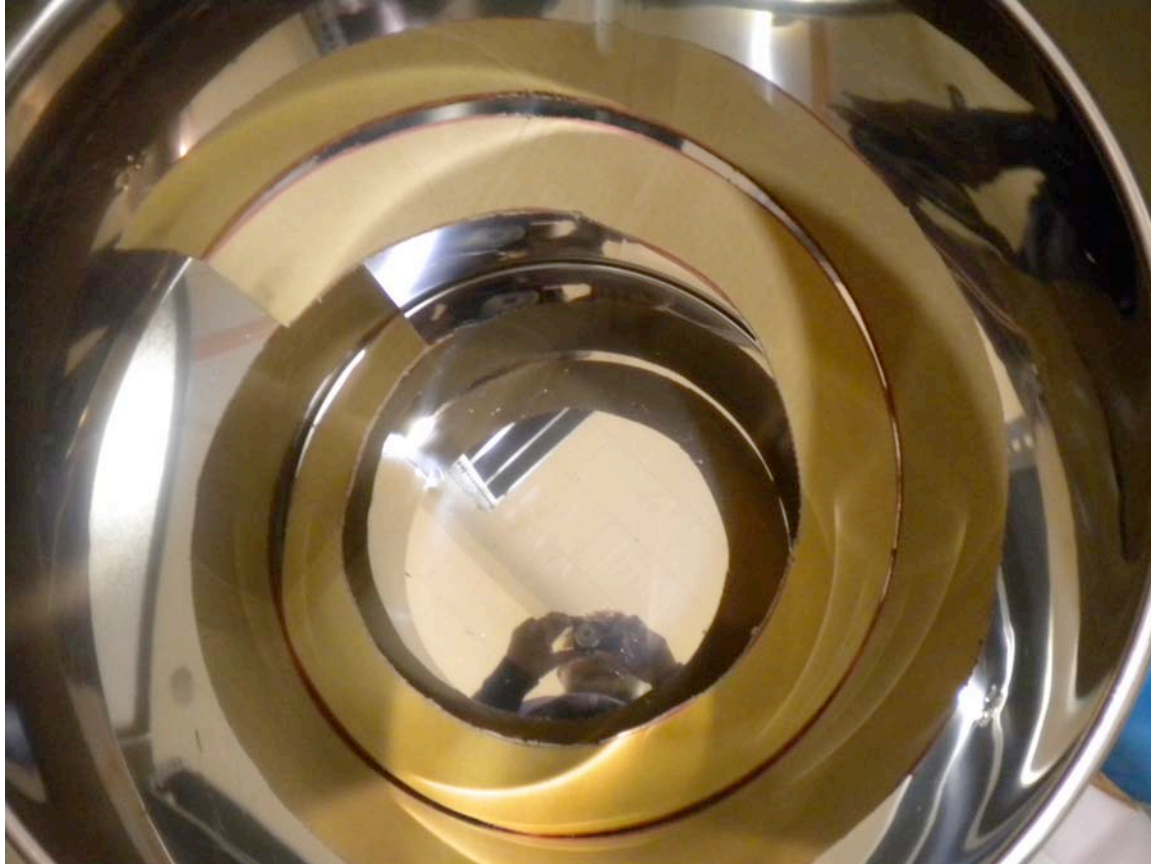
The inner diameter of the ring ID_{ring} is simply $\text{ID}_{\text{ring}} = \text{OD}_{\text{ring}} - (\text{ID}_{\text{pipe}} - \text{ID}_{\text{baffle}})$

After insertion into the pipe, pulling the two edges of the spiral closer to each other causes the cylinder containing the spiral to increase, and the spiral automatically locks into the pipe.

A prototype made with a piece of cardboard was made, cutting a ring 505 mm outer diameter and 375 mm inner diameter to fit into a pipe of 470 mm diameter.



Then I lifted one edge and inserted it into the pipe, and obtained a nice spiral with a nice fit. Despite the crude model, I obtained a pitch not far from the calculated 537 mm.



Note, the fit is not perfect at the beginning and end in my quick test, because the cardboard was bent, but when I helped it straight, the fit was perfect.

This makes it a very easy piece to manufacture, to install, to coat with DLC, and to store and transport between two flat panels. It is also substantially cheaper than a cone, which needs two parts connected together.

The desired pitch angle can be easily determining by choosing the desired starting diameter.

The natural elasticity of the material keeps the spiral firmly in place. The spiral can be locked even more firmly in place by simply adding a wire pulling the two edges to each other, but this is not necessary if the thickness of the ring is chosen suitably. **The baffle could be attached fore and aft to a thin expansion ring that locks into the ID of the pipe. [MS]**

There is an advantage of the spiral. Any longitudinal beam will be deflected at the first bounce into a death spiral along the pipe as I illustrate with the green laser beam in the figure below.

Because all the bounces are on the pipe surface, which is shielded from the mirrors by the baffle itself, there is no chance whatsoever, after the first bounce, that any BRDF send some light back to the mirror.

In a cone there is always the probability that at all the odd bounce the BRDF scatter some light back to the mirror.



Next one need to consider the coherent Fresnel diffraction of the baffle edge towards the mirror. An ideal truncated conical baffle forms a perfect circle, which is the optimal shape to make coherent diffraction to the mirror. To destroy the coherence and stop this the shark teeth are added. The shark teeth length has to be sufficient so that at least a de-phasing of 360° occurs between the tip and the base of the tooth, as measured from a mirror for back scattering, and from a mirror to the other for forward scattering.

In a spiral baffle the edge moves longitudinal with the pitch. The coherence for back scattering is completely washed out.

Unfortunately the de-phasing for longitudinal scattering is only a second order effect and the de-phasing is not sufficient. Shark teeth may still be necessary to avoid coherent Fresnel forward diffraction to the mirror. Note that the side surface of the teeth will be off angle with respect to the beam axis, therefore there will be no glint. Note though that if you ideally segment the spiral in a series of rectilinear edge elements, each element tend to radiate on the plane perpendicular to the element itself, which does not contain the mirror, and therefore the shark teeth may not be necessary at all. For prudence, and because the teeth can be made a marginal cost when the disk is, or water-jet or shear cut cut from a sheet metal, one may want to retain the teeth even if not strictly necessary.

5 Teeth structure

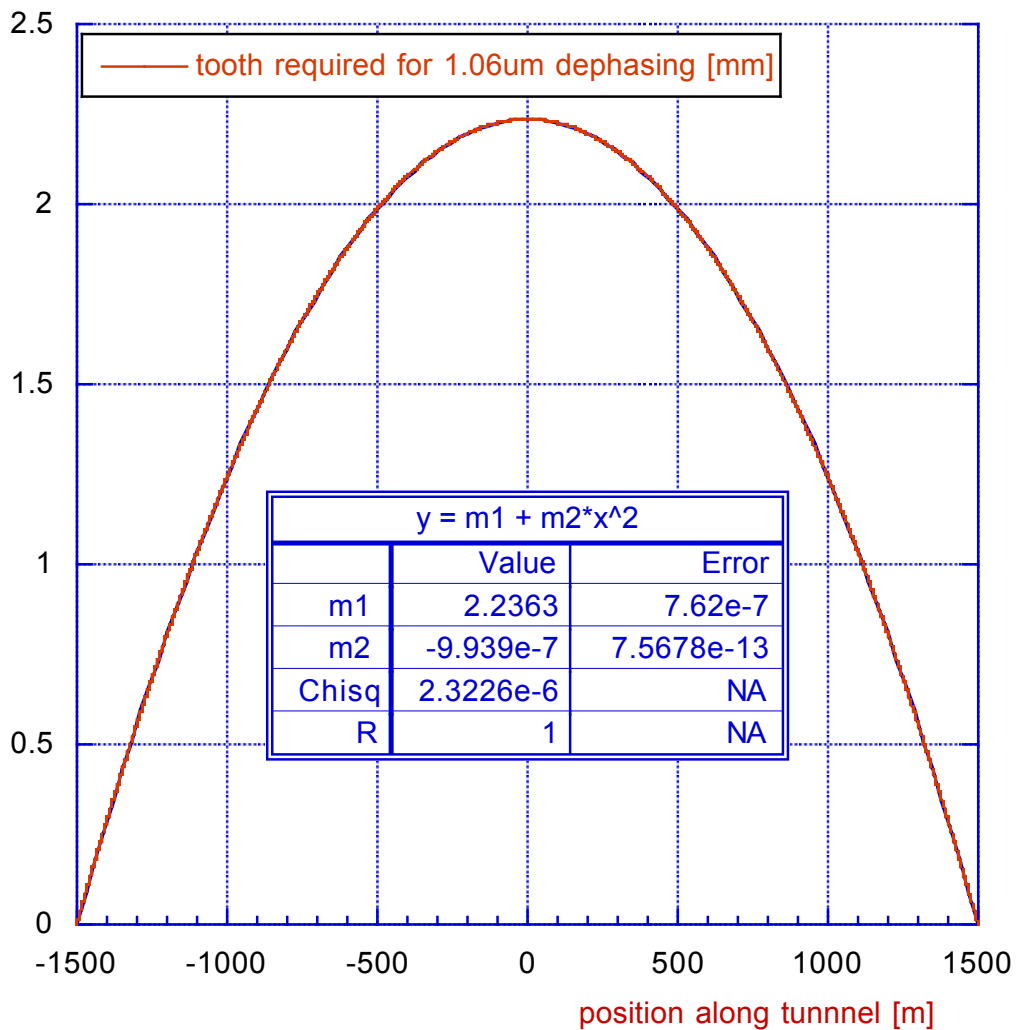
About teeth structure, there are arguments that apply equally to the conical and to the spiral baffles.

First, shear cut teeth are sharper, they do not have characteristic rough surface finish of laser and water-jet cuts. Shear cut teeth are to be chosen if they do not cost much more.

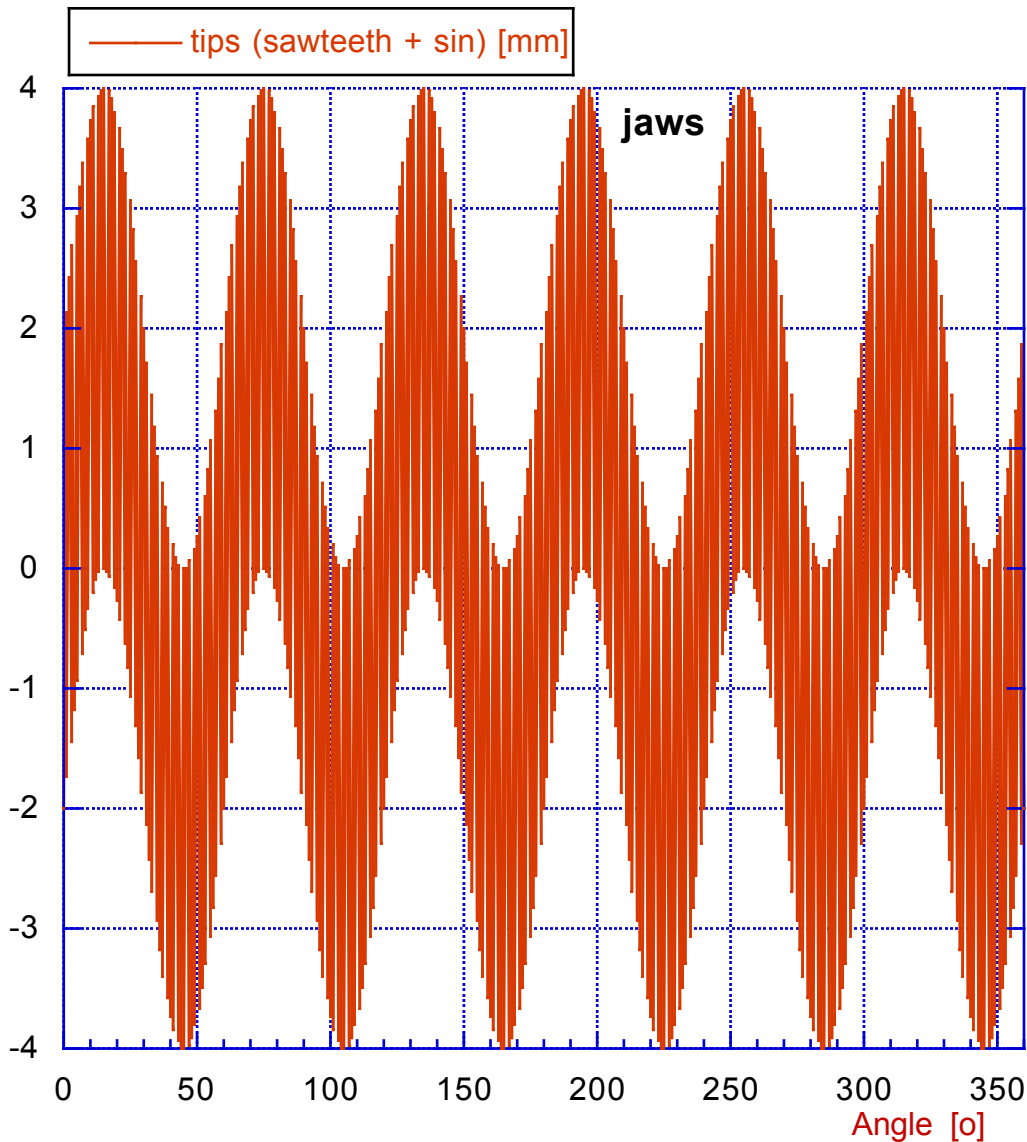
Second, random length teeth have been used so far, mainly because of the limited precision of laser cutting 10-15 years ago.

The random length teeth destroy the coherence of the edge diffraction.

However at any given distance from the mirror there is a specific tooth height that precisely adds up to zero the effects of diffraction. This height, that correspond to a 360° light de-phasing, is illustrated in figure



Therefore uniform teeth with this tooth height are probably advantageous. The tips and bottoms of the teeth may still form some coherent scattering. One may conceive to destroy even this residual coherence by waving the baseline of the teeth by the same amplitude in a sinusoidal or sawtooth structure repeating around the beam circumference as illustrated in figure.



K. Thorne recommends that the teeth should be random in pitch and height, and that the height of the teeth in the middle of the beam tube should be > 2 Fresnel zones, which requires a tooth height > 4 mm; if all the baffles have this same teeth height, the baffles near the mirrors will encompass $\gg 2$ Fresnel zones. Calculations using Thorne's formalism indicate an improvement in displacement noise by factor 0.16 using random teeth. [MS]

Optimized tooth height may yield a better optimization factor, one should be careful, about the rough part from the laser or water-jet cut.