Beam expander telescopes for the Michelson beam splitters in third generation Gravitational Wave Observatories.

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Abstract

The third generation of Gravitational Wave detectors, the Einstein Telescope or the Cosmic Explorer, will still be Michelson interferometers with Fabry-Perot cavities in the two arms. They will need the widest possible stored beams to reduce thermal noise, using mirror test masses with diameter at the limit of technical feasibility. A serious problem is how to feed the beams of the two arms into the beam splitter for recombination. The problem is worse in Einstein Telescope, where the 60^o angle between the arms would require beam splitters double in size and 8 times in weight than the 90^o case. It is proposed here to move the beam expander telescope inside the Michelson, between the Fabry-Perot cavities and the beam splitter. In addition to allowing use of smaller beam splitters, the proposed solution allows change of the recombination angle from 60^o to 90^o, offers additional and easy degrees of freedom for beam alignment, a method for optimizing the match of the modes of the two arms on the beam splitter and a natural way to separate in different beam splitter halls multiple detectors housed in the same tunnels.

Introduction.

Future Gravitational Wave observatory will be Michelson interferometers [1] with very large test masses [2]. The primary problem is how to contain the size of the Beam Splitter (BS) while recombining the two beams with optimally overlapped light spots, maximizing contrast and therefore sensitivity to Gravitational Waves (GW). The more complicated Einstein Telescope (ET) [3] problem is discussed first. It is foreseen that ET will be triangular with three 10 km long tunnels at 60^o to detect both the x and the + polarizations of incoming GWs. Cosmic Explorer (CE) [4], being foreseen with arms at 90^o, is simpler. Each ET tunnel will house four beam pipes, two pipes for the high-frequency detectors and two for the low-frequency ones to implement the xylophone concept [5]. Each corner will house two beam splitters. The ET configuration is sketched in figure 1.

The main mirrors of the Fabry Perot cavities of a GW detector must be as large in diameter and mass as technically feasible to minimize thermal noise[6] and radiation pressure noise, and maximize sensitivity to GWs [7]. The sensitivity of even the present "advanced" GW detectors [8,9,10] is limited by coating thermal noise. The coating thermal noise evaluation method proposed by Levin [6] shows that the noise dominating the sensitivity is inversely proportional to the beam spot diameter. Large mirror thickness dilutes the coating thermal noise by providing stiffness. These reasons set the requirement of the largest possible mirror for the third generation GW detectors. All these requirements apply only to the FP cavity mirrors, the beam splitter can in principle be small, with a size dictated mainly by the thermal load of the feed and return beam.

The GW signal is extracted from the precise subtraction of the two FP return beams on the BS. Any lateral, angular, size, power and shape mismatch of the two beams on the recombination surface will strongly reduce the contrast of the recombined beam and therefore the sensitivity to GWs. The GW signal is extracted at the dark MI output port while most of the power of the returning beams exit from the input port. In addition, the rejected power returning in the input line is recovered by a power recycling mirror and reused. Any loss of contrast at the BS robs power from the recycling mirror, thus reducing its efficiency.

The problem of containing large diameter beams onto the Michelson beam splitter is already serious at 90° crossing angle, it becomes worse for beams recombining at 60°, as illustrated in figure 2. Using the largest manufacturable mirrors for the FP test masses, the beams stored in the arms are too large to be fully re-combined on the available-size beam splitter. In present interferometers the tails of the beams from the Fabry-Perot cavities are clipped just in front of the beam splitter by seismically isolated baffles, which is not an ideal solution. Clipping introduce loss of power but, more importantly, any difference in clipping of the two arms tends to reduce the all-important contrast. A beam diameter reduction strategy is needed to avoid requiring prohibitively large beam splitter mirrors.

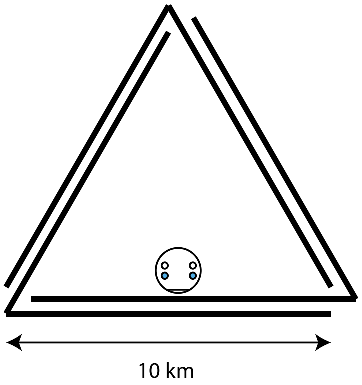

Figure 1: ET beam pipe configuration. Each tunnel contains two pairs of vertically separated interferometer arms. A total of six interferometers is foreseen, the cross sections show a possible arrangement of the vacuum pipes in each tunnel.

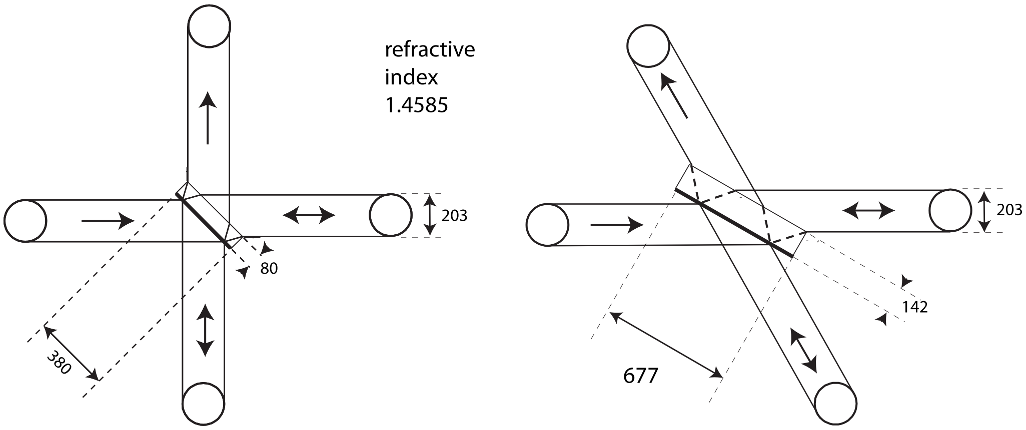

Figure 2: Beam splitter size comparison for the 90^o and 60^o configurations. An arbitrarily chosen beam size of 203 mm in diameter is chosen for the illustration of both configurations. Similarly, an arbitrary but reasonable thickness to diameter ratio of 0.21 is chosen for both the 60^o and the 90^o recombination mirrors.

For argument sake, an equal thickness-to-diameter ratio of the BS substrate and the same arbitrarily chosen 203 mm incoming beam diameter are considered to illustrate the geometrical problem. These sizes are arbitrary, they need to be scaled to the dimensions required by ET or CE. Figure 2 shows that without clipping or focusing, the beam splitter would have to be 3.5 times wider than the impinging beam for the 60^o case and ~2 times wider for the 90^o case. The proposed ET mirror size is 620 mm in the warm interferometer; without beam diameter reduction a beam splitter of about 2 m in diameter and more than 2 T in weight would be required, a prohibitive size. A beam diameter reduction by a factor of ~3 (to 203 mm) is hypothesized in the example of figure 2. It brings a surface reduction of 9 times and a mass reduction of 27 times . Careful thermal load evaluation beyond the scope of this work would be necessary to determine an optimal beam-size reduction factor. With 203 mm beams the 60^o mirror would weigh ~140 kg, still at the limit of feasibility, while the 25 kg of a BS operating at 90^o is quite feasible.

In addition, the 60^o solution has another disadvantage with respect with the 90^o, the length traversed by light inside the substrate and the deposited power and thermal lensing, are twice as serious. The steeper angle introduces larger power-dependent aberrations.

Reducing the beam size between the individual Fabry Perot cavities and the beam splitter is necessary to have manageable size beam splitters. Beams crossing at 90^o at the beam splitter, the most advantageous configuration, is desirable as well.

Intra-cavity beam reducing telescopes

The ET preliminary design envisions a convex curvature on the back surface of the Input Test Mass (ITM) to focus the beams onto a small BS. This solution has the disadvantage of mixing transversal and angular beam modes at the recombination point and does not provide easy degrees of freedom to control the recombination alignment and mode-matching on the beam splitter. In addition, any differential and time-dependent thermal lensing in the two arms would project different image sizes on the BS and can be dealt with only with corrections at the ITM level. The configuration proposed here offers four to six additional degrees of freedom to address the alignment control issues, and two locations well removed from the sensitive test masses where to apply compensation for thermal lensing, these are issues that were only partially solved in the ET preliminary design document and are still lingering even in present observatories. Thermal compensation is presently applied directly on the test masses or on compensation plates mounted next to them [11,12]

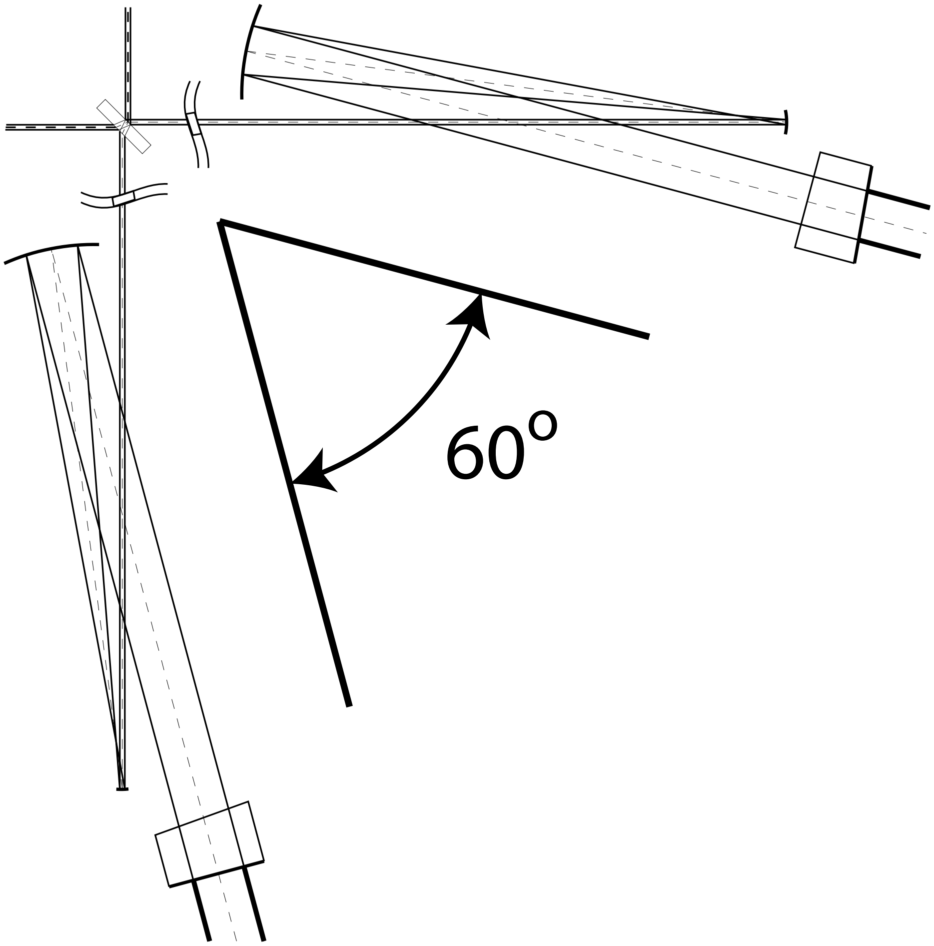

Figure 3: The beams from the Fabry Perot cavities encounter a primary parabolic mirror tilted at 3.75° from the beam line. The reflected beam emerges at 7.5° and is focused at a distance of several meters, sufficient to extract the beam from the beam pipe. A secondary mirror tilted by an additional 3.75° produces a reflection propagating at a combined 15° from the Fabry-Perot beam line. The collimated beam crosses the beam pipe. After a distance determined by the separation of the two main tunnels at the point of extraction (see figure 4) the two beams recombine at 90° on a standard, reduced-size beam splitter.

It is worth reminding that somewhere in the Michelson reflective beam-expanding telescopes are necessary to match the main beam diameter to the smaller size of the power-recycling and the signal-recycling optics. In present interferometers these telescopes at the outer ports of the Michelson interferometer. It is also worth reminding that relay mirrors are required between the Fabry-Perots and the beam splitter in at least one of the two interferometers to separate the recombination point of different interferometers in different locations.

It is proposed to relocate the two beam expanding telescopes inside the Michelson so that smaller size beams impinge on the BS. This can be done with no net increase of the number of optical elements. Tilting each telescope mirror by 3.75^{o} can bring the beam crossing angle from 60 to 90^{o}. At this inclination the beam moves sideways by one m in only 7.5 m of longitudinal distance. The scheme is shown in figure 3.

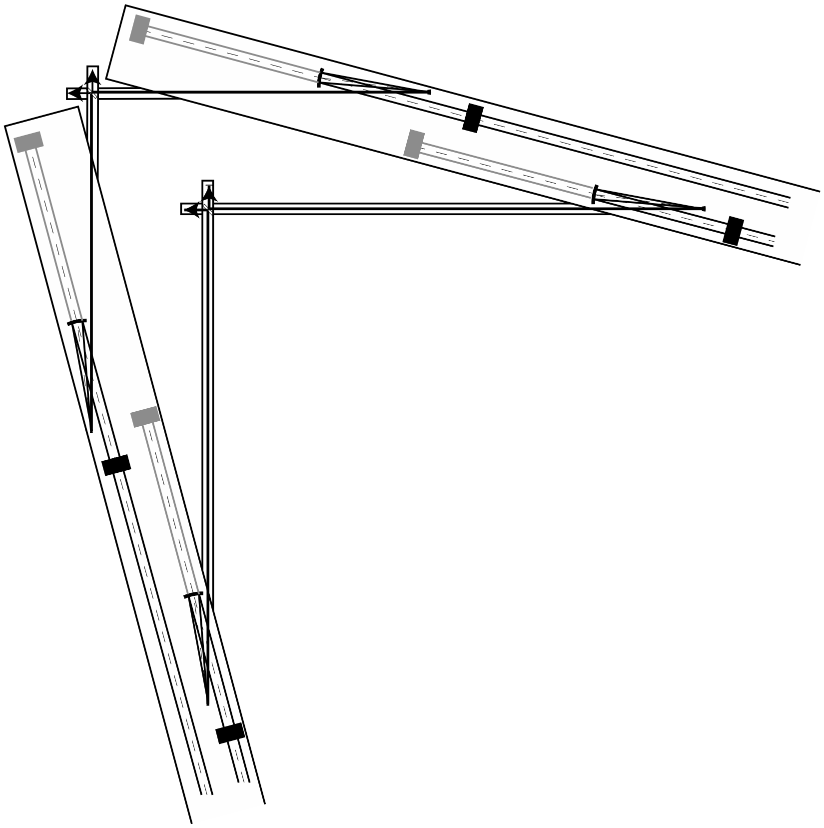

Figure 4: Scheme for extracting multiple interferometers from a common tunnel. The interferometers can be extracted independently and brought to the beam splitter using small diameter tunnels. The End Tst Masses of the interferometers with beam splitters at the other corners of the triangle are drawn in grey.

Introducing separate beam expanding telescopes inside each Michelson arm has a number of advantages.

- Recombination can be brought to the optimal 90° on the beam splitter.
- A beam splitter of almost arbitrarily size can be used while accepting the entire beam profile from the Fabry-Perots.
- The convexity for the back surface of the ITM proposed in the ET preliminary design cannot be large, resulting in a focal length of several hundred meters. The beam reducing telescope are 7 to 10 m long, a distance necessary to exit the beam pipe, thus leaving more tunnel length for the Fabry Perot cavities and sensitivity to GWs.
- A flat, easier to manufacture, back surface for the ITM can be used.
- The independent angular control of the two mirrors in each telescope make it possible to achieve best lateral mode matching on the beam splitter, independent from the relative alignment of the two Fabry-Perot cavities, which is recognized to be a great advantage from the interferometer controls point of view.
- Thermal compensation techniques can be applied on the telescope mirrors instead of on added compensation plates [13], to precisely match the shape and sizes of the two beam spots on the beam splitter, even dynamically correcting for power-dependent aberrations and thermal lensing in the arms [14,15,16,17,18]. The ITM compensation plates used in Advanced Virgo and LIGO [8,9] may become unnecessary.
- Monitoring a few ppm of mirror transmission from either the primary or secondary telescope mirror can also be used for sensing and control feedback in the same way used with the leak field from the LIGO end test masses.
- A wedge is usually necessary in the Fabry-Perot input mirror substrates to avoid parasitic interference; it produces a ghost image that is an important diagnostic tools that provides a feedback signal for controls of the mode matching of the two beams on the BS. The focusing offers the opportunity to cleanly and independently separate the ghost images, as illustrated in figure 5.
- The beams from different detectors can be sequentially extracted from the tunnel with beam splitters located in well separated places, as illustrated in figure 4.

Mirror requirements

Offset parabolic mirrors will be necessary, like the ones already in use in GW detectors. The angular, length and vibration requirements are reduced by the Finesse of the Fabry Perot. As a consequence, the mirror optical specs, the seismic attenuation and control requirements for beam reducing telescopes inside the Michelson are similar to the beam splitter's. The controls of the internal beam expander telescopes degrees of freedom would be practically the same as in the KAGRA external ones.

The telescope mirrors are outside the FP and therefore practically insensitive to thermal and radiation pressure noise and can be lightweight. Therefore, while the primary mirror must have the same diameter as the ITM they can be thinner. For the same reason the seismic isolation requirements are reduced and they can be supported by short Seismic Attenuation chains housed in relatively small vacuum chambers similar to those that the author designed for TAMA [19] and the KAGRA input and output telescopes [20]. Each vacuum chamber can be contained in a small alcove with locally raised tunnel ceiling, reducing the need for large caverns.

An inconvenience is that while focusing the beams to smaller diameter allows for much smaller beam splitters, it comes at the price of increased power density on the beam splitter. Because only one of the two FP return beams traverses the beam splitter substrate, relatively large differential thermal lensing and aberrations can be produced. The effect can be mitigated by using higher quality substrates, which is possible only for substrates of small volume. The residual aberrations can be compensated with differential thermal lensing of the telescope mirrors upstream or the BS itself. As already mentioned, a tradeoff study is necessary to determine the optimal beam reduction factor.

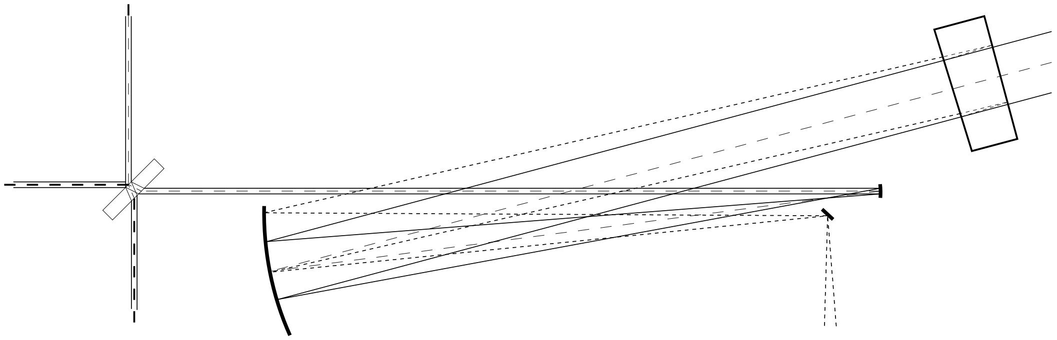

Figure 5: Scheme for extraction of a ghost beam for diagnostics and controls. The ITM wedge angle and distance of the two mirrors can be adjusted to produce best ghost beam separation.

Reducing beams in the L-configuration

The concept of beam reducing telescopes within the individual arms can be implemented also in 90° Michelsons to reduce the beam splitter size and better mode-matching. The constraint telescope mirrors inclined by 3.75° does not apply and different angles and focal lengths can be used. If multiple interferometers are implemented, the 45° relay mirrors used to spatially separate the beam splitters can also be smaller, as illustrated in figure 6.

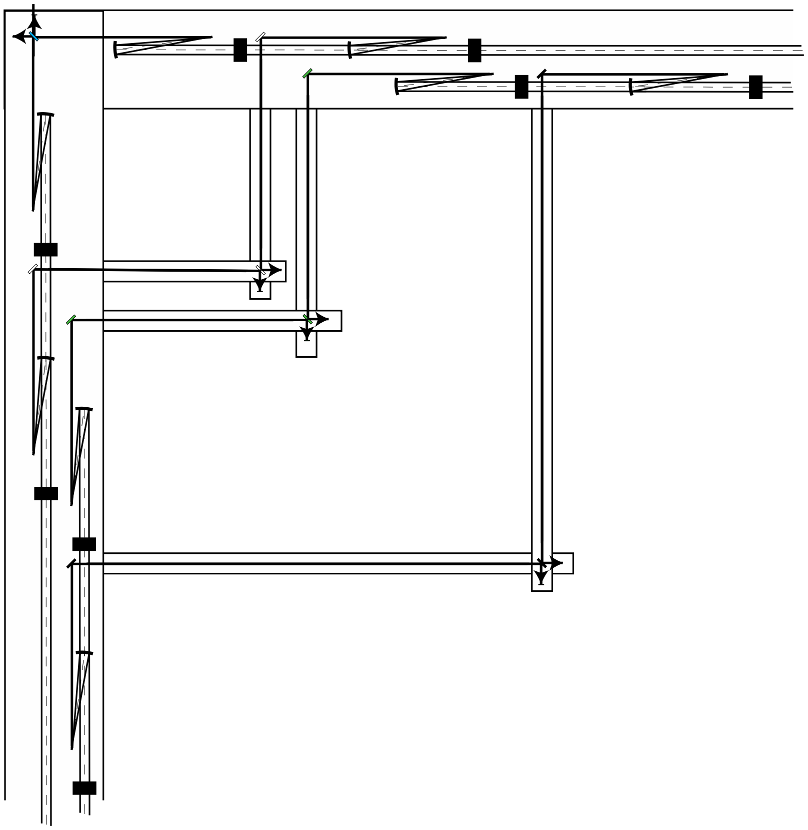

Figure 6: Scheme for extracting multiple interferometers from a common tunnel in a 90° configuration.

Observational considerations

It is very important to maintain continuous observations of GWs, any significant activity near any test mass impedes Gravitational Wave Detection. If all elements of each corner station were positioned in a single large experimental hall, access for commissioning, tuning or maintenance of a single detector would degrade or even impede the operation of all the other. Great advantage may derive from segregating recombination, controls and the complex input/output optics of different interferometers in separate tunnels. The geometries of figures 4 and 6 permit to do that with the beam splitters positioned in separate tunnels or alcoves, away from the test masses in the main tunnel. Staggered maintenance and staged commissioning may become possible.

Conclusions

Installing beam expanding telescopes inside each Michelson arm of a GW detector has the advantage that smaller beam splitter mirrors can be used, and the recombination can be brought back to the ideal 90° even for interferometer arms at 60°.

The angular controls of the two telescope mirrors introduce additional degrees of freedom useful for better alignment of the two beams on the recombination mirror for increased contrast and improved sensitivity to gravitational waves. Imaging of ghost beams provide sensing options for the beam modes, and thermal compensation techniques applied on the telescope mirrors provide the necessary degrees of freedom for non-axisymmetric adaptive waveform controls, including dynamic thermal lensing corrections, and mode matching to improve the observatory performance and stability.

The beam reducing telescopes offer an easy way to route the beams in separate tunnels and small caverns for recombination and I/O optics, which would allow continued astronomical observations, even during access for maintenance of some of the detectors. The excavations are smaller in cross section than multi-purpose, large caverns and therefore more geologically stable and easier to dig.

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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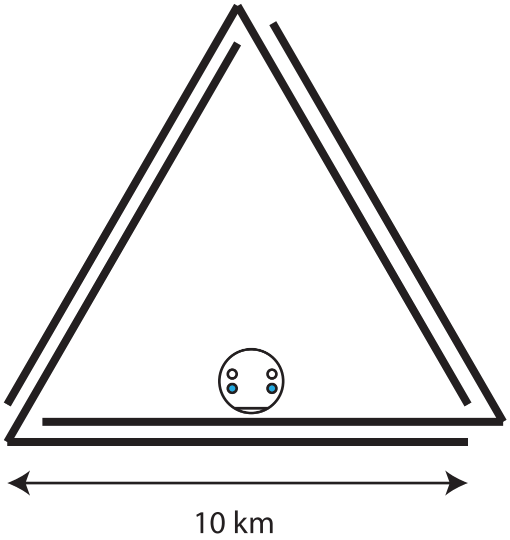
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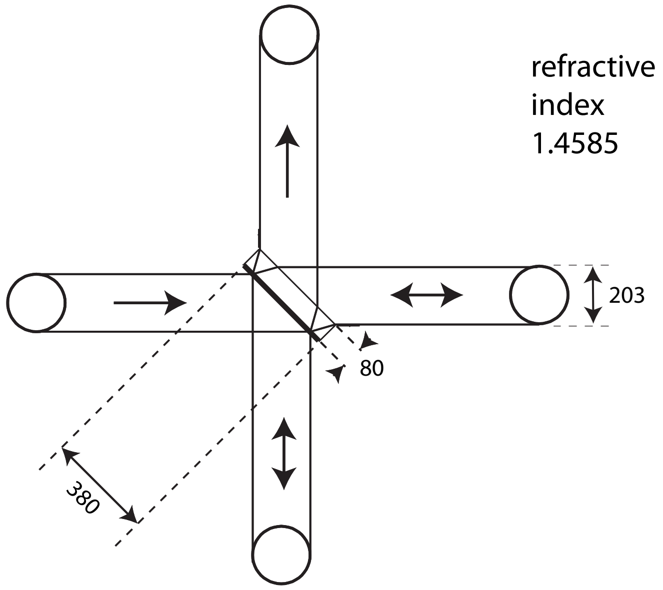
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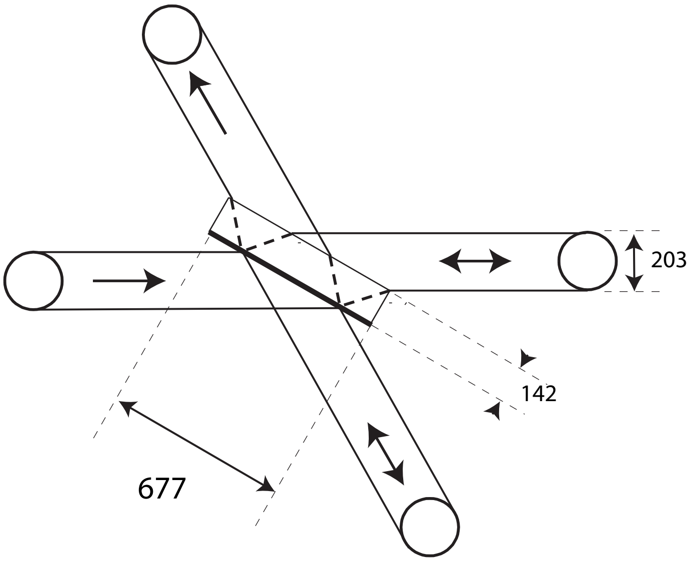
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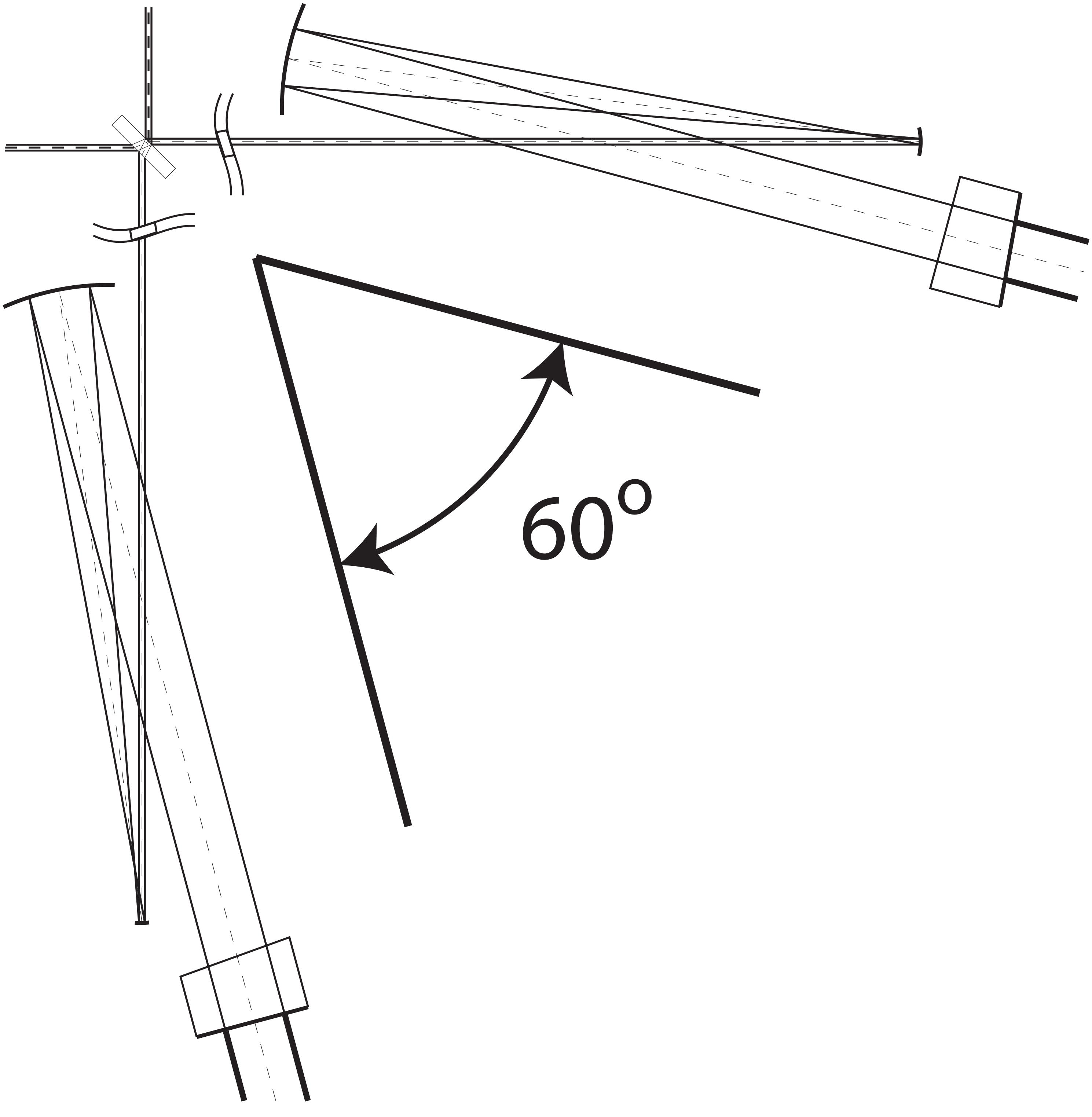
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