

## Considerations about triangular vs. x and + Michelson configurations for third generation Gravitational Wave Observatories.

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### Geometry description.

It is foreseen that the Einstein Telescope, third generation Gravitational Wave observatory will have 30 km of tunnels. Each tunnel will house the beam pipes of two separate detectors and each detector is formed by a xylophone of two instruments, one high-frequency and one low-frequency.

Two configurations of interferometers have been compared:

- The baseline triangular configuration with 10 km arms crossing at  $60^\circ$ , illustrated in the right panel of figure 1. Two side-by-side interferometer arms, with opposed directions, would be housed in each tunnel as illustrated in the right panel of figure 1.
- Traditional L-shaped Michelson interferometers with arms crossing at  $90^\circ$ , each with 7.5 km arms, oriented in the x and + configuration, i.e. at  $45^\circ$  from each other, as illustrated in the left panel of figure 1. To make the same pipe length, each tunnel would contain two identical interferometers, side-by-side, like in the case of the triangular configuration.

Both geometries are designed to detect with equal sensitivity the x and the + polarizations of incoming gravitational waves.

Tunnel and vacuum tube length are the largest driving costs of an observatory. To make a meaningful comparison, a zero-sum rule of the same 30 km of tunnel length, and the same 120 km of vacuum tube length was applied in both case studies. Each tunnel will house two pairs of vacuum pipes to allow for the xylophone concept, with interferometers arranged as in figure 1.

Only the Michelson configuration is considered, comparison of different configurations (violating the tunnel and pipe zero-sum rule) are reported in Class. Quantum Grav. **26** (2009) 085012, A. Freise, *et al.*

It is easy to see that “at equal arm length” a single detector with triangular ( $60^\circ$ ) geometry is less effective to detect the quadrupolar gravitational waves than a  $90^\circ$  Michelson, which fully matches the GW topology. That handicap is compensated by the longer arm assigned by the sum rule to the three arms. The detection sensitivity equilibrium is re-established when considering that the L-shaped x and + configuration would have twin side-by-side interferometers in each tunnel, for a total of four (eight) interferometers versus the three (six) of the triangular geometry. In first approximation, considering the zero-sum rule, i.e. maintaining the same tunnel and pipe length, sensitivity-wise there is no clear preference for one configuration or the other.

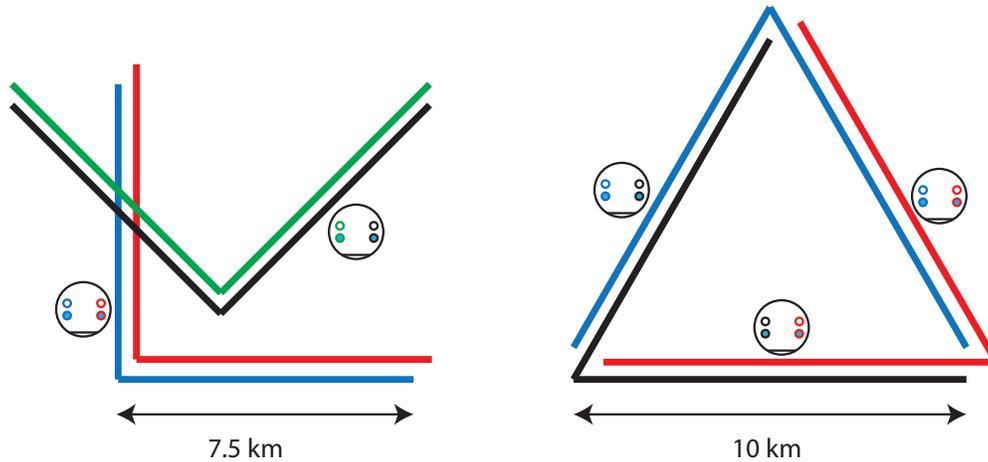


Figure 1: Considered interferometer configurations. Left: double Michelson case. Right: triangular configuration. In both cases each tunnel contains two pairs of vertically separated interferometer arms to implement the xylophone concept. Possible tunnel cross sections and beam arrangements are shown as well.

### Beam Splitter problem and solutions for the 60° option.

The main mirrors of the Fabry Perot cavities of a GW detector are large and the beams stored in the arms would be too large to be combined on a reasonably sized beam splitter. In present interferometers the beam tails are clipped just in front of the beam splitter by seismically isolated irises. The problem is already serious at 90°, becomes substantially worse for beams recombining at 60°, as illustrated in figure 2. Without beam diameter reduction unreasonable clipping or prohibitively large beam splitter mirrors would be required.

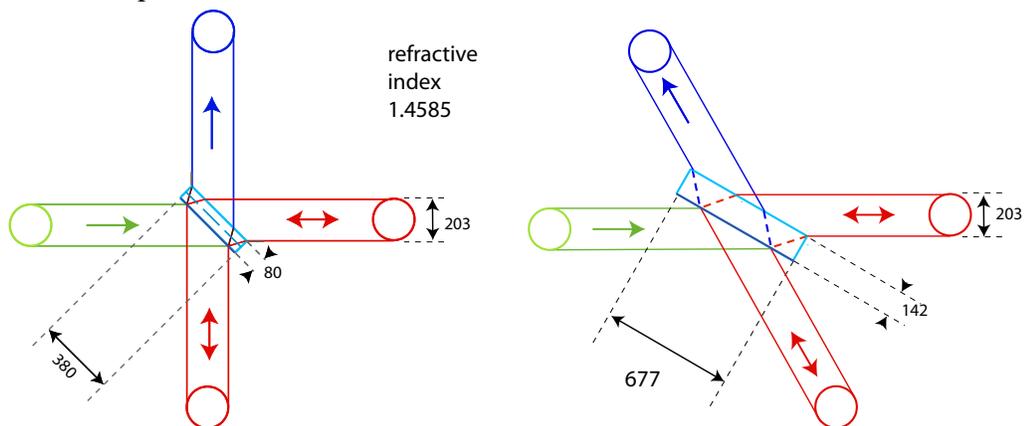


Figure 2: Beam splitter size comparison. An iris of arbitrarily chosen 203 mm in diameter is chosen for both configurations. Similarly, a thickness vs. diameter ratio of 0.21 is chosen for both the 60° and the 90° mirrors.

At equal thickness-to-diameter ratio of the substrate and same incoming beam diameter, the 60° beam splitter would be 1.8 times larger, and almost 6 times heavier than the 90° one. Even with a clipping iris of 200 mm in diameter, the 60° mirror would weigh ~140 kg, vs. the 25 kg of the 90° beam splitter. If one was to attempt to re-combine the beams from 500 mm diameter test masses without focusing or clipping, the 60° beam splitter would weigh more than 2 tons.

In addition, the length traversed by light inside the 60° substrate and therefore the deposited power and thermal lensing, is twice as much, and at a steeper angle, thus introducing larger power-dependent aberrations. Unless focusing or clipping of the FP beams, the beam splitter becomes wider than the main mirrors, which would represent a serious limiting factor. Reducing the beam size just outside the individual Fabry Perots eliminates the iris requirement and allows for manageable size beam splitters.

### Proposed beam reduction scheme

The ET preliminary design proposed a convex curvature on the back of the ITM to focus the beams onto a small BS, illustrated in figure 3.

This geometry has the disadvantage of turning transversal beam motion on the FP mirrors into angular changes at the recombination point and does not provide degrees of freedom to control the recombination alignment and quality. Any lateral, angular, size and shape mismatch of the two beams on the recombination surface strongly reduce the contrast of the GW-carrying optical signal. Any thermal lensing, especially if different in the two arms, would modify the design focalization power of the ITM. In this geometry differential thermal lensing can be dealt with only with thermal corrections at the ITM level.

In addition, the lensed ITM solution would still require relay mirrors like the ones used in the 2 km Hanford interferometers to separate in different locations the recombination point of the four interferometers of each tunnel.

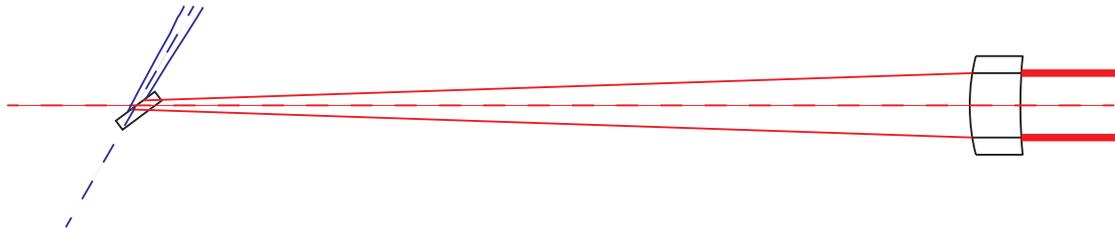


Figure 3: Schematic of the lensed ITMs proposed to reduce the beam size in the ET original proposal.

### Beam reducing telescopes

In present interferometers two reflective beam-expanding telescopes are placed at the outer ports of the Michelson interferometer to match the beam diameter to the smaller power-recycling and the signal-recycling optics.

It is proposed here to solve the beam-size problem by relocating the two beam expanding telescopes inside the Michelson. This can be done with no net increase of the number of optical elements, as shown in figure 4.

Reflective optics have a clear advantage over refractive optics in high power environments because even the best Suprasil 3001 has an absorption of  $\sim 0.2$  ppm/cm that produce thermal aberrations, while dielectric mirrors may absorb less than 0.25 ppm total.

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

- A beam splitter of almost arbitrarily small size can be used accepting the entire beam profile from the Fabry Perots without beam tail clipping.
- The ITM with a flat back surface would be simpler to manufacture.

- The focal lengths of the telescope mirrors can be adjusted to reduce the beam size within a relatively small distance, thus leaving more tunnel length for the Fabry Perot cavities and maximizing the sensitivity to GWs.
- Independent angular control of the two mirrors in each telescope allows for best lateral and angular mode matching on the beam splitter, nominally independent from the relative alignment of the two Fabry-Perot cavities.

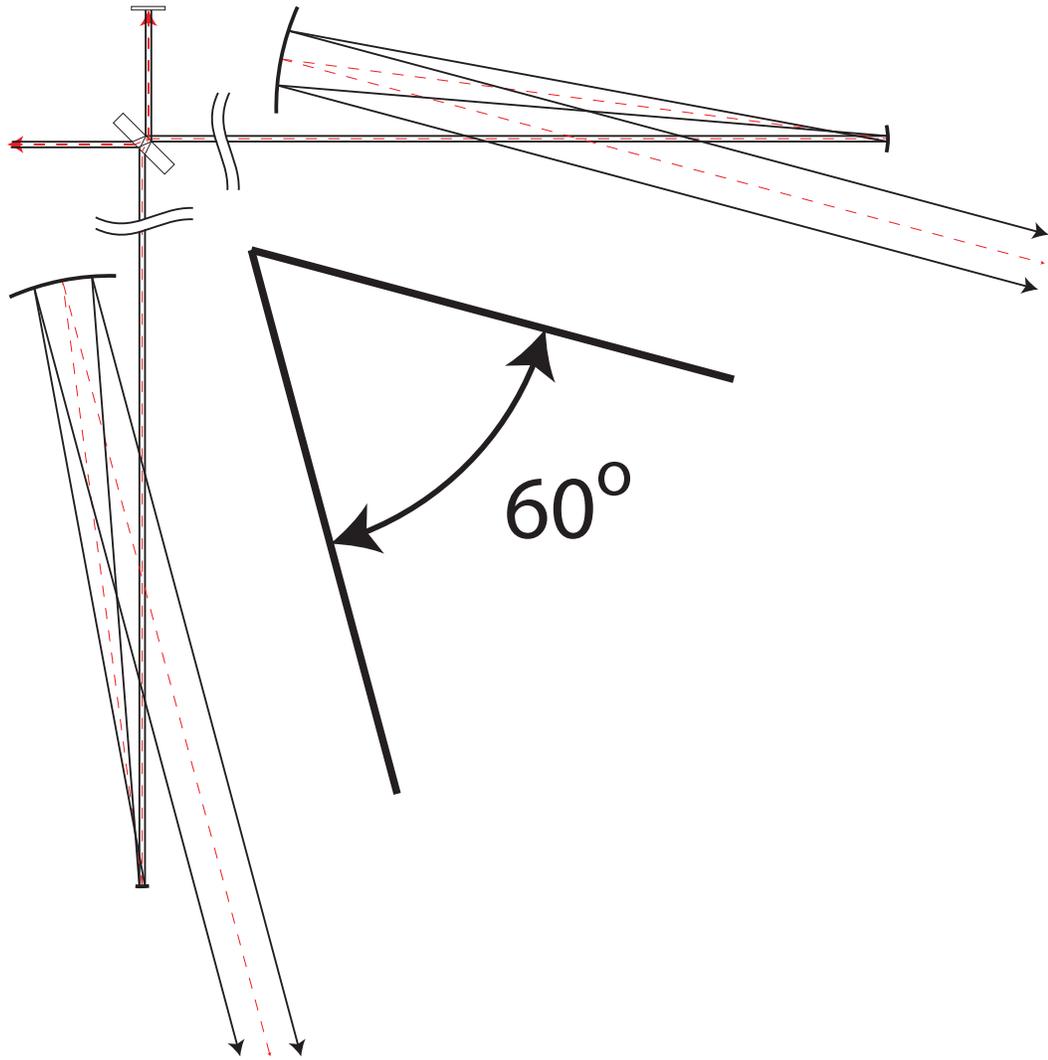
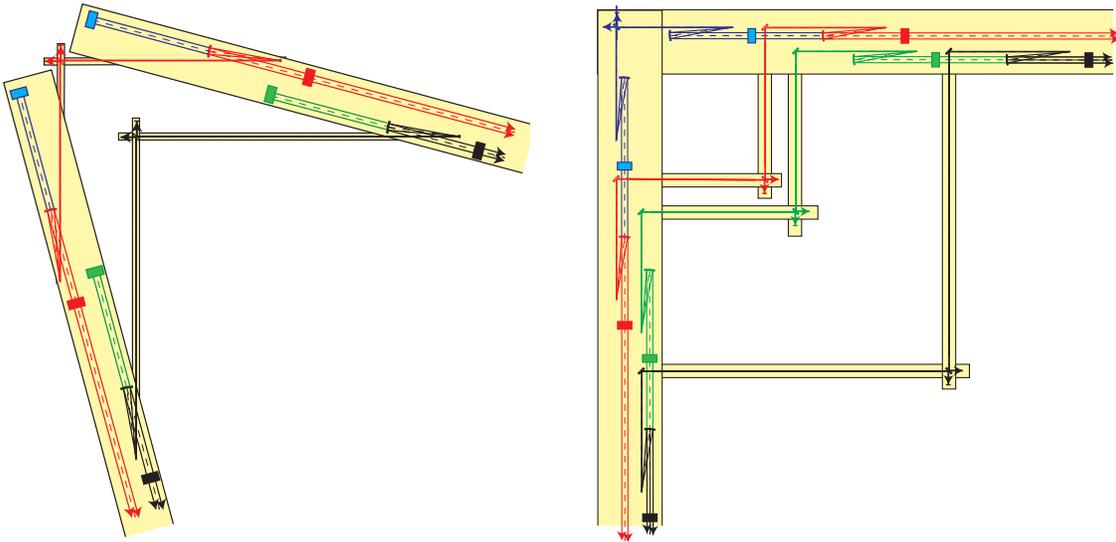


Figure 4: The beams from the Fabry Perot cavities encounters a primary parabolic beam tilted at  $3.75^\circ$  from the beam line. The reflected beam emerges at  $7.5^\circ$  and is focused at a distance of several meters, sufficient to extract the beam from the beam pipe. After the focusing, a secondary mirror tilted by an additional  $3.75^\circ$  produces a reflection propagating at a combined  $15^\circ$  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 5) the two beams recombine at  $90^\circ$  on a standard, reduced-size beam splitter.

- Thermal compensation techniques on the telescope mirrors allow the opportunity of precisely matching the shape and sizes of the two beam spots on the beam splitter by dynamically correcting for power-dependent

aberrations arising from either the beam splitter or from thermal lensing in the main test mass mirrors. The ITM compensation plates may become unnecessary.

- The beams from the multiple detectors can be sequentially extracted from the tunnel with beam splitters naturally located in well separated places, as illustrated in figure 5.



**Figure 5: Scheme for extracting multiple interferometers from a common tunnel. The interferometers can be extracted independently, using smaller tunnels which are much more stable and cheaper than a single large experimental hall. Tunnel sizes not to scale.**

- The relatively long distances required to extract the beams from the main vacuum pipes offer the opportunity to cleanly and independently separate the ghost images of the two ITM wedges for diagnostic and control use, as illustrated in figure 6. The ghost images provide an imaging feedback signal for the mode matching of the two beams.
- The length of the telescopes can be adjusted to extract the ghost images while using smaller ITM wedge angles.

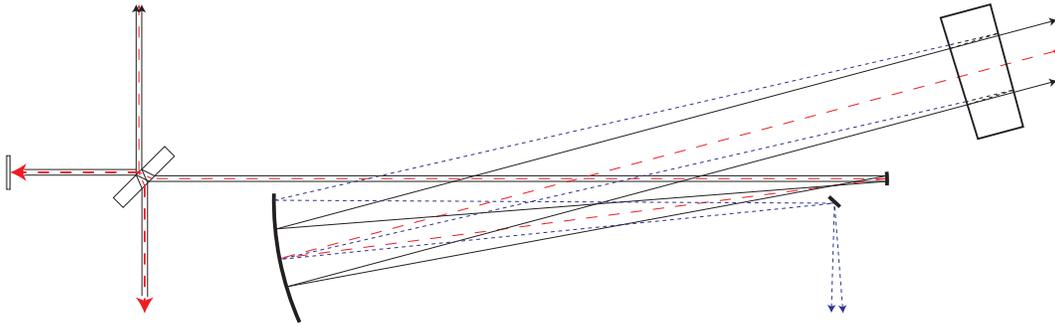
### **Beam reducing telescope requirements**

The seismic attenuation and control requirements on beam reducing telescopes inside the Michelson are not too different than for external ones or those of the relay mirrors used in the old Hanford 2-kilometer interferometer. Being outside the Fabry-Perot cavities, all relay mirrors (like the beam splitter mirror) are less sensitive to seismic noise than the test masses and practically insensitive to thermal noise. They are lighter than the test masses and can be supported by smaller and cheaper SAS chains housed in smaller vacuum chambers, similar to those designed for TAMA and KAGRA. They can be contained in small and stable tunnels and alcoves, without the need of large and expensive caverns.

On the minus side, offset parabolic mirrors would be necessary for the beam reducing telescopes. These mirrors are available and already of common use.

An additional 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 for the beam that traverses the beam splitter substrate. This, despite the shorter distance and less power deposited in the glass, can potentially produce larger thermal lensing and aberrations. The effect can be mitigated by using higher quality substrates, which is not in general possible for substrates of very large volume. The residual aberrations can be compensated with differential heating of the telescope mirrors, as discussed above.



**Figure 6: Scheme of extraction of ghost beam for diagnostics and controls. The angle and distance of the two mirrors can be adjusted to produce best ghost beam separation as long as the cumulative beam rotation is 15°.**

The wedge necessary in the Fabry-Perot input mirror substrates to avoid parasitic interference produces a ghost image. The ghost image is used for beam position monitoring and controls. With a suitably choice of wedge and focal length the ghost beam can be cleanly separates from the main beam and easily extracted as illustrated in figure 6.

### **Reducing beams in the L-configuration**

The concept of beam reducing telescopes within the individual arms can be implemented also in the 90° Michelson case, figure 5, right panel. In this case the almost spherical telescope mirrors may be assembled at smaller angles. Relay mirrors at 45° would be necessary to locate the four beam splitters of each corner station in four separate location and smaller caverns. The beam reduction can be applied before the relay mirrors, which, like the beam splitter, may become substantially smaller.

### **Observational considerations**

From the observational point of view one needs to consider that any significant human activity near any test mass impedes Gravitational Wave Detection. If all elements of each end station are positioned in a single large experimental hall, access for commissioning or maintenance would impede the operation of all interested detectors. In the triangular configuration all six interferometers use all three end stations and the entire observatory would be affected. In the double L-shape the problem is reduced because the eight Michelson interferometers are divided in two independent observatories in physically separated tunnels and one can always remain in observation mode.

The geometries of figure 5 permit to positioning all beam splitters and test masses in separate tunnels or alcoves, thus allowing maintenance of an interferometer while the other detectors continue normal observation. This is very important to maintain

continuous observation, especially when observing in conjunction with a second observatory.

### **Advantages of the 90° option.**

The two 90° Michelson interferometer option offers better staging options. An example of staging scenario that maintains continuous observation after initial commissioning would be:

- Install a room temperature detector in the x interferometer and debug it while the + tunnels are still being excavated and instrumented. Start observations in the x detector.
- Fully tested and debugged warm detectors are installed in the + tunnels. Observations start in + detectors.
- Install the missing warm detector in the x detector and, if necessary, upgrade the previously installed one while observations continue with the + detector.
- Install a cryogenic detector in the x tunnels while maintaining observation with the + detectors. Then restart observations.
- Fully tested and debugged cryogenic detectors are installed in the + tunnels. Observations re-start in + detectors.
- Install the missing cryogenic detector in the x detector and, if necessary, upgrade the previously installed one while observations continue on the + detector.

One should also consider that the 90° option is extensible at the only cost of extending the tunnels and moving the end stations, while the triangular option is not extensible.

Pairs of identical detectors in the same tunnel are ideal for stochastic signal searches and allow for trivial null stream for performance control, which may be less than ideal or more complicated in the triangular configuration.

The double L-shaped Michelson retains operational advantages for staging of commissioning, as well as the option of extensibility of the arms.

### **Conclusions**

The 90° Michelson had a clear advantage over the triangular (60°) configuration for what regards beam recombination on the beam splitter. That advantage is largely eliminated by installing beam expanding telescopes inside each Michelson arm. Using parabolic mirrors the recombination is brought back to 90°, and smaller beam splitter mirrors, accepting even the tails of the Fabry Perot beams can be used.

The angular controls of the proposed telescopes introduce additional degrees of freedom useful for better steering and mode matching on the recombination mirror. As a result one can expect increased contrast and improved gravitational wave signal to noise ratio.

The beam reducing telescopes steer the beams away from the main tunnels, onto widely separated beam splitters and I/O optics, in separate tunnels. Sensitive mirror in separate tunnels and test masses widely separated in the main tunnel allow continued astronomical observations with most of the installed detectors even during access for maintenance.

Tunnels and small alcoves, even if more numerous, are much cheaper and stable than large caverns. This may result in significant facility cost reductions.

A detailed comparative study between the baseline lensed-ITM system slowly reducing the beam size and the off-axis fast telescopes proposed here is still required. The comparison should budget-in aberrations, thermal lensing corrections, alignment and control options, maintenance and any other variable that may affect the observatory performance, stability and ease of commissioning.