**Considerations about triangular vs. x and + Michelson configurations for the Einstein’s telescope.**

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**Geometry description.**

It is foreseen that the Einstein Telescope, third generation of Gravitational Wave observatory are expected to 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 60o, 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.
* Two traditional L-shaped Michelson interferometers with arms crossing at 90o, each with 7.5 km arms, oriented in the x and + configuration, i.e. at 45o from each other, 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 easy to see that “at equal arm length” a single detector with triangular (60o) geometry is less effective to detect the quadrupolar gravitational waves than a 90o 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 60o 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 serious at 90o, becomes substantially worse for beams recombining at 60o.

The problem is already serious at 90o. The 60o beam splitter geometry, as in the originally proposed ET geometry, with no beam diameter reduction would require unreasonable clipping or prohibitively large beam splitter mirrors, as illustrated in figure 2.



Figure 2: Beam splitter size comparison. For proper comparison an iris of arbitrarily chosen 203 mm in diameter is chosen for both configurations, to define the FP beams. Similarly, a thickness vs. diameter ratio of 0.21 is chosen for both the 60o and the 90o mirrors. Reducing the beam size upstream of the beam splitter would eliminate the iris requirement with all of its drawbacks.

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

The length traversed by light inside the 60o 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.

**Proposed beam reduction scheme**

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

This geometry has the disadvantage to turn transversal beam motion on the mirrors into angular changes at the recombination point, and to allow for little degrees of freedom to control the recombination 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 and would need to be dealt with 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.

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 to solve the beam-size problem by moving 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 ~ 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 have 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.
* 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 Fabry-Perot cavities.



Figure 4: The beams from the Fabry Perot cavities encounters a primary parabolic beam tilted at 3.75o from the beam line. The reflected beam emerges at 7.5o 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 3.75o produce a reflection propagating at 15o 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 90o 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, and even steered out of the plane of the Michelson if needed.



Figure 5: Scheme for extracting multiple interferometers from the common tunnels. The four interferometers can be extracted independently from the main tunnel, 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 increased if necessary to extract the ghost images while using smaller ITM wedge angles.

**In-Michelson beam reducing telescope requirements**

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 and can be supported by smaller and cheaper SAS chains in smaller vacuum chambers, similar to those designed for KAGRA. They can be contained in small and stable tunnel widening without the need of large and expensive caverns.

On the minus side, offset parabolic mirrors would be necessary for the beam reducing telescopes.

Also on the minus side, while focusing the beams to smaller diameter allows for much smaller beam splitters, it comes at 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 substrate, 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 wedge necessary in the Fabry-Perot input mirror substrates to avoid parasitic interference produces a ghost image, which is used for beam position monitoring and controls. With a suitably chosen wedge, the long distances required to extract the beam from the beam pipe also separates the ghost beam from the main beam, which can then be easily extracted.

**Reducing beams in the L-configuration**

The concept of beam reducing telescopes within the individual arms can be implemented also in the 90o Michelson case. In this case the telescope mirrors would be assembled at smaller angles and almost spherical. Relay mirrors at 45o like those used in the Hanford 2 kilometer interferometer before it was dismantled would be necessary to point to the four beam splitters f each corner station in separate location and smaller caverns. The beam reduction can be applied before the relay mirrors, which, like the beam splitter, may become substantially smaller.

**Advantages of the 90o option.**

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

* Install one room temperature detector in the x interferometer and debug it while the + tunnels are still being excavated and instrumented. Start observations.
* 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 on 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.

The extra flexibility of the 90o option is even more relevant for staging when the low frequency interferometer implementation is considered.

From the observational point of view one needs to consider that any significant human activity close to any test mass impedes Gravitational Wave Detection. Therefore, access to any end station for commissioning or maintenance in the triangular configuration may impede the operation of the entire observatory while shutting down only half of its capabilities in the x and + case.

This is a very important factor observation-wise.

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

Finally pairs of identical detectors in the same tunnel are ideal for stochastic signal searches, which may not be the case in the triangular configuration.

**Conclusions**

The 90o Michelson had a clear advantage over the triangular (60o) configuration for what regards beam recombination on the beam splitter.

That advantage is largely eliminated by installing beam expanding telescopes inside the Michelson arms. Using parabolic mirrors at a 3.75o angle brings the recombination back to 90o and allows use of a smaller beam splitter mirror while eliminating the need for clipping the beam tails of the Fabry Perot cavities. The controls of the proposed telescopes introduce additional degrees of freedom for better steering and mode matching on the recombination mirror.

The use of telescopes to shrink and steer the beams onto a smaller beam splitter may be advantageous for the double L-shaped Michelson as well.

The double L-shaped Michelson retains the operational advantages for staging of commissioning and continued astronomical observations during maintenance periods, as well as the option of extensibility of the arms.