Feasibility study of beam-expanding telescopes in the interferometer arms for the Einstein Telescope

LIGO-P2000417

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December 2020

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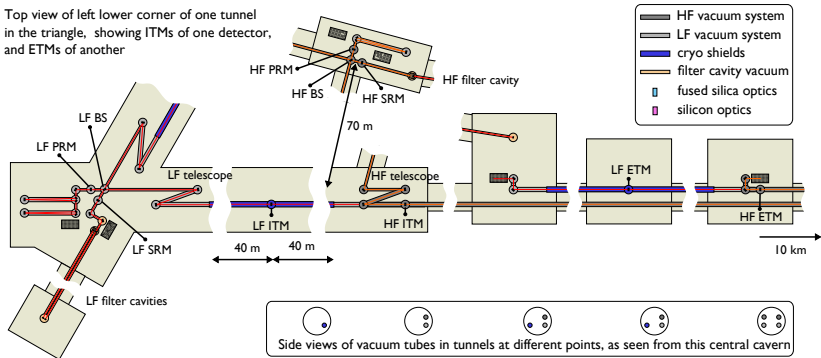
Motivation

WHY ARM TELESCOPES? — LARGE BEAMS

- - - - HF detectors, 1064 nm beam
——— LF detectors 1550 nm beam
▯ fused silica optics
▯ silicon optics

10 km

10 km

- ► Longer arm cavities result in larger beams:
  - ► $w_{LF} = 9$ cm (45 cm mirror diameter)
  - ► $w_{HF} = 12$ cm (62 cm mirror diameter)
- ► Large central BS optic required if no telescope used[1]

[1] "Einstein Telescope design report update 2020", ET Steering Committee Editorial Team

WHY ARM TELESCOPES? — BEAM STEERING FLEXIBILITY

- ▶ Z-shaped telescopes provide flexibility in beam steering
- ▶ For example: potential to steer ET-HF beam around suspension system of ET-LF ITM.
- ▶ Decouple the angle of incidence of central BS from angle between long IFO arms[2].

[2] See LIGO-G1900927 — "Considerations on Michelson beam splitters for third generation gravitational wave observatories", R. DeSalvo
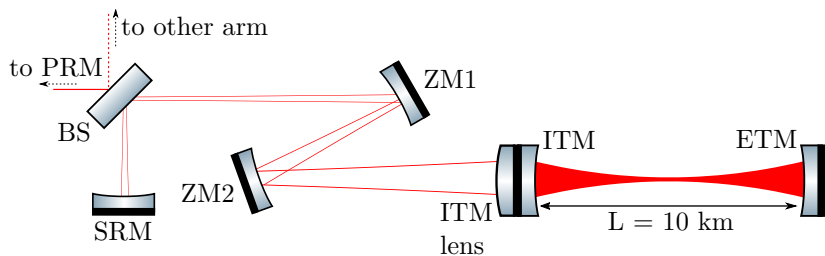
MOTIVATION
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CONSTRAINTS
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ET-LF TELESCOPES
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SOLUTIONS
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PARAMETER SENSITIVITY
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Summary
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EXAMPLE OPTICAL LAYOUT

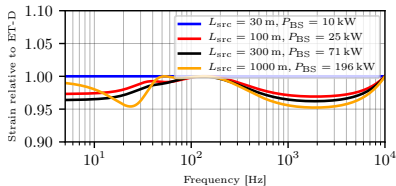Top view of left lower corner of one tunnel in the triangle, showing ITMs of one detector, and ETMs of another

HF PRM

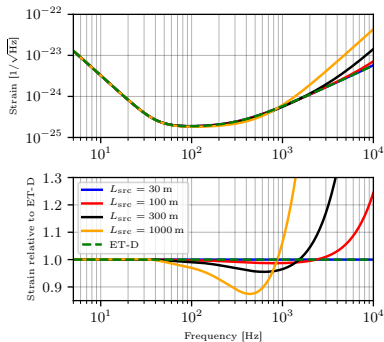HF BS   HF SRM

HF filter cavity

70 m

LF BS

LF PRM

LF telescope

HF telescope

LF ETM

LF SRM

LF ITM

HF ITM

HF ETM

40 m   40 m

10 km

LF filter cavities

Legend:
- HF vacuum system
- LF vacuum system
- cryo shields
- filter cavity vacuum
- fused silica optics
- silicon optics

Side views of vacuum tubes in tunnels at different points, as seen from this central cavern

Constraints

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SIMPLIFIED SCHEMATIC

SRC LENGTH

- ET-LF will make use of cryogenics. Cryoshields of $\sim 40\,\mathrm{m}$ length will extend from the test masses.
- Conversely, a short SRC length (100 m or less) is preferred for ET-HF to improve quantum-noise limited higher-frequency sensitivity[3].

[3] See LIGO-P2000066 — "Implications of the Quantum Noise Target for the Einstein Telescope Infrastructure Design", P. Jones *et. al*

SPOT SIZE ON BEAM SPLITTER

▶ Assuming a beam splitter radius of 15 cm and 60 degree intersection angle of two incident beams, sub ppm clipping losses are achieved with $w \lesssim 10\,\text{mm}$.

▶ ET-HF will operate with $\sim$ kW levels of power on the central BS, inducing thermal lensing in the substrate (as is the case for GEO600[4]).

▶ Thermal noise contribution from BS is still much smaller than that from arm cavity mirrors when taking into account the arm cavity finesse (~ 900); assuming beam size of several mm on BS.

[4] "Matrix heater in the gravitational wave observatory GEO 600", H. Wittel *et. al.*

Considered ET-LF telescope configurations

FLAT Z MIRRORS

The required distance from ITM to BS is $\sim 1\,\mathrm{km}$ to achieve $w_0 = 6\,\mathrm{mm}$ at the beam splitter.
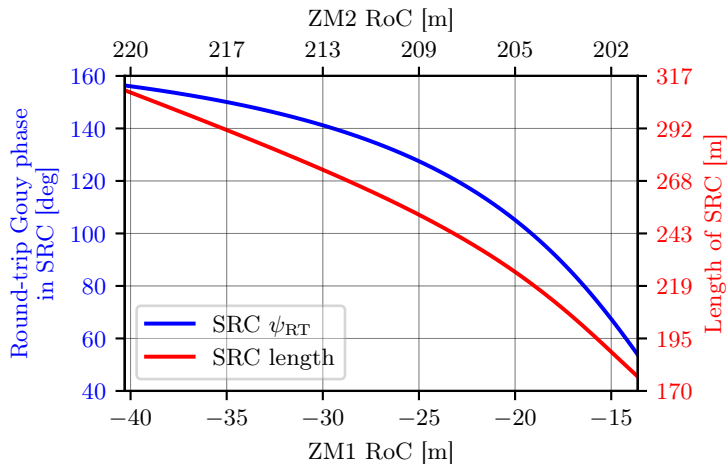
CURVED Z MIRRORS (NO ITM LENS)

- ▶ Significant number of degrees of freedom now:
    - ▶ RoCs of ZM1 and ZM2,
    - ▶ telescope length (i.e. distance between ZM1 and ZM2),
    - ▶ and other free spaces in the SRC.
- ▶ We can ignore accumulated Gouy phase contribution from ITM to ZM2 as this distance is much smaller than the Rayleigh range, z_R, of the beam from the arm cavity ($z_R \sim 1.7\,\text{km}$) and Gouy phase is,

$$\psi = \arctan\left(\frac{z}{z_R}\right). \tag{1}$$

CURVED Z MIRRORS (NO ITM LENS)

We found that a minimal telescope length of $\sim 100\,\mathrm{m}$ is required to maintain stable SRC of length less than $\sim 300\,\mathrm{m}$, whilst retaining a 6 mm beam waist.
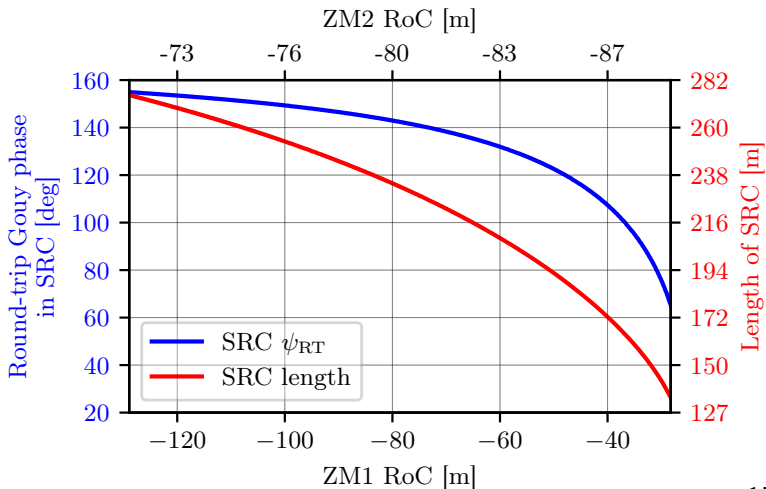
CURVED Z MIRRORS (WITH ITM LENS)

▶ Previous case gives solutions yielding relatively long SRC. Introducing a lens at the ITM to pre-focus the beam can help to reduce this length.

▶ We find that short focal lengths ($f \lesssim 100$ m) give solutions satisfying our requirements. For the figures that follow, an ITM lens focal length of 75 m was chosen.

CURVED Z MIRRORS (WITH ITM LENS)

Adding a lens allows for a shorter SRC, with the option of a less demanding ZM1 RoC.
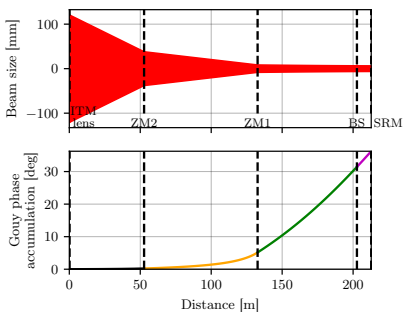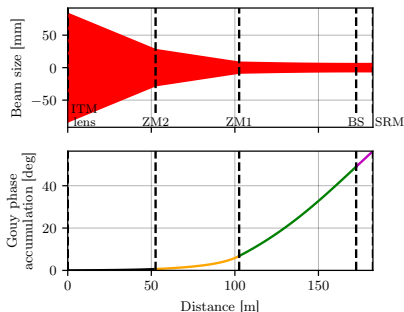
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Telescope design solutions

PROPAGATED BEAM PROFILES

Propagations of the SRC beams from ITM to SRM for the
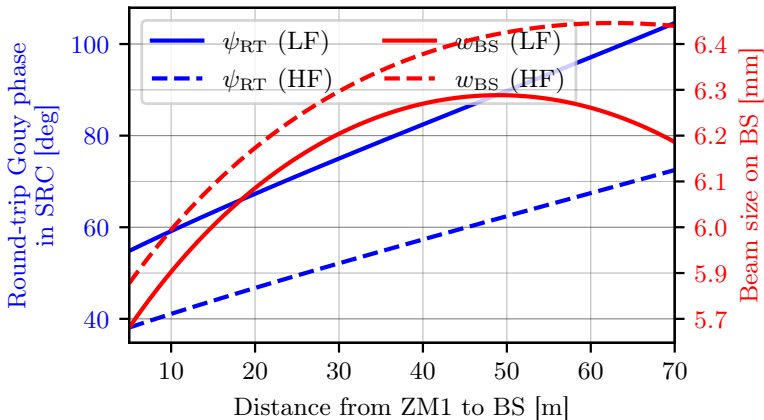telescope solutions obtained.

(ET-LF)   (ET-HF)

Note that the beam is roughly collimated from ZM1 to SRM.
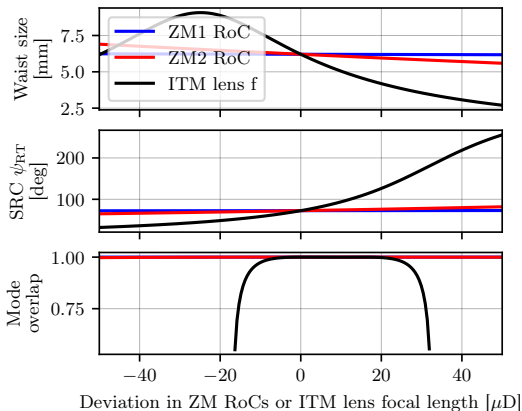
FURTHER SRC LENGTH REDUCTION

Due to this collimation, we can reduce the distance between ZM1 and BS significantly whilst maintaining a stable SRC; with changes of only a few hundred microns to the beam size on BS.

Sensitivity to parameter deviations
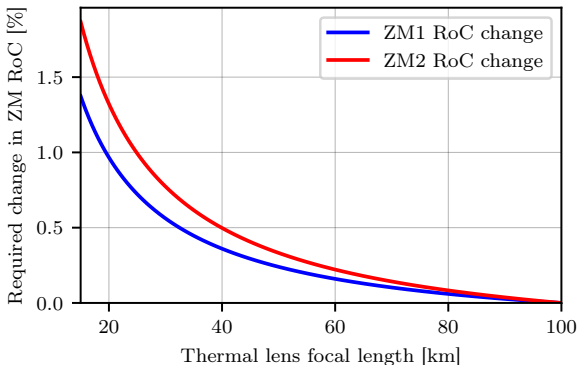
OPTIC CURVATURE DEVIATIONS

The mode overlap here refers to the mode matching between the SRC and an arm cavity.

It is clear that the ITM lens focal length is the most critical parameter here.
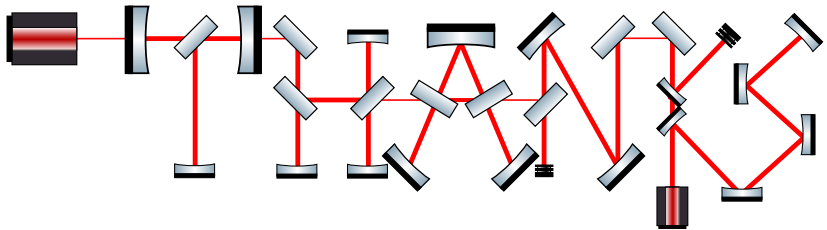
CASE STUDY — THERMAL LENSING CORRECTIONS

Thermal lensing will alter effective ITM lens focal length, requiring adaptive optics to reduce resulting mode mismatches.

This is a task which could, potentially, be performed by the arm telescopes. The figure here gives the required, simultaneous, changes to ZM RoCs to recover $> 99.9\%$ mode matching.

SUMMARY

- ▶ Larger arm cavity beams require very large central beam splitter, or beam-expanders in the interferometer arms.
- ▶ The unique layout of ET provides further incentive for steering optics in the arms.
- ▶ Limiting the SRC length to a few hundred metres requires a Z-shaped telescope with curved mirrors.
- ▶ Further optimisations (including SRC length reductions) can be achieved via:
  - ▶ introducing a lens at the ITM,
  - ▶ reducing the distance between the telescope and the SRM.
- ▶ Changes of $\sim 0.5\,\mathrm{mD}$ in both ZM RoCs result in full mode-matching recovery (from SRC to arm cavity) in the presence of a thermal lens with $f_{\mathrm{th}} = 15\,\mathrm{km}$.

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Additional Slides

DATA FOR TELESCOPE SOLUTIONS

The table below lists the data, for both ET-LF and ET-HF, used
as the baseline solutions for the geometries of the telescopes
and signal recycling cavities. These values result in $> 99.9\%$
mode-matching from the SRC to the arm cavities, in both cases.

Optic		*SRM*	*BS*	*ZM1*	*ZM2*		
RoC [m]	LF	-9410	inf	-50	-82.5		
	HF	-630			-63.2		
Beam radius [mm]	LF	6.1	6.2	8.9	30		
	HF	6.3	6.4	8.3	38		
Space		*SRM-BS*	*BS-ZM1*	*ZM1-ZM2*	*ZM2-ITM*		
Length [m]	LF	10	70	50	52.5		
	HF			80			
Gouy phase [deg]	LF	7.5	39	5.3	0.6	Total accumulated	52
	HF	4.8	26	4.9	0.2	Gouy phase [deg]	36