Design of Mode Matching Telescope in Einstein-Podolsky-Rosen(EPR) Experiment for Gravitational Wave Detection

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Abstract

The EPR Experiment aims to demonstrate alternative Frequency-Dependent Squeezing (FDS) for reducing broadband quantum noise in gravitational wave detectors. We designed two reflective mode-matching telescopes (MMT) for an Einstein-Podolsky-Rosen (EPR) squeezing experiment. It can provide high mode matching for EPR entangled squeezed light. To ensure precise alignment and reproducibility of the MMT, we placed optomechanics on a base plate with a reference plane. Beam profiling results and pre-simulated alignment process calculate the misalignment compensation length.

EPR Squeezing Experiment

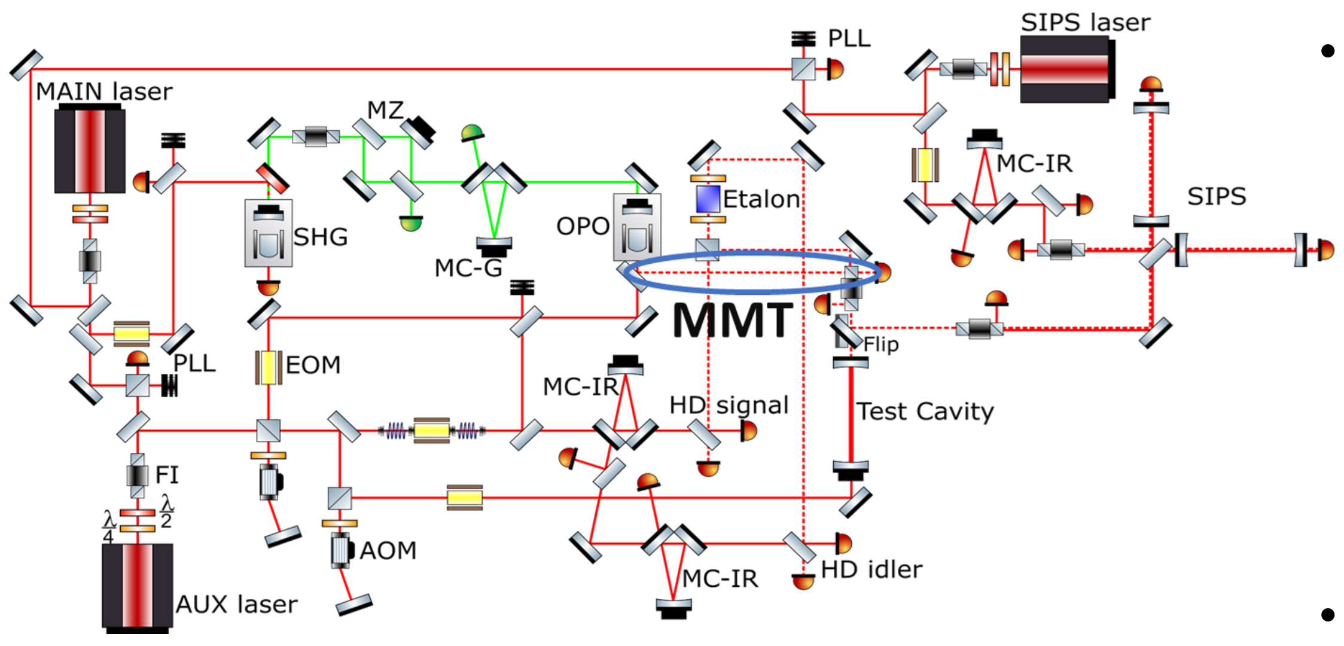

Fig 1. EPR setup diagram

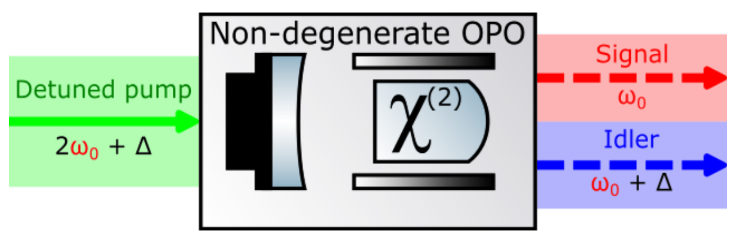

Fig 2. Non-degenerate OPO diagram

- The EPR entangled squeezed light generation technique is an alternative Frequency-dependent squeezing (FDS) method compared to the filter cavity (FC) in gravitational wave detectors [1-3]. **(For details, See Francesco De Marco's poster)**
- The non-degenerate OPO produces EPR-entangled signal and idler squeezed beams when injecting a detuned green pump beam from the Second Harmonic Generator (SHG).
- Changes in the idler beam's squeezing ellipse led to a corresponding rotation in the signal beam's ellipse due to EPR entanglement.
- The challenge is to match the mode of the EPR squeezed beams from the OPO to the Test cavity (TC). To address this, a mode-matching telescope (MMT) has been designed. The target is to ensure the coupling losses lower then 1.5% [4].

MMT Optical design

Requirements

- •Reflective telescope is required to avoid lens scattering and absorption [4-6]
- •Space constraints (300mm X 700mm)
- •Large input beam divergence (1.7×10^2 rad)
- •Mode mismatching loss of less than 2%.
- •Fixed input and output beam parameter

Position	$w0$ [um]	z [mm]
OPO	19.79	40.02
TC	406.8	0

Table 1. MMT input and output beam parameter(before OPO modification)

Design

- Modifying the OPO enables a spherical-type MMT of two curved and two flat mirrors [5-6].
- Mode mismatching in the spherical version, as calculated by the OSCAR[8] code, was low at 1×10^{-5}.
- During design, linear astigmatism-free (LAF) confocal off-axis optics [7] MMT is proposed for placement flexibility and zero polarization loss.

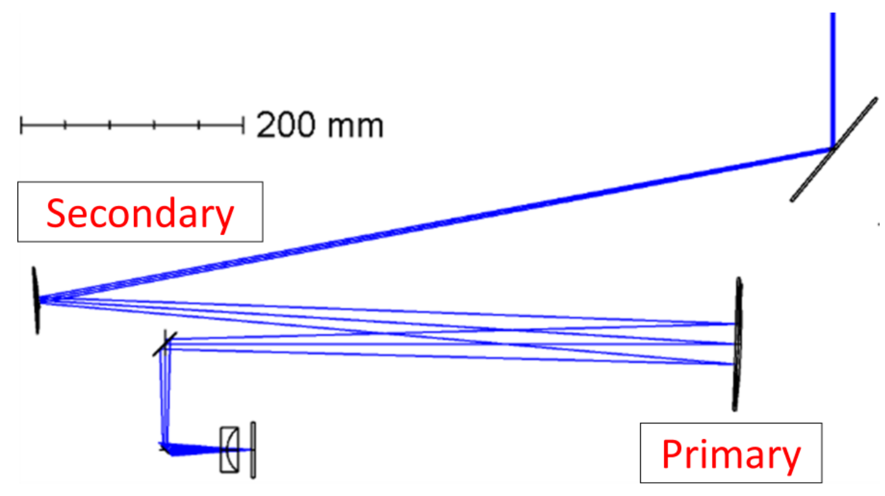

Fig 3. Spherical MMT optical design

Magnification	X 12
Power loss by mode mismatching	$1x10^{-5}$

Table 2. Spherical mirror MMT design

MMT Opto-mechanical design

Semi-kinematic matching design

- Following the MATS optomechanics design [9]. It has key features including a guide bump design and alignment based on a beam profiler.
- Each mirror mount is furnished with an 'adapter' component featuring a guide surface, which effectively limits the degree of freedom of the mount, ensuring precision and stability (Fig 4).

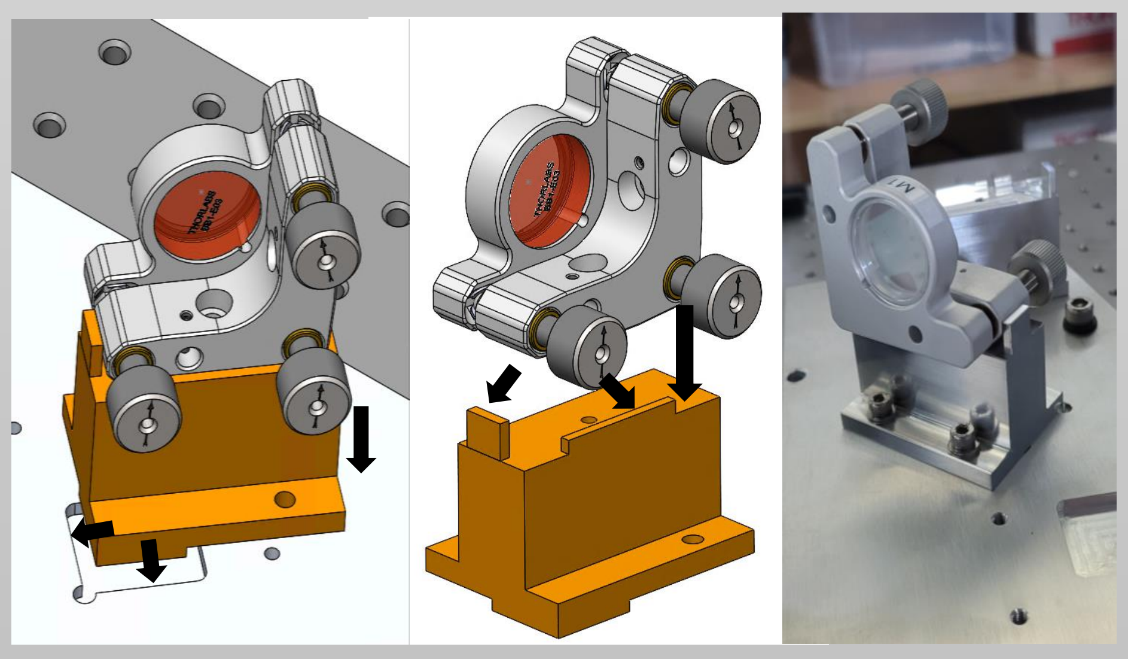

Fig 4. Contact between the guide surface and the reference planes

Baseplate system

- All optics are positioned on a common base plate (Fig.5), facilitating precise pre-positioning with an accuracy of approximately 100 µm.

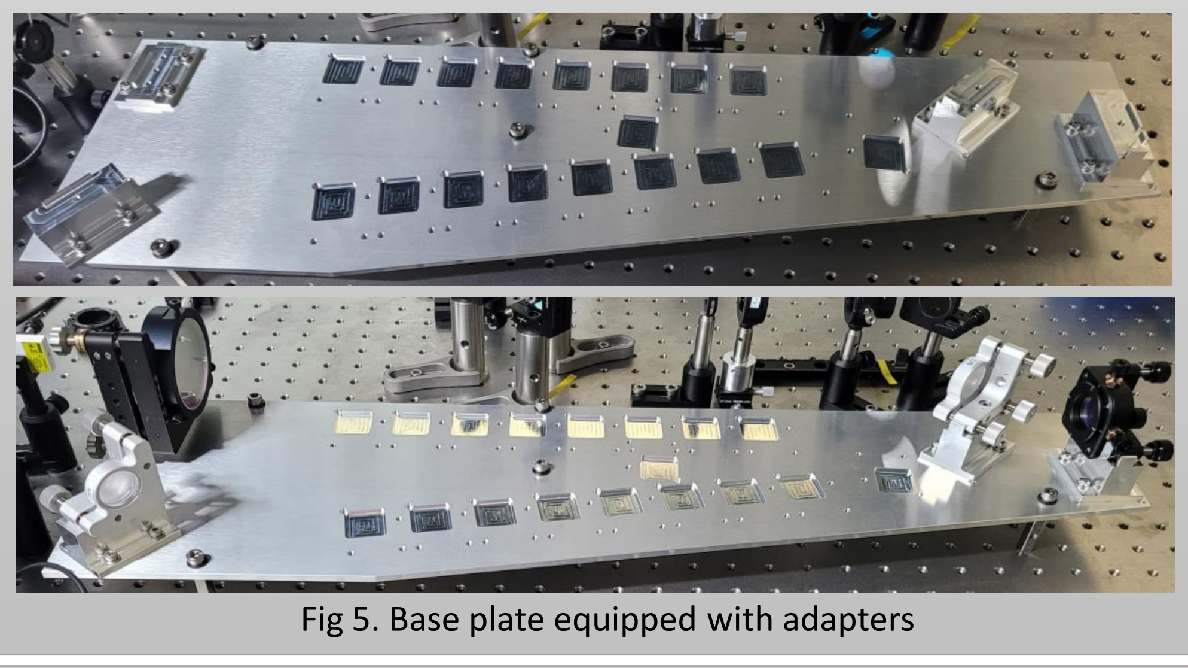

Fig 5. Base plate equipped with adapters

MMT alignment procedure

Prototype

- The prototype alignment procedures using a Zeiss Contura G2 Coordinate Measurement Machine (CMM) (Fig 6-7) [10].
- Alignment errors were reduced by reprocessing the 'adapter' component.

Fig 6. CMM measuring mirror module

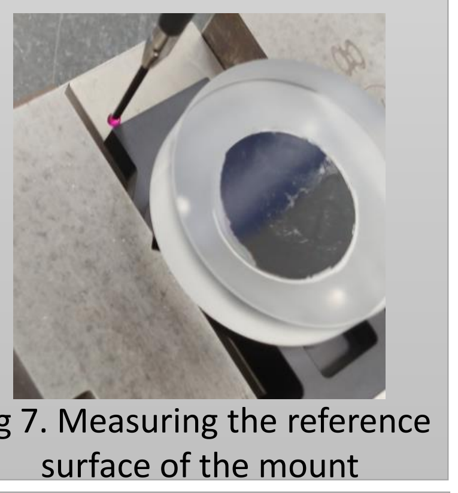

Fig 7. Measuring the reference surface of the mount

Waist fitting and compensation method

- The beam profile measurement involves the installation of a beam profiling camera using an 'adapter' system and rail (fig.9) for the waist fitting.
- This setup utilizes two irises and a camera for boresight alignment (Fig.10).
- Alignment errors were compensated by translating the kinetic mount.

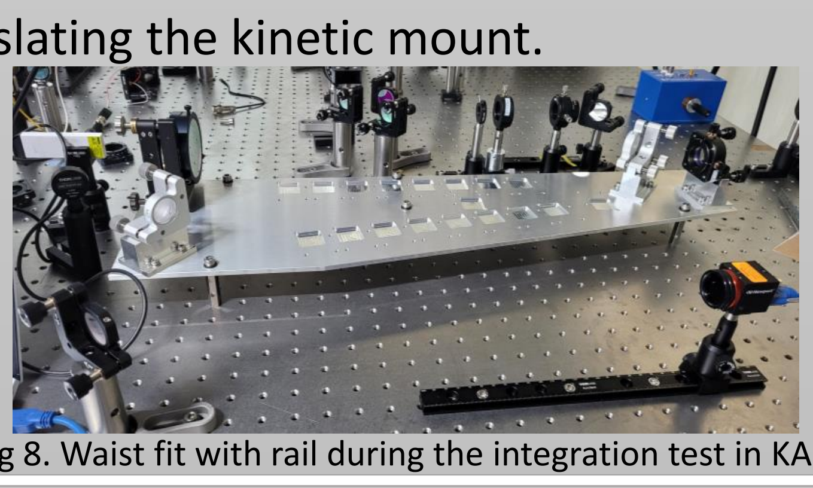

Fig 8. Waist fit with rail during the integration test in KASI

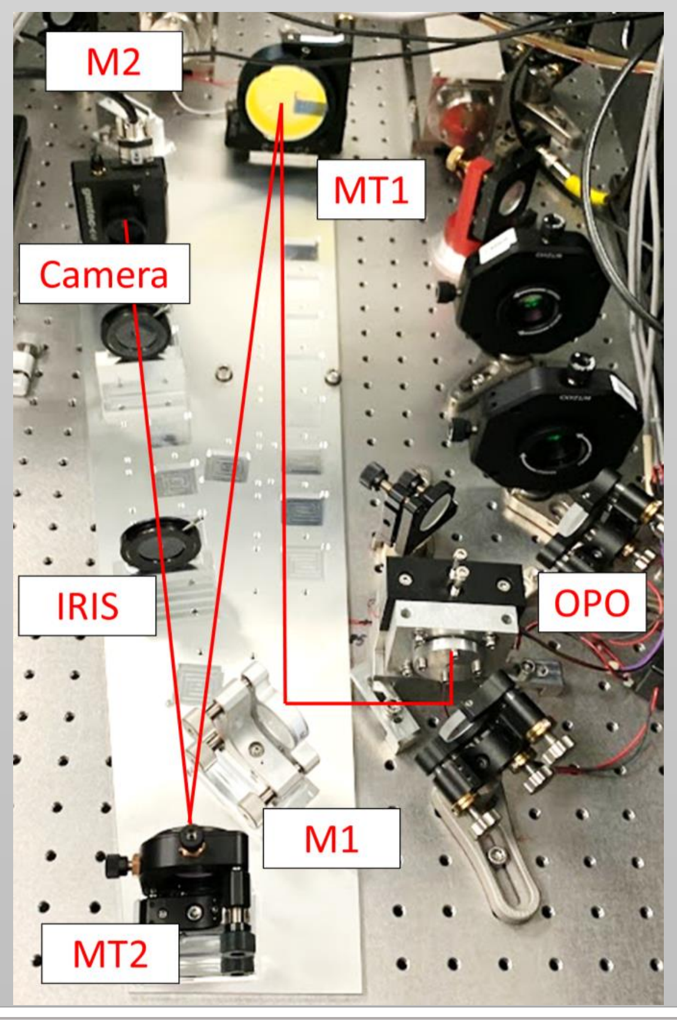

Fig 9. Iris pair and the camera

MMT Alignment results(preliminary)

Waist fitting results

- Beam parameter is measured at the exit port of the MMT (Fig.9 and Fig. 10 and Table 3)
- This result is archived with the initial boresight alignment result (without fine-tuning procedure).
- We expect at least 94% mode matching if we inject this beam into the test cavity. After the compensation, we expect better mode matching.

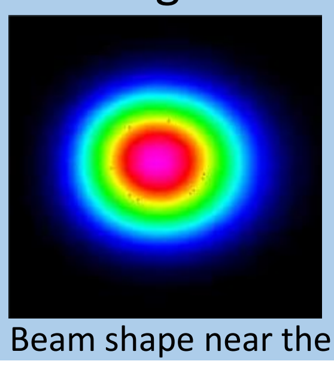

Fig 11. Beam shape near the waist

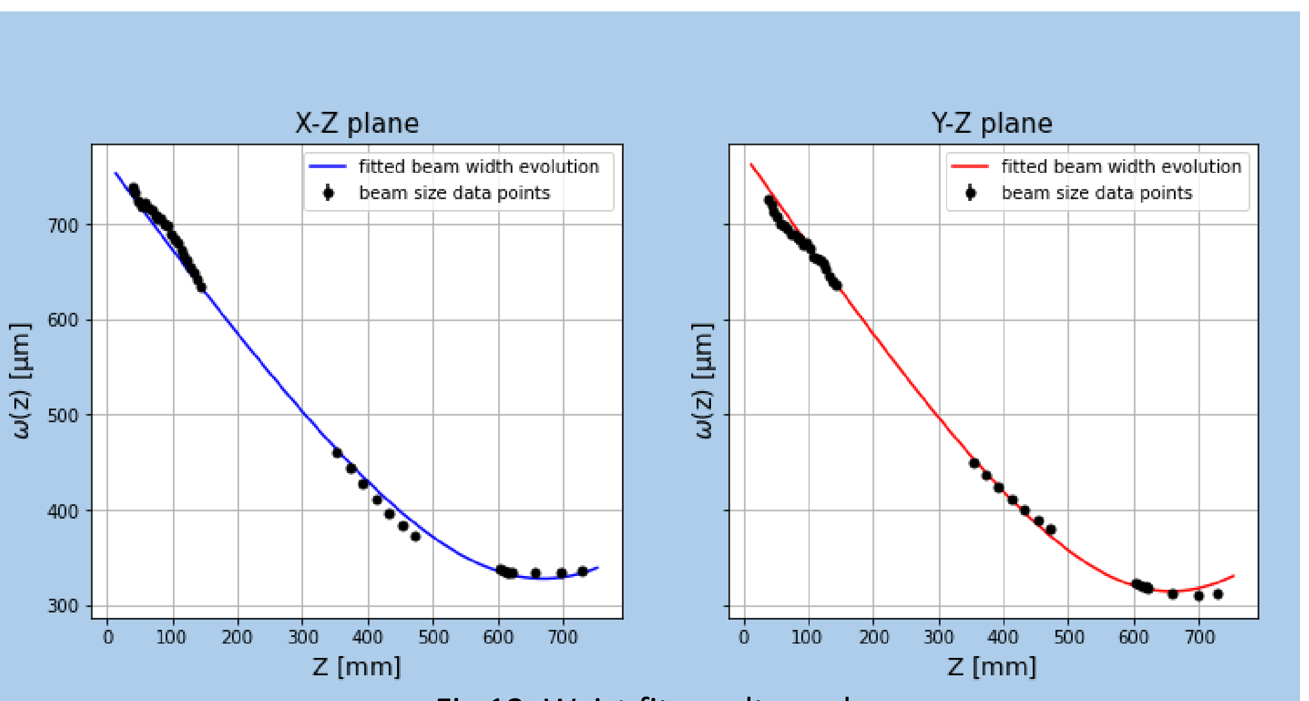

Fig 12. Waist fit result graph

Parameter	Designed x	Designed y	Fitted x	Fitted y
ω_0[µm]	336	342	328±1	315±1
Z_0[mm] from M2	818	823	670±3	658±2

Table 3. Waist fit result table

Compensation strategy

- We can calculate the compensation length of the kinetic mount with waist-fitting data
- By changing the despace (Z-axis distance) between the curved mirrors (MT1, MT2), the Waist size and the waist size error can be compensated.

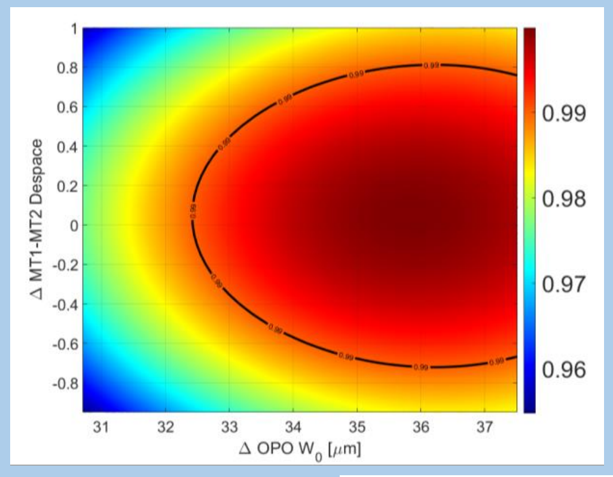

Fig 13. Input beam(OPO) waist size compensation simulation with despace between curved mirrors (black curve: 99% mode matching contour)

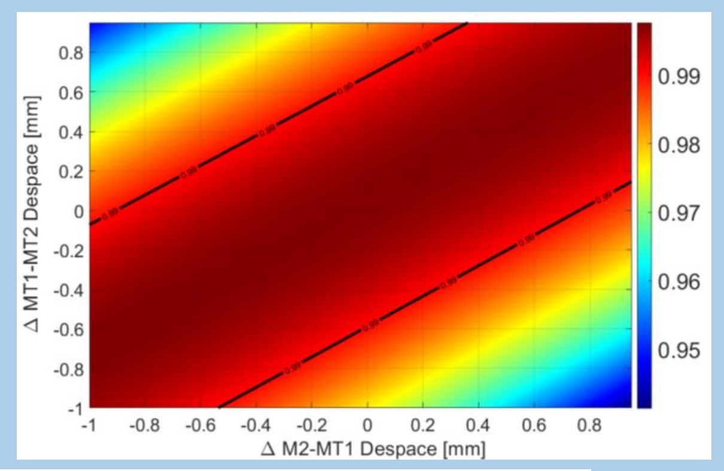

Fig 14. Simulated relationship against the despace between the mirror and the mode matching (black line: 99% mode matching contour)

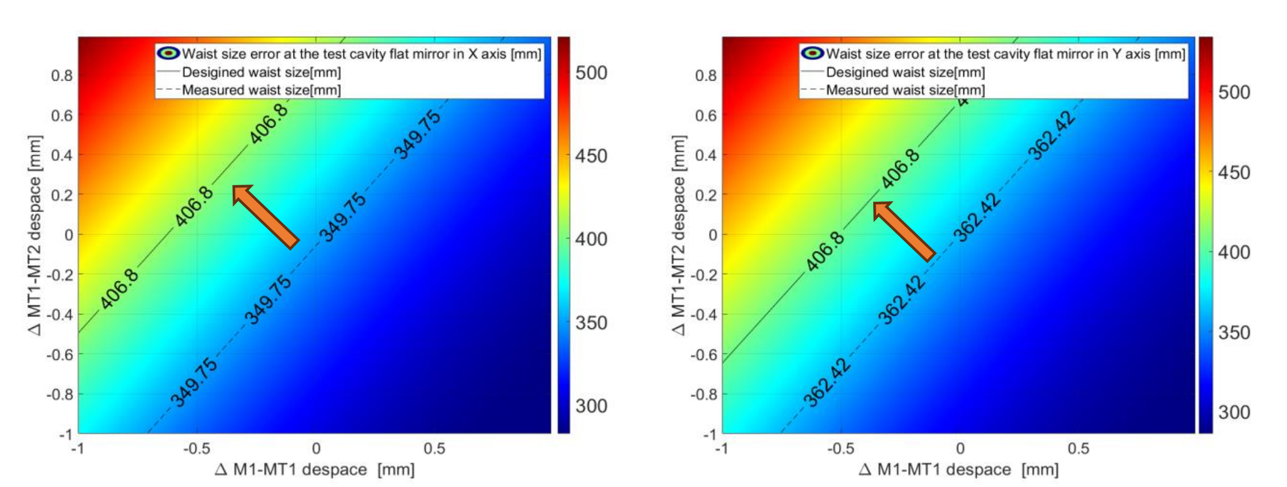

Fig 15. Output beam (test cavity) X-axis and Y-axis waist size compensation calculation sheet with the measured data

Conclusion

- We developed the reflective MMT and its alignment method for the EPR Squeezing Experiment ongoing at EGO/VIRGO, Italy.
- Having many degrees of freedom increases the number of feedback processes in alignment.
- To avoid this, semi-kinematic mounting between the base plate and adapter is made with the reference surface.
- We will develop an active MMT with a deformable mirror for more precise mode-matching.

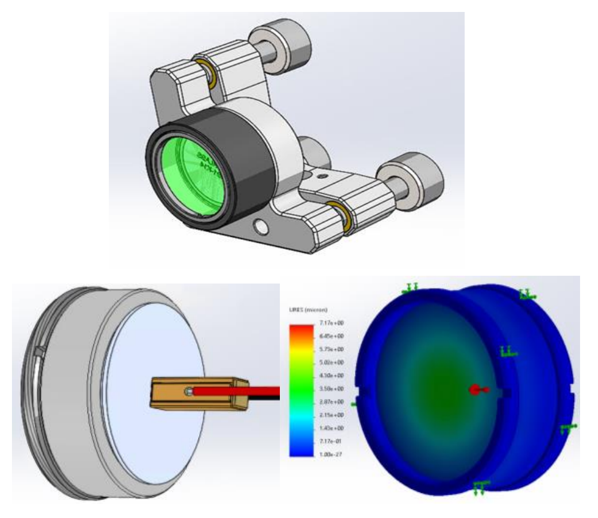

Fig 14. Images of active MMT deformable mirror under development

References

[1] Y. Ma, H. Miao, B. H. Pang, et al., "Proposal for gravitational-wave detection beyond the standard quantum limit through EPR entanglement," Nat. Phys. 13, 776-780 (2017).
[2] J. Südbeck, S. Steinlechner, M. Korobko, et al., "Demonstration of interferometer enhancement through Einstein–Podolsky–Rosen entanglement," Nat. Photonics 14, 240-244 (2020).
[3] M. J. Yap, P. Altin, T. G. McRae, et al., "Generation and control of frequency-dependent squeezing via Einstein–Podolsky–Rosen entanglement," Nat. Photonics 14, 223-226 (2020).
[4] A. Perreca, A. F. Brooks, J. W. Richardson, et al., "Analysis and visualization of the output mode-matching requirements for squeezing in Advanced LIGO and future gravitational wave detectors," Phys. Rev. D 101, 102005 (2020).
[5] P. Hello and C. N. Man, "Design of a low-loss off-axis beam expander," Appl. Opt. 35, 2534-2536 (1996).
[6] M. Tacca, F. Sorrentino, C. Buy, et al., "Tuning of a high magnification compact parabolic telescope for centimeter-scale laser beams," Appl. Opt. 55, 1275-1283 (2016).
[7] S. Chang, J. H. Lee, S. P. Kim, et al., "Linear astigmatism of confocal off-axis reflective imaging systems and its elimination," Appl. Opt. 45, 484-488 (2006).
[8] J. Degallaix, "OSCAR: A MATLAB based package to simulate realistic optical cavities," SoftwareX 12, 100587 (2020).
[9] W. Park, A. Hammar, S. Pak, et al., "Flight model characterization of the wide-field off-axis telescope for the MATS satellite," Appl. Opt. 59, 5335-5342 (2020).
[10] J. Han, H. Ahn, J. K. Ham, et al., "CMM-based Freeform Off-axis Three Mirror System Alignment Modeling," in Optica Design and Fabrication Congress 2023 (IODC, OFT), Technical Digest Series (Optica Publishing Group, 2023), paper OW2B.2.