LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
CALIFORNIA INSTITUTE OF TECHNOLOGY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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The Advanced LIGO ETM transmission monitor

S J Waldman

California Institute of Technology
LIGO Project, MS 18-34
Pasadena, CA 91125
Phone (626) 395-2129
Fax (626) 304-9834
E-mail: info@ligo.caltech.edu

Massachusetts Institute of Technology
LIGO Project, Room NW22-295
Cambridge, MA 02139
Phone (617) 253-4824
Fax (617) 253-7014
E-mail: info@ligo.mit.edu

LIGO Hanford Observatory
Route 10, Mile Marker 2
Richland, WA 99352
Phone (509) 372-8106
Fax (509) 372-8137
E-mail: info@ligo.caltech.edu

LIGO Livingston Observatory
19100 LIGO Lane
Livingston, LA 70754
Phone (225) 686-3100
Fax (225) 686-7189
E-mail: info@ligo.caltech.edu

`http://www.ligo.caltech.edu/`

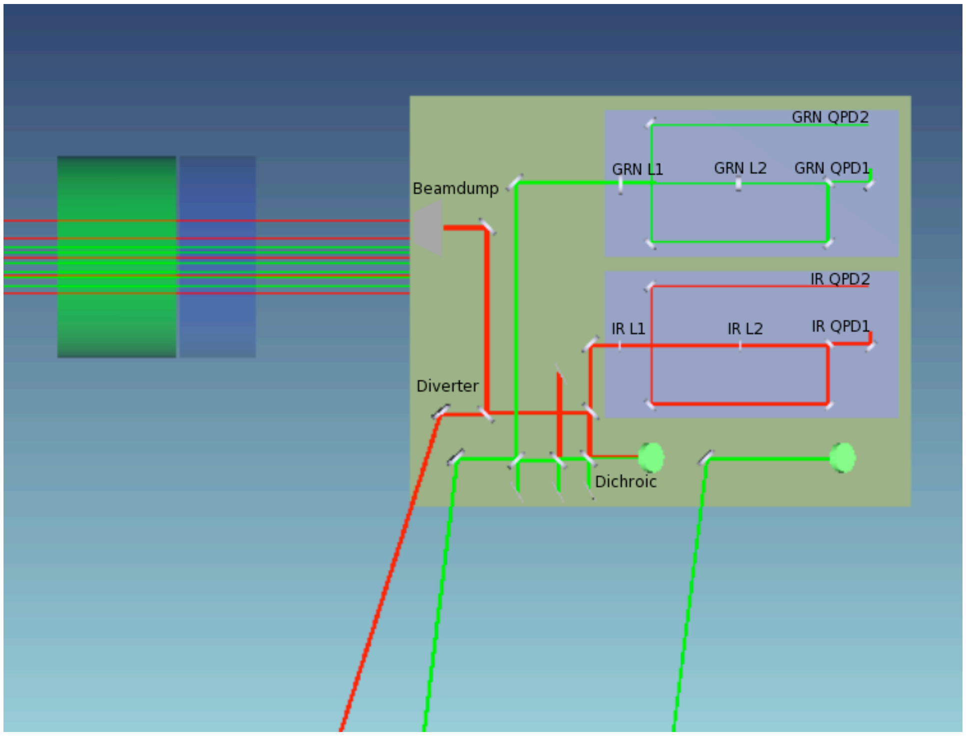

Figure 1: Annotated transmon top view.

1 Overall layout

The transmon table is designed as a single plate with the folded beam reducing telescope mounted below the table and the ISC optics mounted above. The layout is shown in Figs. 1-3. The red beam traces the infrared beam from the arm cavity, through the ETM and reaction mass, and into the telescope. The primary role of the transmon table is to sense the position and angle of this IR beam using two quadrant photodiodes. In Fig. 1, the diodes are mounted on the purple QPD "sled" with a Gouy telescope that sets the angle and position sensitivity of the two QPDs and labeled "IR QPD1" and "IR QPD2". The QPDs are arranged symmetrically around a focus to set the Gouy phase difference at 90°and minimize sensitivity to length errors. During lock acquisition, the transmon table delivers the beam through a viewport to an in-air table with high gain sensors. During science mode, the IR beam is diverted to a beam dump using an actuated beam diverter (shown in Fig. 1 as a beam splitter) .

The green beams shown in the layouts are the auxiliary 532 nm beam used for the Lock Acquisition Interferometer (LAI) and the Hartmann sensors. The beam is injected from a viewport (the middle viewport off the bottom of Fig. 1) and is used to lock the arm cavity using a PDH lock. The beam must be aligned to the transmon table (and hence the arm cavity) using a second QPD sled, shown by the upper purple rectangle in Fig. 1. The beam is then overlapped with the IR beam on a dichroic beam splitter (labeled "dichroic") and sent through the beam reducing telescope. The beam reflected off the ETM is delivered both to a PDH RF photodiode and to a Hartmann sensor on the in-air table through the entrance

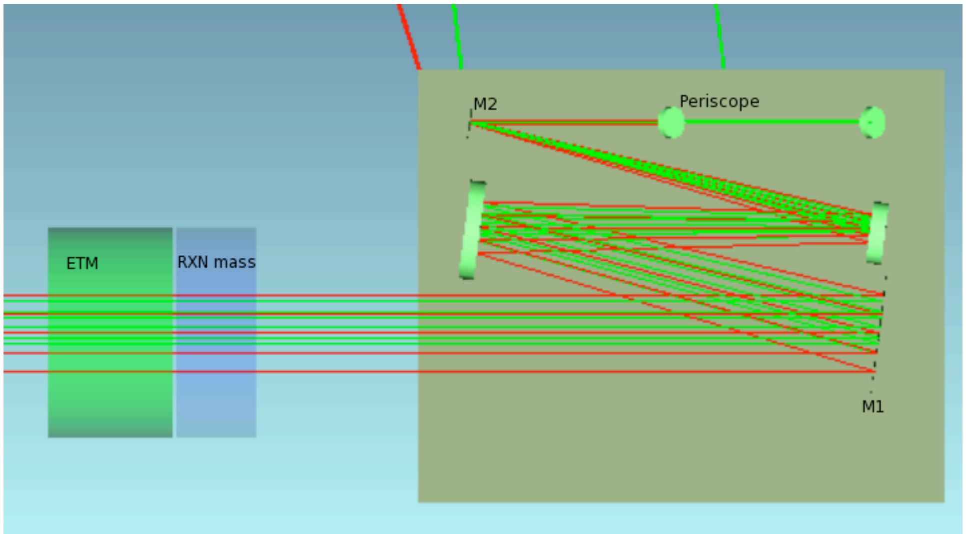

Figure 2: Annotated transmon bottom view.

Optic	Radius of curvature	$\delta\phi_G$ [mm]	$\delta\omega$ [mm]
Telescope parabolic M1	4.00 m	-0.4, +0.3 mm	-0.1, +0.2mm
Telescope parabolic M2	-0.133 m	-0.6, +0.3 mm	-0.1, +0.2mm
Gouy tel. plano-convex L1	154.5 mm, 4 mm thick	-2.5,+2.0mm	-0.8, +1.5mm
Gouy tel. plano-concave L2	-64.4 mm 2 mm thick	-2.3,+3.2 mm	-2.0, +0.1 mm

Table 1: Transmon optics and their radii of curvature. The ROC sensitivities in $\delta\phi_G$ and $\delta\omega$ are the ROC changes required to reduce the Gouy phase 20°and the waist by 10%, respectively.

viewport. The green beam incident on the ETM is also reflected off the ETM AR surface which is oriented with a vertical wedge of 0.07°. This Hartmann reference beam emerges from the beam reducing telescope at a large vertical angle and is picked up by a second periscope and delivered to the top of the table. This reference beam is then delivered to a viewport here shown as the rightmost viewport in Fig. 1 but which could also be the central viewport.

The transmon table size is 85 cm long and 70 cm wide. The thickness is not here specified. The beam reducing telescope has 30x de-magnification, and consists of two off-axis parabolic mirrors. The mirror is folded to fit into the total length of the transmon table and has a total length of approximately 2 m. Each of the QPD sleds is 50 cm long by 25 cm wide. The transmon optics have been modeled using the Zemax physical optics propagation, using Mathematica models, and using Matlab ABCD matrices. For consistency and clarity, the physical lengths stated in the following are based on the Matlab model in *TransmonABCD.m*. The optics used in the model are listed in Table 1. Note that the matlab model treats the off-axis parabolic mirrors as standard on-axis mirrors and the lengths are quoted accordingly in Table 2. The waist size through the telescopes is shown in Fig. 4. The two panels show identical data with different y-axis scales.

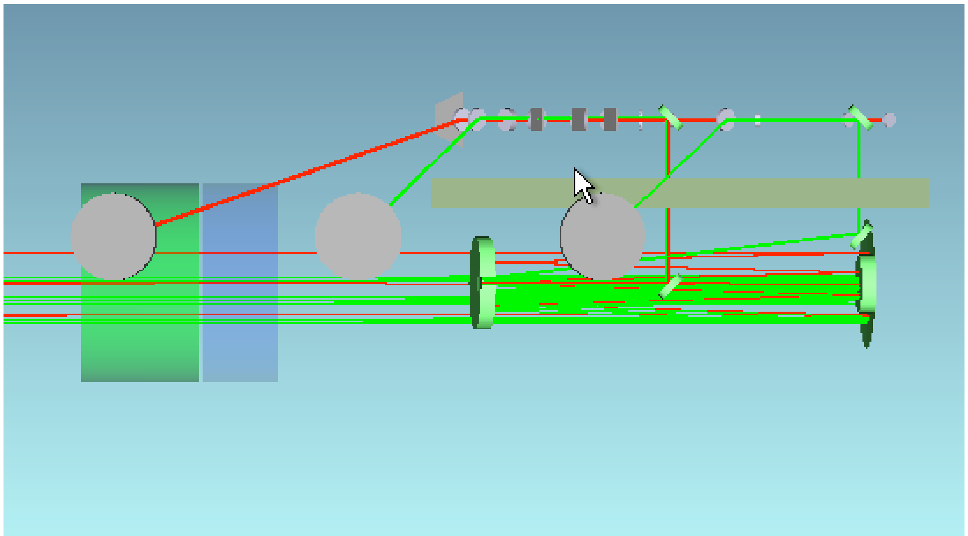

Figure 3: Transmon side view.

Description	Length [mm]	$\delta\phi_G$ [mm]	$\delta\omega$ [mm]
Telescope M1 to M2	1936.1	-0.17,+0.75	-0.11,+0.060
Telescope M2 to Lens L1 front	937	∞	∞
Lens L1 back to Lens L2 front	220	-4.0,+6.2	-3.1,+1.5
Lens L2 back to QPD1	315	$\pm$340	-80,+50
QPD1 to QPD2	740	-220,+300	-90,+50

Table 2: Transmon lengths for the IR beam path. The length sensitivities in $\delta\phi_G$ and $\delta\omega$ are the length changes required to reduce the Gouy phase 20°and the waist by 10%, respectively.

2 Layout tolerances

The transmon table signals are sensitive to both the Gouy phase difference at the two QPDs and the spot size at the QPDs, which varies the optical gain. The sensitivities quoted in Table 2 are the shift in length required for a Gouy phase change of $\phi_G \pm 20°$and a waist change of $\omega \pm 10\%$. The sensitivities quoted in Table 1 are the minimum radii change required to violate the condition. Note that in all cases, the most sensitive lengths and optics are related to the beam reducing telescope. The telescope must maintain its length to $\pm 60\mu m$ and the mirror radii of curvature must remain constant to a similar factor. Note that the mirror cannot possibly be spec'd for such tight tolerances and we must design an assembly procedure capable of measuring and positioning the optics in the required locations. The telescope has been designed with its waist at the output mirror and the QPD sleds are placed well within the Rayleigh range of the beam. Thus, the QPD sleds can be assembled independently of the telescope.

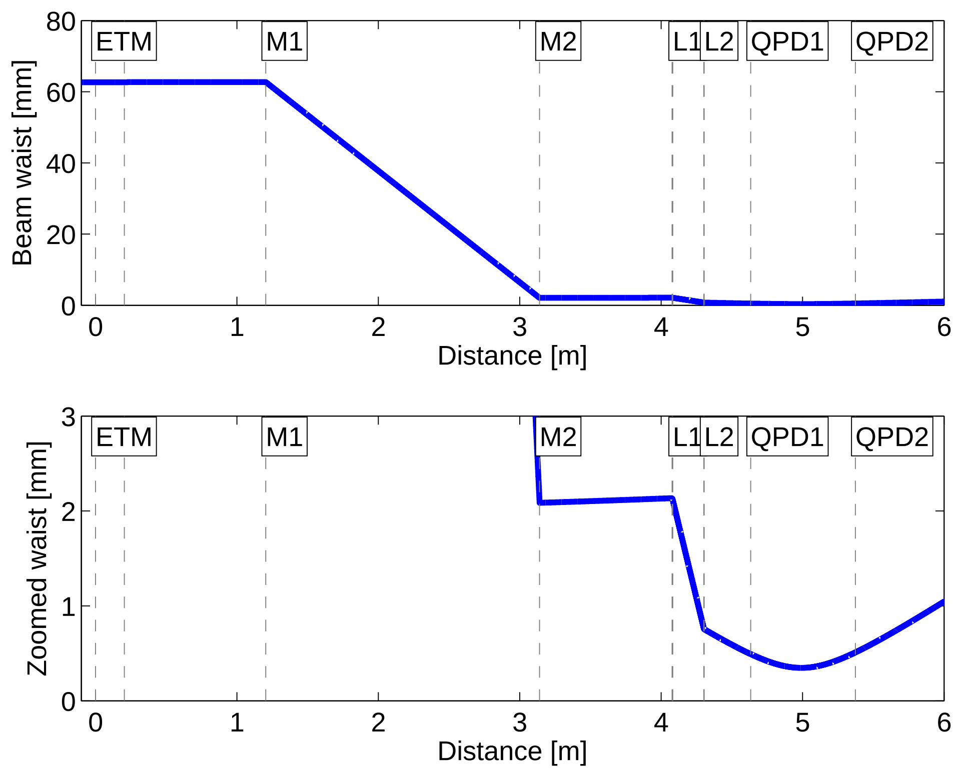

Figure 4: Waist size through the telescope.

3 Required apertures

The model *TransmonABCD.m* calculates the ray tracing matrices from the table motion to each of the optics listed in Table 1. The beam displacement at each optic as a function of table displacement and angle is shown in Table 3. Because of the 30x de-magnification, the beam displacement is dominated by the angle of the transmon table.

Optic	Transmon disp. [mm/mm]	Transmon tilt [mm/mrad]
M1	1	1
M2	0.032	1.9
L1	0.014	30
L2	4.3e-4	17.3
QPD1	0.017	36.9
QPD2	0.060	83.3
Beam dump	0.006	60.3
Viewport	0.021	83.0

Table 3: Beam displacement as a function of transmon table displacement and tilt.

The QPD sensitivity to the transmon table is irrelevant as there will be pico-motors before the QPDs to control beam centering. However the sensitivity to tilt at the lens L1 is problematic and indicates that the beam will translate by more than 1 inch for a 1 mrad table motion.

Before lens L1 the beam is transported by several optics at 45°angle of incidence. Assuming a 25.4 mm diameter optic has 18 mm of clear aperture and a 50.8 mm optic has 36 mm, then the transmon beam will begin clipping when the table is tilted by 100 μrad and 400 μrad, respectively. Finally, note that the beam dump and viewport sensitivities to table motion will have to be accounted for in the system design.

4 QPD sensitivity

The signals measured on each QPD for the cavity displacement and angle are:

$$\begin{pmatrix} QPD_1 \\ QPD_2 \end{pmatrix} = \begin{pmatrix} -9.5 \times 10^{-3} & 16.9 \\ -42 \times 10^{-3} & -4.5 \end{pmatrix} \begin{pmatrix} x \\ \theta \end{pmatrix}_{cavity} . \tag{1}$$

The motion at each QPD, QPD_1 and QPD_2 is a function of the cavity motion, x_{cavity} and θ_{cavity} are at the cavity waist. The units here are meters and radians. If we invert the matrix in Eq. 1 and determine the orthogonality of the x, θ reconstruction, we find the signals are orthogonal, in good agreement with the Gouy phase calculated by the ABCD matrices. Similarly, the QPD signals as a function of the table motion are:

$$\begin{pmatrix} QPD_1 \\ QPD_2 \end{pmatrix} = \begin{pmatrix} -18 \times 10^{-3} & 36.9 \\ -60 \times 10^{-3} & 83.3 \end{pmatrix} \begin{pmatrix} x \\ \theta \end{pmatrix}_{table} . \tag{2}$$

Note that QPD1 is roughly twice as sensitive to table motion, both position and angle, as it is to cavity motion. QPD2 is slightly more sensitive to table position and much more sensitive to table angle than it is to the cavity motion. These signals are not orthogonal; in fact, the two QPDs respond almost identically to motion of the table.

5 Optics and components lists

The optics are listed in Table 4. Note the pick off for the IR QPDs, *IRTRANS B1*, was chosen assuming 800 kW of arm power, 5 ppm ETM transmission, and 100 mW per QPD. The corresponding green pick off, *GNTRANS B1*, was arbitrarily chosen to be 5%. Where the reflectivity is not explicitly specified, it should be OK to leave it uncontrolled. The beam diverter is in the optics list and Zemax model as *IRTRANS M3* and is chosen to be 25.4 mm in diameter. If it should be changed to 50.8 mm diameter, both the optic for the diverter, the diverter itself, and the steering mirror before the beam dump should be change.

Label	Description	Quantity	ROC	Reflectivity IR / GRN	Diameter
ETMXPO M1	Off-axis parabolic mirror	1	4.00 m	HR / HR	200 mm
ETMXPO FM1, FM2	Telescope folding mirror	2		HR / HR	
ETMXPO M2	Off-axis parabolic mirror	1	-0.133 m	HR / HR	50.8 mm
ETMXPO P1-P4	Periscope mirrors	4		HR / HR	50.8 mm
IRTRANS D1, D2	Dichroic mirrors	2		HR / AR	50.8 mm
IRTRANS B1	Beamsplitter	1		95% /	50.8 mm
IRTRANS M1-M4	beam steering	4		HR /	50.8 mm
IRQPD L1	Gouy telescope lens	1	154.4 mm	AR /	50.8 mm
IRQPD L2	Gouy telescope lens	1	-64.4 mm	AR /	25.4 mm
IRQPD M1-M4	beam steering	4		HR /	25.4 mm
IRQPD B1	beam splitter	1		50% /	25.4 mm
GNTRANS B1	Beamsplitter	1		/ 5%	25.4 mm
GNTRANS M1-M3	beam steering	3		HR /	25.4 mm
GNQPD L1	Gouy telescope lens	1	154.4 mm	/ AR	25.4 mm
GNQPD L2	Gouy telescope lens	1	-64.4 mm	/ AR	25.4 mm
GNQPD M1-M4	beam steering	4		/ HR	25.4 mm
GNQPD B1	beam splitter	1		/ 50%	25.4 mm

Table 4: Optics required for Transmon table.

Description	**Quantity**
Telescope mounting	1
45° kinematic periscope mirror mounts	4
50.8 mm kinematic mirror mounts	7
50.8 mm lens mount	1
25.4 mm lens mount	3
25.4 mm kinematic mirror mount	9
25.4 mm actuated mirror mount	4
25.4 mm beam diverter	1
3 mm QPD and mount	4
High power beam dump	1

Table 5: Components required for transmon table.