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/

1 Introduction

Here we describe the Transmon optical layout. The Transmon assembly is an in vacuum optics table suspended immediately behind the End Test Mass (ETM) of each interferometer arm. The Transmon incorporates a telescope for reducing the large diameter arm cavity beam to a manageable size, beam steering optics, and in-vacuum QPDs. During science mode, all infrared beams transmitted through the ETM are dumped on the Transmon table. During lock acquisition the Transmon relays the interferometer beam to an in-air optics table. Finally, the Transmon table provides the input optics and alignment reference for the green beams of the Lock Acquisition Interferometer (LAI) and the Hartmann wavefront sensor.

In the following sections, we describe the overall layout of the Transmon table, calculate the beam reducing telescope parameters, calculate the sensitivity of the QPDs with an ideal telescope, evaluate the effects of astigmatism, determine the layout tolerances, and describe alignment procedures for each of the subsystems. We conclude with a parts list for the optical table.

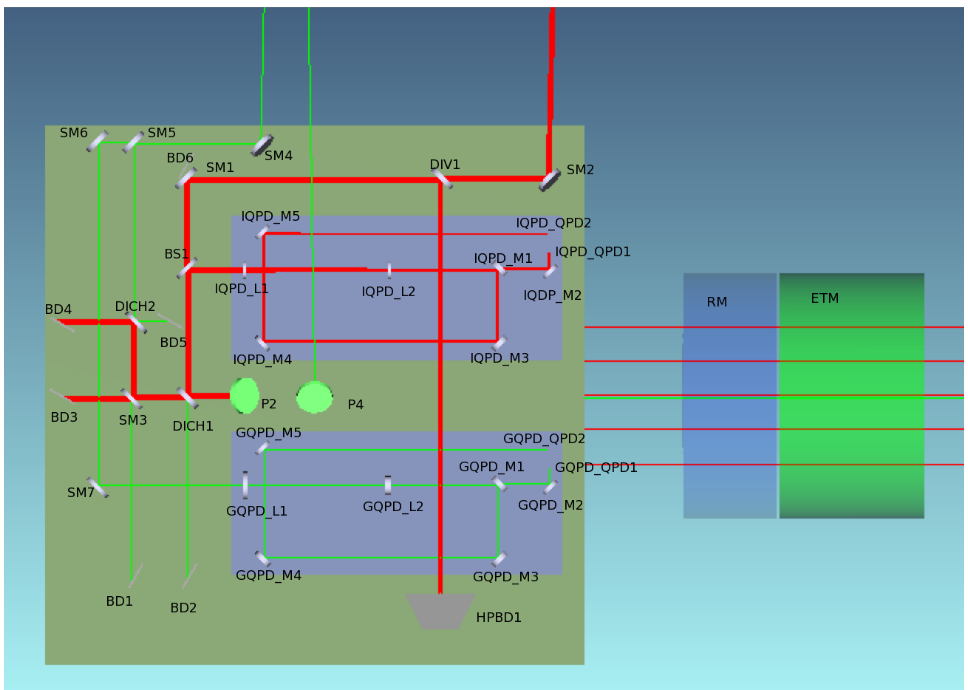

Figure 1: Annotated Transmon top view.

2 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 and 2. The red beam traces the infrared beam from the arm cavity, through the ETM and reaction mass (here labeled “RM”), and into the telescope. The primary role of the Transmon

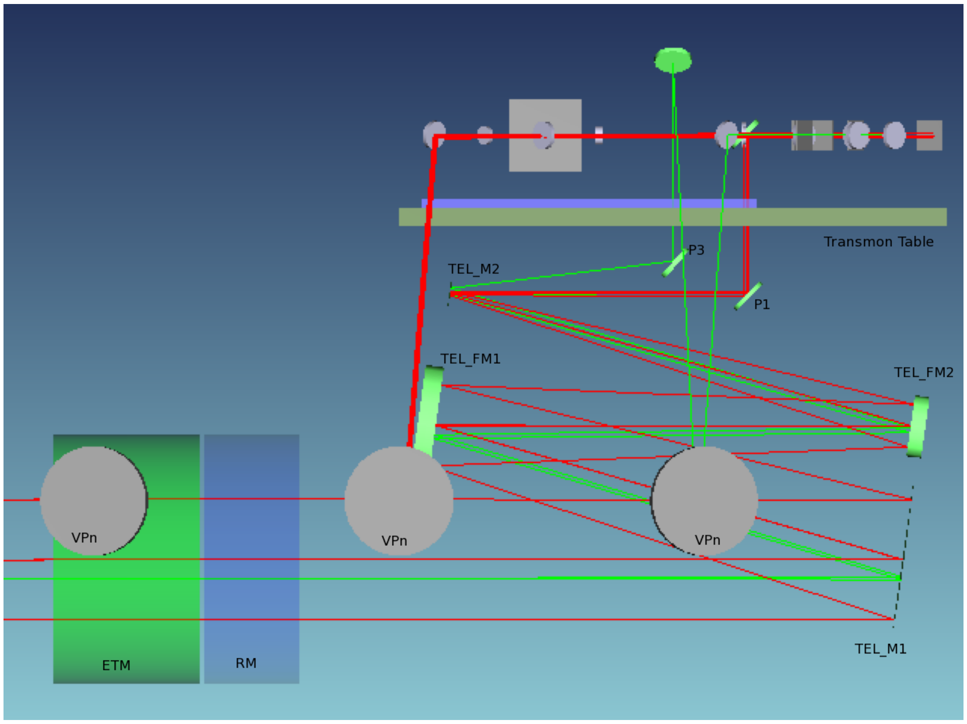

Figure 2: Transmon side view.

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 breadboard with a Gouy telescope that sets the angle and position sensitivity of the two QPDs and labeled "IQPD_QPD1" and "IQPD_QPD2". The QPDs are arranged symmetrically around a focus to set the Gouy phase difference at 90° and minimize sensitivity to length errors. Together, the two QPDs are sensitive to the arm cavity waist position and angle. During lock acquisition, the Transmon table delivers the beam through a viewport to an in-air table with high gain sensors. The viewport beam selection and beams are described in the viewport interface document Ref. [**?**]. During science mode, the IR beam is diverted to a beam dump using an actuated beam diverter (labeled "DIV1"in Fig. 1 and drawn 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 is aligned to the Transmon table (and hence the arm cavity) using a second QPD breadboard, shown by the lower purple rectangle in Fig. 1. The beam is then overlapped with the IR beam on a dichroic beam splitter (labeled "DICH1") and sent through the beam reducing telescope. The beam retro-reflected off the ETM is returned to the in-air table through the entrance viewport.

The green beam incident on the ETM is partially reflected off the ETM AR surface which is oriented with a vertical wedge of 0.07°. Note that the vertical wedge is specified to have a wedge less than 0.1°. This "Hartmann reference beam" emerges from the beam reducing telescope at a large vertical angle as shown in Fig. 2 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

Optic	Radius of curvature [mm]
Telescope parabolic T1	4000
Telescope achromat T2, f 125	n/a
Gouy tel. plano-convex L1, f 343.6	154.5, (4 mm thick)
Gouy tel. plano-concave L2, f -114	-51.5, (2 mm thick)

Table 1: Transmon optics and their radii of curvature.

here shown as the rightmost viewport in Fig. 2 but which could also be the central viewport.

The Transmon table size is XX cm long and XX cm wide. The thickness is not here specified, but should be sufficient to preserve the table alignment during assembly, testing and installation. The beam reducing telescope has a 16x magnification and consists of an off-axis parabolic primary and an achromatic lens secondary. The telescope is folded to fit the Transmon table and has a total length of approximately 2 m. Each of the QPD breadboards 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*, listed in §A. The optics used in the model are listed in Table 1. The matlab model treats the off-axis parabolic mirrors as standard on-axis mirrors and the lengths are quoted accordingly in Table **??**.

3 Telescope parameters

The nominal Advanced LIGO arm cavity consists of an ITM with a radius of curvature (ROC) of 1970 m and an ETM with a radius of curvature of 2190 m.[?]. The resulting arm cavity waist radius is $\omega_0 = 1.2$ cm located 2100 m in front of the ETM. On its way to the BRT, the beam passes through the ETM which acts like a diverging lens with -4.4 km focal length. As a result, the beam at the telescope is described by a waist $\omega_{in} = 8.0$ mm located 1460 m in front of the telescope. At the telescope, the beam waist is 6.2 cm. The complex beam parameter at the telescope input is

$$q_{in} = 1460 + 189.5i. \tag{1}$$

The beam at the output of the BRT should have a Rayleigh range of ≥ 10 m to minimize the effects of beam divergence between the Transmon table and the in-air table. We choose a BRT magnification of 16x, such that the BRT output beam has a waist of $\simeq 4$ mm and a Rayleigh range of 42 m. The input beam at the BRT has a divergence angle of 42 μrad. After an infinity adjusted telescope, the divergence angle would be 1 mrad and the beam would grow significantly during transport. Consequently, the telescope must be focusing so that the beam has a waist at the BRT output. In effect, the telescope must have a focal length of 1460 m. The ray transfer matrix for the BRT is:

$$\begin{aligned} M_{BRT} &= \begin{pmatrix} 1 & 0 \\ -2/R_2 & 1 \end{pmatrix} \begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -2/R_1 & 1 \end{pmatrix} \\ &= \begin{pmatrix} 1 - 2L/R_1 & L \\ -2/R_1(1 - 2L/R_2) - 2/R_2 & 1 - 2L/R_2 \end{pmatrix}, \end{aligned} \tag{2}$$

where R_1 and R_2 are the ROC of the primary and secondary, respectively. L is the distance between the telescope mirrors. To set a waist at the telescope output, the cavity length must satisfy

$$\left[-\frac{2}{R_1}(1 - 2\frac{L}{R_2}) - \frac{2}{R_2}\right] \Re(q_{in}) + 1 - 2\frac{L}{R_2} = 0, \tag{3}$$

$$L = \frac{R_1}{2} \frac{1}{1 - \frac{R_1}{2}\frac{1}{\Re(q_{in})}} + \frac{R_2}{2}, \qquad \text{and}$$

$$L \approx \frac{R_1 + R_2}{2} + \frac{R_1^2}{4} \frac{1}{\Re(q_{in})}. \tag{4}$$

The approximation is valid in the limit that $\Re(q_{in}) \gg R_1$. For the telescope optics listed in Table 1, the telescope length is $L = 2127.6 \pm 0.3\ mm$. Note that the telescope length changes linearly with changes in the mirrors' ROC. With the telescope set to its nominal focus, the output beam has a waist of 2.1 mm located at the telescope output. Figure 3 shows the output waist position and size as a function of the telescope length. The waist position is normalized to the Rayleigh range. To create an output waist within one Rayleigh range of the telescope output, the telescope length must be set to $2127.6 \pm 0.3\ mm$, over which range the output waist varies from 2.7 to 3.9 mm. This represents a telescope detuning from infinite conjugate of almost 3 mm.

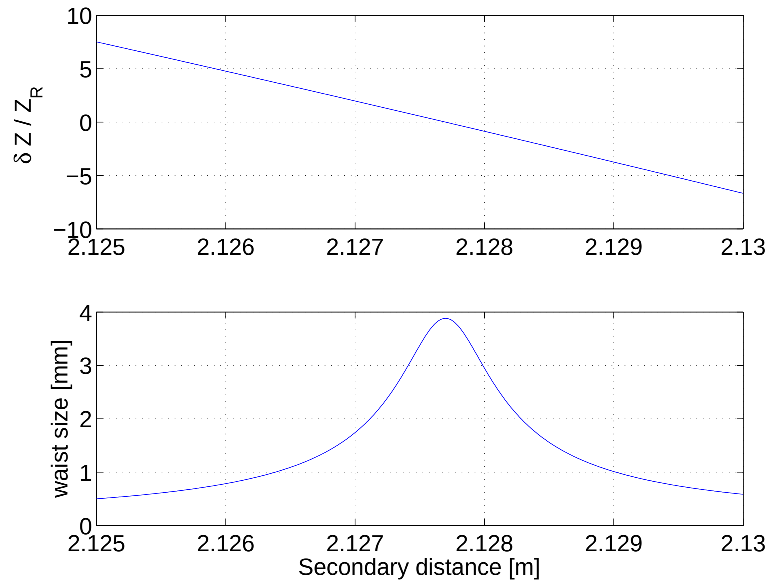

Figure 3: Variation of the output waist position and radius as a function of the telescope length. The calculation assumes perfect optics.

4 Gouy telescope

The Transmon table has two QPDs to sense the displacement and angle of the arm cavity. Naively the detectors would be set in the near field and the far field. Unfortunately, this configuration maximizes the sensitivity to the BRT length and ROC errors. More generally, the two QPDs should be 90°of Gouy phase apart. This condition is most readily met by setting the QPDs at $\pm z_R$ from a beam focus. The focused waist sets the QPD optical gain and should be matched to the 3 mm QPD diameter. Obviously, the waist must be located more than a Rayleigh range after the telescope. We choose an output waist size of $\omega_{gouy} \approx 250\ \mu m$ which has a Rayleigh range of 0.18 m, well matched to the size of the Transmon optical table.

To design the Gouy telescope, we assume a telescope formed with standard lenses from CVI having focal lengths of 343 mm and -114 mm. Such a telescope produces an appropriate output beam at an appropriate distance from the output. We find the telescope spacing using the Matlab package ALM. Finally, we adjust the telescope focus and the QPD positions to maximize the range of BRT lengths that provide a good error signal for the horizontal and vertical DOFs.

The optimum Gouy telescope configuration has a lens separation of 243 mm, a lens to QPD1 spacing of 680 mm, and a spacing between the QPDs of 338 mm. Fig. 4 shows the position of the optics and the waist size along the beam path. Also shown is the spacing from the telescope output to the first QPD, assuming that QPD is set one Rayleigh length from the waist. The spot size at the QPDs will be 350 μm.

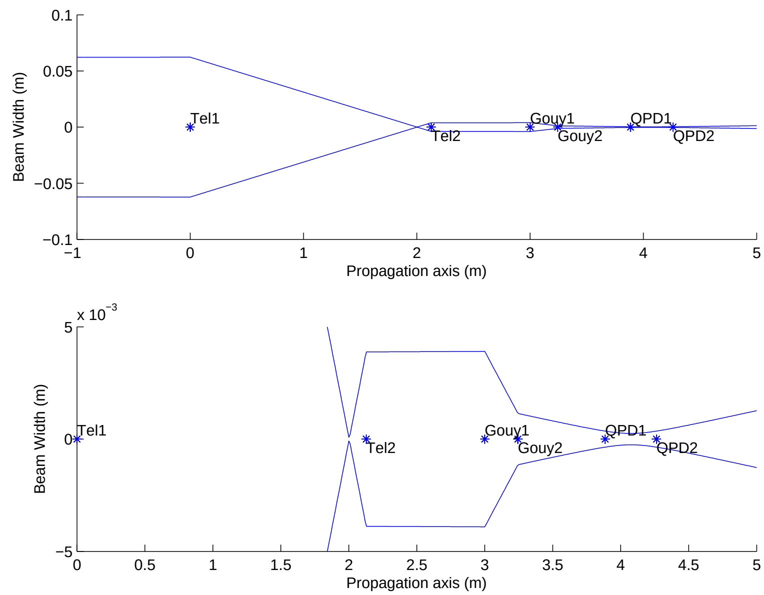

Figure 4: The beam waist as it propagates through the telescope and Gouy optics to the QPDs.

5 QPD sensitivity

Assuming an ideal beam reducing telescope (ie. one without astigmatism), the signals measured on each QPD for the cavity displacement and angle are:

$$\begin{pmatrix} QPD_1 \\ QPD_2 \end{pmatrix} = \begin{pmatrix} 12\times10^{-3} & -11.9 \\ 29\times10^{-3} & 5.0 \end{pmatrix} \begin{pmatrix} x \\ \theta \end{pmatrix}_{cavity}. \tag{5}$$

The motion at each QPD, QPD_1 and QPD_2, is a function of the arm cavity degrees of freedom, x_{cavity} and θ_{cavity}, defined at the cavity waist. The units here are meters and radians. This matrix has been calculated using the Matlab script TransmonTable.m included in §**??**.

Similarly, the QPD signals as a function of the table motion are:

$$\begin{pmatrix} QPD_1 \\ QPD_2 \end{pmatrix} = \begin{pmatrix} 20\times10^{-3} & -38.2 \\ 41\times10^{-3} & -57.3 \end{pmatrix} \begin{pmatrix} x \\ \theta \end{pmatrix}_{table}. \tag{6}$$

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, up to a relative gain.

6 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.

This section still needs poking.

7 Required apertures

The model *TransmonTable.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 2.

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]
needs work		

Table 2: 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.

8 Telescope focusing procedure

in progress

9 Gouy optics alignment procedure

in progress

10 Optics and components lists

The optics are listed in Table 3. 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.

needs to be checked

A TransmonABCD.m

```
% Plot up the Transmon table
close all
clear classes

disp(' Transmon table.')
disp(' ')


%% Parameters
% Our seedwaist comes from the arm cavity
armlength = 3995;
R_itm = 1970;
R_etm = 2190;
lambda = 1.064e-6;
zETM = 2;                    % this is the distance from the ETM to Telescope

lensmakers = @(n, R1, R2, d) ( (n-1)*(1/R1 -1/R2 + (n-1)*d/(n*R1*R2)) )^-1;

[z0,z1,z2] = cavHG(armlength, R_itm, R_etm); % The waist from by the arm


%% Telescope design
goo = beamPath;
goo.seedWaist(sqrt(z0*lambda/pi),-z2-zETM);

% Put down fixed components.  OAPs and mirror are treated as lenses
f_ETM = lensmakers(1.45, -R_etm, inf, 0.2);
goo.addComponent(component.lens(f_ETM, -zETM, 'ETM'));
goo.addComponent(component.lens(2.0,0,'Tel1'));
goo.addComponent(component.lens(0.125, 2.1276,'Tel2'));
goo.addComponent(component.lens(0.344, 3, 'Gouy1'));
goo.addComponent(component.lens(-0.114, 3.243    , 'Gouy2'));

% To put down the QPDs, we find the output waist location and go +/- Zr
zout = 3.5;
qout = goo.qPropagate(zout);
waist_z = zout - qout.waistZ;

goo.addComponent(component.lens(inf, waist_z-qout.rayleighRange, 'QPD1'));
goo.addComponent(component.lens(inf, waist_z+qout.rayleighRange, 'QPD2'));


%% Plot figure
figure(101)
zdomain = -2.1:.01:5;
clf;
subplot(2,1,1)
hold on;
orighandle=goo.plotBeamWidth(zdomain);
goo.plotComponents(zdomain)
goo.plotBeams(zdomain)
hold off;
axis([zdomain(1) zdomain(end) -7e-2 7e-2]);
ylabel('Beam Width (m)')
```

```
xlabel('Propagation axis (m)')

subplot(2,1,2)
hold on;
orighandle=goo.plotBeamWidth(zdomain);
goo.plotComponents(zdomain)
goo.plotBeams(zdomain)
hold off;
axis([zdomain(1) zdomain(end) -5e-3 5e-3]);

ylabel('Beam Width (m)')
xlabel('Propagation axis (m)')


%% print the component list to the command window
disp(' ')
disp(' Optimized Path Component List:')
display(goo.components)

%% And calculate the sensitivities
disp(' QPD sensitivity ');
ABCD_qpd1 = goo.getTransferMatrix(-z2-zETM, goo.component('QPD1').z);
ABCD_qpd2 = goo.getTransferMatrix(-z2-zETM, goo.component('QPD2').z);

QPD_from_Arm = [ABCD_qpd1(1,:); ABCD_qpd2(1,:)]


ABCD_qpd1 = goo.getTransferMatrix(-0.5, goo.component('QPD1').z);
ABCD_qpd2 = goo.getTransferMatrix(-0.5, goo.component('QPD2').z);

QPD_from_Table = [ABCD_qpd1(1,:); ABCD_qpd2(1,:)]
```

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	Achromat	1	0.125 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	-51.5 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 3: 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 4: Components required for Transmon table.