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

**Document Type T050076-00-D** April 28, 2005

# Preliminary Study for a 40m Suspension Point Like IFO (SPLIFO)

Virginio Sannibale

*Distribution of this draft:*

This is an internal working note
of the LIGO Project.

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 - MS 20B-145
Cambridge, MA 01239
Phone (617) 253-4824
Fax (617) 253-7014
E-mail: info@ligo.mit.edu

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

# Contents

# 1 Introduction

The construction of two suspension point interferometer could be a necessary step to guarantee an easier R&D of the LIGO 40m interferometer. In fact, reducing the rms motion between the IFO vertex and the corner stations can substantially reduce the time necessary to lock the interferometer especially during intermediates study characterized by a not robust control scheme.

The SPLIFO (suspension point-like interferometer) basic idea is to use the main IFO input mirrors optical tables as reference, and move the end mirrors tables to keep the relative distance constant. Such motion reduction is achieved by making a Fabry Perot cavity in each arm with mirrors rigidly attached to the optical tables, and acting on the base of the stacks.

Considering the actual IFO optical layout, the SPLIFO implementation is quite straightforward and reasonably simple. In fact, the use of the already available initial pointing beam (a pick-off of the main input beam) simplifies considerably the optical layout reducing the amount of changes and light reroutings.

The already installed stacis 2000 units can be used as actuators to control the SPLIFO cavities. Below stacks resonances such control scheme should be quite straightforward.

# 2 Optical Resonant Cavities Design

One of the major concerns about the realization of such subsystem is the reflected light of the two SPLIFO cavities, which goes back directly into the reflected port of the main IFO. The result is a contamination of the SP signals.

One solution is to place at the input of each SPLIFO cavity a Faraday optical isolator. This solutions can increase considerably the complexity of this project. For example, inside the vacuum envelope the beam must be reduced to match the Faraday isolator aperture and then expanded to mode match the resonant cavity.

The complexity of introducing in-vacuum Faraday isolator could be avoided if a different beam from the initial pointing beam is used. Anyway, injecting another auxiliary bea\m is probably as much complex as the in-vacuum isolator solution.

A more viable and simpler solution is the use of triangular cavities to separate the SPLIFO input beams from the reflected beam. The output can be even the curved mirror.

## 2.1 Geometry

Due to space constraints inside the vacuum chamber it will be easier if one can duplicate the 40m flat concave suspended cavity geometry for the suspension point IFO. This will

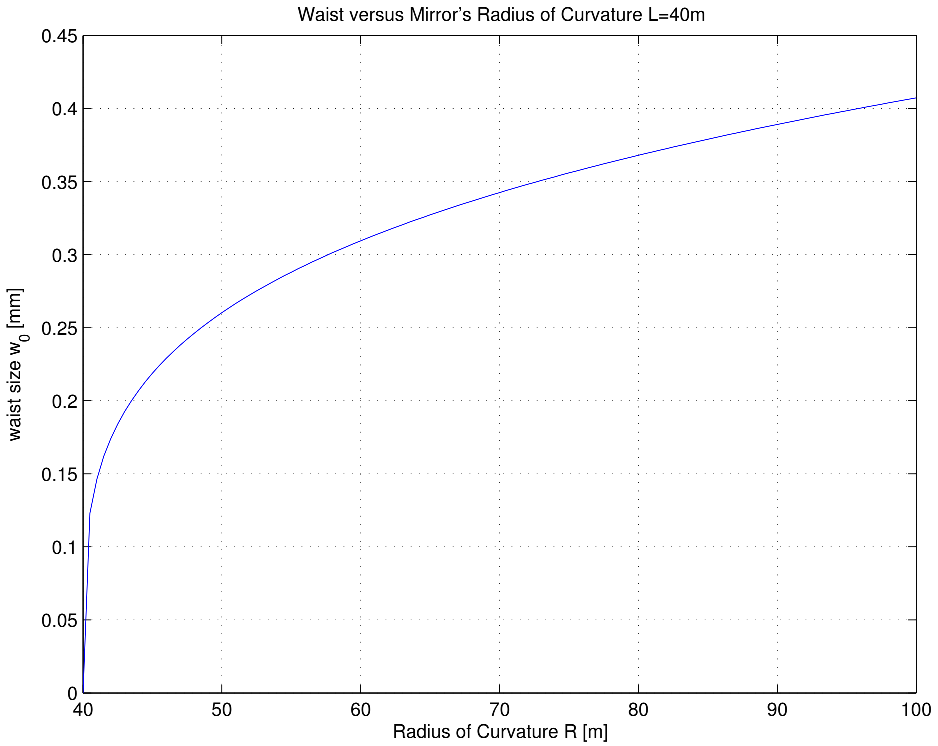


Figure 1: Waist size versus cavity mirror´s radius of curvature.

avoid to find a spot for an extra matching telescope under vacuum. The down-side is that the 40m suspended concave mirror is a custom made optics with $R = (57.4 \pm 0.6)$m. CVI 2¨ off the shelf mirrors have a maximum radius of curvature of $R = 20$m which makes a concave concave $L = 40$m long cavity unstable $(R > L/2)$. Even, considering the room available on the in vacuum optical tables that allows to shorten the length by 1m, and the CVI mirror the cavity will be practically too unstable vis-a-vis a stability factor $g_1 g_2 = 6.3 \cdot 10^{-4}$ too close to zero.

Quasi-standard radius of curvature, i.e. multiples of 10 are probably easy to obtain from mirror´s manufacturers. Figure 1 shows the waist size $w_0$ as a function of the radius of curvature $R$ . One single lens can be used to focus the output of the IFO mode matching telescope to the desired size.

The considered cavity topology is plane concave triangular optical resonator with the input taken from one of the two $45^0$ mirrors, and the output taken from the curved mirror.

Finally, here is a possible design:

| | | | |
|---|---|---|---|
| Cavity length | $L$ | = | 40m |
| Input Mirror Radius | $R_1$ | = | $\infty$ |
| Output Mirror Radius | $R_3$ | = | 50m |
| Stability factor | $g_1g_2$ | = | 0.2 |
| waist | $w_0$ | = | 2.6mm |
| Spot size on Input Mirror | $w_1$ | $\simeq$ | $w_0$ |
| Spot size on Output Mirror | $w_2$ | = | 5.8mm |
| Mirrors diameters | $D_{1,2}$ | = | 50.8mm (2¨) |

## 2.2 Optical Characteristics

Experience acquired with the lock of just one 40m IFO suspended Fabry-Perot cavity shows that even with a very high finesse ($\mathcal{F} \sim 1500$) it is possible to acquire lock in few seconds. Therefore, the Finesse cavity mainly depends on the residual rms differential length noise $\delta l_{rms}$ we want to achieve.

If we want to lock the cavity using the transmitted power $P_t$, the optimal slope is at 3/4 of the maximal power.

Supposing that we want a maximum dynamic range for the error signal, and the finesse is sufficiently high such that $\max\{P_t\} \gg \min\{P_t\}$ then the optimal point is $P_t/2$. This set the point where the Airys´ s function should be linearized.

A design parameter for this cavity is sensitivity, i.e. power per length change $dP_t/dL$. Then the resolution in length is set by the minimum power change the photo-detector can measure. For a triangular cavity and considering the mirror reflectivity to be $r_1^2, r_2^2, r_3^2$ and transmittivity is $t_1^2, t_2^2, t_3^2$ the cavity sensitivity is

$$\frac{dP_t}{dL} = \frac{T\sqrt{4R - (1 + R^2 - 4R)^2}}{2(1-R)^2}\,\frac{2\pi}{\lambda}$$

where

$$R = r_1 r_2 r_3 \qquad T = t_1^2 t_2^2.$$

Figure 2 shows the optical cavity sensitivity (Power/length change $dP_t/dL$) versus the reflectivity $R$ of the input and output mirrors imposed to be equal. The third mirror is chosen to be totally reflective.

Supposing we want to reduce the differential displacement to a fraction of a micron, i.e. $\delta L_{rms} \sim 1/10\mu$m, it is clear from the plot any mirror´s reflectivity is plenty. The major mirrors´ optical parameters are finally:

| | | | |
|---|---|---|---|
| Input Mirror Reflectivity | $r_1^2$ | $=$ | 0.98 |
| Output Mirror Reflectivity | $r_2^2$ | $=$ | 0.98 |
| Third Mirror Reflectivity | $r_3^2$ | $=$ | HR |
| Finesse | $\mathcal{F}$ | $\simeq$ | 156 |

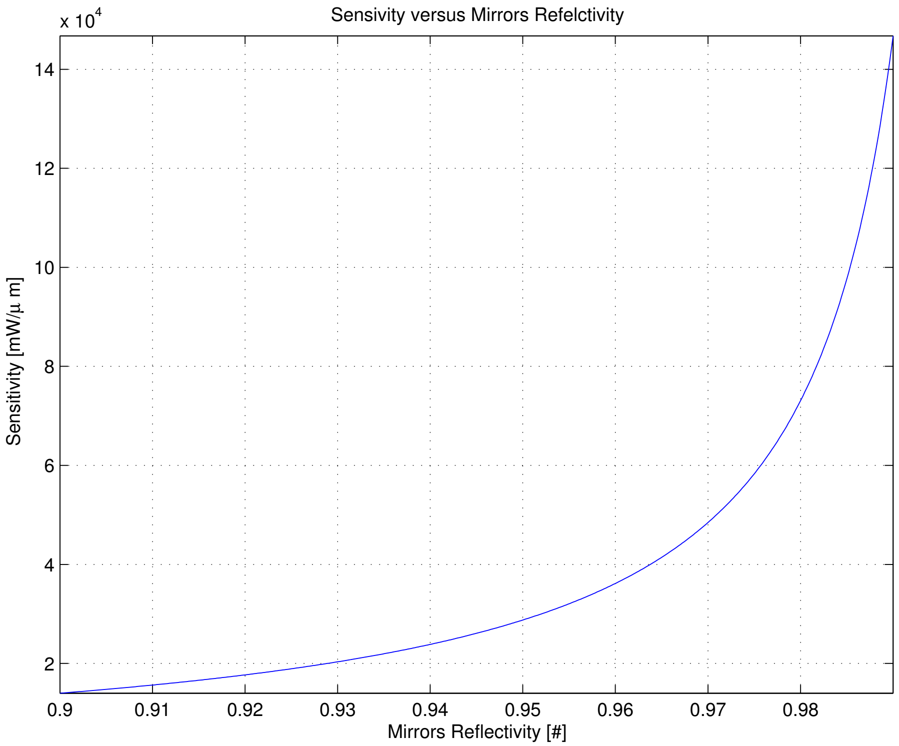


Figure 2: Cavity Sensitivity (Power/Displacement) versus input and output mirrors´ reflectivity supposed to be equal. Third mirror´s reflectivity is set to one.

# 3 Control Scheme

Conceptually the two cavities are completely independent and have the same topology. Therefore we describe just one of the two. The basic idea is to sense cavity length changes and servo the PZTs actuators of the stacis units located at the end test mass. This will essentially reduce the relative displacement between the two test masses without substantially increasing the relative displacement between the other vertex IFO optics (BS, PR, SR).

Because the stacks are between the actuators (stacis units) and the SPLIFO mirrors, the controls becomes trickier above where the stacks are not sufficiently rigid. A very simple control design is to choose a unitary gain frequency below the stack resonances. Otherwise a more accurate knowledge of the stack response is needed to apply sensor correction/predictions techniques.

## 4 Input Beam

The SPLIFO input beam is a pick off of the main input beam called initial pointing beam IPB after the in vacuum Faraday isolator and the IFO mode matching telescope. Practically, it has already size and enough power to fulfill the requirements of SPLIFO. A measurement of the IPB was $P_{IPB} = (4.8 \pm 0.1)$mW which means that the total available power is about $P \sim 10$mW.

## 5 Alignment Scheme

Two beam folding mirrors per cavity are necessary to perform the in air alignment. To ensure the proper cavity alignment after the pumping down it is then necessary to have remotely controlled pico-motors on the two folding mirrors mounts.

Pico-motors can be also used to compensate expected long term drifts that can compromise the alignment.

Old 40m in-vacuum compatible mounts with pico-motors are available.

## 6 Control Scheme

Conceptually, the two cavities are completely independent and have the same topology. Therefore, we will describe just one of the two. The basic idea is to sense cavity length changes and servo the PZTs actuators of the stacis units located at the end test mass. This will essentially reduce the relative displacement between the two test masses without increase substantially the relative displacement between the other vertex IFO optics (BS, PR, SR).

Because the stacks are between the actuators (stacis units) and the curved SPLIFO mirror, the controls becomes trickier where the stacks are not sufficiently rigid. A very simple control design is to choose a unitary gain frequency below the stack resonances, otherwise a more accurate knowledge of the stack response is needed to apply sensor correction/predictions techniques.

## 7 Major Noise Sources

The major source of noise is seismic. Laser´s intensity and frequency noise shouldn't be relevant because the IFO and the SPLIFO see the same noise during the locking acquisition phase.

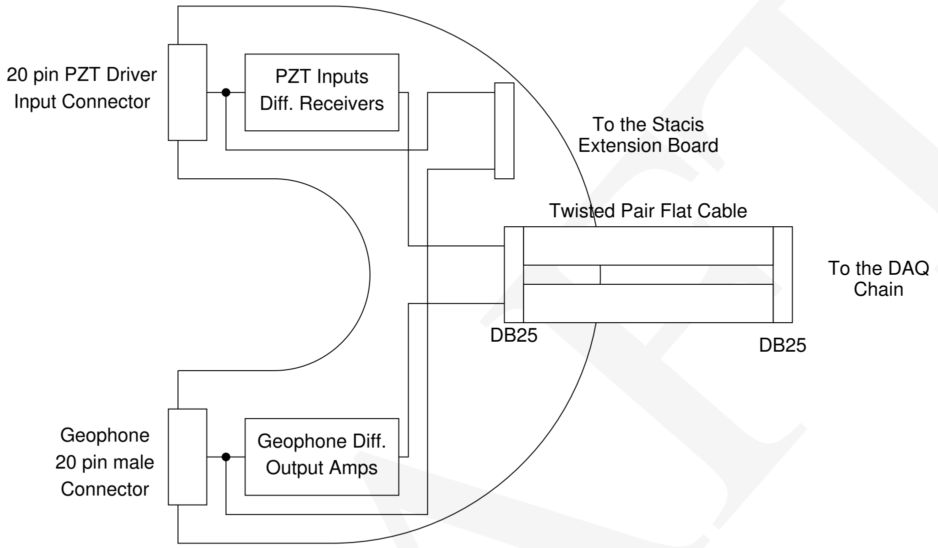


Figure 3: Stacis digital interface card with PZT differential receivers and geophone differential output amplifiers. The extra connector allows to interface the card to a standard TMC stacis controller card or to an intermediate board for open loop transfer gain changes and maintenance.

## 7.1 IFO Longitudinal Noise Versus SPLIFO Longitudinal Noise

TBD

## 7.2 Transverse Noise Crosstalk

TBD

## 7.3 Vertical Noise Crosstalk

TBD

## 7.4 Angular Noise Crosstalk

TBD

## 7.5 Actuator (PZT) Noise

TBD

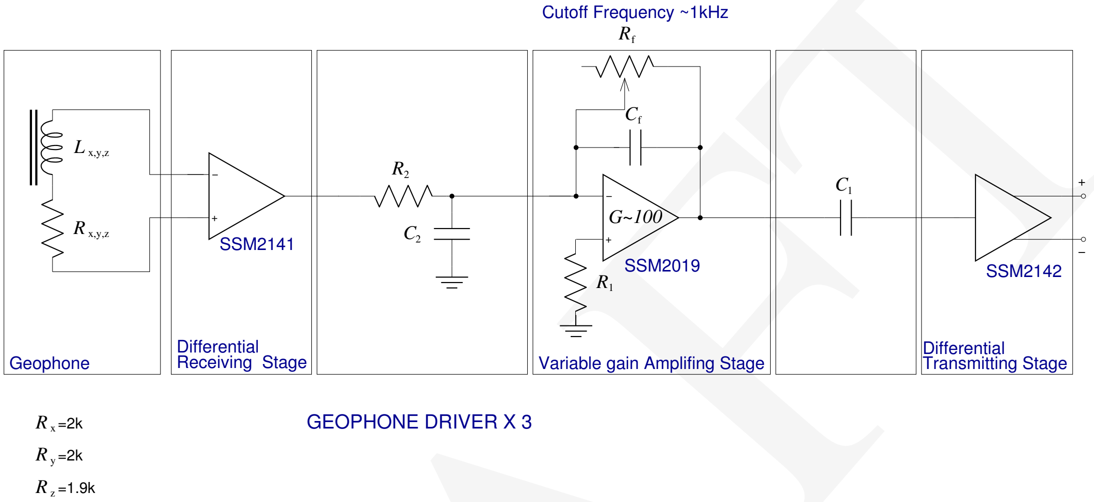


Figure 4: Basic design for the geophone differential output amplifier

## 7.6 Sensor (Photo-detector) Noise

TBD

## 7.7 Digital Noise

# 8 Stacis 2000 Modifications

The basic idea is to use the stacis 2000 units as actuators of the SPLIFO control loop, therefore some changes/retrofits on the stacis electronics is needed.

A solution (the kludge solution) is to add a summing point to the control loops in the existing control cards and keep the functionalities of the attenuation system. The summing point requires operational amplifiers and differential receivers to minimize EM noise injection.

Another solution is to completely remove the stacis controller board and implement PZTs differential receivers to interface the DAC channels to the high voltage PZT drivers. Because of the horizontal PZTs orientation it is necessary to implement at least two receivers.

To keep the active isolation functionalities via a SPLIFO digital control system, a proper conditioning circuit for the geophones signals is necessary. Figure 4 shows a basic design for the geophone drivers. Differential inputs and outputs are mandatory to minimize common mode noise on cables. AC coupling through $C_1$ should minimize geophone excess noise at low frequency. The passive low pass filter is then placed in series to compensate the pole introduced by $C_1$.

Figure 3 pictures all these ideas, plus an extra feature, an additional connector, to provide a way to do the tuning and maintenance of the standard stacis 2000 units.

And additional connector can be used to interface the stacis unit to an extension board with the inputs and outputs necessary to perform standard maintenance procedure, and control loop tuning such as open loop transfer function measurements and gain settings.

Suppling powers, supposed regulated, are the same ones used for the stacis controller board.

# 9 Optical Layout

The IPB is the only beam used to build the two SPLIFO. The layout has been designed to minimize as much as possible the number of interventions and changes inside the vacuum envelope and in the IFO optical layout. The actual IFO´s core optics layout is not touched at all.

Mode matching the beam to the cavity is not a major issue because of the small amount of power that needs to couple inside the cavity. Introducing a mode match telescope will marginally increase the complexity of the optical layout.

The optic mount used in the drawing are just indicative to show that there is enough room for everything. Old 40m optical mounts for 1-1/2" diameter mirrors should be used as much as possible due to their good availability .

Due to the soft stacks, the placement of new optics will require to move around counterweights to re-level the in-vacuum optical tables. Therefore, some interventions on the alignment of the main IFO will be required.

Some other arrangements of the optics are necessary on some of the external optical tables to accommodate the new beams transmitted from the viewports.

## 9.1 BS Vacuum Chamber

In the BS vacuum chamber it should be necessary to just add a 2″ 50% beam splitter to the initial pointing beam as shown in figure 5. In principle, this operation should change just the alignment of the IPB transversely shifting beam due to the thickness of the beam splitter.

## 9.2 ITMX Vacuum Chamber

In the ITMX vacuum chamber. it necessary to add a 2″ 90% reflective beam splitter to the initial pointing beam, and three 1-1/4″ $45^o$HR mirror. Two of the $45^o$HR mirrors mounts must be equipped with pico-motors for the in vacuum alignment of the cavity. The SPLIFO input mirror is then added in the optical train as shown in figure 6. In principle, this operation should change just the alignment of the IPB. One of the optical lever mirror must be shifted to give more room for the SPLIFO beam path. If necessary, the cavity reflected light can be sent outside the vacuum tank as shown in 6.

## 9.3 ETMX Vacuum Chamber

Just a placement of new components, i.e. the output SPLIFO curved mirror, two 2″ $45^0$HR mirror., and a lens to reduce the beam size from $\sim 6$mm to about 1mm. See figure 7.

## 9.4 ITMY Vacuum Chamber

Just a placement of new components is necessary, i.e. the input SPLIFO curved mirror, and three $45^0$HR mirror, and a 2″ lens to reduce the beam size from $\sim 6$mm to about 1mm .Two of the 45HR mirrors mounts must be equipped with pico-motors for the in vacuum alignment of the cavity..If necessary, the cavity reflected light can be send outside the vacuum tank. See figure 8

## 9.5 ETMY Vacuum Chamber

Just a placement of new components is necessary, i.e. the output SPLIFO curved mirror, two 2″ $45^0$HR mirror., and a 2″ lens to reduce the beam size from $\sim 6$mm to about 1mm. See figure 9.

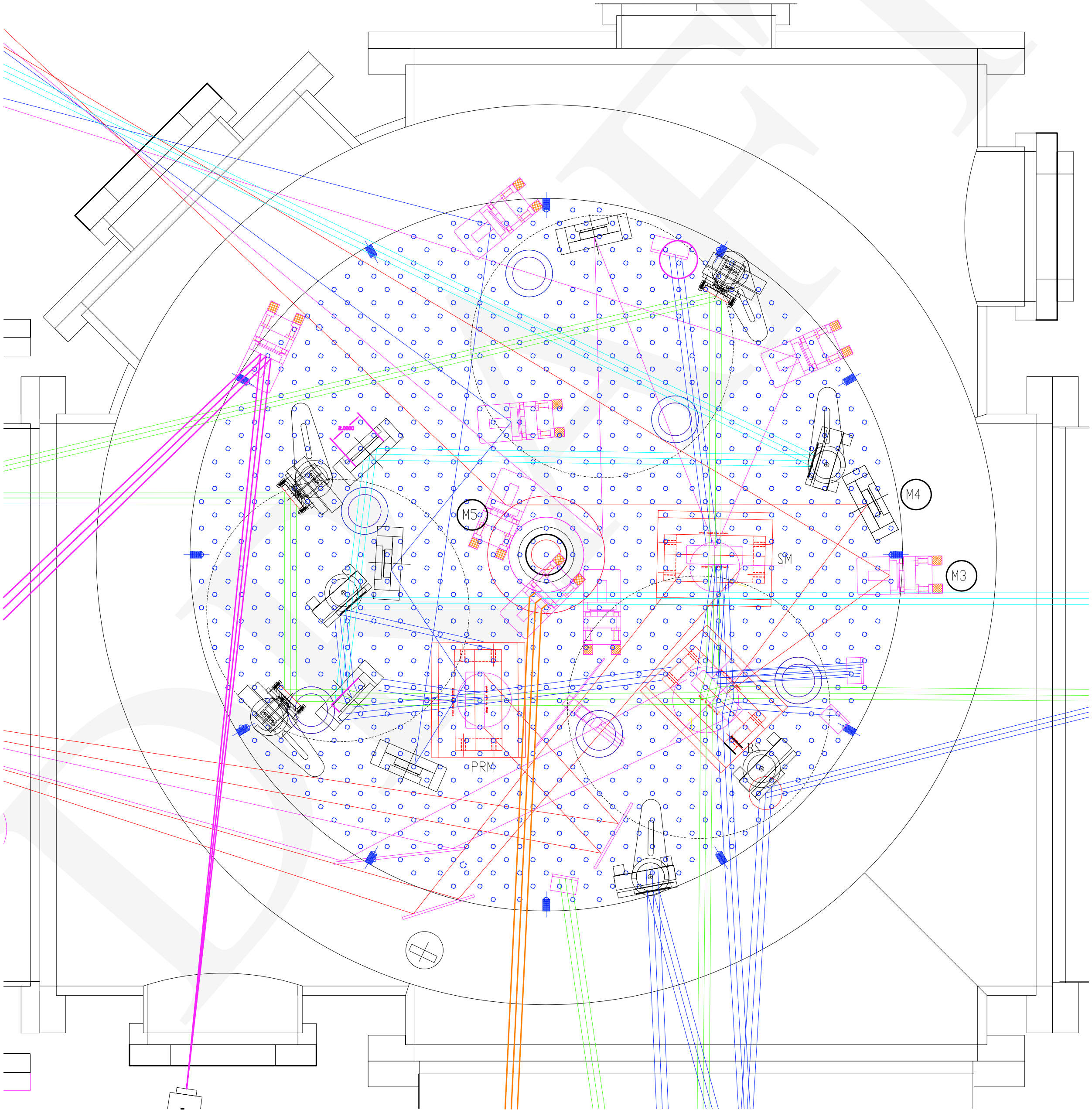


Figure 5: Beam splitter chamber. SPLIFO beams are in orange.

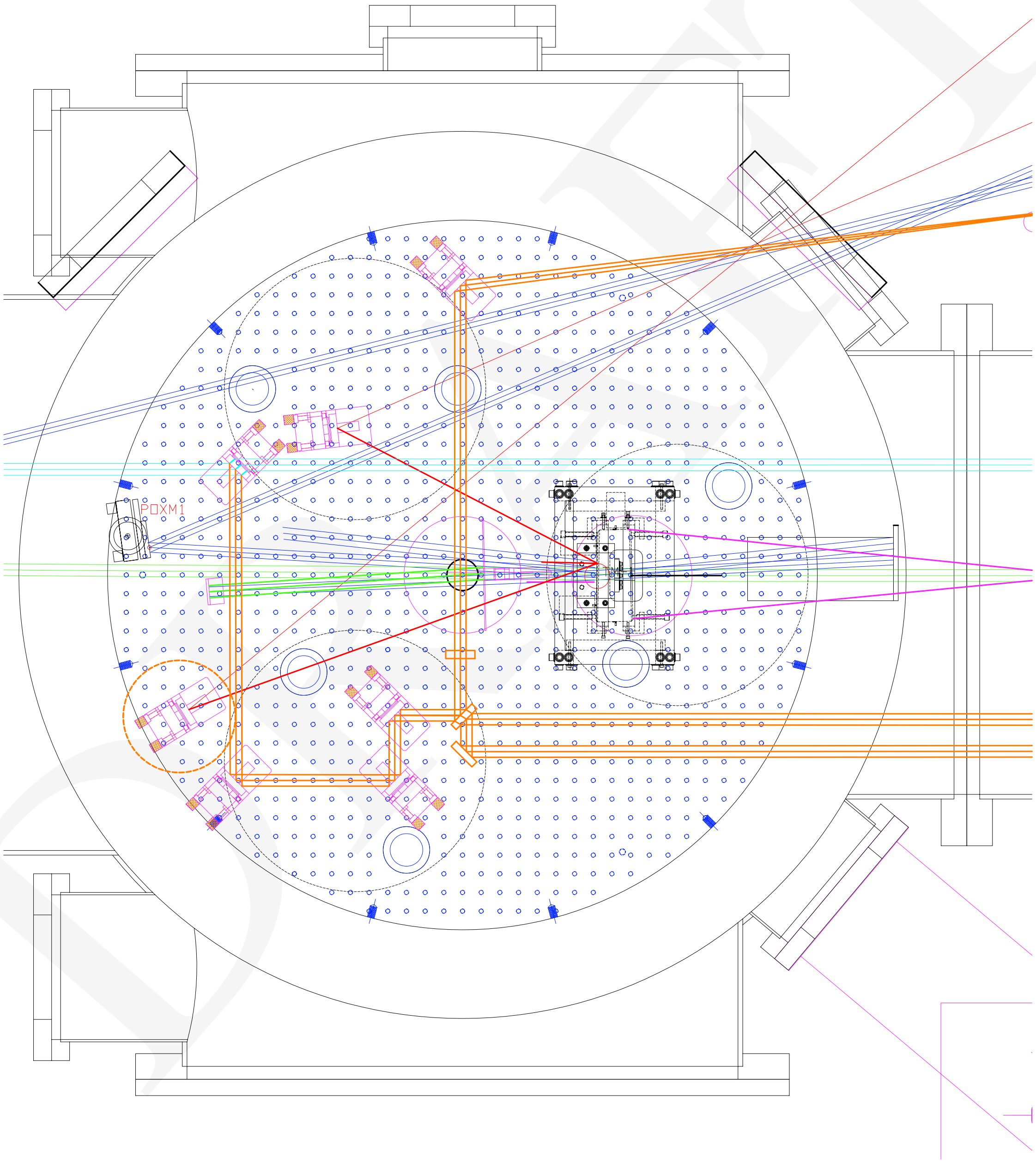


Figure 6: ITMX vacuum chamber with the SPLIFO input mirror. SPLIFO beams are in orange. One optical lever mirror must be moved.

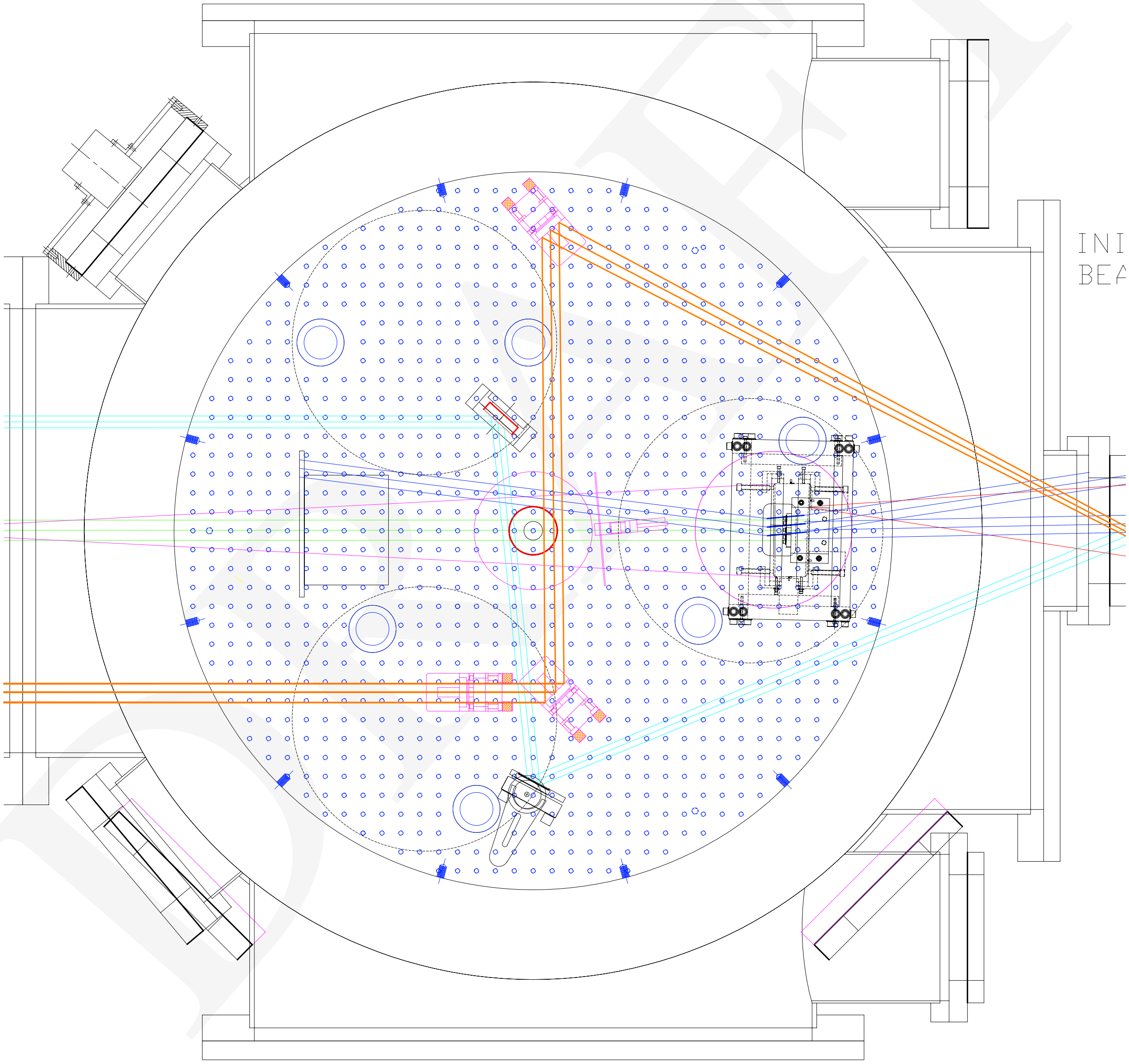


Figure 7: ETMX vacuum chamber with the SPLIFO output mirror.

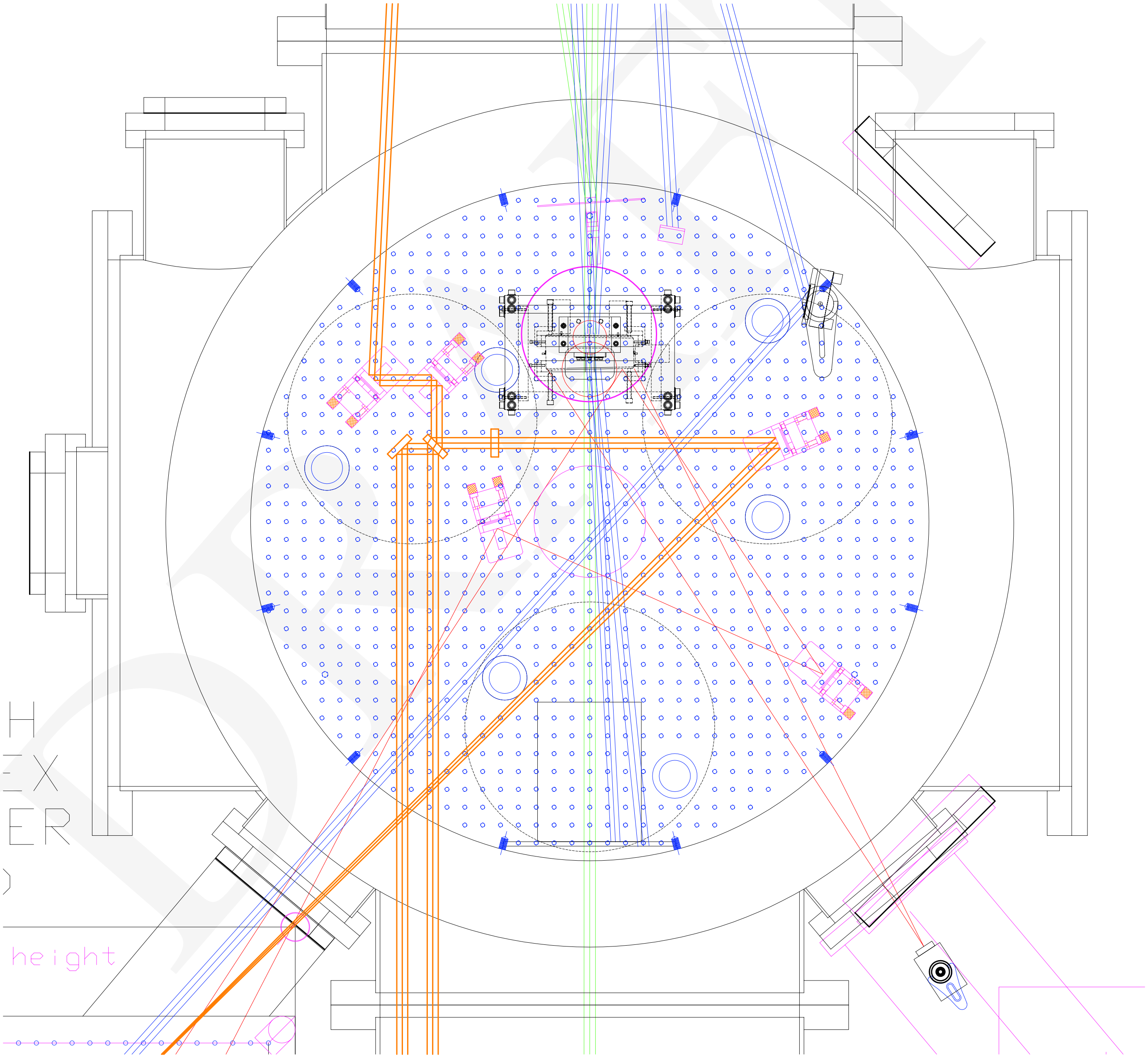
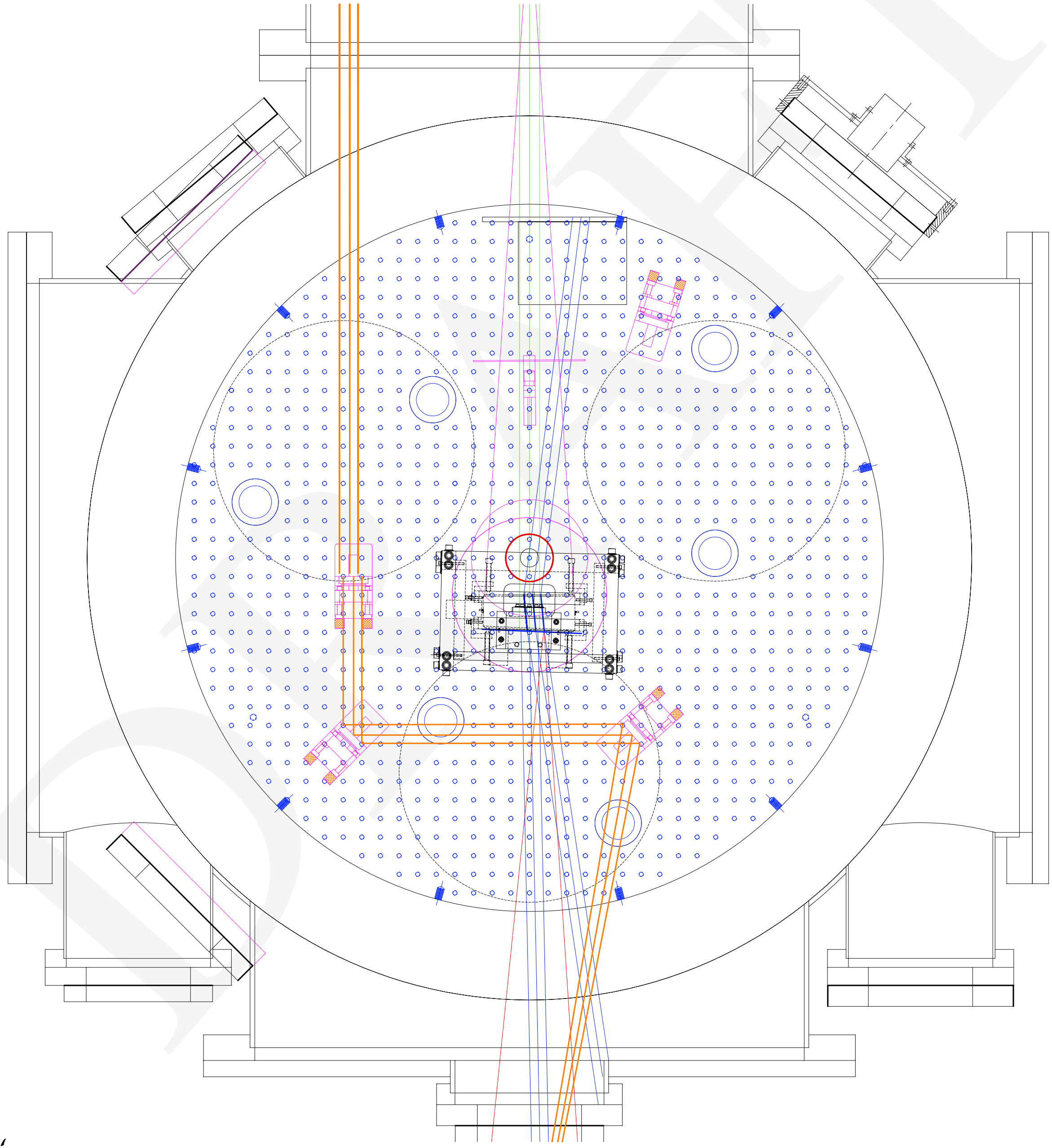


Figure 8: ITMY vacuum chamber with the SPLIFO input mirror.



“

Figure 9: ETMY vacuum chamber with the SPLIFO output mirror.