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LIGO Output Mode Cleaner HAM Seismic Attenuation System.

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Output Mode Cleaner (OMC) optical bench general design features.

The OMC optical bench Seismic Attenuation System (SAS), given the relatively modest seismic isolation requirements, has been designed to be as simple as possible, a single stage of low-frequency, passive attenuation. It is composed of an Inverted Pendulum (IP) table for horizontal attenuation and Geometric Anti-Spring (GAS) filters in the vertical direction. An attenuation performance of 60 dB broadband, reaching its nominal attenuation factor below 10 Hz in all directions, is expected.

The proposed OMC optical table is a standard HAM optical bench. The large size is chosen to make space for the mode matching and steering optics, for the detection and monitoring diodes, to provide spare space for future developments, and considering the fact that the cost differential between a large and a small table is marginal.

The HAM SAS was therefore designed to simply replace the LIGO seismic stacks between the standard HAM optical bench and its support tubes.

A rectangular symmetry, instead of the commonly used triangular symmetry, is used in the HAM SAS to adapt to the vacuum chamber geometry and to match the HAM table symmetry and dimensions.

Since the OMC chambers have no external pre-isolator for earthquake protection, a free stroke of at least 10 mm in all directions is required from the OMC HAM SAS to passively absorb, with no damage, any earthquake up to that amplitude.

The proposed SAS design is UHV and bake-out compatible, and compatible with both the LIGO and Advanced LIGO beam heights. The transition from LIGO to Adv-LIGO is obtained by simply removing a number of 115 mm spacers.

The HAM SAS is tentatively designed payload of one ton. The payload is tunable and can be canged to match virtually any desired load by simply mounting different flexures on a standard frame.

Voice coil actuators and precision LVDT position sensors are foreseen to provide tidal and other daily drift corrections. Mechanical correction actuators are implemented to null any other static force required from the voice coil actuators. The optical table remains aligned in case of power failure. The position sensors provide a high-resolution memory to restore balance and alignment of the optical tables after interventions on the optics.

The expected performance of the HAM-SAS, operated in passive mode, gives it the potential to replace the three layers of stiff active attenuation units, while providing all of their combined attenuation, controls and positioning performance.

Optional accelerometers are foreseen for diagnostics and for complementary active attenuation. The SAS attenuation performance is augmentable by means of active attenuation, achieved using the signal of accelerometers and external electronics, with no other additional sensors and actuators. The implementation of this active stage would provide a reserve of attenuation power.

A simple clamping mechanism is foreseen to immobilize the optical bench and allow human access over the bench during maintenance of the optics.

1 HAM SAS schematic design

Horizontal attenuation.

The horizontal section of the seismic attenuator is composed of a base platform supporting a set of four 0.5 m tall Inverted Pendula, shown in blue in figure 1, disposed on a diamond configuration. The four IPs mount on a base platform sitting on the LIGO support tubes and support an intermediate platform (which contains the vertical attenuation filters). The flex joints at the top and bottom of each IP leg allow any movement of the intermediate platform in the horizontal plane.

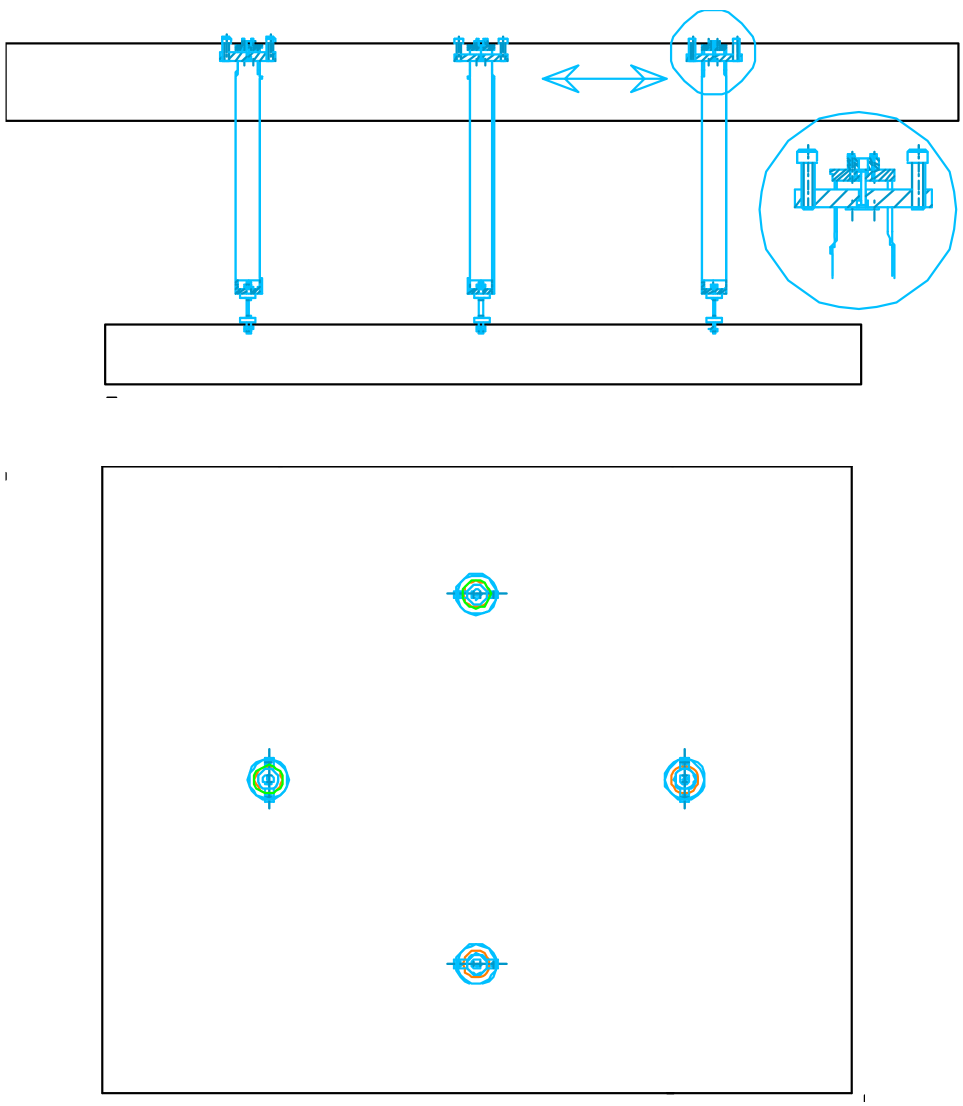

Figure 1: Disposition of the 4 IP legs between the base and intermediate platforms. The diameter of the flex joints at the bottom of the legs is chosen to match the required payload.

Table dynamic positioning and alignment.

Four co-located, nanometer-resolution LVDT [i] and voice-coil-actuator [ii] units (TAMA SAS model), shown in red in figure 2, are mounted at the periphery of the intermediate platform for horizontal low frequency dynamic controls. They act between the intermediate and the base platforms for horizontal tidal controls (the actuators and sensors are of course also available for supplemental active attenuation).

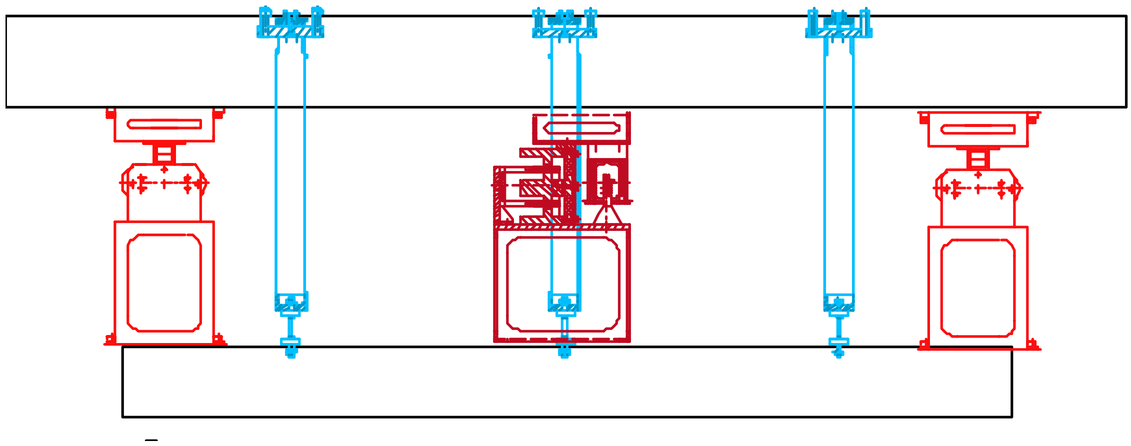

Figure 2: The positioning of the 4 LVDT voice-coil-actuator units is radially outside the IP legs.

Each of the four groups of collocated voice-coil-actuators and LVDT position sensors, shown on figure 3, are pre-aligned and pre-calibrated before installation. They are a scaled version of the TAMA-SAS models.

The co-location helps reducing the non-diagonal terms of the control matrix.

Transport jigs are used to move the units from the test bench to their working location.

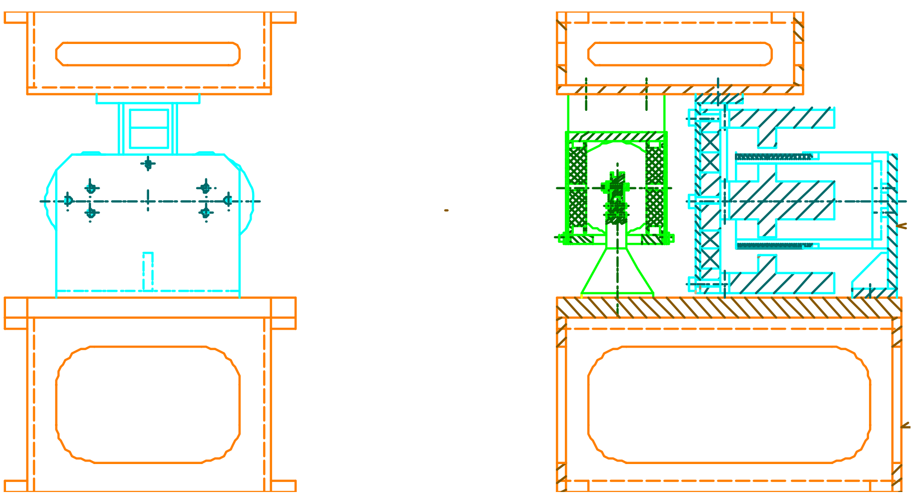

Figure 3: LVDT (green) and voice-coil-actuator (light blue) units. The bottom orange box is a spacer to be removed to match the Advanced LIGO lower beam height.

Thermal and electro-magnetic actuator's perturbations.

The actuators are a single coil racetrack type to generate forces independent of the table positioning. It is conceivable to use inverted-field twin coils to reduce e.m. interferences, but this is deemed a superfluous precaution for HAM-SAS because of the low level of forces required. The force requirement of the actuators in this system can be calculated from the mechanical stiffness. Assuming an upper passive resonant frequency of 0.1 Hz (a very conservative value), and 1 ton load, the effective elastic constant will be:

$$k \le (2\pi f)^2 M = 400 N/m$$

assuming a 1 μm seismic motion, the maximum required dynamic force is:

$$F_{dynamic} = 400 \cdot 10^{-6} = 0.4 mN$$

which, with a typical force of 1 N/A, requires a negligible control current and is expected to generate negligible e.m. interference.

If one considers the static force needed to compensate a 500 micron tidal motion (a requirement due to the lack of external pre-isolators in the OMC chambers) the maximum required static force is:

$$F_{static} = 0.1 N$$

also a negligible value.

The design foresees that all static forces (changing slower than the tidal, and other daily period corrections) will be nulled by soft, remotely tunable springs discussed below.

The actuator's power dissipation is so low (the power consumption is proportional to the fourth power of the mechanical resonant frequency) of the order of the mW or less, that no thermal problems are foreseen, even in vacuum, in ordinary operation.

Some care has to be taken to control temperature if the actuators are used as vibration exciters for calibration.

Optical bench static alignment.

Soft springs are positioned just inside the LVDT-actuator units (figure 4) to null the static force requirements. They connect between the intermediate platform and micrometric slides sitting on the base platform. They fine tune the static horizontal alignment of the intermediate table. Using 40 N/m springs and one μm resolution micropositioners, the static force requirement from the voice-coil-actuators can be reduced to 40 μN, a negligible value.

AML C17.2 stepper motors will be used for actuation of the micro positioning slides. Kapton and Peek, the only organic insulators used to build these UHV compatible motors and slides, are fully bakeable and UHV compatible.

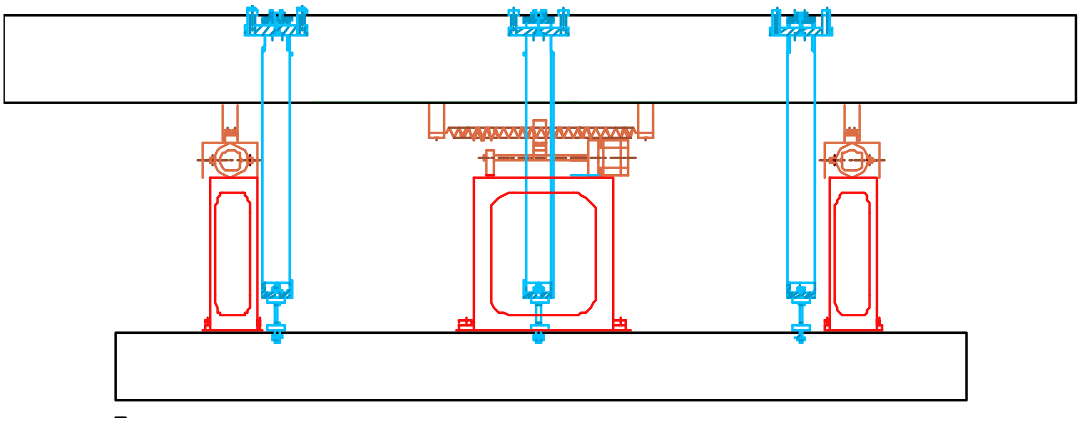

Figure 4: Tuning spring assembly (brown): Soft springs, connected between a micropositioner and the intermediate platform, provide the static horizontal positioning

Accelerometer instrumentation.

Optional horizontal accelerometers [iii,iv] are foreseen on the intermediate platform (green in figure 5) for horizontal active attenuation and/or monitoring. The accelerometers, like the position sensors, are roughly co-located with the actuators to simplify the control matrix. TAMA model Marwan accelerometers are chosen because the intermediate platform is short circuited to the ground seismic motion in the vertical direction. The sensitivity of ordinary accelerometers to off-axis motion would cause some of the vertical noise to be re-injected in the horizontal direction by the active attenuation loops. To avoid this problem, very large insensitivity to off-axis excitation has been engineered into this accelerometer design, thus allowing for effective active attenuation despite the perturbations from the vertical seismic noise. The horizontal sensitivity of this accelerometer is comparable with that of a STS-2 seismometer. The Marwan accelerometers are of all metal construction and have no active electronics onboard. Peek and Kapton are used as insulators. These accelerometers are therefore intrinsically UHV compatible.

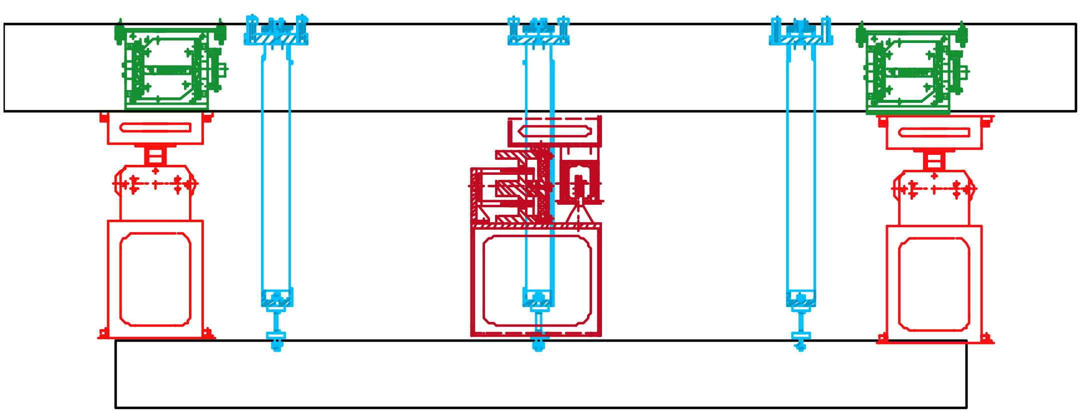

Figure 5: Positioning of the horizontal accelerometers (green) inside the intermediate platform.

Expected passive horizontal attenuation performance.

Typical IP passive seismic attenuation performances in excess of 60 dB are achieved by means of balancing of the leg's counterweight. Due to space constraints it is not possible to implement counterweights on all four legs. We achieved the required performance even without counterweight by building legs of extra light design (light legs are possible due to the small size geometry). It has been measured that both similar Minus-K IP attenuators and our tests units exceed the required 60 dB of attenuation performance without counterweights. As an additional safety, and for spare attenuation power, we designed two counterweights for the two beamline legs, where there is sufficient implementation space, as shown in figure 6. Double-sized counterweights on two opposite IP legs is kynematically equivalent to implementing them on all four legs. This configuration is possible both in the case of LIGO (figure 6, left) and for the lowered bench level of the Adv-LIGO (right).

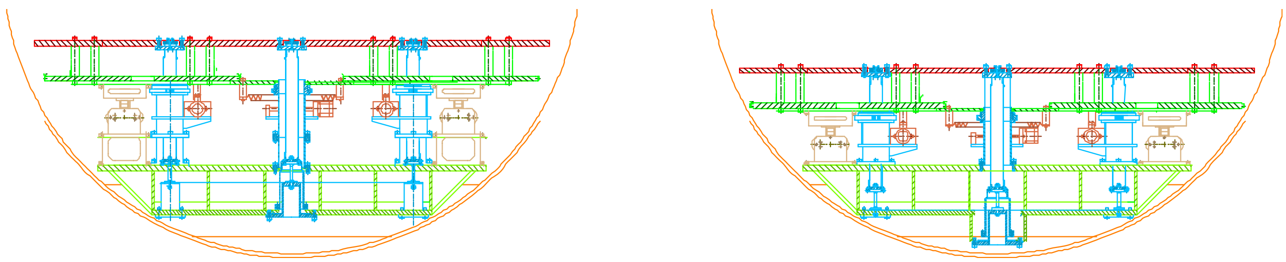

Figure 6: IP counterweights are implemented in the 2 beamline IP legs only. The present LIGO configuration is shown on the left and the Advanced LIGO configuration of the right.

Although the chosen 60 dB attenuation requirement is not extraordinary for an IP, we built a quick test to verify the performance of the short IP leg using the TAMA-SAS IP calibration facility in the Galli & Morelli factory in Lucca. A small table built with three full-size HAM SAS IP legs, (no counterweights) and half size flex joints were used. The test setup is shown in figure 7.

The frequency to load curve of this test, is shown in figure 8. The IP frequency tuning was not pushed to very low frequency, a 100 mHz tuning was deemed sufficient for this quick test of transfer function (lower frequency tuning would make the IP table more sensitive to the tilting induced by the shaking mechanism and make the transfer function measurement more difficult and less significant).

The Transfer Function measurement was taken with a couple of twin accelerometers, courtesy of Virgo. The TF measurement, shown in figure 9, was very coarse, taken by hand, one point at a time, in the lunch break of the noisy Galli and Morelli factory. Even at lunch, ongoing automatic machining and other service machines generated large ambient noise coupling to the accelerometers and interfering with the measurement sensitivity.

Despite the measurement noise, one notices the expected attenuation slope starting from the 0.1 Hz resonance. The slope appears to be even steeper than the $1/f^2$ expected one, probably because of the pull of the zero at 2.8 Hz, which is generated by the absence of the counterweights, and is the limiting factor of the attenuation at 60 dB. Measurement errors probably make the zero point look narrower than it should be.

The implementation of counterweights balanced with 10% accuracy, will move the 2.8 Hz zero at higher frequency thus extending the $1/f^2$ slope and pull down the attenuation saturation level by an additional 20 dB. This level of balancing can be easily achieved with Finite Element calculations.

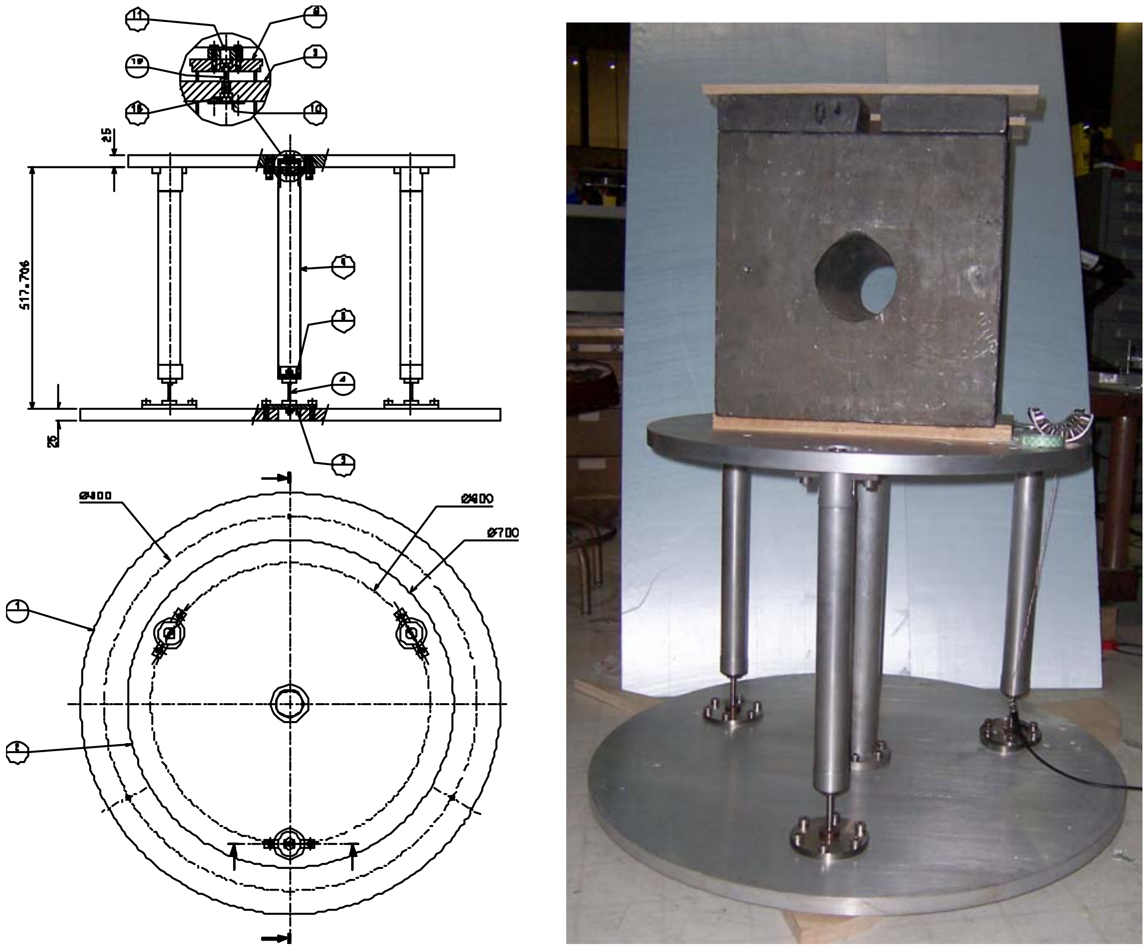

Figure 7: Small IP leg test setup (without counterweights) design and photo. The lead cube is a 500 Kg block (2/3 nominal load). Visible on the right of the block is one of the magnetic dampers to neutralize the first leg resonance. The central leg is a safety stop.

At high frequency one then notices in figure 1 the 75 Hz flex joint-and-leg resonance. This resonance, although in the detection band, is of little concern because it can be eddy-current damped with no attenuation performance loss (figure 10) and it is at high enough frequency that it is only weakly excited by seismic noise.

One should also notice that the measured transfer function saturation level is proportional to the ratio of the leg's mass to the payload's mass. The attenuation plateau will improve, moving to larger attenuation values, for larger loads.

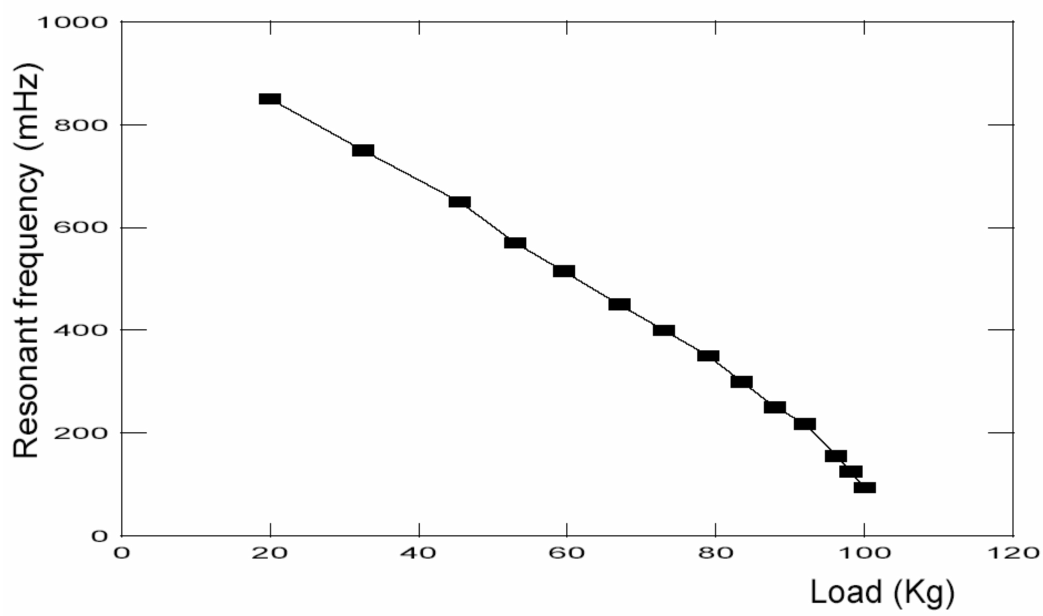

Figure 8: HAM SAS small IP prototype load curve (1/2 size flex joints, 1/8 payload).

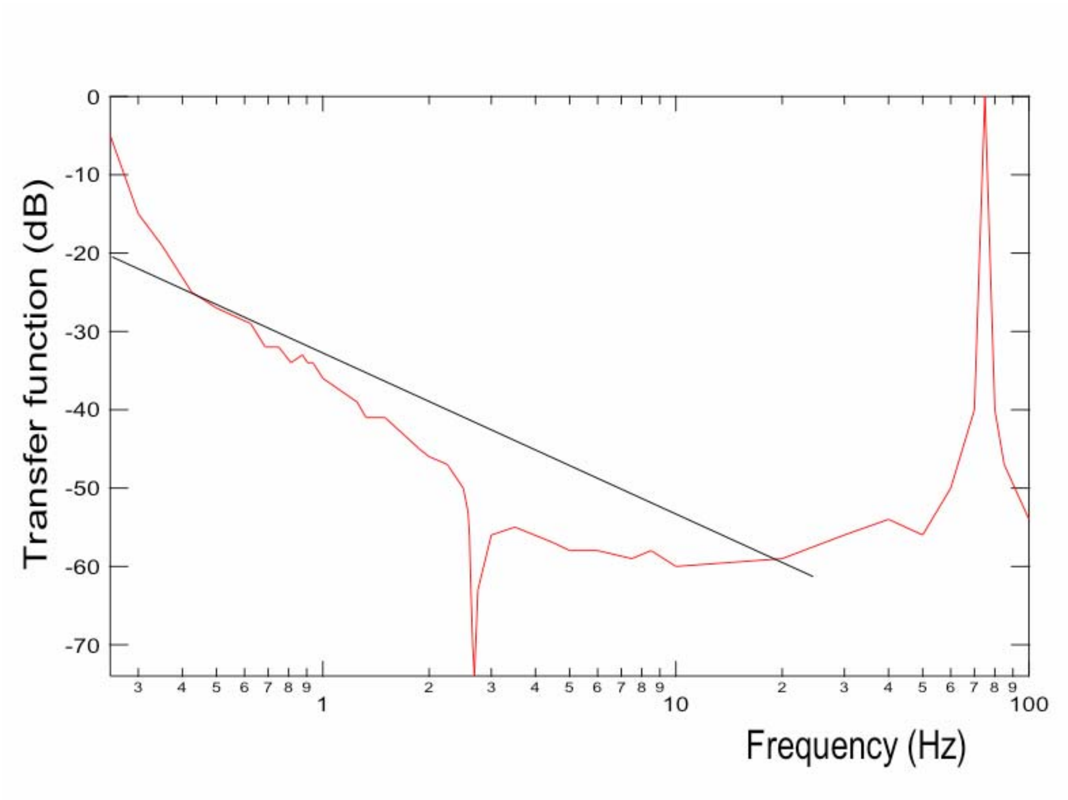

Figure 9: Small leg IP TF performance; no counterweight installed and 1/8 of nominal payload (on half size flex joints). The grey line is the expected $1/f^2$ behavior.

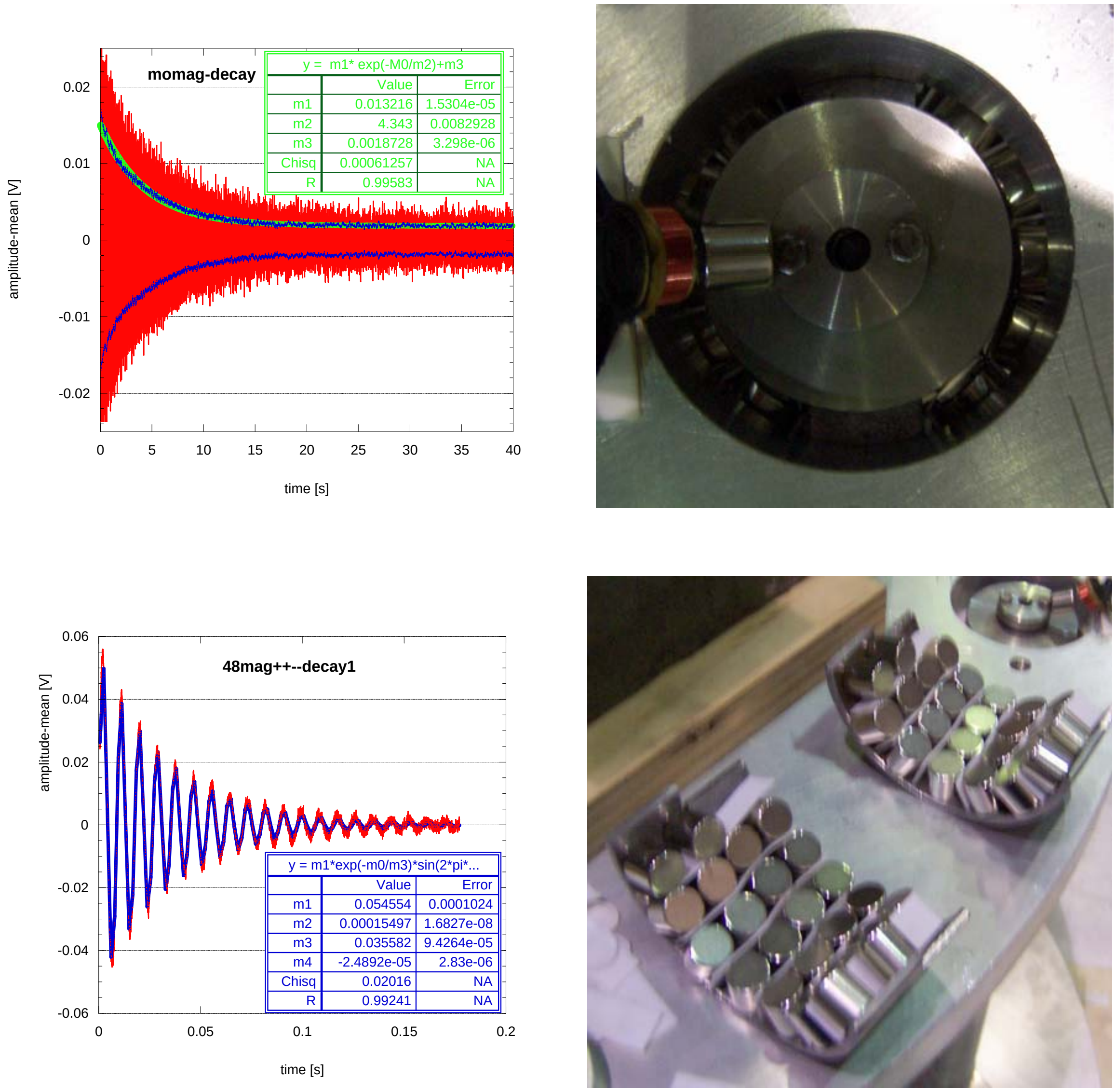

Figure 10: Q factor measurements for the IP leg first resonance. The top left graph shows the resonance measurement without damper, with a lifetime of 4.3 seconds. The top right photo is a top view of an IP leg; the pickup coil and magnet used in the measurement is visible on the left of the photo. Below it, in the same photo, one can see the crown of damper magnets surrounding the leg circumference. The two halfs of the crown are shown in the bottom right photo. The Bottom left graph shows the measurement of the same resonance after installation of the Eddy current damper. The resonance lifetime is reduced to 35 ms.

Since this first test was done with full size and full weight legs, but only 1/8 payload (half size flex joints), the 60 dB transfer function saturation level is expected to naturally improve by an additional 18 dB. This prediction was partially tested, mounting on the same test setup a second set of, full-size, flex joints. The lack of space on the small prototype table top surface did not allow proper ballast plate stacking on the Galli&Morelli test station and a 12-13 Hz resonances of the ballast plates stack spoiled the quality of the measurement. Three points were still verified.

1. The full size flex joint was tested with full nominal payload (250Kg per leg) and behaved as expected as a function of load (see figure 11). A resonant frequency of 60 mHz was achieved simply placing the test setup on concrede floor. Much lower frequency tune (<30 mHz) is possible in vacuum with more adequate supports.
2. The 2.8 Hz zero point of figure 9 moved at higher frequency and below detection level (masked by the payload internal resonances at ~ 13 Hz) indicating that the attenuation saturation level has actually moved at larger dB values. The presence of the 13 Hz payload resonance did not allow meaningful measurement of the attenuation saturation level. All it can be said is that it was below 60 dB.
3. The 75 Hz leg resonance moved to 113 Hz, due to the higher stiffness of the flex joint, making this resonance even less relevant and easier to damp.

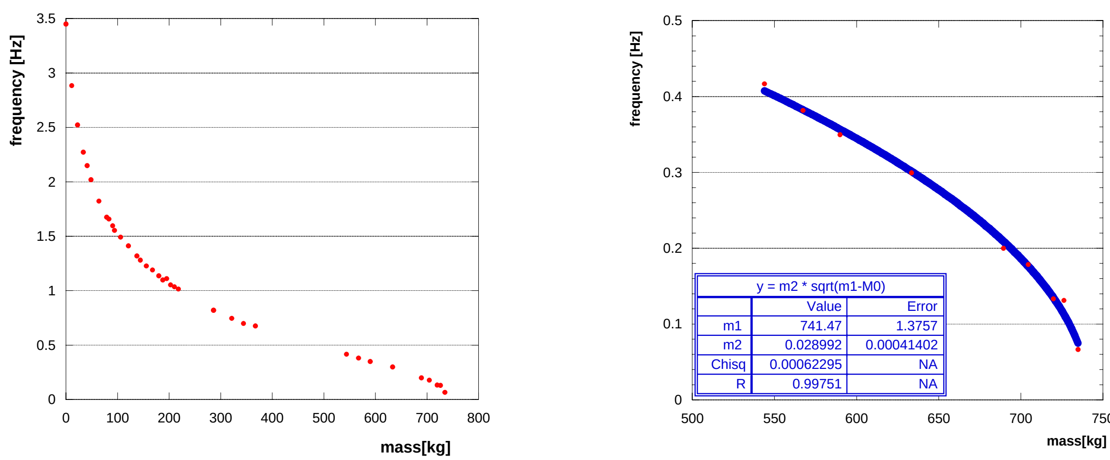

Figure 11: Frequency versus load tuning of the three-leg IP of figure 7, with full-size flex joints and full load (250 Kg/leg). Tuning below 60 mHz was not possible because of the poor flatness of the synchrotron lab floor. The full curve is shown on the left and an expanded view of the terminal section is shown on the right. The last three points between 133 and 67 mHz are separated by 7 and 14 Kg illustrating the ease of tune of the IP main frequency. A fit of the √m terminal frequency plunge is shown as well.

We performed a damping test of the IP leg first resonance

This resonance shows up @75 Hz for 1/8 load and @113Hz at full load. The test was performed at full load with full size flex joints. The damper, was a crown of 1/2”x1/2” cylindrical magnets lining the inside of a steel pipe with a 1/8” radial gap to the IP leg and was not optimized for the scope. An optimized damper with less gap between the magnets and the leg’s head would of course be much more efficient. The implementation of this damper around the leg’s head reduced the resonance by more than 2 orders of magnitude, as illustrated in figure 10, and eliminated the problem.

An ANSYS study of IP counterweights is ongoing. Balancing the IP legs to within 10% would add 40 dB to the IP attenuation performance. Although better leg balancing is possible, no finer balancing is sought because the (double) counterweights can be applied only to two out of the four legs and other asymmetries could take place. No fine tune is necessary to get this level of balance.

The counterweights performance improvement will simply add over the performance measured in the small IP table tests.

The IP performance may turn out to be sufficient to drive the seismic attenuation below the sensitivity level of accelerometers and make horizontal active attenuation impossible for lack of accelerometer sensitivity.

Vertical attenuation

The intermediate platform houses four GAS filters [[v],[vi],[vii]] for vertical attenuation, as shown in figure 12.

The GAS filter blade dimensions and design are identical to those of the well-tested TAMA filter zero. Each filter houses 8 blades, each carrying 10 to 30 Kg of load (depending on the blade’s width). The lift provided by the GAS filters can be matched to the optical bench table by varying the number and width of the blades.

The four support points between the GAS filters and the HAM optical bench are arranged as follows. The first support point is a point in a cone for x-y positioning (right on figure 13), the diagonally opposite one is a point in a groove for angular positioning, while the other two are free points on a flat (left figure 13). This arrangement is commonly used for precision kinematics positioning. Four-point support is allowed by the elasticity of the filters.

Each GAS filter is equipped with its own voice coil actuator (blue in figure 13, left) and LVDT position sensor (red) for dynamic controls.

Vertical attenuation from GAS filters is well measured and saturates at about 60 dB due to the blade to payload mass ratio. These GAS filters have been operated at frequencies as low as 30 mHz yielding substantial attenuation already at the microseismic peak frequency. At these low frequencies, natural internal damping in the material makes any other damping superfluous.

Static positioning is obtained, like in the horizontal direction, by means of 4 soft springs (orange in figure 14) mounted between the optical bench and micrometric movements on the intermediate platform.

Like in the horizontal case, optional vertical accelerometers (dark blue figure 14) mounted in the optical bench are foreseen for diagnostics and for supplementary active attenuation. Accelerometers based on the GAS geometry, but electrically similar to the horizontal version, are also intrinsically UHV compatible.

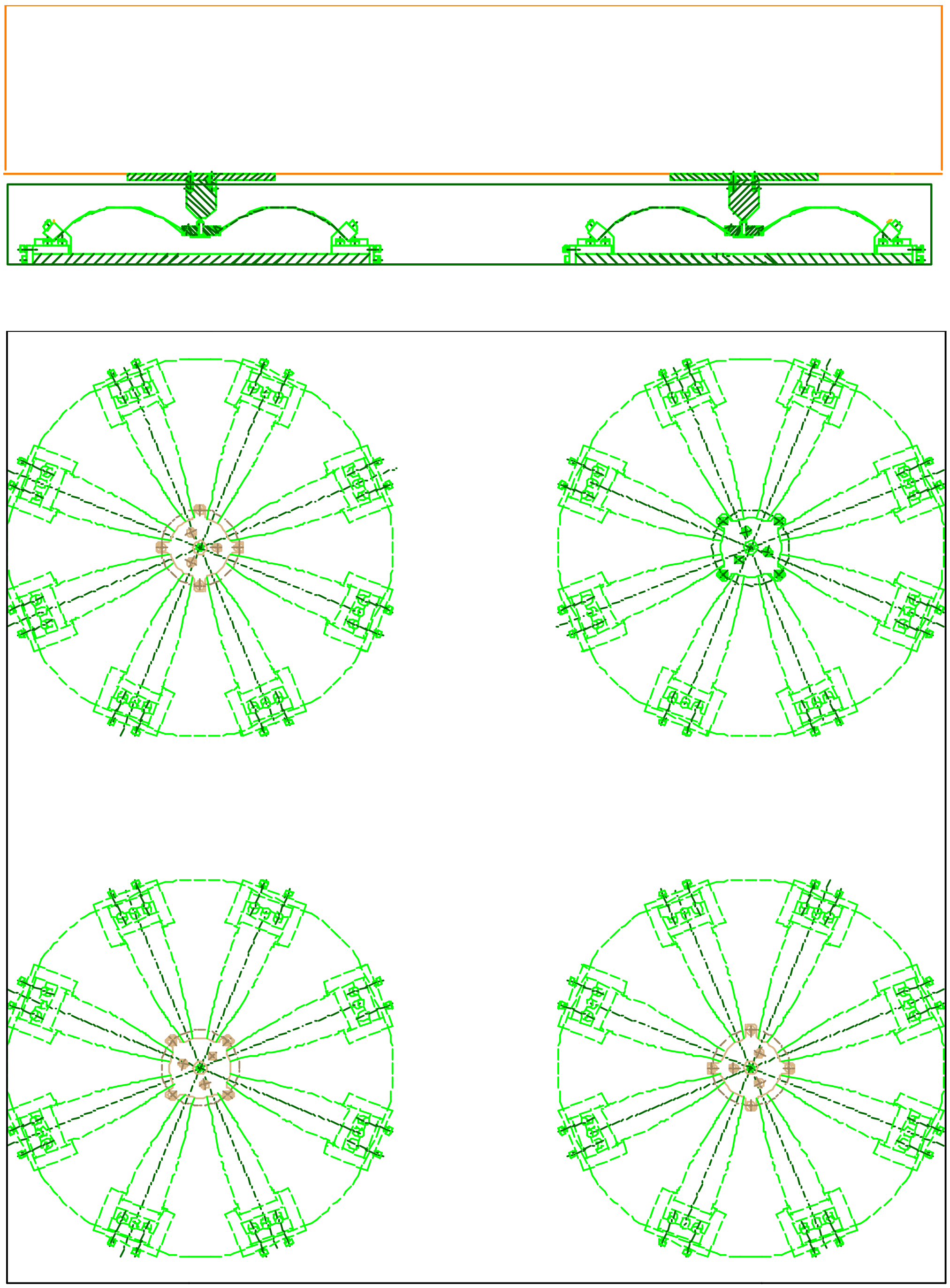

Figure 12: The top part of the figure show the GAS filters embedded in the intermediate platform (green), supporting from below the optical bench (orange). The bottom part of the figure illustrates the disposition of the four GAS filters below the HAM optical bench.

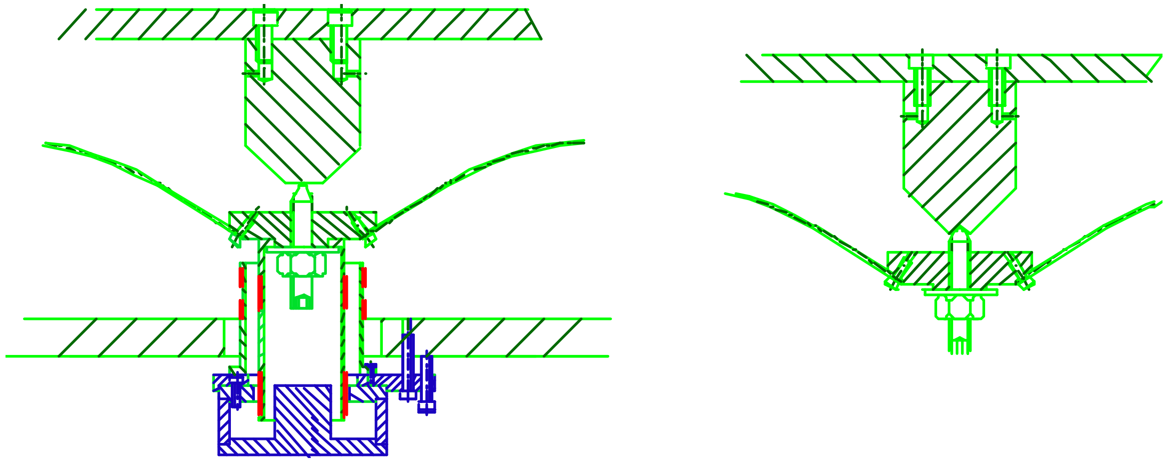

Figure 13: Support point configuration between the GAS filters and the optical table.

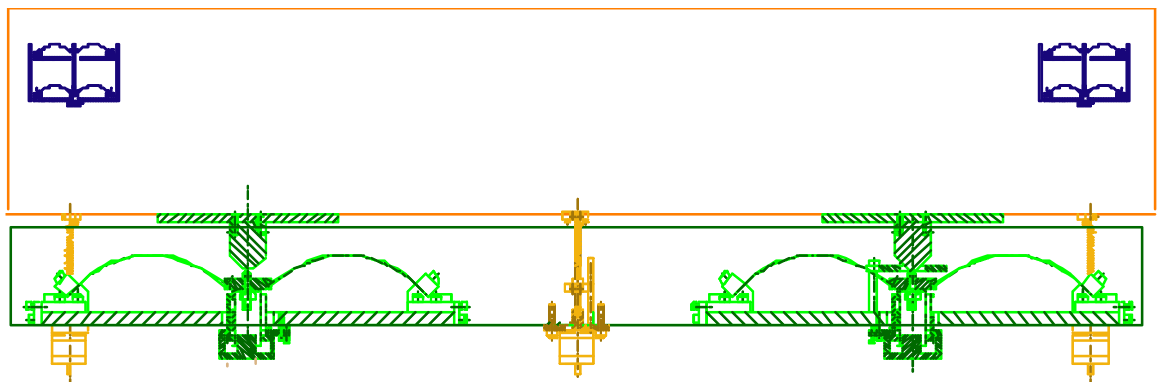

Figure 14: Disposition of remotely tunable parasitic springs (orange) for vertical position and tilt tuning.

The horizontal and the vertical degrees of freedom are mechanically independent in the SAS design. As a consequence, the active attenuation control loops for the three vertical directions (vertical, pitch and roll) are naturally independent from the ones in three horizontal directions (x,y, and yaw). Therefore the 6 d.o.f. (8 including the redundant d.o.f.) control matrix splits into two simpler and much easier to handle 3 (4) d.o.f. ones.

Four actuators are used to control the three degrees of freedom of both the horizontal movements of the intermediate table and the vertical movements of the optical bench. In both cases, the fourth actuator is redundant to control the 3 d.o.f. movements and could conceivably excite platform internal modes. The actuators are dimensioned to work against the soft (<300 mHz) springs, and have little strength to significantly excite the stiff optical bench's butterfly mode or the corresponding intermediate platform warp mode.

Technical design drawings

A quick overview of the assembly drawings of the HAM SAS is shown in the following figures (The full HAM SAS drawings are available in

www.LIGO.caltech.edu/~desalvo/HAM-SAS).

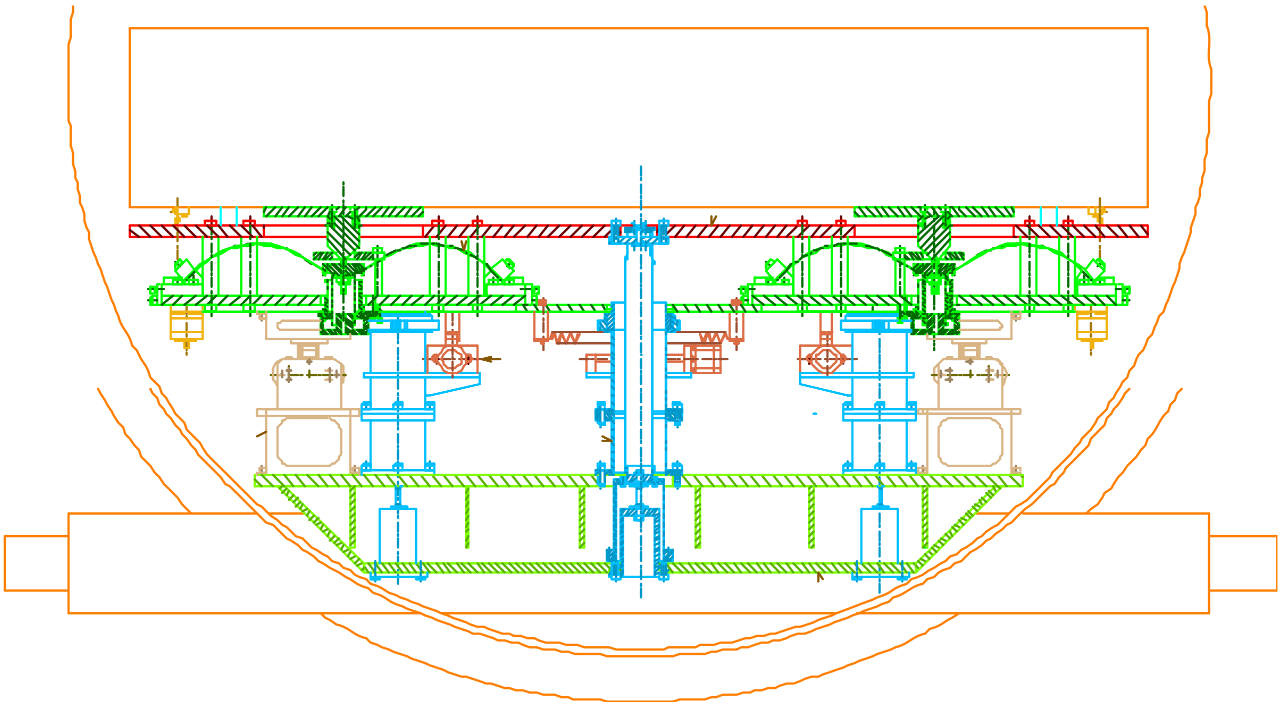

Figure 15: HAM SAS system, access door view: The vacuum chamber and the support tubes are shown in orange, the base platform in light green, the IP and their range limiting columns in blue, the LVDT-actuator pairs in light brown and the horizontal remotely tunable springs in dark brown, the top plate of the intermediate platform is shown in red. The remotely tunable vertical springs are shown in light orange. The intermediate platform is stiffened by the assembly of the GAS filters and a bottom plate (dark green). The optical bench is shown in orange. The bolts tying the bottom plate of the intermediate platform to the GAS filters are tightened only after setting the platform under load on its IPs to provide the initial compliance necessary to mount a rigid table over four legs. The load sharing between the four legs is maintained when the bolts are tightened to stiffen the platform.

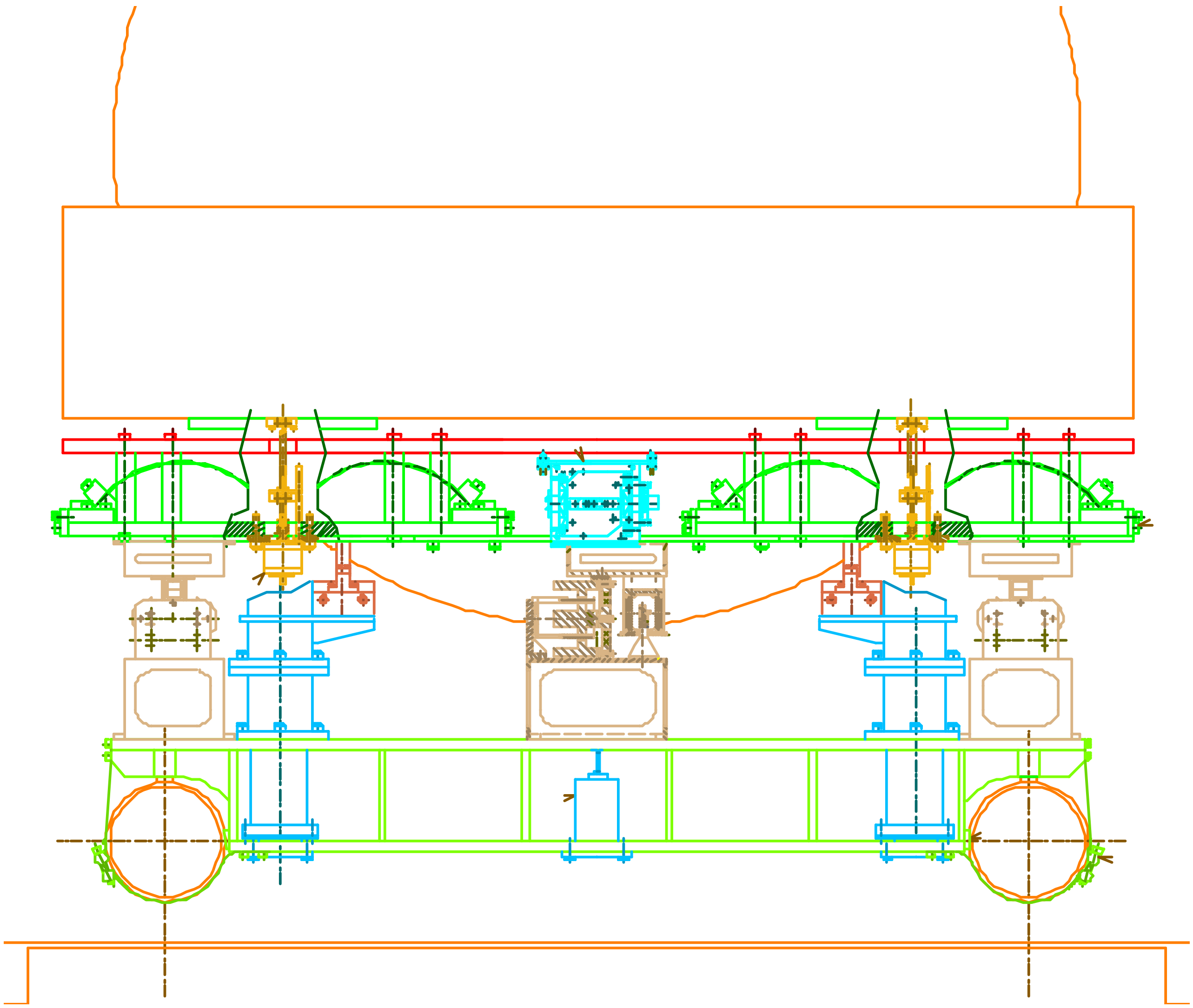

Figure 16: HAM SAS system, beamline view. The same color coding of figure 15 is used. The horizontal accelerometers mounted on the top plate of the intermediate platform are shown in light blue.

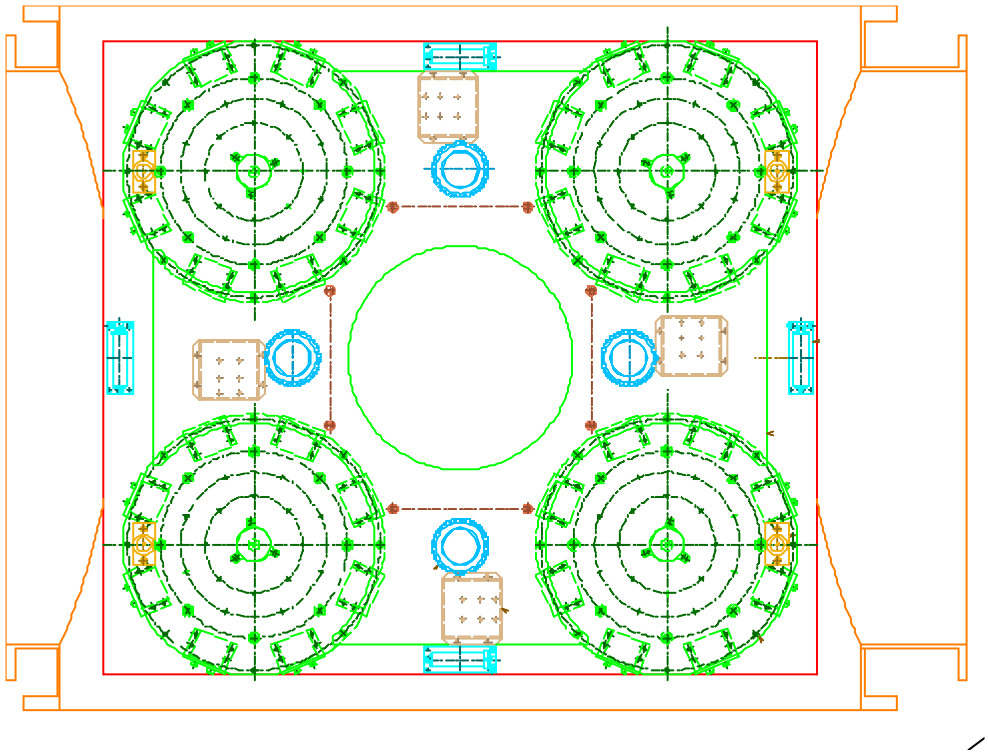

Figure 17: HAM SAS system, Intermediate platform and optical bench, bottom view. The same color coding of figure 15 is used.

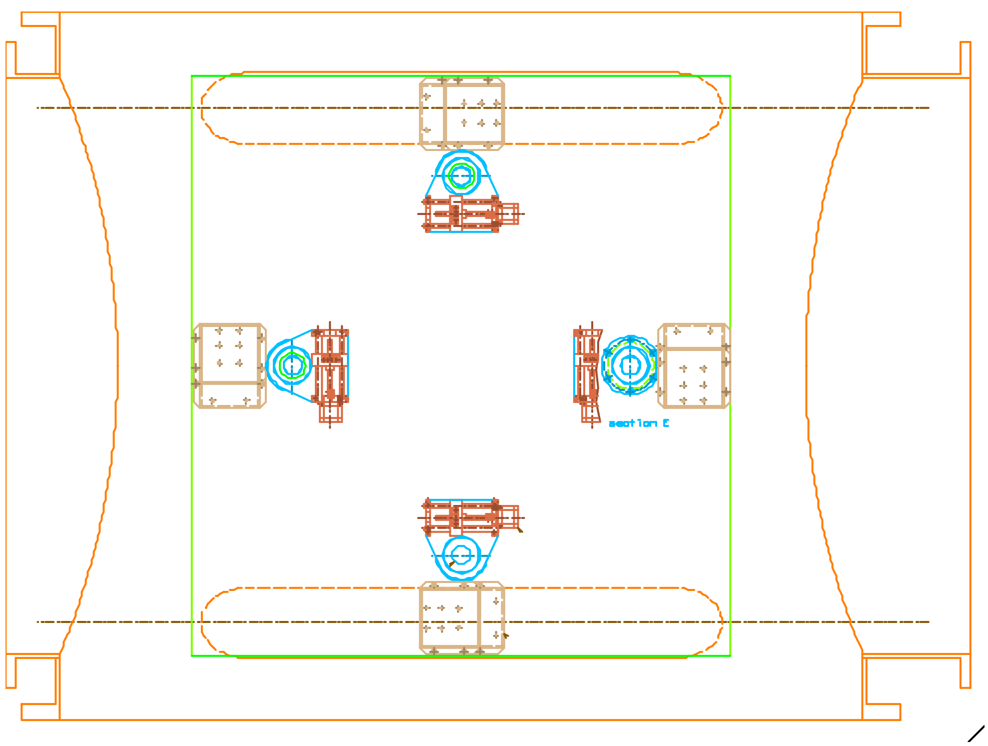

Figure 18: HAM SAS system, Base platform, top view. The same color coding of figure 15 is used.

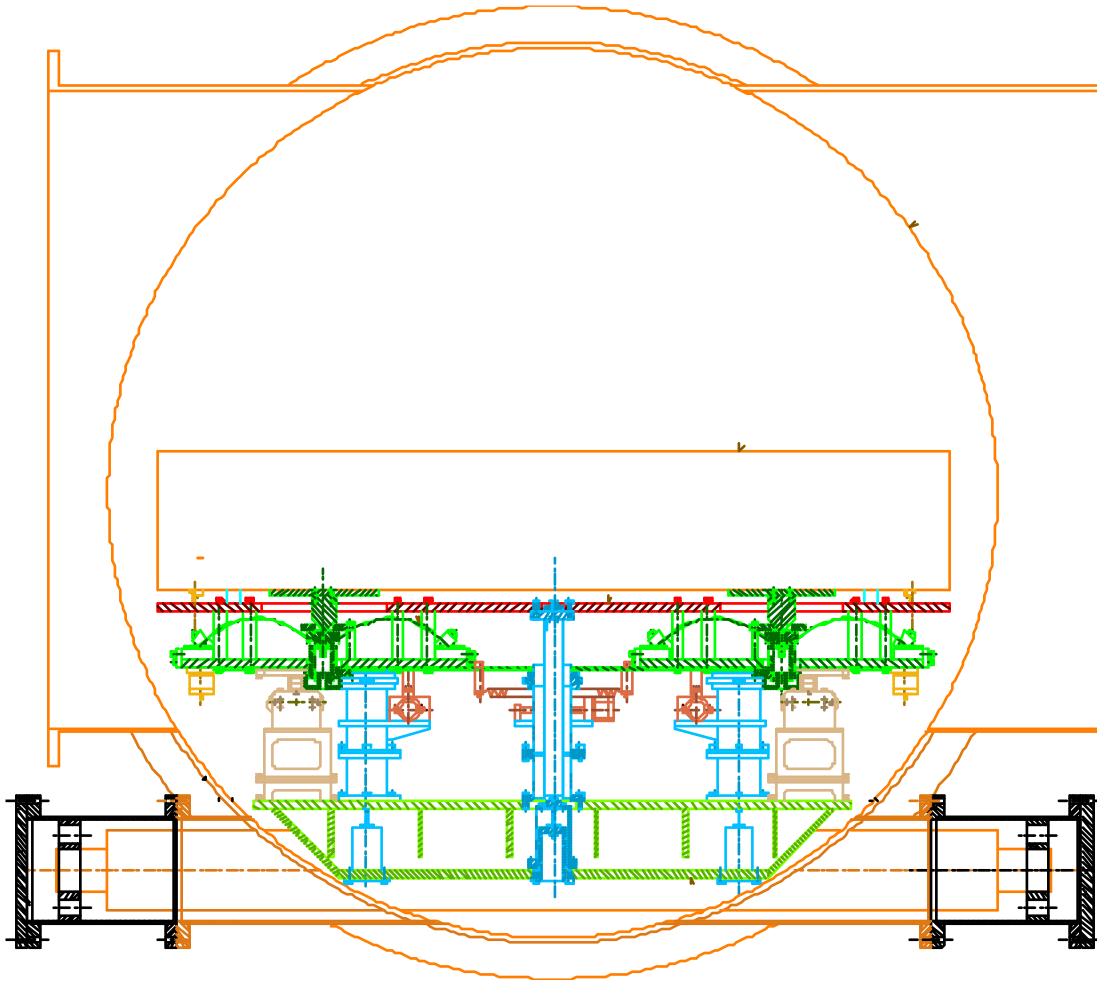

Figure 19: The OMC HAM chambers are not provided with support tubes, bellows and external pre-attenuator or other support structure. They would be supported off the vacuum chamber. For forward compatibility, to allow for possible implementation of external pre-isolators, a pair of standard support tubes will be built to carry the base platform. In the interim the support tubes would be held by four spool-bushings, as illustrated below (black). Support jacks mounted between ground and the spools would avoid overstressing the vacuum chamber structure.

GAS Springs and IP tuning procedures

GAS filters and IPs will be designed to float more than the nominal required weight with the balance being provided by ballast masses.

Each GAS spring is mounted on its own support disk and pre-tuned to the desired vertical resonant frequency at its optimal load and working point.

Once the GAS springs are assembled into the HAM-SAS structure and the optical bench is loaded on them, the four GAS springs need to be brought back to their working point. Since the GAS springs float only their own fixed payload, the optical table needs to acquire exactly the right weight and balance. This, as for the present LIGO stacks, can be obtained by means of ballast masses. The desired optical bench height and the optimal spring working point are matched using the set screws of figure 13.

Since changes of the optical configuration and of optical components will change load and balance, a sufficient number of ballast blocks have to be foreseen to cover all reasonable possibilities. The number, width, and thickness of the GAS blades can be chosen to float the desired overall weight (bench + optics + ballast) with –0 +5% accuracy, with final tuning being achieved adding/removing ballast mass.

The LVDT readout values, and the positioning of the motorized tuning vertical springs, combined by a suitable program, will provide prescriptions on how much mass to add/remove, and where to position it, to rapidly achieve balancing.

The LVDTs provide a sub-micron table positioning memory after changes of optical component configurations. After the necessary ballast corrections, final vertical tuning is made by means of the four motorized tuning vertical springs. The motorized springs also allow for corrections for the change of buoyancy when pulling vacuum, and for large changes in ambient temperature.

Ballast positioning ideas.

In present LIGO, ballast is placed on top of the HAM optical benches. That prime real estate space should be reserved for the optics components. We solved the problem by carving V-shaped slots in the bench stiffening ribs and storing ballast rods inside the optical bench structure. The resulting shelves allow the positioning of steel "logs" (black spots in figure 20) below the bench surface with no loss of rigidity. Varying the number and positioning of the logs will achieve the required balance without using precious bench-top surface. Given the not overconstrained geometry, bolting of the ballast weights is not required. Of course this convenient opportunity is not available if present-design HAM optical benches are used.

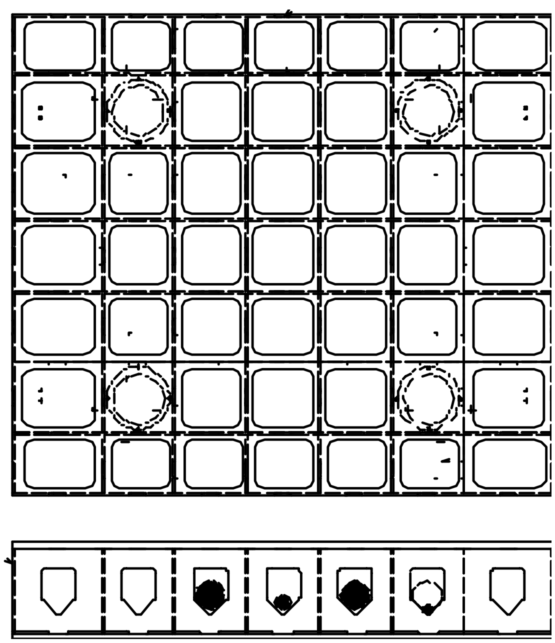

Figure 20: Ballast positioning inside the optical bench structure.

Horizontal frequency tuning.

Once reached the corrected GAS table loading and balance, the IP can be tuned to the desired resonant frequency by simply adding or removing ballast mass in or under the intermediate platform (black rectangles in drawing below). The LVDT readout and the actuators can be used to generate the excitation and to readout the resonant frequency response and automatically prescribe the missing amount of ballast mass.

Final position tuning is obtained by means of the four motorized tuning springs. Their movement does not change the IP resonant frequency tuning.

The IP tuning has to be performed once only. If changes of optical configuration cause changes of load, restoring the correct load for the GAS filters would automatically restore the IP frequency tune as well.

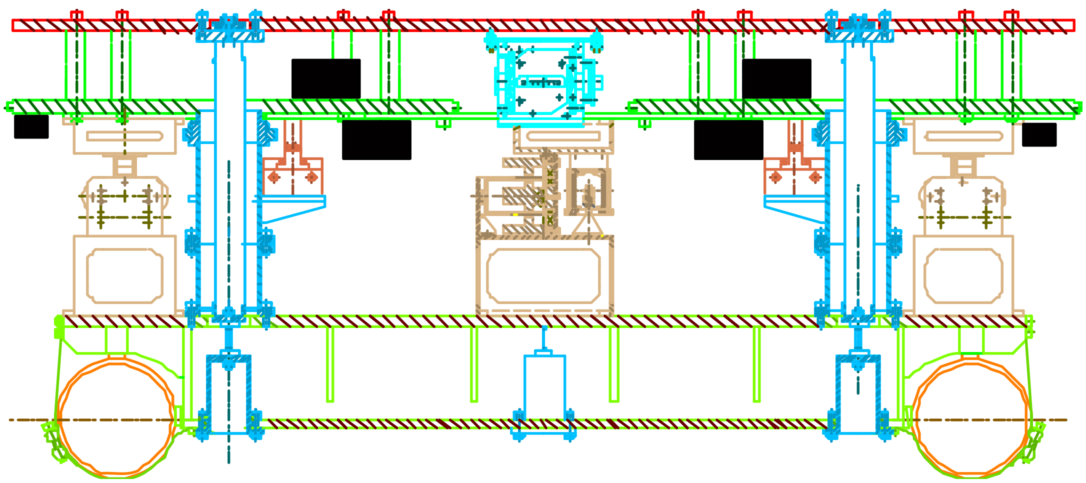

Figure 22 Possible positioning of the IP tuning masses of all components of a complete HAM SAS IP.

As in the vertical direction, the LVDT readouts provide high precision positioning memory and can used to restore the optical bench original positioning and orientation after accesses and modification to the bench's payload.

Performance estimation and Attenuation Frequency boundaries

The proposed system is based on tested components, the only two partially untested points were the use of IP without counterweights (on two out of four IPs) and the use of GAS springs to support a table (as opposed to suspend a load from them). The first point has already been tested with full satisfaction. The second point has been tested on Minus-K commercial systems. Minus-K seismic attenuation systems routinely support optical table loads from below delivering more than 60dB of broadband attenuation. Therefore we expect at least 60 dB attenuation in all directions with no significant surprises.

The IPs are routinely tuned well below 100 mHz, and GAS filters below 300 mHz[viii]. With the above frequency tunings, both systems typically show 60 dB broadband attenuation above 3 Hz and 10 Hz respectively.

Ten times lower resonance frequency tunings have been achieved by remote-control e.m. antisprings, a technique recently developed and tested for the vertical direction by Maddalena Mantovani [ix,x]. Attenuation of 40 dB starting at 1 Hz has been measured with the e.m. antisprings. Implementation of this configuration is recommended to reduce the effects of the micro-seismic peak at 150 mHz. At least one order of magnitude of passive reduction of the microseismic perturbation is possible.

Passive seismic attenuation, has no high frequency cut-off points, except for the perturbations introduced by internal resonances.

The passive attenuation performance of IP and GAS filters should be, by itself, more than adequate to satisfy the OMC requirements. The HAM SAS soft suspensions, with their separate horizontal and vertical functions, are ideal platforms to implement active attenuation. The voice coil tidal actuators, the accelerometers and the LVDTs have sufficient sensitivity and are designed for dynamic control use.

Active attenuation is probably an unnecessary optional for the OMC optical benches, but it may be important in case that cost considerations would require the use of the cheaper HAM SAS to isolate all other HAM optical benches.

Complementary active attenuation can be implemented with no additional in-vacuum hardware, by means of adequate electronics and control software. Due to the favorable geometry and actuation situation, the performance contribution from the active attenuation is expected to be at least comparable to that of a stage of stiff active attenuation. The combined active and passive attenuation performance of the HAM SAS is expected to substantially exceed the cumulative performance of the three Adv-LIGO active attenuation stages.

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Tentative cost breakdown

A preliminary cost breakdown, based on an orientative bid made by Galli & Morelli, is shown in the following table.

It is based on the design available in: http://www.ligo.caltech.edu/~desalvo/HAM-SAS/ .

Part	Qty	Price/Euro	Total	Note
Inverted pend. and platform	1	18,000	18,000	
Vertical GAS springs	4	5,000	20,000	
Base platform	1	11,000	11,000	
Attenuator components totat			€ 49,000	
			$ 63,700	
LVDT/actuators	4	2,200	8,800	
Kapton coated Coils	64	50	3,200	
Motorized slides	8	1,500	12,000	excluding-motors
Total sensor/actuators			€ 24,000	
			$ 31,200	
Hor. accelerometers	4	3,750	15,000	excluding r/o electronics
Vert. accelerometers	4	3,750	15,000	excluding r/o electronics
Optical bench	1	19,800	19,800	
Support tubes	2	13,100	13,100	
Chemical/Heat treatment	1	7,000	7,000	
Total structures			€ 69,900	
			$ 90,900	
Total price **(Euro)**			€ 142,900	packing/shipping excluded
			$ 185,800	

The estimated production delivery schedule is 3 months from receipt of drawings and order.

This price, for prototype construction, is only indicative; competitive bidding, possibly entailing price reductions, will be required before ordering the production units.

The cost of the construction design, including all the assembly drawings, was $14,600.

Production, Testing and Installation

A prototype HAM SAS would be tested at LASTI using the existing optical bench and support tube.

The units can be factory pre-assembled and baked at ~200^{o}C in neutral atmosphere. The bakeout would evaporate all outgassable contaminants and "burn out" any creep of the springs. The residual droop of the springs will then be limited to below a micron over the lifetime of the experiment.

A pre-assembled, pre-tuned, and pre-cabled base plate, IP, intermediate platform and GAS filter unit could be installed in a HAM in a single step using guide bolts. The optical table would be subsequently be lowered in place over it.

Applications beyond the OMC optical benches.

Although the proposed HAM SAS could replace all existing HAM stacks while meeting the adv-LIGO specs, a modified SAS design would be necessary to similarly instrument the BSC optical benches.

The geometry of the BSC chambers requires the use of an optical bench suspended in a fashion described in figure 23. Larger GAS springs would be necessary to float the larger required weight. These GAS springs would be sized half way in between the HAM SAS and the passive EPI [[xi]] springs, already proposed and tested as a passive HEPI replacement.

This scheme would require the introduction of a wire suspension stage between the GAS filters and the optical bench, effectively adding one more attenuation stage and a reserve of horizontal attenuation power. The additional wire pendulum stage would bring a bonus of extra attenuation.

Costs and performance for BSC SAS would be very similar to the HAM SAS system discussed above.

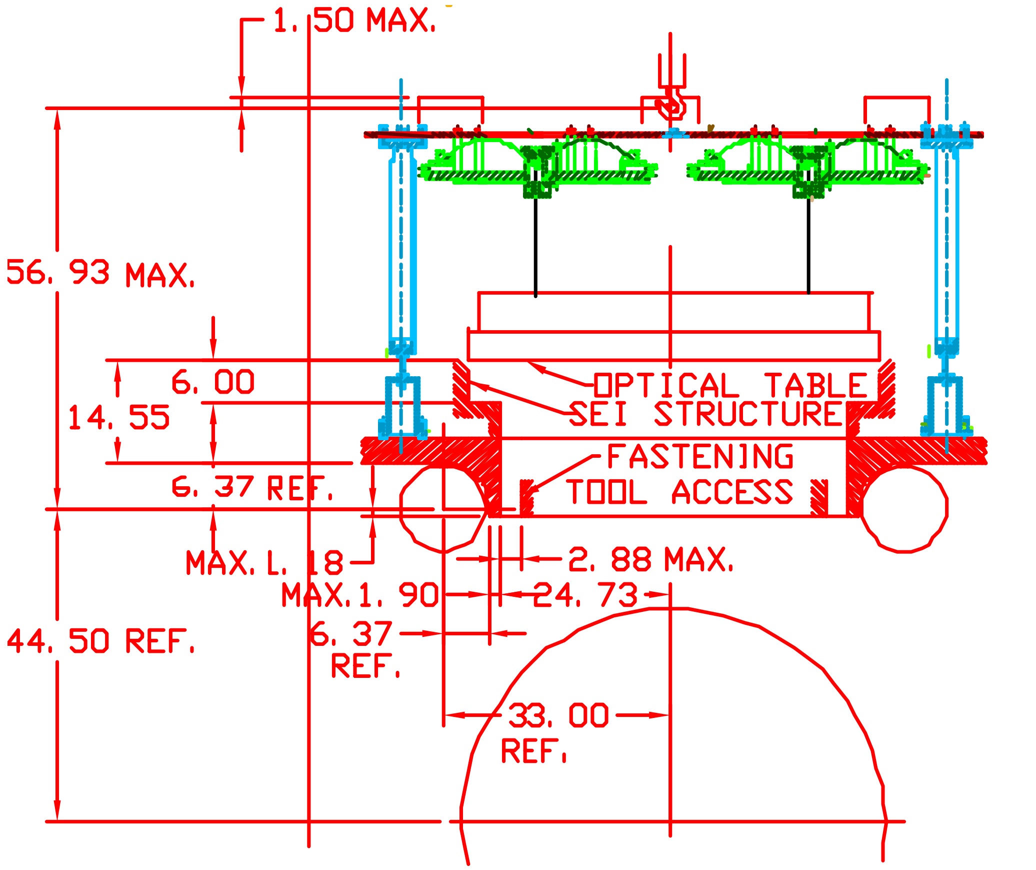

Figure 23: Sketch of the geometry of SAS replacing the adv-LIGO baseline active attenuation stages in BSC chambers. While no detailed design has been made as yet, no major problems are foreseen.

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