DRAFT
Recycler and Beam Splitter suspension structure
Seismic group

JGW-T1100571

This document reports some of the considerations used in the design of the final suspensions of the Recycler beam mirrors of LCGT, and of the solutions adopted.

Although some of the solutions adopted for these secondary mirrors are not adequate for the main test mass mirrors, which will need tighter requirements and more sophisticated solutions, this report is also intended as a guideline and a (not exhaustive) summary of the required functions for the test masses suitable for good interferometer operation, warm or cryogenic alike.
The described geometry is designed so that it can be turned into cryogenic suspensions with as little topological changes as possible.

Generalities

Interferometer controls requirements.

Each interferometer test mass must be kept, at all times, in resonance conditions to its matching test mass three km away, which means that its positioning must be achieved with a precision exceeding 10^{-12} m. The beam splitter and recycler mirrors have less stringent, but otherwise similar requirements.
The test mass mirrors are suspended from wires to allow free longitudinal movement under the action of Gravitational Wave forces, which are expected to generate movements in excess of 10^{-20} m. The beam splitter and recycler mirrors are also suspended with wires, but only to allow proper seismic isolation and low noise interferometer controls.

Mechanical noise requirements.

The seismic attenuation chain and the mirror suspensions and control stage are expected to suspend and position the mirror with a mechanical noise inferior than the movement expected from the action of the Gravitational Waves (i.e. less than 10^{-20}m) for the test masses. The beam splitter and recycler mirrors are subjected to similar, but substantially less stringent requirements.

The description from now on refers only to the recycler mirrors. The beam splitter mirror case is similar and will be discussed as well.
The case of the test mass mirrors is not discussed here but, despite the more stringent requirements, it is perfectly analogous to what discussed here.

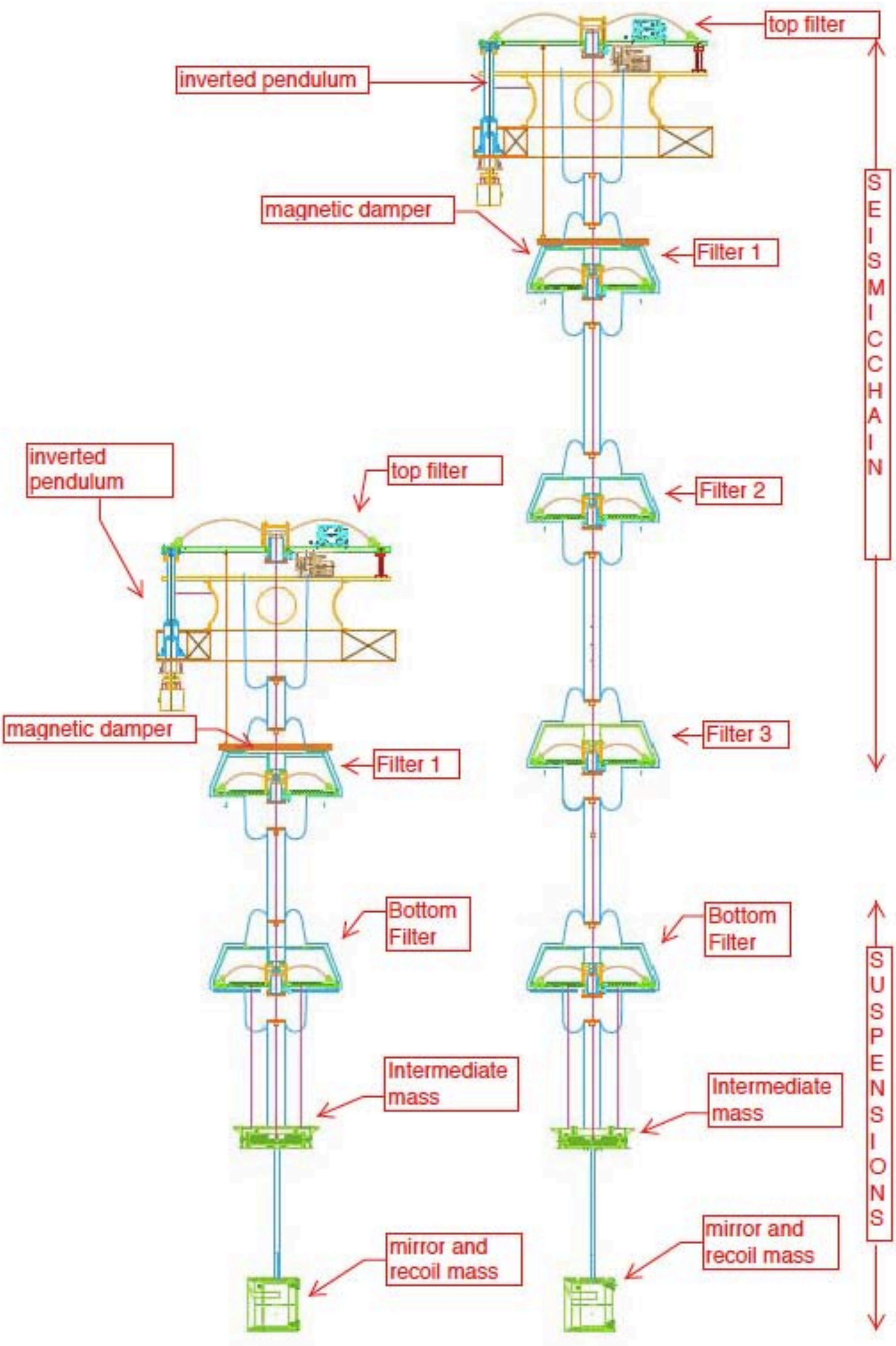

Figure1: Schematic, topological (not to scale) view of the seismic attenuation and mirror suspension chains. On the left: recycler or beam splitter mirror chains (type-B). On the right: test mass mirror chains (type-B). Most components are common to both chains. Only the intermediate mass and mirrors are different, and, of course, the spring's strength and the wire lengths and sizes.

System Topology

The system topology is illustrated in figure 1.
The Inverted Pendulum, the Top Filter and the one or three Standard Filters form the attenuation chain, which suspends the mirror suspensions form the seismic attenuation chain.
The mirror suspensions are formed by the bottom filter, the intermediate mass surrounded by its recoil mass and the mirror with its concentric recoil mass.
The seismic attenuation chains are discussed elsewhere. The mirror suspensions are provided with a number of magnetic dynamic control actuators used to guarantee proper interferometer locking and alignment. All the suspension actuators are expected to work with null static current, to reduce control non-linearities. All required static forces are nulled with motors acting on the top of the chain (see figure 2, 3 and 4) or from motors balancing the center of mass of the intermediate mass.

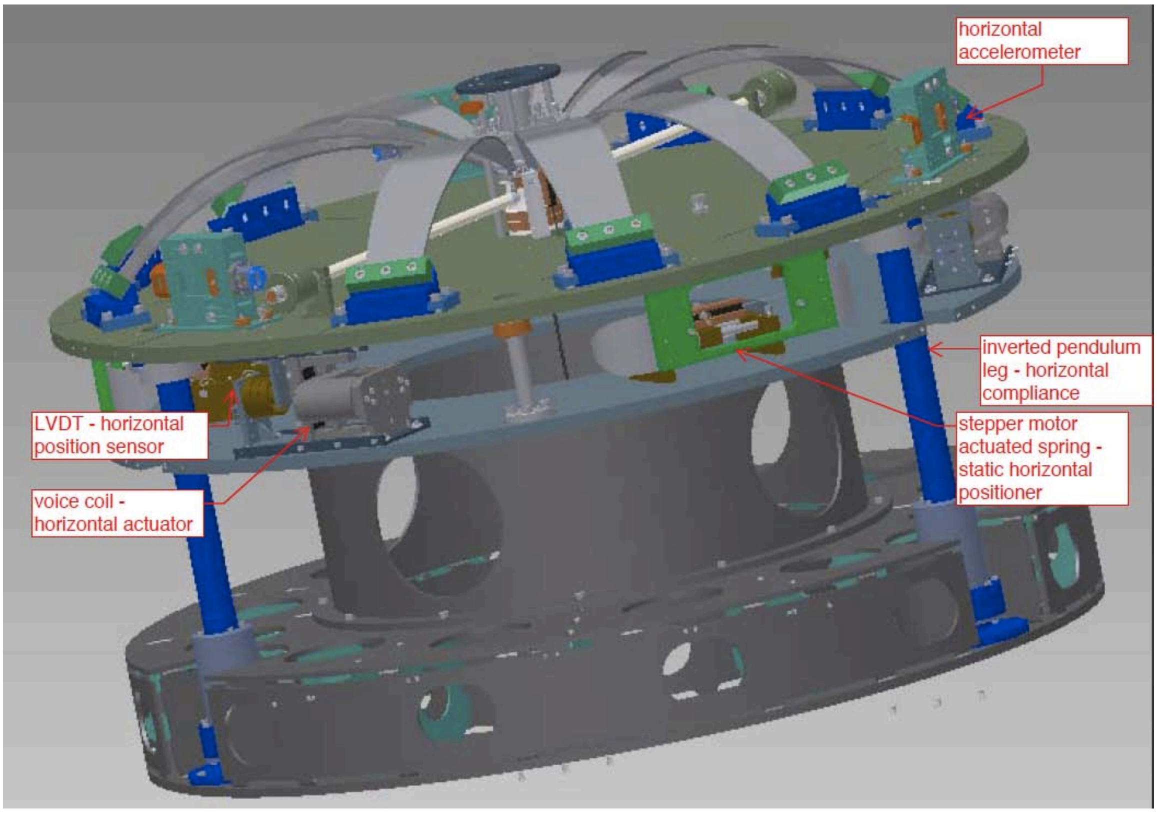

Figure 2: Top Filter and Inverted Pendulum unit. The inverted pendulum legs provide horizontal compliance. The static positioning of the Inverted pendulum is achieved by means of the 3 stepper-motor-actuated springs. The LVDT-position-sensors/voice-coil-actuator units are used for dynamic controls like inertial damping of microseism excitations and tidal corrections. To operate the Inverted Pendulums perfectly straight, precision external longitudinal position adjusters and leveling pistons are foreseen.
The Inverted Pendulum offloads any static horizontal force requirement from the suspension dynamic actuators.

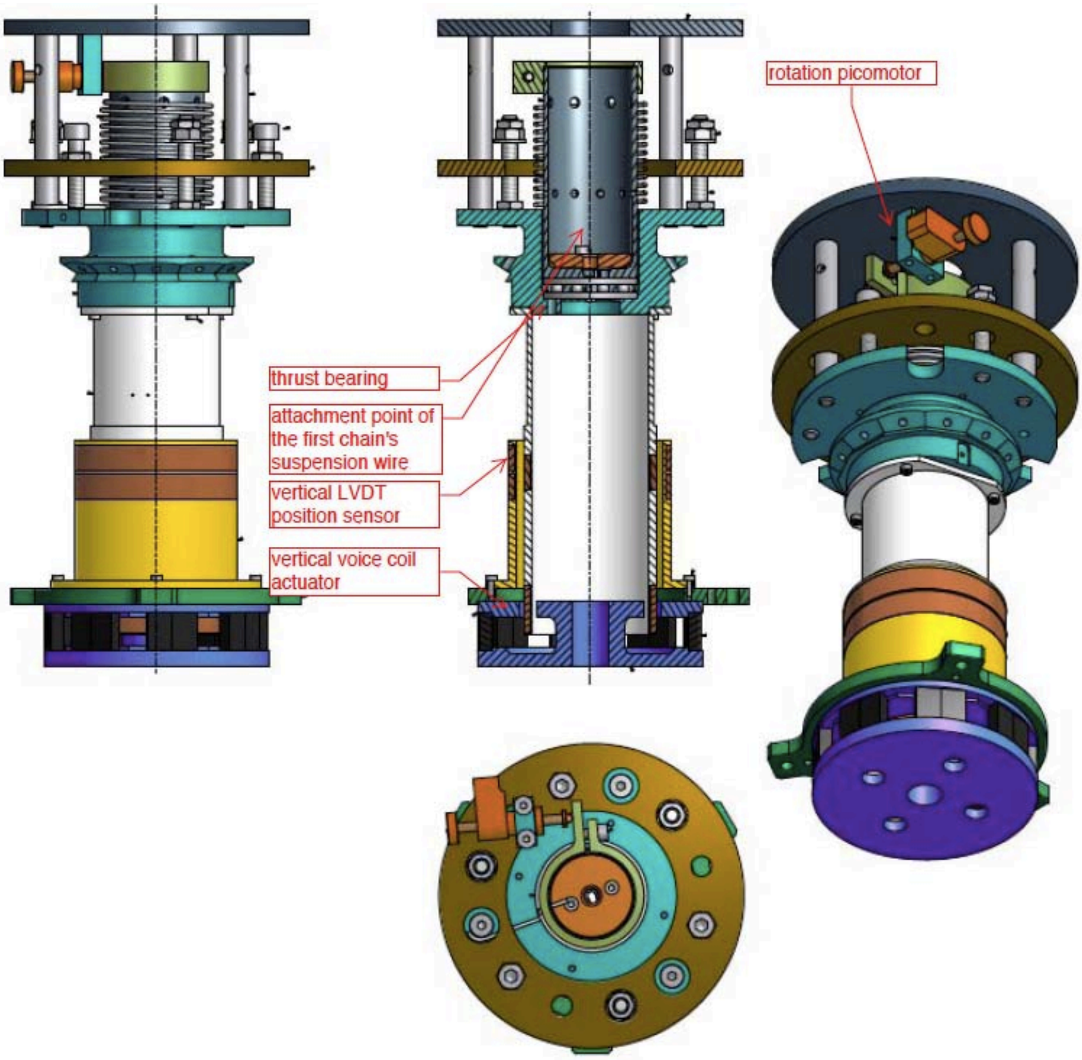

Figure 3: Close-up of the top filter suspension point rotational mechanism. A picomotor acting on a thrust bearing against a recoil springs can rotate the suspension point of the seismic chain and offloads any static yaw force requirement from the suspension dynamic actuators.

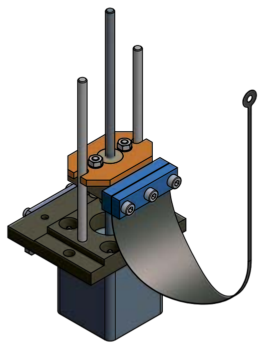

Figure 4: Close-up of the top filter vertical working point adjustment stepper motor mechanism. A stepper motor acting on a soft spring adjusts the vertical working point of the top filter and offloads any static vertical force requirement from the suspension dynamic actuators.

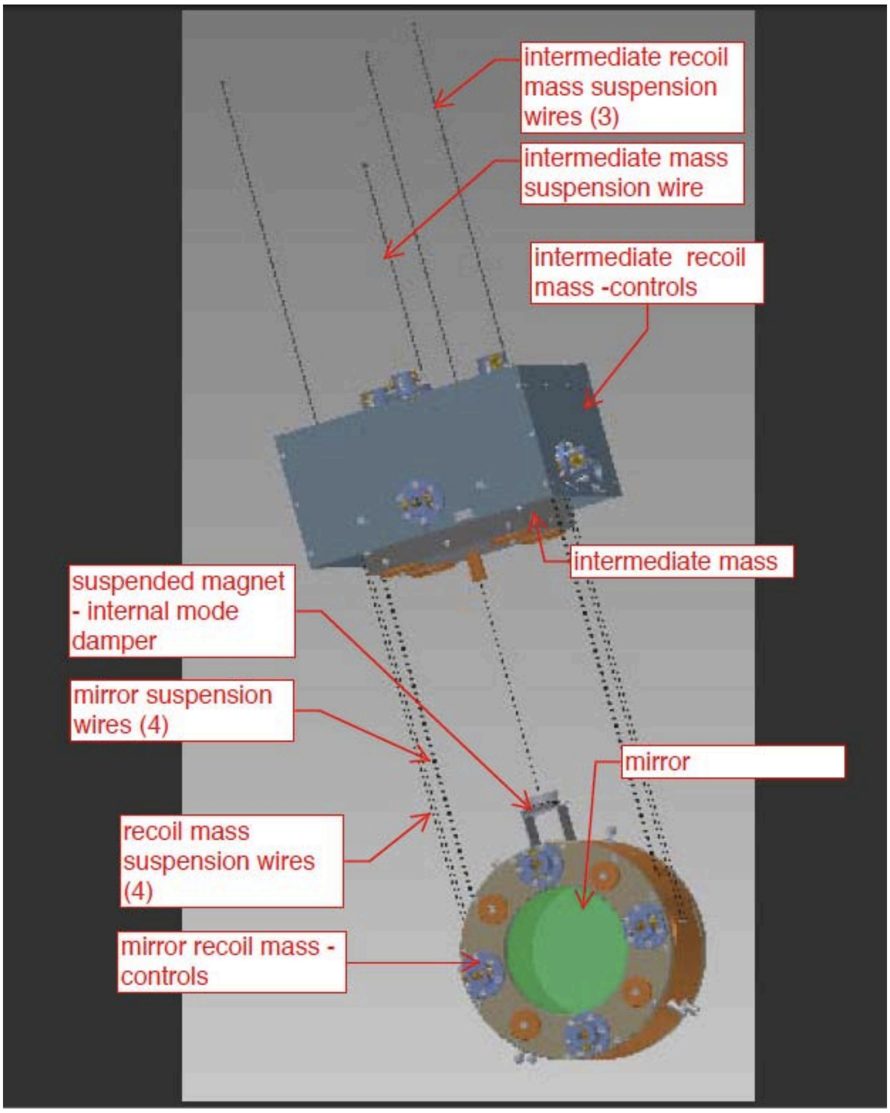

Figure 5: Schematic view of the mirror suspended from the intermediate mass.

Structure of the mirror and its recoil mass

The Structure of the mirror and its recoil mass is illustrated in figure 5.
The mirror and its concentric recoil mass are suspended from the intermediate mass, with 4 wires each.
The fine position controls of the test mass are operated from magnetic actuators mounted on the recoil mass. Direct test mass controls can only be applied with a very small authority (dynamic range limited to $\sim 10^{-12}$ m in the test masses, somewhat larger authority allowed on the other mirrors), and only at relatively high frequency, to ensure that no actuation noise is injected on the test mass to the level of 10^{-20} m in the Gravitational Wave detection frequency band. No static or low frequency actuation should be applied from the recoil mass to avoid actuation non-linearities. The mirror actuation is limited to the longitudinal direction, and to the orientation degrees of freedom (pitch and yaw), by means of 4 magnetic-actuation/position-sensor units mounted on the back plate of the recoil mass. No transversal or roll actuators are foreseen.

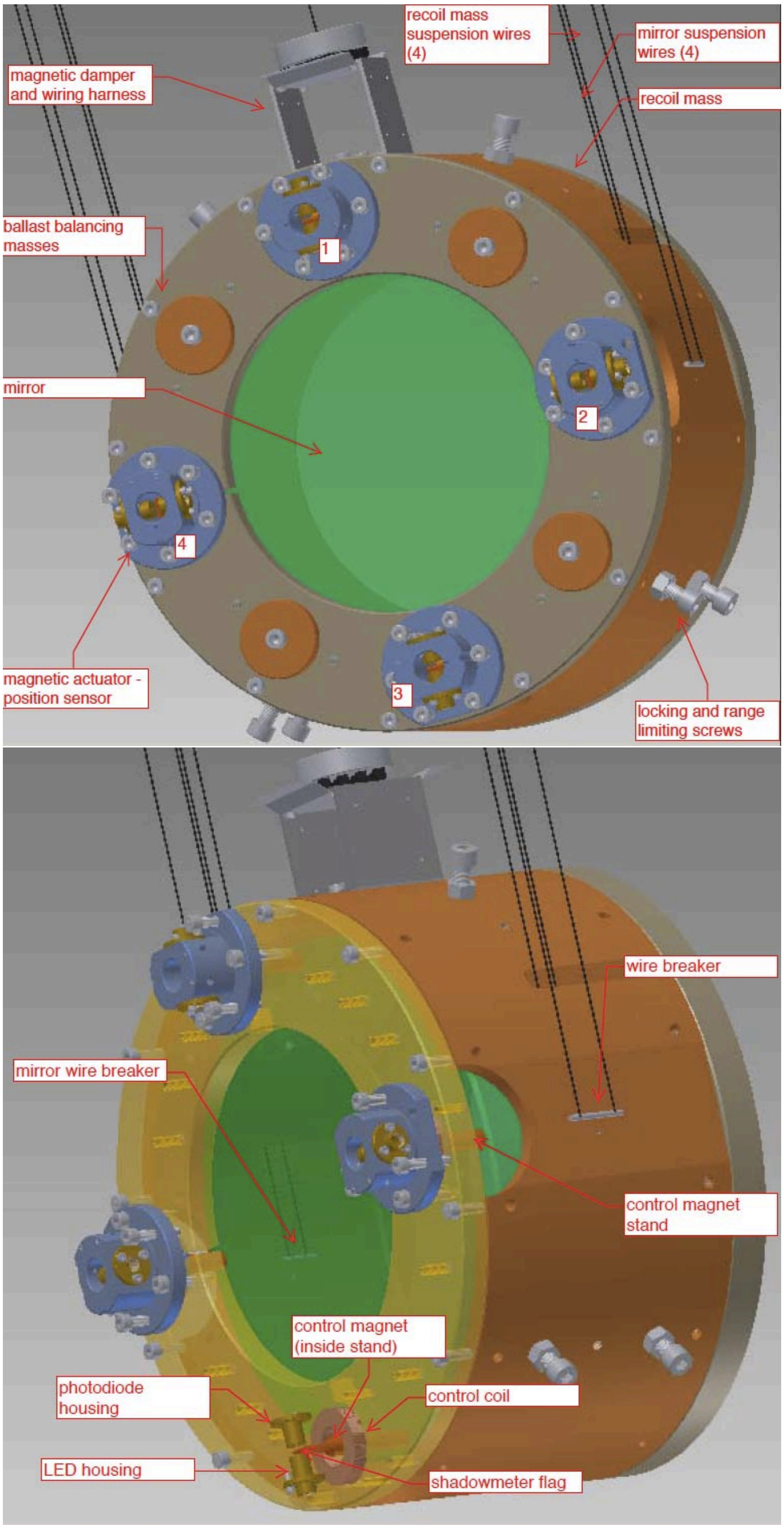

Figure 6: Recycler mirror mounted inside its recoil mass. In the lower image the back plate is made transparent and the body of one of the actuators have been removed for illustration purposes. The wires below the wire breakers are not shown.

The two pairs of suspension wires cradle the cylindrical surface of mirror and recoil mass, and break off on grooved cylindrical breakers, see figure 6. The wire separation, fixed by the groove separation on the breaker, together with the wire diameter and the height below the center of mass define the pitch frequency of the mirror and its recoil mass. The wire separation is presently 10 mm for the mirrors and 20 mm for the recoil mass. The resulting rigid body motion resonant frequencies, and the shapes oscillation of the modes are discussed in a separate chapter.

The recycler mirrors are housed inside the recoil mass, which encase them even in care of wire failure. The recoil mass is constituted by a cylinder, a front plate and a back plate.

The cylinder outer radius is limited to 292 (??) mm by the presence of folded beams passing side by side.

The magnetic actuator position sensor units are mounted on the recoil mass back plate, as illustrated in figure 6. They act on small magnets (2-3 mm diameter 2-3 mm length, TBD) mounted on four posts glued on the back face of the mirror. The posts are made of PEEK or Titanium.

The posts are glued on the mirror's back surface. They also act as occultation flag for the shadowmeter position sensors.

The shadowmeter working principle is shown in the bottom of figure 6: the light produced by an LED is occulted by a fraction proportional to the longitudinal position of the flag. The remaining light is collected on a facing photodiode whose current is thus proportional to the position of the flag. The sensor body also carries a coil, which therefore can apply a collocated force on the flag pole.

The magnetic actuator position sensor units are derived from the LIGO OSEMs. Their precise positioning is achieved by means of 6 screws at 60^{o}, of which three are in push and three are in pull mode to guarantee a rigid and stable mount of the sensor even when the actuator applies forces on the magnets.

The body of the shadowmeter also carries six-pin insulation-displacement connectors for the 30 AWG wire ribbons feeding to the LED, the photodiode and the actuation coil.

To minimize couplings with external magnetic fields, the magnets mounted on the mirror will have alternate polarity, e.g. #1 N, #2 S, #3 N, #4 S.

Therefore the actuation control matrix will be 1-2+3-4for longitudinal actuation, 1-3 for pitch, and 2-4 for yaw. Because the shadowmeter signal has always the same sign, the control matrix will be 1+2+3+4for longitudinal sensing, 1-3 for pitch, and 2-4 for yaw.

The cylinder and the back plate are made out of titanium grade 5, which has been chosen because it is not magnetic and because of its high electrical resistivity (more than 150 μOhm-cm to be compared with ~45 μOhm-cm for other titanium alloys, ~10 μOhm-cm for bronze and 2.8 μOhm-cm for aluminum), thus reducing the Eddy current perturbations to the control magnetic fields. In addition cuts in strategic places are made to further reduce Eddy currents ill effects on controls. Eddy currents are transients that oppose the propagation of the magnetic field of the control actuators, thus introducing a phase delay growing with frequency.

The front plate of the recoil mass shown in figure 7 is made of electropolished aluminum to reduce light scatter in random directions, and with Fresnel-lens-like 40^{o} grooves to disperse halo light back at 10^{o} from the beam axis, safely away from optical components.

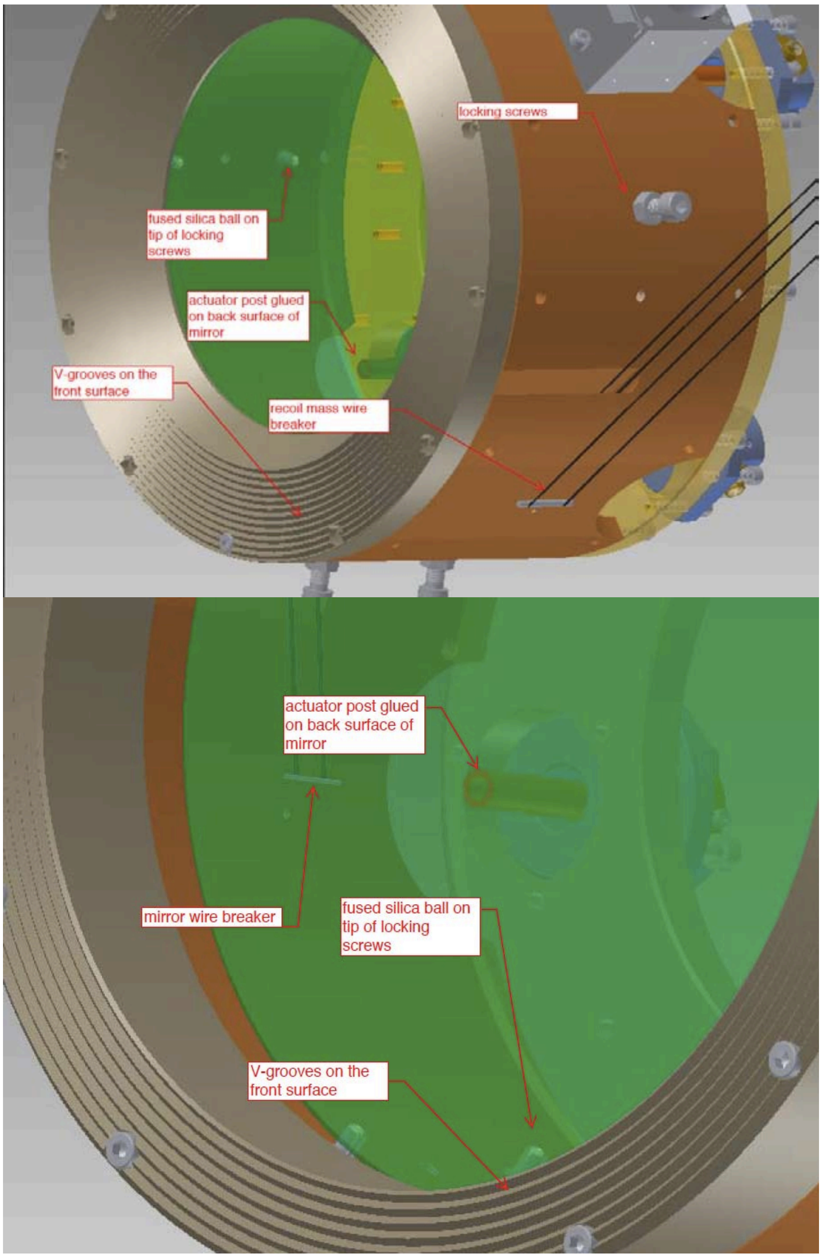

Figure 7: Top, front view of the PR2, PRM, SR2 and SRM mirrors. Bottom, front view of the PR1, and SR1 mirrors, with the wider clear aperture. In both cases the mirrors are imprisoned inside the recoil mass for safety.

Six screws, capped with a fused silica sphere to avoid electrostatic problems, are used to clamp the mirror for transport, and as range limiters when unscrewed by a pre-determined amount.

The recoil mass wires are chosen of large diameter so that they can support the mirror even in case of mirror wire breakage or earthquake.

The recoil mass wires are kept in place on the wire breaker by a small clamp (not shown), to keep them from sliding and dropping the recoil mass in case of accident.

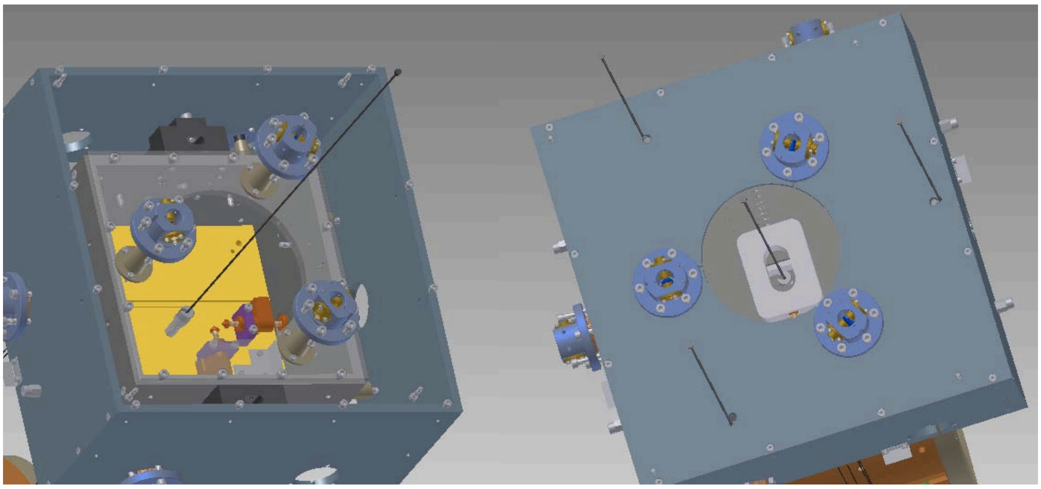

Figure 8: support point for the intermediate mass (left) and its recoil mass (right).

On the top of the recoil mass a small raised aluminum platform offers a highly conductive surface for Eddy current damping of the mirror and recoil mass transversal modes. The damping is applied by a 4x4 matrix of small 5 mm cube magnets attached on a whip dangling down from the intermediate mass. The transversal modes are excited by small misalignments of the mirror actuators, which are intended to act only longitudinally, and generate angular noise. The Eddy current damping solution is adequate to damp these modes for the secondary mirrors. This method is probably too dissipative to damp the modes of the test mass mirrors where it would cause excess suspension thermal noise. In the test mass case, additional transversal actuators may be necessary to damp transversal modes.

The Eddy current platform also carries winglets for clamping of electrical wiring. The wiring is made with four six-wire 30 AWG copper wire ribbons looping to the intermediate recoil mass and from there routed to the bottom filter where a switch to 26 AWG ribbon is performed.

The recoil mass design is made with the center of mass slightly forward of the center of the suspension wires, so that balancing is achieved with the addition of four small ballast masses on the back plane. Precision balancing can be achieved by changing the size of these ballast masslets.

The front plate for the PR1 and SR1 mirrors shown in figure 7-bottom have a wider clear aperture, to allow reflection of the wide beam over the entire 250 mm diameter mirror.

The front plate for the PR2, PRM, SR2 and SRM mirrors shown in figure 7-top has a smaller clear aperture because the beams they reflect are one order of magnitude smaller.

The back plates have large clear aperture to allow pickoff of the PR2 and SR2 transmitted beams.

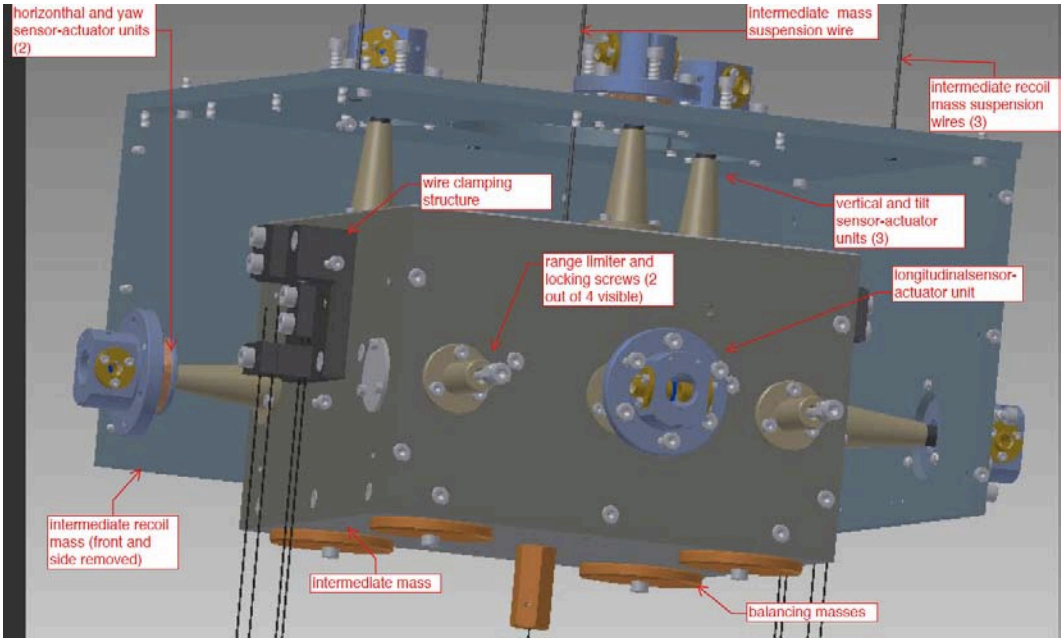

Figure 9: Illustration of the intermediate mass surrounded by its recoil mass. The front and side plate of the recoil mass have been removed to allow observation of the components and their functionalities.

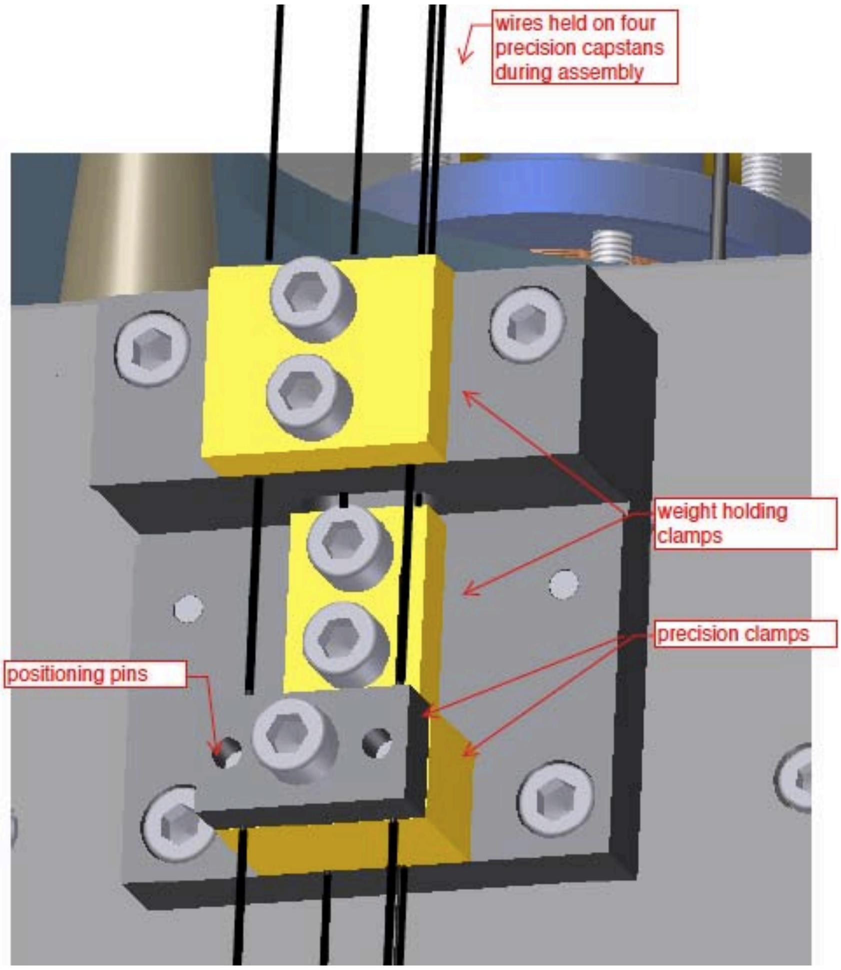

Figure 10: Illustration of the wire-clamping scheme with separate clamping for weight support and for pendulum flexure point definition.

Structure of the intermediate mass and its recoil mass

The Structure of the intermediate mass and its recoil mass is illustrated in figures 6 and 8. The main function of the intermediate mass is to suspend and control the mirror and its recoil mass.
The eight ends of the four suspension wires are clamped to the sides of the intermediate mass. The wire clamping, illustrated in figures 9 and 10, is made in two stages. In the top stage the wire is clamped strongly to support the load. In addition different clamping forces are necessary for the two thin mirror suspension wires and the two thicker recoil mass suspension wires. The two top clamps of the clamping block are intended for this function. During this operation the mirror and its recoil mass must be aligned precisely to each other, and to the horizontal plane. This is achieved with loose clamps, holding the eight wire ends on precision capstans designed by NIKHEF.
After alignment is achieved, the two top clamps are locked. To hold the wires firmly against the mirror or recoil mass weight, some plasticity is caused in the clamp and/or wire. Plasticity generates a massive amount of dislocations which can cause anomalous bending dissipation noise.
The lower clamps are mounted in tandem, with the wire breakoff points on the plane of the intermediate mass center of weight. The height of the breakoff point can be changed, if necessary, by changing or re-positioning the clamping block. The lower clamps are only tightened the amount necessary to hold the wires transversally, against the oscillatory motion, but not to hold the weight. This arrangement does not cause plasticity and dislocation accumulation at the wire bending point. The central component of the lower clamp is grooved with a 60^o groove (see figure 11-left) to allow for a symmetric, three-point clamping of the wire as well as wire positioning. Internal positioning pins guarantee the perfect alignment of the clamping jaws, and machining of the clamping surface (see figure 11-right)assures proper force concentration on the clamp-wire break point.
The intermediate mass is supported by a central double nail head wire (see figure 8-left) whose effective bending point can be tuned to fall at the center of mass as well. The intermediate recoil mass is also suspended by nail head wires, three in number, illustrated in figure 8-right. All of them hook onto a keyhole fast mount.
Intermediate amplitude and frequency interferometer controls are applied, in all degrees of freedom, on (or from) the intermediate mass. The intermediate mass is actuated upon from its own recoil mass, which is provided with 6 magnetic-actuation/position-sensor units, working on all 6 degrees of freedom, as illustrated in figure 9. These magnetic actuator/position sensors are positioned to generate, as much as possible, a diagonal or block-diagonal sensing and control matrix. The sensor and actuator matrices are identical; it is 1+2+3 for vertical, $2-(1+2)/\sqrt{3}$ for pitch, 1-3 for roll, 5 for longitudinal, 4-6 for transversal and 4+6 for yaw motion. The actuation units are the same as those of the mirror controls, only they operate with much larger authority, which is achieved by the use of 10 mm diameter, 10 mm long permanent magnets on the intermediate mass. The permanent magnet stands are built out of Peek.
Like the mirror recoil mass, both the intermediate mass and its recoil mass are built out of titanium grade 5.
Obviously, actuation applied on the intermediate mass is transmitted to the test mass (and its recoil mass) only at frequencies below its pendulum suspension

frequency (or resonant frequency in the other degrees of freedom). Therefore only low frequency actuation is possible from the intermediate mass. The magnetic actuators of the intermediate mass is also intended to operate around zero current, to avoid non-linearities.

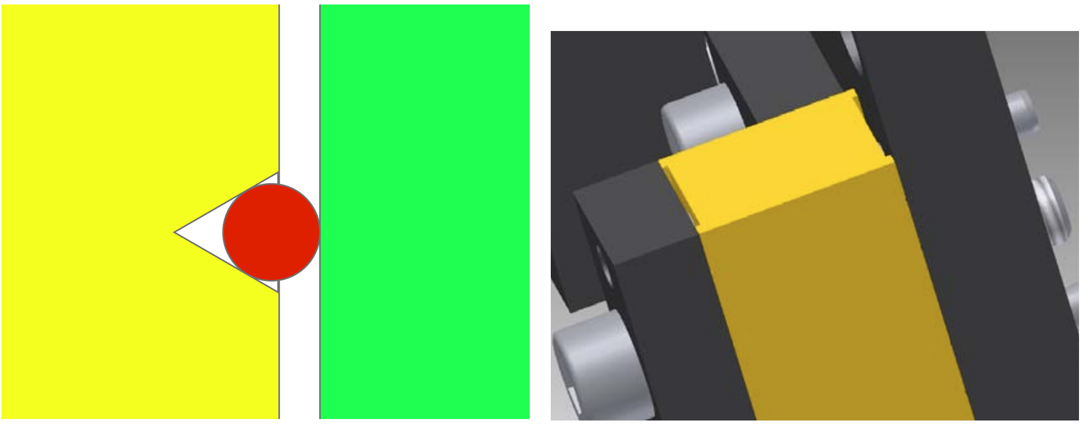

Figure 11: Illustration of positioning groove geometry with three-point 120^{o} contact point on the clamp (left) and compression force concentration on clamp edge points (right).

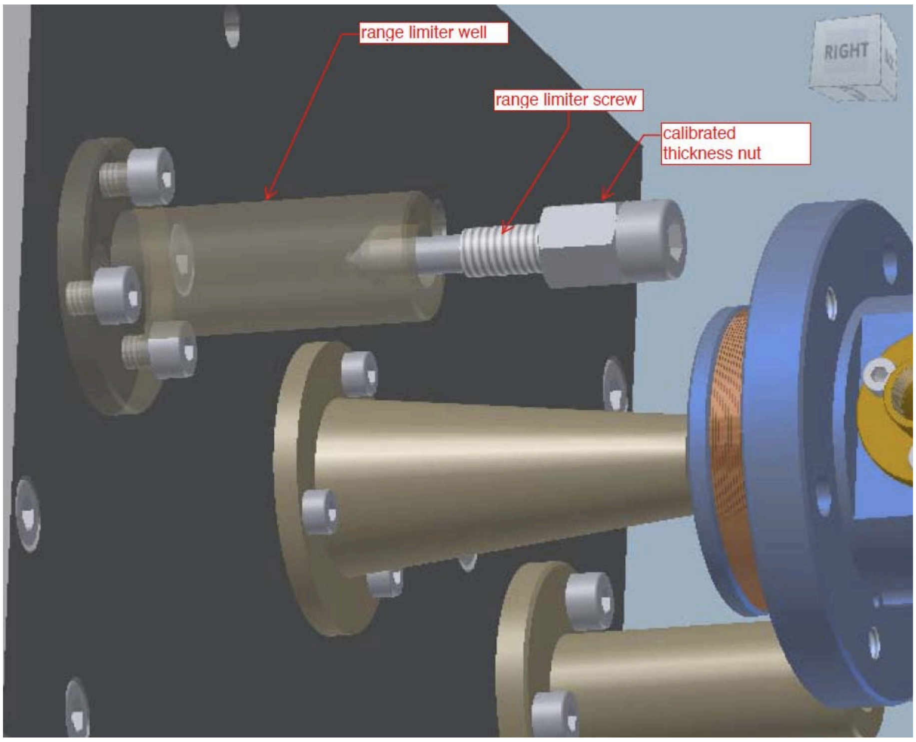

Figure 12: Illustration of the range limiters that keep accidental motion from damaging the magnetic actuators (the plate supporting the screw has been removed to allow view of the structure. When fully engaged the calibrated nuts of the range limiters lock the position of the intermediate mass at the exact center of its recoil mass.

Four range limiter screws, shown in figure 12, mounted on the intermediate recoil mass limit the movement range of the intermediate mass, thus preventing breakage of the position sensor flags. The calibrated thickness nut is such that if the screws are screwed all the way in, the intermediate mass is precisely positioned at the center of the intermediate recoil mass, for sensor installation, calibration or transport. If the screws are pulled back one turn and locked with the nut, the play is 1 mm, to be compared with the 1.5 mm sensor play.
A whip supporting a plate with a 4x4 matrix of small magnets, shown in figures 5 and 13 provides Eddy current damping of the mirror roll and transversal modes, which would otherwise be uncontrolled.

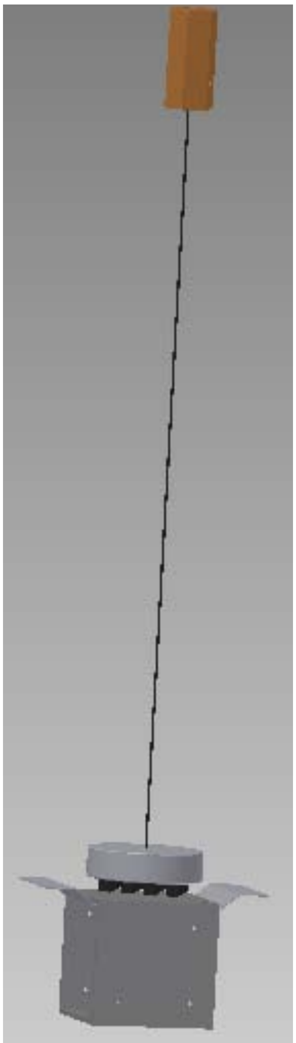

Figure 13: Whip extending from intermediate mass, carrying 4x4 damping magnets, hovering above damping plate on top of the mirror recoil mass. The gull wings are for electrical cabling.

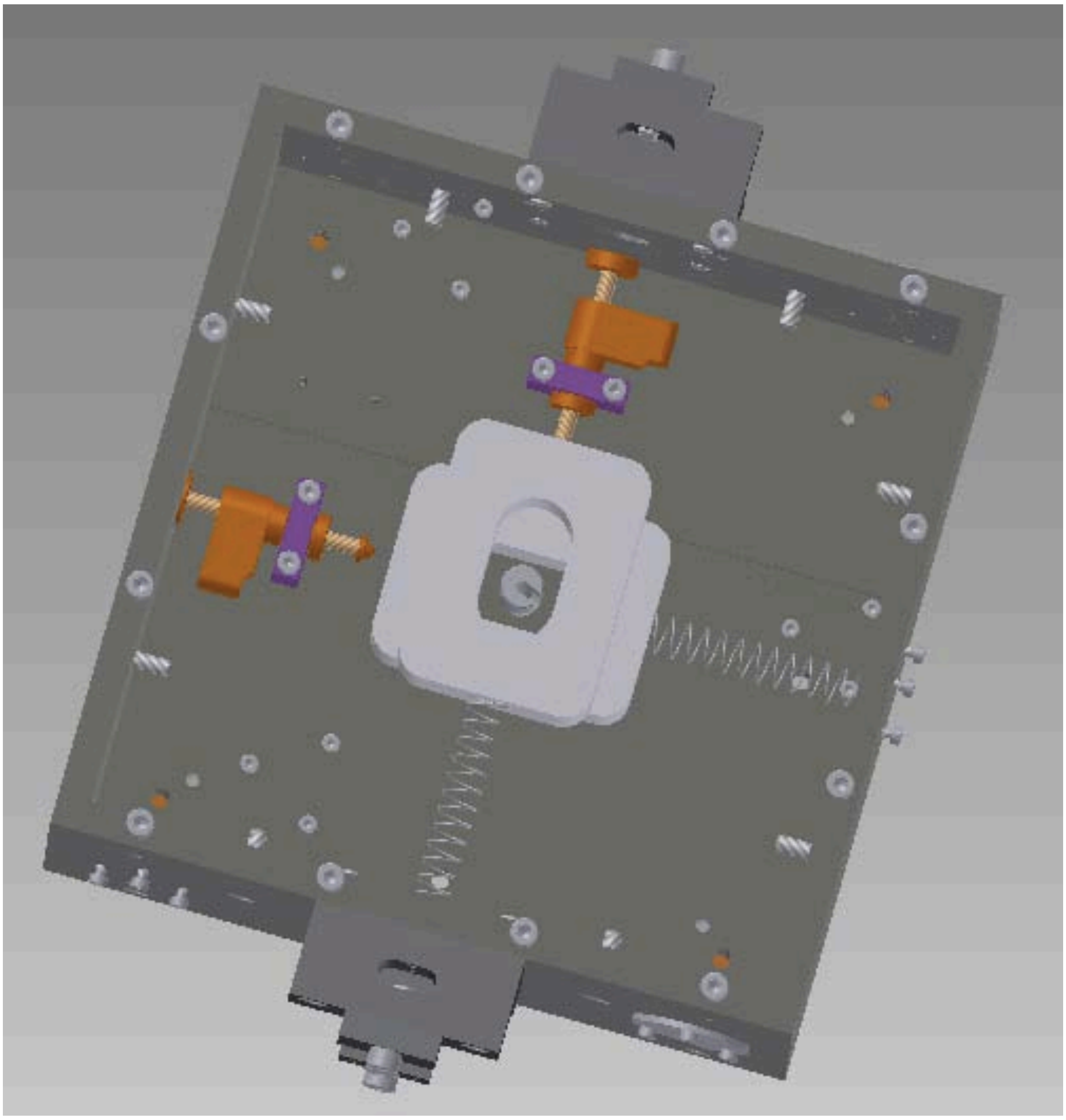

Figure 14: structure of the picomotor actuated balance masses. The cover plate and the guide plates have been removed to allow observation.

Static force elimination from all dynamic actuators.

The intermediate mass applies static controls of pitch and roll (not yaw) to the test mass. These static controls are obtained by means of remotely controlled moving masses placed inside the intermediate mass, illustrated in figure 14, which change the intermediate mass center of mass position and thus its tilt. Because the test mass is attached to the intermediate mass with 4 wires, any intermediate mass angular motion is directly transmitted to the test mass as well (and to the test mass recoil mass).

As already mentioned above, static positioning of the test mass in the longitudinal and transversal directions are applied from the Inverted Pendulum at the beginning of the attenuation chain of figure 2, while static vertical and yaw positioning are applied from the top filter, mounted on the inverted pendulum (figure 3 and 4).

The intermediate mass is suspended with a single wire from the GAS spring of the bottom filter (figure 8-left), while the intermediate recoil mass is suspended with three wires from the body of the bottom filter (figure 8-right). Therefore the tip and tilt of the bottom filter control the tip and tilt of the intermediate test mass as well. Two remotely controlled moving masses control the static tilt of the bottom filter and allow precision tilt centering of the intermediate recoil mass actuators on the intermediate mass. Vertical centering is achieved via internal magnetic actuator, and by control of the working temperature of the bottom filter. Like the top filter, the bottom filter is equipped with a rotational mechanism. This lower rotational mechanism is reserved for the yaw centering of the intermediate recoil mass actuators to the intermediate mass only, and is not intended to change the test mass static yaw positioning.

Structure of the bottom filter

The bottom filter is a modified standard filter, with the addition of the already mentioned rotation stage and two remotely controlled tip-tilt control masses.
The bottom filter is supported by a single wire, which allows its tip and tilt. It hangs from the seismic attenuation chain, which in the main test mass case is a three standard filter chain, and in the recycler and beam splitter case a single filter.

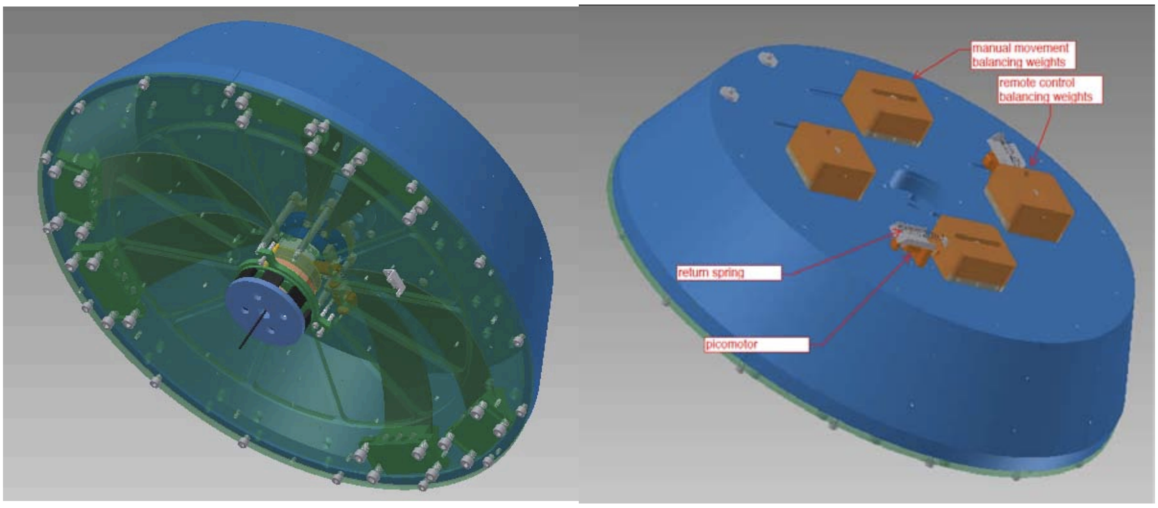

Figure 15: Bottom filter bottom and top view.

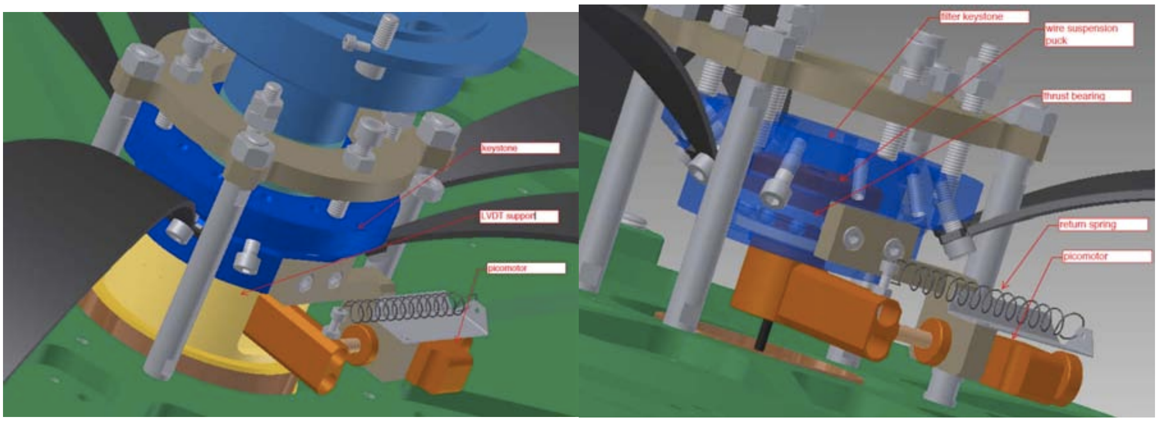

Figure 16 Rotation mechanism, Keystone made transparent on right panel.

The Intermediate Mass hangs from the bottom filter keystone, while its Recoil Mass hangs from the body of the bottom filter, as shown in figure 17. As the intermediare mass is sensed and actuated from its recoil mass, precision mutual alignment is necessary. The remotely controlled tip tilt mechanisms (figure 15) and rotation mechanism (figure 16) are intended for precision positioning of the Intermediate Recoil Mass with respect to the Intermediate Mass. The vertical positioning is obtained through thermal controls of the vacuum chamber and the filter voice coil.

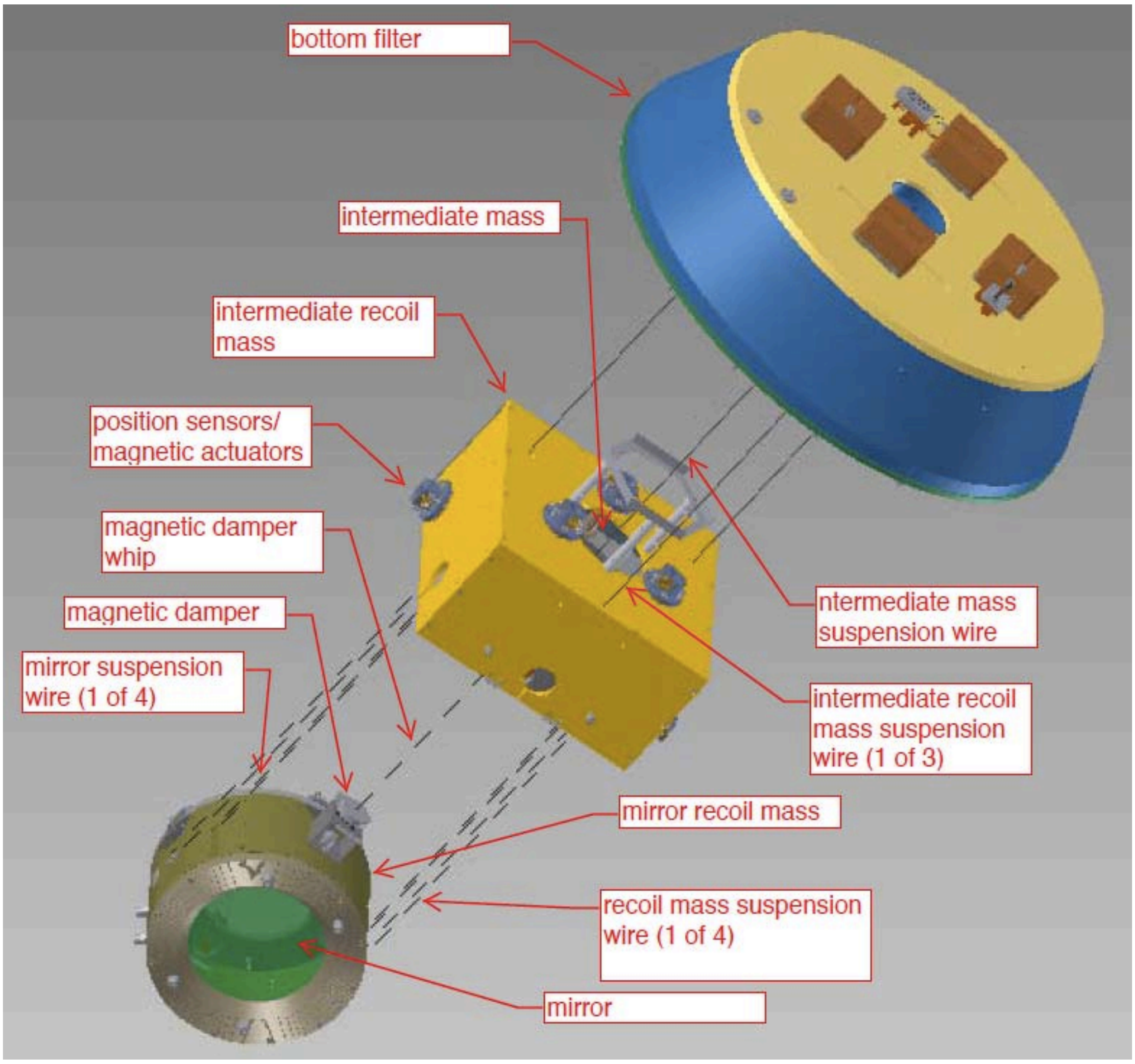

Figure 17: Full payload assembly.

Structure of the Beam splitter suspensions.

The beam splitter is 38 cm in diameter and 8 cm in thickness, with 2 mm bevel. One face has reflectivity of 50%, while the other is treated with an anti reflective coating. Because the beams hit the beam splitter at 45°, and the beam shifts while it traverses the mirror thickness at 29°, only a fraction of the beam splitter surface is useful as illustrated in figure 15. The resulting clear aperture of the beam splitter is only 200 mm. This is acceptable because the 200 mm diameter beams injected in the Michelson's Fabry-Perot cavities will rapidly expand to fill the entire 250 mm diameter of the mirrors.

Similarly, the beams returning from the Fabry Perot cavities are sufficiently sampled by a 200 mm acceptance, with a loss of only several ppm.
The most relevant problem is that the mirror edges and it actuators would clip the direct and the transmitted beams in different ways, which would result in different and astigmatic feedings into the two Fabry Perot cavities. Most importantly, the return beams are also clipped in different ways, which would result in an improper subtraction in the recombined beam. This improper subtraction would directly affect the GW signal.
To avoid this, careful beam stripping is necessary on all four sides of the beam splitter to reduce the beams to within its full acceptance. This is done with precision located and seismically isolated ~200 mm diameter baffles.
Because of the beam shift inside the glass thickness, a much larger free space is available on the reflective face. Therefore the control instrumentation has been positioned on the front face. On the other side, the recoil mass back cover has been notched to avoid clipping the beams.
Topologically the beam splitter suspensions are identical to those of the recycling mirrors, and the materials the same. The sizes, masses and the moments of inertia are much larger. All solution adopted for the recycler beams are simply scaled for the beam splitter.

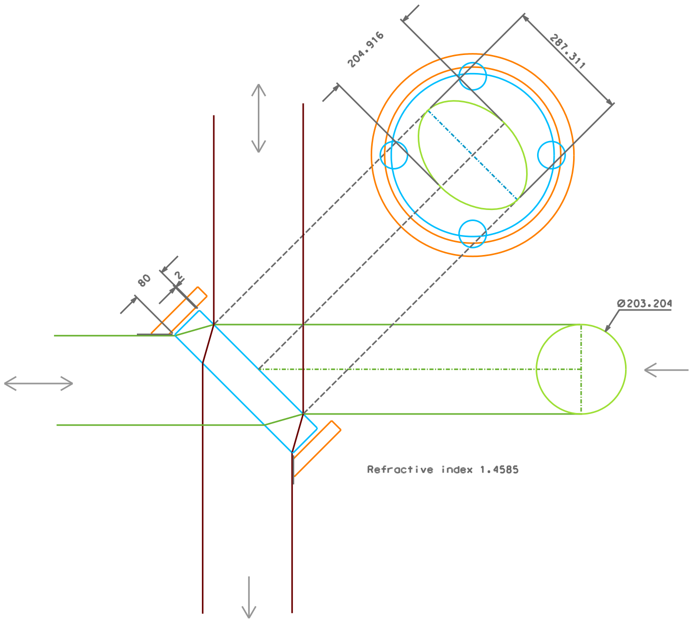

Figure 18: Scheme of the maximum circular clear aperture of the beam splitter. There is substantial free space for the actuators above and below the beam profile in the front face (50% reflectivity face).

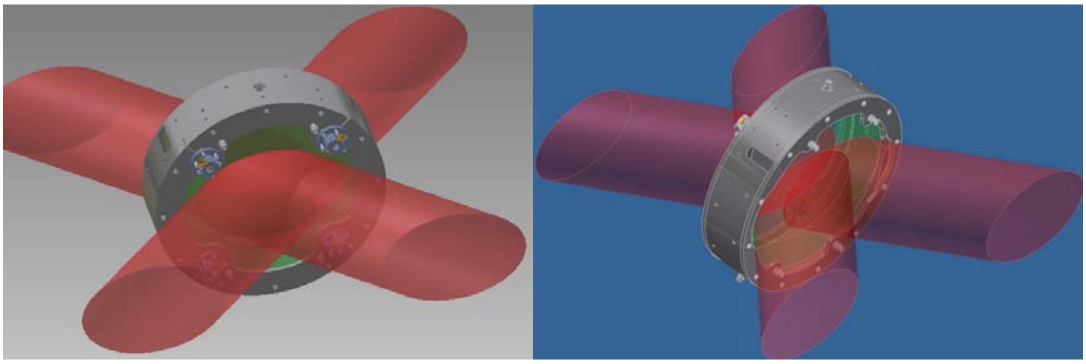

Figure 19: Illustration of the surface occupancy of 203 mm diameter beams on the front (reflective surface, top image) and back face (anti-reflective) of the beam splitter, and of the maximum allowable occupancy for the recoil mass and its instrumentation.

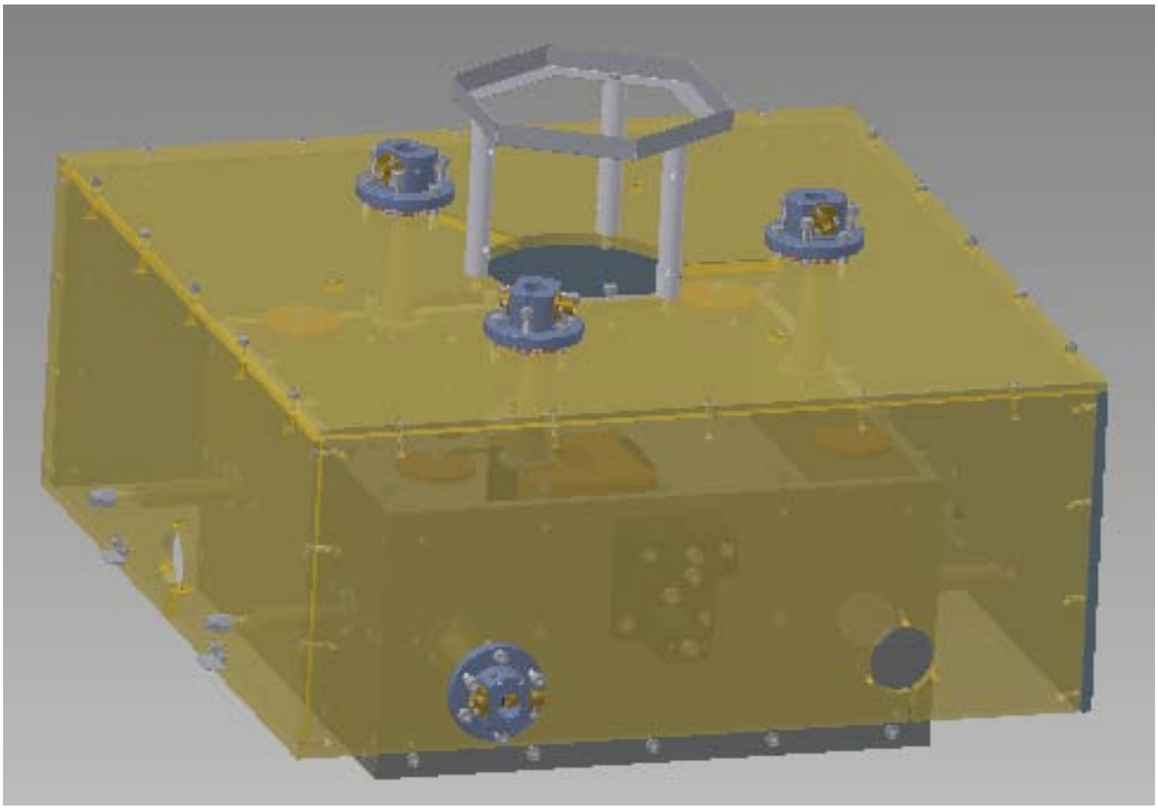

Figure 20: beam splitter intermediate mass.

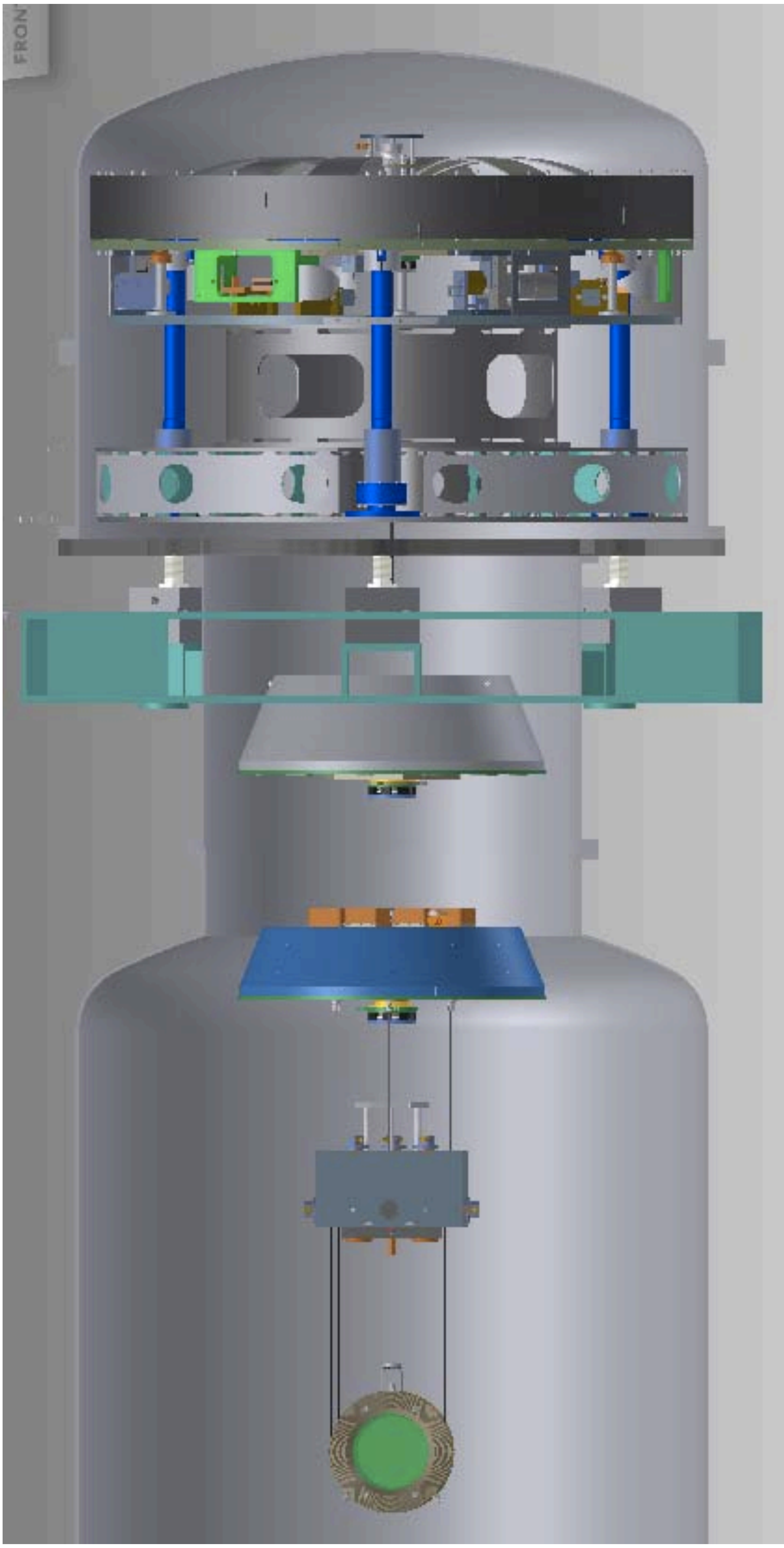

Figure 21: Three-D view of general assembly of the Type-B recycler seismic attenuation and suspension chain.

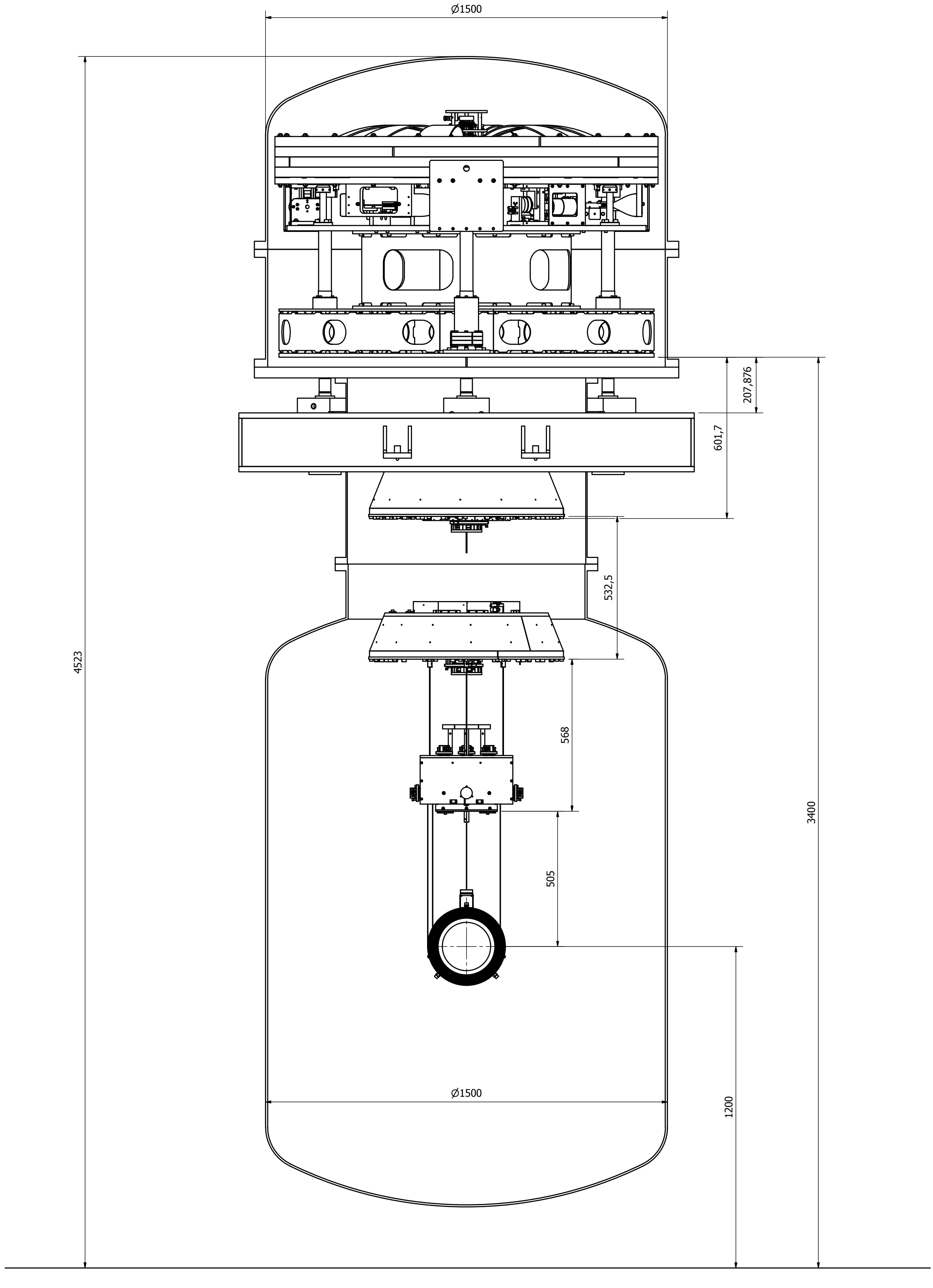

Figure 22: Two-D view of general assembly of the Type-B recycler seismic attenuation and suspension chain.

Payload masses, moment of inertia, wires and resonances

The mass and moment of inertia of the components are listed in the table below:

Recycler mirror	Mirror	Mirror Rec. mass	Inter. Mass	Inter. recoil mass
Mass [kg]	10.7	13.4 (12.3)	15.6	12.2
Mx [kg-mm^2]	50,649	184,385 (161,223)	122,973	248,032
My [kg-mm^2]	50,649	176,878 (153,506)	146,361	241,352
Mz [kg-mm^2]	83,496	230,032 (208,926)	189,847	402,393

Beam splitter	Mirror	Mirror Rec. mass	Inter. Mass	Inter. recoil mass
Mass [kg]	19.8	69.8	36.5	24.5
Mx [kg-mm^2]	187,815	2,483,519	573,256	1,004.337
My [kg-mm^2]	187,815	1,609,972	659,427	988,617
Mz [kg-mm^2]	254,723	2,412,201	953,988	1,735,800

Bottom filter	Filter
Mass [kg]	103
Mx [kg-mm^2]	6,355,863
My [kg-mm^2]	3,810,482
Mz [kg-mm^2]	3,809,358

	Recyclers Mass [kg]	Beam splitter Mass [kg]
Mirror	10.7	19.8
Mirror recoil mass	13.4	69.8
Intermediate mass	15.6	36.5
Intermediate recoil mass	12.2	24.5
Bottom filter payload	51.9	150.6
Bottom filter	103	103
Total payload	154.9	253.6

	Top filter	Standard filter	Bottom filter	Intermediate recoil mass	Intermediate mass	Recoil mass	Mirror
Mass [kg]	370.	100.	100.	12.2	15.6	12.3	10.7
Moix [kg-m]	48.0	4.00	4.00	0.25	0.12	0.16	.051
Moiy [kg-m]	95.0	6.40	6.40	0.40	0.19	0.15	.051
Moiz [kg-m]	48.0	4.00	4.00	0.24	0.15	0.21	.083
numw		1	1	3	1	4	4
Lenw [m]		1.300	0.500	0.384	0.500	0.500	0.500
Diaw [mm]		2.20	1.60	0.30	0.85	0.60	0.20
Matw		Mar	Mar	C70	Mar	Tun	Tun
Dyuw [mm]		0.0	5.0	70.0	5.0	0.0	0.0
Dylw [mm]		5.0	5.0	50.0	-2.0	0.0	0.0
Dxuw [cm]		0.0	0.0	18.0	0.0	14.5	12.5
Dzuw [cm]		0.0	0.0	18.0	0.0	1.0	0.2

dyuw(dylw): vertical break-off between the attachment point of the wire and the center of mass of the upper(lower) mass
dzuw(dxuw): z(x)-separation of the wire and the center of mass of the upper mass

Quality factors and tunings

	Inverted pendulum	Top filter	Standard filter	Bottom filter	Intermediate recoil mass	Intermediate mass	Recoil mass	Mirror
benQ			10^5	10^5	10^5	10^5	10^6	10^6
F.tuning	0.03	0.06	0.25	0.25	0.25			
Q	1-2	1-2	10	10	10			