The mechanics and cryogenics of GIANO-TNG

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ABSTRACT

GIANO is a cryogenic cross-dispersed spectrometer whose optics consist of aspheric aluminum mirrors, glass flats, cross-dispersing prisms and a grating fixed onto a $\simeq$1.5 × 1.0 m aluminum bench. The primary aim of the project is to achieve the highest possible image quality and spectral stability essential for precise radial velocity measurements. The instrument also includes other observing modes which are obtained by inserting a flat mirror or a prism at different positions in the optical path. This flexibility is achieved without affecting the stability and performances of the primary, high resolution mode. We describe here the cryo-mechanical design which has been optimized to these purposes.

Keywords: Ground based infrared instrumentation, infrared spectrometers

1. INTRODUCTION

GIANO is a cross-dispersed, high resolution (RS=23,000 and R=46,000 with a 0.5" slit) infrared spectrometer covering most of the 0.9–2.5 μm range in a single shot[1,2] It will be mounted on the 3.58 m TNG telescope at La Palma.

One of the primary aims of the project is to achieve the highest possible image quality and spectral stability/-repeatability in order to obtain very precise (few m/s) radial velocity measurements. This ambitious aim translates into demanding requirements not only on the mechanics holding the optical systems, but also on the cryogenic optical bench whose temperature distribution and absolute value must remain constant within $\simeq$0.1 K on time scales of several days or weeks.

Another important aim of the project is to build a flexible multi-mode instrument which can also attract the interest of the broad astronomical community accessing the TNG telescope. For this reason the spectrometer also includes a low resolution mode (RS$\sim$400) with very high efficiency and complete spectral coverage from 0.75 to 2.5 μm. All the mechanics and optics have been designed to guarantee that this flexibility does not have any impact on the instrumental performances in the high-resolution mode.

2. OVERALL DESCRIPTION OF THE SYSTEM

The mechanical design was developed by the firm "Tomelleri s.r.l." in strict collaboration with the GIANO team. The design was somewhat simplified by the fact that the instrument will operate at a fixed position with the gravity vector always perpendicular to the optical bench. Fig. 1 is a 3D rendering of the GIANO spectrometer mounted on the optical bench inside the cryostat and with all the covers removed.

The instrument is contained within a $\oslash$1300 x 1900 mm cylindrical cryostat of stainless steel. Just inside the dewar is a standard 30-layers thermal shield which isolates the inner part. The lower part of the shield is fixed while the upper can be removed separately from the dewar cover.

The aluminum optical bench is isostatically mounted on a hexapod system (see Fig. 2). The hexapod arms and joints are made of stainless steel to achieve a reasonably low heat conduction while maintaining a rigid and easy to manufacture system. The total heat input expected from this system when the bench is cooled to 77 K is about 11 W.

The optical bench also acts as tank for the liquid nitrogen, hence its name "BeTank". The direct contact with liquid nitrogen guarantees an uniform temperature distribution of the optical bench surface. A very accurate long term temperature stability can be also achieved by controlling the pressure of the N_2 boiling gas. Since $\Delta T_{boil}/\Delta P$=0.01 K/mbar, a maximum variation of a few ×0.01 K can be achieved using a servovalve control fed by the signal coming from a barometer.

Above the optical bench lays a relatively thick (~4 mm) aluminum cover in close thermal contact with the BeTank structure. Its main purpose is to minimize the heat input on the optics mounted on the bench. The large thermal conductivity of the cover guarantees that the temperature of the upper part of the cover remains within <2 K of the bench temperature. Noticeably, this bulky structure cannot be rigidly mounted on the BeTank, otherwise it would deform the optical bench.

3. MOVING SYSTEMS

The optical elements necessary for the high resolution (HR) mode, namely the aspheric (FR, TMA) and flat (PM) mirrors, the cross-dispersers (CRD) and the grating, are all fixed onto the bench. This guarantees the maximum mechanical stability in the main observing mode.

The other observing modes are obtained by inserting a flat mirror or a prism in the optical path (see Fig. 1). The shifted high resolution mode (SHR, useful to access the spectral range not included in the normal-HR echellogram[1]) is obtained by inserting (lowering) the SHR prism. The low resolution mode (LR) is obtained by inserting (lowering) the LR mirror. The IMA mode (IMA) is obtained by inserting (lowering) the IMA mirror. All these movements are non-critical IN/OUT mechanical systems with large backlash to minimize the risk of seizing when operating at cryogenic temperatures. The only strict positioning requirement is that the orientation (α, β angles) of the optical element in its IN position should be repeatable within a few arcsec. This is achieved by positioning the holder on a system magnetized kinematic points (see Fig. 3).

The spectrometer requires 7 short (6.5" sky-projected angle) slits for the HR/SHR modes, 5 longer (30" sky-projected angle) slits for the LR mode, a pin-hole for maintenance/calibration, and an open position for the IMA mode. To simplify the calibration-plan of the instrument, the positioning of each slit should be repeatable with an accuracy of <1/10 of the slit width, i.e. a few microns. Although this positioning accuracy could be in principle achieved with a gear-driven wheel, we however not considered this possibility because of the high risks that such a "tight" system could seize at cryogenic temperatures. Instead, we have chosen a toothed wheel - endless screw combination with large backlash and added an IN/OUT mechanism which positions/presses the slit holder against three fixed kinematic points (see Fig. 4).

The filter wheel is mounted on the same structure as the slit wheel. It does not require an accurate positioning and, therefore, consists of a simple combination of toothed wheel - endless screw with large backlash and driven by a stepper motor.

The stepper motors are powered when a movement is required, and switched off when the movement is terminated. This minimizes the thermal input to the system but does not allow using sub-step resolution in the movements.

4. THE BETANK

Fig. 5 is a 3D rendering of the optical bench and liquid nitrogen tank (the “BeTank”) which is manufactured by the Italian firm Criotec s.r.l.

The choice of the aluminum alloy for the optical bench was not trivial. The quality of the optical system, which is based on Al-6061 aspheric mirrors, does not deteriorate at cryogenic temperatures as long as the thermal expansion coefficient of the optical-bench is within 0.5% of that of the mirrors. Since Al-6061 is rare and very expensive in Europe, we have verified if the much more common alloy Al-6082 could be used instead. To this purpose we accurately measured the relative difference between the thermal expansion coefficients α of the the two alloys. The results yield $\Delta\alpha/\alpha < 0.3\%$ (3σ) and well within the requirements.

The inner part of the BeTank is divided into “two-floors” vertically symmetric cells fed by vacuum-tight welded pipelines which carry the liquid nitrogen and evacuate the out-boiling gas. The geometry of the system is designed to avoid deformations of the optical bench both at steady-state and during the thermal cycling. In particular, it avoids that relatively small temperature differences between the upper and lower parts of the structure could bend the optical bench by significant amounts, e.g. $\simeq$0.1 mm for ΔT=3 K. To achieve this aim the cells and pipelines are organized so that the liquid nitrogen is poured and stored in the middle part of the tank.

At the beginning of the cooling phase the liquid nitrogen evaporates as soon as it touches the surface and, in practice, creates a cold-spot whose cooling power is determined by the flow rate of the liquid. Being at the center of the cell structure, the thermal gradients (and deformations) are symmetrically distributed and, most important, equal in the upper and lower surfaces of the BeTank. This guarantees that the optical bench does not bend, as also demonstrated by detailed FEA modelling of the transient phase.

Thermal induced deformations on smaller scales are unavoidable but quenched by the very efficient thermal conduction of the Al structure which has a characteristic cooling time of only 5 minutes. Given the typical cooling time of 1.0–1.5 days (see below), these deformations are totally negligible.

The heat input from the hexapod below the BeTank introduces an asymmetry in the thermal balance of the system. It does not have any effect on the optical bench at steady-state because the thermal input is directly discharged into the liquid nitrogen reservoir. Nonetheless, it has an effect during the cooling and heating transients but, given the relatively small input power (11 W when the BeTank is at 77 K) and the very large conductivity of the BeTank ($\simeq$0.01 K/W), the transient bending and deformation induced on the optical bench are <0.01 mm and totally negligible.

The cooling time of the system is primarily determined by the ratio between the thermal capacity of the system and the rate of liquid nitrogen input. Given a total mass of about 350 kg (including optics and mechanics), a liquid N_2 flux of 0.2–0.3 lit/min yields a cooling time of about 1–1.5 days and a total consumption of about 400 liters of liquid N_2 (also including the heat losses described below). We consider this an appropriate cooling time because it guarantees that the mechanics, optics and electronics are not stressed during the transient. For this reason we include a valve at the input of the liquid N_2 pipeline which limits the flux to 0.3 lit/min during the cooling phase. This valve can be by-passed when the instrument is cold to allow fast re-fillings.

The thermal inputs to the BeTank at steady-state are summarized in Table 1. To maintain the instrument cold one therefore needs to provide about 22 lit/day of liquid N_2. This can be conveniently achieved with a commercial and relatively inexpensive liquefier such as the LNP60 system by Cryomec which can produce up to

60 lit/day.

Table 1. Thermal inputs to the GIANO BeTank

Heat source	Input power	Comments
Radiation from cryostat	5 W	30-layers thermal shield
Gas conduction	10 W	for P=$1 \cdot 10^{-5}$ mbar
Radiation from optical window	2 W	∅80 mm fused-silica
Conduction from hexapod	11 W	see Fig. 2
Electronics and cables	12 W	w/o motors, see end of Sect. 2
Total	40 W	

The relatively low thermal inputs to the GIANO BeTank and its large mass and thermal capacity (about $3 \cdot 10^5$ J/K) yield a warm-up time of about 2 weeks(!), far too long for normal operations. To speed the operation up we include a number of electrical heaters with a total power of 700 W thus achieving a warming-up time of about 1 day. The heaters are distributed outside the BeTank and separated from it, in such a way the heat is uniformly transmitted to the BeTank by radiation.

5. ACKNOWLEDGEMENTS

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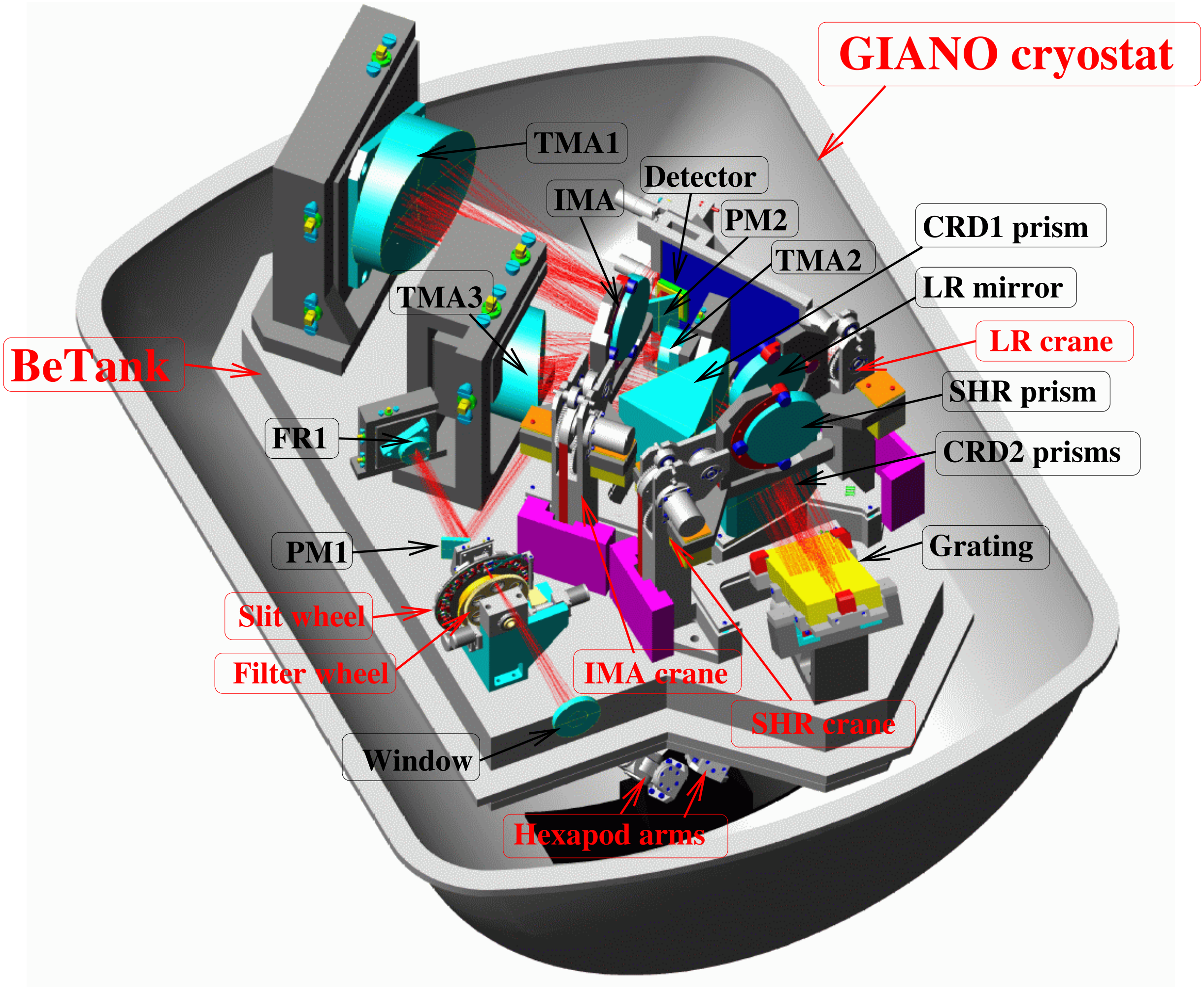

Figure 1. 3D view of the GIANO spectrometer mounted on its optical bench ("BeTank") inside the cryostat. The optical elements necessary for the high resolution mode, i.e. the aspheric (FR, TMA) and flat (PM) mirrors, the cross-dispersers (CRD) and the grating, are all fixed onto the bench. This guarantees the maximum stability of the spectrograph in its primary observing mode. The switch to the other observing modes is performed using the three vertical in/out systems ("cranes"). The shifted high resolution mode (SHR) is obtained by lowering the SHR prism. The low resolution mode (LR) is obtained by inserting the LR mirror. The IMA mode (IMA) is obtained by lowering the IMA mirror.

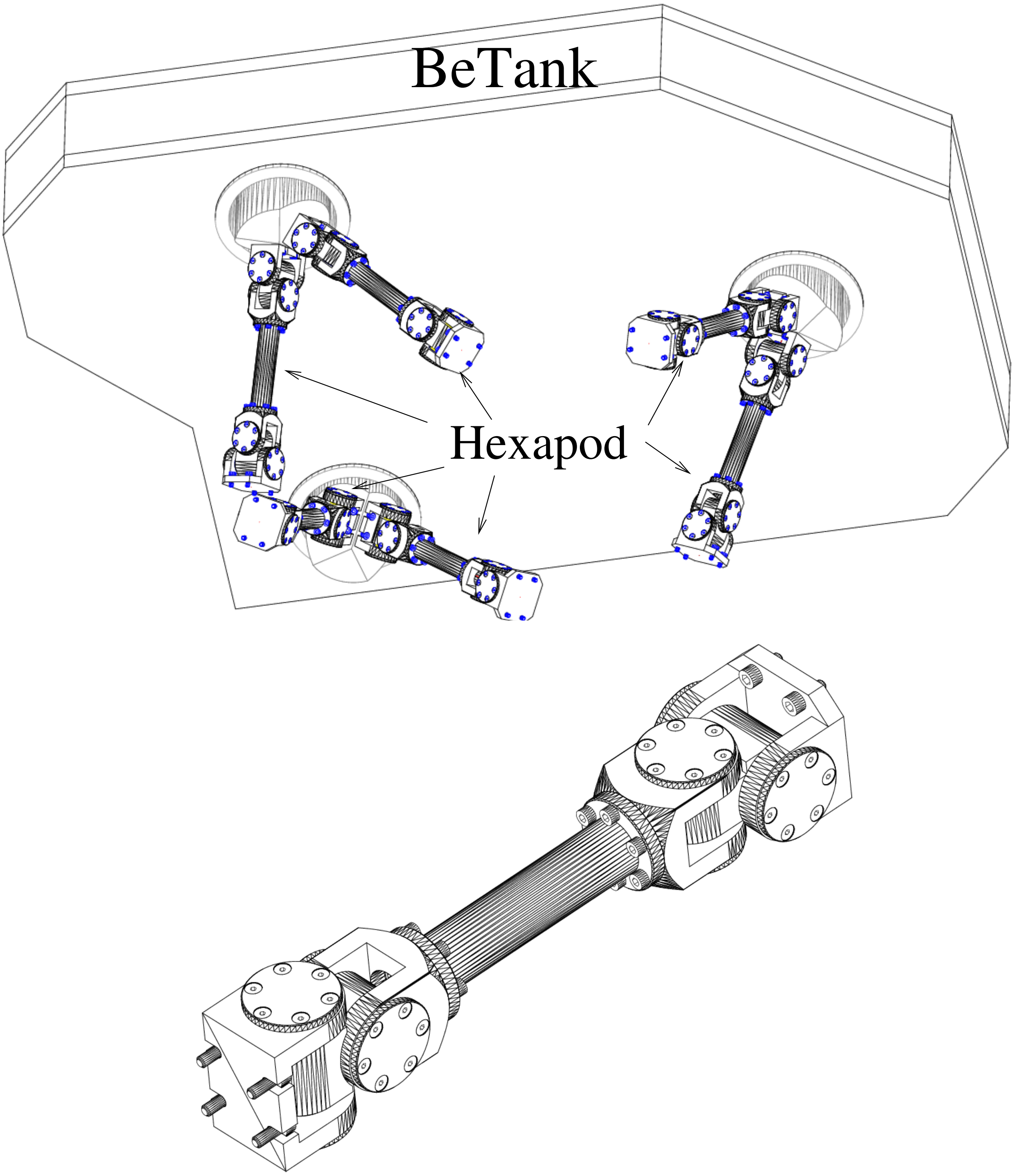

Figure 2. View of the hexapod system supporting the BeTank, i.e. the aluminum structure acting as optical bench and liquid nitrogen tank. The hexapod arms (see details in the lower panel) are composed by a cave cylinder of stainless steel coupled with cardan joints. The relatively low cross-section and thermal conductivity of steel yield a quite high thermal resistance for each arm, i.e. ≃110 K/W. Therefore, the total heat input from the hexapod is only ≃11 W when the BeTank is at 77 K.

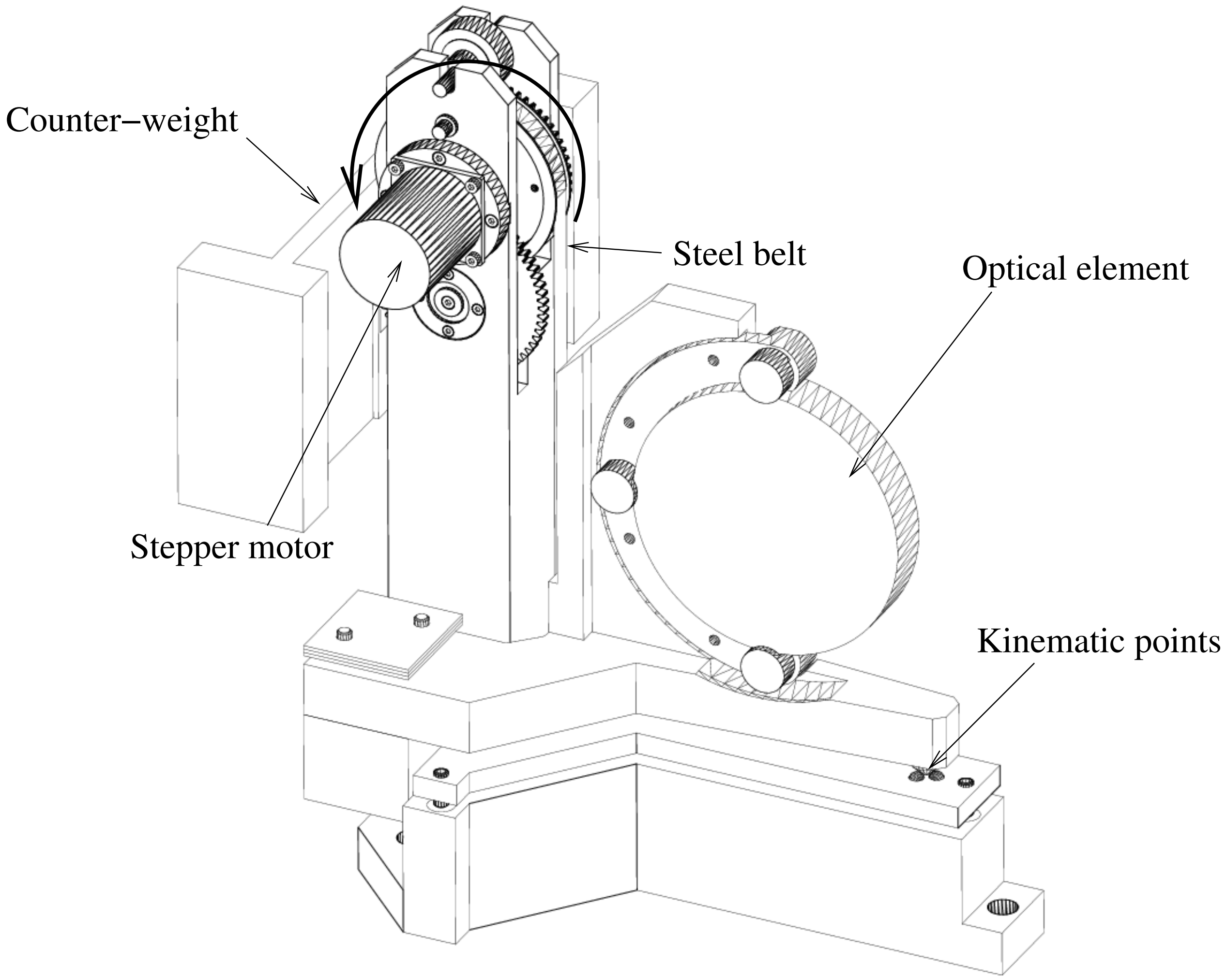

Figure 3. The “crane”, i.e. the mechanical system used to insert/remove the LR and IMA mirrors and the SHR prism from the optical beam. The optical element and the counter-weight are mounted on a steel belt driven by a stepper motor through gears. All the gears and guides are loose to avoid large frictions and seizing when operated in vacuum and at cryogenic temperatures. The drawing shows the system in the "IN" (i.e. down) position with the mirror positioned in the optical path. The mechanical holder is magnetically pressed onto three kinematic points which guarantee that the angle of the optical element relative to the optical axis is repeatable within a few arcsec. This is the only strict positioning requirement for this system.

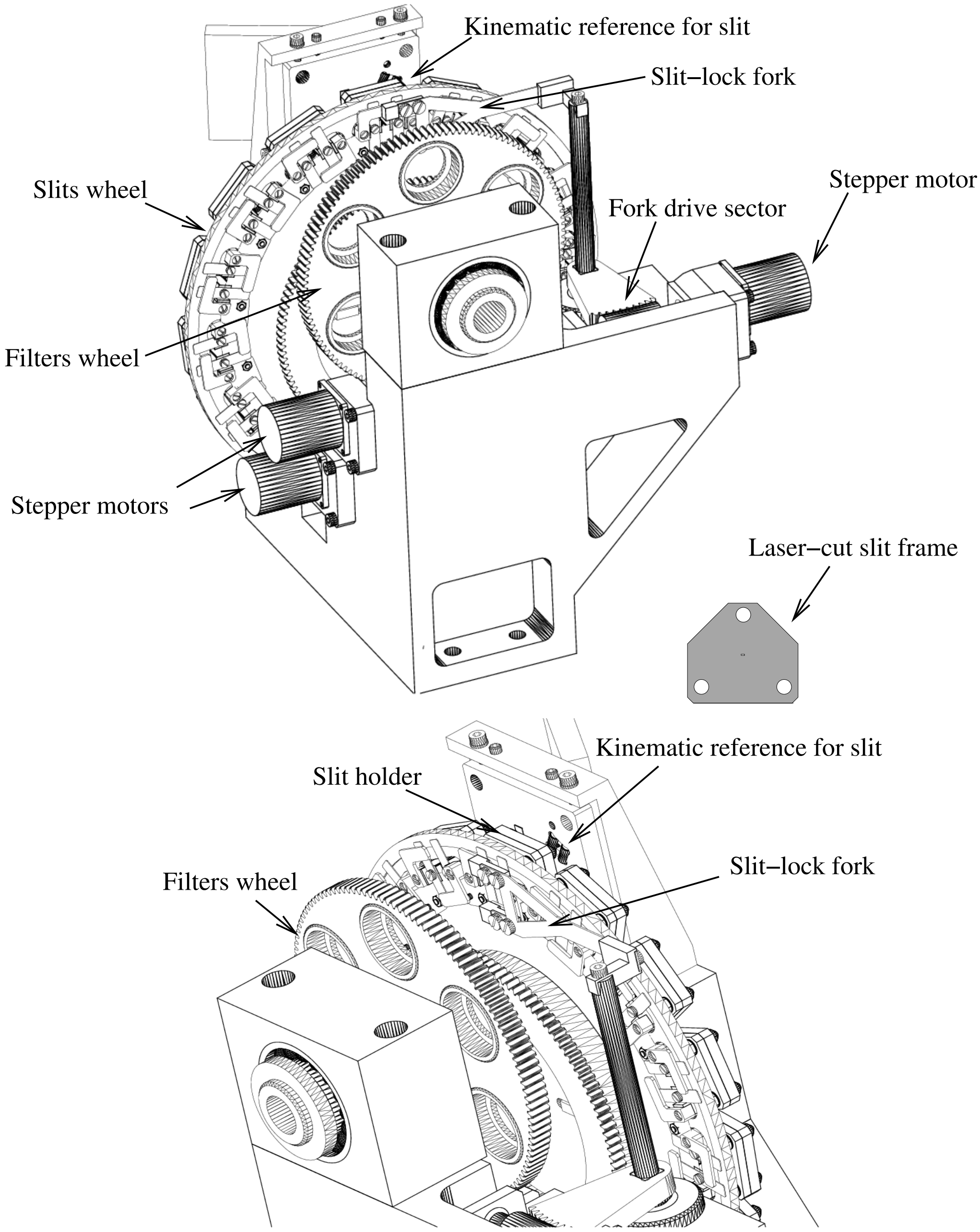

Figure 4. View of the mechanical system holding the slits and filters wheels. Each wheel is driven by a stepper motor (left in the upper panel) through a endless screw - toothed wheel combination with large backlash to prevent seizing when operated at cryogenic temperatures. The slit frame is a laser-cut sheet of steel with very precise (μm) positioning of the slit and reference holes. The slits are mounted inside steel holders with accurately machined cylindrical pins matched to the slit frame holes. The holders are elastically mounted in the wheel holes. To guarantee an accurate positioning of the slit relative to optical axis the slit holder, once in position, is extracted from the wheel and pressed against three kinematic points mounted on a rigid system behind the wheel. This movement is performed by the slit-lock fork which is driven by the third stepper motor. An electrical interlock system fed by micro-switches avoids collisions between the wheel and the fork movements.

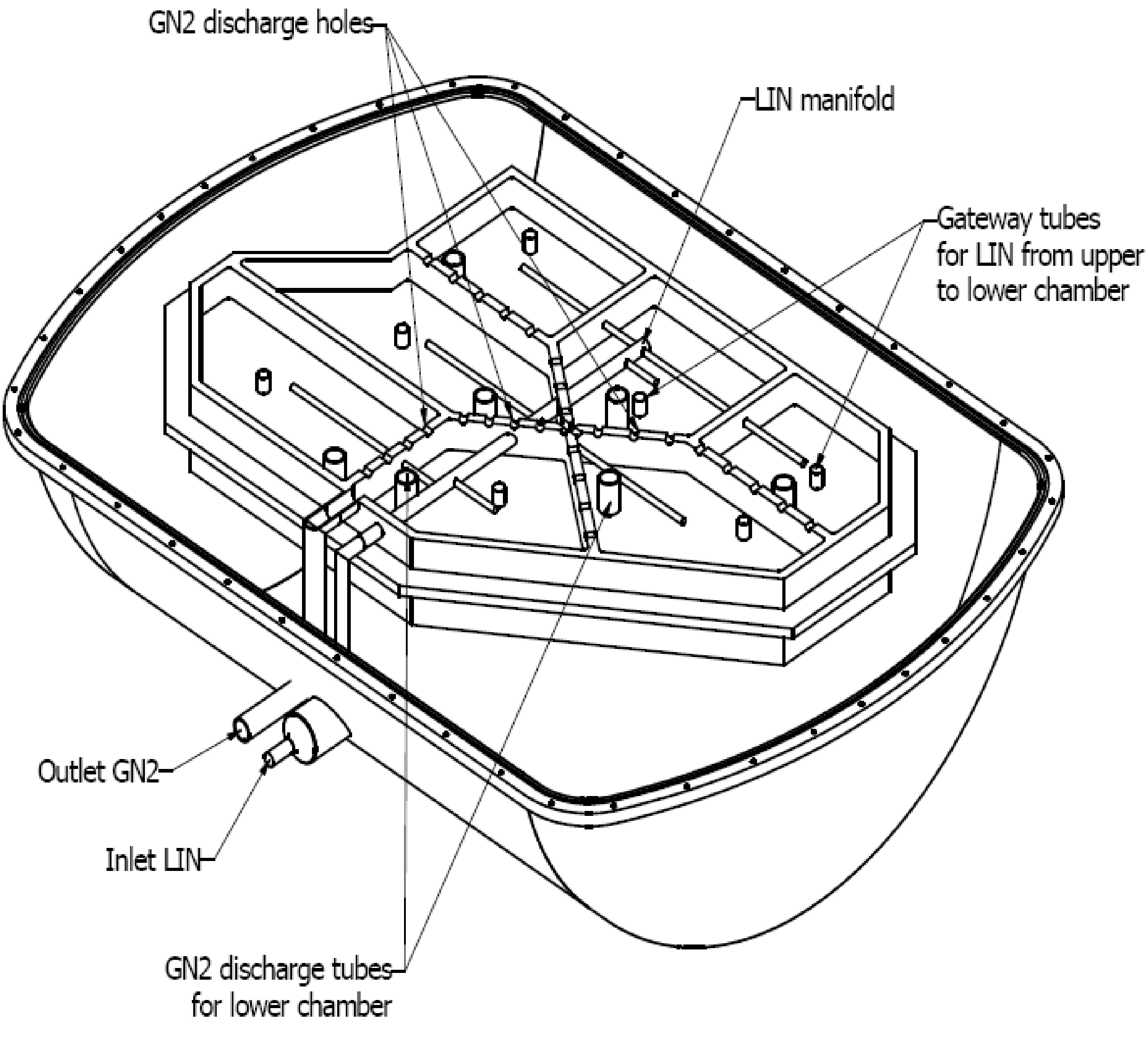

Figure 5. 3D view of the BeTank, i.e. the aluminum structure acting as optical bench and liquid nitrogen tank. To achieve the maximum symmetry, the structure is divided into "two-floors" cells. The liquid nitrogen is carried to the central part of each cell by a system of welded pipelines (the LIN manifold). The cells and pipelines are organized so that the liquid nitrogen is poured and stored in the middle part of the tank, thus minimizing the vertical temperature gradients inside the structure. A separate pipeline is used to evacuate the out-boiling gas coming from the discharge holes. The upper and lower parts of each cell communicates so that the excess of liquid nitrogen can be stored in lower part and the gas can freely move inside the structure.