# Cold optics of MIDI: the mid-infrared interferometric instrument for the VLTI

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## ABSTRACT

ESO's new Very Large Telescope will consist of four 8.2m telescopes and three moveable 1.8m telescopes. Light from these can be combined in the Very Large Telescope Interferometer (VLTI) providing milli-arcsecond resolution with high sensitivity. The VLTI will first operate in the infrared and will produce first fringes in 2001. MIDI is the VLTI instrument for interferometry in the mid-infrared (10-20 microns) and is under development by a German-Dutch-French consortium [MPIA Heidelberg, NOVA/NFRA Netherlands, Observatoire Meudon France]. The initial aim of MIDI is to combine the beams of two telescopes in the 10 micron `N-band' and to achieve spatial resolutions of 20 milli-arcseconds at a spectral resolution of 200-300. Modulation of the optical path difference can be done using piezo-driven mirrors at room temperature, but beam combination and detection of the interferometric signal has to be done at cryogenic temperatures due to the `thermal' wavelength domain. The MIDI cold bench is therefore mounted inside a cryostat, cooled by means of a closed cycle cooler to about 40K for the cold optics and 8 K for the detector. This poster describes the design and implementation of the MIDI cold bench.

Keywords: Interferometry, MIDI, infrared, VLTI, VLT, cryogenic

## 1. GENERAL DESCRIPTION

### 1.1 Optical layout

The aim of MIDI is to combine interferometrically the parallel beams of two different VLT telescopes, which can be either 8.2m Unit Telescopes (UTs) or 1.8m Auxiliary Telescopes (ATs). The wavelength range of MIDI is centered around 10 microns (N-band). In a later phase this can be extended to the 20-micron region (Q-band). An overview of the MIDI design can be found in Leinert (1999)(2000)[4 5].

The layout of the MIDI cold optics on top of the cold bench is relatively simple and consists of four sections. From the cryostat entrance window to the detector (most likely a Raytheon 240x320 Si:As BIB array) light passes the ‘re-imager’, the beam-combiner, the dispersion/filtering section and the camera optics. Up to the beam combiner the system is purely reflective and all optical elements are in pairs, one set for each beam. After the beam combiner, all beams pass through the same refractive elements. The optical configuration is shown in Figure 1 and a more detailed description of the MIDI optical design is given in Glazenborg (1999)[1].

The two MIDI input beams enter the cryostat with 18 mm beam diameter, separated by 30 mm to allow for baffling. In the re-imager section both beams first pass an undersized cold pupil stop. The off-axis paraboloids M1 then create an intermediate focal plane where pinholes, slits or fibers can be selected for spatial filtering. A second pair of off-axis paraboloids M2, mounted on a focusing stage, re-collimates the beams to a diameter of 10 mm. A folding flat reflects these beams upwards into the beam combiner.

In the beam combiner (made of ZnSe) both beams are split and the four partial beams are recombined crosswise into the two beams that contain the interferometric information. A fraction of the light of the input beams bypasses the beam combiner and is used for photometric monitoring.

After the beam combiner there are thus four beams: two interferometric channels and two photometric reference channels. Via the filter wheel (choice of 10 passband filters) and the dispersive element (grism or prism; spectral resolution ~300 or ~30 ) and the camera optics these beams are imaged as four parallel spectra on the detector, with the dispersion in the horizontal direction. The camera optics are mounted on a slider mechanism that allows a choice between the main spectroscopic camera (with toroidal optics optimized for different pixel matching in the dispersion and field directions), a spherical camera optimized for the imaging mode (without grism/prism) and a simple pupil imaging camera for diagnostic purposes. Figure 2 shows an overview of the cold bench.

All optics exchange mechanisms contain spare positions for extra components, such as additional filters and grisms or the special beam combiner and camera optics that will be needed if the wavelength range is extended to the Q-band. The beam combiner slider has six positions, providing selections with/without photometric channels, N-band or Q-band optics, or two positions for alignment checks.

The wavelength range of MIDI is the 'thermal infrared' and therefore the entire cold bench has to be cooled down to about 40 K and the detector even to 8 K. The whole instrument will be mounted in an isolated vacuum chamber of about 57x60x80 cm (lxwxh) size.

### 1.2 Subsystems

The main subsystems of the cryogenic MIDI optics are:

1. *Shutter* – the shutter can independently switch on and off the incoming light beams
2. *Cold stop* – defines the pupil of the incoming beams and blocks stray light
3. *Parabolic mirrors M1* with focusing mechanism – re-images focal plane and allows adjustment of the intermediate focus
4. *Intermediate focus* – a range of pinholes and slits are available for spatial filtering in the focal plane; a position for spatial filtering by a fiber is foreseen
5. *Parabolic mirrors M2* – recollimates the beams to a diameter of 10 mm
6. *Fixed folding flat M3* – directs the beams into the beam combiner
7. *Beam Combiner* – splits and recombines the 2 incoming beams to produce 2 interferometric beams and also allows for some light to be split off to form 2 photometric reference beams, one for each incoming beam
8. *Filters* – ten filter positions are available
9. *Dispersion* – a full N-band grism and a low resolution prism are available initially, however the mechanism has 4 spare positions
10. *Camera* – 3 cameras are included, one for spectroscopy, one for imaging and a pupil imaging test camera, a fourth position is reserved for a Q-band camera
11. *Detector* – detects the incoming signals in the two interferometric beams and the two photometric reference beams
12. *Autocollimation* – a number of autocollimation flats for alignment checks are foreseen in various places on the cold bench
13. *Cold bench* – an aluminium optical table (~42x57 cm) supports the entire cryogenic optics

## 2. DESIGN ISSUES

Through the entire mechanical design, specifications are set by the interferometric requirements of the instrument. Therefore the optical model and tolerance analysis dictate most of the design constraints (Glazenborg(1999)[2]). The second very important consideration comes from the cryogenic requirements. The cold bench operating temperature is about 40 K and the detector temperature is about 8 K. All optics, mountings and structures should be designed to guarantee optical alignment and stability at cryogenic temperatures and to withstand cooling down and warming up over a range of about 270 K in ~20 hours (pre-cooling to 100 K in ~6 hours). The fact that all moving parts of the cold optics operate at 40 K in vacuum puts extra constraints on the design of the cryogenic mechanisms. In the following paragraphs we summarize the main design strategies applied in MIDI.

**a) Monolithic structures.** It is well known that mounting techniques like welding or brazing introduce stresses in materials. Bolted connections can result in slip-stick effects and in poor thermal connections. To prevent such sources of mechanical instability and improve thermal behaviour, structures are manufactured where possible from one monolithic piece.

**b) Homogeneity**. When different materials are used, differential thermal shrink will occur. In order to minimize thermal effects on the optical alignment of the instrument, all structures and reflective optical elements will be made of one material: aluminium alloy Al 6061-T651. The total thermal shrinkage from 300 to 40 K is 0.42 % for this material. This homogeneous design ensures homologous shrinking, which means that the cold bench internal optical alignment (apart from focus effects in the cameras) is maintained between room temperature and 40 K.

**c) Isostatic mountings**. Hyperstatic mountings can transmit stresses between structures. The only correct way to avoid this is by applying isostatic mountings, which constrain each of the six degrees of freedom of a component only once. This means that no stiffness can be passed on from one structure to another and thus that every unit should be stiff in itself. There are standard mechanical design methods to achieve this. Isostatic mountings are particularly useful in a cryogenic instrument like MIDI to avoid problems with differential thermal shrinkage. Stress-free mountings are also very important for positioning of the optical elements. Mechanical stress can not only cause displacements but it can deform the optical surfaces, resulting in optical quality loss or damage. The isostatic design strategy is therefore driven by mechanical, thermal and optical considerations and it is applied throughout the optomechanics of the MIDI cold bench.

**d) Mirror mountings.** For the reflective optics special mountings are applied, making use of the experience gained in the development of VISIR, the VLT mid-infrared imager/spectrograph. For the attachment of mirrors with different size and weight different versions of the isostatic 'Three-Point' or 'Wineglass Foot' mountings are used. The Three-Point-Mounting consists of three stress-released lugs at the mirror edge. The Wineglass Foot Mounting, named after its shape, is a special kind of single point mounting that was also modeled and tested extensively for VISIR by NFRA in Dwingeloo. In MIDI it is used for the parabolic mirrors. This kind of stress-free mounting is attractive because of its simplicity and low weight.

**e) Mounting of refractive elements.** Special attention has to be given to the mounting of the refractive optical elements: grisms (KRS5), prism (NaCl/Ge), beam combiner plates (ZnSe), filters and lenses (Ge). Thermal expansion differences are particularly dangerous here and KRS5 is known to be very sensitive to stress. To avoid stress problems, the isostatic mountings of these optical elements include spring-loaded contact points.

**f) Adjustments.** Since the cold optics is mounted inside a vacuum enclosure, it is important to keep the number of mechanisms and adjustments to a minimum. Using the optical tolerance analysis, we have verified that for nearly all cold bench components optical and mechanical manufacturing precision is sufficient to obtain the required positioning accuracy without provision for fine-adjustments. There are three exceptions: parabolic mirrors M1, parabolic mirrors M2 and the detector. To allow on-line adjustment, the M1 paraboloids and the detector are mounted on focusing stages with external motor drives. The parabolic mirrors M2 have fine-adjustments for alignment during assembly of the instrument.

**g) Lightweighting.** The instrument will go through many cool-down/warm-up cycles during its lifetime. To decrease cooling and warming time the total mass of the instrument is minimized. Weight reduction is also desirable from the point of view of structural flexures. Material choice and light-weighting can accomplish this weight reduction. The 6061 aluminium alloy is a low-mass material with a good stiffness/weight ratio. With light-weighting, this ratio is optimised.

Furthermore, from extensive testing of 6061 mirrors for the VISIR instrument, we know that this alloy is suitable for CNC diamond-cutting of lightweighted mirrors that are accurate and stable at cryogenic temperatures.

**h) Uniformity.** Wherever possible, the same construction principles will be used for the different mechanisms. The optics will, as far as possible, get similar mountings. All mechanisms will have the same motor drives. This way an orderly design is created, and research and development effort can be minimised. Easy maintenance and minimisation of spare parts is another advantage of a uniform design.

**i) Instrument lifetime.** The expected lifetime of MIDI will cover about 10000 observing hours (thousand 10-hour nights). The most frequently used functions (cold shutter and filter wheel) are expected to make ~$10^5$ movements over this lifetime. This means that instrument wear is not a major design issue.

**j) Material treatment.** After manufacturing, all mirror blanks and structural cold bench components are stress-released by thermal treatment. Mirror surfaces will be coated by vacuum-deposited gold coating on a Ti bonding layer. Refractive optical elements receive multilayer filter-, beamsplitter- or anti-reflection coatings. Baffles will be black-anodized and a 'alodine' protective chromate layer is given to all aluminium structure surfaces.

**k) Stability.** The MIDI cold optics is mounted inside a cryostat on a fixed optical table in the temperature-stabilized VLTI beam combination room. Therefore, instability due to temperature variations or orientation-dependent flexure is not an issue. However, since MIDI is an interferometer, it is very sensitive to vibrations. Special attention is therefore given to elimination of vibrations from the cooling system. For this reason the Sumitomo closed-cycle cooler, which has been selected for its low vibration noise, is mounted on a separate support, mechanically de-coupled from the MIDI cold bench.

## 3. THE MECHANISMS

All mechanisms are driven by identical electric motors; the only differences are in the gear ratios of the transmission gear-boxes. The design of the motor-encoder units is adopted from the VLT instrument CONICA. The units are placed on the outside of the cryostat wall and magneto-fluid vacuum feedthroughs are used to connect to the drive shafts inside the cryostat. The latter are thermally linked to the cold bench and isolated from the vacuum chamber. The cryogenic bearings used inside the cryostat have stainless steel rings and ceramic balls without lubricant, but bearing races will probably be treated with molybdenum bisulphide. Motor drives are foreseen for the following mechanisms:

| Nr. | Mechanism | Type of mechanism |
|---|---|---|
| 1 | Cold shutter | Wheel |
| 2 | Focus M1 paraboloids | Leaf spring |
| 3 | Intermediate focus apertures | Slider |
| 4 | Beam combiner | Slider |
| 5 | Filters | Wheel |
| 6 | Dispersion elements | Slider |
| 7 | Camera s | Slider |
| 8 | Detector focus | Leaf spring |

Table 1. Cold bench mechanisms

### 3.1 Focusing mechanisms

The foci of the M1 paraboloids have to coincide exactly with the intermediate focus apertures. The M1 mirrors are therefore mounted on a focus mechanism with external motor drive. It has a total travel of 5 mm, so even the length of an optical fiber feed (expected length ~2 mm) in the focal plane can be compensated. The two paraboloids are mounted on the focusing platform with 'wineglass foot' mountings. Both the mirrors and the focusing mechanism are made of the same AL-6061 alloy. The focus mechanism (see Fig. 3) is a two-stage leafspring construction to reduce lateral movement and building height. It is manufactured monolithically from one piece of aluminium by electron discharge manufacturing (EDM). The rotation of the drive axle is converted to linear movement by an excenter. The moving force is applied to the middle of the mirror platform to exclude tilt deviations. The direction of linear movement is to and from the intermediate focus, i.e. in the direction of the outgoing M1 beams.

The detector focus mechanism is needed primarily to adjust for small focus differences between the different cameras. It is a simpler one-stage version of the M1 focus mechanism and is also cut out of one piece by EDM manufacturing. Both focus mechanisms are adaptations of the leaf-spring mechanism developed for VISIR.

### 3.2 Generic slider mechanism

The slider (see Fig. 4) - applied in four mechanisms - is in fact a little cart, rolling on two rails with three ball bearings for wheels. Spring-loaded rollers on an opposite track of the rail eliminate play and prevent the cart jumping out of the rails during an earthquake. This gives an isostatic mounting, which is free in the longitudinal direction of the rails. The longitudinal movement is transferred by a rotating motor mechanism outside the cryostat but the accurate positioning is achieved with a spring-loaded locking mechanism on the rail itself. The connection to the drive axle must therefore have some additional freedom to avoid over determination of the movement.

In order to check the performance of the carriage design, which is most critical for the beam combiner mechanism, a prototype carriage has been manufactured. The first test results indicate that the accuracy and reproducibility in the positioning of this mechanism is at the level of less than 2 microns in all coordinates. For the given design this corresponds to a tilt stability better than 4 arcsec. which is fully within specs.

### 3.3 Beam combiner

To fulfill several functions, the beam combiner mechanism (see Fig. 5) should be able to move to 6 positions. This is done with a slider type mechanism. The tolerances on stability and repeatability are only strict with respect to rotation. The maximum tilt repeatability error should be less than 5 arcsec in all three rotations. The requirements on translation errors are not strict at all and can easily be met with standard machining accuracy. The mechanical design aims for high eigen frequencies to minimize sensitivity to vibrations. The beam combiner optics will be mounted in stress-free isostatic mountings.

The carriage is supported by three wheels in one plane and two in the other. This ensures isostatic mounting. The movement is provided by a rack and pinion drive. The position accuracy is provided by mechanical stops at each position. These mechanical stops are made by an accurate roller that falls into a V-groove. The roller is mounted to the carriage with a leafspring. The reproducibility of the position in a certain groove depends on the accuracy of the roller, which is in fact a small bearing. The accuracy of a position depends on the accuracy of the V-grooves. There are mechanical end stops at the end positions.

## 4. REFERENCES


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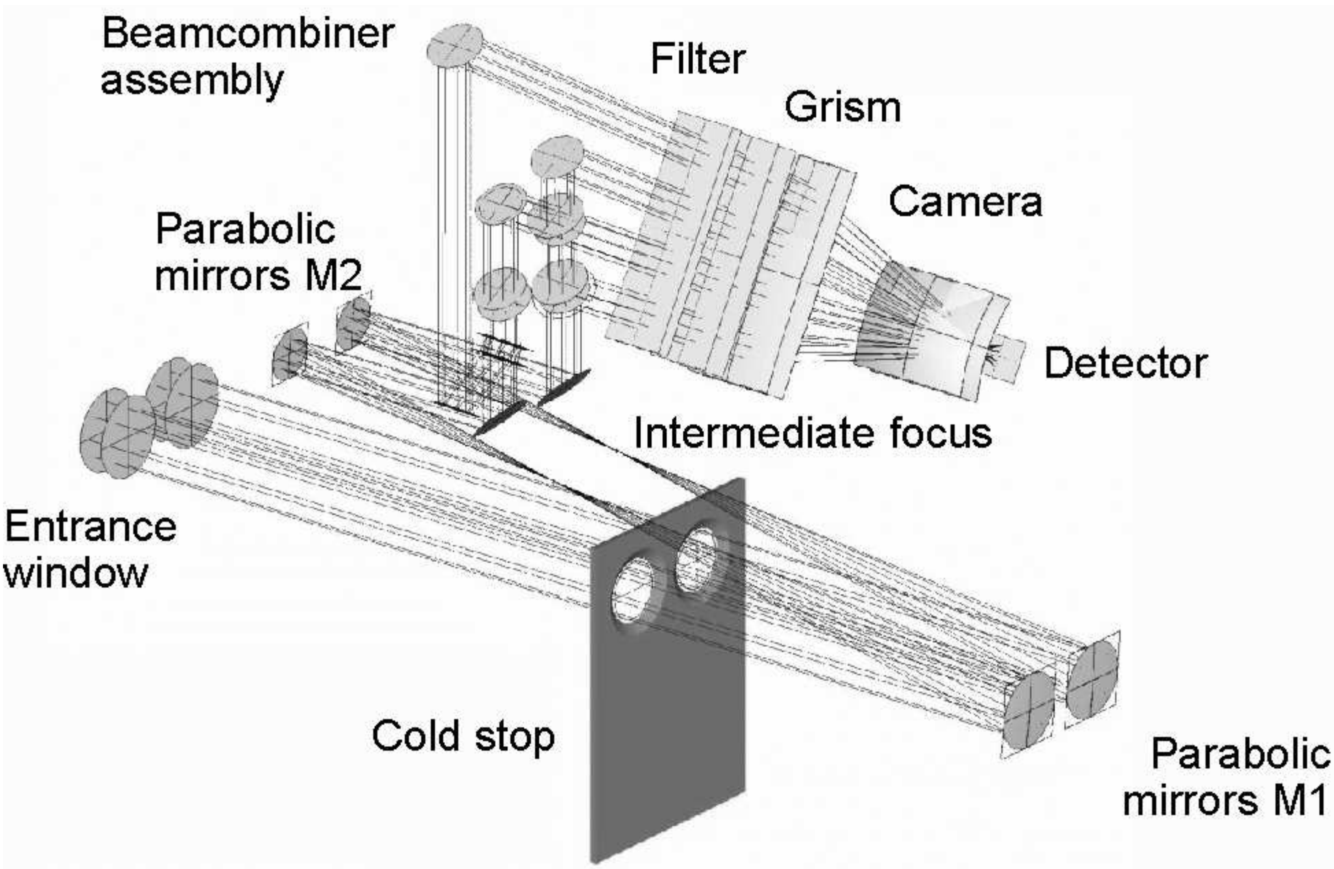


**Figure 1:** The optical path of MIDI. Only the cryogenic part is shown, from the entrance window to the detector.

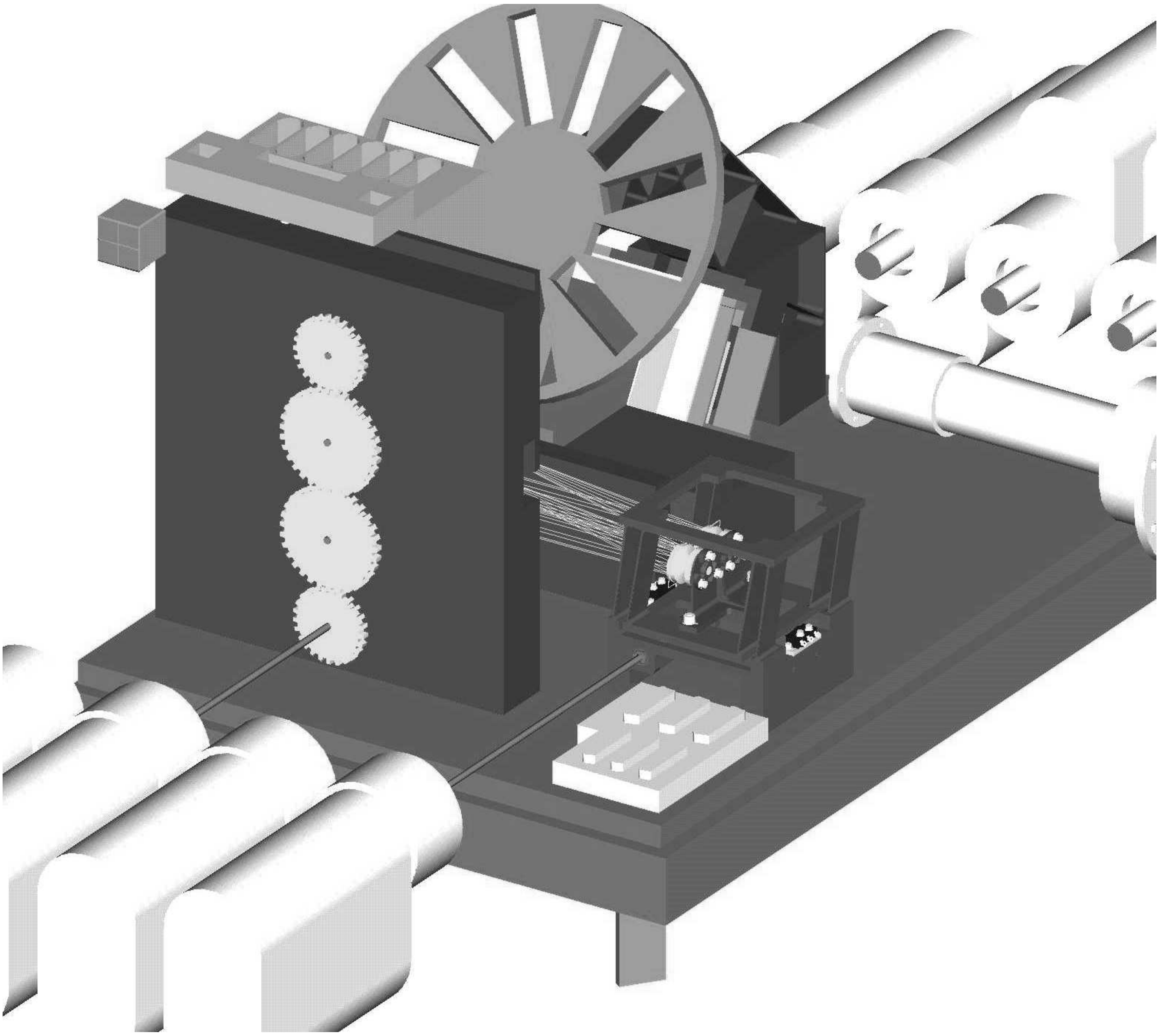

**Figure 2:** Overview of MIDI. The cold bench, on which everything is mounted, mirrors M1, the beam combiner and filter wheel can be clearly seen. In the top right and bottom left corners, the motors can be seen. The feedthroughs are not included in this picture. The axles are all placed as low as possible in order to improve access.

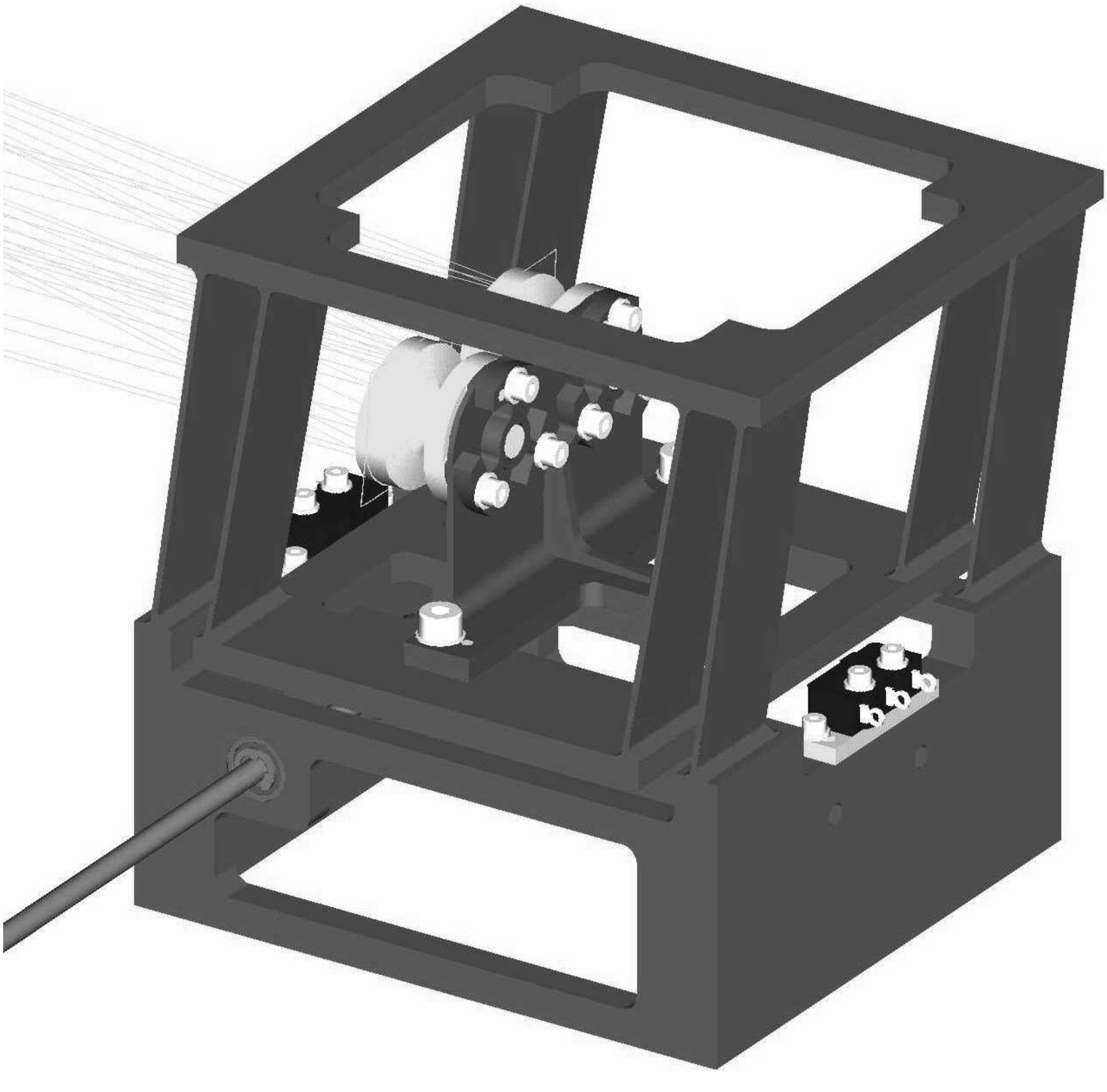

**Figure 3:** Close-up of the focusing mechanism of the M1 mirrors. The double leaf-spring minimizes the vertical movement of the mirrors which follow the path of the outgoing beams..

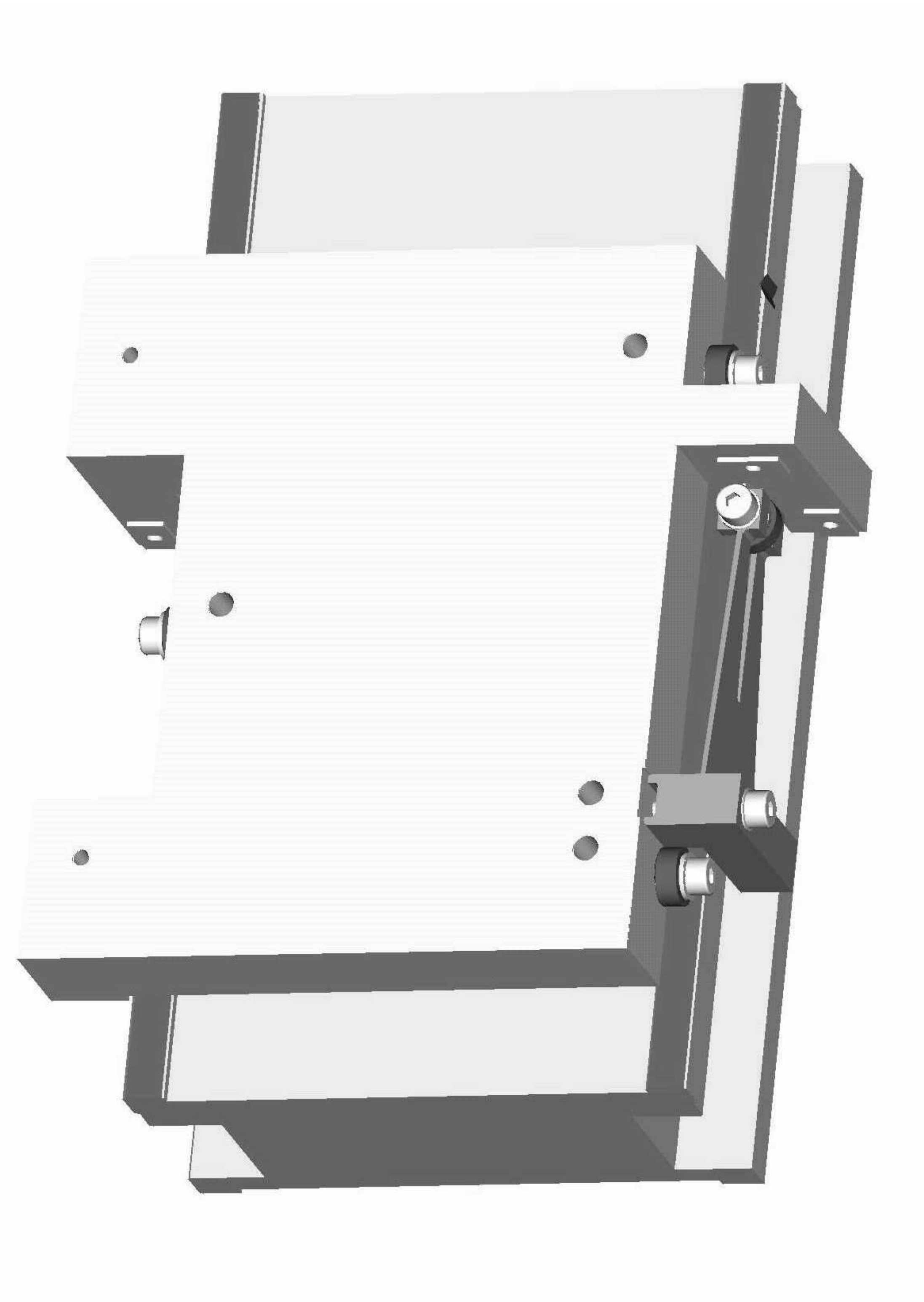

**Figure 4:** The slider mechanism prototype. The generic slider mechanism consists of a carriage and rail. The leaf spring and roller that are used to lock the carriage in position can be seen on the right-hand side.

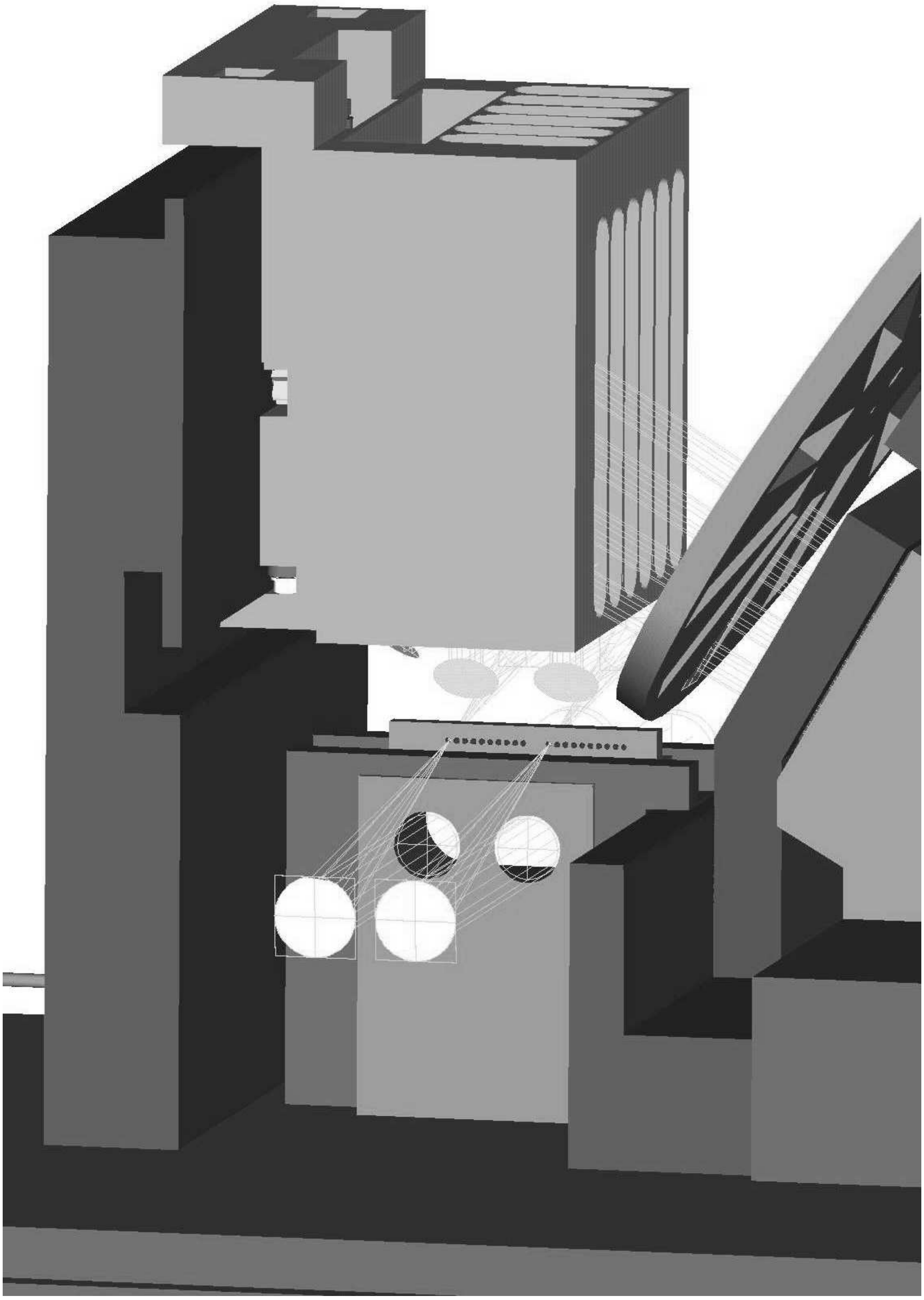

**Figure 5:** Close-up part of the cold bench. The beam combiner and the slider with spatial filters can be seen. The grism/prism and the camera slider mechanisms are indicated schematically on the right below the filter wheel. The focusing unit of the M1 mirrors is omitted for clarity.