**OCA** Observatoire de la Côte d'Azur **UNSA** Université de Nice Sophia-Antipolis
**LAOG** Laboratoire d'Astrophysique de l'Observatoire de Grenoble
**MPIfR** Max-Planck Institut für Radioastronomie **OAA** Osservatorio Astrofisico di Arcetri

VERY LARGE TELESCOPE

# Astronomical Multi-BEam Recombiner
# AMBER

## AMBER Spectrograph Design Report

Doc. No VLT-TRE-AMB-15830-20000-0001
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# Contents

# Acronyms and abbreviations

| | |
|---|---|
| AD: | Applicable document |
| AMBER: | Astronomical Multi-BEam Recombiner |
| AO: | Adaptive optics |
| AT: | Auxiliary telescope (1.8m) |
| DL: | Delay lines |
| FT: | Fringe tracking |
| ICD: | Interface Control Document |
| SPG: | Spectrograph |
| UT: | Unit telescope (8m) |
| VIMA: | VLTI Main Array (array of 4 UTs) |
| VISA: | VLTI Sub Array (array of ATs) |
| VLT: | Very Large Telescope |
| VLTI: | Very Large Telescope Interferometer |

# 1 Scope

We describe the major issues concerning the design of the cold spectrograph of AMBER (SPG) in view of the Final Design Review (FDR). The design itself respects most of the specifications issued in the Lower Level Specifications for AMBER Spectrograph (doc. No. VLT–SPE–AMB–15830–20000–0001, issue 2.0). Respect to the cited document, the only function the SPG module does not implement is the spectral low–pass filtering at 2.4$\mu$m (see paragraph 4.2 of VLT–SPE–AMB–15830–20000–0001, issue 2.0), this function being included in the DET module.

# 2 Documents

## 2.1 Applicable documents

| Code | Title | Number |
|---|---|---|
| AD 1 | AMBER Spectrograph Lower Level Specifications | VLT-TRE-AMB-15830-20000-0001 issue 2.0 dated 15.11.2000 |
| AD 2 | AMBER Spectrograph Analysis Report | VLT-TRE-AMB-15830-20000-0002 issue 2.0 dated 16.03.2001 |
| AD3 | AMBER Spectrograph Cryostat Preliminary Design | VLT-TRE-AMB-15830-20000-0003 issue C dated 30/08/2000 |
| AD 4 | Vacuum and Cryogenics Standard Components | VLT-TRE-ESO-15800-2315 issue 1.0 dated 18.09.2000 |
| AD 5 | Liquid Nitrogen Connection Interface | VLT-TRE-ESO-15800-2316 issue 1.0 dated 12.09.2000 |
| AD 6 | Liquid Nitrogen Distribution for Amber | VLT-TRE-ESO-15830-2402 issue 1.0 dated 12.12.2000 |
| AD 7 | Interface Control Document between VLTI and its Instruments | VLT-ICD-ESO-15000-1826 issue 2.0 dated 27.02.2001 |
| AD8 | AMBER Spectrograph Cryostat Mechanical Design | VLT-TRE-AMB-15830-20800-001A issue C dated 16/03/2000 |

## 2.2 Interface documents

| Code | Title | Number |
|---|---|---|
| ICD 1 | AMBER Hardware Interface Control Document | VLT-ICD-AMB-15830-0001 issue 1.0 dated 15.11.2000 |
| ICD 2 | Detector Design report | VLT-TRE-AMB-15830-30000-0002 issue 1.2 dated 31.10.2000 |

# 3 Spectrograph General Description

The cold spectrograph of AMBER (indicated by the acronym SPG in AMBER documentation), besides operating the spectral dispersion of incoming beams, includes the following functions:

- formation of an image of the fiber outputs at cryogenic temperature and filtering of thermal radiation from this image by means of suitable spatial filters
- formation of a parallel beam

- accurate spatial filtering of the pupils
- separation of spectroscopic beams from photometric beams
- spectral analysis at three resolving power values
- formation of images on the detector plane

All these functions are accomplished in the spectral range which covers the astronomical near-infrared bands J, H, and K, that is from 1.0 to 2.4 $\mu$m. The optics and the the support structure are contained in a vacuum tight cryostat which allows the cooling of all functions to the working temperature of about 77 K by means of liquid nitrogen at atmospheric pressure. The design itself respects all the specifications issued in the Lower Level Specifications for AMBER Spectrograph (doc. No. VLT–SPE–AMB–15830–20000–0001, issue 2.0), but one. Respect to the cited document, the only function the SPG module does not implement is the spectral low–pass filtering at 2.4$\mu$m (see paragraph 4.2 of VLT–SPE–AMB–15830–20000–0001, issue 2.0), this function being included in the DET module.

# 4 SPG Optical Design

## 4.1 General description

The optical design of SPG (see fig. 1) follows the general pattern of optics for a grating spectrograph, with the necessary modifications dictated by the optical and mechanical accuracy requested by interferometry and the complexity of the interface with the detector assembly (DET).

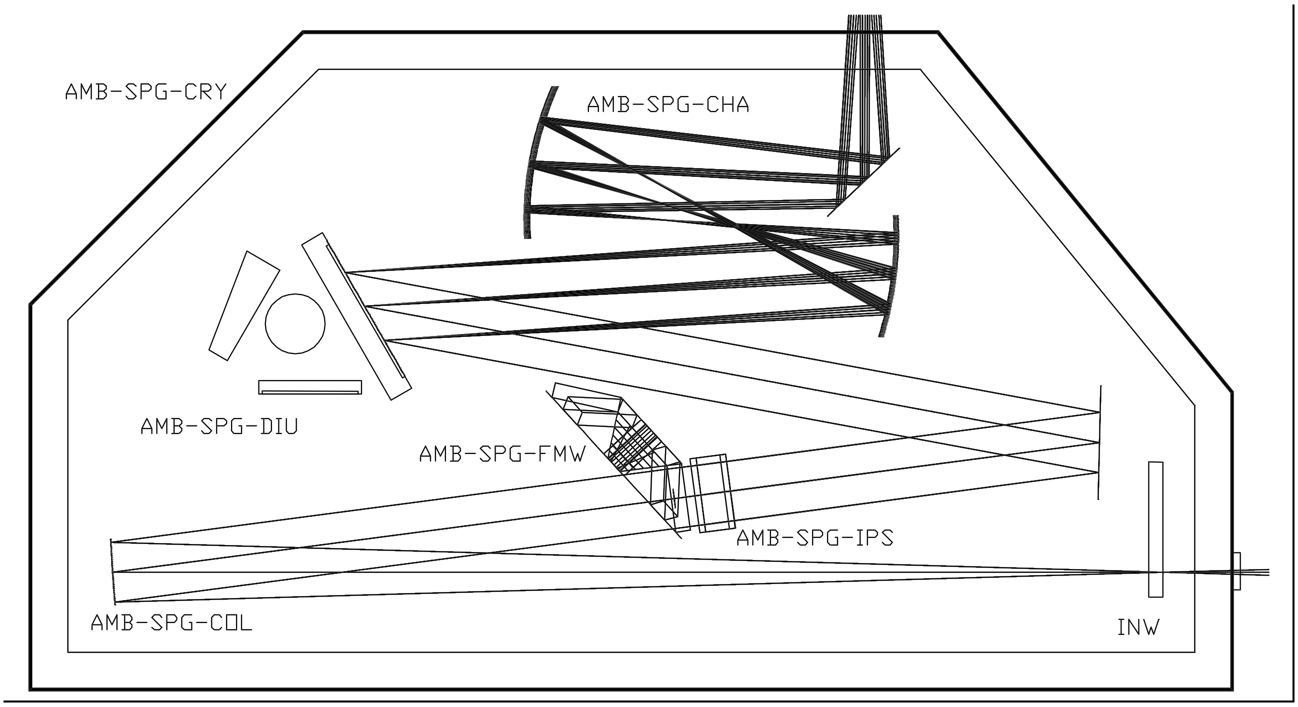


Figure 1: Drawing of the optical system.

The beam from OPM is collected by the focaliser FOC, located out of the cryostat, and gets into the spectrograph through a $CaF_2$ window (see drawing VLT-DWG-AMB-15830-0-201200-000A). The focalised beam is spatially filtered by the slit, mounted on the wheel INW which carries also several components useful in the calibration and alignment operations. The collimating mirror COL makes the beam parallel again; the wheel AMB-SPG-FMW follows which carries the pupil masks. The optical component labeled AMB-SPG-IPS is a beam splitter which steers part of the flux from the parallel beam for photometric calibration; while the largest fraction of the beam flux interferes on the detector, the fraction defined by means of the beam splitter runs along the same optical path, but it is suitably directed to form separate images on the detector. For purpose of spectral analysis, a rotating device (AMB-SPG-DIU) allows the choice among three dispersing components (two gratings, and a prism coupled to a mirror).

The final optical function before the detector is the camera, designed around two mirrors, which forms an image of the focal plane onto the detector. To this end, the camera's mirrors steer the beams outside the cryostat, so that they enter the DET cryostat which contains the detector, with the help of a plane mirror. For a general view of the cold bench assembly, see also drawing VLT-DWG-AMB-15830-0-200000-000A.

## 4.2 Input wheel (INW)

The focal plane spatial filter is a slit selected from a set, the smallest being $4370\mu\text{m}\times74\mu\text{m}$, with a positioning accuracy of 10 $\mu$m on the short side. This accuracy is achieved by mounting the slit with the long side perpendicular to the radius of the input wheel; this way the accuracy (or better, the stability after the alignment) is guaranteed by the stability of the supporting axis, designed around two pre–loaded ball–bearings (see drawing VLT-DWG-AMB-15830-0-202200-001A). The wheel has a total of five positions; the step motor resolution (0.36 degrees) and the 1:136 reduction ratio of the worm-wheel gear give an angular resolution of about 10 arcsec. To get the specified accuracy we use an anti-backlash system based on a clockwork spring on the wheel axis (not shown in the drawing) which gives a pre-load all along the run of the wheel.

## 4.3 Collimating mirror (COL)

The collimating mirror is a paraboloidal mirror which is symmetric, respect to the focal point, of the focalising mirror; this configuration has the purpose to minimize the optical aberrations. It has a focal length of 700 mm and an aperture of F/3.

## 4.4 Pupil mask wheel (AMB-SPG-FMW)

The functions of spatial filtering is performed by means of a single 8-position wheel which carries suitable apertures, in a arrangement which allows an accurate spatial filtering of the pupil image (see drawing VLT-DWG-AMB-15830-0-202300-001A). The requirements in accuracy are less stringent than in the case of the input wheel, but the mechanical concept is similar, in that we use the same type of gear and of anti-backlash mechanism as the input wheel (the spring is not shown in the drawing). The resolution we get with the 0.36 degree step motor and the 1:140 reduction gear is about 10 arcsec. The peculiar shape of the wheel is due to the path of the beams which form a sharp angle and leave little space in that area that contains also the beam splitter sub-system.

## 4.5 Beam splitter (AMB-SPG-IPS)

The beam splitter is composed by a dicroic mirror that transmit about 35% of flux and reflect the remaining 65%. The light reflected on the beam splitter is redirected by a plane mirror to the dispersing unit to finally interfere on the detector (interferometric beam), while the transmitted beams are firstly reflected by a composite mirror made by three mirrors, slightly angled to give different directions to the reflected beams, then reflected again toward the dispersing unit by the same plane mirror as the interferometric beam with the purpose to keep separated the beams coming from different telescopes and let them impinge the array detector without interference (photometric beam). The beam splitter and the composite mirror are in glass, while the other mirror is in aluminum; the first two mirrors (see drawing VLT-DWG-AMB-15830-0-202500-001A) are referenced against three orthogonal sides of the supporting structure by means of spring–loaded braces, while the mounting of the metallic mirror follows the general method used for the aluminum mirrors of the spectrograph (see below).

### 4.6 Dispersing unit (AMB-SPG-DIU)

This unit is a rotating device supporting two gratings (300 g/mm and 30 g/mm), for the resolution 10000 and 1000, and a $BaF_2$ prism coupled to a flat mirror, to have all the bands J, H and K on the array in the low-dispersion mode. We based the mechanical design (see drawing VLT-DWG-AMB-15830-0-202400-001A) on the same concept as the other two wheels; in this case the axis is driven by two different ball-bearings with a suitable pre–load and it gets through the optical bench. The moving plate is thermally connected to the cold bench with a copper strap designed to control the heat conduction and avoid large thermal stresses to the glass of the dispersing elements at the contact points on their mechanical supports. The dispersing elements are elastically referenced on three sides to avoid any effect of differential dilatation at time of thermal cycling.

The cryogenic step motor (0.36 degrees/step) drives a worm-wheel gear with a reduction ratio of 1:190, getting a resolution of about 7 arcsec. The backlash is greatly reduced using a clockwork spring (not shown) which loads the axis along all its motion.

### 4.7 Camera (AMB-SPG-CHA)

The camera is composed by two aspherical mirror with total focal length of 350 mm and an aperture of about F/2. A plane mirror steers the beams coming from the camera unit to send it to the DET cryostat.

### 4.8 Optical tolerancing

The document AD 2, AMBER Spectrograph Analysis Report (VLT-TREE-AMB-15830-20000-0002 issue 1.0 dated 27.07.2000) contains the optical parameters of each mirror, the optical performance, and the tolerance analysis as a function of the fringe visibility.

The main result of the tolerance analysis is that the fringe visibility loss is of the order of 5% at most when the positioning error of the optical elements is of the order of 0.1 mm and their angular positioning error (tilt) is of the order of 8 arcmin (errors are summed as random values). This result depends on the possibility to use as compensator the detector position along the optical axis, with a total displacement of $\pm 2.3$ mm; the positioning system of the dewars is designed to allow this relative displacement. For more details, see AD 2 (AMBER Spectrograph Analysis Report VLT-TRE-AMB-15830-20000-0002 issue 2.0, dated 16.03.2001).

The surface quality, or micro–roughness, of the metallic mirrors has an impact on the efficiency of the optical train. To avoid the use of nickel–plating on aluminum with the associated deformations due to differential of the thermal expansion coefficients, we require to push the machining of the aspheric mirrors up to roughness of 10 nm RMS (or better), while the plane mirrors are polished following the standard method up to 5 nm (or better). This way, the loss of light due to the surface roughness is less than 1.5% on each mirror.

### 4.9 Mounting of optics

The needed positioning accuracy is well at reach of mechanical practice for cryogenic system, allowing the use of simple concepts for mounting optics and designing moving functions; the fact that the instrument stays in a constant gravity field helps a lot to reach the specification in term of mechanical stability. The mirrors are manufactured in aluminum, using the diamond tooling method for the aspheric surfaces and the traditional polishing for the plane mirrors. The optical bench is machined by a single block of the same material, on it we weld the supports for all the optical components. In turn, the welded supports are machined to obtain the three seating planes of each mirrors. Mirrors mounting is based on a set of six forces, perpendicular to the mirror's sides, which pull the mirrors against the three orthogonal sides of a reference cube by means of six precisely machined shims (see drawings VLT-DWG-AMB-15830-0-202100-001A, -002A, -003A, -004A). This way, the mirrors are not over-constrained, instead they are free to follow the deformations imposed by the difference of temperature during cooling or warming cycles of the cryostat, keeping their design position under the effect of the shims when the temperature is stabilized. The six forces are applied by six spring-loaded screws (three on the back of each mirror, two on the side, one on the top) referred to six blind tapped holes on the mirror body. We plan to machine a set of shim to test the optical system at room temperature and a similar set for checking the alignment at working temperature. Once the good set of shims is found, following a full temperature cycle or after taking apart some optical component, the original alignment is kept. As we saw before (see drawing VLT-DWG-AMB-15830-0-202500-001A), we use a different concept to mount all the other optical components made in glass; in this case, each component is pushed against its three orthogonal reference surfaces using springs to get constant forces under the deformation imposed by the thermal cycles.

# 5 SPG Mechanics: Vacuum and Cryogenic System

## 5.1 General description

The AMBER cold optics, manufactured mostly in aluminum by diamond tooling or in glass, are mounted upside down respect to gravity on an aluminum optical bench which is also the backplate of the vessel where the liquid nitrogen is stored, giving uniform thermal contact between optics and cold bath.

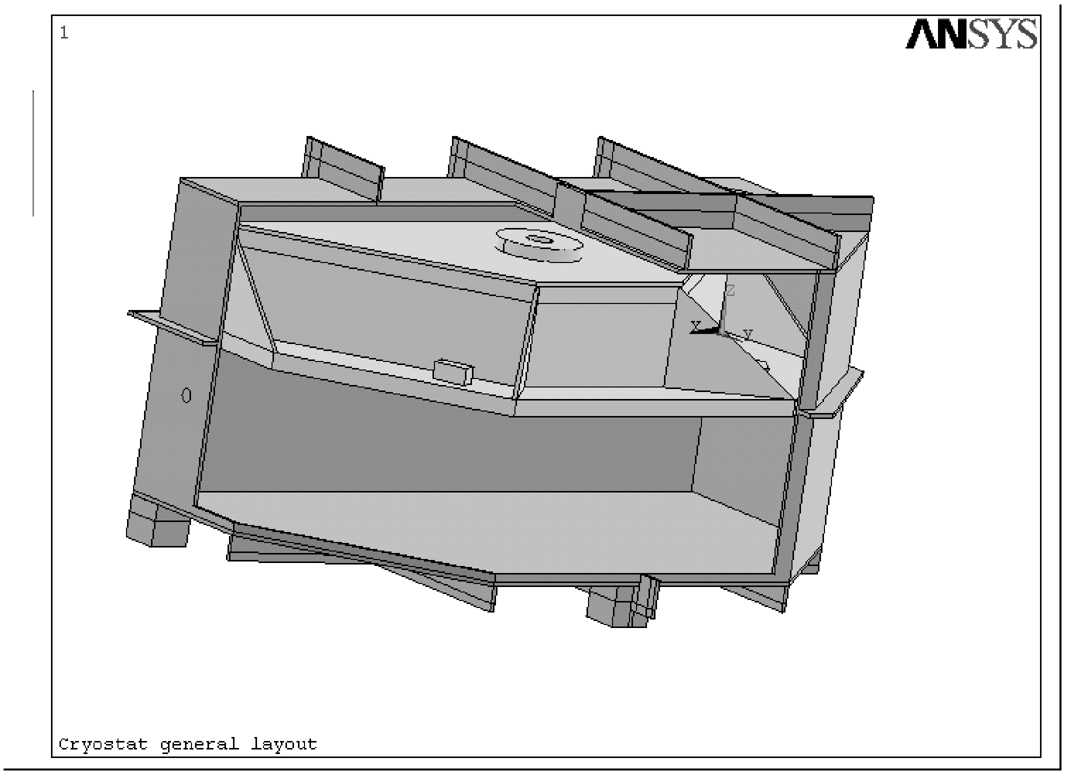


Figure 2: Exploded view of the external case with the cold bench structure.

The whole system is lodged inside a vacuum-tight shroud (see fig. 3), made of welded steel plates with suitable reinforcing ribs, whose size and shape are determined by the optics layout and by the available space on the optical table that supports all the experiment in the VLTI Interferometric lab. This external case, besides providing a good vacuum level, acts against gravity and pressure loads and connects SPG to the DET cryostat, leaving the possibility of a first alignment to OPM by means of limited positioning adjustments on the optical table. Moreover, it supports the cold bench by a hexapod (composed of six fine steel beams), dimensioned to allow the SPG system be placed on a side without suffering permanent deformation (see drawing VLT-DWG-AMB-15830-0-203100-000A). The FE analysis and the description can be find in documents AD 3 and AD 8.

The liquid nitrogen vessel is a box–like structure (worked out by a single aluminum block completed by welded elements), whose bottom plate protrudes to form the cold optical bench (see drawing VLT-DWG-AMB-15830-0-202000-000A). To respect the requirements of the optical design, the shape of this plate must not change too much under the combined loads of gravity, pressure and temperature. To this end, the design makes use of FEA to model the general behavior of the cold bench. The full analysis is found in AD 3; to summarize, the main deformation of the plate is a deviation from the ideal plane by about 17 $\mu$m under the load of the external pressure. While this deformation is well inside the allowed tolerance, we can reduce it to zero just by machining the plate with the vessel loaded by a differential pressure equivalent to the medium level of Paranal pressure.

All the optics is enclosed in the radiation shield (see drawing VLT-DWG-AMB-15830-0-202900-000A), that is in tight thermal contact with the cold bench. The model of its thermal behavior shows that all its points are at most two degrees over the cold bench temperature.

## 5.2 Cryogenic motors

The SPG optical system includes a total of three moving wheels, that is the aperture wheel, the pupil mask wheel, and the grating wheel.

To simplify the mechanics, these three functions are implemented by means of cryogenic motors. We use Berger Lahr 5-phase stepper motors, modified according to ESO experience as in VLT–TRE–ESO–14100-0483. They are well proven motors, with a more than sufficient torque at working temperature and a long operating life demonstrated in ESO infrared instrumentation. Recently, ESO brought up the issue of reliability for these motors, suggesting the use of Phytron motors specifically sold for cryogenic applications. The present design of SPG cryostat is ready to mount Phytron motors VSS 42 (equivalent to the Berger Lahr motors, if we accept a loss of resolution two that is well inside the specifications) without mechanical or electrical modifications.

During the observations, the motors are normally off and they are switched on only when needed; the positioning of the associated wheels is demanded to the worm-wheel gear that is substantially irreversible and acts as a stop to the force exerted by the spiral spring used to overcome the backlash. The temperature of the three motors is constantly monitored by the control system using local Pt100 sensors.

Regarding the limit switch and the reset functions, we use mechanical switches (Honeywell micro-switches series 11) to simplify interfacing; the mechanical resolution of these switches is set by the differential travel of the arm, which is of the order of 25 $\mu$m. We have been using these switches in infrared instrumentation since 1992 without any single failure after a great number of thermal cycles. We note also that we designed all the moving functions with limit-switches (two for each direction, OR connected for redundancy) to avoid any mechanical failure due to anti-backlash springs.

## 5.3 Cryogenics

The nitrogen vessel can store up to 19 dm$^3$ of liquid $N_2$, while the mass of aluminum to be cooled is about 24 kg. The total radiated power toward the case is of the order of 21 W, the power conducted through the supporting elements which connect the cold bench to the case (hexapods) is about 0.4 W, the power conducted through the cables and wiring is estimated to about 2.2 W, while the thermal losses at the level of the filling necks are about 2 W; the entrance window contribution to radiated power is negligible. The total thermal load of the order of 25 W suggests that we should boil liquid nitrogen at a rate of about 0.56 dm$^3$/h, and the full supply should last well over 24 hours in normal operation. This allows for an easy schedule of the refilling process, in particular freeing the observing time from this task.

At test time, the exit port toward the DET cryostat will be sealed by a suitable window. As of the integration phase, this window will be removed and the exit port equipped with a tube protruding inside the DET cryostat to shield most of the thermal radiation out of the detector area. This oblige to devise operative procedures which take into account both the needs of the SPG system and the of the DET system, as the two cryostats will be mechanically and optically connected starting from integration phase, and they will share the same environment from the point of view of pressure and temperature; to avoid possible surface contamination of the detector and the mirrors, we have to implement procedures for cooling and worming that keep the detector's temperature higher than the rest of the spectrograph.

Regarding the pumping process, we note that the estimated free space inside the cryostat is about 70 dm$^3$. To pump the cryostat up to the suitable level of internal pressure (10-4 torr, 0.01 pa) and to keep that pressure inside acceptable limits for weeks or months, we propose a solution compatible with ESO requirements (see AD 4). A split system, with a dry roughing pump outside of the Interferometric lab is connected to the high vacuum pump (STP-H 301 Seiko) via a vacuum tubing, a vacuum insulating valve, and a pressure switch (Leybold 288 66). The outgassing inside the two cryostats will contribute to raise the pressure, and the pump should be switched on during periods that are free from observations, with a frequency to be defined at time of test phase. In any case, the pumping system and the pressure monitor should be remotely controlled. The cryostat is equipped by vacuum gauge (PKR 250 Balzer) permanently wired, a second to be connected as a back-up just in case of failure is mounted on the DET cryostat.

During operations in Interferometric lab the filling of liquid nitrogen and the venting of the gas is mandated to the insulated pipes which connect the instruments to the storage tank. The SPG cryostat provides three necks, two whose design follows the specification of the related ESO document to guarantee the correct interface (see AD 5 and drawings VLT-DWG-AMB-15830-0-201400-000A, VLT-DWG-AMB-15830-0-201400-001A). One of them is dedicated to the filling operation, the second is used to vent the cold gas, while the third carries two temperature sensors (Pt100 or similar) that are used as fixed–point level gauges to keep note of the level of the liquid nitrogen inside the vessel (see drawing VLT-DWG-AMB-15830-0-201400-002B).

Both in test operations and in occasion of maintenance, we would like to be able to pass from the operating temperature to the temperature where we can safely break the vacuum in a reasonable amount of time. To this end, we provide a set of heating elements inside the cryostat, for a total of about 400 W of power. The operation of these heaters should be coordinated with that of the heating of the DET cryostat, avoiding as much as possible any contamination of the detector surface.

### 5.4 Thermal interface to the interferometric laboratory

ESO specifies 10 W of convected heat load and a total of −20 W for the total convected cooling load from each instrument inside the Interferometric lab. While the thermal balance of AMBER is not fully assessed, the thermal load of SPG alone (about −25 W from the cold walls of the cryostat) gets over the permitted value. To meet the ESO policy, we plan to use heating elements for a total power of about 30 W glued on the case of SPG to keep the balance of dissipating power as close to zero as possible. The control of the process is demanded to a local loop supervised by ICM.

The whole cooling and heating process should be monitored and actively controlled at ICM level, using the procedures and the parameters developed at test and integration tome. To this purpose, a total of ten internal and four external temperature sensors are provided; these sensors and the associated control electronics are selected to be compatible with ESO requirements, as in AD 4.

## 6 SPG Control Electronics and Software

During the test phase at AAO, all the functions (motors, sensors which monitors temperatures and pressure, heaters) will communicate with a control computer by means of suitable interfaces (power modules, indexers, data loggers) connected to a standard communication bus. When possible, the project will specify ESO standard components, as in AD 4, for measuring temperature and pressure. The number of custom electronics will be limited to what is not commercially available.

At the integration time, motors and sensors will be connected to the standard AMBER modules, by means of ESO-compliant interfaces that are not part of the SPG package. The experience of the test phase will be transferred to the ICM group for translating all the needed functions and controls to the standard software of the instrument.

## 7 SPG Interfaces to DET and OPM

### 7.1 Interface to OPM

The OPM sub–system sends the beam to the spectrograph through a special module called OSI (or “the periscope”) that makes possible the fine alignment. The spectrograph in turn offers the range of adjustment that is required to reach the the position where the OSI can take care of the beam alignment; in practice, the spectrograph is referred to the optical table with three supports, equipped with screws that allow adjusting the height of the cryostat above the table, and kinematically constrained to a plate that stays on the optical table and can be moved on the plane of the table by means of micrometric movements. This way, the entrance slit can be centered on the beam, and the direction of the beam can be roughly aligned to the spectrograph axis. After that operation, all fine adjustments are left to the OSI module.

### 7.2 Interface to DET

The detector chip does not offer any possibility of adjustment in position, so that we are compelled to move the whole DET cryostat to align the detector itself. We constrain the DET cryostat and the associate electronics to the SPG cryostat by means of a suitable hardware that supports its weight, and permits to adjust the position with the required accuracy (see drawing VLT-DWG-AMB-15830-0-200000-000A). We remember that during operations the two cryostats share the vacuum and have the same internal temperature, so the mechanical interface is vacuum–tight; in practice, we use a steel bellow to mechanically decouple the two ensembles, at least to a certain level, with suitable O-ring seals. We designed the support of DET having in mind the possibility to change the position of DET cryostat respect to the SPG cryostat without disrupting the common vacuum, so to keep the working temperature during the alignment. To this end, we plan to use the force of the atmospheric pressure that loads the O-ring and to move the bellow end by means of micrometric movements, both in the x-y plane and in rotation, where the bellow is rather rigid, simply loosing the screws that fix the bellow end to the SPG cryostat; these screws are free to move in suitable oversized holes. The bellow itself is deformable along the optical axis, so the focusing movements are possible without preliminary operations with the help of the threaded shafts that links the two cryostats.

The drawing VLT-DWG-AMB-15830-0-200000-000A gives more details on the mechanics of the interface, that, notwithstanding its preliminary stage, is well based.

Regarding the shielding of the stray light, two coaxial tubes, one connected to the radiation shield of the SPG cryostat, the second connected to the radiation shield of the DET cryostat, serves as an efficient light trap to shield most of the radiation from the warm walls.

# 8 SPG manufacturing plan

## 8.1 Mechanics

The mechanics of SPG presents little problems in manufacturing; most of components can be machined using standard techniques. Probably the most complicated part is the liquid nitrogen tank, that we plan to manufacture from a single block of aluminum to which the plate top is welded. The welding technique is important, in that it must keep the vacuum against the atmospheric pressure when repeatedly cycled between room temperature and liquid nitrogen temperature; in any case, we are going to use well known welding techniques.

## 8.2 Optics

The metallic mirrors for SPG are at grasp of diamond tooling techniques. The appendix 1 to this document is a copy of the letter we sent to four European companies for requesting a quotation, it includes the specifications on each mirror and other details. We got answers from two companies, substantially equivalent for what concern the total costs and the offered quality of the final mirrors. We selected the company that offered a time delivery of six months ARO including tests, the other company offering to built and test in nine months.