Design and performance of a portable ^3He cryogenic system for ground based instrumentation

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Abstract.

The availability of compact cryogenic refrigerators is of importance for the development of both ground and space-borne instrumentation based on cryogenic detectors. In this paper we report on the design and performance of a complete ground based cryogenic system consisting of a ^3He cryosorption refrigerator, and designed to cool a 6x6 element detector array of tantalum based Superconducting Tunnel Junctions (STJs). The refrigerator provides an operating temperature of 330 mK, with a hold time in excess of 7 hours. The system is designed to be portable, to provide a very stable focal plane, and to minimise the use of magnetic materials. Such a system has been used to host the Focal Plane Assembly of *S-Cam*, the first optical camera for ground based astronomy utilising an array of STJs, recently installed at the William Herschel Telescope, in La Palma.

Keywords: ^4He cryostat; ^3He refrigerator; ground based instrumentation for astronomy; superconducting tunnel junctions.

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1. Introduction.

Despite the advances made in the development of photon detectors operating at temperatures above 100K (such as photomultipliers, Charge Coupled Devices, and semiconductor photodiodes), cryogenic detectors are now beginning to play a major role in modern astrophysics [1]. Their utilisation is driven by the need to achieve very high sensitivity in a wide photon energy range, from the sub-mm wavelengths (at photon energy $E \approx 1 \text{ meV}$) to the X-rays ($E \approx 10 \text{ keV}$). In the recent past, cryogenic detectors have also found applications in the field of single photon counting at X-ray energies, offering very high responsivity, coupled to good detection efficiency and fast response times [2].

In addition to bolometers and photoconductive sensors, Superconducting Tunnel Junctions (STJs) provide very interesting performance, with single photon counting capabilities from the X-ray to the NIR. STJs have demonstrated energy resolutions of order 1 eV at 1 keV and a responsivity of order 10^4 e-/eV ; the photon absorption efficiency is of order 70% in the VUV and visible range, and of order 20% at 1 keV ; typical response times are of order $10 \mu\text{s}$ [3].

Instrumentation developed for ground or space borne astrophysics research include several cameras based on cryogenic detector arrays and operated at the focus of telescopes, onboard balloons and from space. In the first category there is SCUBA (Sub-mm Common-User Bolometer Array), based on two arrays of bolometers (with respectively 37 and 91 pixels) operating at 75 mK and dedicated to sub-mm astronomy; such an instrument is presently operating at the J.C..Maxwell Telescope in Hawaii. Several experiments based on cryogenic instrumentation have flown or will fly on balloons at altitudes of order 50 km, such as PIROG 8 and PRONAS. Numerous satellites carry cryogenic detectors in space: among them is worthy of mention ISO, the Infrared Space Observatory, operated by the European Space Agency (ESA) for a total period of 24 months with a payload working just below the ^4He lambda point. Several additional ESA projects containing cryogenic instrumentation are under development, such as Planck and FIRST. FIRST (Far Infrared and Submillimetre Telescope) will perform photometry and spectroscopy in

the 85-600 μm range, using a radiatively-cooled telescope and three cryogenic instruments based respectively on SIS mixers (operating at 2 K), Ge:Ga photoconductive detectors (working at 1.7 K) and a bolometer detector array (operating at 0.3 K) [4]. Planck will perform a full survey of the sky to image any temperature anisotropies of the cosmic microwave background radiation. The sky will be mapped in nine frequency channels, ranging from 30 to 1000 GHz; the High Frequency Instrument (120 - 1000 GHz) is based on an array of bolometers operating at 100 mK [5].

The cryogenic system described in this paper is based on already existing units, but it also contains several new design features. These features are: a) the use of non-magnetic materials in the construction of the He tank; b) the optimisation of the heat exchanger and of the thermal shield to fully exploit the vapour-cooled design; c) the solutions adopted to provide a highly stable focal plane; d) the original design of the sample holder; e) the emphasis on system mobility for the use of the system on test campaigns, outside the laboratory environment. The complete cryogenic system has been explicitly designed for *S-Cam*, a cryogenic camera for ground based optical astronomy built around the world's first 6x6 array of Ta-Al-AlOx-Al-Ta superconducting tunnel junctions [6]. Due to a number of highly innovative characteristics, *S-Cam* has been designed as a technology demonstrator, aimed at exploring the advantages of photon counting detector arrays based on STJs for optical astronomy [3, 7, 8]. The development of the camera has been entirely performed within the Astrophysics Division of the European Space Agency; the feasibility study started in the summer 1995, while the final was completed at the end of 1998. The complete system is now installed at the Ground High Resolution Imaging Laboratory of the William Herschel Telescope, in La Palma (Spain). The first astronomical results are described in [9].

1. STJ arrays.

The *S-Cam* 6x6 element array is based on 36 diamond shaped, 25 μm devices, with a separation between adjacent pixels of about 4 μm [6]. The detectors are fabricated from an original Ta-Al-AlOx-Al-Ta multilayer, deposited by sputtering onto a highly polished sapphire substrate. The Ta films (base and top electrode) have a typical thickness of order 100 nm; the AlOx is typically 1 nm thick. The devices have leakage limited subgap current densities of order 0.01 $pA/\mu m^2$ at a bias voltage of 100 μV . The I-V characteristics of the array elements are dominated by the leakage current up to a temperature of about 500 mK. In order to operate the detectors it is necessary to apply a magnetic field of order 100 G, parallel to the barrier plane. Stray magnetic fields originated by the earth magnetic field or by residual magnetisation must be eliminated to avoid flux trapping phenomena in the STJ electrodes which would degrade the detector performance [9].

Following the photo-absorption event occurring in one of the superconducting electrodes of the STJ, the photon energy E is transferred into a large number of carriers (quasiparticles) in excess of any thermal equilibrium population. The number of charge carriers produced is then $N_0 = E/\epsilon$, where ϵ is the mean energy required to produce a quasiparticle by breaking a Cooper's pair (in Ta ϵ is of order 1.2 meV). The excess charge is detected as a current pulse, driven by a dc voltage bias applied across the tunnel barrier.

The spectroscopic performance of STJs is related to the capability to measure the total electric charge generated by each photo-absorption event and detected by tunnelling through the insulating barrier. A Charge Sensitive Amplifier, which is connected to each element of the array, integrates this tunnel current and converts it into a measurable voltage; the amplitude of this voltage is proportional to the total tunnelled charge and therefore to the energy of the detected photon. This read-out approach, is different from more conventional detectors such as CCDs, and cannot take advantage of any multiplexing without compromising the detector performance. This implies that the total number of signal connections from the detector to the Front End Electronics is equal to the number of elements in the array.

2. Refrigerator requirements.

The *S-Cam* refrigerator has been designed and built to host a 6x6 element array of Ta-Al superconducting tunnel junctions. The main system requirements are therefore based on the intrinsic operating conditions of the Focal Plane Array (FPA). Operating constraints related to the need to operate at the Nasmyth focus of a telescope have also played an important role. Finally, the approach of reading out the array by means of a set of room-temperature preamplifiers has contributed to the overall refrigerator architecture.

The refrigerator base temperature is matched to the utilisation of Ta-Al STJs and to the need to minimise the thermally activated bias current in order to maximise the detector signal to noise ratio. In the case of the *S-Cam* FPA [6], by operating at a base temperature lower than 500 mK we have achieved leakage limited (rather than thermally limited) bias currents, thereby minimising the shot noise associated to the detector biasing. Such a temperature range is well within the capabilities of a ^3He sorption cooler.

The heat input requirements applying to the ^3He cooler are a consequence of the signal wiring (related to the specific read-out technique) and of the radiative load induced by the optical access window. An important design requirement is represented by the need to avoid as much as possible any ferro-magnetic materials: such a choice eliminates the danger of permanent magnetisation effects induced by the field applied to the devices during operations. Such a magnetic field is produced via a superconducting (SC) magnet, whose presence plays an important role in the definition of the cryostat geometry.

Finally, the position of the FPA must be maintained with a rather high level of mechanical stability since the overall size of the detector array is only $200 \times 200 \mu\text{m}^2$ and it is necessary to provide a reproducible positioning of the detector with respect to the external optical unit. The detector illumination takes place via a lateral sapphire window and a number of thermal IR filters. The main system requirements are summarised in table 1.

3. Refrigerator design and manufacturing.

System architecture.

The requirements listed in table 1 have been translated into design solutions, thus defining the refrigerator architecture. The adoption of a ^3He cryosorption cooler has been the first choice to achieve the required base temperature within a compact system, suitable for observations at a telescope site. The choice of a bottom loading cryostat has allowed the presence of the lateral window in combination with a compact and robust structure, suitable for test campaign activities. A large area cold-plate was imposed by the required He tank volume, and used to host the ^3He cooler, the superconducting magnet and the cold IR filters necessary to suppress the thermal background radiation.

The adoption of room temperature Front End Electronics (FEE) has simplified the requirements on the internal geometry of the cryostat, and allowed an optimisation of the design of the inner shields on the basis of purely thermal requirements.

In consideration of the estimated heat input (see section 4) and of the corresponding He evaporation rate, we have decided to exploit the residual enthalpy of the boil-off gas by using a vapour-cooled shield configuration.

Due to the geometrical constraints imposed by the external optical unit ($f/2$, with a reduced back-focal distance) it was necessary to position the access window inside the cryostat vessel envelope and to use a single thermal shield. The choice to operate a single, vapour cooled thermal shield has had a significant impact on the cryostat architecture. It has in fact required a careful design of the cryostat venting line; this line has two roles: 1) it is used to fill the tank; 2) it is the pumping line through which the ^4He vapour is evacuated. The cryostat performance is critically related to the temperature of the single thermal shield, which must be cooled down by exploiting the residual enthalpy of the He vapour, leaving the tank through the venting port. Considerable attention has been given to the design of a heat exchanger located inside the vessel, along the vapour venting line, just above the top part of ^4He tank. This heat exchanger is responsible for the cooling of the thermal shield, playing a major role in the definition of the refrigerator performance.

In order to achieve the required mechanical stability of the Focal Plane (less than 25 μm shift in all directions during the refrigerator hold time), the cold plate is supported by four Kevlar plates connected to the top plate of the vessel. This solution differs considerably from the more common neck-suspended designs, which suffer from thermal expansion, and pressure related shifts.

The design of the refrigerator architecture, as derived from the requirements and choices discussed above, is shown in figure 1.

The ^4He cryostat.

Before proceeding with the detailed design and manufacturing phase, several techniques have been tested on an existing bottom loading dewar, used as ‘test-bed’. Specific investigations have been conducted on the role of the heat exchanger, on the behaviour of the vapour cooled thermal shield and on the utilisation of Multi-Layer Isolation (MLI). In parallel with the testing activity, additional information has been obtained from specific thermal models (see section 4).

The overall design, final integration and testing of the cryostats have been carried out within the Astrophysics Division of the European Space Agency, while the detailed design of dedicated parts, the manufacturing and the assembly of the cryostat have been carried out by *Bradford Engineering BV* (NL).

In order to proceed with the detailed design, the total heat load on the cryostat has been fixed at 500 *mW*. This load is larger than what is offered by more conventional commercial units, but it is satisfactory when considered with respect to our specific operating requirements (large number of wires, presence of a large lateral window, absence of LN_2 tank, single thermal shield, support struts connecting the cold plate with the external vessel). This heat input budget has then allowed us to dimension the ^4He tank capacity (12 litre) to meet the hold time requirements. One of the innovative features of this cryogenic system is the fact that, in order to minimise the presence of any residual magnetisation, the helium tank has been constructed from Manganin plate material of 1.0 *mm* thick. The cryogenic properties of the Manganin tank were successfully demonstrated using a dedicated test unit.

The cold plate is represented by a 20 *mm* thick OFHC copper disc, with a diameter of

240 *mm*. The plate thickness was dimensioned to deform less than 5 μm under the effect of 2 *bar* pressure difference and in presence of a static load of 3.5 *kg*.

The external vessel was then dimensioned, including the geometric requirements imposed by the presence of the lateral access optical window, with a clear diameter of 35 *mm* and by the need to mount the FEE box directly onto the signal wiring connector. This approach has allowed the minimisation of any Electro-Magnetic Interference (EMI) and of the wire stray capacitance (see figure 1). The external vessel is divided in two parts, both in aluminium:

- a) the top plate (hosting the thermometry, the magnet and signal wire connectors, together with the Isolation Vacuum KF port and the tank entry port);
- b) the main vessel cylinder (including lateral and bottom surfaces, a μ -metal shield to exclude external magnetic fields and the window aperture).

The thermal shield is fabricated in pure aluminium, 1.0 *mm* thick and thermally connected to the heat exchanger on the venting line.

The shield plays a major role in minimising the heat input into the helium tank by intercepting the thermal radiation generated by the inner surface of the vessel. In order to improve the system performance, a limited number of MLI layers (of order 5) has been used to cover the external surface of the thermal shield. The shield is closed at the bottom by a removable aluminium cover, which ensures access to the inner copper cover of the FPA chamber (see figure 1). Both covers are kept in position by a locking mechanism, which ensures a good degree of thermal contact along the lateral walls and avoids the use of screws.

The support structure is made of 2 *mm* thick Kevlar composite: they connect the copper cold plate to the vessel top plate over a length of about 350 *mm*. Kevlar was selected because of its mechanical properties, its low thermal expansion coefficient and low thermal conductivity. The plates are made of impregnated fabric layers, with one layer orientated in the load force direction.

The cold plate surface has been provided with a grid of M3 tapped holes on a 10 *mm* pitch in order to simplify the installation of the ^3He cooler and of the other components of the FPA. The tightness of the weld between the Manganin walls of the tank and the copper cold plate has been demonstrated both at room and cryogenic

down to 1.7 K (i.e. well below the temperature at which any superfluid He leak would become evident). The manufacturing and fabrication of the heat exchanger on the tank venting line has also required specific welding skills, and it represents a critical step in the cryostat manufacturing. The heat exchanger was designed to serve three main purposes: a) exploit the gas enthalpy to cool the thermal shield (by including a number of fins along the vapour path); b) minimise the heat input into the He tank (by using thin wall stainless steel pipes and maximising their length); 3) allow an efficient pumping of the main bath (ensuring a large conductance). In addition, connecting the heat exchanger with the main He tank via a short bellow has reduced any mechanical strain induced on the inner cryostat structure by the pumping action.

The ^3He cryo-sorption cooler.

The cryosorption ^3He cooler has been manufactured by DTBT/CEA (F). The cooler is represented in figure 2 and its working principles are discussed in details in [10]. The envelope dimensions correspond to a cylinder with a diameter of 80 mm and a height of 137 mm; the total weight is 980 g. In absence of any thermal load and with the ^4He bath at 1.5 K, the cooler achieves a base temperature of about 0.26 K; the unit has then a cooling power of 50 μW at 295 mK and of 100 μW at 320 mK. The hold time corresponds to about 12 hours with the sorb pump maintained at 1.5 K and a cooling power of about 50 μW . The final temperature of the evaporator can be controlled by regulating the temperature of the sorb pump, i.e. the pumping speed applied over the ^3He bath. The cooler is mounted on the cold plate of the cryostat, thus ensuring that the condenser temperature coincides with the ^4He bath temperature. The sorption pump can be heated up via a resistor or thermally connected to the cold plate by means of a gas heat switch, also manufactured by DTBT/CEA (F) and visible in figure 2 [11]. Such a gas switch is not strictly required for operating the cooler, but it ensures a faster cooling of the pump, thereby shortening the recycling process; it has provided reliable operations in absence of any moving parts and it has proved very effective.

The Focal Plane Assembly.

The Focal Plane Assembly (FPA) represents a crucial part of the *S-Cam* refrigerator and consists of three main parts: 1) a copper detector holder; 2) an aluminium base structure; 3) four supporting Kevlar blades (figure 3). The detector holder is thermally connected to the ^3He cooler evaporator via a high conductivity copper strap, approximately 220 mm long and 20 mm wide. The strap is composed of two copper layers, each 0.3 mm thick, in order to achieve a large thermal conductance. The detector holder is supported and thermally isolated by the four thin blades, each 40 mm long, 5 mm wide and 0.2 mm thick, which connect it to the aluminium base. This base is attached to the cryostat cold plate by means of four M3 screws. The use of the 4 thin blades ensured a very high degree of mechanical stability in all directions, while minimising the heat conduction from the Al support structure (at approx. 2.0 K) to the detector holder (at approx. 0.3 K). The Assembly is completed by a copper baffle connected to the holder and limiting the array FOV to the nominal solid angle to minimise the effects of any residual IR radiation. The inner surface of the baffle is blackened to minimise any stray light contribution.

The complete FPA is located in the bore of the SC magnet, while the array is positioned in the geometric centre of the magnetic field. The assembly provides the thermal anchoring for the signal wiring, which is connected to the contact pads on the array via alumina interface plates. The final connection between the array substrate and the interface plates is performed via wedge-bonding, with Au wire. The thermal contact between the detector substrate and its holder is provided by beryllium-copper clamps, which ensure a controlled amount of pressure at room as well as at base temperature.

The SC magnet.

The SC magnet is a split pair, conduction cooled unit manufactured by *Oxford Instruments* (UK). The split pair geometry allows for lateral optical access, while guaranteeing a magnetic field parallel to the STJ barrier plane. The Nb-Ti wiring is wound on a copper former connected to the cryostat cold plate and designed to meet the field of view requirements of the cryogenic camera. The current wires of the

magnet are running along one of the stiffening Kevlar struts, up to the connector installed on the vessel top plate. The magnet has been designed to provide a maximum field of about 500 G at a current of 2 A , with a field homogeneity of about 1 part in 10000 within a 2 mm diameter sphere volume.

Thermometry and wiring.

The refrigerator has a complete suite of thermometers, which allows us to monitor the thermal performance in each of the different operating phases. Different thermometers are used depending on the temperature range and the required measurement accuracy. Table 2 provides a summary of the thermometers and of their characteristics. The thermometry wiring runs from the different sensors to a dedicated connector which is heat sunk on the cryostat cold plate and from there to a warm connector on the vessel top plate. All the thermometry wiring is provided with passive filters designed to reduce any EMI generated by the read-out instrumentation.

The temperature sensor wires are in Manganin, with an external diameter of 0.10 mm and a typical room temperature resistance of about 200 Ω/m . A similar approach is used for the signal wires (for a total of 40 single strand lines), running via a separate route (to minimise any EMI interference from the thermometry read out electronics) to the FEE connector. In this case the wiring is divided in two sections: the first one running from the detector holder to the cryostat cold plate (Manganin wire external diameter of 0.15 mm), and the second one from the cold plate to the FEE connector (wire external diameter of 0.10 mm). The single strand wires are attached together to form a compact ribbon cable, approximately 5 mm wide and approximately 60 cm long. Typical wire-to-wire stray capacitance is of the order of 50 pF/m . The signal ribbon cable is secured to the cryostat structure in order to minimise microphonics.

4. System performance.

Thermal modelling.

The refrigerator performance has been modelled by means of a finite difference thermal analysis. The thermal models have allowed an improved assessment of the experimental results and have provided support to detailed design and final material choices. The analysis has focused on the total heat input received by the cryostat and on the heat input to which the FPA is subject. The main results for both the 0.3 K stage (FPA and ^3He cooler) and the main cryostat (^4He tank) are summarised in table 3 and table 4.

^4He cryostat: test results.

The *S-Cam* refrigerator has been tested at different stages of integration in order to systematically study the role and characteristics of each different component. The very first tests have verified the vacuum integrity of the vessel while still at room temperature. Once the vacuum integrity of the system was demonstrated, the cryostat was fitted with several temperature sensors, to validate the design assumptions: sensor locations included the thermal shields and the related bottom covers, as well as the heat exchanger. Several tests at liquid nitrogen temperature were performed to highlight any shortcoming in the functioning of the heat exchanger, of the thermal shields and of the bottom covers. Five layers of MLI were then added to the external surface of the thermal shield and the first He transfer was performed. In addition to verifying the thermal performance of the system at 4.2 K, we pumped on the bath to achieve a base temperature of 1.7 K, well below the lambda point of liquid helium. Such tests were performed to highlight any superfluid helium leaks in the tank Manganin to copper welding. Following confirmation of the tank vacuum tightness, a series of runs were performed to refine the design of the heat exchanger and to improve the cover locking mechanisms. In this phase the sapphire window was replaced with a blind Al flange, and the related opening in the thermal shield was provisionally closed. Each test included the temperature as well as the evaporated gas volume measurements. The main test results are summarised in table 5 (liquid N_2

performance) and table 6 (liquid He performance).

³He cooler and Focal Plane Assembly: test results.

After the completion of the cryostat characterisation and its validation against the thermal model, we have assembled the cooler, the SC magnet and the FPA onto the cold plate and proceeded with additional testing. The tests have focused on the monitoring of the base temperature and hold time in realistic operating conditions; these included the presence of the nominal IR filters and the exposure of the array to the radiative load originating from the lateral window.

After helium transfer, the ⁴He bath is pumped down to about 2.5 K (corresponding to a bath pressure of about 100 *mbar*). Then the sorption pump heater is activated and the ³He gas desorbed while the charcoal temperature reaches 40 K. The condenser temperature is low enough to guarantee the ³He condensation and its collection, by gravity, in the cooler evaporator. The condensation process lasts about 30 minutes, after which the pump heater is switched off, while the sorb is cooled down to the cold plate temperature by activating the thermal switch described in figure 2 and in [11]. In about 20 minutes the refrigerator achieves its base temperature, 320 *mK* at the detector holder, when the cold plate is in equilibrium at about 2.0 K, with a bath pressure of about 25 *mbar*. From such a base temperature, albeit obtained with the ⁴He bath at 2.0 rather than at 1.5 K, we deduce that the total heat load is probably exceeding 50 μ W. Figure 4 provides an overview of the refrigerator operations, including pre-cooling and condensation phase. The plot refers to the special case in which pumping on the main ⁴He bath is stopped after achieving condensation of the ³He gas and the cold plate temperature returns to 4.2 K. The temperature at critical locations is also indicated.

Temperature stability is typically better than 1 *mK/hour* and limited by temperature variations in the thermal shield (i.e. variations in the system heat load) rather than by the intrinsic cooler performance. Figure 5 shows the temperature recorded at the FPA as a function of time over a period of about 200 minutes, with the ⁴He bath at atmospheric pressure: the maximum temperature variation is just above 1 *mK*, with a time profile matching the thermal shield behaviour. The temperature stability

performance could be improved by controlling the sorption pump temperature via a dedicated PID controller. Such a system would guarantee a more constant pumping speed over the ^3He bath. In addition, the controller could be used to work at any intermediate temperatures between 0.3 K and the cold plate temperature.

The refrigerator has been tested over more than 20 complete thermal cycles (300 to 0.3 K) and showed an excellent reliability and a very high level of performance reproducibility. The main test results are summarised in table 7.

It is interesting to notice that tests over two consecutive thermal cycles (300 to 0.3 K) have shown that the optical unit alignment on a given array pixel is preserved; this implies that the mechanical stability of the complete system is within specifications.

The detector array performance has shown the correct cooling of all elements on the substrate and the absence of any magnetic flux trapping phenomenon. Such results have confirmed the validity of the wiring approach, both in terms of material selection and of heat sinking techniques. Finally, the optical tests have shown the proper and uniform illumination of the array together with the absence of any stray light or image ghosting effects. More details on the electro-optical performance of the camera will be given in a further paper.

S-Cam operations.

The refrigerator described above is part of a cryogenic camera installed at the Nasmyth focus of the Ground based High Resolution Imaging Laboratory of the *William Herschel Telescope* (Isaac Newton Group, La Palma). Within this system, the cryostat is located on an optical table and interfaced to a dedicated focal converter via its lateral window (see figure 4). A 6m long KF50 pumping line connects the cryostat venting port with a $33\text{ m}^3/\text{hour}$, double stage rotary pump. The pumping line includes an expansion chamber designed to damp any parasitic oscillations and avoid artificial increases of the observed He evaporation rate. LN_2 pre-cooling takes place at least 12 hour before He transfer. During operations liquid He is transferred twice: about 3 hours before starting on-sky observations and then 10 hour later, to keep the system at 4.2 K until the next observation period (following night). Due to the fact that the telescope site is located at 2500 m above sea level, the boiling point of ^4He is reduced

to about 3.7 K, simplifying the ^3He condensation procedures. During observations the rotary pump is always on, in order to keep the ^4He bath at a temperature of about 2 K.

5. Conclusions.

The portable ^3He cryogenic system built for the *S-Cam* project has demonstrated that all the project requirements can be met. It is a reliable system, which offers swift operations in the field. In particular, base temperature stability and hold time have proved to be very satisfactory, together with an excellent mechanical stability of the FPA. A base temperature of 320 mK and a hold time in excess of 7 hour have been obtained when pumping on the ^4He bath; the system guarantees 450 mK for a total duration in excess of 12 hour when the ^4He bath is kept at room pressure. In this case operations can be continued indefinitely by topping the main bath and recycling the ^3He , with a 12 hour on and a 3 hour off duty cycle. The in-house design and construction has offered a flexibility for the overall camera project which was simply inconceivable with commercial products. In addition to the specific *S-Cam* application, the cryostat is ideally suitable for experimental activities at beam-line facilities and for the laboratory characterisation of detectors irradiated by external sources. Several improvement areas have already been identified. The optimisation of the emissivity of the inner surfaces should improve further the thermal performance. The stiffening strut cross-section and material choice could be reconsidered so as to minimise the conductive heat input. Weight reductions could also be achieved by compromising on the overall mechanical stability of the FPA (e.g. by thinning the external vessel and/or the cold plate). As far as *S-Cam* is concerned, a considerable effort will be invested in enlarging the detector array format, thereby increasing the number of channels and the related wiring. This will clearly require different connectors and FEE interface. Preliminary investigations show that it should be possible to operate as many as 100 elements (corresponding to a 10x10 array) by stretching the present system approach. Larger array formats require drastic changes to the refrigerator architecture, with particular regard to the FEE and signal wiring.

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8. Figure captions.

Fig. 1

Overall refrigerator architecture. The schematic drawing shows the main cryostat features and the position of the ^3He cooler as well as the experimental volume and the Front End Electronics.

Fig.2

Schematic view of the ^3He sorption cooler and of the gas gap heat switch.

Fig.3

Schematic view of the Focal Plane Assembly. The copper detector holder, the Kevlar blades and the aluminium base are included, along with the detector and wiring configuration. Baffle and back cover are omitted for clarity sake.

Fig.4

Overview of the refrigerator operations, including pre-cooling and condensation phase. The plot refers to the special case in which pumping on the main ^4He bath is stopped after achieving condensation of the ^3He gas. The temperature at critical locations as a function of time is also shown.

Fig.5

Stability of the detector holder temperature as a function of time over a total period of about 3.5 hours. The thermal shield temperature (related to the He boil-off rate) influences the detector temperature stability.

Table 1: Main refrigerator requirements.

Detector operating temperature (^4He bath at 2 K):	< 350 mK
Detector operating temperature (^4He bath at 4.2 K):	< 500 mK
^3He cooler heat load at base temperature:	> 10 μW .
Operating temperature stability (over hold time):	< +/- 5 mK.
^3He cooler hold time (^4He bath at 2.5 K):	> 10 hour
^4He cryostat hold time (^4He bath at 4.2 K):	> 12 hour
^4He cryostat hold time (^4He bath at 2 K):	> 6 hour
Total number of wires to the FPA:	41 (36 signal wires + return).
Optical access:	<ul style="list-style-type: none"> - Via lateral window (35 mm clear diam.). - External optical unit (f/2). - Presence of cold IR filters.
Additional requirements:	<ul style="list-style-type: none"> - SC magnet on the ^4He cold plate. - Absence of remnant-magnetic fields. - FPA shielded from ext. magnetic fields. - Accurate shielding from external EMI. - Wire microphonics minimisation. - High stability of the FPA position.

Table 2. *S-Cam* thermometry: type and location of the temperature sensors.

Sensor location.	Temperature range.	Sensor type.
³ He cooler condenser	300 - 1.5 K	Carbon Resistor
³ He cooler sorption pump	300 - 1.5 K	Carbon Resistor
Detector holder	6 - 0.3 K	Germanium resistor
Cryostat bottom cover	300 - 30 K	Pt-1000
IR filter holder (1)	300 - 30 K	Pt-1000
IR filter holder (2)	300 - 1.5 K	Carbon Resistor

Table 3: Estimated heat loads on the 0.3 K stage.

Source of dissipation.	Heat input (W).
Detector Array (biasing of all elements)	10^{-12}
Temperature sensor (Ge resistor)	$3 \cdot 10^{-9}$
Support struts (4x Kevlar blades)	$11 \cdot 10^{-6}$
Harness (signal and T sensor wiring)	$0.4 \cdot 10^{-6}$
Total radiation input.	$2 \cdot 10^{-10}$
Total load	$1.14 \cdot 10^{-5}$

Table 4: Estimated heat loads on the ^4He tank.

Source of dissipation.	Heat input (W).
Stiffening struts (4x Kevlar)	0.15
Harness (signal and thermometry wiring).	0.001
SC coil leads (conduction)	0.04
SC coil leads (dissipation)	0.04
Access window (radiation)	0.085
Thermal shield radiation and neck conductivity	0.20
Total load	0.48

Table 5. Performance at liquid N_2 .

Typical Isolation Vacuum base pressure:	$8 \cdot 10^{-6}$ mbar
N_2 gas flow at equilibrium temperature (77 K):	1.5 slm
Corresponding heat input at LN_2 :	5400 mW (*)
Shield bottom cover temperature (LN_2):	160 K

(*) The residual pressure of the isolation vacuum directly influences heat input at LN_2 temperature.

Table 6. Performance at liquid He.

He gas flow at equilibrium temperature (4.2 K):	8.5 slm (room pressure)
Corresponding heat input at LHe:	530 mW
Shield bottom cover temperature (LHe):	70 K
He gas flow at equilibrium temperature (2 K):	11 slm (pumping on ^4He bath, $P = 20$ mbar)
Corresponding heat input:	690 mW
Shield bottom cover temperature (pump on):	50 K

Table 7. Performance of the ^3He cooler.

Typical cool-down time (4.2 to 0.3 K):	2.5 hour
Base temperature (cold plate at 2.0 K):	320 mK
Hold time at base temperature:	10 hour
Base temperature (cold plate at 4.2 K):	450 mK
Detector holder temperature stability:	+/- 2 mK over the entire hold time
^4He hold time (with cold plate at 2.0 K):	7.0 hour.

Figure 1.

Figure 2.

Figure 3.

Figure 4.

Figure 5.

Stability of detector holder temperature.