THERMAL CONTROL SYSTEM FOR THE MAIUS ATOM INTERFEROMETER PAYLOADS ON A VSB-30 SOUNDING ROCKET

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ABSTRACT

The QUANTUS consortium started activities to perform atom interferometry on a sounding rocket in the year 2011. Three sounding rocket missions (MAIUS-1 to MAIUS-3) have been planned to demonstrate Bose-Einstein condensation and atom interferometry with rubidium and potassium atoms. Two different payloads MAIUS-A and MAIUS-B have been designed qualified and integrated in the time frame from 2011 until 2020.

The MAIUS-A scientific payload is capable of performing single species experiment with rubidium only and was used as a technology demonstrator in the MAIUS-1 mission. The MAIUS-1 mission was conducted in fall 2016. On the 23rd of January 2017 the payload MAIUS-A was launched on a VSB-30 sounding rocket. The payload created the first Bose-Einstein condensate (BEC) and performed atom interferometry aboard a sounding rocket with rubidium 87 atoms [1]. Its successor MAIUS-B will be able to perform simultaneous experiments with Bose-Einstein Condensates of Rubidium-87 and Potassium-41 atoms. In order to achieve this ambitious scientific goal the experiments use various sensitive instruments imposing strong requirements on the thermal and mechanical design of the scientific payload.

This paper gives a summary of the MAIUS-A and MAIUS-B scientific payload design with a focus on the thermal control system. Furthermore, the design of the GSE and the water cooling umbilicals is presented. The paper closes with an outlook on future atom interferometry payloads on sounding rockets and beyond.

1. INTRODUCTION

In 2011 the QUANTUS-III project was initiated by the DLR space administration as a successor of the QUANTUS-I and QUANTUS-II projects, which demonstrated the first Bose-Einstein condensates in microgravity at the Drop Tower Bremen [2]. Aside from ongoing activities at the drop tower, it was the objective of the project to develop, build and launch a sounding rocket payload for cold-atom experiments in space.

The scientific objective of sounding rocket mission MAIUS-1 was to demonstrate the first Bose-Einstein condensate (BEC) in Space by cooling Rubidium-87 atoms. In order to create BECs, the atoms are cooled using laser light, magnetic fields and radio frequencies. The atoms are pre-cooled in an atomchip-based magneto optical trap (MOT) and finally brought below the critical temperature for the phase transition by evaporative cooling. These atoms are subsequently manipulated in a light-pulse interferometer sequence [3]. The MAIUS-A payload used in this mission thus included the complex scientific apparatus necessary for cooling, trapping and manipulation of the alkali metal atoms. These instruments have been ruggedized and miniaturized to allow a flight on a sounding rocket.

After integration and successful qualification of all MAIUS-A systems in 2015 the project QUANTUS-IV MAIUS was started. In this project a new apparatus MAIUS-B was developed, which will be capable of performing experiments with two atomic species (Rubidium-87 and Potassium-41). The MAIUS-B apparatus shall be launched twice in the missions MAIUS-2 and MAIUS-3.

The scientific objective of MAIUS-2 is to perform sequential experiments with rubidium and potassium atoms, based on the results from the MAIUS-A experiment and the QUANTUS drop tower experiments. The MAIUS-3 missions aims to perform simultaneous experiments with Rubidium and Potassium atoms. This will allow to study the behaviour of mixtures of ultra-cold bosonic gases in microgravity and on time scales not accessible on Earth.

All three missions are launched using the two-staged VSB30 sounding rocket, which is operated by the DLR MORABA and launched from Esrange in the north of Sweden. The flight ticket for the MAIUS missions includes all systems needed for rocket operation as well as the Brazilian S-30 and S-31 motors [4].

During ascent the motors cause strong accelerations and vibrations. Moreover the payload hull is heated up due to aerodynamic friction, which has to be considered during the design of the thermal control system.

This paper focuses on design of this thermal control system in chapter 3, after giving an overview on the scientific payload designs in the following chapter.

2. SCIENTIFIC PAYLOAD DESIGN

2.1. MAIUS-A

The MAIUS-A scientific payload consists of five hull segments with an overall length of 2790 mm and a total mass of 309 kg. As shown in Figure 1 the hull segments house four systems needed to perform atom interferometry.

The modules of the MAIUS-A scientific payload are 500 mm in diameter with a wall thickness of 5 mm. The increase of the wall thickness from standard 3 mm to 5 mm reduces the impact of aero-thermal heating on the inside of the payload by increasing the thermal capacity of the outer structure.

During flight the scientific payload is sealed and pressurized to 1200 mbar using standard rubber o-ring seals between the modules and between sealing plates and the hull [6]. The instruments of the experiment are mounted to four platforms, attached to the payload hull by brackets equipped with passive vibration isolation devices [6] [7].

To create Bose-Einstein condensates it is essential to provide a good vacuum environment and the magnetic and light fields mentioned above for manipulating the atoms. Thus the physics package consisting of the UHV pumping system providing the vacuum quality inside the experiment chamber, where the experiments are carried our [5].

The physics package consists of two platforms. The pumping system is mounted to the upper side of the first platform. Between both platforms the experiment chamber, optics and coils are placed inside a three layer magnetic shielding to protect the experiment from outside magnetic fields disturbing the experiment [8]. The laser system is providing the required light fields [9] and is mounted below the lower platform to ease the connection and routing of the optical fibres to the physics package.

The electronic system is driving the lasers, coils, cameras and all the other instruments of the experiment, thus it is the system generating the most heat. It is mounted to both sides of an individual platform. The on-board computer is attached to the lower cover of the electronic system housing. The platform at the bottom of the sealed area carries the batteries on the one side and the power distribution on the other.

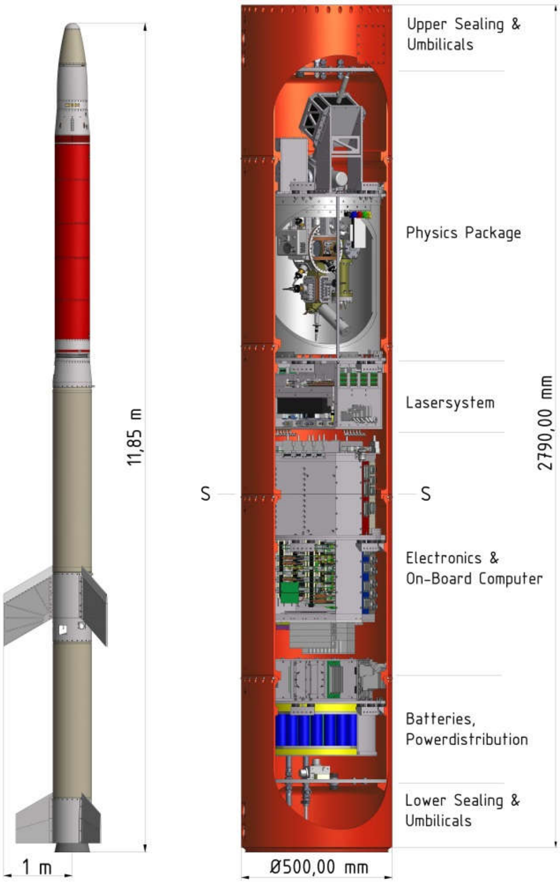

Figure 1. Overview of MAIUS-A payload

2.2. MAIUS-B

The dual species capabilities of the MAIUS-B apparatus require additional hardware to cool, manipulate and detect potassium atoms. For experiments with potassium, lasers with a different wavelength are needed. Moreover, experiments with mixtures of ultra-cold rubidium and potassium require a third set of light and magnetic fields.

Thus a second laser system and appropriate driver electronics are required. In order to not violate the requirements of the VSB-30 launcher, all systems of the scientific payload haven been optimized in mass and size.

The final design of the scientific payload is depicted in Figure 2. The MAIUS-B payload is housing 5 systems:

- Physic Package Electronic System (EL)
- Physics Package (PP)
- Laser System (LS)
- Laser Electronic System (LE)
- Batteries (BA)

Compared to MAIUS-1 the order and distribution of the systems has been changed. The electronic subsystem was divided into two separate sections, the laser electronic system and the PP electronic system. To ensure that the centre of gravity of the payload is close to the position of the atoms the PP electronics system is now situated above the physics package [10].

The subsystems are integrated into seven hull segments with an outer diameter of 500 mm, a wall thickness of 4 mm and an overall length of 2806 mm. To keep the subsystems under atmospheric pressure, the payload is sealed at top, bottom and between the hull segments using the same sealing methods as in MAIUS-A apparatus [6] [7]. The payload systems are mounted to the rocket hull using a passive vibration isolation identical to the one used in MAIUS-A [6] [7].

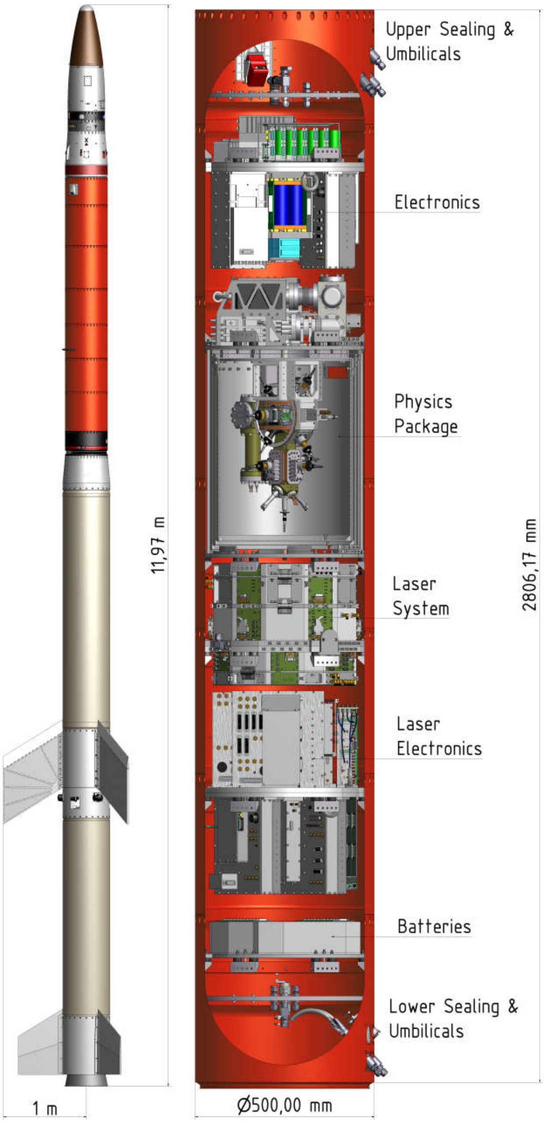

Figure 2. Overview of MAIUS-B payload

3. Thermal Control System

3.1. MAIUS-A

A stable thermal environment is needed for long-time operation in the lab as well as during the flight. The thermal control system of the payload uses different strategies to archive both. For long-term operation water cooling is used to extract the heat from the payload, while during flight the heat is stored passively in aluminium heatsinks.

The MAIUS-A payload used two separate cooling cycles as depicted in Figure 3. The water of the lower cooling cycle first cools the batteries and power distribution unit and then passes through the bottom and top electronic system heatsink. It is separated from the cooling cycle of the lasers to ensure that the high power that is dissipated at the electronic system does not disturb the temperature control of the laser system heat sink.

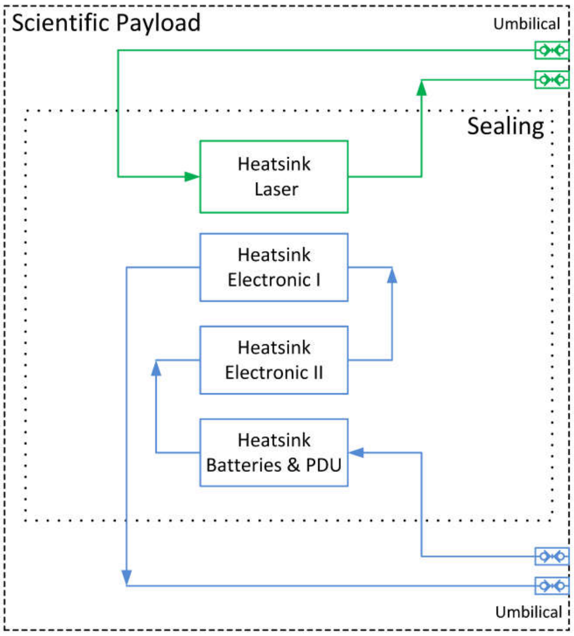

Figure 3. Schematic of the thermal control system of the MAIUS payload

The water is provided from the chillers to the payload via a Swagelok series W thermally insulated PTFE hose. The hose is protected by a fire jacket made of woven fiberglass with specially compounded aerospace-grade silicone rubber as depicted in Figure 4. The fire jacket withstands short-term flame exposure even at temperatures of more than 1000°C. Thus the water umbilical hoses will survive the harsh environment in the launch tower and can be used again.

As part of the ground support equipment two chillers (Huber Ministat 125 and Ministat 240) are placed on the launch pad, close to the rocket. The smaller thermostat is connected to the laser system circuit and has a cooling capacity of 300 W. The larger one is connected to the electronics loop and has a cooling capacity of 600 W. Both use the same pumps capable of overcoming a pressure loss of 700 mbar and a maximum delivery rate of 25 L/min. In the MAIUS-A setup the flow rate was tested to be 3.4 L/min, which is mainly due to the high pressure losses in the long hoses.

For protection of the chillers those are integrated in a flightcase as illustrated in Figure 4. The flightcase is made of aluminium and is designed to withstand the rough environment inside the launch tower. The Umbilical is connected to the chiller flight case with a quick coupling connector as used on the rocket side.

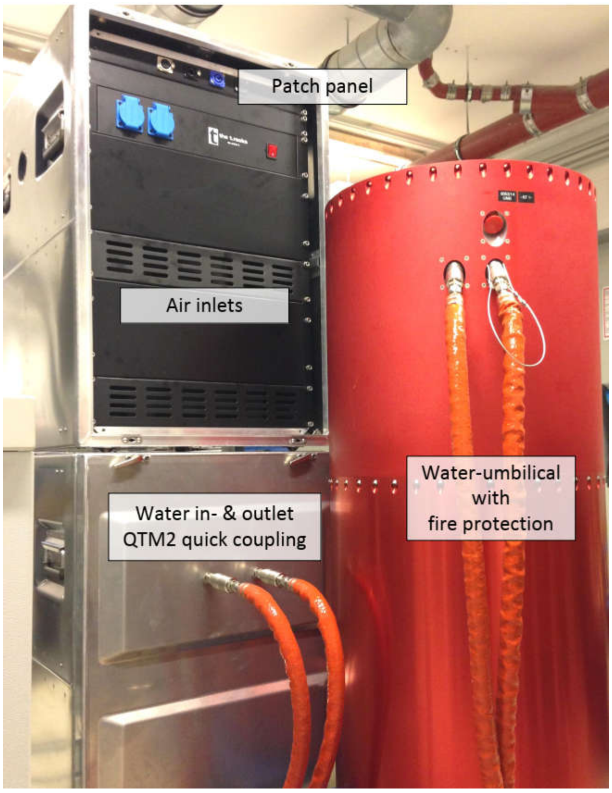

Figure 4. Two thermostats in cases with water umbilicals connected to a payload module

On the rocket side cooling water is provided by four umbilicals, which are separated during lift off. Such a water cooling umbilical connector is not available commercially. For this reason one had to be developed within this mission based on industrial quick coupling connectors. These connectors have to be small in size and should be equipped with seals at the body and the stem to prevent water from spilling out when the connectors are disconnected. For simplicity of the design the connection should allow bidirectional flow and the connectors should be disconnected by pulling to allow a passive decoupling by a lanyard as it is done with regular power or data umbilicals.

Review of different concepts and suppliers revealed the stainless steel PTFE-sealed quick connector series (QTM) from Swagelok to be most suitable for this application. Due to the limited space the smallest QTM2 connector with a 3/8" Swagelok tube fitting has been chosen. This connector is capable of handling a maximum flow of 56 l/min and will allow a maximum pressure of 6.89 MPa uncoupled and 31 MPa coupled.

The Swagelok bulkhead fitting SS-600-R1-6 is mounted to the umbilical shoe by the bulkhead jam nut providing a 3/8" tube fitting at the inside and a 3/8" tube at the outside. The quick coupling stem SS-QTM2-D-600 is directly mounted to the short 3/8"tube to the outside. This quick coupling stem is the actual interface of the payload. Its counterpart is the SS-QTM2A-B-600 quick coupling body connecting the payload to the chillers.

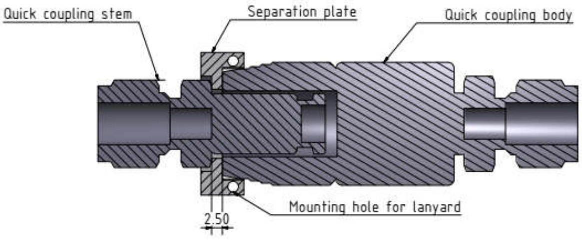

Figure 5. Schematic of the thermal control system of the MAIUS payload

For separation of the connectors a small plate made of aluminium is placed between coupling stem and body. As shown in Figure 5 the plate is only 2.5 mm thick, thus the locking of the coupling will not be affected. The separation force was tested to be < 50 N, which is acceptable for the use as umbilical. The seals in the stem and the body will prevent the water from flowing out at both, the rocket segment and the ground segment.

Inside the payload the water is fed through the hermetic sealing plate and distributed to the different payload system heatsinks as shown in schematic 3.

The temperature of the electronic system heatsink and housing is required to be kept in the range between 15 and 50°C. This provides enough reserve to keep all electronic boards below 70°C. To minimize the drift in the coil current drivers, which results in a drift of the magnetic fields at the atoms, the temperature of the heat sink should not rise by more than 10 K during flight.

During the flight electronic cards with power dissipation below 1 W store their heat in the printed circuit board, while cards with higher power are attached to the solid walls of the housing using copper heat pipes. During flight the average dissipated heat of 300 W is stored in the heatsinks and housing of the electronic system consisting of 29.8 kg of aluminum.

Special care has been taken to assure the temperature stability of the laser system. Its temperature requirements are driven by the laser modules installed within. Their temperature has to be controlled with an accuracy of +/- 0.1 K to maintain the frequency stability of the laser light. This is achieved by a two staged temperature control.

The first stage is the individual water cooling cycle of the laser system that controls the temperature of the laser heatsink with an accuracy of +/- 1° K during ground operation. The second stage is formed by Peltier elements, which are placed below the laser modules to achieve the desired accuracy in temperature stabilization. In contrast to the water cooling, which is disconnected at launch, the Peltier elements operate during the entire flight. For reliable operation of the Peltier element, the temperature of the 7.3 kg aluminium heatsink should not rise by more than 5 K.

3.2. MAIUS-B

Overall the MAIUS-B thermal control system is similar to its predecessor with improvements in some details. As the MAIUS-A thermal control system was performing well [11], no major changes were required.

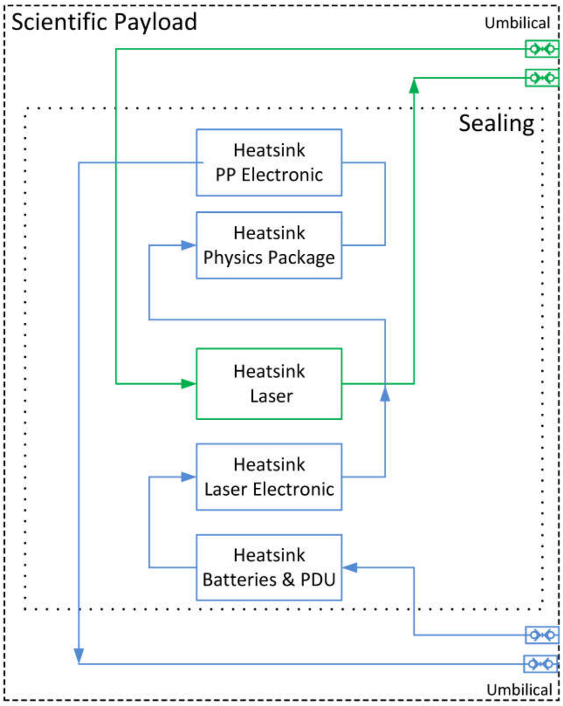

Figure 6. Schematic of the thermal control system of the MAIUS-B payload

However, the additional instruments needed for the dual species operation and the new setup of the apparatus (compare section 2.2.) made it necessary to change the water cooling routing slightly as shown in Figure 6. The MAIUS-B payload is still having two separate cooling cycles and utilizes the same water cooling umbilical technology as MAIUS-A to provide constant water cooling of the payload until lift off.

The length of the water path has increased and more hose and fittings are required in MAIUS-B, which increases the overall pressure loss in the circuit. As the pumping capacity was already at the edge in MAIUS-A a new chiller model had to be chosen.

MAIUS-B now uses a Huber Unichiller 007 for the laser system cooling loop and Unichiller 010 for the remaining systems. These chillers provide a maximum flow rate of 25 L/min and allow for compensation of a pressure loss of up to 2.5 bar. The powerful pump allows the usage of a mixture of Glykol and water as coolant to cope with the low ambient temperatures at the launch site in Sweden. The two chillers have again been integrated in Zarges case as shown in Figure 7.

Figure 7. Thermostat integrated in the ZARGES case

In the payload the most of the requirements remained the same. The electronic system heatsink and housing is required to be kept in the range between 15 and 50°C, while the current driver has been redesigned to be less temperature sensitive and there is no requirement on the rise of the heatsink temperature any more.

For flight the heat of the two electronic systems and the battery system is stored in three heatsinks, which include a meander made of stainless steel as shown in Figure 8. For connection of the meander with the other heatsinks or the umbilicals Swagelok fittings and hoses are used. The heatsinks are at the same time the mounting platforms of the electronic system components and will be mounted to the rocket hull using the same vibration isolation as in MAIUS-A [6].

Due to the payload mass constraints of the launcher the heatsinks are currently optimized in mass.

The laser system heatsink requirements remained the same, while the new laser modules have to be controlled with an accuracy of +/- 0.01 K at certain locations of the modules, which is achieved by a new setup of the Peltier elements. The laser system uses the same heatsink design as the electronic system.

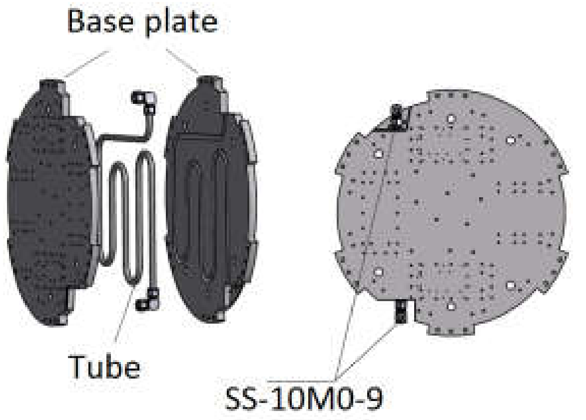

Figure 8.MAIUS-B water cooled heatsink design

The physics package was not connected to the water cooling loop in MAIUS-A. This has changed, as radio frequency and microwave amplifiers are mounted to the physics package platform, which require water cooling. As the heat input concentrated to a single electronic stack, the water cooling will only be applied onto the stack, while the remaining heat will still be stored passively in the physics package structure.

Currently the design of the heatsinks is optimized using FEM simulations. This also takes into account the aerodynamic heating of the rocket hull during flight, which is simulated using ANSYS CFD and thermal transient simulations [12]. After integration stress tests of the payload with and without water cooling as well as intense flight simulation tests are planned to ultimately verify the thermal control system design.

4. SUMMARY & OUTLOOK

This paper presented the payload and thermal control system design of the payloads for the MAIUS missions.

The MAIUS-1 mission demonstrated the first Bose-Einstein Condensate in Space. Throughout the mission the thermal control system and the water cooling umbilicals presented in this paper performed perfectly. Thus only minor changes needed to be implemented for the MAIUS-B apparatus about to be launched in the missions MAIUS-2 and MAIUS-3.

The design phase for the MAIUS-B apparatus has been completed with the critical design review in August 2018. The hardware is currently produced and assembly, integration, verification and testing of the payload will start shortly. This will include a verification of the MAIUS-B thermal control system. The launch of the payload MAIUS-2 is scheduled for autumn 2021.

In parallel, activities have been started to design a Bose-Einstein condensate and cold atom laboratory (BECCAL) in cooperation with NASA for operation onboard the international space station based on the design and technologies of the MAIUS payloads [13].

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