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Quantum Technologies for Space: Atom Interferometry Chamber for a Compact Gravity Gradiometer in Space

Executive Summary

ESA-RAL-AIC-ES

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CHANGE LOG

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1 INTRODUCTION

This document provides a top-level summary of the activities carried out during this project.

2 GLOSSARY AND REFERENCES

2.1 Glossary

AIC	Atom Interferometry Chamber
CAI	Cold Atom Interferometer
CVC	Compact Vacuum Chamber
RAL	STFC Rutherford Appleton Laboratory, UK
STFC	Science and Technology Facilities Council
TBC	To Be Confirmed
TBD	To Be Determined
UK	United Kingdom
UKRI	United Kingdom Research and Innovation

2.2 References

Ref ID	Description
RD01	A spaceborne gravity gradiometer concept based on cold atom interferometers for measuring Earth's gravity field, O. Carraz, C. Siemes, L. Massotti, R. Haagmans, P. Silvestrin, Microgravity Science and Technology 26(3), 139-145 https://doi.org/10.1007/s12217-014-9385-x

3 EXECUTIVE SUMMARY

The objectives of this project were to design and build a vacuum chamber that would allow the free drifting of a cloud of ultra-cold atoms for the implementation of a Gravity Gradiometer based on Cold Atom Interferometry (CAI) in space. The initially proposed implementation [RD01] consisted of two main sections (see Figure 1), the ultra-cold atom source and an Atom Interferometry Chamber (AIC) connected to it that is the object of this activity.
The first part of the activities consisted in reviewing the requirements that apply to the vacuum chamber. These requirements emanate from the concept above, through the required interrogation time needed to achieve the goal sensitivity. In Table 1.1, we present the top-level requirements.

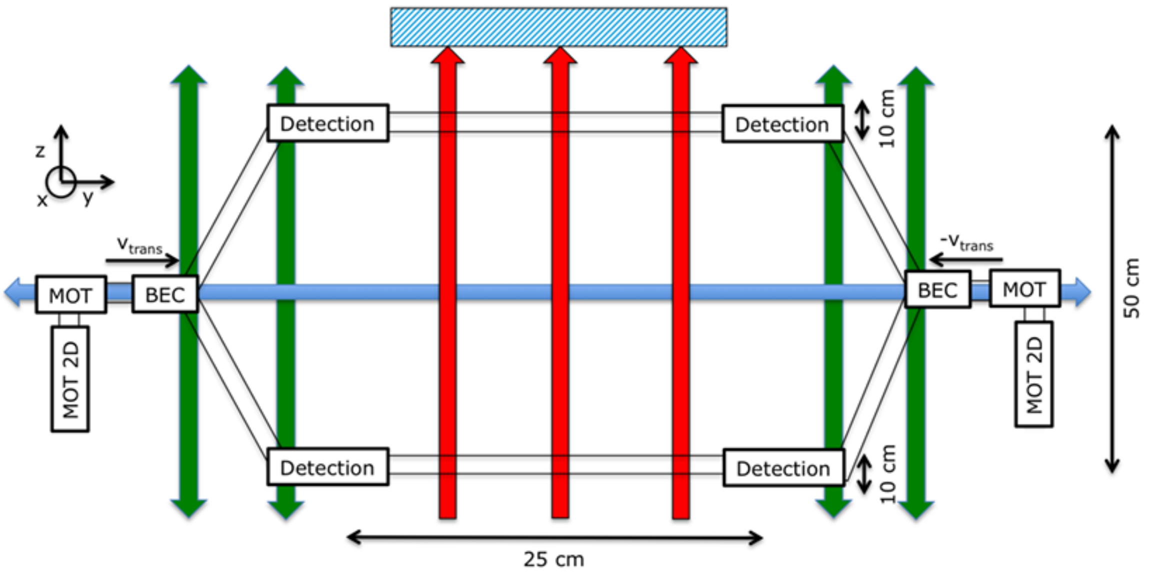

Figure 1: Schematic of the concept proposed for the implementation of a spaceborne Gravity Gradiometer based on laser-cooled atom interferometry. The sections at both ends (labelled MOT2D-MOT-BEC would be the ultracold atom source, and the area in the centre (between and containing the detection areas) would be the atom interferometry chamber (extracted from RD01)

Table 1.1: Top-level requirements for an Atom Interferometry Chamber for a Compact Earth Gravity Gradiometer in Space

Req ID	Description
REQ01	Dimensions allow for a Time-of-Flight (TOF) expansion of a Bose-Einstein-Condensate (BEC) and interferometry sequence over 10s in microgravity
REQ02	Vacuum pressure below 1×10^{-10} mbar.
REQ03	Optical access to perform the required interferometry sequence
REQ04	Interface with the existing ESA compact vacuum chamber (CVC)

Based on those requirements, the team developed a conceptual design of the system as shown in Figure 2. This concept was developed taking into account mainly considerations on size, weight, machinability, inner surface outgassing and optical access.

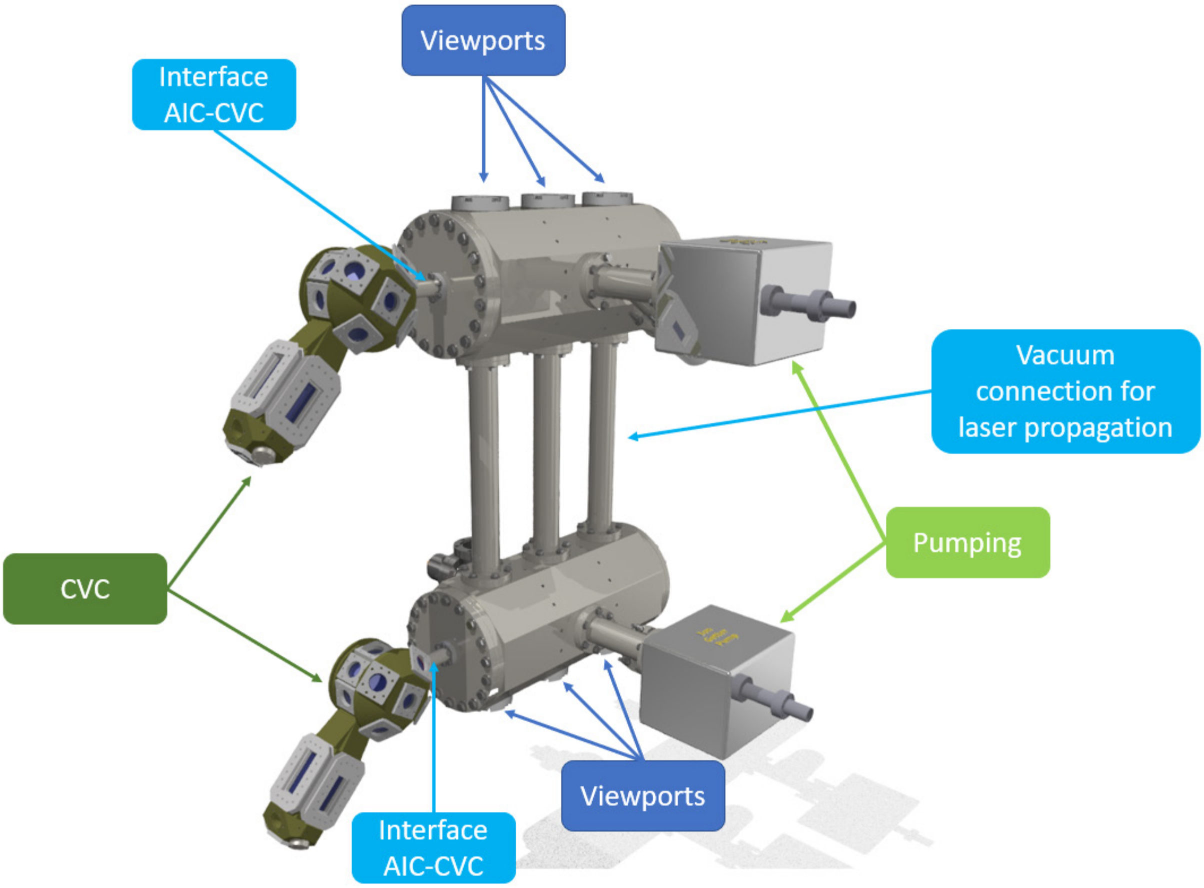

Figure 2: Conceptual design of the AIC. Labelled are the key features.

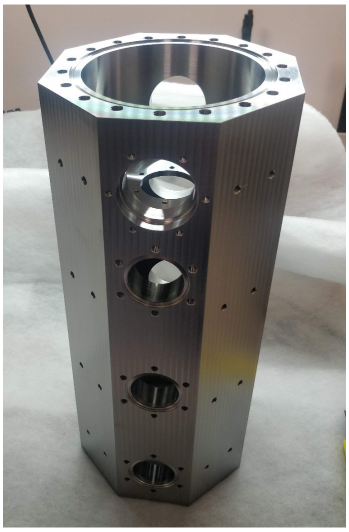

Figure 3: Photograph of the main chamber body

During the later stages of the project, the concept was refined, and it was decided to breadboard only one of the two chambers depicted in Figure 2. As a result, a full CAD model of the system was produced, and all the parts, made in grade 5 titanium, were procured. In Figure 3, a photograph of the main chamber body before assembly can be seen.

The vacuum chamber was sealed using a combination of techniques. Namely, we used conventional CF sealing for metal-to-metal joints and indium sealing for the optical access ports where glass-to-metal joints are required. The choice of indium sealing for the optical ports derives from the requirement of low mechanical stress on the windows. Mechanical stress may induce birefringence and transmitted optical wavefront distortions. Figure 4 shows a photograph of the fully assembled chamber.

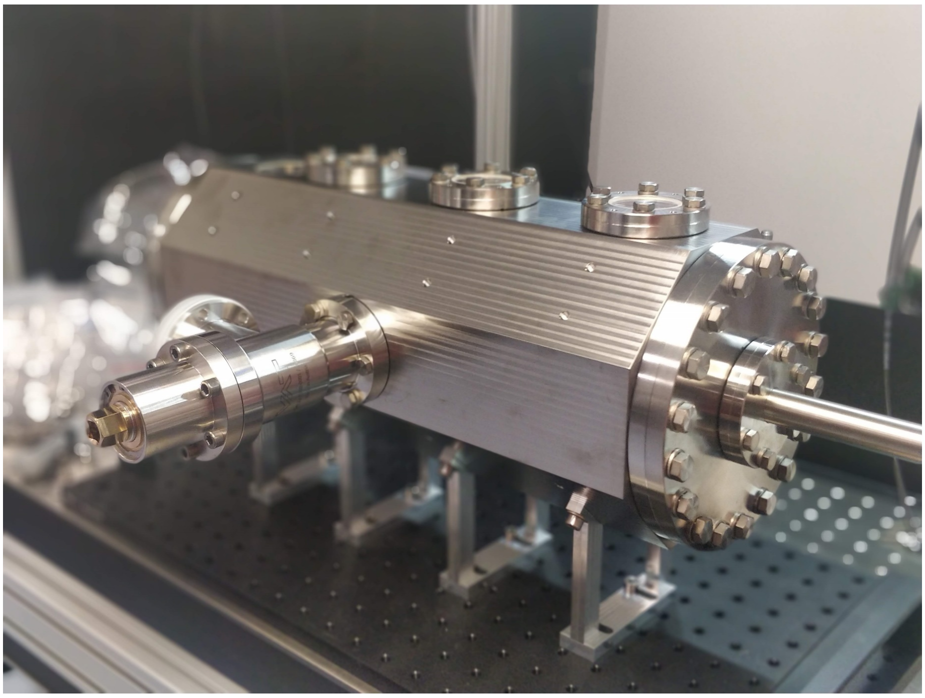

Figure 4: Photograph of the fully assembled AIC

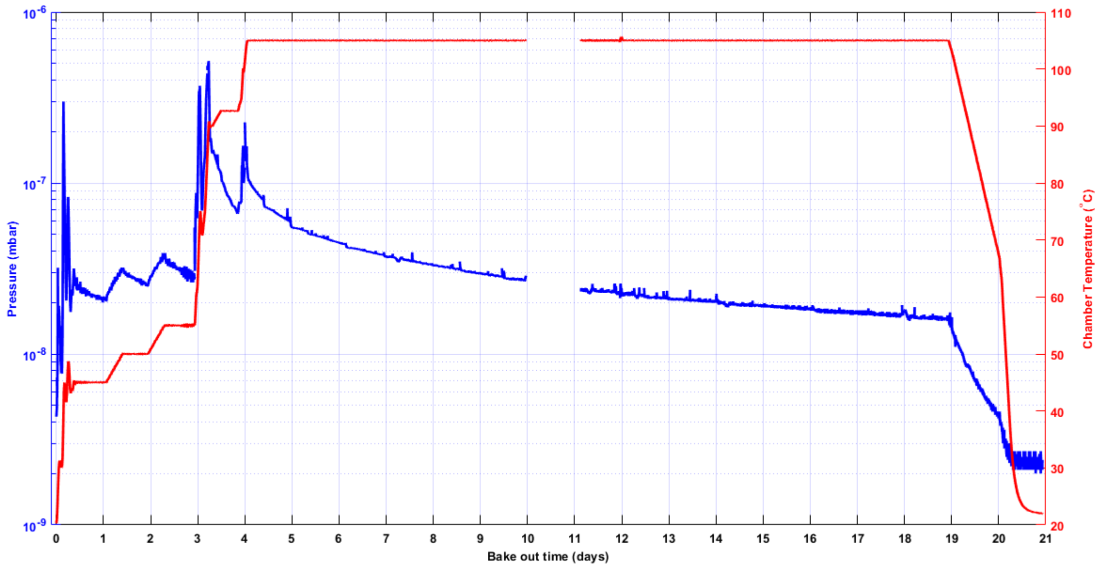

Figure 5: Pressure (blue) and Temperature(red) vs time during the bake-out time[1]. The normal trend in pressure is that pressure sharply increases as temperature is increased and then it decays, following a double exponential, as temperature is kept constant. Very sharp spikes in the pressure data are due to the activation of the RGA to monitor the evolution of the background gases.

After the assembly was completed, a preliminary leak test was performed. Some minor leaks (at the level of $10^{-9} - 10^{-10}$ mbar $\cdot$ l/s) were detected and sealed. Finally, the leak rate was reduced

[1] The gap in the data between day 10 and day 11 is due to the data file being corrupted due to a computer communication error during the data backup process.

to a level undetectable by our He-leak detector ($< 10^{-11}$ mbar $\cdot$ l/s). At this point we proceeded to the evacuation of the system to the base pressure of our pumping system. Once the base pressure was achieved, we proceeded with a bake-out of the system at a temperature of 105 ℃ (limited by the melting point of the indium seals, including some margin for risk mitigation). Before, during and after the bake-out, analysis of the composition of the atmosphere inside the vacuum chamber was performed using a residual gas analyser, and no significant contamination was detected. The bake-out was performed using a fully automated bake-out oven that allows accurate control of the temperature and temperature gradients within the oven. The accurate control is of particular importance to mitigate the risk of window breakage due to slight mismatch in thermal expansion coefficients between glass and titanium. Figure 5 shows the evolution of the temperature and pressure during the bake-out time. After the bake-out was finalised, the ion getter pump and non-evaporative getter pump were activated and the roughing pump isolated and disconnected. The final pressure achieved, a few days[2] after the chamber was sealed, is at the level of 3×10^{-11} mbar.
After all the vacuum work was finalised, the optical windows were tested for degradation. We could not observe any relevant change with respect to the specification of the optical glass.

As a conclusion, the activity resulted in the successful development of a vacuum chamber for atom interferometry that complies with all the requirements defined initially.

[2] It has now improved, and at the time of writing is at the level of 1.2×10^{-11} mbar. This level is very close to the limit of the sensitivity of the vacuum gauge used.