Cryogenic Design for the SAFARI Test-Setup Calibration Source

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Abstract: For the SAFARI Imaging Spectrometer, part of the SPICA satellite payload, a Calibration Source is under development. Challenges in the design include the low cooling power (few mW) available at cryogenic temperatures. COMSOL Multiphysics simulations were used extensively in the design process of the calibration source, allowing optimization of the thermal, electro-magnetic and mechanical properties of cryogenic Iris and Shutter mechanisms and the suspensions of a 'Hot-Source' and Integrating Sphere. The design of the calibration source is now past the conceptual stage and the actual hardware is being made and tested. The first tests of the Hot Source, Shutter and Iris showed that the results predicted by the COMSOL modeling match the measurements very well.

Keywords: Cryogenics, Mechanisms, Voice-Coil Actuator

1. Introduction

In a European consortium led by SRON Netherlands Institute for Space Research, the SpicA Far-infraRed Instrument (SAFARI) is being developed. The SAFARI Imaging Spectrometer working in the far-infrared wavelength range is to fly on the joint JAXA-ESA SPICA mission (SPace Infrared telescope for Cosmology and Astrophysics) and is planned to be launched in 2022. The instrument and all components in the test-setup are placed in a vacuum and are actively cooled to 4.5 Kelvin to minimize the background radiation and cooling power is limited to a few mW. To perform absolute calibration of the detectors a calibration source is needed that covers the full dynamic range of the detectors in the SAFARI bands with accurate knowledge of both the power level and its spectral distribution.

The calibration source concept is shown in Figure 1. The CAD design of the Calibration Source is shown in Figure 2. A 'Hot-Source' black body cavity (3) is heated up to 150 Kelvin to provide the desired spectrum. A bi-stable shutter mechanism (2) can be used to provide a flash function and to close the aperture to allow other measurements during the warm-up and cool-down time of the hot source, increasing the efficiency of the test-setup. An Iris mechanism (4) will be used to fine-tune the absolute power output of the calibration source. This can create arbitrary attenuation versus time functions so the response of the detectors to time varying signals can be verified. Finally, the radiation is redistributed inside an integrating sphere (1) that is thermally anchored to 1.7 Kelvin to provide a flat output field for the instrument with negligible background to the detectors. A light-tight thermal break (5) separates the 1.7 Kelvin integrating sphere from the 4.5 Kelvin environment.

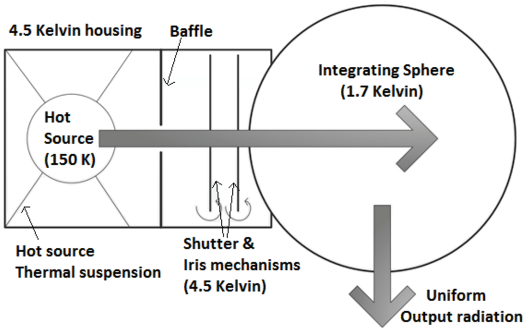

Figure 1. Working principle of the calibration source.

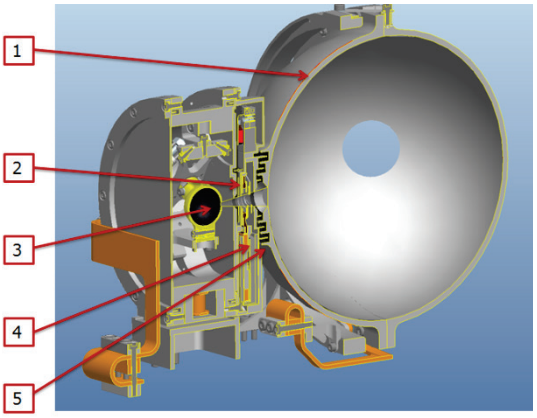

Figure 2. CAD (Pro/ENGINEER) model cross-section of the Calibration Source. Items are referred to in the text.

2. The Hot-Source

The 'Hot-Source' is a black body cavity acting as a Planckian radiator to produce a power spectrum that is only determined by the source temperature. It can be heated up to 150 Kelvin by driving a current through two internal resistors and can be controlled with two built-in temperature sensors.

A single AISI 304 stainless steel string consisting of twelve wire sections (Figure 3) is used to suspend the Hot-Source to a stainless steel frame that is coupled to the fixed world at 4.5 K. Because the wire thickness is only 100 µm and stainless steel has a low thermal conductivity at cryogenic temperatures, the suspension is thermally insulating.

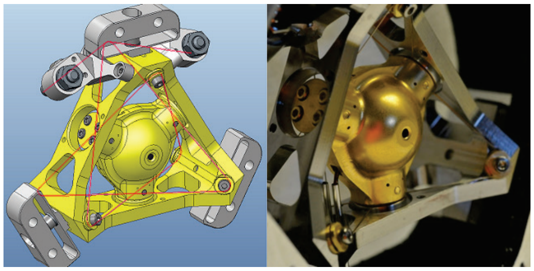

Figure 3. Left: CAD-Model of the Hot-Source. The stainless steel suspension wire is highlighted in red. Right: Photograph of the Hot-Source.

2.1 Heat Load

The heat load on the 4.5 Kelvin cooler due to conduction through the suspension can be calculated analytically by:

$$\dot{Q}_{suspension} = \mathrm{N}\frac{\pi(D/2)^2}{L}\int_{T_{frame}}^{T_{src}} k(T)dT_{src}$$

with T_{src} being the source temperature, T_{frame} the frame temperature (4.5 K), N the number of wires sections, L the length of each wire section being 22mm and D the wire diameter of 0.1mm. Because of the large temperature gradient over the suspension strings (from 150 to 4.5 Kelvin), a temperature depending thermal conduction k for Stainless Steel has been used (Figure 4) and implemented in COMSOL with an interpolation.

In addition to the conductive load through the suspension, there is a radiative load from the Hot-Source, that can be calculated with:

$$\dot{Q}_{surf-ambient} = \varepsilon A\sigma(T_{frame}{}^{4} - T_{src}{}^{4})$$

where A is the Hot-Source surface area (2494 mm^2) and σ the Stefan-Boltzmann constant. The outside surface of the hot-source has been gold-coated to minimize the surface emissivity (ε ≈ 0.08).

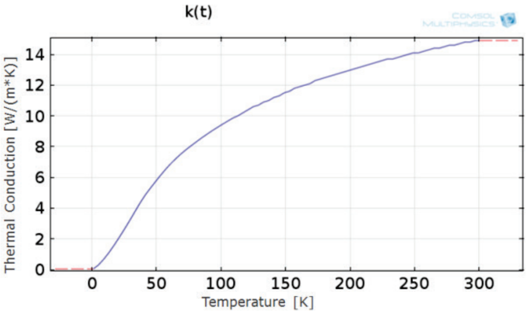

Figure 4. Thermal conductivity of Stainless Steel.

The COMSOL model of the Hot-Source with suspension is displayed in Figure 5. The thermal load on the 4.5 Kelvin level, from the surface to ambient radiation and the conduction through the suspension wires are listed in Table 1.

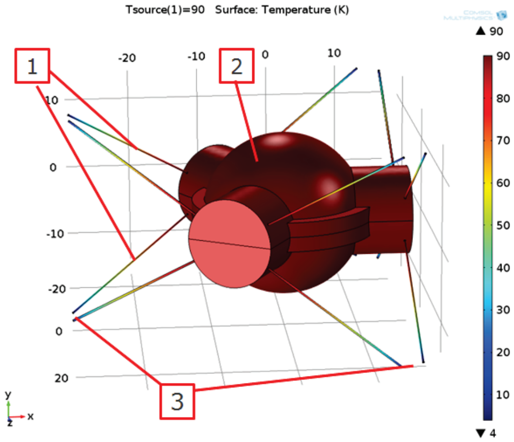

Figure 5. Thermal model of the hot-source with (1) 12 stainless steel suspension strings, (2) the 150 Kelvin Hot-Source and (3) the 4.5 Kelvin fixed world.

Table 1. Heat load on the 4.5 Kelvin cooler.

Source Temperature	Analytical	COMSOL
90 K	2.60 mW	2.59 mW
120 K	5.42 mW	5.41 mW
150 K	10.17 mW	10.18 mW

2.2 Modal Analysis

The vibrational modes of the hot-source suspension have been determined with a modal analysis. The first modal mode (translation in Z direction) is at 720Hz (Figure 6).

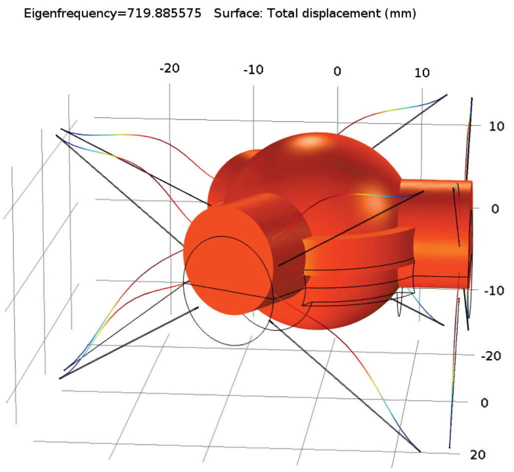

Figure 6. The first resonant frequency (720Hz).

3. The Shutter Mechanism

The shutter mechanism is a magnetic latching device with two unpowered stable positions where the magnetic circuit is closed. Coils are used to reverse the magnetization in the circuit and flip the shutter. The shutter has the following components (Figure 7):

(1) A flex-pivot (stainless steel rotational leaf-spring) friction free bearing.
(2) 2 coils with ~4000 windings.
(3) A Vacoflux (soft magnetic iron) anchor.
(4) Permanent magnets integrated into each coil.
(5) The aluminum shutter blade.

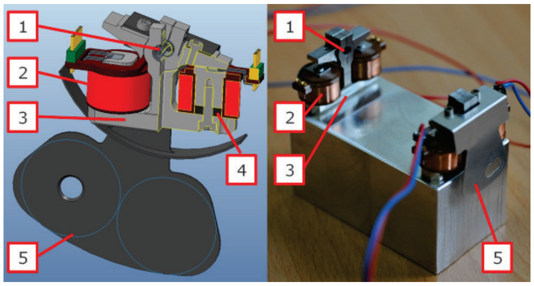

Figure 7. CAD Model and photograph of the shutter.

Since the shutter rotates around a flexural-pivot, a third stable position can be created although with less position accuracy. In this intermediate position it is possible to drive the shutter mechanism into oscillation and thus create a modulating chopper.

A magnetic model of the shutter has been made in COMSOL (Figure 8 - 10) using a 'live-link' between COMSOL and Pro/ENGINEER and performing a parametric sweep over the coil currents and the blade angle. To model the coils, multi-turn coil domains are used. After optimization of the magnetic circuit, a coil current of 75 mA will completely cancel out the permanent magnetic field. Due to the preload of the leaf-spring bearing, in reality the shutter 'flips' with a current of 60 mA.

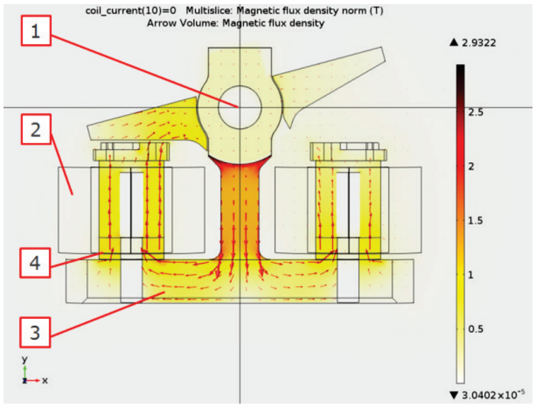

Figure 8. COMSOL model of the magnetic circuit (coils off).

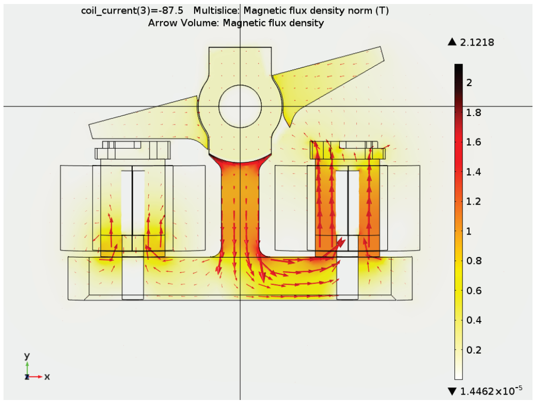

Figure 9. The shutter with a coil current of 87.5mA. The shutter will 'flip'.

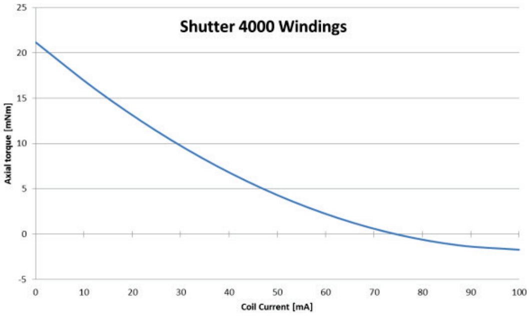

Figure 10. The shutter torque as a function of coil current. The shutter will 'flip' with a current of 75mA.

For thermal analysis it is better to look at the switch energy than at the power consumption. Typical switch energy is around 6 mJ, thus heating of the coils is not considered an issue.

4. The Iris Mechanism

The Iris Mechanism (Figure 11) is a controllable aperture used to fine-tune the absolute power output of the calibration source and create arbitrary power versus time functions to generate transients that are acceptable to the instrument. An 'arc-type' rotary voice coil is the actuator (Figure 12) for the Iris.

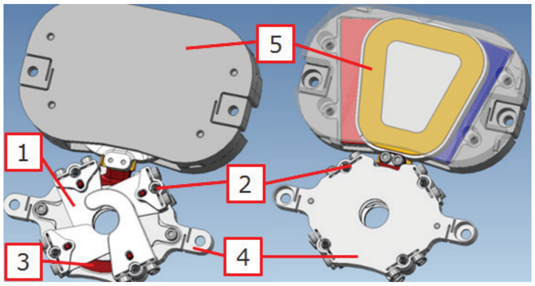

Figure 11. CAD Model of the Iris. Four aluminum blades (1) that rotate around flex pivots (2) are driven by a Vespel-SP3 ring (3) that rotates in a stainless steel housing (4).

The magnetic circuit of the actuator of the Iris was modeled in COMSOL (Figure 13) to calculate the magnetic flux across the air-gap (Figure 14) and the torque generated by the voice-coil. A Hall-Sensor is placed in the steep gradient part in the center for maximum position accuracy.

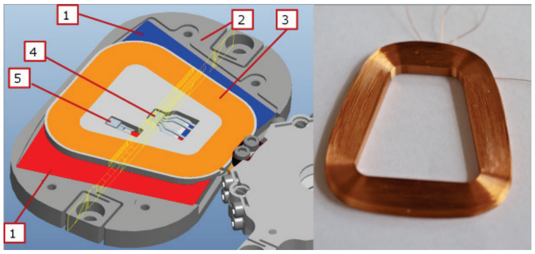

Figure 12. The voice-coil actuator, with: permanent magnets (1), Vacoflux stator (2), Coil (3, photograph on the right), Hall Sensor for closed loop PID control (4) and Temperature Sensor (5).

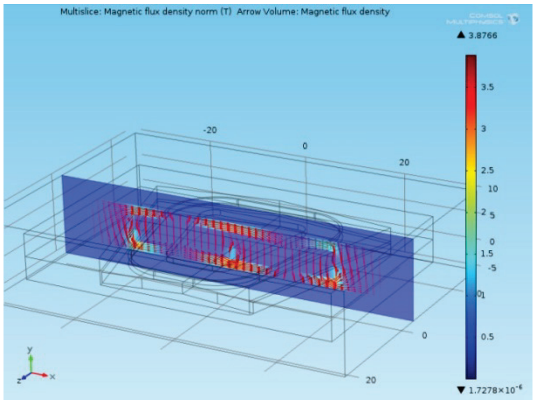

Figure 13. COMSOL model of the flux in the magnetic circuit of the Iris actuator.

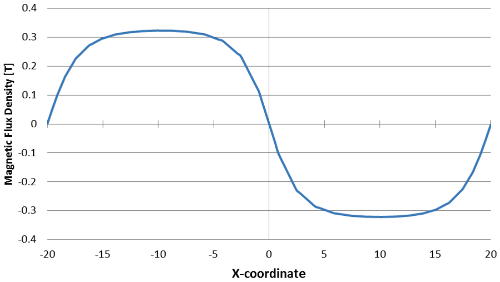

Figure 14. Magnetic flux density across the air-gap.

Adding more windings to the coil increases the electromagnetic force but also the thickness of the coil and thus the air-gap which then reduces the magnetic flux. By performing a parametric sweep over the air-gap and coil-windings, the optimum was found with COMSOL to be 1200 windings (Figure 15).

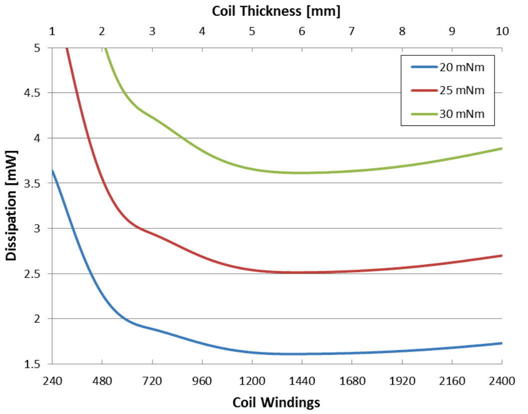

Figure 15. Dissipation vs. coil windings for a given torque.

Figure 16 shows a prototype of the actuator. The prototype rotates around a single pivot and does not yet feature the Iris blades. It is used for the development of the coil driver electronics and position feedback loop with the hall-sensor. The next steps will be cryogenic verification and adding the Iris blades.

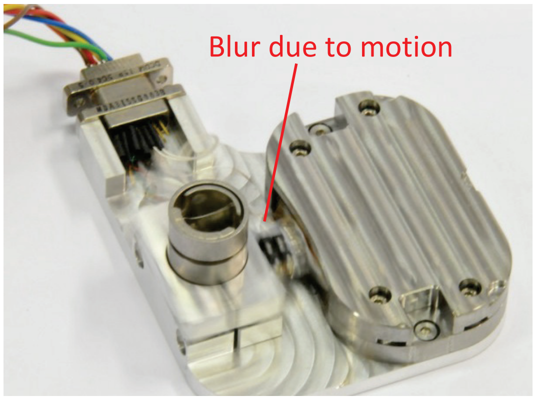

Figure 16. Prototype of the voice-coil actuator.

5. The Integrating Sphere

The integrating sphere redistributes and dilutes the radiation of the hot-source. To accomplish this, the inner surface of the sphere is highly reflecting but rough, causing many reflections of the incoming radiation within the sphere. It is cooled to 1.7 Kelvin to reduce the background radiation and is suspended in a 4.5 Kelvin environment. The sphere is made out of Aluminum 6061-T6, has an internal diameter of 180 mm and 3 mm thick walls.

The sphere is suspended by three triangular suspension brackets (Figure 17) to a circular frame that is attached to the 4.5 K fixed world. The integrated sphere itself is cooled to 1.7 K by a copper strap that is connected to the cooler.

Two thermally insulating materials for the suspension brackets have been considered: Vespel-SP1 and AISI 304 Stainless Steel. Vespel is a high-performance polyimide based plastic, with low outgassing and very low thermal conductivity at cryogenic temperatures. Stainless steel has a higher thermal conductivity than Vespel, but it is stronger so the thickness of the suspension brackets could be decreased from 4 to 0.5mm reducing the cross-section and thus the thermal conduction.

5.1 Thermal

The dilution (absorption) of the incoming radiation results in a load of 0.45 mW on the integrating sphere. Due to the temperature gradient of 2.8 K over the suspension, there is an additional thermal load on the 1.7 K cooler. The length and thickness of the suspension brackets will have a significant impact on the heat being conducted from the frame to the sphere. A thermal model (Figure 17) of the integrating sphere has been built in COMSOL to compare the Vespel and Stainless Steel suspension brackets.

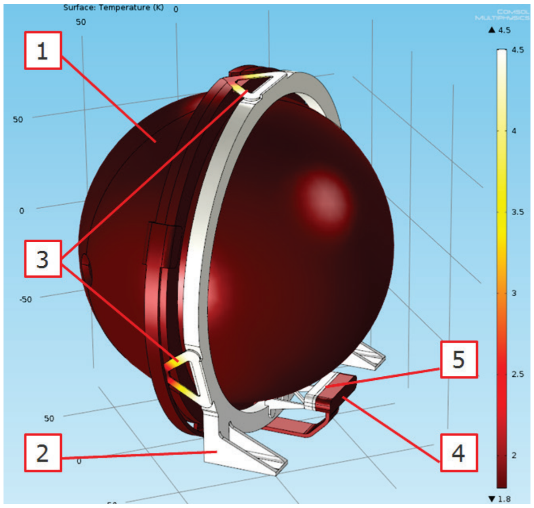

Figure 17. Thermal model of the integrating sphere, with (1) the 1.7 K integrating sphere, (2) the 4.5 K frame, (3) three triangular suspension brackets and (4) the cooler interface.

5.2 Stiffness

As with the Hot-Source, for the Integrating Sphere suspension a modal analysis has been performed, and the first modal mode (for Stainless Steel suspension brackets) is found to lie at 647 Hz (Figure 18), which is sufficient.

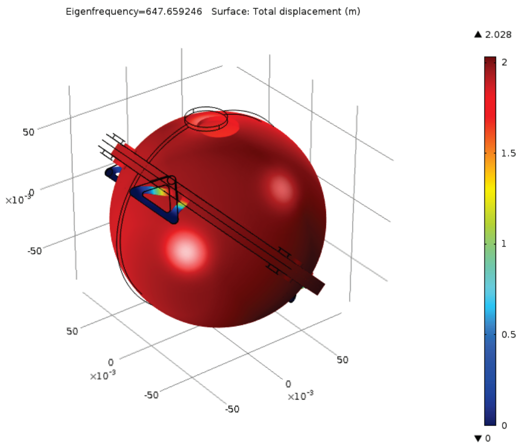

Figure 18. The first modal mode of the suspended integrating sphere is 647 Hz.

5.3 Summary

Table 2 lists the results of both materials for the suspension frame. While both solutions meet the requirements, stainless steel was chosen as the final design, since it is stiffer, easier to manufacture and there is sufficient headroom in the heat load on the cooler, the requirement is <1 mW heat-load.

Table 2. Integrating Sphere Suspension Results.

	4 mm Vespel-SP1	0.5 mm Stainless Steel
First modal frequency	309.601 Hz	647.659 Hz
Heat-load	0.5579 mW	0.8252 mW

6. Conclusions

COMSOL Multiphysics simulations were used extensively during the development of the SAFARI Imaging Spectrometer Calibration Source. COMSOL allowed for minimizing the thermal dissipation of the cryogenic Iris and Shutter mechanisms and optimize the thermal suspensions of the 'Hot-Source' and Integrating Sphere. The design of the calibration source has past the conceptual stage and the actual hardware is being manufactured and tested. The first tests of actual hardware of the Hot Source, Shutter and Iris show that the results predicted by the COMSOL modeling match the measurements very well.