FFG-Program/Instrument: ASAP 12

INTERIM REPORT / FINAL REPORT

FFG Project number	854036	**eCall number**	6199094
Short title	ULE-Cavity-Access	**Applicant**	Universität Wien
Consecutive number of the report		**Reporting period**	1.4.16 – 5.5.17
Author	Rainer Kaltenbaek		

Please note: length approx. 10 - 20 pages, upload to eCall in PDF format

1. Goals and results

- Have the objectives defined in the funding agreement been achieved? Are these objectives still valid or realistic? (Please note: changes to objectives require the consent of the FFG)
- Compare the objectives with the results achieved.
- Describe the “highlights” and problems that occurred in achieving the objectives.

The project has been progressing well, and we introduced some changes to the timing of the work packages to accommodate an increased level of detail in the design considerations of the cavity setups. We do not expect these changes in scheduling to lead to any delays in achieving the final goals of the project. In particular, we increased the duration of the work package on cavity design (WP4) compared to the initial plan scheduled. This extension of the timeline for WP4 is due to a more diligent approach to defining the optimal design of cavities such that they will optimally perform under cryogenic conditions and due to careful design considerations such that the cavity assembly will survive the cooling from room temperature to cryogenic temperatures. We decided to investigate the potential designs more carefully than originally anticipated such that they will work at room temperature as well as at cryogenic temperatures. Given the expense of ordering custom-made components for this purpose, we found that we should be particularly careful in ensuring that the designs could cope with the large change in temperature when cooling them to cryogenic temperatures. In particular, one needs to take care in ensuring that different coefficients of thermal expansion for the components of the setups will lead to as little thermal stress as possible. Such thermal stress could lead to coupling between of the cavity modes used for optomechanical control in the envisioned experiments, or it could even lead to damages of the cavity setup. Moreover, the careful planning of the design also takes into account the optimal alignment procedure.

The advantages of this new approach are an expected speed up in the actual realization of the cavity designs, and an increase in confidence that the implemented designs will comply with the technical requirements we aim to achieve. For these reasons, we are confident that this will allow us to stick to the overall time schedule. A further advantage is that this more careful approach for the cavity design allowed us to begin already with the thermal finite-element design of the cavity design (WP9). This will also be integral for the later thermal simulation of the optical bench (WP10).

The project management (WP1) is proceeding as planned despite the fact that there have been

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some delays in setting up and signing the contracts with the sub-contractors due to novel legal requirements set by the University of Vienna for subcontractors. Due to these delays, subcontractor C (ZARM Technik AG) could only sign their contract close to the end of the first reporting period. The same delays have affected the contract with subcontractor B (Airbus), but we expect these issues to be resolved very soon. Despite the delays in signing the contracts, the subcontractors upheld their part of the contract and supported us in our work on the project as planned. In particular, I have been in contact with both subcontractors continuously with respect to the design of the cavities, the thermal analysis and with respect to project management. As a result, we have acquired several integral components of the cavity design (WP5) already. For some components, we will have to complete WP4 before placing the respective orders. Part of the reason for needing to restructure the schedule of the work packages has certainly also been that the PI of the project was only employed for 65% of his time on this project due to budget cuts compared to the grant application.

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2. Work packages and milestones

2.1 Synoptic tables

- Scheduled dates according to the funding application
  Current date: date according to the plan valid at the time of reporting.

Table 1: Work packages

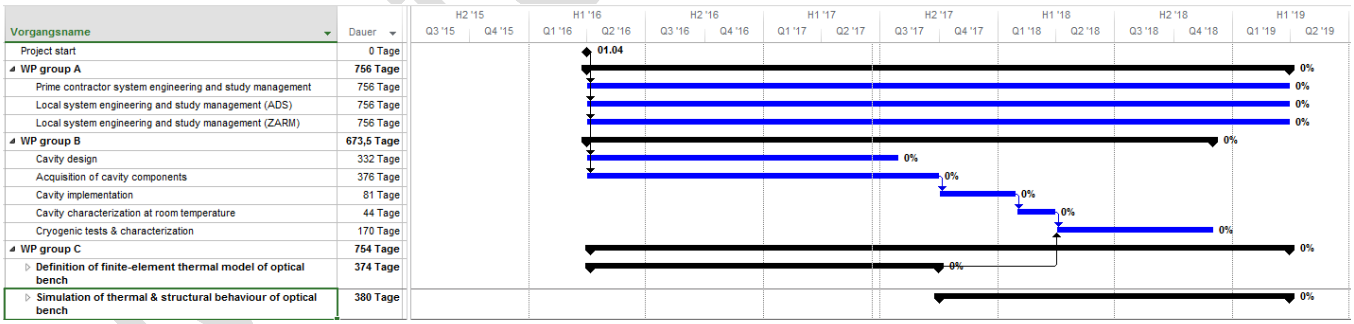
WP No.	Work package title	Stage of completion	Scheduled date		Current date		Results achieved / Deviations
			Start	End	Start	End	
1	WP1	36%	3/16	2/19	4/16	3/19	The project management is operating within expectations.
2	WP2	36%	3/16	2/19	4/16	3/19	The project management is operating within expectations despite the delays in signing the contract.
3	WP3	36%	3/16	2/19	4/16	3/19	The project management is operating within expectations despite the delays in signing the contract.
4	WP4	85%	3/16	5/16	4/16	7/17	The design of the cavities is still ongoing. We decided to work on this WP with higher scrutiny to ensure a more speedy completion of the follow-up WPs and a higher probability of success.
5	WP5	43%	6/16	9/16	4/16	9/17	The acquisition of components is delayed due to the delays in WP4. While we already acquired a sizable number of components, some acquisitions depend crucially on the completion of WP4.
6	WP6	0%	10/16	3/17	10/17	1/18	The implementation of the cavity designs will start once we have acquired all necessary components. Implementation of the test setups will start earlier as part of WP5
7	WP7	0%	4/17	12/17	1/18	3/18	After implementing the cavities, we will first characterize them at room temperature.
8	WP8	0%	1/18	6/18	4/18	11/18	Once we have fully characterized the cavities at room temperature, we will start conducting tests at cryogenic temperatures and during the cool-down cycle.

9	WP9	70%	6/16	9/16	4/16	9/17	We defined preliminary geometric models of the cavity setup for finite-element analyses, and we created material models for the materials used in the model. We performed first tests to simulate thermal stress during cool down. These definitions will form the basis for finite-element simulations of the optical bench.
10	WP10	0%	7/18	2/19	10/17	3/19	Once we complete the preliminary finite-element tests of the optical bench, we will analyse the overall performance of the optical cavity design and the optical bench based on our earlier results.

Table 2: Milestones

Milestone No.	Milestone title	Scheduled date	Current date	Milestone achieved on	Results achieved / Deviations
1	Critical review of cavity designs	1.6.16	10.8.17	NA	Achievement of the milestone delayed due to delays in concluding WP4.
2	Critical review of components and of the optical-bench finite-element model.	28.10.16	2.10.17	NA	Achievement of the milestone delayed due to delays in concluding WP5 and WP9.
3	Critical review of adhesively bonded cavities.	7.12.17	30.3.18	NA	Achievement of the milestone delayed due to delays in concluding WP6 and WP7.
4	Critical review of adhesively bonded cavities with respect to performance in cryogenic environment	6.7.18	7.12.18	NA	Achievement of the milestone delayed due to delays in concluding WP8.
5	Final review	25.2.19	22.3.19	NA	Achievement delayed due to later project start (04/16 instead of 03/16).

Updated Gantt chart of work packages



2.2 Description of the work carried out during the reporting period

- Describe the work carried out during the reporting period broken down into the work packages.
- Have the work steps and packages been completed according to plan? Have there been relevant deviations?
- The description must also include any changes to the methodology applied (please note: changes to the methodology and relevant changes to the work plan require the consent of the FFG).

In the following, we will describe the work performed so far, and we will describe the changes of the work plan, which we outlined in the earlier subsections, and why the modified work plan should allow achieving the goals of the project better than if we had followed the original work plan. We are confident that the modified work plan will find the approval of the FFG.

The main part of the work performed so far are the design considerations for the cavity setup(s) we will implement. In particular, we concerned ourselves with the following questions:

- Which materials should we use for the various elements of the design?
  In particular, the materials should allow alignment at room temperature but also allow operation at the target, cryogenic temperatures.
- How should we bond the various components?
  Due to the thermal expansion of the constituents of the setup when cooling the setup from room temperature to the cryogenic operating temperature, thermal stress can be a serious issue that can lead to deteriorated performance or even to damage due to mechanical stress.
- What adhesives should we use for bonding the various components?
  As we described in reports for our earlier FFG project MAQROsteps (Project No.: 840089) that one of the adhesives we used for one of our earlier cavities (Hysol EA9361) was not available anymore from European distributers. The readily available other adhesive we used in MAQROsteps (Hysol EA9313) has, so far, not been tested at cryogenic temperatures. Hysol EA9313 is also difficult to use for bonding the cavity mirrors to the spacers holding them. Because of the low viscosity of the adhesive, it can very easily creep on the back surface of the cavity mirrors and ruin them. Hysol EA9361, on the other hand, is qualified for use at cryogenic temperatures, and it can be applied very precisely. For that reason, we have been looking into adhesives that could be a good alternative for Hysol EA9361 with favourable properties at room temperature as well as at cryogenic temperatures. A short time ago, colleagues from subcontractor A have also found an American supplier able to deliver Hysol EA9361, and they acquired a sufficient quantity of it to implement the proposed cavity designs. In addition, we also plan to test alternative adhesives in order to be less reliant on the availability of a particular type of adhesive.

The original work plan was too optimistic with respect to the time needed to study these questions in the detail needed.

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A considerable challenge in **Work Package 4** (**WP4**, Cavity Design) has been that the cavities we want to design first have to be assembled and characterized at room temperature before they are cooled down to their intended operating temperature below 20K. In the cool-down process, the various parts of the cavity setup may experience different thermal expansion – not only due to the use of different materials, but also in the cases where different parts of the setup cool down at different rates due to the lack of thermal conductivity in the interfaces between the elements. This renders it paramount to (1) use adhesive-bonding techniques that allow for good thermal conductivity, and (2) to use materials with identical, or at least very similar, thermal properties.

To allow us to better cope with this challenge, we soon began to implement and to investigate finite-element models of the cavity setup to investigate the occurrence of thermal stress during the cool-down procedure. That means, we essentially began work on **Work Package 9** (**WP9**, Definition of finite-element thermal model of optical bench) at the same time as our work on WP4. A central prerequisite for implementing such a finite-element model is to have good models for the materials used valid from cryogenic temperatures up to room temperature. Figure 1 illustrates how different coefficients of thermal expansion can influence optical assemblies.

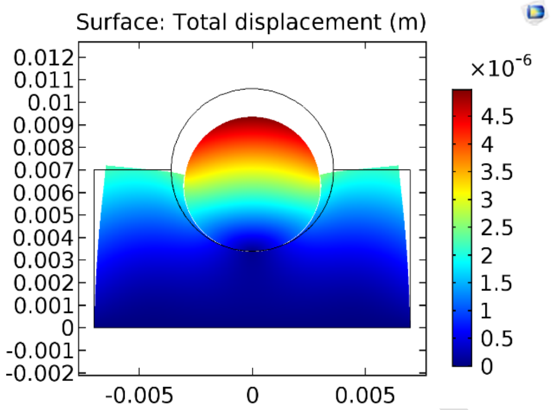

Figure 1: This image illustrates the distortion of a simple optical assembly where a lens made of Pyrex glass is adhesively bonded into a U-groove of a silica substrate. While the overall displacement could conceivably be compensated for, the different coefficients of thermal expansion lead to thermal stress throughout the lens, which would also distort optical beams transmitted through the lens.

The simplest solution would be to use the same material for all elements of the optical bench. There are, however, additional considerations that have to be taken into account. In particular, we plan to implement optical cavities with a finesse on the order of 10^5. This corresponds to a full width at half max (FWHM) cavity linewidth of $2\kappa \simeq 10^5\ \mathrm{rad/s}$. For a 10cm long cavity, that means that changes in cavity length should be much less than a half micrometre, which corresponds to a relative change in cavity length on the order of 1ppm or less. This is a very tight restriction on the material for the baseplate of the cavity. For an operating temperature around room temperature, Zerodur would be an adequate material for this purpose. For the cryogenic operating temperature we aim for around 20K or less, Silicon Carbide (SiC) is better suited.

That means, we need a SiC baseplate while the optical elements will be made of highly transparent glass. In the context of space-based experiments, the material of choice typically is Fused Silica as in the case of LISA Pathfinder [1]. Reasons for this choice are the radiation hardness of Fused Silica as well as its low absorption at the design wavelength of 1064nm. The use of SiC as a baseplate for optical instruments has significant technological heritage from the GAIA mission [2].

For the GAIA mission, a novel type of SiC material was developed that can be polished to optical grade and that can be brought into pretty much arbitrary shapes. For example, SiC was used in GAIA to realize the baseplate of the optical assembly as well as a large optical-grade mirror. These developments have led to the foundation of the companies Boostec and Optosic (now both part of the Mersen group), which specialize in the manufacture of SiC products.

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Of course, using SiC for the baseplate of fused-silica optical components will lead to stress during cool down due to the difference in the thermal expansion coefficients. We plan to minimize this effect by the following means:

- Keep as much distance as possible between the location of interfaces between different materials and the location of optically sensitive areas (e.g. mirrors, lenses)
- Use adhesives with high thermal conductivity to minimize thermal stress during cool down
- Use tightly localized and tensile adhesive bonds for the interfaces between materials with different coefficients of thermal expansion (Hysol 9361 or similar)

The last point in this list still has to be investigated more closely. While the use of localized adhesive bonds should lead to less thermal stress in the bonded components, this approach may result in unpredictable displacements of the optical elements during cool down because it will be difficult to achieve identical bond strengths for all bonds involved. Typically, each element would be held in place by four adhesive bonds (see e.g. Figure 2).

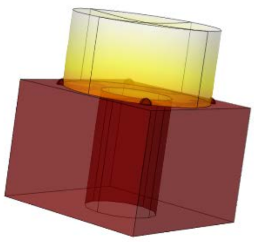

Figure 2: Finite-element simulation of heat transfer from a silica spacer ($14 \times 14 \times 10$ mm^3) with a clearance hole for the optical beam and a spherical mirror. The mirror in this simulation is adhesively bonded to the spacer via four localized positions (the small spherical spots).

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While it will be relatively straightforward to acquire cavity mirrors and spacers made from fused silica as we did for our earlier FFG project MAQROsteps (Project No 840089), there are several components of the proposed setup that will need more careful consideration:

- <u>The lenses to couple into the fibres</u>

  In order to prevent imaging errors due to the small waists of the fibres used, it may be advisable to use aspheric lenses. In the case of LISA and LISA Pathfinder, that was indeed the case. We will have to consider this more thoroughly because fused-silica aspheric lenses would probably have to be custom made. This might go beyond the budget available. However, for the purpose of this project, small imaging errors due to the use of plane-convex lenses may be admissible. We do not want to use standard aspheric lenses because they often are made from material that is not space-proof, and it would have significantly different thermal expansion than the fused-silica spacers used (see Figure 1).
- <u>The fibres themselves</u>

  The goal is to could multiple modes into the cavity using a single, fused silica few-mode fibre.

We investigated which fibre would best suit this purpose or whether we would have to have a fibre custom made.

- <u>The ferrules holding the fibres inside their spacers</u>
  Most ferrules available commercially are from materials other than fused silica. We found a company, though, that was able to deliver fused-silica fibre ferrules according to our specs and for a very reasonable price.
- <u>The fibre strain relief</u>
  This is still an open question. We will have to contact Glasgow University who designed and implemented the fibre injectors for LISA Pathfinder in order to see where they got their strain reliefs.

An additional point we have had to consider is that we will have to somehow fix the optical setup inside the cryostat we are going to use for our tests. The challenge is that we would like to hold the setup in place without introducing stress due to thermal expansion. This would automatically occur because the material surrounding and holding the optical setup would not be made of SiC.

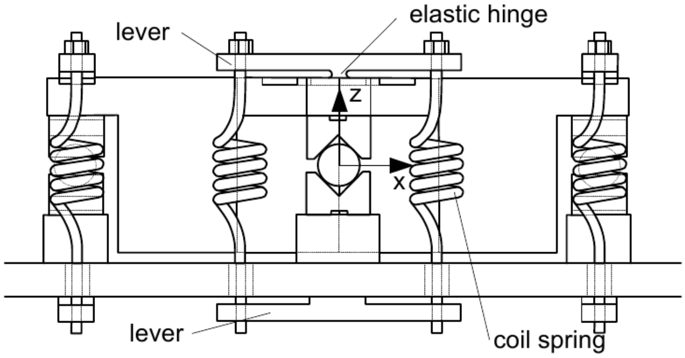

Figure 3: Beam-splitter mount used in GAIA to allow keeping optical alignment during cool down despite thermal expansion [3].

A very interesting possible solution we found is the method they used in GAIA to clamp a central beam splitter. In their case, the considerations were similar to our situation because the beam splitter was essentially the only optical element that was made of a different material (fused silica) than the rest of the setup (SiC). By clamping the structure using SiC balls rolling along V-grooves, they managed to realize a setup that would not experience thermal stress during cool down [3] (see Figure 3). An interesting side note: using this clamping approach would have been very difficult in the cryostat available for our purposes at Airbus. The combination of conditions of the inner diameter of that cryostat being only one inch and the diameter of SiC balls for the clamping mechanism having to have a diameter of at least 6mm would have been fairly difficult to meet. Being able to use the new cryostat of the Aspelmeyer group in Vienna will, therefore, be a significant advantage in this respect.

Now, let us discuss the design of the optical setup so far. In order to avoid having to acquire custom-made few-mode optical fibres, we were investigating standard fibres for 1310nm and for 1550nm light to see whether they would allow few-mode guiding at 1064nm. Indeed, we found that the SMF-28 fibre, which is an easily available single-mode fibre for 1550nm should fulfil our needs. For

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1064nm, this fibre should guide the LP_{01}, and the $LP_{11a,b}$ modes, which correspond to TEM_{00}, TEM_{10} and TEM_{01} in free space.

We then acquired fused-silica glass ferrules from Laser Components GmbH that should fit the SMF-28 fibre. They are 5mm long, and they have an outer diameter of 1.8mm and an inner diameter of 127µm. Moreover, the ends have a slight angle to reduce back reflections.

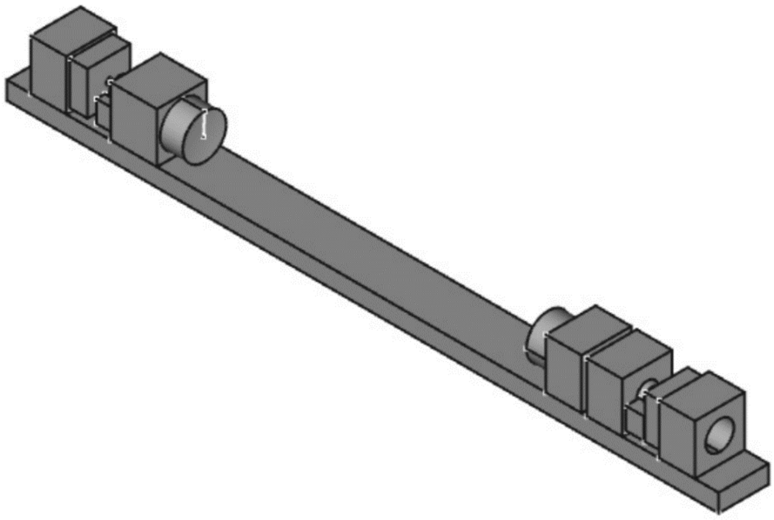

Figure 4: Preliminary CAD model of the cavity design. The cavity design is two sided, i.e. with a fibre coupler on either end. The fibre ferrule is mounted in a fused-silica spacer ($12 \times 12 \times 5$ mm^3) with a 1.8mm central hole. This “fibre-spacer” is in turn mounted on a spacer with a much larger central hole to accommodate the fibre stress relief and to allow XY- alignment of the position of the fibre. The lens is to be mounted on a U-groove that is itself mounted on a spacer. This way, we will have full freedom in XYZ to adjust the position of the lens relative to the fibre. The mirrors are adhesively bonded to spacers as in our earlier FFG project MAQROsteps (Project No 840089).

The corresponding fused-silica spacers to hold the various optical components have not been ordered yet. In particular, we first wanted to finish the design considerations regarding (1) the aspheric (or plane-convex) lens and how best to mount it, and (2) to optimize our design for using the clamping approach of the GAIA mission. The first point determines the distances of the optical elements on the bench. The second point will influence the final design of the SiC optical bench.

The next steps will be: (1) to make a decision on the lenses to use for fibre coupling, (2) to adapt the design to allow for clamping the SiC baseplate similar to the GAIA mission (see Figure 3), (3) use the results of the earlier two points to finalize the cavity design and order the respective components, and (4) begin implementing the setups for testing the cavity designs at room temperature.

2.3 Changes in the further course of the project

- Are there any changes? What effects do they have? How does the plan need to be adjusted?

As we described in the previous sections and as we describe in section 3 and 5 below, we made changes to the work plan to accommodate more diligent design considerations as well as changes in the project budget compared to the originally submitted proposal. Within the next few months, working packages WP4 and WP5 will have been completed, and then we should be back to schedule without any delays to the project as a whole. At the same time, we already started working on the work package WP9 ahead of time, and we will be able to use a cryostat in Vienna for WP8. These developments will speed up the completion of WP8, WP9 and WP10 so that any apparent delays at the moment will be counterbalanced in the future.

3. Project team and cooperation

- Have there been major changes to the project team (internal key personnel and third party service providers)?
- For consortium projects: describe the cooperation within the consortium.
- Please describe changes in the work allocation. Do they have an effect on the cost/financing structure and objectives?

The budget of the project for personnel is significantly lower than in the proposal. For that reason, the PI of the project, Rainer Kaltenbaek, has been paid by the project for only about 65% of his salary. Markus Aspelmeyer has covered the remaining 35% from one of his research grants. The work allocation in the various work packages has been adapted accordingly except for WP1 where we still assumed 10% of the PI's time. For the last 19 ½ months of this project, the PI will be employed in the project for 100% as originally planned. This is possible due to a reallocation of budget as described in section 5.

4. Final Report only: Dissemination and exploitation

- Describe the exploitation and/or dissemination activities carried out so far. Is it possible to exploit the project results?
- List all publications, PhD theses, diploma theses and patent applications that have resulted from the project.
- What further R&D activities are planned?
- How will the prototypes created during the project be used further?

>Text<

5. Explanatory notes on cost

For the last 18 months of the present project, we propose to reallocate funds in this project in order to allow the PI to be covered 100% from this project. In particular, we propose to make the following changes in the assignment of budget within the project (we also attach this table to this intermediate report):

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FFG-Program/Instrument: ASAP 12

Personal-kosten alt	Sach & Material-kosten alt	Dritt-kosten alt	F&E Infrastr. alt	Reise-kosten alt	Gesamt-kosten alt
187.265	50.000	64.500	21.125	13.000	335.890

Kosten NEU					
Personal-kosten neu	**Sach & Material-kosten neu**	**Dritt-kosten neu**	**F&E Infrastr. neu**	**Reise-kosten neu**	**Gesamt-kosten neu**
228.307	26.333	51.500	21.125	8.625	335.890

In particular, we reallocated money from subcontractor B, from travel budget, and from material costs to the budget for personnel. We made these changes in agreement with subcontractor B as well as with Markus Aspelmeyer, who will support the PI in-kind in terms of travel costs and material costs. This way, we will be able to achieve the experimental goals of the project even more reliably because the PI can be employed in this project for 100% of his time for the last 19 ½ months of the project. The reallocation of funds from subcontractor B will not have a negative influence because it could be affected in the following way:

- The Aspelmeyer group acquired a new cryostat for a different project, and I will be able to use it for the tests to be performed in this project. This actually has the advantage that the new cryostat poses less strict requirements on the geometry of the cavity design than the one available at Airbus D & S.
- Because I can use the cryostat in Vienna, I will also require less travel budget for stays in Friedrichshafen.
- The reduction in material costs is possible because of Markus Aspelmeyer's support.

6. Specific conditions and requirements

- ➢ Please elaborate on any project-specific conditions and requirements (acc. to §6 of the funding agreement) specified in the funding agreement or contract for work or services.

There are no specific conditions or requirements to report.

7. Reportable incident

Have there been special events or incidents concerning the project that must be reported to the FFG, e.g.

- ➢ changes in legal or economic influences on the funding recipient
- ➢ bankruptcy proceedings
- ➢ incidents that delay or prevent the performance of the funded work
- ➢ additional funding for this project

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There are no incidents to report.

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