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**	6.5.17 – 15.10.17
Author	Rainer Kaltenbaek		

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

1. Goals and results

This is an intermediate report made because the project is transferred in the middle of October 2017 from the University of Vienna to the Institute for Quantum Optics and Quantum Information Vienna of the Austrian Academy of Sciences. The intermediate report reports the progress made until that time since the last intermediate report a few months earlier.

There have been minor additional delays due to the unexpected complexity of designing the aspheric lenses for coupling from optical fibres directly into our optical cavity. We will discuss this in more detail below. In order to avoid any further delays and to keep finish the project in time, apart from project management, the PI of the project currently concentrates fully on completing the design of the aspheric lenses and the optical bench. We plan to complete WP4 by the beginning of 12/2017. At this point, we will order the aspheric lenses and the baseplates for the optical bench, which we then hope to acquire by the beginning of 03/2018. This will complete WP5. Then we can implement the bonded cavities. Given the complexities of the task at hand, we are pleased how the design is progressing, and we are confident that there will be no further delays in this respect, and we expect achieving the final goals of the project as scheduled by 03/2019.

The project management (WP1) is proceeding well, and we are confident that the current increased effort in finishing the design of the optical bench will pay off in well-designed optical setups and a timely conclusion of the project. We are currently setting up the new contract between subcontractor C and the new host (Institute for Quantum Optics and Quantum Information – Vienna, Austrian Academy of Sciences). We are also setting up a similar contract with subcontractor B. Subcontractor C has already been informed of the transfer of the project, and they agreed with it. All necessary preparations for the transfer are in place, and the only thing missing at this point is the submission of this intermediate project report.

2. Work packages and milestones

2.1 Synoptic tables

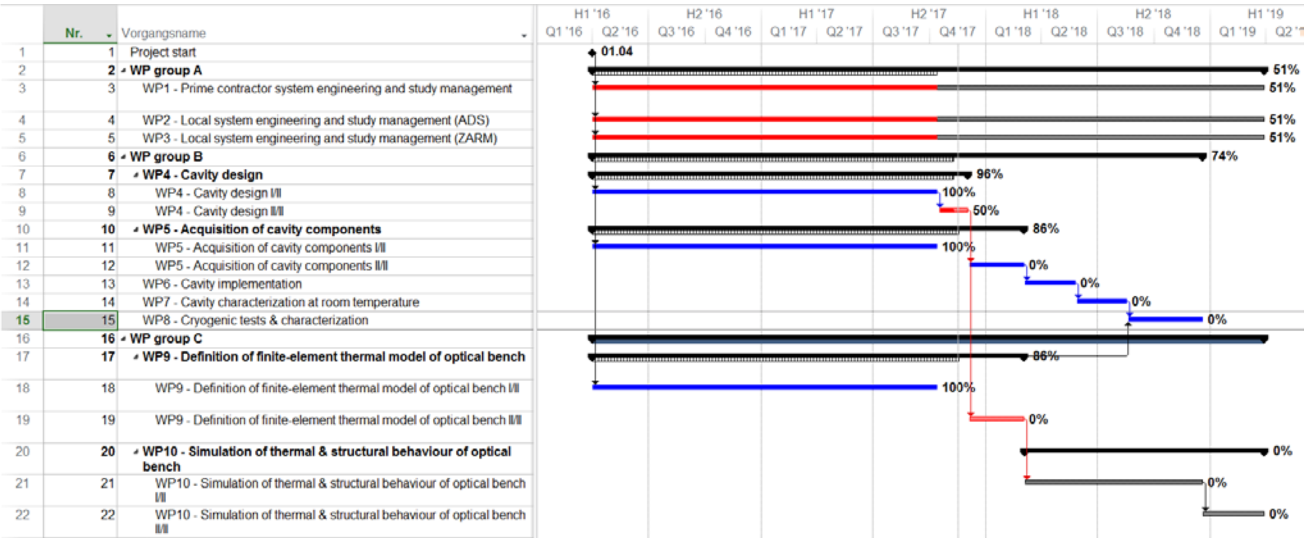
Table 1: Work packages

WP No.	Work package title	Stage of completion	Scheduled date		Current date		Results achieved / Deviations
			Start	End	Start	End	
1	WP1	51%	3/16	2/19	4/16	3/19	The project management is operating within expectations.
2	WP2	51%	3/16	2/19	4/16	3/19	The project management is operating within expectations despite the delays in signing the contract.
3	WP3	51%	3/16	2/19	4/16	3/19	The project management is operating within expectations despite the delays in signing the contract.
4	WP4	96%	3/16	5/16	4/16	12/17	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	86%	6/16	9/16	4/16	3/18	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	3/18	5/18	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	5/18	8/18	After implementing the cavities, we will first characterize them at room temperature.
8	WP8	0%	1/18	6/18	8/18	12/18	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	86%	6/16	9/16	4/16	3/18	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	3/18	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	5.3.17	NA	Achievement of the milestone delayed due to delays in concluding WP5 and WP9.
3	Critical review of adhesively bonded cavities.	7.12.17	31.8.18	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	21.12.18	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

Given the delays already caused by the longer-than-expected duration of WP4, most of the work during the reporting period concentrated on finalizing the design of the optical cavity. In particular, starting mid-October 2017, i.e., following the period covered by this report, the PI of the project will focus all his attention (apart from project management) on completing WP4.

During the reporting period, the work carried out focused on the following issues:

- Which lenses should we use to couple light from a fibre into the cavity and from the cavity into a fibre again?
- Which lens material should we use and how should we mount it in order to ensure that the alignment at room temperature would later lead to a working alignment at the cryogenic environment (20K)?

- How should we best place the cavity into a cryostat, how large can it be, how should we mount it to minimize detrimental effects due to vibrations of the cryostat or its environment?

In the last report, we described how using a lens material different from the spacers holding the lenses could lead to thermal stress when cooling the cavity from room temperature to the targeted operating temperature of about 20K. At the same time, we wanted to use a lens material that ideally would be space-proof. We contacted several lens manufacturers to see whether we could find a suitable material. Unfortunately, this was not the case for relatively cheap lenses available on stock.

In particular, we were in contact with Edmund Optics, Thorlabs, and Asphera Incorporated. The first two could not produce aspheric lenses with the required specification at the low number of lenses required. In lengthy discussions, Asphera Incorporated proved to be very unresponsive to the particular needs of our design in terms of the materials required.

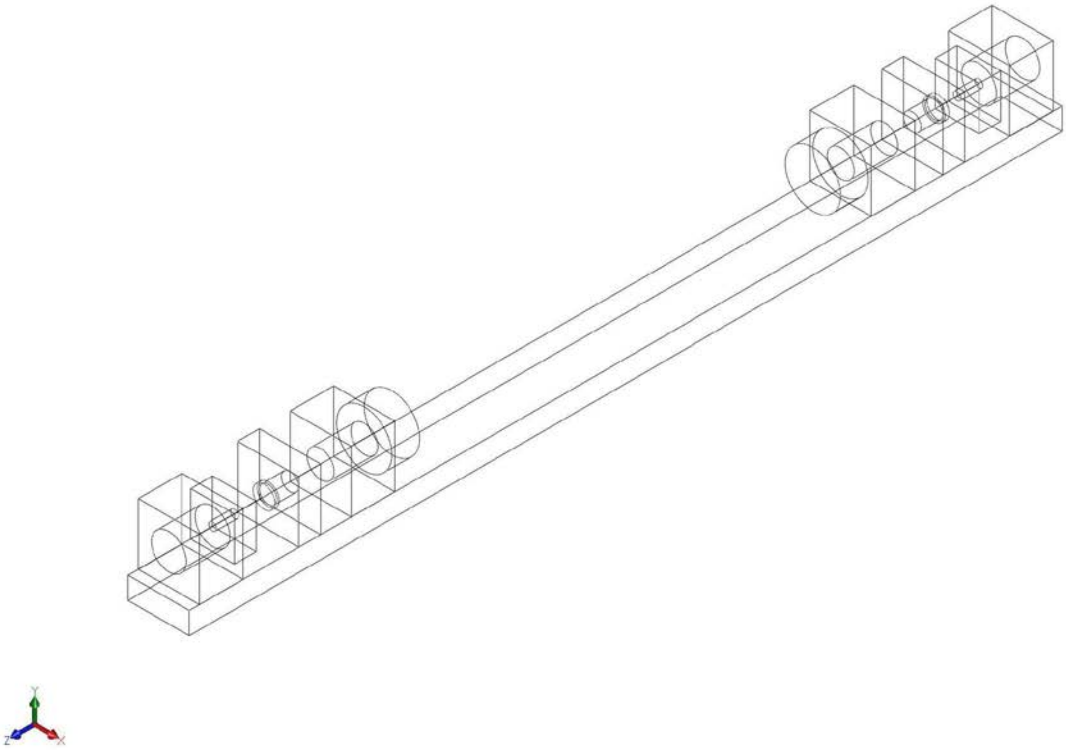


Figure 1: Isometric view of the cavity assembly. The image shows the cavity assembly without the mounting and the mounting extensions of the baseplate. The figure also does not include the fibres and the fibre strain reliefs. All optical elements are mounted on "spacers" (blocks of fused silica with drill holes). Details of the assembly are described in the text. Detailed dimensions of the components are given in Figure 2. In the current view, dimensions can be seen relative to the dimensions of the baseplate, which are 14x200x5mm³.

Figure 1 shows an isometric view of the layout of the optical elements on the optical bench. The cavity itself consits of two high-finesse dielectric mirrors using a fused-silica substrate. The thickness of the substrate is 6.36mm, the diameter of the mirrors is 12.7mm. The cavity is asymmetric with the radii of curvature being 30mm and 75mm, with a cavity length of 97.5mm. This is the cavity geometry currently planned for the optical assembly of the MAQRO mission proposal.

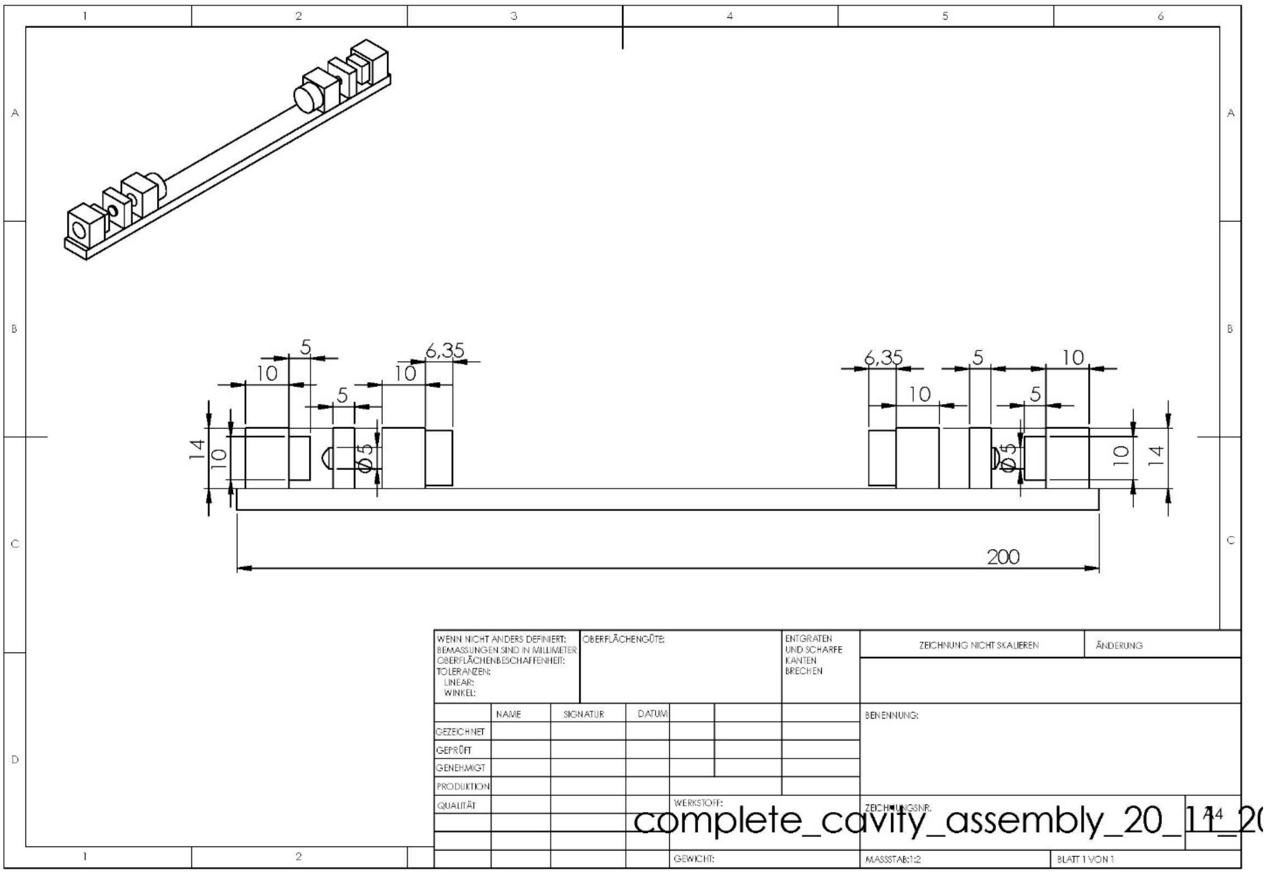


Figure 2: Dimensions of the cavity assembly in **mm**. The in the left-hand upper corner shows an isometric view of the cavity assembly as is also given in Figure 1.

The assembly shown in Figure 1 and Figure 2 is based on using the aspheric lenses described above. Because it was difficult to get aspheric lenses of a suitably space-proof and cheap material, and because any such material would most likely lead to thermal stress because it is different from the fused silica of the spacers used to mount the lenses, we finally decided to design and order our own aspheric lenses for this project. These lenses are to be made of fused silica – the same material as the spacers holding the lenses. Moreover, we planned to design the lenses such that they would be flat on one side. This will make it easier to mount and to position them in the same way we plan to mount and position the cavity mirrors.

After discussions with colleagues, I decided that the German company Asphericon should be a good choice for this project. I am currently finalizing the shape of the aspheric lenses and determining the corresponding manufacturing tolerances. The shape is already pretty well define at this stage, but small deviations can make a significant difference in the quality of the optical focus.

The purpose of the lenses is to take light emitted by a fibre on one end, focus it into the cavity and then coupling light existing from the cavity back into a fibre of the same type on the other end. Given the limited space available on the MAQRO platform (20cm) and the relatively long optical cavity, we need lenses of short focal lengths on both ends in order to have room for the whole optical assembly. This is also the central reason why we will need aspheric lenses.

In order to design the aspheric lenses, we first assume that we have ideal, infinitely thin lenses. This allows us to estimate the distances involved and the radii of curvature of the lenses. The design goals for this stage is that we match the optical mode of the fibre to the mode inside the cavity, and that we can do that within the limited space we have available.

In the following, we will refer to the cavity mirror with a radius of curvature of 75mm as C1. With C2, we will denote the other cavity mirror with a radius of curvature of 30mm. We will denote the corresponding lenses as F1 and F2, respectively. We can describe the fundamental mode of the cavity as a Gaussian mode with a waist of 63µm at a wavelength of 1064nm. We can describe the mode exiting the cavity at C1 using a complex parameter (in mm) $q_{\mathrm{C1}} = -129.84 + i\, 36.56$. At C2, the corresponding complex parameter (in mm) is $q_{\mathrm{C2}} = -34.85 + i\, 27.00$.

The mirrors are to be mounted on 10mm thick spacers with a central drilling hole with a diameter of 6.2mm. We assume to have some space to accommodate F1 and F2. These spaces are assumed to be 2.0mm and 2.5mm, respectively. We arrived at these thicknesses iteratively by improving the lens design. The lenses themselves are assumed to be mounted on spacers with a thickness of 5mm, and we assume there to be 7mm of space between the spacers of the lenses and the mirrors. These 7mm originate from our original assumption to have a minimum of 2mm of space in between these spacers. However, originally, we assumed the same thickness of 10mm also for the spacers used to mount the lenses. Given that the lenses will be pretty small, we decided that a 5mm thickness will be sufficient for the spacers holding the lenses. This increased the gap between the spacers from 2mm to 7mm. We could have stuck to a 2mm gap, but that would have meant even shorter focal lengths for F1 and F2. On the other hand, we could have relaxed our requirement on F2 slightly by reducing the gap size of the C1 side while increasing the gap size on the C2 side. This would have resulted only in a 10% change in F2, and this did not seem worth redoing all calculations, because the simplification on the F2 side would have resulted in a similar complication on the F1 side.

We assume in our calculations, that the fundamental mode coupled out of our optical fibre would have a mode waist of 4.05µm (radius) at 1064nm. In particular, we assumed that we would use an SMF-28 fibre from Corning. This fibre should also support the LP_{11a} and LP_{11b} modes at 1064nm, which we want to couple to the corresponding TEM_{01} and TEM_{10} modes in the cavity for optomechanical 3D cooling in MAQRO.

We start our estimation for the geometry using thin lenses by assuming that the distance from the focal point after the lens to the lens is:

$\Delta_{\mathrm{F1}} = 2 \times s + g + d_{F1} - \mathrm{Re}(q_{\mathrm{C1}}) = 153.84\mathrm{mm}$,

where we assumed $s = 10\mathrm{mm}$ for the spacer thickness and $g = 2\mathrm{mm}$ for the gap between them as described above $d_{\mathrm{F1}} = 2\mathrm{mm}$ is the room reserved for the thickness of F1.

To match the cavity mode to the fibre mode, we then need a thin lens with 5.56mm focal length that is 5.75mm from the fibre tip.

For the F2 side, we can do the same and get a corresponding value of
$\Delta_{\mathrm{F2}} = 2 \times s + g + d_{F2} - \mathrm{Re}(q_{\mathrm{C2}}) = 59.35\mathrm{mm}$,
and we need a lens with focal length 2.66mm a distance of 2.76mm from the fibre tip.

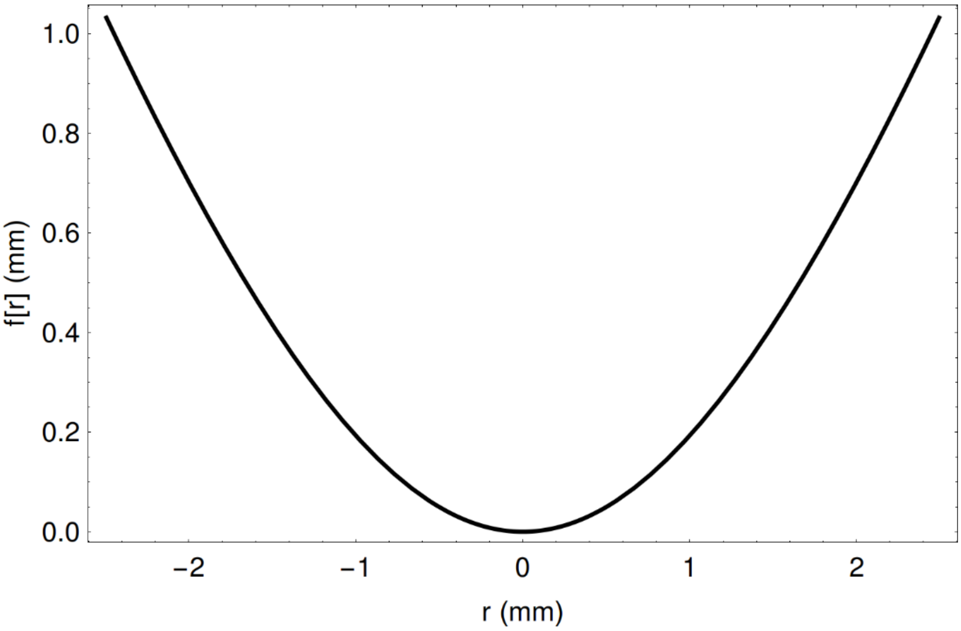


Figure 3: Shape of aspheric lens F1.

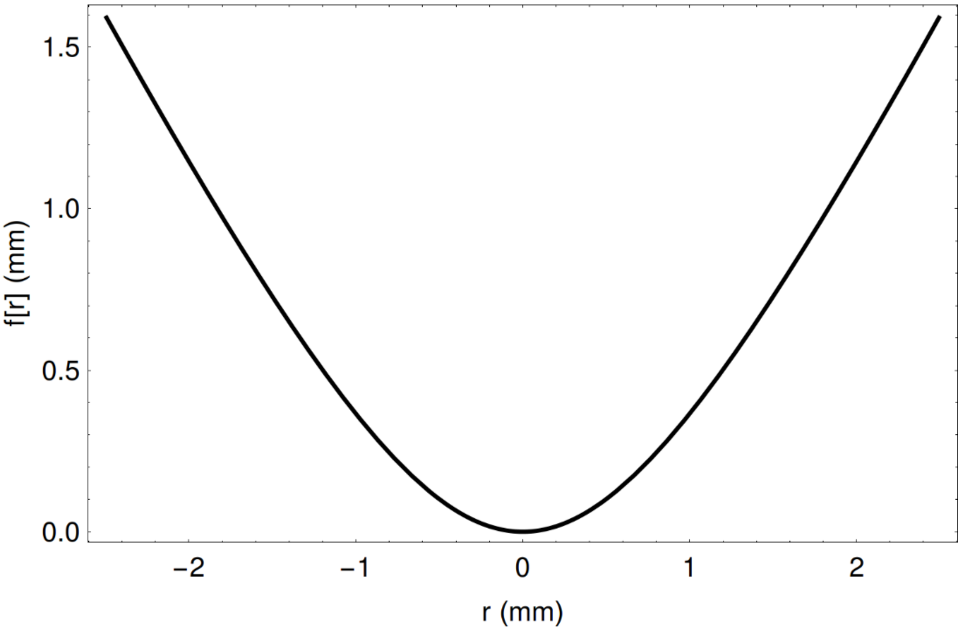


Figure 4: Shape of aspheric lens F2.

Now that we have these distances, we can use them to design aspheric lenses for F1 and F2. We can do this by assuming that the distances we just derived between each fibre tip and the corresponding focus after F1/F2, will be the same if we use aspherical lenses, and we will assume that the distances $\Delta_{\mathrm{F1/F2}}$ corresponds to the distances of the foci from the flat sides of their respective lenses.

To derive the shape of the aspheric lenses, we assume ray-optics propagation from a point like source at each fibre tip. These rays are then to be focussed again after F1/F2 such that the position of the resulting focus fits the distances calculated above, and such that the optical path from the fibre tip to the focus will be the same, independent of the distance of each ray from the axis of beam propagation (i.e., no lens errors). We illustrated this concept in Figure 5. The shapes of the corresponding solutions are given in Figure 3 and Figure 4. These figures also show that F2 has to be about 0.5mm thicker than F1 due to its shorter effective focal length.

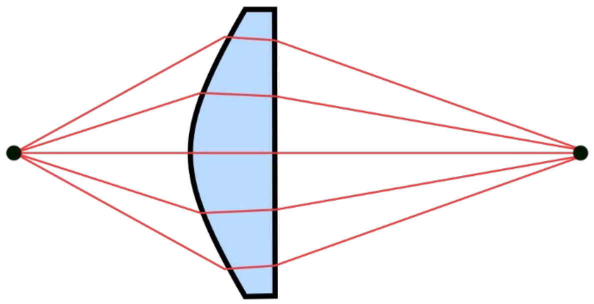


Figure 5: We design the aspheric lens such that rays emitted from an idealized point-like focus on the left-hand side are focused by the lens into a point-like focus on the right-hand side at a given distance. The lens is assumed to be made of fused silica, the wavelength of the light is 1064nm. The optical path from one focus to the other has to be independent of the distance from the central axis.

Now, the shape of the lenses drawn in Figure 3 and Figure 4 are the result of numerically solving non-linear, first-order differential equations in Mathematica. These results are given by Mathematica as interpolating functions. For accurate results and to specify the lens shapes to the supplier, we approximate this shape using the following, general form for aspheric lenses:

$$f(r) = \frac{r^2}{R\left(1+\sqrt{1-\frac{r^2}{R^2}(1+k)}\right)} + \sum_{m=2}^{n} A_{2m} r^{2\,m},$$

where R is the radius of curvature of the lens at $r = 0$, k is the conic constant, and A_m are constants. The shapes derived go up to order 10 for F1 and F2.

Here is the result for F1:

$$f_{F1}(r) = \frac{0.3997098 \times r^2}{\left(1+\sqrt{1-0.0718962 \times r^2}\right)} - 0.011801 \times r^4 +$$

$$+\,0.0005383 \times r^6 + 6.708 \times 10^{-5} \times r^8 + \ 4.2548 \times 10^{-6} \times r^{10} - 2.048 \times 10^{-7} \times r^{12}$$

For F2, we get:

$$f_{\mathrm{F2}}(r) = \frac{0.842194 \times r^2}{\left(1+\sqrt{1+\ 0.71925 \times r^2}\right)} +$$

$$+\,0.0011394 \times r^4 - \ 0.0001509 \times r^6 + 1.411 \times 10^{-5} \times r^8 - 5.9921 \times 10^{-7} \times r^{10}$$

In both cases, the shape is to be cut off at a maximum radius. This is 2.5mm for F1 and 2mm for F2. The clear aperture of the lenses is than significantly larger than the beam waist passing through the lenses, i.e., the aperture has to be larger than five times the waist.

While the discussion here shows that we already have a pretty good impression what the aspheric lenses should look like, this does not mean that it is feasible to manufacture such lenses. The question is: what tolerances can we allow on the various parameters in those lens-defining equations. That means, if there is a small imperfection in any of these parameters, will it lead to astigmatism we cannot correct for? Is the precision needed possible given existing technology?

We are currently investigating these questions. We are re-evaluating the above results, checking for inconsistencies and analysing whether we can relax the requirements on some of the tolerances that may be challenging to meet. Once we are satisfied with the lens shapes we need, we will contact Asphericon to discuss whether they can manufacture the lenses within the required tolerances. Of course, it will also be a question of cost.

Given that the lens shapes depend on a lot of parameters, we will discuss only the most important ones for the case of F1. The discussion is similar for F2, but in this case we will only provide the tolerances we think we need at the moment. These estimates still need to be double-checked.

In general, the rough shape of the lens is determined by the term:

$$\frac{r^2}{R\left(1+\sqrt{1-\frac{r^2}{R^2}(1+k)}\right)},$$

The added polynomial corrects this shape to match the solution of the first-order non-linear differential equation resulting from equating the optical path lengths through the lens (see Figure 5).

In the case of F1, we get:

$$R_{\mathrm{F1}} = 2.4945\mathrm{mm} \pm 0.5\mathrm{\mu m}$$

and

$$k_{\mathrm{F1}} = -2.0328 \pm 0.0014$$

Especially in the case of R_{F1}, it is obvious that the tolerance is very narrow. It is unclear right now, if it is possible to manufacture the lens to such accuracy and whether it would be affordable. The values and tolerances in the polynomial parameters are the following for F1:

$$A_{4,\mathrm{F1}} = (130 \pm 6) \times 10^{-6}\mathrm{mm}^{-3},$$
$$A_{6,\mathrm{F1}} = (-6.4 \pm 1.5) \times 10^{-6}\mathrm{mm}^{-5},$$
$$A_{8,\mathrm{F1}} = (3 \pm 4) \times 10^{-7}\mathrm{mm}^{-7},$$
$$A_{10,\mathrm{F1}} = (-1 \pm 10) \times 10^{-8}\mathrm{mm}^{-9},$$

We determined the tolerances by requiring that the deviation of the resulting lens shape from the “ideal” lens shape over the size of the clear aperture is less than $\lambda/10$.

For F2, we get:

$$R_{\mathrm{F2}} = 1.1874\mathrm{mm} \pm 0.2\mathrm{\mu m},$$

$$k_{\mathrm{F2}} = -2.0181 \pm 0.0004$$
$$A_{4,\mathrm{F2}} = (1416 \pm 7) \times 10^{-6}\mathrm{mm}^{-3},$$
$$A_{6,\mathrm{F2}} = (-292 \pm 2) \times 10^{-6}\mathrm{mm}^{-5},$$
$$A_{8,\mathrm{F2}} = (592 \pm 4) \times 10^{-7}\mathrm{mm}^{-7},$$
$$A_{10,\mathrm{F2}} = (-95 \pm 1) \times 10^{-7}\mathrm{mm}^{-9},$$
$$A_{12,\mathrm{F2}} = (107 \pm 3) \times 10^{-8}\mathrm{mm}^{-11},$$
$$A_{14,\mathrm{F2}} = (7 \pm 1) \times 10^{-8}\mathrm{mm}^{-11},$$

In the following weeks, we want to discuss these tolerances not only in terms of deviations from the "ideal" lens shape, but we also want to investigate whether we could compensate for resulting deviations in the beam focus, e.g., by tilting or translating the lens or the fibre coupler. If that is possible, we can allow for larger tolerances.

In addition to finalizing the lens design, we also have to finish the design for the baseplate. In particular, we should include a mounting option into its design such that vibrations of the cryostat will not negatively influence the performance of our cavity. The way we will proceed is to make an eigenfrequency analysis of the cavity setup. We will add mounting clamps at the nodes of the fundamental mode. This should reduce the risk of exciting that mode via vibrations.

2.3 Changes in the further course of the project

As we described in the previous sections, there have been some additional delays in WP4. In order to avoid any further delays, we decided to focus our full attention on WP4 in the coming weeks. By accurately defining the aspheric lenses, the spacers for the optical elements as well as the baseplate, we hope that the manufacturing of the lenses will be done quickly such that WP5 will not cause any additional delays. Given the increased focus on WP4, we are confident that there will not be any further delays, and that we will be able to finish the project in 03/2019 as originally planned.

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?

At the end of this 2nd reporting period, the PI of the project as well as the project itself will be transferred from the University of Vienna to the IQOQI-Vienna. The contracts with the subcontractors will be adapted accordingly, and adapting the contract with the FFG will commence as soon as this intermediate report is submitted.

The transfer of the project from the University of Vienna to the IQOQI-Vienna will not have any negative influence on the project.

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

We would ask to reallocate the total budget from devices to material as indicated below:

Kosten laut Förderungsvertrag					
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 laut 1stem Zwischenbericht					
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

Kosten NEU					
Personal-kosten neu	Sach & Material-kosten neu	Dritt-kosten neu	F&E Infrastr. neu	Reise-kosten neu	Gesamt-kosten neu
228.307	47.458	51.500	0	8.625	335.890

In the last reporting period, we forgot to make some reallocation of budget within the project. In particular, in the application for this project, we accidentally put the budget for the COMSOL finite-element analysis software into the budget for devices. However, since these are software licences that are always only valid for one year, these are actually material costs. In addition, the other costs for the baseplates and optomechanical components that we originally had in the device budget, also should have been material budget instead. The reason is that the corresponding components will only be used for this project – they will be glued (adhesively bonded) to each other to form one final "product", which we will not be able to disassemble to use the used components for anything else.

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

There are no incidents to report.