Public call for co-financing of research projects in 2025

DESCRIPTION OF THE RESEARCH PROJECT

23.1. Scientific background, problem identification and objective of the proposed research

Quantum technologies are driving transformative changes in science and technology [1,2]. Slovenia has made significant strides to establish itself as a key player in this field, supported by initiatives like the establishment of my research group at the Faculty of Mathematics and Physics of the University of Ljubljana (UL-FMF). Increasing local expertise in quantum technologies is vital for maintaining the EU's global competitiveness and fostering groundbreaking scientific discoveries.

Fundamental principles of quantum physics like superposition and entanglement [3,4] lie at the core of emerging quantum technologies. These concepts fuel the ongoing 2nd quantum revolution [1], which has paved the way for cutting-edge quantum applications in sensing [5], communication [6,7], simulation [8], and computation [9,10] – the four pillars of the EU's Quantum Flagship initiative. Entanglement [3] is a critical resource for many of these technologies. It underpins the establishment of quantum networks [2], connecting distant quantum devices such as sensors and computers. This will facilitate their remote usage, and it has the potential to further boost the precision and accuracy of such devices [11,12].

Establishing such quantum networks is the central goal of the European Quantum Communication Infrastructure (EuroQCI) initiative [13]. For a future quantum internet, this will require entanglement [2]. But the distribution of entanglement is hindered by losses. Unlike classical signals, quantum information that is, e.g., encoded in the polarization of single photons cannot be amplified. In long distances, these losses are exponential in optical fibers. Even though fibers for telecommunication are very low loss, the exponential loss will quickly become overwhelming. Currently, this limits the distribution of entanglement to distances of a few hundred kilometers [14]. Addressing the issue of losses is crucial for unlocking the full potential of quantum networks.

To overcome the losses in the long-distance distribution of entanglement, quantum repeaters provide a promising solution [15–17]. In this protocol, long transmission paths are typically divided into segments that are sufficiently short to allow the reliable distribution of entanglement. The entangled photons are distributed across these shorter distances and stored in quantum memories. Noise in the transmission can be mitigated through entanglement distillation [18–20], a probabilistic protocol that generates pairs of maximally entangled photons from a higher number of photon pairs with lower-quality entanglement. Once high-quality entanglement is established across all segments, these entangled photon pairs can be used to teleport [21–23] entanglement or quantum states along the segments to connect the distant end nodes. This makes it possible to bypass the losses and noise that would otherwise accumulate over long distances.

Realizing this protocol therefore relies on four essential ingredients: (1) bright sources of entanglement that can then be distributed efficiently over short segments. (2) at the end nodes of these segments, the entanglement needs to be efficiently stored in quantum memories, sufficiently long to (3) successfully distill maximally entangled photon pairs from the entangled pairs distributed and stored, and (4) the entanglement must be teleported to the end node of the next segment.

Research goal (A) of the research we propose here, will address points (1) and (2) by implementing a bright source of entanglement that is sufficiently narrowband to allow efficient storage in a quantum memory. The necessary bandwidth for that is typically on the MHz scale [24,25].

As we quickly progress towards the establishment of large-scale quantum networks, it becomes increasingly important to enable the interfacing of quantum networks and quantum devices at the network nodes [26,27]. Quantum sensors have seen tremendous progress over the last decade [5]. These developments have given rise to a whole new field of physics known as quantum optomechanics [28], where the radiation pressure of light is used to control and/or measure the center-of-mass motion or other degrees of freedom of massive mechanical resonators.

A particularly promising architecture for quantum sensing is optomechanics with optically trapped particles [29]. It has proved a very powerful tool for high-precision sensing of forces and accelerations, and it provides a very promising platform for testing the foundations of physics on ground and in space [30]. Several groups by now have demonstrated that it is possible to bring the motion of such trapped macroscopic particles into the quantum regime [31–34].

In such optomechanical systems with trapped particles, the mechanical frequencies and their differences are often less than 100 kHz [31]. Coupling specific degrees of freedom of such quantum sensors to entangled photons therefore requires photons with a bandwidth narrower than 100 kHz.

Research goal (B) will be to achieve such an extremely narrow bandwidth. This goes significantly beyond the goals of research goal (A). The coupling of entangled photons to optomechanical quantum sensors will provide exciting new possibilities like coupling them to atomic systems or preparing nonclassical states of motion [35–37]. This will be a central goal of future research in our laboratory. We will aim to couple single entangled photons generated by the source in this proposal to the center-of-mass motion of a quantum optomechanical system we are currently implementing. This will allow us to prepare the trapped dielectric particles in coherent cat states of motion [38]. This will enable the realization of superpositions of massive particles traveling in two directions. This is a key technique for the implementation of Mach-Zehnder-type matter-wave interferometers for high-mass dielectric particles. Such interferometers have the potential to be orders of magnitude more sensitive than the best atom interferometers, and that could revolutionize high-precision sensing.

23.2. State-of-the-art in the proposed field of research and survey of the relevant literature

Let us first consider the prerequisites for achieving research goal (A) and the state-of-the-art relevant to it. This goal is to implement a source of entanglement that addresses two of the central needs for implementing a quantum repeater: (1) the source should be sufficiently bright and of an appropriate wavelength to allow distributing entanglement efficiently between the end nodes of a repeater segment. (2) the wavelength and the bandwidth of the photons needs to be compatible with an efficient storage in quantum memories.

The best sources of entanglement for the distribution over long distances are based on a nonlinear optical effect known as spontaneous parametric downconversion (SPDC) [14]. For this purpose, a pump beam is sent into a nonlinear optical crystal, and there will be a small probability for each pump photon to create a pair of photons with well-defined polarization and frequency correlations [39,40]. Entanglement can then be generated by ensuring that there are multiple, indistinguishable processes that can lead to the creation of one pair of photons. Some important features of SPDC-based sources of entanglement are:

- They allow high-quality entanglement. This can, e.g., be quantified by the purity and the tangle of the generated state.
- They can have a high brightness – i.e., a high rate of emitted pairs per mW of pump power and per nm of source bandwidth.
- They feature excellent timing between the photons generated. It is always pairs of photons generated simultaneously. For this reason, the detection of one photon will herald the presence of its partner photon with high reliability. This is called the heralding efficiency.

Despite these advantages, SPDC sources face key challenges, including their probabilistic nature and multi-pair emissions at higher pump powers. Moreover, SPDC sources are very broadband and typically require spectral filtering to achieve narrow bandwidths. Usual “narrowband” SPDC sources often still have a bandwidth of many GHz [41] while the bandwidth of many atomic transitions like the D2 line of Rubidium is in the MHz regime [25].

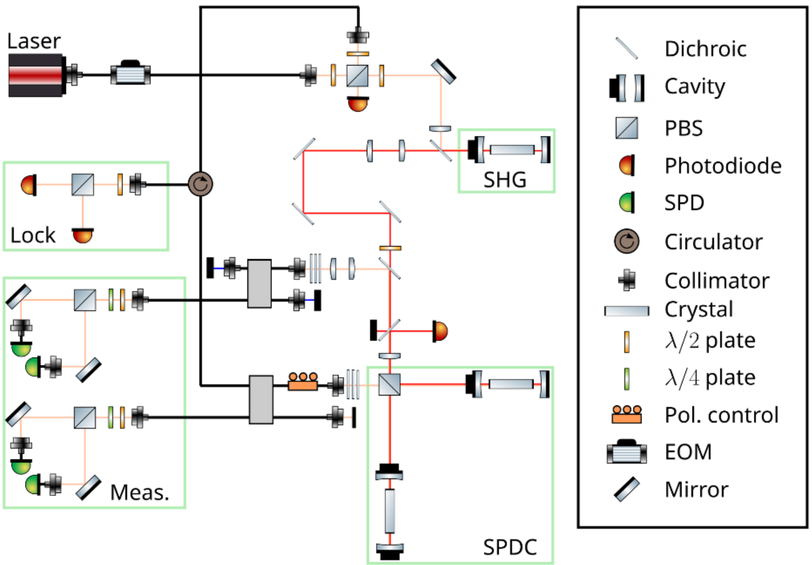


Figure 1: A narrowband source of wavelength-degenerate polarization-entangled photons. A pair of photons with a wavelength of 1310 nm can be generated via SPDC in one of two cavities. The pump beam is generated via cavity-enhanced second-harmonic generation (SHG). Mechanical switches are used to operate the setup in a “locking mode”, where the SPDC cavities are locked to the laser and during which we stabilize the polarizing interferometer generating the entanglement. PBS: polarizing beam splitter, EOM: electro-optic modulator, SPD: single-photon detector.

It is possible to achieve a significantly narrower bandwidth by using cavity-enhanced SPDC [42]. In this case, the SPDC crystal is placed inside an optical cavity. Such cavities consist of two or more mirrors that are highly reflective for the SPDC photons generated and sometimes also for the pump photons. If the optical path length inside such a cavity is a multiple of the wavelength of a photon, this wavelength is “on resonance” with the cavity. In this case, interference between photon amplitudes that are reflected many times from the mirrors can interfere constructively. This can lead to very high intra-cavity fields due to photons being reflected many times inside the cavity.

If we have a cavity that is resonant for one or both SPDC photons, this can significantly enhance the efficiency of the SPDC process. Because this only occurs for very well-defined wavelengths that are on resonance, the spectrum of the photons generated will be defined by the width of the cavity resonances. This can be made very narrow by properly choosing the reflection coatings of the cavity mirrors, antireflection coatings of transmissive elements inside the cavity, and the optical path length photons must travel for a full round-trip in the cavity. We will denote that distance as cavity length.

Significant progress has been achieved towards implementing cavity-enhanced SPDC sources of entanglement to achieve a sufficiently narrow bandwidth to efficiently couple to quantum memories [24,43]. Until recently, many of these works focused on using cavity-enhanced SPDC to generate narrowband pairs of photons without entanglement [44]. In some works, where the generated pairs were entangled, the necessary narrow bandwidth was achieved by spectrally filtering the photons [45]. However, this leads to significant losses rendering this approach unfit for implementing quantum repeaters. Moreover, spectral filtering of the photons emitted by an SPDC source drastically reduces its heralding efficiency.

Over the last years, my group has been implementing a prototype of a cavity-enhanced source of polarization entangled photons. This experiment is now nearing completion and will generate wavelength-degenerate, polarization-entangled pairs of photons with a bandwidth of a few MHz. A simplified layout of this experiment is presented in **Figure 1**.

In this setup, the entanglement is created in a polarizing interferometer. Depending on its polarization, a pump photon can create an SPDC pair in the crystal embedded in one of two cavities. If these processes are indistinguishable, the corresponding amplitudes will add up at the polarizing beam splitter where their spatial modes are overlapped.

While this setup has been an excellent opportunity for us to gain experience in the design and the stabilization of optical cavities, the setup is very complex and hard to stabilize. It involves the stabilization of one interferometer and four cavities (2 x SPDC, 1 x second-harmonic generation, 1 x for laser stabilization). To create entanglement, four cavity modes must be on resonance simultaneously: two polarization modes each for two cavities.

For this approach to be feasible, we used simple and compact cavity geometries, where each of the non-linear crystals is placed in a simple Fabry-Pérot cavity. A disadvantage of this approach is that the length of Fabry-Pérot cavities is typically kept short because they are mechanically unstable compared to, e.g., bow-tie cavities. As a result, the bandwidth of such cavities is comparatively broad. In particular, the 1310 nm source we are currently completing will generate entangled photons with a bandwidth of a few MHz. This would be sufficient to achieve research goal (A), but it is orders of magnitude to broad to fulfil research goal (B).

What limits the bandwidth of this source design are two things: (a) it is not possible to increase the length of our Fabry-Pérot cavities without a significant impact on their stability, (b) for a fixed cavity length, the cavity bandwidth is determined by the intracavity losses. The main contribution is the reflection of SPDC photons from air-to-crystal interfaces. The anti-reflection (AR) coatings we use to achieve a bandwidth in the MHz range are already exceptionally good. We will aim to find a supplier that can provide even better, custom designed AR coatings, and this would allow us to achieve sub-MHz bandwidths. To achieve research goal (B) to go significantly below a MHz will require longer cavity lengths. In particular, the bandwidth of a cavity is $\Delta\nu = c/2\mathcal{F}L$, where c is the speed of light, L is the cavity length, and $\mathcal{F}$ is the finesse of the cavity. If we assume the light to propagate in air or vacuum, we can only improve the bandwidth by increasing the finesse (i.e., reducing the losses at the AR coatings), or by increasing the cavity length. To do the latter, we need a different cavity geometry.

If we use a more complex cavity geometry, we must find a different method to generate entanglement – not by generating SPDC in multiple cavities. To achieve that, we developed a new source concept [46] where entangled photons are generated in a single cavity containing multiple crystals (see **Figure 2**). This can be any cavity, but the schematic shows a Fabry-Pérot geometry for simplicity.

For this approach to work, the photons generated must be non-degenerate in their wavelength, and the type of SPDC used must be type-II. That means the polarizations of the photons in an SPDC pair must be mutually orthogonal. If we assume that the pump polarization is

$$|\chi\rangle = \frac{1}{\sqrt{2}}\left[\cos(\alpha)\,|H\rangle + e^{\phi}\sin(\alpha)\,|V\rangle\right],$$

where we use $|H\rangle$ and $|V\rangle$ to denote horizontal and vertical polarization, respectively.

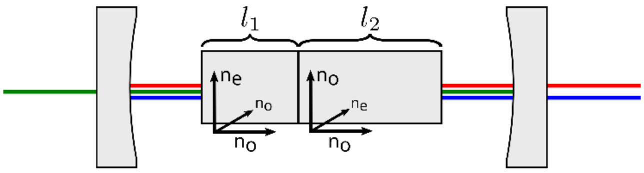


Figure 2: Generating entangled photons using cavity-enhanced SPDC in a single cavity. The cavity contains two crystals of lengths l_1 and l_2. Their optical axes are oriented perpendicular to each other. The cavity is resonant for the SPDC photons, the pump is reflected from the second mirror.

Each pump photon can then generate an SPDC pair in the first or the second crystal. This will result in the generation of pairs of photons in the state:

$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(\cos(\alpha)\,a_H^\dagger(\omega_1)a_V^\dagger(\omega_2) + e^{i\phi}\sin(\alpha)a_V^\dagger(\omega_1)a_H^\dagger(\omega_2)\right)|vac\rangle.$$

Here, α and ϕ result from the polarization of the pump beam, $a_{H,V}^\dagger(\omega)$are the creation operators for a horizontally or vertically polarized photon of frequency ω, and |vac⟩ is the vacuum state. The state describes two photons that are entangled in frequency and in polarization. If one separates the two photons by their wavelength, one will get a polarization-entangled state. We recently showed that this approach is feasible for realistic experimental parameters.

For photon pairs in that state to be generated efficiently, the following conditions are met:

a) The cavity is resonant for all four processes involved – H and V for two wavelengths.
b) The bandwidth for SPDC in each crystal individual crystal must be sufficiently narrow.

Condition (a) for a quadruple resonance is necessary because only in that case will all four processes be cavity enhanced. Condition (b) requires that the SPDC bandwidth is narrower than the frequency distance between subsequent "double resonances". These are cases where both SPDC photons generated in the respective crystal are resonant with the cavity. The frequency difference between the occurrence of such double resonances is called the "cluster spacing". If condition (b) were not fulfilled, there would be multiple frequency combinations for the SPDC photons generated to be on resonance with the cavity. As a result, summands for additional frequencies would appear in the expression for the state generated.

These additional terms would significantly reduce the state's entanglement. One can suppress them via spectral filtering, or one can add additional dispersive elements to the cavity to increase the cluster spacings compared to the SPDC bandwidths. The latter approach allows generating high-fidelity entanglement without the need of any additional spectral filtering.

Using this approach, only a single optical cavity is required to generate narrow-band entangled photons with non-degenerate wavelengths. This has several significant advantages compared to the approach we described above for generating degenerate entangled photons at 1310 nm:

- We can choose a more complex cavity geometry – for example a bow-tie cavity.

- A bow-tie cavity allows us to use a longer cavity length and therefore achieve narrower linewidths.
- In a bow-tie cavity, the intra-cavity losses are halved because the SPDC photons only travel through the crystals once.
- We do not need to implement multiple cavities and stabilize them with respect to a frequency reference. That means, (i) we do not need to stabilize a reference cavity against long-term drifts, (ii) we can directly use a laser to pump the SPDC processes without the need for second harmonic generation (SHG) – that means, there is no SHG cavity to stabilize.
- We do not need to implement and stabilize an interferometer to generate entanglement.

These advantages mean that the new source we proposed will allow us to achieve bandwidths that are significantly more narrowband than the 1 MHz bandwidth we can achieve for the 1310 nm case. We will base our proposed research on this novel source design because it will allow us to achieve research goal (B) – a sub-100 kHz bandwidth.

23.3. Detailed description of the work programme

The project consists of three work packages (WPs). The project management will be covered by WP1. In WP2, we will do a detailed design of our extremely narrowband source of highly non-degenerate polarization entangled photons. This will include the design of a stable bow-tie cavity containing prisms to introduce negative dispersion, the design of a stable baseplate for the cavity and the design of ovens to keep the two crystals at stable temperatures for SPDC. We will find suitable suppliers and order all the components required for implementing the experimental setup. In WP3, we will implement and test the crystal ovens and temperature controllers to stabilize the temperatures of the crystals with mK precision. We will assemble the prisms for introducing dispersion. As a first step, we will align everything to generate narrowband biphotons (no entanglement). In the final step, we will create narrowband entanglement and characterize it.

WP1 – Project Management

The project will be led by Rainer Kaltenbaek – the head of the laboratory for Quantum Optics and Quantum Foundations, and the scientific lead of the national Slovene Euro-QCI project SiQUID. The project team will include five PhD students (Shreya Gupta, Fatemeh Pourkhavari, Hadis Torbatiyan, Adrian Udovičić, Bedir Halcı). WP1 will deal with the on-time delivery of the milestones of the project, the successful completion of the review meetings, the supervision of the young researchers, the dissemination of the results, and the preparation of administrative and technical reports for the funding agency.

WP2 – Source design

Figure 3 shows the preliminary design for the source of entanglement we plan to implement. The goal of WP2 will be to define this source design in more detail. The precise geometry of the source will depend on the cavity length we have to achieve, and that will depend on the quality of AR coating we will be able to get for the nonlinear crystals and the prisms we will use for introducing negative dispersion.

In the first task, **T2-1**, we will choose the best type of crystal for type-II SPDC to generate pairs of photons at the wavelengths 780.24 nm and 1544.8 nm with a pump wavelength of 518.4 nm. Moreover, we will choose the ideal lengths and transverse dimensions of the two crystals. The length should be large as possible to increase the brightness of the source, and to minimize the SPDC bandwidths. For example, if we use periodically poled 5% MgO-doped Lithium Niobate (PPLN) crystals, these typically have a maximum thickness of 1 mm, and the maximum useful length is then around 50 mm for Sagnac sources of entanglement. In the context of the high-finesse cavity we want to implement, we will aim for a shorter crystal length to minimize the losses that may otherwise result from beam clipping. We anticipate a total crystal length of $l = l_1 + l_2 \leq 40$ mm. Choosing the best crystals will also depend on what options this will make available for the AR coating. This will be crucial for our cavity design because we will need to minimize the intracavity losses.

Once the crystal dimensions and the AR coating of the crystals are defined, in task **T2-2** we will calculate how much negative dispersion we will need to introduce to avoid the need for spectral filtering. This determines the prisms we need to acquire. We will aim to get the best AR coating possible. This, in combination with the AR coatings of the crystals will define the intracavity losses. From these considerations, we can determine the cavity length L we need to achieve a sub-100 kHz bandwidth, and impedance matching will define the optimal reflectivities we need to choose for the cavity mirrors. The radii of the mirror substrates and their radii of curvature will be defined by the crystal length, which can be used to estimate the optimum waist size for the SPDC photons and the pump beam.

For example, if we assume that we have comparable intracavity losses as in the 1310 nm case due to the AR coatings of the nonlinear crystals, we will overall have 2 x 0.25% losses for passing once into each of the two crystals per round trip. If there were no losses from the prisms, that would allow a bandwidth below 50 kHz for a cavity length of 3.6 m.

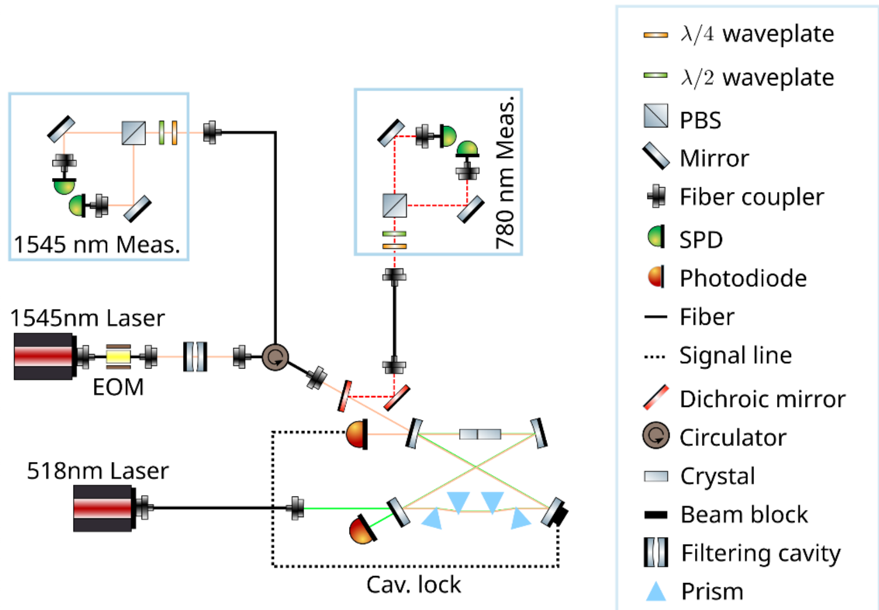


Figure 3: Two-crystal SPDC source of entanglement. A 518.4 nm laser pumps SPDC in two orthogonally oriented crystals. The SPDC photons have highly non-degenerate wavelengths of 780.24 nm (Rubidium D2 line) and 1544.8 nm (C-band). An electro-optic modulator (EOM) creates sidebands that are separated by the FSR of the cavity. A beam that is shifted by one FSR from the frequency of the C-band SPDC photon is used to stabilize the cavity. One filtering cavity (FC) is used to choose the intended EOM sideband. A second FC is used to prevent light from the locking beam reaching the single-photon detectors (SPDs). PBS: polarizing beam splitter.

If we assume that the nonlinear crystals used are PPLN, the ratio $l_1/(l_1 + l_2)$ for the crystal lengths l_1 and l_2 should be between 0.3 and 0.4 to ensure it is possible to find a quadruple resonance to generate entanglement. Otherwise, the “joint cluster spacing” will diverge. That is the spacing between occurrences of a simultaneous double-resonance for SPDC in both crystals.

The resonance frequencies of the cavity will be very sensitive to temperature changes of the nonlinear crystals. This becomes particularly critical if one needs to stabilize multiple resonances simultaneously. For that reason, we will design and implement our own crystal ovens with the goal of achieving mK temperature stability in the crystals. Moreover, we will aim to control the temperatures of the two crystals independently of each other to facilitate finding quadruple cavity resonances.

To prevent the need for spectral filtering, we will need to introduce negative dispersion into the cavity. We aim to realize that using two prism pairs as shown in **Figure 3**. Adding these additional optical elements will, of course, increase the intra-cavity losses. Finding the best supplier for good AR coating will be essential.

Given that we must achieve a quadruple resonance of the cavity, i.e. a resonance for both polarizations of both wavelengths of the non-degenerate SPDC process, we do not plan to additionally get a resonance for the pump light. This is not necessary to achieve narrow bandwidth SPDC. Nonetheless, it may be beneficial to have a low-finesse resonance for the pump light. This could help in stabilizing the cavity against long-term drifts, and it could help in reducing the SPDC bandwidth compared to the cluster spacings of the SPDC processes in the two crystals. We will investigate this question in more detail in WP2. We will choose the reflectivities of the cavity mirrors at the pump wavelength based on this investigation. All cavity mirrors will be placed on stable posts and mirror mounts that provide the minimum necessary degrees of freedom and high mechanical and thermal stability.

Negative dispersion will be introduced by two prism pairs. In each pair, one of the prisms splits/combines the light into its spectral components, and the second prism will ensure that these spectral components are parallel to each other. The amount of dispersion this setup adds will depend on the refractive indices of the prisms and on the distance between the prism pairs. One prism pair will be placed on a motorized translation stage to allow us to fine tune the dispersion.

Task **T2-3** will be to finalize the cavity design. This includes how to mount the various components, what the baseplate should look like and an enclosure for the setup. One of the cavity mirrors will be attached to a piezoelectric actuator. This actuator will be used to stabilize the cavity length using Pound-Drever-Hall (PDH) locking. To generate the laser beam for the PDH stabilization, we use an electro-optic modulator (EOM) in combination with a filtering cavity (FC) to create a laser beam that is shifted in frequency by one free spectral range (FSR) of the cavity with respect to the C-band SPDC photons we want to generate. The goal is to operate this stabilization continuously while we generate SPDC photons. To do so, it is crucial that we achieve a good spectral separation between the SPDC photons and the laser we use for the cavity lock. We get a significant suppression by having the locking beam travel in the opposite direction compared to the SPDC photons. A second filtering cavity will help to further suppress the background from the locking laser (see **Figure 3**).

An important step to achieve the targeted narrow cavity bandwidth will be to (i) prevent air currents from disturbing the beam path, and (ii) to prevent air humidity from covering the high-finesse cavity mirrors. In experiments we performed in Vienna, we saw that the initial bandwidth of our high-finesse cavity there quickly increased from by several 100 kHz due to a high air humidity. By cleaning the cavity mirrors, sealing the cavity off from the lab environment and flooding the cavity with nitrogen, we were able to keep the cavity linewidth stable for several years without noticing any increase in the bandwidth.

Although the humidity conditions in our laboratory in Ljubljana are better than in Vienna, these conditions vary over time. To avoid any unnecessary complications, we will design an air-tight cover for the cavity setup and flood it with nitrogen. This also means that any optics mounts within the cavity setup that we may want to adjust for alignment must be motorized such that we can make the necessary adjustments without needing to break the seal.

Task 2-4 will be to order all the components and materials necessary for implementing the cavity in the next work package.

WP3 – Source implementation and characterization

After designing the source and ordering all the necessary equipment and material, we will begin implementing the source design. Many lessons have been learned from building and stabilizing our 1310 nm cavity-enhanced source of entanglement and from building and stabilizing a high-finesse, space ready cavity in Vienna. This will help us to speed up the process from the design stage to the implementation stage. We have gained significant experience in choosing the right piezos, piezo amplifiers, mixers, amplifiers, and in implementing the electronic circuits necessary to generate PDH signals for stabilizing cavities.

Some challenges will, of course, go significantly beyond what we have done so far. For example, the building of an extremely long bow-tie cavity, the finding and stabilization of a quadruple resonance. Careful planning during the design stage in WP2 will facilitate addressing these challenges.

The first task, **T3-1**, will be to implement ovens for the two nonlinear crystals, and to integrate them with high-precision temperature controllers. As soon as the ovens are operational, we will send the 1545 nm and a 780.24 nm laser beam into the crystals to perform second-harmonic generation (SFG). If the polarizations of the two beams are set correctly, a scan over the temperature of the crystal will allow us to find the phase-matching (PM) temperature for SFG. This is the same temperature we will later need for SPDC.

We will be able to do task **T3-2** in parallel with task T3-1. The goal will be to implement the dispersion setup with two prism pairs, where one pair can be moved with respect to the other using a motorized translation stage. After implementing this setup, we will characterize the amount of dispersion the setup introduces as a function of the distance moved, and we will calibrate the setup such that the motor allows covering a range of dispersion values we expect to require in our source of entanglement. As part of this task, we will also set up the locking beam by creating the necessary sidebands with an EOM as described above and filtering out the wanted sideband.

The next task, **T3-2**, will be to set up the cavity and to integrate the oven assembly and the dispersion assembly. Once this is done, we will attempt to guide the pump into the cavity and ensure that the beam path is properly aligned. Then we will send in the locking beam from the other direction and align it to the cavity. This process will take some iteration to achieve good alignment.

Once the cavity is reasonably well aligned, we will aim in task **T3-3** to optimize the alignment by trying to see optical parametric oscillation (OPO) for each of the individual crystals. To this end, we will set the two SPDC crystals to their respective PM temperatures and then pump the crystal with horizontal or vertical polarization. We will then aim to find a double resonance for one crystal, and then we will repeat the procedure for the second crystal.

Once we have achieved that, we will aim in task **T3-4** to overlap these double resonances, e.g., by slightly changing the crystal temperatures or by moving a prism pair to achieve a quadruple resonance. This alignment will be one of the most challenging parts of this project, but we are confident that we will succeed eventually. Once we have achieved this, we will operate the cavity in the SPDC regime to generate entangled photon pairs and to characterize the entangled state and its the spectral properties.

23.4. Available research equipment over 5.000 €

The research will be performed in the »Quantum Optics and Quantum Foundations Lab« of the Faculty of Mathematics and Physics of the University of Ljubljana (UL-FMF). UL-FMF built our laboratory from 2019-2020, and it has been fully operational since 2021. Over the last years, we have increasingly equipped our laboratory to create a state-of-the-art research laboratory for quantum optics, quantum communication, and quantum optomechanics. In the following, we will provide an overview of the equipment available in the lab worth over 5000€:

Narrowband and tuneable lasers at wavelengths of 519, 775, 780, 1064, 1310 nm, and 1550 nm. For the present project, we need the 518 nm, the 780 nm and the 1550 nm lasers. We also have two superconducting nanowire single-photon detection (SNSPD) systems, each of them containing 4 detectors for photons between 1300 nm and 1600 nm. One system also contains 4 detectors for visible and near infrared photons. We also have two single-channel **InGaAs single-photon detector (SPD) modules**, and a home-made, **two-channel Si SPD module** for visible and near infrared photons. We have **one 5-channel time-tagger** with 10 ps resolution and **two, 8-channel time taggers** with 20 ps resolution, **two optical tables** for precision experiments. One large, **octagonal ultra-high-vacuum (UHV) chamber**. **One turbo-molecular pump**, and **two UHV pump stands**, each consisting of a membrane pump and a turbo-molecular pump. For aligning infrard cavities, we have **one highly sensitive InGaAs camera**. To operate the cryostats of the SNSPDs, we have **one air-cooled and one water-cooled helium compressor**. To operate the water-cooled compressor, we bought **one 5 kW circulating chiller**. Recently, we acquired a low-noise **fiber amplifier** for continuous-wave light with a wavelength from 1550 to 1560 nm, and a **20 GHz function generator** with low phase noise.

The PI is also the scientific lead of the new SiQUID project, which is funded by 50% by the EU, and by 50% by the Slovene government. This is part of the EuroQCI initiative, and in this project, we will realize several prototype realizations of quantum key distribution using weak laser pulses, and we will implement a state-of-the-art Sagnac source of entanglement with a target bandwidth of about 100 MHz similar to Ref. ??. Some of the equipment listed above was bought for the SiQUID project, but we will also be able to use it for the present project. There are several PhD and MSc students in the team, who work on SiQUID.

In addition to the equipment available in the PI's lab, more research equipment is often available for short-term use in coordination with other research groups at FMF and at the nearby Jozef Stefan Institute (IJS) and the faculty of electrical engineering.

23.5. Project management: Detailed implementation plan and timetable

The research will be conducted in the "Quantum Optics and Quantum Foundations" laboratory at the Faculty of Mathematics and Physics (FMF) of the University of Ljubljana. The goal of the present project is to build a new type of entanglement source that is orders of magnitude more narrowband than comparable sources without the need for spectral filtering. The source will be sufficiently narrowband, and it will have the correct wavelengths to be compatible with efficiently coupling the entangled photons to optomechanical quantum sensors as well as to atomic quantum memories. This research will pave the way to coupling high-precision quantum sensors to a quantum network, to other quantum sensors, or to atomic systems. Moreover, our research will pave the way for revolutionary experiments on the foundations of quantum physics and for a new type of matter-wave interferometers with unprecedented precision.

The investment necessary for developing this novel source and to strengthen Slovene expertise in quantum technologies is **70.384 EUR in equipment**. This needs to be put in relation to the investment of the UL-FMF over the last years into existing infrastructure and equipment, which will benefit the present project, and which we estimated to be around **2.5 million EUR**.

In the following, we will list the participating researchers:

- **Rainer Kaltenbaek** (RK)
  Head of the Quantum Optics and Quantum Foundations research group at the FMF, scientific lead of the Slovene national Euro-QCI project SiQUID. Did his Master and PhD with Prof. Zeilinger at the University of Vienna, the first postdoc with Prof. Resch at the Institute for Quantum Computing, Canada. During this time, RK worked on sources of entanglement, quantum communication, quantum computation and quantum information processing. He authored key parts of the first ESA-funded study towards using quantum entanglement in space. This and related efforts led to the first quantum satellite, launched by China. In 2010, RK joined Prof. Aspelmeyer in Vienna. Since then, RK has led efforts to realize a future space mission to test and to use quantum physics with macroscopic test particles. RK was one of the leaders of the "Quantum Technologies in Space" COST action. In 2017, his mission concept MAQRO was selected by ESA as a New Science Idea for a future space mission. RK was the scientific lead of the resulting QPPF feasibility study at ESA's Concurrent Design Facility in 2018. In 2021, RK led an international team to propose a research campaign to NASA. RK's team consists of six PhD students, two master students, and a postdoc.
- **Shreya Gupta** (SG)
  SG joined RK's group in September 2023. She is a young researcher (MR), and she has been working on Slovenia's quantum communication infrastructure project SiQUID. In particular, she has been working on industrialized sources of entanglement, the implementation of a prepare-and-measure quantum-cryptography demonstration using FPGAs. She is eager to gain experience in cavity quantum optics, and her experience in FPGA programming will be useful for implementing the locking electronics for stabilizing the cavity.
- **Hadis Torbatiyan** (HT)
  HT joined RK's group in September 2023. She has worked on optical trapping, and on using hollow-core fibers to guide dielectric test particles between vacuum chambers. Her PhD will

be on implementing a quantum optomechanical setup using optically trapped particles, and to eventually couple her system to the narrowband entangled photons produced in the present work. HT has gained significant experience in beam shaping, beam characterization, and in imaging. Her experience will be valuable when setting up the cavity and monitoring it.

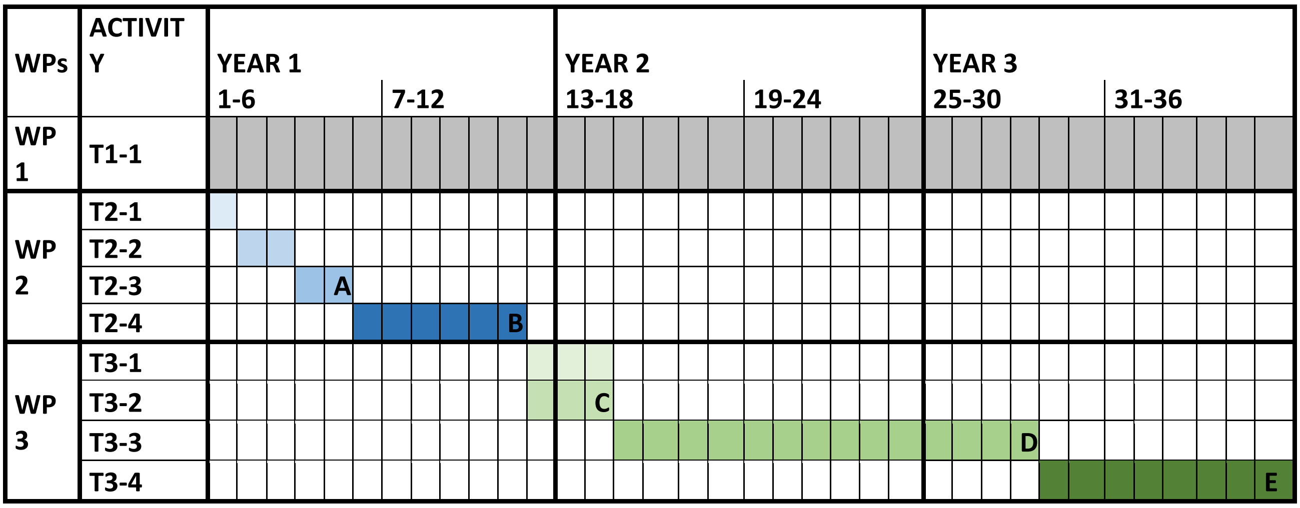
- **Fatemeh Pourkhavari** (FP)
  FP joined RK's group in September 2023, and we have been training her in experimental work in quantum optics and with optical cavities. She is working on cavity-enhanced SPDC with a few MHz linewidth and compatible with Cs atomic quantum memories at 852 nm. Her work will have some overlap with the research source we aim to build in this project. The working principle of the sources is the same, but she will use spectral filtering instead of adding dispersion. Her source will eventually be used to distribute entangled 852 nm photon free space to colleagues at the Jozef Stefan institute and to store them in Cs atoms.
- **Adrian Udovičić** (AU)
  AU joined RK's group in April 2023. He has been working on the design and setting up of a Sagnac source of entanglement using type-0 phase matching as well as type-II phase matching. He helped build an identical source at the Jozef Stefan Institute, and he is working on the realization of entanglement swapping with these two sources. His experience with setting up SPDC sources and characterizing them will be very helpful for this project.
- **Bedir Halcı** (BH)
  BH joined RK's group in early 2024. He has been working on the design and setting up of a GHz-speed demonstration experiment for prepare-and-measure quantum cryptography for Slovenia's quantum communication infrastructure project SiQUID. He has also been working on phase randomization, quantum random number generation, and on frequency-bin entanglement. Given his experience in quantum optics and his extensive experience with FPGA programming even in the GHz regime, he will be a great asset for our work.

Overview of the work packages, the time schedule, and a short description of the activities:

Work package	Activity	Start (month)	End (month)	Short description
WP1	**T1-1**	1	36	Project management
WP2	**T2-1**	1	1	Determine ideal type of nonlinear crystal for SPDC, ideal geometry, and best available AR coating.
	T2-2	2	3	Design oven and setup for dispersion compensation.
	T2-3	4	5	Finalizing cavity design – base plate, optics mount, enclosure
	T2-4	6	11	Frequency-shifting one of the photons and measuring two-photon interference of the photon pairs generated by our source.
WP3	**T3-1**	12	14	Implementing the crystal ovens and temperature control, characterizing the crystals.
	T3-2	12	14	Assembling and aligning the prism assembly for dispersion

				compensation. Characterize dispersion.
	T3-3	15	28	Assemble and align the cavity, characterize it. Implement OPO for each of the two crystals separately. Determine cluster spacings.
	T3-4	39	36	Find and stabilize quadruple resonance, determine joint cluster spacing if possible. Switch to SPDC operation, characterize two-photon state generated, characterize polarization entanglement, characterize spectral properties.

The following table represents a Gantt-chart of the project timeline with an indication of when the various milestones are scheduled to be achieved:



Legend of important milestones:

A Completion of the detailed design of our ultra-narrowband source of entanglement + design review.
B Review of the acquired components and equipment.
C Completion and characterization of the crystal ovens and the setup for dispersion compensation.
D Completion of the implementation and characterization of OPOs for the two nonlinear crystals in the cavity.
E Review of the source characteristics, comparison with expectations.

The following table shows implementation risks and proposed mitigation measures:

Risk No.	Description of risk	WP	Proposed mitigation measures
R1	Insufficient performance of AR coatings available for the prisms and/or the nonlinear crystals, tasks **T2-1** and **T2-2**.	2	Concerted effort to find other suppliers, try to adapt mirror reflectivities to compensate, estimate source performance without dispersion compensation.
R2	Can not achieve the necessary temperature stability in the ovens, task **T3-1**.	3	Investigate if we can monitor the temperature variation with sufficient precision, and if we can compensate the drift in some other way – e.g., by small

			variations of the prism distance, by small variations of the cavity length or similar.
R3	Dispersion of the prism setup cannot achieve the values we aimed for, task **T3-2**	3	Identify the precise reason and replace the prisms with prisms that will achieve the desired dispersion. If possible, order these. In the meantime, operate the source without dispersion compensation. If necessary, spectrally filter the photons generated.
R4	Can not find a quadruple resonance.	3	Characterize the occurrence of double resonances and their behavior as we change the dispersion in the cavity. Compare these results with theoretical expectations. Identify possible causes for deviations, make new predictions for the joint cluster spacing. Find out if we can improve the situation by adding negative dispersion.
R5	Poor quality of entanglement	3	Characterize the spectrum of the produced photons – in the OPO regime and, if necessary, also in the SPDC regime. Measure the SPDC bandwidth, compare it to the cluster spacings. Characterize the entanglement as a function of the added dispersion. Characterize the entanglement if one adds spectral filtering.

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