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A Novel Frequency Conversion Source for Creating Bichromatic Entangled Photons

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Introduction

The following report summarizes the efforts made by the Qunnect team within the 6 months leading to February 2024 towards the technical and commercial milestones of DOE awarded proposal on developing a two-in-one frequency converter-entangled photon source, a source which natively generates bichromatic entangled photons.

For this final report, **it is our pleasure to announce that Qunnect has successfully accomplished all of the proposed milestones, while significantly surpassing the proposed performance metrics during the Phase II proposal period**. As a result, we have received multiple purchase orders for this device from US and EU scientists. We are projecting more than $500,000 in revenue by the end of this year, surpassing $1,000,000 by mid-2025.

The Gantt chart below summarizes the milestones and the timeline promised for this project at the time of the submission of the proposal. These results supported two provisional patent filngs and the submission of the first scientific paper generated under this work. In table 1 we briefly summarize our achievements compared to what was proposed and other commercial sources

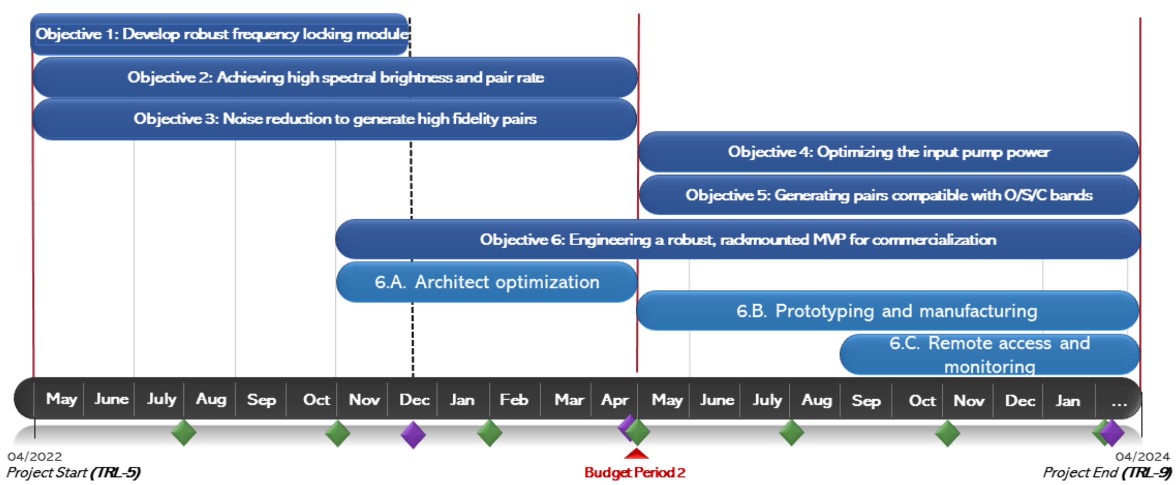


Figure 0 - The proposed Gantt chart for this project at the time of proposal submission.

Source Type	SPDC[1]	OPA-SPDC[2]	SPDC+ frequency conversion[3]	Commercial SPDC[4] (Thorlabs)	Qunnect (PROPOSED)	Qunnect (ACHIEVED) [5]
Pair generation rate	~200kHz	5kHz	<10kHz	~30kHz	~10kHz	Up to 80MHz
Photon linewidth	~2-10THz	~1MHz	~2-10THz	~2.5 THz	~20-500MHz	~500MHz
Spectral Brightness	<0.1s^{-1}/MHz	>1000s^{-1}/MHz	<0.01s^{-1}/MHz	~0.01 s^{-1}/MHz	>100 s^{-1}/MHz	160,000 s^{-1}/MHz
Heralding efficiency	<25%	-	~<10%	~15%	~15%	Up 40%
Operating wavelength	Telecom or NIR	795nm	Hybrid telecom + NIR	810nm	Hybrid telecom + NIR	Hybrid
Technology Readiness[4]	Research level only	Research level only	Research level only	On market	Sales ready by end of Phase-2	Commercialized
Multiplexing potential[5]	Very hard	Unlikely	Unlikely	Very hard	Suitable for multiplexing	Up to 3x, scalable

Table 1. *A comparison between the current state of the art in source development methods, our proposed metrics and the results achieved. Now commercially available, our source offers the highest pair rate compared to all other commercial sources while achieving unseen spectral brightness values.*

Table Notes:

[1] SPDC is the only available entanglement source technology on the market. They have limited applications due to ultra-low spectral brightness.

[2] The numbers in the table are for a single photon OPA source (no entanglement) performed as a bench-top experiment.

[3] Estimated values for a hypothetical setup with a typical SPDC entanglement source and a typical frequency converter to generate bichromatic photons

[4] While the generation rate of our source is comparable to SPDC, we offer approximately a factor of 10,000 improvement in spectral brightness.

[5] For a source to be suitable for multiplexing, two factors play a key role: The available interaction area and the required pump power. Compared to SPDC, our proposed source has an interaction area of 100x larger and requires 100x less laser pump power, making it a very suitable candidate for a multiplexed, ultra-bright source.

Accomplishments

Here, we briefly summarize the project before describing the progress we've made towards the milestones since the start of the phase II award.

It is a widely held belief that practical long-distance quantum-communication will require the development of quantum repeaters, devices which aid in the distribution of entangled photonic qubits over large distance. Commonly, quantum devices, such as repeaters, have native wavelengths which must be then frequency converted if they are to be transmitted along existing telecom infrastructure. For this project we proposed a novel solution of a two-in-one frequency converter-entangled photon source, which a source of bichromatic entangled photons with one photon at 795 nm, perfect for interfacing with rubidium atomic systems, and the other at 1324 nm, in the telecom O band making it well suited for fiber propagation. Such a source would be an integral part of a telecom-compatible quantum repeater.

This phase II project was focused on taking the work from the phase I feasibility study and improving and commercializing the source.

Milestones

To determine the feasibility of the bichromatic entanglement source we outlined the following milestones:

- **Milestone 1 –** Develop robust locking module for simultaneous stabilization of both pump lasers.
- **Milestone 2 –** Achieve high spectral brightness and pair generation rate
- **Milestone 3 –** Improve the purity of the source, resulting in high fidelity entanglement generation
- **Milestone 4 –** Optimize the input power of the pumps to move towards multiplexing
- **Milestone 5 –** Generating photon pairs compatible with O, C, and S telecom bands
- **Milestone 6 –** Engineering a robust, standard rack mounted MVP for commercialization.

In the previous reports we discussed milestones 1-4 in depth so here we will very briefly show the data while focusing more on the last two milestones.

Milestone 1 – Develop robust locking module for simultaneous stabilization of both pump lasers.

As was explained in the previous report, Qunnect has successfully finished this section of the project. The very note worthy update due this research support, Qu-LOCK was launched as a commercial device in the Qunnect product suite in 2023. To our knowlegde, QU-LOCK A big advantage of QU-LOCK is the only product in the market allowing for precise control of telecom wavelengths for quantum networking. Although the device is limited to applications where the wavelength must be on/near the resonance of an atomic transition, it is a cost effective method to provide the essential accuracy (sub-MHz) in wavelength to assure the indistinguishability of the photons in the future large-scale quantum networks.

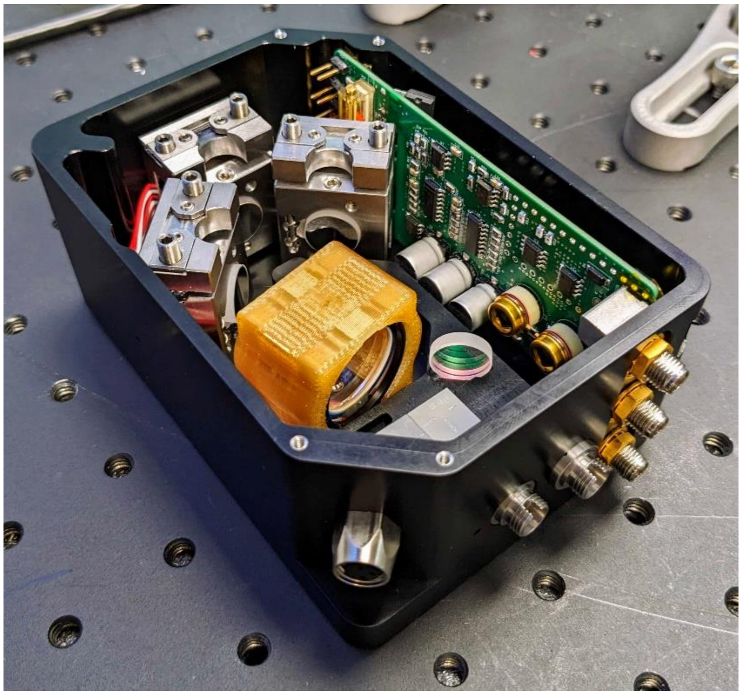


Figure 1: QU-LOCK device

Milestone 2 – Achieving high spectral brightness and pair generation rate.

We are proud to announce that upon a much more in-depth optimization of the system, we managed to achieve groundbreaking rates of higher than 10^7 pairs/s while maintaining a lower bound fidelity of 95%. We have also demonstrated the possibility of **generating entangled photons at rates as high as 8×10^7 pairs/s** while maintaining a CHSH factor greater than 2. Due to the narrow linewidth nature of the photons, this results in a spectral brightness of ~10^5 pairs/s/MHz, which to the best of our knowledge, is the highest recorded spectral brightness for any thermal entanglement source, and possibly, even among deterministic entanglement sources.

Figure 2A demonstrates the source pair generation rate for different pump powers. This figure shows the measured number of pairs for a single mode using which we can calculate the photon pair rate at the output of the source (including the fiber coupling losses). Here we achieved rates as high as 10 million pairs per second using 1mW of the 780nm pump power and 20mW of the 1367nm coupling power. In comparison to other commercially available source, this design requires very low power consumption per photon pair generated.

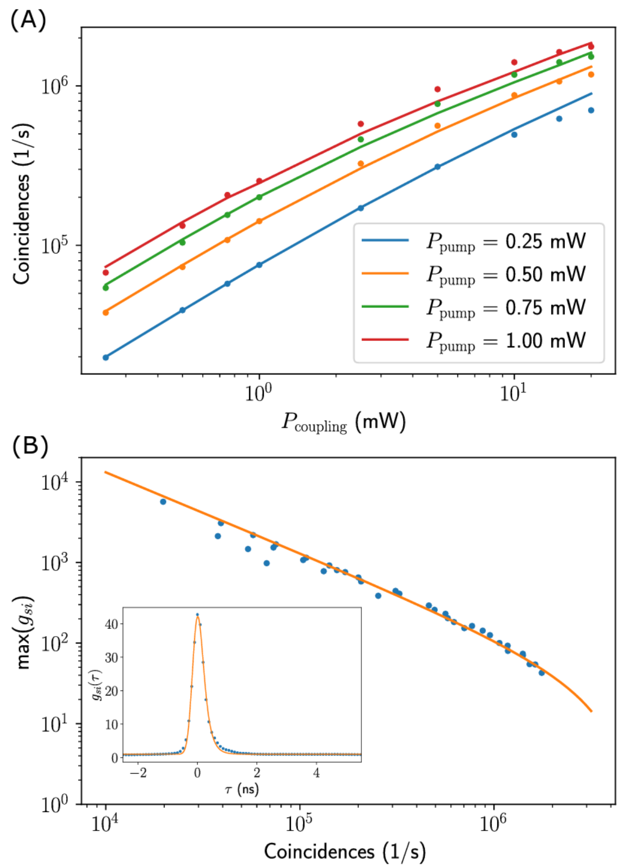


Figure 2: Scaling behavior of the source with pump and coupling power:

(A) Displays measured signal-idler coincidence rate as a function of coupling power, for various pump powers. We use a fit that accounts for the finite detector dead times. From a linear fit to the data we calculate a measured scaling constant of the coincidence rate ≈3×10^5/s/mW^2 (≈6×10^5/s/mW^2 when accounting for detection efficiencies).

(B) shows the peak value of the signal-idler cross correlation, gsi, as a function of the coincidence rate. Inset displays a typical gsi curve, using100-psbins. The orange line is a fit, taking into account the finite detector dead time in the system.

Milestone 3 – Improving the purity of the source, resulting in high fidelity entanglement generation.

Figure 2B shows how the source purity is maintained as the pair generation rate increases. We achieve cross correlation factors of ~50 at 10^7 pairs/s which corresponds to a very high Bell State fidelity. Figure 3 shows a direct measurement of this fidelity using quantum state tomography.

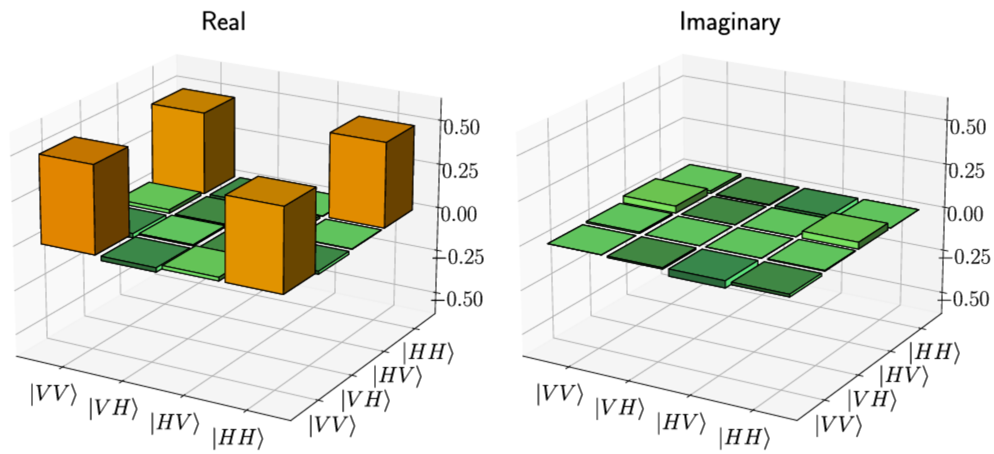


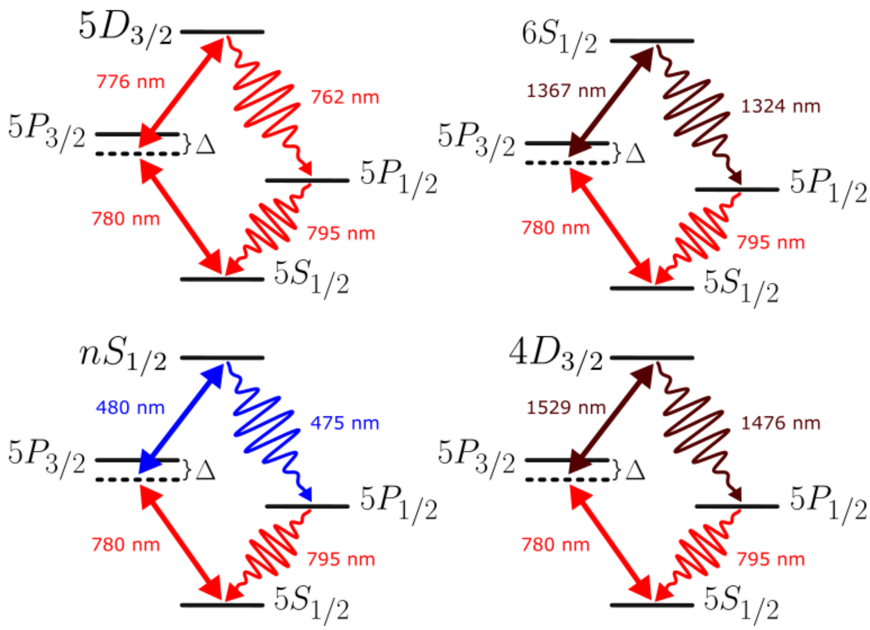
Figure 3: Real and Imaginary part of the maximum likelihood density matrix reconstruction with a measured lower fidelity bound of 95%

Milestone 4: Optimizing the input power of the pumps to move towards multiplexing.

Our current commercial unit (milestone 6) only requires 5mW of pump power to achieve 10M pairs/sec rates which put the device at the lowest pump/1M pairs range compared to all other available modules. It is worth mentioning that this value is mostly bottlenecked by the limitations of off-the-shelf vapor cell geometries. As a part of our production roadmap, and beyond the scope of this proposal, we are partnering with a large global photonic company to design a customized cell for our product. We expect to achieve a 5x reduction in pump power by the end of 2024.

Milestone 5 – Generating photon pairs compatible with O, C, and S telecom bands

As we discussed in the proposal, an advantage of using Rb atoms is the availability of transitions at all the major telecom bands. Our commercial devices are designed to generate pairs of photons at 795nm and 1324nm. This allows us to be at the low loss region of the O band while benefiting from the wavelength distance from the high traffic C band. Due to the symmetry of the atomic systems, one could expect to achieve same brightness and purities if they operate the device to create photons at 780nm and 1367nm.



Examples of possible entangled pairs' wavelengths
795nm & 1324nm
780nm &1367nm
780nm & 1529nm
795nm & 1476nm
795nm & 762nm
780 nm & 776nm
795nm & 475nm
780nm & 480nm

Figure 4: Examples of Rb atomic transmissions for entangled pair generation. *These examples are chosen because of the specific application of each wavelength. 1324nm, 1476nm, and 1529nm each respectively correspond to O, S, and C telecom bands, suitable wavelengths for long-haul fiber communications. 795nm and 780nm are commonly used for quantum buffers and sensors. 776nm and 762nm are suitable for free-space communication, while the 480nm and 475nm can be used to interface with some Rydberg and ion technologies such as neutral quantum computers and sensors.*

Figure 4 briefly shows the other possibilities using Rb atoms. Since this source is designed for telecommunication, out of the options above, we only focus on the 6S and 4D structures.

The 4D transitions give access to photons at C (1539nm) and S (1476) bands. Like the 6S case, one expects symmetry when it gets to creating 780nm/1529nm pairs and 795nm/1476nm. For this milestone we chose to generate the latter, mostly due to the compatibility of 795nm with our quantum memories. Figure 5 shows the achieved rates and g_{si} for 795nm/1467nm pairs. At 1mW 780nm and 20mW 1529nm pump powers we can achieve rates as high as 400k pairs per second. The signification difference between this rate and the values achieved for the 6S case has to do with the Clebsch-Gordan coefficients of the 4D transitions vs the 6S. Since these values are 5x smaller than the 6S, we would need 25x more power to achieve the same Rabi frequencies in order to reach the 10M pairs/s rates. That is particularly a disadvantage for generating photons at 1529nm since 1479nm lasers tend to be power limited. However, it is possible to achieve very high rates using the customized micro vapor cells mentioned under milestone 4.

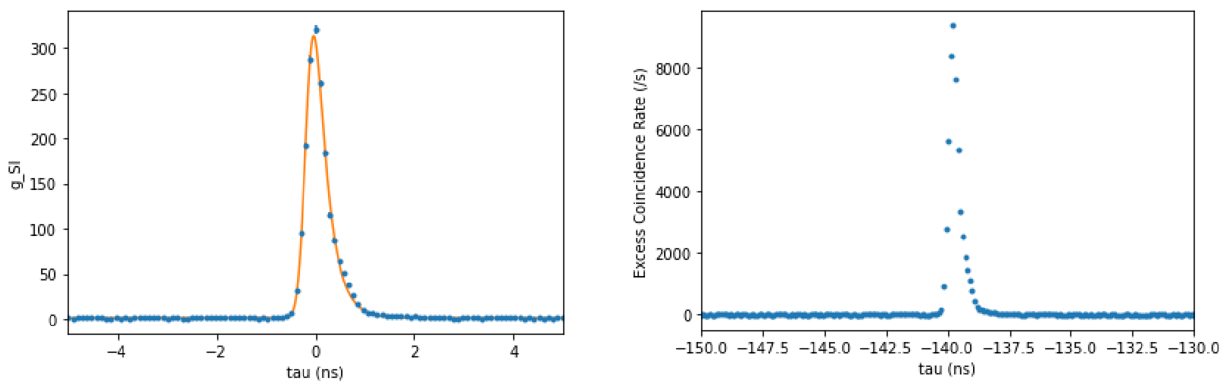


Figure 5: Achieving high rate and purity for pairs generated on the S/O bands.

Lastly is the question of entanglement quality and type for the 4D transition. In order to study the entanglement, we performed a full quantum state tomography on the photon pairs at 795nm and 1476nm.

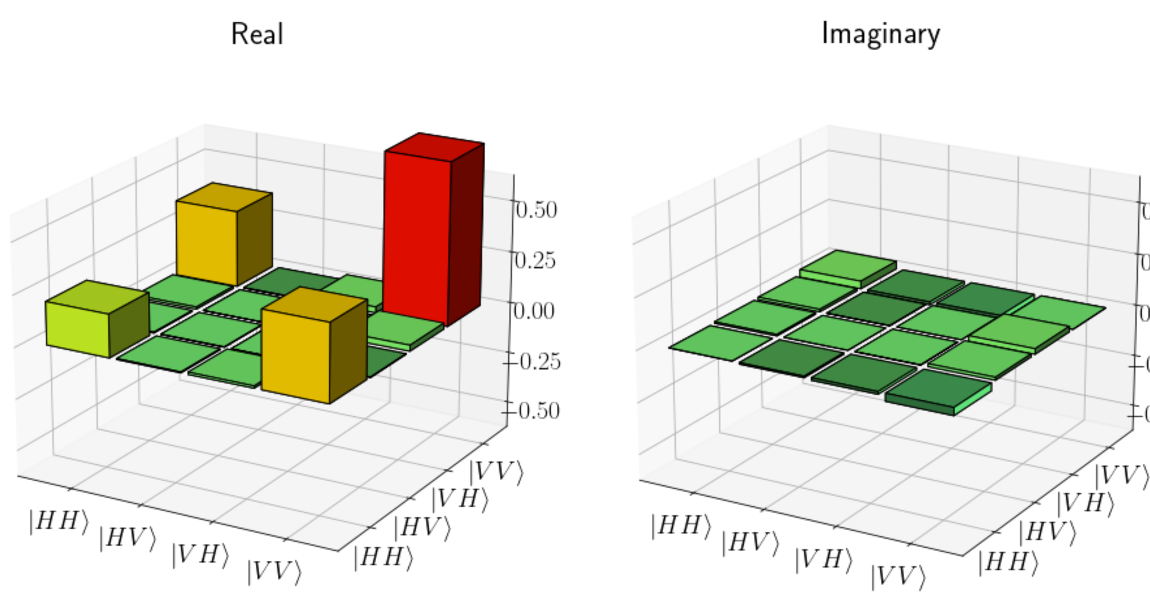


Figure 6: Reconstructed two-photo density matrix for the 4D state.

Figure 6 is an example of such a measurement. It is very easily evident that unlike the 6S transition, the Bell state here is not balanced. In fact, from the measurement above we can construct the state to be roughly 0.44|HH>+0.90|VV>. This can be explained by looking at the Zeeman splitting of the atoms when it gets to comparing the 6S to 4D transitions. In the case of the 6S, atoms start on a 3 Zeeman degenerate state of 5S and are pump to an identical state, 6S. Such symmetry allows the atoms to choose their decay path without any bias, resulting in a perfect |HH>+|VV> state. In the case of the 4D transition which has 7 Zeeman splitting, this symmetry is gone and atoms are biased towards the VV path.

It is worth mentioning that regardless of this asymmetric behavior, atoms are still generating polarization entangled states at very high rates at both 1479nm and 1529nm wavelength, proving that this scheme works for all the available telecom transition of Rb atoms. As our main commercial product, we have chosen to continue with the 795nm/1324nm pairs due to the low loss of transmission of 1324nm photons in optical fibers and the superior performance of the 6S structure.

Milestone 6 – Engineering a robust, standard rack mounted MVP for commercialization.

After derisking the scientific challenges in this project, we turned our efforts to developing a commercially robust product. Our engineering team worked very closely with our research scientists tor transition the table top experiment to a field deployable rack mounted system. To build a true rack-mount product, we needed to design not only a baseplate for the source optics, but the complimentary laser and locking solution to drive it.

The Qu-Source contains the optical layout of the entanglement source, designed on a baseplate compatible with our rackmount system (Figure 7). Additionally, we needed to include all the electronics for stabilizing the vapor cell temperature and to compensate for the phase shift caused by optical elements. Figure 7 shows the QU-Source optical module inserted in our the 2U rack unit, previously designed for our quantum memory (QU-MEM) product. The rack enclosure system can host up to 3 Qu-Source baseplates and their electronics. Similar to our quantum memory devices, the rack is designed to thermally and mechanically isolate the optical baseplate from the rest of the unit in order to increase the long term stability of the product.

The locking product (QU-Lock) is the atomic reference designed for stable wavelength locking of the both 780nm and 1367nm pumps simultaneously. This was the core part of milestone 1 which we have talked about in depth in the path.

Figure 8 shows a photos of the final QU-Source optics module mounted in the rac kenclosure and ready for characterization. As mentioned above, two third of the optical space is left empty by choice so in the future costumers who use multiple fibers can have up to 3 entanglement sources.

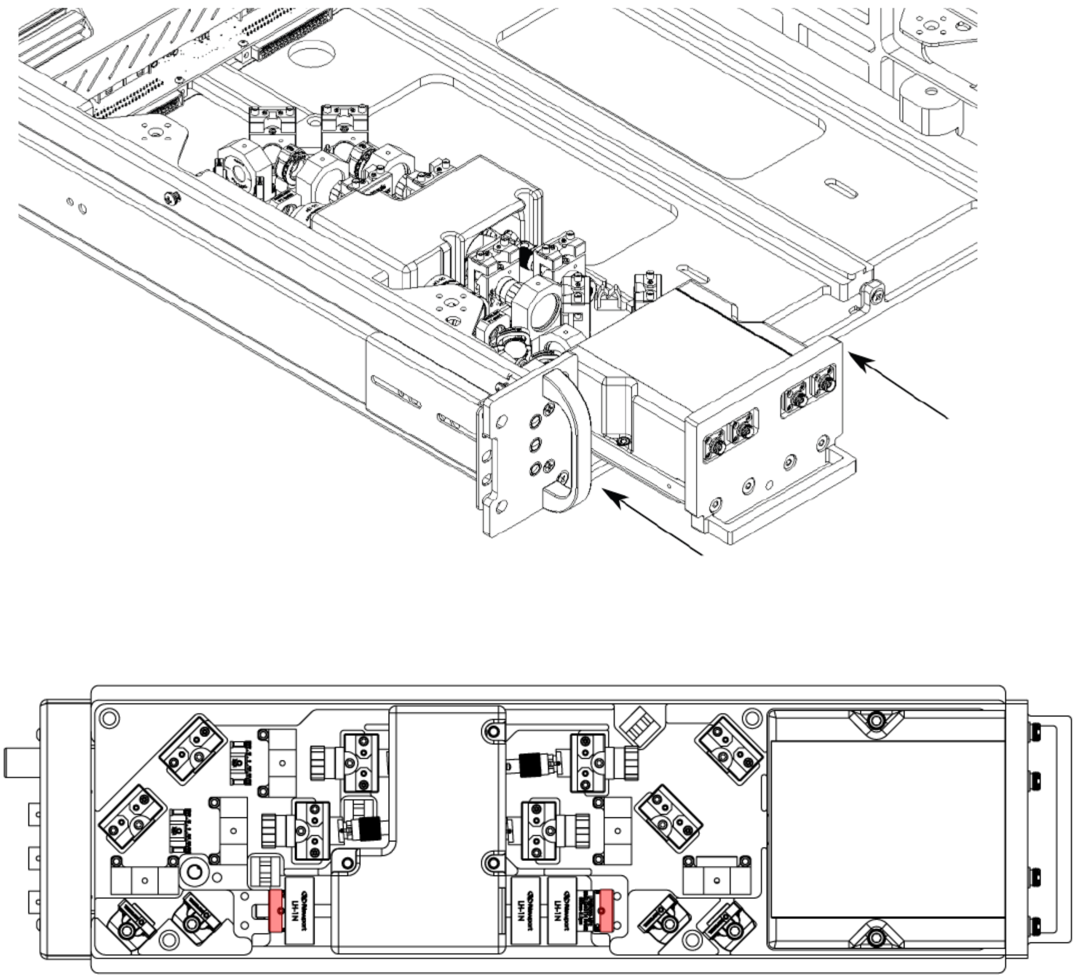


Figure 7: The form factor of the source baseplate compared to Qunnect’s 2U quantum racks.

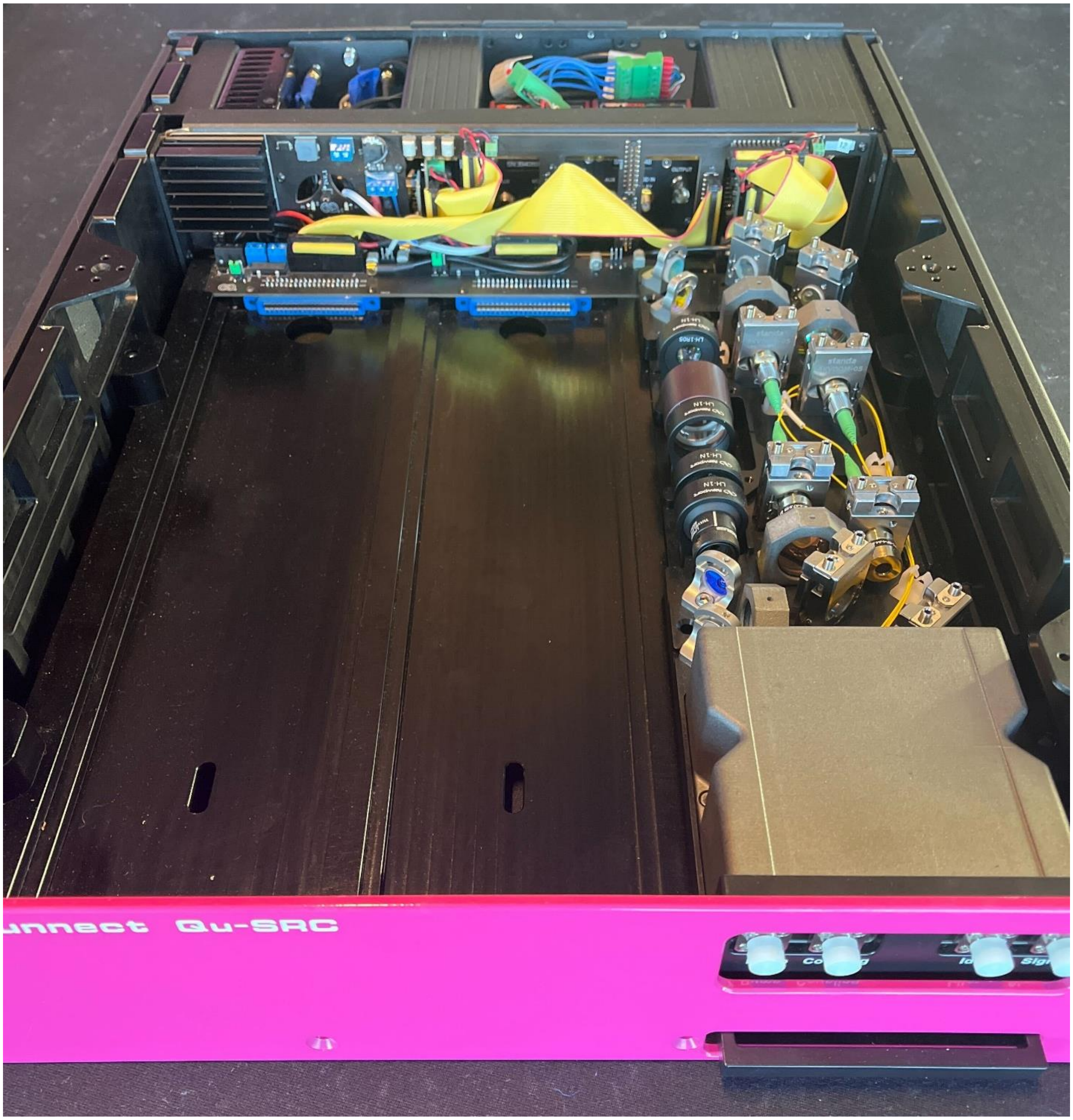


Figure 8: The photo of Qu-Source with inputs for the pump lasers and outputs for the entangled photons on the front. This unit comes with all the electronics needed in the back.

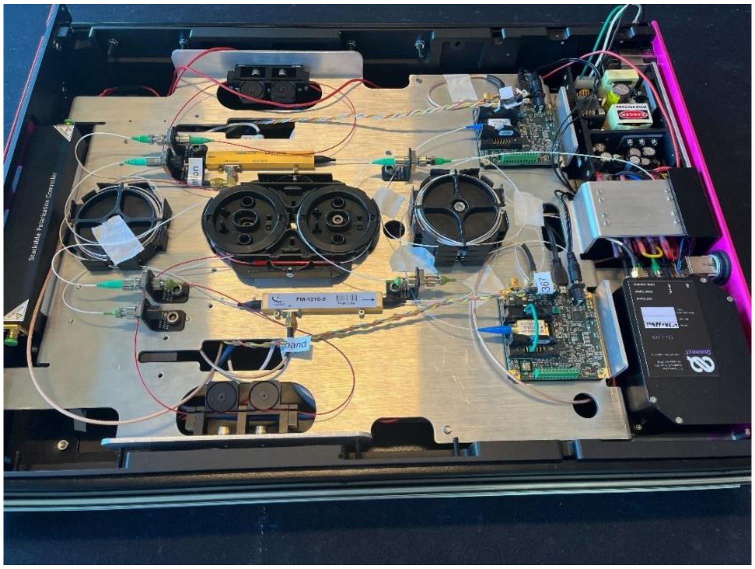
Another signification challenge with commercializing this entanglement source was the integration of the laser units. Originally when we proposed this idea to the US Department of Energy, we planned to use lasers provided by one of the established laser vendors. Unfortunately, one of the wavelengths, 1367nm, is not commonly available. The lead times were 6-12 months, depending on the vendor. As supply chain delays have impacted most laser vendors, even the 780nm laser was 4-6 months lead time when considered "in stock". We received considerable interest for the device from customers, but all were concerned about the laser lead time. Realizing this problem was gating sales, we decided to commit to building an in-house laser solution.

Our Qu-Lase product contains all the necessary parts to drive the Qu-Source (Figure 9). This includes both lasers at the adequate power to achieve 10M pairs/s, integration of Qu-Lock, all the necessary electronics to wavelength lock both lasers to Rb transitions, and all the electro-optical modules to create the correct 1 and 2 photon detunings and controlling the input power.

The combination of all the above systems results in a 2x2U modules, designed to run up to 3 entanglement sources.

A)

B)



C)

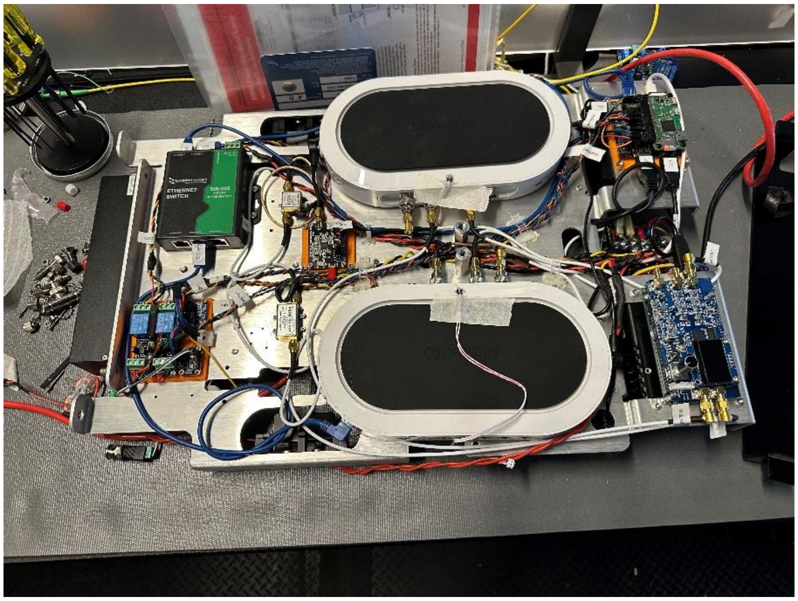


Figure 9: Photos of Qunnect's Qu-Lase MVP. A) Front Panel, B) The laser driver electronics, optics and QU-Lock product mounted to the top of the interior plate, C) Locking electronics mounted to the bottom of the interior plate

It is worth mentioning that our software team has designed a full interface for the QU-Source so the user does not need to physically touch the system with the exception of some polarization adjustment for this MVP. By the end of the year, the combined device should be fully controlled using the software interface.

SUMMARY

Building the first ever atomic entanglement source was certainly a journey with lots of scientific and technical challenges. A journey would be otherwise impossible without the support of the US Department of Energy. We are all thrilled that the outcome of this project resulted in a product which currently is on high demand and expect to generate high revenues, advances the quantum networking projects at Qunnect and other quantum hubs, and create multiple jobs at Qunnect and other locations. As always, we work closely with national labs to make sure our devices, sponsored by the Department of Energy, play a major role in the advancement of the quantum internet in the United States.

Impact

A high spectral brightness source is the key to low-loss interfacing with any atomic quantum device that supports networking, sensing or computing. At the present state of development, our source performs 100-1000x better than any commercially available system. Additionally, the source's spectral brightness is higher than any available system by a factor of larger than 1,000,000x, rending this source as a perfect candidate for the future quantum internet testbeds.

Training Opportunities

Qunnect's R&D team includes a number of recent science and engineering graduates with BS, BE and MS degrees who are mentored by our senior scientists. We emphasize a culture of diversity and inclusion, and our R&D team is international, representing several countries and ethnicities. All team members are encouraged to pursue self-guided and peer-mentored learning. Recently Qunnect became an industry partner to New York University's Center for Quantum Information Physics (CQIP). We are in the process of setting up a network connection between our R&D facility and the CQIP which will provide training opportunities for students to use the entanglement source device supported by this research award.

Results Communicated to Communities of Interest

Results from this project have been shared widely with the community through public presentations. Specific conferences from the past 6 months include: SPIE Quantum West, CLEO, and IQT The Hague. Qunnect also published a preprint on the physics of the entanglement source in April 2023 (Arxiv: 2304.05504) which is currently under review for publication.

Next Period Reporting Goals

The major goal of the next period of R&D is the demonstration of a fully packaged, commercially available entanglement source capable of producing the same performance as the table top experimental setup.