

AL FreSQQO



QUANTERA

Atom-Light Free-Space Quantum Optics Networks

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Introduction

Quantum memories (QMems) will be essential components of quantum networks, enabling long-distance distribution of entanglement with quantum repeaters, acting as quantum information buffers, and providing synchronisation and coordination functionality. QMems will need to interface with a diverse set of quantum links, operating at different wavelengths, and will often have to operate in remote and challenging environments. QMems will also need to be able to accept high bandwidth quantum signals for greater compatibility with a large range of single photon and entangled pairs sources.

The AL FreSQQO project aims to advance the readiness of QMems for deployment by demonstrating cold atom QMems operating in conjunction with free-space quantum optical channels, together with quantum frequency conversion (QFC) from telecoms wavelengths, as well as the development of compatible single photon sources based on hexagonal boron nitride. These physical platforms have the potential to obviate the need for cryogenic systems, making them more suitable for mobile and remote applications, such as on satellites as part of a global space-based quantum entanglement distribution network.

The project will implement high bandwidth QMems and QFC, together with optimised free-space optical channel links, and identify suitable solid state quantum emitters for cold atom coupling. Ultimately, AL FreSQQO will advance the practicality of QMems by demonstrating their integration within a quantum link together with QFC, together with quantum signal sources, expanding their compatibility, and greatly improving their performance.

Methodology

Long-distance quantum networks are a key enabling technology for applications ranging from distributed sensing to secure communication. Optical fibre links suffer from exponential transmission losses with distance, which motivates free-space and satellite-based links [1,2]. Quantum memories (QMems) are essential for such networks, enabling reversible storage, synchronisation and on-demand retrieval of quantum states, allowing entanglement swapping, multiplexing and quantum repeater operation. Large-baseline, non-local interferometers [3] also benefit from free-space coupled and high bandwidth (>GHz) QMems. While photon sources with such bandwidths are now well-established, QMems with required performance that can interface with them remain challenging to develop. Time-bin qubits are particularly attractive for long-distance scenarios because they are robust against polarisation drifts and many forms of optical misalignment.

In this project we target a GHz-bandwidth emitter-ready and memory-ready free-space interface between a room-temperature solid-state source and a cold-atom QMem, as a step towards a full emitter-to-memory connection (Fig. 1a). We combine (i) a single-photon source (SPS) based on colour centres in hexagonal boron nitride (hBN) at ~630 nm, engineered for time-bin qubit generation, (ii) high-bandwidth 630 nm → 795 nm and 1529 nm → 795 nm quantum-frequency-conversion (QFC) stages, and (iii) a GHz-bandwidth Autler-Townes-splitting (ATS) Bose-Einstein-condensate (BEC) memory on the 795 nm Rb-87 D1 line [4]. A key breakthrough is demonstrating high-bandwidth time-bin qubit storage by mapping early/late time bins to and from distinct spatial modes of the memory. Within this project, the hBN source [5] and the QFC-memory interface will be developed and optimised in separate but tightly coordinated setups, as shown in Figure 1b. A single-photon hBN-to-memory link is reserved for a follow-up demonstrator.

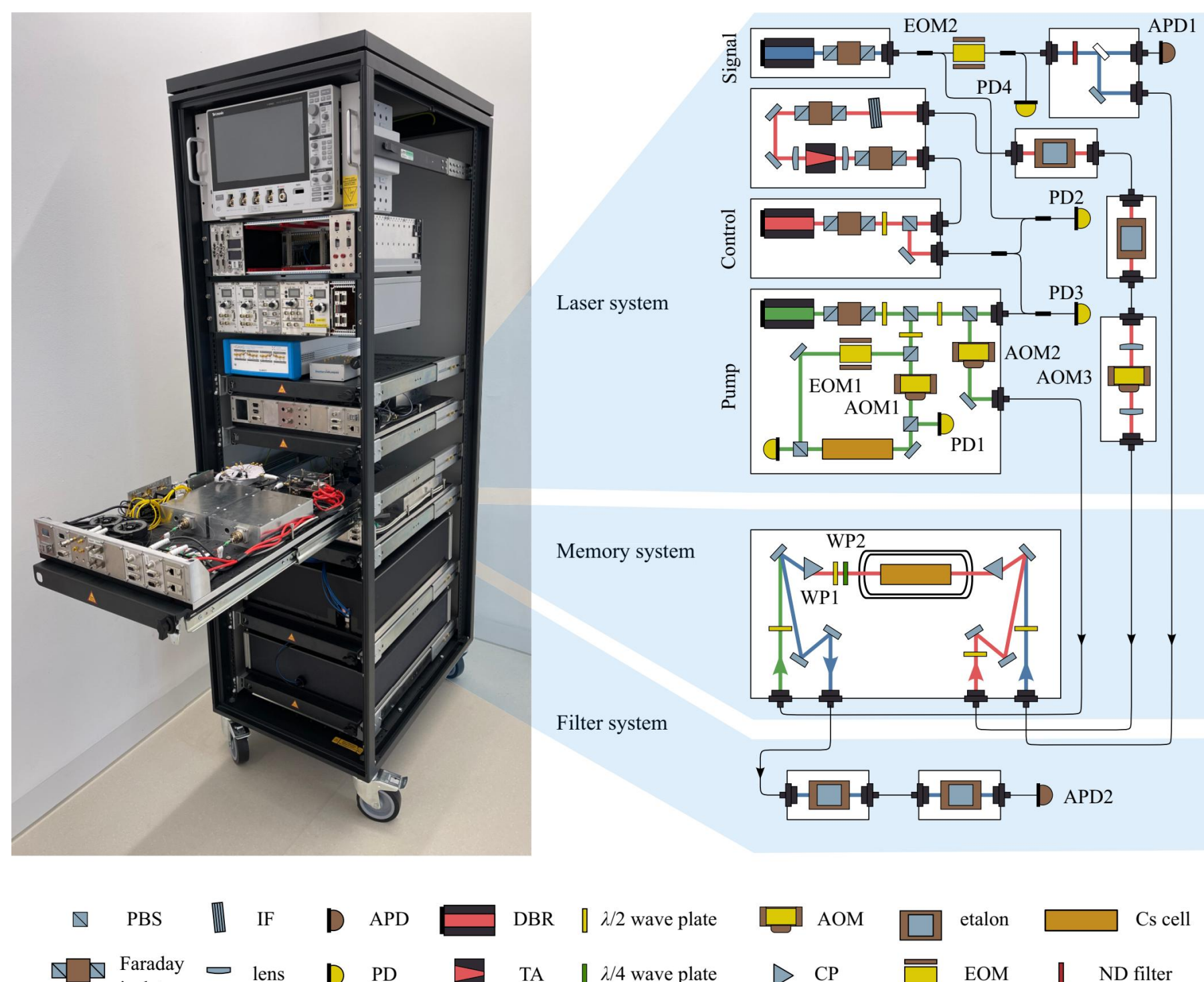


Fig. 4 (right): Mobile Quantum Memory previously develop [8]. Schematics, including the laser system, the memory system, and the spectral filtering system. PBS, polarizing beam splitter; IF, interference filter; APD, avalanche photodiode; DBR, distributed-Bragg-reflector laser; AOM, acousto-optic modulator; PD, photodiode; TA, tapered amplifier; CP, calcite prism; EOM, electro-optic modulator; ND filter, neutral-density filter. AL FreSQQO will develop a cold atom memory that has the potential for longer storage time.

Free-Space Quantum Link

The project will develop a free-space quantum link (FSQL) optimised for daylight operation working at Telecom C wavelengths, building upon existing quantum key distribution systems resilient against the solar background (Fig. 3) [6]. We will investigate high coupling efficiency between the source guided modes, free space quantum transmission, and the collection and injection back into fibre. The receiver optimally implements three filtering processes required for free-space links: (i) Spatial filtering, intrinsic to single-mode guidance and crucial for background light suppression, especially in daylight and with solar impingement onto the receiver optics; (ii) Spectral filtering, matched to source and memory; (iii) Temporal filtering, i.e. the ability to identify windows within which valid transmission must come tight timing constraints.

Fig. 3 (left): Free-space test-bed in the centre of Padua. Quantum networks will need to be operated over non-terrestrial links, such as to/from satellites [7], drones, high-altitude platforms, and through the atmosphere. A major consideration is operation during daylight despite the solar background. AL FreSQQO will show that quantum memories and repeaters can utilize such with quantum frequency conversion.



Cold Atom Quantum Memories

We will develop Rubidium cold atom (BEC) memories that have GHz acceptance bandwidth utilising previous experience with warm vapour memories (Fig. 4). We will investigate different methods of achieving high multi-mode storage capacity of time-bin qubits [14]. We will develop a large bandwidth quantum memory based on the Autler-Townes-Splitting (ATS) protocol [4]. In contrast to Raman or EIT memories, ATS relies on direct absorption, with relaxed optical depth (OD) requirements and favourable noise behaviour. For a 1 GHz bandwidth input signal, an OD of ~100–200, which is already available in experiments with Bose-Einstein condensates (BECs), is sufficient to reach memory efficiencies of around 25%, whereas conventional schemes require an order of magnitude higher OD to achieve comparable performance.

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Conclusion

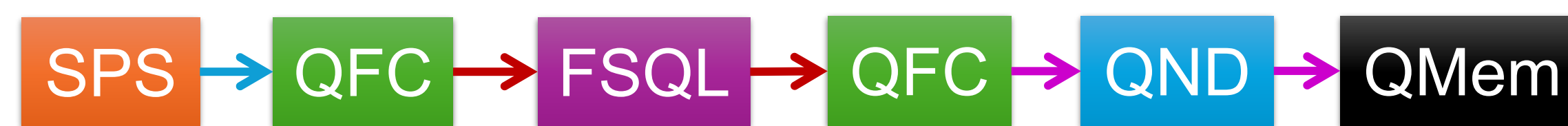
AL FreSQQO will deliver the enabling technologies required for high-bandwidth, free-space communication channels to interface atomic processing nodes, addressing strategic needs across quantum communications, networking, and secure information infrastructure. By integrating GHz-bandwidth quantum memories, high-signal-to-noise quantum frequency conversion, quantum non-demolition heralding modules, and robust free-space optical links, AL FreSQQO will provide the physical layer toolkit required for future quantum networks spanning ground-to-ground, ground-to-air, and ultimately space-based deployments. The heterogenous networking approach provides a means to bring together optimised physical systems that are wavelength disparate, allowing for flexibility in layout, design, and operation.

Project Details

This project will begin in December 2026 and run until November 2029. Targeted results include:

- Time-bin qubit storage in a GHz-bandwidth ATS BEC memory
- Single photon hBN source at 630 nm
- QFC for 630 nm → 795 nm & 1529 nm → 795 nm optimised for a GHz-bandwidth Rb-87 memory
- Single Photon Quantum Non-Demolition (QND) Heralding
- Free-Space Quantum Link (FSQL) compatible with GHz bandwidth QMems
- Integration blueprint and network performance

a) AL FreSQQO full end-to-end channel concept



b) Sub-system development

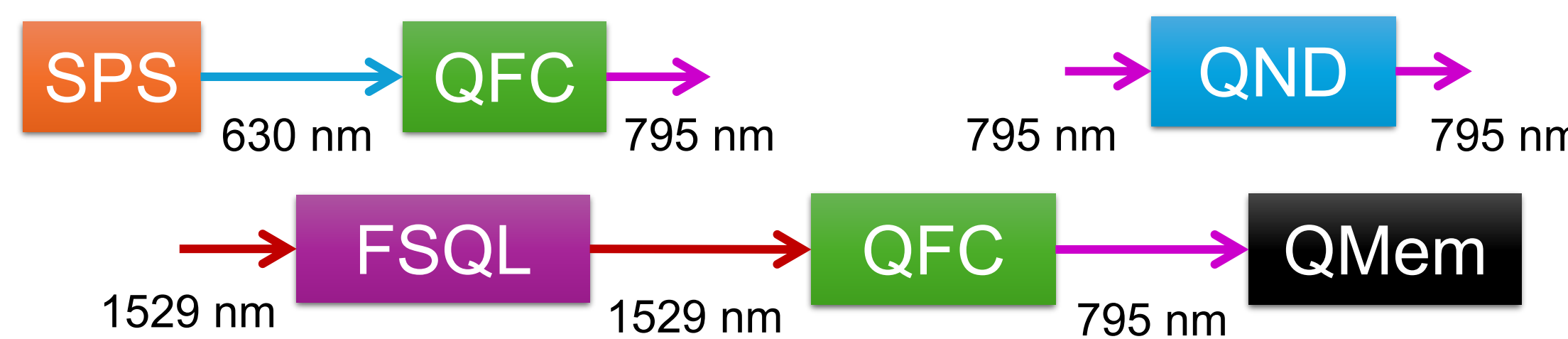


Fig. 1 (above): Overall AL FreSQQO concept and project implementation. a) Quantum channel with a single photon source (SPS), quantum frequency conversion (QFC), Free-Space Quantum Link (FSQL), QFC, and Quantum Non-Demolition (QND) heralding measurement, and Quantum Memory (QMem). b) Within AL FreSQQO we will develop elements of the system and demonstrate their interoperability. A key objective is to show that the SPS, QFC, QND, and QMem sub-systems have compatible spectral, temporal, and spatial mode structures. We will demonstrate high bandwidth operation of the atomic system elements (QMem, QFC, QND), high background rejection & link efficiency of the FSQL, and compatible SPS emission characteristics. A future full end-to-end link in a) will build on the results from b) in the project.

Single Photon Source

The project will develop a single photon source, based on Hexagonal Boron Nitride (hBN) with a bandwidth and pulse shape compatible with the quantum memory after QFC (Fig. 2). Our concept exploits hBN defects emitting near 630 nm, spectrally coincident with the Rubidium 6D transitions, to engineer a platform that converts bright solid-state emission into the spectrally coherent input required for Rb-based 4WM-QFC. The atomic vapour then acts as an active spectral filter, addressing both linewidth and frequency mismatch that currently limit hybrid quantum networking.

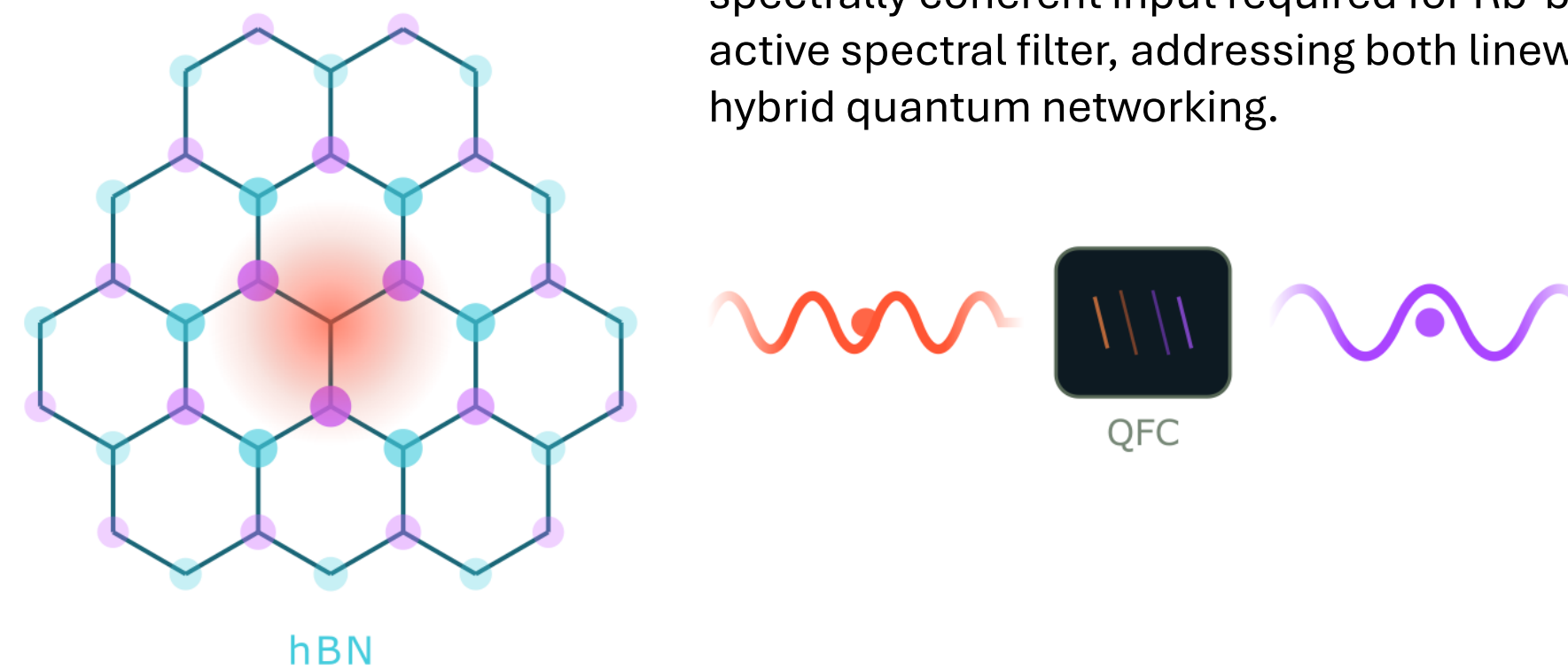


Fig. 2 (left): Hexagonal Boron Nitride (hBN) single photon source [9,10] input into quantum frequency conversion (QFC). hBN is a solid-state platform for atomic quantum interfaces, combining high optical brightness, room-temperature stability and 2D tunability [11].

Quantum Non-Demolition Measurements

To enable quantum repeater operation, we will develop quantum non-demolition (QND) of the arrival of photons at the receiver using Rubidium vapour cross-phase modulation of a probe beam. The QND measurement will herald successful transmission of a photon through the link which can then trigger entanglement swapping in a quantum repeater link. Unlike heralded photon-pair sources, single-photon inputs to a quantum memory must either be deterministic or accompanied by a herald that signals its arrival or successful storage, for example by QND measurement on the travelling field (or stored excitation). Such a capability is at a lower maturity than quantum memories, hence the efforts within AL FreSQQO are to establish the foundations in the context of a full end-to-end system with required characteristics, rather than achieve world-leading performance. State-of-the-art single-photon and photonic-qubit QND demonstrations rely on single atoms strongly coupled to high-finesse cavities [12]; here we instead pursue a simpler, warm-vapour implementation that can be integrated in line with the AL FreSQQO interface. Starting from the double Λ 4WM geometry in warm Rb vapour [13], which report large, π conditional phase shifts on single-photon-level probe pulses induced by few-photon signal fields with low added noise, we will adapt it to the 795 nm wavelength and time-bin modes relevant for our memory.

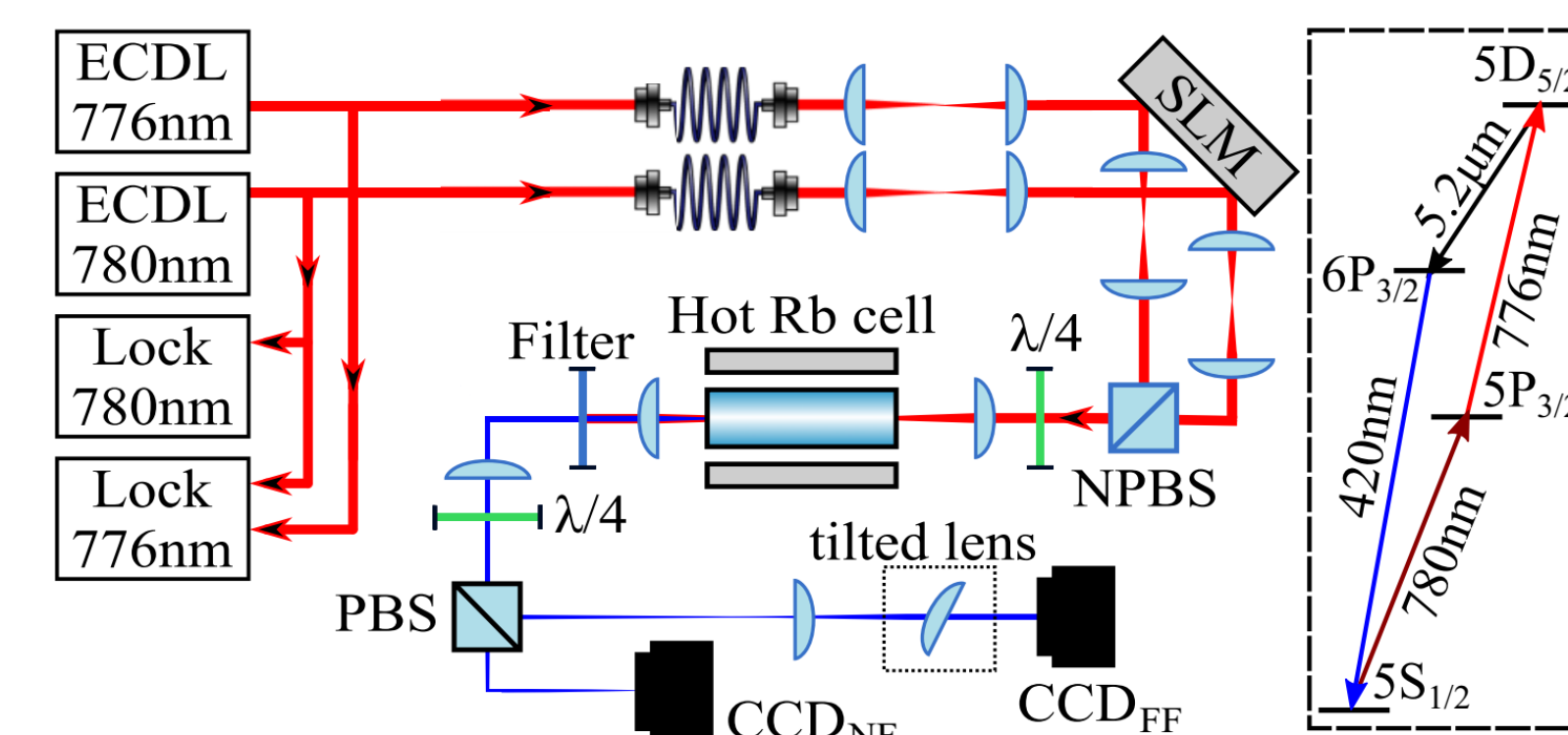


Fig. 5 (left): Multi-mode 4-wave mixing experimental setup and level scheme [15]. Fiber-coupled 780- and 776-nm pump beams from extended-cavity diode lasers (ECDCs) are independently shaped on an SLM (incidence angle exaggerated) into pure LG ℓp modes. They are relayed through beam telescopes, combined on a nonpolarizing beam splitter (NPBS), co-circularly polarized with a quarter-wave plate ($\lambda/4$), and focused into a hot rubidium vapour cell. A filter isolates the blue light generated by 4WM. The near and far fields from the Rb cell are imaged on cameras CCDNF and CCDF and analysed using a removable tilted lens.

Quantum Frequency Conversion

Different parts of the quantum link operate at different frequencies, thus requiring conversion of photons that preserves quantum coherence. Quantum frequency conversion (QFC) will allow the coupling of quantum signal sources, daylight-optimised free-space links, and quantum memories. We will utilise four-wave-mixing in Rubidium vapours (Fig. 5) to translate between wavelengths whilst preserving signal bandwidth [15,16,17]. We will implement two complementary GHz-bandwidth quantum frequency-conversion (QFC) interfaces based on diamond 4WM in warm Rb vapour: (i) visible (630.1 nm) → NIR (795 nm) and (ii) telecom (1529.3 nm) → NIR (795 nm). Together they enable frequency translation between free-space links, hBN single-photon sources, and Rb quantum memories.

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