QDrive by Welinq is the first commercial quantum memory (QM) system designed specifically for quantum data centers with world-record performance. Quantum computing is reaching a turning point: with more than 100 individual quantum computers deployed in dedicated infrastructures, the next challenge is networking them into scalable, high-performance architectures. Just as classical data centers rely on distributed computing and high-speed interconnects, the future of quantum computing depends on optical networking and resource sharing between quantum processors.

Today, quantum processors operate in isolation, limiting their computing power. Welinq's QM enables quantum processors to work together, forming a distributed quantum architecture—the only viable way to scale quantum computing beyond single QPUs. As a quantum buffer, Welinq's memory allows for entanglement distribution and qubit synchronization across processors. For quantum communication, it enables the creation of large-scale secure networks, forming the backbone of the emerging quantum internet.

QDrive is a fully integrated system allowing for plug-and-play deployment in quantum data centers and quantum communication networks. This advanced system, enclosed in a transportable, compact 19-inch rack form factor, leverages a laser-cooled atomic cloud as its core storage medium, ensuring high coherence and fidelity in quantum state preservation. QDrive features storage-and-retrieval efficiencies better than 90% at 795 nm with storage times greater than 200 µs. It operates at room temperature using a proven neutral-atom approach with technological maturity, eliminating the need for cryogenic systems thanks to the precise cooling and trapping of atoms by laser beams.

Figure 1: Welinq's QDrive quantum memory rack system.

Welinq's QM roots go back 15 years to groundbreaking research conducted by our founding team at Sorbonne University-CNRS Kastler Brossel Laboratory (LKB), where Prof. Julien Laurat has been at the forefront of developing high-efficiency QM using laser-cooled neutral atoms. A major milestone was achieved in 2018 when Laurat's team more than doubled the existing QM storage-and-retrieval efficiency, reaching 60% [Vernaz-Gris 2018]. Continued theoretical and experimental advancements pushed this record further to 90% by 2020 [Cao 2020]. In 2022, Welinq was founded to become the leader in quantum interconnection solutions, pushing the development of highly-efficient QM products to enable the scaling of quantum computers, ultimately achieving a meaningful quantum advantage. The first step is achieved today with the release of QDrive.

QDrive's QM is implemented using dynamic electromagnetically induced transparency (EIT) in a laser-cooled atomic cloud of ^{87}Rb. EIT protocols allow controllable photon absorption and emission, both critical for a functional QM, with many desirable characteristics. It offers high storage-and-retrieval efficiency (the success probability of each write/read operation), extended storage time (the maximum duration between writing and reading), high fidelity (the similarity between input and output quantum states), and on-demand readout (photon re-emission at a precise, non-predefined time).

In the dynamic EIT protocol, shown schematically in Figure 2, the signal photon carrying quantum information is resonant with an atomic transition, and an auxiliary laser field (control beam) resonant with another transition sharing the same excited state is used to control the interaction between the signal photon and the atomic medium. The atomic medium is rendered transparent to the signal by shining the control beam such that, when the signal photon arrives on the cloud, it can be coherently converted into a collective atomic excitation called a spin wave that stores the photon's quantum information by rapidly and adiabatically ramping down the control beam power. After the desired storage time, the spin wave is converted back into a photon in the same state as the initial photon by ramping back up the control beam power.

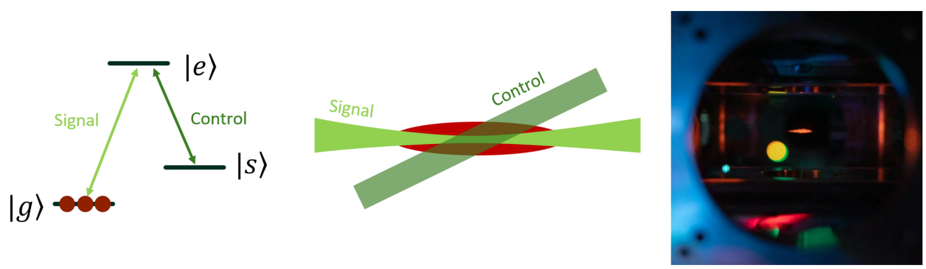

Figure 2: QDrive's dynamic EIT protocol. Left panel: the energy levels involved in the EIT protocol. Atoms in the lower ground state $|g\rangle$ and resonant with the signal field are coupled to the higher ground state $|s\rangle$ by the auxiliary control beam via the excited state $|e\rangle$. Center panel: the signal beam is weakly focused on the atoms while the control is collimated and propagates with a small angle, intersecting it at the center of the atomic cloud. Right panel: a picture of the dense atomic cloud at the core of QDrive's QM.

To achieve high efficiency, the key parameter to optimize is the optical depth (OD) of the medium. In QDrive, this is accomplished by utilizing an elongated magneto-optical trap (MOT) of ^{87}Rb atoms. A combination of an asymmetric magnetic field potential and three retroreflected, high-power optical beams tuned to the D_2 line of Rb at 780 nm allows one to reach an OD larger than 400 along the elongated trap axis. This OD ensures storage-and-retrieval efficiency larger than 90% performing the EIT protocol on the D_1 line at 795 nm, where off-resonant excitations from additional excited states are largely reduced.

The QM storage time corresponds to the time scale at which the memory efficiency is preserved. It is limited by the decoherence of the system, that is the loss of information of a system coupled to an environment. Collective excitations are subject to decoherence which, in the context of a QM, degrades the overall performance of the storage and retrieval process. The main sources of decoherence for a cold-atom-based QM are motional dephasing, which is inherently linked to atomic temperature, and residual magnetic fields. In QDrive, we addressed these two decoherence mechanisms to achieve a long coherence time.

In QDrive, the atomic cloud preparation and memory sequence is performed at a repetition rate of 20 Hz. Each preparation begins by loading a MOT from a dispenser for 50 ms by switching on magnetic field gradients and both cooling and repumping lasers. To achieve high densities, we ramp up the magnetic field gradient during the last 15ms of the MOT and reduce the repump power during the last 10ms of the MOT to implement a compressed, temporal dark MOT. After the MOT, we perform 5 ms of polarization gradient (PG) cooling by switching off the magnetic field gradients and ramping both the power and frequency of the cooling laser. The repumper is turned off in the last 0.5 ms of the PG stage such that the cooler optically pumps the atoms to the $F = 1$ level. With this preparation, we achieve ~ 2 cm-long clouds with an OD greater than 400 at temperatures below 50 µK.

The signal and control beams have the same circular polarization and are resonant with the $F = 1 \rightarrow F' = 2$ and $F = 2 \rightarrow F' = 2$ transitions of the D_1 line respectively. The signal beam is weakly focused on the atoms while the control is collimated and propagates at an angle of 0.6° relative to the signal, intersecting it at the center of the atomic cloud. We also suppress residual magnetic fields below the milliGauss level. In this way, the motional and magnetic dephasing is reduced and a storage time of > 200 µs is achieved.

To demonstrate QDrive's performance, we have performed QM operations using parameters for the signal and control pulses typical in future applications. In these demonstrations, we derive the control and signal beams from two external cavity diode lasers; the control is frequency-locked via saturated absorption spectroscopy to a Rb vapor cell, and the probe is offset-locked to the control. To perform a single memory cycle, the control beam is turned on and a Gaussian signal pulse with a full width at half maximum pulse width $T_p = 140$ ns is sent to the cloud and stored by switching off the control beam when the pulse is fully contained within the cloud. The input pulse is then read out after the desired storage time by switching the control beam back. We attenuate the coherent pulse to contain on average 0.5 photons per pulse on the atoms. The retrieved signal pulse is injected into a single-mode, polarization maintaining optical fiber and the residual control light is filtered out before being detected by a single photon counting module. The power of the control beam is tuned to maximize the storage and retrieval efficiency by compromising between maximizing transmission and minimizing compression losses, ensuring that the pulse is not attenuated by spontaneous photon scattering but is still sufficiently compressed

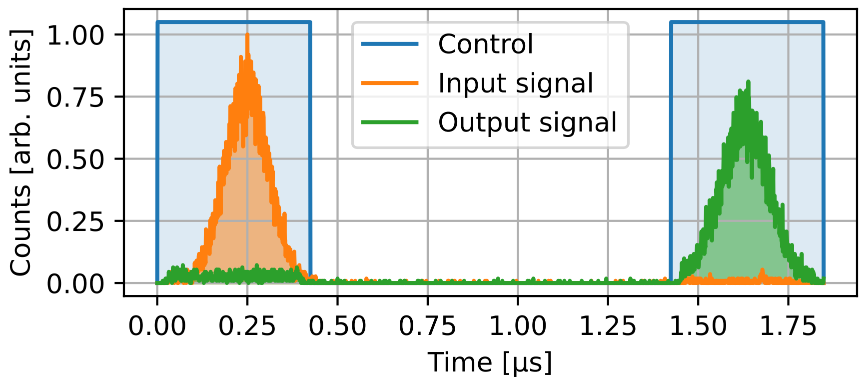

Figure 3: Quantum memory with $94 \pm 1\%$ storage and retrieval efficiency. The input and output signals are histograms of photodetection events over 10^5 memory cycles, showing the stored and retrieved pulses. The memory efficiency is given by the shaded area below the output signal pulse divided by the shaded area below the input signal pulse. The blue lines indicate when the control beam is turned on in the write and read pulses. The input photon has 140 ns FWHM duration with a mean photon number of 0.5. The signal-to-noise ratio is around 50.

and captured in the cloud when the control beam is switched off. This compromise results in a group delay of $1.9T_p$. To store the signal pulse with minimal compression losses, the control beam is switched off $1.2T_p$ after the peak of the signal pulse in the absence of the atoms ($0.7T_p$ before the peak of the signal pulse in the presence of the atoms). For short storage time, we perform between 100 and 1000 memory cycles per MOT cycle.

Figure 3 demonstrates the functioning of the QM by storing and retrieving a pulse with a world-record $94 \pm 1\%$ efficiency. It shows both the stored and retrieved signal pulses after a storage time of 1 µs as well as the two pulses of control light to write and read the signal. Figure 4 plots the efficiency of the memory as a function of the storage time, demonstrating simultaneous high efficiency and long-lifetime performance.

QDrive represents a major step toward scalable quantum networks and quantum computer interconnects by offering a reliable, high-performance quantum memory solution that can function beyond laboratory conditions. Improvements of QDrive are underway to achieve millisecond-range storage time in a next generation quantum memory product.

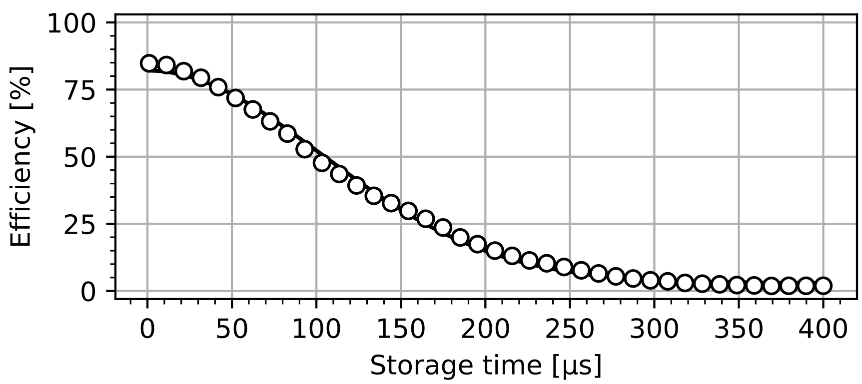

Figure 4: Simultaneous high-efficiency and long-lifetime quantum memory. We repeat the experiment in Figure 3 with varying storage time and fit the measured efficiency, yielding a Gaussian lifetime of 145 μs. This result agrees with a model accounting for the known dephasing mechanisms. These data were taken with bright pulses.