First International Quantum Communication Conclave 2023

Organized by TEC, C-DOT and TSDSI in technical collaboration with IEEE Communications Society

Quantum Memories and Repeaters: Challenges

Presented By:

Nixon Patel
Founder/CEO Qulabz Inc
Adjunct Professor
Department of Artificial Intelligence & Electrical Engineering
Indian Institute of Technology, Hyderabad

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ABOUT US

Qulabs, has the unique credential of being India's first and leading company in the emerging and disruptive field of Quantum Communications and Quantum AI. The company is founded by Mr. Nixon Patel (CEO), a visionary leader, an exemplary technocrat, and an Artificial Intelligence and Electrical Engineering adjunct professor at IIT Hyderabad.

- First private quantum optics lab setup for Quantum Communication
- First Fintech Company in India utilizing Quantum Advantage
- 12+ IPs in the area of Quantum Communication
- Signed Center of Communication MoU with IIT Hyderabad
- Research Collaboration with IIT Roorkee, IIT Kanpur & IIT Dharwad
- Signed MoU with Center For Quantum Network (CQN) with University of Arizona
- 35+ Quantum Scientists working in the innovation of Quantum communication
- 5 Cr Revenue generation using Quantum technology
- Trained 500 skilled resources in India & abroad.
- First Quantum Fintech Company in India authorised by IFSCA in GIFT city Gandhinagar.

Our vision is to provide India and the world its first Quantum Internet and as a result establish a completely secure internet and communication system equipped with immense speed and security.

One of the Top 6

We were recognized as one of the six companies globally to watch out for in Quantum ML in 2022 by the most recognized global quantum reporting media! https://lnkd.in/gFB9QS9z

Top Quantum Start-up

Analytics India Magazine mentioned Qulabs as a top Indian Quantum Computing start-up. https://analyticsindiamag.com/8-top-quantum-technology-startups-in-india/

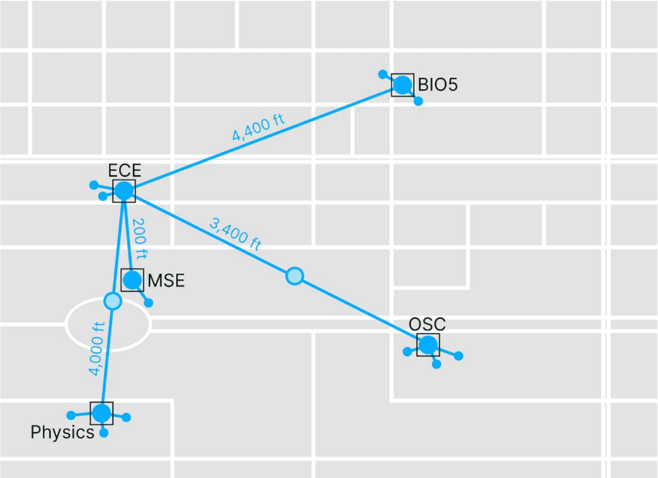
Endorsed alongside leaders like Google & Xanadu

In August 2022 we received another endorsement which puts Qulabs on the same platform with the world leaders of the likes of Google, Xanadu, Quantinuum and Zapata in Quantum AI. https://thequantuminsider.com/2022/08/23/quantum-computer-ai-powering-computers-with-quantum-brains/

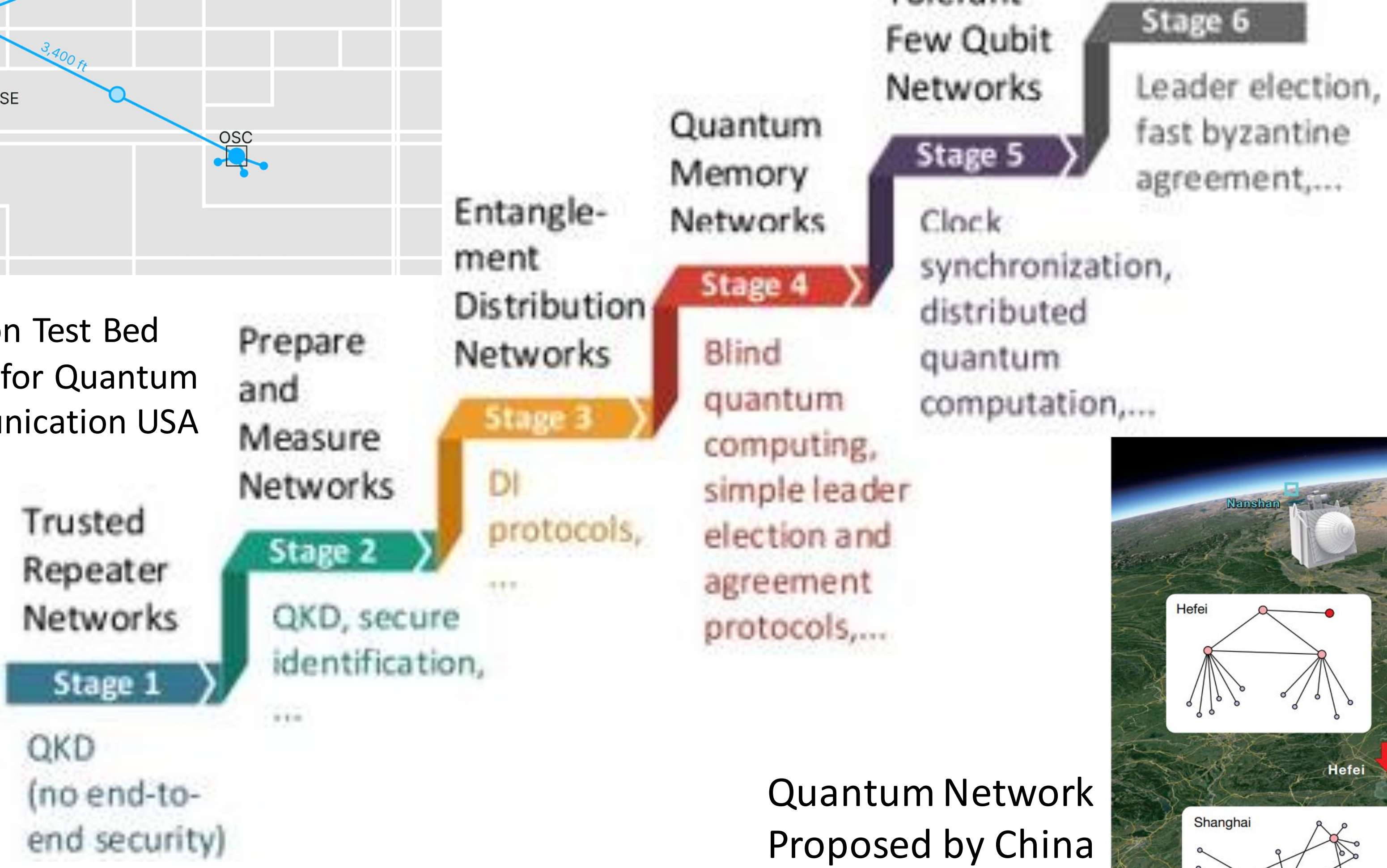
Classical v/s Quantum Communication

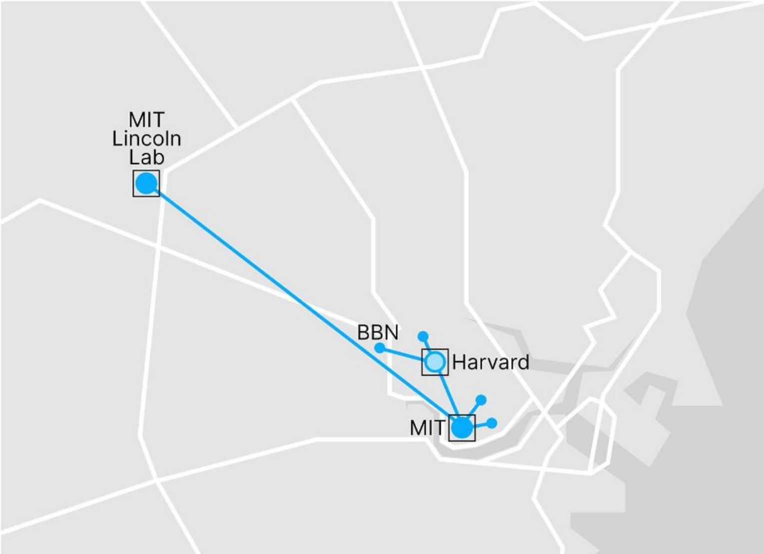
Classical Communications	Quantum Communications
Uses classical light to encode information	Uses qubits such as single photons to encode information
Optical amplifiers are used to boost the signal due to fiber losses	No-cloning theorem prevents the use of amplifiers: entanglement distribution using quantum repeaters used to overcome fiber losses
Vulnerable to eavesdropping and interception	Principles of quantum mechanics provide enhanced security with protocols such as QKD and QSDC
Tough to support high-dimensional data transfer	High dimensional data transfer possible with qutrits and qudits using properties of photons

Stages And Examples of Quantum Network



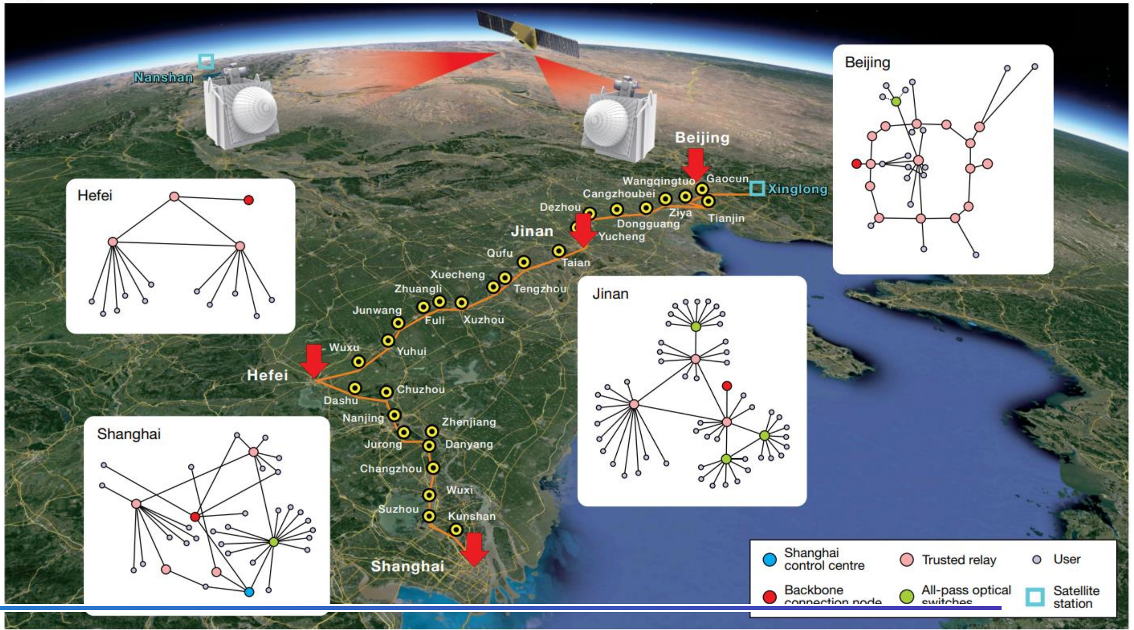
Tucson Test Bed Centre for Quantum communication USA





Boston Test Bed Centre for Quantum communication USA

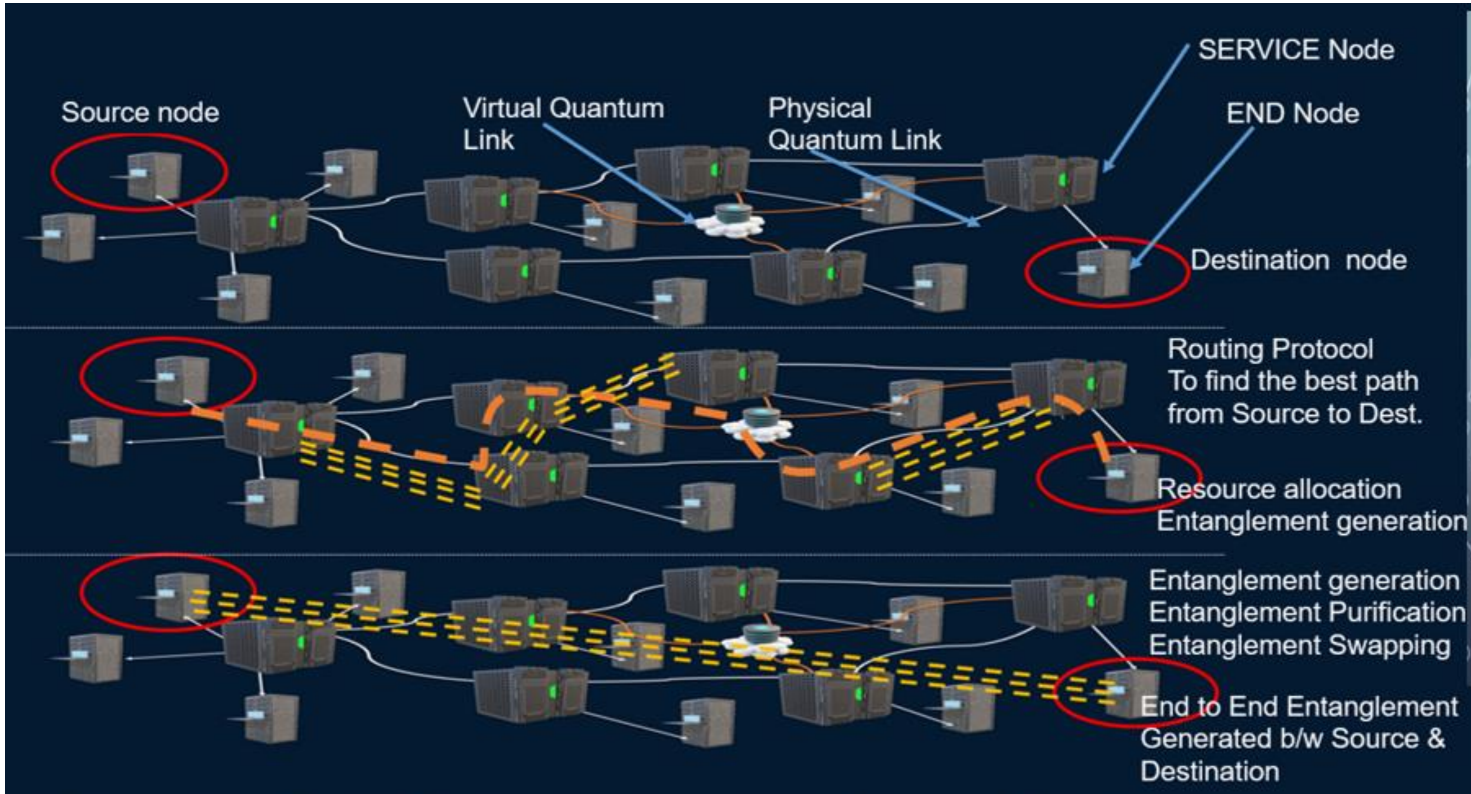
Quantum Network Proposed by China

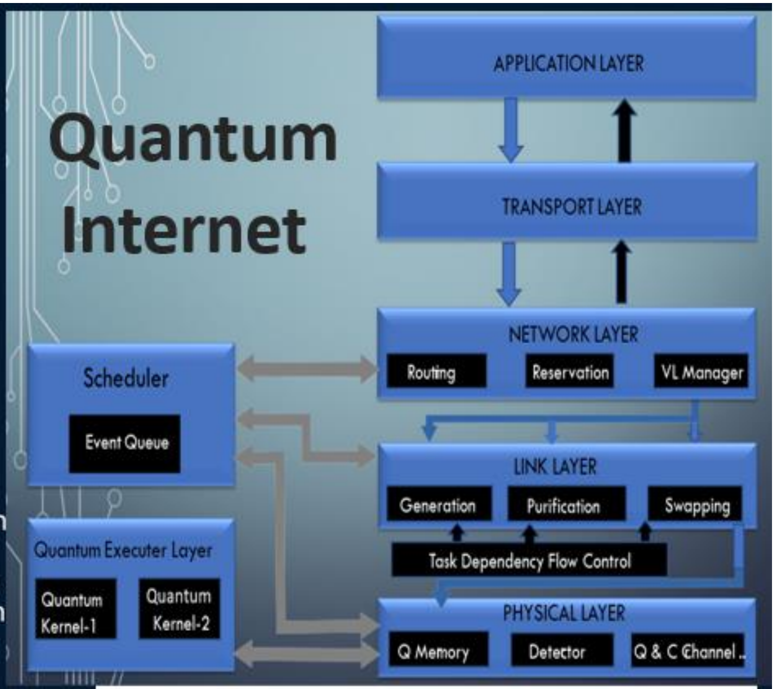


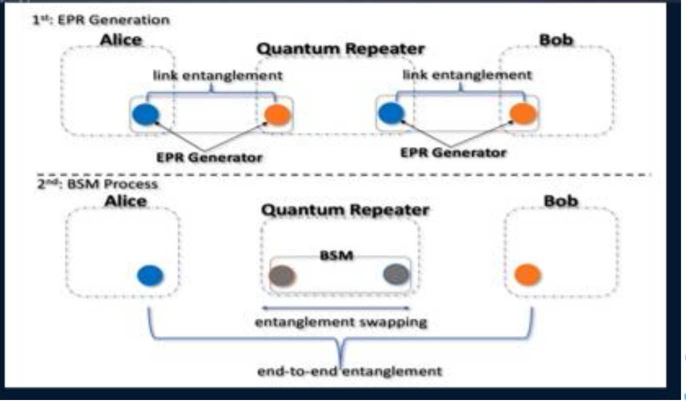
https://cqn-erc.org/research/
https://www.nature.com/articles/s41586-020-03093-8

Background of Quantum Communication

Qulabs' Quantum Network Architecture





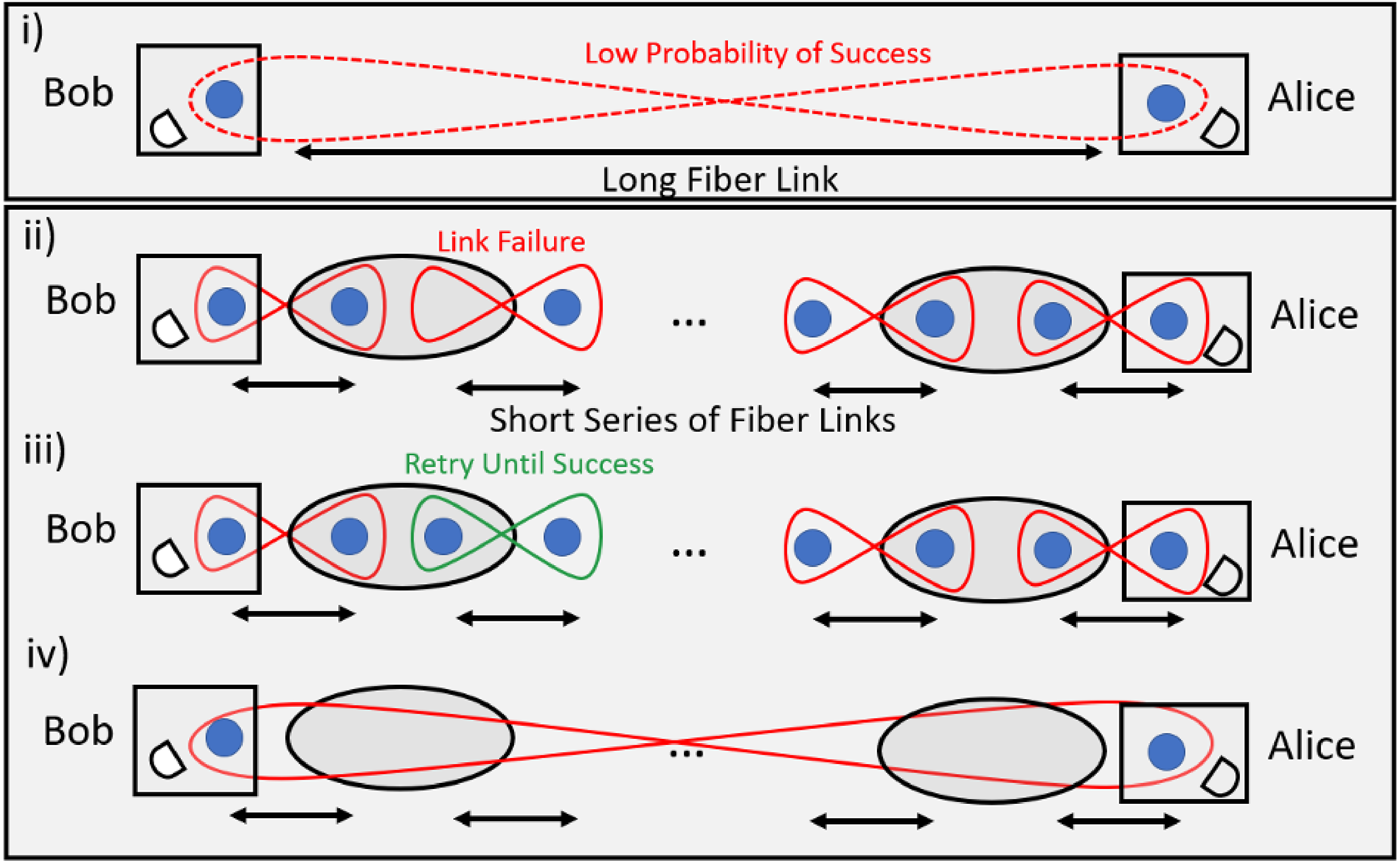


After getting End to End Entanglement b/w Source & Destination

- QKD
- Quantum Secure direct Communication
- Quantum Secret Sharing
- Multiparty Entanglement Generations Protocol

A. S. Cacciapuoti, IEEE Network, vol. 34, no. 1, doi: 10.1109/MNET.001.1900092.

Quantum Repeater Networks



Entanglement swapping and distribution process in a quantum repeater network

https://aws.amazon.com/blogs/quantum-computing/an-illustrated-introduction-to-quantum-networks-and-quantum-repeaters/

Quantum Repeater Networks

Quantum Network utilizes photons to

- Transmit
- Store
- Exchange quantum information

without measurement & replication

Inevitable Fiber Losses

Need of Quantum Repeaters to

- Generate
- Swap
- Purify

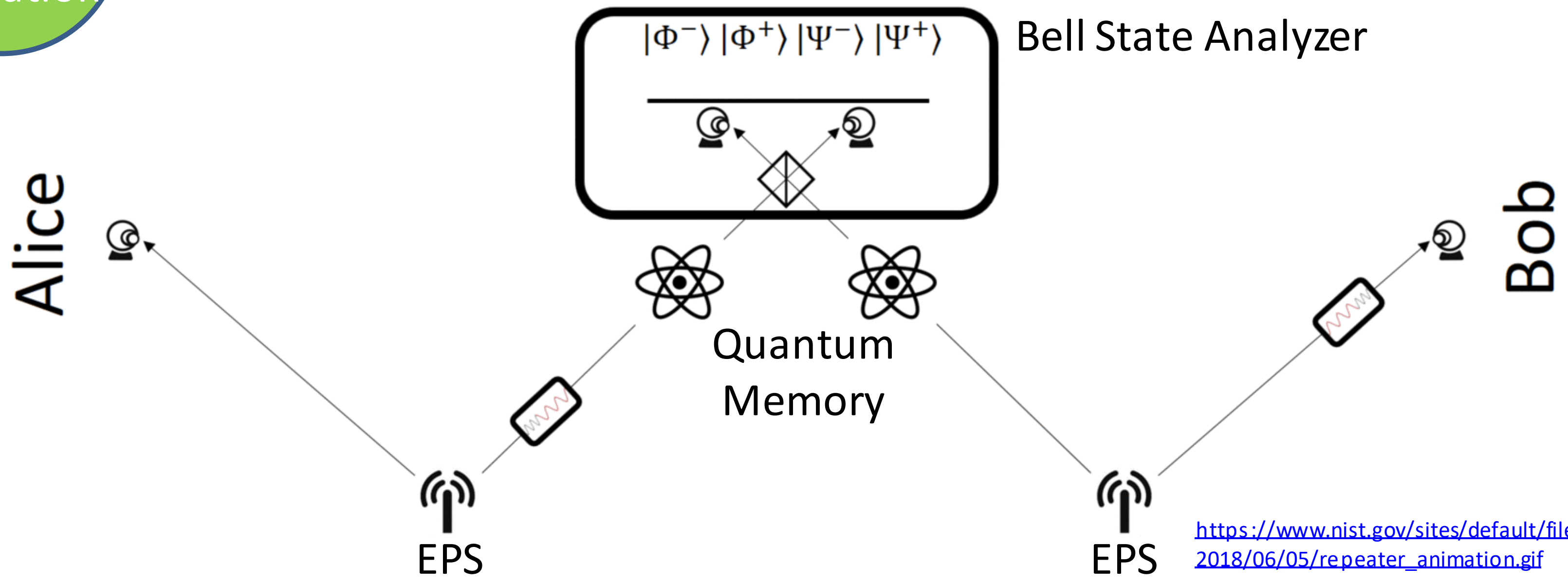
Entanglement between remote parties

Abilities

These stations should be equipped with the ability to

- Store photons for long times
- Convert frequencies
- Maintain states with high fidelity
- Time Synchronization using control electronics

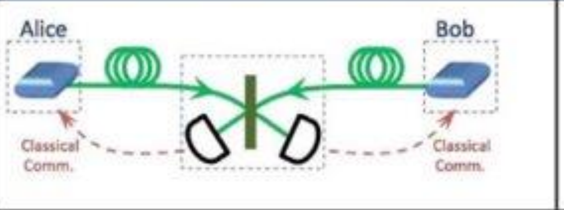
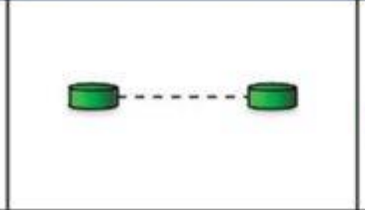
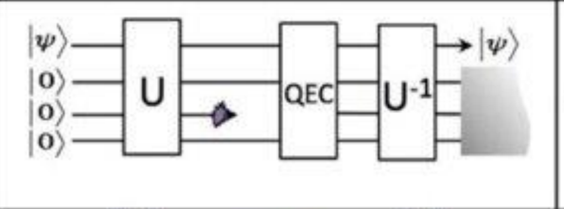
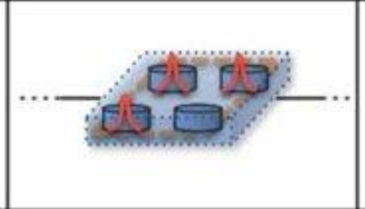
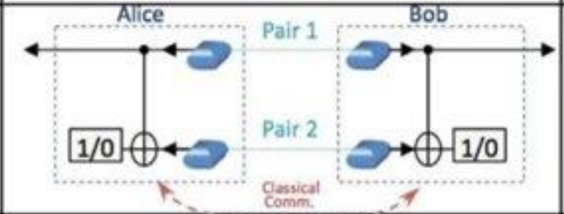
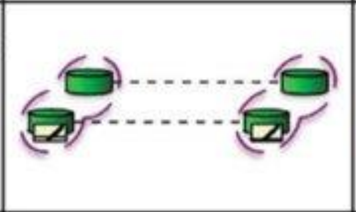
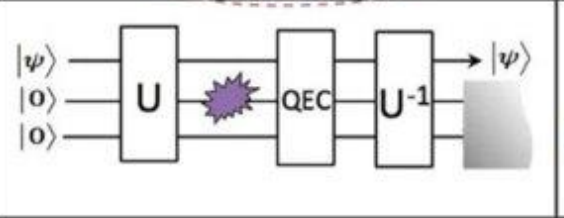
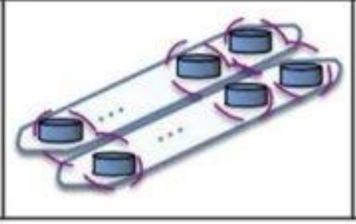
Active mechanisms are also employed at every repeater station to correct operation errors, i.e. imperfections induced by the channel, measurements and gate operations.



- Quantum Memory
- Entangled photon source
- Frequency Converter
- Bell State Analyser
- Control Electronics
- Classical signal processing

https://www.nist.gov/sites/default/files/images/2018/06/05/repeater_animation.gif

Generations of Quantum Repeaters

Errors	Approaches	Examples	Schematics	1G	2G	3G
Loss Error	Heralded Entanglement Generation (HEG)			✔	✔	
	Quantum Error Correction (QEC)					✔
Operation Error	Heralded Entanglement Purification (HEP)			✔		
	Quantum Error Correction (QEC)				✔	✔

https://www.nature.com/articles/srep20463

- Depending on the methods used to correct loss and operation errors, all the proposed QR schemes can be classified into three categories (generations)
- The optimum generation of QR is decided by the efficiency of components and the distance of communication

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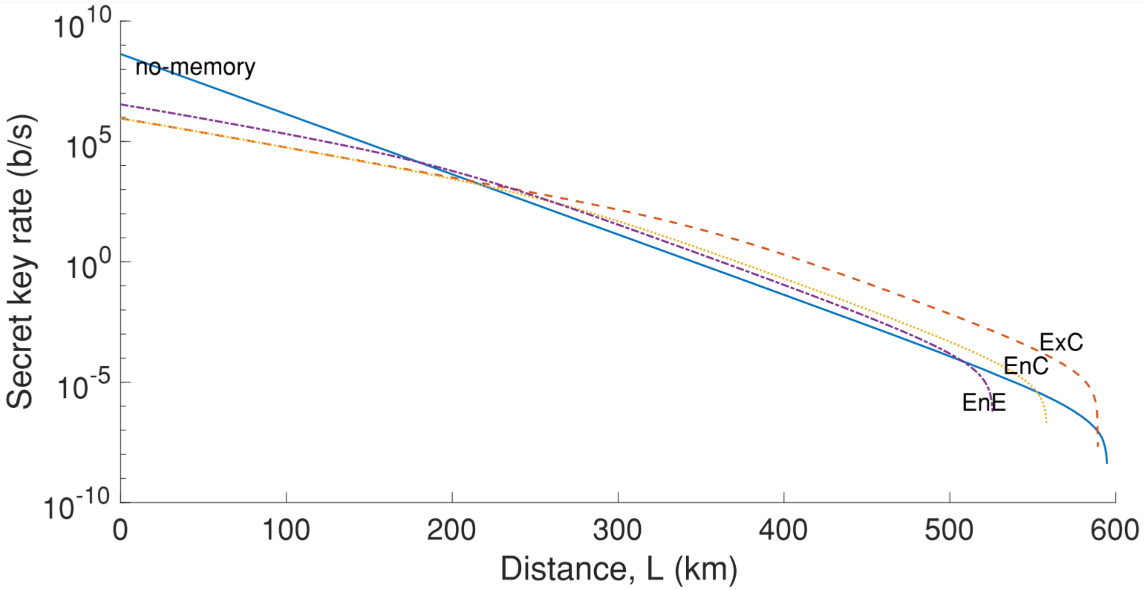
Quantum Repeater Challenges: Memory Efficiency & Storage Time

Memory Efficiency and Storage Time: Need for efficiency to support robust communication, a storage time of the order of ms and multiplexing capabilities for faster Gbps level data transmission

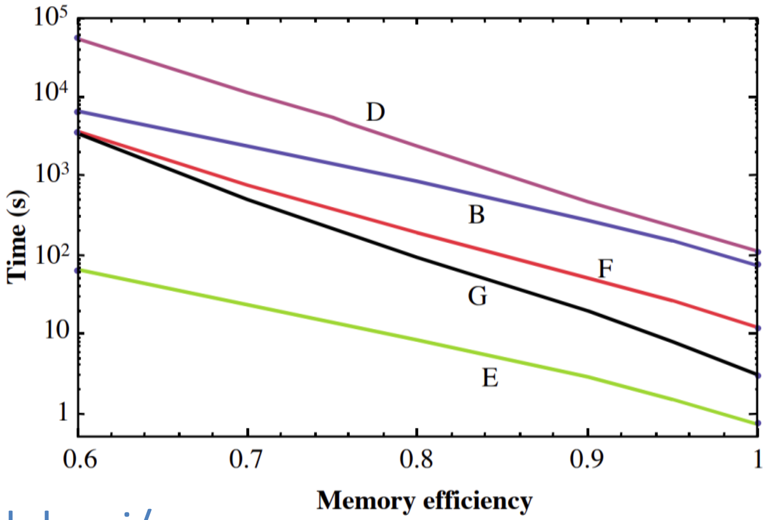
	ExC	EnC	EnE
Efficiency, $\eta_w \eta_{r0}$	0.30	0.30	0.60
Coherence time, T_r	120 μs	10 μs	1.5 μs
Repitition rate, R_S	1.25 GHz	1.2 GHz	1.2 GHz

Properties of a selection of future warm vapor memories



Secret key rate v/s Distance using the parameters of the warm vapor memories featured in the table (right)

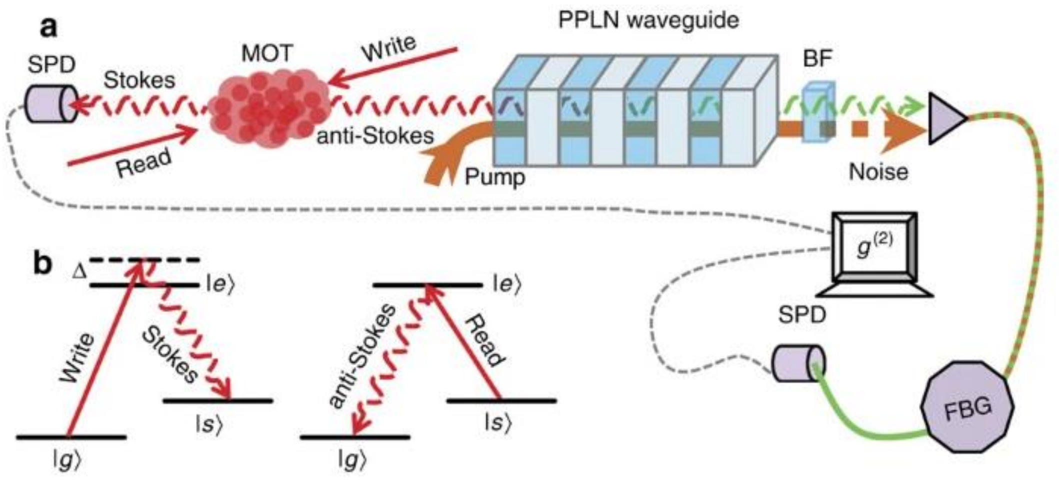
https://iopscience.iop.org/article/10.1088/2058-9565/aa9cfb/pdf
https://journals.aps.org/rmp/abstract/10.1103/RevModPhys.83.33



Robustness of various DLCZ type protocols with respect to non-unit memory efficiency when an entangled pair is distributed with L=600 km (QR Survey paper)

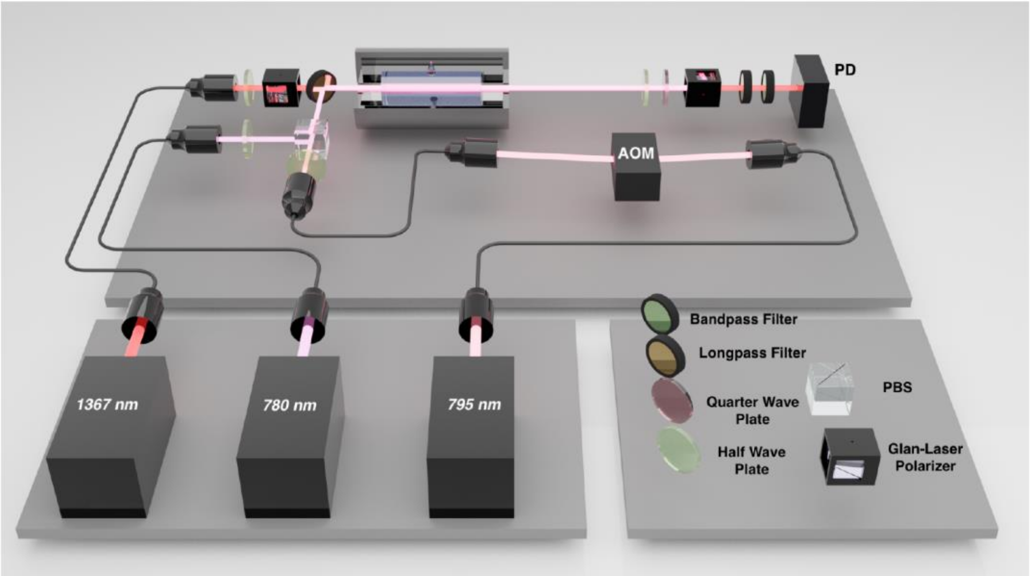
Quantum Repeater Challenges: Frequency Conversion

- **Telecom Wavelength Enabled Qubits: Frequency conversion is required to interchange frequency of qubits to enable storage in QM as well as transmission at telecom wavelengths**



Frequency Conversion using PPLN waveguide with a low efficiency of 17.6 % using SFG

https://www.nature.com/articles/ncomms4376



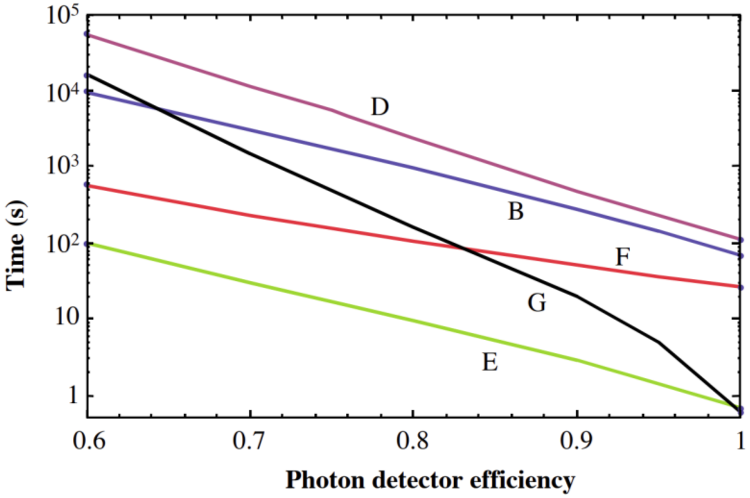
Frequency Conversion using Four Wave Mixing with a very low efficiency of 0.1%

https://opg.optica.org/abstract.cfm?uri=QUANTUM-2022-QM2B.3

- **Clock synchronization and time stamping: Need time tagging modules with picosecond precision and highly accurate clocks for schemes like QKD**

Quantum Repeater Challenges: Source and Detector Efficiency

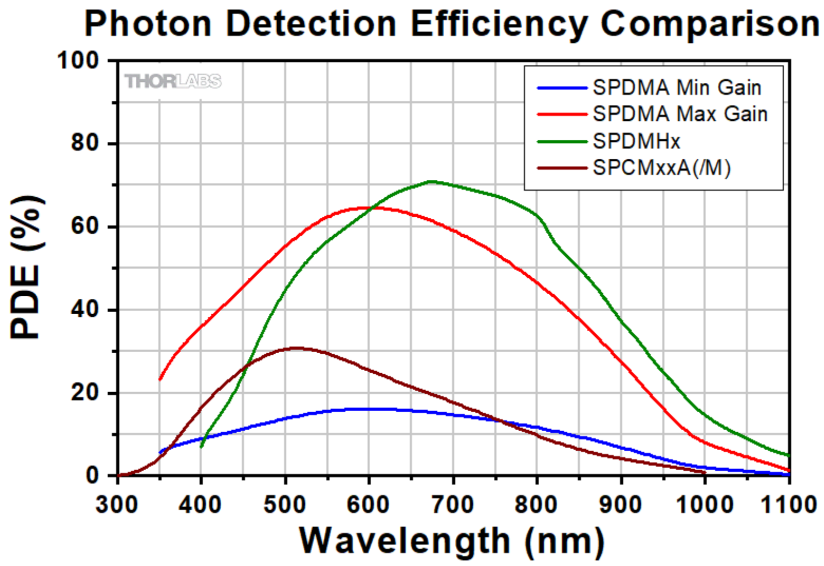
- **EPS/SPS Efficiencies: Need for highly efficient, preferably deterministic single photon sources to increase probability of entanglement generation/swapping**
- **Photon Detector Efficiencies: Need for high efficiency at 1330/1550 nm with low dark count and low dead time for faster data transmission**



Robustness of various protocols with respect to imperfect photon detector efficiency when an entangled pair is distributed with L=600 km

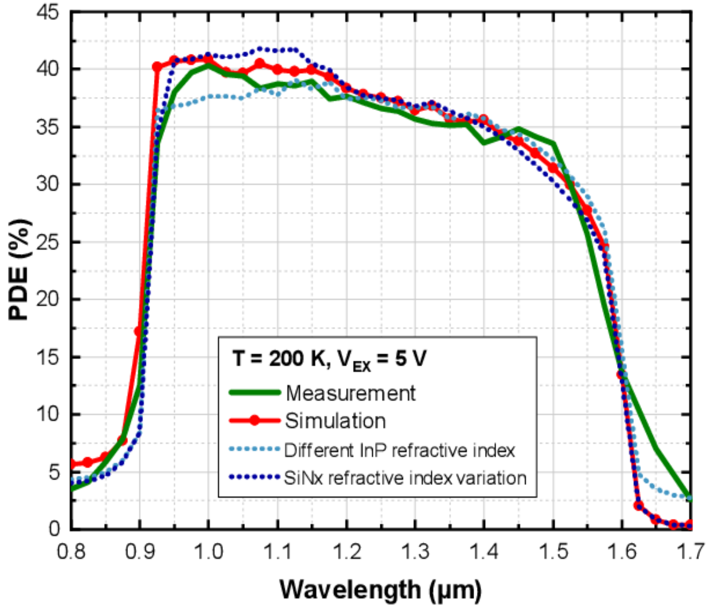
https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=285

Silicon Based SPAD (Visible)



Photon Detection Efficiency vs Wavelength

InGaAs Based SPAD (NIR/IR)



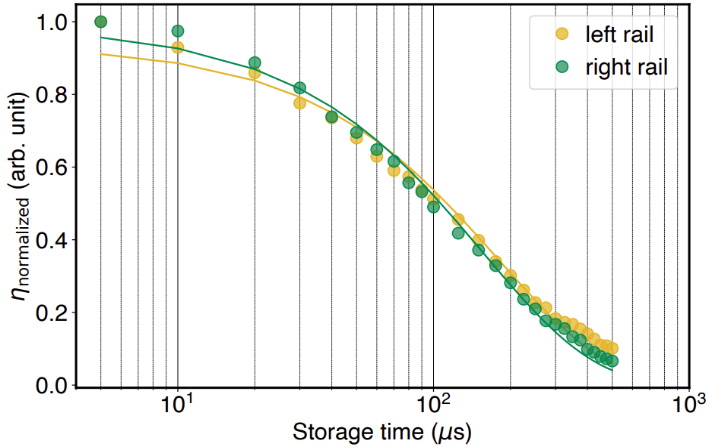
Photon Detection Efficiency vs Wavelength

Low efficiency of 35% at 1330 nm and even lower at 1550 nm

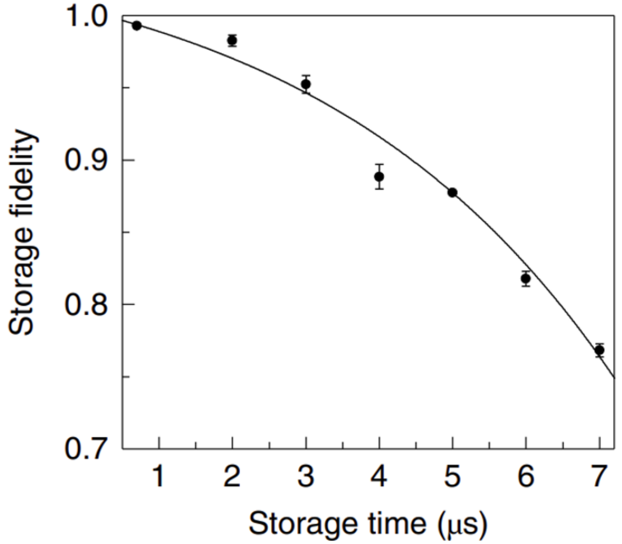
State-of-the-Art Quantum Memories

QM System		Highest Efficiency	Highest Storage Time	Cost	Size	Portability
EIT	Warm Vapor	17 %	1.5 µs	Low	Small	High
	Cold Atom	92 %	325 µs	High	Large	Low
Raman	Warm Vapor	27 %	27 µs	Low	Small	High
	Cold Atom	42.8 %	5 µs	High	Large	Low
AFC: Solid State		53 %	0.53 s	Very High	Very Large	Very Low
GEM	Warm Vapor	84%	14 µs	Low	Small	Medium
	Cold Atom	73 %	10 µs	High	Medium	Low

https://www.nature.com/articles/s41566-019-0368-8
https://journals.aps.org/prapplied/abstract/10.1103/PhysRevApplied.18.044058



Efficiency v/s Storage Time Trade-Off



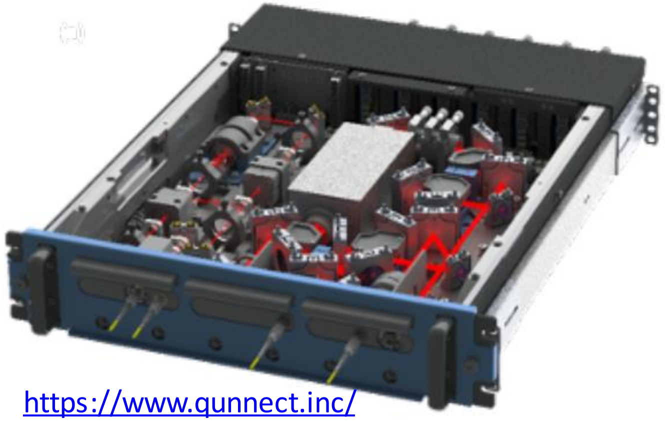
Fidelity v/s Storage Time

Atomic Vapor Quantum Memories: Advantages

Room Temperature : Warm Rb vapor-based Quantum memories work at room temperature can provide a **field deployable** solution towards a scalable quantum repeater network

Compact size: Can be delivered in a 2U form-factor rackmount, hence field deployable

Cost effective when compared to cryogenic setup required for REIC based quantum memories and laser cooled memories



QM in an enclosure with standard 2U rack mount form factor

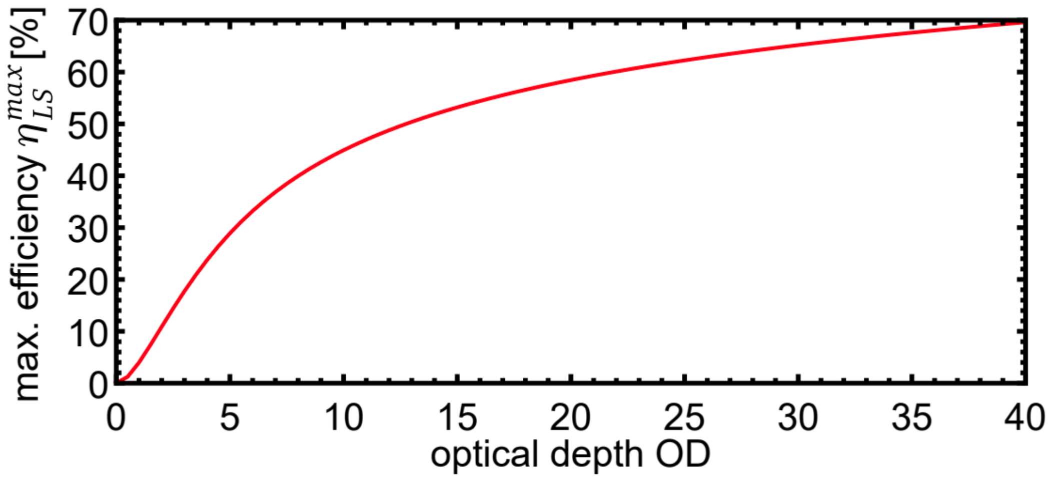
https://www.qunnect.inc/

Atomic Vapor Quantum Memories: Challenges

Decoherence and Dephasing: Mechanisms such as doppler broadening and atomic collisions

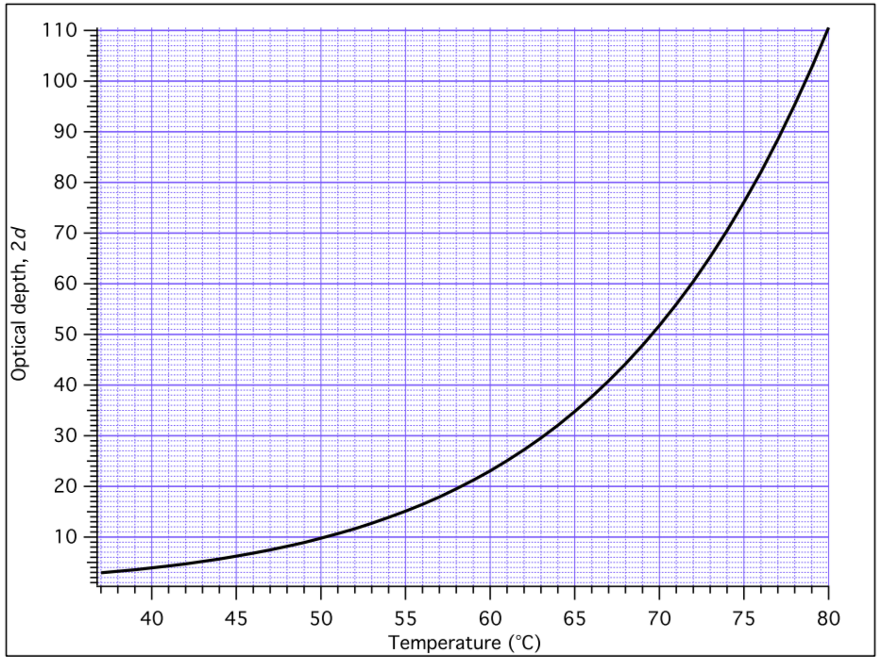
Environmental Interferences: Fluctuations in temperature, magnetic fields

Low storage time: Results in low bit rate



Efficiency v/s Optical Depth

https://tuprints.ulb.tu-darmstadt.de/19257/1/Dissertation_Marcel_Hain_v3.pdf

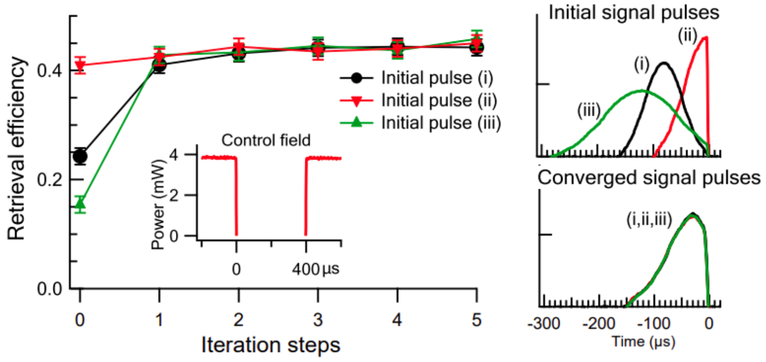


Temperature v/s Optical Depth

Increased OD results in increased storage time and efficiency

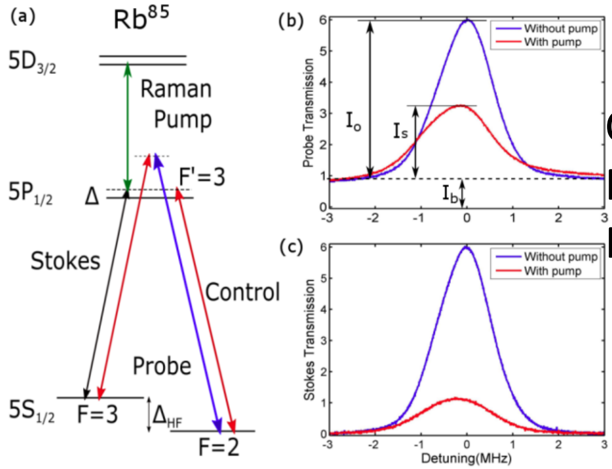
Atomic Vapor Quantum Memory: Improvement

Optimal pulse shaping and **reverse retrieval** techniques for better storage time

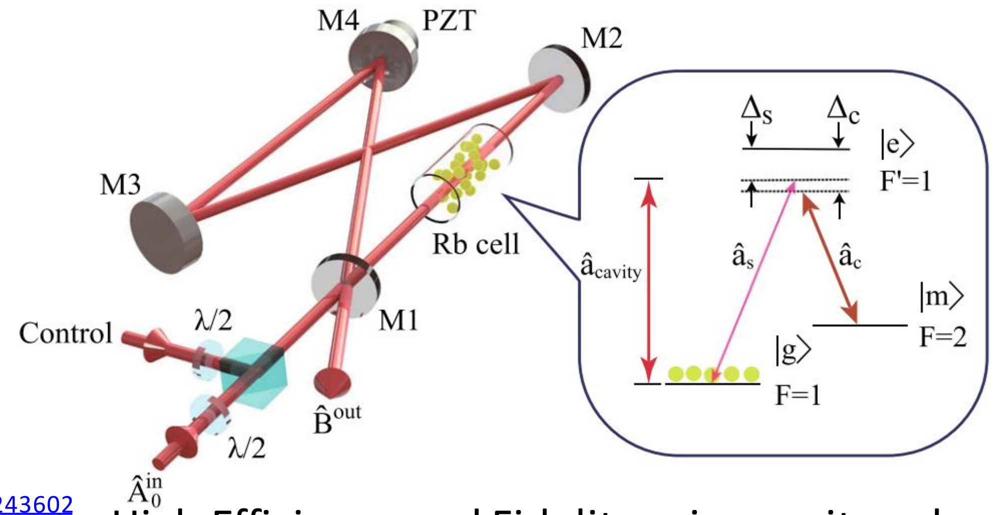


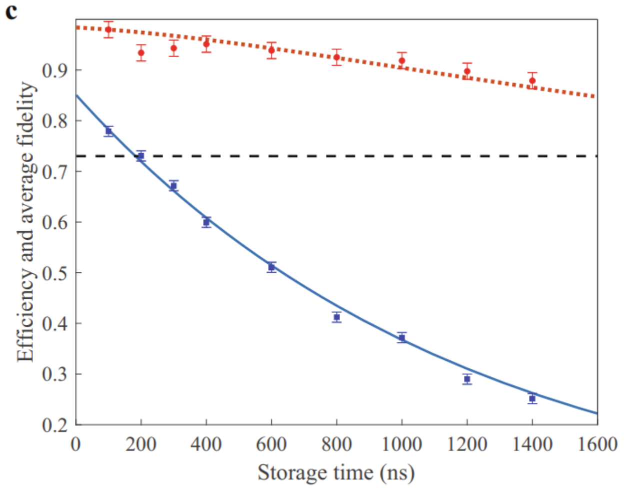
Iterative optimization procedure converges to the same signal pulse-shape and maximum efficiency

Suppression of Four-Wave Mixing in hot Rb vapor using Raman Absorption



Configuration used for the FWM suppression in the Raman configuration

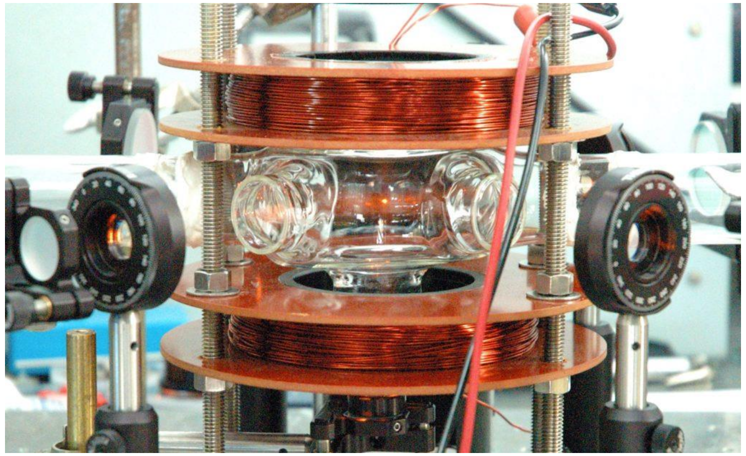




High Efficiency and Fidelity using cavity enhanced warm vapor memory

https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.98.243602
https://doi.org/10.1038/s41467-022-30077-1
https://scholarworks.wm.edu/cgi/viewcontent.cgi?article=1146&context=aspubs

Cold Atom Quantum Memory (MOT)

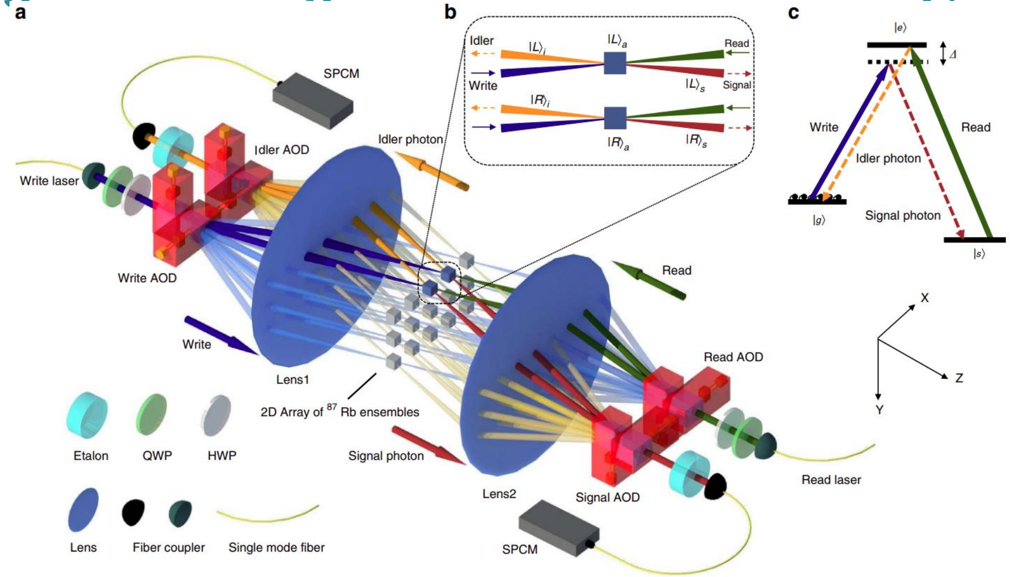


Challenges:

- Large setup: Difficult to miniaturize
- Very Costly

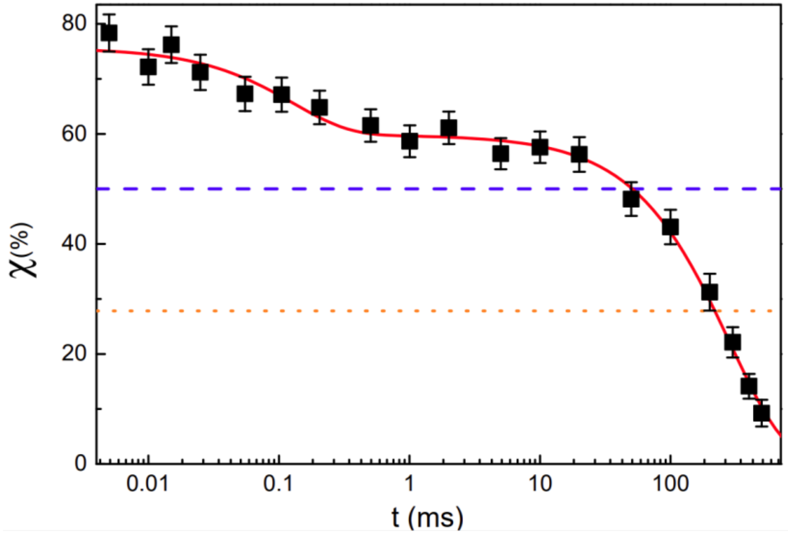
Advantages:

- Higher multiplexing capacity than warm vapor
- Higher storage time and efficiency, especially when used in a cavity



Experimental setup for demonstration of a multiplexed quantum memory with 225 memory cells

https://www.nature.com/articles/ncomms15359
https://www.nature.com/articles/nphoton.2016.51



Intrinsic retrieval efficiency χ versus storage time for DLCZ storage in cavity enhanced MOT

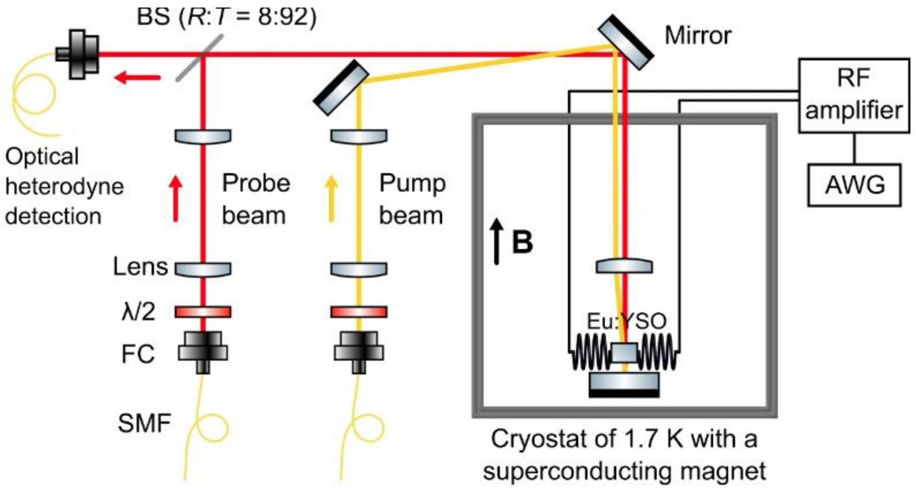
Atomic Frequency Comb Based QM

Challenges:

- Large setup: Difficult to miniaturize
- Requires huge cryogenic setup to cool down the REID crystal to 3-4 K
- Extremely Costly

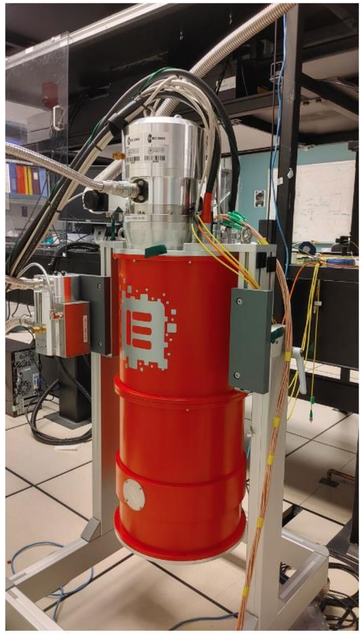
Advantages:

- Extremely high multiplexing capacity
- Very high storage time and efficiency

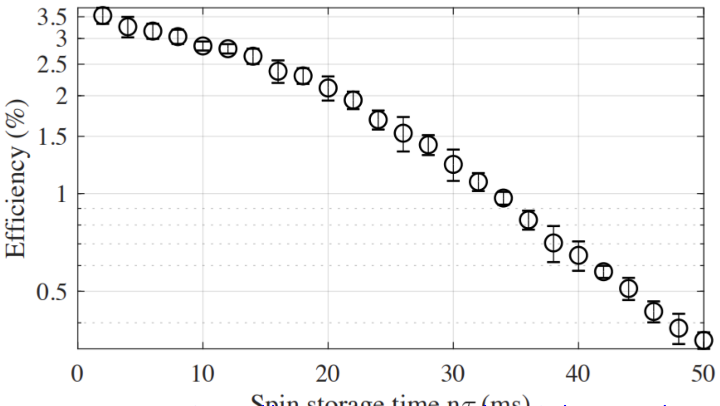


Big Cryogenic Setup with a superconducting magnet

https://www.nature.com/articles/s41467-021-22706-y



[Daniel Oblak's QCloud AFC Setup]()



Efficiency as a function of storage time

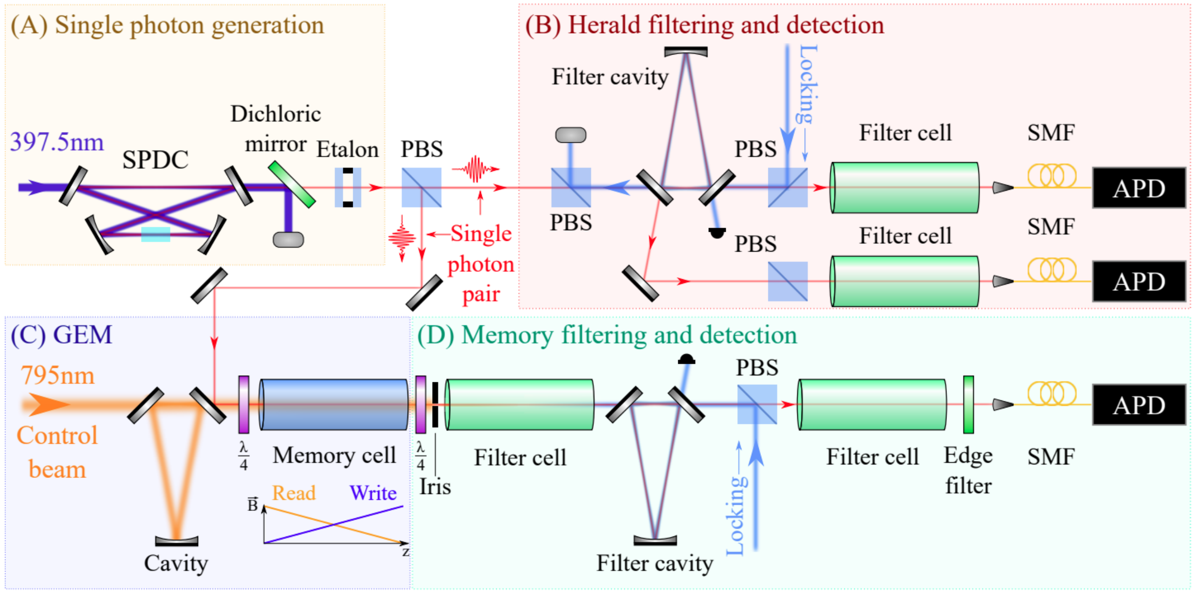
https://iopscience.iop.org/article/10.1088/1367-2630/ab8aac

Gradient Echo Memory

Challenges:

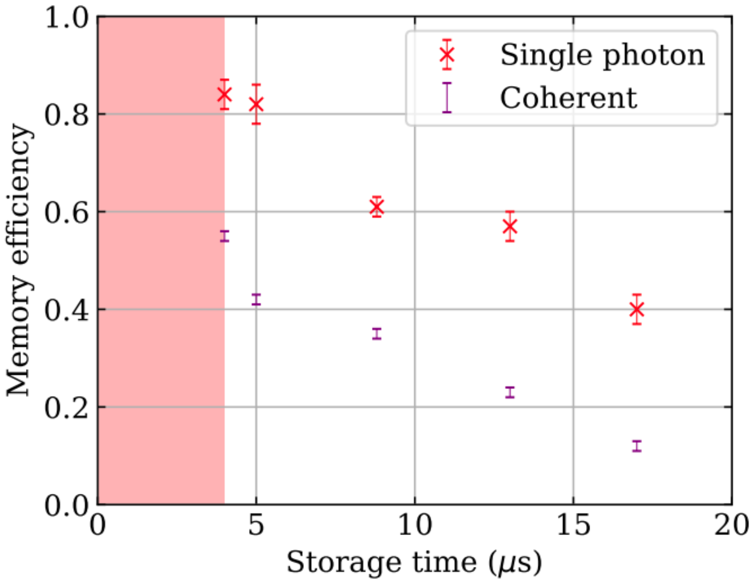
- Moderately Large Setup
- Moderately Costly

Advantages: High recall efficiency (84%) with microsecond storage times



Setup by Weinhold et. Al.

https://equs.org/news/efficient-ever-ready-memory



Memory recall efficiency at different storage times for single photon and coherent input states

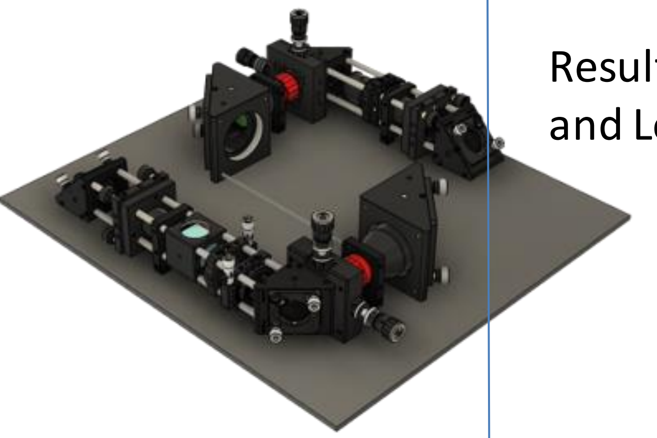
Qulabs' approach for Rb based Quantum Memories

Our Optical Setup - Stage 1

Predicted Efficiency: 10%

Fidelity: 85%

Storage Time: 1-3 μs



Problems to Tackle

Warm Vapor: High Dephasing and Decoherence Rates

Information loss due to collisions

Highly susceptible to environmental fluctuations

Result: Short Storage Time and Low Efficiency

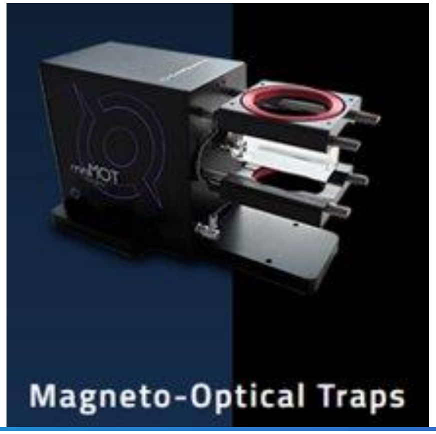
Stage 2 - MOT

Trapping atoms using laser cooling and magnetic fields

Reduced interaction due to cooling: Higher coherence time

Reduced susceptibility to environmental noise: Higher Fidelity

Predicted Efficiency: 69%
Storage Time: 100 μs



Miniaturized MOT by Cold Quanta

Stage 2 - GEM

Theoretical efficiency can reach 100%

The protocol eliminates unwanted reabsorption

Experimental results confirm that no noise is added to stored states

Predicted Efficiency: 50%
Storage Time: 12 μs

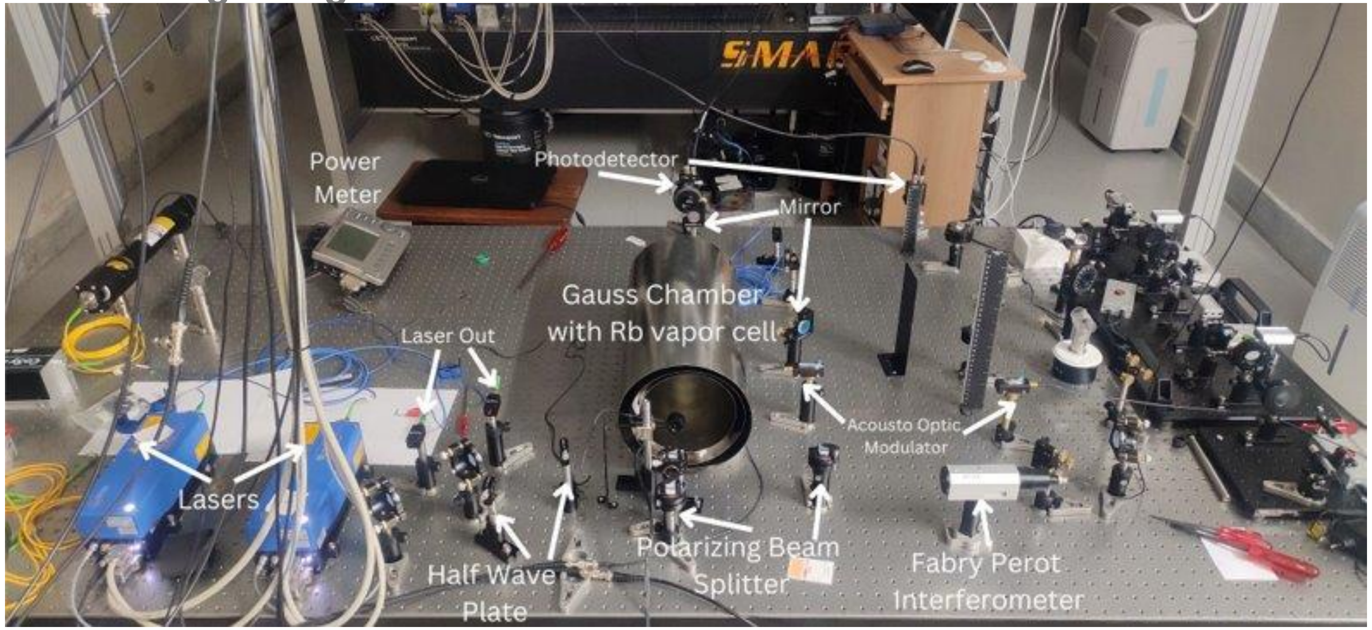
Quantum Memory Development at Qulabs

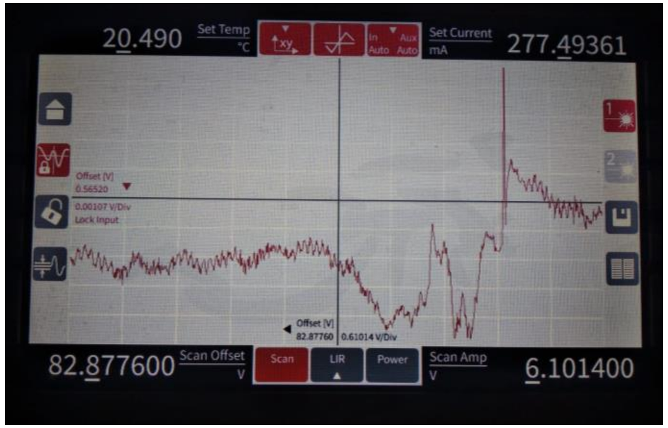
We have conducted the experiment in collaboration with IITR around July 2022.

- Table-top POC of Rb-based EIT : 2022 at Qulabs@IITR.
- Phenomena of EIT was demonstrated.

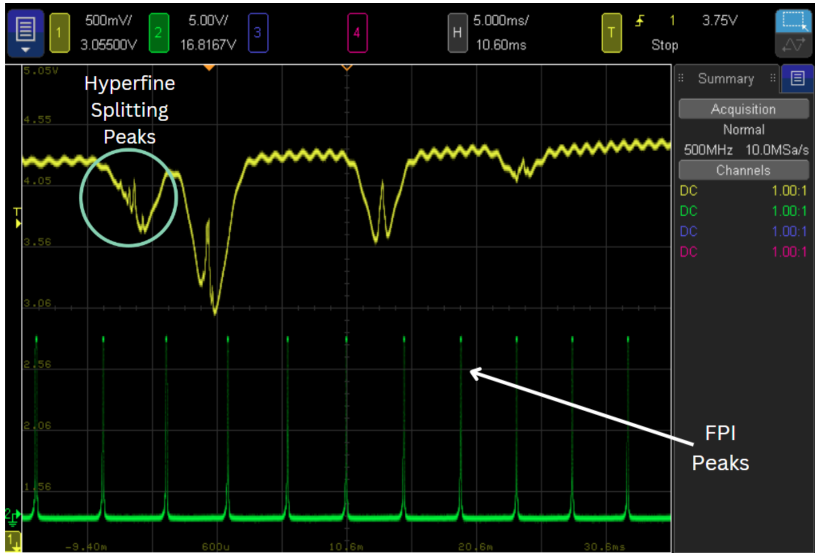
Highlights of the Experiments:

- Two external cavity diode lasers at 780 nm complemented by various optical components.
- Transparency window of 6.657 MHz.
- Slowing of light for 66.21 nanoseconds.

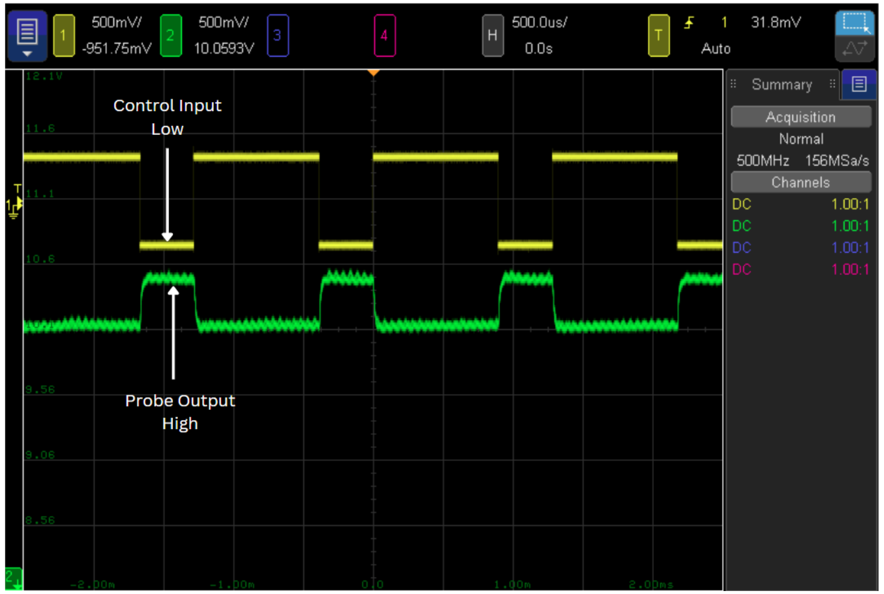




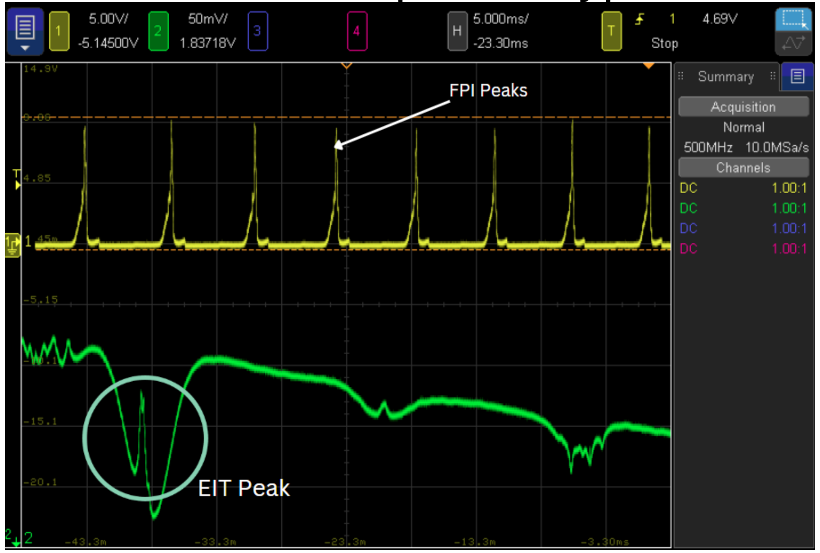
Quantum Memory Development: Results



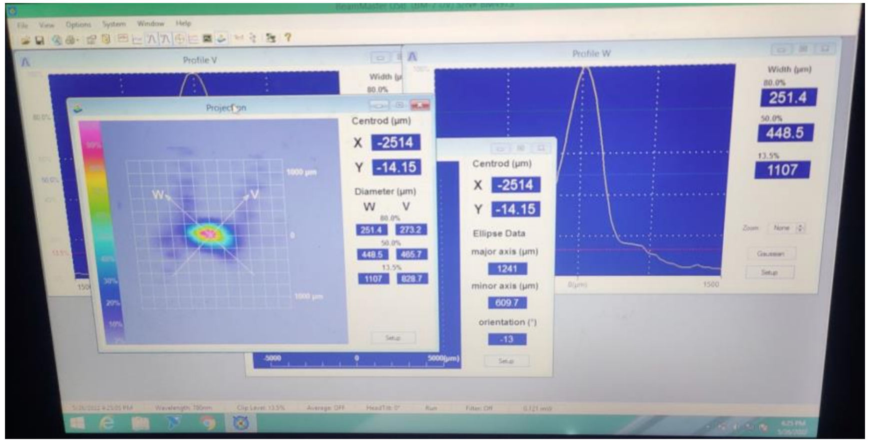
SAS to Lock Laser at Specific Hyperfine Transition



Optical Switch Using AOM and RF Drivers



EIT Peak Observed on Oscilloscope with FPI Output



Spot Size Calculation Using Beam Master

Value proposition and Market impact

First time in India:

- Field trial of Quantum Networks for the first time in India.
- Quantum Repeaters development for long distance quantum communication.
- First Quantum Network Test-Bed in India.

Value add:

- Today quantum devices can only be imported from USA & Europe.
- The components developed through this project will be targeted to be commercially producible in India.

India among Global leaders:

- India will become self-reliant in Quantum communication .
- Unconditionally secure Quantum network can be developed for strategic and civil sector.
- This will attract Quantum communication market globally.
- Quantum Scientists in India.

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THANK YOU!