KEYSIGHT

Test and Measurements - Quantum Challenges

Benjamín García
Solutions Engineer

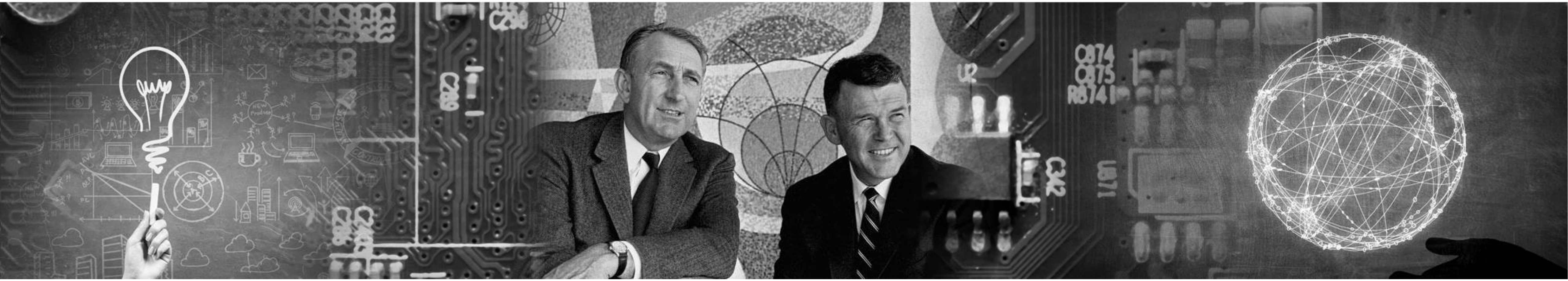
Agenda

- Introduction
- Quantum Technology
- Quantum Computing
- Quantum Communications
- Quantum Sensing
- Summary
- Q&A

Introduction

Keysight Technologies is at the heart of the quantum revolution

We help you create. Innovate. And deliver what’s next.



The innovation leader in electronic design and test for over 80 years

Founded in 1939 by Bill Hewlett and Dave Packard as HP with an ongoing mission to help create new markets

Trusted hardware, innovative software and a global network of experts

Keysight is at the Heart of the Digital Revolution

Accelerating innovation to connect and secure the world

SMART TECHNOLOGY CONNECTS THE WORLD

INNOVATION IS EVERYWHERE

- ✓ Devices
- ✓ Infrastructure
- ✓ Cities
- ✓ Defense
- ✓ Vehicles
- ✓ Wearables

80+
years of innovation, measurement science expertise

1700+
US and foreign patents issued or pending

29
of the Top 30 Tech companies use Keysight

KEYSIGHT

$5.3B
in revenue

130
countries where we have offices to reach customers

78
of the Global 100 companies are Keysight customers

Keysight in Quantum

2016 – Signadyne

2018 – Joined QED-C

2018 – Boulder Cryogenic Quantum Testbed

2019 – Labber QUANTUM

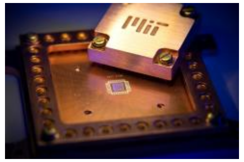
2020 – Quantum Software Center Cambridge, MA

2021 – quantum benchmark: Helping *you* make quantum work.

2022 – MIT EQuS 64-Qubit Testbed

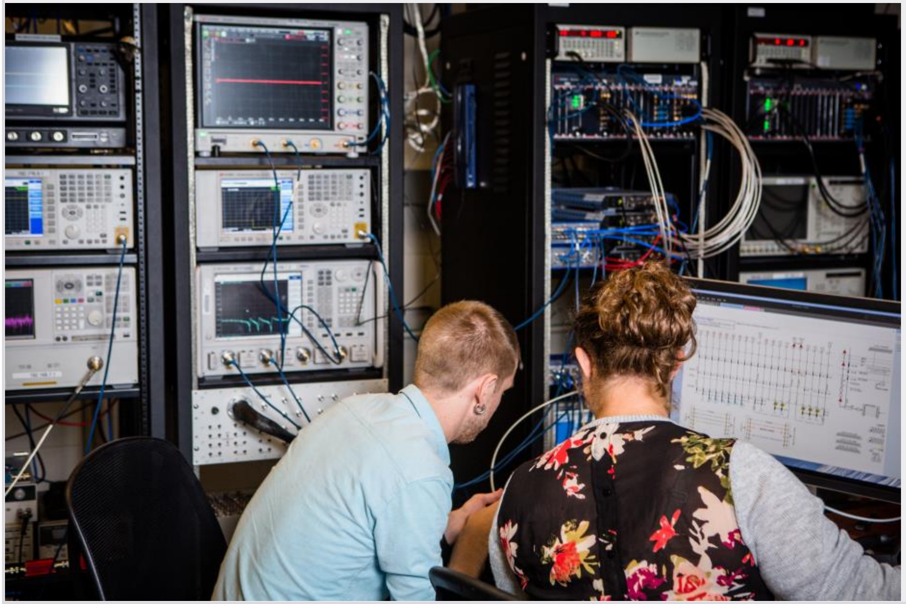
MIT University

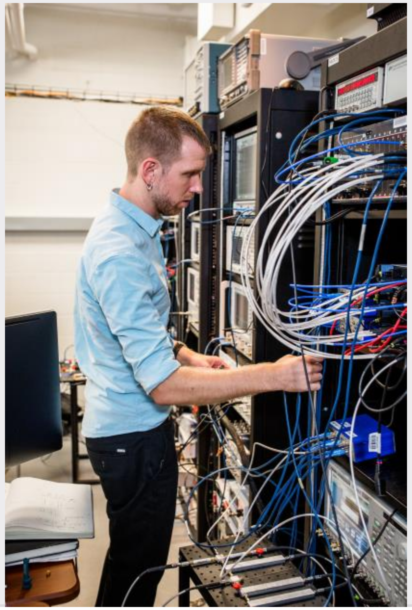
KEYSIGHT TECHNOLOGIES + Labber QUANTUM + EQuS Engineering Quantum Systems

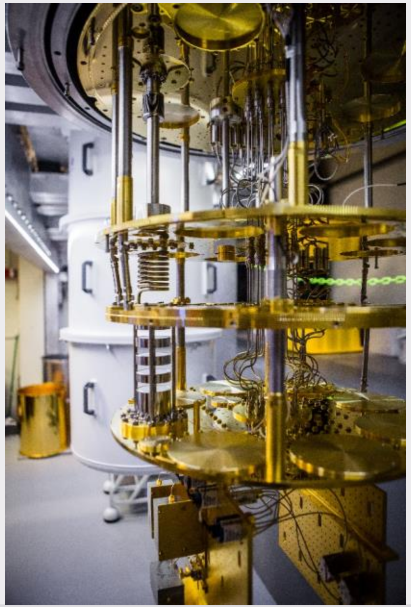


- **Announcing the creation of a new Quantum Research Center in Cambridge, MA**
  → expanding operation of Labber Quantum team
- **Continuing our multi-year partnership with the MIT Engineering Quantum Systems Group**
  → expanding current software and hardware capability to create 64-qubit capable test bed

Keysight's high-precision instrumentation enables quantum engineering





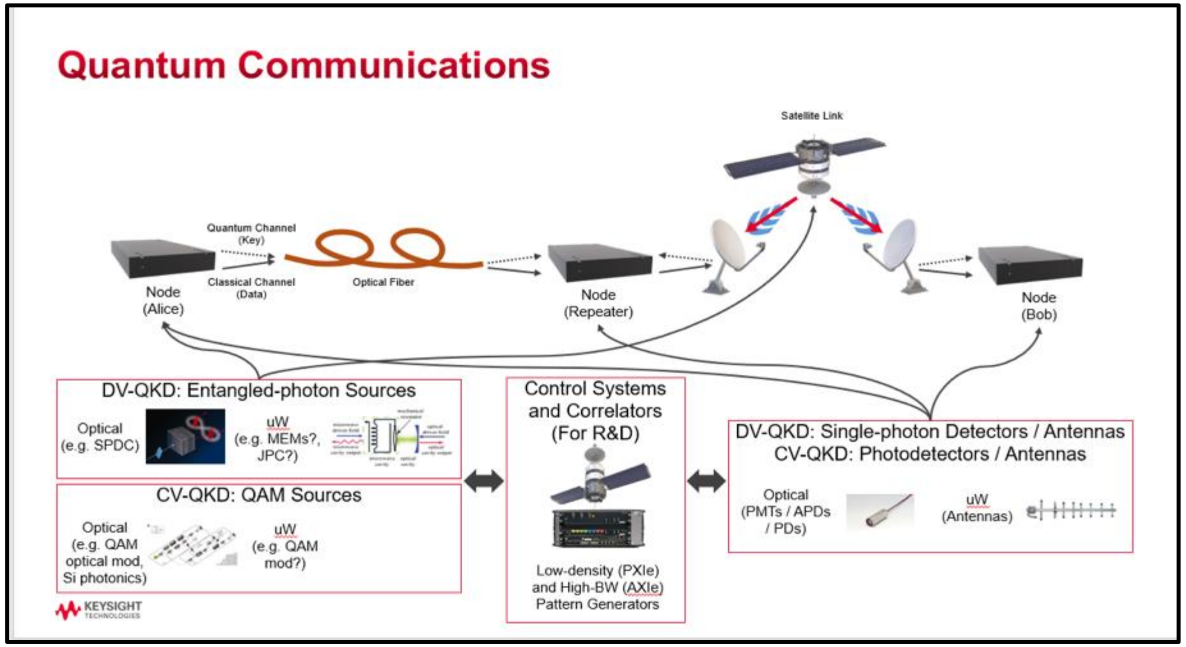


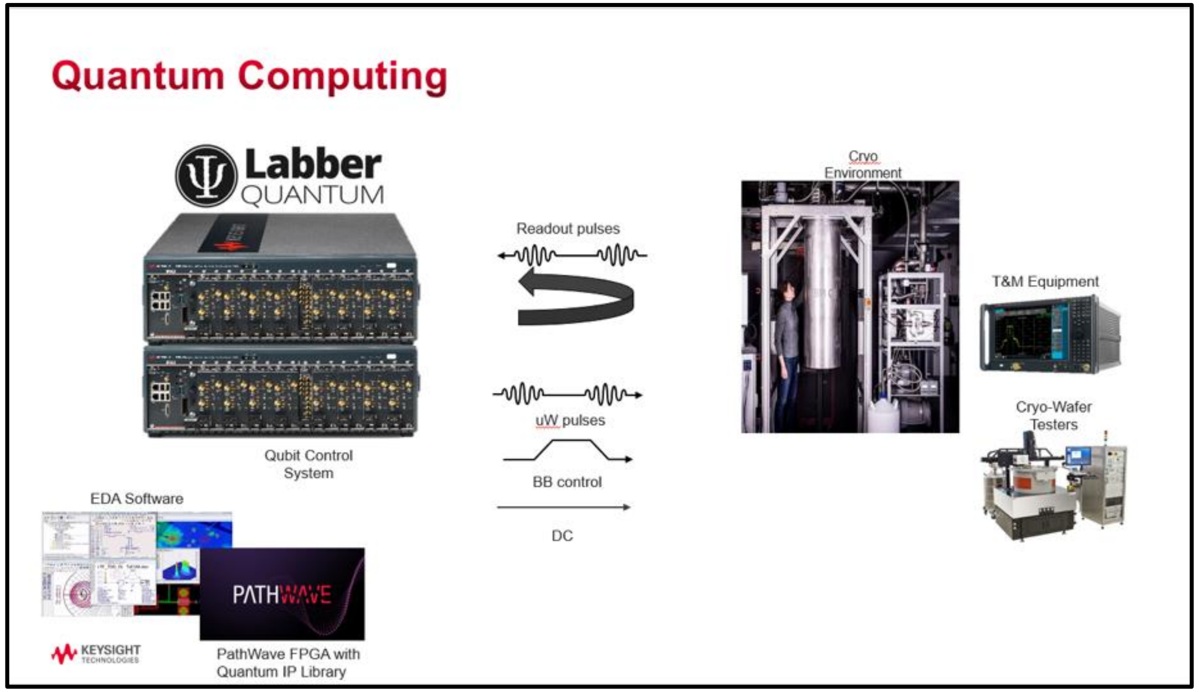
William D. Oliver, Ph.D.
Associate Professor, Electrical Engineering
Professor of the Practice of Physics
Director | Center for Quantum Engineering
Massachusetts Institute of Technology

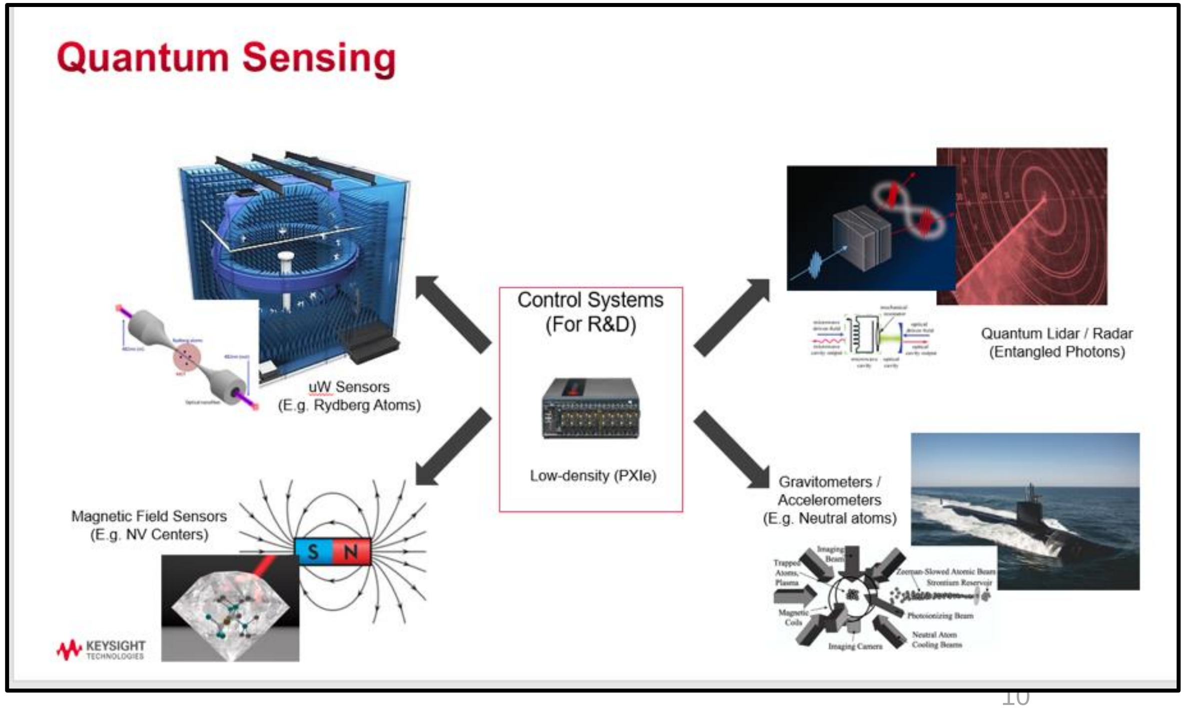
"Early access to Keysight's technology has been key to enabling our research for the past few years.
EQuS looks forward to applying Keysight's emerging quantum software and hardware solutions to our new 64-qubit test bed"

Quantum Technology

Quantum Markets



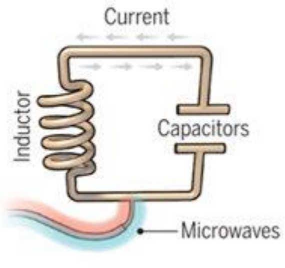


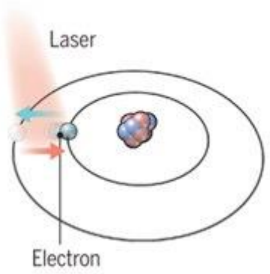


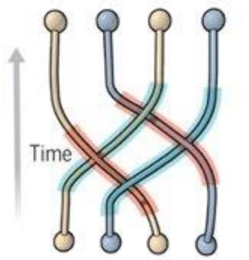
Many types of qubits

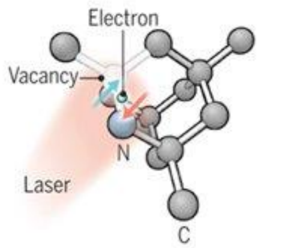
A bit of the action

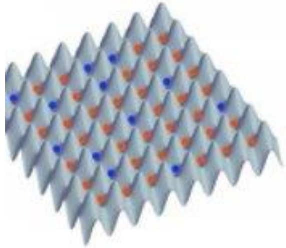
In the race to build a quantum computer, companies are pursuing many types of quantum bits, or qubits, each with its own strengths and weaknesses.

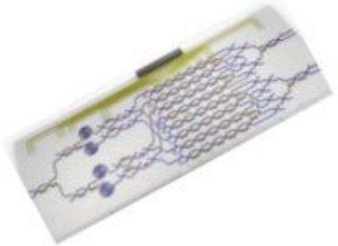












	Superconducting loops	Trapped ions	Silicon quantum dots	Topological qubits	Diamond vacancies	Neutral atoms	Photonics
	A resistance-free current oscillates back and forth around a circuit loop. An injected microwave signal excites the current into super-position states.	Electrically charged atoms, or ions, have quantum energies that depend on the location of electrons. Tuned lasers cool and trap the ions, and put them in superposition states.	These "artificial atoms" are made by adding an electron to a small piece of pure silicon. Microwaves control the electron's quantum state.	Quasiparticles can be seen in the behavior of electrons channeled through semi-conductor structures. Their braided paths can encode quantum information.	A nitrogen atom and a vacancy add an electron to a diamond lattice. Its quantum spin state, along with those of nearby carbon nuclei, can be controlled with light.	Neutral atoms, like ions, store qubits within electronic states. Interactions through excitation to Rydberg states	Photonic qubits interact via linear elements
Longevity (seconds)	0.00005	>1000	0.03	N/A	10	1	
Logic success rate	99.4%	99.9%	~99%	N/A	99.2%	97%	
Number entangled	9	14	2	N/A	6	20	
Company support	Google, IBM, Quantum Circuits	ionQ	Intel	Microsoft, Bell Labs	Quantum Diamond Technologies	Atom Computing QuEra ColdQuanta	PsiQuantum Xanadu
Pros	Fast working. Build on existing semiconductor industry.	Very stable. Highest achieved gate fidelities.	Stable. Build on existing semiconductor industry.	Greatly reduce errors.	Can operate at room temperature.	Many qubits, 2D and maybe 3D	Linear optical gates, integrated on-chip
Cons	Collapse easily and must be kept cold.	Slow operation. Many lasers are needed.	Only a few entangled. Must be kept cold.	Existence not yet confirmed.	Difficult to entangle.	Lasers needed, spaghetti physics, atoms escape	No memory, not clear how to scale

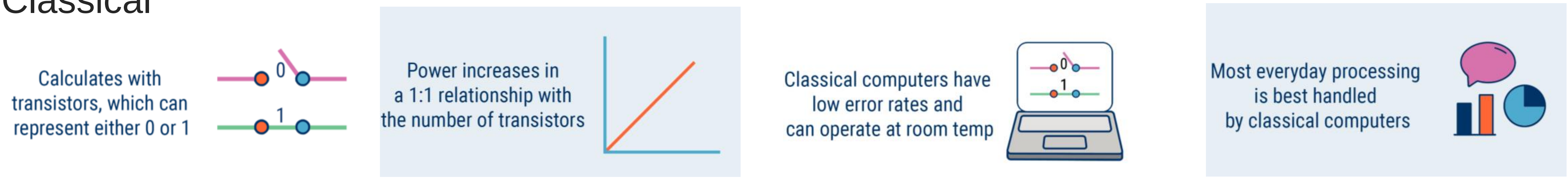
Note: Longevity is the record coherence time for a single qubit superposition state, logic success rate is the highest reported gate fidelity for logic operations on two qubits, and number entangled is the maximum number of qubits entangled and capable of performing two-qubit operations.

Quantum Computing

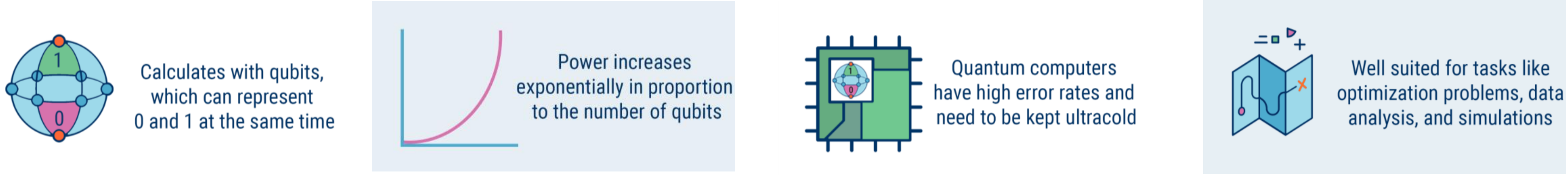
Classical vs. Quantum Computers

A big picture comparision

Classical

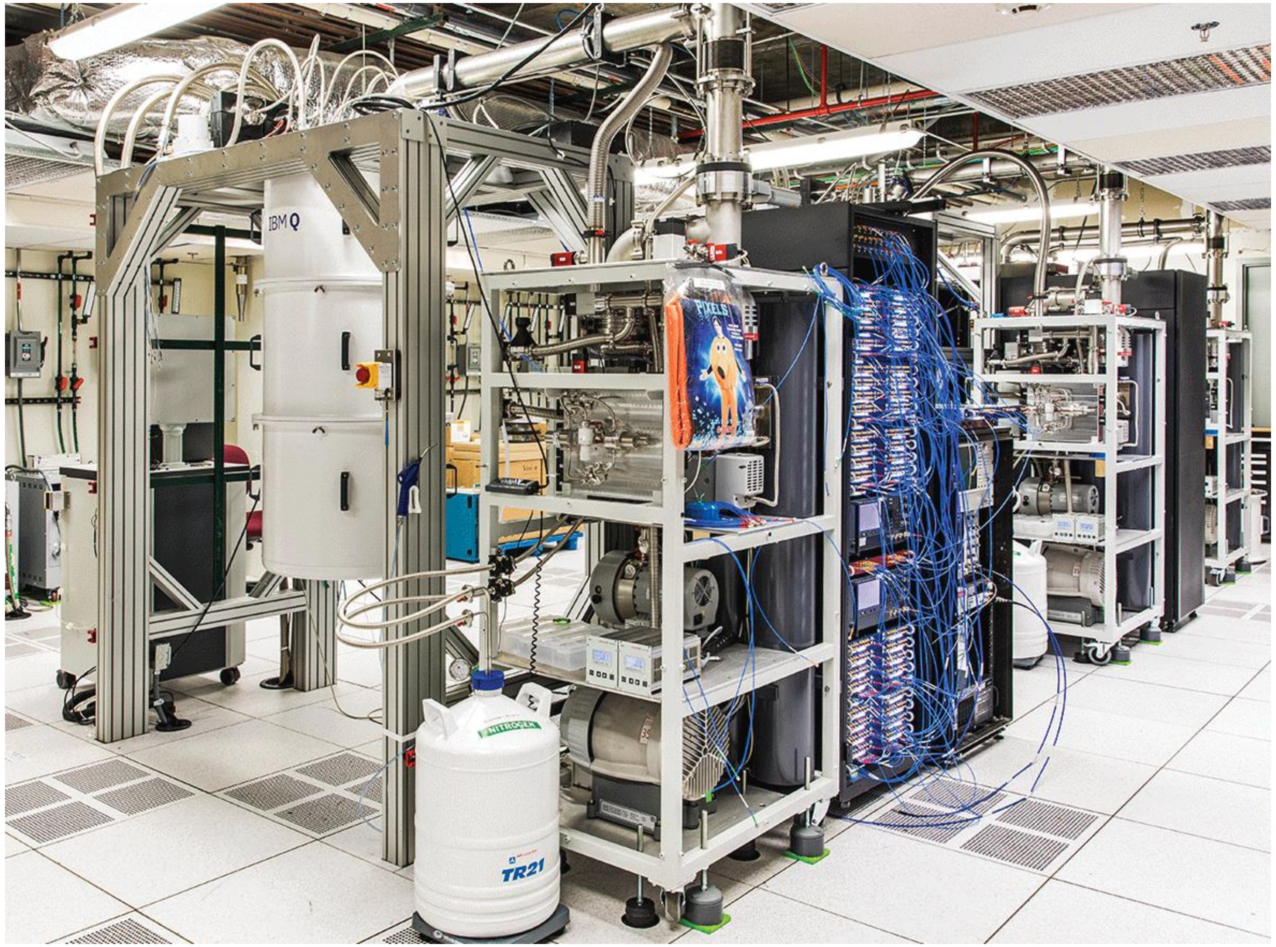


Quantum



https://www.cbinsights.com/research/quantum-computing-classical-computing-comparison-infographic/

What does a Quantum Computer look like?

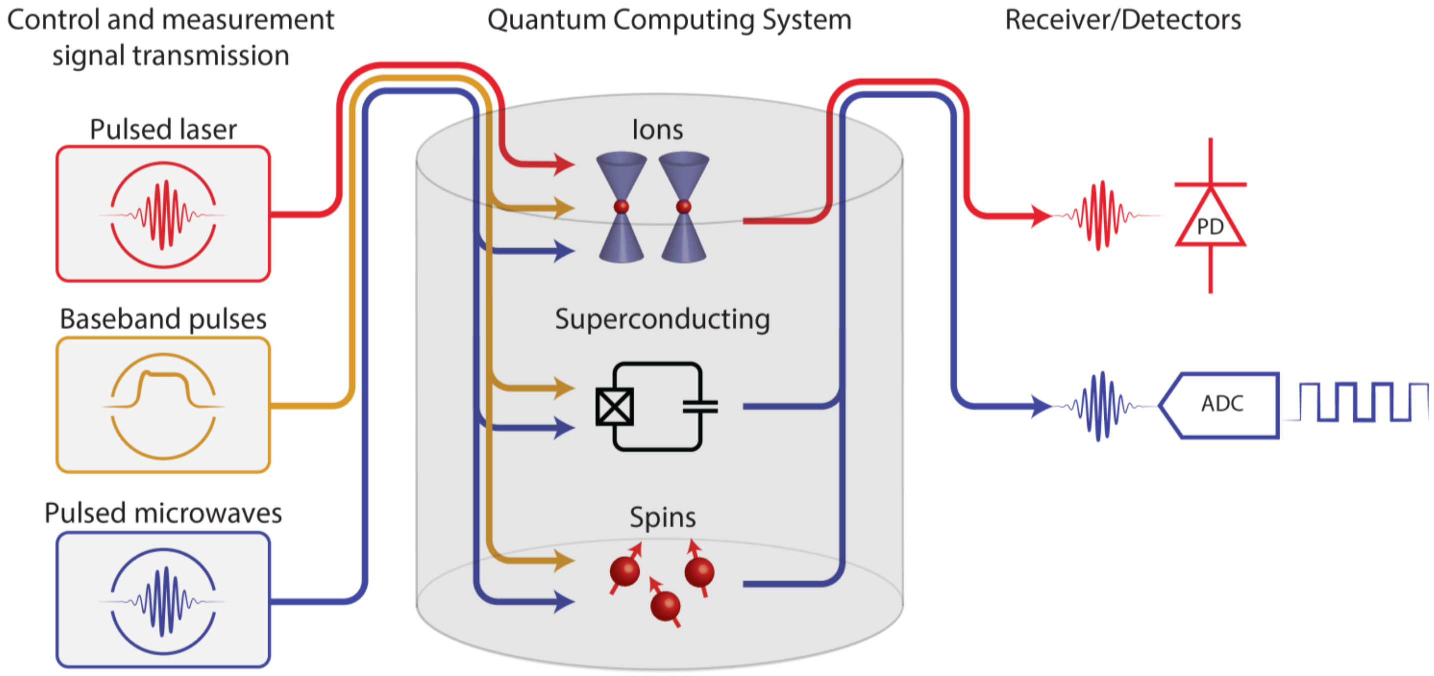


Photos courtesy of IBM-Q

Why would a customer need Keysight?

How does a customer interact with different types of qubits?
And what does qubit "Control" and qubit "Readout" mean? Is this like "Stimulus" and "Response"?

Qubit Control **Qubit Readout**



QPU
Quantum Processor Unit

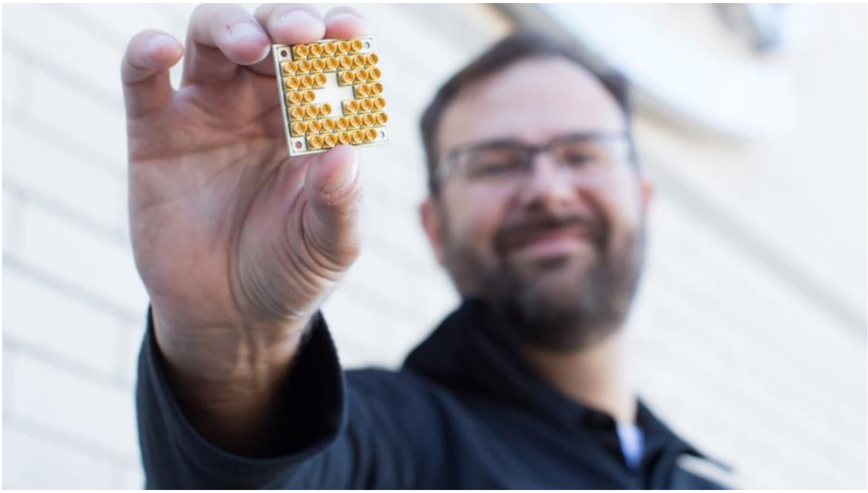
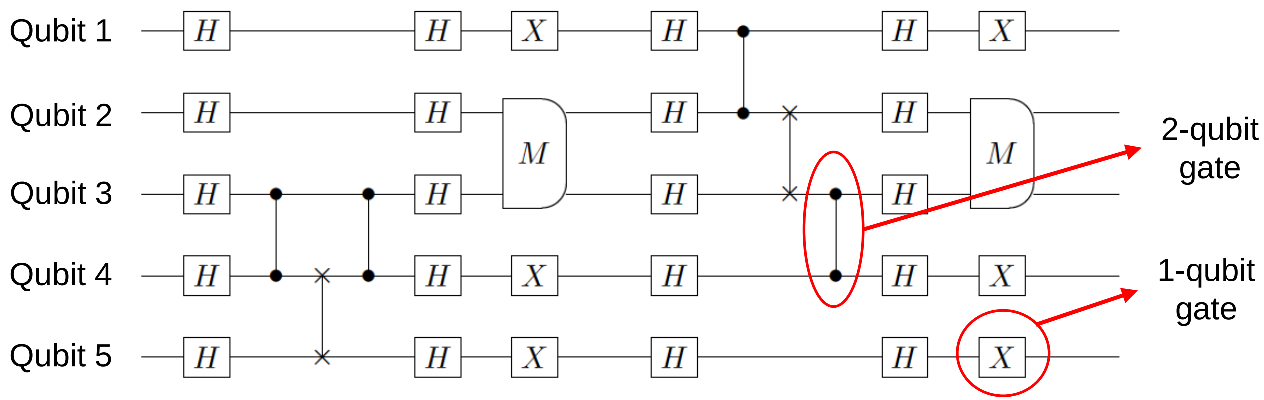


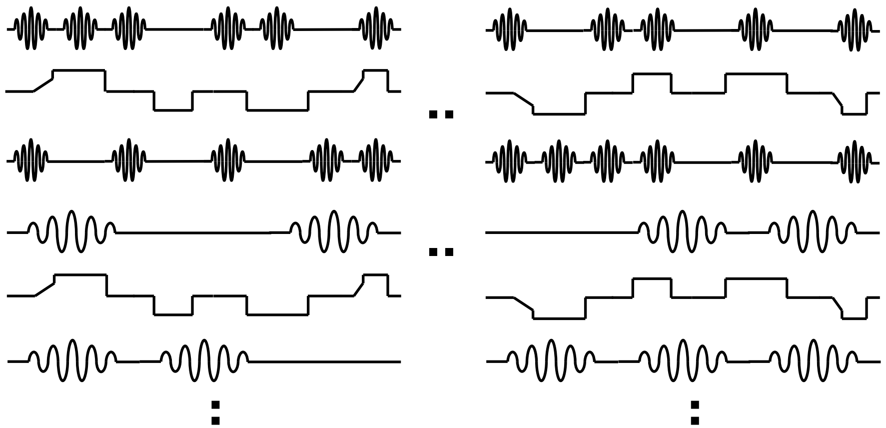
Photo courtesy of Intel

Running Quantum Algorithms

Signal quality, timing, and synchronization is key

Quantum algorithm notation



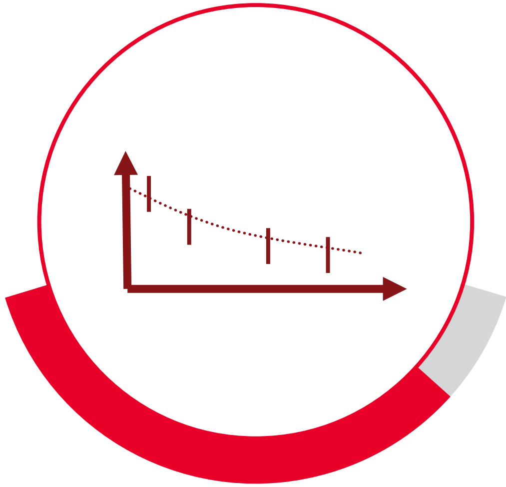


Quantum algorithms are in reality pulse sequences

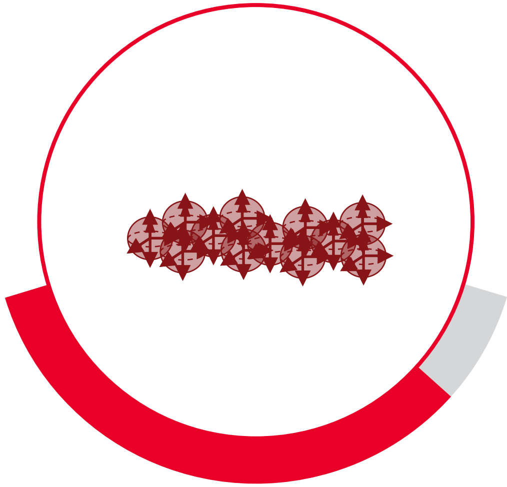
Challenging control system

- **Generation**
  - Phase-coherent uW and/or RF pulses
    - Different lengths (ns-us), frequencies (3-12 GHz), amplitudes and phases (IQ modulations)
    - FDM to address several qubits with the same channel
    - Spectral purity
  - Baseband pulses
- **Acquisition**
  - uW acquisition with real-time IQ demodulation
  - FDM to address several qubits with the same channel
  - Pulse counting and timestamping
- **Scalable to hundreds/thousands of channels**
- **Tight inter-channel synchronization and phase control**
- **Real-time feedback for Quantum Error Correction (QEC)**

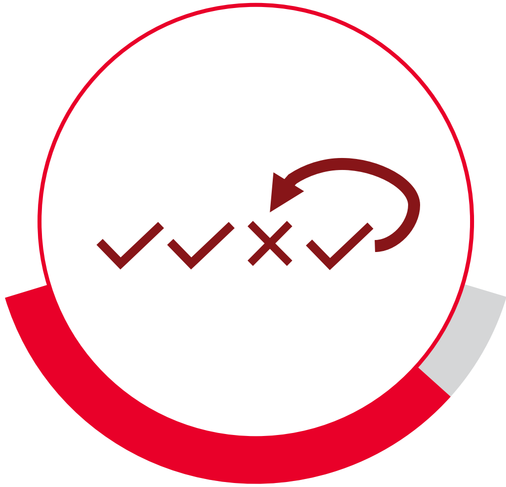
Practical quantum computing sets challenging control requirements



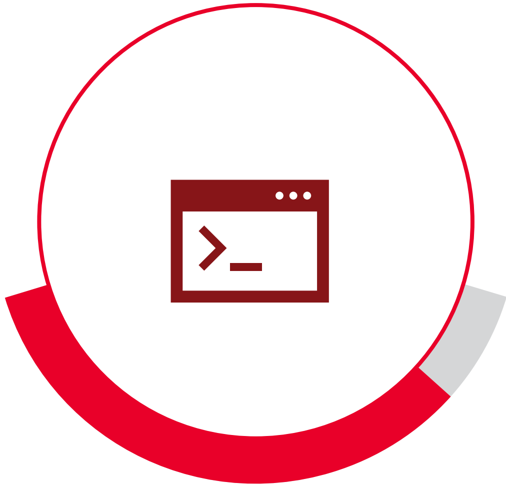
High-fidelity Gates and Readout



Scalability



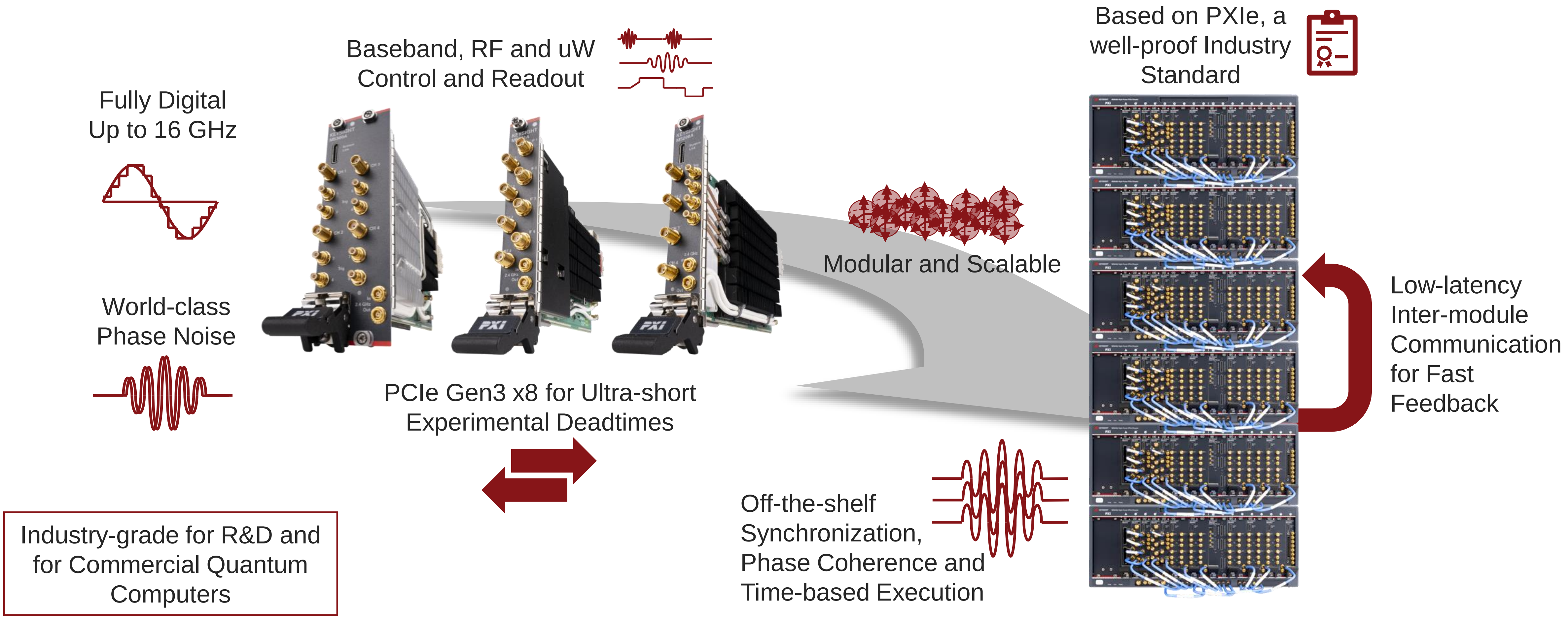
Feedback and Quantum Error Correction



Quantum-oriented Operating System

Unveiling Keysight’s new control system - Hardware

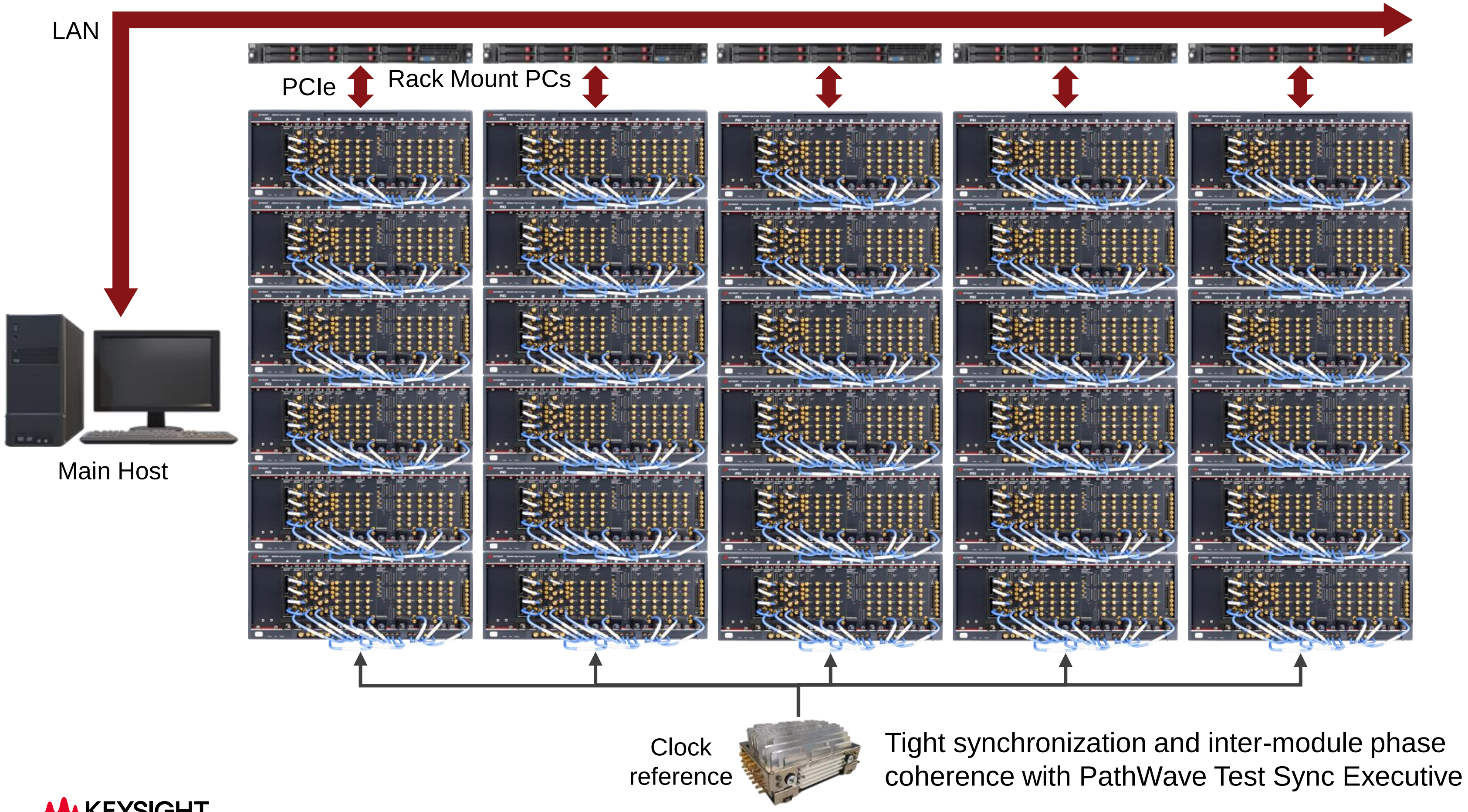
A control system for state-of-the-art quantum computing



A control system for thousands of qubits for the next decade

Scalability beyond 10^3 qubits

Example of a 500-qubit control system (without FDM in control)



What is the max #chassis supported?
Not defined yet, the underlaying technology is truly scalable

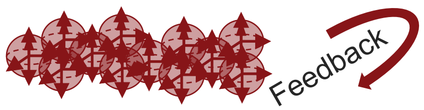
2 GHz BW enables massive Frequency Division Multiplexing

(e.g. with 1:4 FDM the same system could control ~2000 qubits)

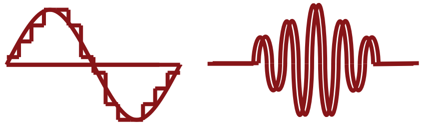
A high-performance control system for state-of-the-art quantum computing

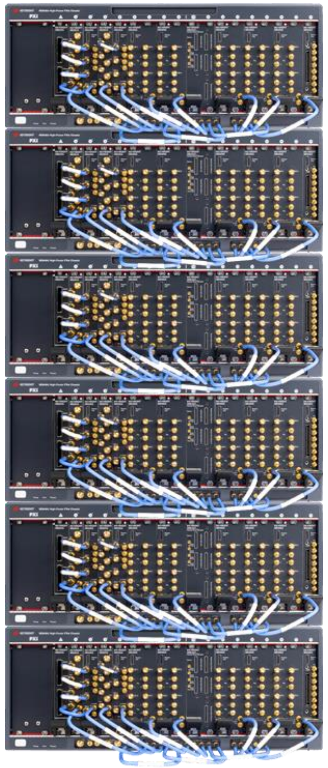
Summary

High-performance and Scalable, for the next decade

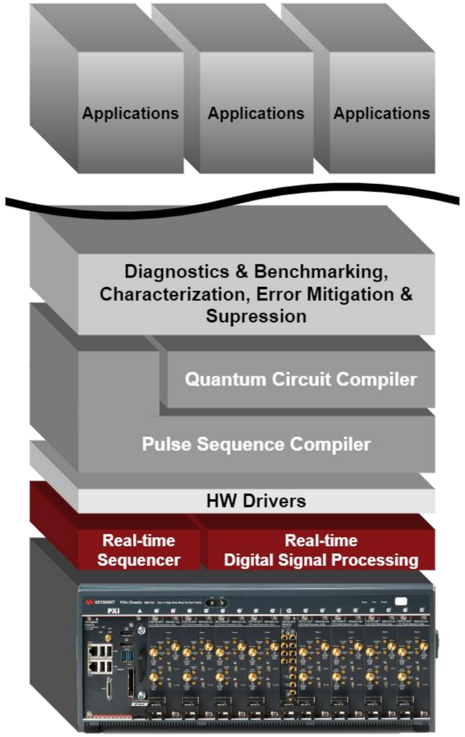


Fully Digital, World-class Phase Noise and Off-the-self Synchronization

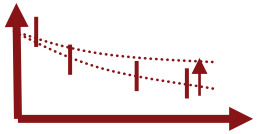




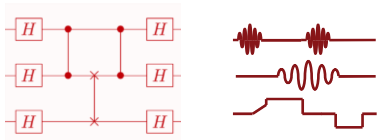
Industry-grade for R&D and Commercial Systems



World-class Error Diagnostics and Error Mitigation



Easy-to-use and Compatible Circuit-level and Pulse-level APIs



Real-time FPGA-based Processing

Quantum Communications

What is Quantum Communications?

Quantum Communications involves using quantum particles to send of information between parties.

- **Quantum Internet**

Network of quantum devices that can exchange quantum information.

- **Quantum Teleportation**

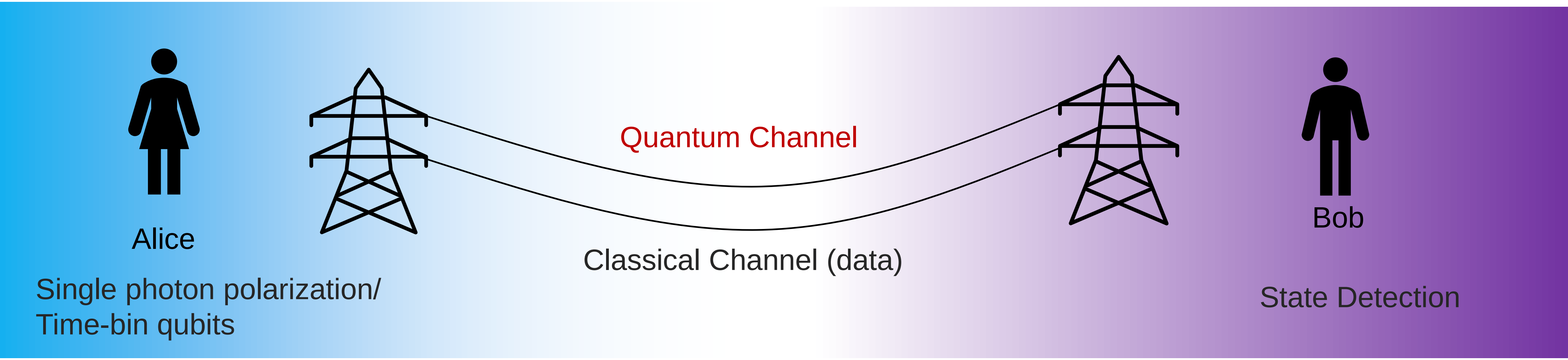
Utilizes entangled qubits to share quantum information without physically sending it.

- **Quantum Key Distribution (QKD)**

A type of Quantum Encryption that works along side traditional communications networks.

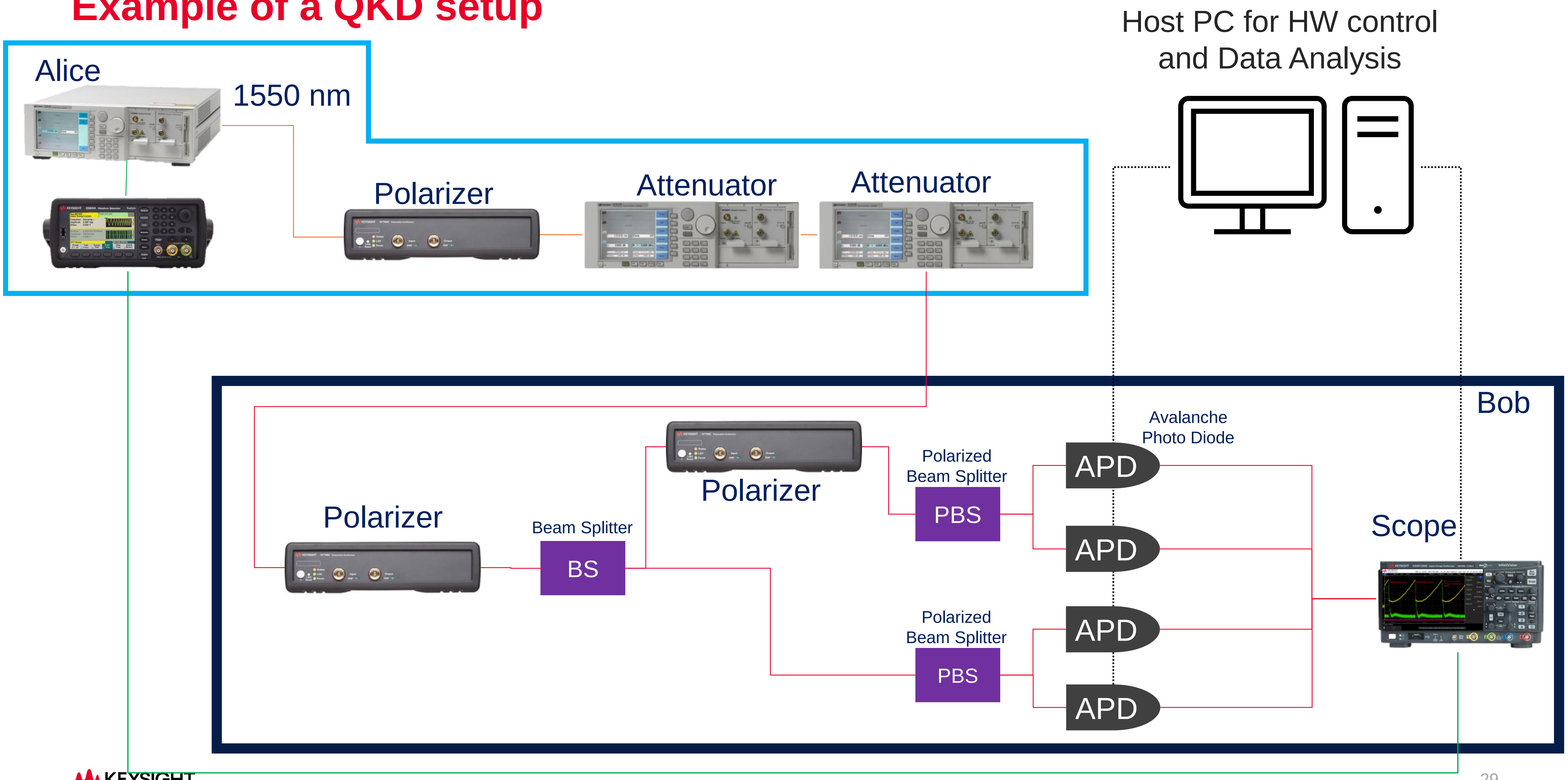
Quantum Key Distribution

Secure encryption method using cryptographic components involving quantum mechanics.



Polarized light signals are being sent over the Quantum Channel.

Example of a QKD setup

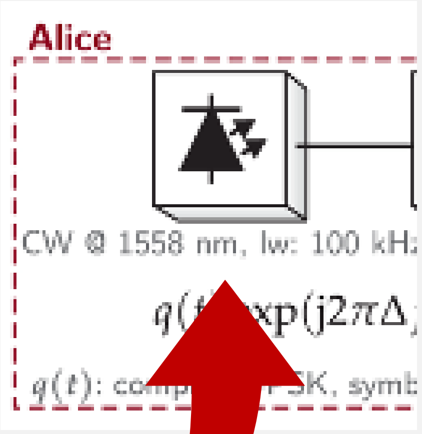


QKD Setup

Tunable Laser Sources

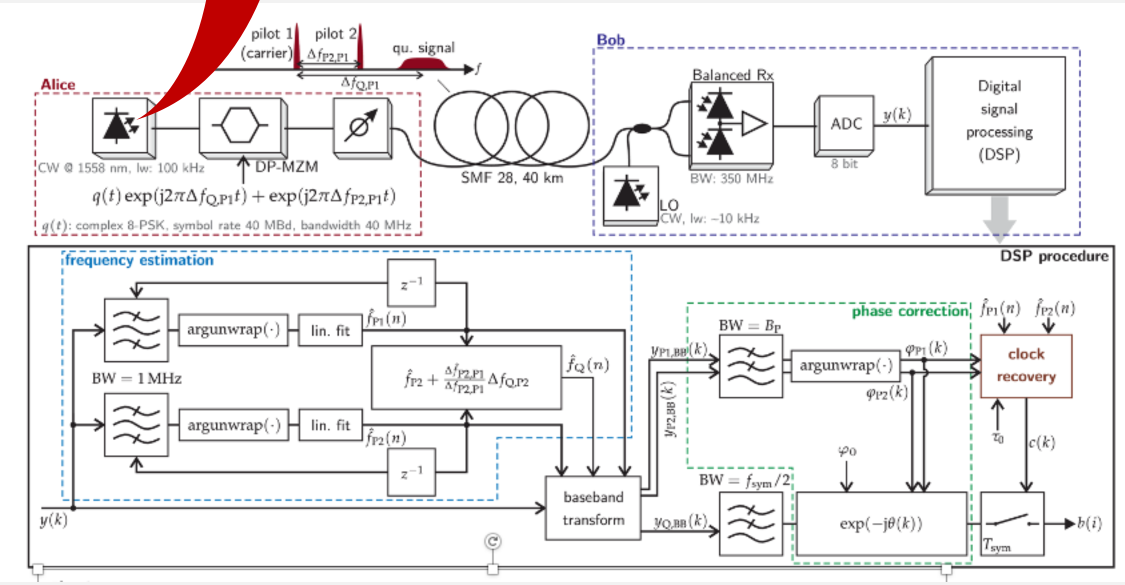
Photon Generation

N777xC Tunable Laser Source
Wavelength: 1240-1640 nm
Linewidth <10 kHz
Wavelength accuracy Typ +/- 10 pm



Helmut Schmidt University
Germany

Continuous Variable -QKD



Citation
Sebastian Kleis, Max Rueckmann, Christian G. Schaeffer, "Continuous variable quantum key distribution with a real local oscillator using simultaneous pilot signals," Opt. Lett. **42,** 1588-1591 (2017);
https://www.osapublishing.org/ol/abstract.cfm?uri=ol-42-8-1588

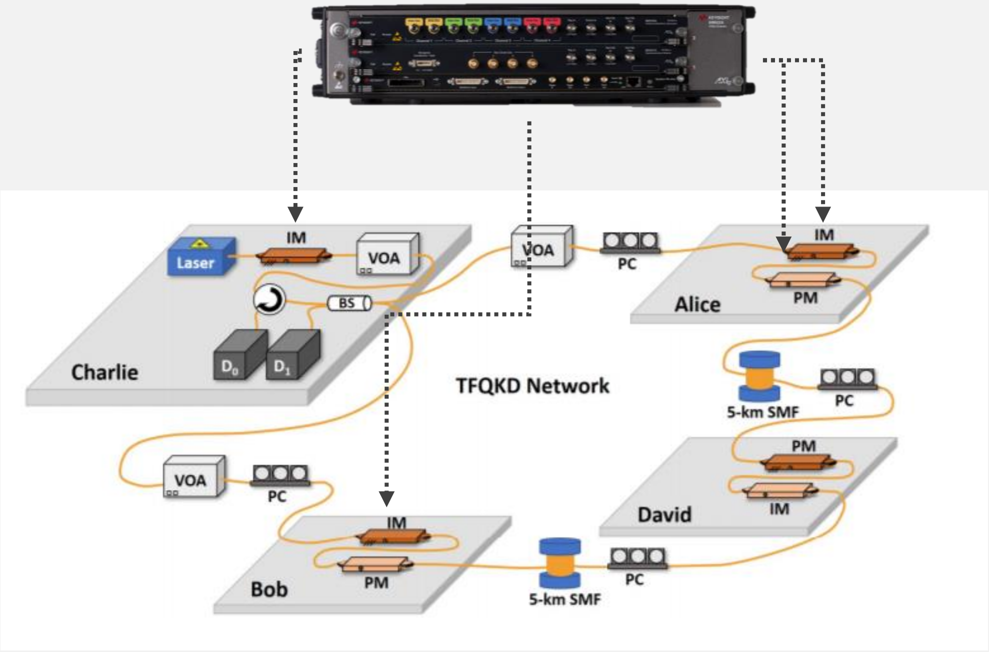
KEYSIGHT

High Speed AWG

Intensity and Phase Modulation

University of Toronto
Canada

M8195A High-Speed AWG



Twin-Field QKD

M8195A high-speed AWG
65 GSa/s sample rate
25 GHz bandwidth on up to 4 channels per module

Citation
X., W., R., H., & L. (jun 2021). Experiment on scalable multi-user twin-field quantum key distribution network. Retrieved July 17, 2021, from https://arxiv.org/pdf/2106.07768.pdf

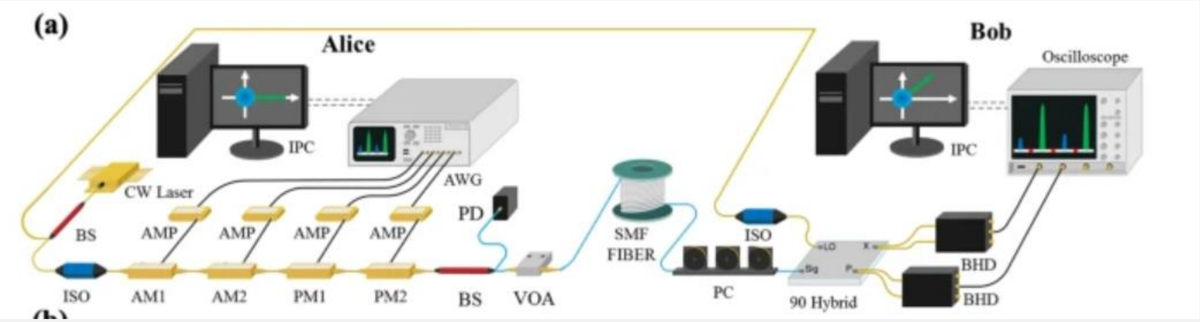
Real-Time Oscilloscopes

imagery and quadrature information

University of Cambridge
Massachusetts

Keysight Real-time Scopes
Superior hardware technology that offers the lowest noise floor, highest effective number of bits (ENOB), and highest bandwidth

Infiniium S-Series Oscilloscopes

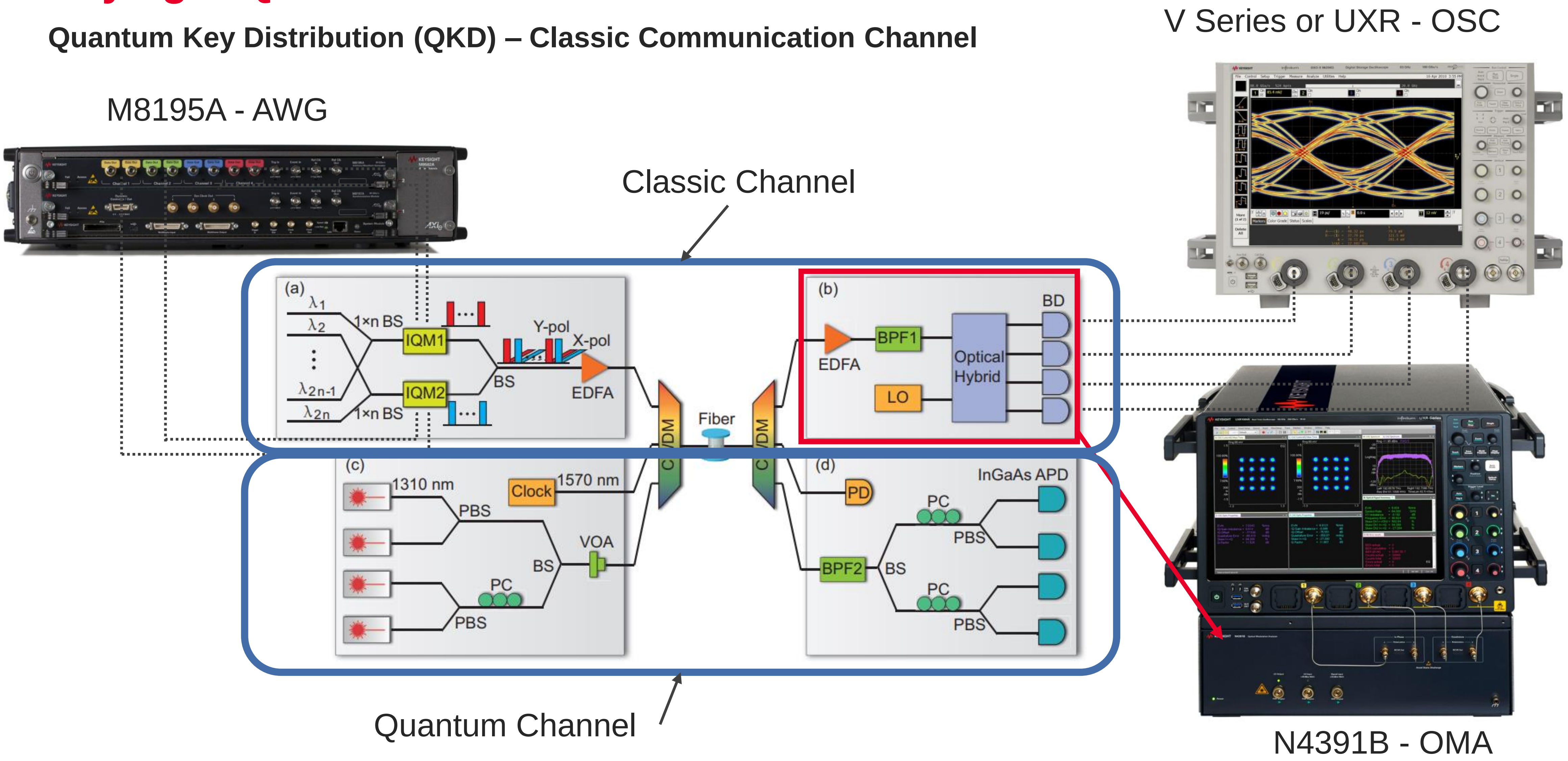


Continuous Variable - QKD

Citation:
Ren, S., Yang, S., Wonfor, A., White, I., & Penty, R. (2021). Demonstration of high-speed and low-complexity continuous variable quantum key distribution system with local oscillator.
https://www.nature.com/articles/s41598-021-88468-1

Keysight Quantum Communication

Quantum Key Distribution (QKD) – Classic Communication Channel



Liu-Jun Wang, et. al., 'Long distance co-propagation of quantum key distribution and terabit classical optical data channels', Phys. Rev. A (2017)

Keysight Products for QKD

Single Photon Generation (Alice)

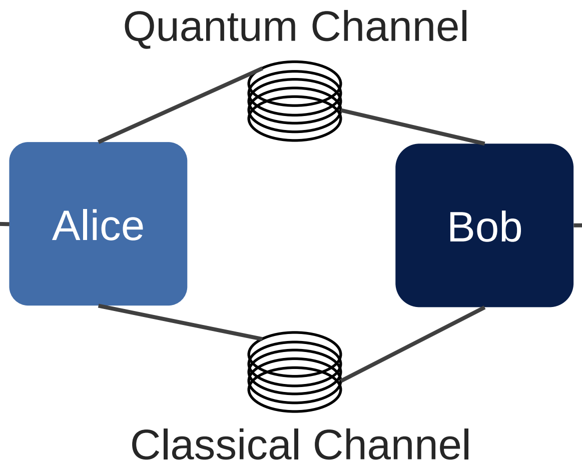
Tunable laser sources (N771xA, N777xC)

Waveform Generator (e.g. 33509B, M8195A)

Polarization Controller (N778xC)

Optical Attenuator (N778xC)

Light Wave Detector and Power Meters (N4377A, N774xC, 8162xC)



Detection (Bob)

Oscilloscopes

PXI/AXI Digitizers and Digital I/O Modules

BERTs (M8000A)

Labber for QKD Research

Single Photon Generation (Alice)

Tunable laser sources (N771xA, N777xC)

Waveform Generator (e.g. 33509B, M8195A)

Polarization Controller (N778xC)

Optical Attenuator (N778xC)

Light Wave Detector and Power Meters (N4377A, N774xC, 8162xC)

Labber QUANTUM

- Easy-to-use
- Programmable
- Automated
- Friendly GUI

Detection (Bob)

Oscilloscopes

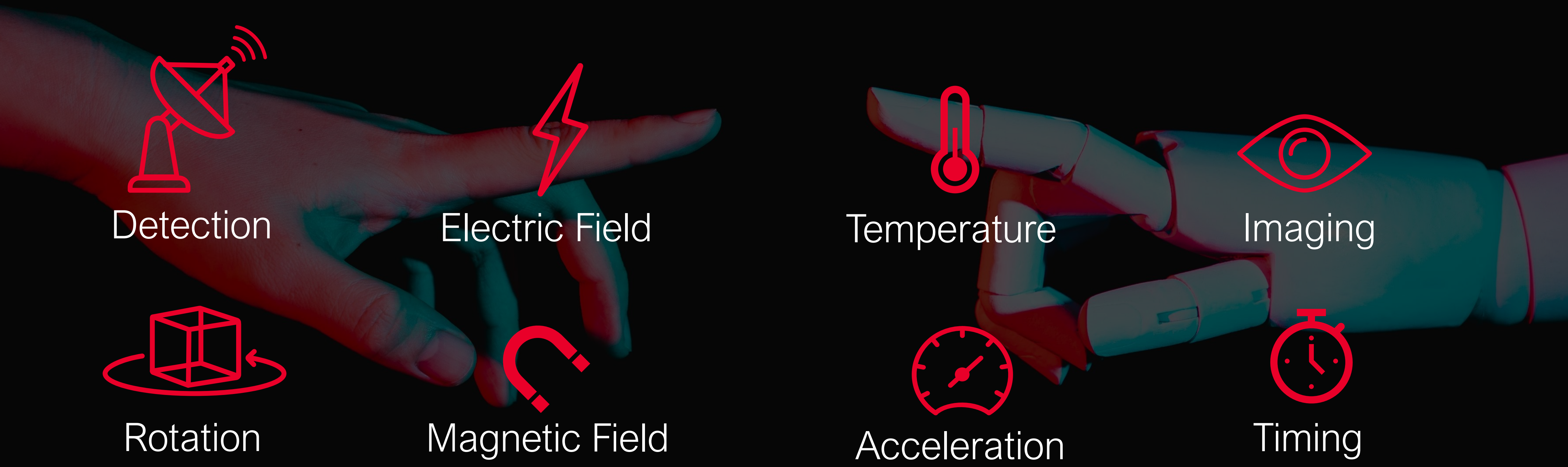
PXI/AXI Digitizers and Digital I/O Modules

BERTs (M8000A)

Quantum Sensing

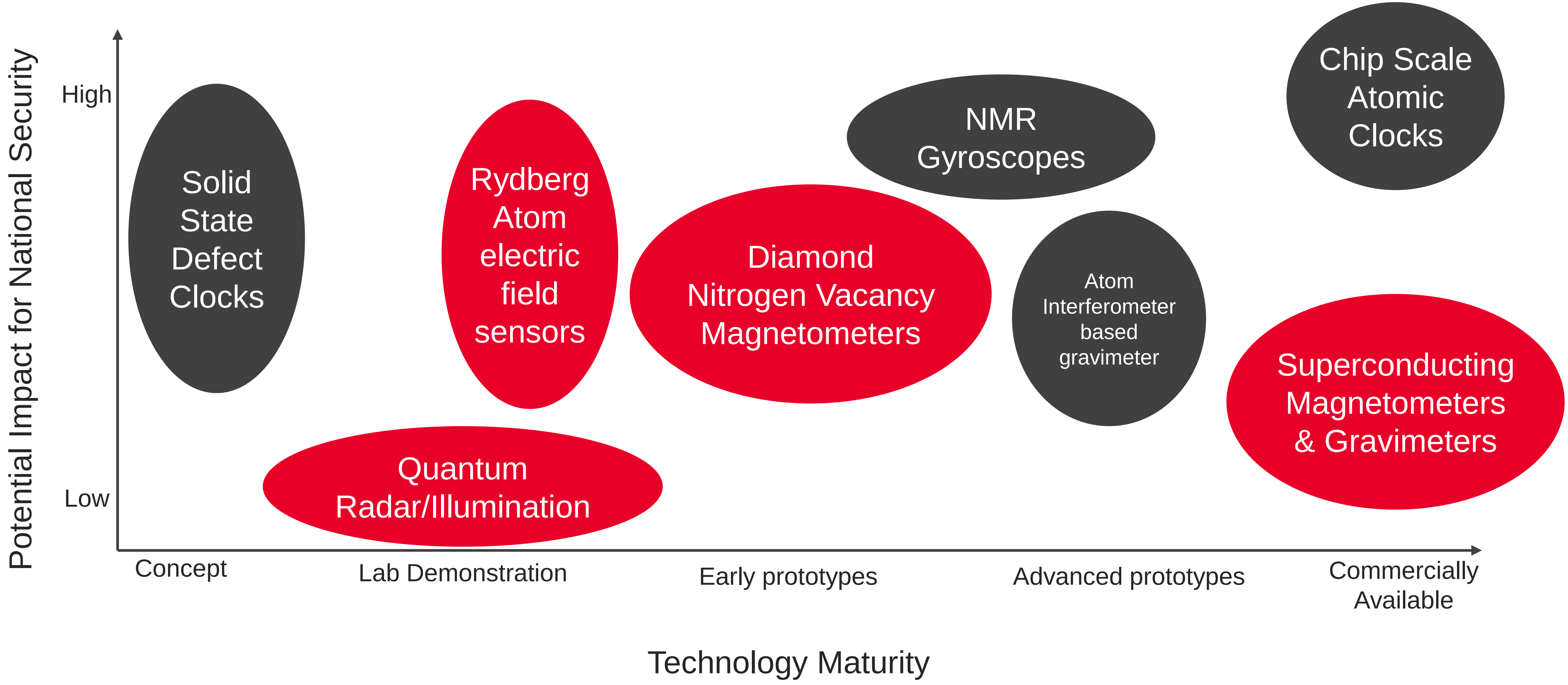
Quantum Sensing

A **quantum sensor** deals with the design and engineering of quantum sources and quantum measurements that improve performance over any classical approach in several technology applications.



Quantum Sensing Technologies

Potential for National Security



Quantum Sensing Technologies

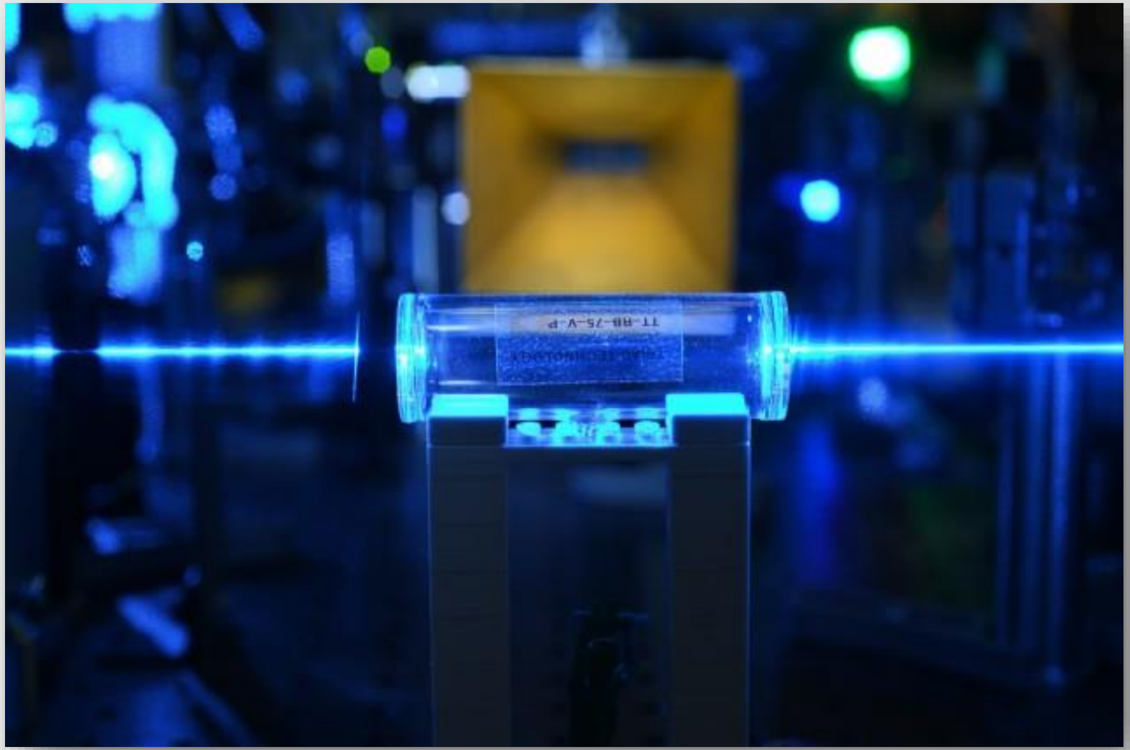
Detection

Electric Field

Rotation

Magnetic Field

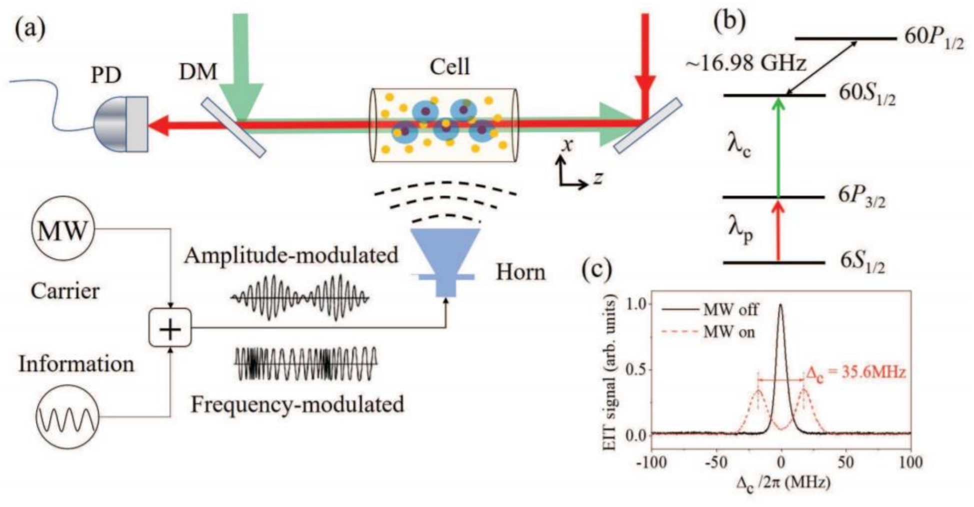
A **Rydberg atom** sensor is used for detecting communication signals over the entire frequency spectrum, from 0 to 1 THz.

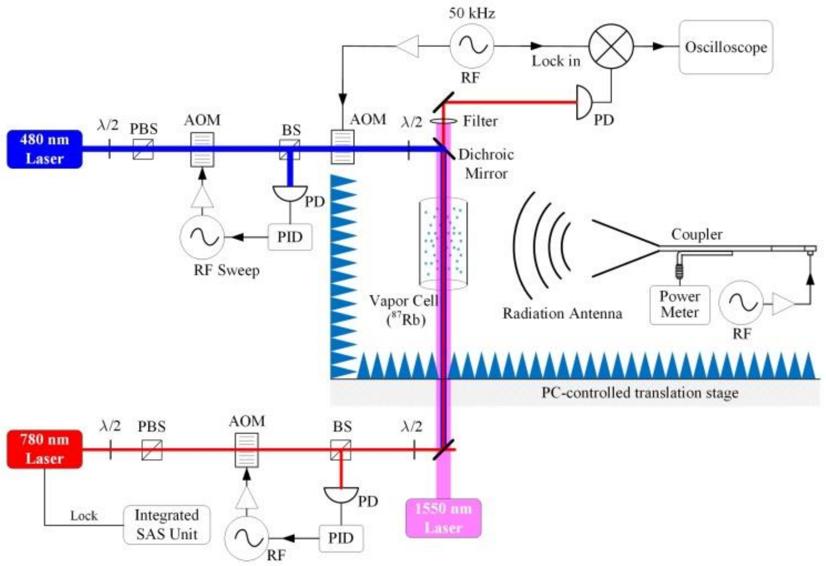


Big Atoms Make Small, Super-Sensitive Quantum Receivers
U.S. Army Research Lab

Rydberg Atoms

Quantum Receivers





N51XXB Microwave Analog Signal Generator

Jiao, Y., Han, X., Fan, J., Raithel, G., Zhao, J., & Jia, S. (2019). Atom-based receiver for amplitude-modulated baseband signals in high-frequency radio communication. *Applied Physics Express*, *12*(12), 126002. doi:10.7567/1882-0786/ab5463

Shanxi University

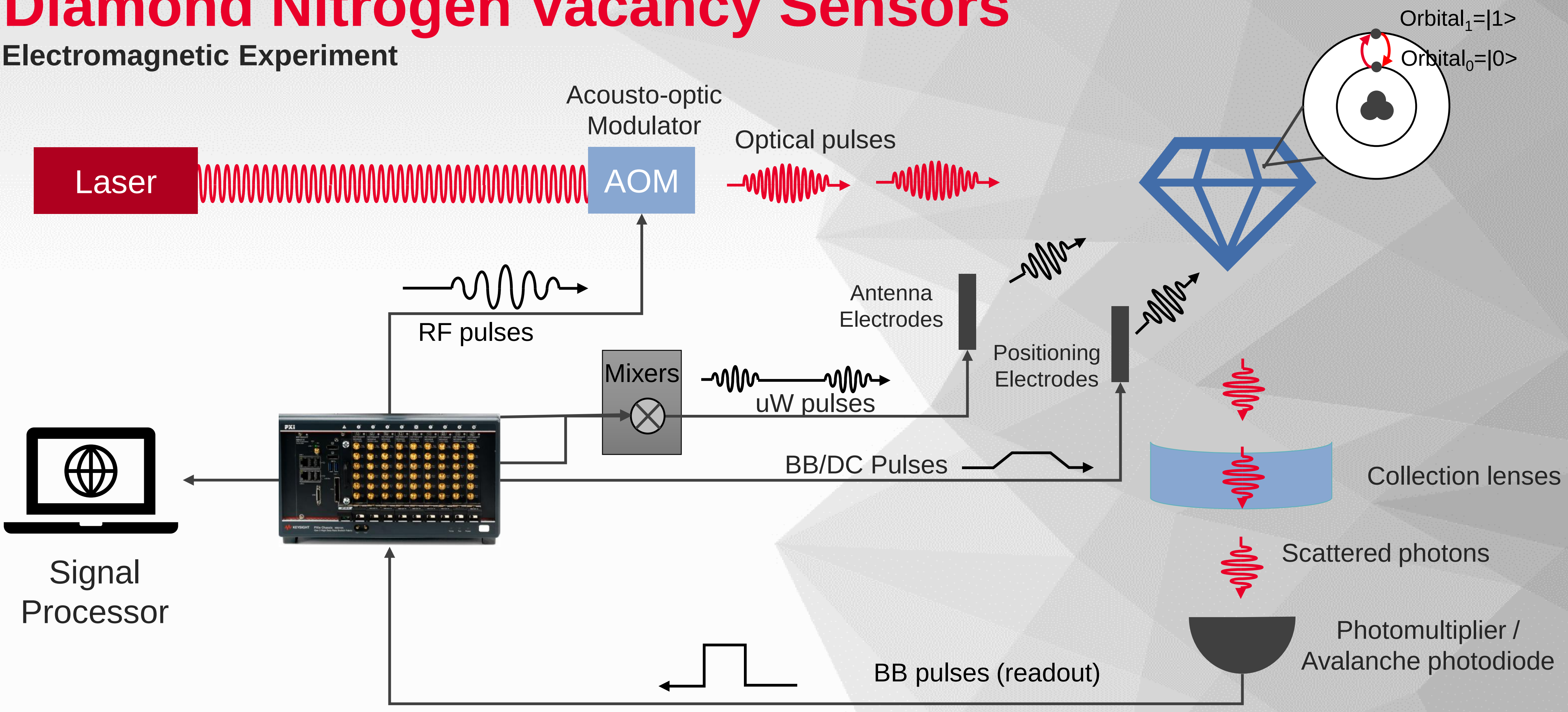
E8257D PSG Analog Signal Generator

Song, Z., Zhang, W., Wu, Q., Mu, H., Liu, X., Zhang, L., & Qu, J. (2018). Field Distortion and Optimization of a Vapor Cell in Rydberg Atom-Based Radio-Frequency Electric Field Measurement. *Sensors*, *18*(10), 3205. doi:10.3390/s18103205

National Institute of Metrology

Diamond Nitrogen Vacancy Sensors

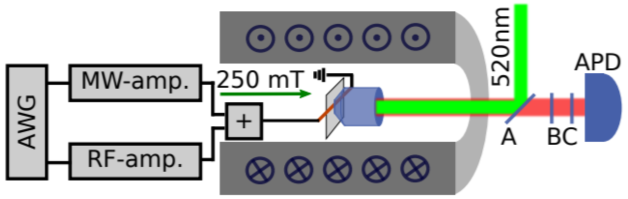
Electromagnetic Experiment



Diamond Nitrogen Vacancies

Electromagnetic Sensors

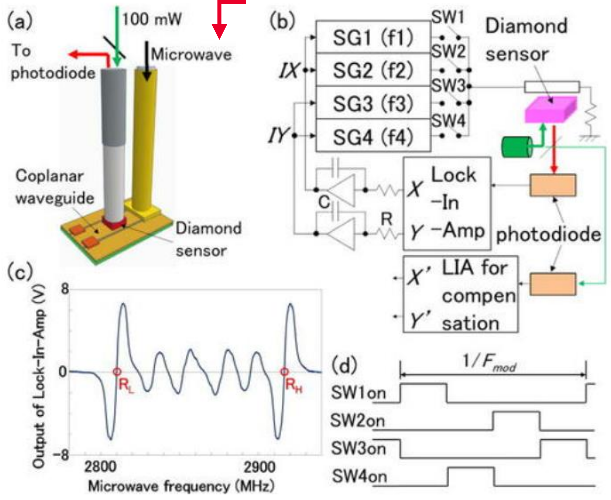
M819XA High Speed AWG



Meinel, J., Vorobyov, V., Yavkin, B., Dasari, D., Sumiya, H., Onoda, S., . . . Wrachtrup, J. (2021). Heterodyne sensing of microwaves with a quantum sensor. *Nature Communications*, *12*(1). doi:10.1038/s41467-021-22714-y

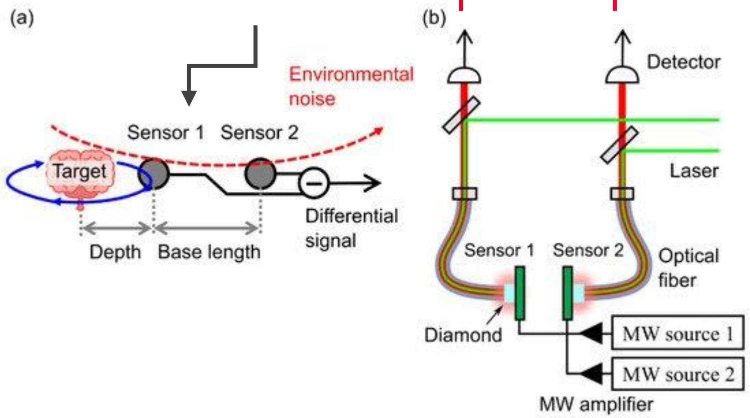
Max Planck Institute, Germany

N51XXB MXG Analog Signal Generator



Hatano, Y., Shin, J., Nishitani, D., Iwatsuka, H., Masuyama, Y., Sugiyama, H., . . . Hatano, M. (2021). Simultaneous thermometry and magnetometry using a fiber-coupled quantum diamond sensor. *Applied Physics Letters*, *118*(3), 034001. doi:10.1063/5.0031502

Oscilloscope DSOS054A



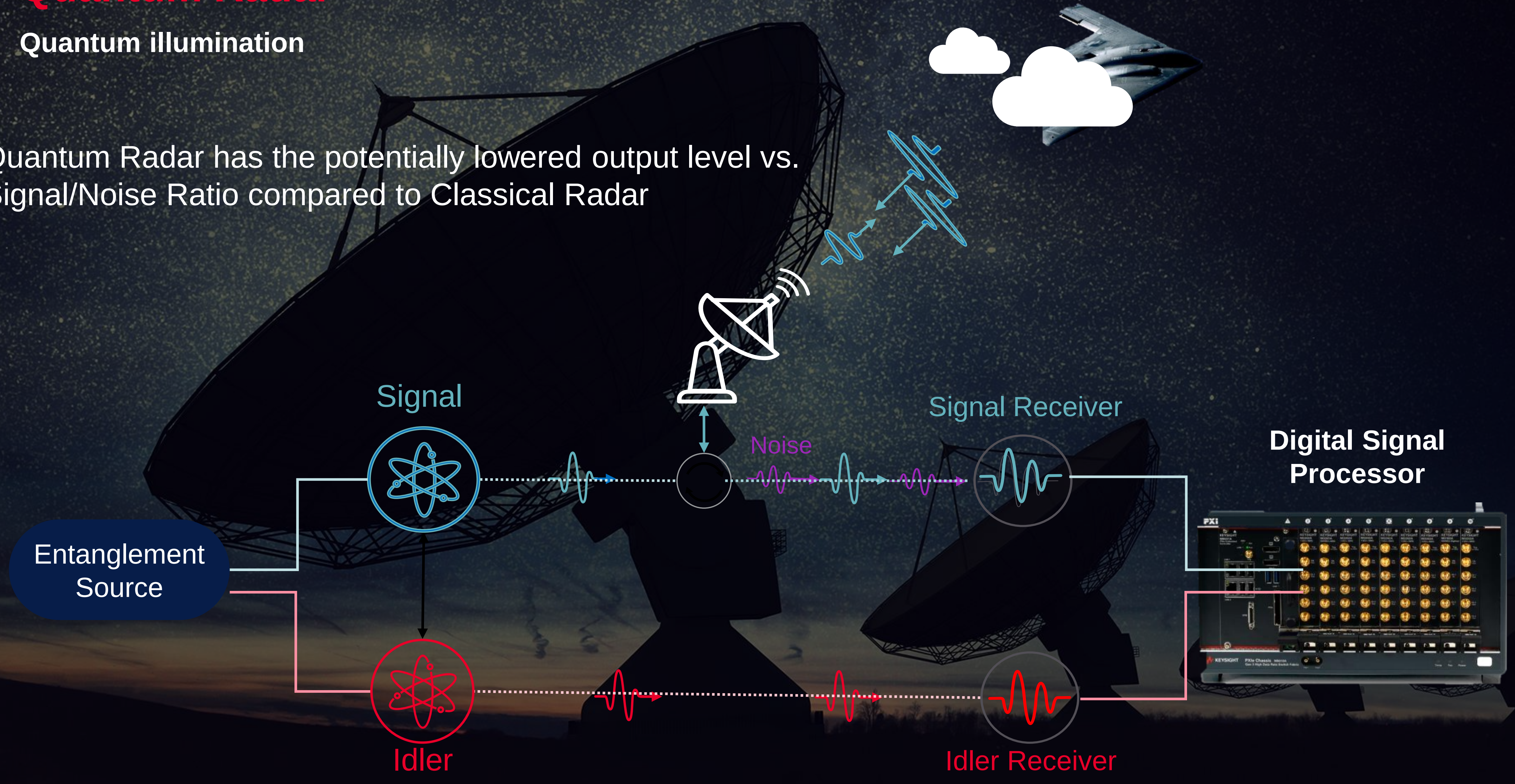
Masuyama Y;Suzuki K;Hekizono A;Iwanami M;Hatano M;Iwasaki T;Ohshima T;. (n.d.). Gradiometer Using Separated Diamond Quantum Magnetometers. Retrieved from https://pubmed.ncbi.nlm.nih.gov/33540515/

Tokyo Institute of Technology, Japan

Quantum Radar

Quantum illumination

Quantum Radar has the potentially lowered output level vs. Signal/Noise Ratio compared to Classical Radar



Summary

Keysight is at the Heart of the Digital Revolution

Accelerating innovation to connect and secure the world

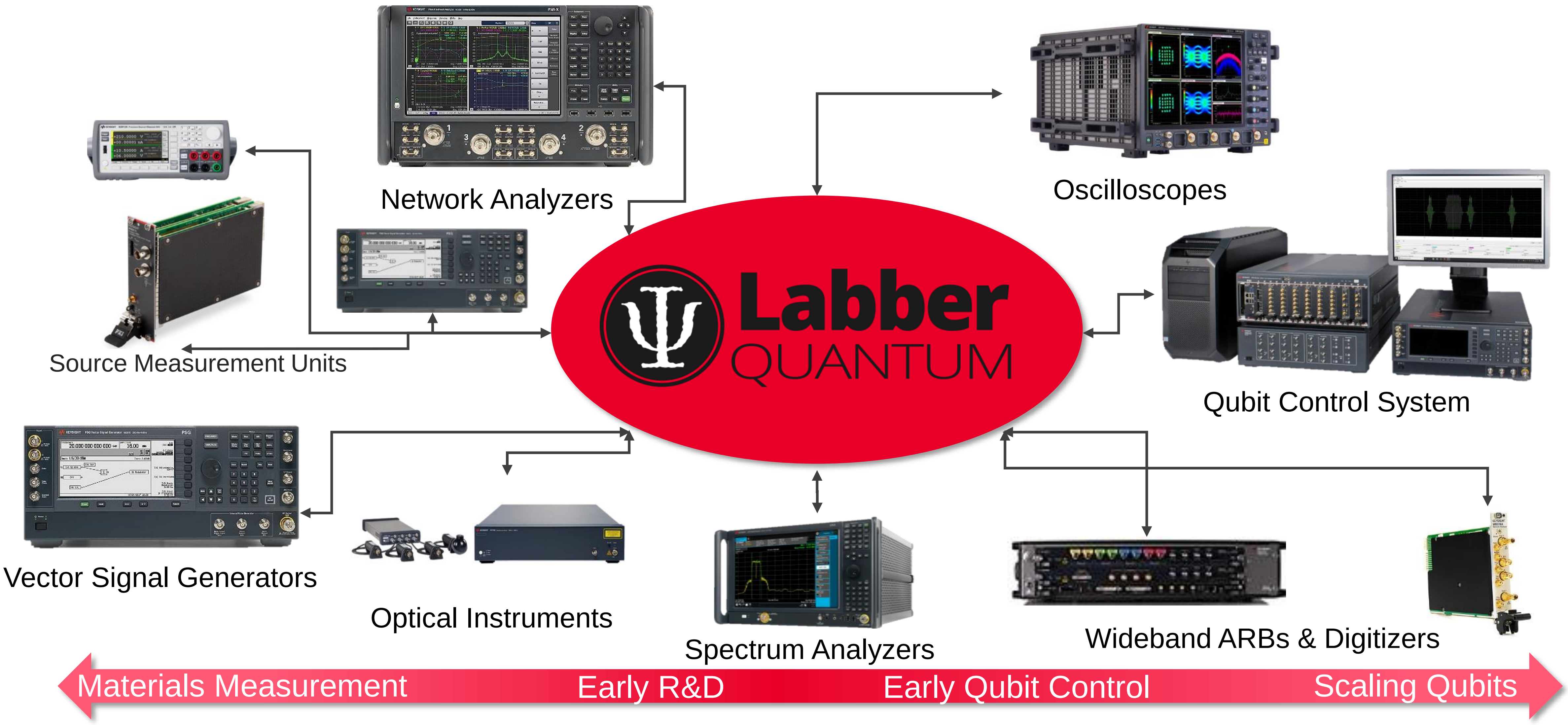
SMART TECHNOLOGY CONNECTS THE WORLD

INNOVATION IS EVERYWHERE

- ✓ Devices
- ✓ Infrastructure
- ✓ Cities
- ✓ Defense
- ✓ Vehicles
- ✓ Wearables

Keysight's Quantum Team Footprint

Keysight Hardware and Software Quantum Ecosystem



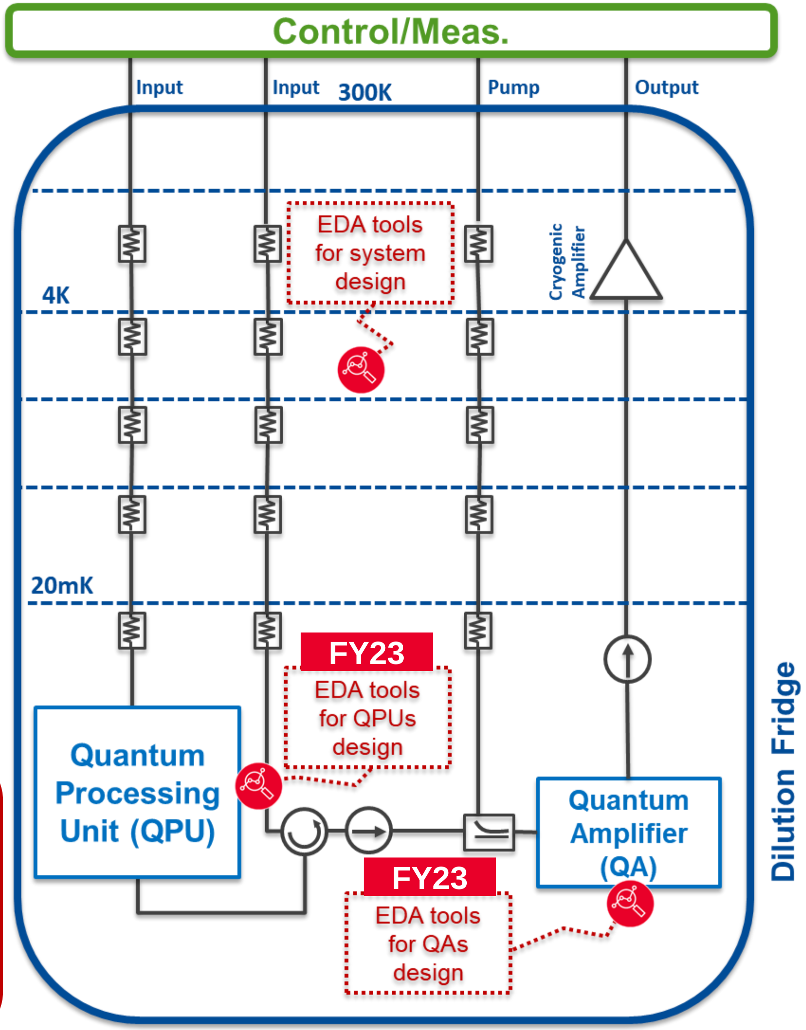
Quantum EDA at Keysight

Solutions for Superconducting Qubits

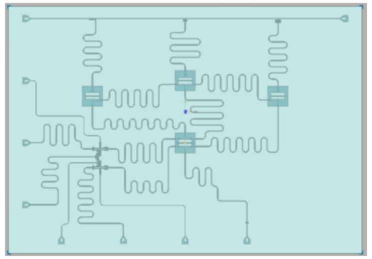
Quantum EDA Strategy

- Make the connection between quantum and EDA worlds
- Translating Quantum parameters into EDA design
- Integrated workflows
- Faster cycle of qubit design
- Extracting Quantum parameters from EDA simulations

Marching towards providing market-leading EDA tools to streamline the design of qubits

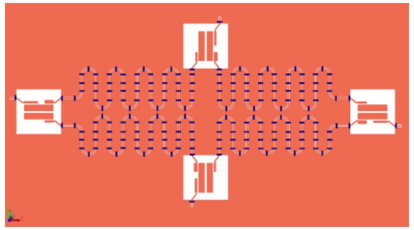


Quantum Systems



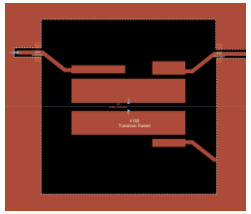
7 Qubits in EMPro

Quantum Circuits



4 Qubits in RFPro

Quantum Devices



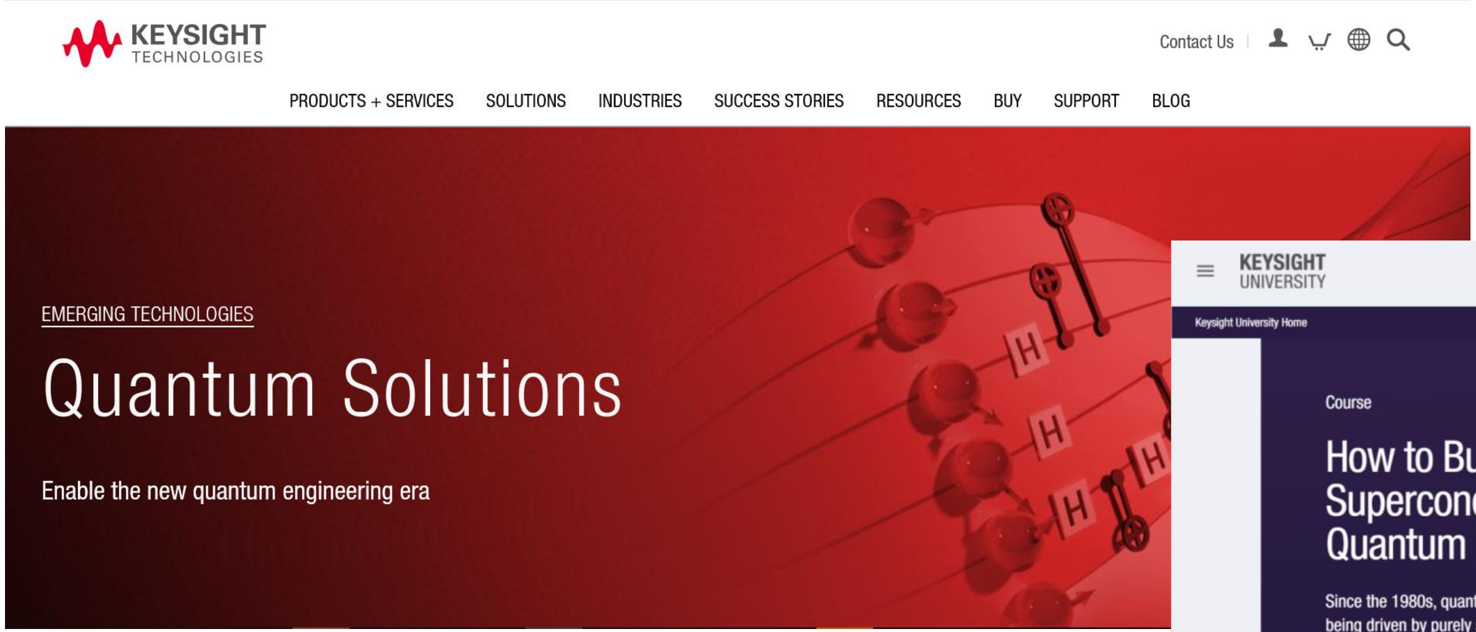
A qubit in ADS Layout

Quantum Junction

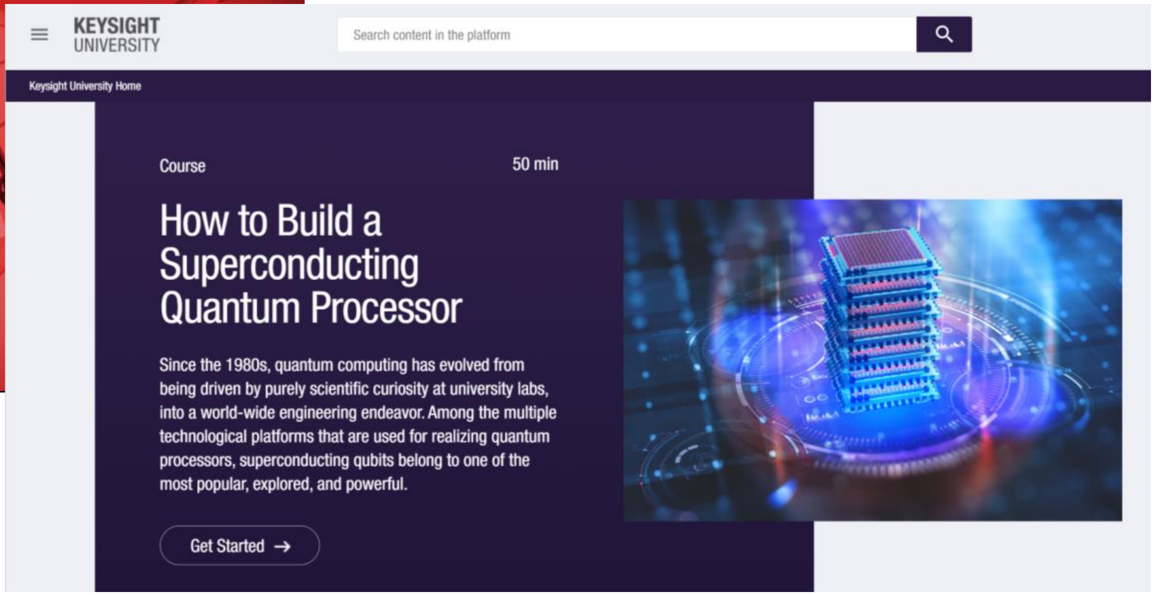
Josephson junction in ADS Circuit

Come find out more on Keysight.com

www.keysight.com/find/quantum



Take a quick tour of the Keysight Quantum web page (LINK)



Take a quick tour of the Keysight University web page (LINK)

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Thank you