Quantum Implementation and Measurement Overview

Dr. Kristine Boone, *Business Development*
Aidin Taeb **(aidin.taeb@keysight.com),** *RF/μwave Solution Engineer*

2023

Agenda

- Introduction to Quantum Technology
  - Quantum applications and typical requirements
  - Control and readout of qubits using real signals
  - Superconducting qubits
- Keysight and quantum ecosystem
- Cryogenic Measurement Challenges & Calibration
  - VNA application in quantum
- Introducing new QCS

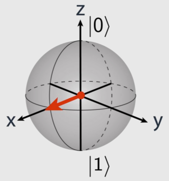
Introduction to Quantum Technology

Quantum Technologies – From theory to practice

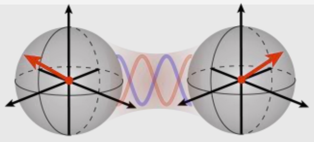
Quantum Mechanics

Superposition states

$$|\psi\rangle = c_0|0\rangle + c_1|1\rangle$$



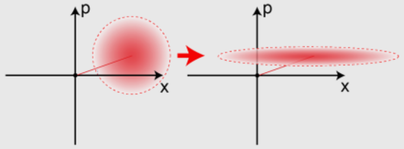
Entanglement



$$|\psi\rangle = c_{00}|00\rangle + c_{01}|01\rangle + c_{10}|10\rangle + c_{11}|11\rangle$$

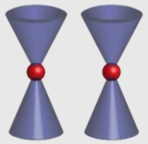
Quantum squeezing

$$\Delta x \Delta p \geq \frac{\hbar}{2}$$

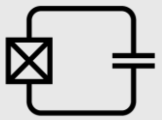


Two-level systems

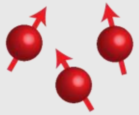
Trapped Ions



Superconducting circuits



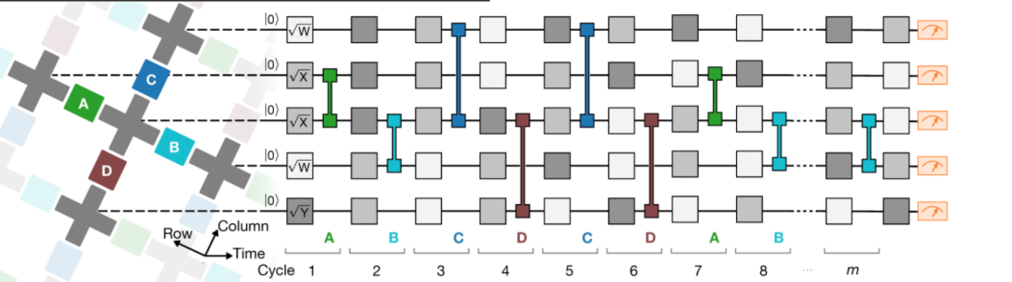
Spin Qubits



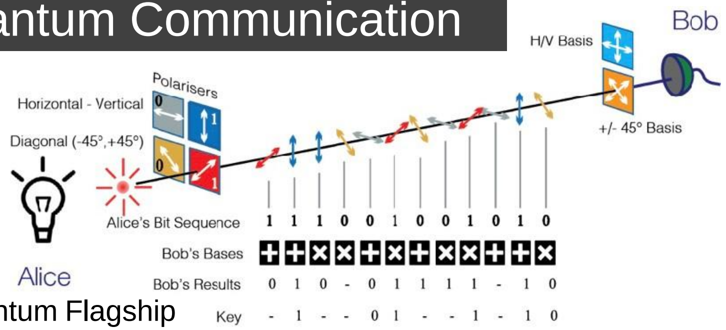
Photons

Quantum Computing

F. Arute et al. **Nature**, 505-510 (2019)

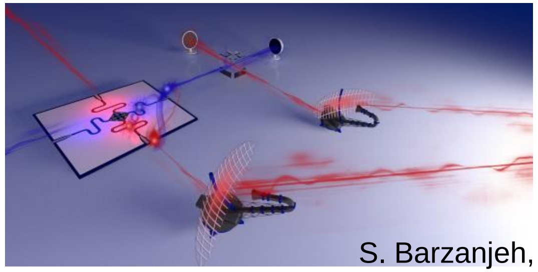


Quantum Communication



EU Quantum Flagship

Quantum Sensing



S. Barzanjeh, et al. Science Advances (2019)

Classical vs. Quantum information

Classical computer

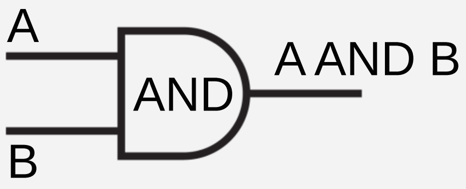
Bit:

0 or 1

Classical (boolean) logic:

NOT, AND, NAND

A	B	A AND B
0	0	0
0	1	0
1	0	0
1	1	1

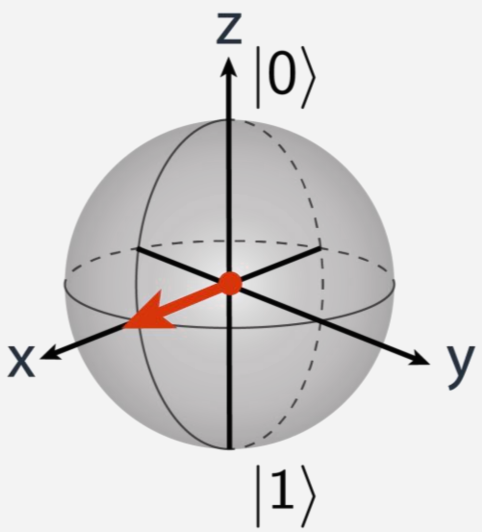


Quantum computer

Quantum bit (Qubit):

$$|\psi\rangle = c_0|0\rangle + c_1|1\rangle$$

- Superposition

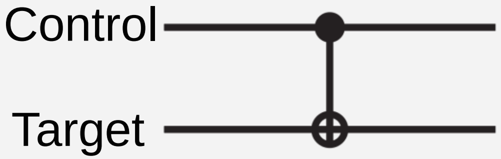


Quantum logic:

Controlled-NOT (CNOT)

- Entanglement

INPUT	OUTPUT
$\lvert 00\rangle$	$\lvert 00\rangle$
$\lvert 01\rangle$	$\lvert 01\rangle$
$\lvert 10\rangle$	$\lvert 11\rangle$
$\lvert 11\rangle$	$\lvert 10\rangle$



Quantum Computing Experiments

What does a quantum computer look like?

Example setup: 1 qubit configuration with XYZ control.

Control HW

↓

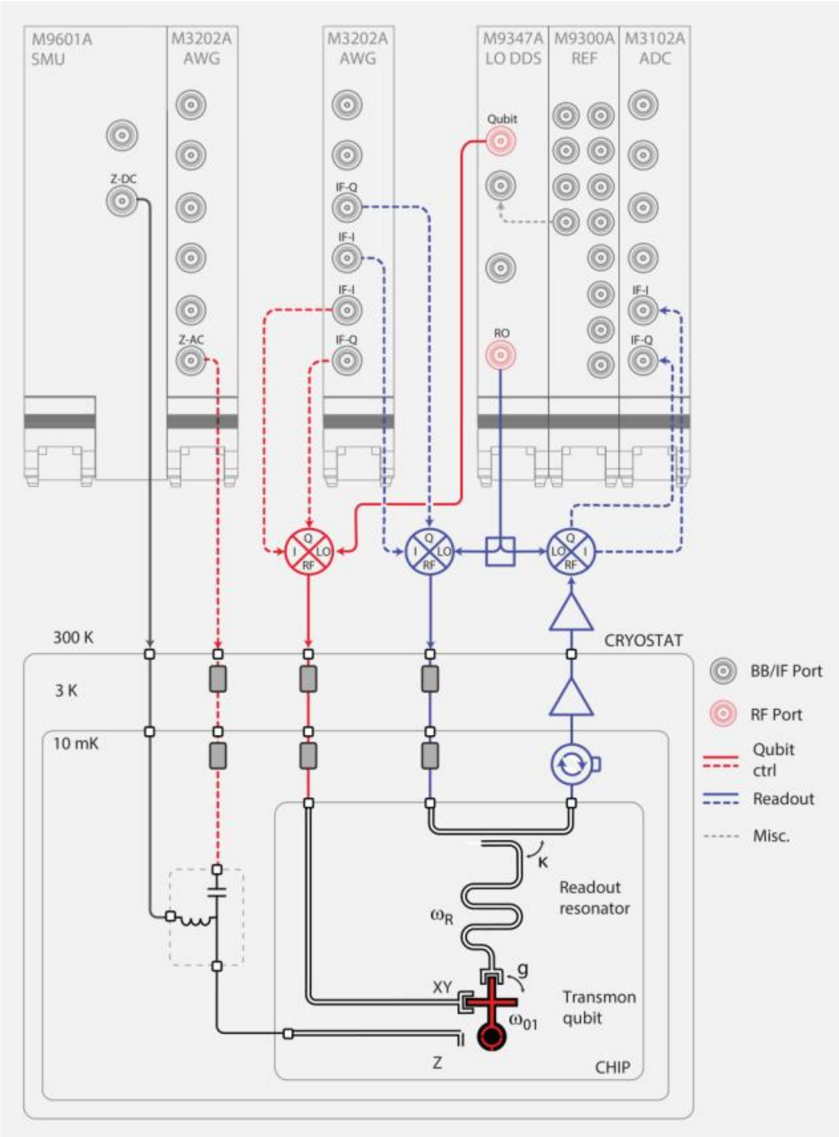
Qubit(s)

↓

Readout Devices

↓

Signal Processing



Classical

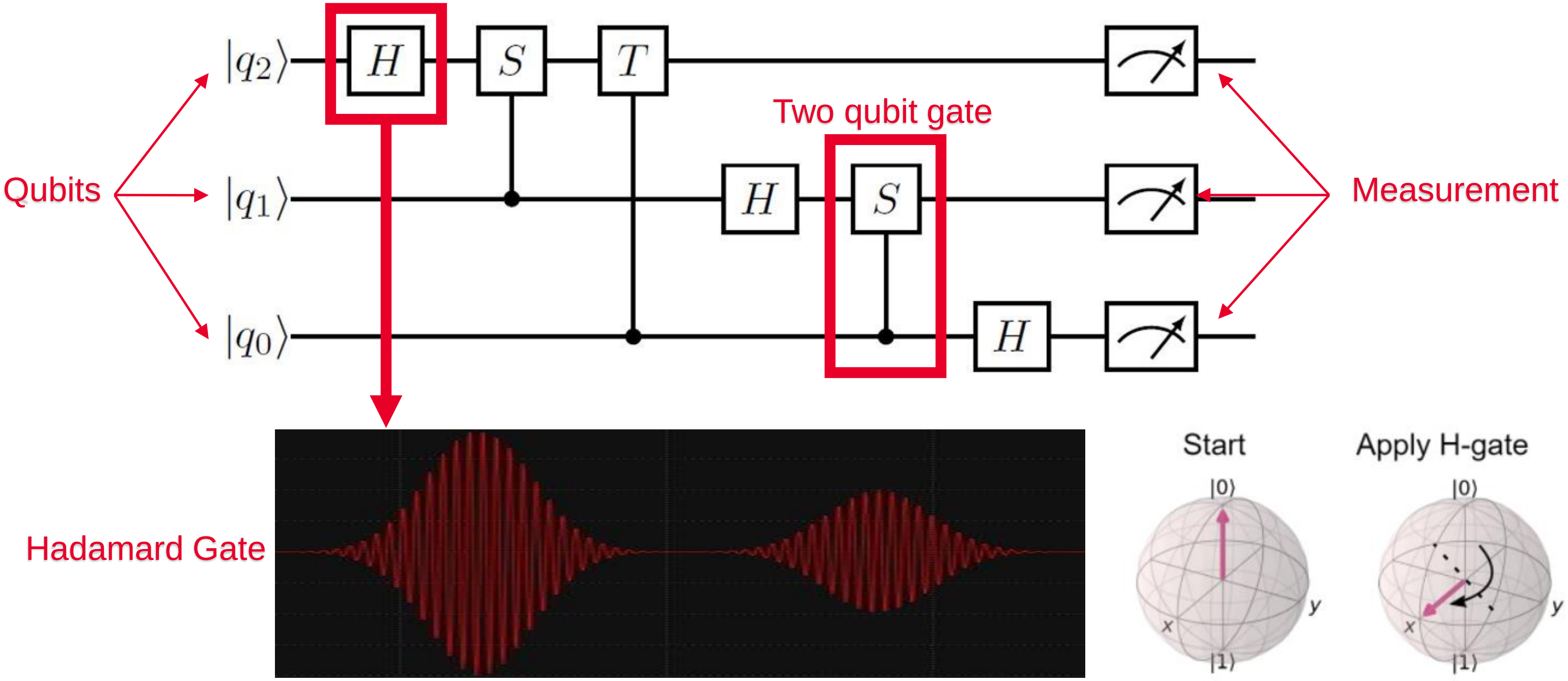
Notice that a quantum computer must seamlessly blend classical and quantum components to function.

Quantum

KEYSIGHT

Quantum Computing Experiments

What does a quantum algorithm look like?



Quantum Circuit:
Quantum equivalent of classical logic circuits.

Gate:
Quantum equivalent of classical logic gates.

Theory:
Quantum physicists use matrix notation to represent qubit states and gate operations.

Experiment:
Qubit states and gates physically translate to different energy levels (or other physical property) which can be manipulated in the lab.

Control and Readout of Qubits Using Real Signals

Qubit Physical Implementation and Control

- **Qubit implementation**

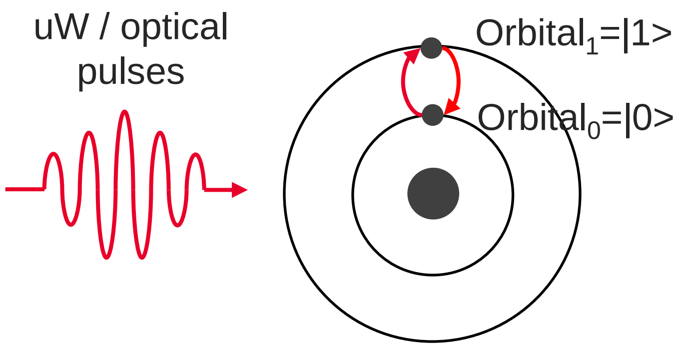
  Any two-level system (|0> - |1>) that has quantum behavior (superposition, entanglement, etc.). E.g.:

  - e^- orbital → trapped ions
  - flux → superconducting flux qubits
  - e^- spin → quantum dots
  - nitrogen vacancy (NV) spin -> NV in diamonds
  - photon polarization → photons
  - …
  - …

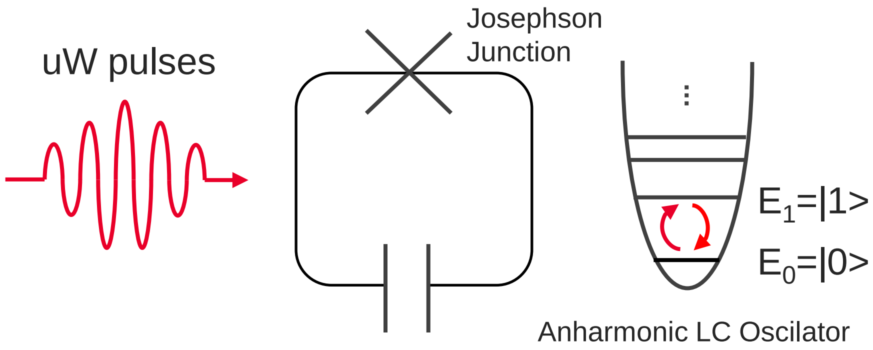
- **Qubit control**

  Performed by applying the energy of the |0> - |1> transition with electromagnetic pulses (RF, uW or optical)

E.g. Trapped ion



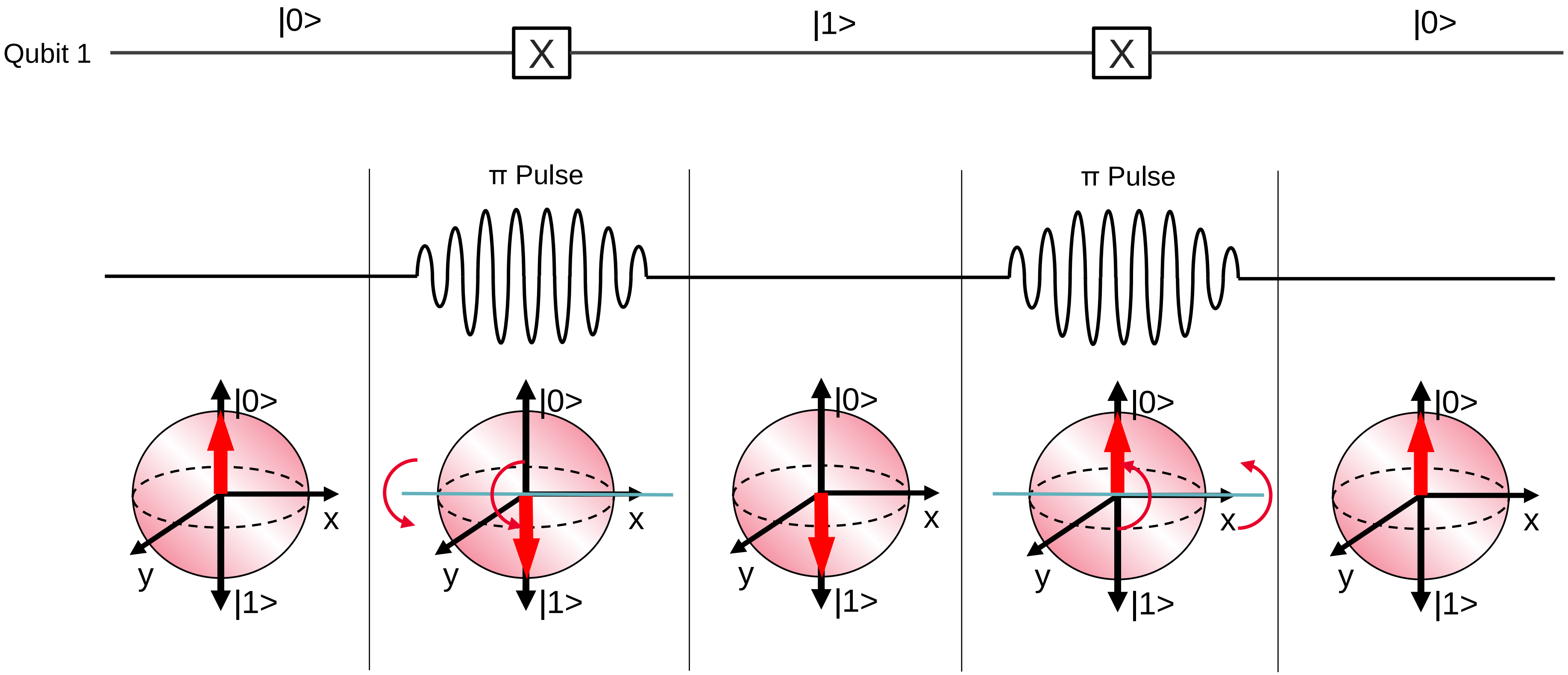
E.g. Superconducting qubit



https://www.keysight.com/us/en/assets/3120-1453/application-notes/Quantum_Computing.pdf

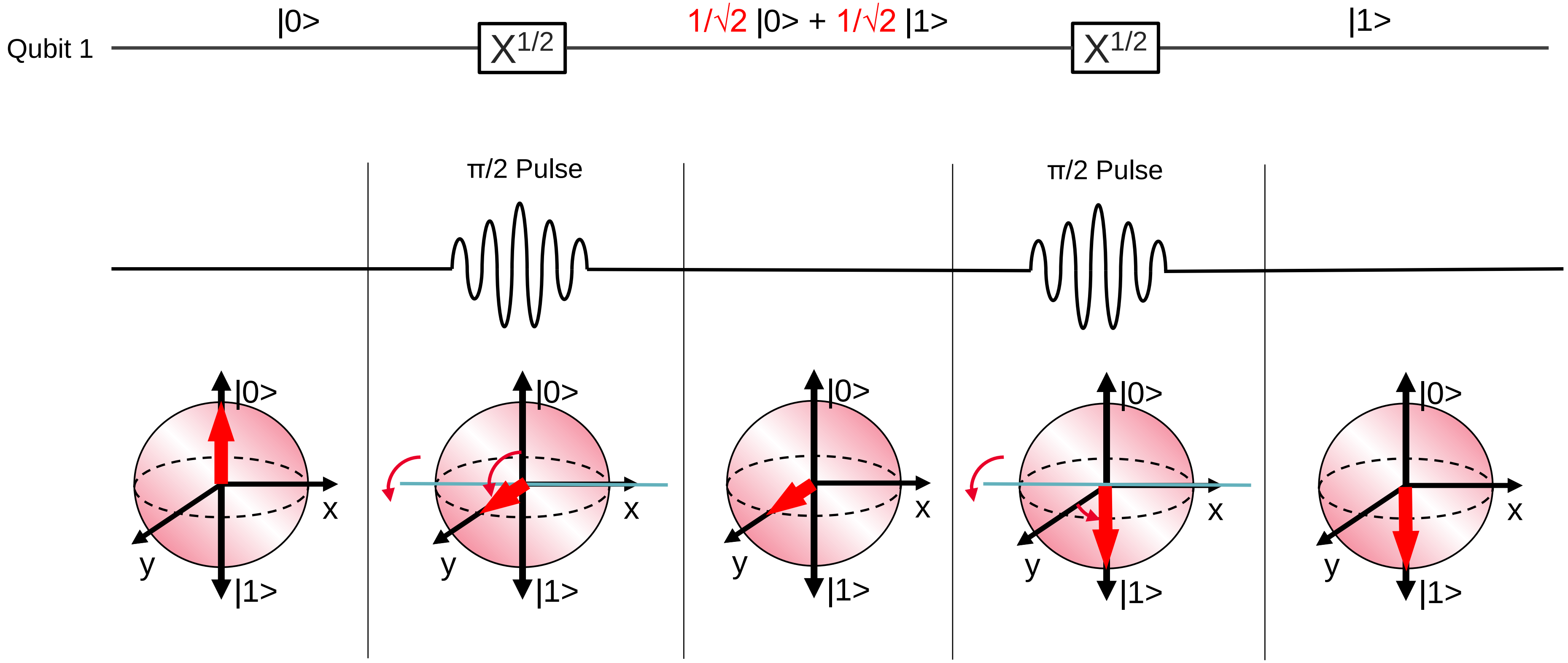
Control of Qubits – Pulse Area

- Pulse area (amplitude and duration) defines the amount of rotation



Control of Qubits – Pulse Area

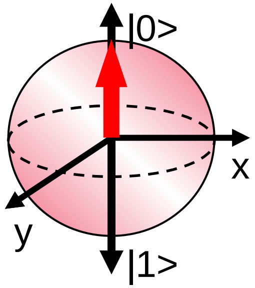
- Pulse area (amplitude and duration) defines the amount of rotation



That is also why amplitude stability is important

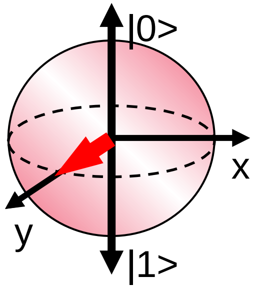
Control of Qubits – Readout

- Readout projects the qubit (destroys the information) into |0> or |1> → readout result is binary (either |0> or |1>)
  - How do we get α and β (α|0> + β|1>)? → statistics



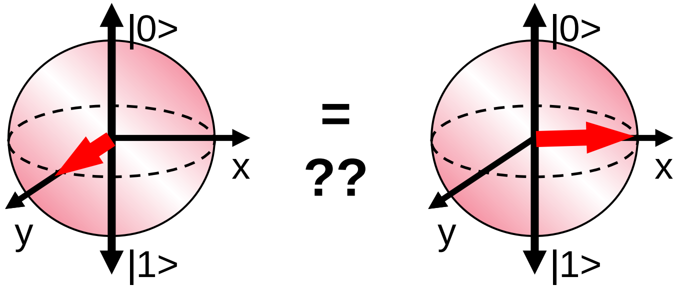
|0>
Means 100% probability of obtaining |0> and 0% of obtaining |1>

Many experimental repetitions are required to get the statistics



$1/\sqrt{2}$ |0> + $1/\sqrt{2}$ |1>
Means 50% probability of obtaining |0> and 50% of obtaining |1>

Phase information??



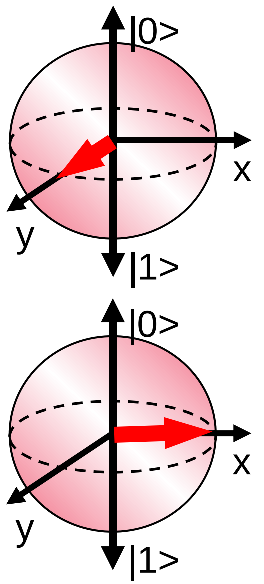
$1/\sqrt{2}$ |0> + $1/\sqrt{2}$ |1> ≠ $1/\sqrt{2}$ |0> + $i/\sqrt{2}$ |1>
But both have 50% probability of |0> and 50% of |1>

Control of Qubits – Readout

- Readout projects the qubit (destroys the information) into |0> or |1> → readout result is binary (either |0> or |1>)
  - How do we get α and β (α|0> + β|1>)? → statistics and ROTATIONS

Step 1: repeat many times

1) Run experiment
2) Measure



50% |0> and 50% |1>

Indistinguishable

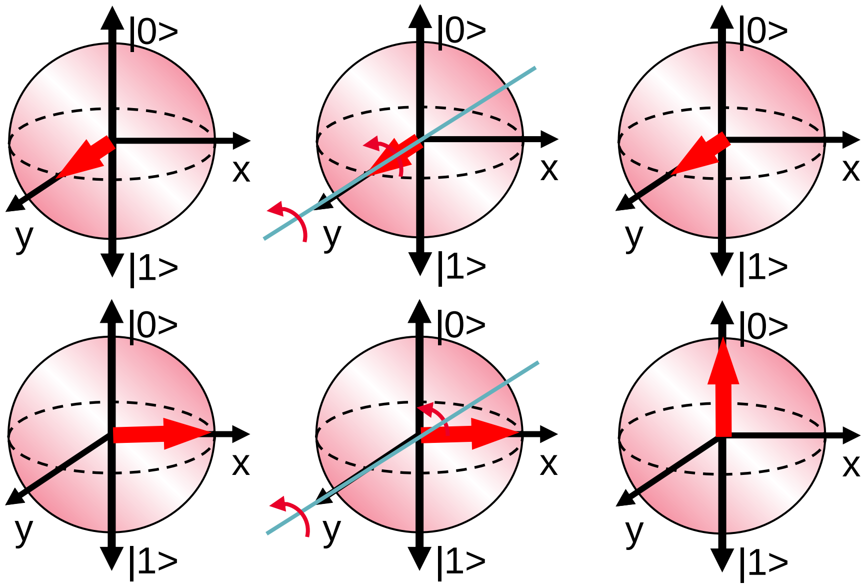
50% |0> and 50% |1>

Step 2: repeat many times

1) Run experiment
2) Pulse to rotate Y 90º
3) Measure

Step 3: do the same for X axis

Full state tomography requires many operations



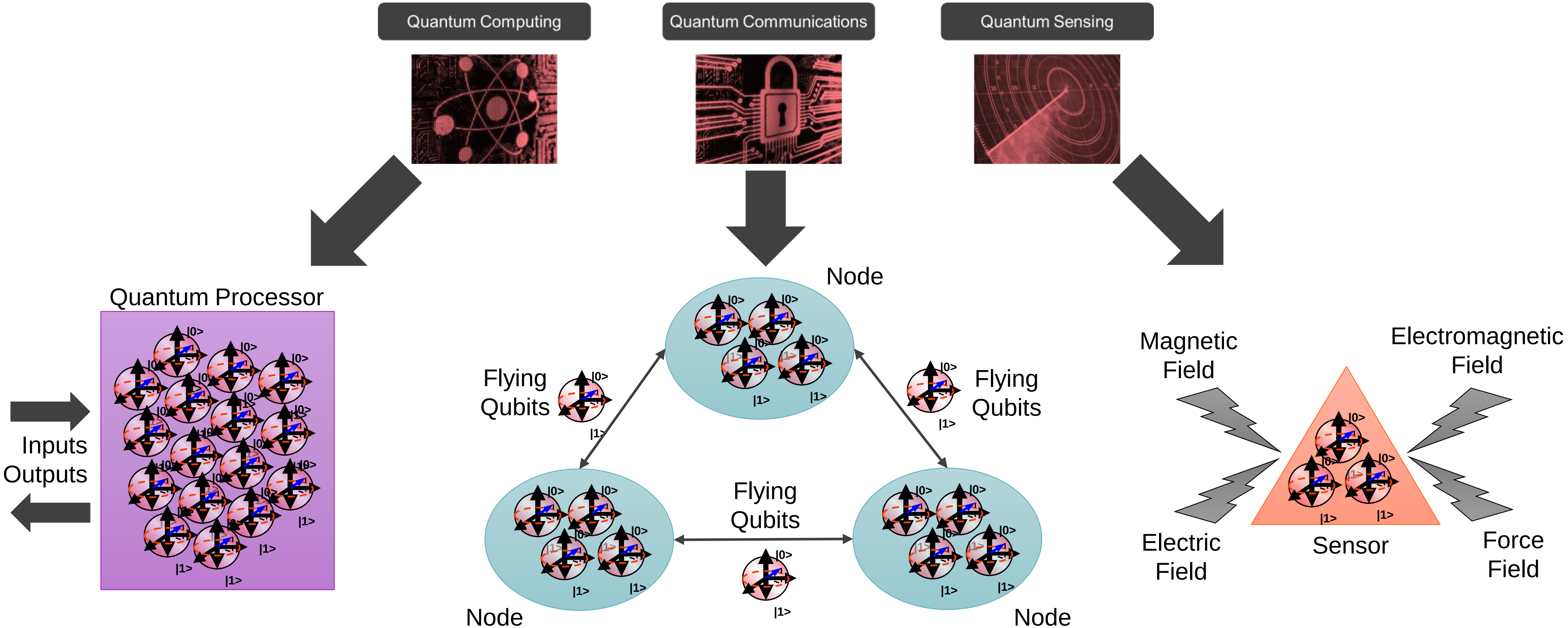
50% |0> and 50% |1>

Distinguishable

100% |0> and 0% |1>

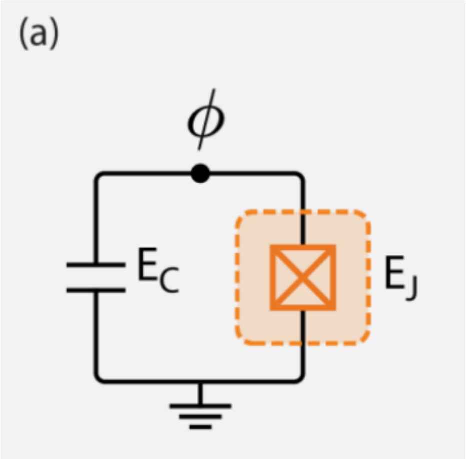
Qubit Types

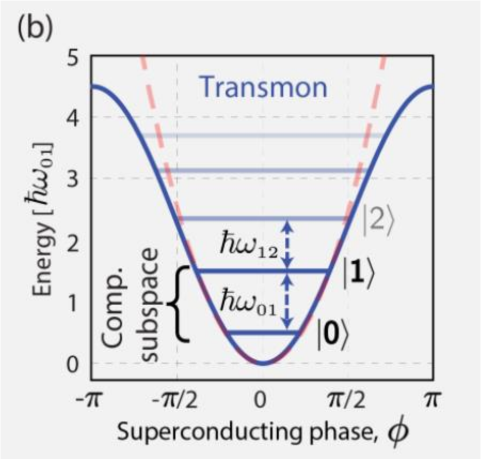
Qubits are the Pillars for all Quantum Applications

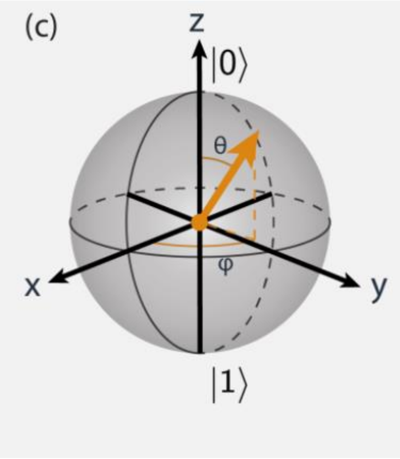


Superconducting Qubits

“Artificial atoms” built out of superconducting circuits







Superconducting Circuit

Resonant circuit.

Leverages collective behavior of electrons in circuit.

Artificial Atom

Qubit has properties of anharmonic multi-level quantum system.

Qubit states are encoded in the lowest energy levels.

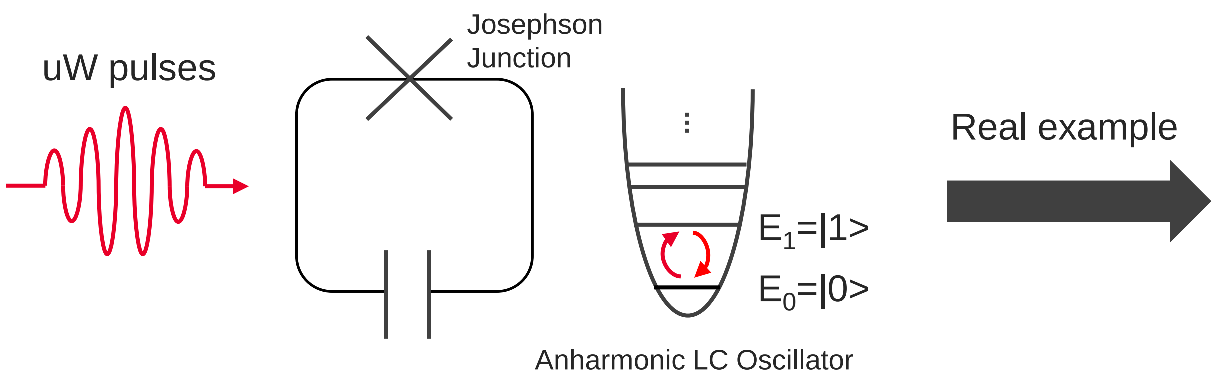
Bloch Sphere Representation

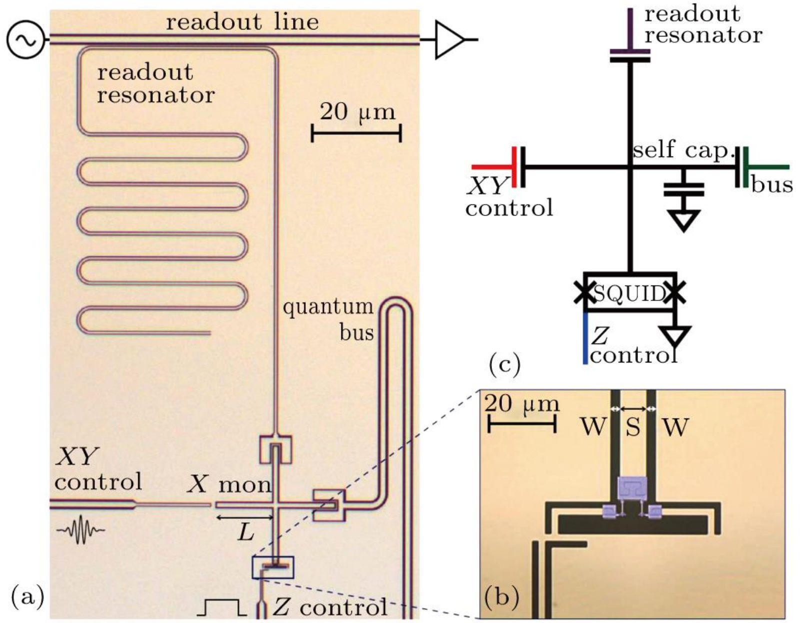
Bloch sphere representation of the qubit state, with the ground state |0⟩ at the North pole and the excited state |1⟩ at its South pole.

https://www.keysight.com/us/en/assets/3120-1387/application-notes/Characterizing-Superconducting-Qubits.pdf?success=true

Superconducting Qubits

E.g. Superconducting qubit





- **Qubit control**
  - Performed by applying the energy of the |0> - |1> transition with electromagnetic pulses (uW pulses)
- **Qubit readout**
  - Performed by applying pulses to a resonator coupled to the qubit and then measure the amplitude or the phase of the transmitted or reflected signal

https://www.annualreviews.org/doi/pdf/10.1146/annurev-conmatphys-031119-050605

Control and Readout of a Qubit

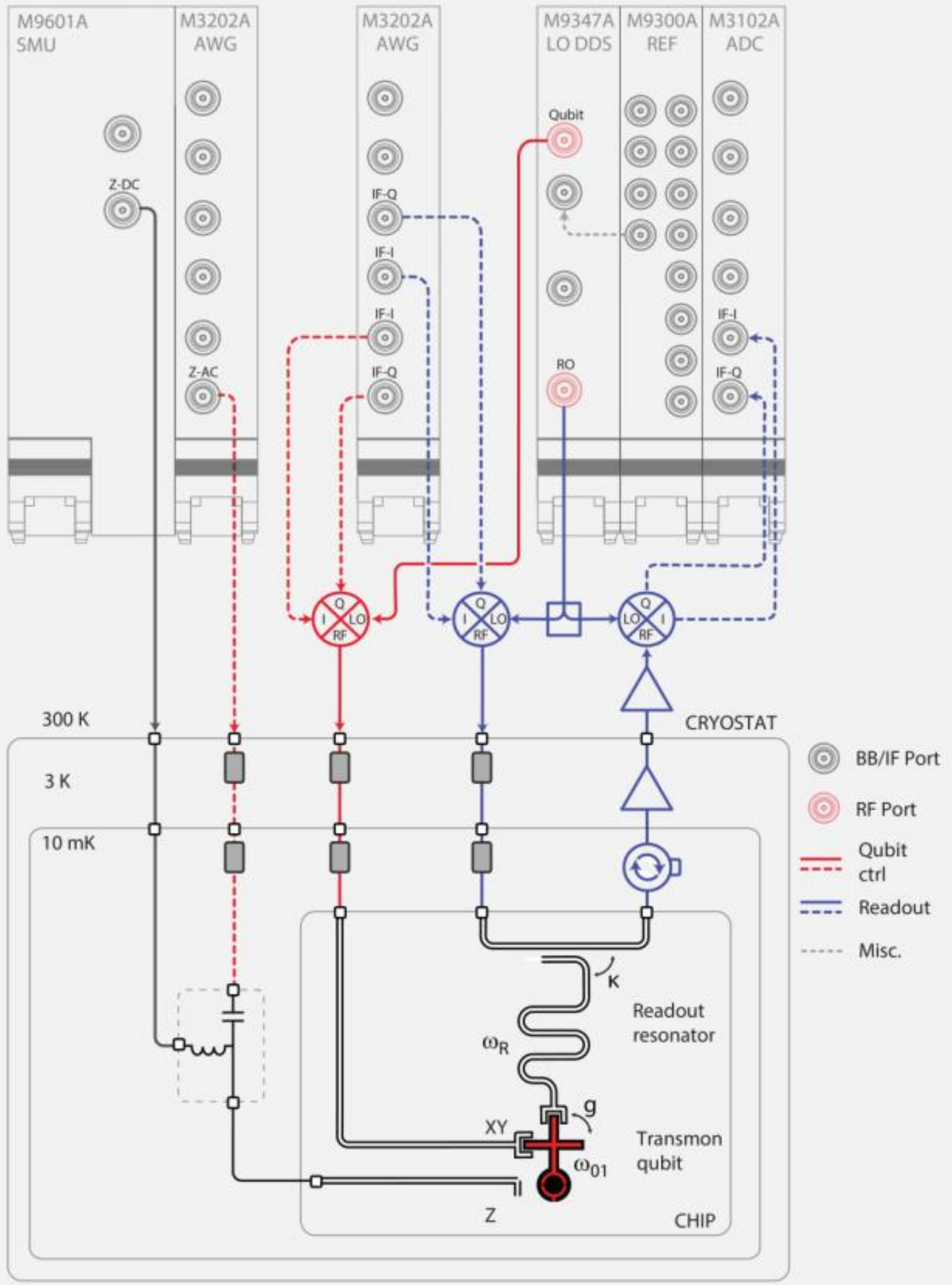
Where Keysight hardware enters the picture

- Keysight hardware is/will be an integral part of the quantum computer, not just a T&M device

- Each computer will look different
  - Qubit type
  - Number of qubits
  - Connectivity

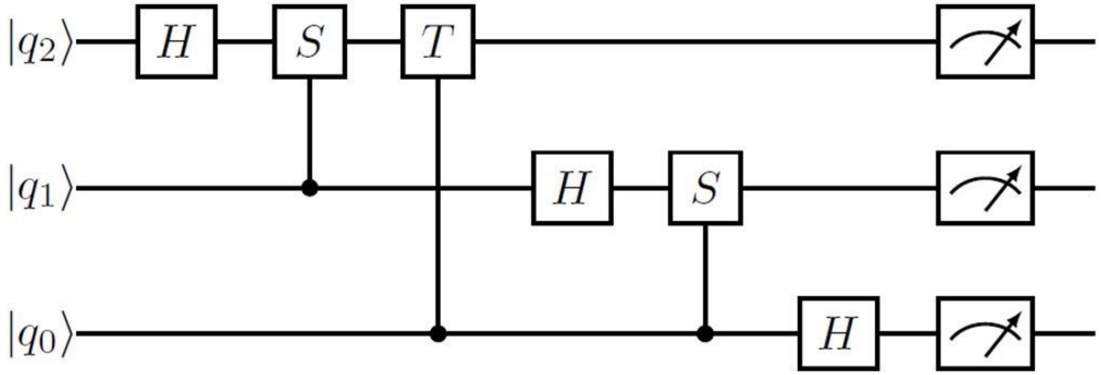
Keysight HW and SW can be a part of many different quantum computers!

https://www.keysight.com/us/en/assets/3120-1387/application-notes/Characterizing-Superconducting-Qubits.pdf?success=true



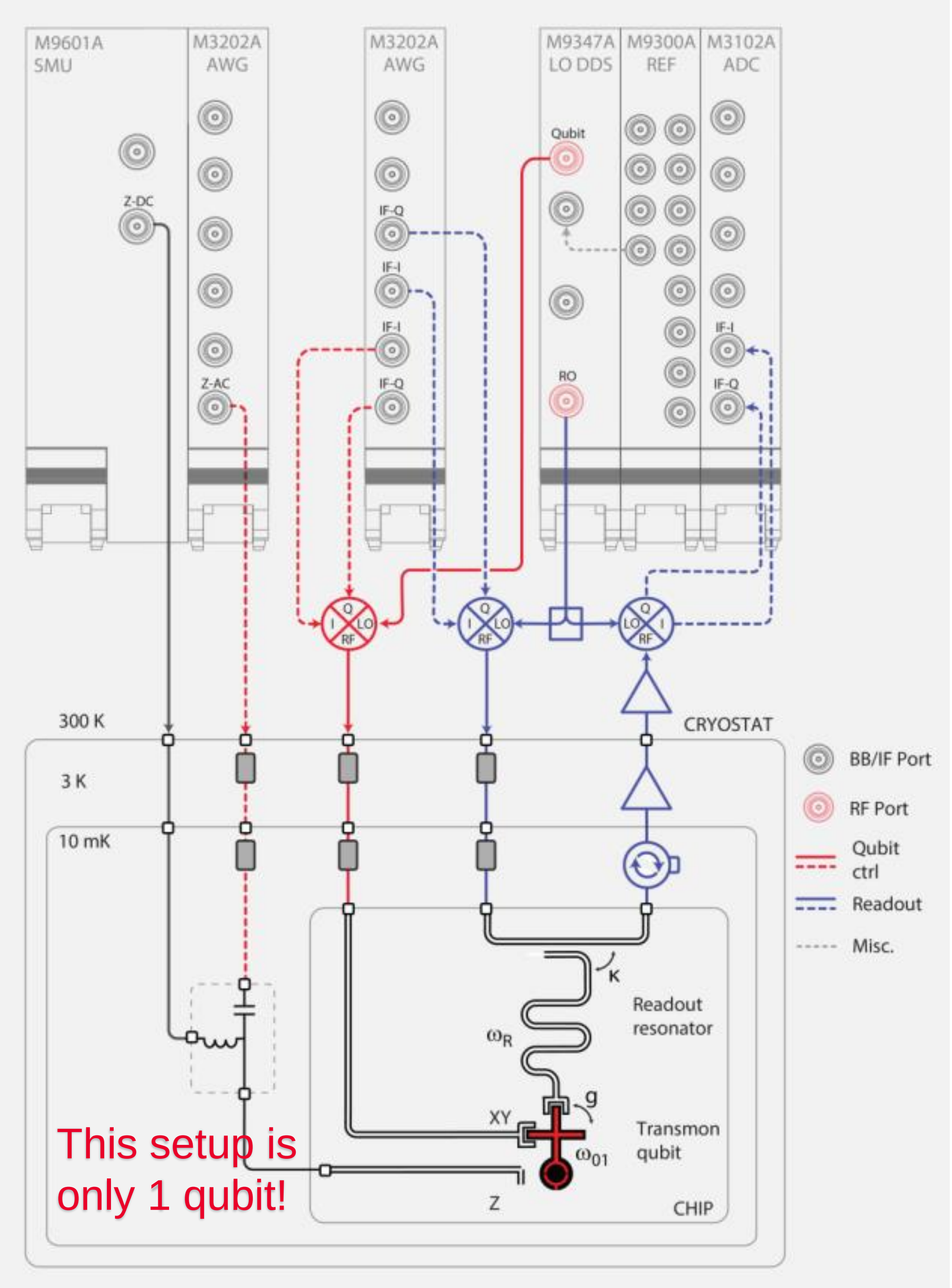
Challenges

Nothing is trivial



- Lots of synchronization
  - Gates (and even time between gates)
  - Hardware/firmware
  - Software
- Qubit control, ‘helper’ qubits, readout devices
- Algorithm *and* error correction

Doing all of this during the qubit lifetime ☺



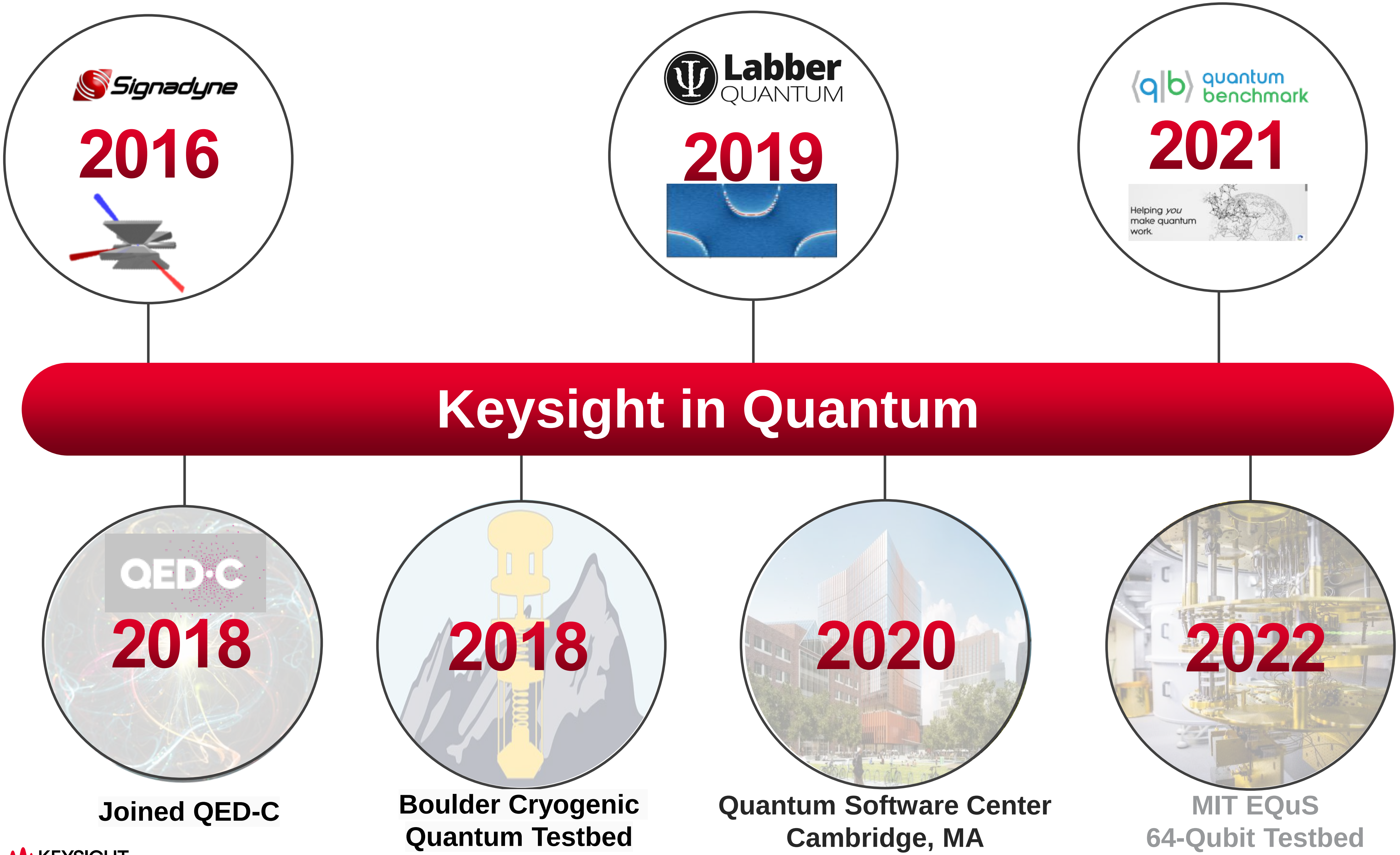
Keysight is at the Heart of the Digital Revolution

Accelerating innovation to connect and secure the world

SMART TECHNOLOGY CONNECTS THE WORLD

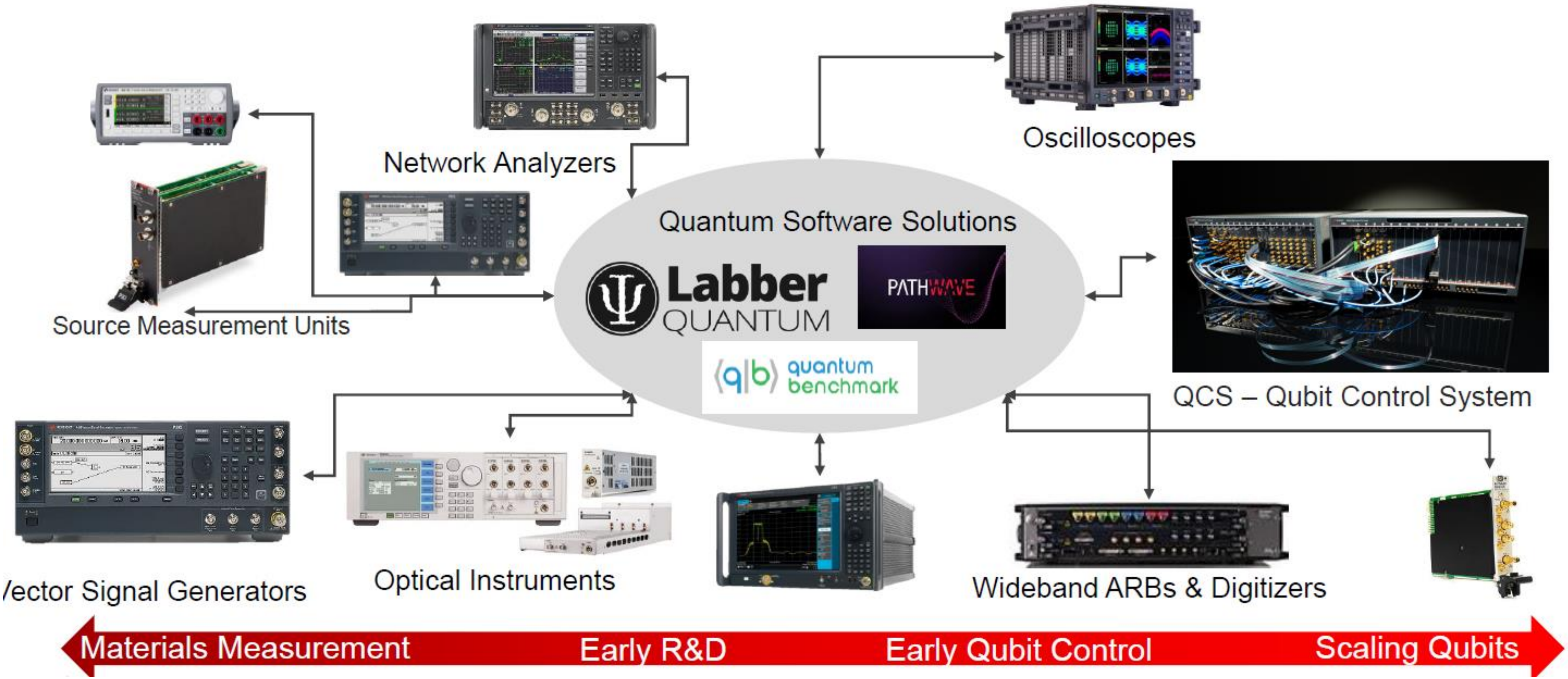
INNOVATION IS EVERYWHERE

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

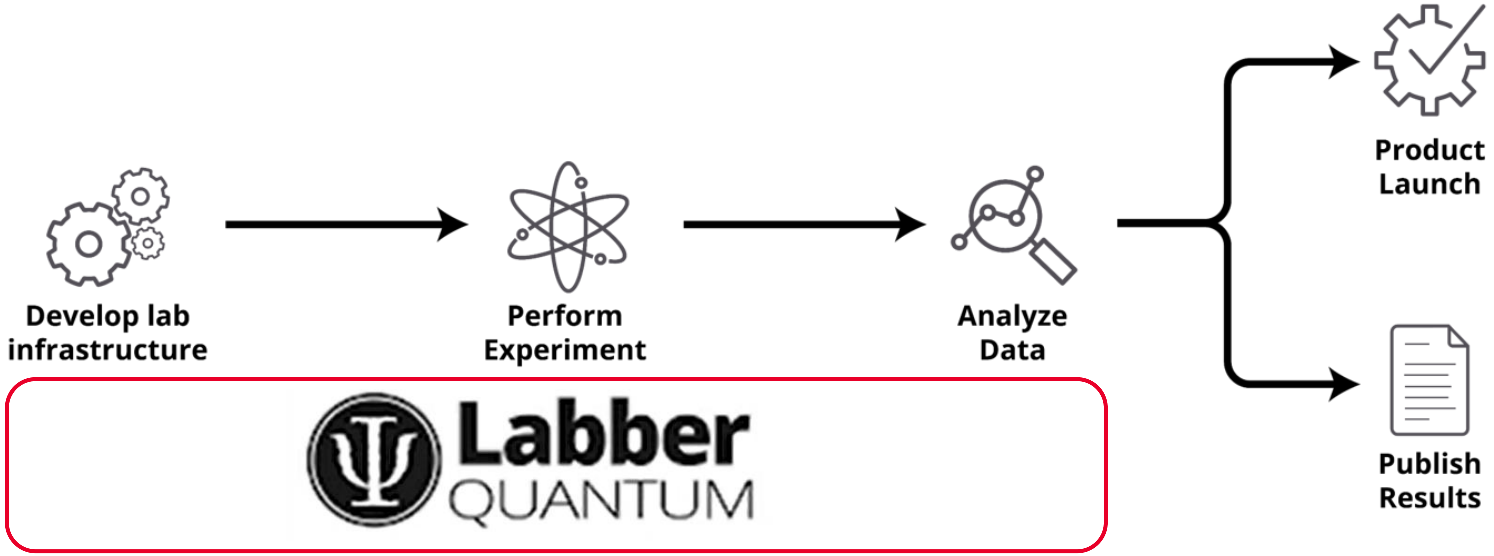

Signadyne
2016
Labber QUANTUM
2019
quantum benchmark
2021
Helping you make quantum work.
Keysight in Quantum
QED·C
2018
Joined QED-C
2018
Boulder Cryogenic Quantum Testbed
2020
Quantum Software Center Cambridge, MA
2022
MIT EQuS 64-Qubit Testbed

Keysight: A Partner for the Quantum Ecosystem

Pulling Control, Measurements, Data Analysis Together



Key Advantages of Labber



- **Modular and extensible**
  Easy to adopt to new types of equipment

- **Standardized procedures for measurements and data storage**
  Facilitates team collaborations and group continuation

- **User-interface driven**
  Removes the need for scientists to write code, allowing them to focus on their research

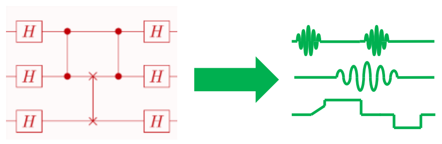
Faster & more efficient experiments

Comprehensive but fully customizable to incorporate your core IP

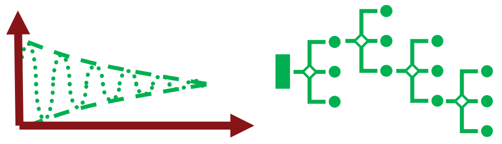
QCS software

User IP

Custom Gate-to-Pulses Mapping

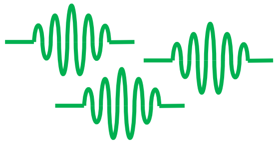


Custom Characterization and Calibration Processes

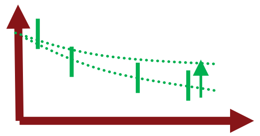


Custom Gate Decomposition, Gate Primitives and Arbitrary Waveforms

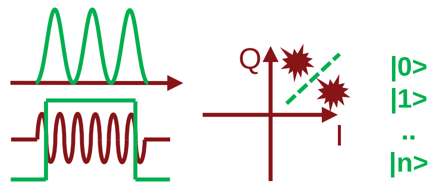
$R_z(\theta_1)$-$R_x(90^o)$-$R_z(\theta_2)$-$R_x(90^o)$-$R_z(\theta_3)$



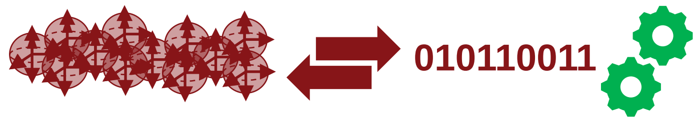
Custom Error Diagnostics and Error Mitigation

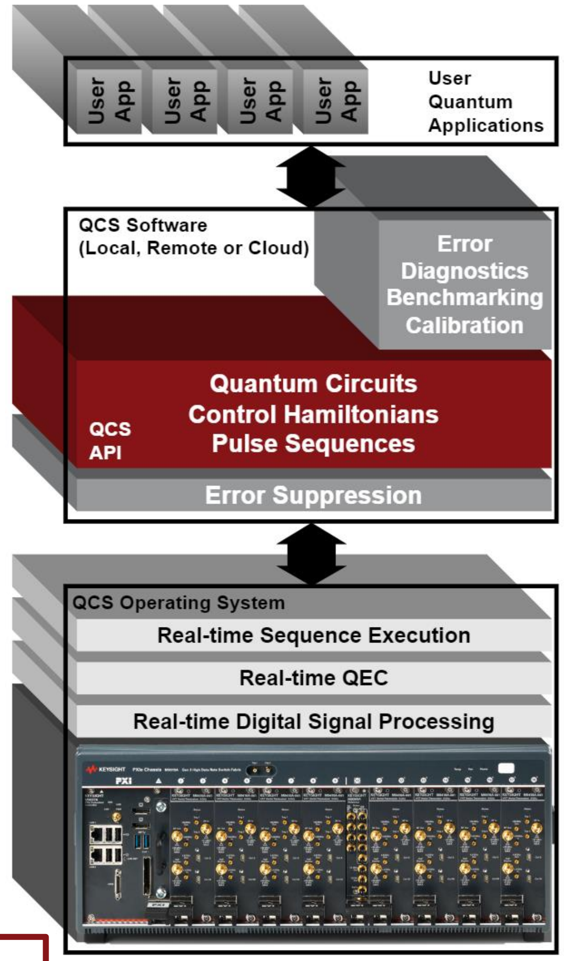


Custom Readout Filters/Integration, IQ Discrimination and Qudit Levels



Custom Real-time Register Processing for Custom Branching and QEC*

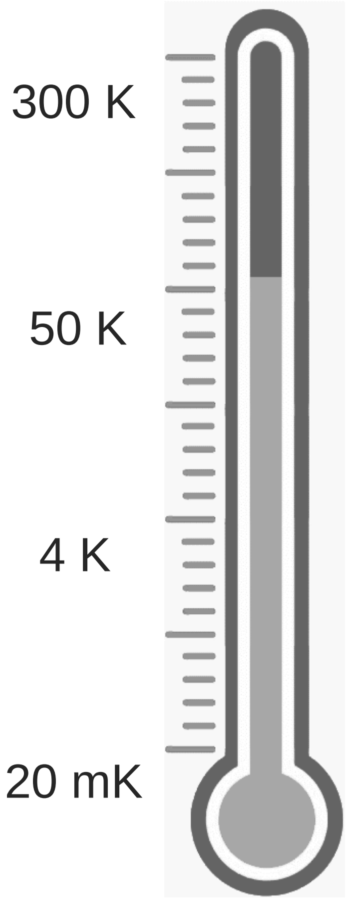


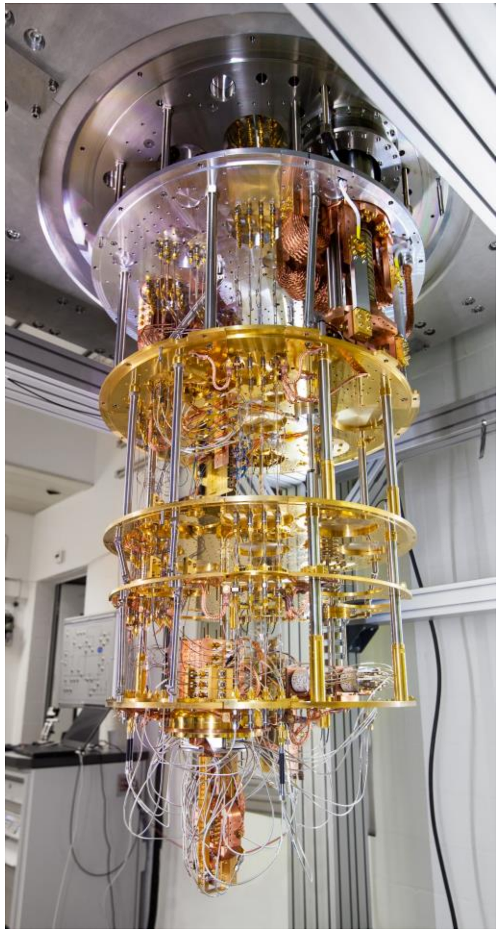


*Available in 2023
Please contact us

Cryogenic Challenges & Calibration - VNA Application In Quantum

Cryogenics for Quantum Computing





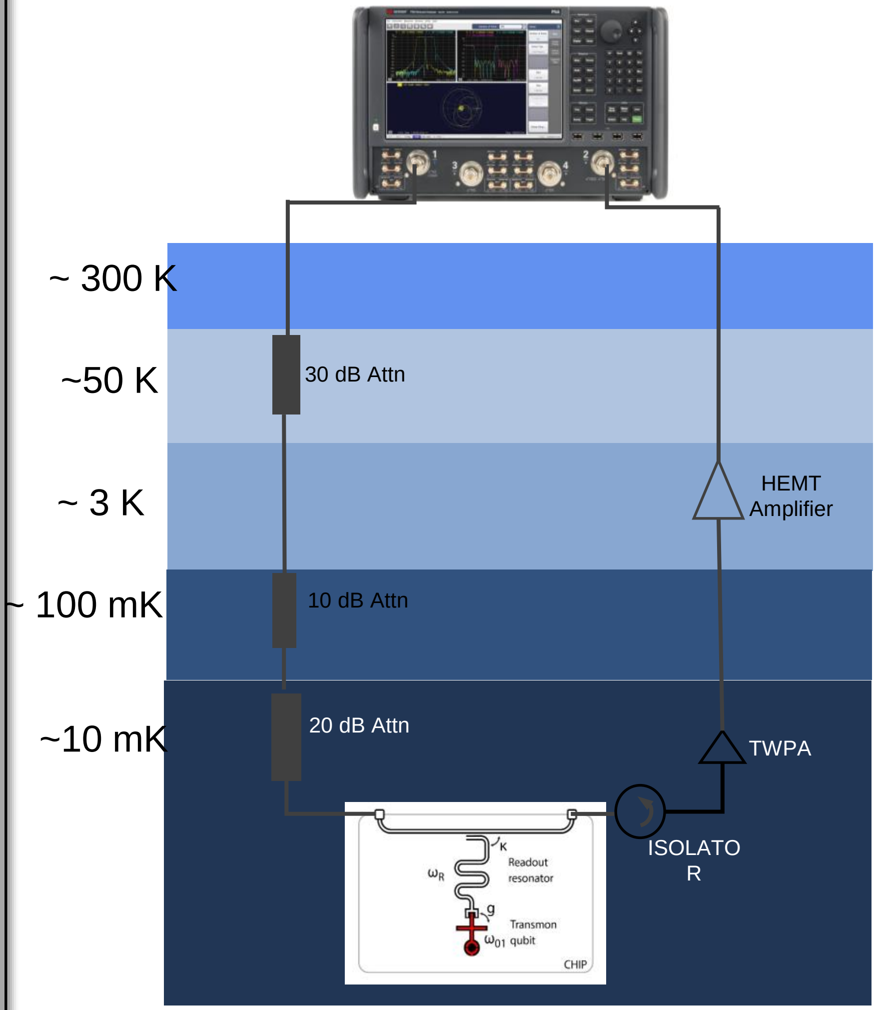
Overall Challenges for Qubit Control

- Disruptions such as vibrations
- Thermal energy can excite vibrational motion of quantum computing operations
- Thermal radiation causing unwanted RF transitions
- Power fluctuations
- Fluctuating magnetic fields alter atomic transitions (Zeeman effect)

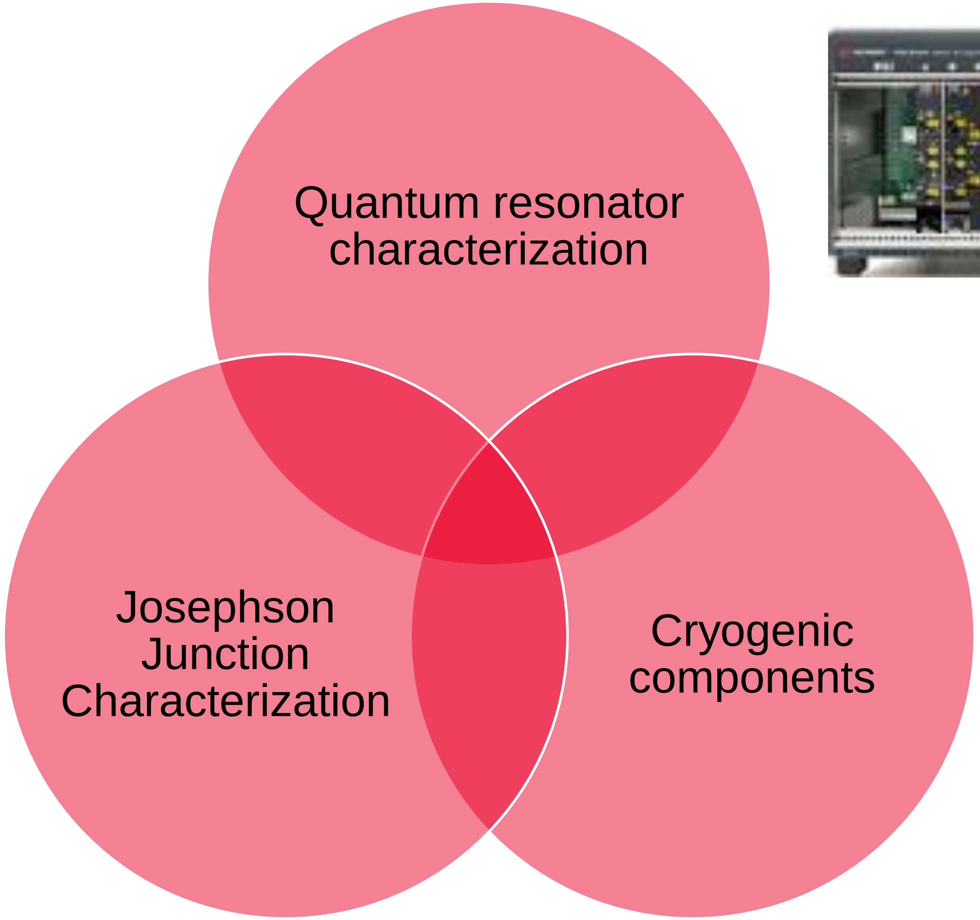
System Level Architectures

Conditions for Measurements

- Measurements are at 10’s of millikelvin temperature
- Attenuators are used to provide thermal isolation and noise reduction to the device being measured
- This means that at the DUT reference plane, we have a very low signal
- The cables used are superconducting, and performance changes with temperature
- Multiple amplifiers are required since signal levels at the coldest stage are around -110 dBm
  - This example architecture is limited to forward s-parameter measurements only



VNA Measurements



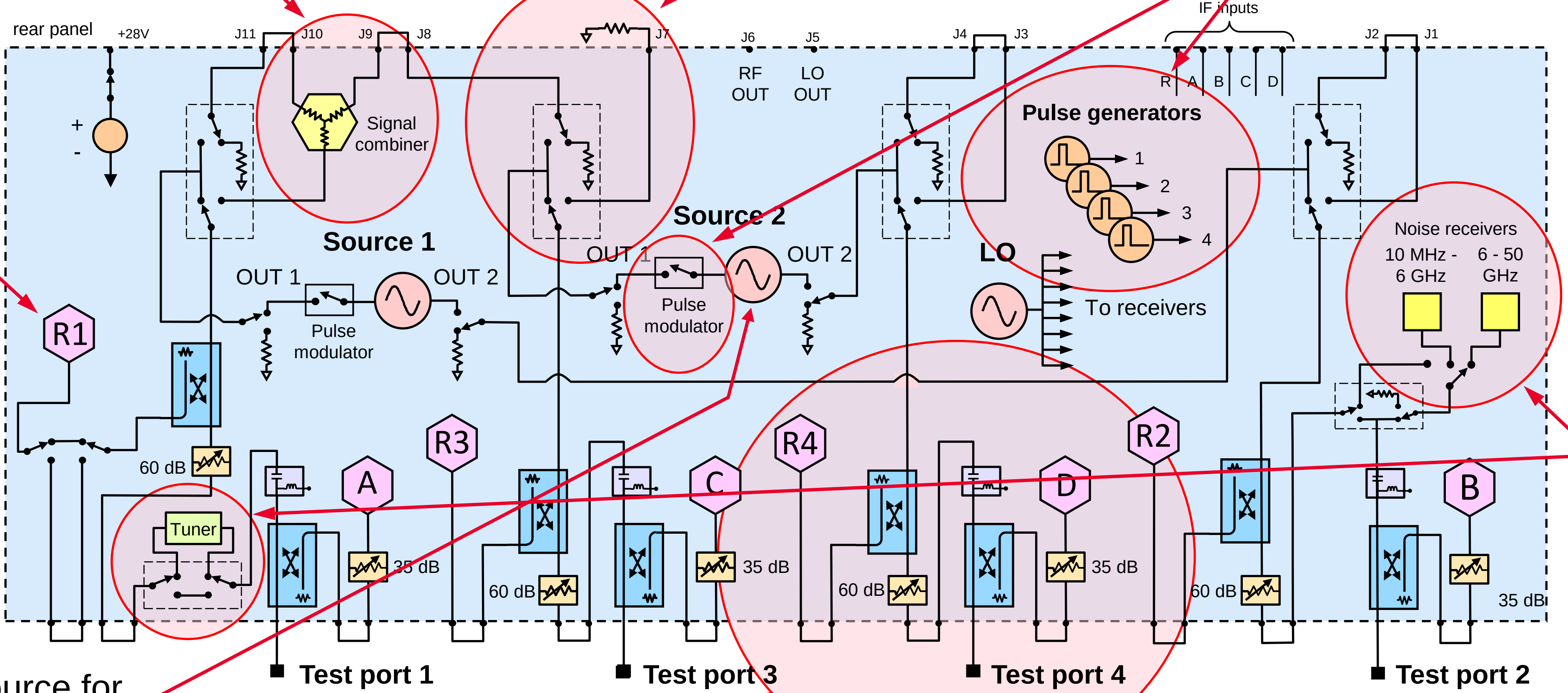
PNA-X – Industry Leader For Active-Device Test

Simplified setup for IMD and NVNA measurements

Add signal-conditioning hardware or route additional test equipment to the DUT

Integrated pulsed-RF test with no external components

Highly linear, wide-dynamic-range receivers with power-meter accuracy



Hardware for industry's most accurate NF measurements

Second source for IMD or LO signals

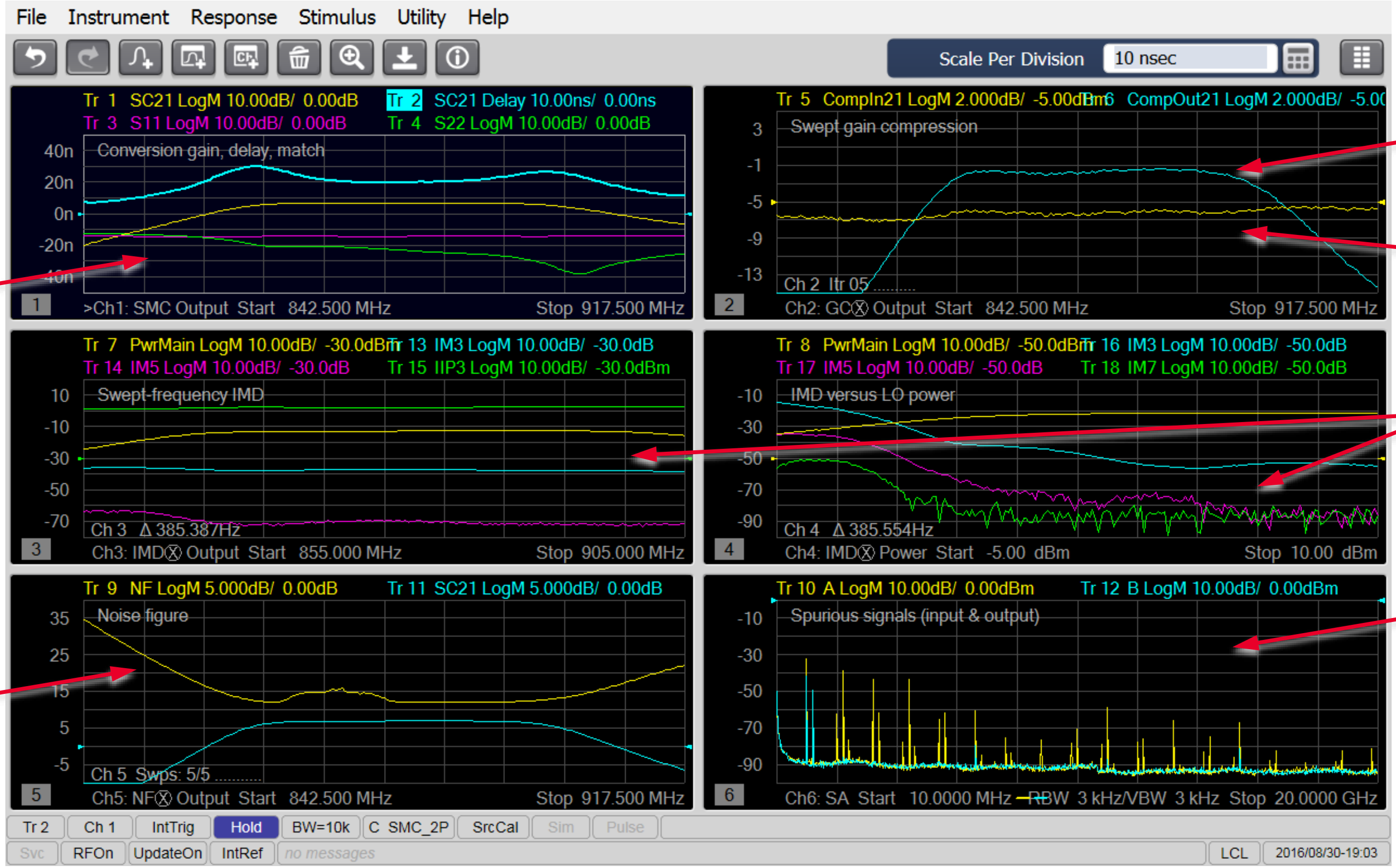
Maximum flexibility and accuracy at each test port

Highly flexible hardware driven by advanced measurement applications

Keysight Advanced-Measurement-Science Example

Conversion gain and group delay through frequency converters, without reference or calibration mixers

Noise figure with industry-leading accuracy



Match-corrected power measurements

Fast gain compression versus frequency

IMD test using fast frequency or power sweeps

Spur searches with fast, multi-channel, calibrated spectrum analyzer

Quantum Resonator Measurements

MILLIMETER WAVE QUANTUM RESONATOR - STANFORD

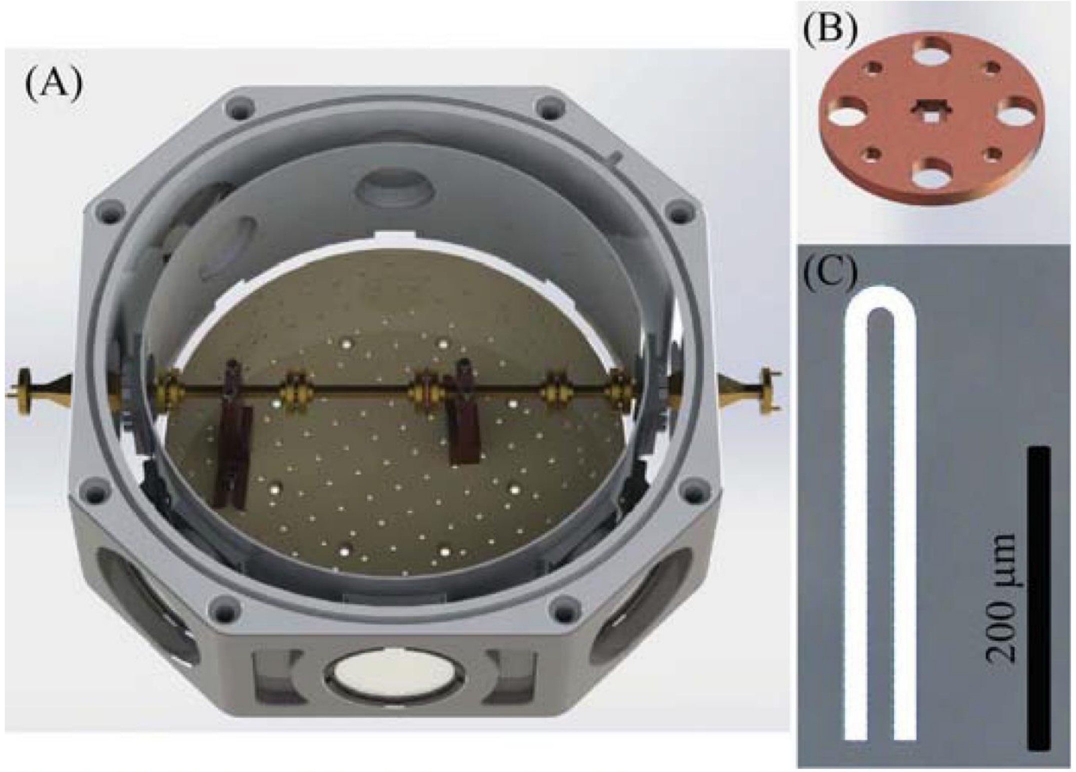
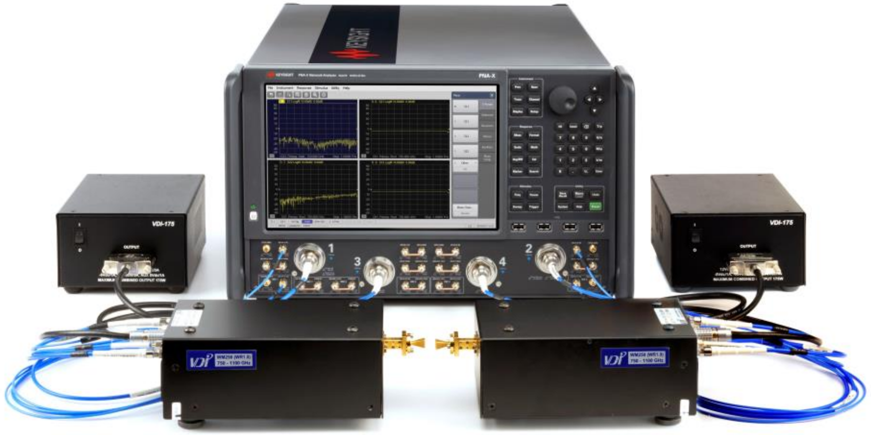


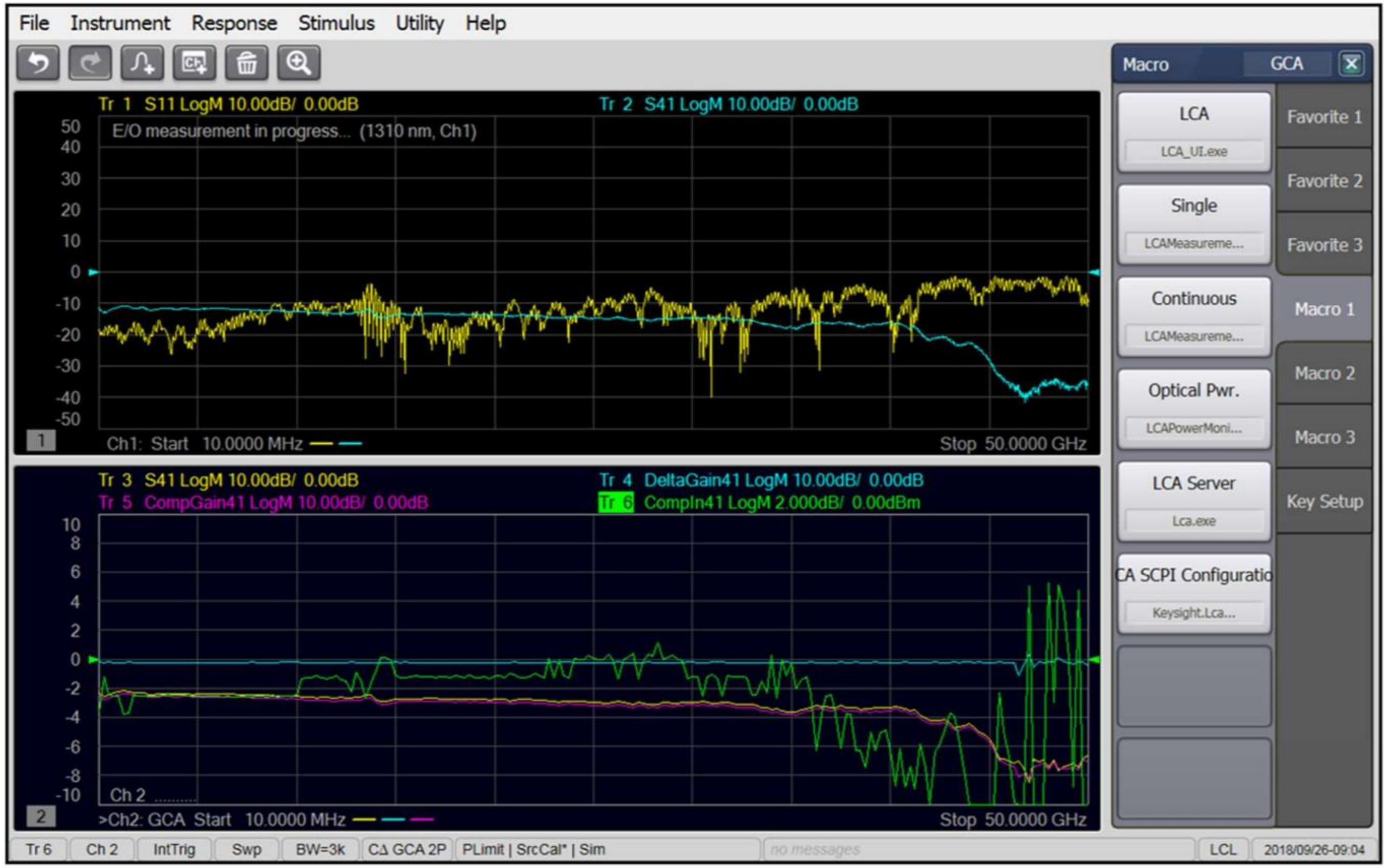
Fig. 1. (A) Design of the 4 K experimental setup – WR10 waveguides are connected via horn antennas and windows to the VNA outside of the cryostat, **(B)** The chip holder can be sandwiched between two waveguide sections, **(C)** Example of Nb resonator with f_{res} = 105 GHz and $Q_{ext} \approx 500$.

- VNA with millimeter wave extenders



Hubert Stokowski1,2, Marek Pechal1,2, Emma Snively3, Kevin K. S. Multani2,4, Paul B. Welander3, Jeremy Witmer1,2, Emilio A. Nanni3, and Amir H. Safavi-Naeini1,2
1Stanford University, Department of Applied Physics, Stanford, CA 94305 USA

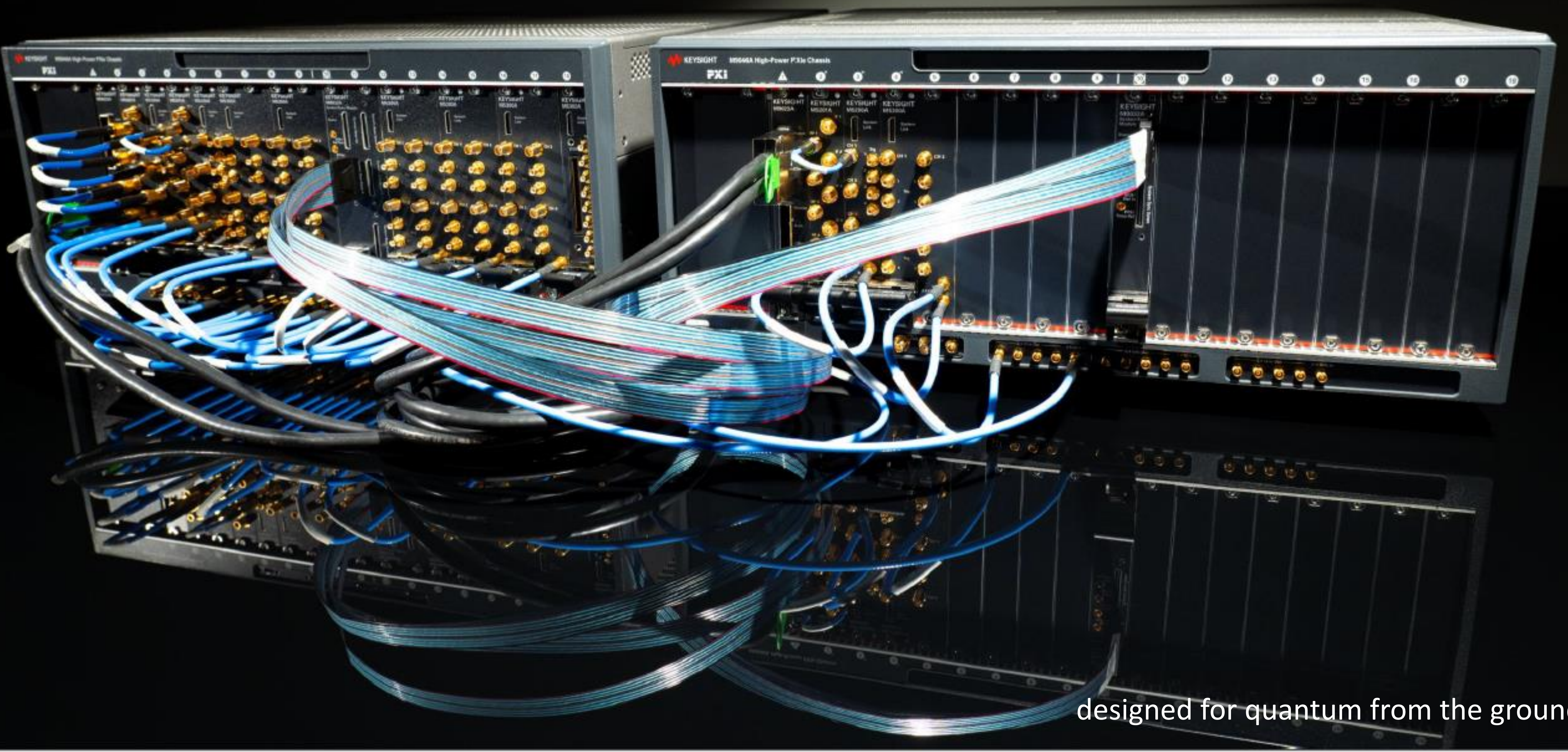
Lightwave Component Analysis



igure 15: Screen with LCA measurement (upper window) and Gain Compression Measurement (lowe

The World’s First Fully Digital Quantum Control System

QCS



designed for quantum from the ground up

Introducing the new Keysight Quantum Control System (QCS)

Building on those advances, Keysight is introducing the <u>world's first fully digital</u> Quantum Control System (QCS)!

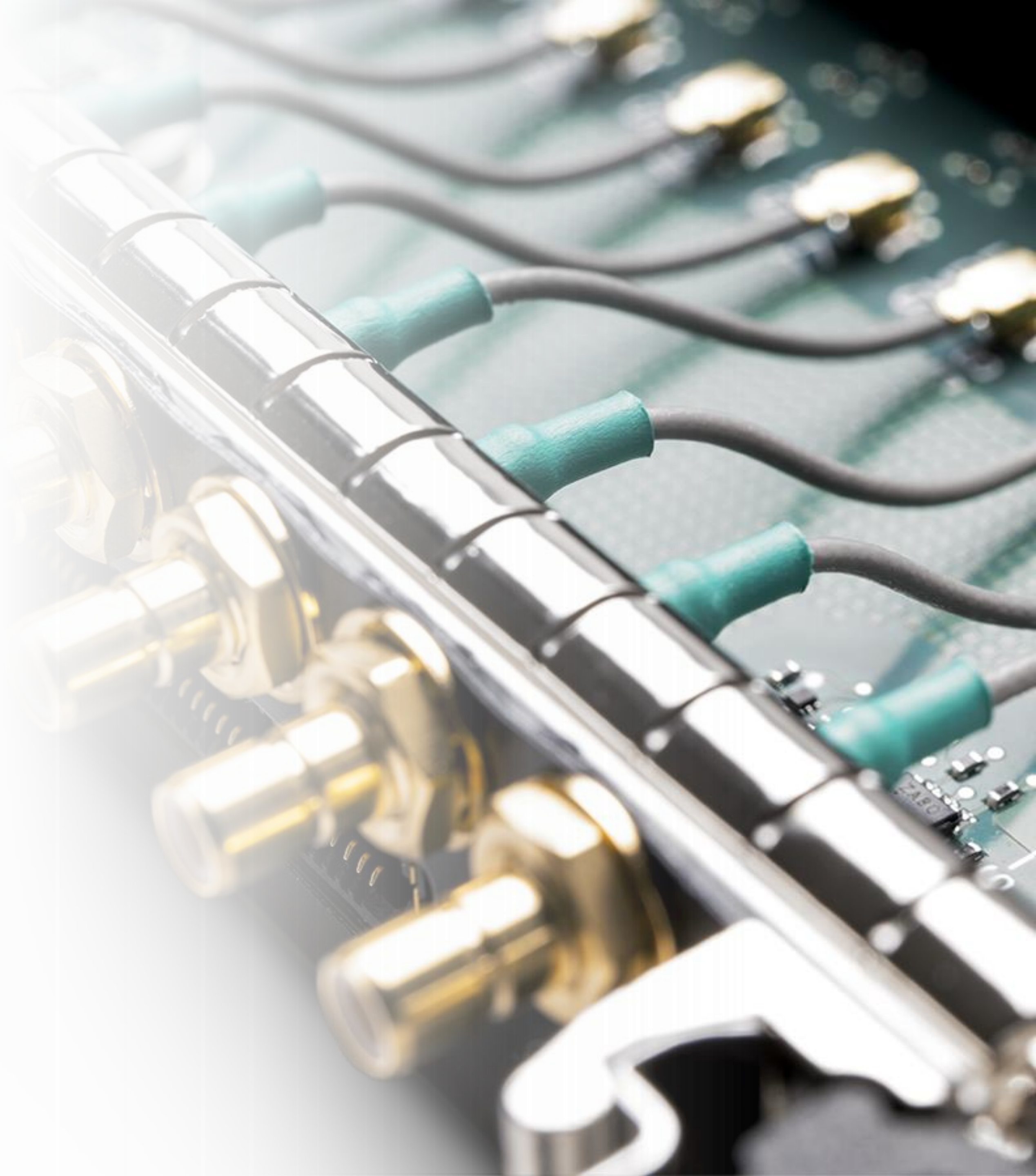
Major advance comes from Keysight ASIC using DDC technology:

- Frequency & Phase are exact
- DDC allows real-time phase updates

M5000 Series

High-performance PXI solutions

- ✓ Consists of a high-power chassis and five PXI modules: RF AWG, Downconverter, Digital IO, and Digitizer, and…
- ✓ Provides industry leading phase noise and coherency required for applications such as quantum control and radar emulation
- ✓ Each card has a programmable FPGA which allows fast distributed processing
- ✓ Integration with other PXIe instrumentation



Meet the M5000 Series

Module	Description
M5200A	**PXI Digitizer** 4 Channels, 2 GHz BW, 4.8 GSa/sec, 12-bit, 1 GSa/ch memory PathWave FPGA and PathWave Test Sync Executive Compatible
M5201A	**PXI Down Converter** 4 Channels, 2-16 GHz RF, 0.01-2.4 GHz IF, Integrated LO
M5300A	**PXI RF AWG** 4 Channels, DC-16 GHz RF, 2 GHz IBW, 14-bit PathWave FPGA and PathWave Test Sync Executive Compatible
M5302A	**PXI Digital IO Module** 28 LVDS Channels, 8 bi-directional triggers PathWave FPGA and PathWave Test Sync Executive Compatible

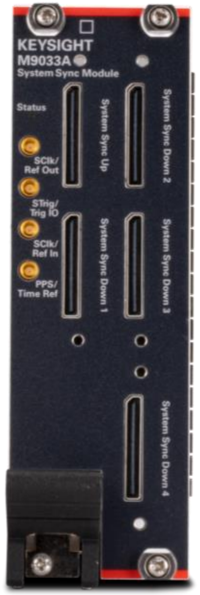
M5200A M5201A M5300A M5302A

QCS – Comprised of new M9000 Series Components designed for Quantum

M9032A

- Single-slot PXIe System Sync Module
- PathWave FPGA
- PathWave Test Sync Executive
- 1 Sync-Up/Down

M9033A



- Dual-Slot PXIe System Sync Module
- PathWave FPGA
- PathWave Test Sync Executive
- 1 Sync-Up, 4 Sync-Down

M9046A

- Next-gen high-power PXIe chassis
- Up to 1675W usable power
- Up to 85W/slot cooling
- PCIe Gen 3

Keysight Quantum Control System (QCS)

Ease of Use

- **NO external mixers**
- **NO IQ calibration**
- **NO FPGA expertise required**
- **New Quantum Centric Python API**
- **Timing and synchronization without external cabling**

High Performance

- **Stable**
- **Phase Coherent**
- **Future Proof**

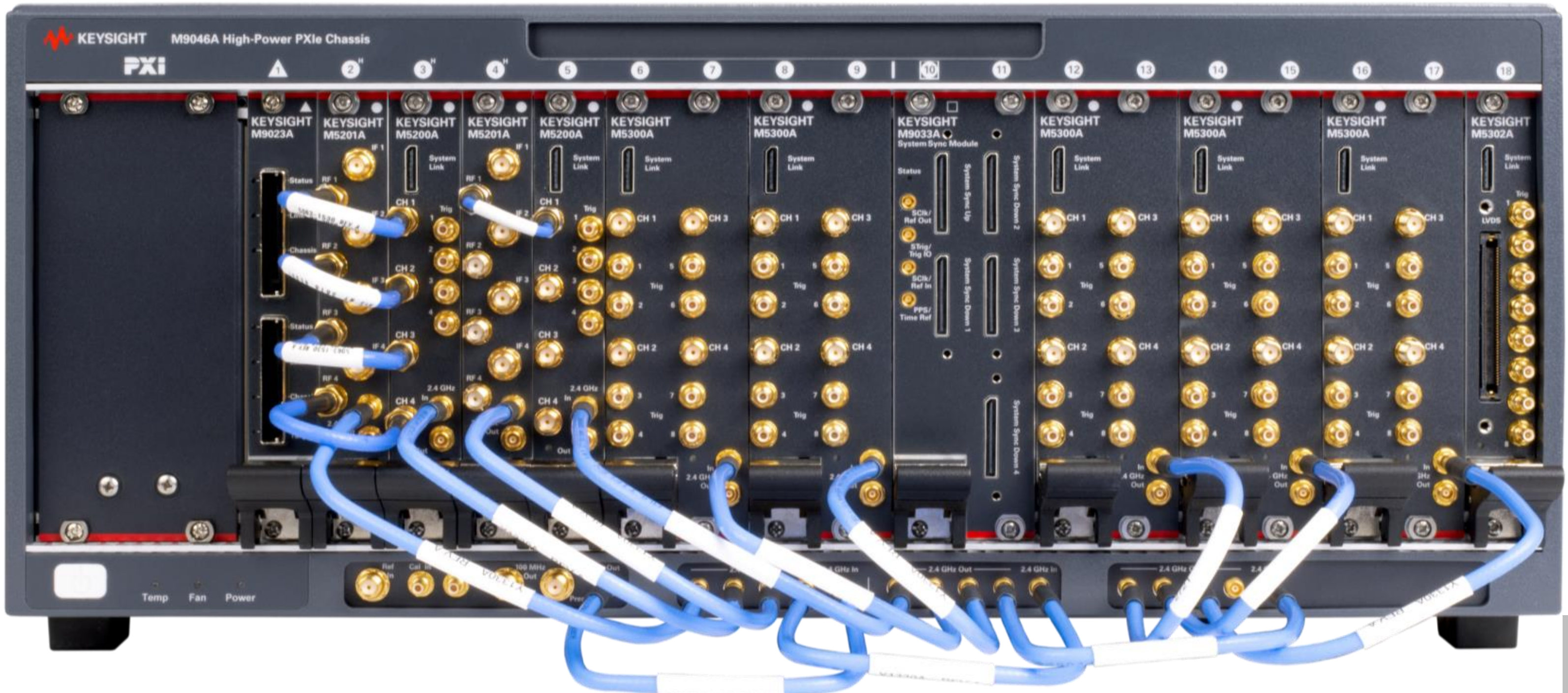
Scalable

- **PXI** – industry standard
- **Buy just the # of channels you need now**, and add on later
- **Add other elements you need in your lab like a network analyzer** (26GHz, 4CH in 1 PXI slot) without more rack space
- **New Quantum Centric Python API**

1. Ease of Use

A solution designed for quantum from the ground up

1. Ease of Use - Hardware

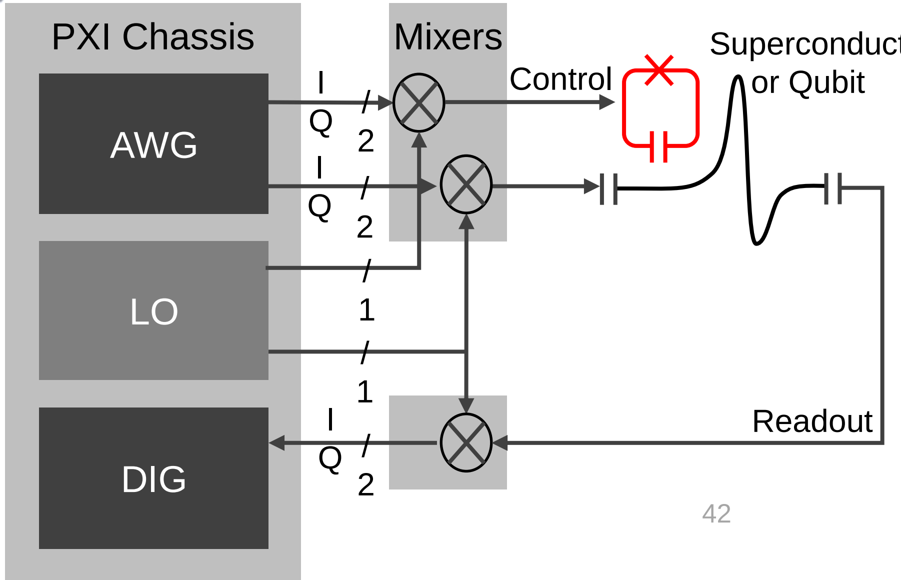


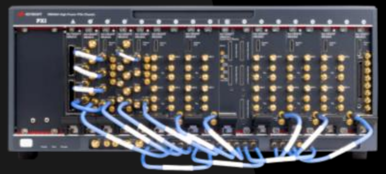
✓NO External Mixers needed!

✓NO External LOs needed!

✓NO I/Q Mixer Calibration needed!

✓NO downtime due to calibration!

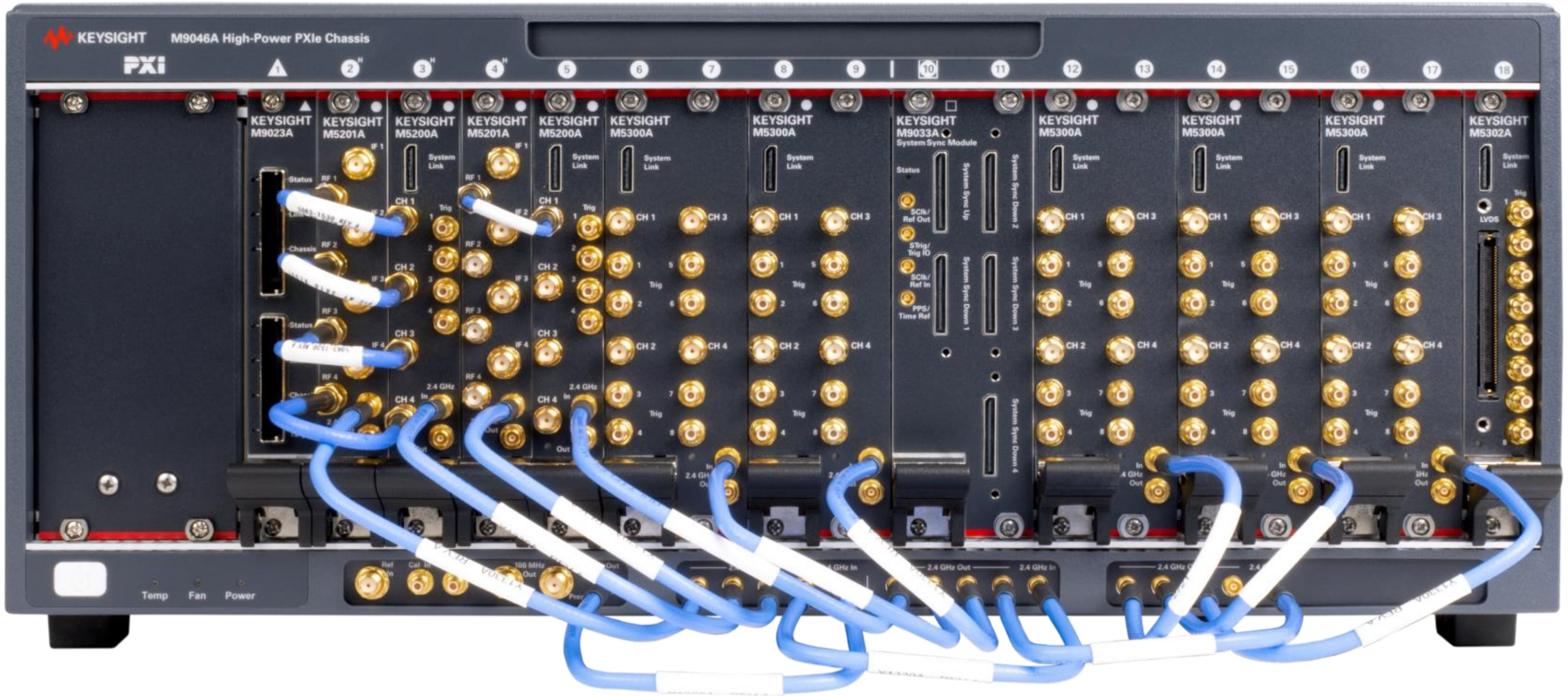




2. Performance

We put our #1 team on this

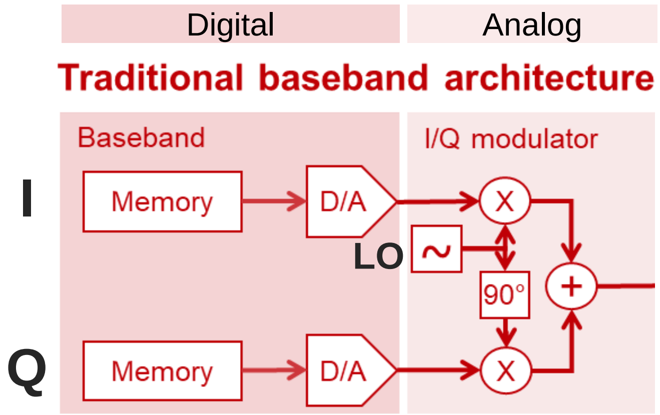
2. Performance

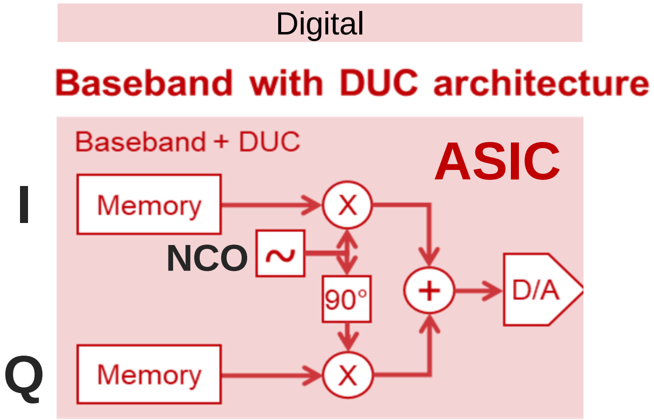


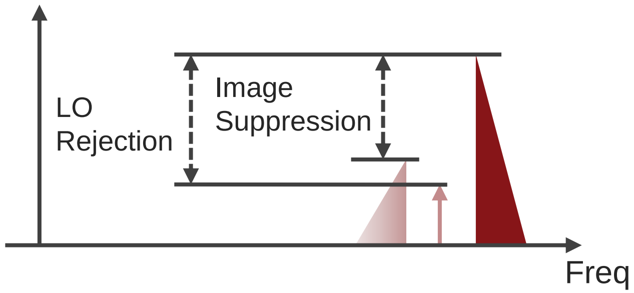
- ✓**Stable**: Extremely low phase noise reference clock embedded in chassis
- ✓**Phase Coherent**: Timing and synchronization all done automatically
- ✓**Future Proof**: DC to 16 GHz, scalable to 1000 qubits and beyond

Clean Signals via Direct Digital Signal Generation

Enabling high-fidelity gates



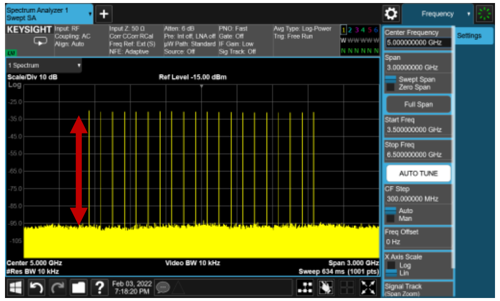




LO rejection and image suppression require IQ imbalance calibration which drifts over time

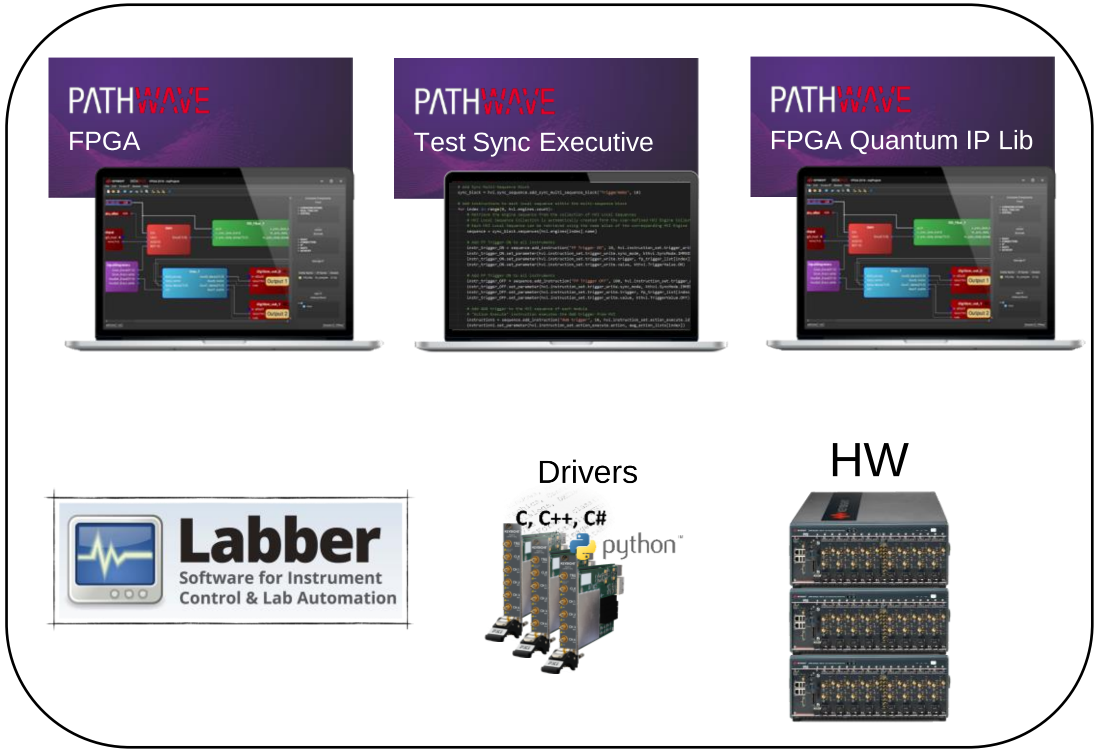
Fully digital generation does not have LO or image, and it does not require any calibration

Improved SFDR (Spurious-Free Dynamic Range)



Quantum Control System (QCS)

≠



The QCS is a full-stack solution. It gives low-level access at the level of quantum devices but is NOT a build-it-yourself toolbox

QCS API Overview and Structure

How does the QCS API lend itself to quantum experiments?

- Before: Customers write quantum experiments in terms of classical hardware and connections.
- Now: Customer write quantum experiments in terms of quantum specific components and language.

Before

1. Send pulse A with xyz parameters from AWG (Slot 3, Channel 1) to Qubit 1.
2. Send pulse B with abc parameters from AWG (Slot 4, Channel 2) to readout line.
3. Read Digitizer Channel 1 signal.

Now

1. Apply H-gate on Qubit 1.
2. Measure Qubit 1 state.

QCS API Overview and Structure

What is the customer workflow?

DEFINE

hardware modules, configurations, and connections.

MAP

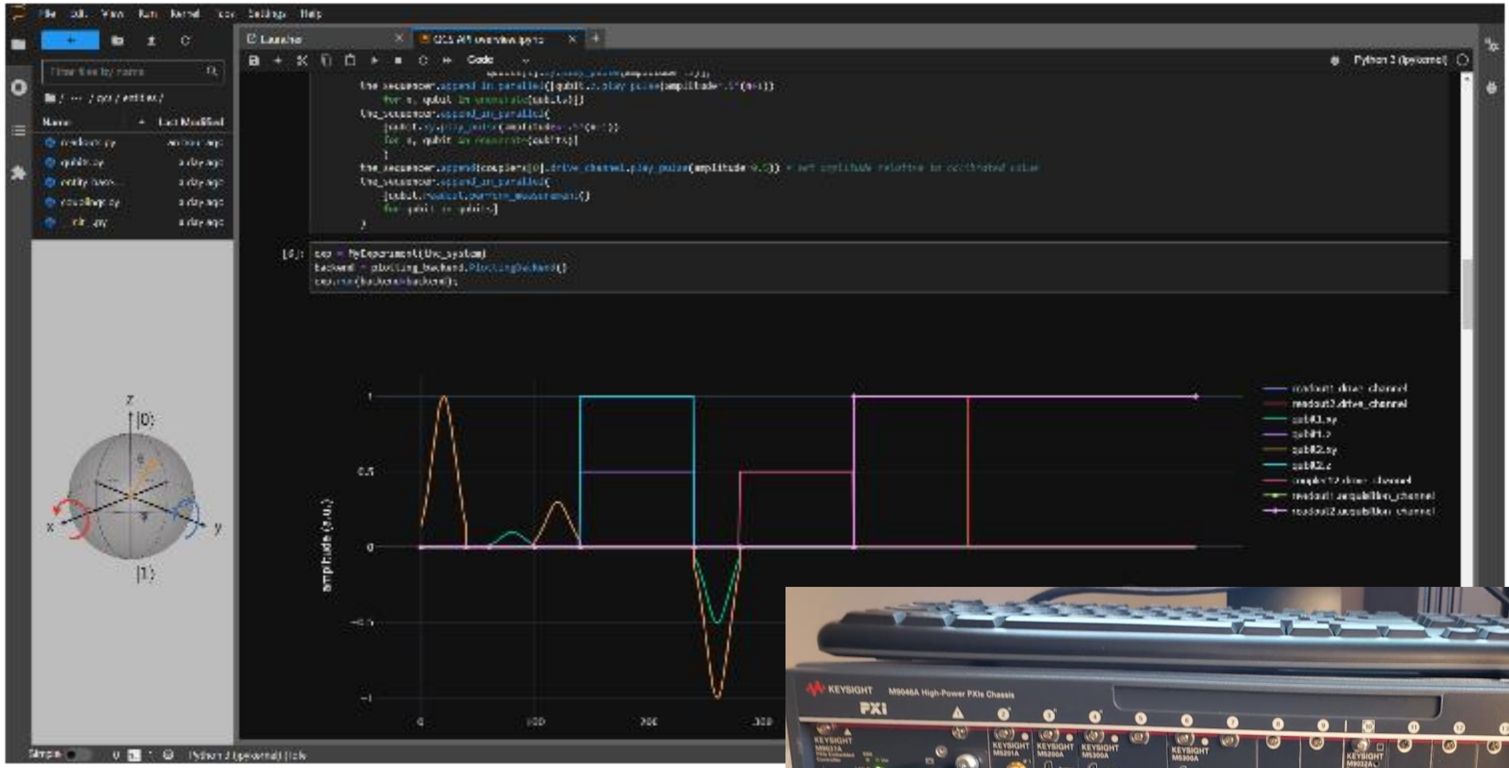
classical components to quantum components.

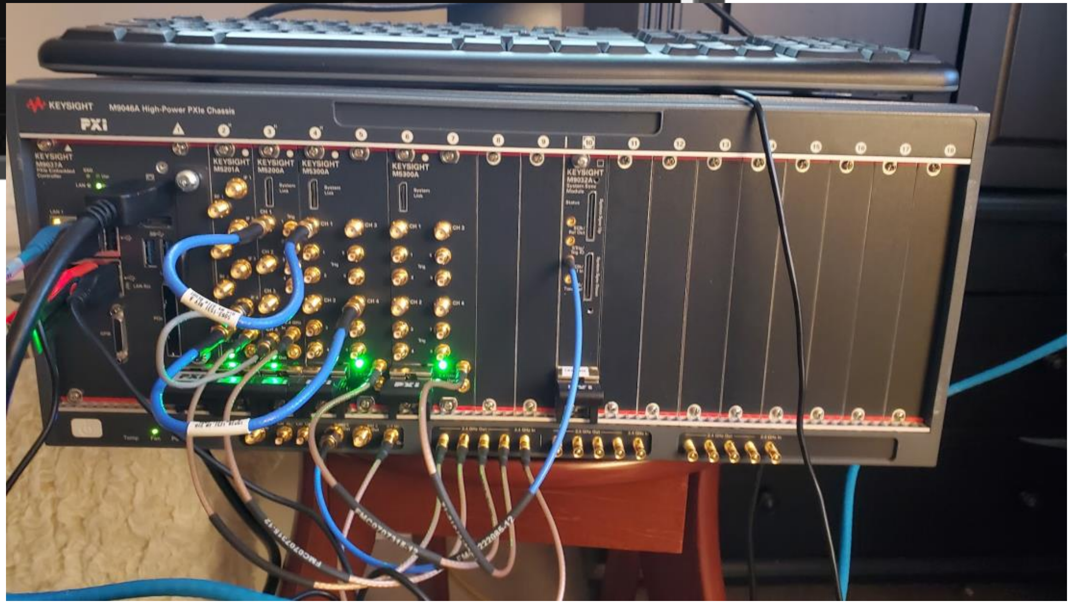
WRITE

experiments easily in the language of quantum.

When a new quantum component and its mapping to classical channels is defined, the software can use that component throughout the stack.

QCS has a 100% new Software API for Ease of Use



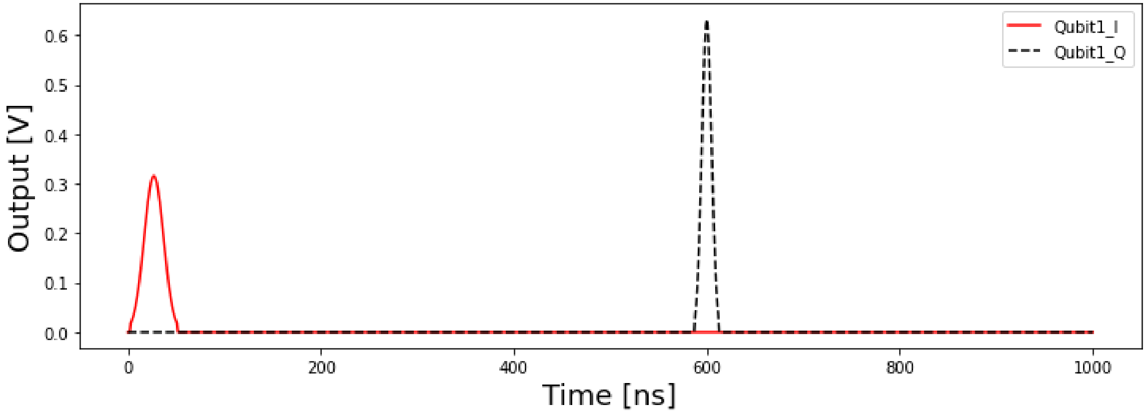


QCS Code Snippet Overview*

Simplicity in Use: Less Lines of Code

Pulse Sequence

```
sequence = [
            q1.xy.pulse(amplitude=0.5),
            q1.delay(500e-9),
            q1.xy.pulse(phase=90, sigma=5e-9)
        ]
```



*Note: not final syntax for API

Qubit to System Mapping

```
entity Transmon q1:
    readout: readout1
    awg: awg1x1
    channel: 1
    pulses:
        entity GaussianPulse
```

Pulse Definition

```
class GaussianPulse(Pulse):
    sigma: float = CalParam(10e-9)
    """Pulse width standard deviation"""
    chop: float = CalParam(4)
    """Total number of standard deviations of width"""
```

3. Scalability

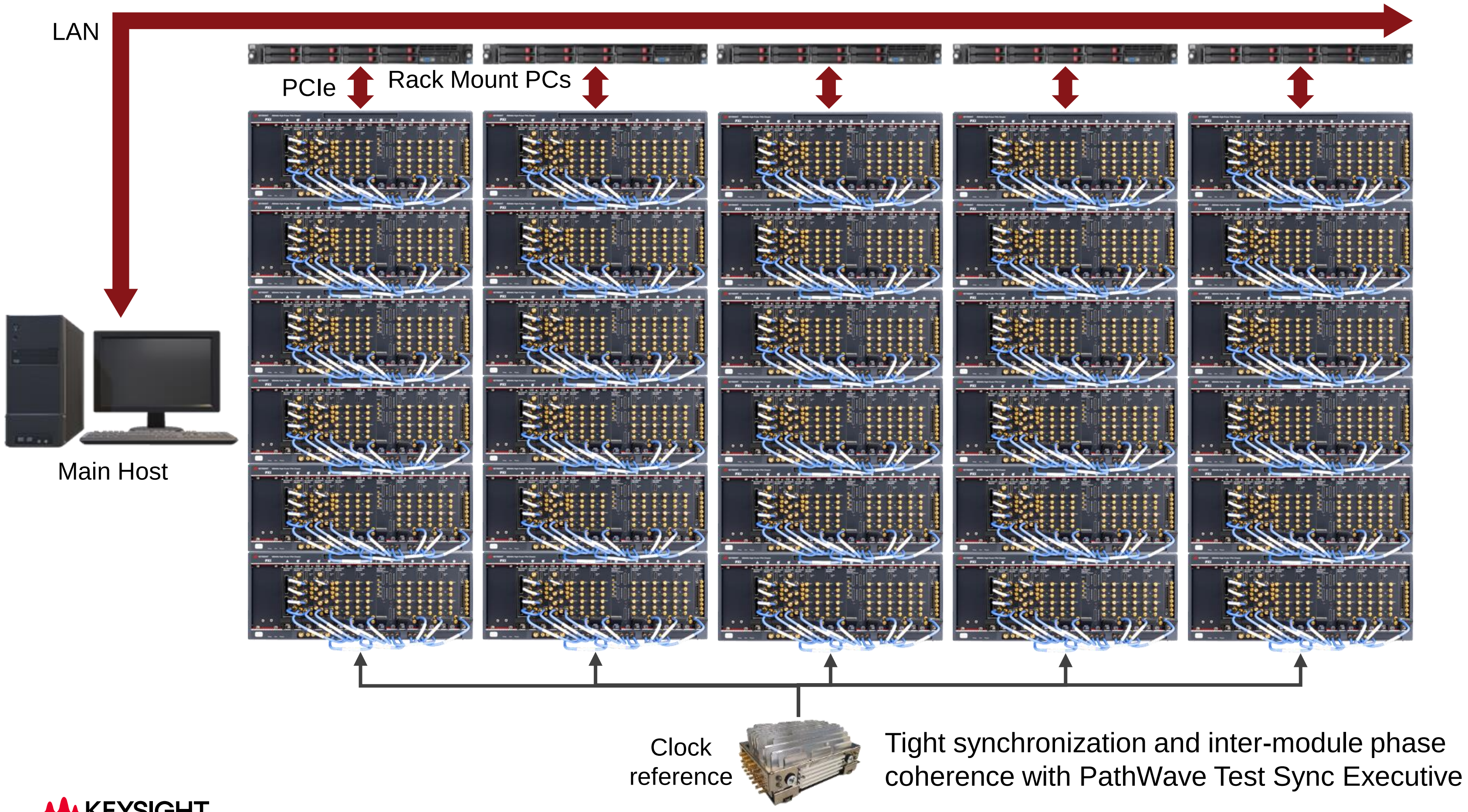
QCS to 1000 qubits and beyond!


KEYSIGHT
M9046A High-Power PXIe Chassis
PXI
KEYSIGHT
M9023A
KEYSIGHT
M5201A
KEYSIGHT
M5200A
KEYSIGHT
M5300A
KEYSIGHT
M9032A

A Scalable Control System

Scalability as your QPU grows

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



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

2 GHz BW enables massive Frequency Division Multiplexing (FDM)

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

Multi-host multi-chassis operation on SW stack roadmap

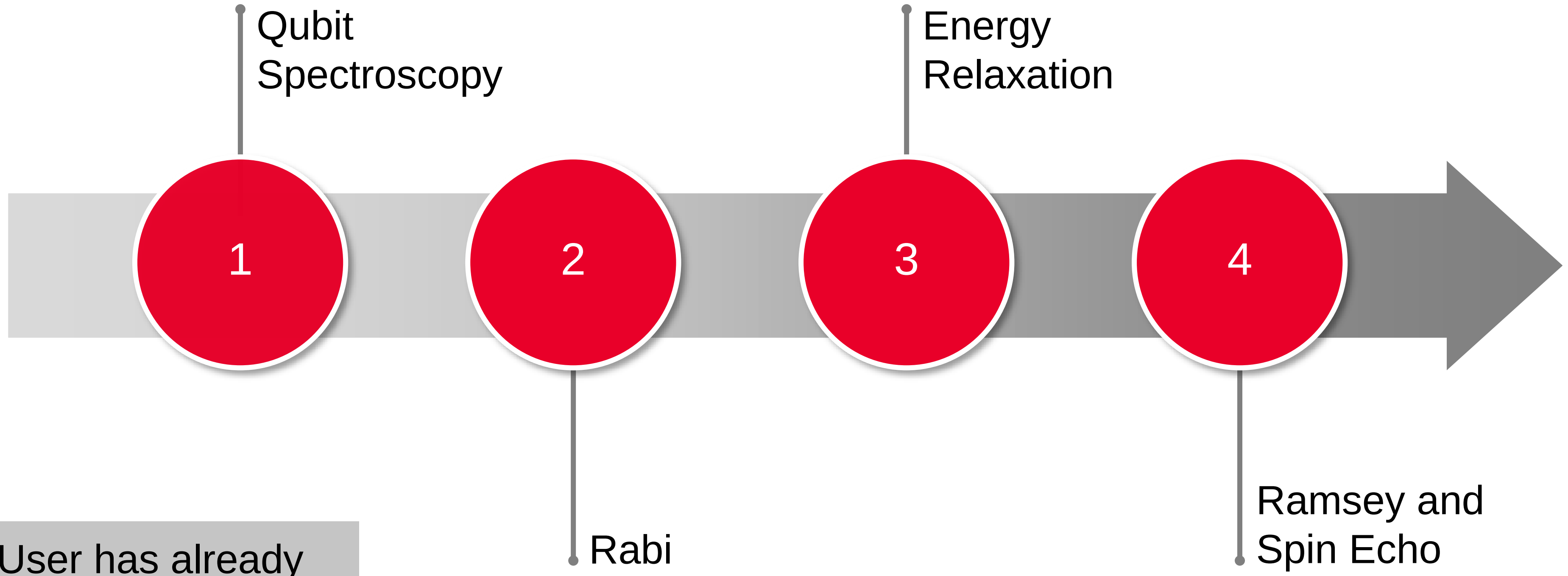
Support for massive number of qubits also on SW stack roadmap

Please contact us

Test Scenario with QCS

Demo Flow

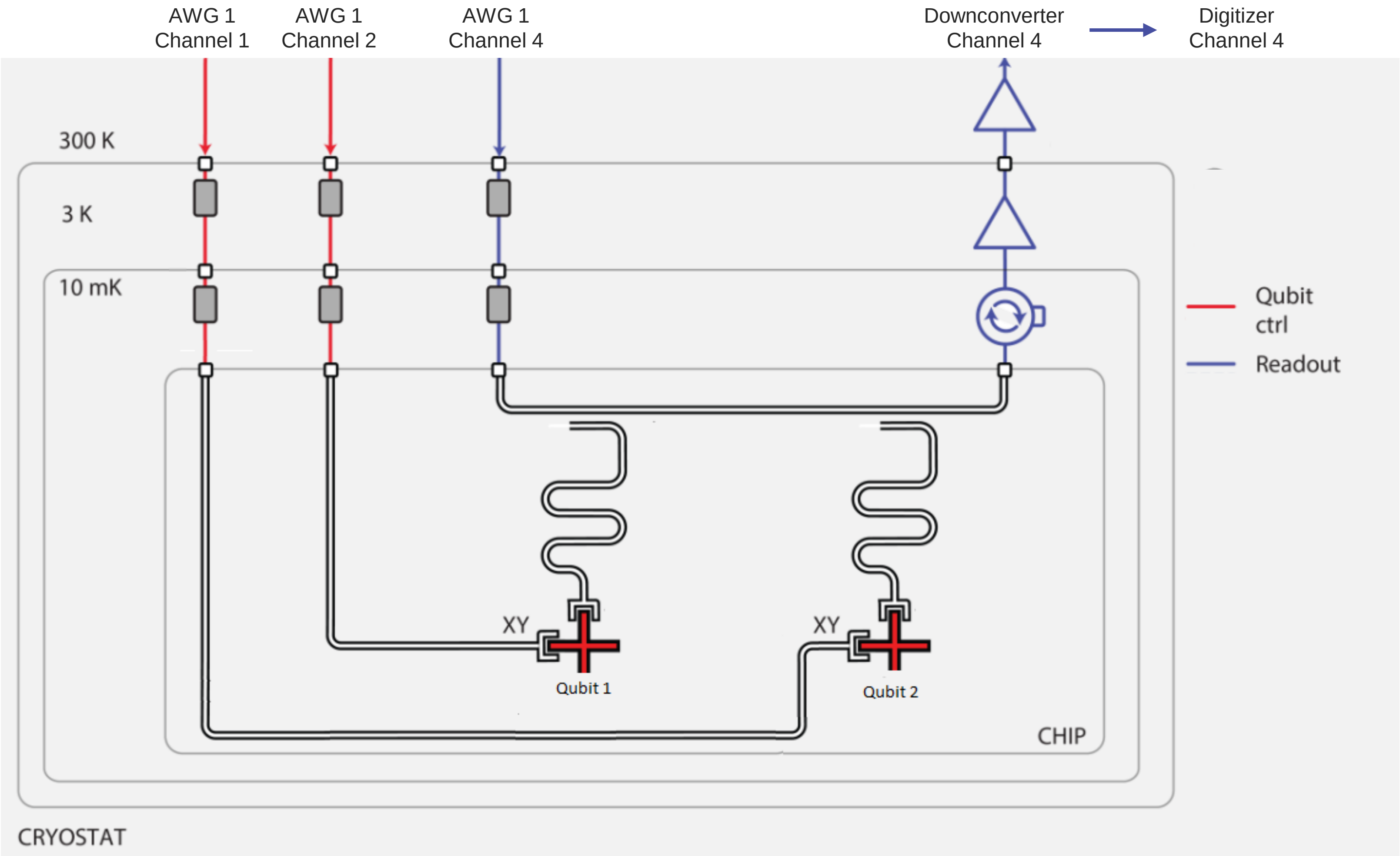
Superconducting qubit characterization



Scenario: User has already calibrated readout and is ready to start characterizing new qubits

Demo Quantum Configuration

Superconducting qubit chip



KEYSIGHT

Qubit Spectroscopy

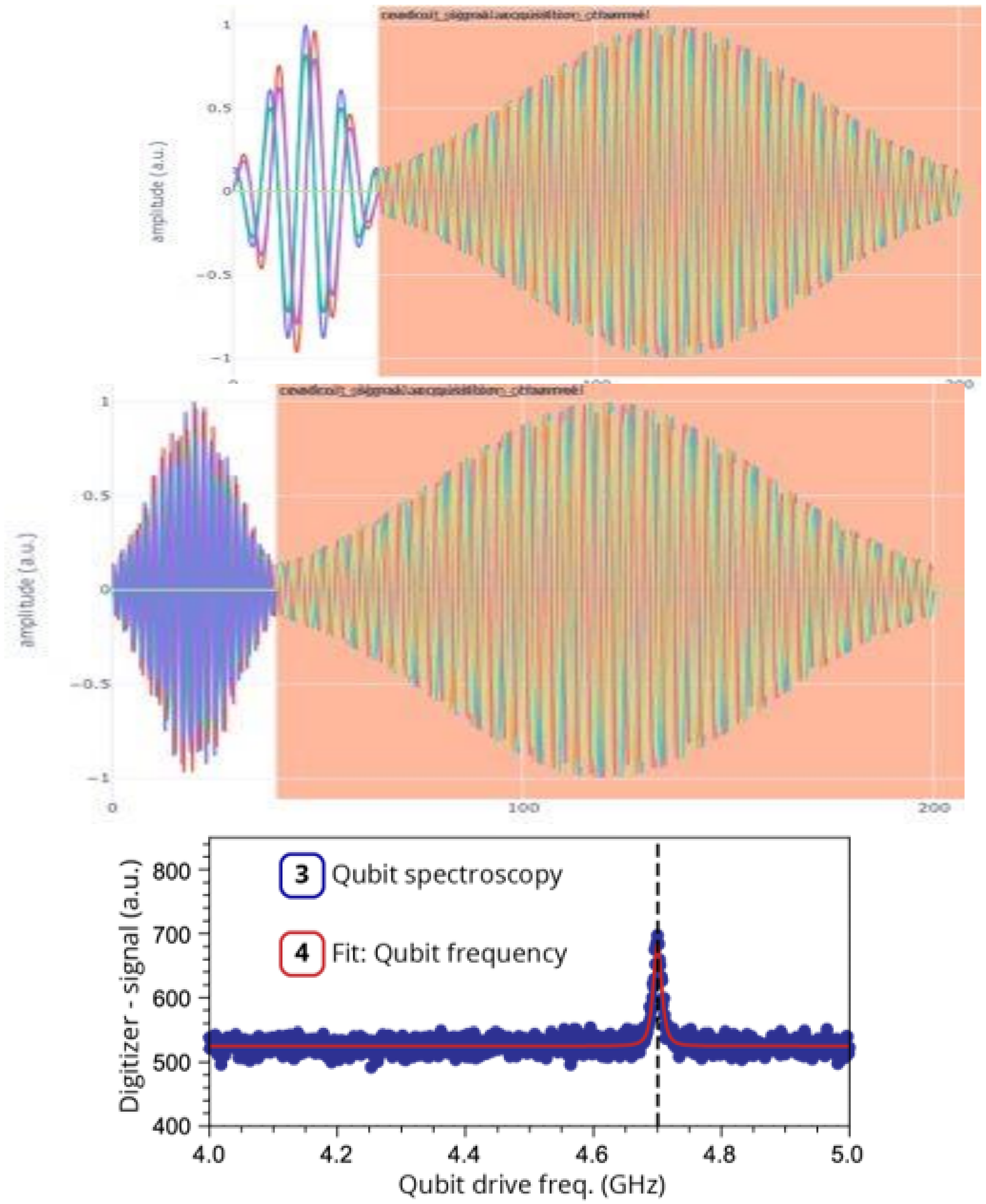
Qubit Spectroscopy – What is it?

Qubit Characterization Pt. 1

Goal: Find qubit frequency

1. Send control and readout pulse.
2. Control pulse is scanned over frequency.
3. Readout signal spikes at qubit frequency.

Qubit frequency: Resonance frequency of qubit.



Rabi

Rabi Experiment – What is it?

A Rabi experiment is used to calibrate the amplitude needed to drive a **pi-pulse**, a foundational element for quantum sequences.

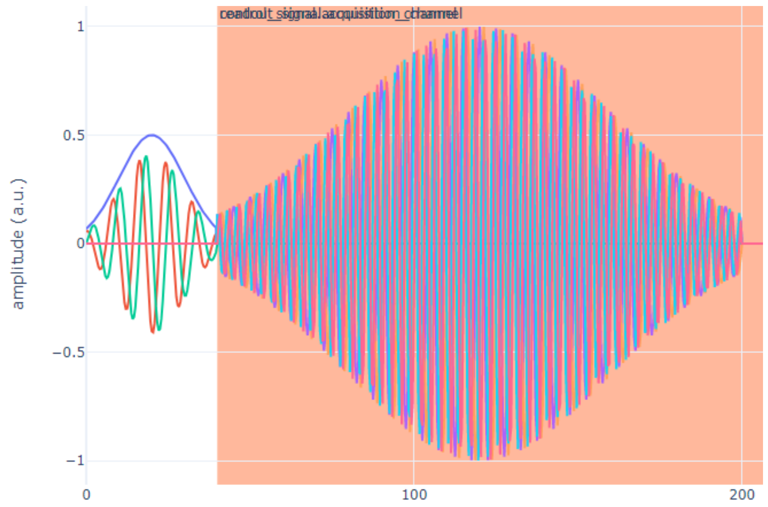
Goal: Find Pi Pulse parameters

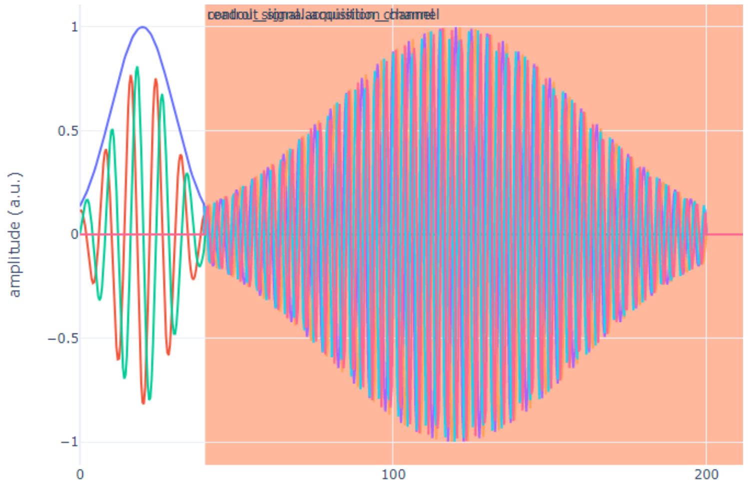
1. Send control and readout pulse.

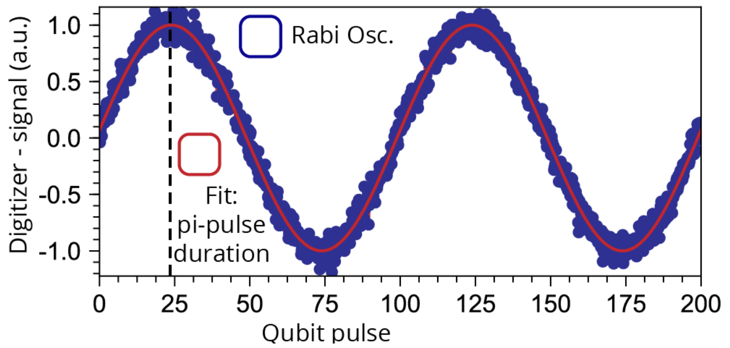
2. Control pulse is scanned over amplitude (pulse duration kept constant).

3. Duration of the pulse that caused a 180 degree rotation is the pi pulse.

Pi Pulse:
What kind of pulse do we need for a 180 degreed rotation on the Bloch Sphere?

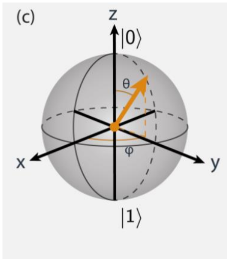


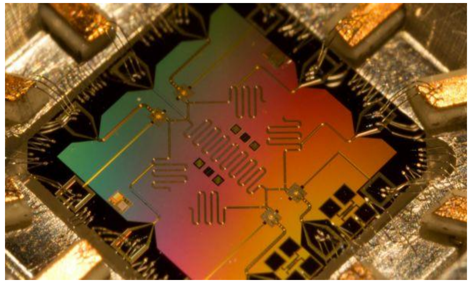




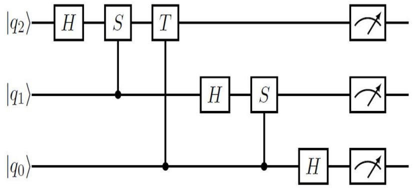
Summary

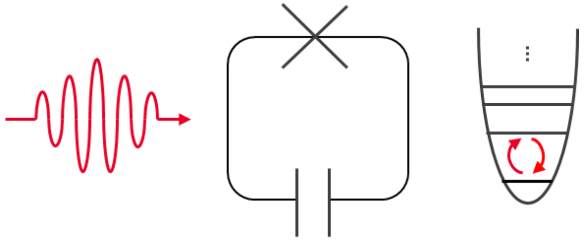
Fundamentals



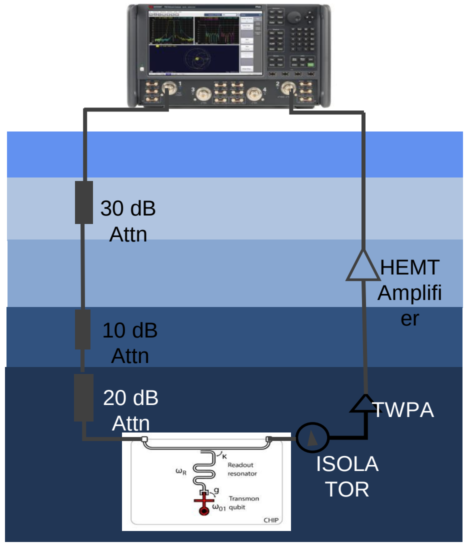


Qubits Control & Read





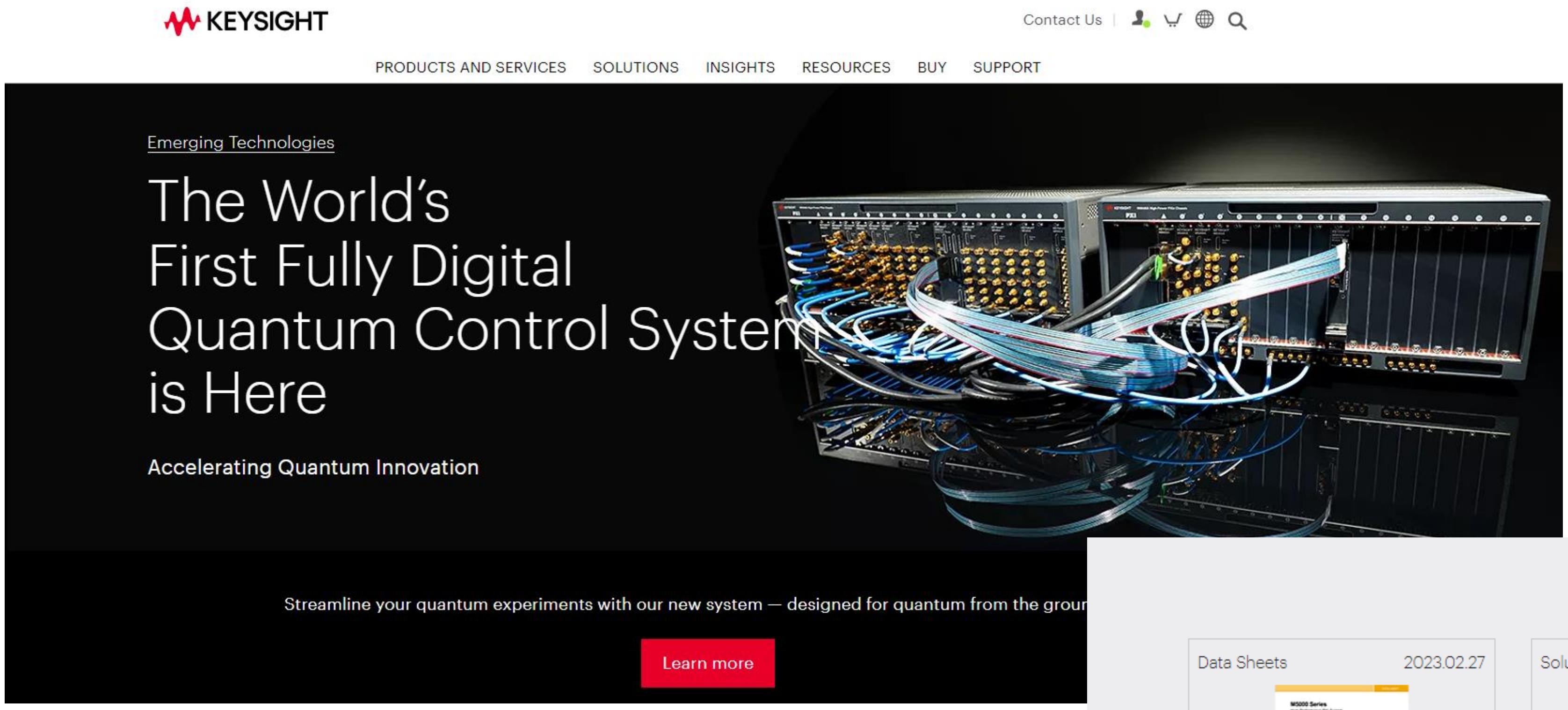
Cryogenic and VNA

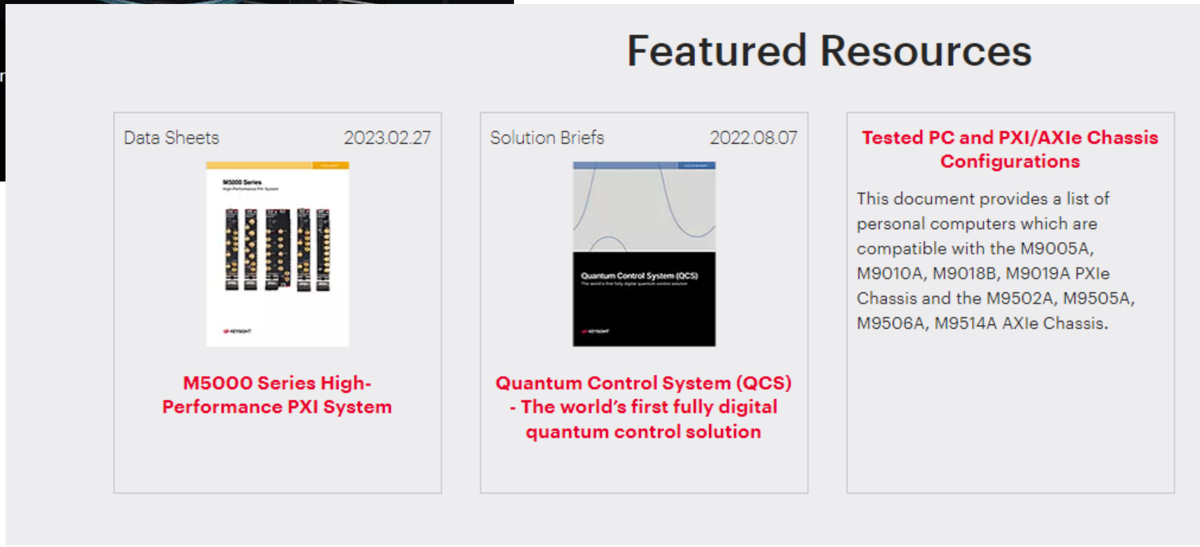


Keysight in Quantum & QCS

Come find out more on Keysight.com

https://www.keysight.com/ca/en/solutions/emerging-technologies/quantum-solutions.html





M5000 Series (LINK)

KEYSIGHT