

Quantum Implementation and Measurement Overview

A faint, stylized quantum circuit diagram is visible in the background on the right side of the slide. It features several horizontal lines representing qubits, with various gates and measurement symbols (circles with a meter icon) connected by vertical lines. Some gates are labeled with 'H' for Hadamard.

Dr. Kristine Boone, *Business Development*

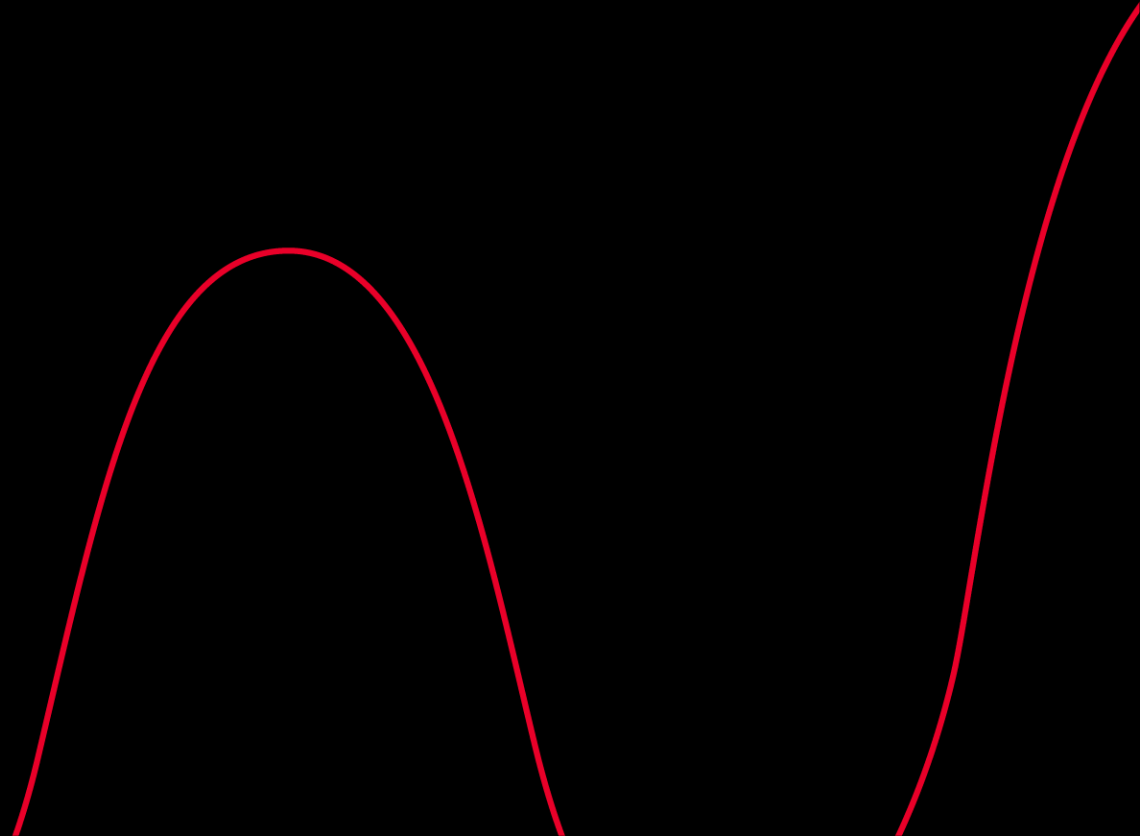
Aidin Taeb (aidin.taeb@keysight.com), *RF/ μ wave Solution Engineer*

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

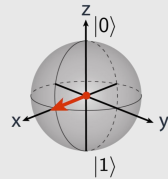


Quantum Technologies – From theory to practice

Quantum Mechanics

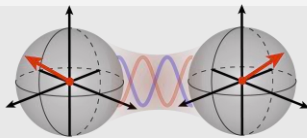
Superposition states

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



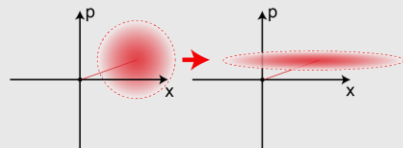
Entanglement

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



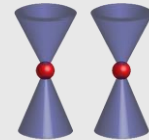
Quantum squeezing

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

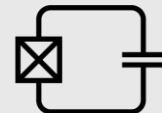


Two-level systems

Trapped Ions



Superconducting circuits



Spin Qubits

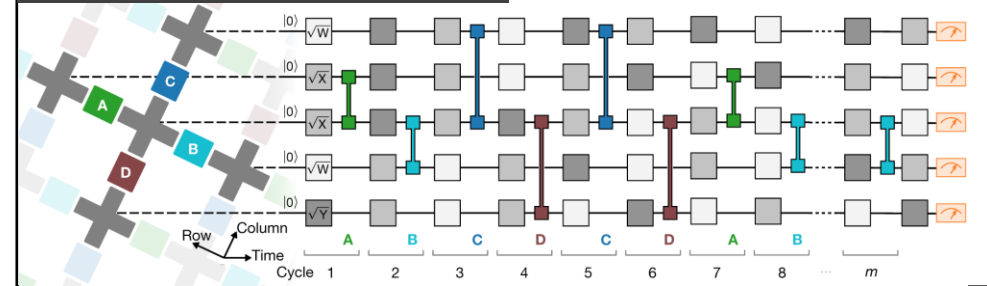


Photons

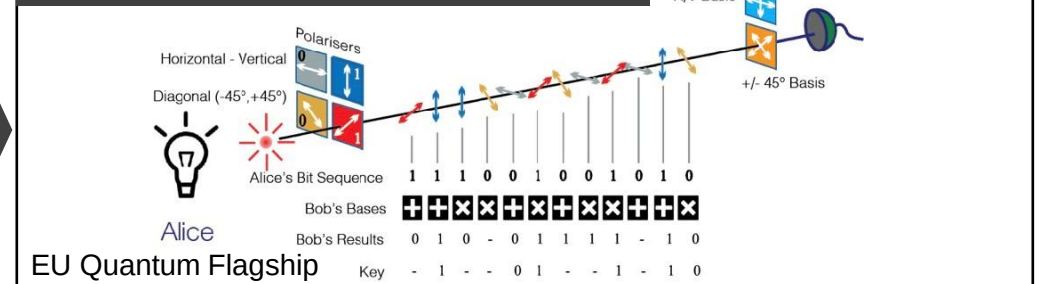


Quantum Computing

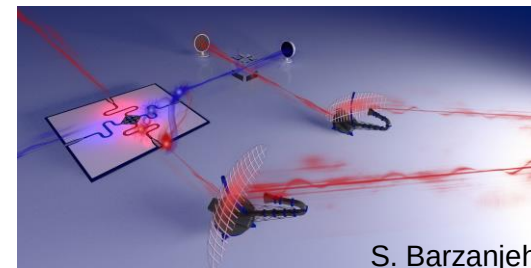
F. Arute et al. **Nature**, 505-510 (2019)



Quantum Communication



Quantum Sensing



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

Classical vs. Quantum information

Classical computer

Bit:

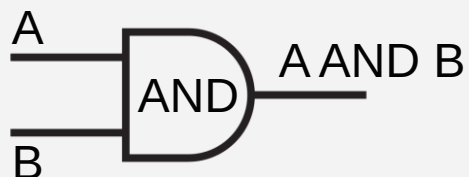
0 or 1



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):

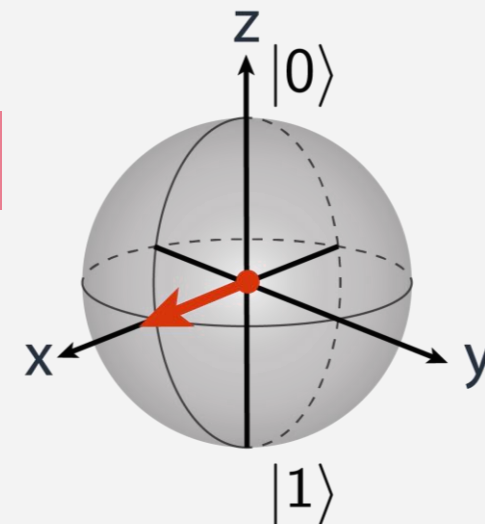
$$|\psi\rangle = c_0|0\rangle + c_1|1\rangle$$

- Superposition

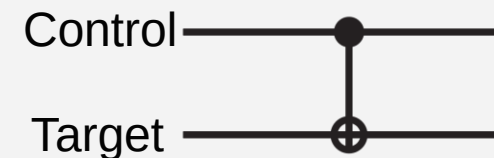
Quantum logic:

Controlled-NOT (CNOT)

- Entanglement



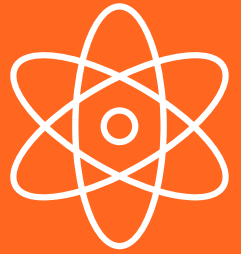
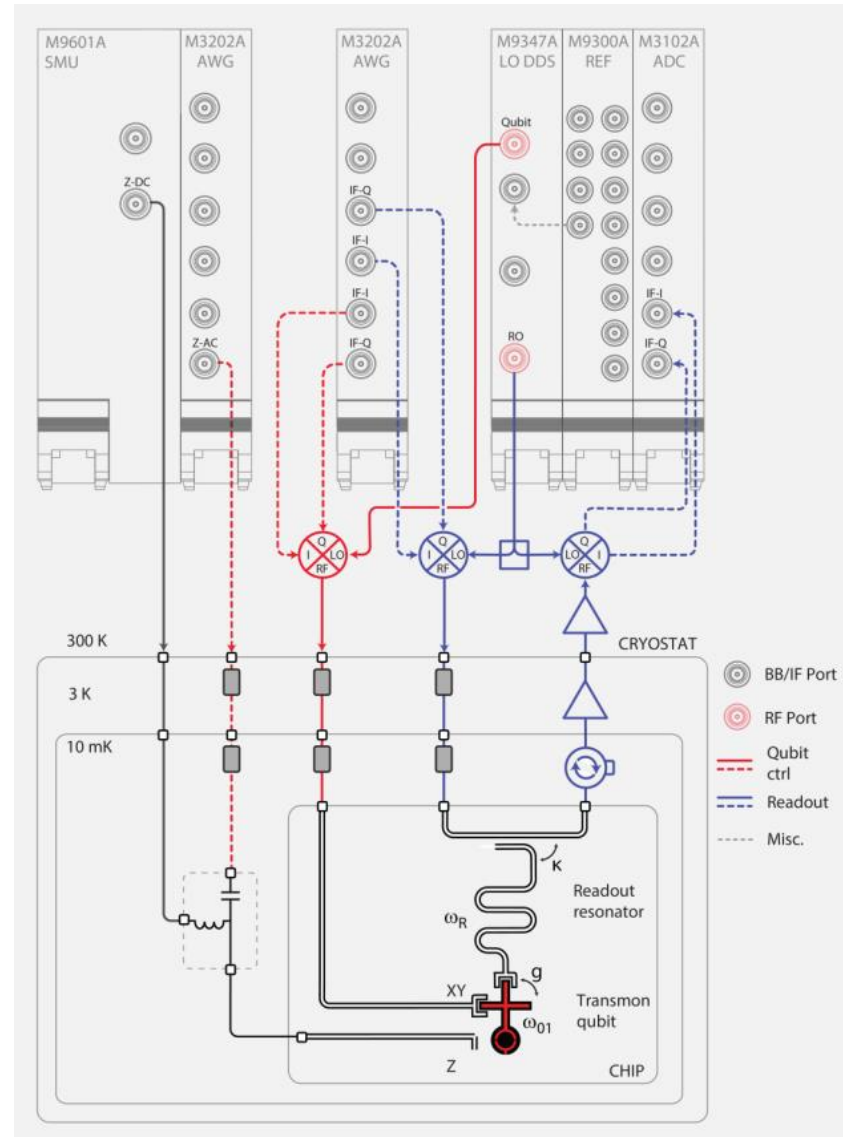
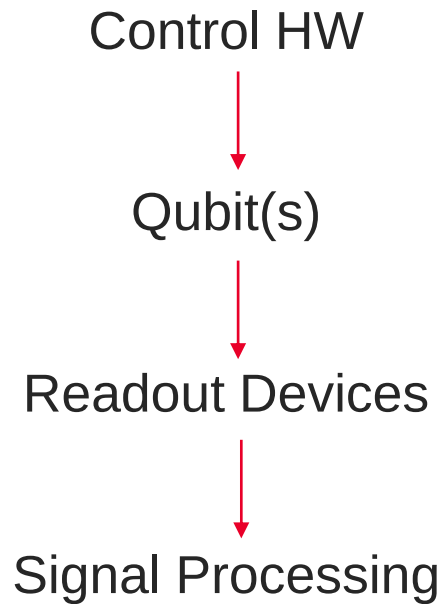
INPUT	OUTPUT
$ 00\rangle$	$ 00\rangle$
$ 01\rangle$	$ 01\rangle$
$ 10\rangle$	$ 11\rangle$
$ 11\rangle$	$ 10\rangle$



Quantum Computing Experiments

What does a quantum computer look like?

Example setup: 1 qubit configuration with XYZ control.



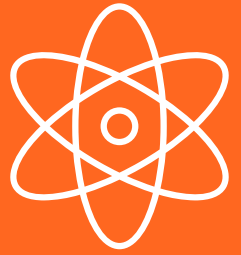
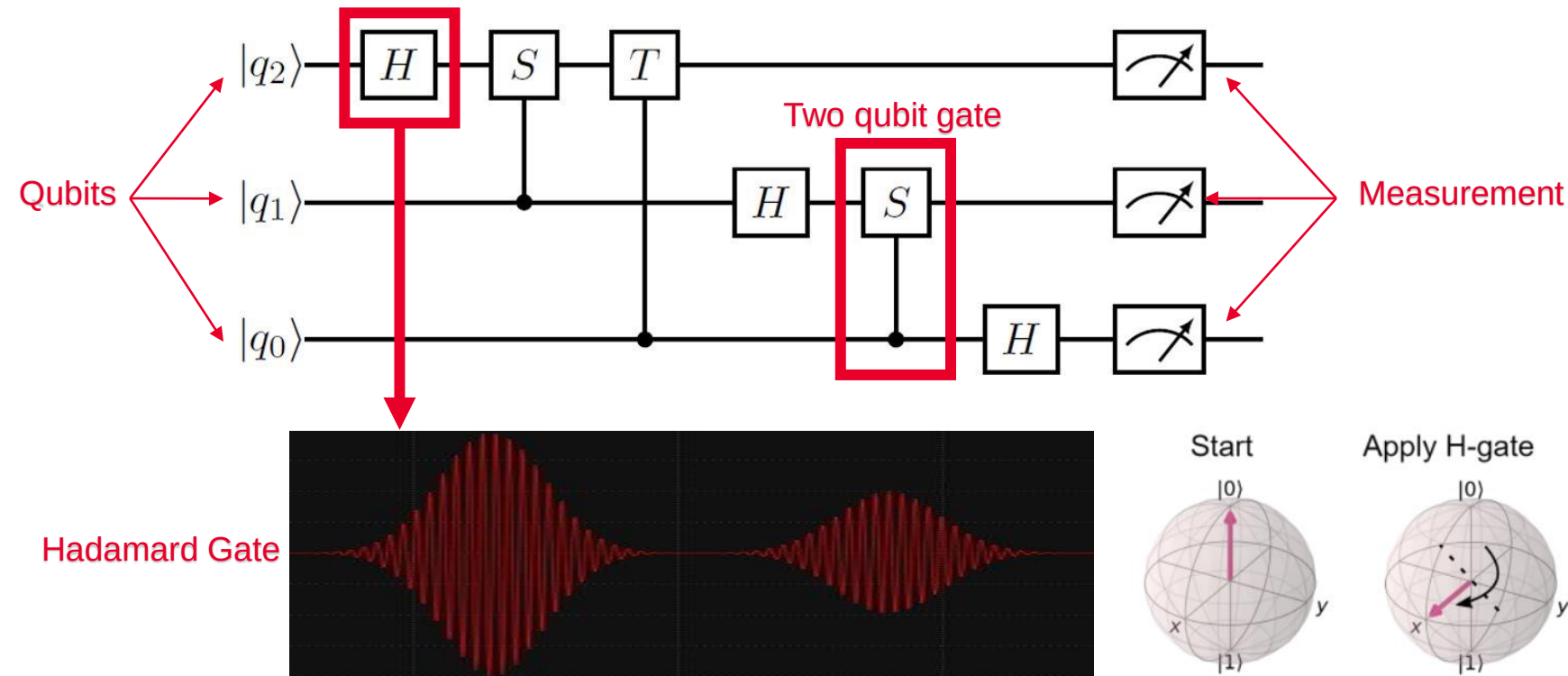
Classical

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

Quantum

Quantum Computing Experiments

What does a quantum algorithm look like?



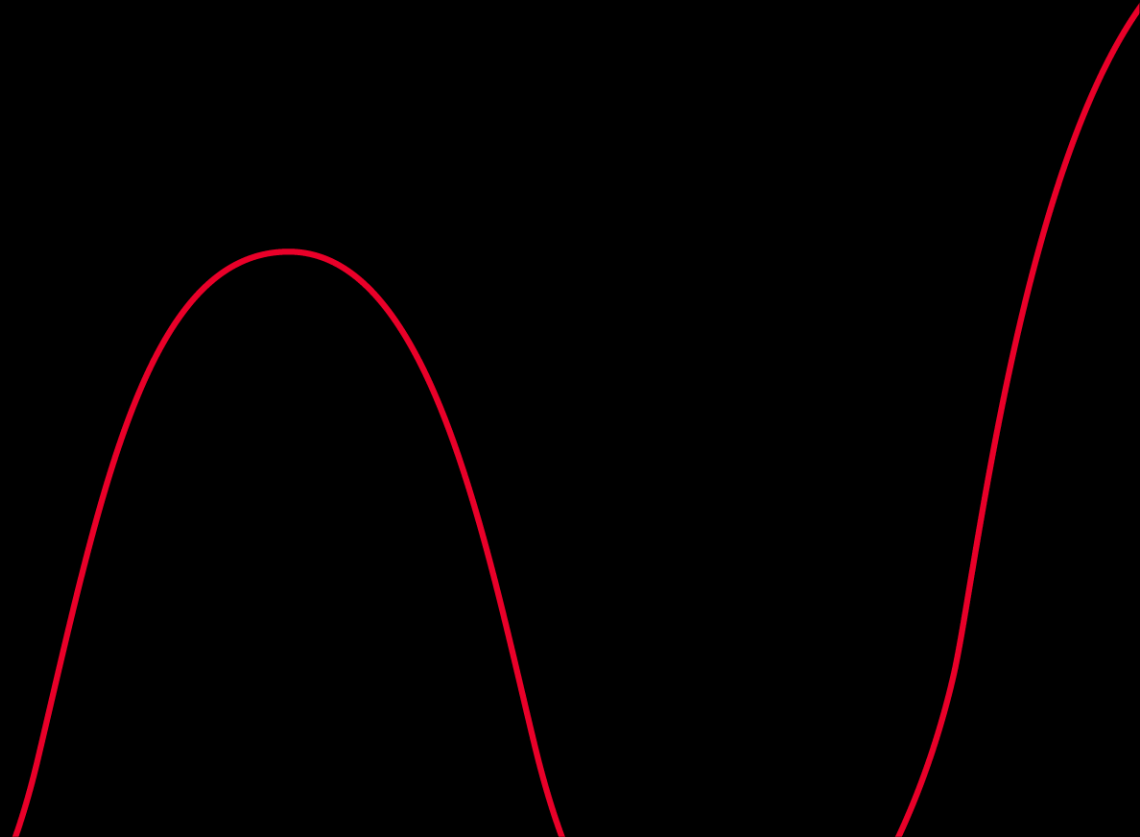
Quantum Circuit:
Quantum equivalent of
classical logic circuits.

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

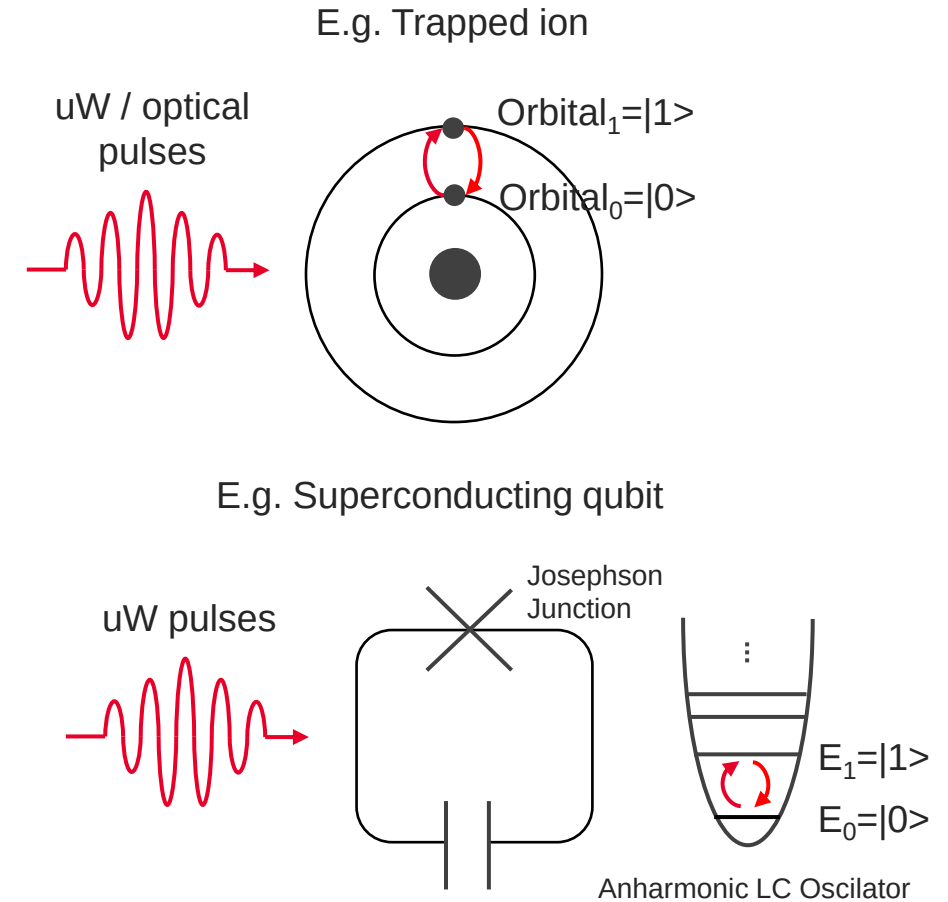
• Qubit implementation

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

- e^- orbital $\rightarrow$ trapped ions
- flux $\rightarrow$ superconducting flux qubits
- e^- spin $\rightarrow$ quantum dots
- nitrogen vacancy (NV) spin $\rightarrow$ NV in diamonds
- photon polarization $\rightarrow$ photons
- ...
- ...

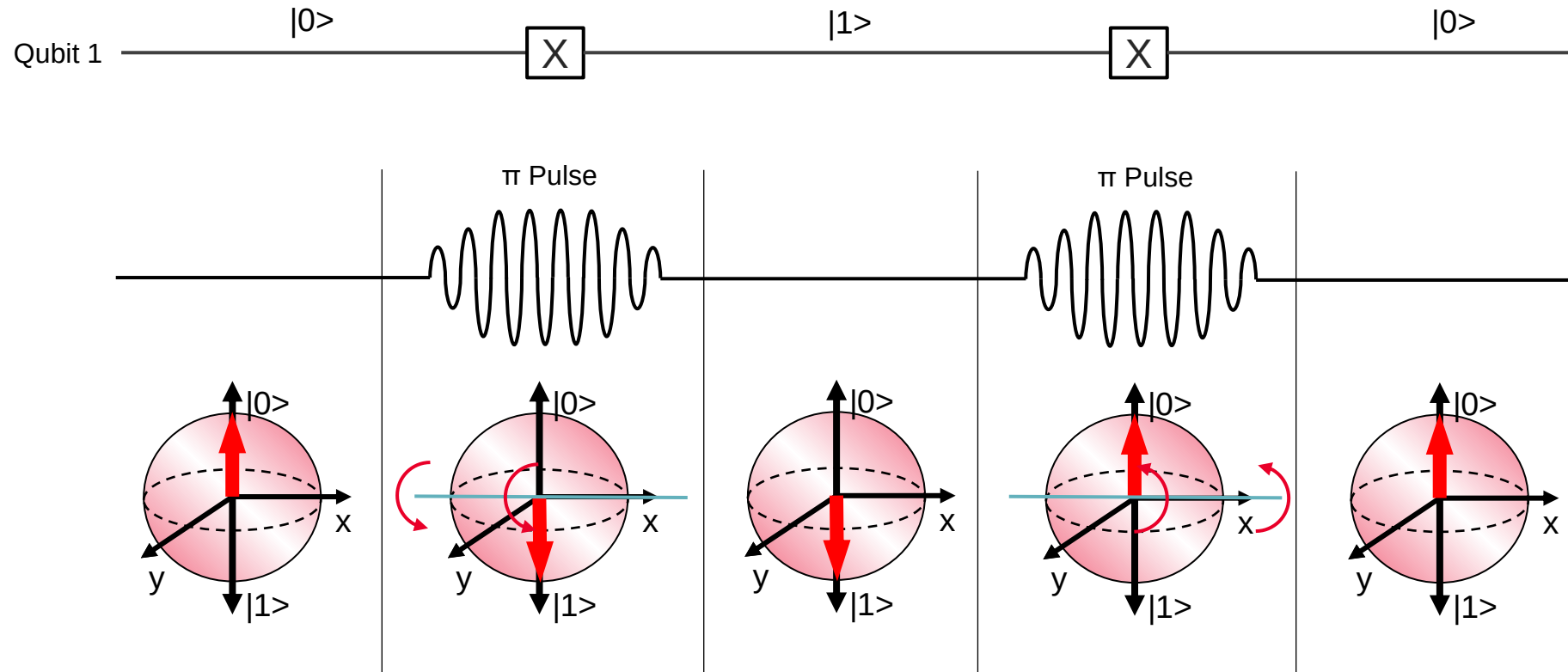
• Qubit control

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



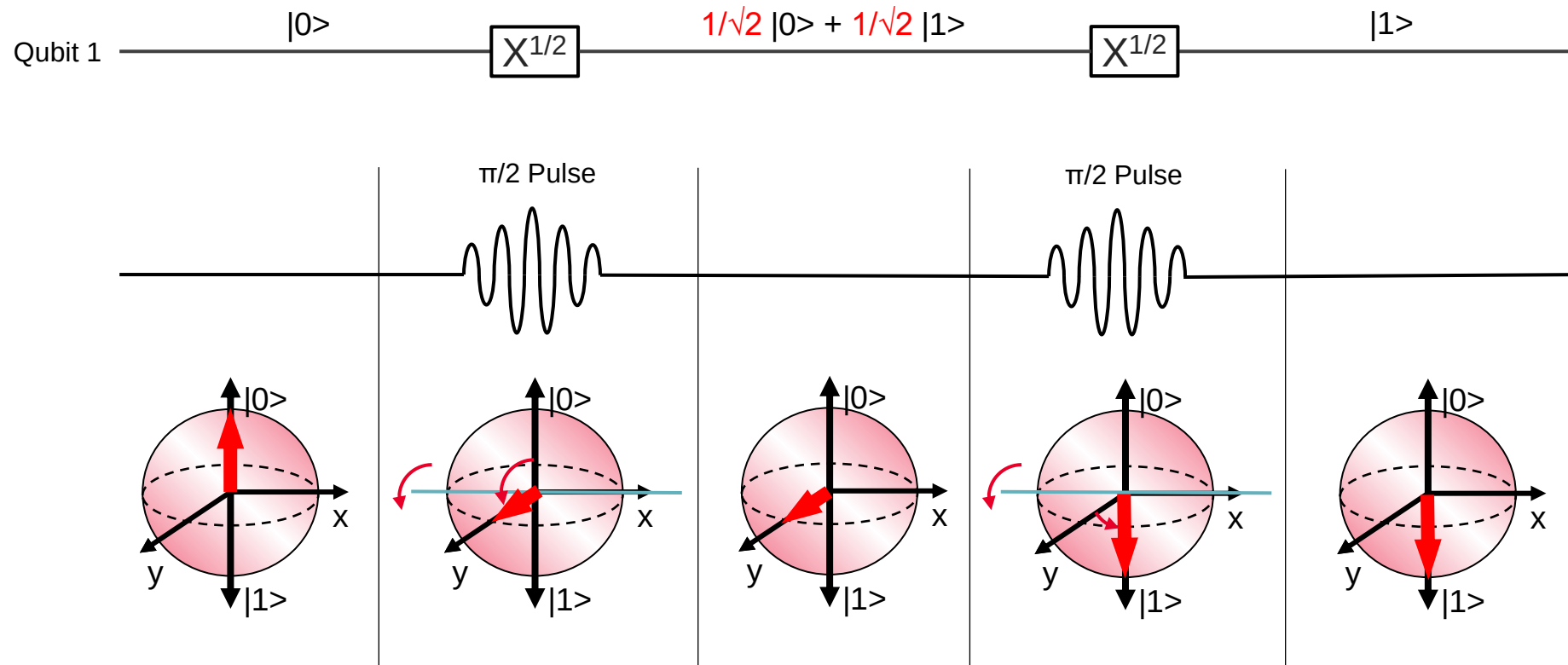
Control of Qubits – Pulse Area

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



Control of Qubits – Pulse Area

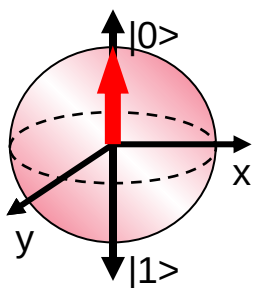
- Pulse area (amplitude and duration) defines the amount of rotation



That is also why amplitude stability is important

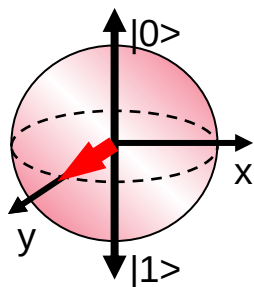
Control of Qubits – Readout

- Readout projects the qubit (destroys the information) into $|0\rangle$ or $|1\rangle \rightarrow$ readout result is binary (either $|0\rangle$ or $|1\rangle$)
 - How do we get α and β ($\alpha|0\rangle + \beta|1\rangle$)? $\rightarrow$ statistics



$|0\rangle$

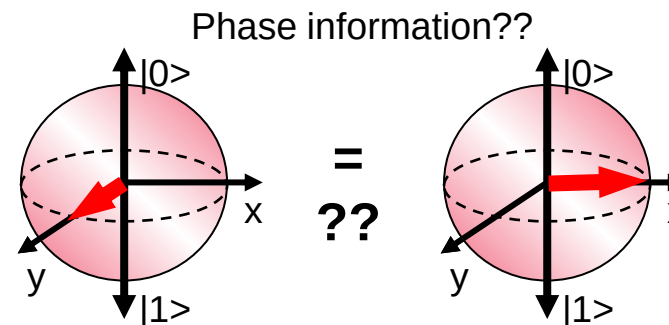
Means 100% probability of obtaining $|0\rangle$ and 0% of obtaining $|1\rangle$



$1/\sqrt{2} |0\rangle + 1/\sqrt{2} |1\rangle$

Means 50% probability of obtaining $|0\rangle$ and 50% of obtaining $|1\rangle$

Many experimental repetitions are required to get the statistics



$1/\sqrt{2} |0\rangle + 1/\sqrt{2} |1\rangle \neq 1/\sqrt{2} |0\rangle + i/\sqrt{2} |1\rangle$

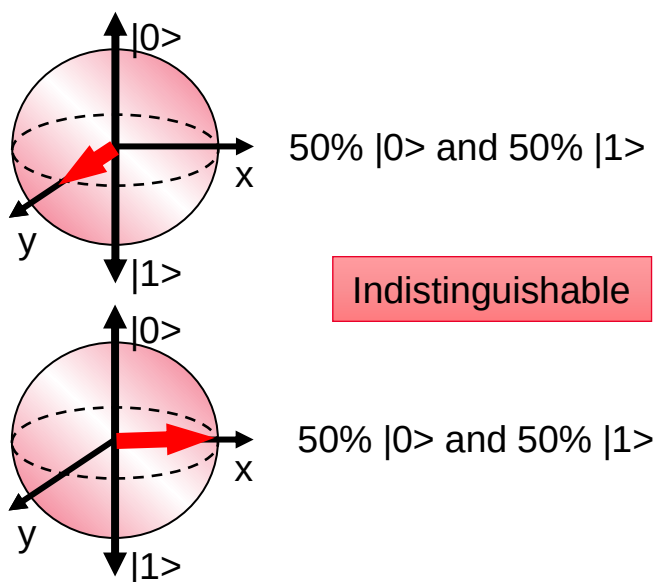
But both have 50% probability of $|0\rangle$ and 50% of $|1\rangle$

Control of Qubits – Readout

- Readout projects the qubit (destroys the information) into $|0\rangle$ or $|1\rangle \rightarrow$ readout result is binary (either $|0\rangle$ or $|1\rangle$)
 - How do we get α and β ($\alpha|0\rangle + \beta|1\rangle$)? $\rightarrow$ statistics and **ROTATIONS**

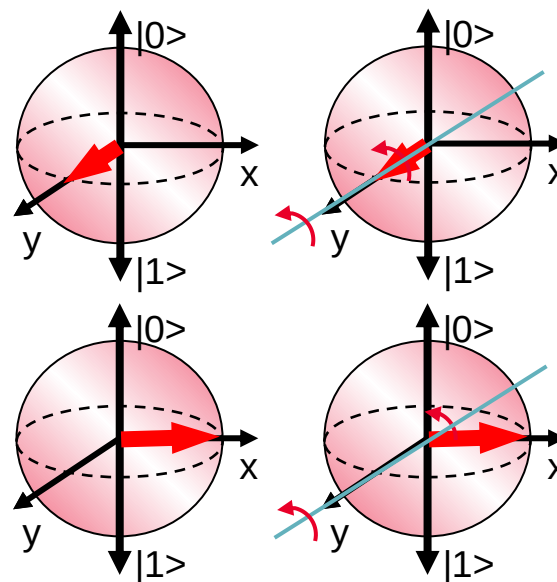
Step 1: repeat many times

- 1) Run experiment
- 2) Measure



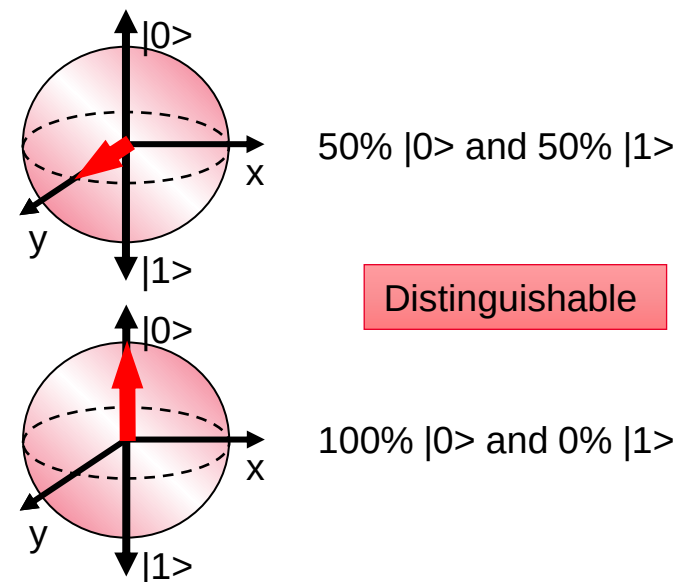
Step 2: repeat many times

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

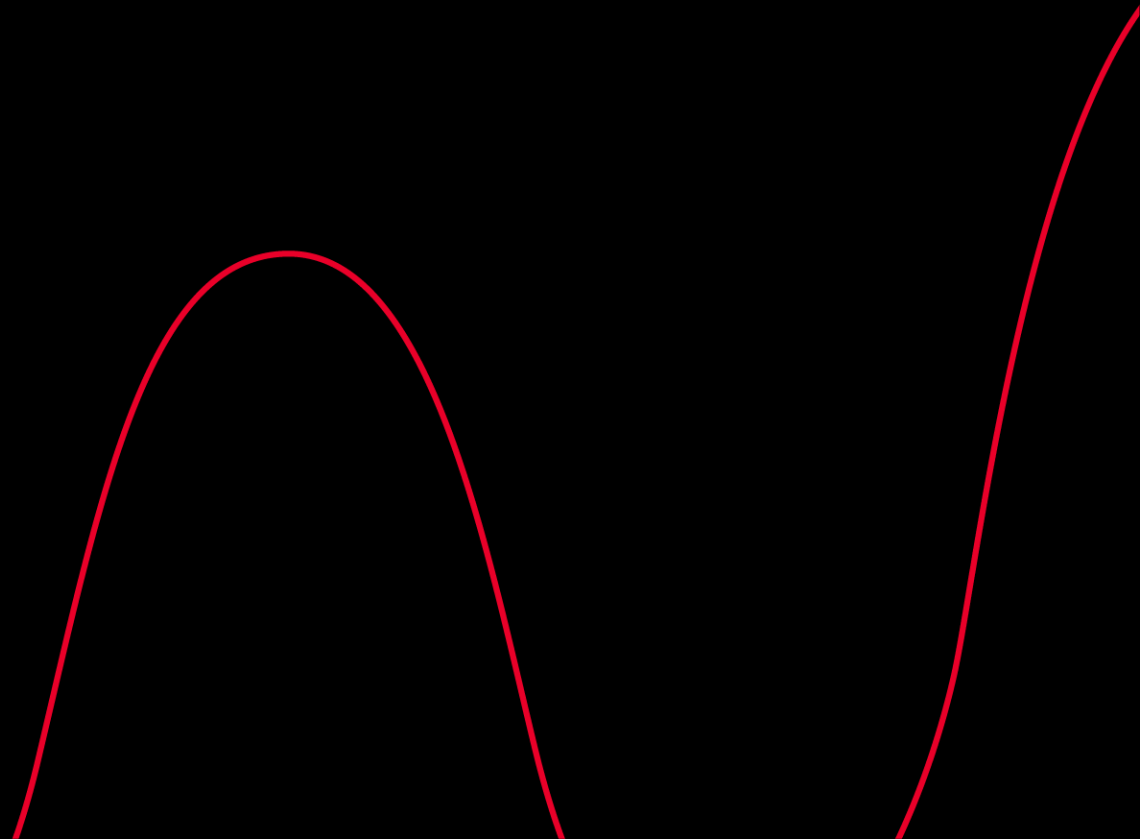


Step 3: do the same for X axis

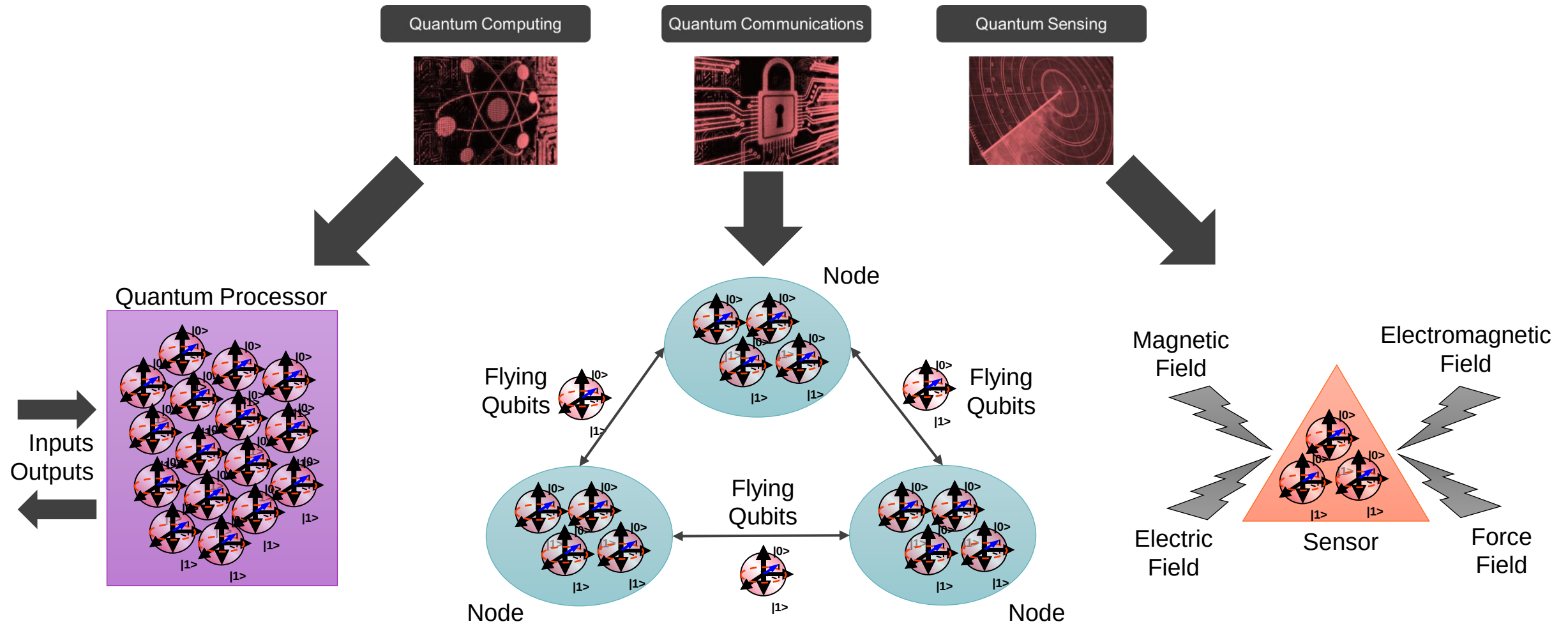
Full state tomography
requires many operations



Qubit Types

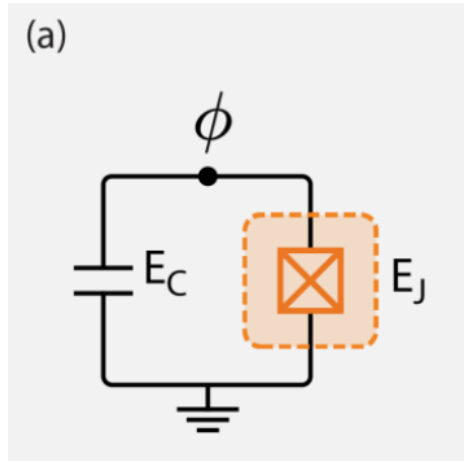


Qubits are the Pillars for all Quantum Applications



Superconducting Qubits

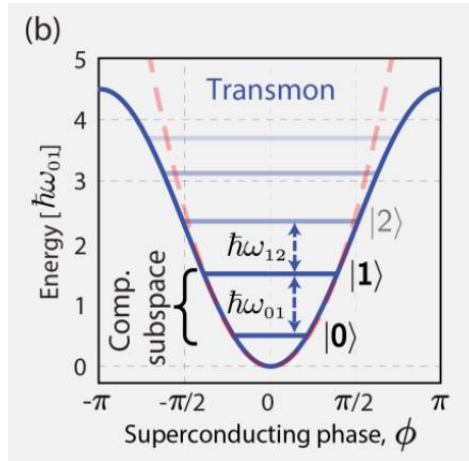
“Artificial atoms” built out of superconducting circuits



Superconducting Circuit

Resonant circuit.

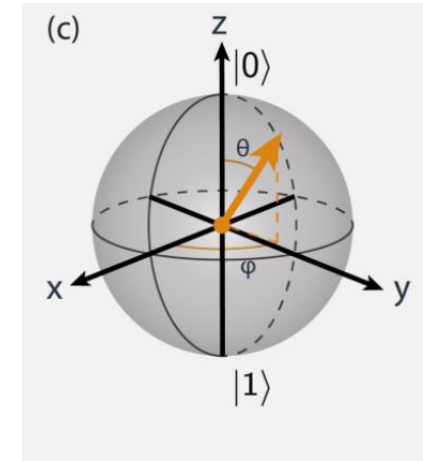
Leverages collective behavior of electrons in circuit.



Artificial Atom

Qubit has properties of anharmonic multi-level quantum system.

Qubit states are encoded in the lowest energy levels.



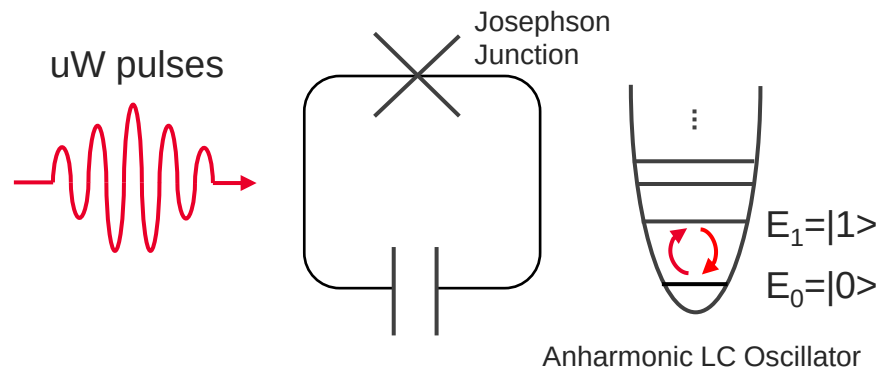
Bloch Sphere Representation

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

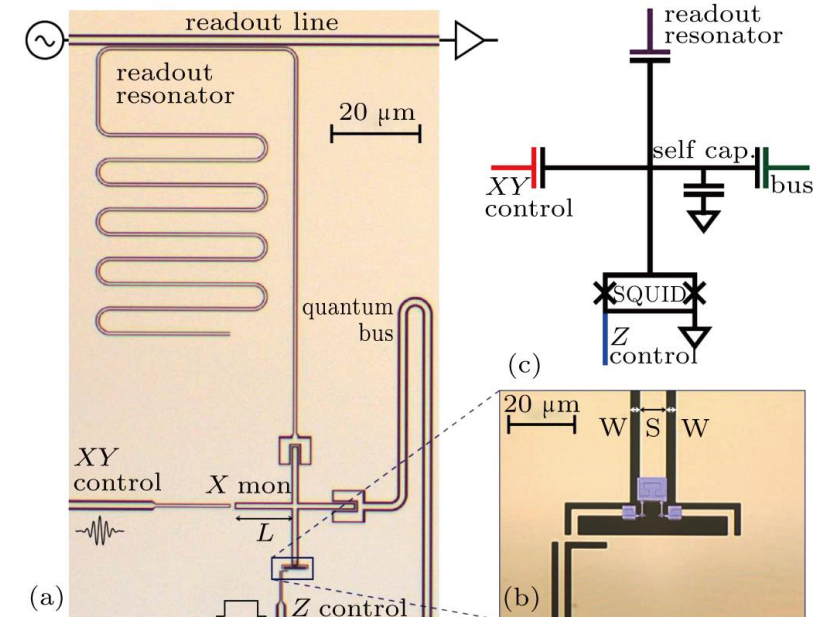
<https://www.keysight.com/us/en/assets/3120-1387/application-notes/Characterizing-Superconducting-Qubits.pdf?success=true>

Superconducting Qubits

E.g. Superconducting qubit



Real example



- **Qubit control**

- Performed by applying the energy of the $|0\rangle - |1\rangle$ 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

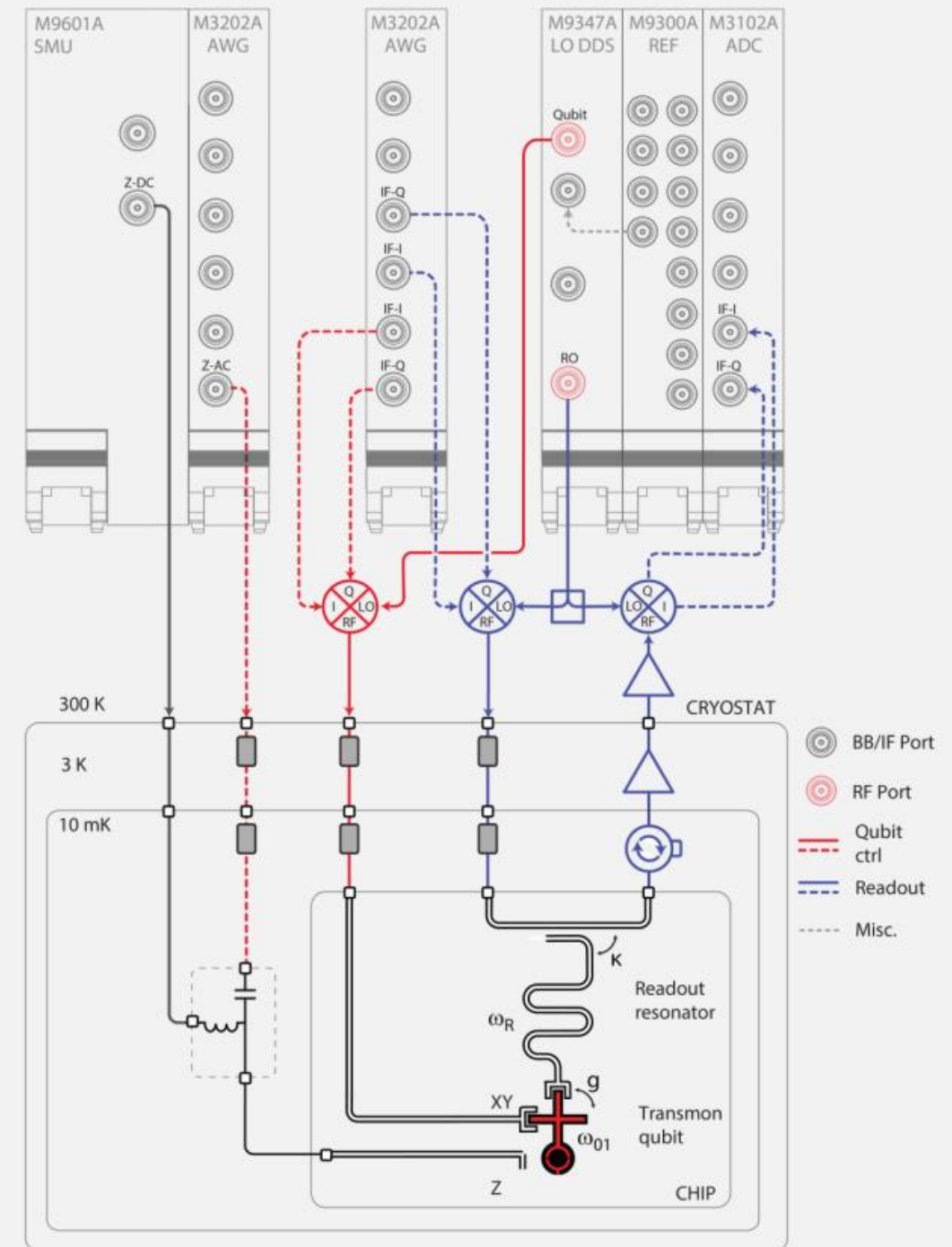
Control and Readout of a Qubit

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

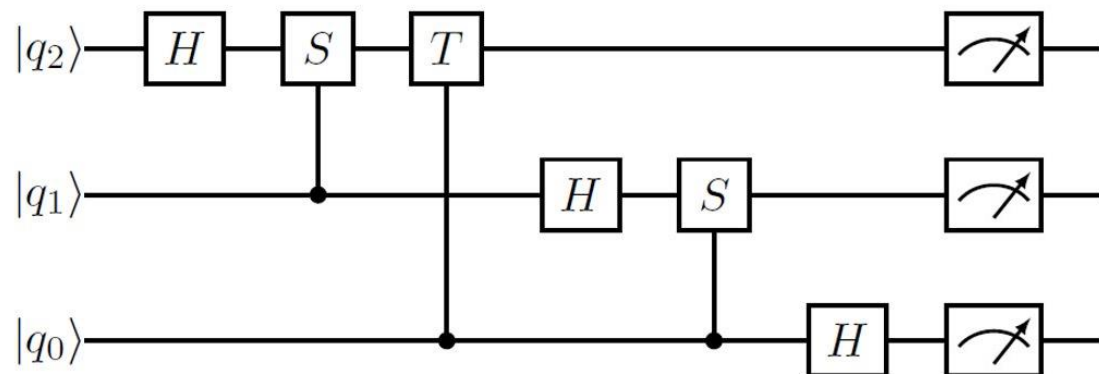
Keysight HW and SW can be a part of many different quantum computers!

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



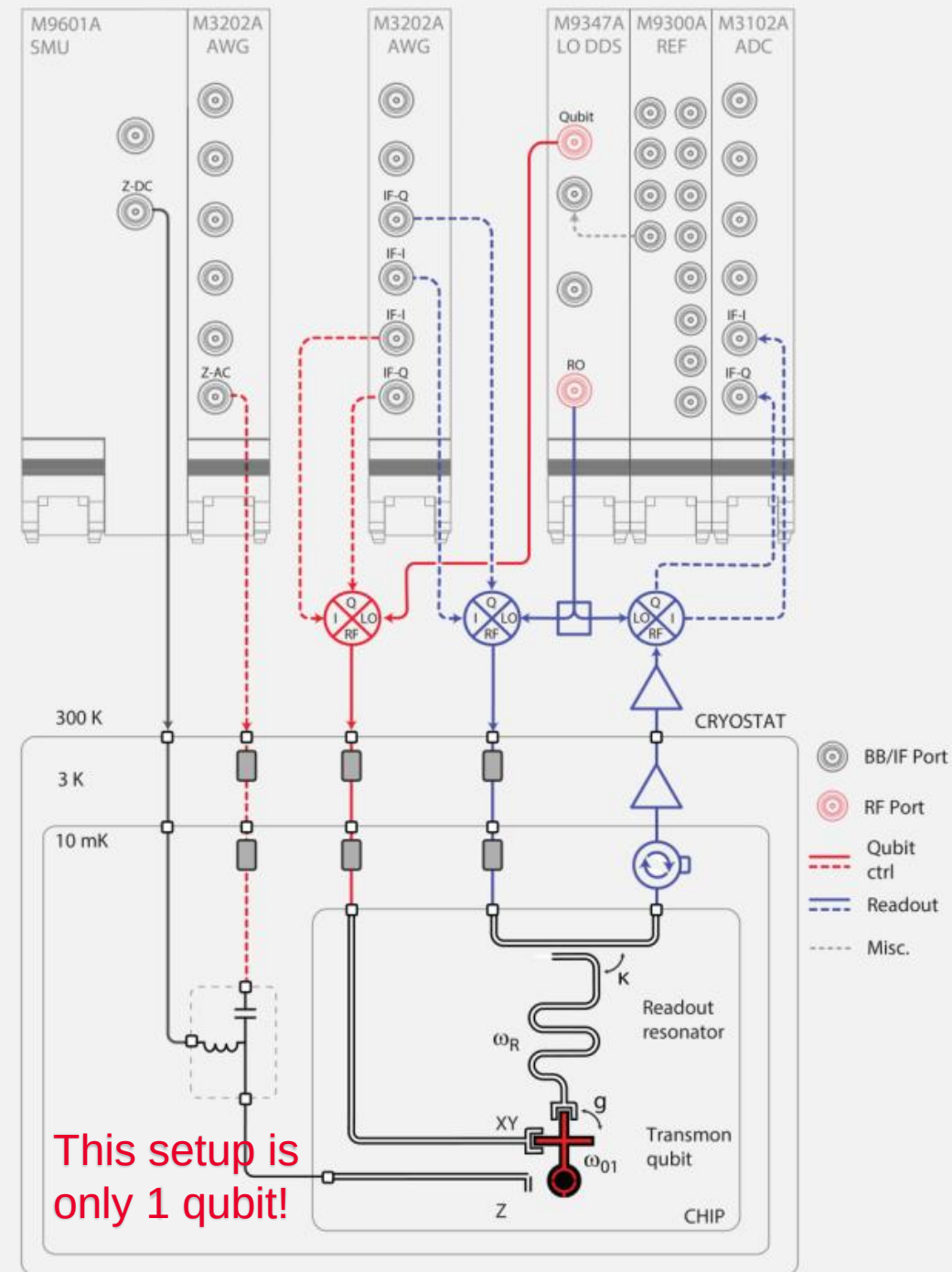
Challenges

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



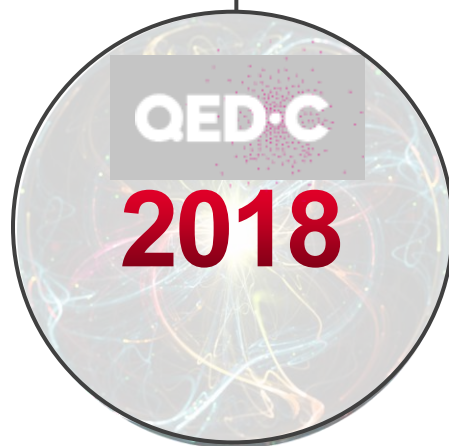
SMART TECHNOLOGY CONNECTS THE WORLD

INNOVATION IS EVERYWHERE

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



Keysight in Quantum



Joined QED-C



Boulder Cryogenic
Quantum Testbed



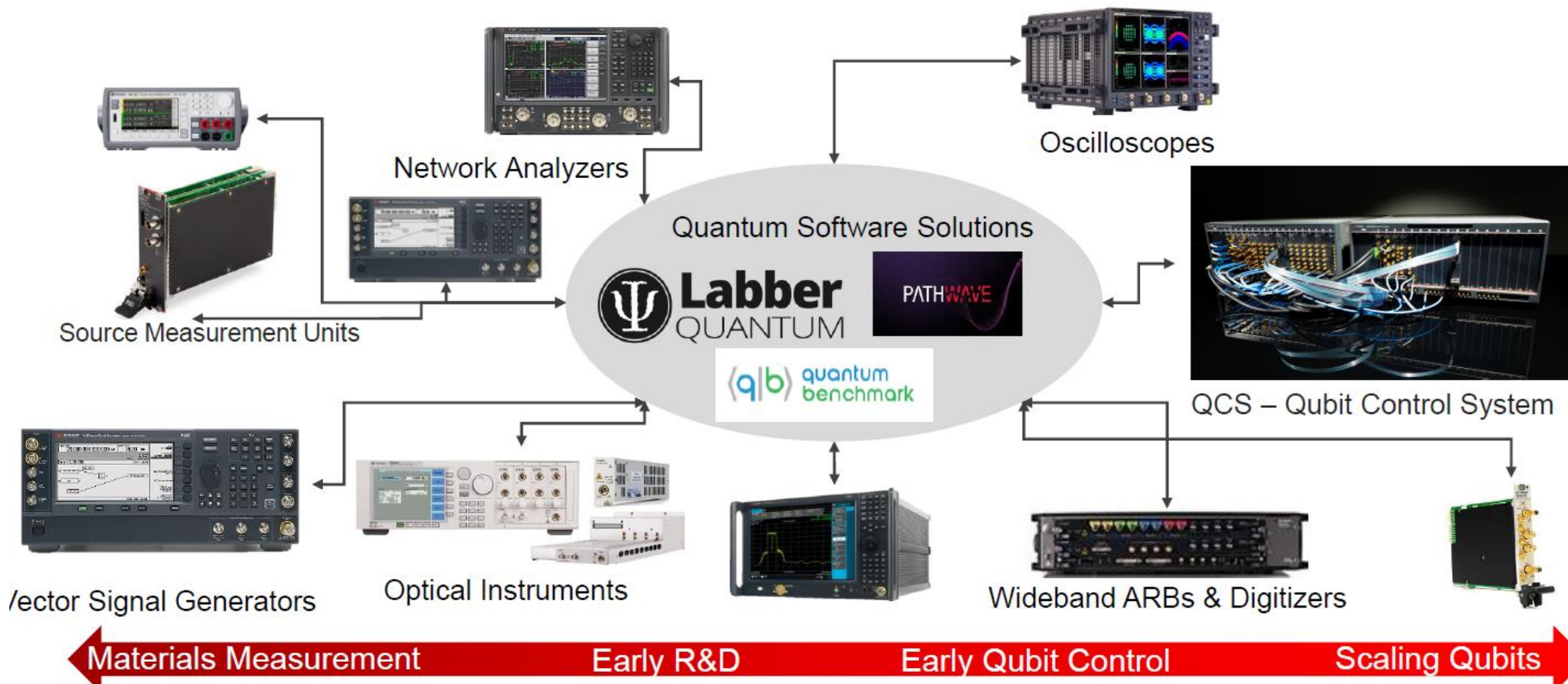
Quantum Software Center
Cambridge, MA



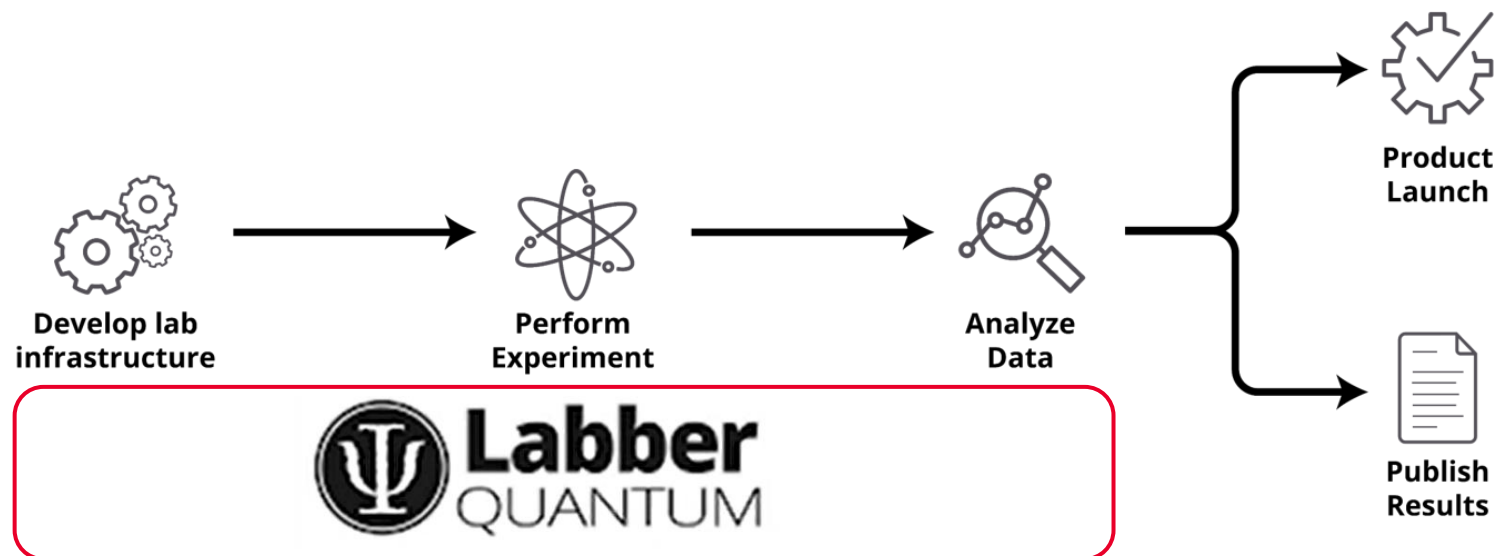
MIT EQuS
64-Qubit Testbed

Keysight: A Partner for the Quantum Ecosystem

Pulling Control, Measurements, Data Analysis Together



Key Advantages of Labber



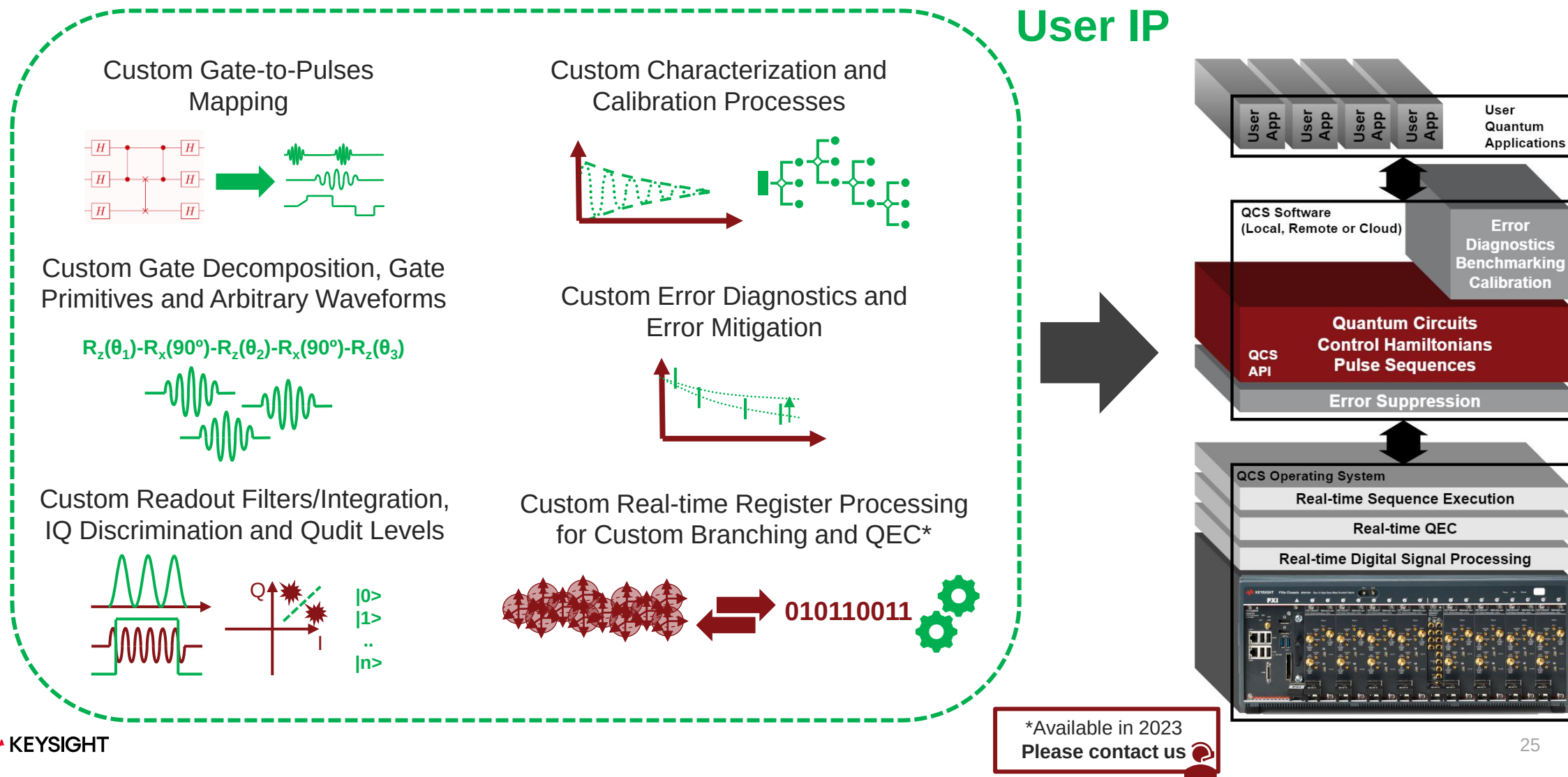
- **Modular and extensible**
Easy to adopt to new types of equipment
- **Standardized procedures for measurements and data storage**
Facilitates team collaborations and group continuation
- **User-interface driven**
Removes the need for scientists to write code, allowing them to focus on their research

Faster & more efficient experiments

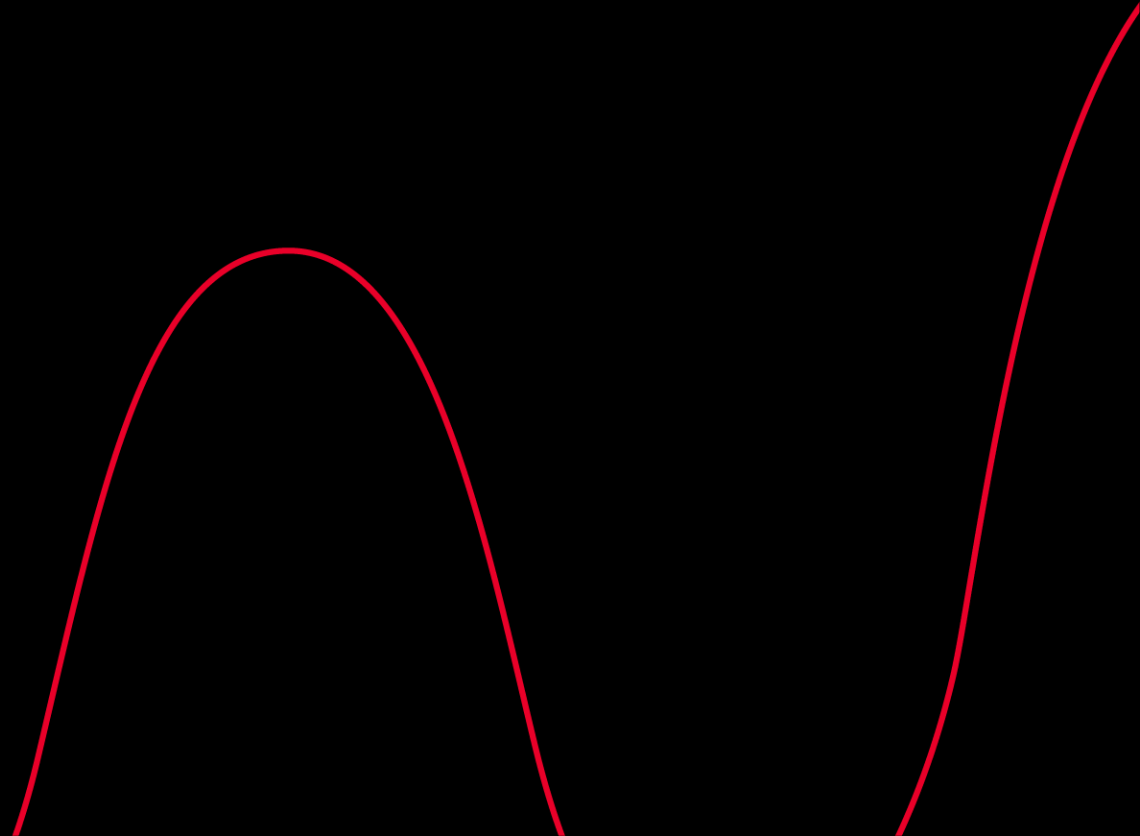
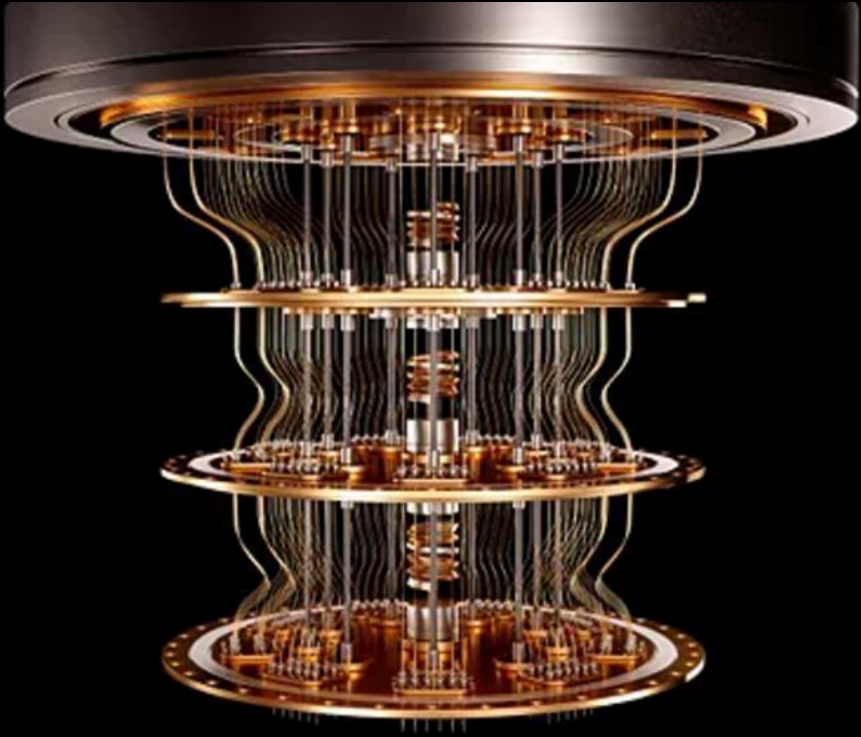
Comprehensive but fully customizable to incorporate your core IP

QCS software

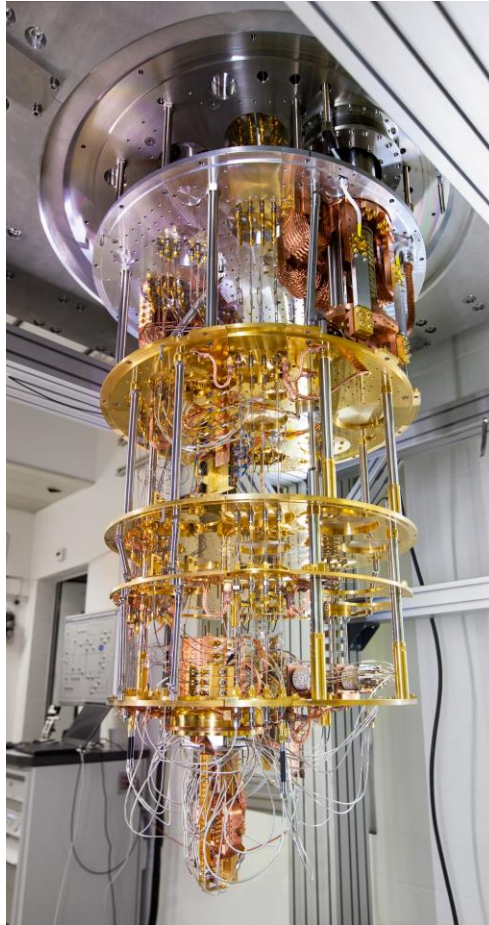
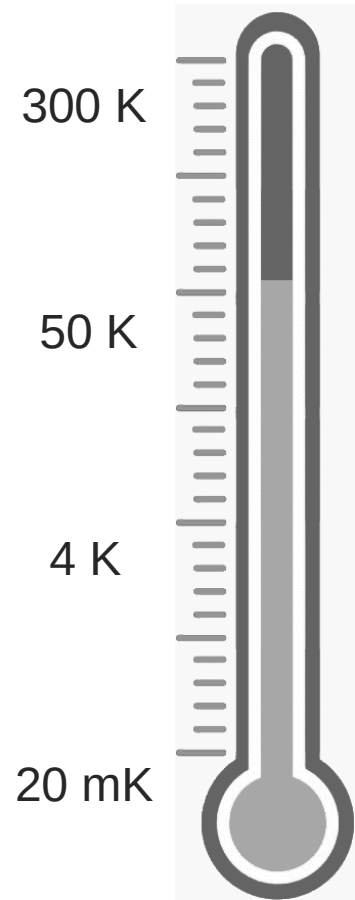
User IP



Cryogenic Challenges & Calibration - VNA Application In Quantum



Cryogenics for Quantum Computing



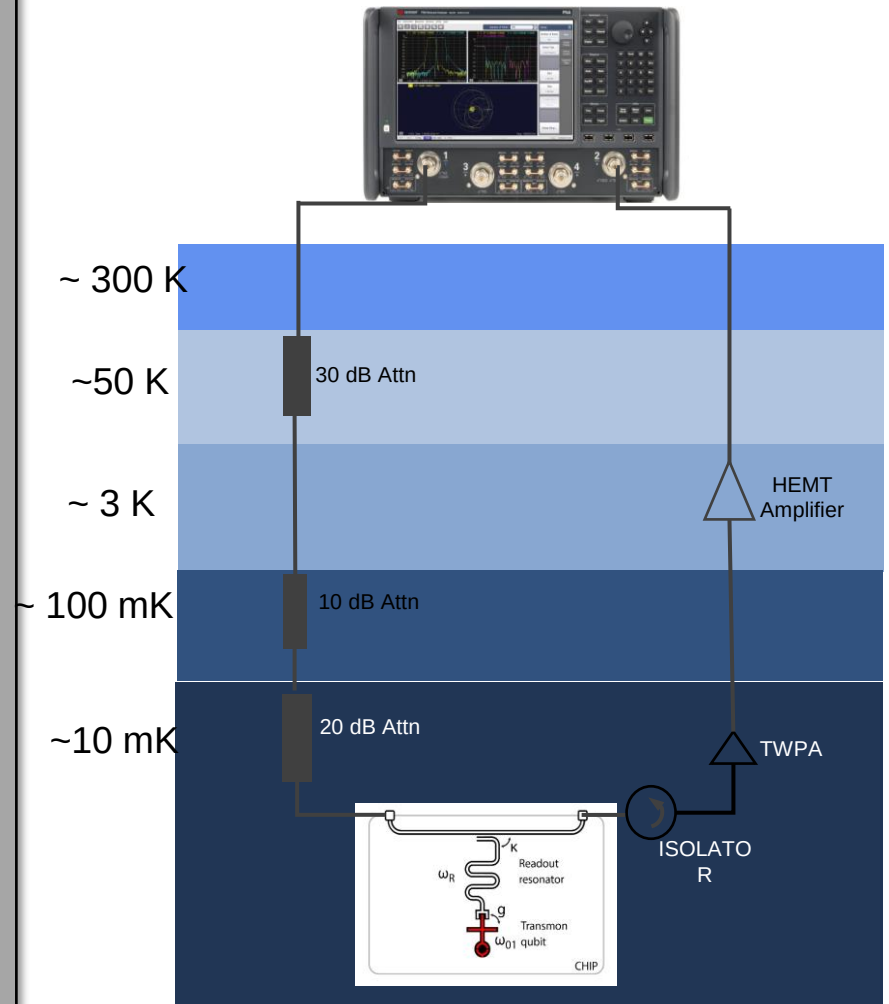
Overall Challenges for Qubit Control

- 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)

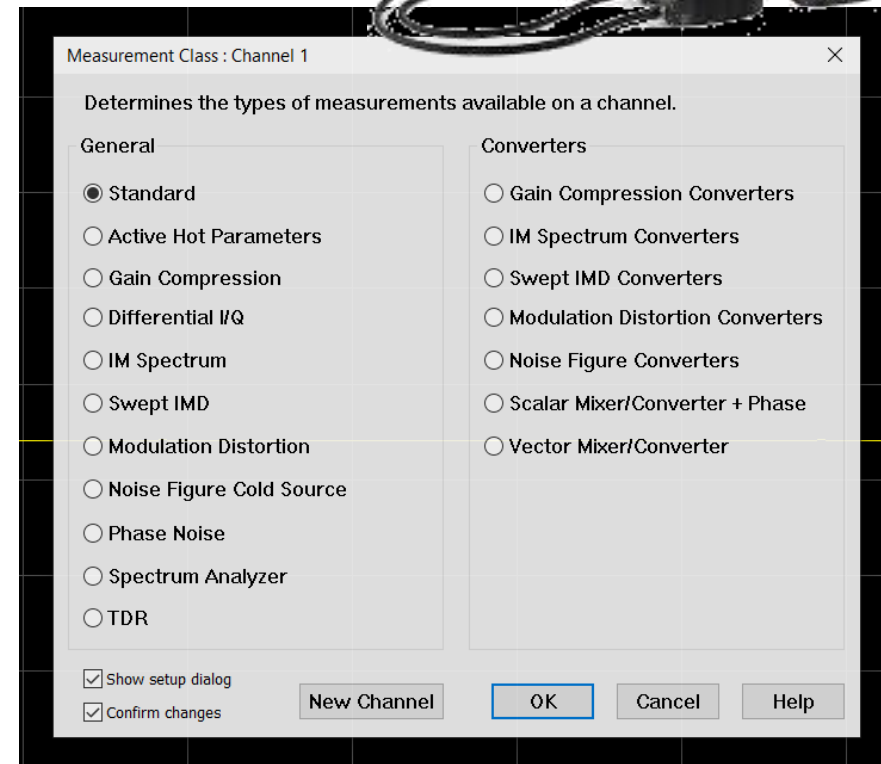
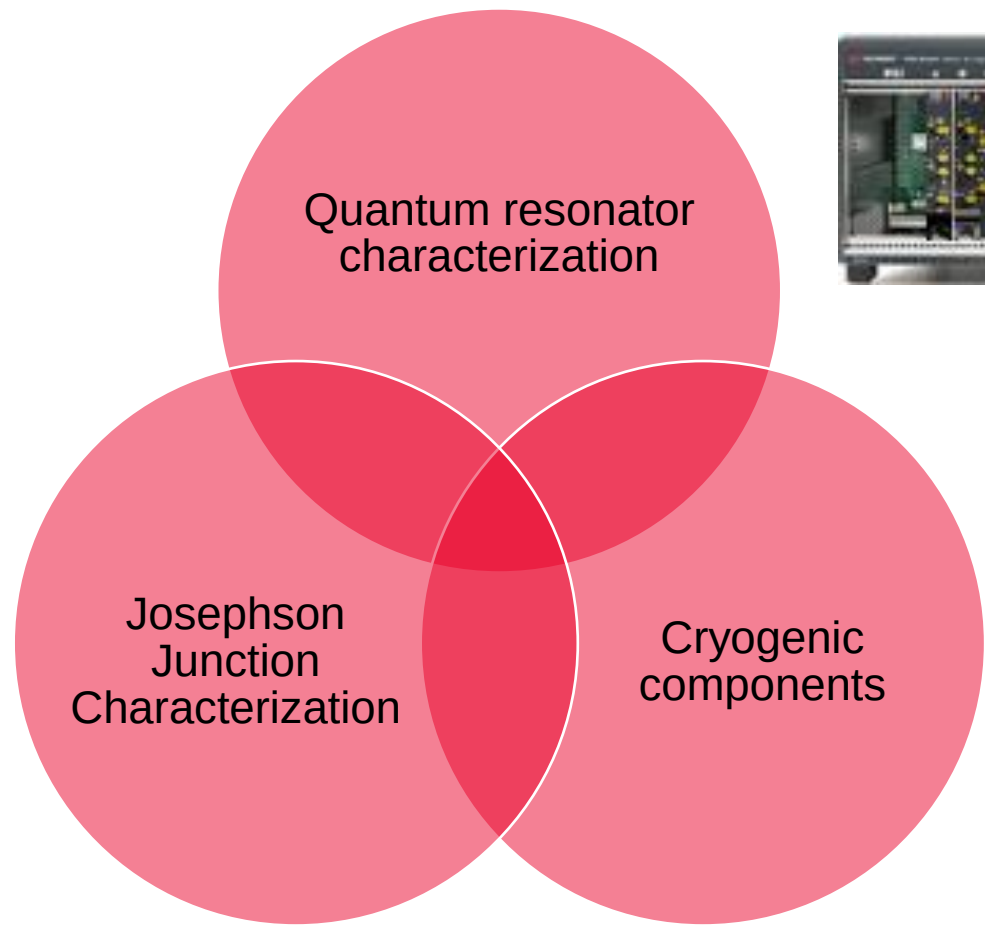
System Level Architectures

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



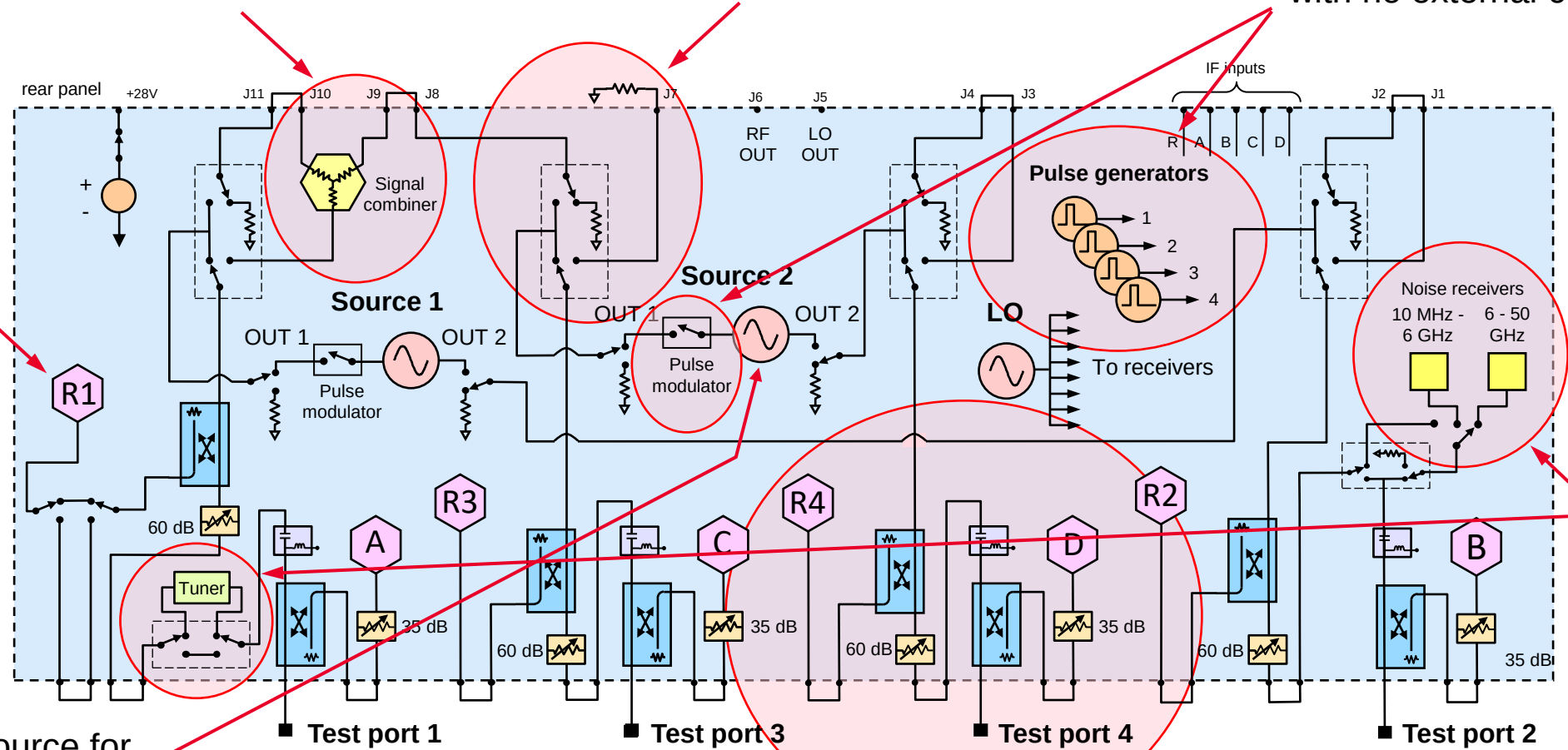
PNA-X – Industry Leader For Active-Device Test

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

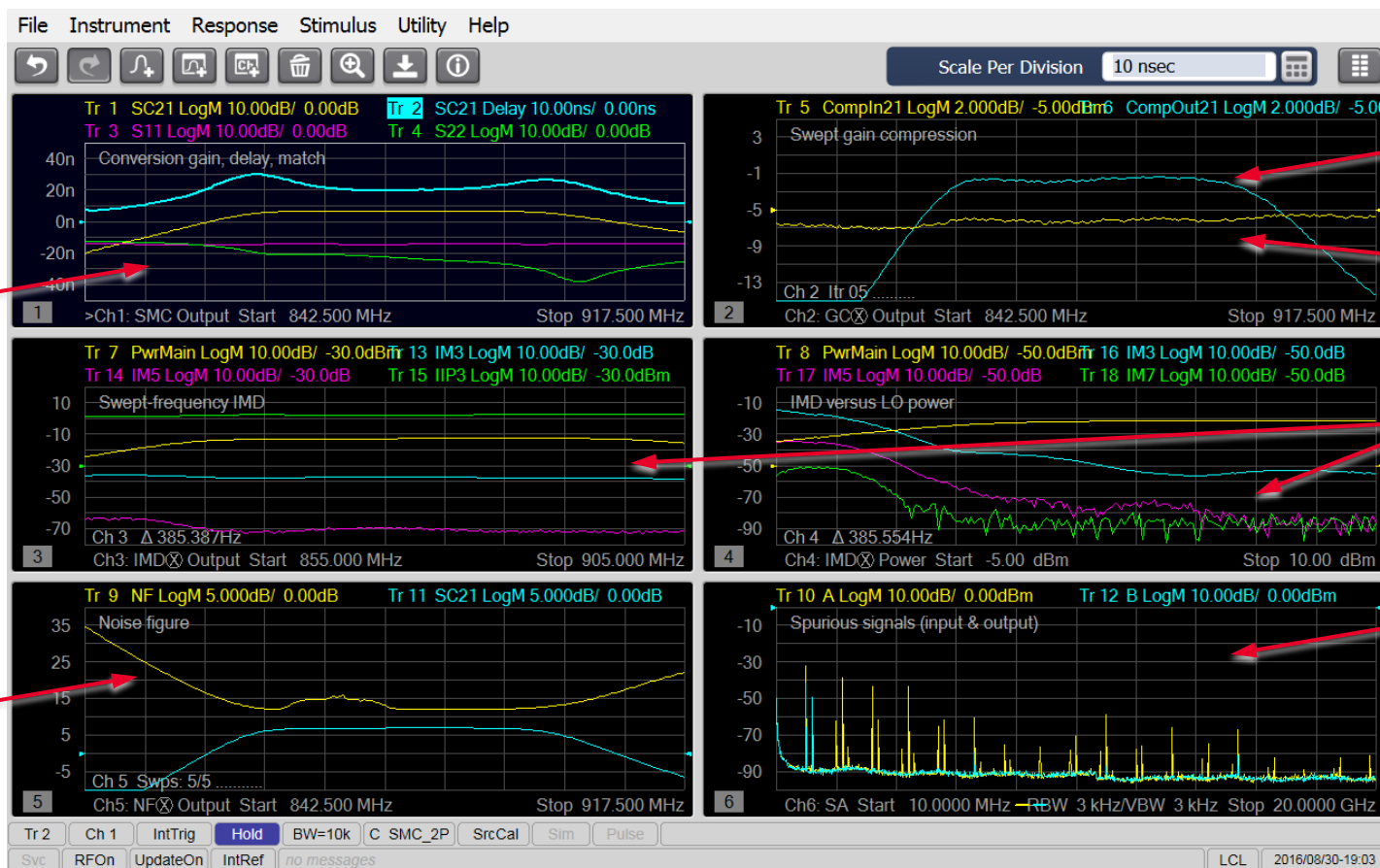
Second source for IMD or LO signals

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



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

Noise figure with industry-leading accuracy

Quantum Resonator Measurements

MILLIMETER WAVE QUANTUM RESONATOR - STANFORD

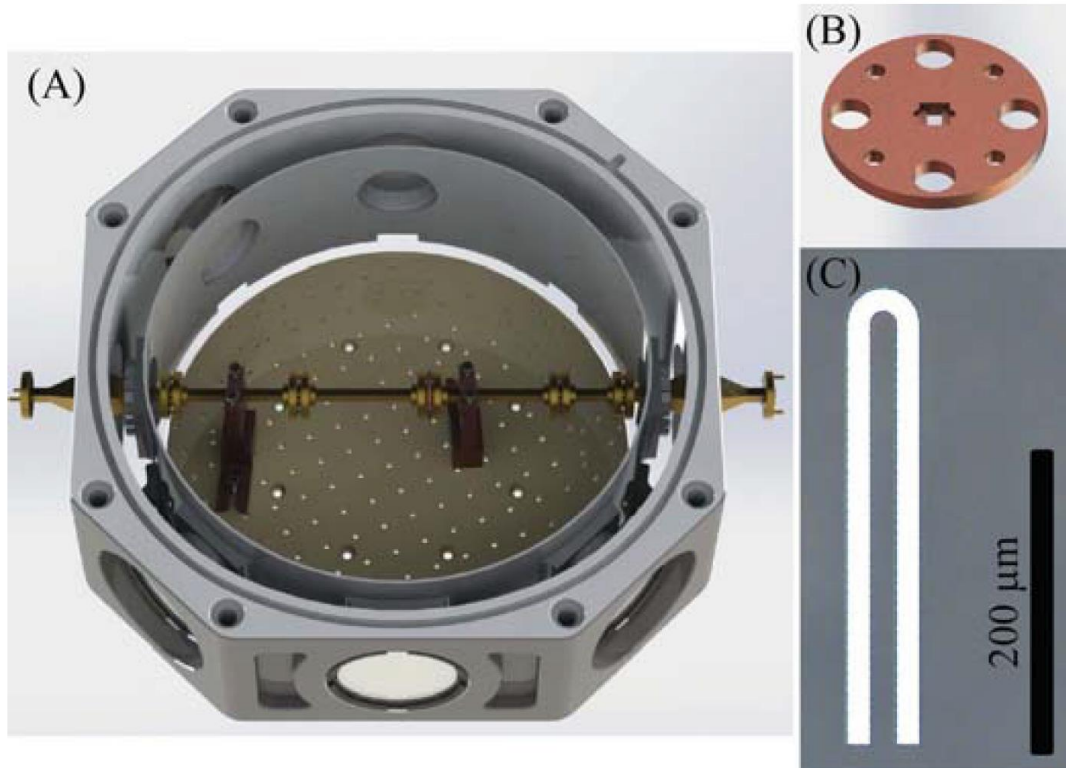
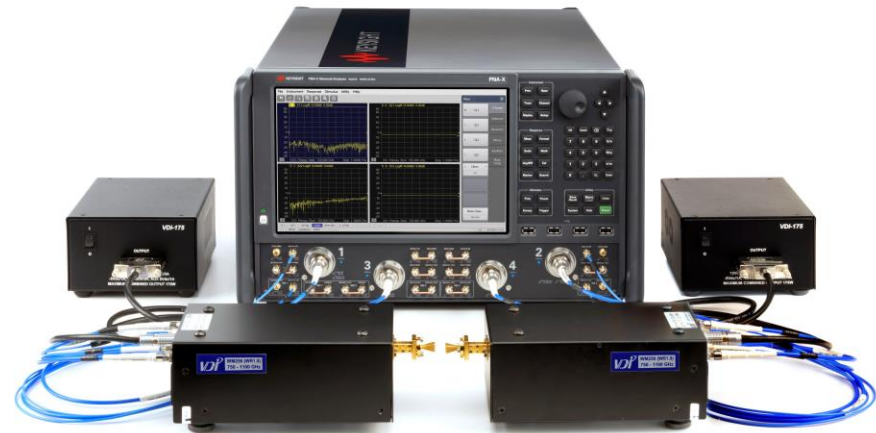


Fig. 1. (A) Design of the 4 K experimental setup – WR10 waveguides are connected via horn antennas and windows to the VNA outside of the cryostat, (B) The chip holder can be sandwiched between two waveguide sections, (C) Example of Nb resonator with $f_{res} = 105$ GHz and $Q_{ext} \approx 500$.

- VNA with millimeter wave extenders



Hubert Stokowski^{1,2}, Marek Pechal^{1,2}, Emma Snively³, Kevin K. S. Multani^{2,4}, Paul B. Welanders³,
Jeremy Witmer^{1,2}, Emilio A. Nanni³, and Amir H. Safavi-Naeini^{1,2}
¹Stanford University, Department of Applied Physics, Stanford, CA 94305 USA

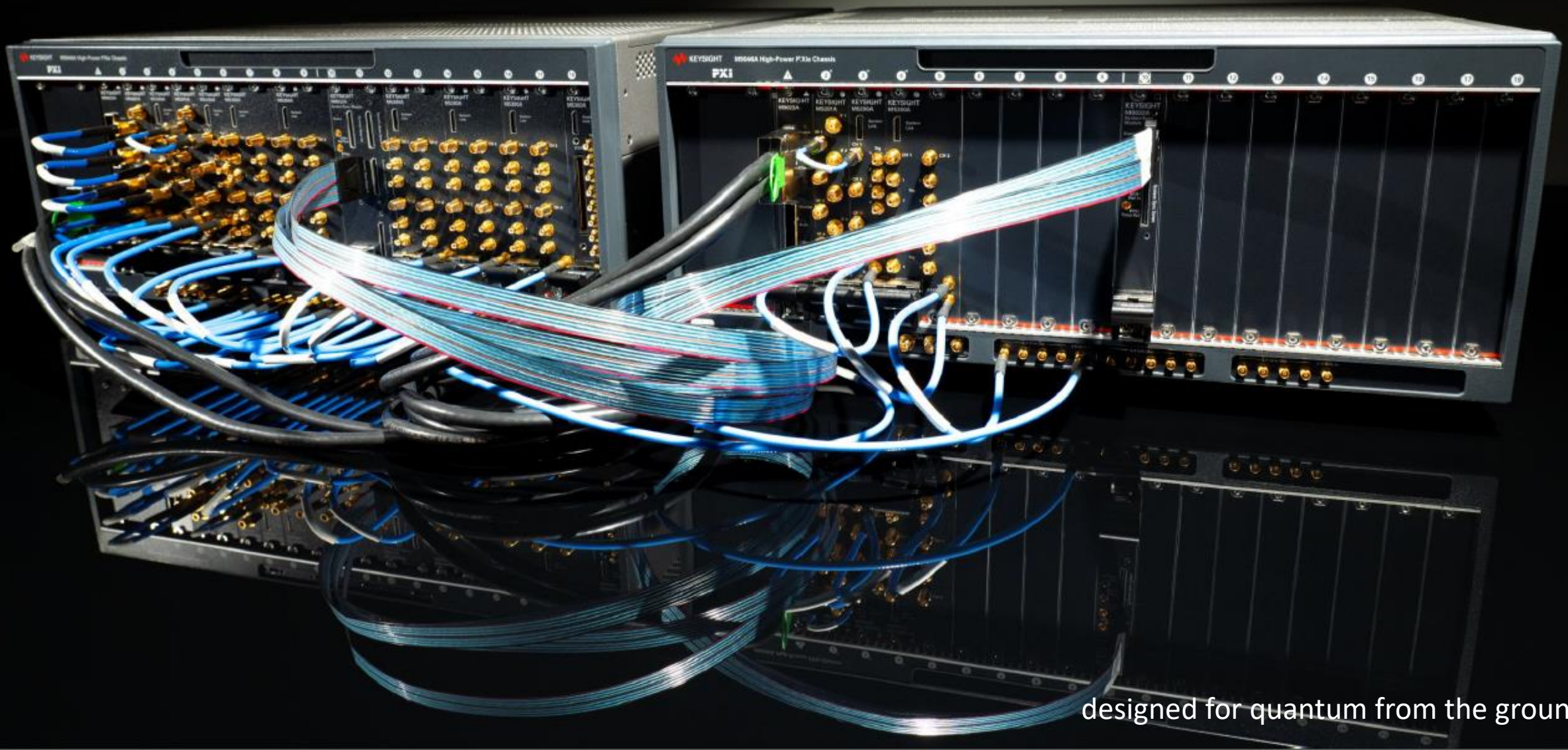
Lightwave Component Analysis



Figure 15: Screen with LCA measurement (upper window) and Gain Compression Measurement (lower window)

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)

2017



Custom ASIC

Direct Digital Conversion (DDC) Technology



Output Amp MMIC



Gateway

Initialization, control and validation
for ASIC & MMIC



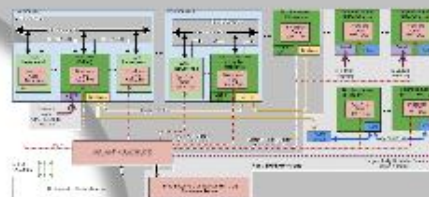
Clock

Adds Ultra-Low Phase Noise References to the Chassis.



Sync Module

Clock Distribution / Data Sharing



Next Gen Sync (NGS)

Enables Real-time Synchronization
and Sequencing in multi-chassis
Tested 6, roadmap of 80

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

Major advance comes from Keysight
ASIC using DDC technology:

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



Quantum Specific Python API

Simple, succinct, python API built for
quantum experiments

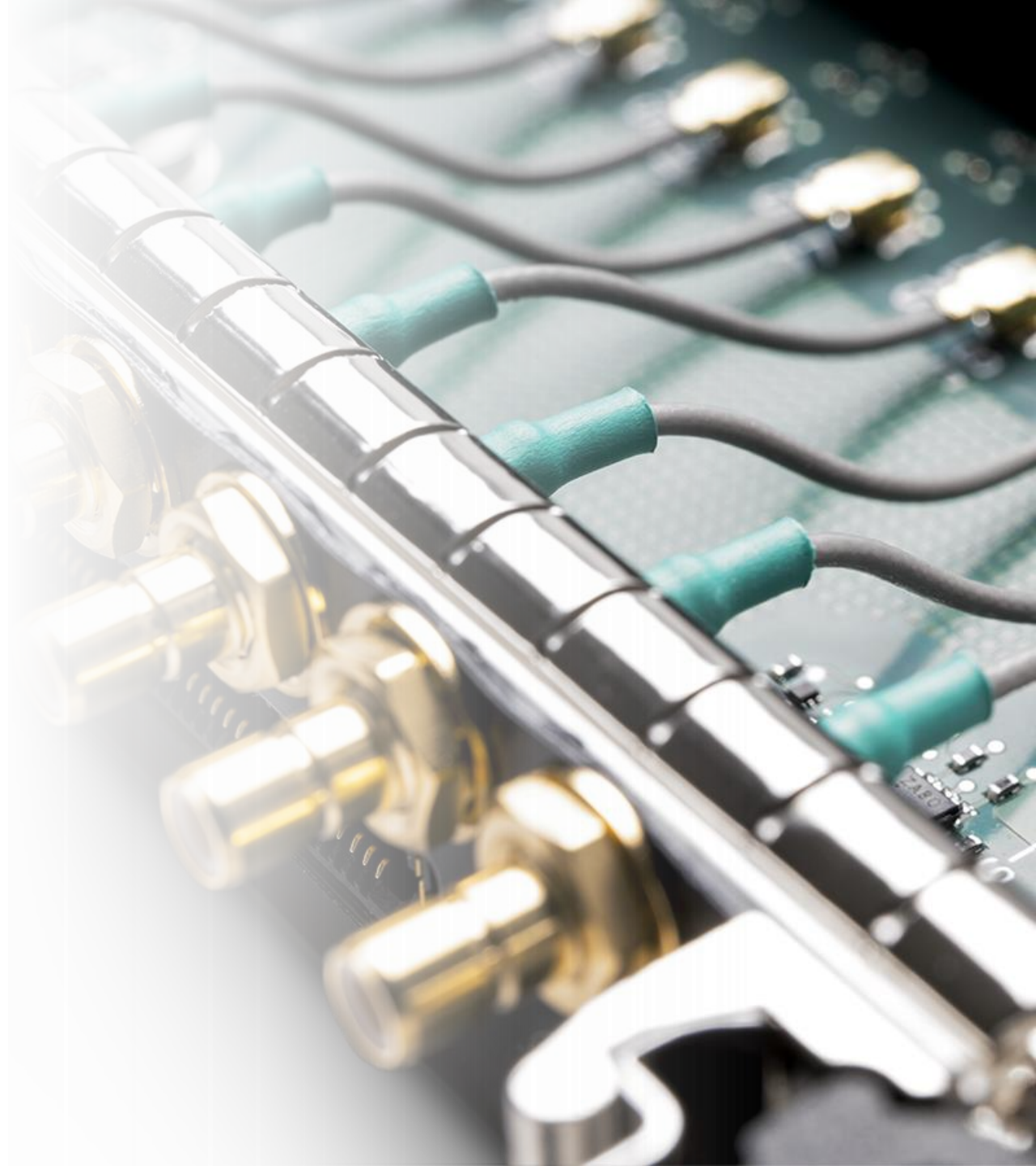
2022



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

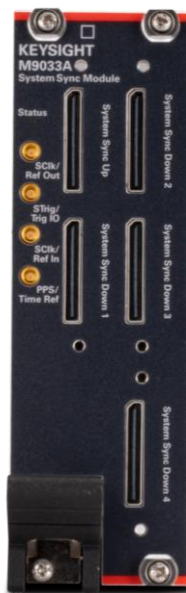
QCS – Comprised of new M9000 Series Components designed for Quantum

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



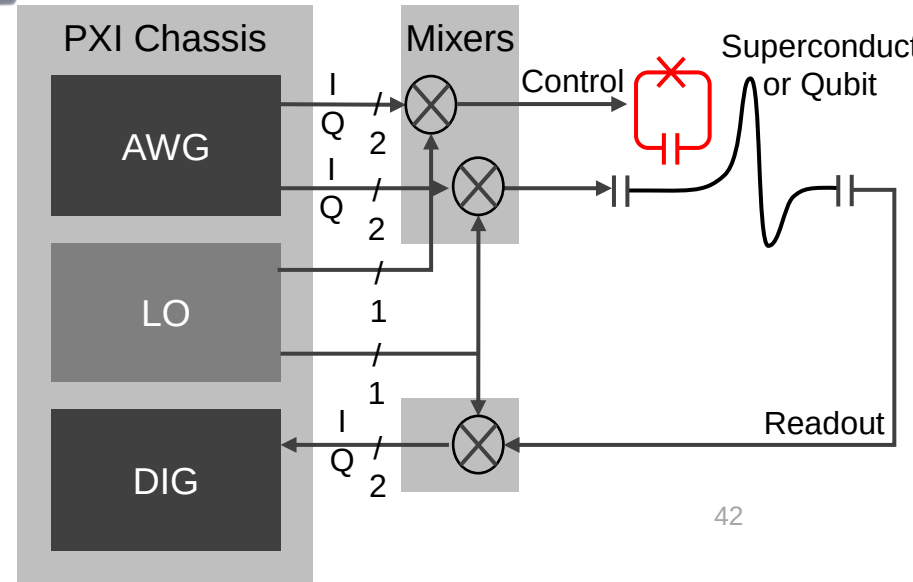
1. Ease of Use

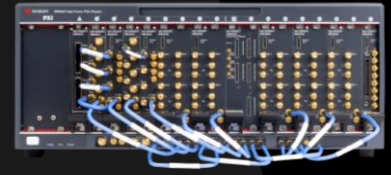
**A solution designed
for quantum from
the ground up**

1. Ease of Use - Hardware



- ✓ NO External Mixers needed!
- ✓ NO External LOs needed!
- ✓ NO I/Q Mixer Calibration needed!
- ✓ NO downtime due to calibration!

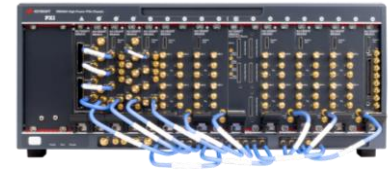




2. Performance

**We put our #1 team
on this**

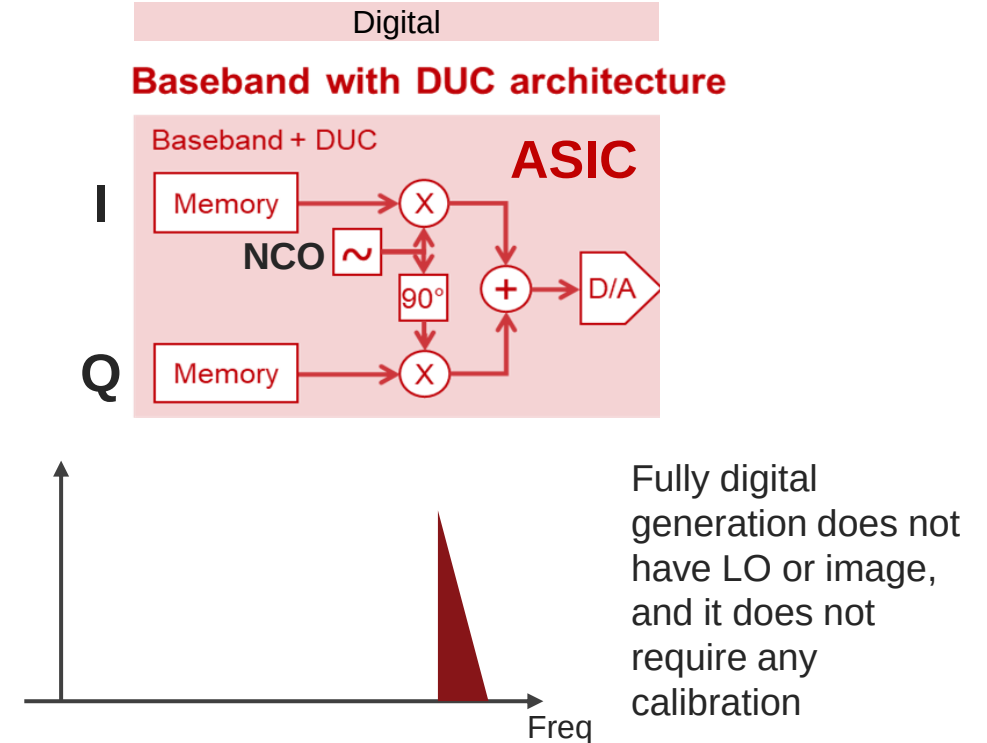
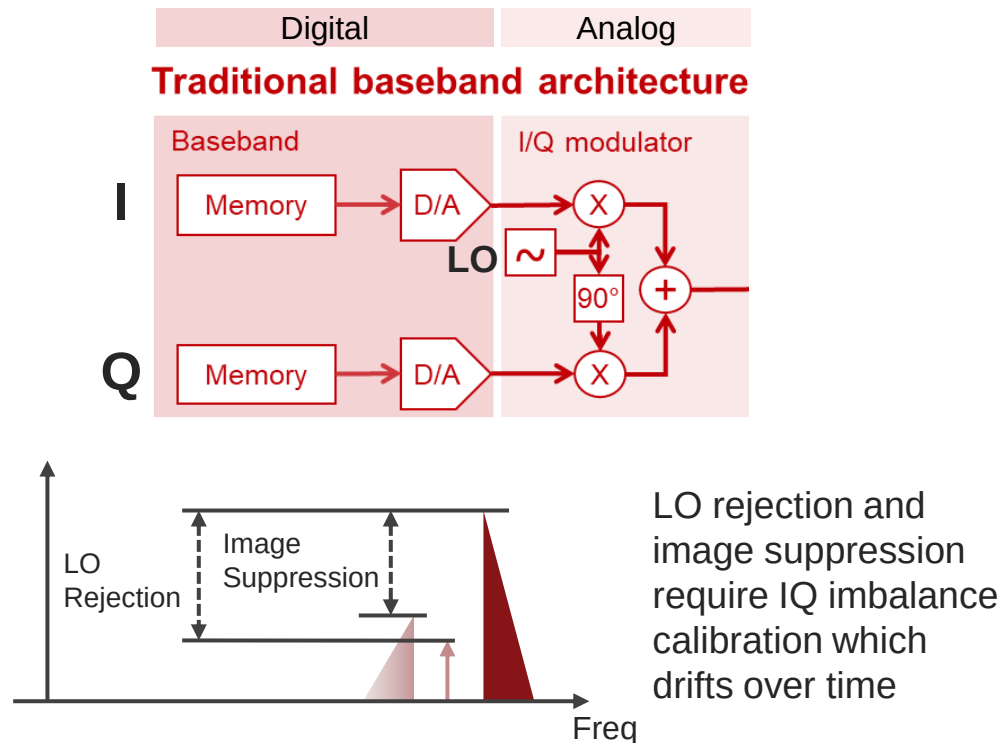
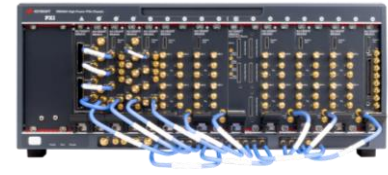
2. Performance



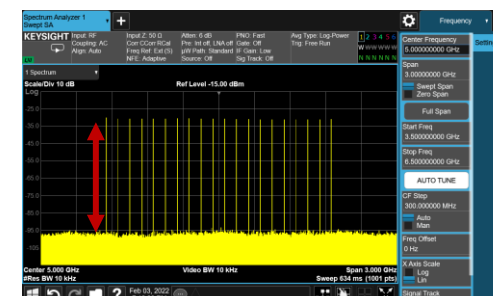
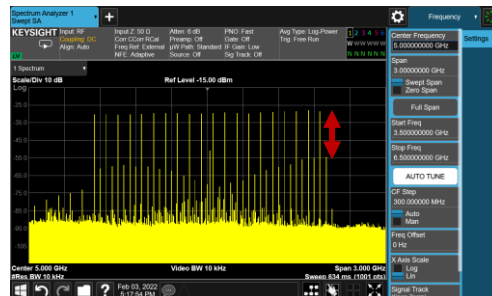
- ✓ **Stable:** Extremely low phase noise reference clock embedded in chassis
- ✓ **Phase Coherent:** Timing and synchronization all done automatically
- ✓ **Future Proof:** DC to 16 GHz, scalable to 1000 qubits and beyond

Clean Signals via Direct Digital Signal Generation

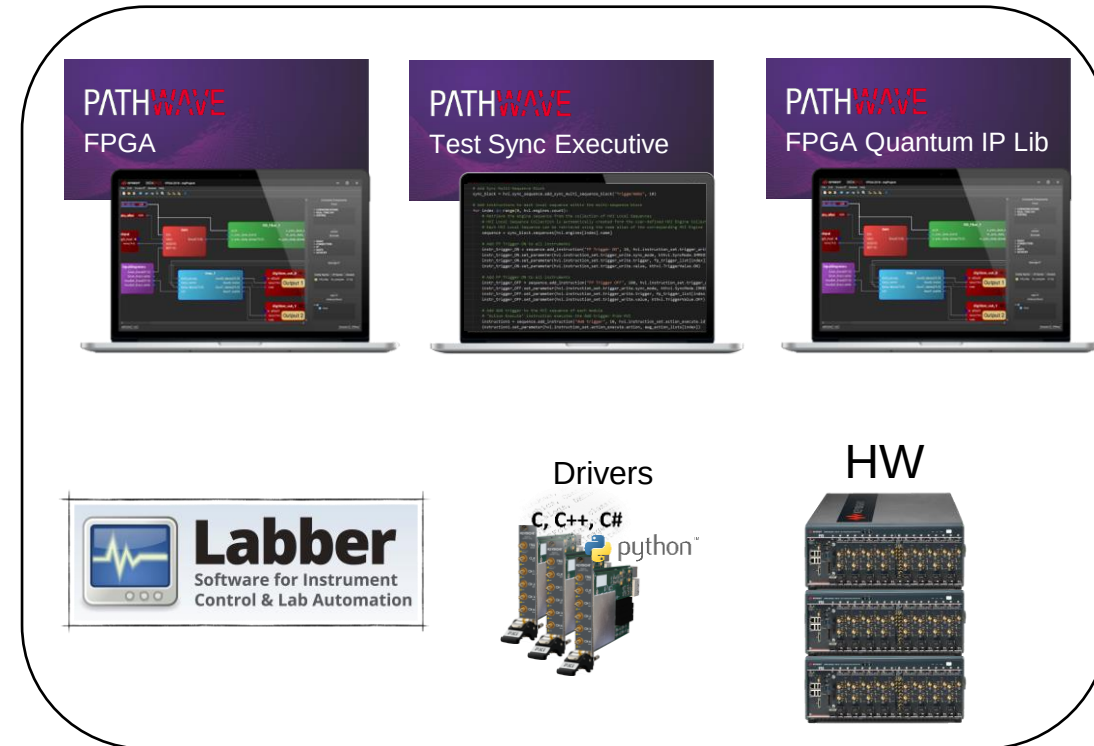
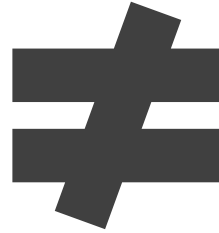
Enabling high-fidelity gates



Improved SFDR
(Spurious-Free Dynamic Range)



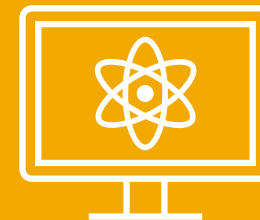
Quantum Control System (QCS)



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

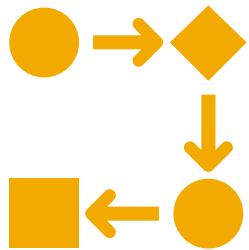
1. Send pulse A with xyz parameters from AWG (Slot 3, Channel 1) to Qubit 1.
2. Send pulse B with abc parameters from AWG (Slot 4, Channel 2) to readout line.
3. Read Digitizer Channel 1 signal.

Now

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

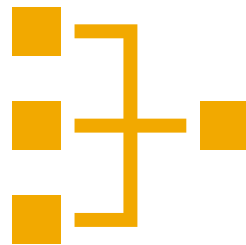
QCS API Overview and Structure

What is the customer workflow?



DEFINE

hardware modules, configurations, and connections.



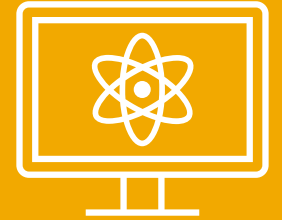
MAP

classical components to quantum components.



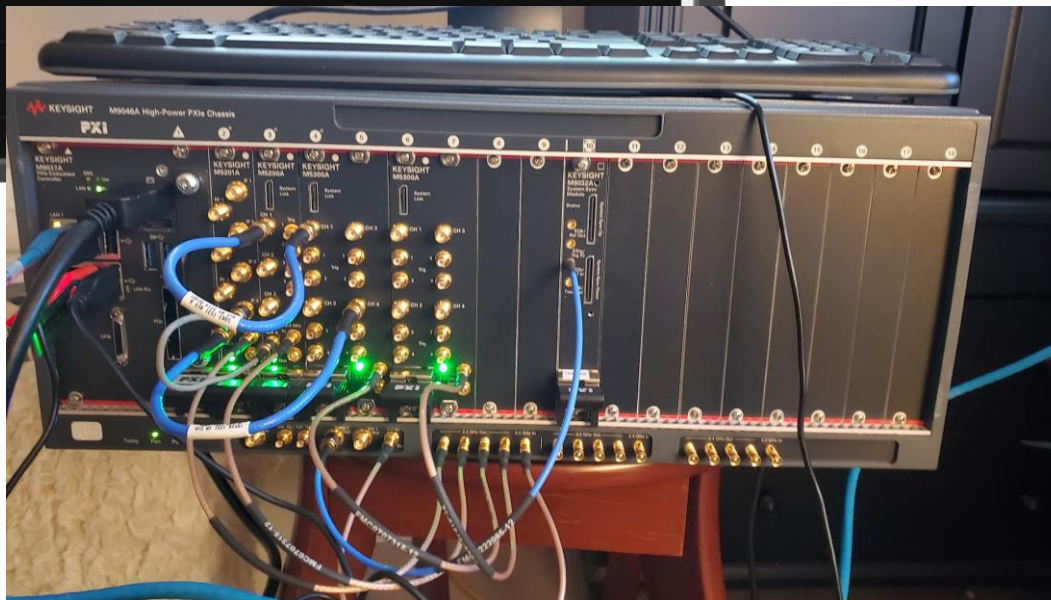
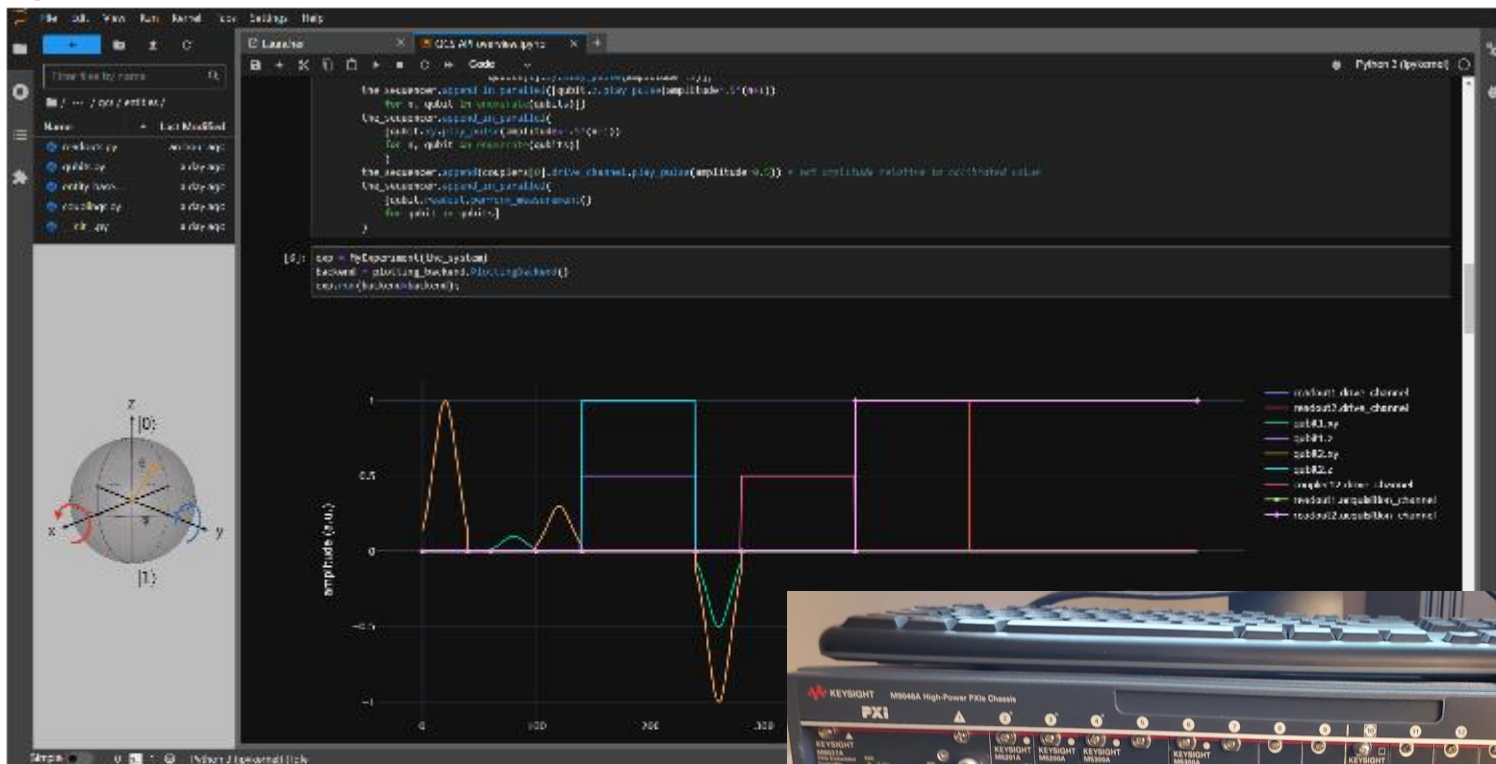
WRITE

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



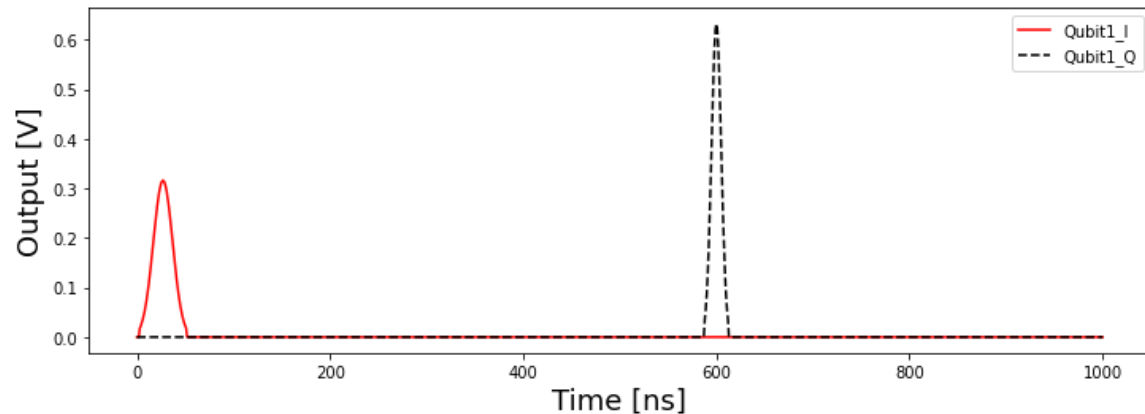
QCS Code Snippet Overview*

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!**

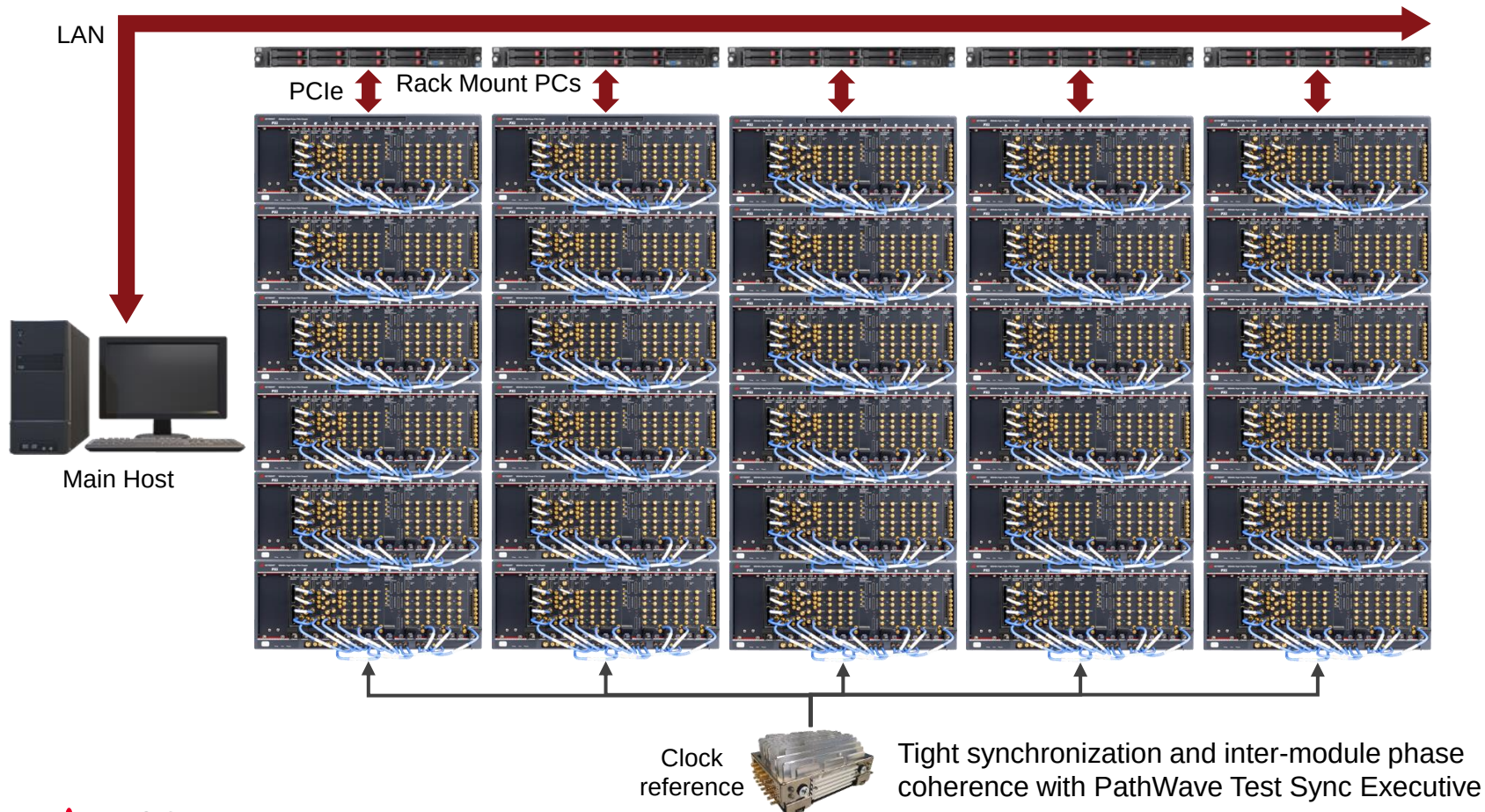


A Scalable Control System

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 underlying 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)

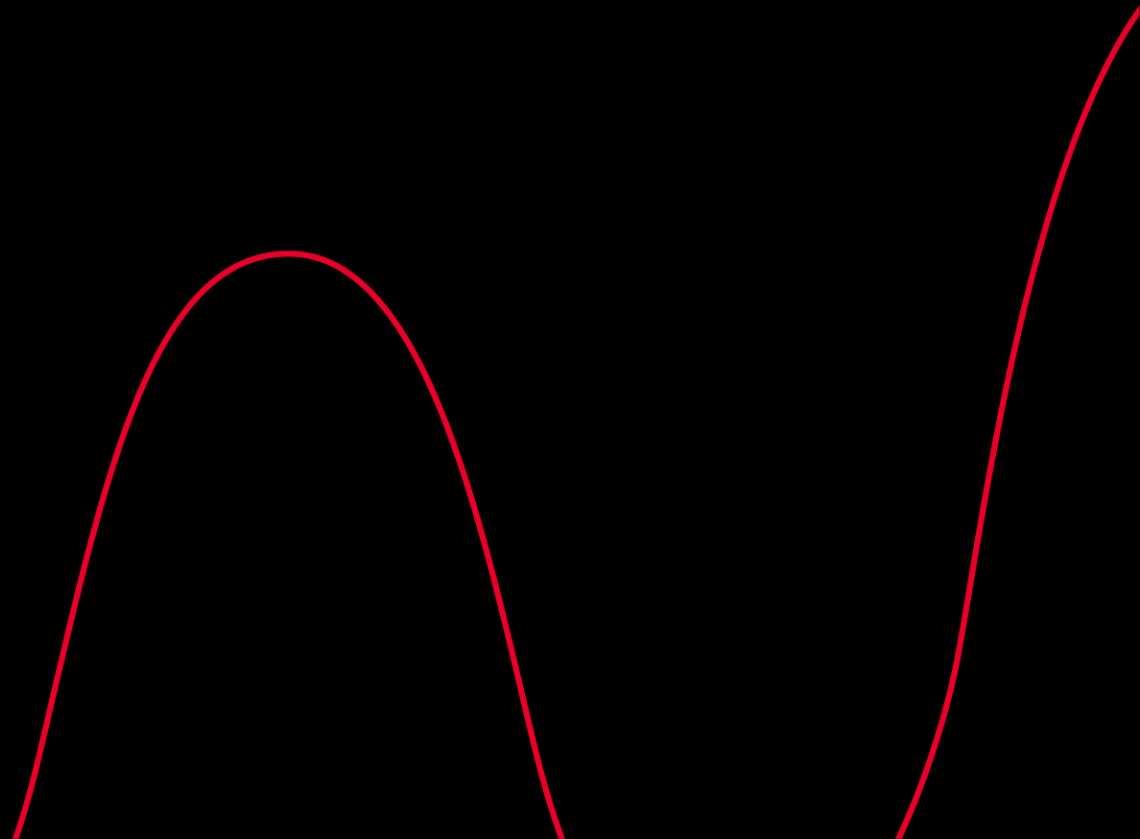
Multi-host multi-chassis operation on SW stack roadmap

Support for massive number of qubits also on SW stack roadmap

Please contact us

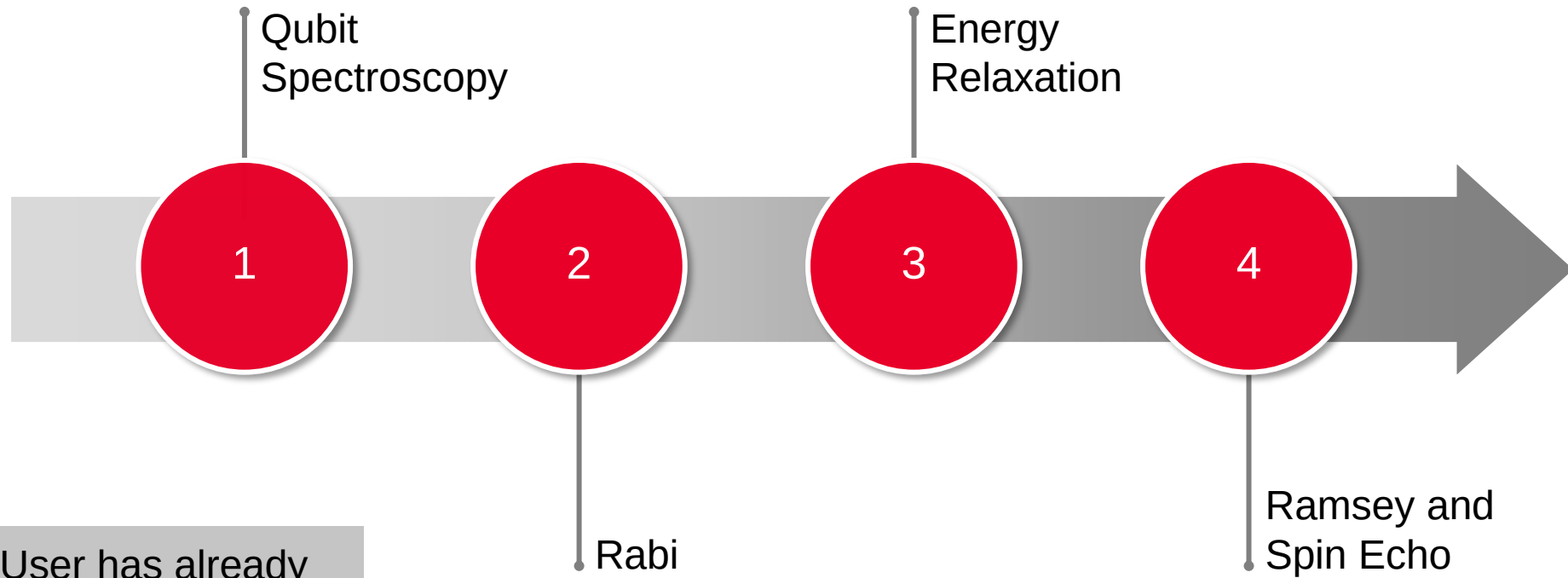


Test Scenario with QCS



Demo Flow

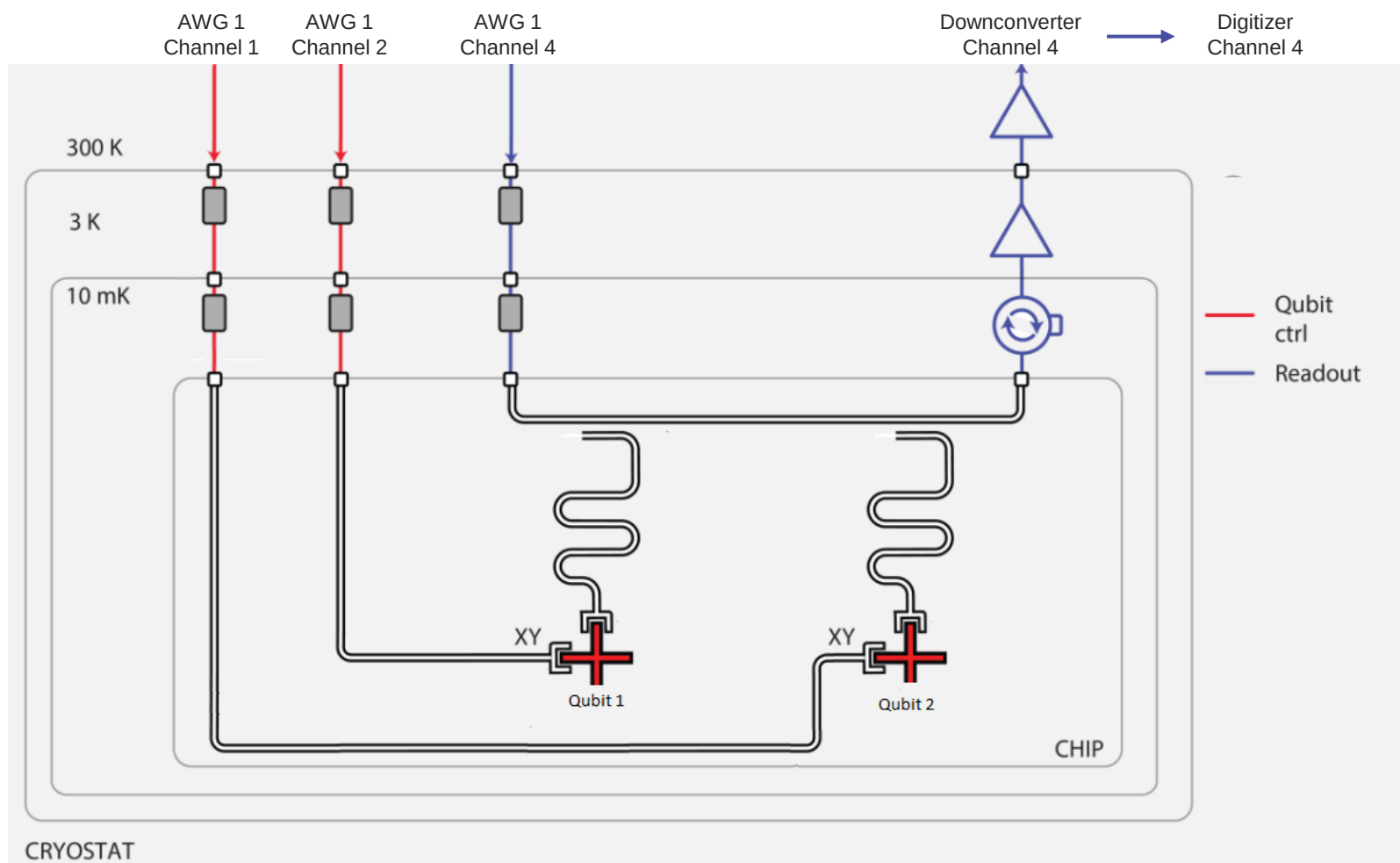
Superconducting qubit characterization



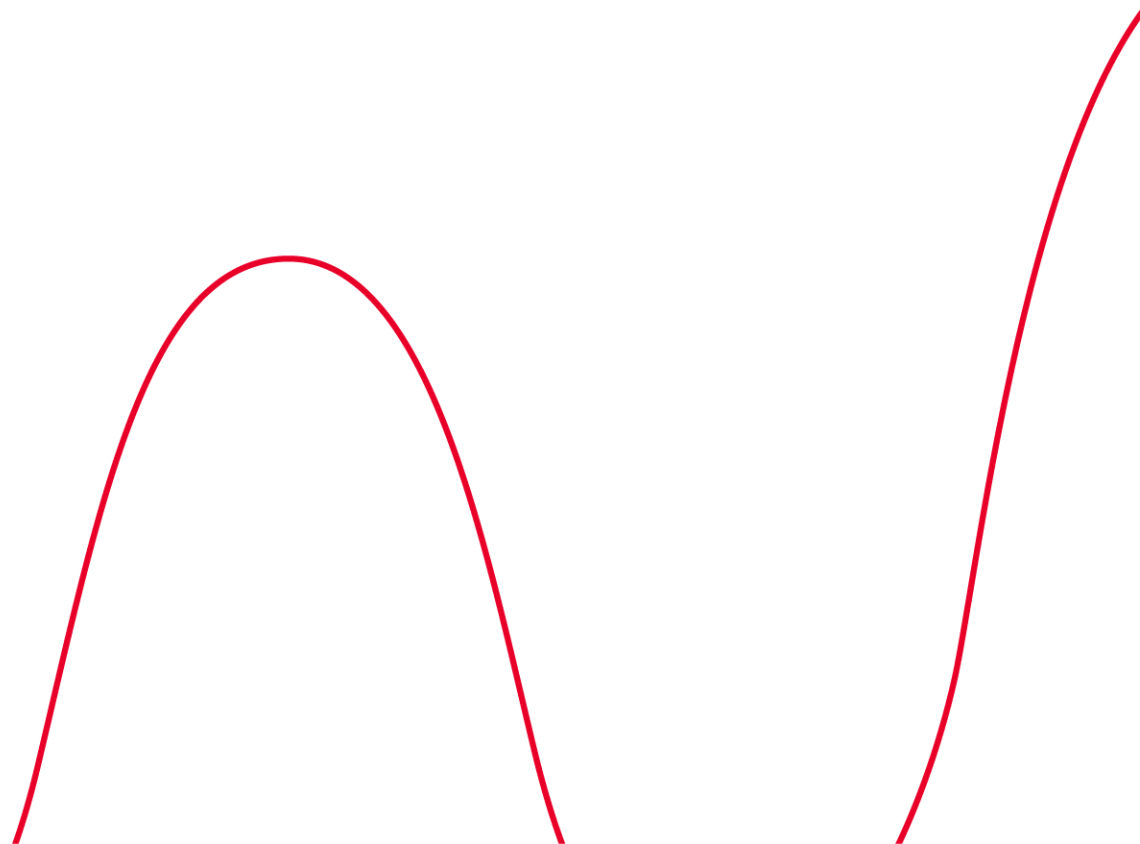
Scenario: User has already calibrated readout and is ready to start characterizing new qubits

Demo Quantum Configuration

Superconducting qubit chip



Qubit Spectroscopy



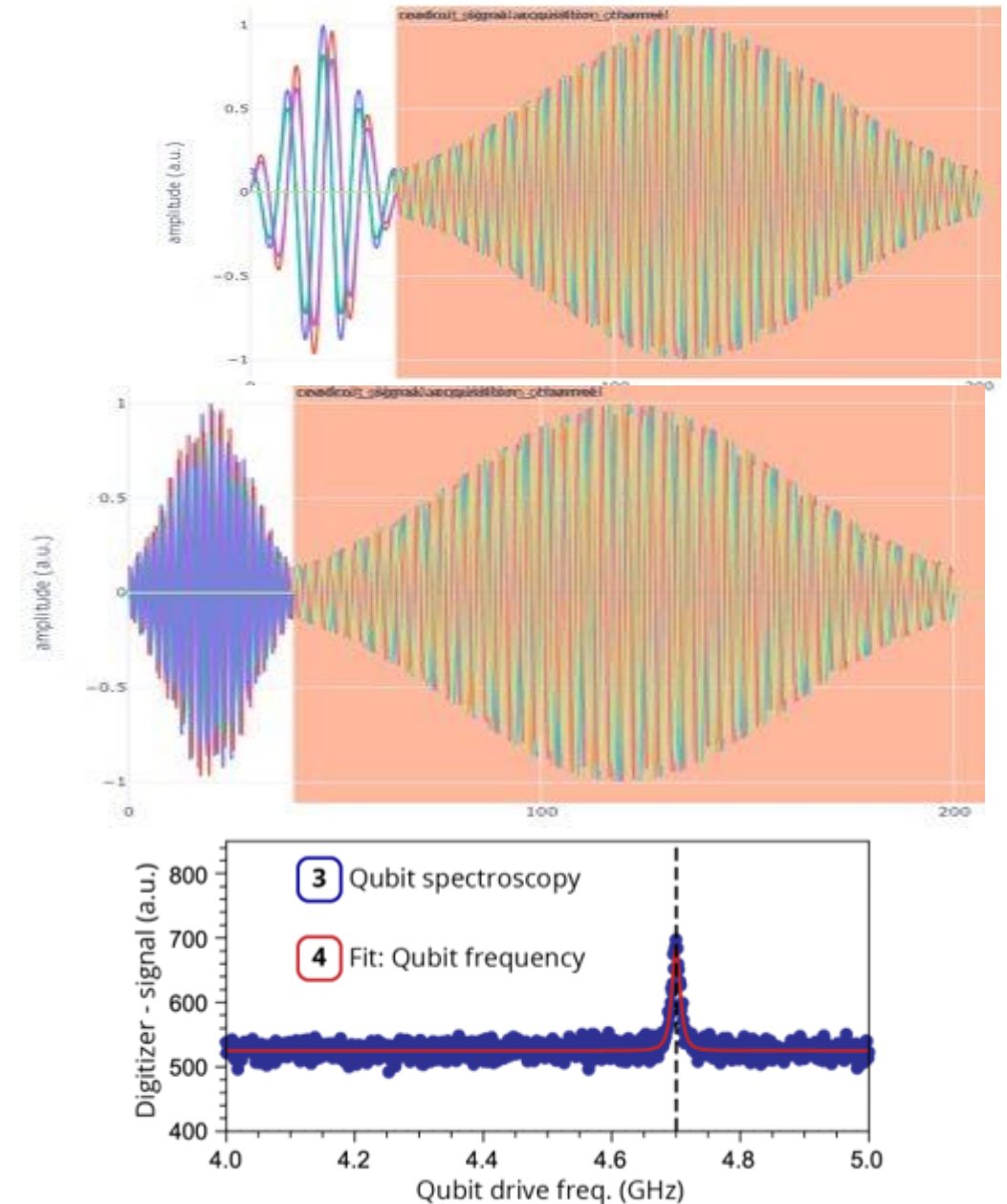
Qubit Spectroscopy – What is it?

Qubit Characterization Pt. 1

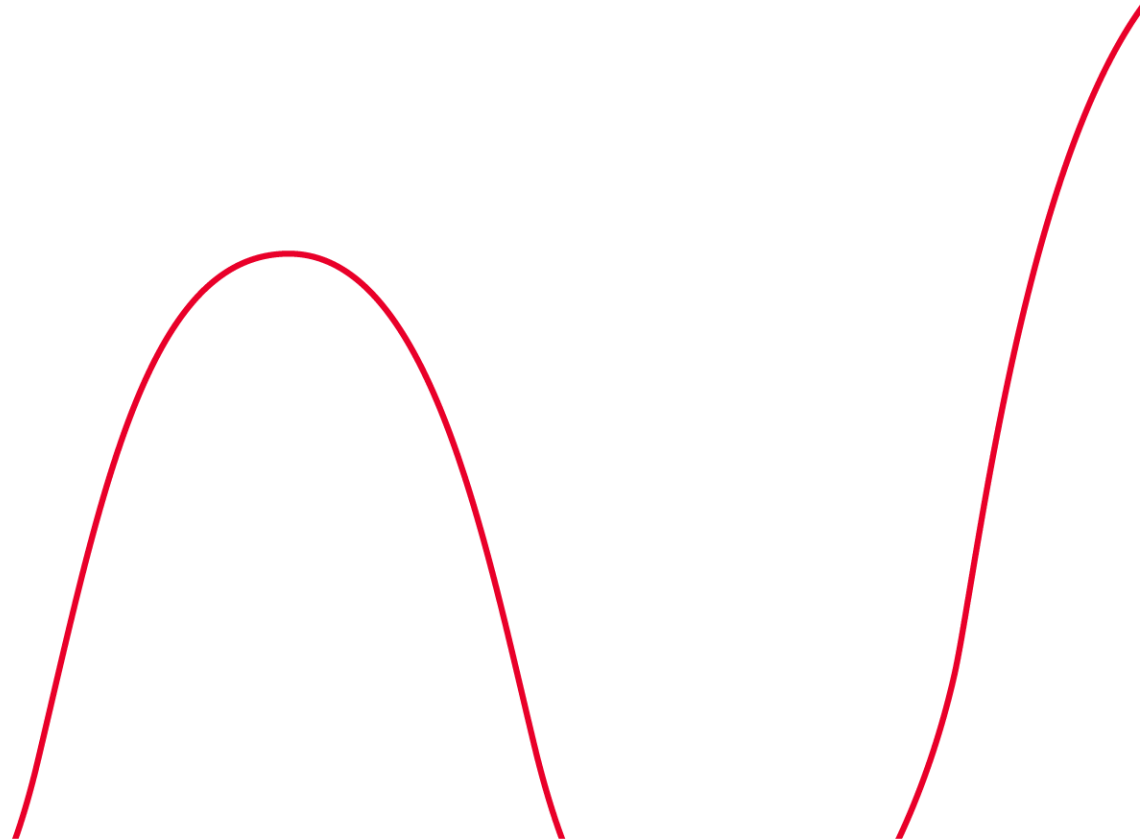
Goal: Find qubit frequency

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



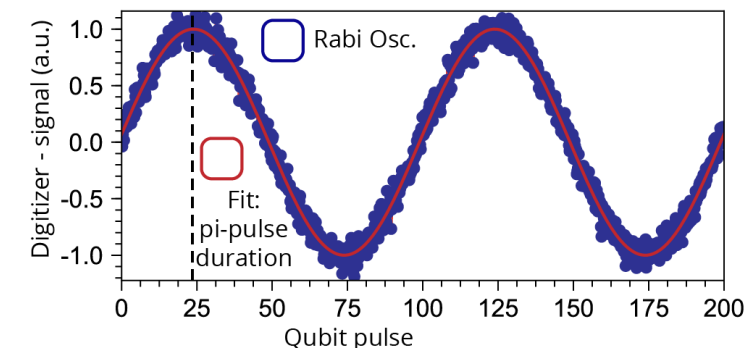
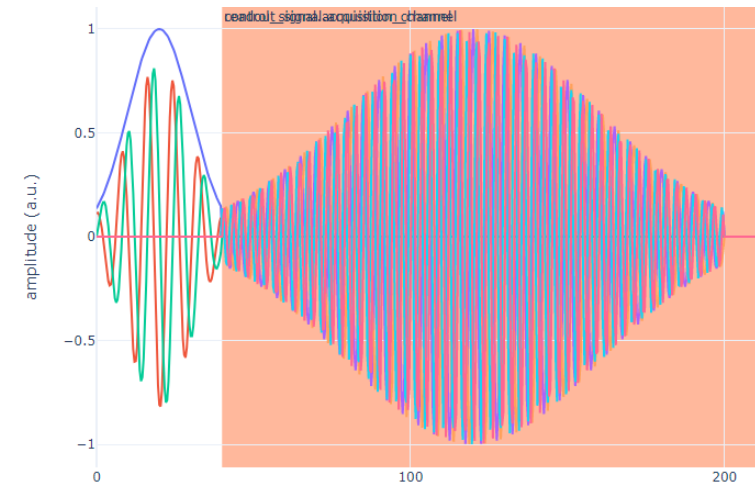
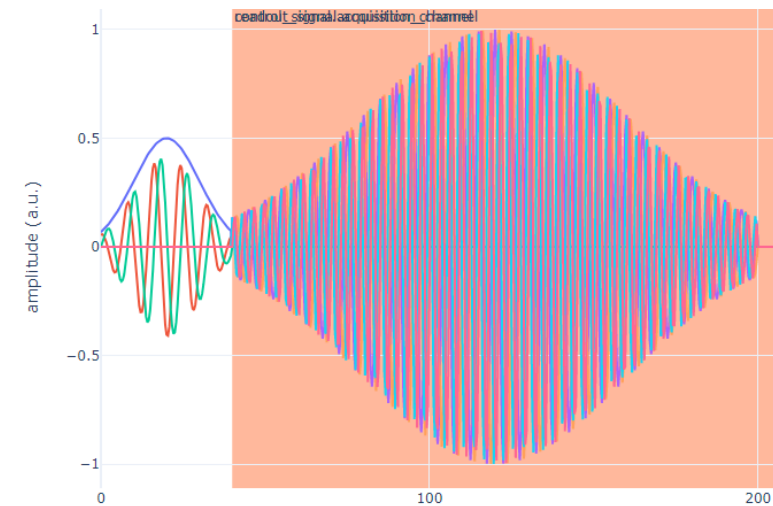
Rabi Experiment – What is it?

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

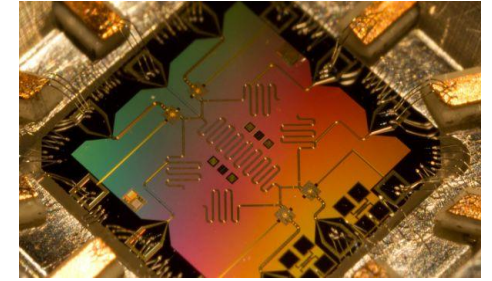
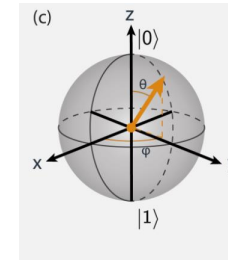
1. Send control and readout pulse.
2. Control pulse is scanned over amplitude (pulse duration kept constant).
3. Duration of the pulse that caused a 180 degree rotation is the pi pulse.

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

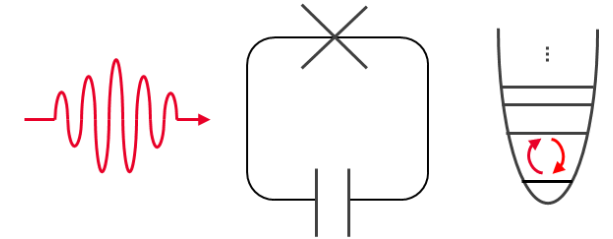
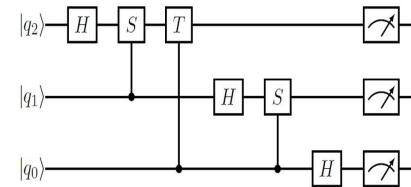


Summary

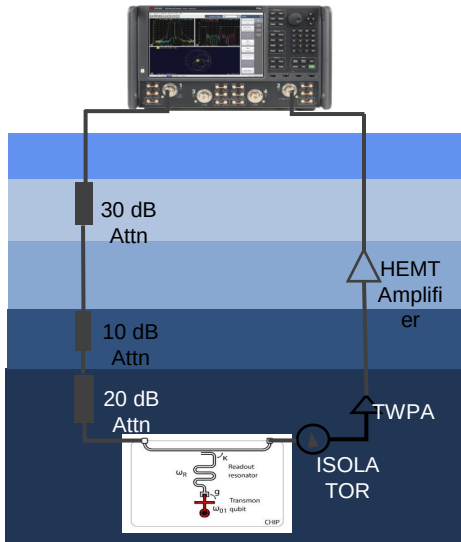
Fundamentals



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>



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Featured Resources

Data Sheets

2023.02.27



**M5000 Series High-
Performance PXI System**

Solution Briefs

2022.08.07



**Quantum Control System (QCS)
- The world's first fully digital
quantum control solution**

**Tested PC and PXI/AXIe Chassis
Configurations**

This document provides a list of personal computers which are compatible with the M9005A, M9010A, M9018B, M9019A PXIe Chassis and the M9502A, M9505A, M9506A, M9514A AXIe Chassis.

