Accelerating Engineering of Quantum Systems

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Project Manager / Keysight Technologies

Agenda

- Global Investment in Quantum
- Challenges in Realizing Quantum Computers
- Keysight Solutions

Global Investment in Quantum

Major Economic Powers Are Ramping Quantum Investments

USA

- National Quantum Initiative passed Dec '18 committing **$1.3B** over 5 years

Canada

- Invested over **$1B** in the last decade

European Union

- Quantum Technologies Flagship Program worth **$1.1B** over 10 years

United Kingdom

- **$397M** quantum program over 5 years, beginning in 2019

China

- Will create an **$11B**, 4M sq-ft national quantum laboratory for centralized research

Japan

- ImPACT project valued at **$267M** over 10 years to realize new quantum computing principles

Russia

- Russia Quantum Center earmarked **$3B** for fundamental scientific R&D in 2018

India

- National Mission of Quantum Technology and Application spending **$1.2 B** over 5 years

Germany

- National plan to promote quantum technologies with **$720M** commitment over 4 years

Americas: Public Investment

US & CANADA

US: NQI (NATIONAL QUANTUIM INITIATIVE)

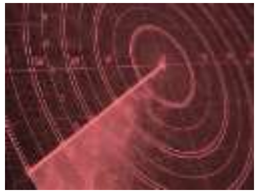
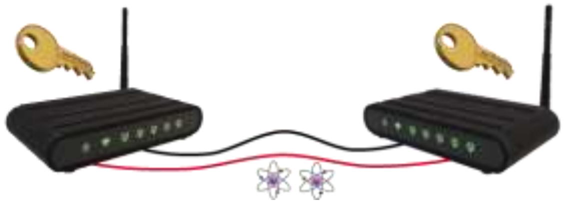
- $1.275B over 5 years, mostly by DOE, NSF & NIST funding a few large quantum centers
  - DOE: QIS Research Centers, $25M/year
  - NSF: Multi-disciplinary research, $10M/year
  - NIST: for quantum & to establish consortium (QED-C) , $80M/year
- US: Federal agencies fund research worth $200M/year
- NIST, DOE, NSF, etc., provide basic research
  - IARPA, DARPA fund universities through grants
- Unknown investments

Canada

- Gov't funded R&D > $100M/year expected to reach >$300M in 2024
- IQC : Institute for Quantum Computing (U Waterloo) $2.7M quantum radar
- NSERC grants $30M to support university research teams

Qubits are the Pillars for all Quantum Applications

QUBITS FOR ENGINEERS

Quantum Computing	Quantum Communications	Quantum Sensing
		
Noisy Gate-based Computers Quantum Annealers Quantum Simulators Universal Quantum Computers	Secure Communications Distributed Quantum Computers	Quantum Magnetometers Quantum Accelerometers Quantum Radar
		

Challenges in Realizing Quantum Computers

The Paradox

- Cannot observe a quantum system without producing an uncontrollable disturbance in the system
- To use the quantum system to store & reliably process quantum information, need to keep it perfectly isolated from the outside world
- At the same time, want the qubits to strongly interact with one another so that we can process the information

These challenges have taken many years of development in materials, control & fabrication to get where we are now

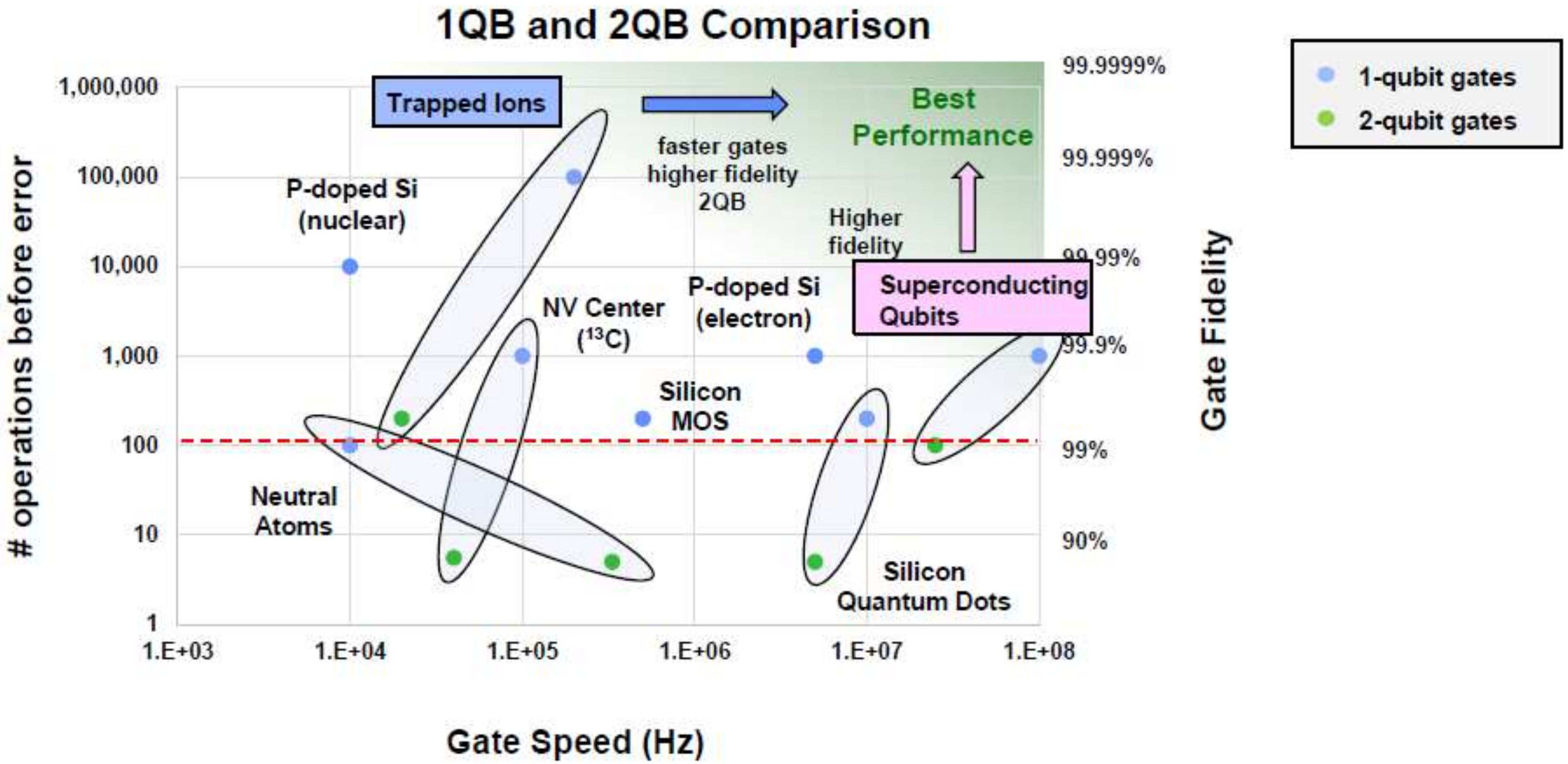
Quantum computing in NISQ era and beyond: John Preskill
arXiv:1801.00862v3[quant-ph]31Jul2018

What Determines Qubit "Quality"?

- Number of qubits
- Decoherence times
- Error rate per qubit, per gate
- Limitations on circuit size
- Time to execute qubit gates
- Preparation & accurate measurement of qubit states
- Connectivity amongst qubits
- SCALABILITY

Quantum computing in NISQ era and beyond: John Preskill
arXiv:1801.00862v3[quant-ph]31Jul2018

Qubit Technology Status: Fidelity & Gate Speed



Thanks to: P. Cappallaro, J. Chiaverini, D. Englund, T. Ladd, A. Morello, J. Petta, M. Saffman, J. Sage

Courtesy of Prof. William Oliver (MIT)

Challenge: Practical Problems

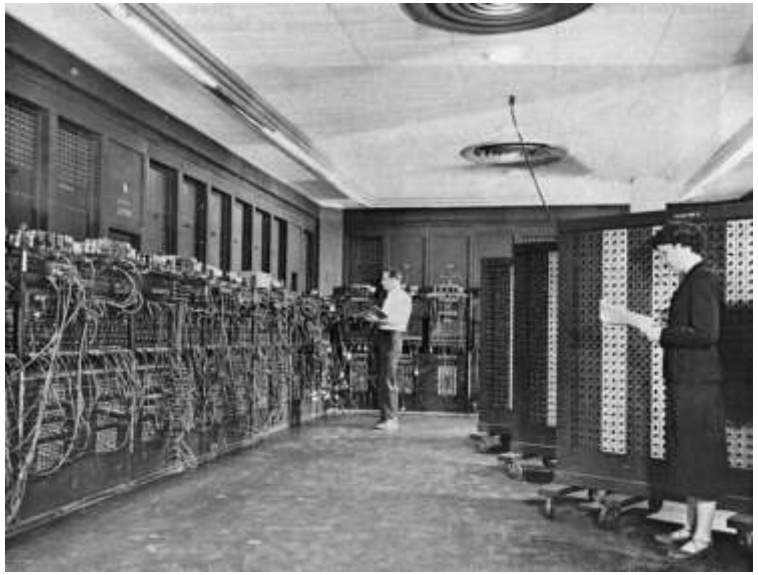
Intelligent Machines

We'd have more quantum computers if it weren't so hard to find the damn cables

Quantum machines will deliver the next great leap forward in computing, but researchers building them can't easily get some of the exotic components they need.

by Martin Giles   January 17, 2019

UNIVERSITY OF CALIFORNIA, BERKELEY/KEEGAN HOUSER



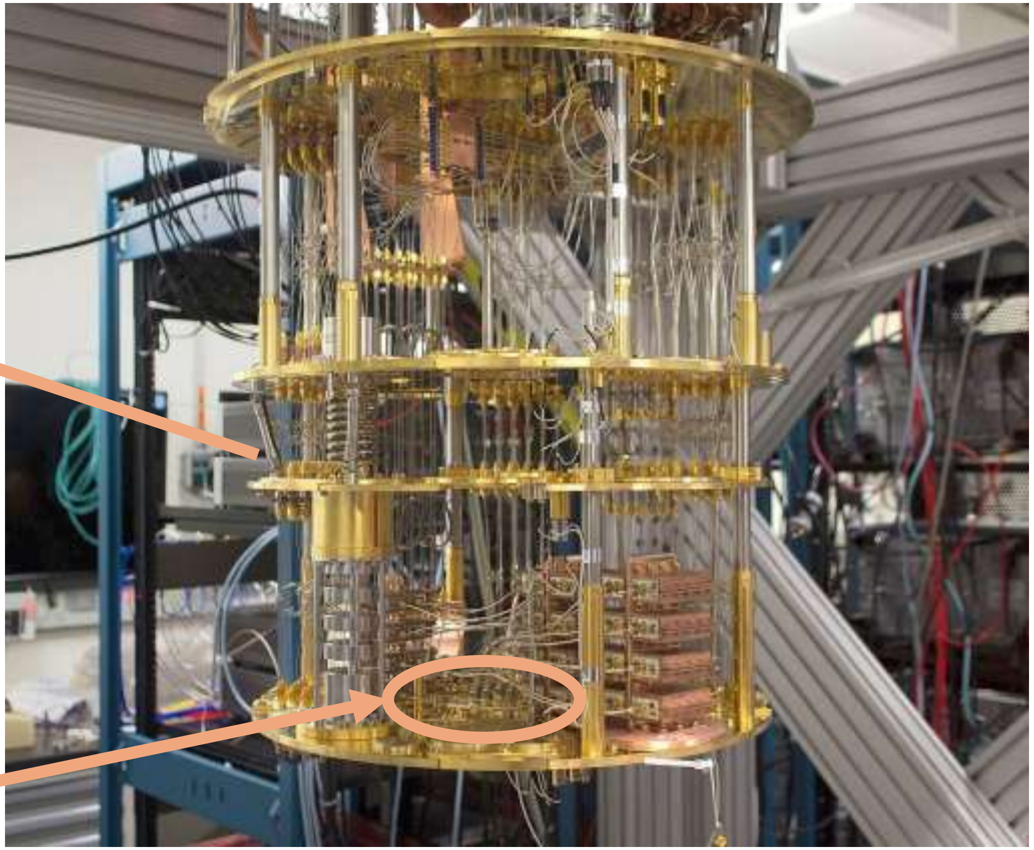
ENIAC: Electronic Numerical Integrator and Computer

Glen Beck (background) and Betty Snyder (foreground) program ENIAC in BRL building 328. (U.S. Army photo, ca. 1947-1955)

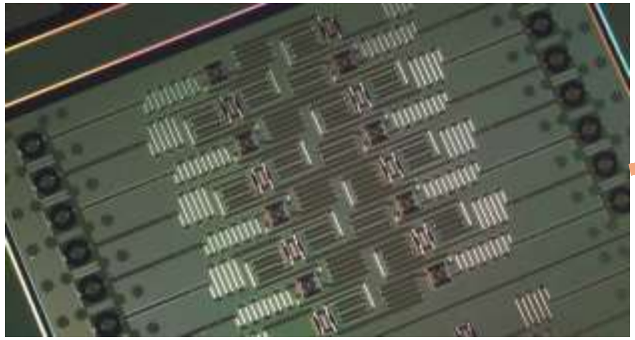
"If you take this chip, I've got 49 qubits and 108 coaxial connectors to the outside world. What would it look if I had a million qubits? I can't have 2 million coax cables to the outside world. Maybe that's what an ENIAC system looked like in the 1940s, but that's not what a conventional system looks like. So what worries me most is wiring your interconnects." – James Clarke, Intel

Challenge: Complex Experimental Setup

SUPERCONDUCTING QUBIT



Cryostat



Superconducting Qubits

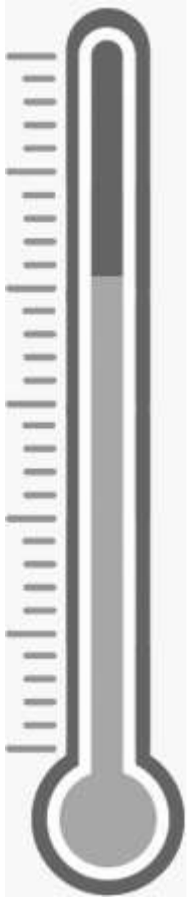
Simplified Block Diagram

Control instrumentation

Attenuation
Cabling
Low-noise amplifiers

Attenuation
Cabling
Low-noise amplifiers

Qubits



300 K

50 K

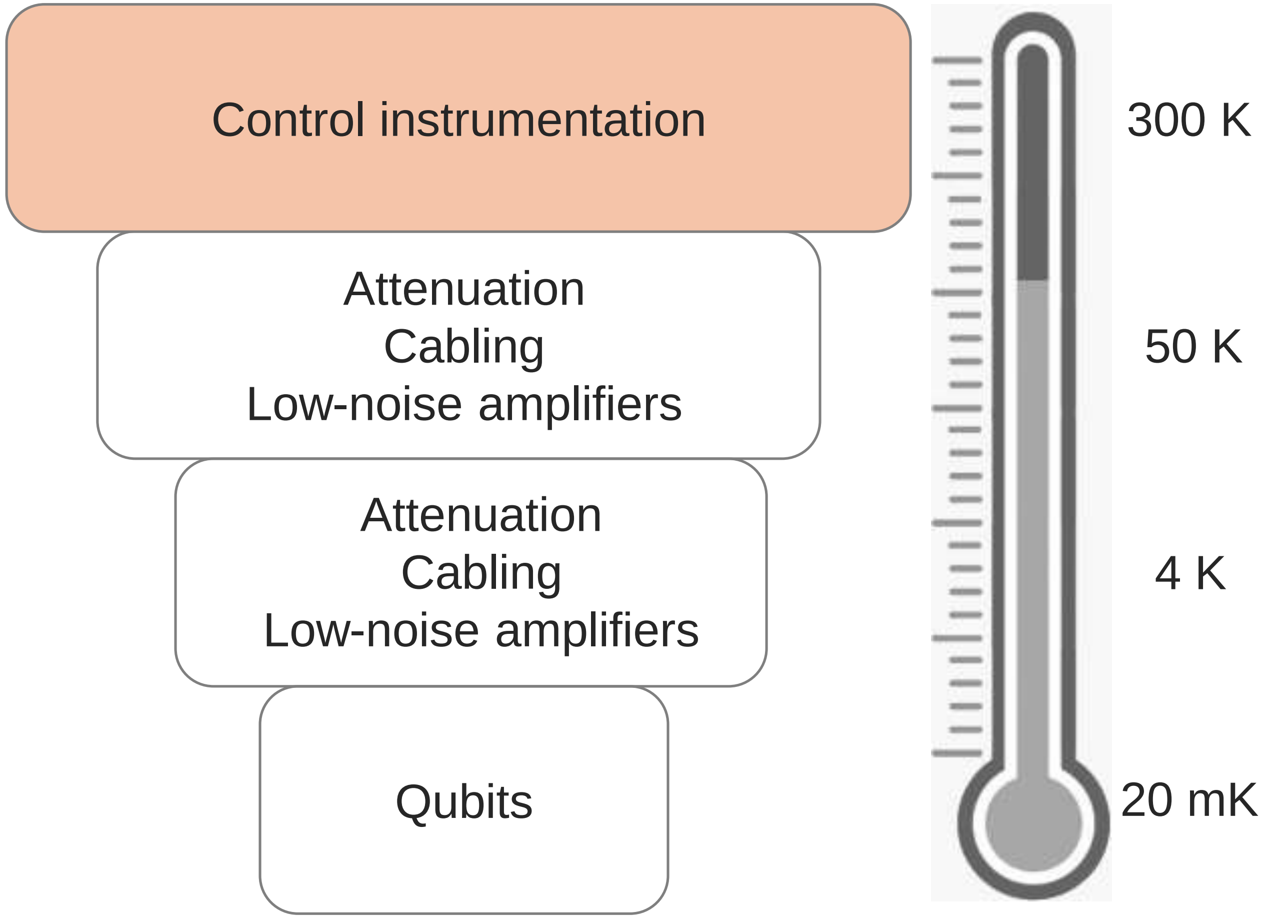
4 K

20 mK

Challenge: Decoherence

Requirements

- Stability
- Synchronization
- Scalability

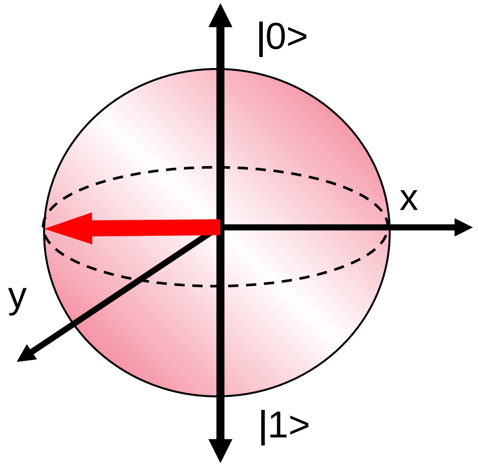


Defining Quantum Decoherence

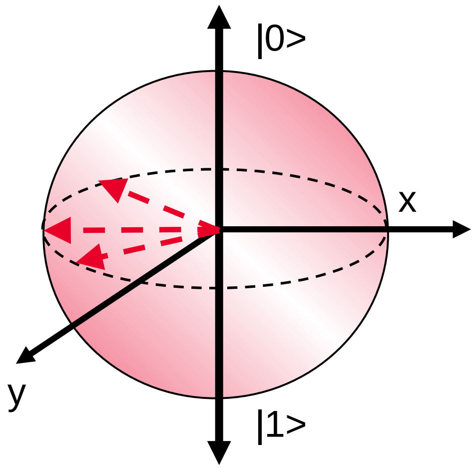
LIMITING QUBIT TECHNOLOGY

Decoherence is the enemy of every quantum system

- **What is decoherence?**
  - Anything that puts the qubit in an uncontrolled quantum state
  - Classical rather than quantum uncertainty
- **Where does decoherence come from?**
  - Imperfect qubits
  - Uncontrolled interactions with environment
  - Errors in classical control



Quantum uncertainty

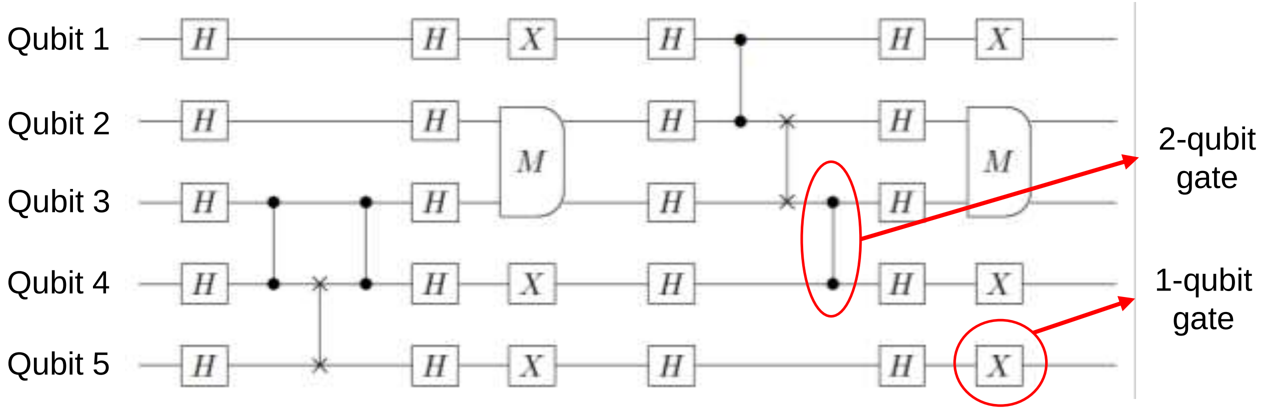


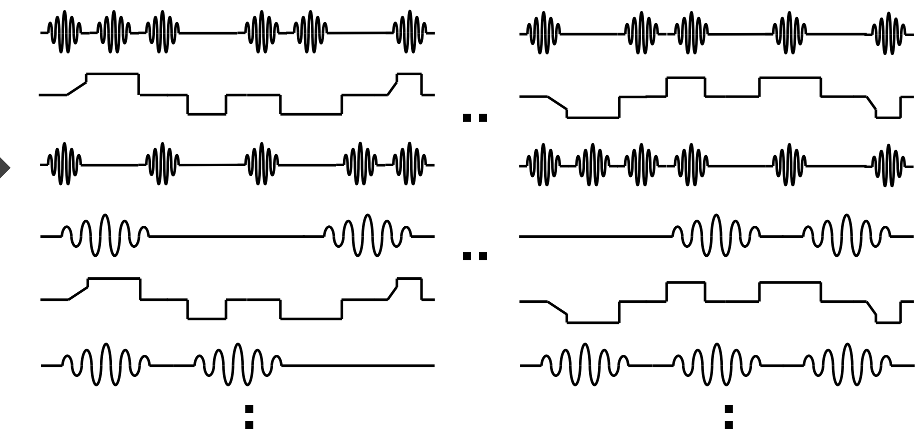
Classical uncertainty

Running Quantum Algorithms

CONTROL CHALLENGES IN QUANTUM COMPUTING

Quantum algorithm notation





Quantum algorithms are pulse sequences

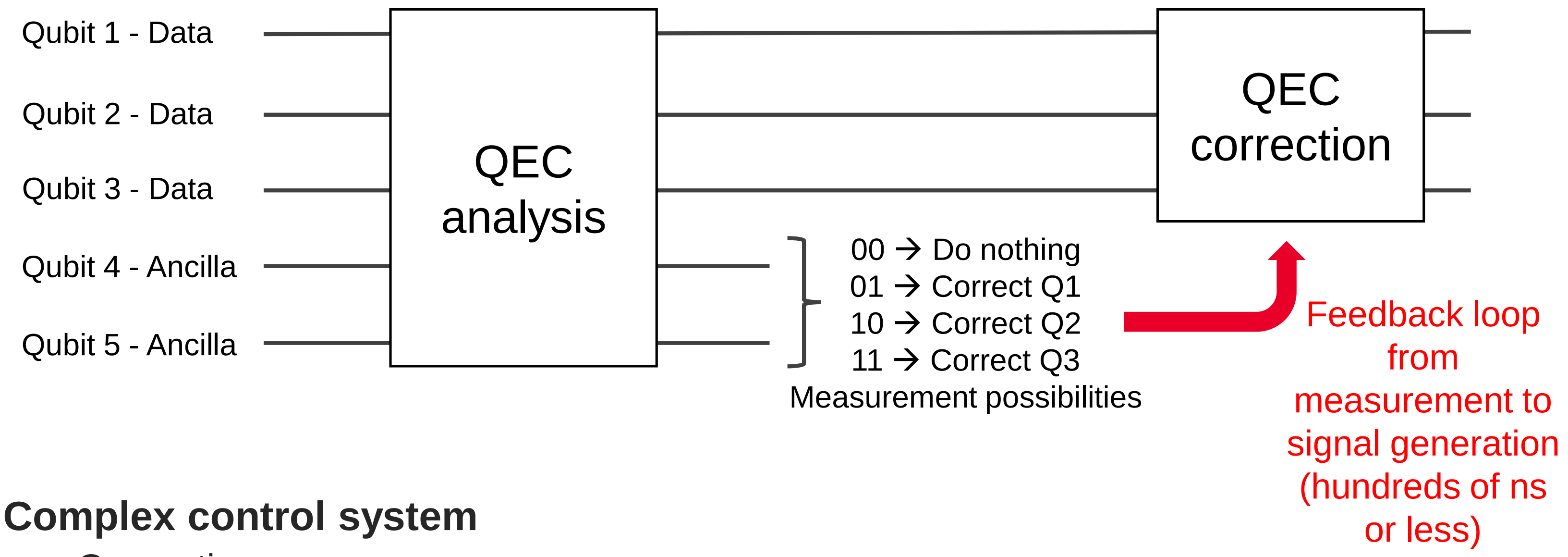
Complex control system

- **Generation**
  - Phase-coherent pulses (µW, RF, or both)
    - Different lengths (ns-µs), frequencies (3-12 GHz), amplitudes & phases (I/Q modulations)
    - FDM to address several qubits with same channel
    - Spectral purity
  - Baseband pulses
- **Acquisition**
  - µW acquisition with real-time I/Q demodulation
  - FDM to address several qubits with same channel
  - Pulse counting & timestamping
- **Scalable to hundreds/thousands of channels**
- **Tight inter-channel synchronization & phase control**
- **Real-time feedback for quantum error correction (QEC)**

Quantum Error Correction (QEC)

CONTROL CHALLENGES IN QUANTUM COMPUTING

- Qubits are delicate, losing their state with time ➔ decoherence
  - Quantum error correction (QEC) must be interleaved in quantum computation to correct qubits



Complex control system

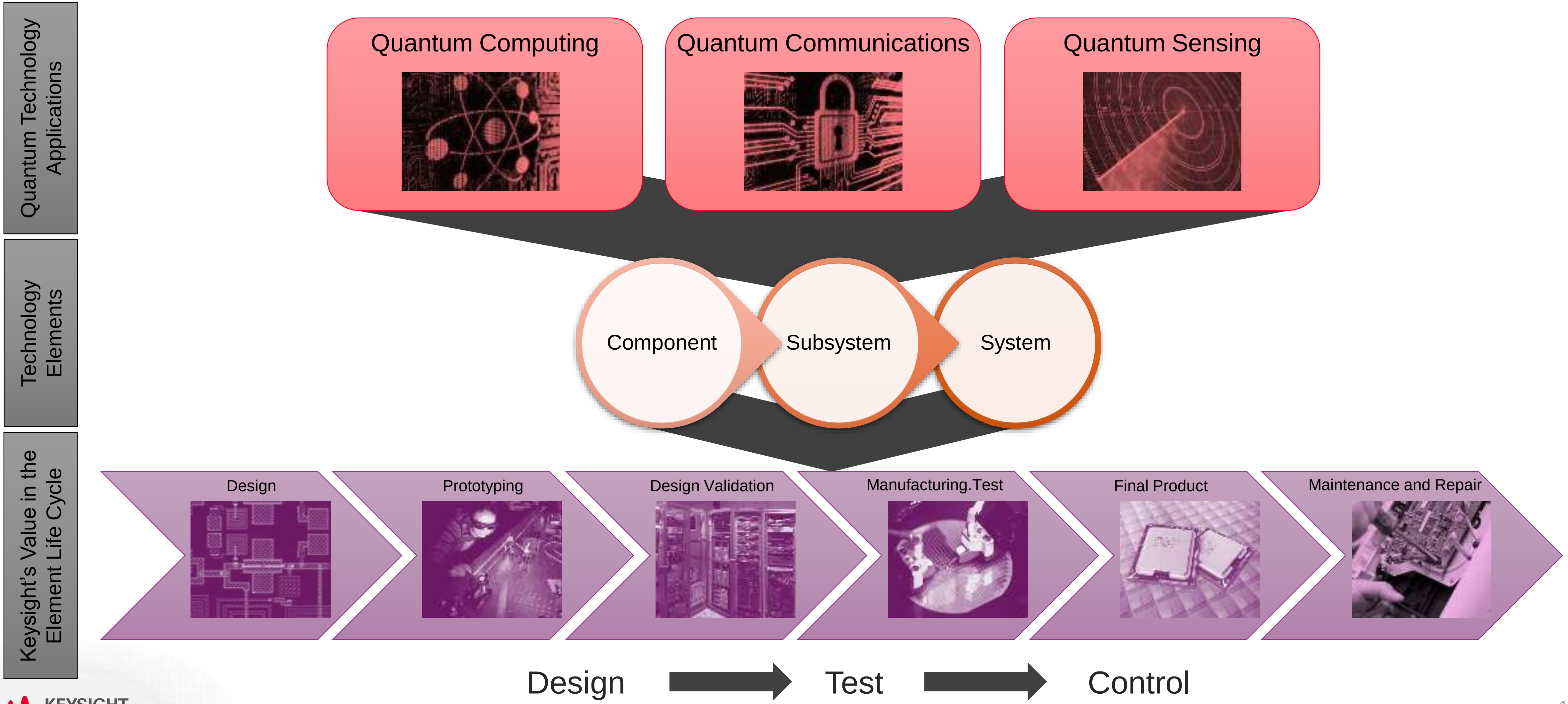
- Generation
  - Agile low-latency waveform selection
- Acquisition
  - Real-time low-latency qubit state decoding (DSP)
- Real-time decision-making feedback
  - Low-latency communication between analyzers & sources

n error corrected physical qubits → 1 logical qubit

Keysight Solutions

Quantum Solutions for Complete Product Life Cycle

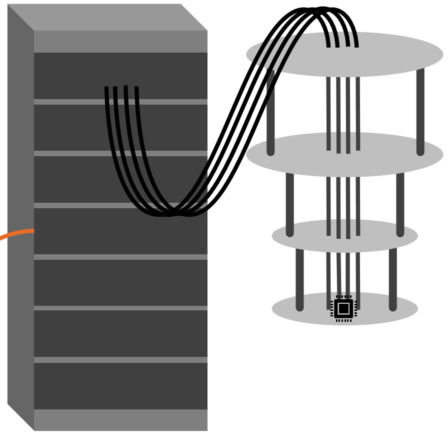
QES SOLUTIONS



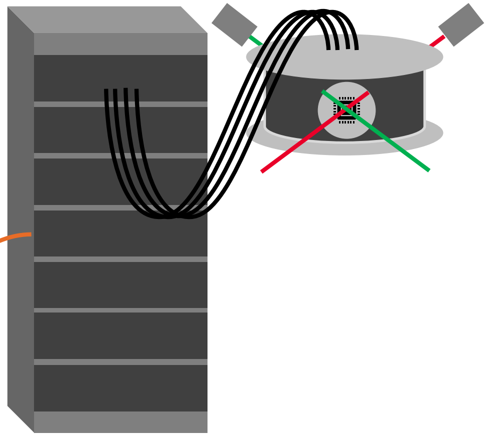
Quantum Computing, Comms, Sensing – Control Solutions

QES SOLUTIONS

- Examples:
  - Superconducting qubits
  - Spin qubits
  - ...



Cryogenic Systems



Non-cryogenic Systems

- Examples:
  - Trapped ions
  - Neutral atoms
  - NV centers
  - Molecules
  - Rare-earth crystals
  - Non-linear crystals
  - Electro-opto-mechanical devices
  - …

End-to-end Qubit Control Systems

MIMO uW/RF/BB Solutions

Open FPGA & HW Sequencer

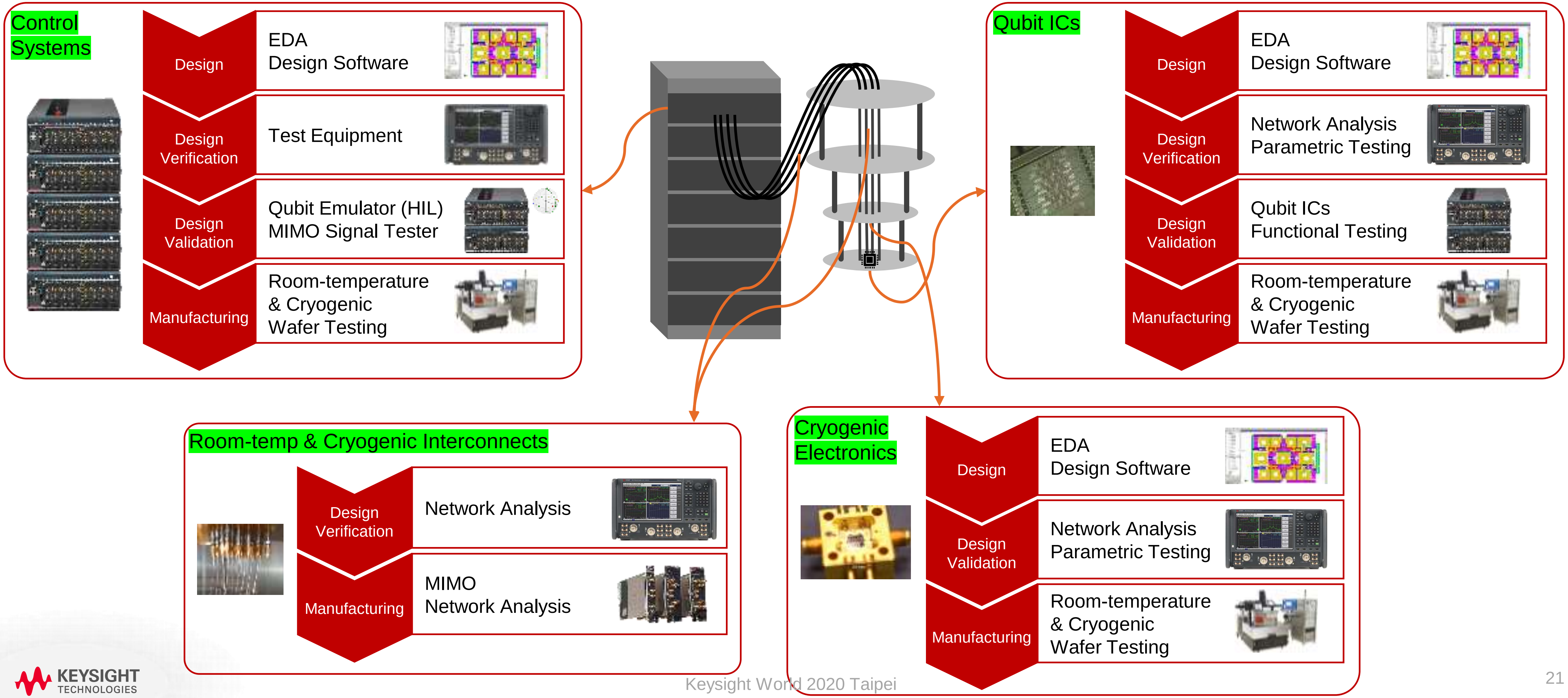
Quantum-specific FPGA & SW IP for Control and Readout

High BW Solutions

Interconnect Solutions

Cryogenic Quantum Systems - From Design to Test

QES SOLUTIONS

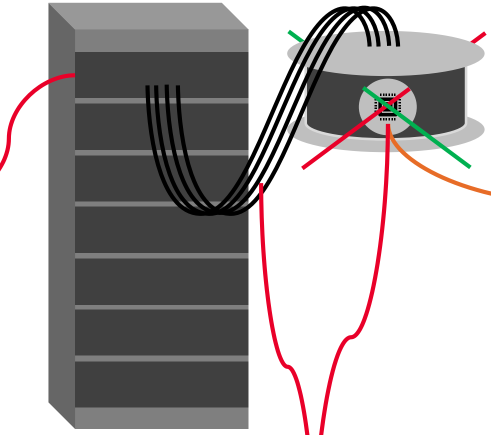


Non-Cryogenic Quantum Systems – From Design to Test

QES SOLUTIONS

Control Systems

Design	EDA Design Software	
Design Verification	Test Equipment	
Design Validation	Qubit Emulator (HIL) MIMO Signal Tester	
Manufacturing	Room-temperature & Cryogenic Wafer Testing	



Qubit ICs

Design	EDA Design Software	
Design Verification	Network Analysis Parametric Testing	
Design Validation	Qubit ICs Functional Testing	
Manufacturing	Room-temperature & Cryogenic Wafer Testing	

Room-temp & Vacuum Interconnects

Design Verification	Network Analysis	
Manufacturing	MIMO Network Analysis	

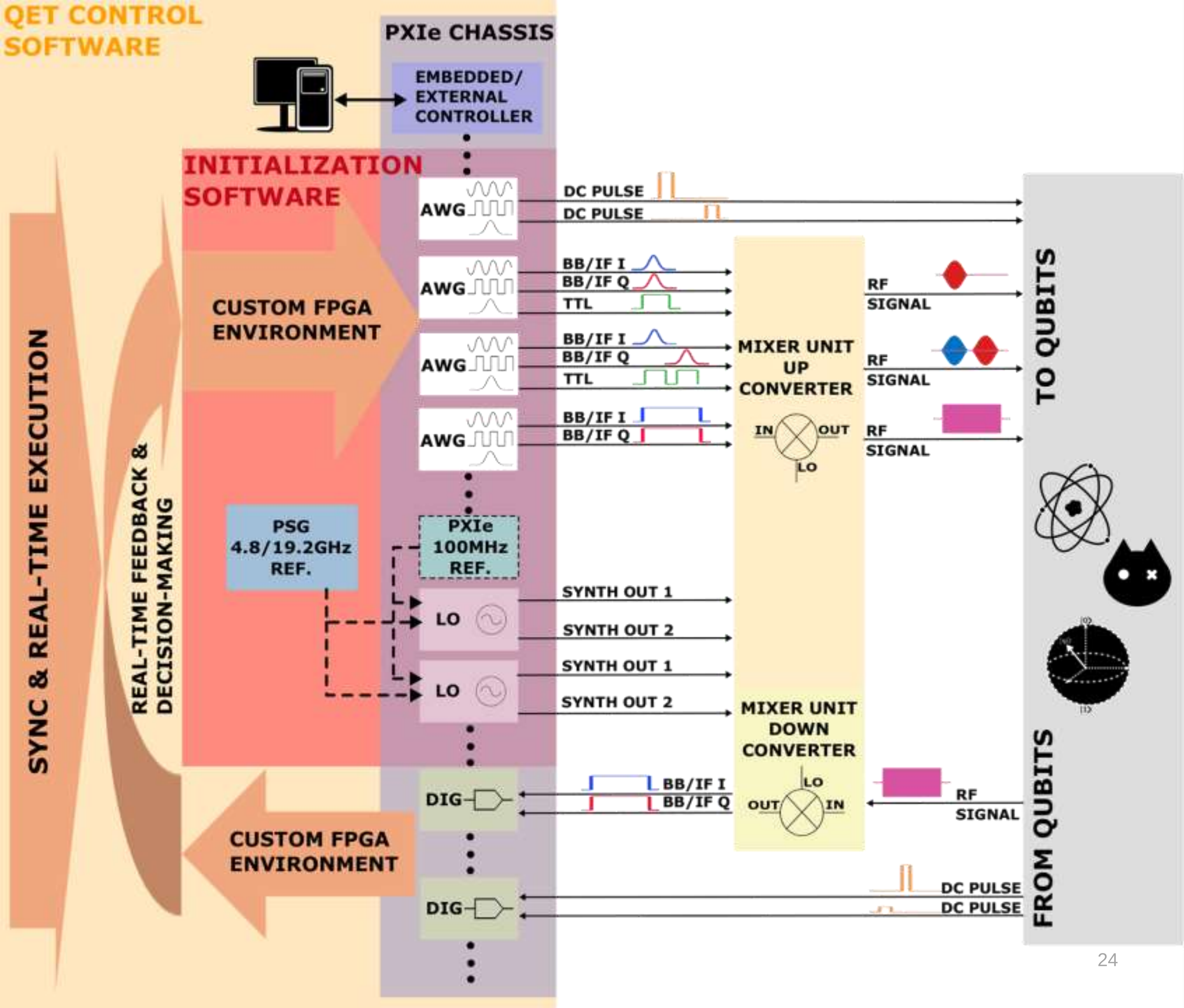
Scalability & Footprint: 5-Qubit Example

QUANTUM COMPUTING CONTROL/TEST SYSTEM

Scalability

- Hundreds of ports of AWGs & digitizers possible
  - With daisy-chained PXIe chassis
- Minimizing footprint & cost
  - With high channel density

Block Diagram: Quantum Engineering Toolkit



For more details visit:
www.keysight.com/find/solution-QET

Hardware Components

[Data Sheet](#)
[Startup Guide](#)

QUANTUM COMPUTING CONTROL/TEST SYSTEM

Modular
PXIe based

M3202A 1 GSPS AWG
4 Channels
1 PXIe Slot
Real-time Sequencer
FPGA Programming

U3022A Mixer Unit
8 U/C or D/C
19” Rack Chassis

M3102A 500MSPS Digitizer
4 Channels
1 PXIe Slot
Real-time Sequencer
FPGA Programming

M9347A 20GHz LO Module
2 Channels
1 PXIe Slot
World-class Phase Noise
Phase Coherence

Ex:50 Qubits

Intruments	#CH	#units	Example (50 Qubit)
AWG - M3202A	200	50	50
AWG - M3202A low cost option	100	25	25
DIG - M3102A	100	25	25
LO - DDS M9347A-H01	100	50	50
MU - U3022A	150	19	19
SW - P5060A Calibration SW (1x set)	13	13	13
REF 19.2 GHz E8257D-UNY PSG (20 GHz)**	1	2	2
Splitter (price is orientative)	2	2	2
M3601A-1FP license	1	1	1
M3602A-1FY license	1	1	1
Chassis M9019A	13	13	13
M9049A PCIe adapter	13	13	13
M9024A System module	13	13	13
Squid board engineering breakout pannel	12	12	12

Keysight Labber Quantum

https://labber.org/

是德科技宣布與麻省理工學院量子工程中心合作並收購Labber Quantum

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Mar 2, 2020

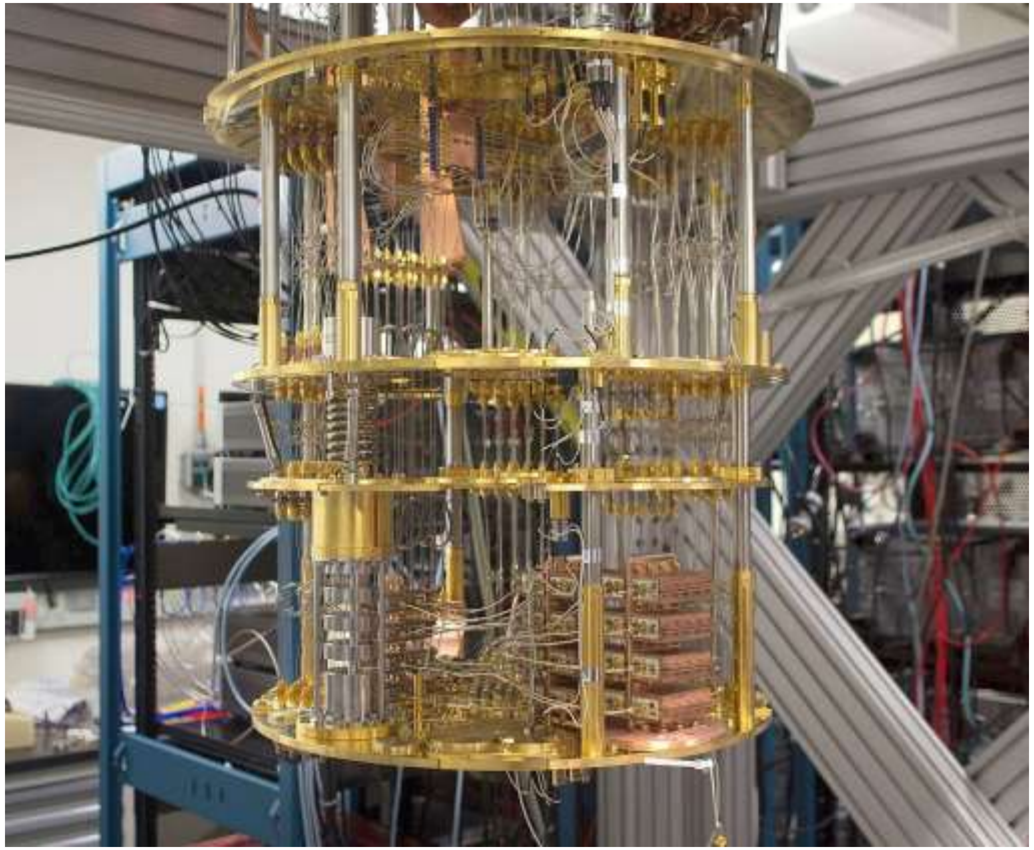
（Newsbreak）幫助企業，服務提供商和政府加快創新的技術公司Keysight Technologies，Inc.宣布與MIT合作，並收購Labber Quantum。

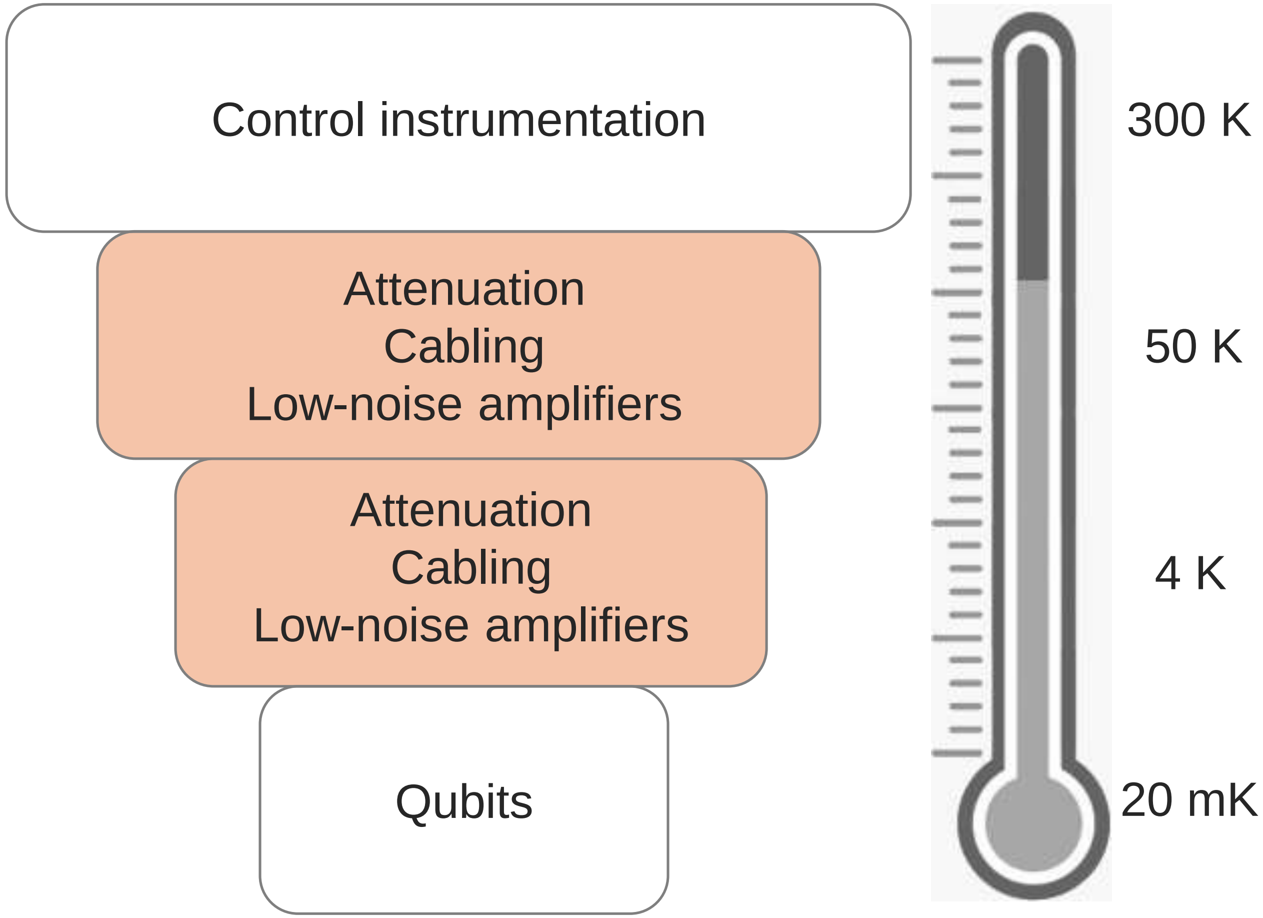
是德科技的大學計劃與麻省理工學院量子工程中心合作，以建立一個新的64量子位量子計算實驗室。該測試平台將利用是德科技的量子工程工具包（QET），該工具包將其一流的硬件與最新收購的Labber Quantum軟件結合在一起。

“是德科技收購了MIT EQuS小組的初創公司Labber，這為推動量子技術的下一代創新提供了令人振奮的新機遇。 EQuS期待將是德科技新興的量子軟件和硬件解決方案應用於我們的新量子計算測試平台，”麻省理工學院量子工程中心主任兼麻省理工學院工程量子系統（EQuS）負責人William Oliver教授說。 ）組，測試床將位於其中。

是德科技通信解決方案事業部高級副總裁兼總裁Satish Dhanasekaran說：“與MIT的合作以及將Labber Quantum添加到是德科技的解決方案產品組合中，表明了我們致力於發展量子計算的承諾。” “我們很高興能夠支持和推動量子生態系統的發展，以加速下一代計算和連接應用程序的創新。”

Challenge: Noise in the System





Component Characterization

VECTOR NETWORK ANALYZER

Key specifications for network analyzer

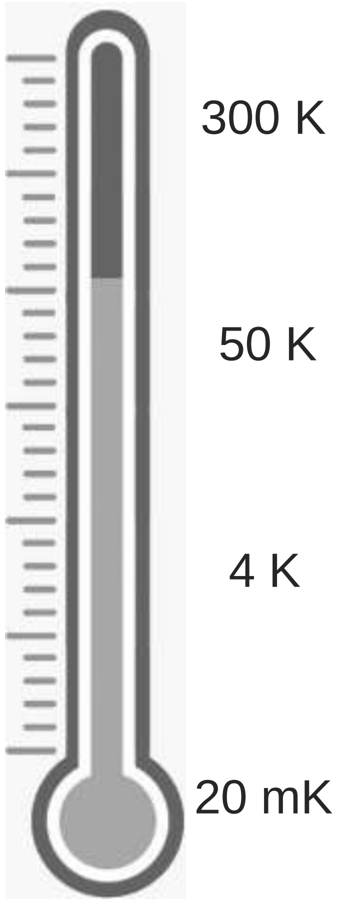
- Stability
- Dynamic range
- Noise floor
- Phase noise
- Trace noise

Control Instrumentation

Attenuation
Cabling
Low-noise amplifiers

Attenuation
Cabling
Low-noise amplifiers

Qubits

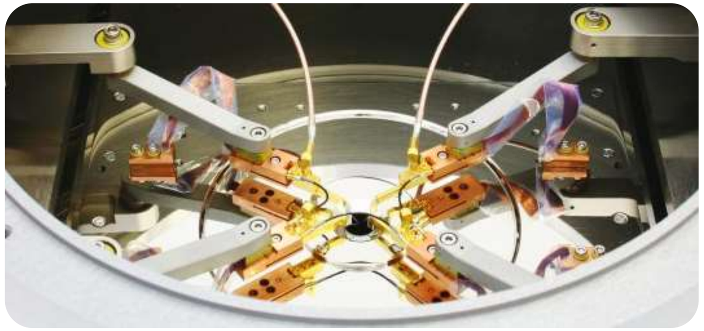


PNA-X Series Network Analyzers

OFFER HIGHEST PERFORMANCE & MORE

- 2- and 4-port versions
- Built-in 2nd source & internal combiner simplify measurement setups
- Unrivaled flexibility & configurability
- Internal modulators & pulse generators for fast, simplified pulse measurements
- High-accuracy noise-figure measurements using unique source-correction method
- Many software applications
- Large touch-screen display with intuitive user interface

Challenge: Wafer Testing at Low Temperature



Cryogenic operating conditions

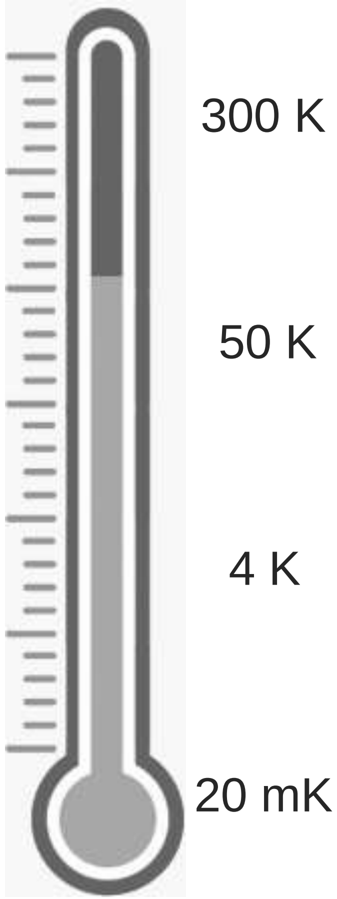
Cryogenic device testing requires highly specialized probe system

Control instrumentation

Attenuation
Cabling
Low-noise amplifiers

Attenuation
Cabling
Low-noise amplifiers

Qubits



Development Stages of Target Devices

CRYOGENIC TOOLS

切割封裝測試
低生產能
低溫探針台
冷卻週期
低溫範圍

Exploration/research	Engineering/development	High-volume engineering/production
Cryostat / dilution refrigerator	Small / manual cryo probe station with probes	Large / automated cryo probe station with probe card

Exploration/research

+ Low-cost entry point
- Packaged devices only; single or small set, easy to load

+ Full cryo range 15mK to 77K

- Low throughput
- Days/weeks delay for packaging
- New cooling cycle per device/set
- Stalled by poor-yielding technologies (replace, then repeat cooling cycle)

- ESD/$H_2$0 risk (dice/bond/handle)
- New load board for every package
- Wafer destruction during dicing

Engineering/development

+ Improved throughput
- + Quicker sample prep (dicing only)
- + Test devices in series with no new cooling cycle; move stage/probes to next test site (select systems only)

+ Positioners for different pad patterns
+ Wafer OK for other tests/production
+ Same package test capabilities, plus simple structures (max 8 probes) on small wafer fragments (e.g., 100 mm with tens of devices)

- Doesn't cover full cryo range
- 2K minimum temp available today

High-volume engineering/production

+ Best throughput
- + Immediate wafer test (no prep)
- + Automated alignment once trained
- + Automated step-and-repeat testing across wafer; no operator delays
- + Higher throughput yields larger sample sizes for better engineering statistics & production output goals
- + Same package/fragment test capabilities, plus full wafers (up to hundreds of probes & devices)

- Doesn't cover full cryo range
- <10K minimum temp available today

FormFactor's Range of Cryo-Probe Systems

FormFactor™
Cascade

INTEGRATION WITH KEYSIGHT INSTRUMENTATION

PLC50 100 mm manual cryogenic probe system
Entry-level manual cryogenic wafer probing < 7 K

PMC200 200 mm manual cryogenic probe system
Advanced manual cryogenic wafer probing < 7 K

PAC200 200 mm semi-automated cryogenic probe system
Semi-automated cryogenic wafer probing < 20 K

PNA - X

B1500A

B1505A

N6705C

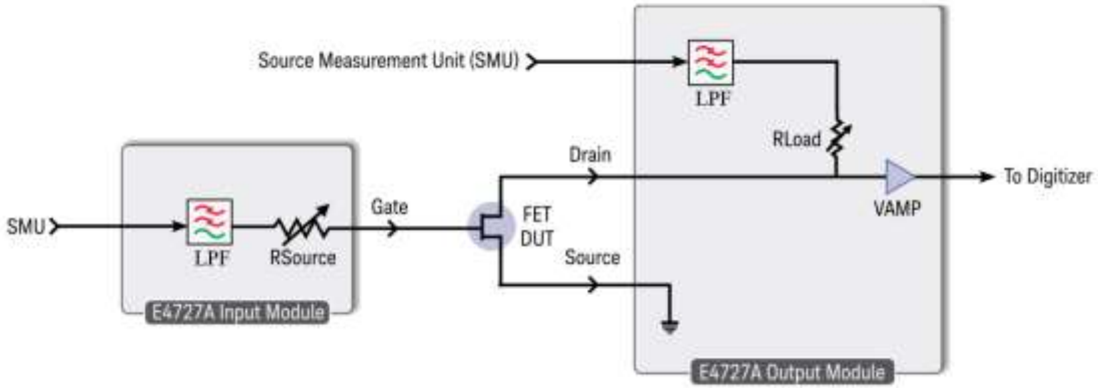
Noise Analysis at Wafer Level

1/F NOISE

- Extraordinary progress in quantum device engineering has reached high levels of isolation from local electromagnetic environment

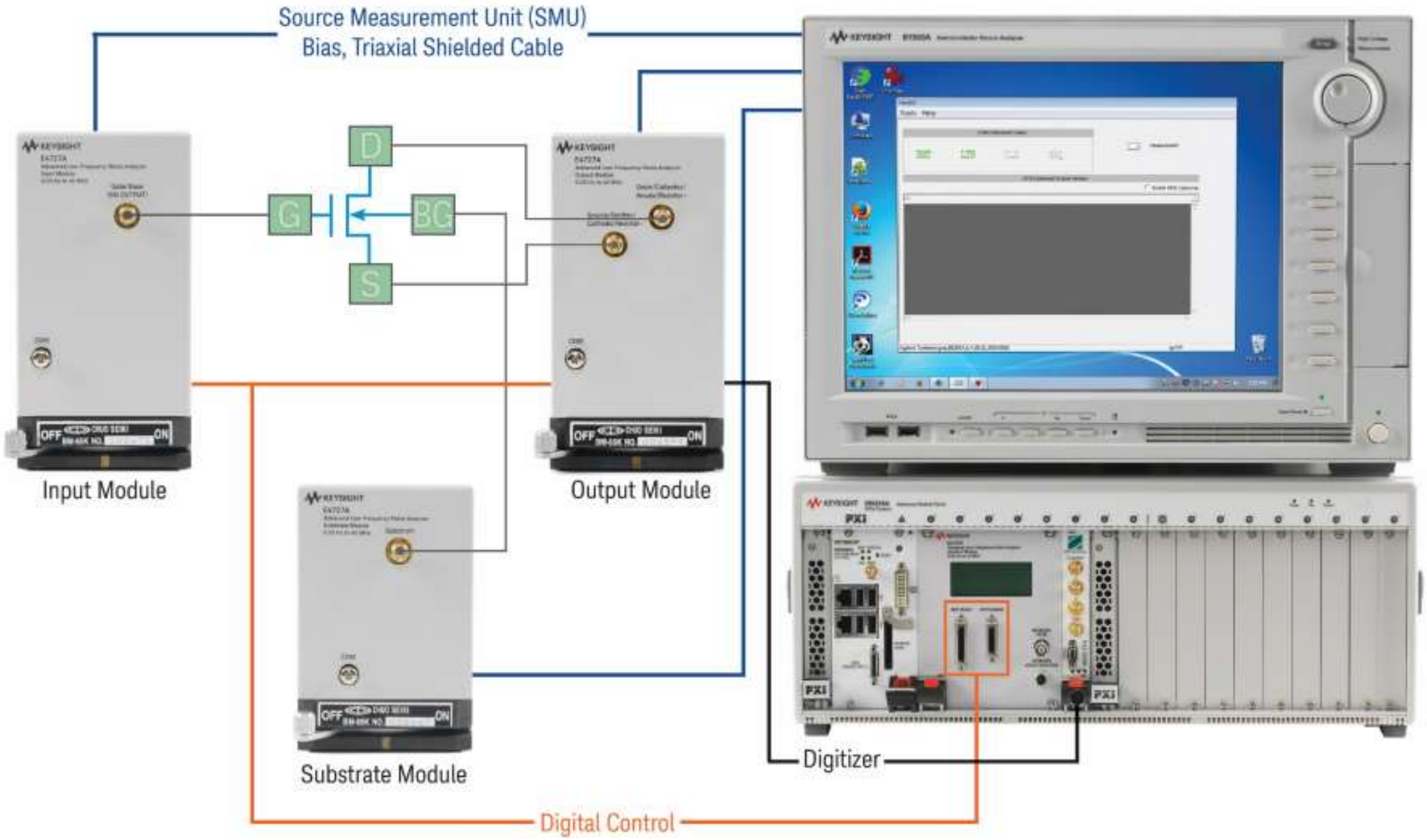
- Under these conditions, inherent material noises play an important role
  - Material-inherent fluctuations with 1/f spectrum present main limiting factor to quantum coherent behavior of nanodevices in present generation

- Has stimulated great effort in understanding & predicting decoherence due to 1/f noise and the closely related RT noise



1/f noise: implications for solid state quantum information
E. Paladino et al
arXiv:1304.7925v2[cond-mat.mes-hall]17Dec2013

A-LFNA Connections



Simulation

CROSS-TALK & OTHER CHALLENGES

- Any electrical circuit for implementing quantum bits will have channels through which microwave signals applied to one qubit will leak onto unirradiated qubits
  - Microwave crosstalk may occur through either *intended* coupling channels or through *unintended* stray elements
- In nanodevice fabrication, inductance, resistance & capacitance values determine resonant frequency of qubits & quality of connections
- Accurate 3D RF simulation of designs is paramount to higher qubit yield & better qubit quality

Summary

WRAPPING UP

- Quantum will enhance communication, computing & sensing
- Investment in quantum is rising around the world
- Realization of quantum computers faces major challenges
- Scalable solutions from Keysight & FormFactor can help

KEYSIGHT
WORLD 2020