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KEYSIGHT TECHNOLOGIES

Accelerated Solid State Qubit Pre-Screening

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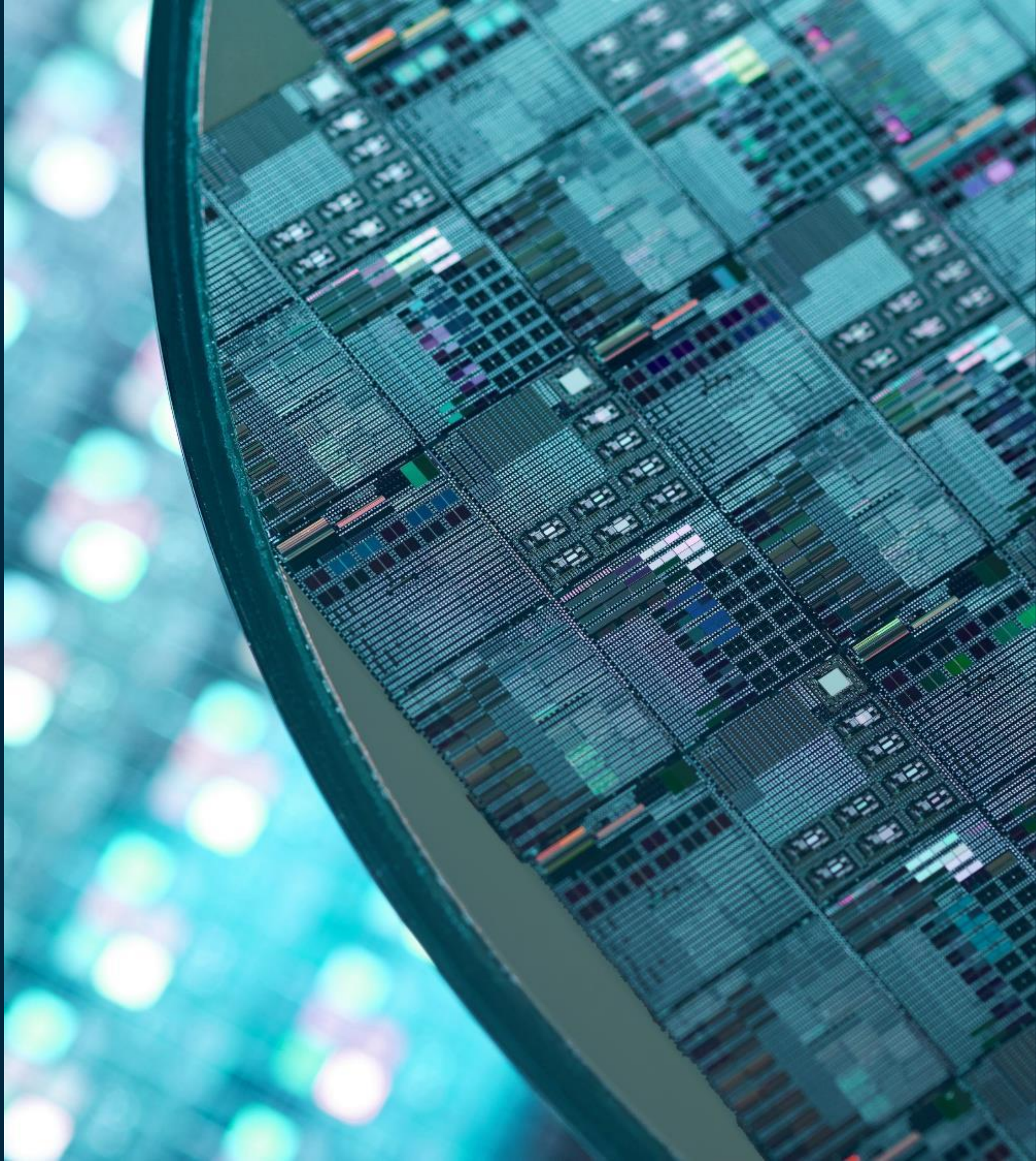


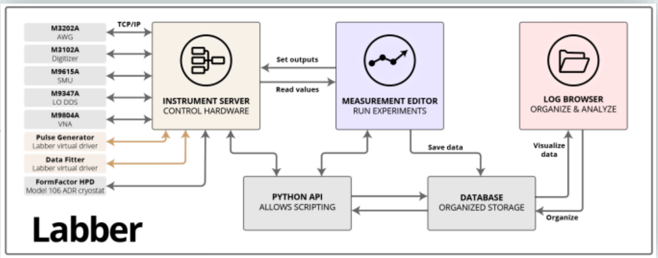
Solution Overview
Model 106 Cryostat + Quantum Control

Superconducting and Spin Qubit Pre-Screening

Qubit control system

Labber Control SW

KEYSIGHT TECHNOLOGIES



Turn-key qubit pre-screening

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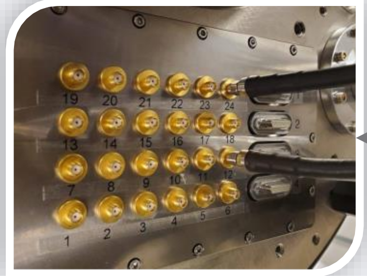
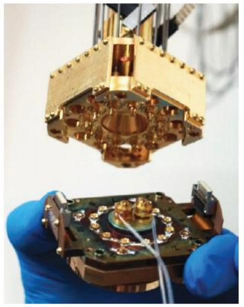


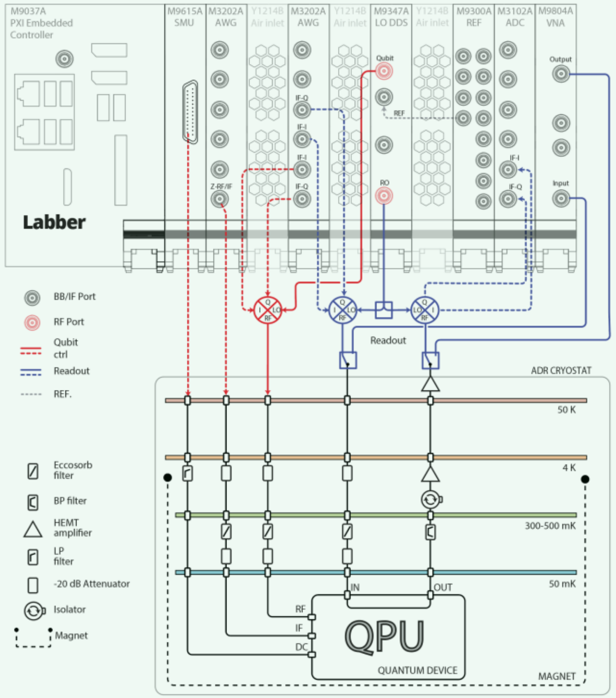
Probe socket



ADR Cryostat

Reduced Cooling time

Automated Characterization of Superconducting Qubits



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50mK

50 mK ADR Cryostat

Chip-Scale and Component Test Solution

Use Cases

Developers

Qubit & Resonator Pre-characterization

Process Control

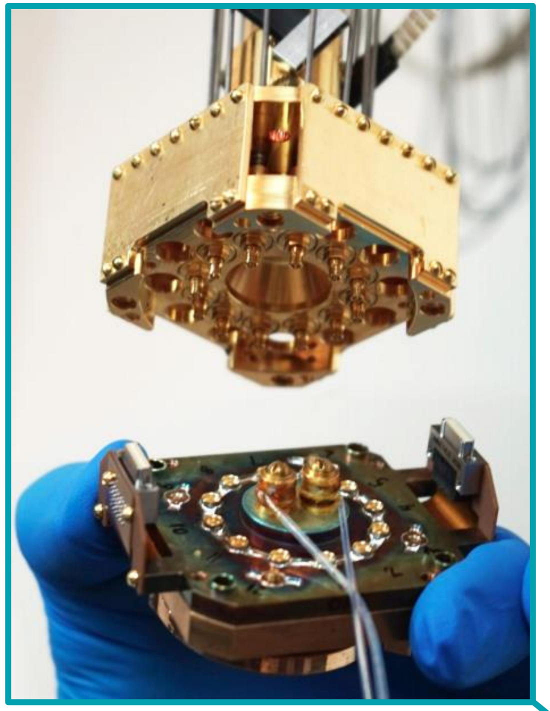
Materials Development

Vendors

Component Qualification

Performance Validation

PQ500 Probe Socket



Model 106 ADR Cryostat

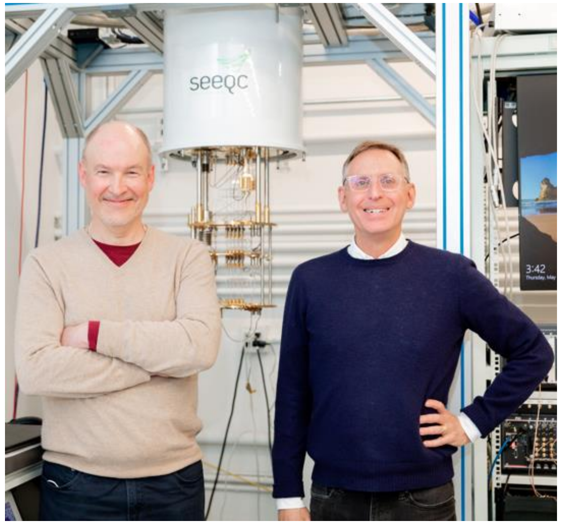
ADR versus DR | Why use an ADR?

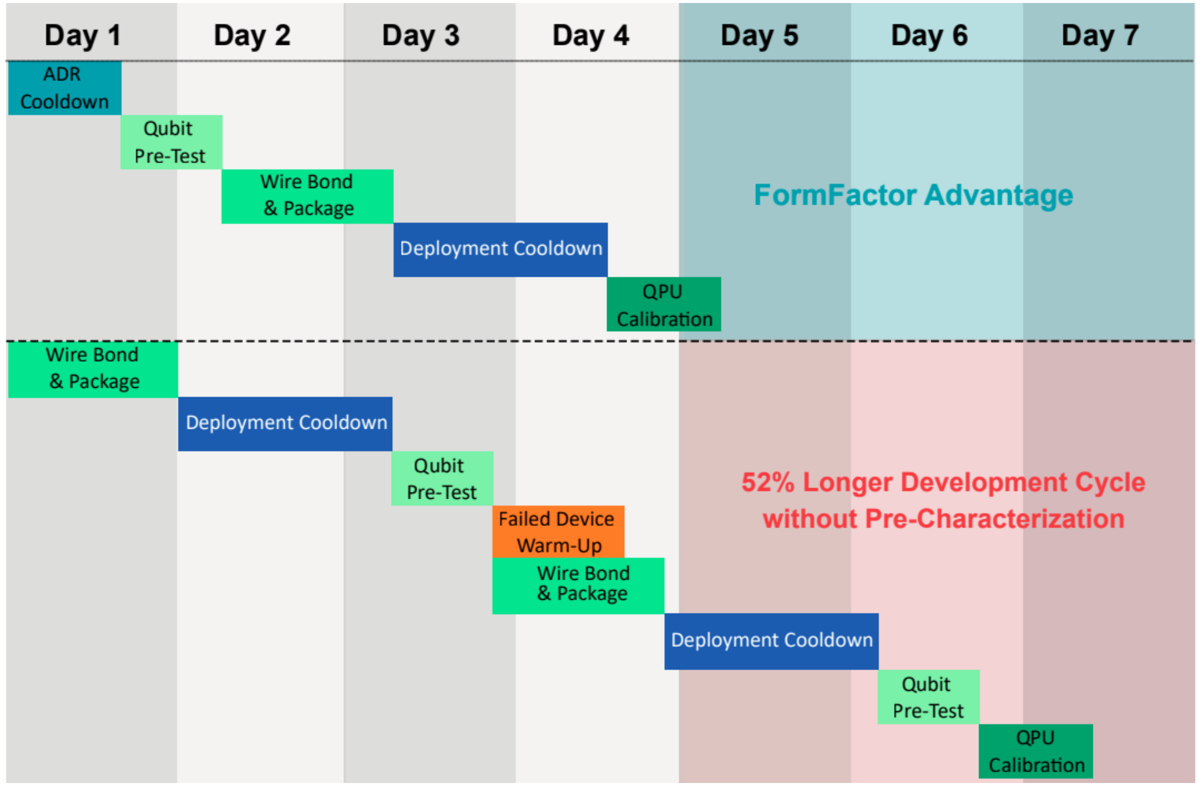
Model 106 ADR

- Qubit Pre-Screen
- Are qubits alive?
- Basic characteristics
- Save time on the DR!

Dilution Refrigerator

- Deploy known good die
- Calibrate and fully characterize qubits





NEW Solution Brochure: HPD Superconducting and Spin Qubit Pre-Screening

Example Measurements in milli-Kelvin Test System

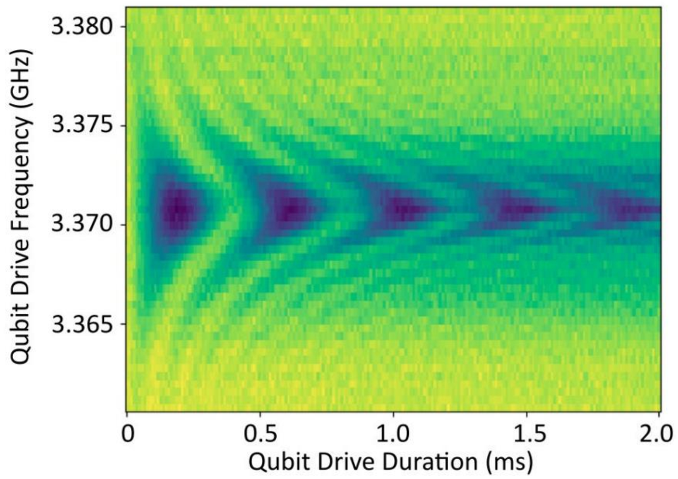
Qubit & Resonator Pre-characterization at 50mK

- Cavity resonance frequency
- Cavity dispersive shift
- Qubit transition frequency
- Rabi oscillations
- Qubit relaxation time (T_1)

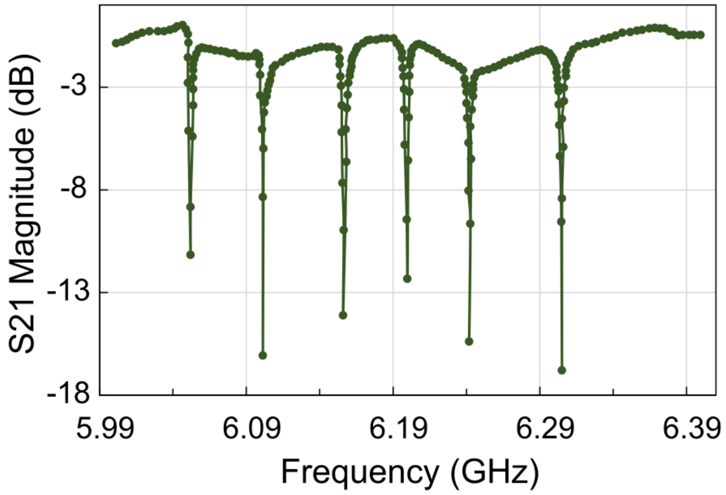
Reduce Device Sort by Days

Data courtesy of seeqc

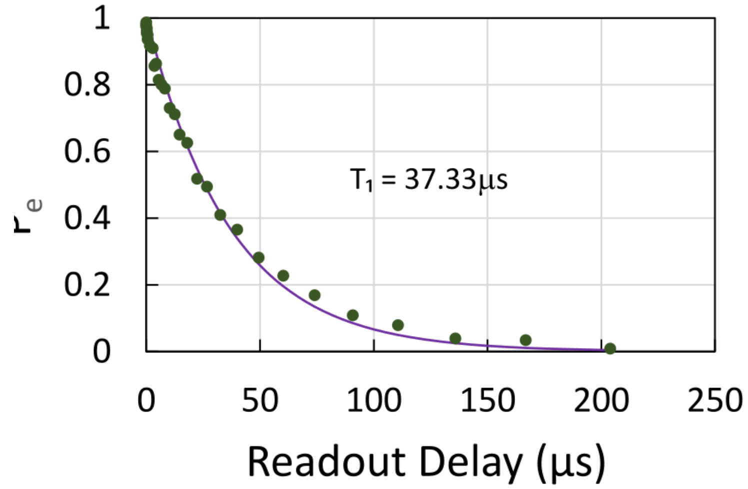
Rabi oscillations



Cavity resonance frequency



Relaxation time

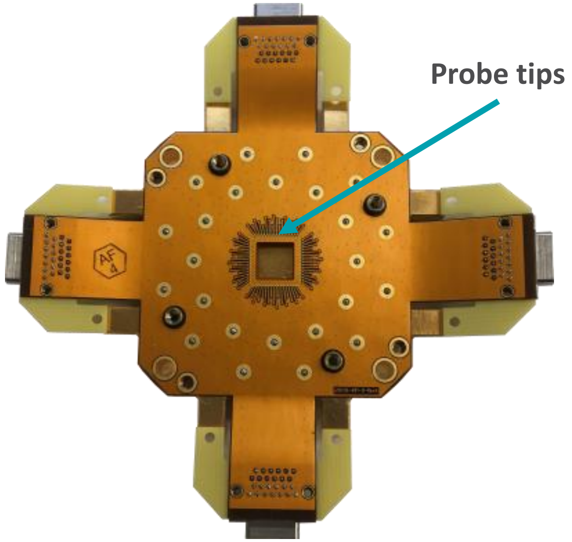


Large I/O DUT Interface for mK Environments

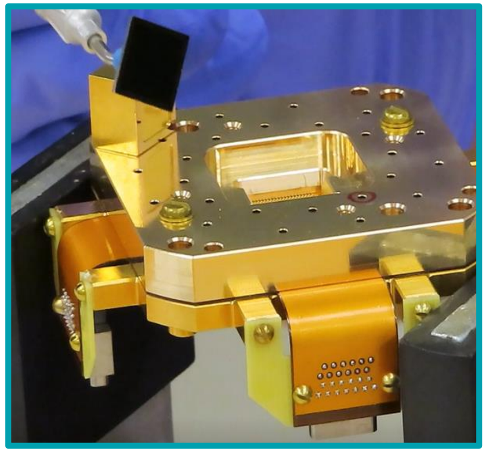
PQ500 Probe Socket

PQ500 Probe Socket Detail

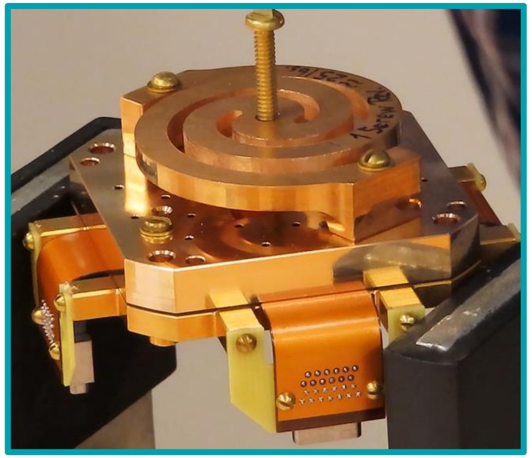
- Flex circuit with bump bonds as the DUT interface
- 24 RF contacts, 10 GHz bandwidth
- 48 shielded twisted pairs
- 10 x 10 mm^2 singulated die



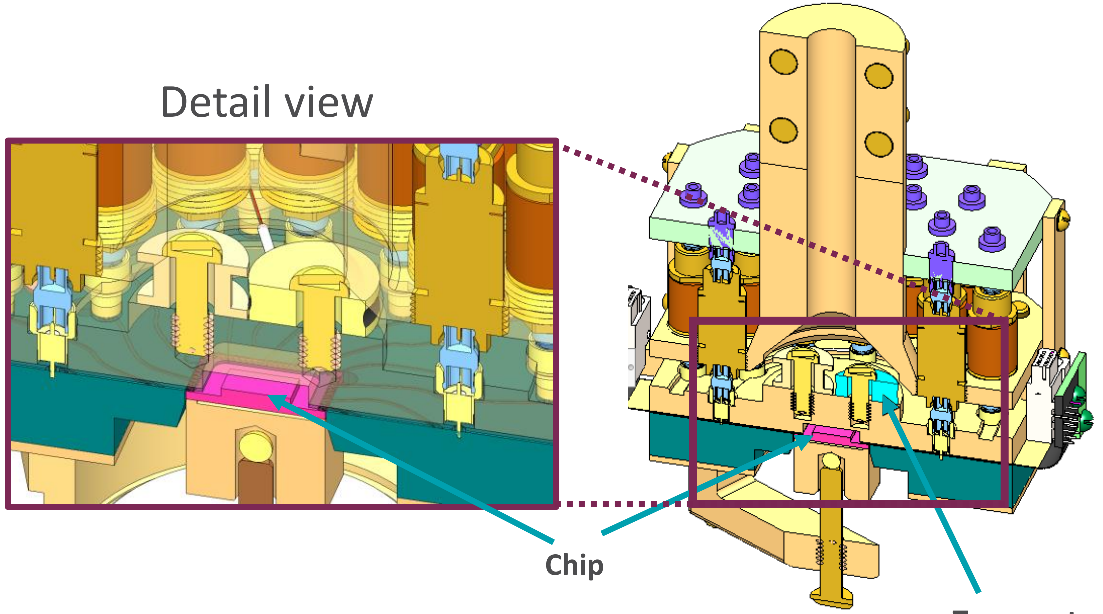
Chip loading



Thermal clamp



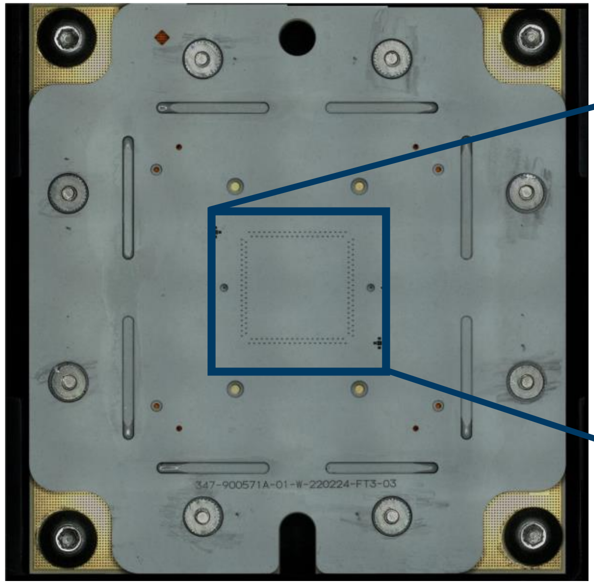
Detail view



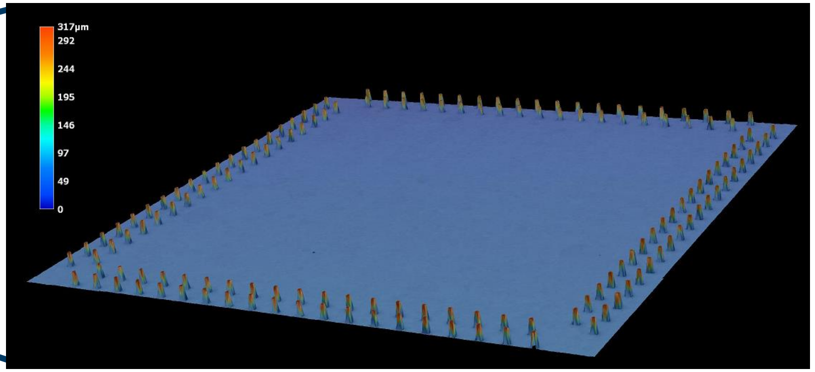
High Bandwidth Cryogenic Probe Head

- High bandwidth (>18 GHz) contact pins
- Customized to the desired layout
  - 150um pitch; 75um^2 pad size
- Accommodates large device areas

Vertical Probe Head

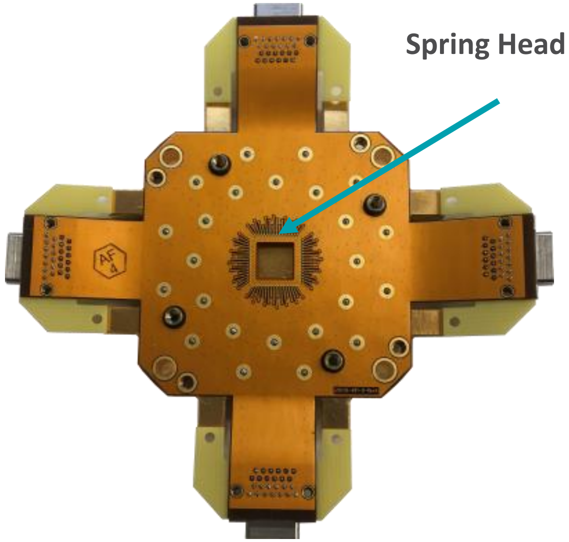


Optical Micrograph



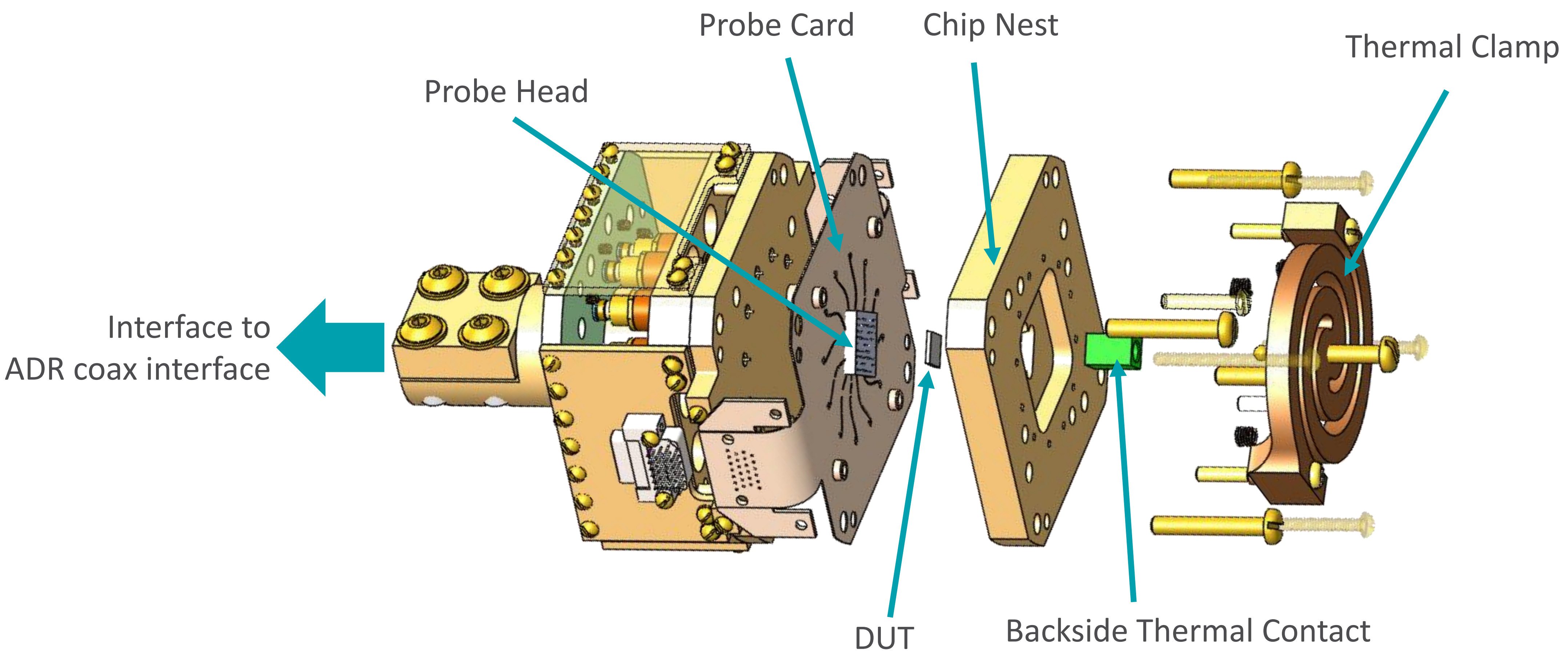
PQ500 Probe Socket

Spring Head or Bump Bonds



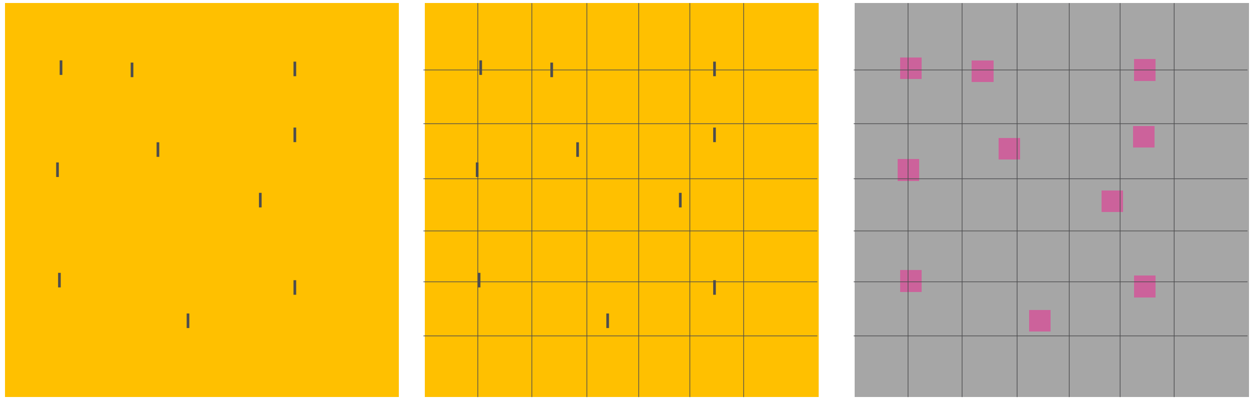
	Number of Probes	Min. Pad Size and Pitch	Pad Materials	Max DC Current	Max Frequency
Bumps	200 DC, 24 RF	250 um^2/ 400 um	Au, Cu	500 mA	8 GHz
Vertical*	200 DC, 28 RF	75 um^2/150 um	Al, Au, Cu, Nb*	1.25 A	>18 GHz

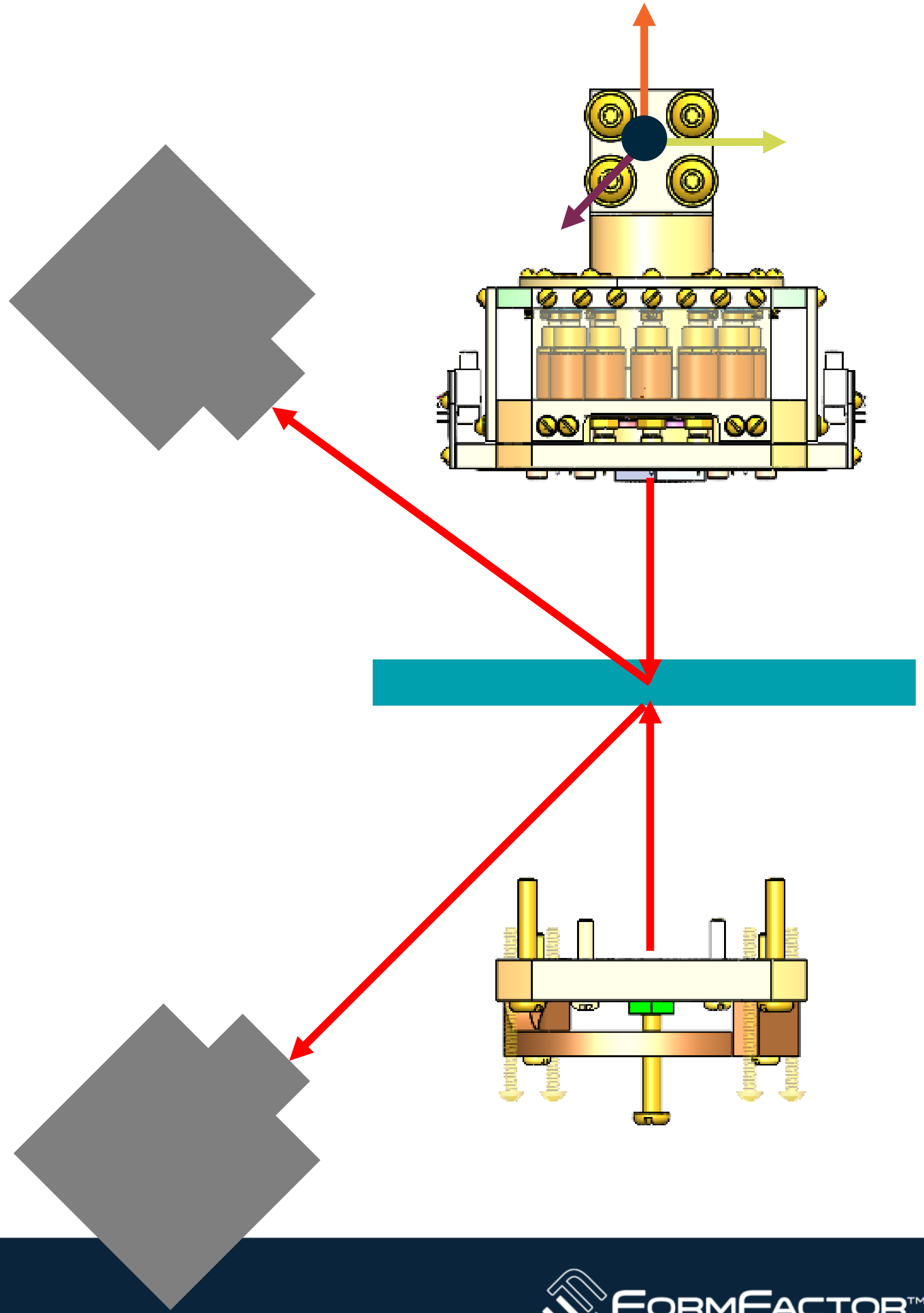
PQ500 Probe Head Detail



Active Probe Head Alignment

- Split optic system, BGA Aligners
- Witness Mark Alignment
- Top View Alignment with Fiducials





Configuring the Cryostat for Pre-Screening

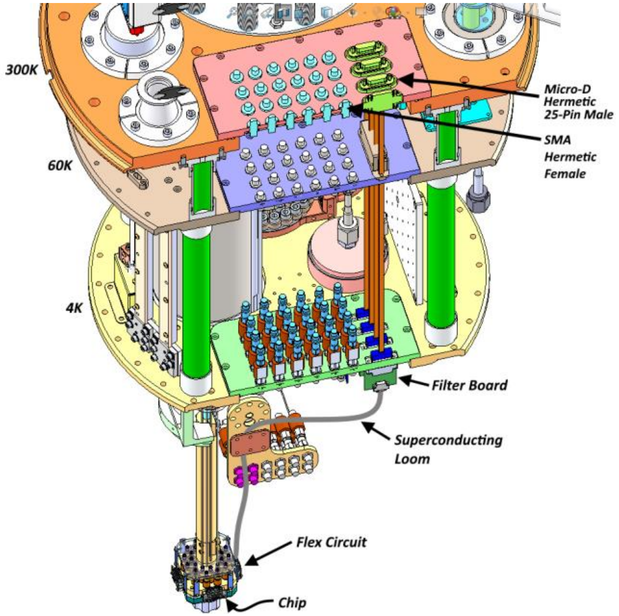
Model 106 Cryostat

Tailored Cryostat Solutions

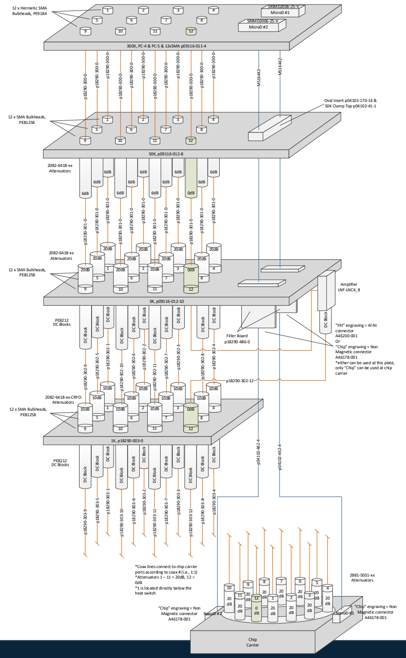
From Concept to Delivery

- Add in-line RF and DC elements
- High density feedthroughs
- Magnetic shielding for sensitive measurements
- Cooldown to 50mK in under 16 hours

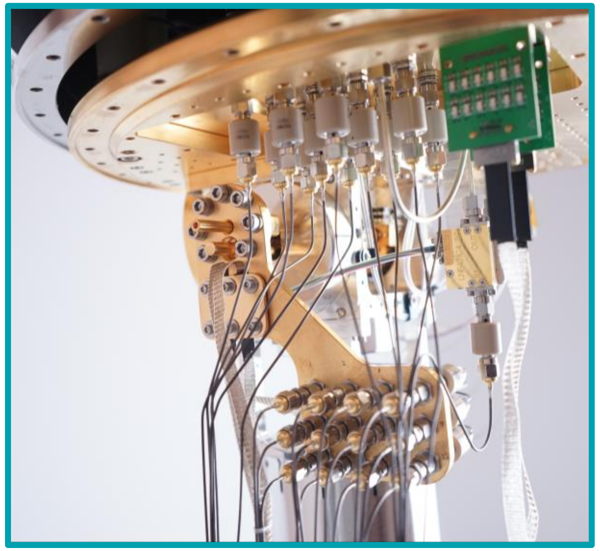
High density wiring



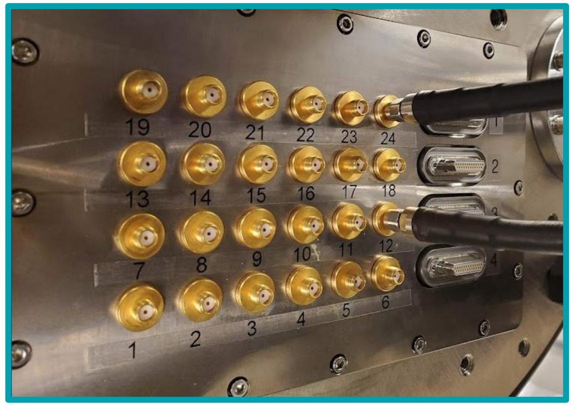
Example wiring diagram



Custom thermal intercept circuit elements



Bulkhead feedthrough



Magnetic shielding around sample

Anatomy of an ADR Closed-Cycle Cryostat

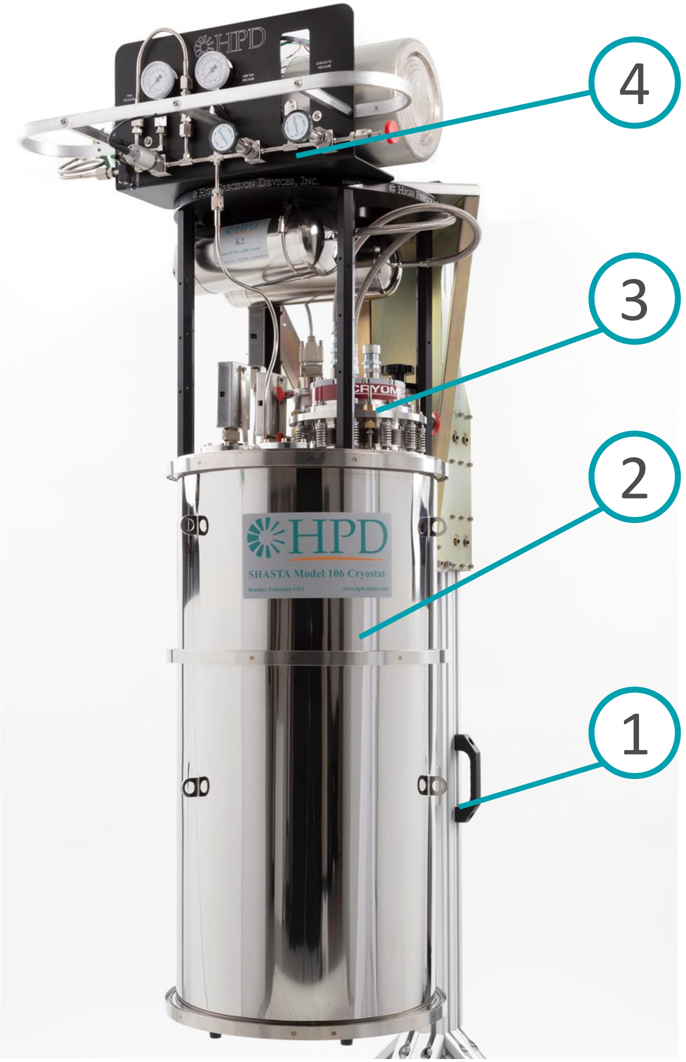
1. Support stand
- Consider the facility and size of the cryostat

2. Vacuum enclosure
- Seals the system against atmosphere

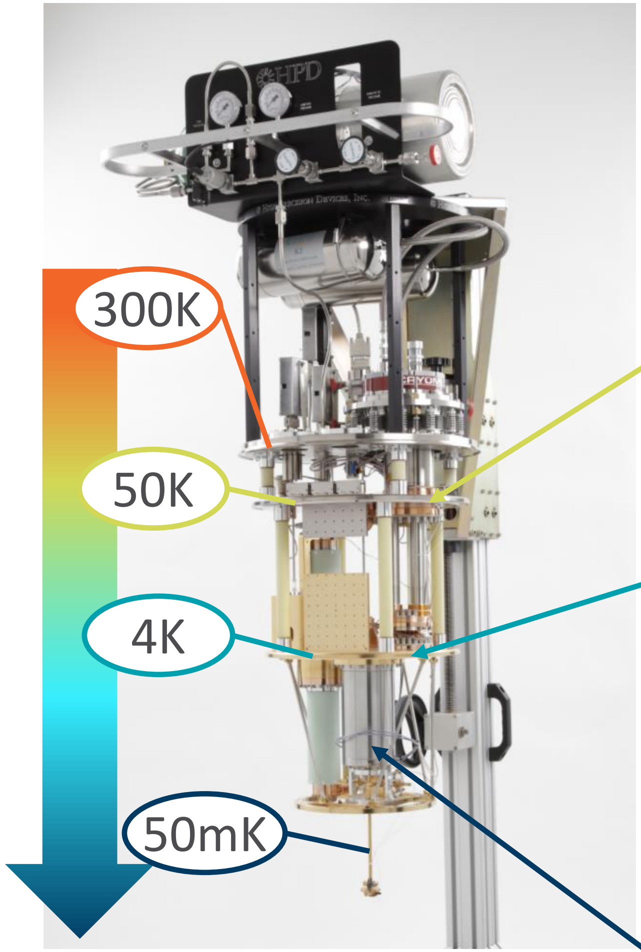
3. Cryocooler
- Provides the refrigeration

4. Gas handling
- Functional valves and controls

5. System control and temperature monitors
- Diagnostic and operational controls



Peeling Back the Vacuum Enclosure



50K Radiation Shield

4K Radiation Shield

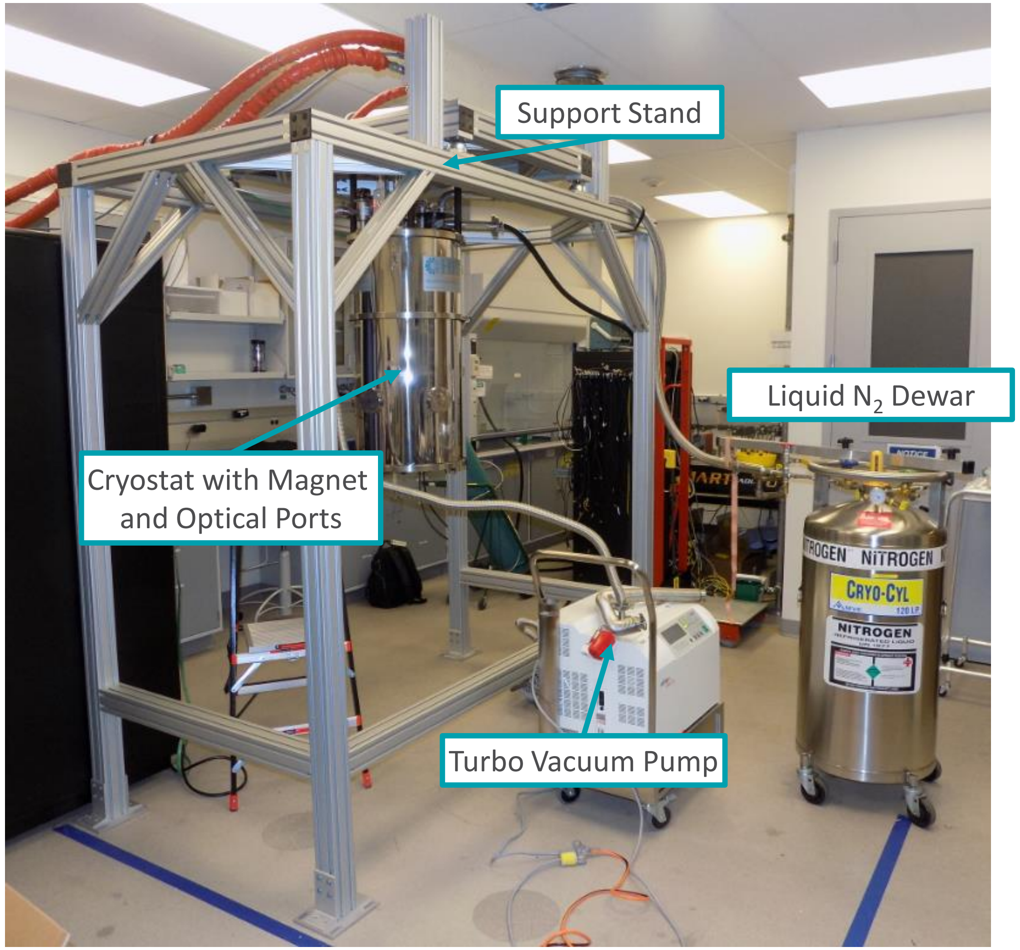
ADR Stage < 50mK

$$P = \sigma \cdot A \cdot T^4$$

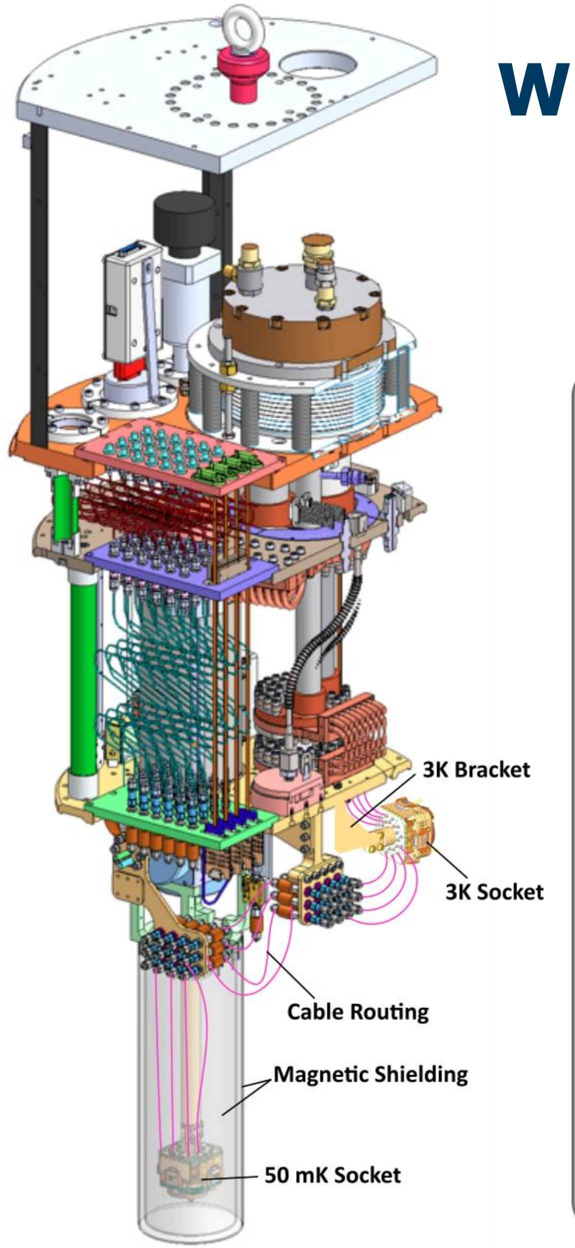
Example Cryostat Setup in the Lab

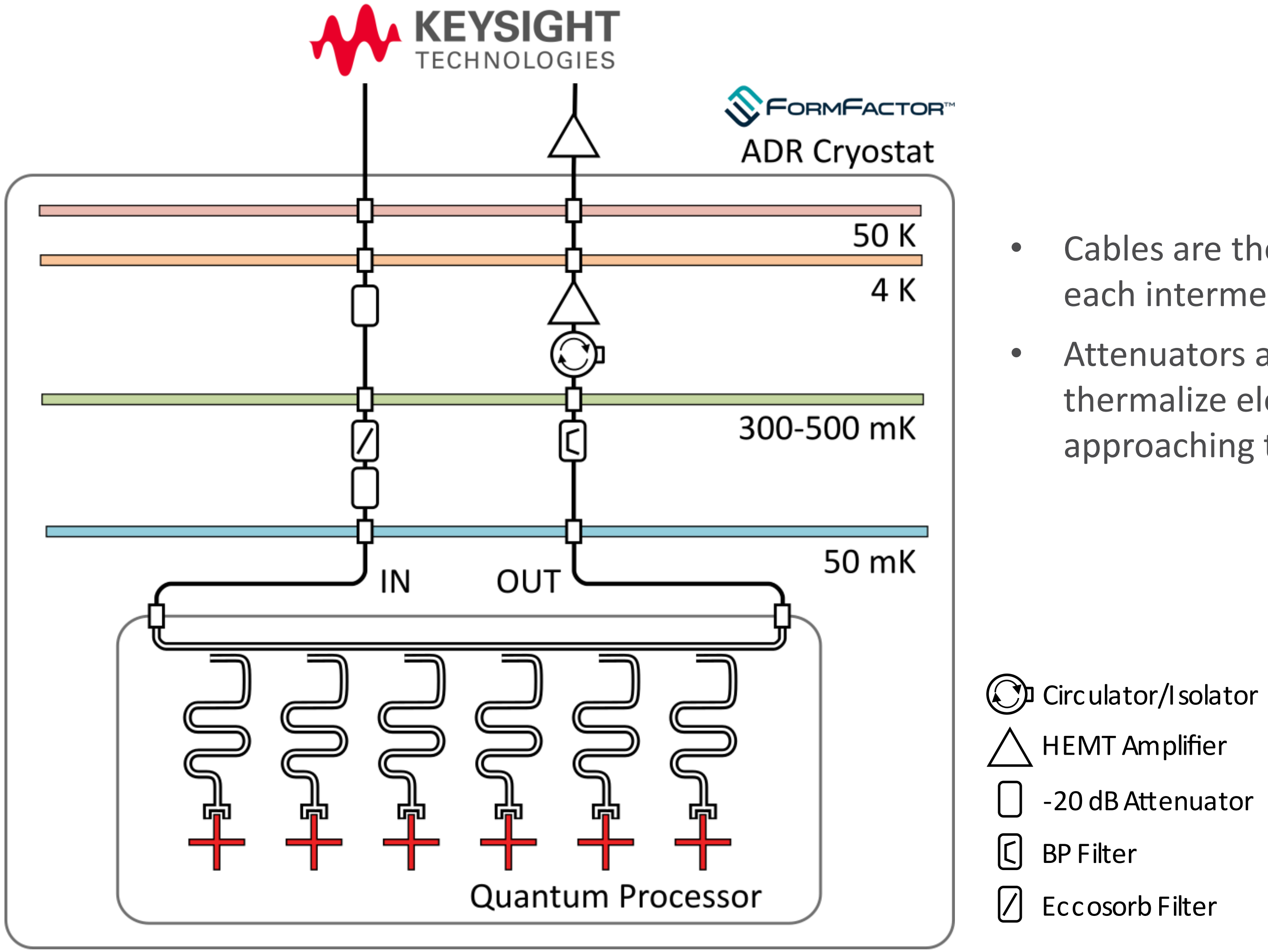
ADR Cryostat with superconducting magnet

- ADR closed-cycle system
- 5T magnet, optical ports, and electrical feedthroughs
- Liquid N_2 provides rapid cooldown
- Turbo vacuum pumping system
- Support stand and facility integration



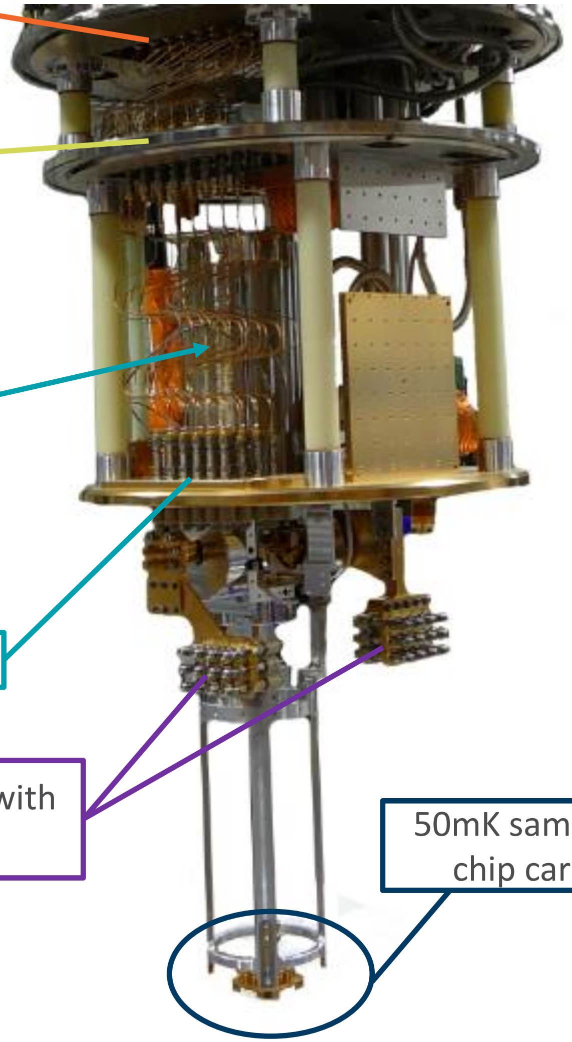
Wiring Details – Setting Up the RF Chain





- Cables are thermally anchored at each intermediate temperature stage
- Attenuators at 50K, 3K, 1K, 50mK thermalize electrons before approaching the QPU

Cabling a Cryogenic Environment for Quantum Applications



$$Q = \frac{A}{L} \int_{T_0}^{T_L} \lambda \, dT$$

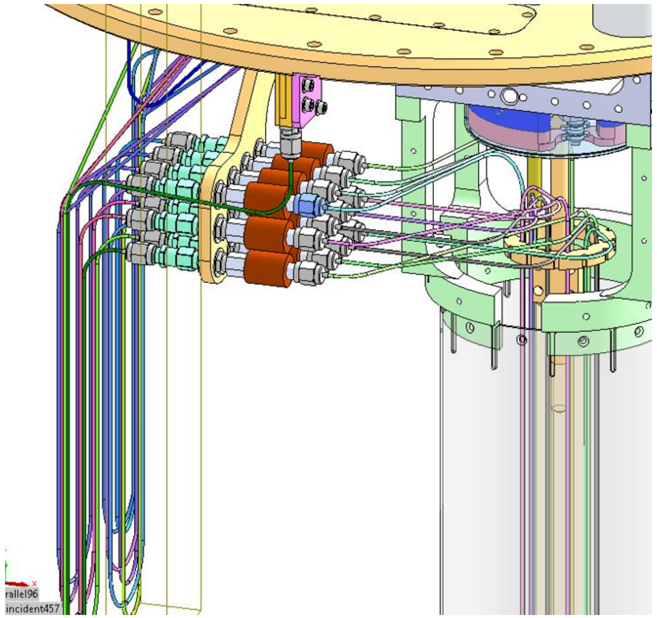
Example Attenuator Setup

- 6dB at 50K
- 20dB at 3K
- 10dB at 1K
- 20dB at 50mK

Types of Cables

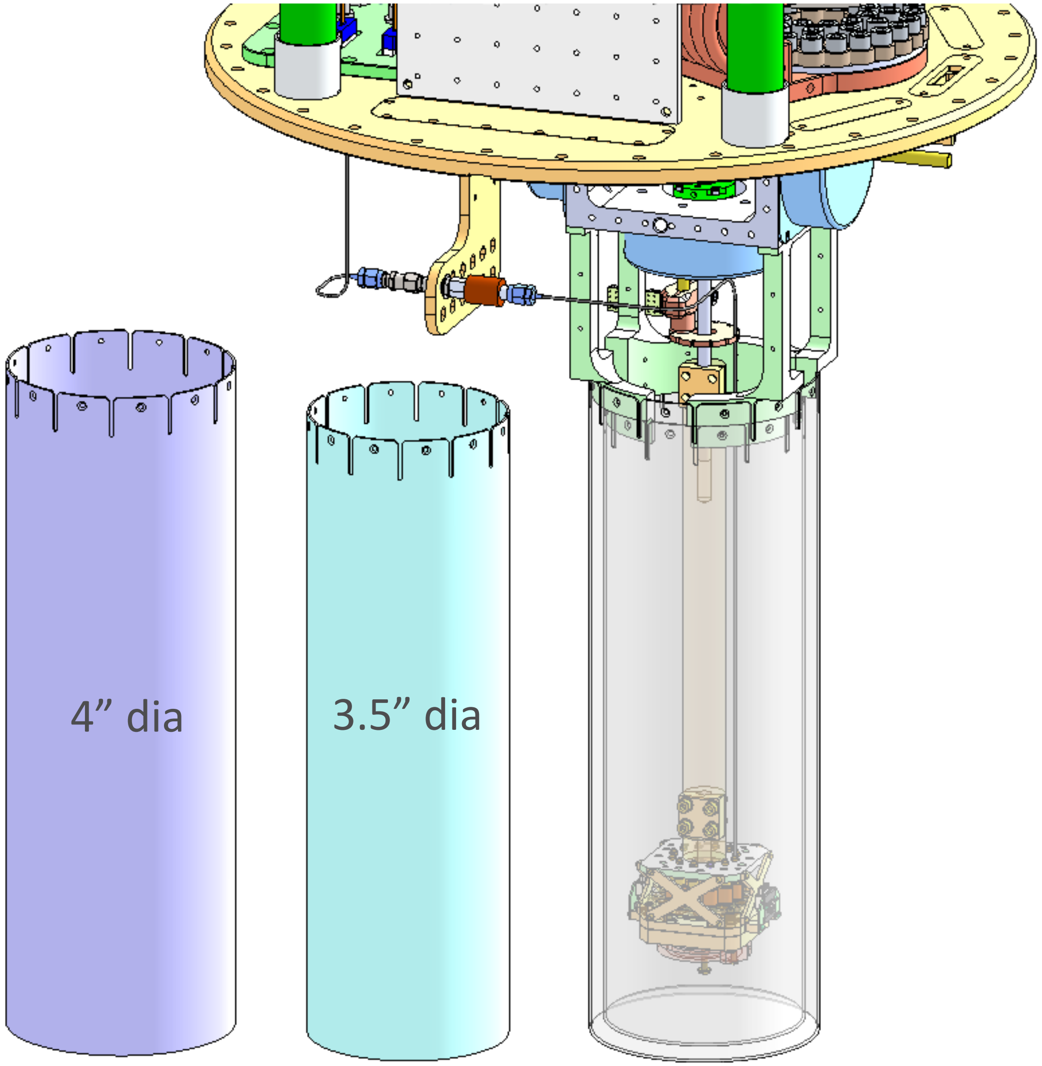
- 300K to 3K = BeCu
- 3K to mK = NbTi

Coax routing from 3K to mK



Magnetic Shielding Configuration
Superconducting Qubits

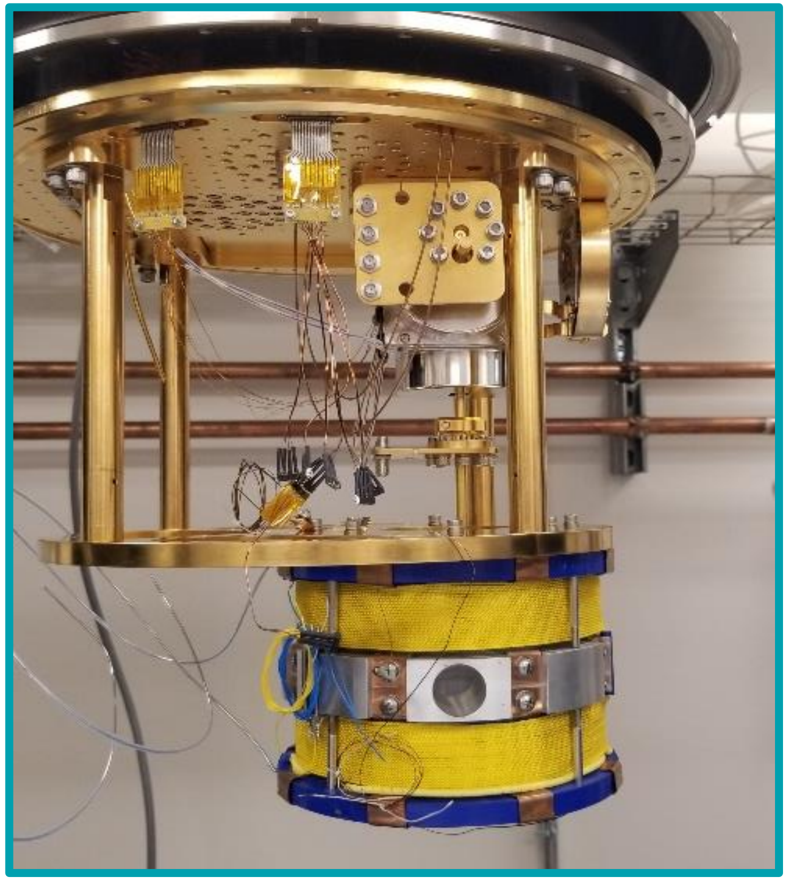
- Ensure minimal disturbance to qubit environment
- Typically require 3:1 length to diameter ratio
- Double-layer shielding
  - 100X reduction in earth's magnetic field
- Passive mumetal is common



50mK

Applied Magnetic Field Configuration
Spin Qubits

- 5T solenoid superconducting magnet
- Compatible with ADR cryostats
- Provides out-of-plane magnetic field for sample at < 50mK temperatures



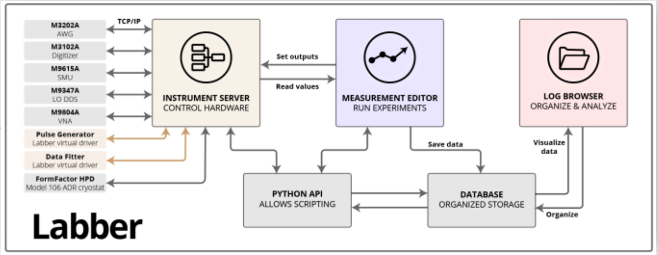
Keysight Quantum Control System

Scalable, flexible and user-friendly quantum control

Superconducting and Spin Qubit Pre-Screening

Qubit control system

Labber Control SW



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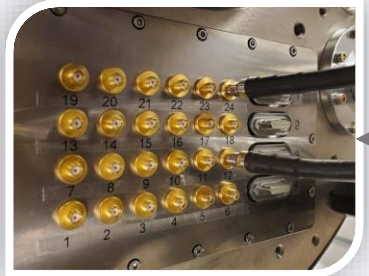
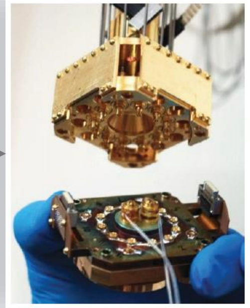


Probe socket

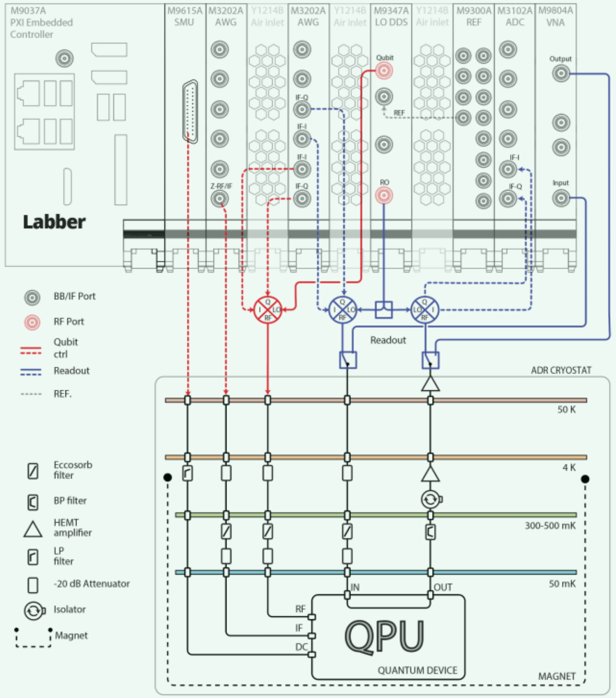


ADR Cryostat

Turn-key qubit pre-screening

Reduced Cooling time

Automated Characterization of Superconducting Qubits



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Part I: Qubit tune-up protocol

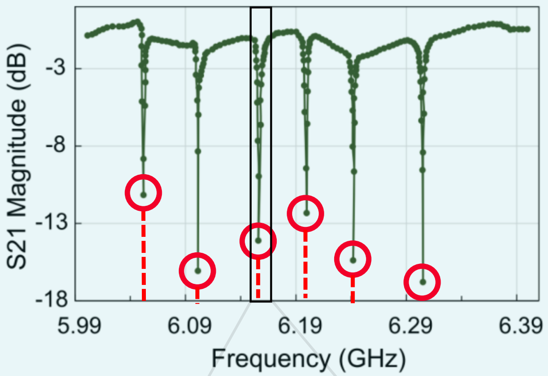
What measurements do we need to characterize a qubit?

Qubit tune-up protocol: Readout calibration using VNA

1

Readout resonator frequencies:

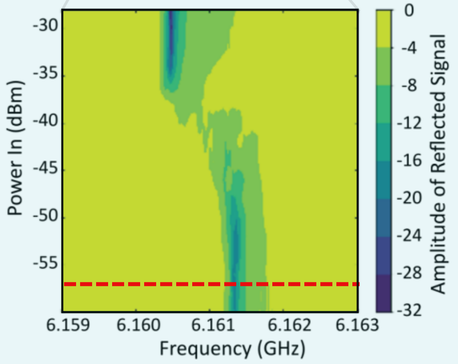
- S_{21} measurement using VNA
- Scan frequency for low power
- Extract: Readout resonator freqs.

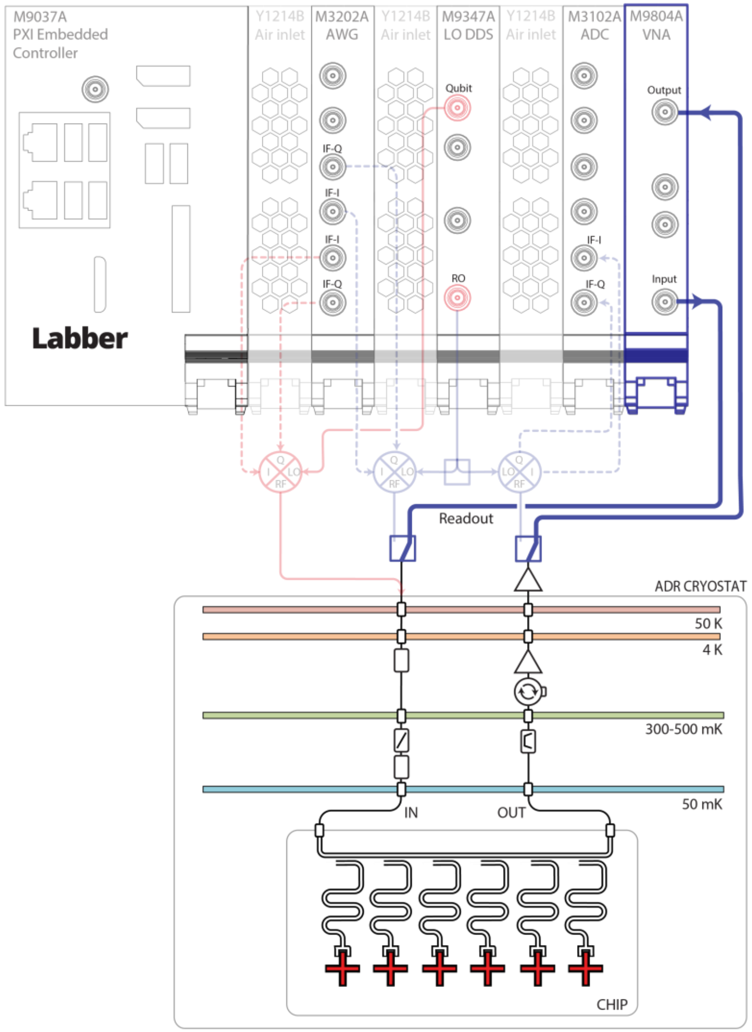


2

Resonator shift vs. power:

- S_{21} measurement using VNA
- Sweep from low to high power
- Extract: Readout frequency bias



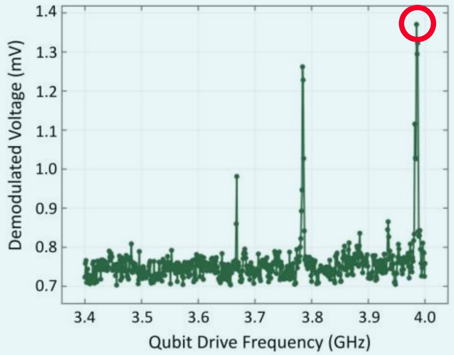


Qubit tune-up protocol: Calibrate qubit drive using AWG/Digitizer

3

Qubit spectroscopy:

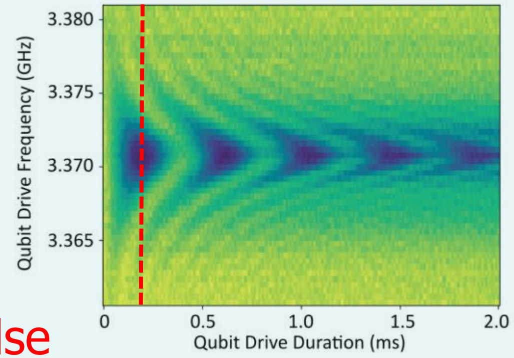
- Fix resonator drive frequency
- Sweep qubit-drive frequency
- Measure resonator using digitizer
- Extract: Qubit-drive frequency

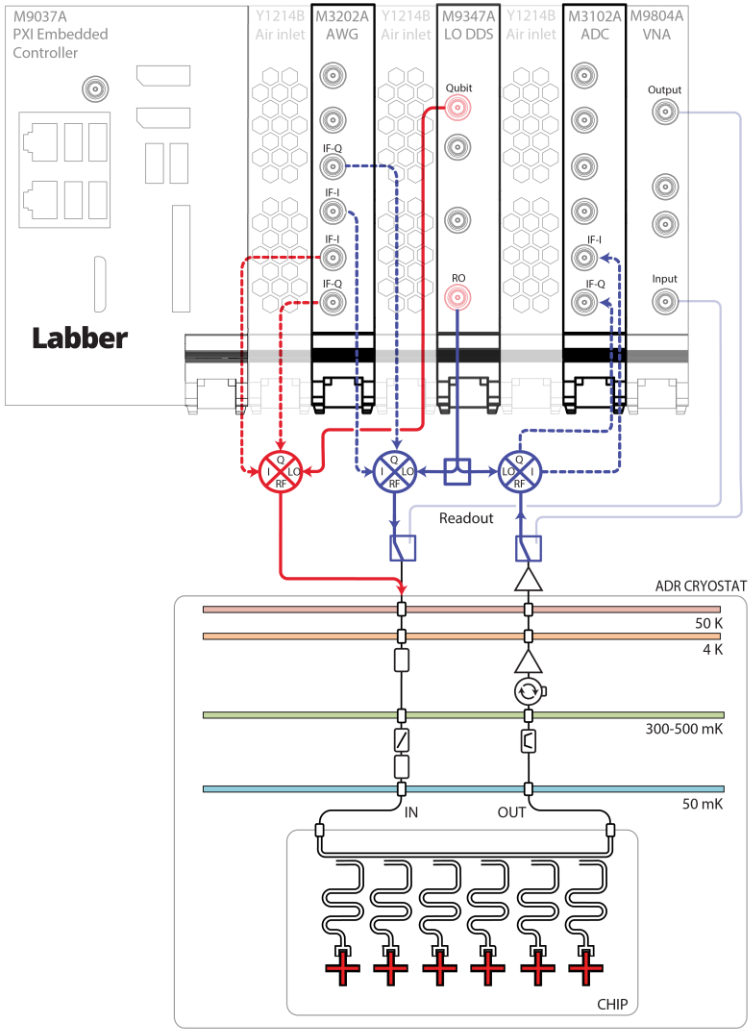


4

Calibrate pi-pulse:

- Fix qubit drive frequency
- Sweep qubit-drive pulse duration
- Measure resonator response
- Extract: Pulse duration needed for pi-pulse





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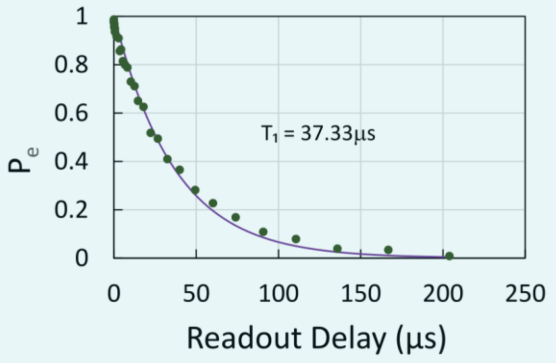
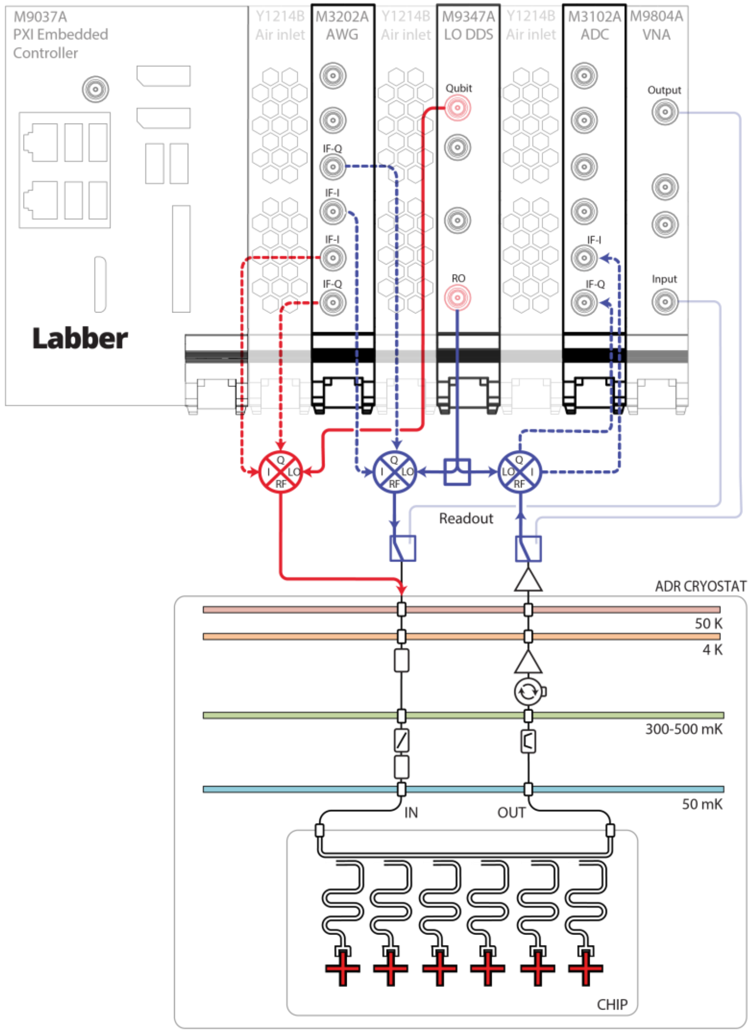
Qubit tune-up protocol: Extract Coherence Times

5

Qubit relaxation time, T_1:

- Fix qubit-pulse duration at t_pi
- Sweep readout delay
- Extract: Qubit relaxation time, T_1





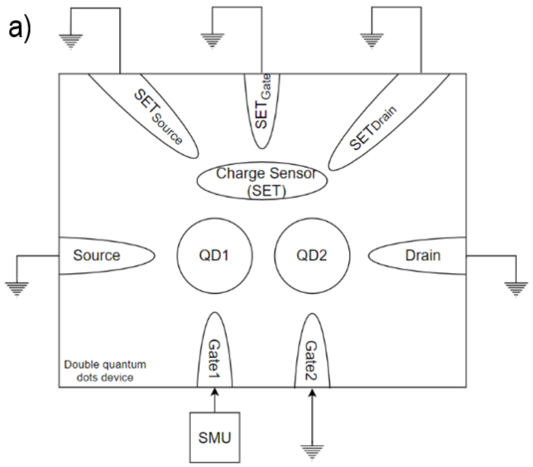
Qubit tune-up: Spin Qubit example

1

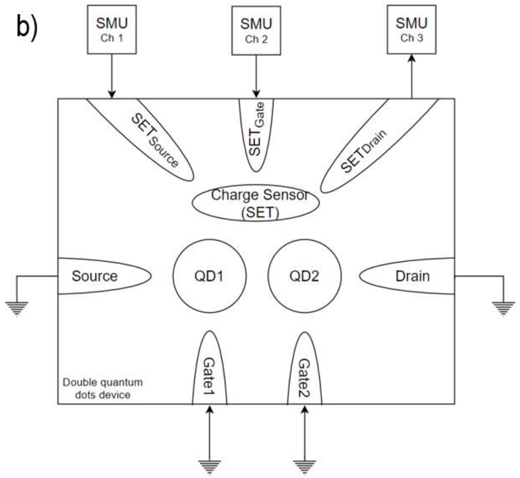
Device Viability:

- DC leakage current of all electrostatic gates and ohmic contacts
- Threshold voltage for enhancement mode devices, pinch point, depletion point and charge sensors

a)



b)

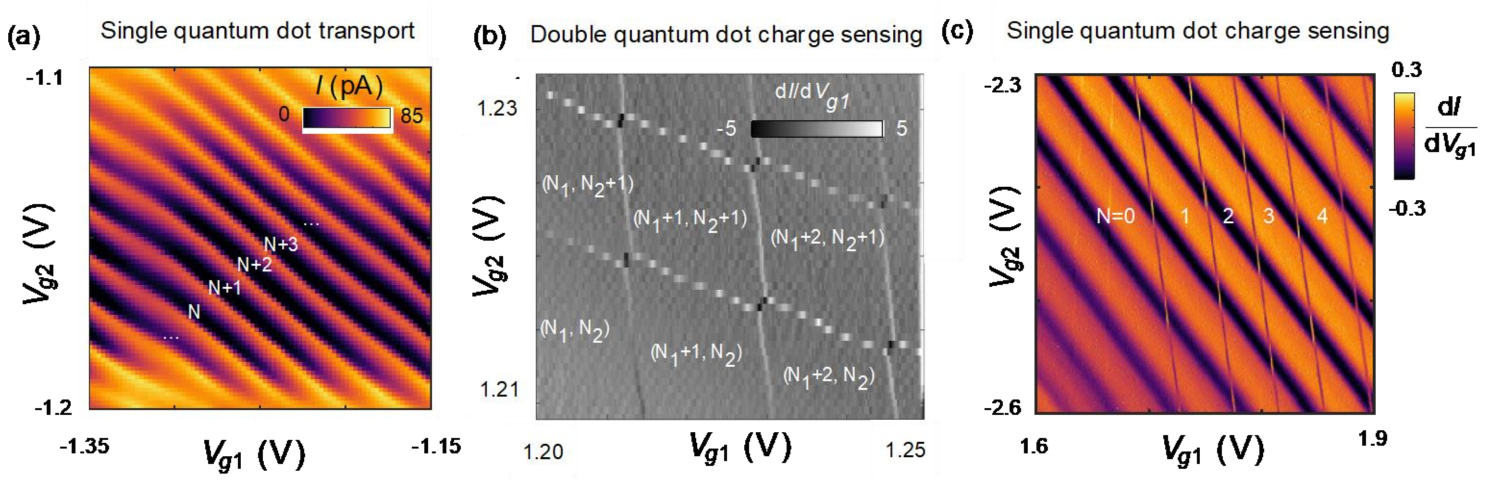


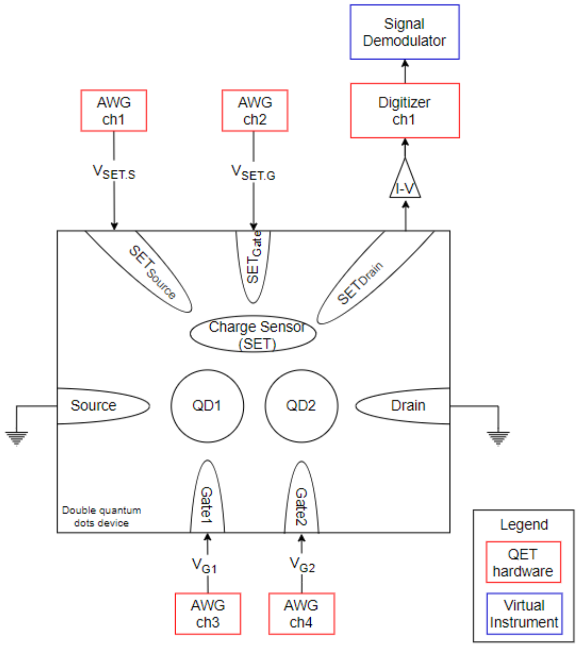
Qubit tune-up: Spin Qubit example

2

Qubit regime via charge-stability diagram:

- Sweep VG1 and VG2 voltages
- Stimulate SET source with small AC signal measure



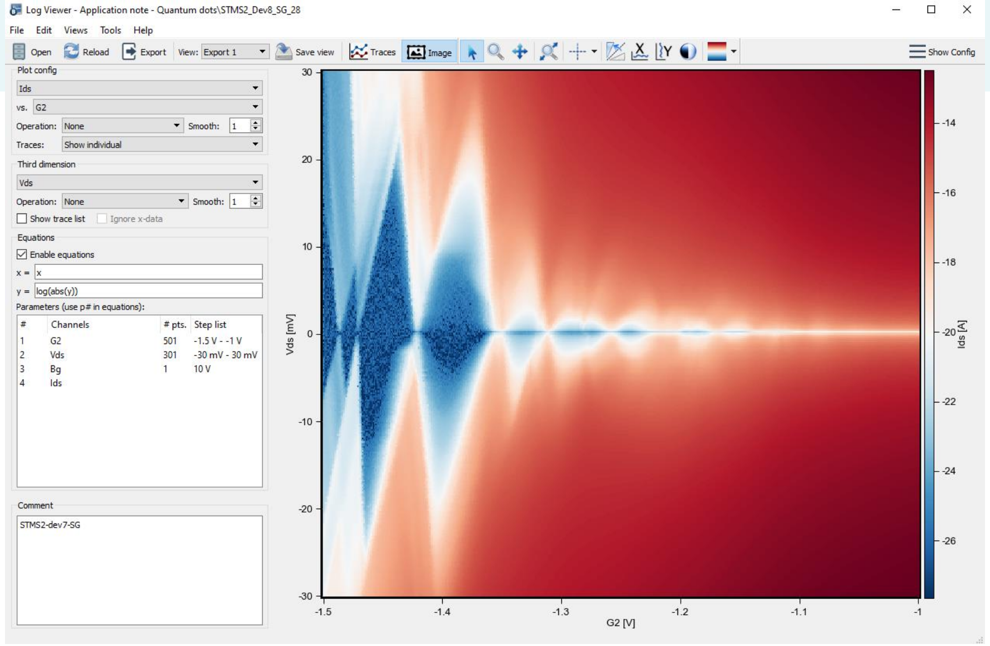


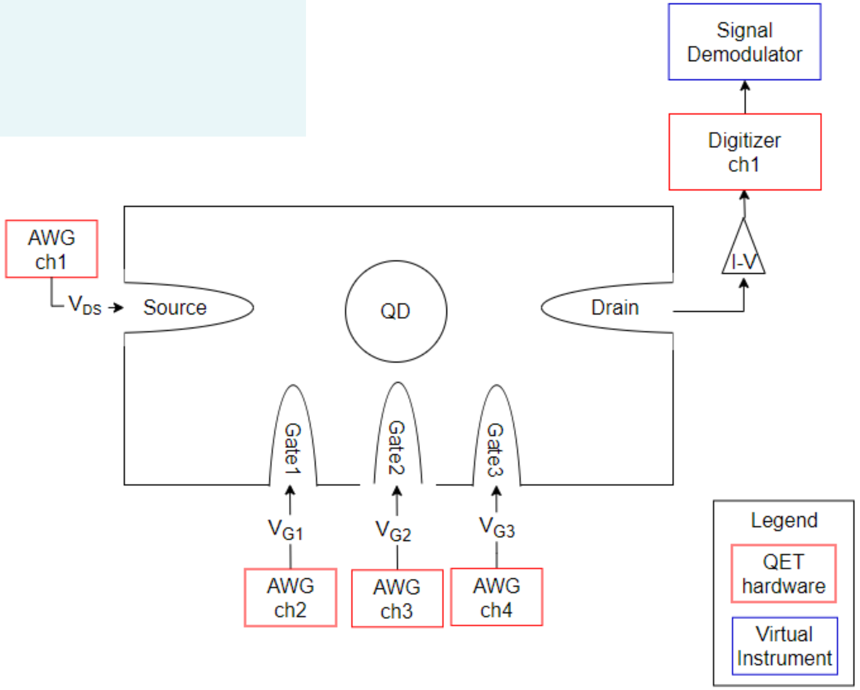
Qubit tune-up: Spin Qubit example

3

Energy Landscape via DC Spectroscopy

- Determine the relative energy separation between ground and excited states

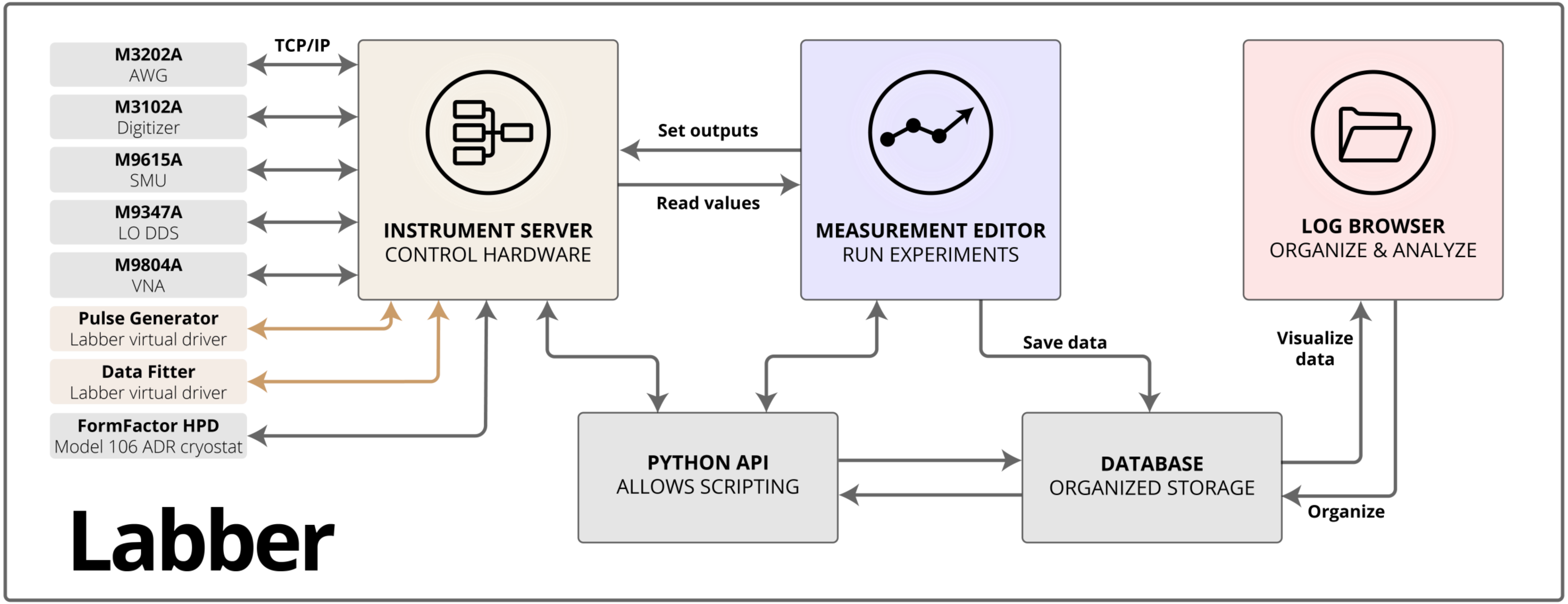




Part II: Labber Control Software

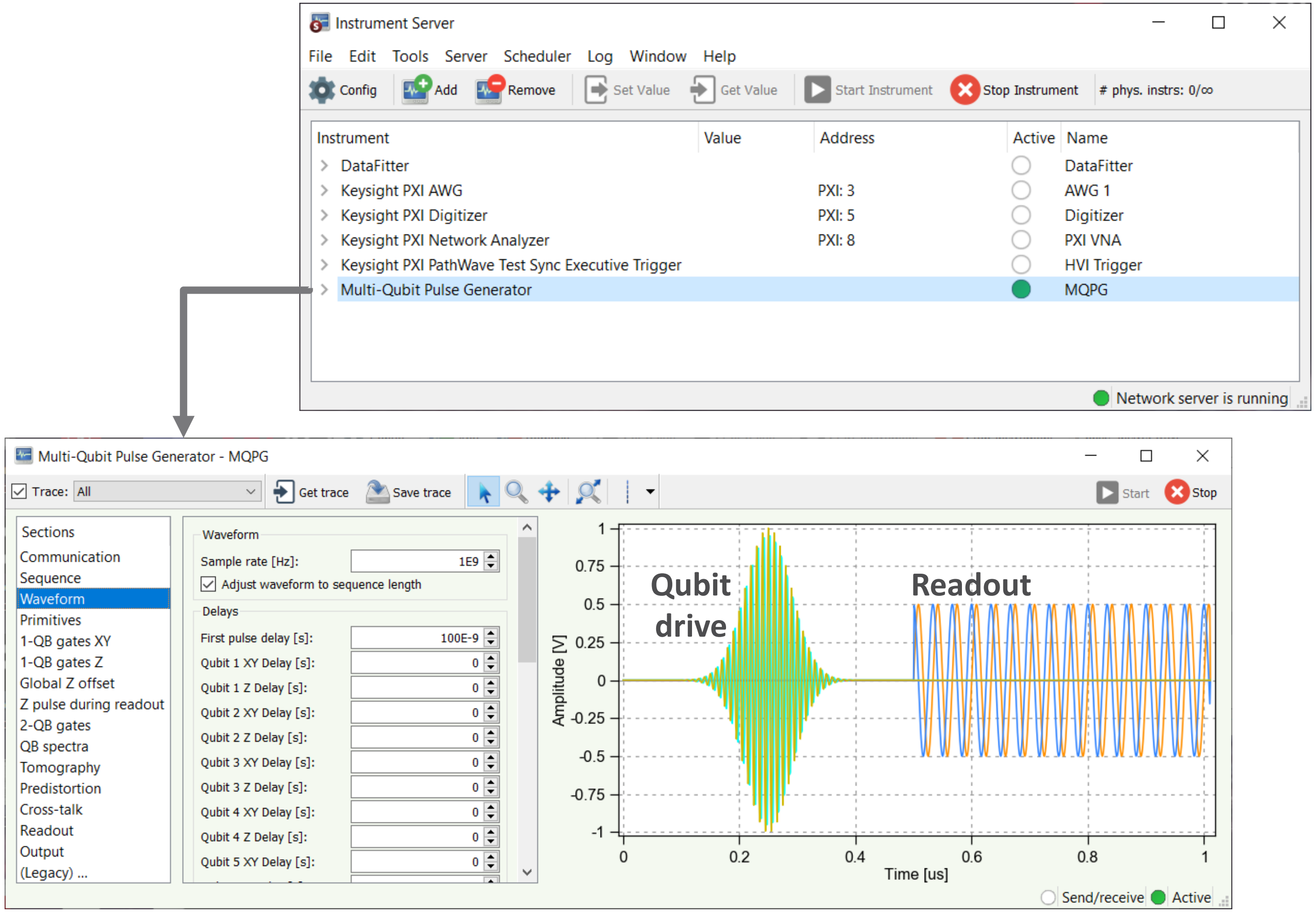
How can we automate the measurements using Labber?

Labber – Lab Control and Automation Software



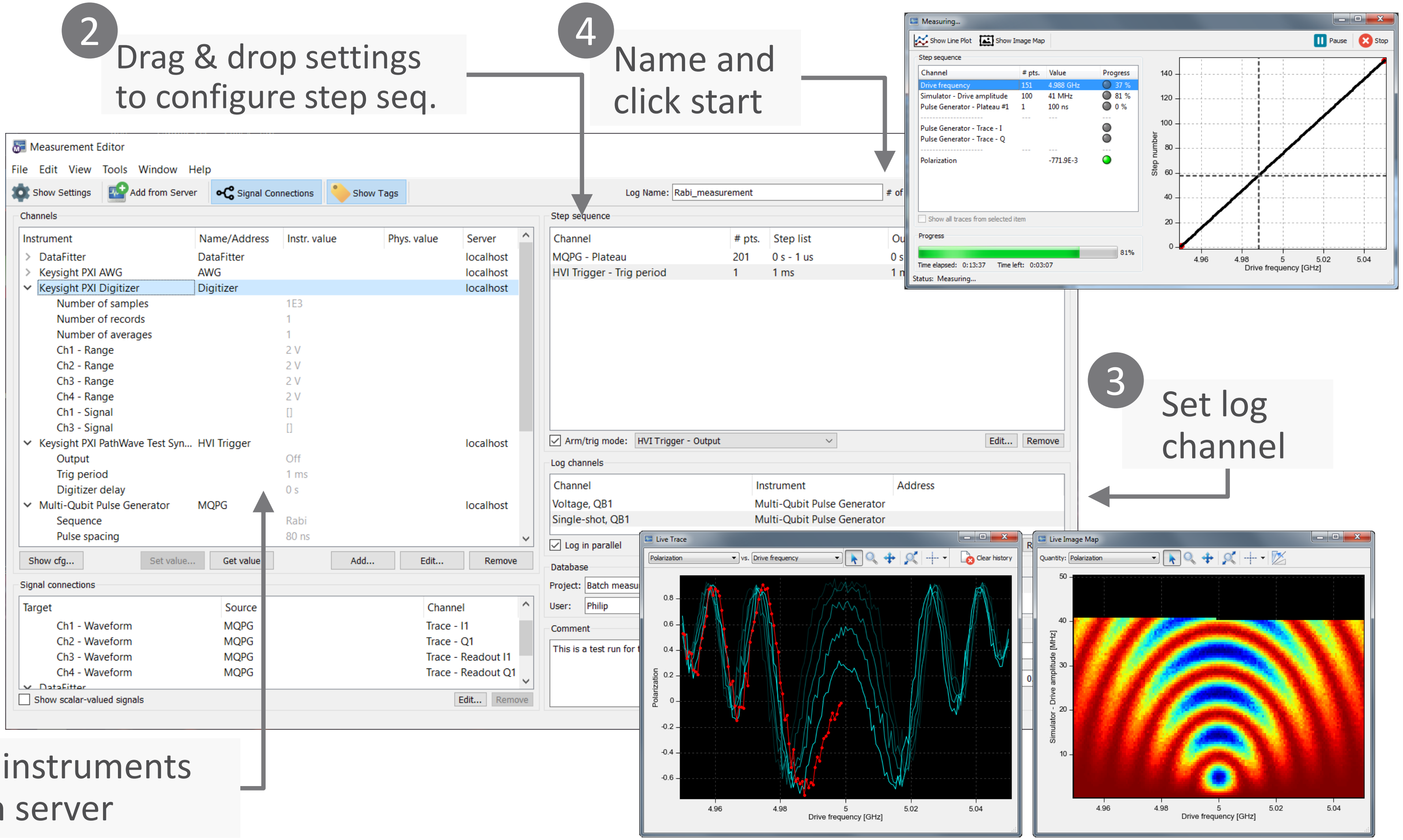
Instrument Server – Connect Instruments

- Server handles instrument **communication**
- Supports communication via **multiple interfaces:** e.g. TCP/IP, USB, serial, GPIB
- **Independent** processes allow **parallel** execution
- **Open-source instrument and virtual drivers** in our GitHub repository: www.github.com/labber-software



Measurement Editor – Run Experiments

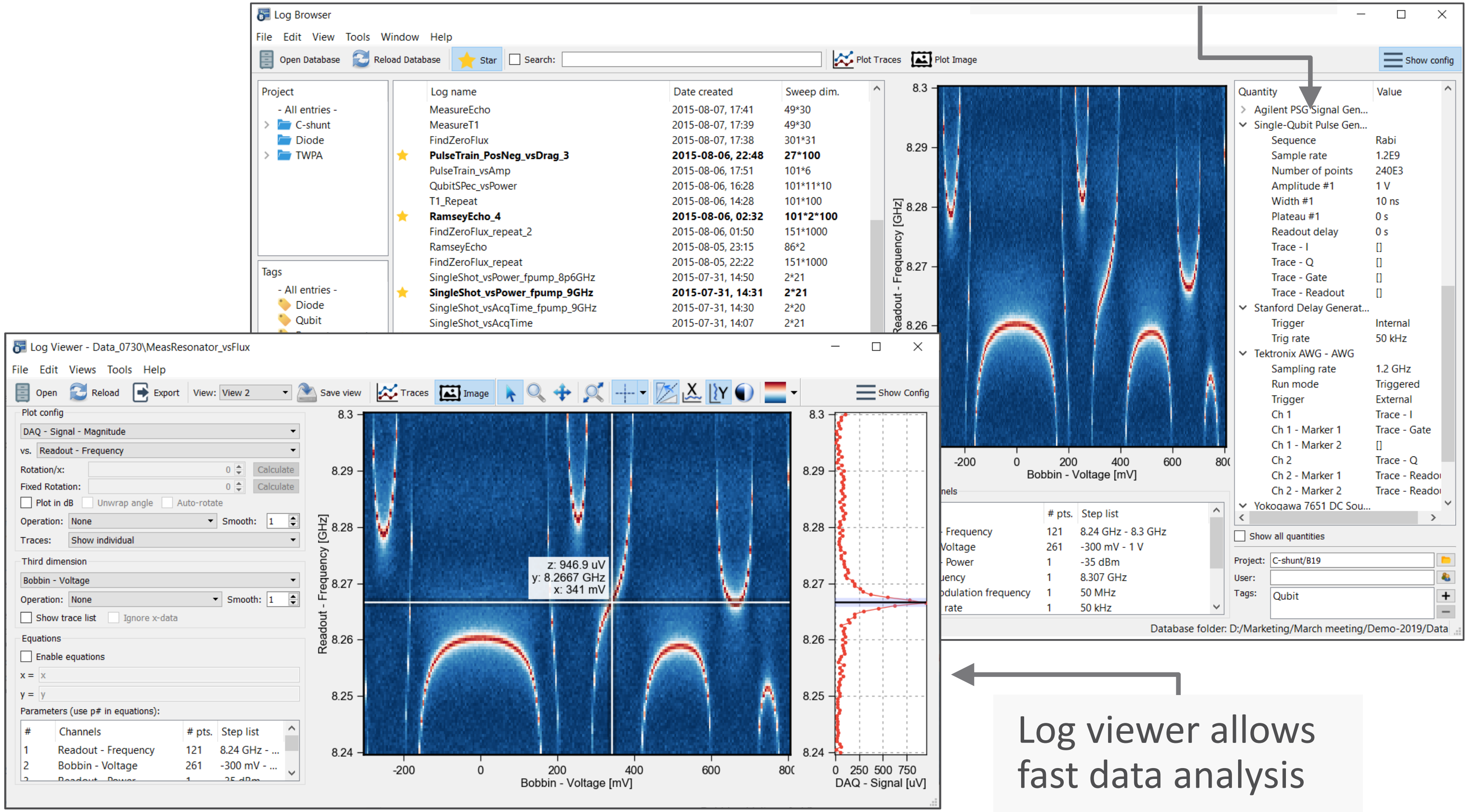
- Measurement **scenarios** configured via **drag-and-drop** interface
- Provides **synchronization**
- Accommodates **multiple servers** and **virtual instruments**
- Fully **programmable** using Python API
- Real-time visualization of **progress** and **acquired data**



Log Browser – Organize & Analyze data

- Sort measurements using **projects**, **tags**, **users**, and **date**
- **Preview** of data
- **Configurations stored** for recalling scenarios
- **Export plots and data**

Stores both data and configuration



Log viewer allows fast data analysis

Labber Python API – For Measurement Automation

- Import the **Labber** API toolkit
- Define a **scenario file**
- **Configure** measurement steps and relations
- **Save** the measurement template and **run the experiment**
- Easy access to the hdf5 **log file** for e.g. plotting or data analysis

```python
import numpy as np
import matplotlib.pyplot as plt
import Labber

#Open the measurement template
scenario_file = r'C:\Users\Demo\Labber\Scenario\DC_Spectroscopy_0.json'
s = Labber.Scenario(scenario_file)

# Retreive the instruments
AWG = s.get_instruments('AWG')

# Edit the values of the Channels section
AWG.values['AWG - Vds AC'] = 0.5e-3

# Remove step from the Step Sequence section and re-add the updated ones
s.remove_step('AWG - Vg1')
s.add_step('AWG - Vg1', index=1, start=0, stop=0.5, n_pts=26)

s.remove_step('AWG - Vg2')
step = s.add_step('AWG - Vg2', index=2)
step.set_config_from_dict({
    'use_relations': True,
    'equation': 'Vg1 * 2'
    })

# Add Vg1 as a variable to create relations between the step sequences
relation = step.relation_parameters[0]
relation.set_config_from_dict({
    'variable': 'Vg1',
    'channel_name': 'AWG - Vg1'
    })
```

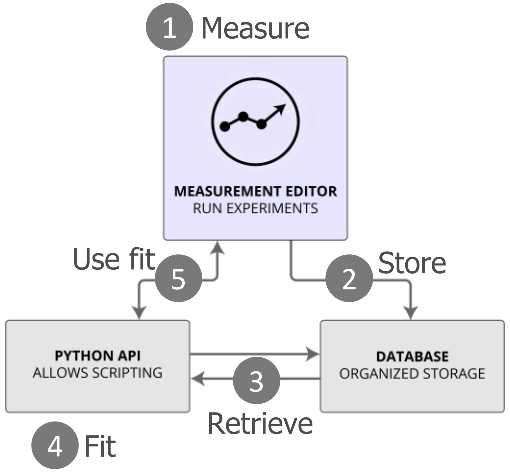
```python
# Save the measurement template
s.save(scenario_file)

# Run the experiment
st = Labber.ScriptTools.MeasurementObject(scenario_file, scenario_file)
st.performMeasurement()
```

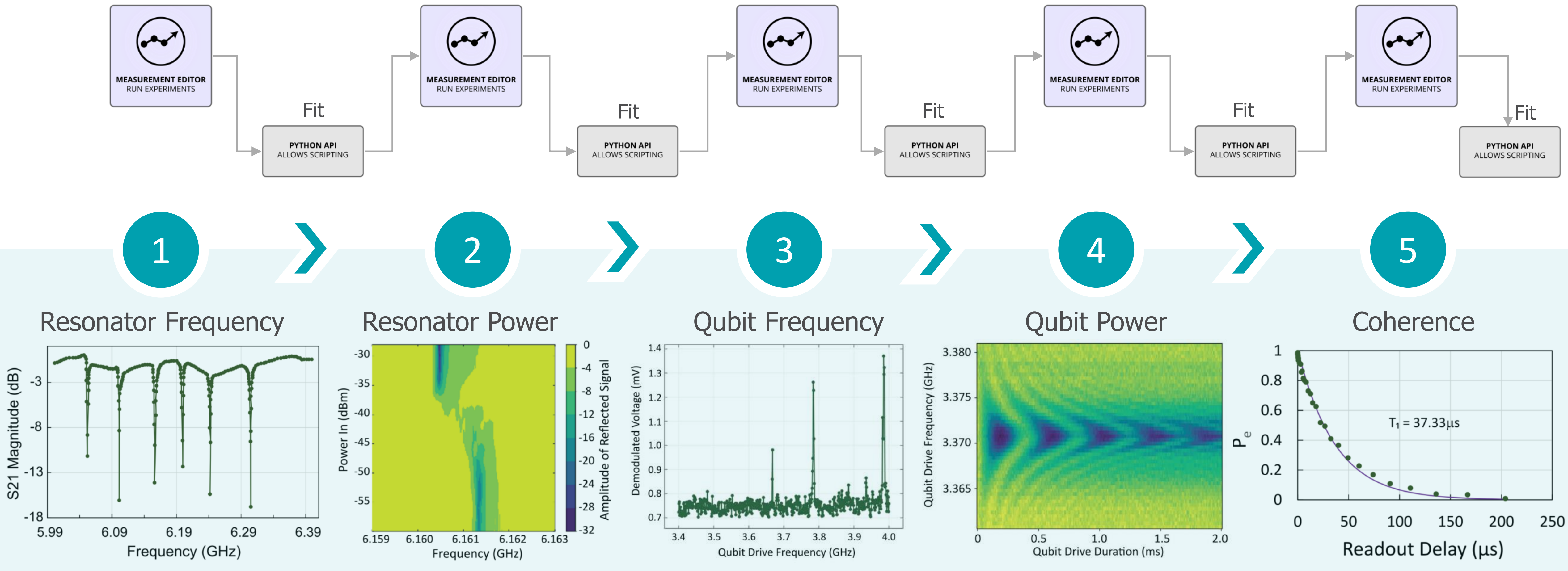
```python
# Open the log file
filename = r'C:\Users\Demo\Labber\Scenario\DC_Spectroscopy_0.hdf5'

# Retreive Vg1, Vg2 and lock-in data
Vds = f.getData('AWG - Vds DC')[0]
Vg1 = f.getData('AWG - Vg1')[:,0]
lock_in = np.abs(f.getData())

# Plot the data
fig, ax = plt.subplots()
ax.pcolormesh(Vds, Vg1, lock_in)
plt.show()
```



Qubit tune-up protocol: Summary



What We Hope That You Have Learned Today…

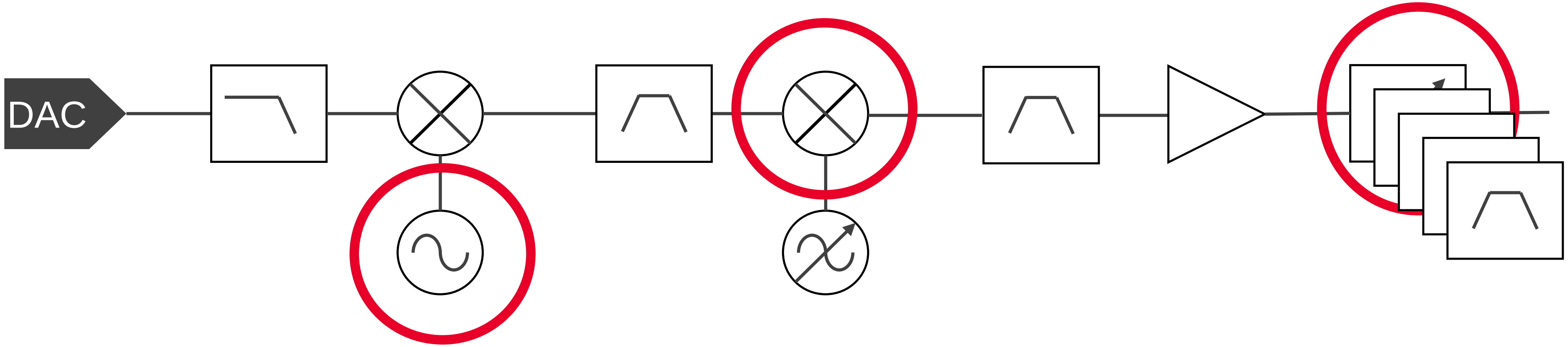
- Reduce development cycle times with qubit pre-screening system
    - Eliminate wasted cooldowns on the dilution refrigerator
- DUT interface for high density RF and DC testing
    - Test qubits without packaging, wire bonding
- Configure a rapid cooldown ADR cryostat for your program

- PXI Based Quantum Control + Labber to streamline qubit characterization
    - Qubit tune-up protocol
    - Labber control and automation software

Part III: Quantum Control System

How can we improve our quality of measurement?

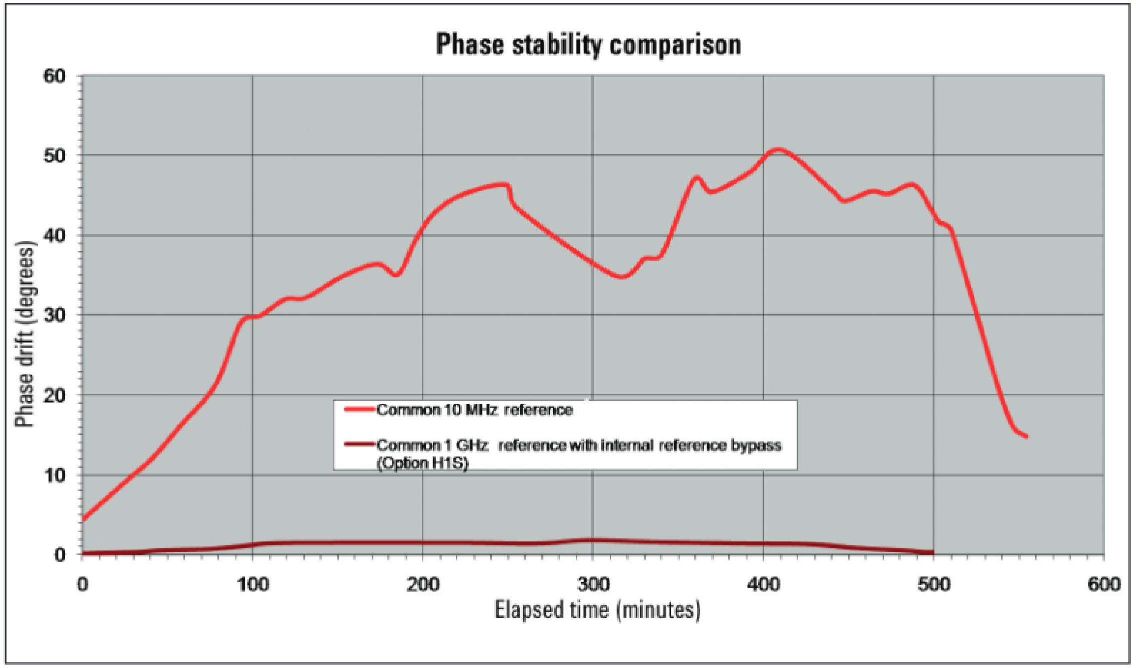
Superheterodyne Control Architecture



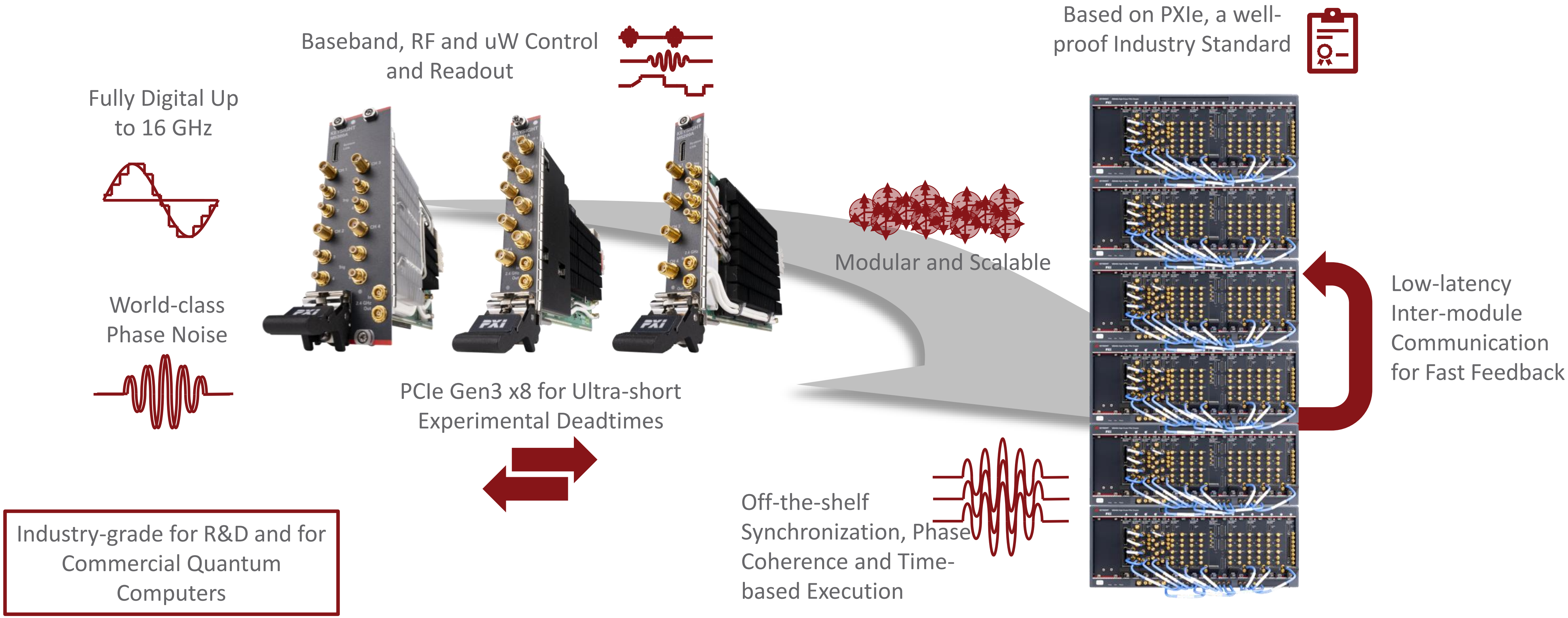
+ Easier to remove image and no LO feedthrough
- Requires many filter banks
- Multi-channel phase coordination is complex
- Mixer loss can lead to elevated generator temperature

Achieving System Phase Coherence

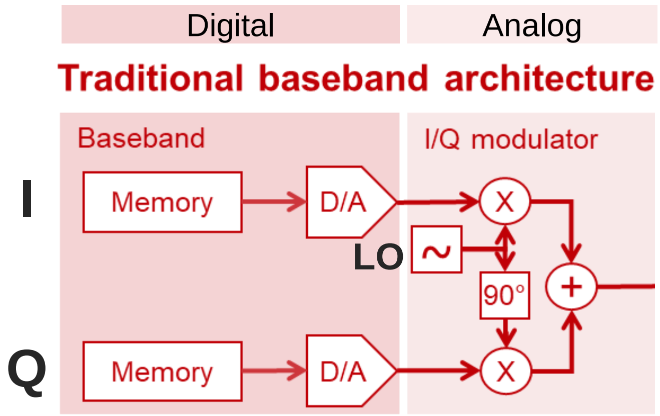
- Achieving phase coherence for analog architectures is complex
- Full digital architecture eliminates issues caused by PLL and synthesizer drift
- Coordinated phase updates across an entire system can be easily achieved

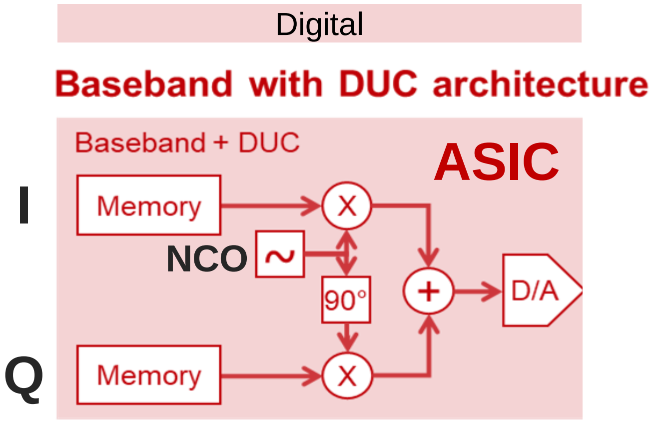


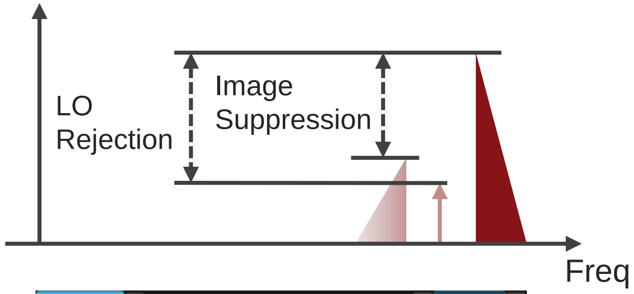
Unveiling Keysight's new control system - Hardware



Direct digital signal generation provides cleaner signals



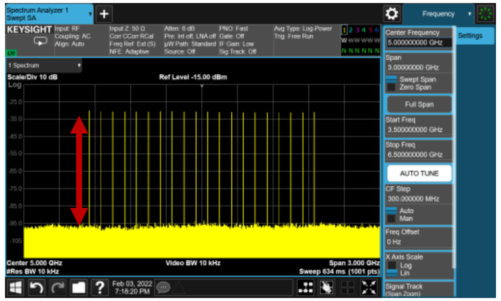




LO rejection and image suppression require IQ imbalance calibration which drifts over time

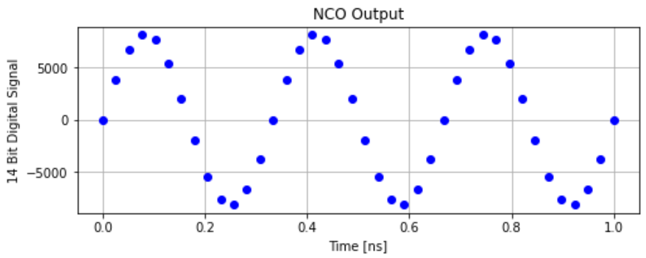
Fully digital generation does not have LO or image, and it does not require any calibration

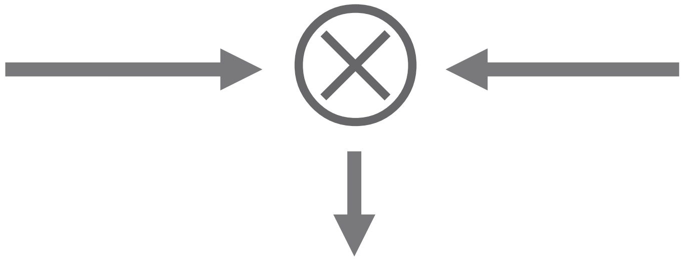
Improved SFDR
(Spurious-Free Dynamic Range)

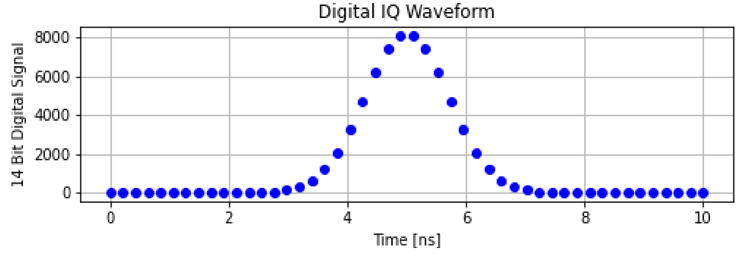


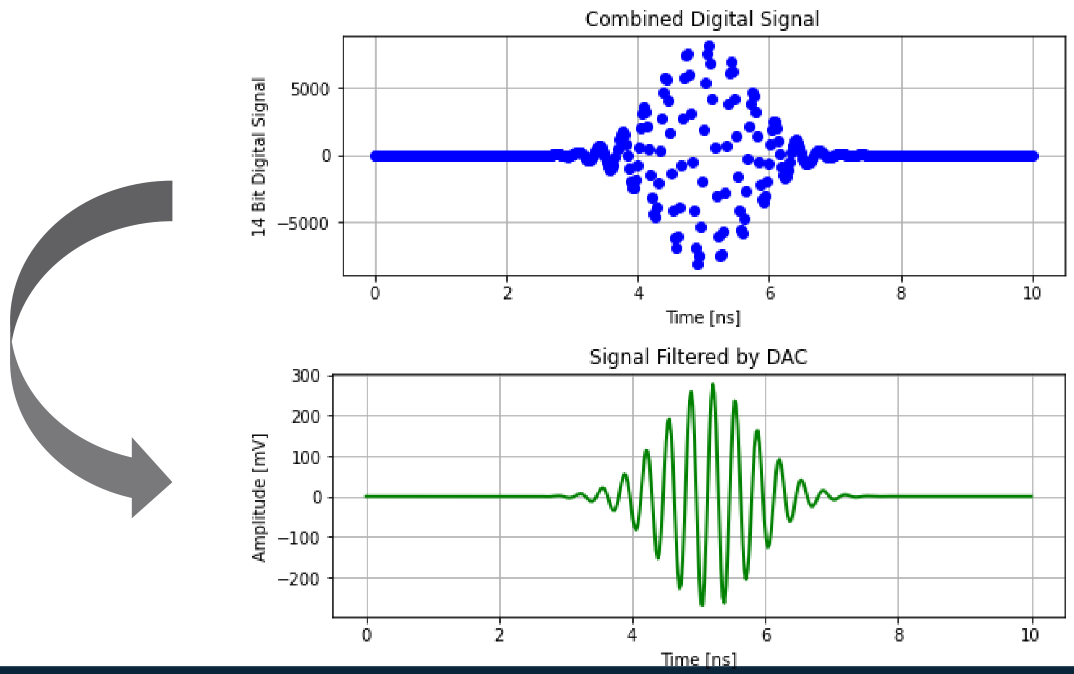
Digital Up-Conversion Example

3 GHz Gaussian Pulse









Low pass filtering and interpolating by highspeed DAC

Questions?