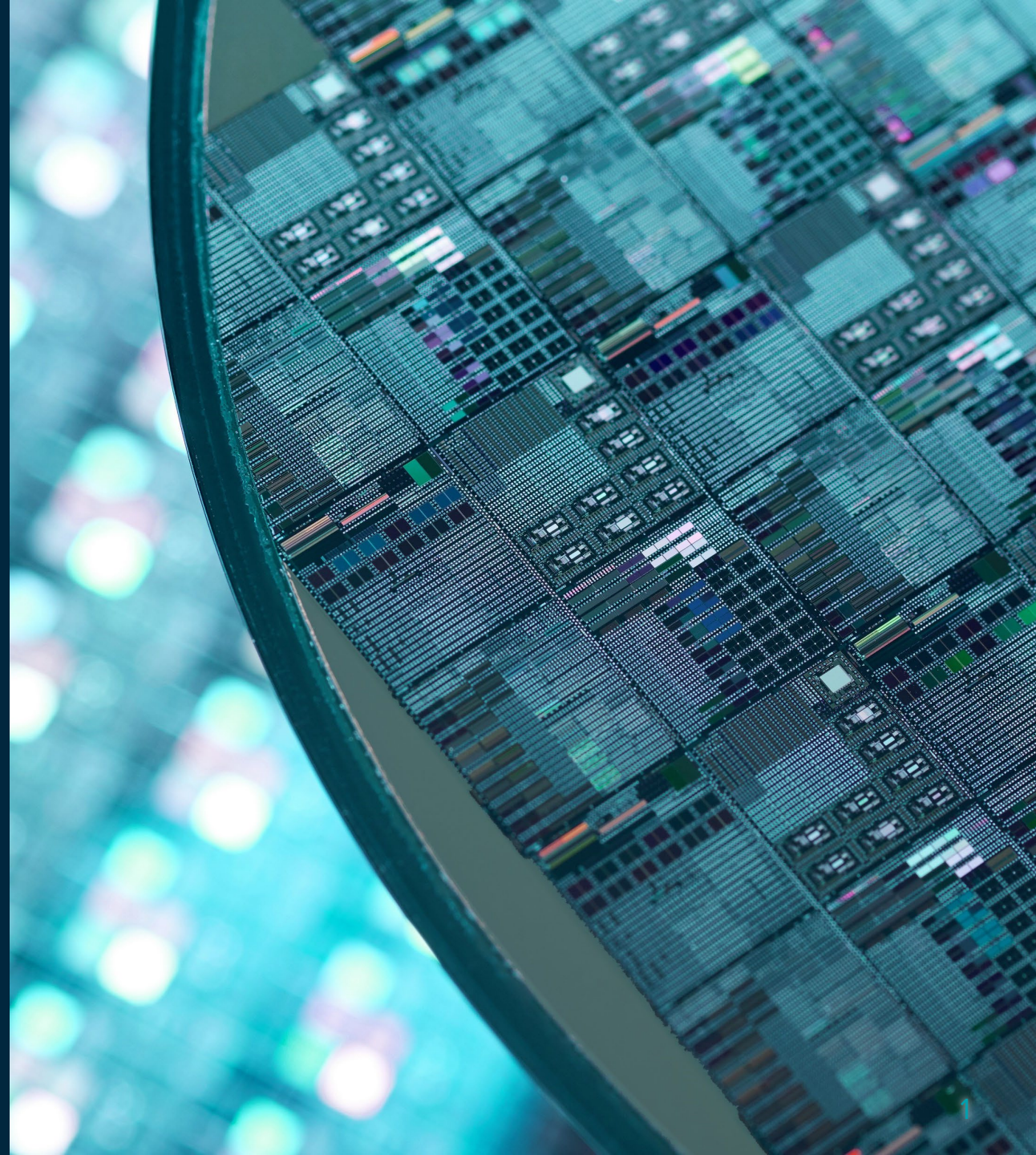




# Quantum and CryoCMOS : Enabling the Future of Computing with Advanced Test & Measurement Tools

Jack DeGrave, FormFactor  
Brandon Boiko, FormFactor

Presented at TestVision | Wednesday, July 12, 2023



# Outline

## IQ3000 Cryogenic Wafer Prober

- Random Telegraph Noise on Cryo-CMOS
- Parametric Measurements of Superconducting Circuits (SFQ)

## IQ2000 Rapid Chip-Scale Probing

- Photonic Integrated Circuit Probing
- Fiber Alignment Optimization at Cryo

## Model 106 ADR Cryostat with PQ500 for QPU Screening

- S-Parameter Measurements
- Dispersive Readout of Quantum Processor



# Cryogenic Wafer-Scale Probing HPD IQ3000

# HPD IQ3000

## 4K Cryogenic Wafer Prober (Wet)

Fully automated cryogenic wafer probing at 4K

### Cryogen Control (Wet Only)

- Warm Water Bath
- Vacuum pump with flow controller and pressure regulator
- Recirculation with Binary Gas Analyzer and a 3-way directional valve

### Vision System

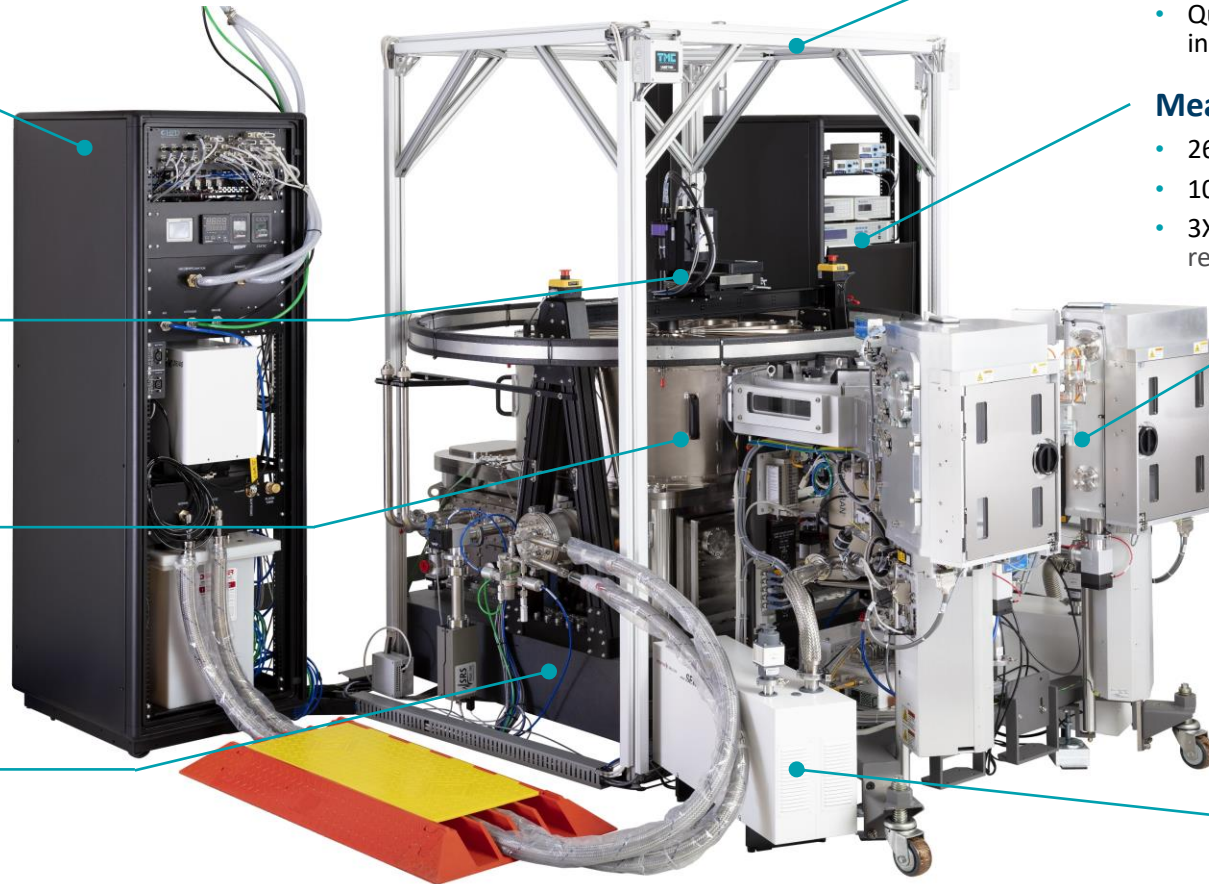
- 50 mm XYZ Travel
- <3 um resolving power
- Pneumatic lift and rotatable beam for easy servicing

### Probe Station

- Gas spring assisted vacuum lid and latchable shield lids
- <4.5 K with 44 RF probes in contact
- +/- 112 mm XY, 0 – 13 mm Z, +/- 10° Theta motion

### Rigid Construction

- A solid granite base with a rigid motion structure
- Allows for rapid die to die movement and fast settling times
- Up to 25 mm/s travel speed



### Magnetic Cancellation

- Active cancellation with passive cryogenic shielding
- Quiescent magnetic field environment of <200 nT in the 4 K wafer space

### Measurement and Control Electronics

- 26X system thermometers
- 10X 50 W heaters for rapid warmup in <8 hrs
- 3X magnetic probes with 0-200 uT range and 1 nT resolution

### Wafer Cassette Loader

- Automated loading for 200 mm and 150 mm wafers
- Up to 25 wafer capacity
- <15 minute exchange time between wafers

### Vacuum Feedthroughs (Not Shown)

- Two large configurable vacuum flanges with additional smaller ports
- Large ports are 12 in x 18 in and 12 in x 26 in
- Base 56 RF (18 GHz) and 520 DC

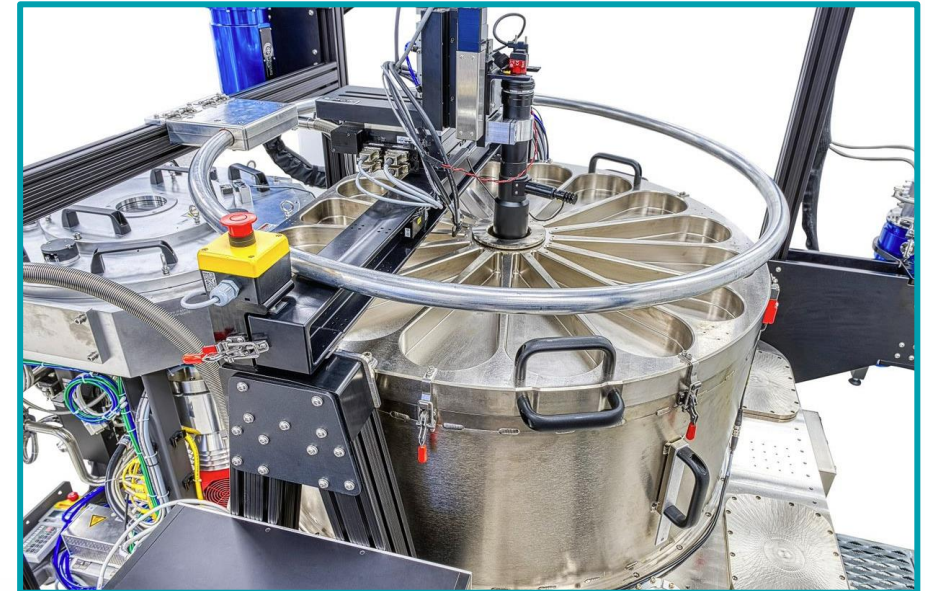
### Automated Pumping System

- Load lock isolated pumping systems for wafer loading while system is at base
- Full system pump down in <40 minutes

# HPD IQ3000 | 4K Cryogenic Wafer Prober (Dry)

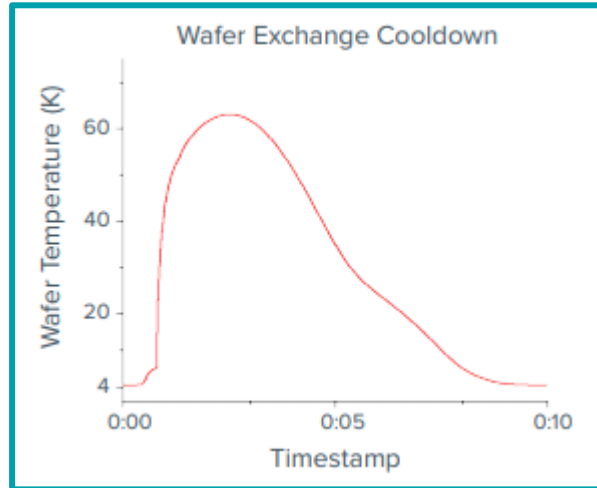
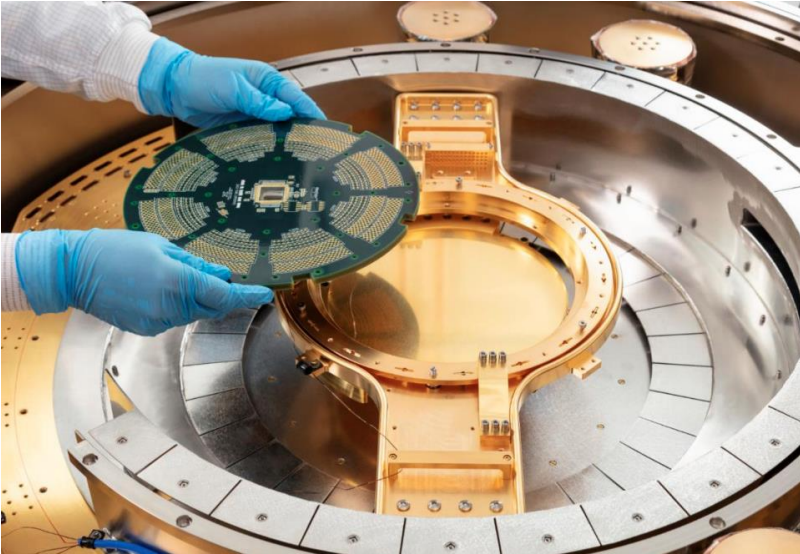
Fully automated cryogenic wafer probing at 4K

- Up to 300mm wafers
- Dry system operation (no liquid cryogen)
- Probe card compatible
- < 15-minute wafer cooldown to 4K



# IQ3000 – Cryogenic Wafer Prober Details

Probe card installation



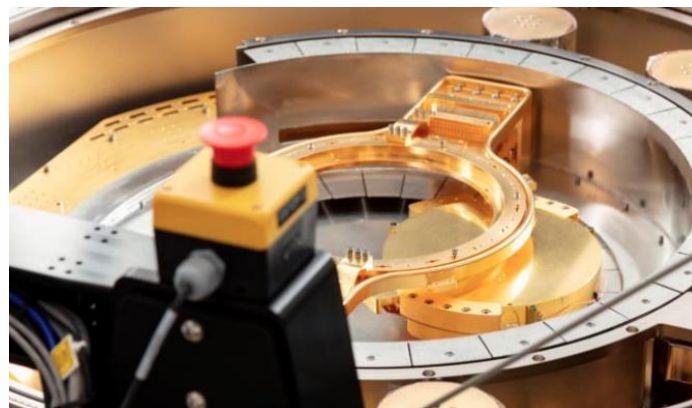
RF Feedthroughs



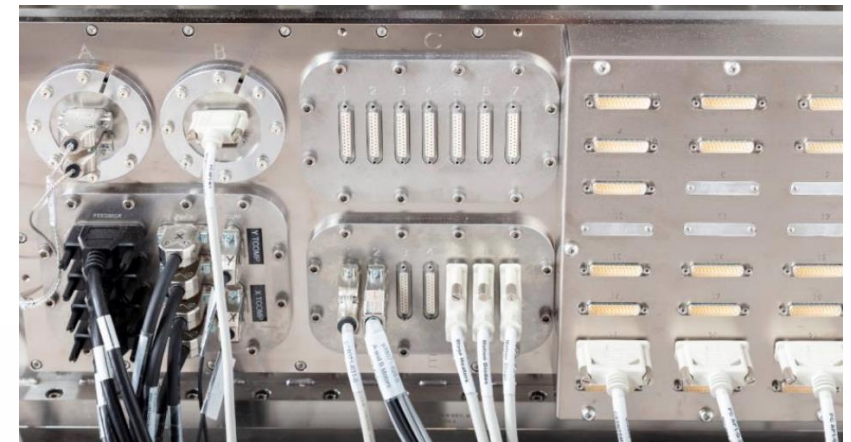
Wafer under probe card fixture



Chuck without wafer



Operational and DC feedthroughs



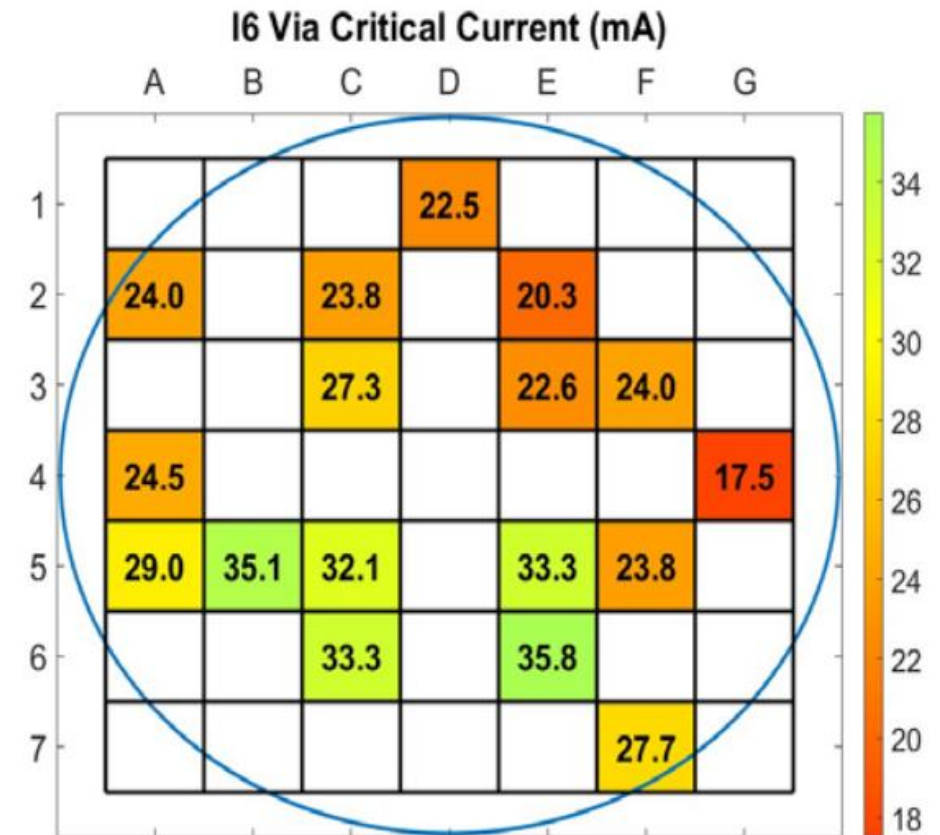
# IQ3000 | SFQ Device Characterization at 4K

# of Devices = 24 SQUID-based Test Circuits

Test Method	Time to Measure at 4K
Conventional singulated die testing (dicing, wire bonding)	> 1 week
IQ3000 4K Cryogenic Wafer Prober with 200mm wafer	5 hours

## Characterization Measurements

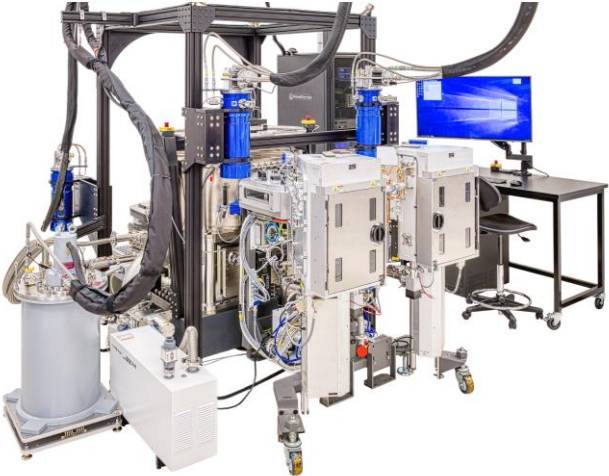
1. SQUIF B field
2. Inductance/unit length
3. JJ critical current
4. Normal resistance
5. Gap current ( $V_g$ )



IEEE Trans. Appl. Supercond., vol. 32, no. 5, pp. 1-12, Aug. 2022, Art no. 9500712  
<https://doi.org/10.1109/TASC.2022.3172660>

# IMS-K-Cryo-LFN Integrated Measurement Solution

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**HPD IQ3000**



**Keysight A-LFNA**

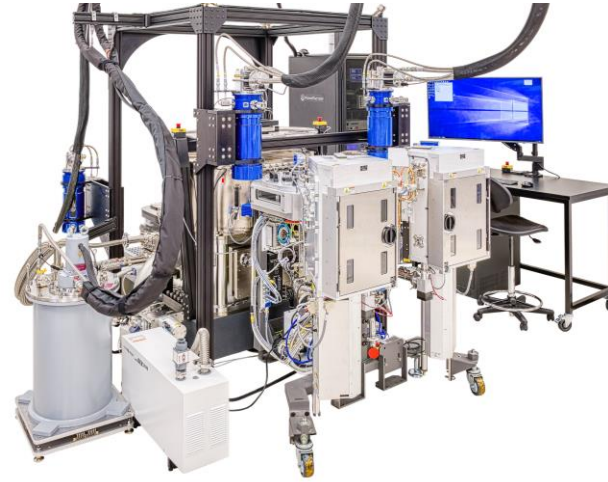


**Premium Solutions  
Partner**

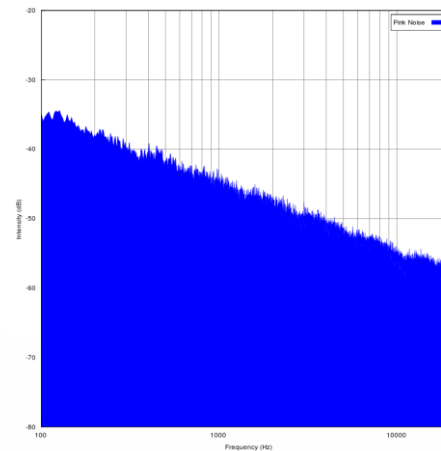


# Wafer Service SkyWater Technology ULN Measurement

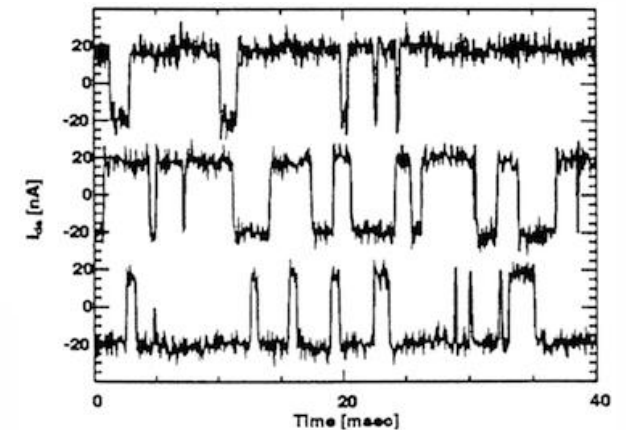
- Measured at 5 temperature points between 4K and 120K
- ULN measurements of  $1/f$ , I/V, and RTS
- Used for testing ROIC in imaging and sensing applications
- IR Sensors, Night Vision, Military Surveillance, Industrial/Automotive imaging



**HPD IQ3000**



**Keysight A-LFNA**

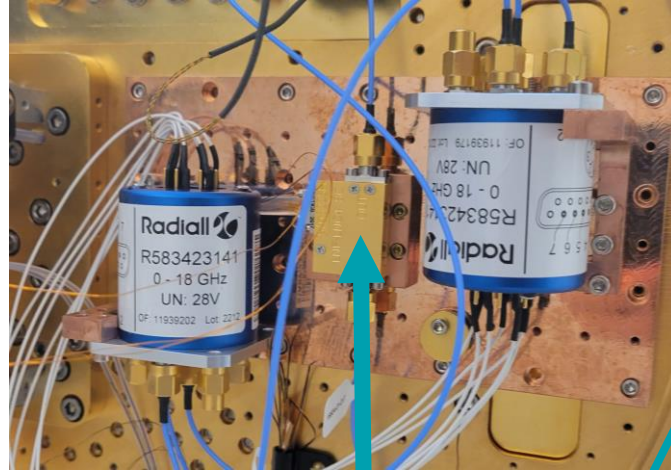
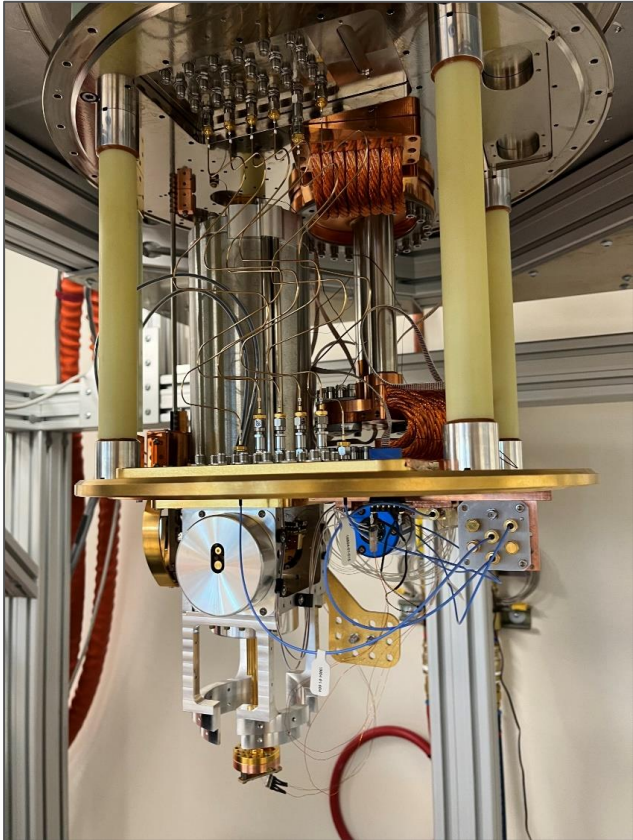


# Component Test Service | LNA Characterization

- Establish a standard service
- Cryogenic LNAs used for Quantum Computing
- 4K measurement for noise temperature as low as 1 K (NF 0.01 dB)
- Calibrated S-Parameters
- Cheaper and more reliable components to scale quantum



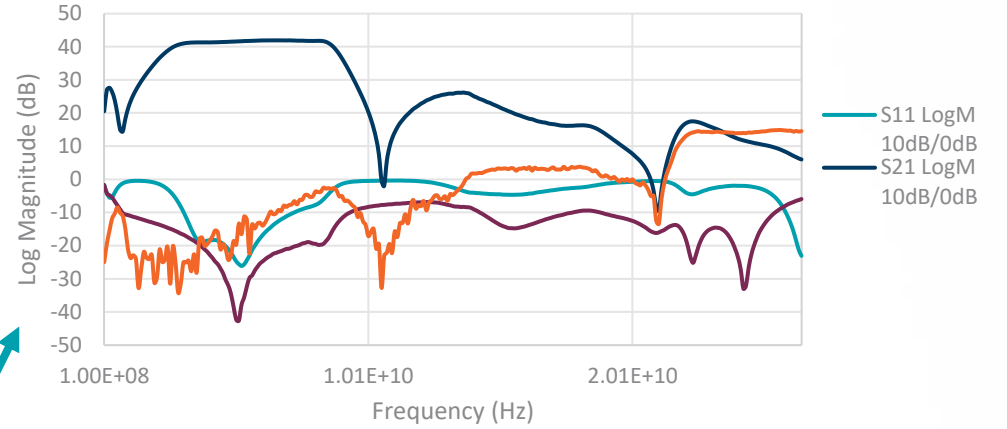
# Measurement Setup Model 106 Cryostat



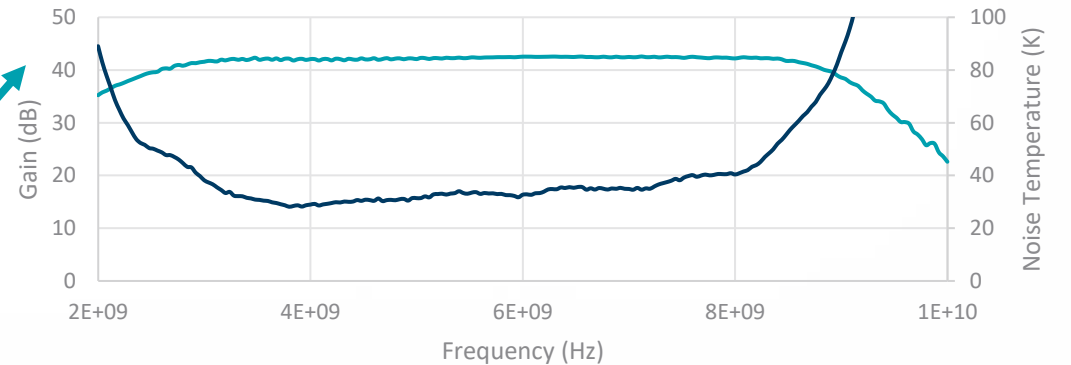
One Device

Two Cooledowns

LNF RT SP  
 $T = 295\text{K}$ ,  $V_d = 1.351\text{ V}$ ,  $I_d = 45.15\text{ mA}$ ,  $V_g = -1.527\text{ V}$



LNF RT NF  
 $T = 295\text{K}$ ,  $V_d = 1.351\text{ V}$ ,  $I_d = 45.13\text{ mA}$ ,  $V_g = -1.494\text{ V}$



**New Product Introduction**  
**Rapid Chip-Scale Probing**  
**HPD Model IQ2000**

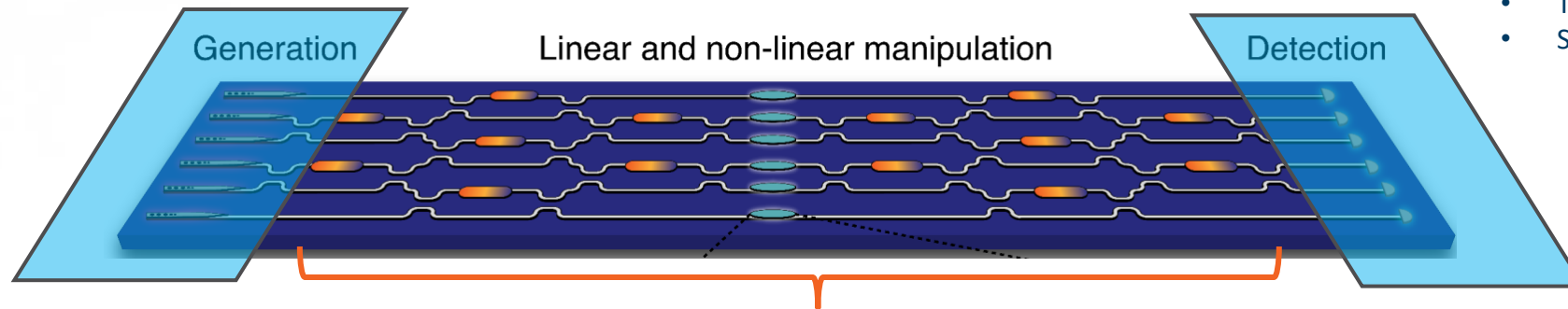
# Photonics Applications in Quantum Computing

## Components of a Photonic Quantum Computer

- Single photon source (ex. quantum dots, color centers, **squeezed light**)
- Single photon detector (ex. SNSPD, TES)
- **Photonic circuit elements (waveguides, couplers, phase shifters)**

## Detector Types

- TES (< 100mK)
- SNSPD (< 4K or < 2K)



## Cryogenic conditions for light source

- Coupled to photonic chip with fiber array
- Edge (low loss) or vertical/surface coupling (higher loss)

## Photonic Circuit may be at room or cryogenic temperature

- RF/DC lines to control/program the circuit

## Cryogenic conditions for single photon detector

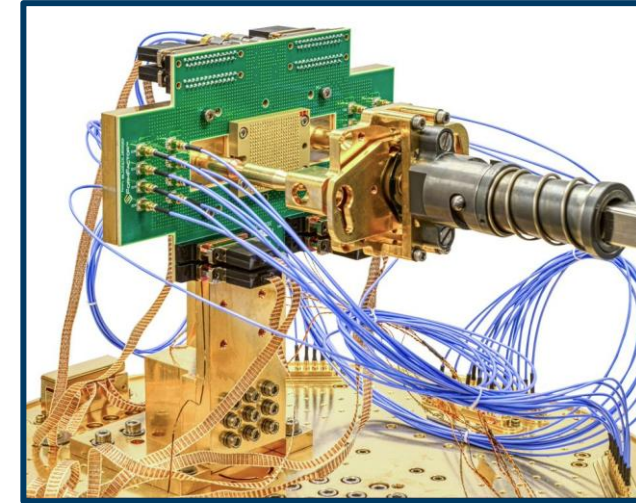
- Coupled to photonic chip with fiber array
- Edge (low loss) or vertical/surface coupling (higher loss)
- Need RF wiring to readout detectors

Test and measurement strategies needed for each of the cryogenic elements

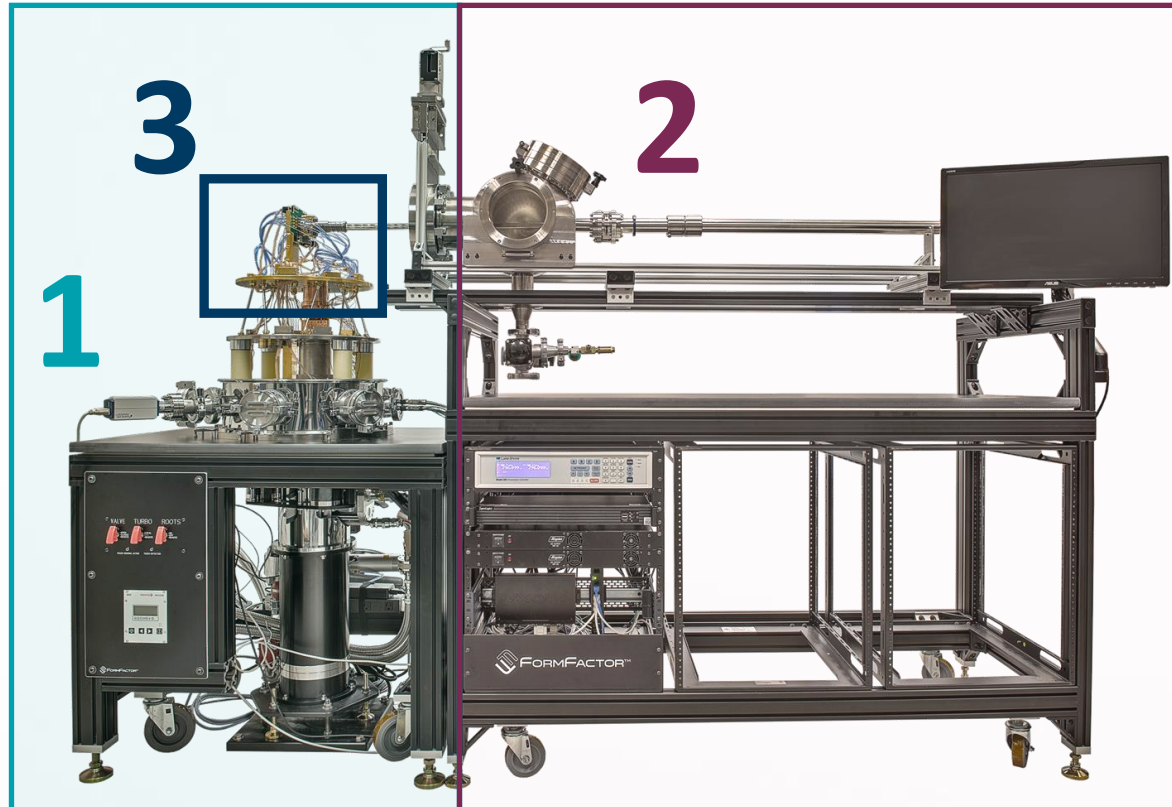
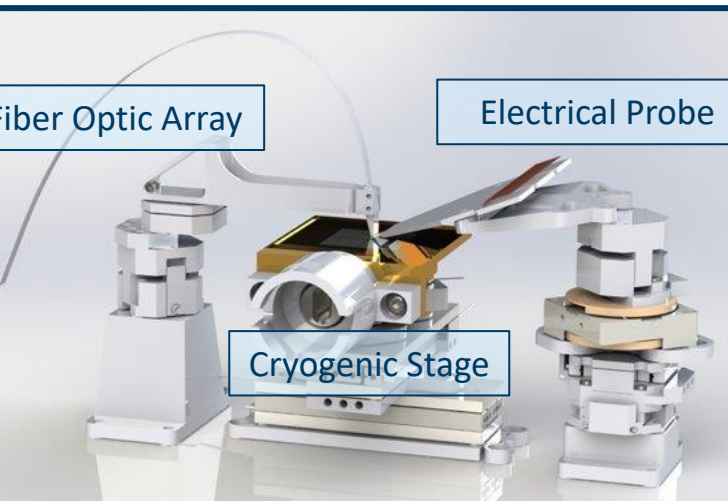
# IQ2000 | Three Configurations for Your Test Suite

1. Base Cryogenic Platform (< 4K or < 2K)
2. Rapid Sample Transfer, High Throughput
3. Configurable Sample Space
  - a) Photonics
  - b) Electrical – high density, high bandwidth
  - c) Electrical – Lab R&D

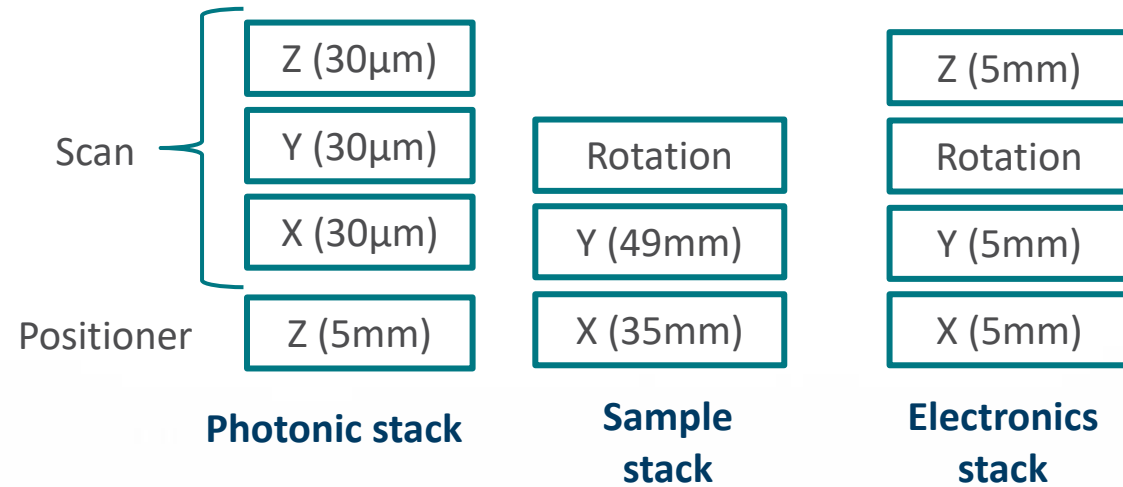
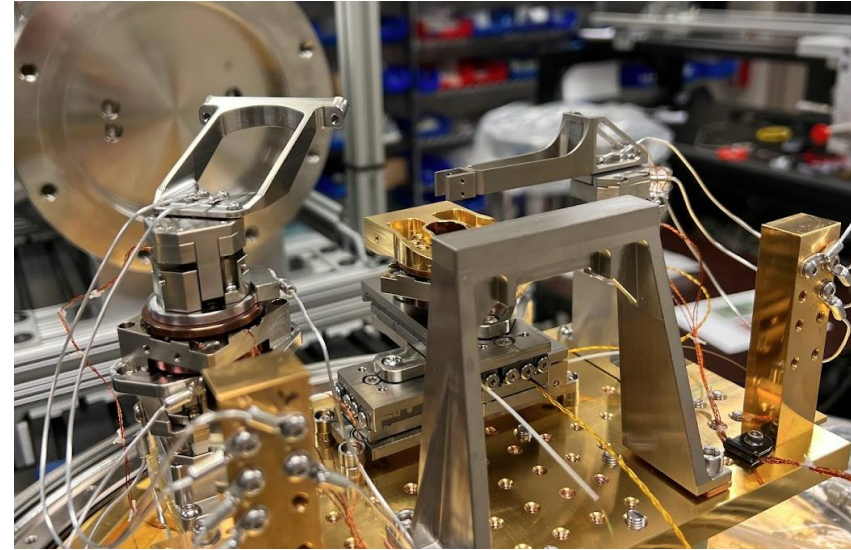
## High Density Electronic



## Photonics



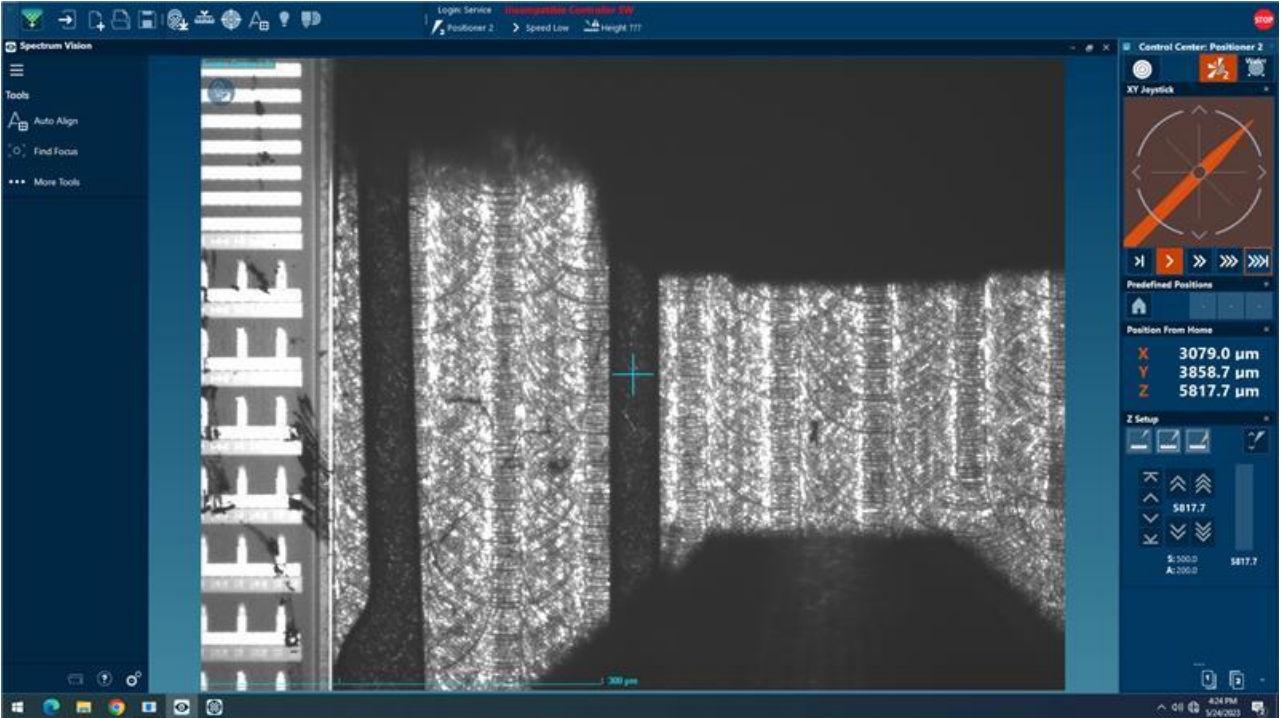
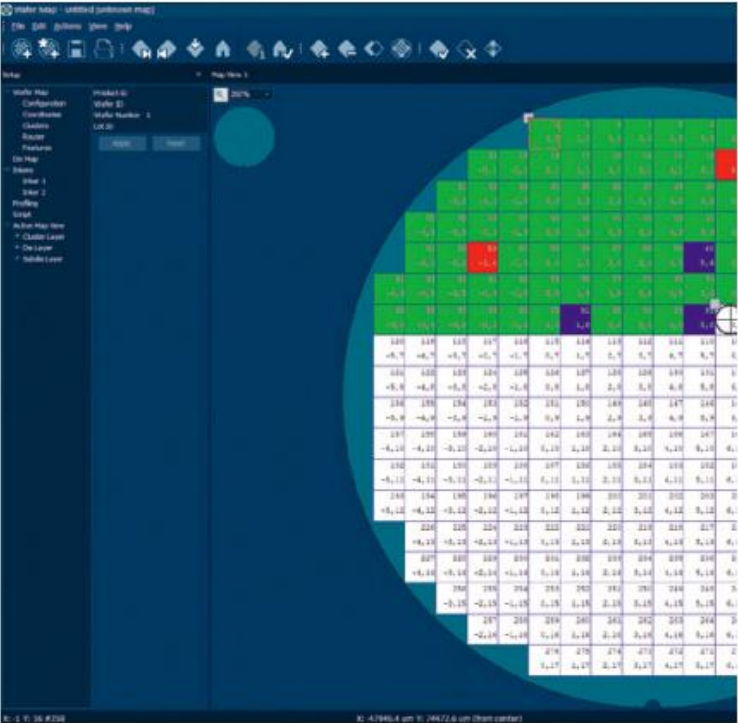
# IQ2000 Rapid Chip-Scale Probing | Photonics Experimental Space



# Velox™ Control Software

- FormFactor’s software for 200 mm and 300 mm wafer probe stations
- Universal standard for semi- and fully-automated systems
- Multi-die testing with integrated positioner control
- Streamlined communication with test & measurement equipment

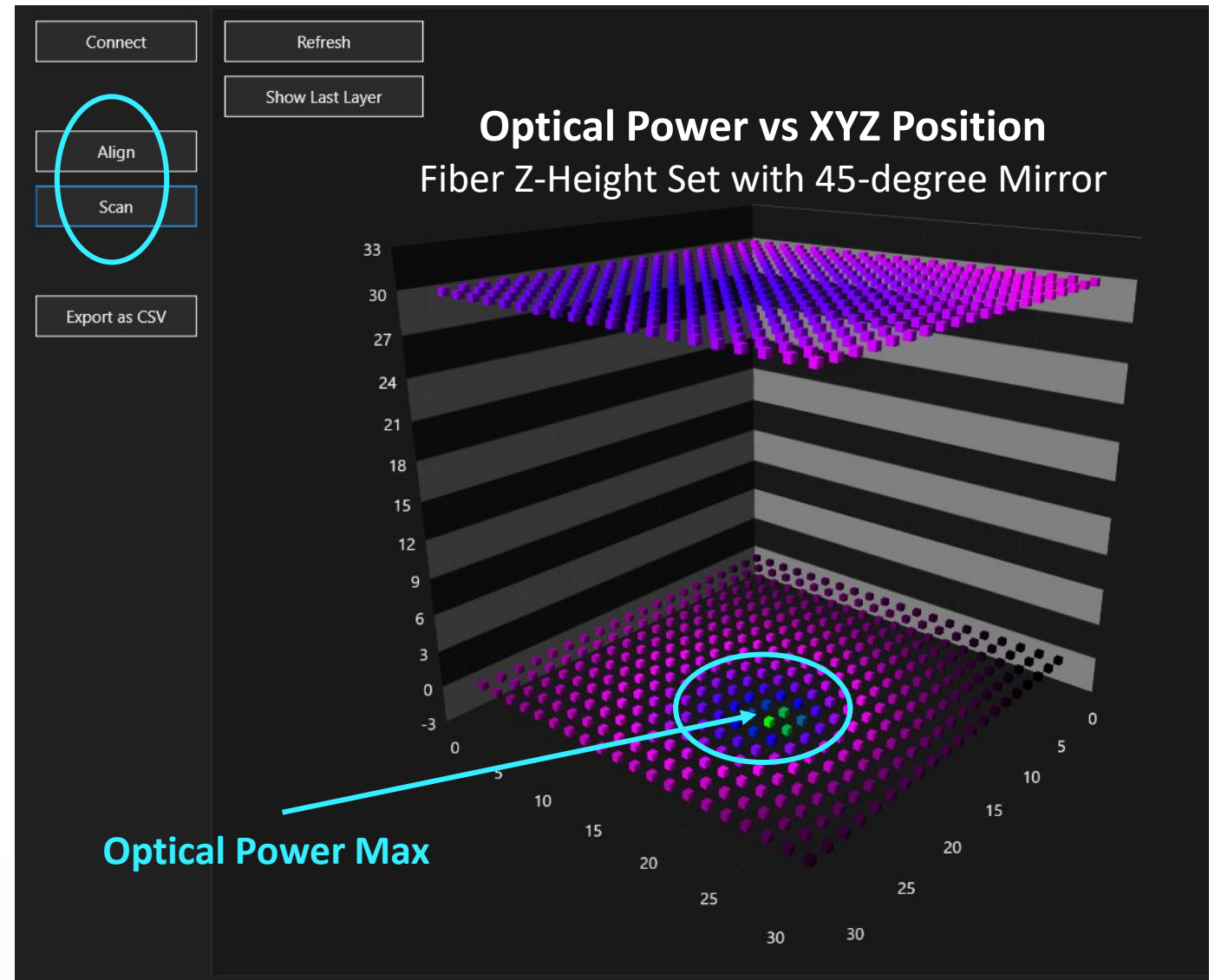
Overhead Microscope & Integrated 45-degree mirror enable fiber alignment to surface grating





# IQ2000 | Fiber Alignment & Position Optimization

- Auto-align fiber array in XYZ
- Scan range:  $30\mu\text{m} \times 30\mu\text{m} \times 30\mu\text{m}$
- FAU with 16 fibers (customizable)
- Loop-back structure to measure optical power



# < 50 mK Test & Measurement HPD ADR Cryostats

4K

300mK

50mK

# ADR Cryostat Product Line Overview

## Research Cryostats

- Model 106 & Model 107 ADR Cryostats
- “Turn-Key” cryogen-free system.
- Low base temperature and fast cycle times:
  - Single-shot, 30 mK Base Temperature.
  - Long, >200 hour, hold time at 100mK under no load.
- Vibration minimizing design.
- Vertical Atlas Stand or flip-able Titan Stand.
- Optional LN<sub>2</sub> rapid cooldown: cooldown to mK in 10-15 hours, model & configuration dependent.

Electronics Bread Board

Two Stage ADR

1K Heat Station

30mK Heat Station

Rapid Cool Heat Exchanger

**HPD Rainier 103**



4K

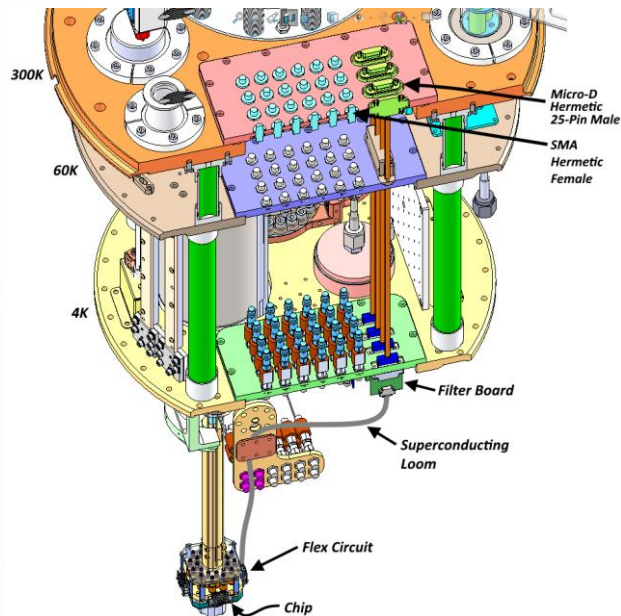
300mK

50mK

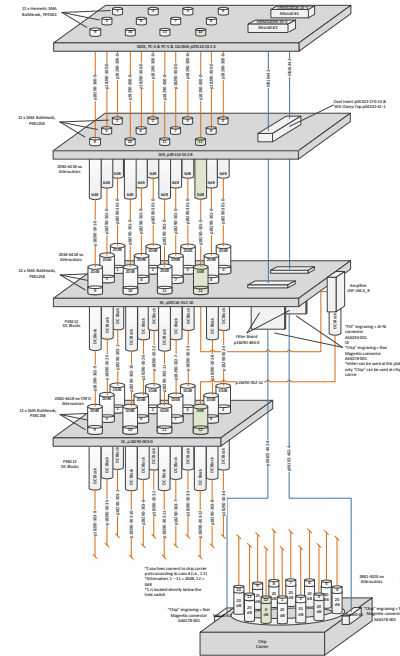
# Tailored Cryostat Solutions From Concept to Delivery

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

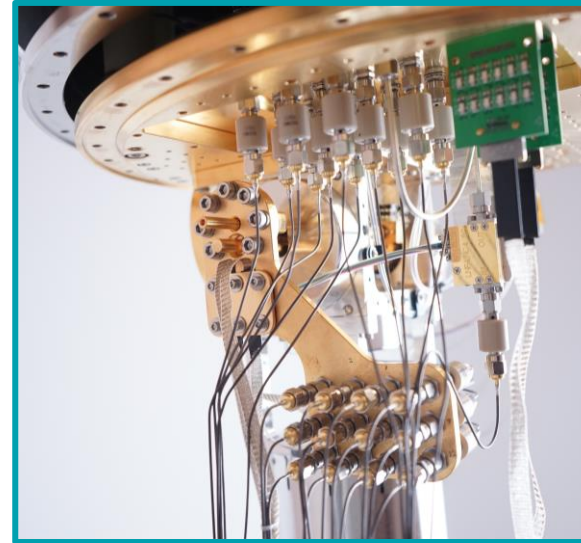
### High density wiring



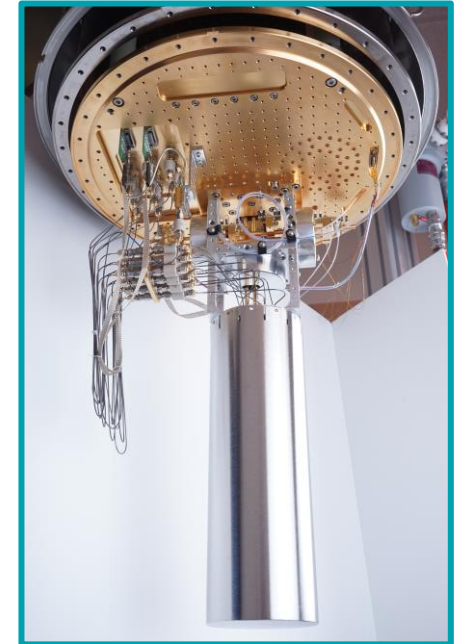
### Example wiring diagram



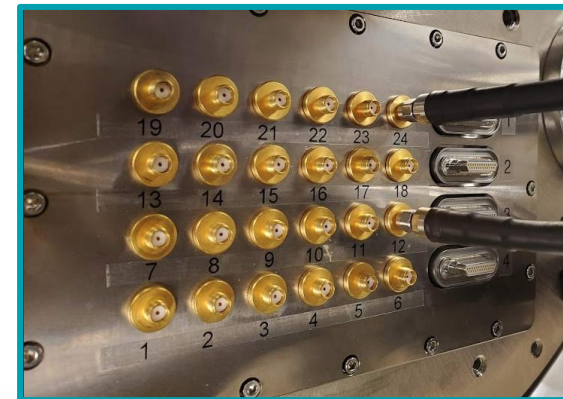
### Custom thermal intercept circuit elements



### Magnetic shielding around sample



### Bulkhead feedthrough



4K

300mK

50mK

# Superconducting QC | Chip-Scale Solution

## Qubit & Resonator Pre-characterization

No wire bonding

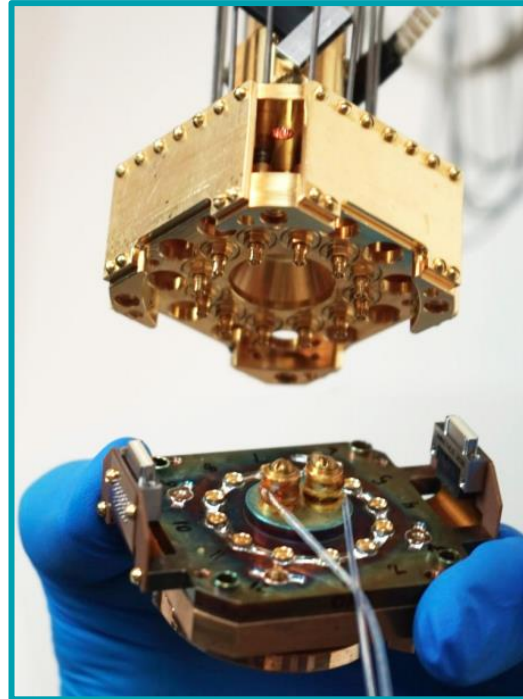
No packaging

< 16 hour  
cooldown

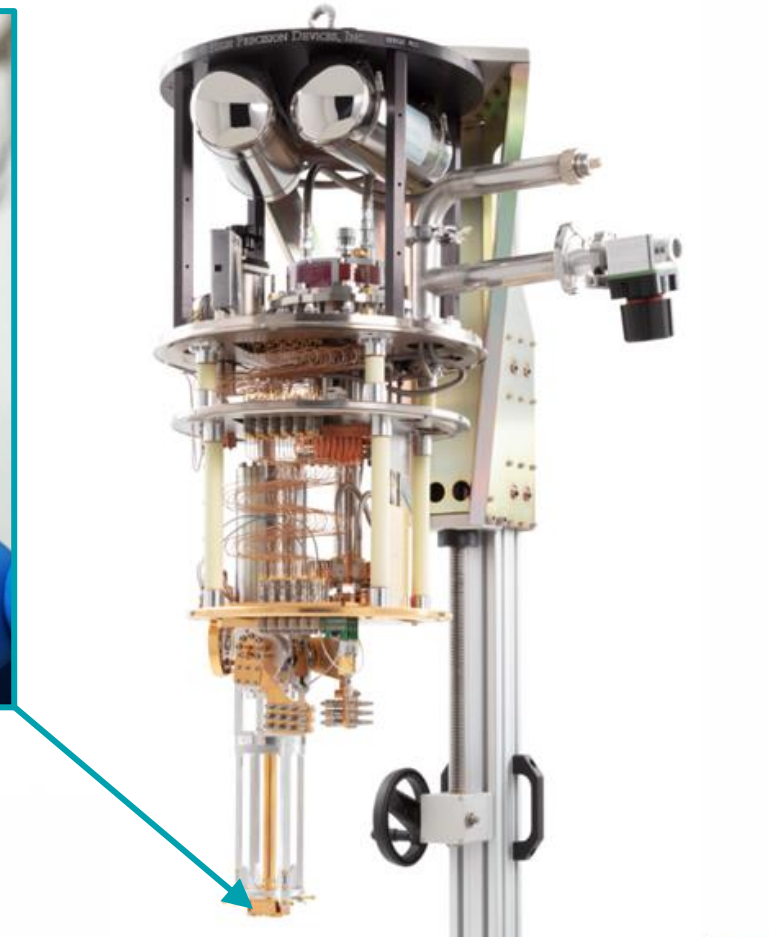
Find High Performing  
Devices Fast

➔ **2X Rapid  
Deployment**

PQ500 Probe Socket



Model 106 ADR Cryostat



# Example Measurements in milli-Kelvin Test System

## Qubit & Resonator Pre-characterization at 50mK

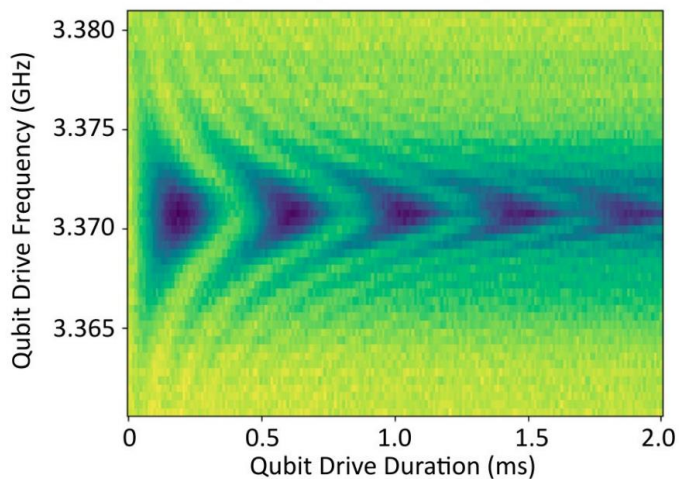
- Cavity resonance frequency
- Cavity dispersive shift
- Qubit transition frequency
- Rabi oscillations
- Qubit relaxation time ( $T_1$ )



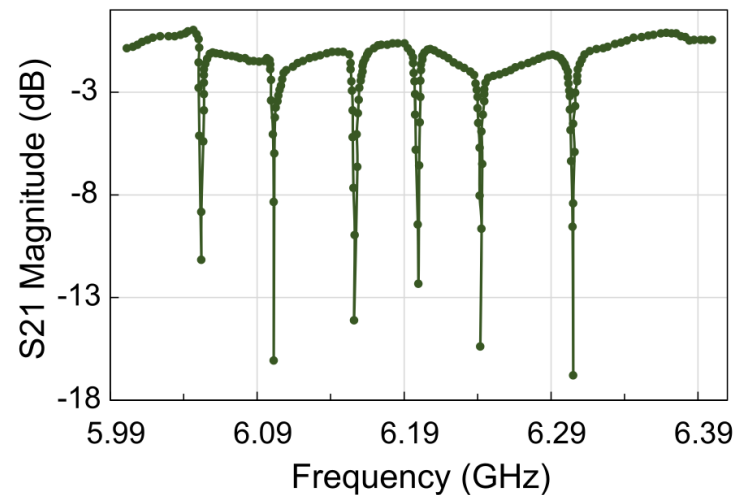
Reduce QPU Bring-Up by Days

Data courtesy of   
**seeqc**

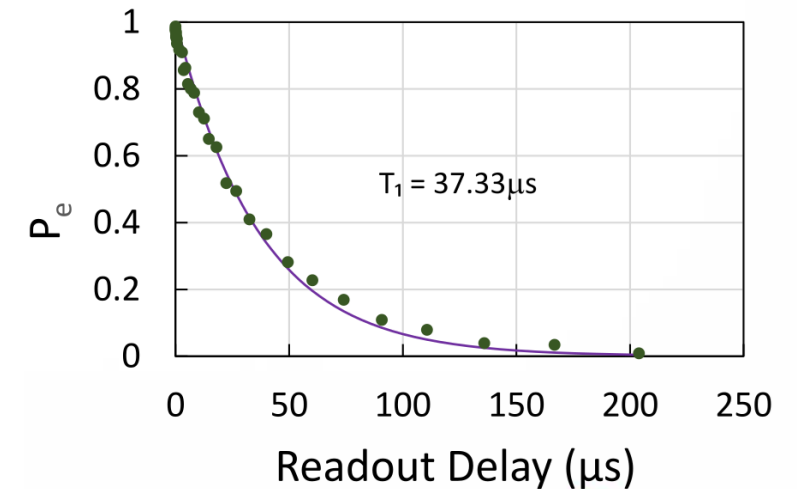
Rabi oscillations



Cavity resonance frequency

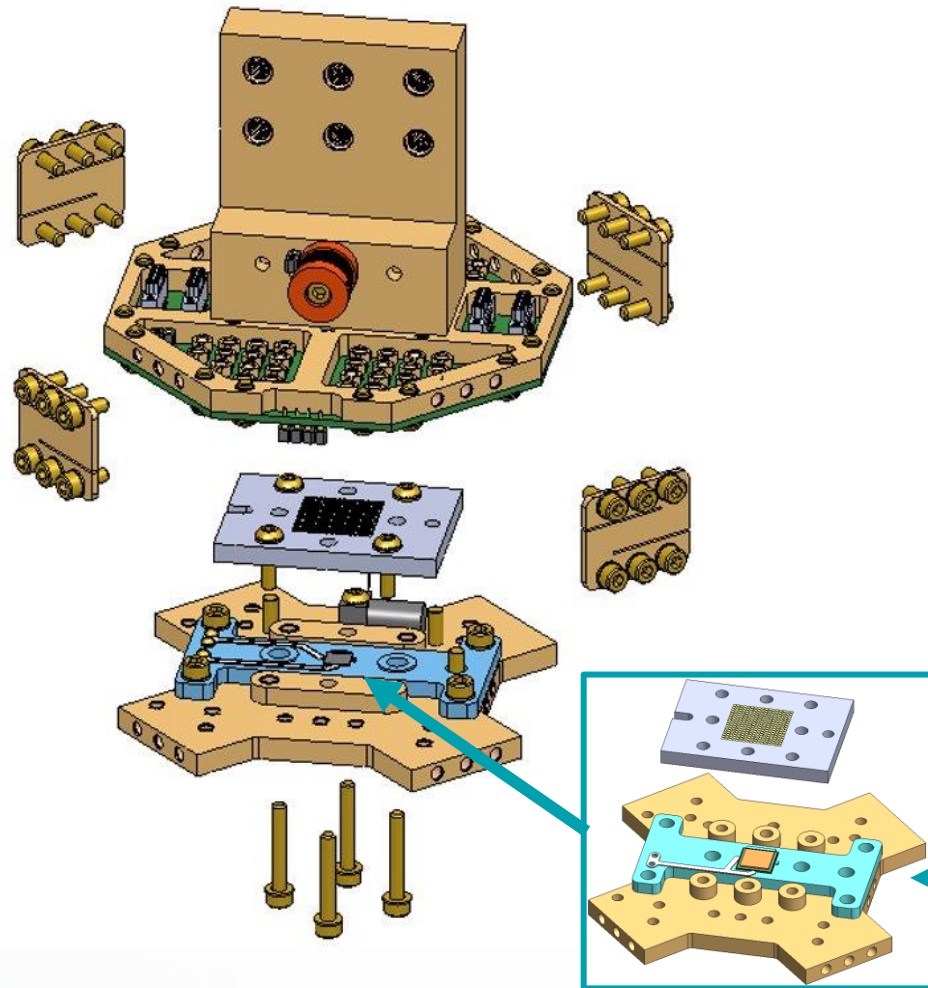


Relaxation time

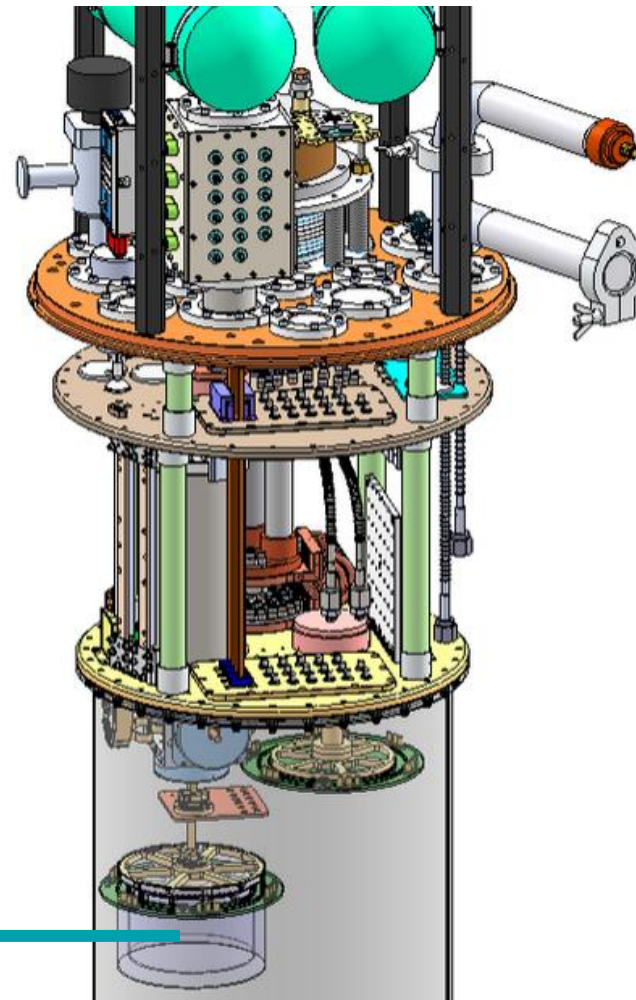


# Probe Socket PQ500 Designs for Different Cryostat

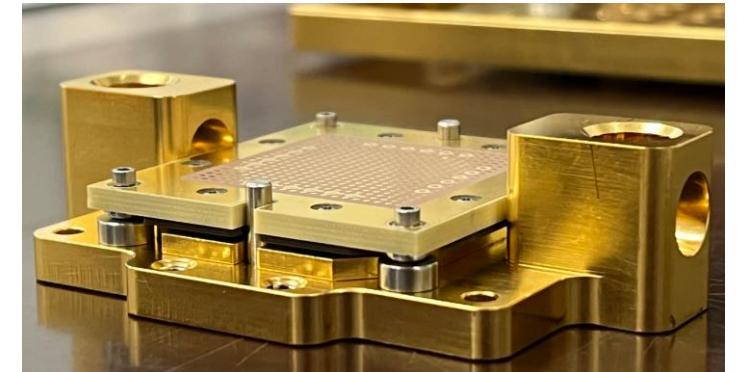
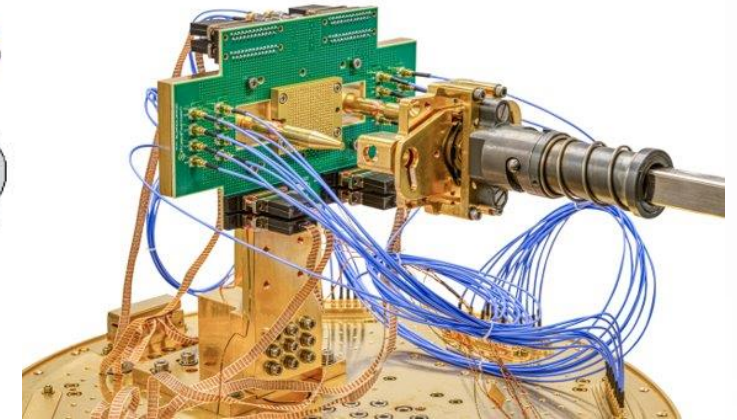
PQ500 Probe Socket with Active Alignment



PQ500 in Cryostat



PQ500 for the IQ2000





[www.FormFactor.com](http://www.FormFactor.com)

FormFactor's HPD Cryogenic Product Line  
4601 Nautilus Court South, Suite 100  
Boulder, Colorado 80301

[HPD-sales@formfactor.com](mailto:HPD-sales@formfactor.com)

Jack DeGrave, PhD  
Director of Business Development

