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Tu3E - 4

Cryogenic measurement and characterization for quantum systems

Joshua West[1], Arthur Kurlej[2], Alex Wynn[2], Chad Rogers[1], Mark Gouker[2], Sergey Tolpygo[2]

[1] HPD/FormFactor, Boulder, CO

[2] MIT Lincoln Laboratory, Lexington, MA

MIT LINCOLN LABORATORY

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Outline

- IQ3000 automated cryogenic wafer prober overview
- RF specifications and performance
- Experiment setup and automation
- Measurement results for MIT/LL SFQ5ee wafers
  - – Digital process for superconducting electronics
  - – All data collected in two days
- Summary

IQ3000 Fully Automated Wafer Prober

Environmental Control
- Wafer temp verified <4.5 K (with 44 RF probes in contact)
- Magnetic field cancellation to <200 nT
- Highly uniform wafer temperature
- Precise thermal stability and control
- Solid construction with granite base enables precision motion and vibration control

Automation
- Options for fully automated wafer load or manual
- Complete software suite for manual, semi-auto, or fully automated probing

Cooling
- Liquid Helium cooled version shown
- Dry option available

IQ3000 Fully Automated Wafer Prober

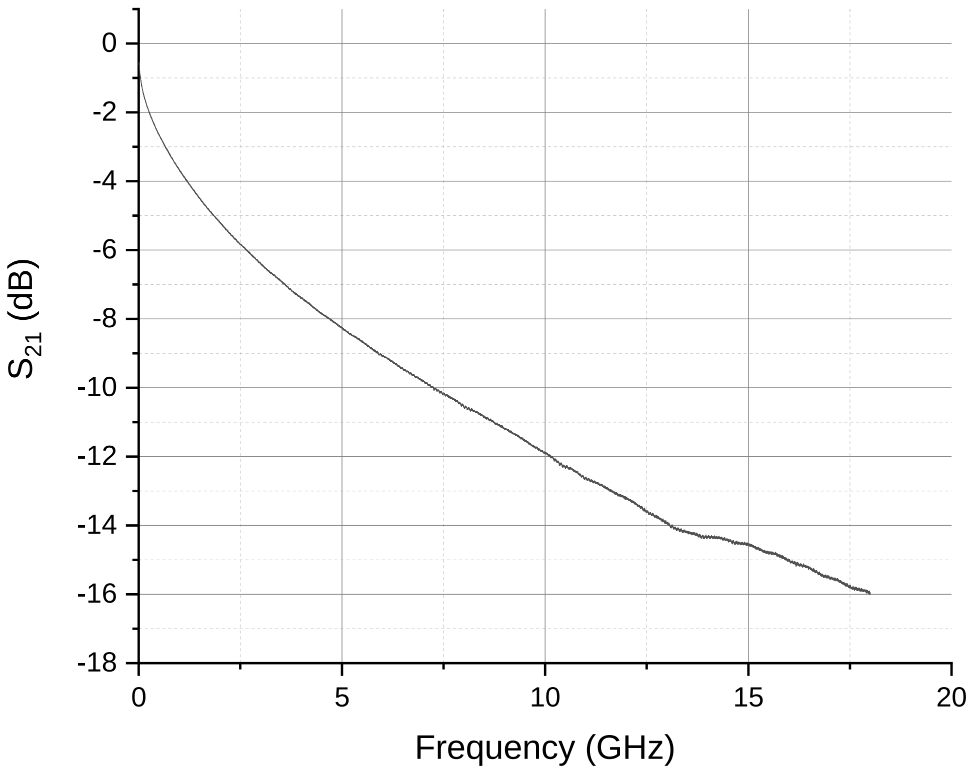
Flexibility
- Easy exchange of customizable probe cards
- Configurable for either 150 mm or 200 mm wafers
- Up to 56 RF coax (up to 18 GHz)
- Up to 520 DC lines

Time to data
- 25 wafer cassette capacity for fully automated testing
- ~15-minute cooldown time per wafer
- High speed motion stages for quick die-to-die movement
- Rigid motion stack for fast settling time
- ~24-hour cooldown time

RF Specifications

DC Wiring
- Twisted pair wiring in PhBr, Cu, and shielded-twisted Brass available

Data shown is for a pair of coax lines connected with a 4 K jumper (round trip)

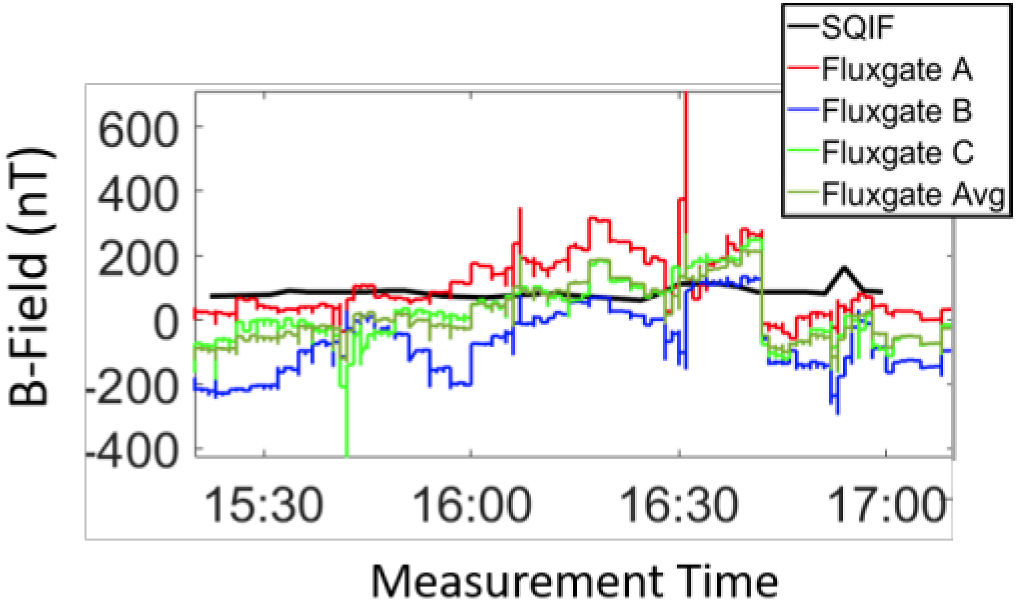


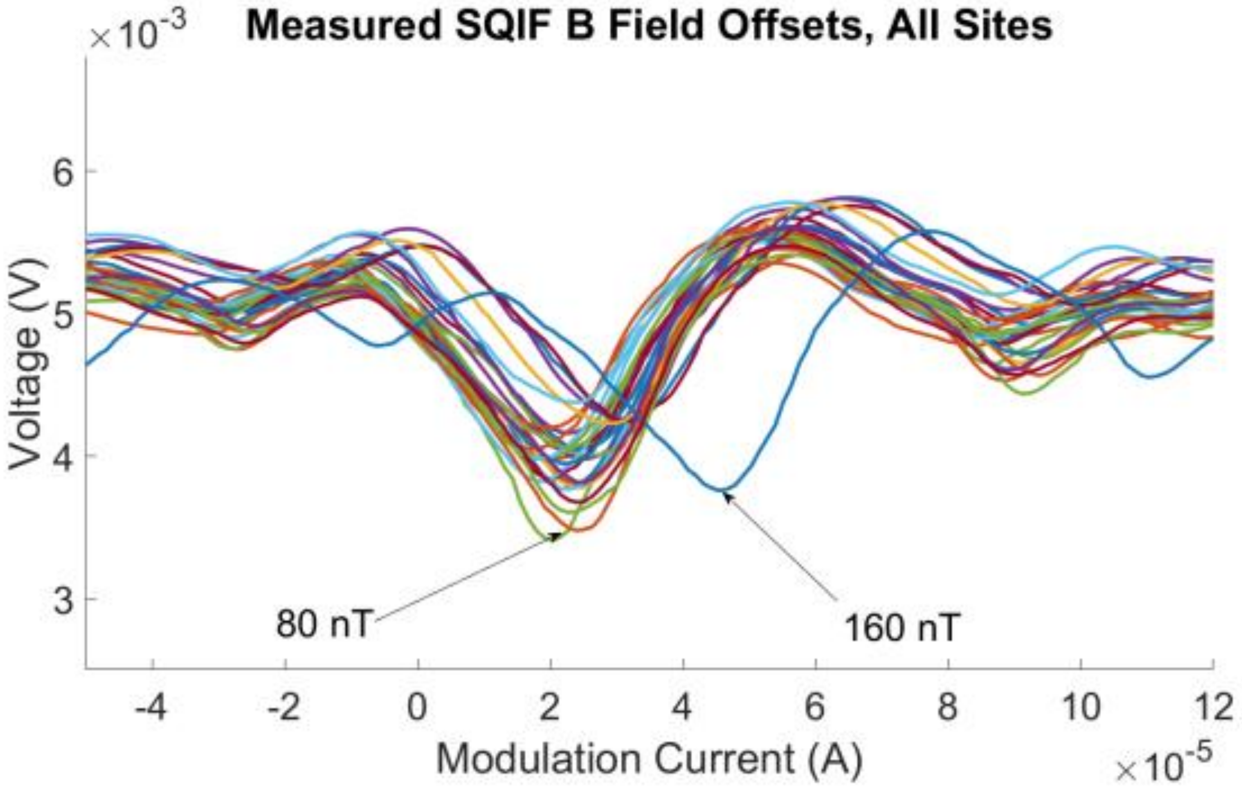
RF Coax
- 1.19 mm (0.047”) BeCu coax
- SMA connectors at 300 K
- GPO connectors at 4 K
- VSWR <1.5 (1.2 avg.) up to 16 GHz
- Insertion loss <8 dB up to 16 GHz
- All coax phase matched to +/- 10 ps
- Cross talk < -40 dB

Magnetic field data

Magnetic shielding

- The IQ3000 combines 3-axis field cancelation coils with a passive cryogenic shield
- Specification is <200 nT





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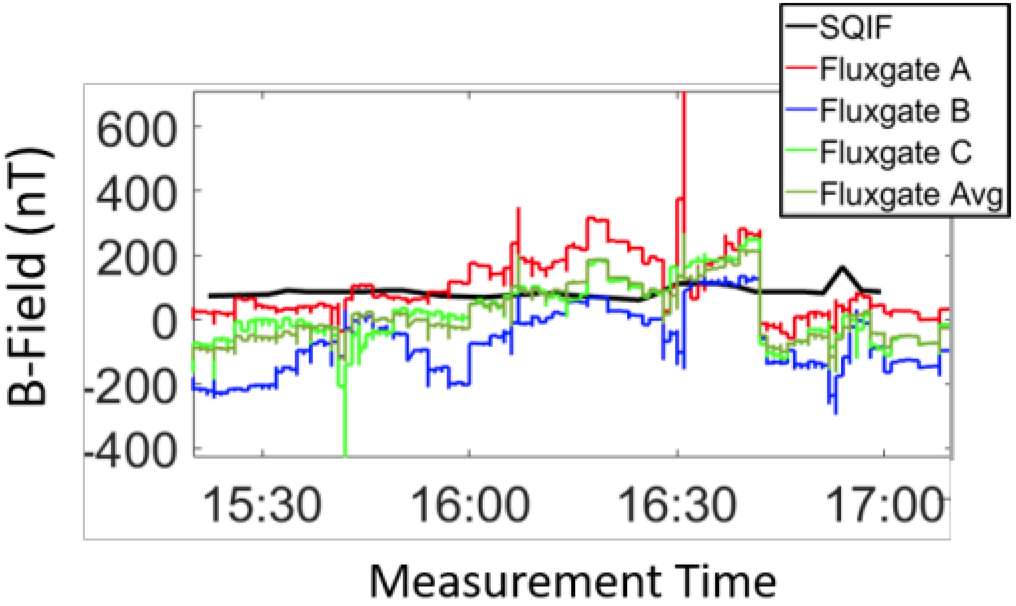
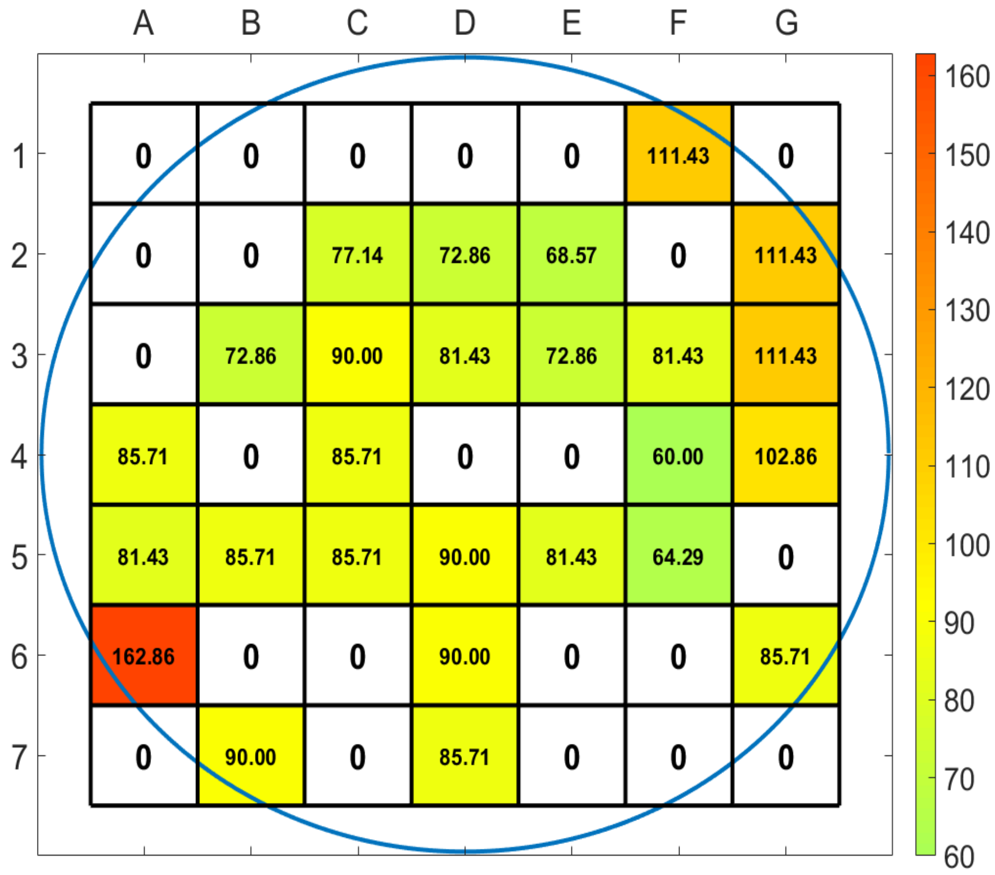


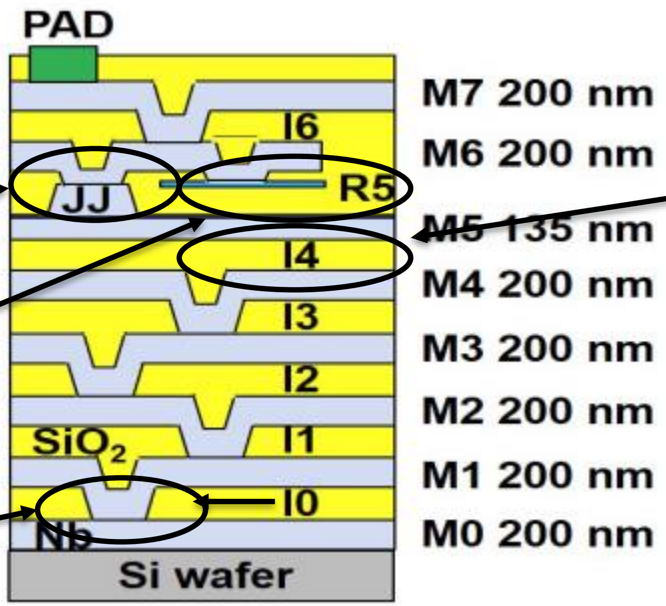


Avg. = 80 nT (Min. = 60 nT, Max. = 163 nT)

MIT/LL SFQ5ee process
What are we able to measure?

Nb/Al-AlO_x/Nb stack
Josephson Junction
- IV curves
- Normal Resistance, R_N
- RRR = R_{300}/R_N
- Gap voltage, $V_g = 2\Delta/e$
- Sub-gap resistance R_{SG}
- R5 is the JJ shunt resistor

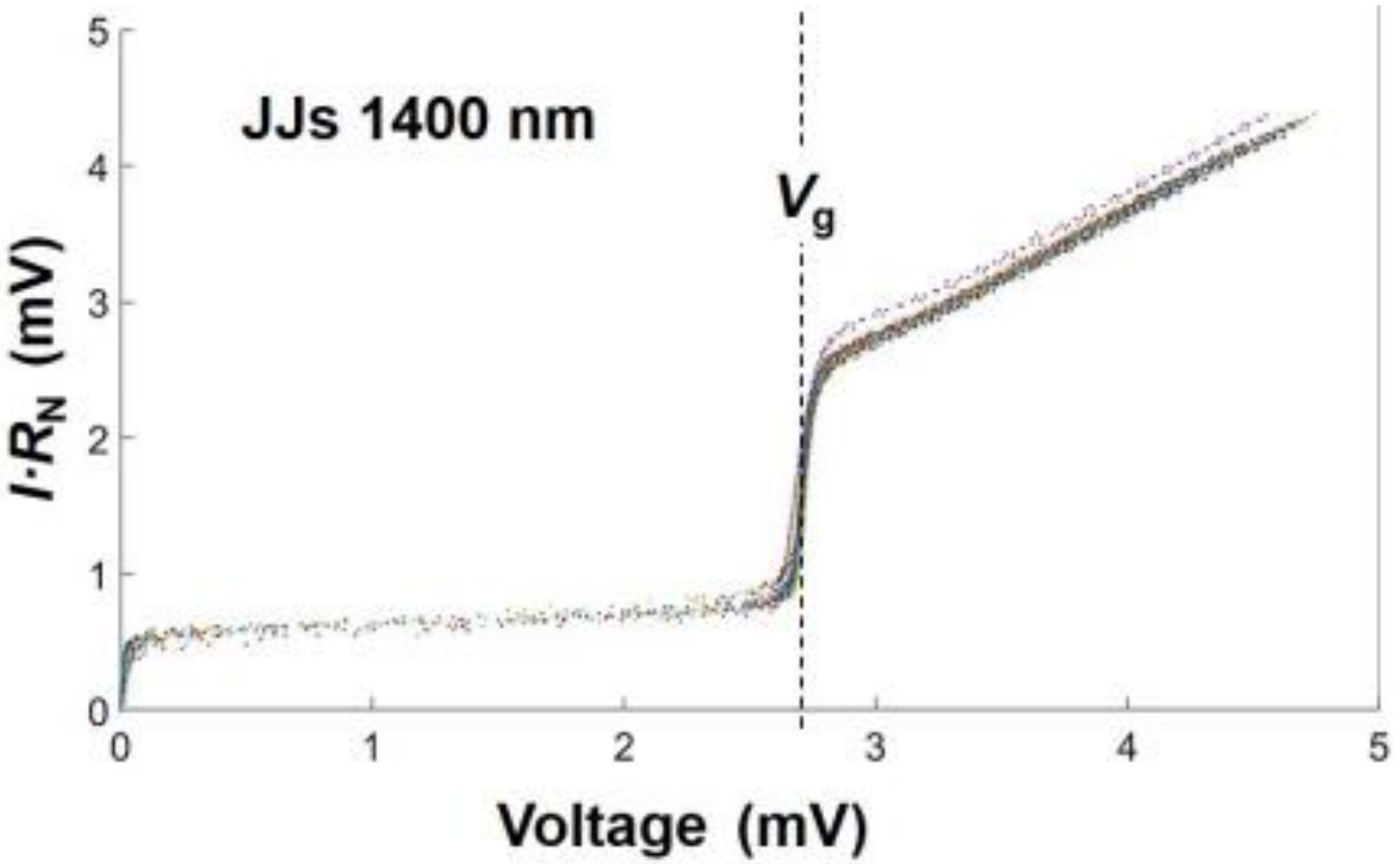
Via Critical Currents, I_C



Layer Inductance

Wafer-Scale Characterization of a Superconductor Integrated Circuit Fabrication Process, Using a Cryogenic Wafer Prober
IEEE Transactions on Applied Superconductivity, vol. 32, no. 5, pp. 1-12, Aug. 2022. DOI 10.1109/TASC.2022.3172660

Josephson Junction IV curve (normalized)



Josephson Junction IV curve (normalized)
Key parameter extraction

Nb/Al-AlO_x/Nb stack
Josephson Junction

- IV curves
- Normal Resistance, R_N
- RRR = R_{300}/R_N
- Gap voltage, $V_g = 2\Delta/e$
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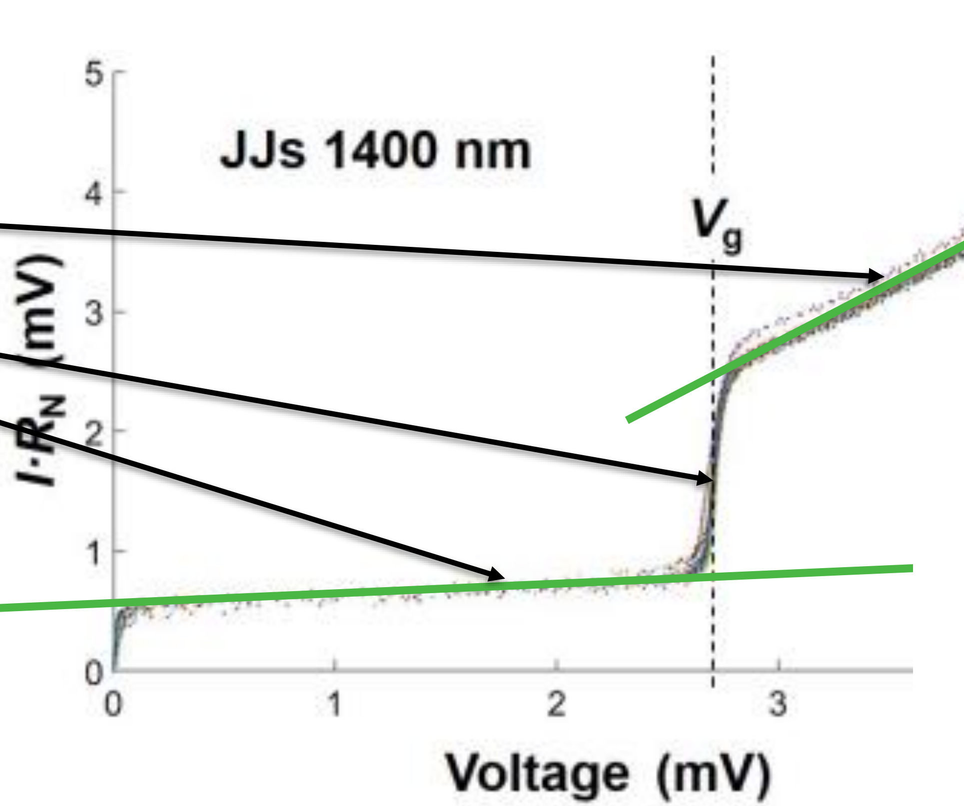
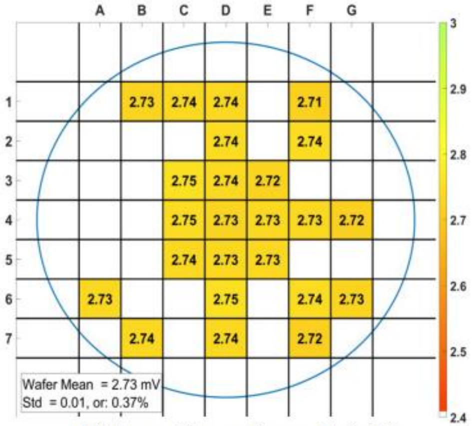
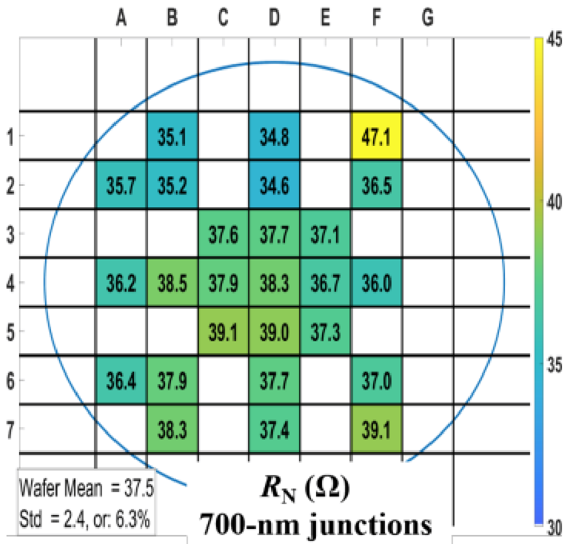




1000 nm, Gap voltage, V_g (mV)

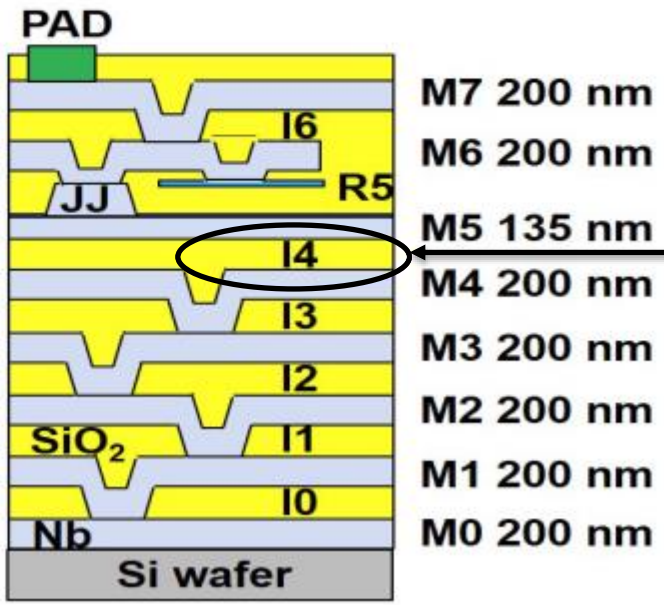


R_N (Ω)
700-nm junctions

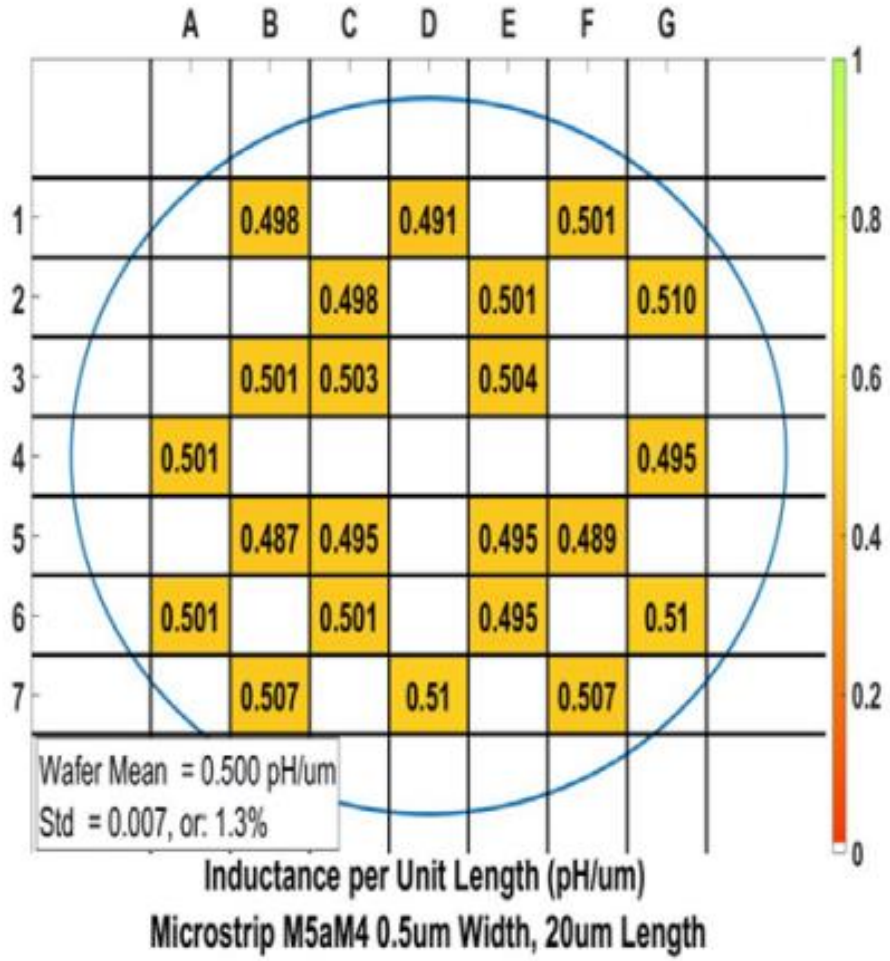
Inductance measurements

Stripline inductance is critical to superconducting electronic design

- Cannot be measured at 300 K



Layer Inductance
M5aM4 stripline



Inductance measurements

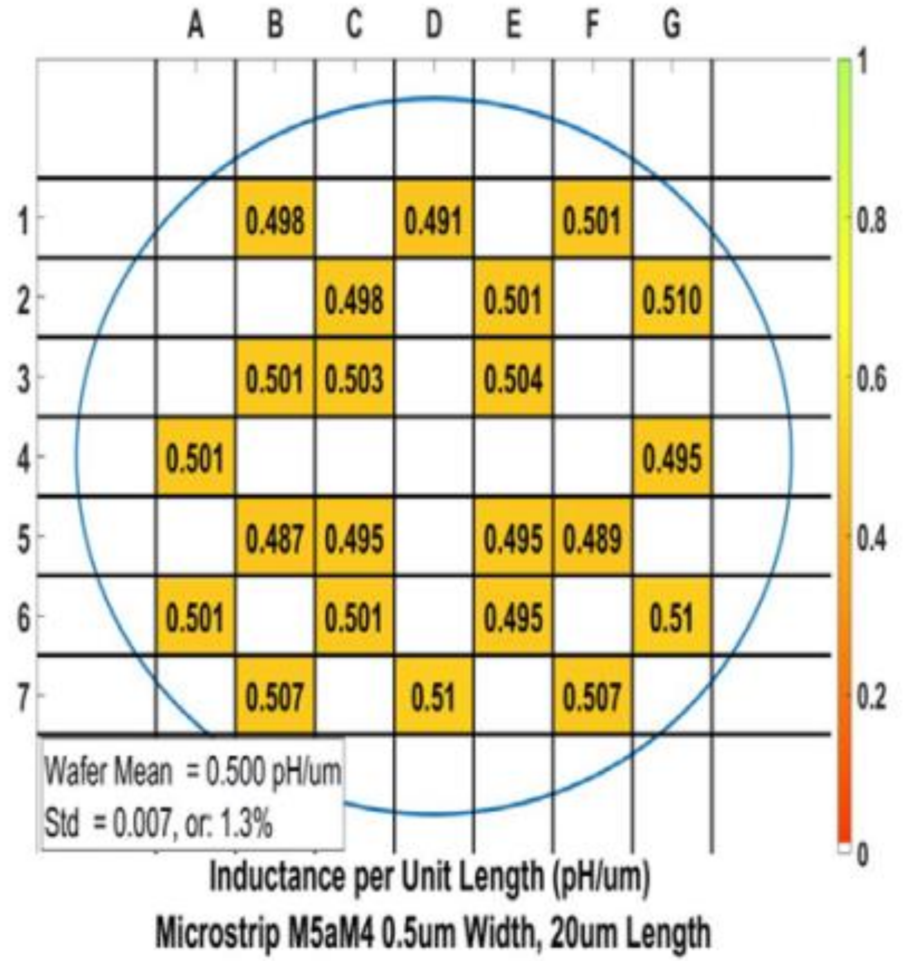
Stripline inductance is critical to superconducting electronic design

- Cannot be measured at 300 K

TABLE I
EXPECTED INDUCTANCE VALUES AND DEVIATIONS OF THE MEASURED MEAN VALUES FROM THE EXPECTED

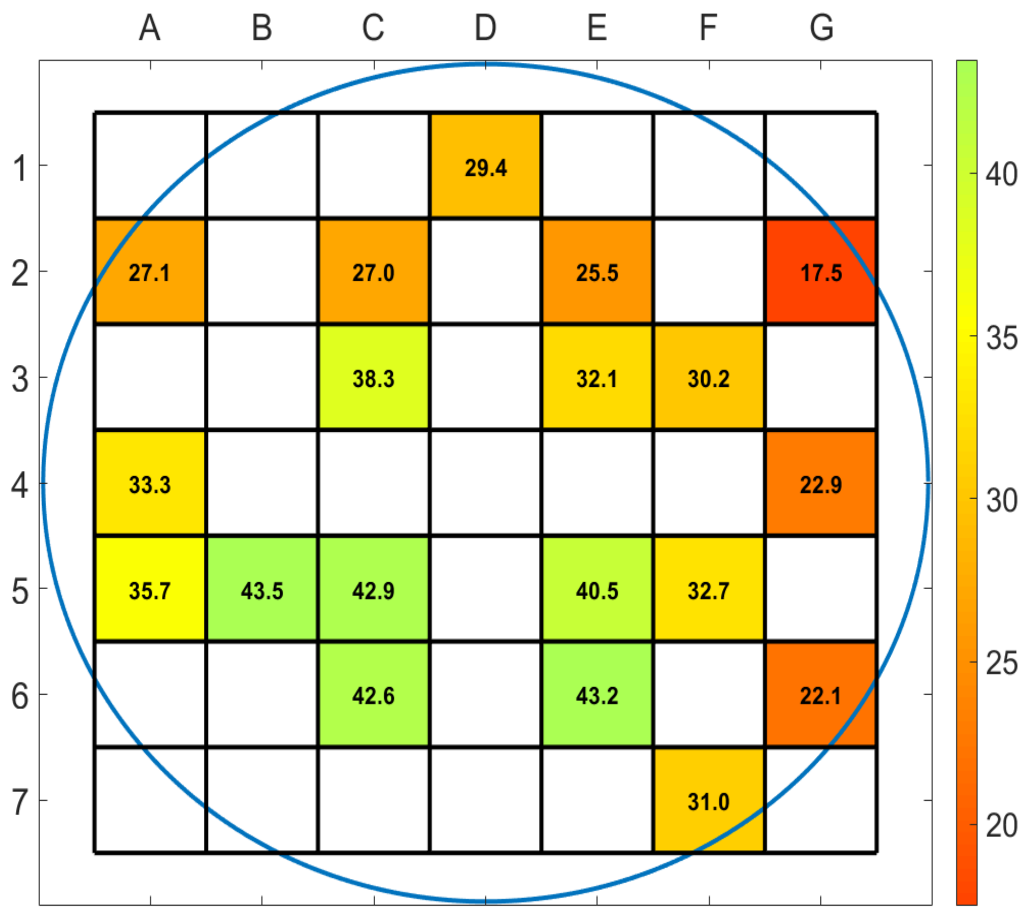
Inductor	d_1 (nm)	L_l (pH/µm) w =0.5 µm	$\frac{\Delta L_l}{L_l^{theor}}$ (%) [a]	L_l (pH/µm) w =0.7 µm	$\frac{\Delta L_l}{L_l^{theor}}$ (%)
M5aM4	200	0.478	4.6	0.383	6.0
M5bM7	680	0.645	−0.8	0.549	−2.6
M6aM4	615	0.569	1.0	0.490	1.4
M6bM7	200	0.427	−3.7	0.350	−3.7
M5aM4bM7	200	0.4472	1.5	0.3556	2.1
M6aM4bM7	615	0.3856	n/a	0.3118	n/a

[a] $\Delta L_l = \langle L_l^{meas} \rangle - L_l^{theor}$, where $\langle L_l^{meas} \rangle$ is the measured wafer mean value of inductance per unit length, and L_l^{theor} is the expected value from (1) with the nominal process parameters. Penetration depth $\lambda = \lambda_1 = 90$ nm was used in (1) and (2).



Critical Current for 700 nm vias

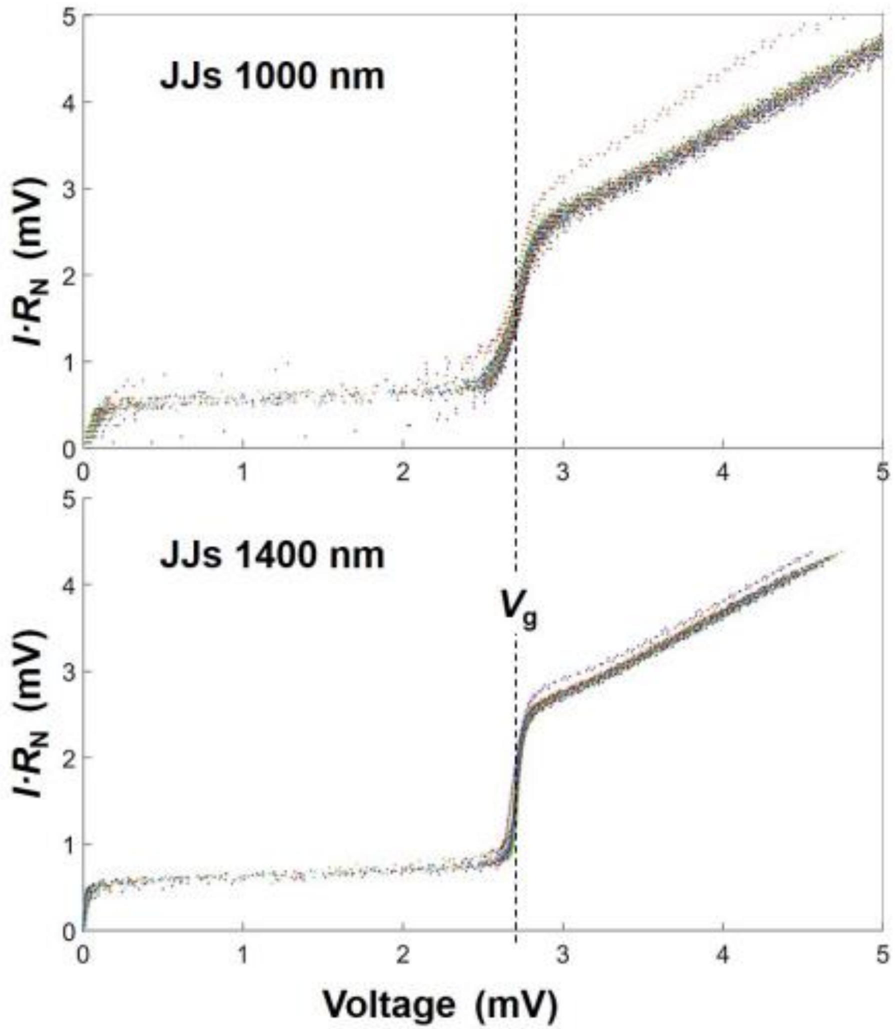
- Critical current cannot be obtained from 300 K measurements
- Measurements of chains of **1848 vias in series**
  - Therefore, measured result is the smallest I_c
- Distribution is not necessary, needs to be above a threshold of 15 mA for 700 nm vias



Summary

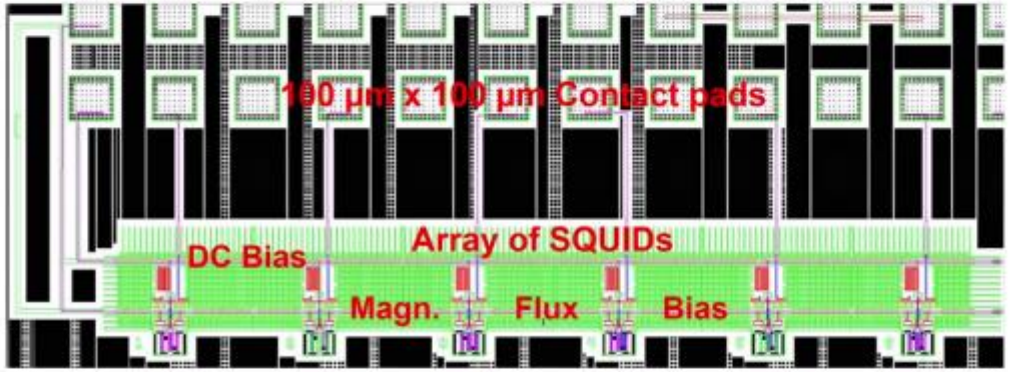
- IQ3000 is a fully-automated 4 K probing system
  - Highly flexible signal I/O for RF and DC measurements
  - Magnetic shielding for sensitive superconducting devices
  - Systems available for purchase, or measurement as a service at our facility in Boulder, CO
- This case study with the MIT/LL SFQ5ee provides a glimpse of the capability to gather valuable data in a short period of time
  - All data presented was gathered in two days
  - Would have taken months on conventional chip-scale systems
  - Measurements not possible at room temperature

Backup slides

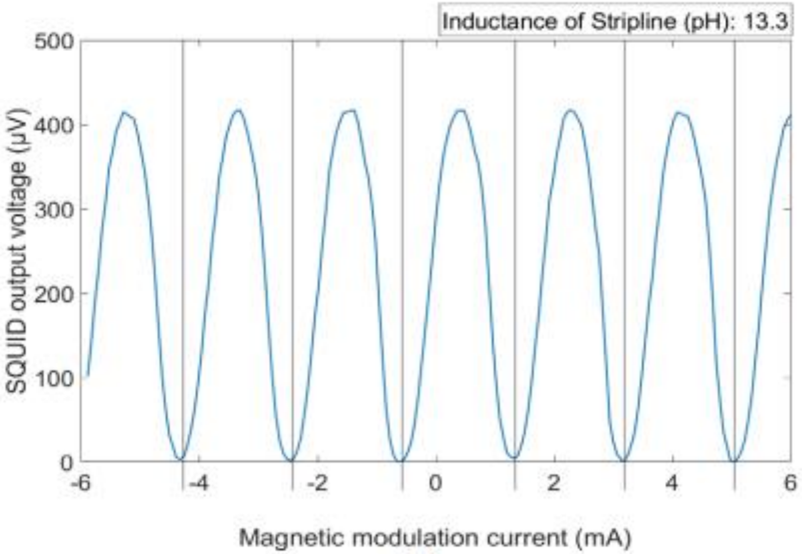

JJs 1000 nm
JJs 1400 nm
V_g
$I \cdot R_N$ (mV)
$I \cdot R_N$ (mV)
Voltage (mV)
0
1
2
3
4
5

Inductance measuremetns

- 6-SQUID layout
- N+2 contacts to measure N inductors
- Period of of the voltage-flux characteristics of differential SQUIDs fed with a common modulation current determines the inductance



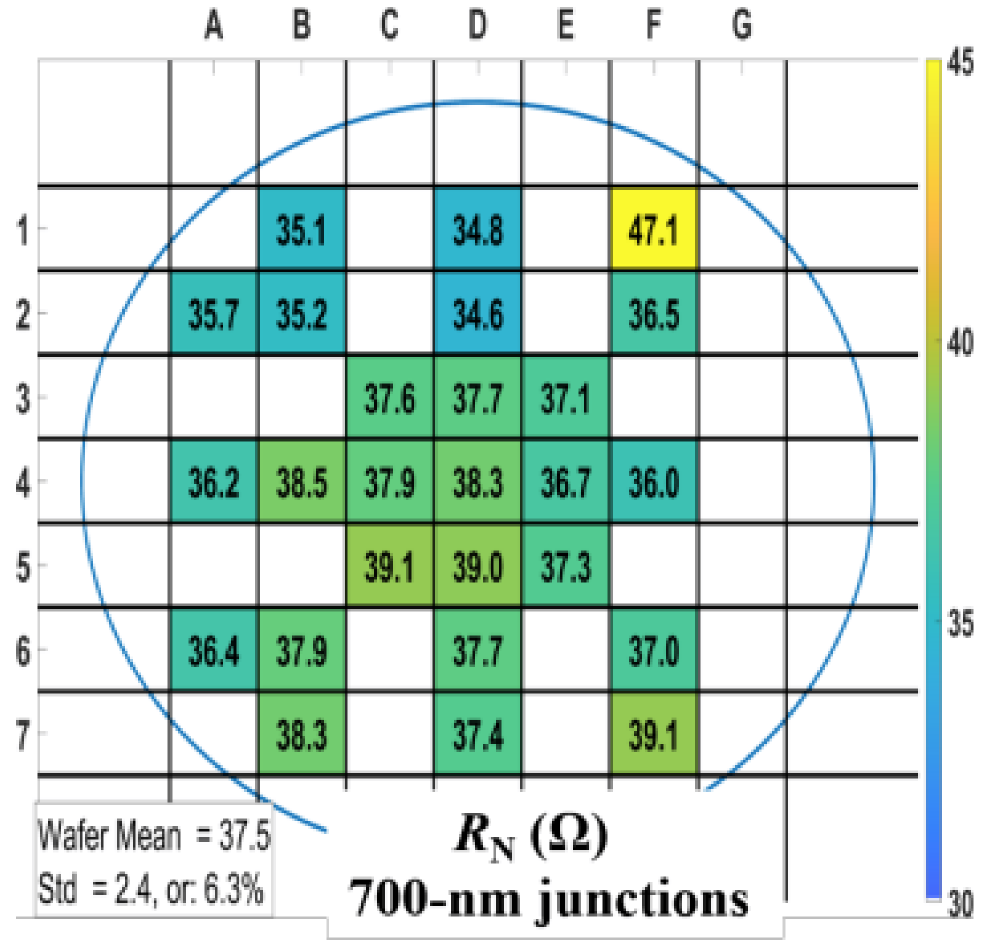
(a)



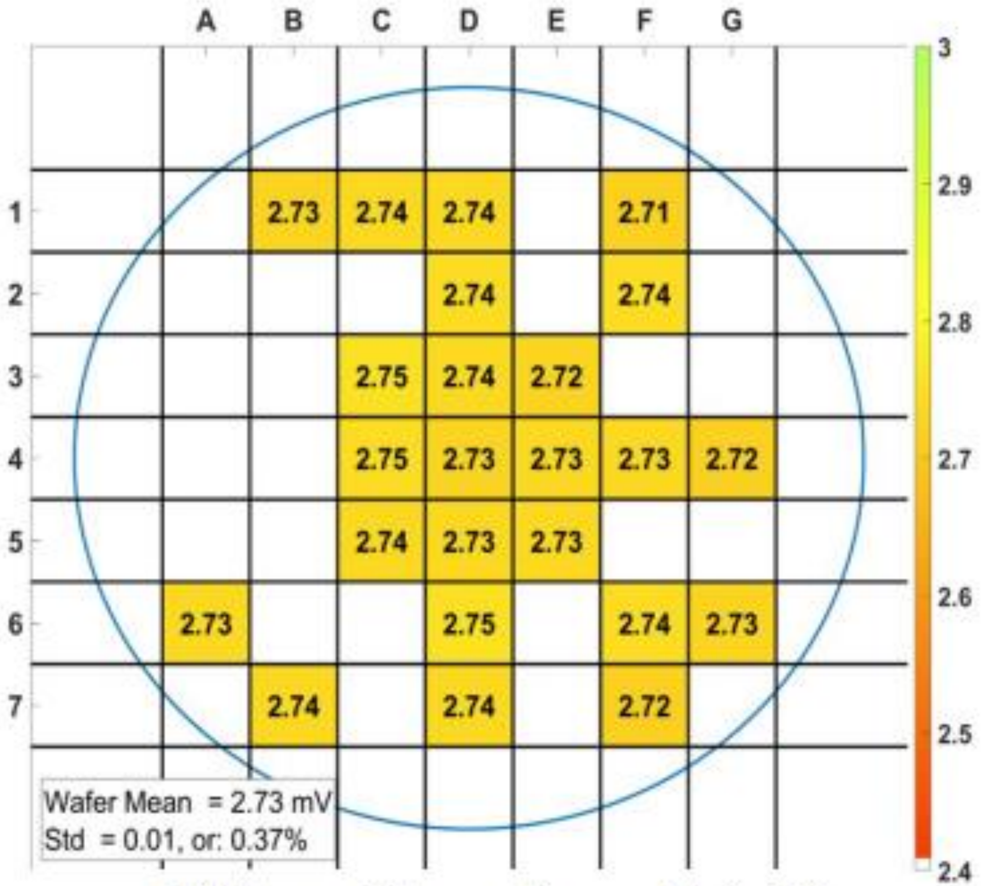
(b)

Normal State Resistance of 700 nm JJ’s

- Normal state resistance
- Target value is 40 Ohm
- High resistance at F1 likely due to poor contact



Gap Voltage



1000 nm, Gap voltage, V_g (mV)

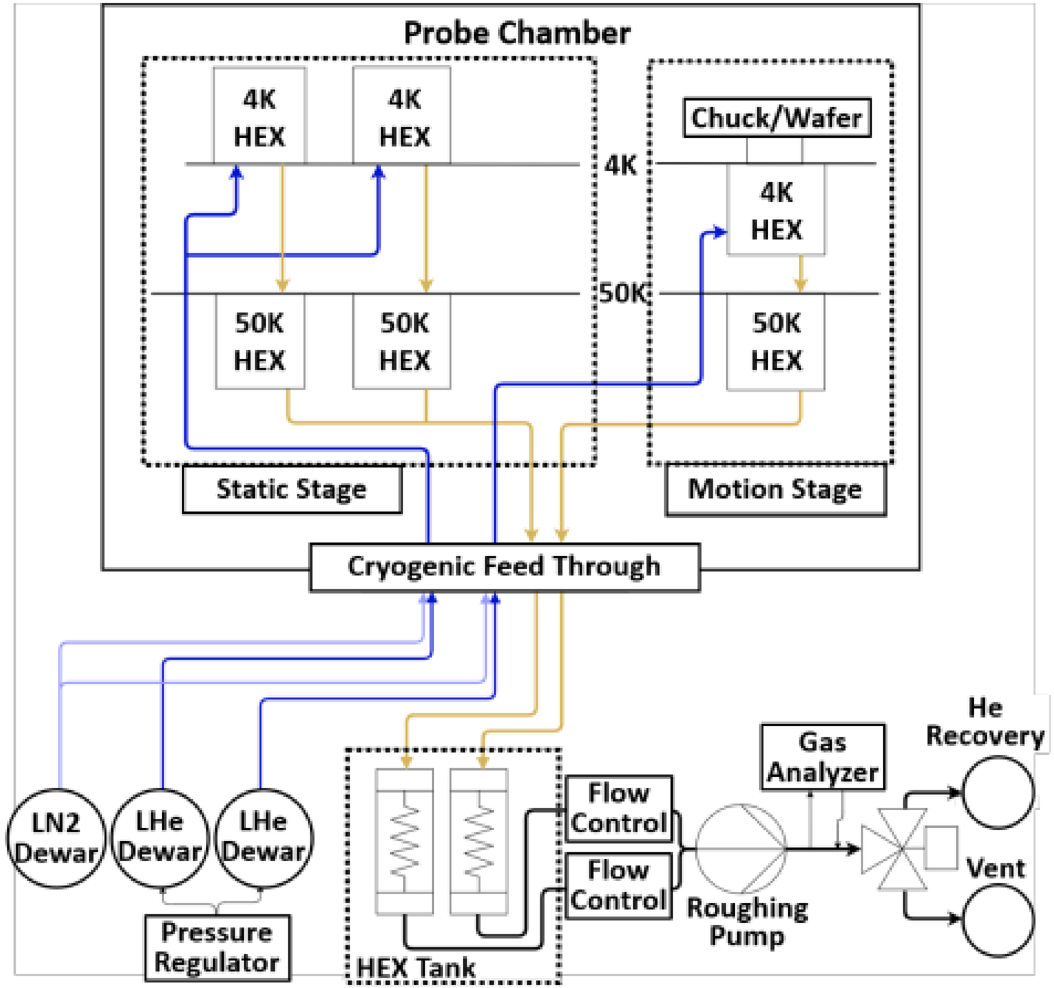


Fig. 2. Schematic of the cooling architecture. Separate cooling loops are used for the static and motion stages of the cryogenic prober. Cryogens exiting the system are returned to room temperature before passing through the flow controllers and pump that are used to control the flow rate.

FormFactor Introduces Automated Cryogenic Wafer Probe System to Enable Superconducting Compute Applications

June 24, 2021

FormFactor, Inc. collaborating with Northrop Grumman Corporation announced today a fully automated cryogenic wafer probe system operating at 4 K

Multiple Systems Installed at Northrop Grumman Supporting Development of Advanced Technology

LIVERMORE, Calif., June 24, 2021 (GLOBE NEWSWIRE) — FormFactor, Inc. (NASDAQ:FORM), a leading semiconductor test and measurement supplier, collaborating with Northrop Grumman Corporation , a technology company focused on global security and human discovery, announced today the availability of a fully automated cryogenic wafer probe system operating at 4 Kelvin and below to accelerate the development of superconducting compute applications. Following unique design specifications, FormFactor's HPD cryogenic systems group worked closely with Northrop Grumman scientists and engineers from concept to construction. The team produced multiple units of fully automated cryogenic wafer probers capable of meeting the challenging test requirements of superconducting circuits.