RF Josephson Arbitrary Waveform Synthesizer: JAWS up to 3 GHz and beyond

Paul Hale
RF Technology Division
Boulder, Colorado, USA

Nathan Flowers-Jacobs, **J.A. Brevik, A.A. Babenko, A.E. Fox, A.S. Boaventura,**
P.F. Hopkins, P.D. Dresselhaus, D.F. Williams, and S.P. Benz

Quantum-Based Signal Sources

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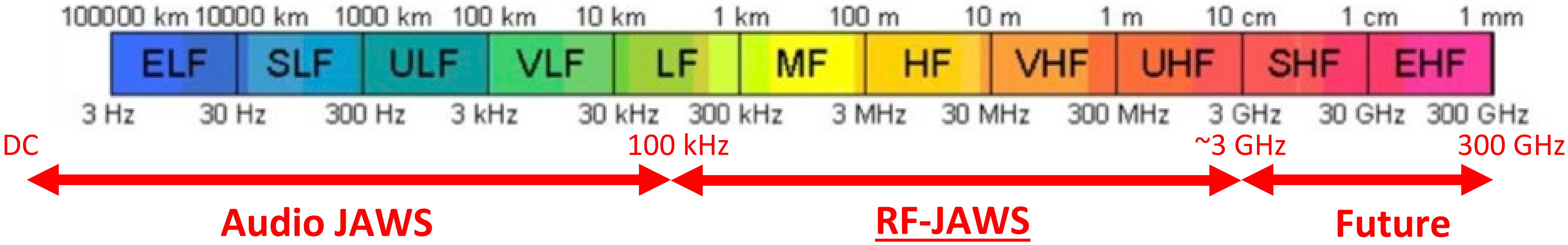


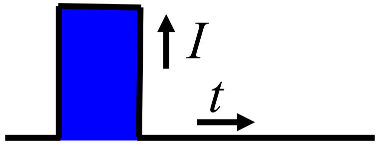
Goal: Create a programmable **quantum-based RF source** for signal & power metrology

Points of emphasis:

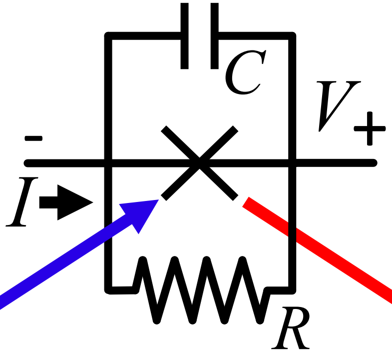
- Calculable, quantum-based SI-traceable signal accuracy
- Quantum Locking Range: stable, reproducible, location-independent
- Arbitrary waveform synthesis using “3-level DAC” → calculable out-of-band signal
- Typical -48 dBm at cryogenic reference plane; demonstrated up to -28 dBm

JAWS Quantum Source: pulse-driven JJs

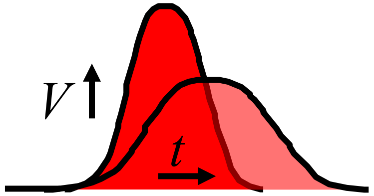
apply input current bias pulse
(imprecise & not quantized)



rotates φ (superconducting phase across JJ) by 2π



outputs voltage pulse
(quantized area)



$$I = I_c \sin(\varphi)$$

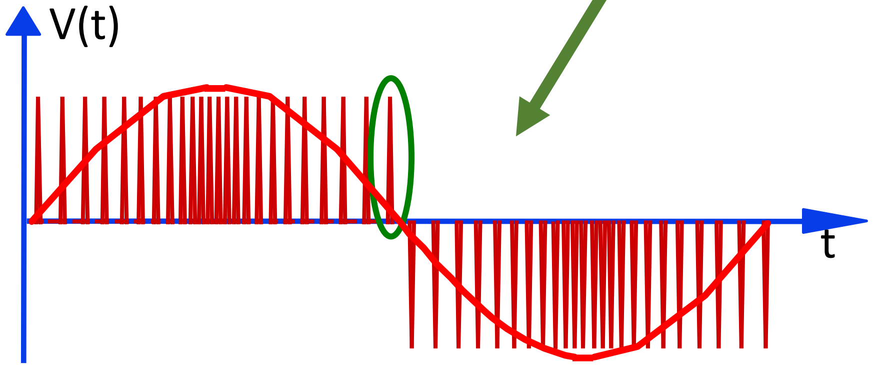
overdamped JJs

$$V = \frac{\hbar}{2e}\frac{d\varphi}{dt}$$

Basis of JAWS* Voltage Standard!

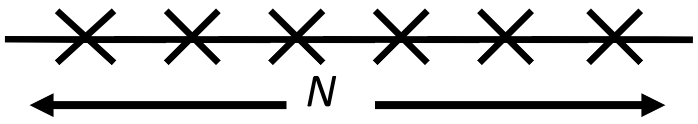
$$\int V(t)dt = \frac{h}{2e}$$

- Only 20 µV/JJ for 10 Gpulses/sec
  → need long JJ arrays & fast pulses
- Sequence of pulses generates ac waveform
  - determine sequence using delta-sigma algorithm
  - quantized area → calculable spectrum

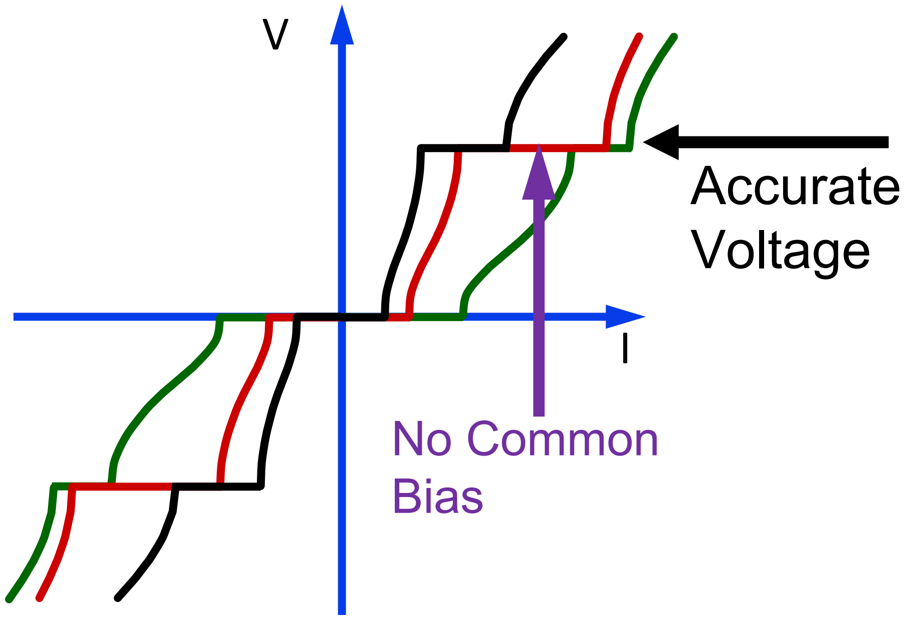


*Co-invented by Przybysz, Worsham, Hamilton and Benz in 1995

Practical Voltages Require Series Arrays



$$V_{n,N} = \frac{h}{2e} nNf$$



- Common bias requires
  - Uniform junctions
  - Uniform microwave power
  - Excellent microwave designs

Example calculated spectrum

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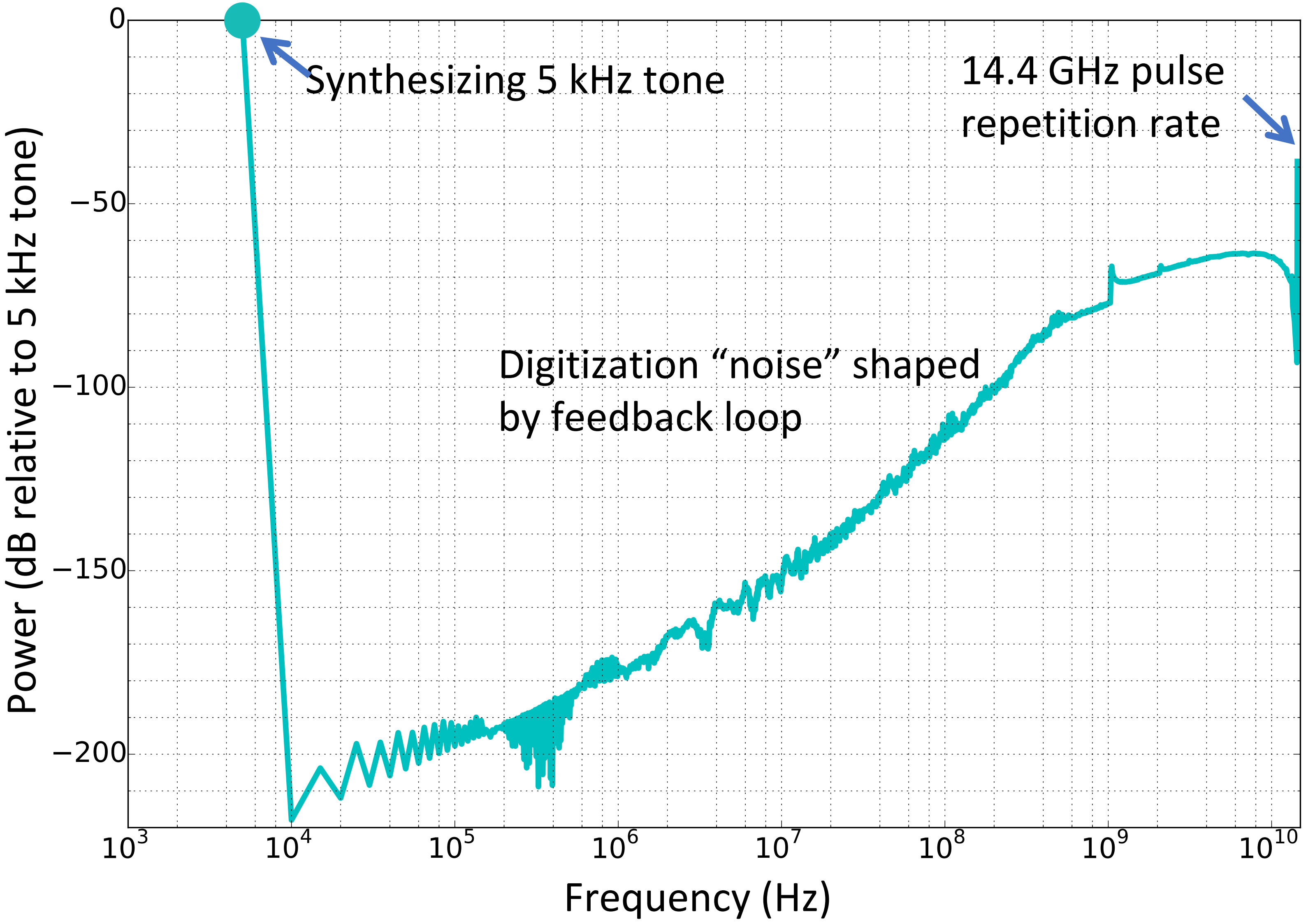
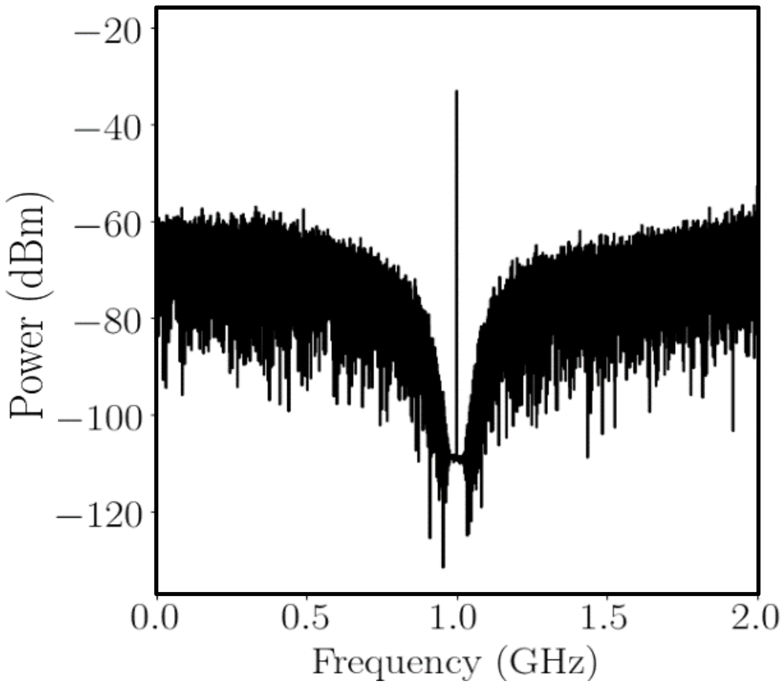


- Delta-sigma algorithm
  - feedback with loop filter
  - RF-JAWS uses bandpass loop filter
- Very small background
  - In filter bandwidth
- Calculation assumes:
  - δ-function JJ pulse shape
  - no feedthrough of bias pulses

$$\int V(t)dt = \frac{h}{2e}$$



Cryogenic Probe Station

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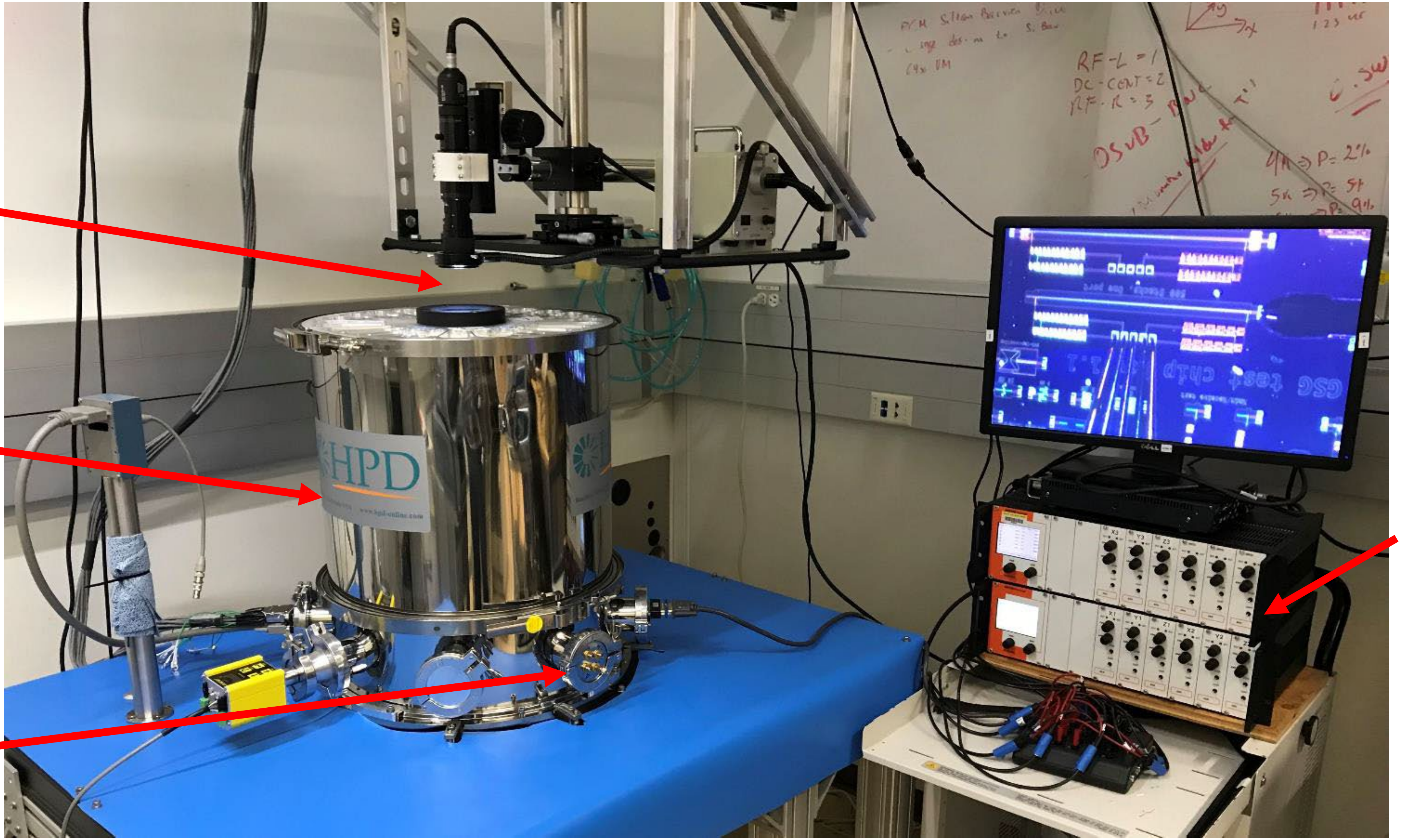
Optical window & camera

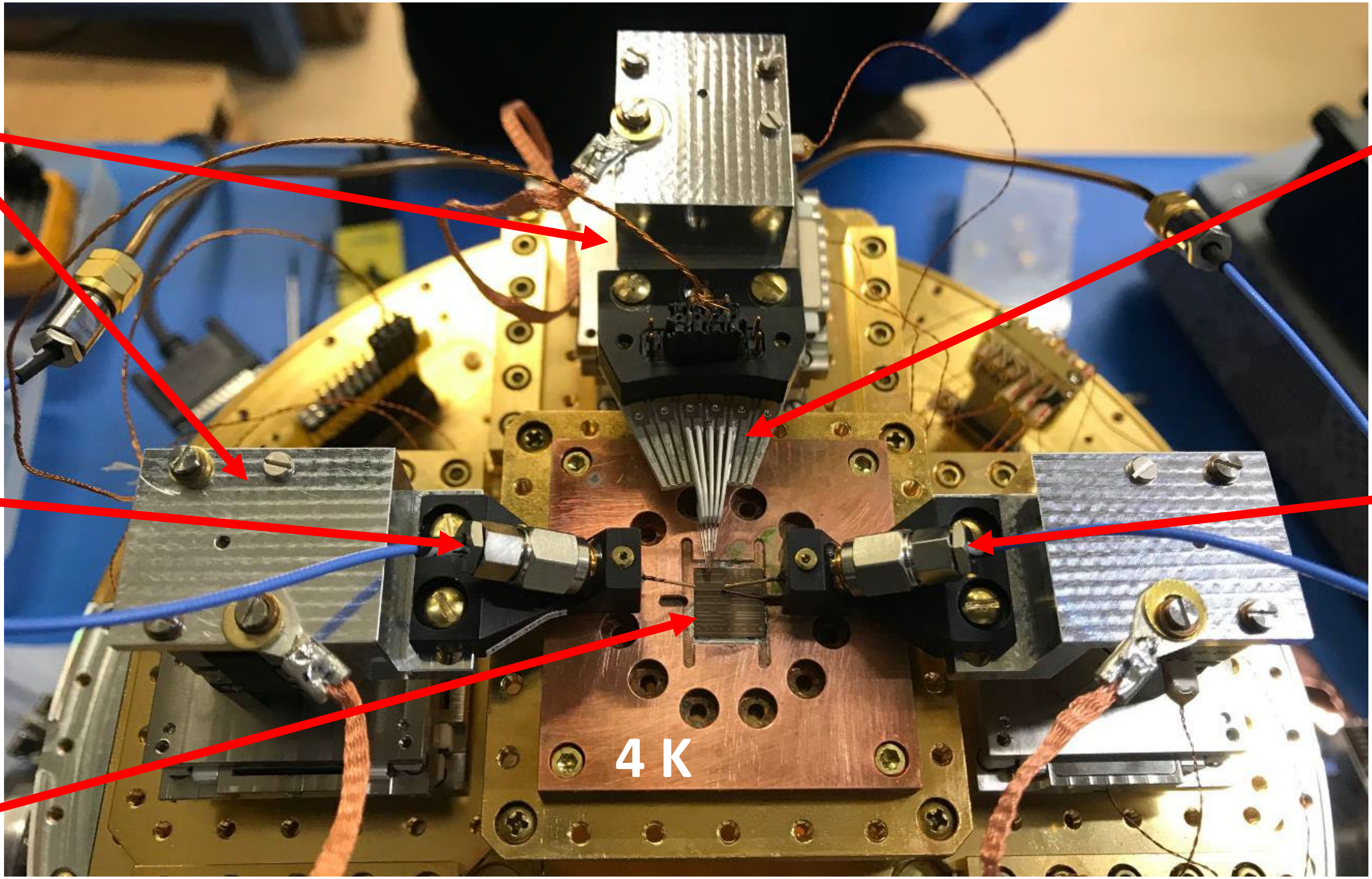
4 K cryocooled cryostat

RF ports



Piezoelectric probe control system

4 K Stage with JJ Devices & Standards



Attocube 3-axis positioners

DC probe

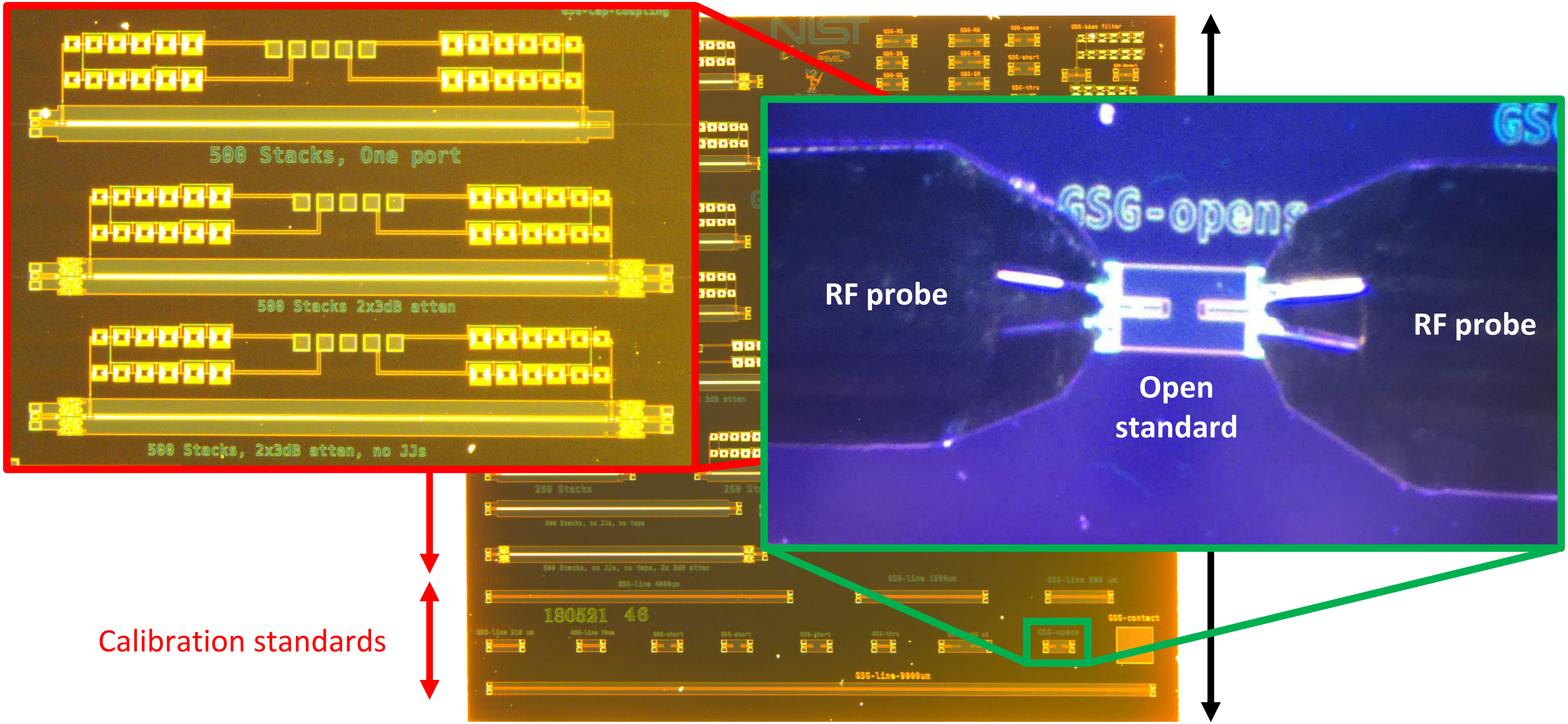
RF probe port 1

RF probe port 2

Device & standards chip

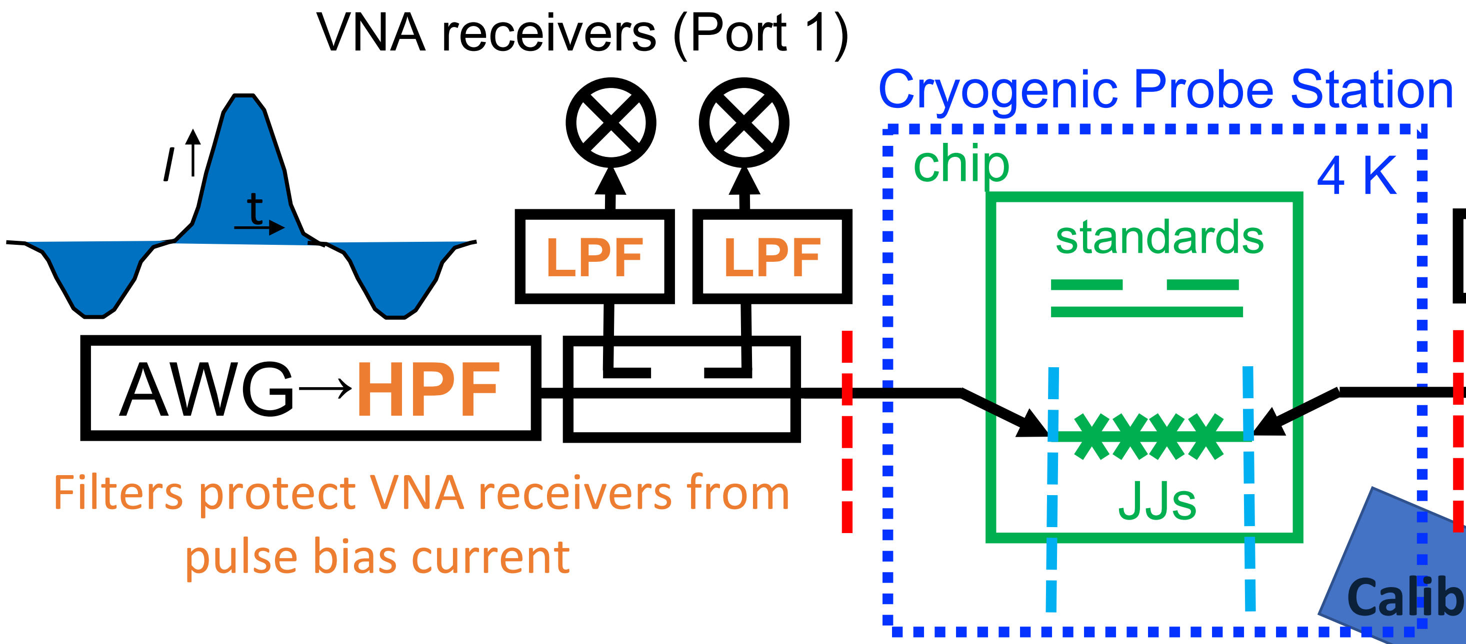
25 cm dia.

Single Chip: JAWS and RF Standards



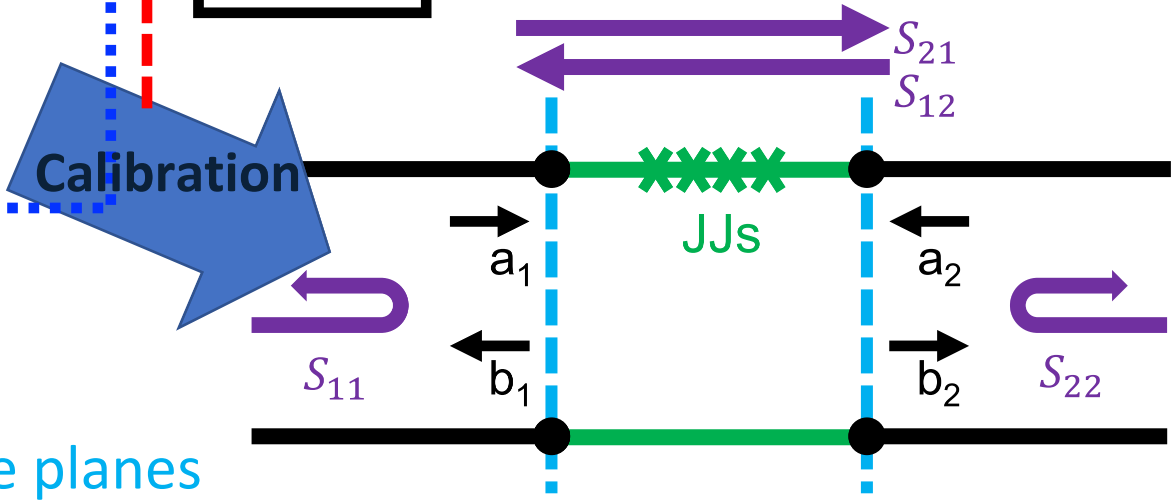
Calibration standards

Calibrated RF measurement of JJ voltage



Measure:

- **Pulsing JJs generate *a* and *b* waves**
- **Low-power scattering parameters *S***



Calibrations move measurements to JJ array

Two-stage LSNA calibration:

300 K coaxial reference planes

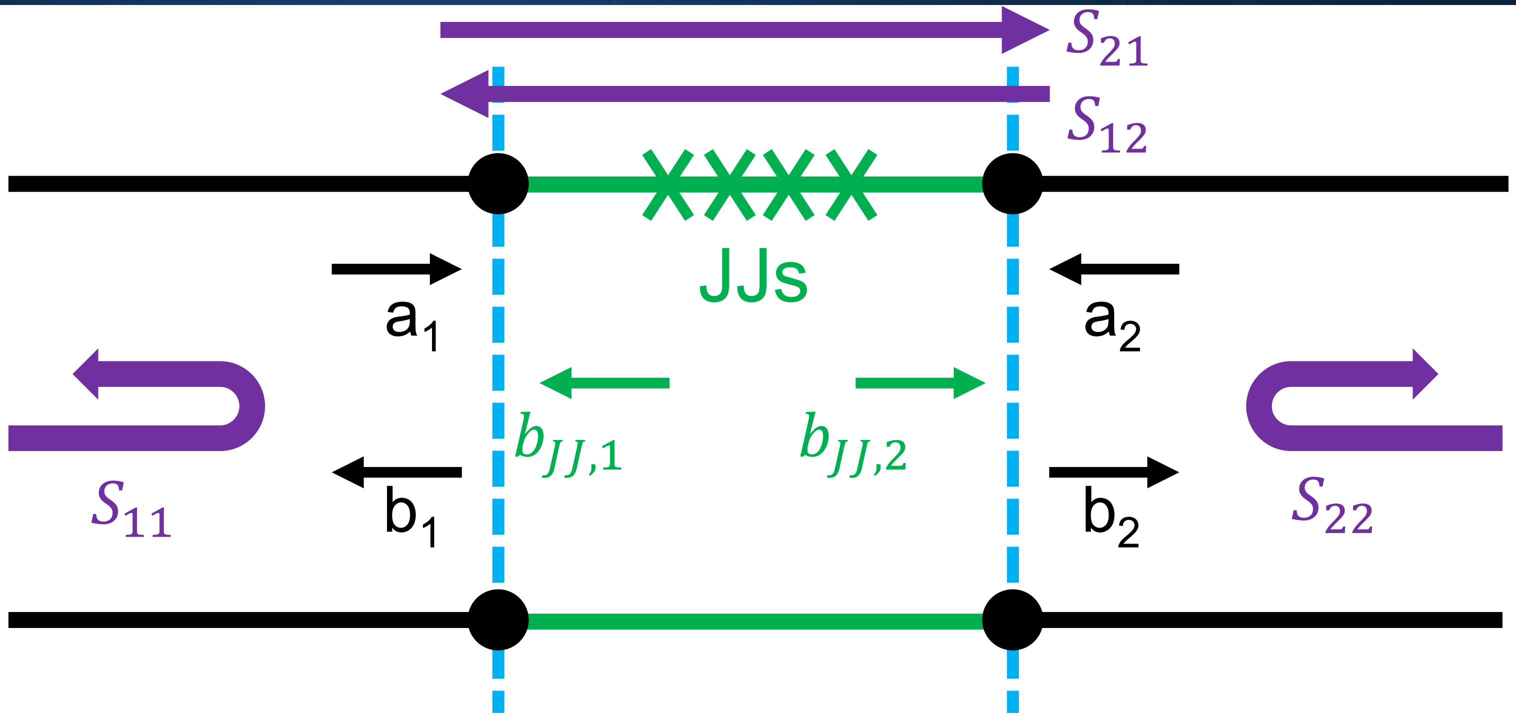
- SOLR calibration
- Absolute power & phase

4 K cryogenic reference planes

- SOLR standards & multiline TRL standards
- JJ devices

A. S. Boaventura et al., “Cryogenic Characterization of a Superconductor Quantum-Based Microwave Reference Source for Communications and Quantum Information”, in IEEE Trans. Appl. Superconductivity (2021), 10.1109/TASC.2021.3117610

Two-Port RF-JAWS



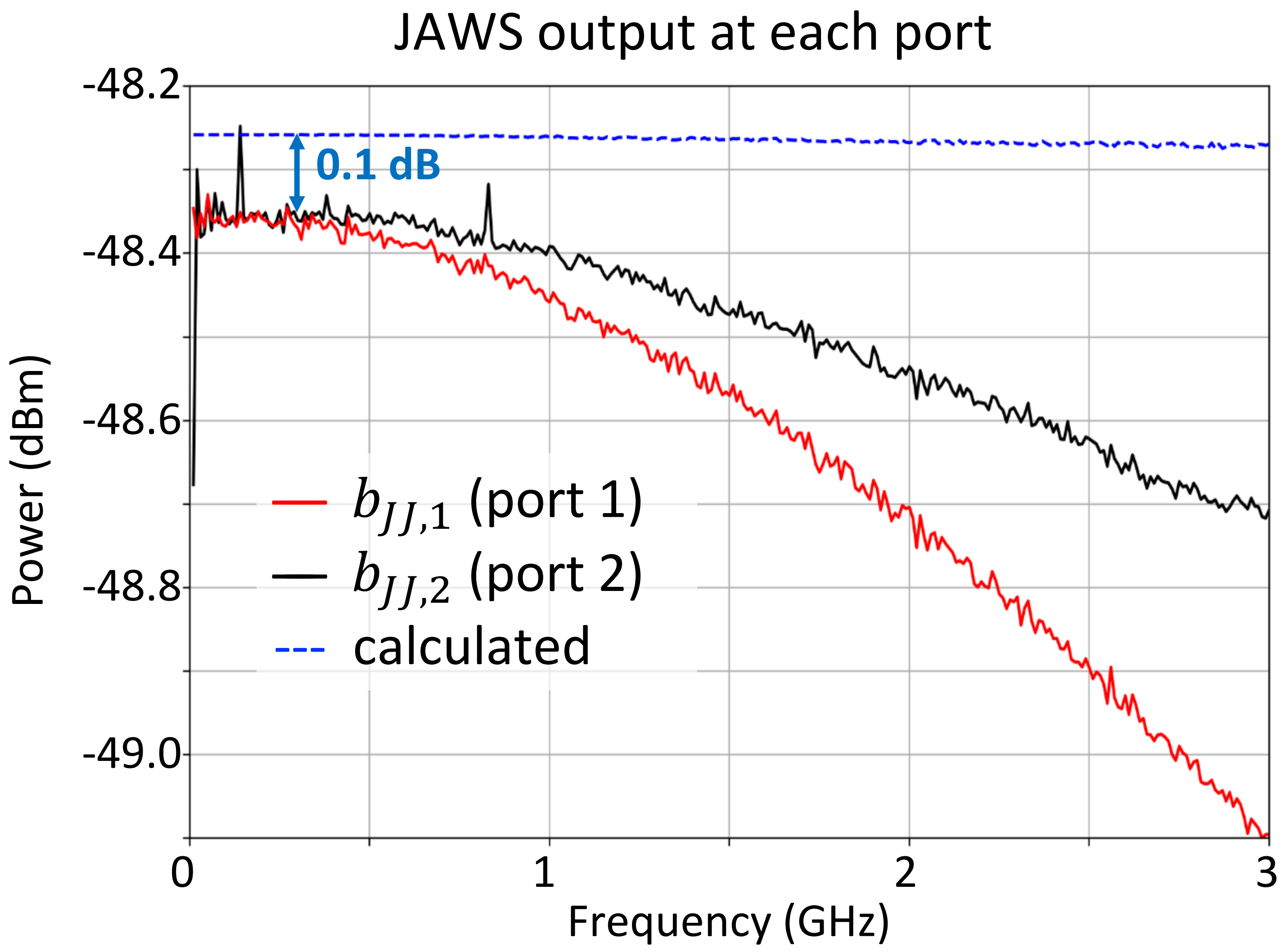
Determine measured JJ waves $b_{JJ,1}$ and $b_{JJ,2}$

from measured ***a*** and ***b*** waves and ***S*** scattering parameters

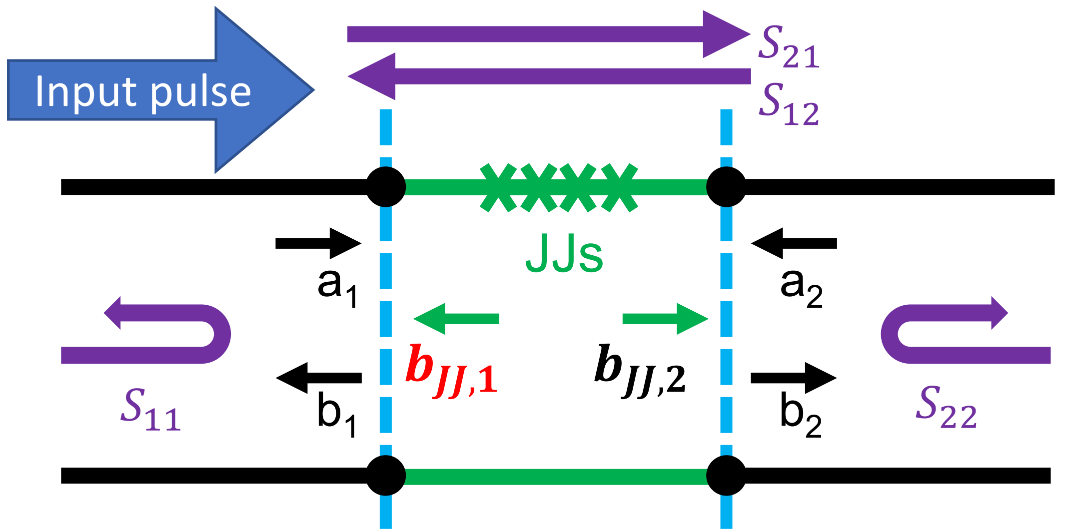
$$b_{JJ,1} = b_1 - a_2 * S_{12} - a_1 * S_{11} \qquad b_{JJ,2} = b_2 - a_1 * S_{21} - a_2 * S_{22}$$

Compare measured/calibrated value to quantum-based calculation (FFT of pulse pattern)

Preliminary Two Port Results



- 0.1 dB low-frequency offset
  - Origin under investigation
- High-frequency roll-off:
  - $b_{JJ,2}$ → finite JJ pulse width
  - $b_{JJ,1}$ → additional time-of-flight broadening of JJ pulse width



RF-JAWS Quantum Locking Range

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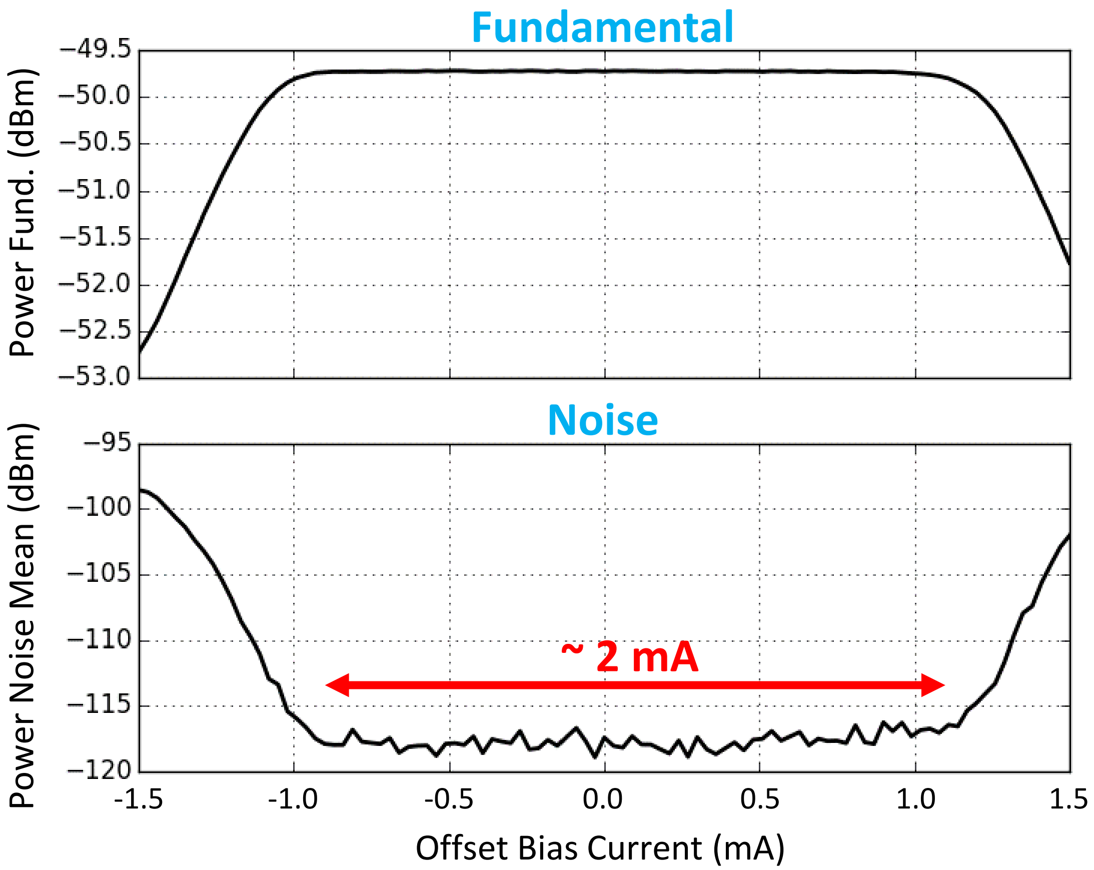
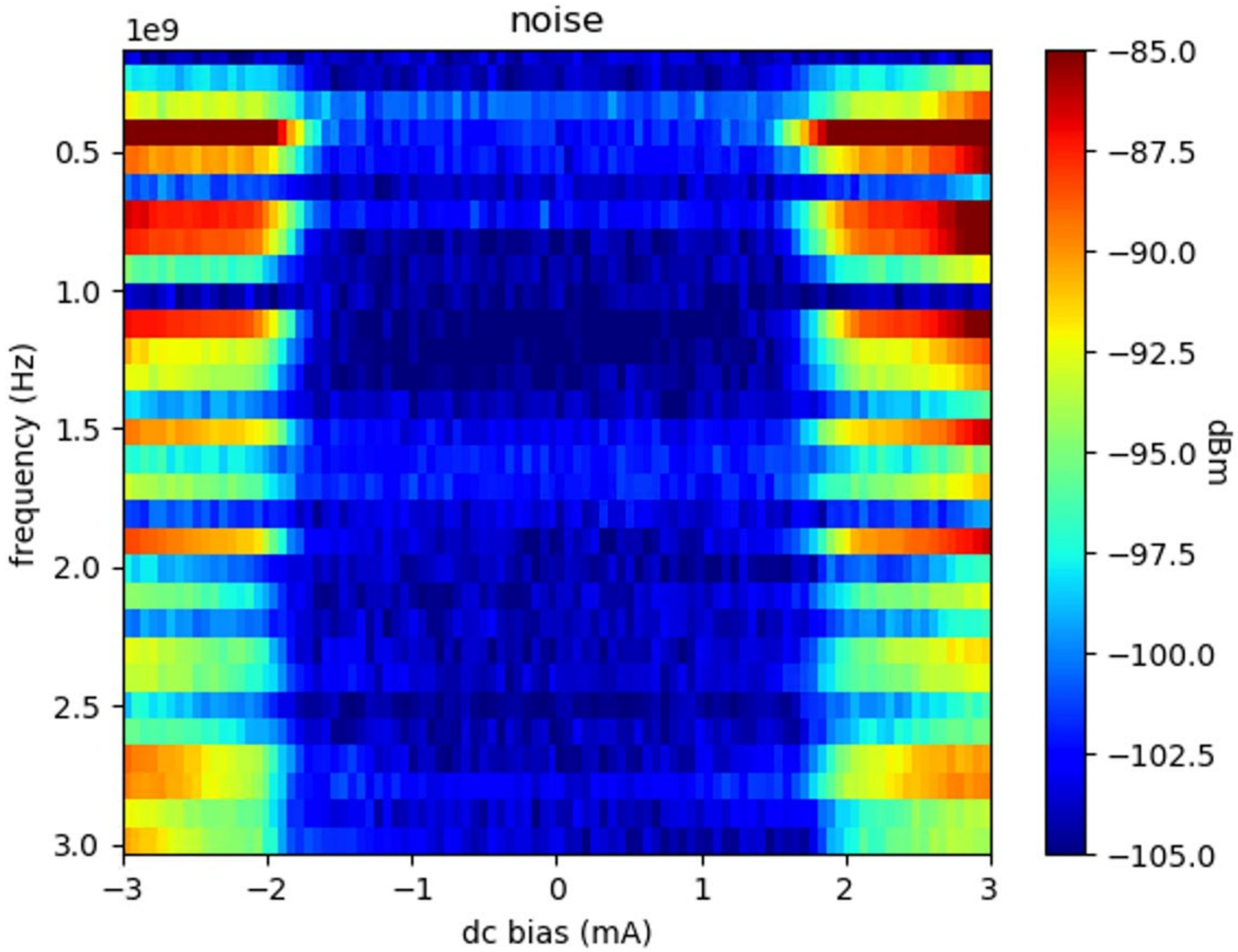
Single Frequency QLR Sweep





Preliminary QLR measurements

Two-Tone Delta-Sigma waveform

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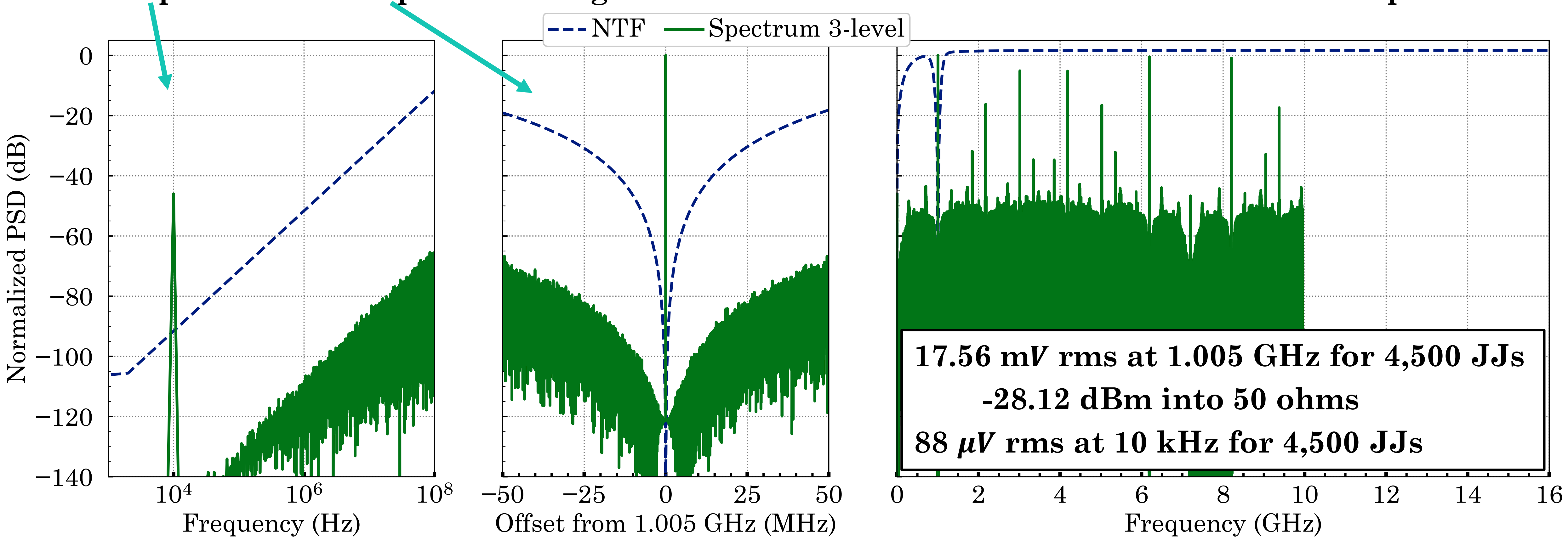
Low-pass and Band-pass delta-sigma modulators can be combined – NTFs are multiplied



Fast measurements at 10 kHz are used to verify and optimize 1.005 GHz synthesis

NTF – noise transfer function

A. A. Babenko et al., “A Microwave Quantum-Defined Millivolt Source”, in IEEE Trans. Microwave Theory and Techniques (2021), 10.1109/TMTT.2021.3121425

Conclusion

- JAWS is a quantum-based voltage source
  - Uses Josephson junctions to convert frequency -> voltage
  - Mature quantum-based DC voltage source (PJVS)
  - Young quantum-based low-frequency voltage source
  - We disseminate PJVS & LF-JAWS as NIST Standard Reference Instruments (SRI)

$$\int V(t)dt = \frac{h}{2e}$$

- Recently started RF-JAWS program: GHz quantum-based arbitrary signal source
  - Generate single-sines for power/phase calibrations
  - Generate multi-tones and pulses for measuring DUT non-linearities
  - Pulsed qubit control
  - Applications increase with frequency and power

- Currently focusing on step 1: Cryogenic probe station measurements
  - Comparing LSNA calibrated measurement to calculated value
  - 0.1 dB agreement at low frequencies and -48 dBm
    - qualitatively understood deviations <0.5 dB up to 3 GHz

- Working on faster JJs and faster pulses, higher frequencies and higher powers