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Development and Applications of Josephson Arbitrary Waveform Synthesizers

Sam Benz
Superconductive Electronics Group
NIST Communications Technology Laboratory
Boulder, Colorado

Workshop on Superconducting Electronics: Devices, Circuits & Systems (USC4SCE), April 6, 2025

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Superconductive Electronics Group

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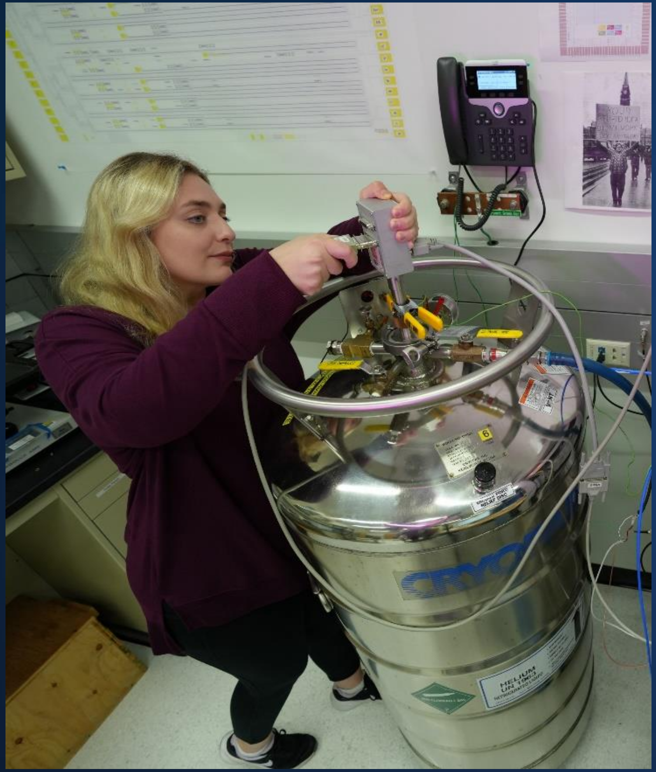
Superconductive Electronics Group Research



- DC, AC & RF quantum-based Josephson Voltage Standards (JVS)
- Independent test & measurement of industry energy-efficient superconducting devices
- Develop precision measurements and scalable control circuits for quantum computing

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Outline

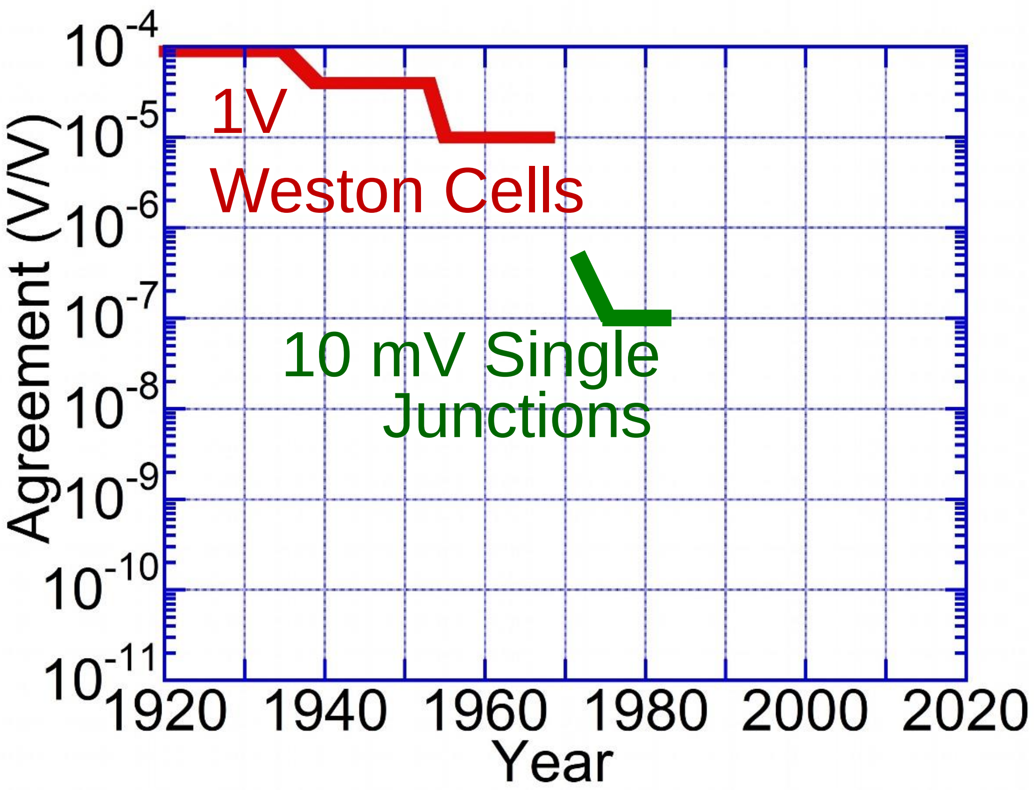
- Josephson Voltage Standard History
  - Junction Development
  - Packaging and system evolution
- Josephson Arbitrary Waveform Synthesizer = **JAWS**
  - Applications
  - Operation
  - Circuit Development
- Making it practically useful for Metrologists
  - Reaching practical voltages above 1 V
  - Pulse generator development
  - Cryogenic integration & System Development
- Extending to Megahertz and Gigahertz Frequencies
  - **VHF JAWS** for power calibration
  - **RF JAWS** for linearity and precise synthesis of arbitrary waveforms

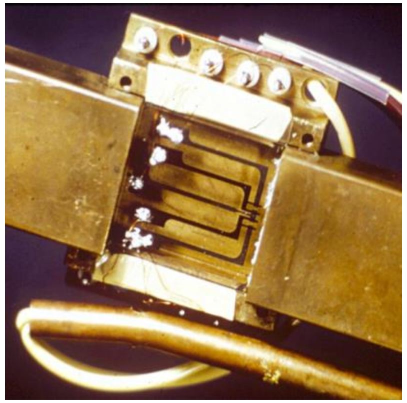
DC Voltage Artifact Standards Replaced by Josephson Standards

Electrochemical Battery

CdHg Weston Cell

Vary in time & with environmental conditions





Single Josephson Junctions

Intrinsically accurate & based on quantum effects

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DC Voltage Artifact Standards Replaced by Josephson Standards

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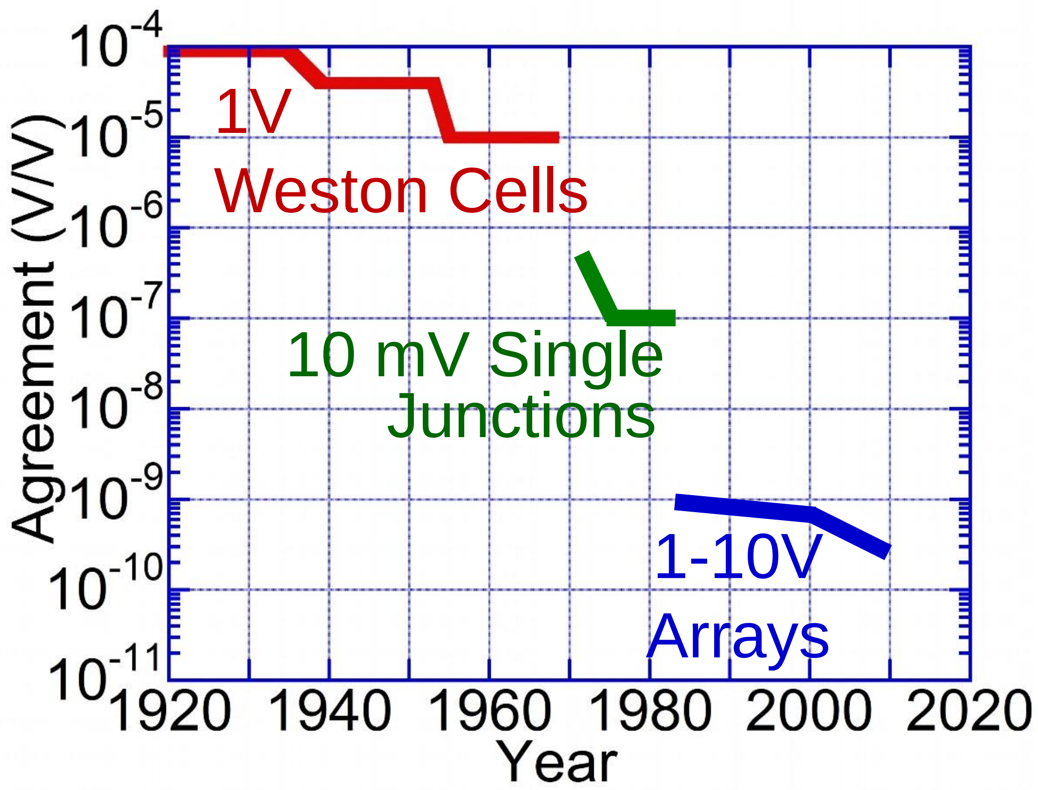
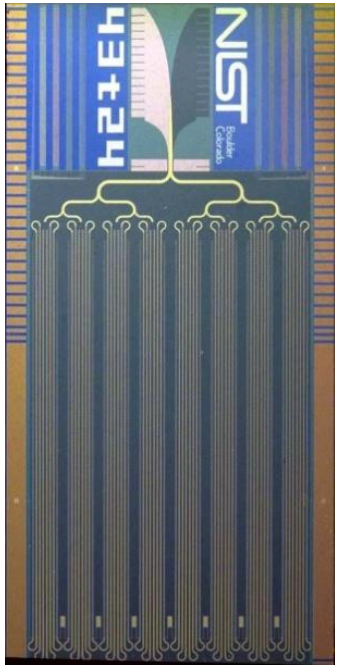
Vary in time & with environmental conditions





Conventional JVS

Intrinsically accurate & based on quantum effects

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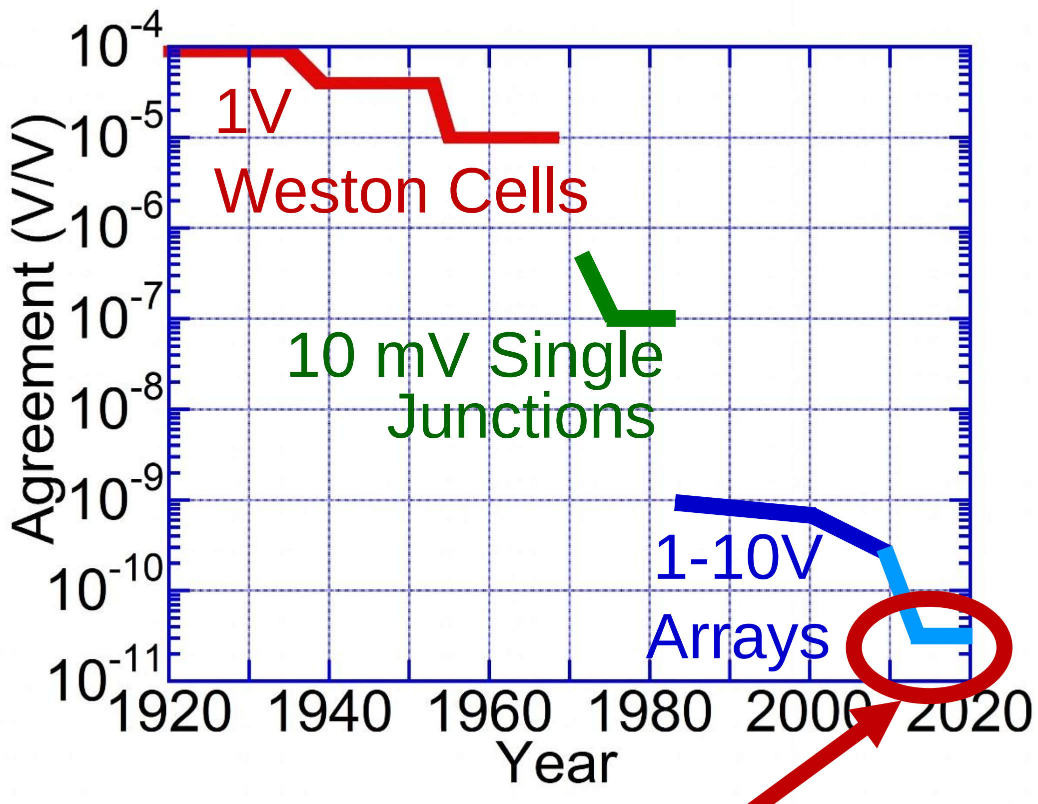
DC Voltage Artifact Standards Replaced by Josephson Standards

Electrochemical Battery

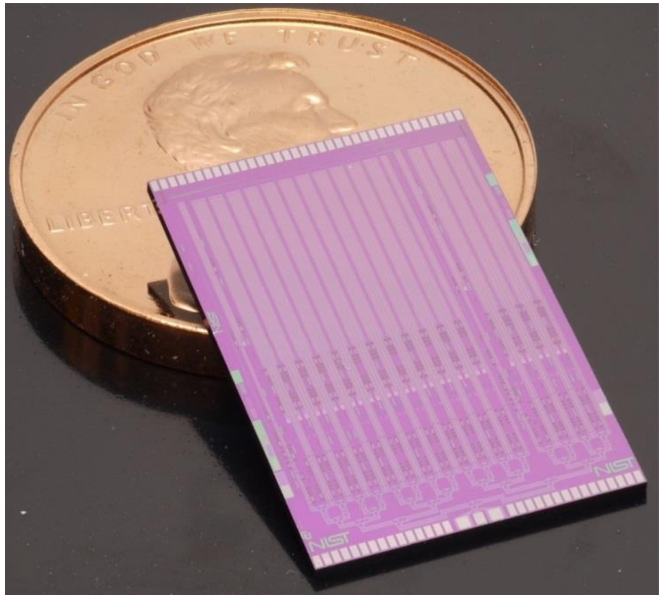
CdHg Weston Cell

Vary in time & with environmental conditions



PJVS DC to DC comparison: 3×10^{-11}

A Rüfenacht, et al., Metrologia vol. 55, no. 5, pp. S152–S173, July 6, 2018



Programmable JVS

Intrinsically accurate & based on quantum effects

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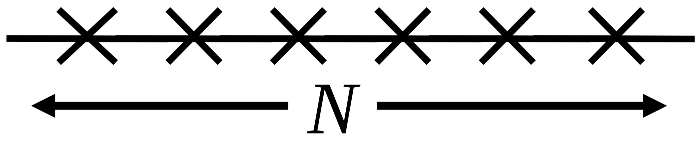
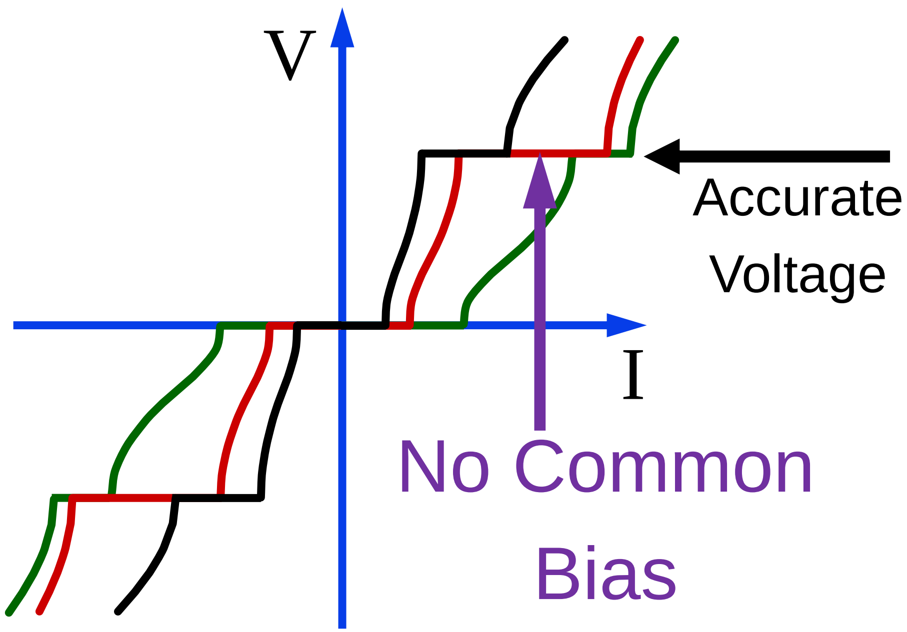
Practical Voltages Require Series Arrays

- h/2e is SMALL ≈ 2 μV/GHz
  - 20 GHz produces ≈ 40 μV steps
- 10 V is the desired output voltage
  - Large series arrays are required



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



- Common bias requires
  - Uniform junctions
  - Uniform microwave power

Practical voltages require
long arrays of uniform junctions
& excellent microwave designs

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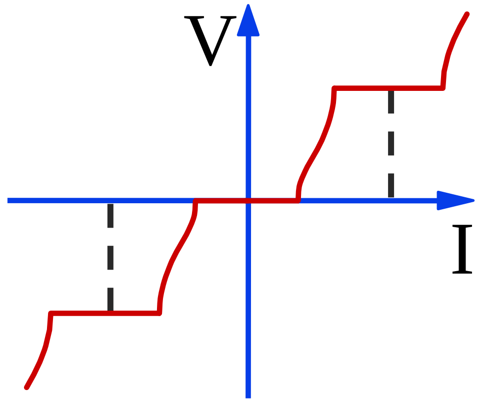
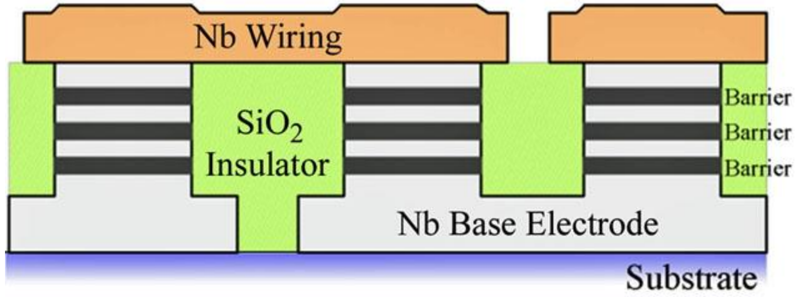
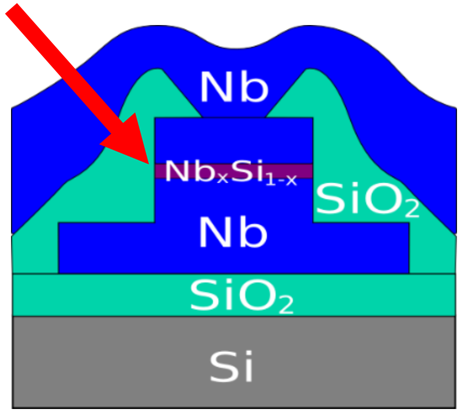
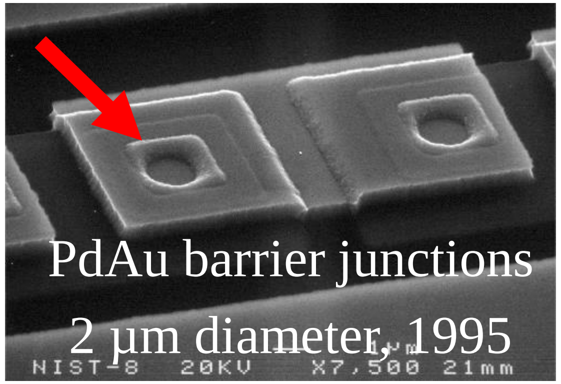
Damped-Junction Development



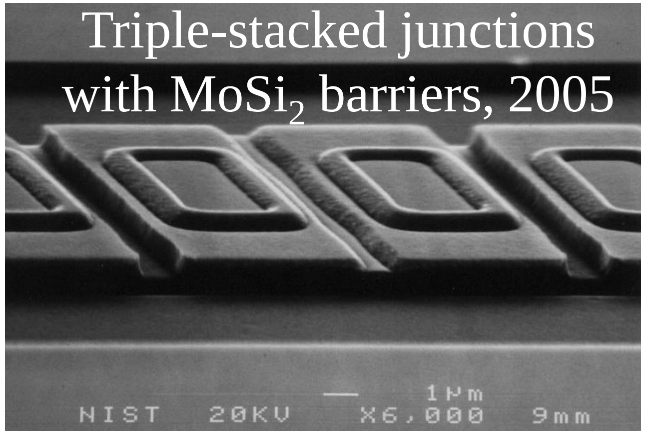


Nb_xSi_{x-1} Barriers

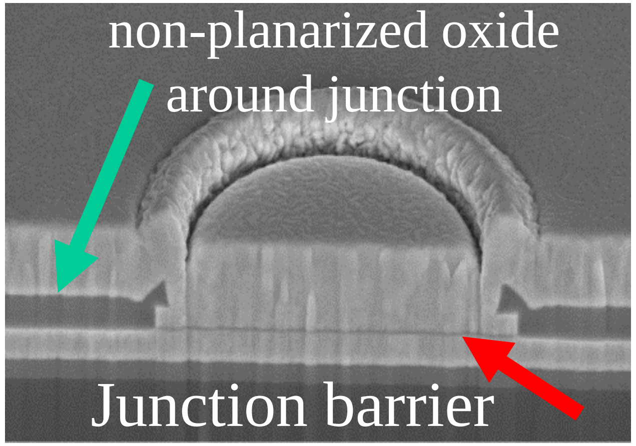




PdAu barrier junctions
2 µm diameter, 1995



Triple-stacked junctions
with $MoSi_2$ barriers, 2005



non-planarized oxide
around junction

Junction barrier

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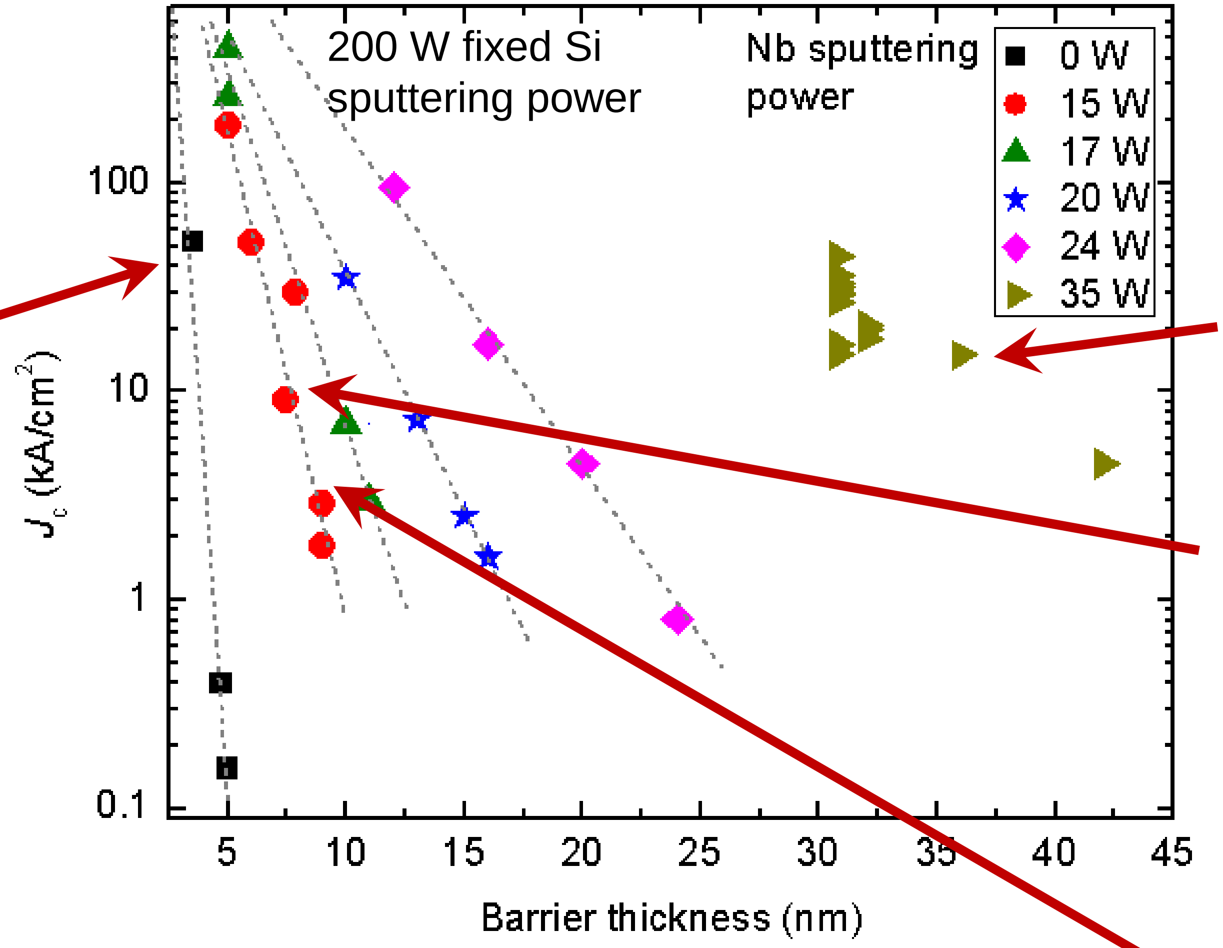
NIST

Tunable Nb_x-Si_{1-x} Barriers for Many Applications

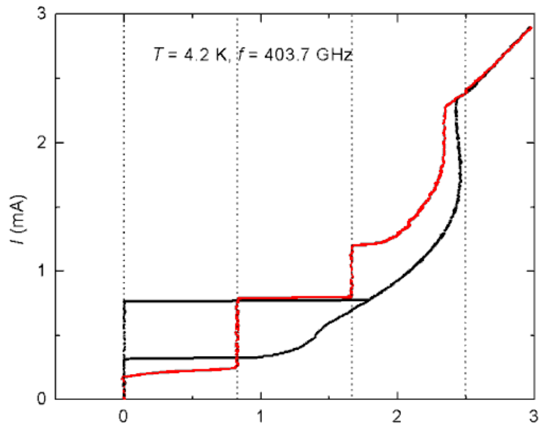


400 GHz FIR optically driven JJ

9 W Nb power, d = 4.6 nm

I_cR_n = 1 mV

J_c = 13 kA/cm²



15-20 GHz pulse-ACJVS & PJVS

x = 0.15, d = 35 nm

$\rho_{4.2K}$ = 1 m Ω cm

I_cR_n = 30 μV

J_c = 11 kA/cm²

170 GHz Digital circuits

15-16 W Nb power, d = 10 nm

I_cR_n = 100-130 μV

J_c = 5.5 kA/cm²

70 GHz NIST/PTB 10V PJVS

x = 0.08, d = 11 nm

$\rho_{4.2K}$ = 700 mΩ cm

I_cR_n = 150 μV

J_c = 2.5 kA/cm²

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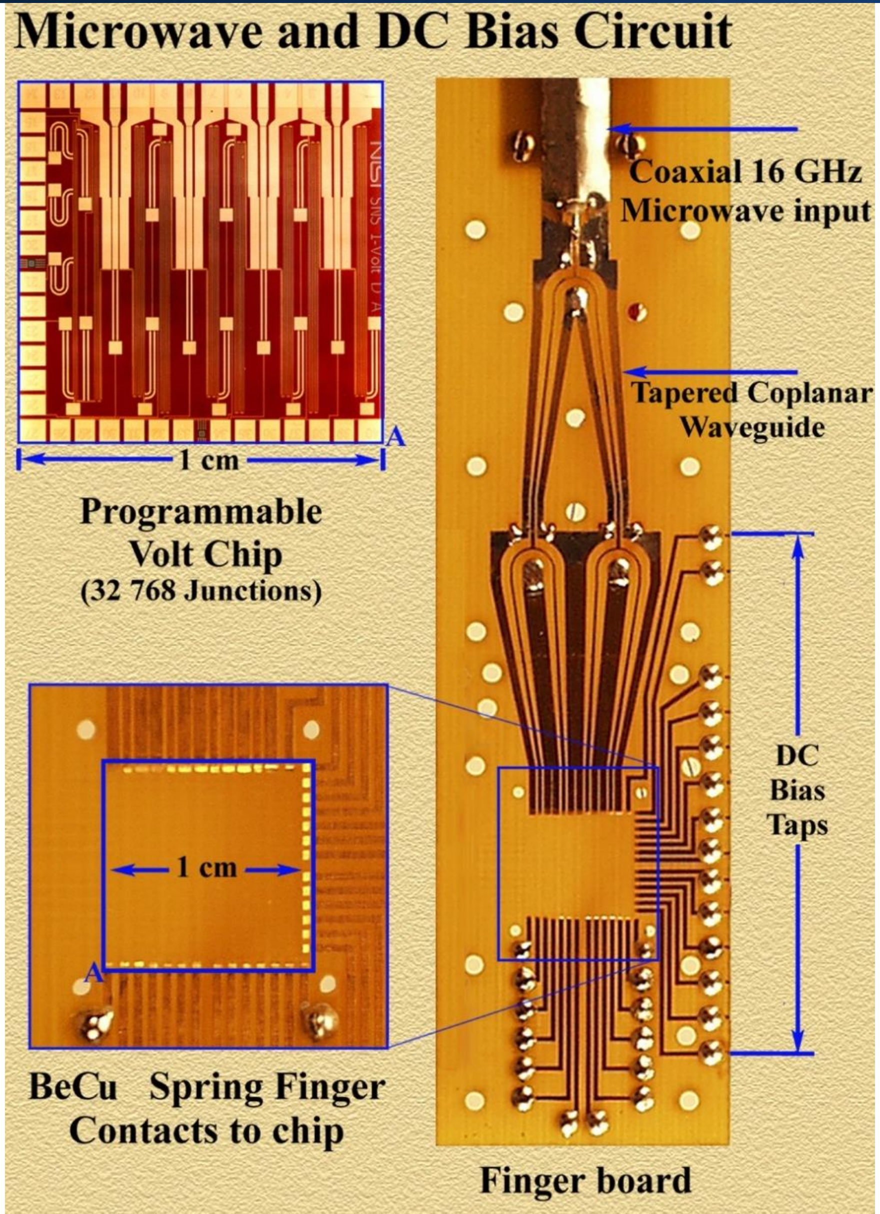
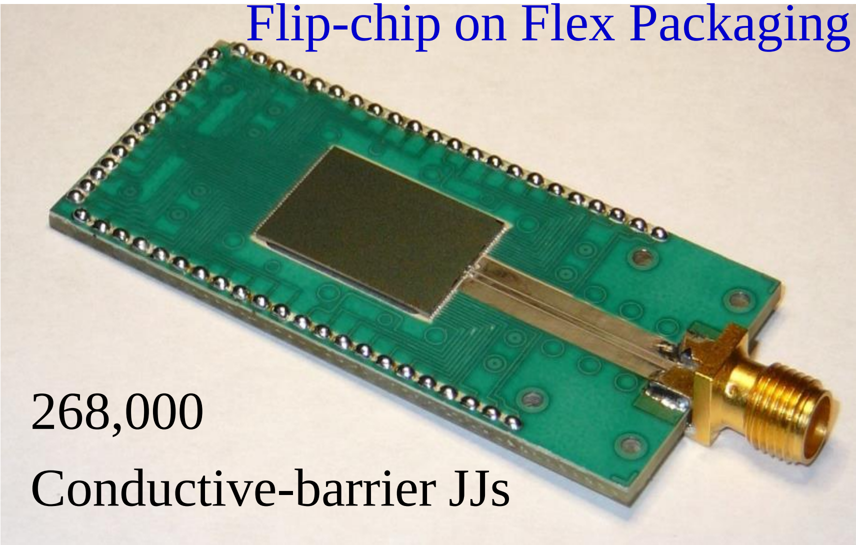
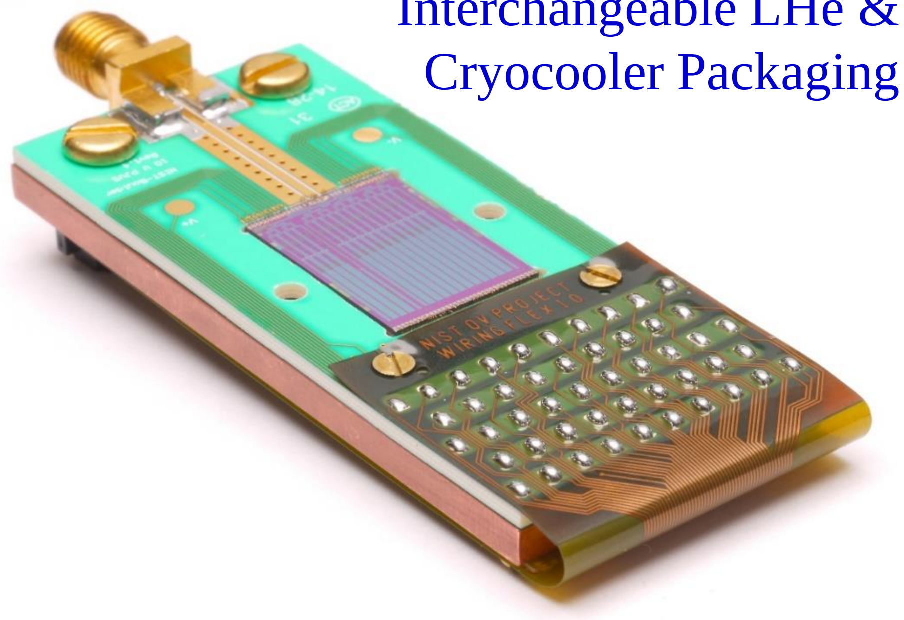
Packaging of Josephson Voltage Standards



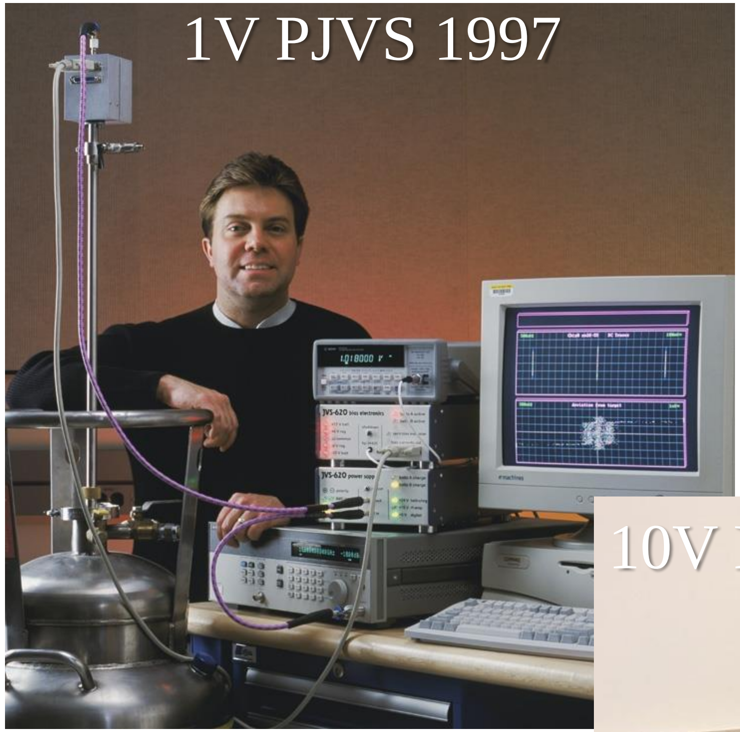


Interchangeable LHe &
Cryocooler Packaging

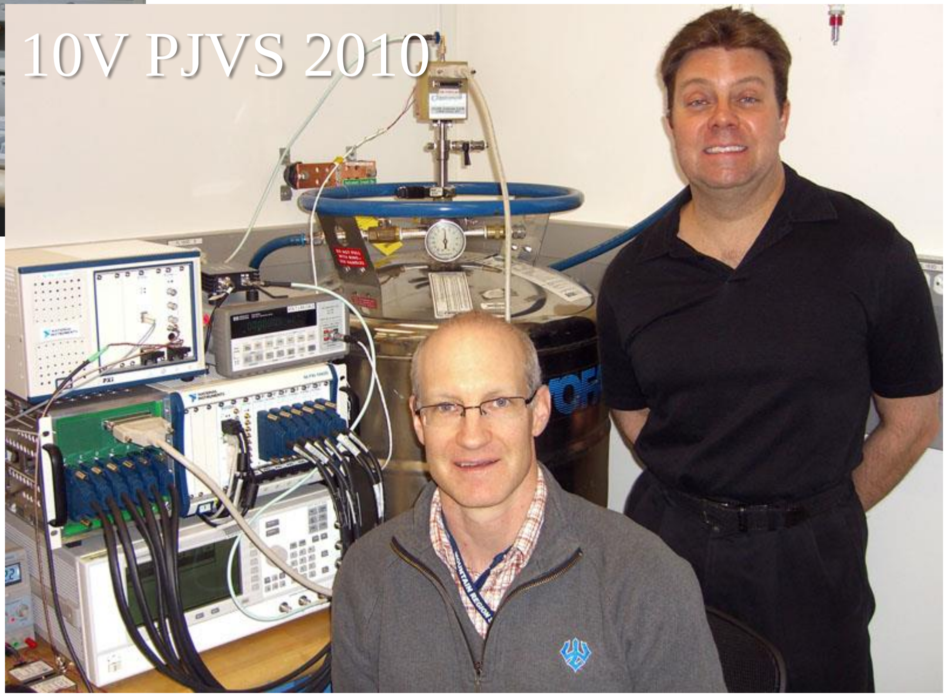


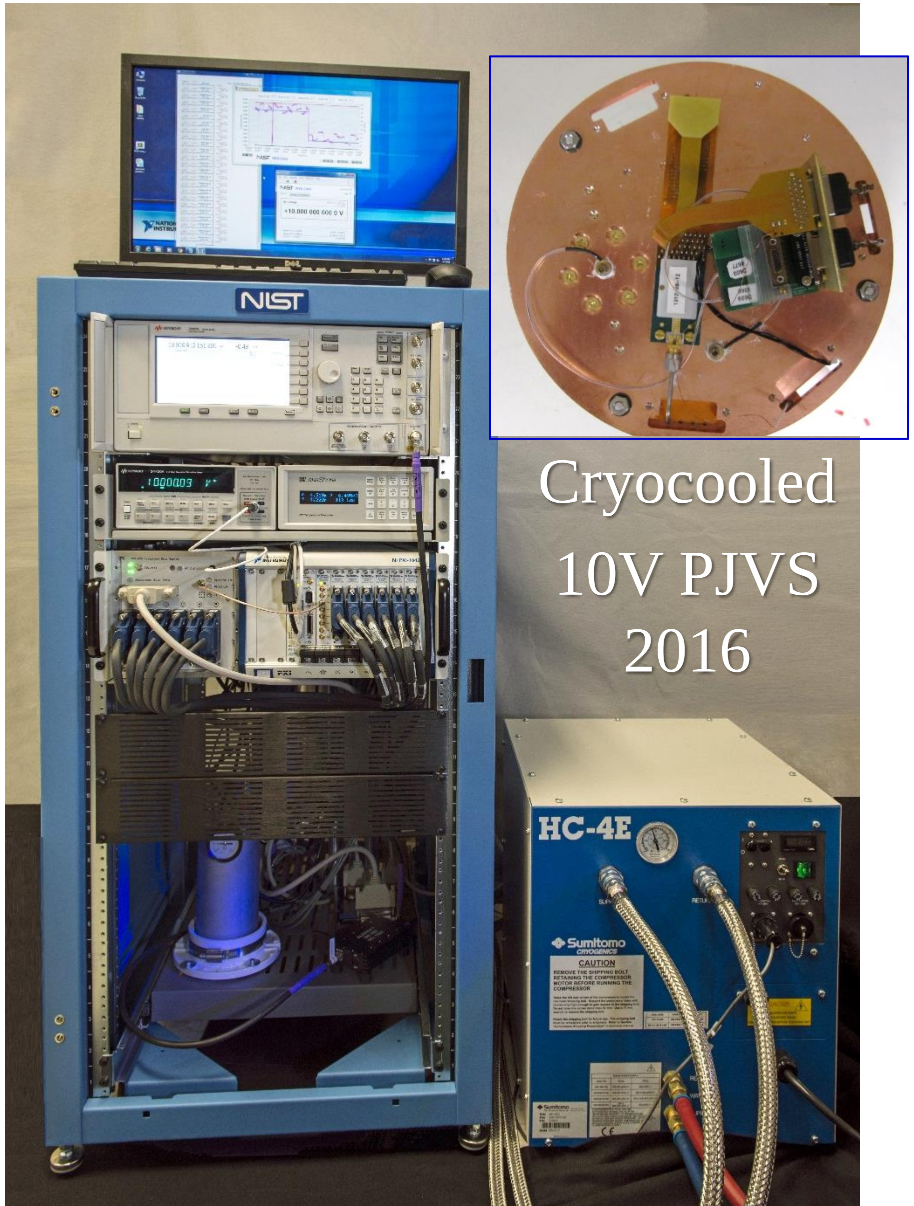
IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 59, May 2025. Presentation given at 22nd Biennial U.S. Workshop on Superconductor Electronics, Devices, Circuits, and Systems Santa Fe, New Mexico, April 6-10, 2025.

PJVS System Development



- Goal: COTS Parts
- Full automation
  - Quantum Operation
  - Applications
- No Liquid Helium





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SRI 6000 Series Programmable Josephson Voltage Standard (PJVS)

The prices listed below are for the individual instrument and do not include costs related to the final measurement calibration performed before delivery or post-delivery installation and training. The related Calibration Service ID for the SRI is 68000S. To obtain a quote for the instrument and calibration services, please contact Sales and Customer Service by phone at 301-975-2200 or email at srminfo@nist.gov.

6000e	Cryo-cooled 10V PJVS, with water-cooled compressor	$332,900
6000h	Cryo-cooled 10V PJVS, with water-cooled compressor, without synthesizer	$329,100
6000i	Cryo-cooled 10V PJVS, with air-cooled compressor	$338,000
6000l	Cryo-cooled 10V PJVS, with air-cooled compressor, without synthesizer	$334,100
6000m	Cryopackaged 10V PJVS chip	$56,900
6000n	Cryopackaged 2V PJVS chip	$29,900
6000f	Cryo-cooled 10V PJVS, with water-cooled compressor (US GSA Authorized)	Superceded by SRI 6000e
6000j	Cryo-cooled 10V PJVS, with air-cooled compressor (US GSA Authorized)	Superceded by SRI 6000i
6000o	Upgrade existing NIST-installed Liquid-helium-cooled PJVS to Cryocooler with water-cooled compressor	Superseded by 6000h
6000p	Upgrade existing NIST-installed Liquid-helium-cooled PJVS to Cryocooler with air-cooled compressor	Superseded by 6000i

Technical Contact: Paul Dresselhaus

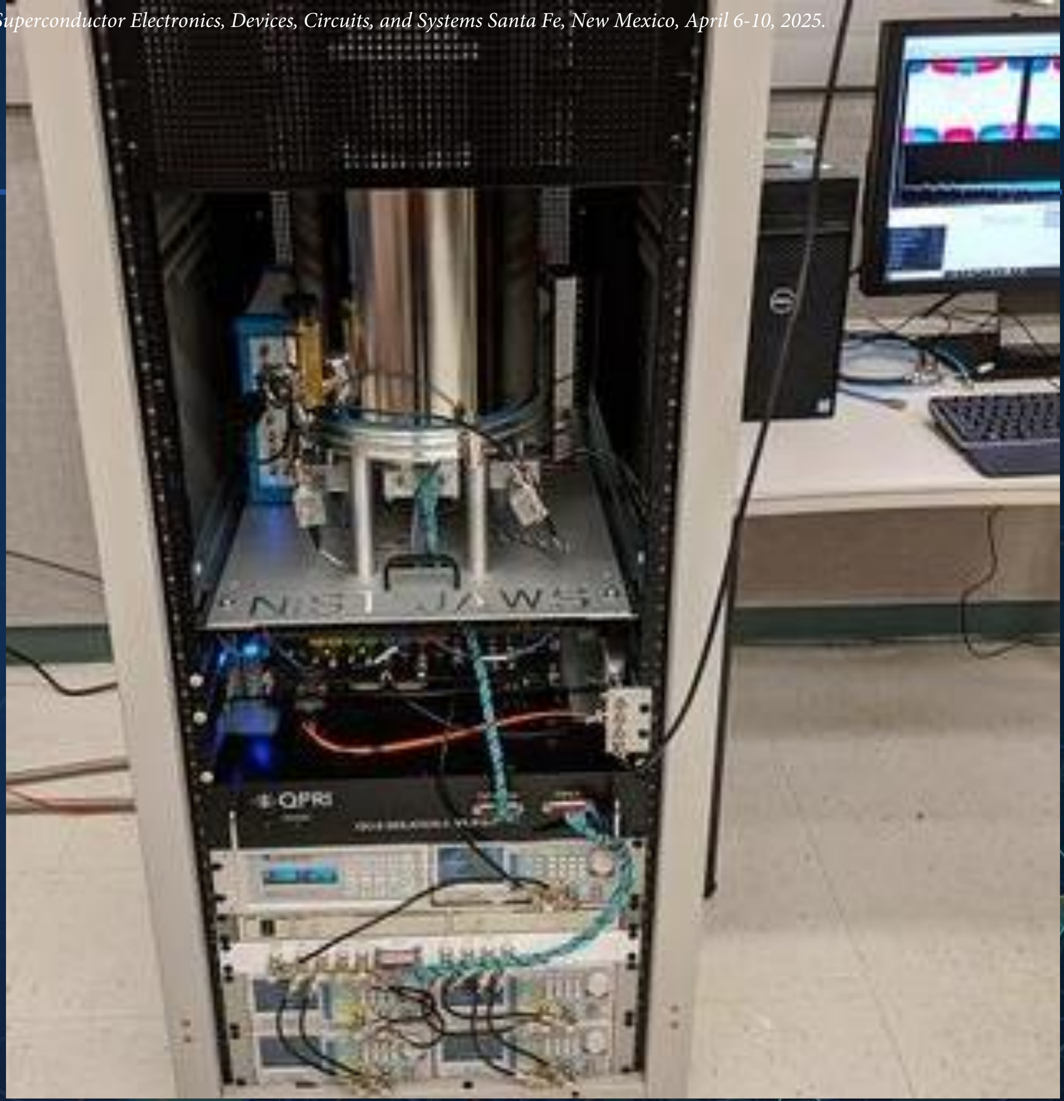
The Programmable Josephson voltage standard (PJVS) is an instrument that generates stable, quantum-accurate, direct-current (DC) voltages that are programmable over the range from -10 volts to +10 volts. The quantum accuracy of these voltages is derived from the Josephson Effect such that every superconducting Josephson junction in the PJVS circuit produces a voltage precisely proportional to the frequency of the applied microwave bias signal.

The PJVS with its quantum accurate dc voltages can serve as a primary voltage standard with accuracy of parts in 10^{10} (determined through intercomparison with another quantum voltage standard) or as a stable, programmable source for precision measurements, metrology experiments or calibrations. For example, the PJVS can be used to calibrate Zener references (typically parts in 10^7 depending on the measurement instruments and Zener noise) as well as the amplitude-dependent gain and linearity of digital voltage meters.

The PJVS is also capable of generating stepwise-approximated waveforms or sine waves with a rise time between voltage steps that is less than 2 microseconds. The AC voltage of the stepwise waveforms do not have quantum accuracy because the transitions between the steps are bias dependent. A differential-sampling measurement technique with an integrating sampling digital voltmeter is used with the step-wise waveforms to calibrate the ac voltage of commercial voltage calibration sources at frequencies up to a few hundred hertz with a typical measurement uncertainty of parts in 10^7, depending on the phase and amplitude stability of the source.

NIST National Institute of Standards and Technology U.S. Department of Commerce

Josephson Arbitrary Waveform Synthesizer JAWS for Audio Frequency AC Voltage Calibrations



- N E Flowers-Jacobs, et al., "Development and Applications of a Four-Volt Josephson Arbitrary Waveform Synthesizer," Proceedings of the 2019 ISEC, 28 July-1 Aug. 2019, Riverside, CA, USA
- N E Flowers-Jacobs, et al., "Calibration of an AC Voltage Source Using a Josephson Arbitrary Waveform Synthesizer at 4 V," 32st CPEM 2020 Digest, Aug. 24 - 28, 2020, Denver, CO.

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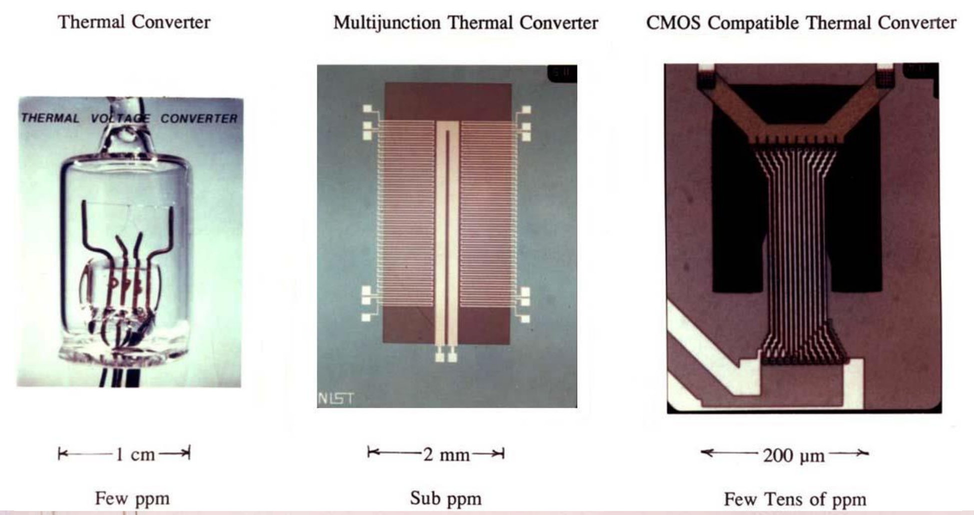
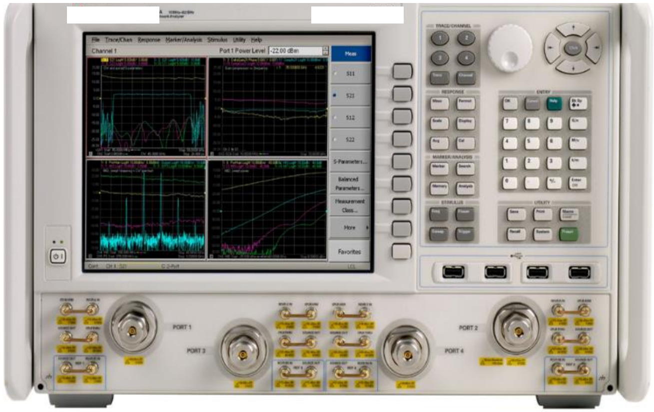
AC Voltage & RF Standards and Instruments

Audio Frequency Thermal Converters



RF Power Meters, Analyzers & Amplifiers



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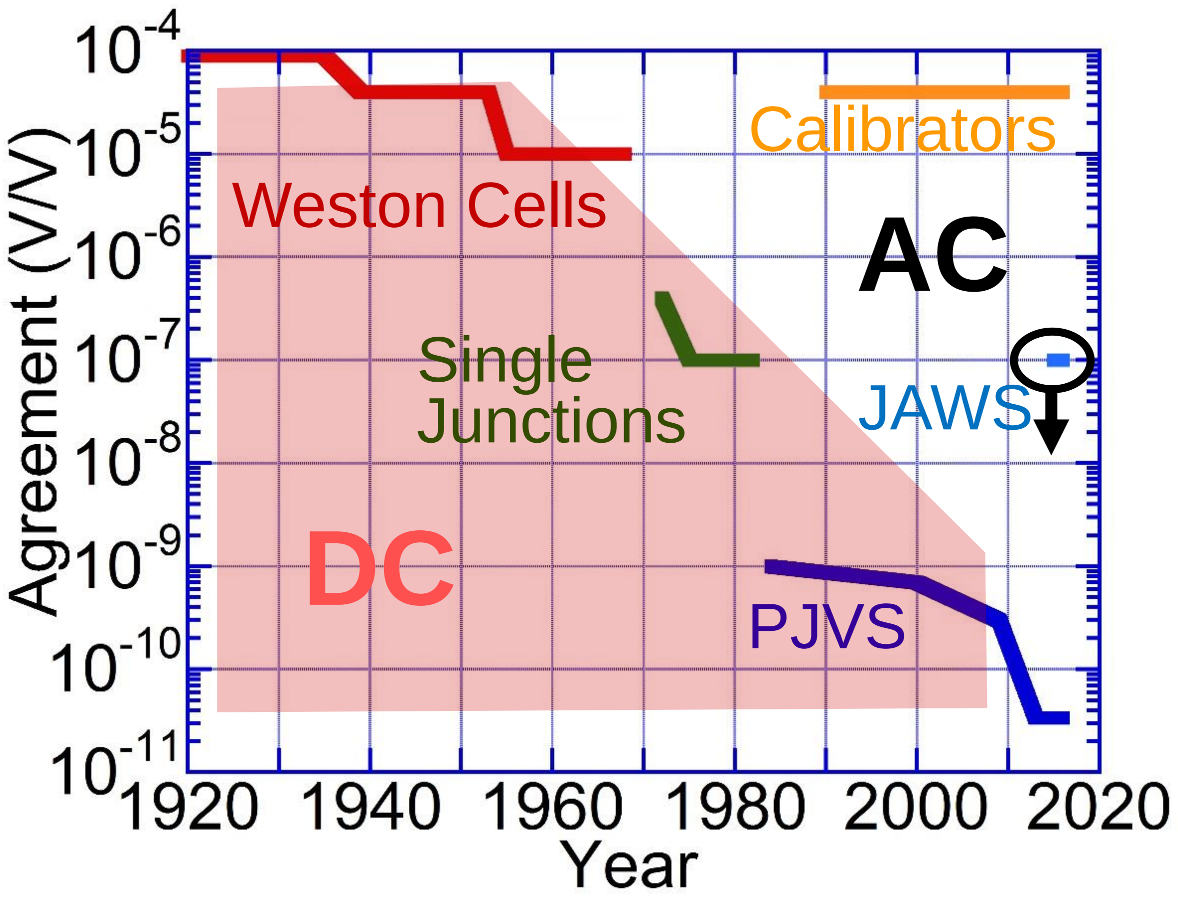
Complement Voltage Calibrators with JAWS Sources



Statistical uncertainty below 10^{-7} for **1 V** JAWS intercomparison

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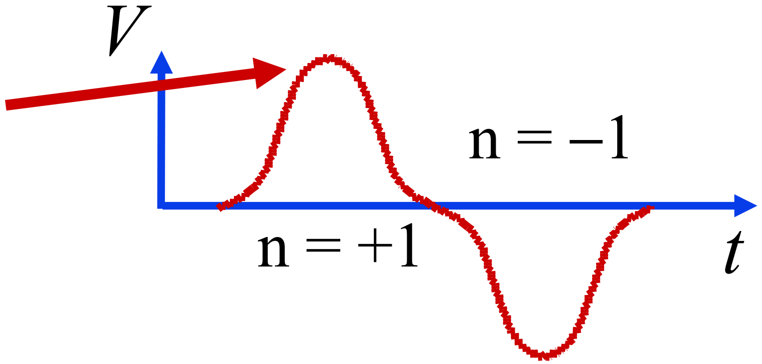
Josephson Arbitrary Waveform Synthesizer

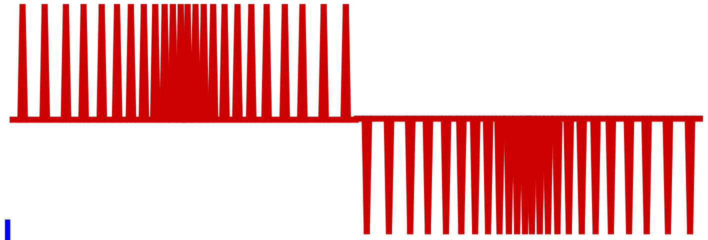
Co-invented in 1995 by NIST & Westinghouse researchers, H. Worsham, J.X. Przybysz, S. Benz, and C. Hamilton

- Synthesized voltage SOURCE
  - Pulse-driven AC Josephson Voltage Standard
  - Josephson DAC
  - Perfectly quantized JJ pulse areas

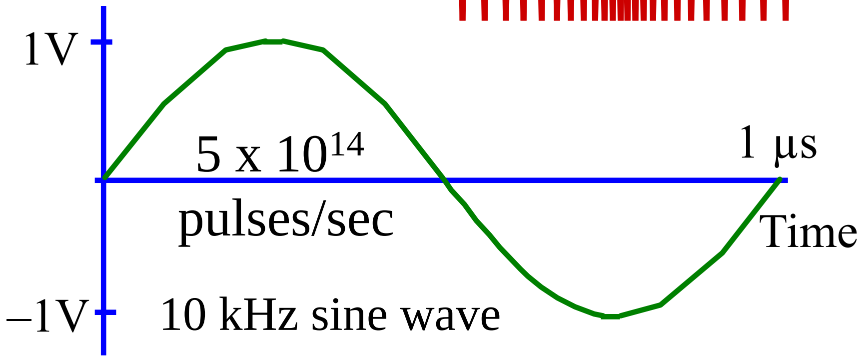
$$\int_{pulse} V(t) = \frac{h}{2e}$$



- Directly control every JJ pulse
  - Digital signal provided by high-speed bitstream generator (or AWG)



- Arbitrary waveform synthesis
  - Timing, placement and polarity of pulses precisely determines the voltage waveform
  - Accuracy ensured



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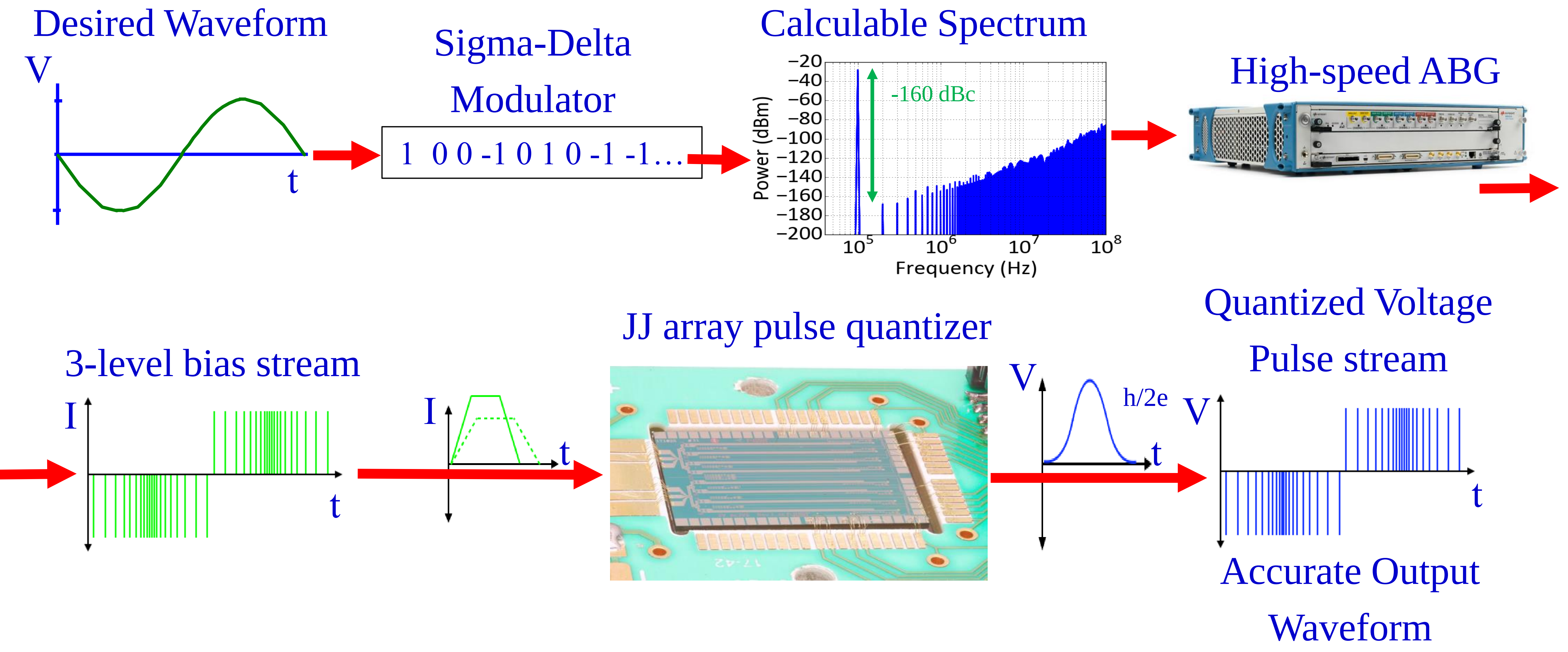
Quantized Pulses Enable Accurate Waveform Synthesis

Josephson Arbitrary Waveform Synthesizer (JAWS)



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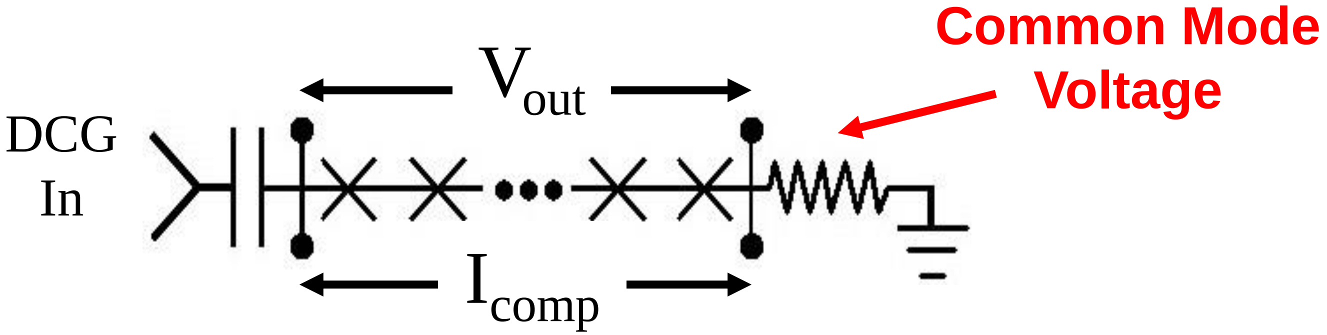
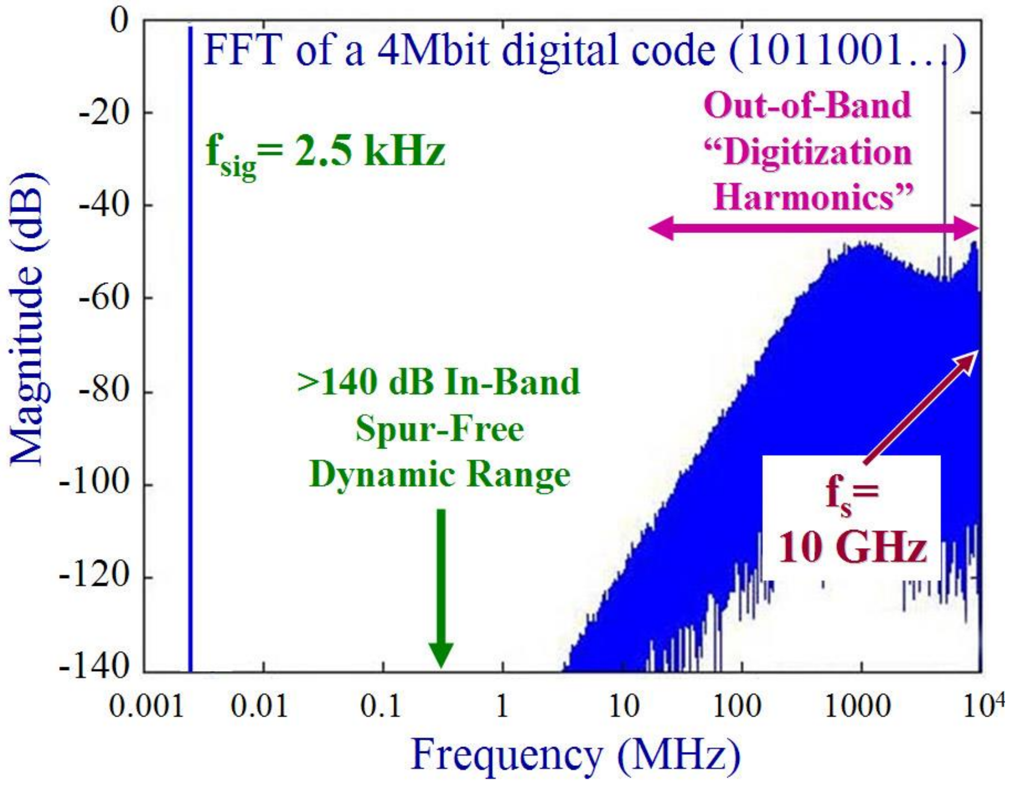
NIST

JAWS Circuit Challenges

- Junction dissipation limits array length
- ABG drive has a signal at the same synthesized frequency
  - 50 Ω microwave termination
  - Output voltage is NOT referenced to ground
  - Multiple arrays cannot be connected in series
  - Inductance between the JJs creates error signals
- Solution: AC coupled bias
  - DC Blocking capacitors
  - Compensation current I_{comp}
  - Zero-compensation pulses biasing





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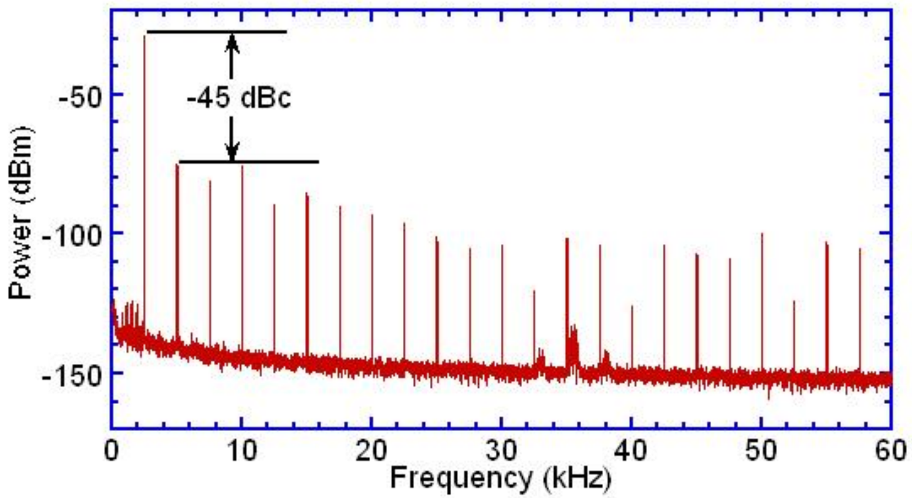
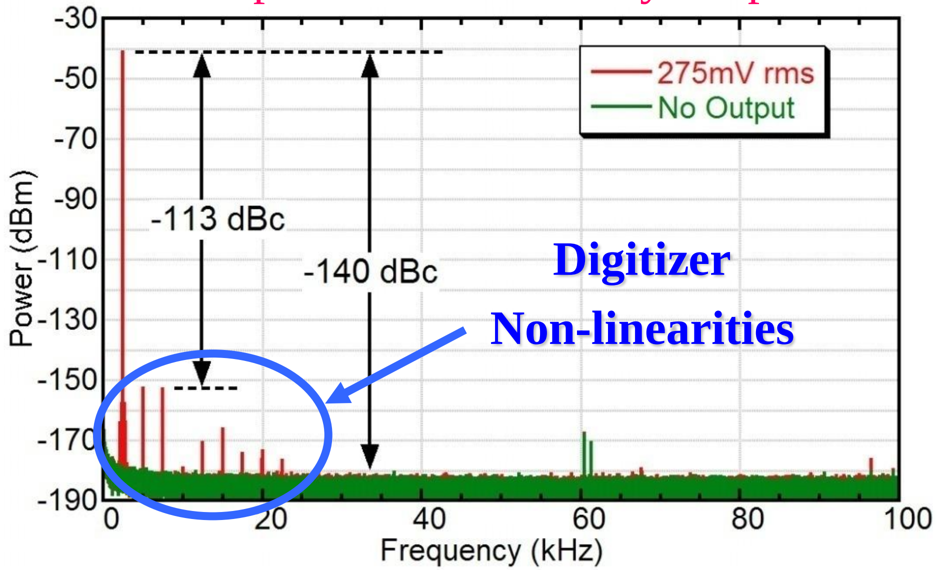
Bitstream Generator Limitations

Semiconductor Code Generator Output



Josephson Junction Array Output



- Sine Wave Synthesis
  - 2.5 kHz tone
  - 4,000,000 bit code length
  - 2-level output, NOT 3-level
  - 15 GHz sine, 10 GHz clock
- Semiconductor code generator (ABG)
  - **-45 dBc** Harmonic distortion
- 2 ac-coupled arrays in series
  - 10,240 junctions
  - 275 mV rms voltage
  - **-140 dBc** Harmonic distortion (to measured noise)

Perfect quantization produces intrinsically accurate waveforms

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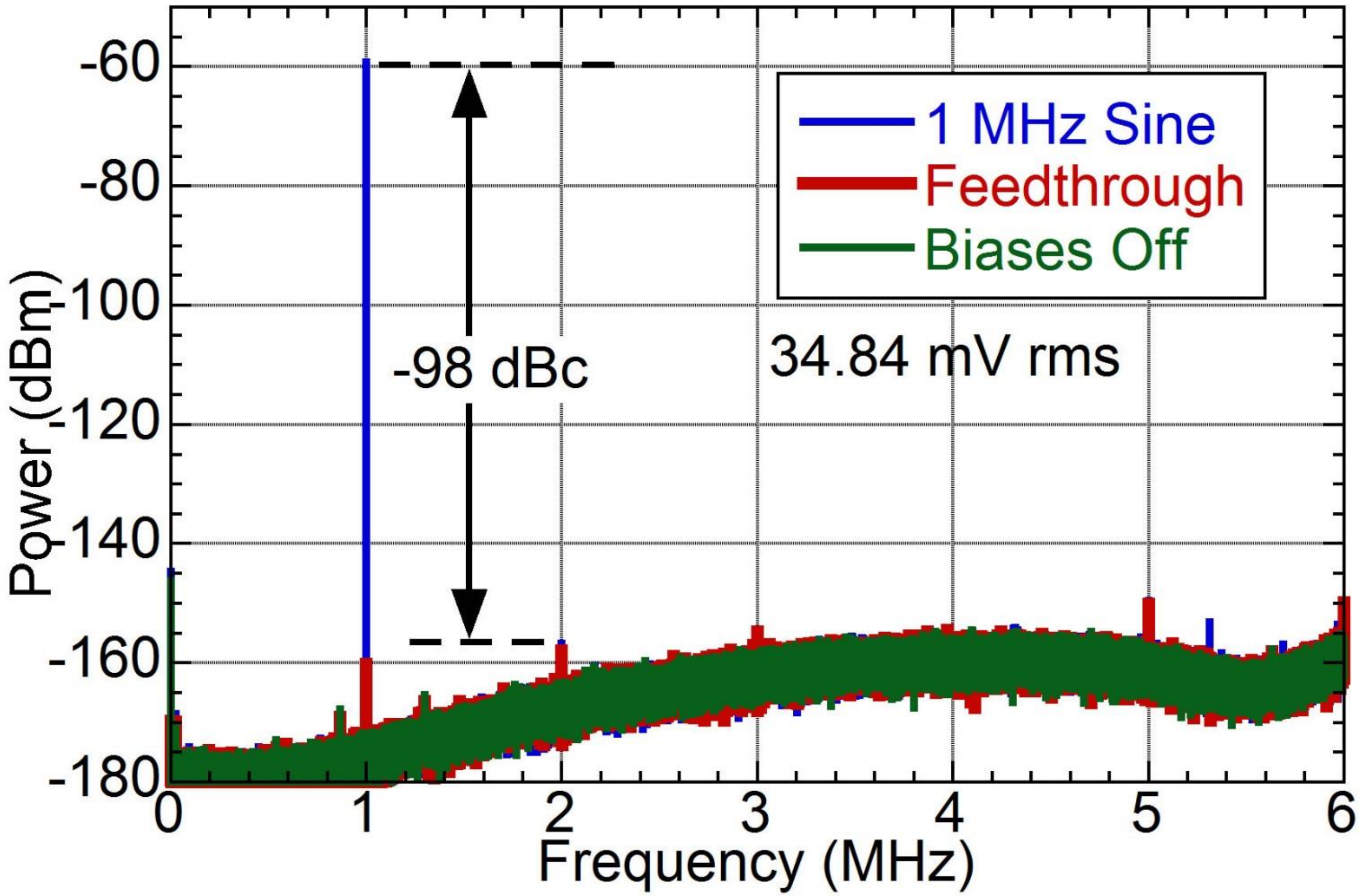
1 V RMS Voltage & Feedthrough Error

1 MHz sinewave, 1 mA margins, 1 array



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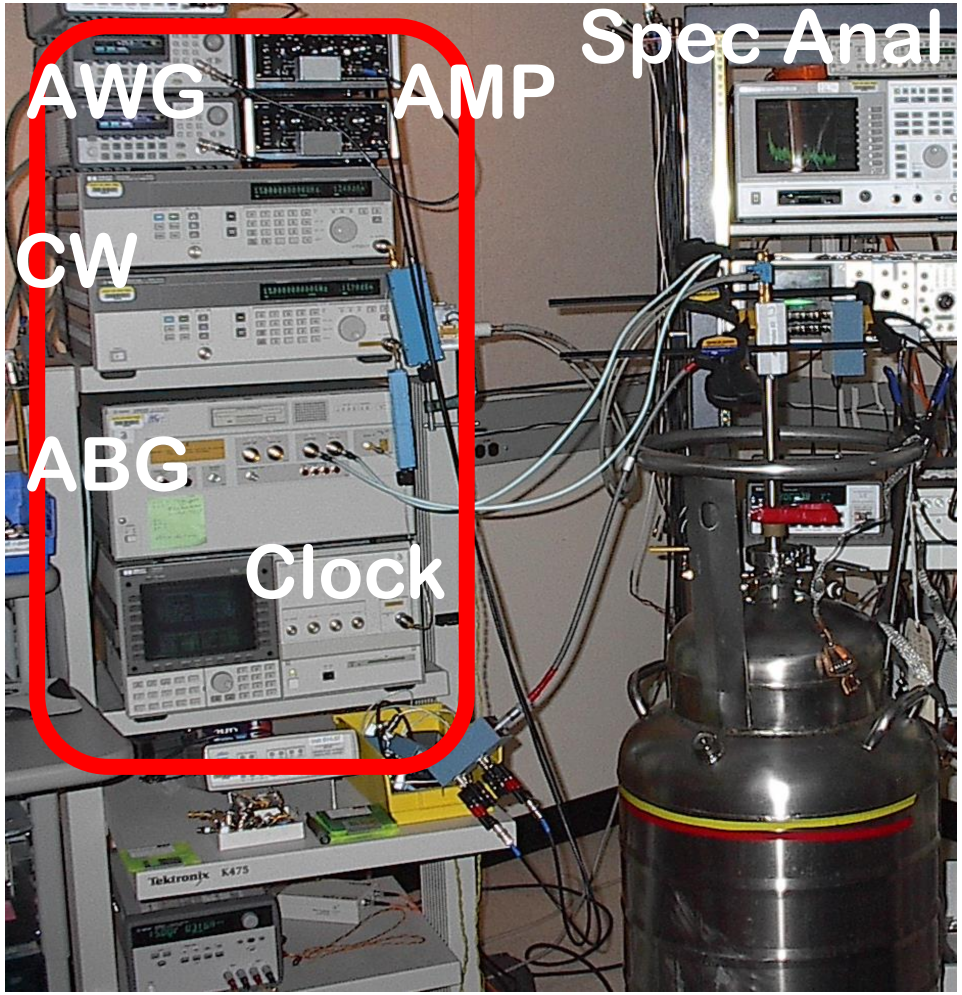
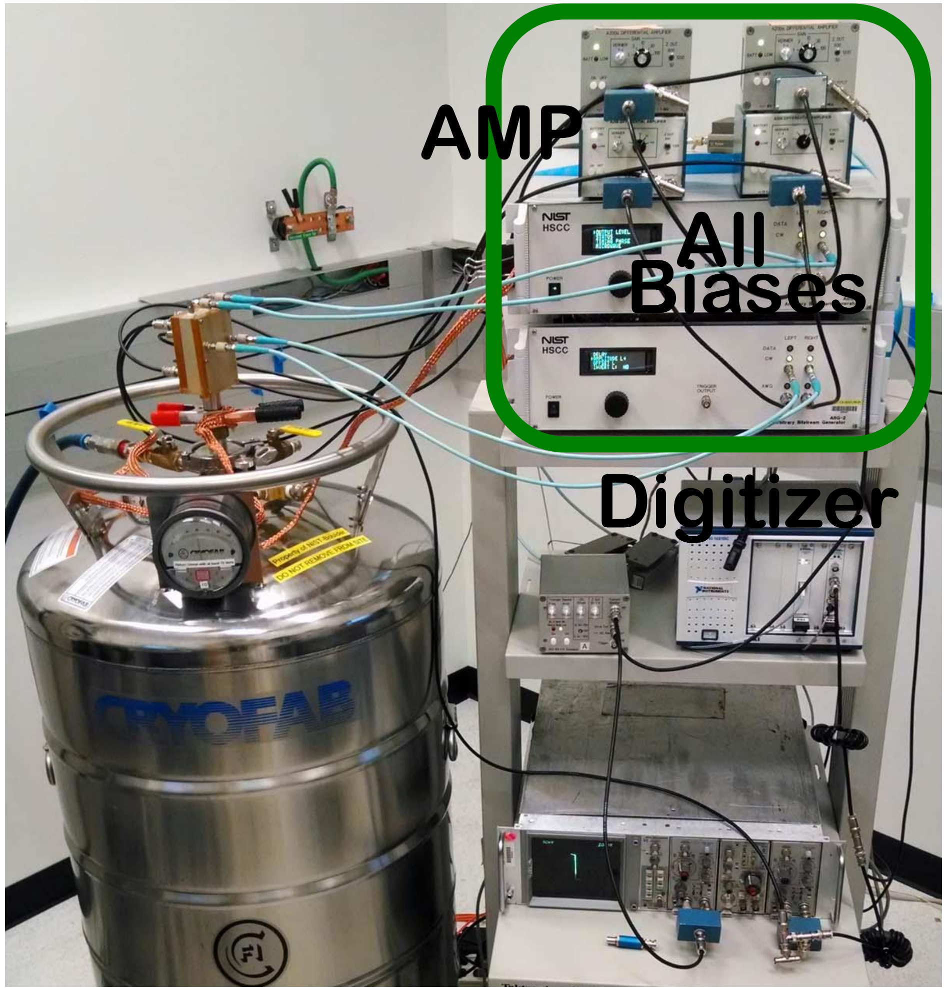
NIST

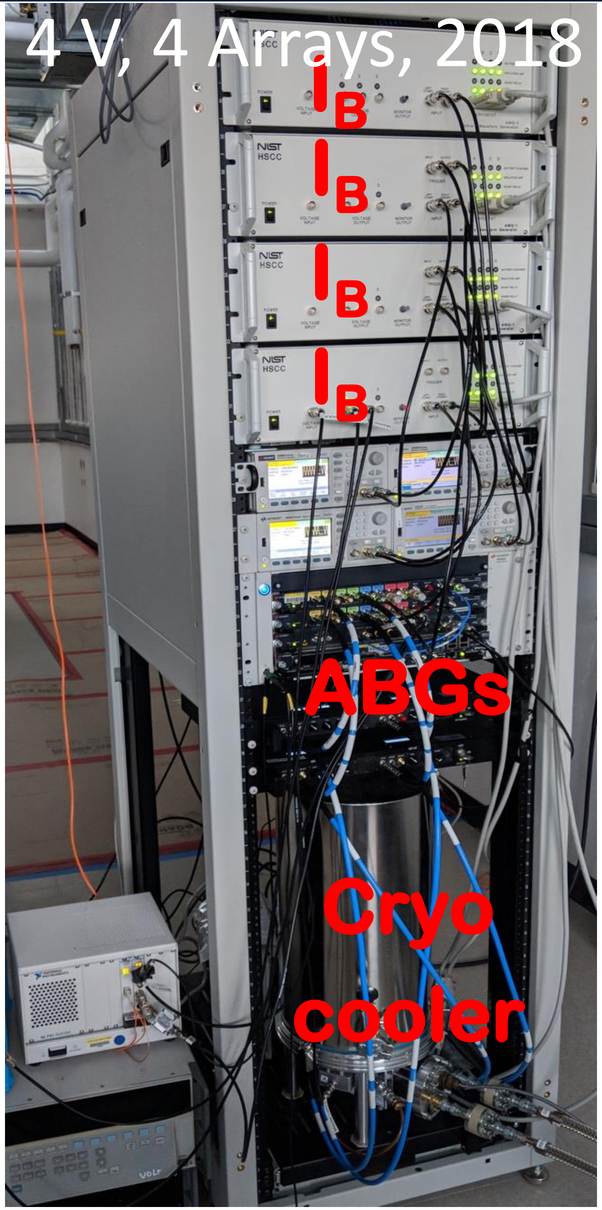
Compare JAWS Systems

100 mV, 2 Arrays, 2006



1 V, 4 Arrays, 2014





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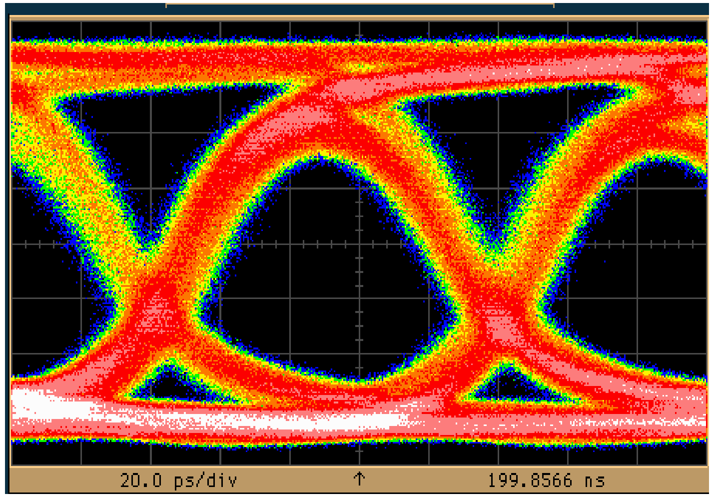
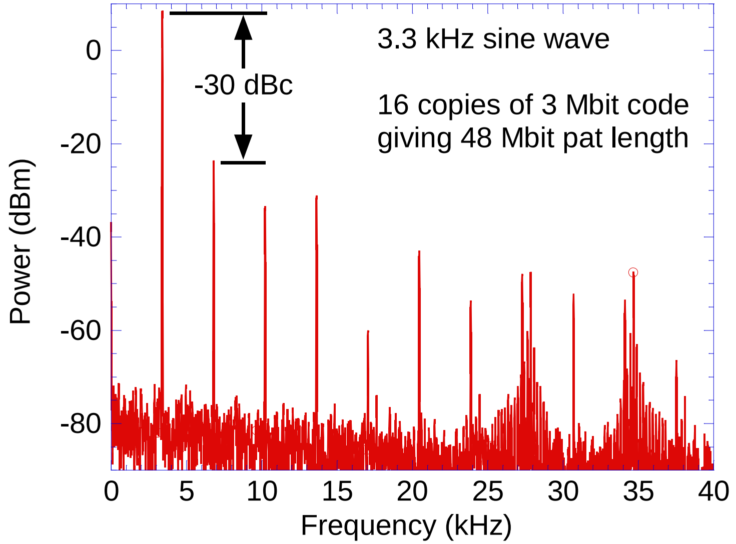
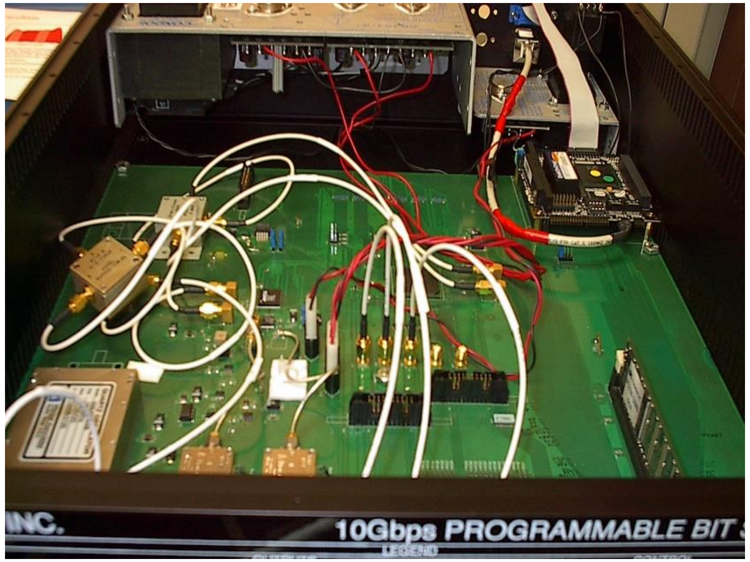
Advanced Arbitrary Bitstream Generator

- 1000X more memory
  - 1 to 8 Gbit
- Software generation/selection of multiple patterns
- 10X cheaper
  - ~$40K
- Collaboration with Tao of Digital Inc.

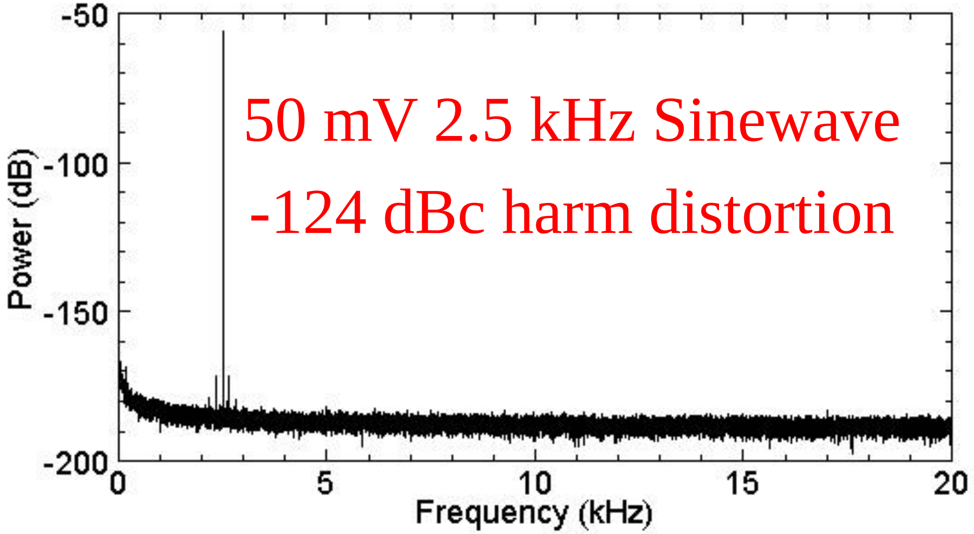


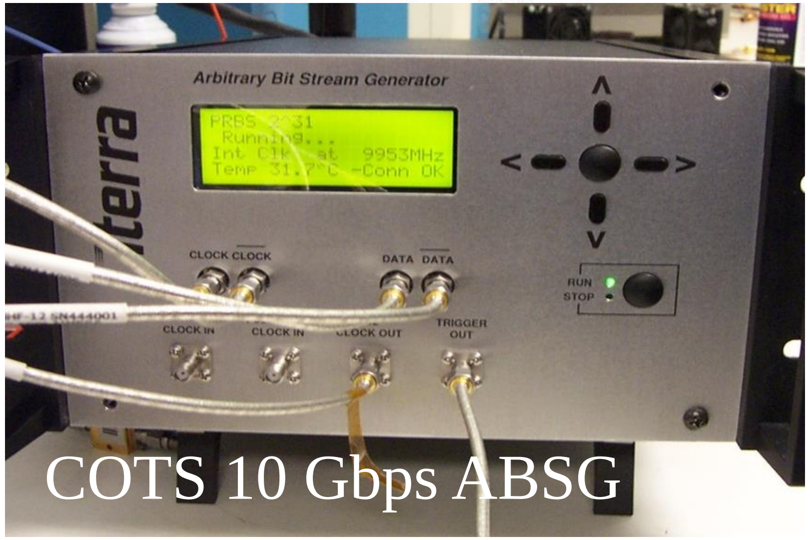




IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 59, May 2025. Presentation given at 22nd Biennial U.S. Workshop on Superconductor Electronics, Devices, Circuits, and Systems Santa Fe, New Mexico, April 6-10, 2025.

2006 ONR Report: Quantum-accurate Waveform Synthesis





With 1 Hz frequency resolution

- NIST is developing more accurate and stable waveform synthesizers.
- Unprecedented and unmatched accuracy and performance are possible only with the quantum properties of superconducting devices.
- Such performance is essential for ac voltage metrology (NIST) and for transmission of high-performance rf and microwave radar and communications (Navy).
- NIST co-invented the pulse-driven Josephson DAC 10 years ago and has spent the intervening period improving the relevant technologies to make it practical.
- This successful program is a direct result of ONR support, namely a COTS 10 Gbps arbitrary bitstream generator that drives the superconducting circuits with high speed pulses and superconducting stacked Josephson junctions to increase the output voltage and operating bandwidth. The complete system technology has become practical in 2005.
- Present systems will directly benefit ac and dc metrology needs of the Navy and have demonstrated quantum-accurate state-of-the-art performance for ac synthesis. Future systems at rf frequencies will improve Navy communications and advanced signal processing.

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 59, May 2025. Presentation given at 22nd Biennial U.S. Workshop on Superconductor Electronics, Devices, Circuits, and Systems Santa Fe, New Mexico, April 6-10, 2025.

NIST

HSCC Bipolar 28.8 Gbps ABG

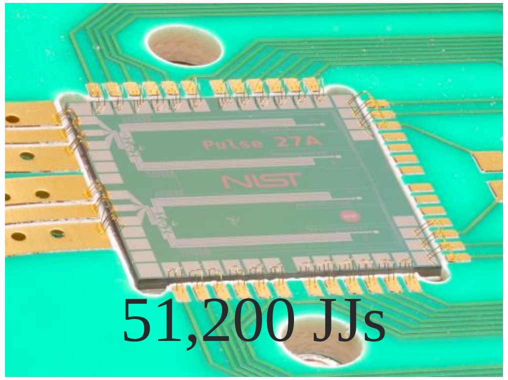
Developed for NIST by High Speed Circuit Consultants

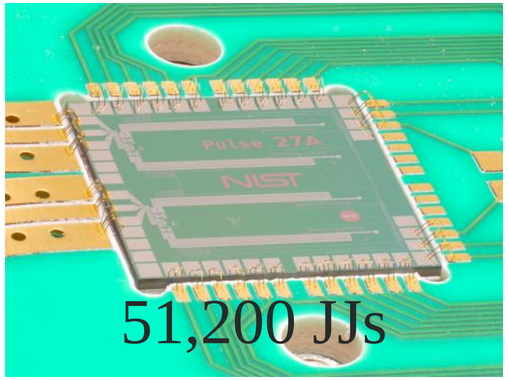
- Advantages of custom ABG
  - 28.8 Gbps is ~3X faster Bipolar Voltage Levels
  - Large 30 Gbit memory size gives 1Hz resolution
  - Integrates all 6 biases for both arrays into one unit
  - One internal 14.4 GHz CW for Quantization
  - Biases remain phase-locked and synchronized

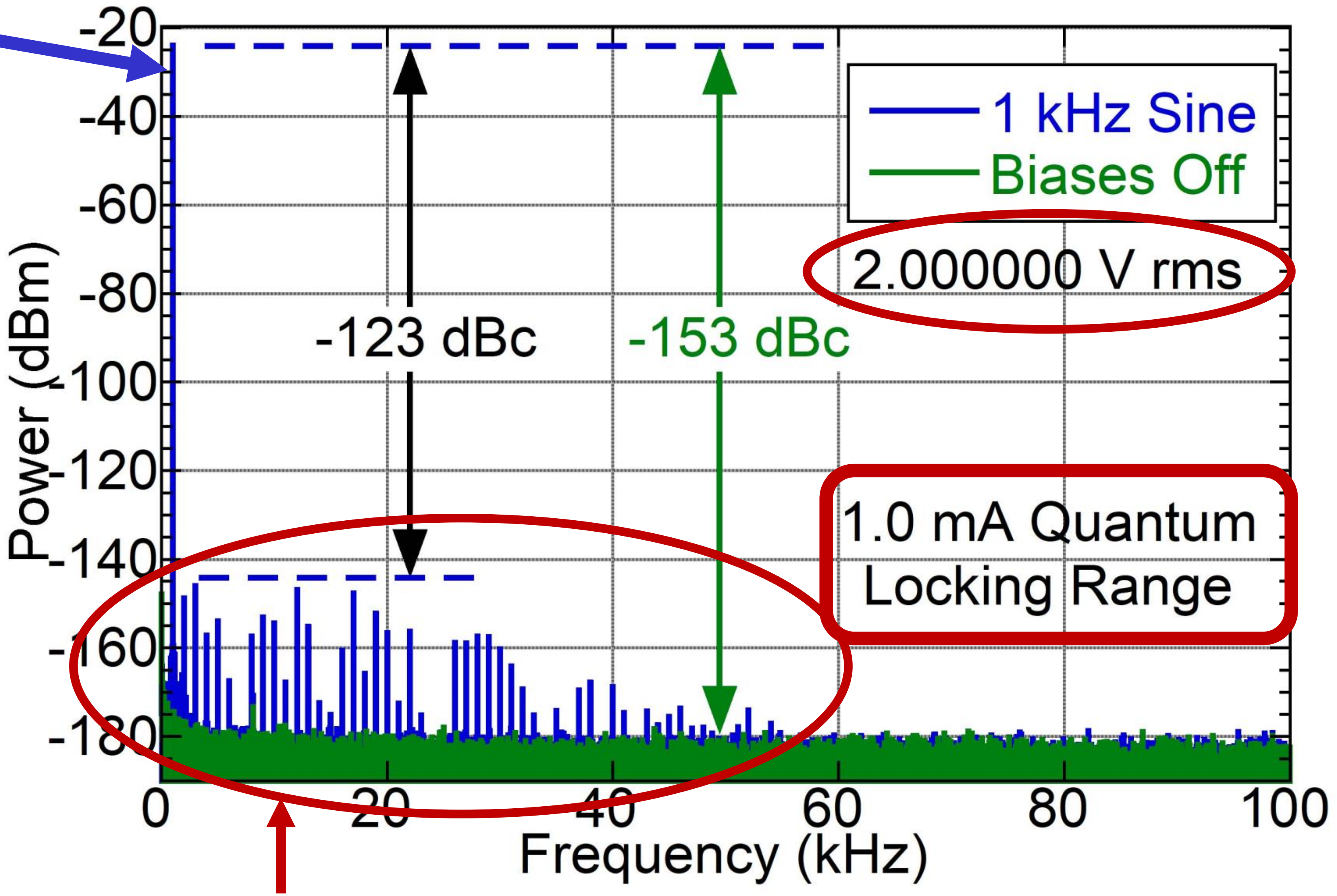
IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 59, May 2025. Presentation given at 22nd Biennial U.S. Workshop on Superconductor Electronics, Devices, Circuits, and Systems Santa Fe, New Mexico, April 6-10, 2025.

Josephson Arbitrary Waveform Synthesizer-JAWS

1 kHz 2 V rms Sinewave







Nathan Flowers-Jacobs et al., IEEE Trans. Appl. Supercond., Feb. 2016

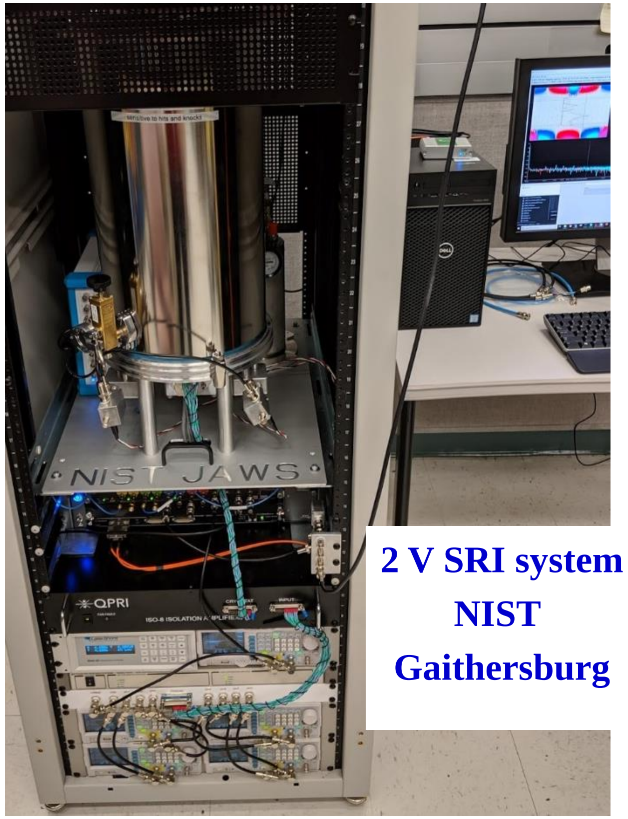
Non-linearities of the ADC Digitizer

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 59, May 2025. Presentation given at 22nd Biennial U.S. Workshop on Superconductor Electronics, Devices, Circuits, and Systems Santa Fe, New Mexico, April 6-10, 2025.

Commercially Available ABG

Keysight M8195A:

- 8-bit, 64 GSa/s arbitrary bitstream generator
- Operating at 14.4 Gpulses/s
- Integrated finite impulse response (FIR) filter
- Large number of tuning parameters - every sample!

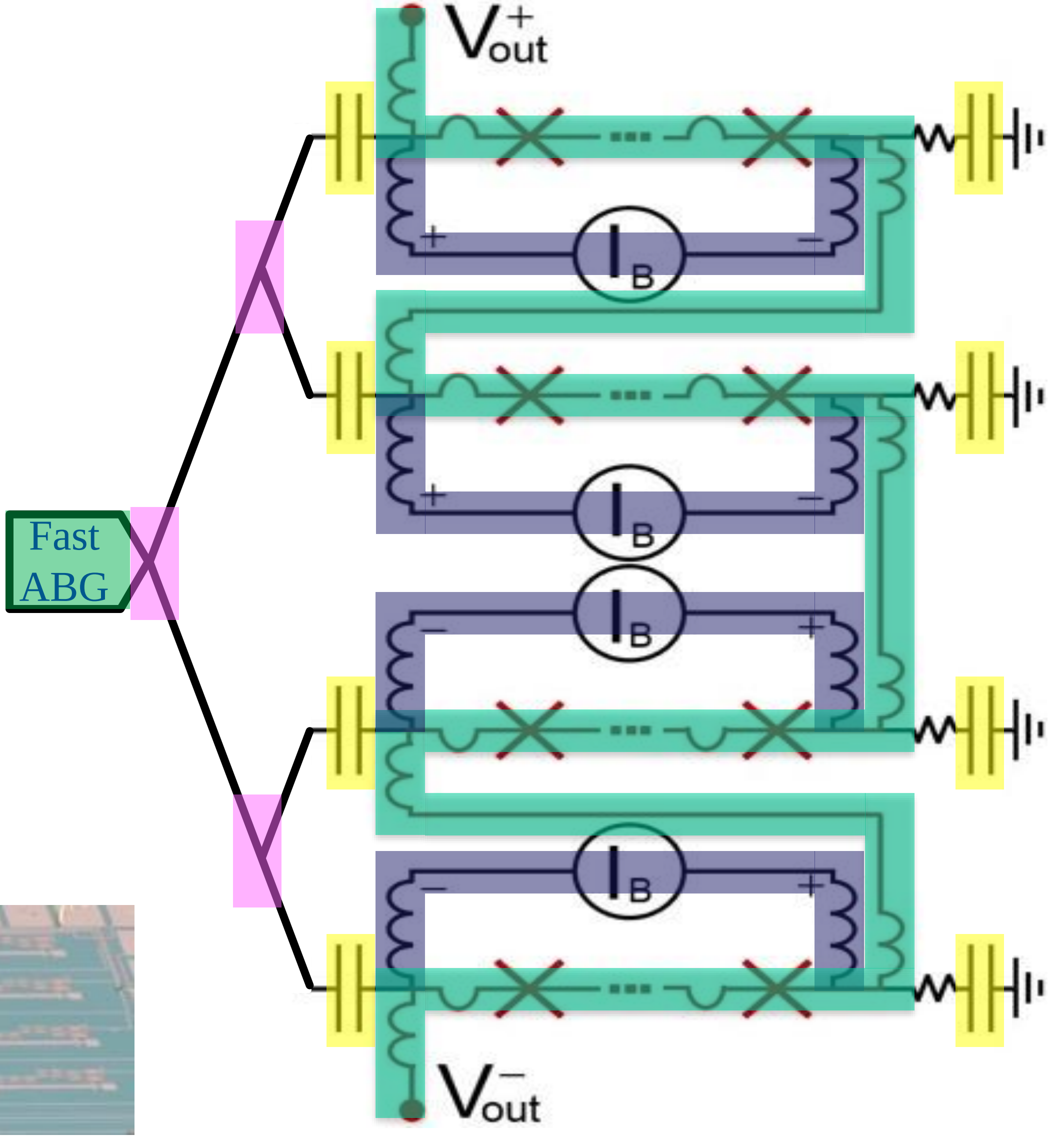


2 V SRI system
NIST
Gaithersburg

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 59, May 2025. Presentation given at 22nd Biennial U.S. Workshop on Superconductor Electronics, Devices, Circuits, and Systems Santa Fe, New Mexico, April 6-10, 2025.

Improvements: 1 V rms / half-chip

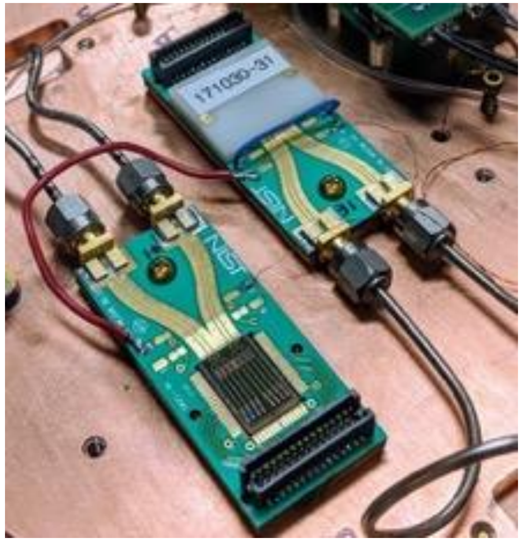
- **Instrumentation upgrade:**
  - –8-bit, 64 GSa/s arbitrary bitstream generator
  - –still operating at 14.4 Gpulses/s
  - –Just ONE pulse generator channel drives this 1V circuit
- **Circuit upgrade:**
  - – two layers of on-chip Wilkinson dividers (4-way split)
  - – Four connected arrays
    - 12 810 JJ/array (51,240 JJs /circuit)
  - – On-chip dc blocks to add arrays
    - and also filter low-frequencies!
    - need to add it back in: I_B



IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 59, May 2025. Presentation given at 22nd Biennial U.S. Workshop on Superconductor Electronics, Devices, Circuits, and Systems Santa Fe, New Mexico, April 6-10, 2025.

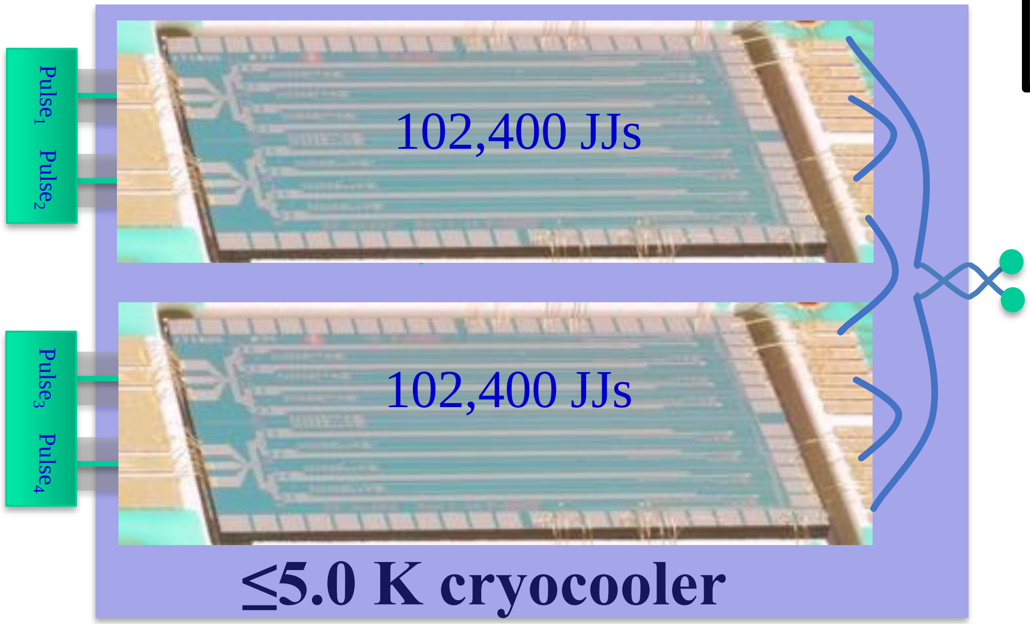
NIST

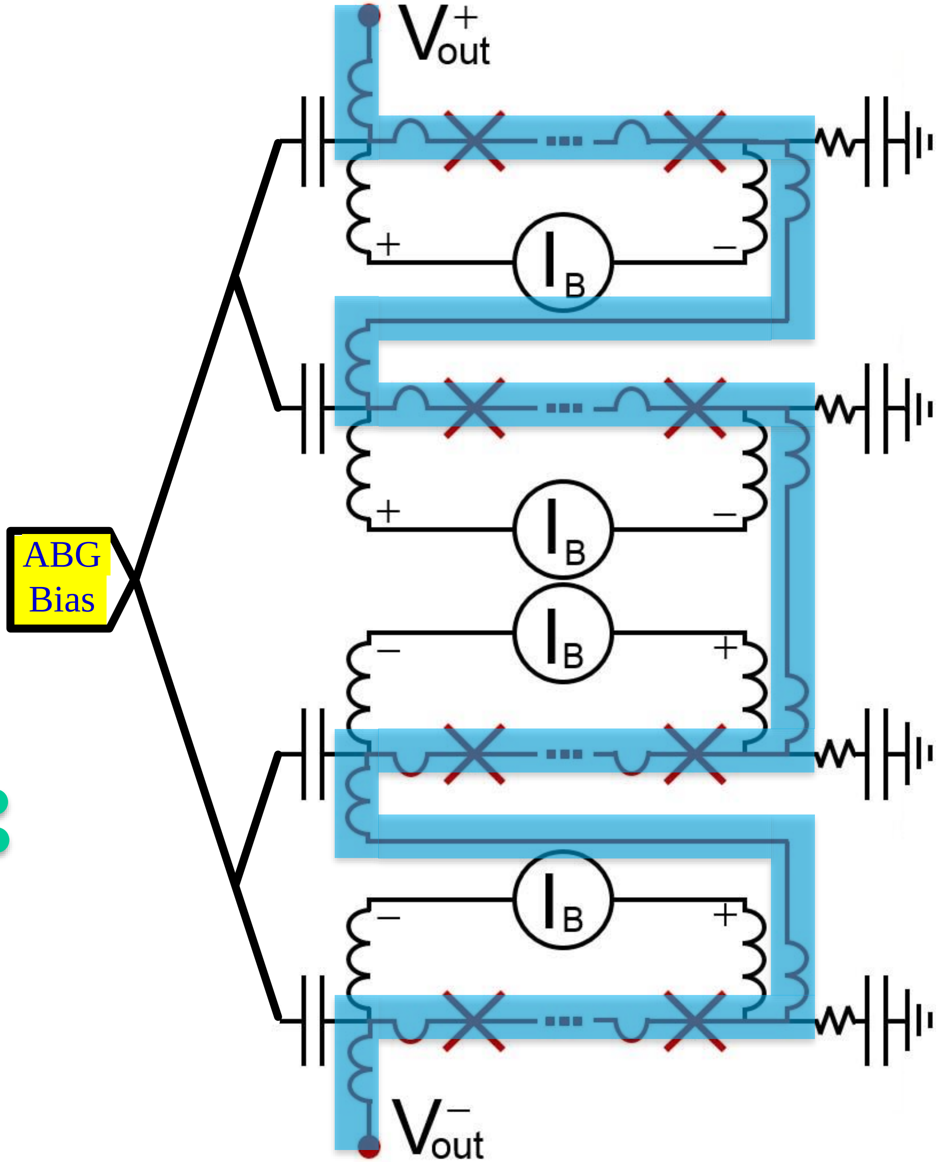
4 V rms Cryocooled JAWS



2 Cryopackaged Chips

- Four series-connected arrays
  - 204,960 total JJs
- One pulse generator bias
  - 14.4 Gpulses/sec





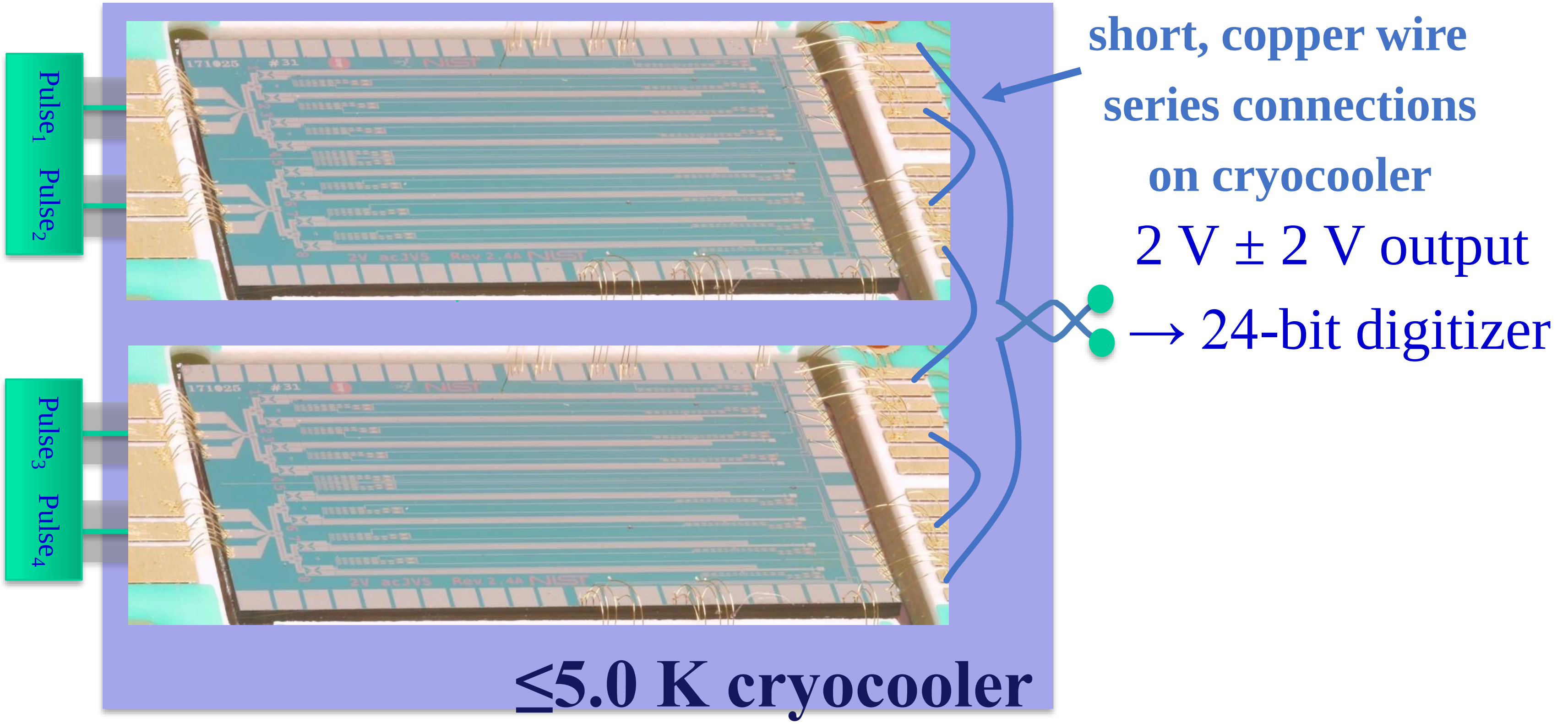
Nathan Flowers-Jacobs, ISEC Proceedings, Riverside, CA 2019

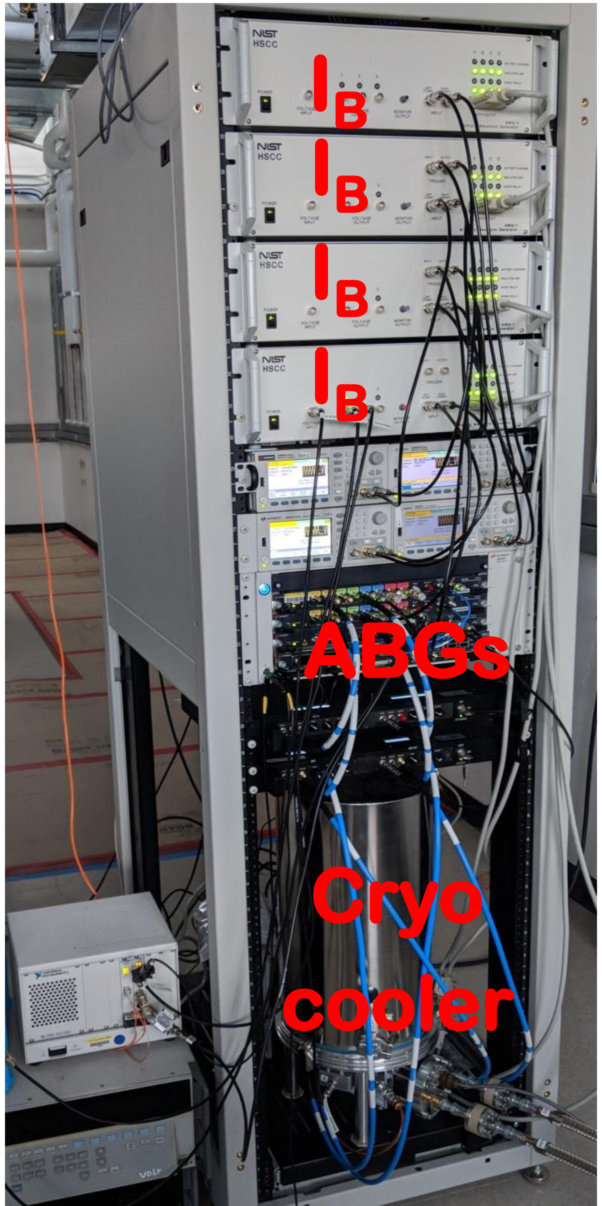
IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 59, May 2025. Presentation given at 22nd Biennial U.S. Workshop on Superconductor Electronics, Devices, Circuits, and Systems Santa Fe, New Mexico, April 6-10, 2025.

2 chips → 4 V Cryocooled JAWS System

2016: **2 V rms** cryocooled system,
4 pulse channels (2 sets of bias electronics, I_B)

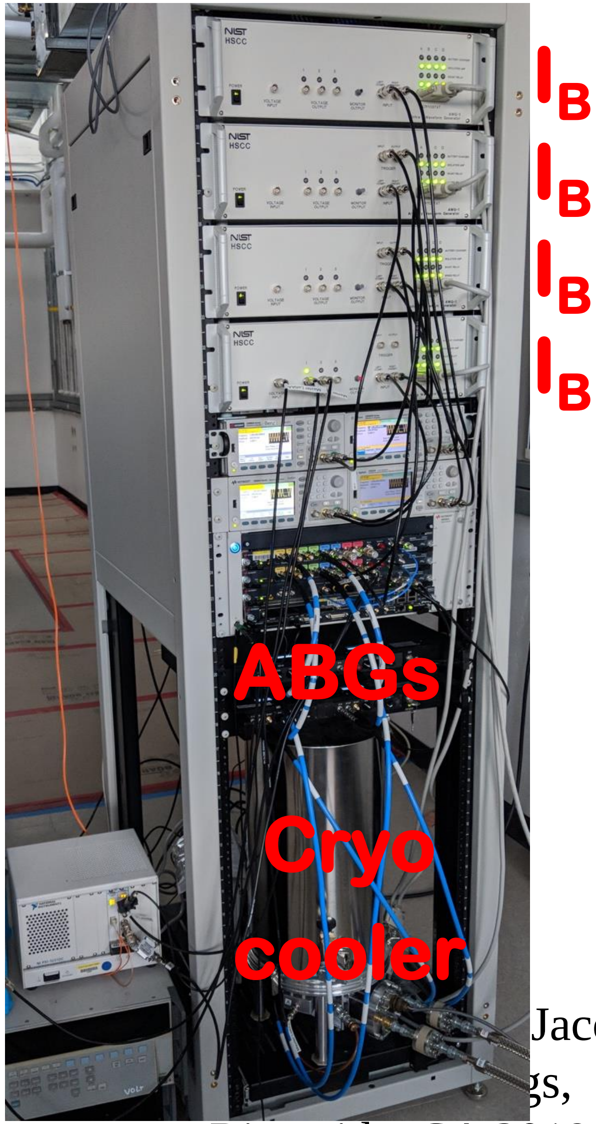
2018: **4 V rms** cryocooled system,
4 pulse channels (4 sets of bias electronics, I_B)

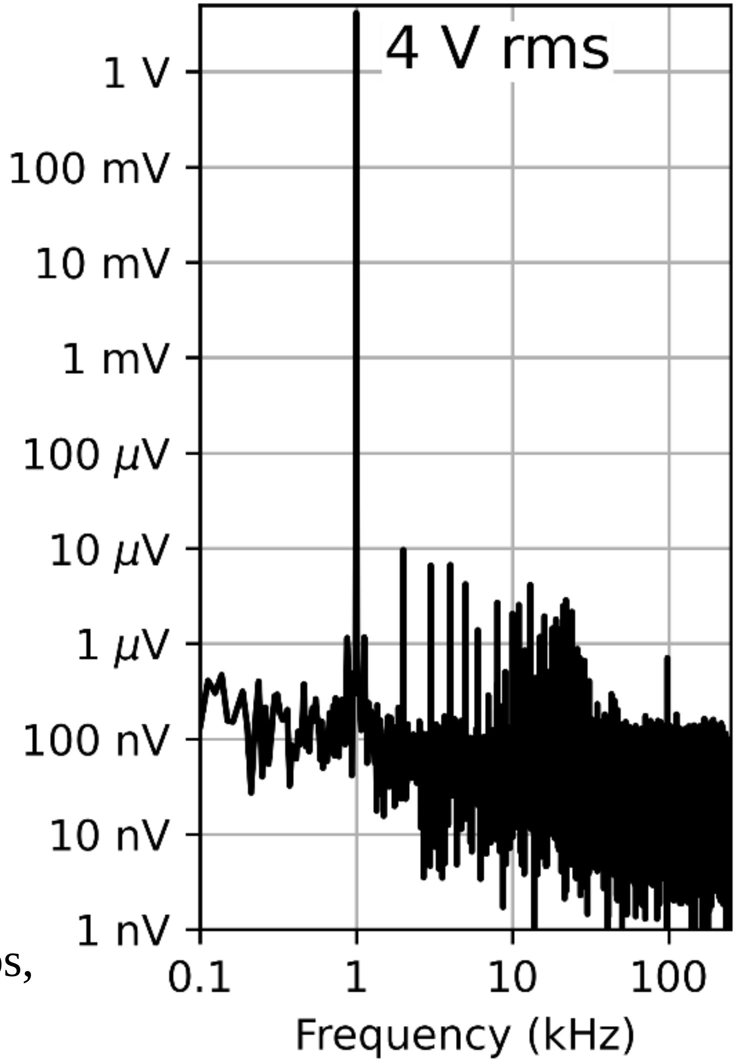


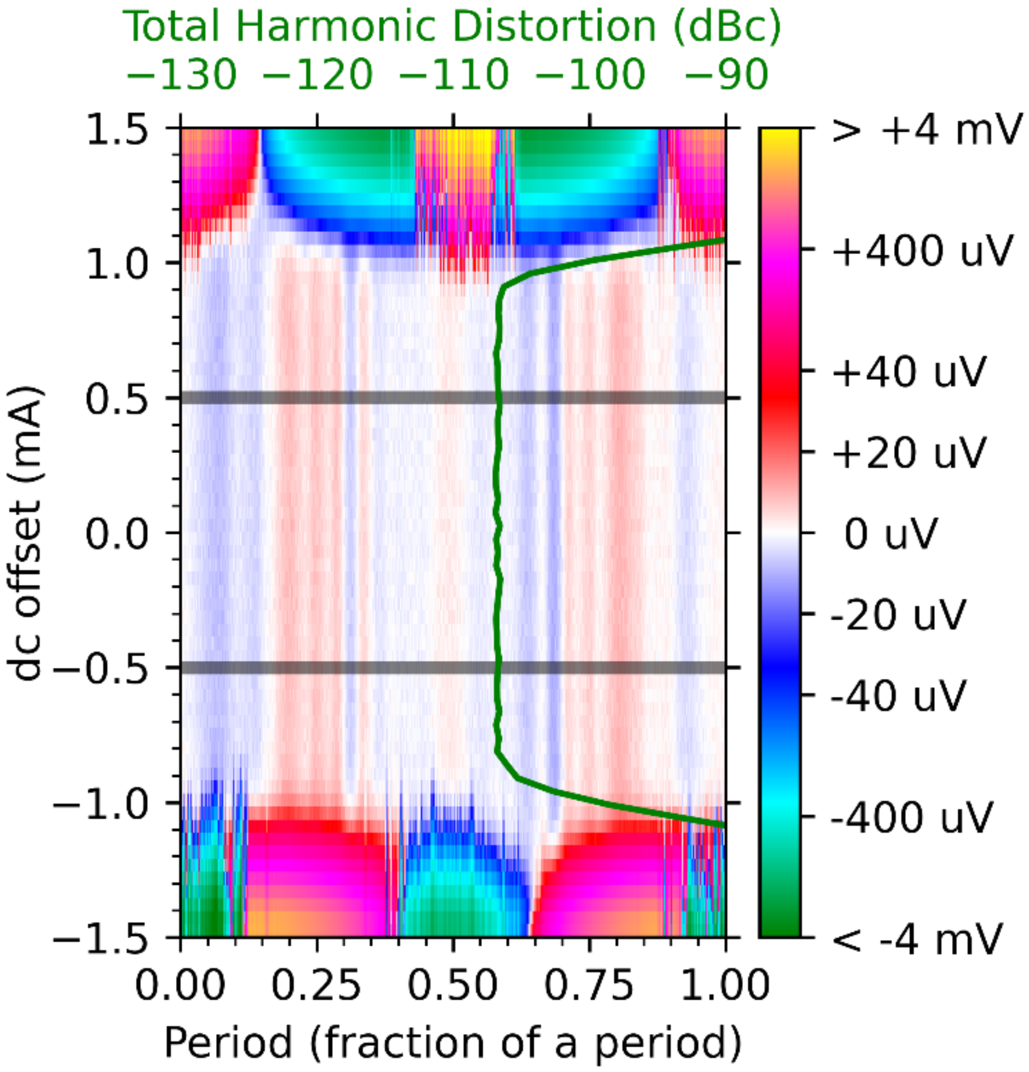


IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 59, May 2025. Presentation given at 22nd Biennial U.S. Workshop on Superconductor Electronics, Devices, Circuits, and Systems Santa Fe, New Mexico, April 6-10, 2025.

4 V rms Cryocooled JAWS







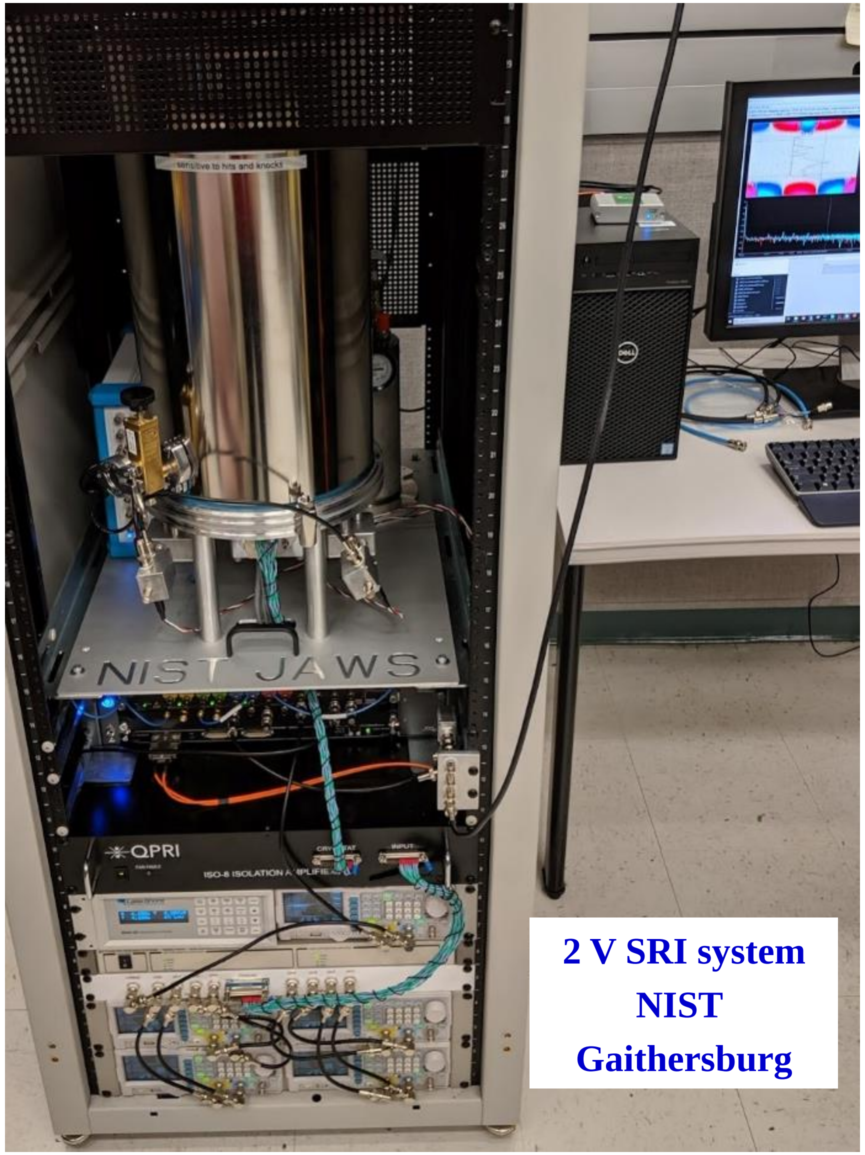
Jacobs,
gs,
Riverside, CA 2019

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 59, May 2025. Presentation given at 22nd Biennial U.S. Workshop on Superconductor Electronics, Devices, Circuits, and Systems Santa Fe, New Mexico, April 6-10, 2025.

JAWS Standard Reference Instrument (SRI)

- **User-friendly operation -> Automation**
  - Full computer control
    - Verify quantum-accurate operation
      - Still can be systematic errors!!
    - Change/load patterns
    - Automatic AC-DC comparison
      - Fluke 792A, 5790, …
  - Available as a standard reference instrument (SRI)
    - Cryocooled 1 V rms system
    - includes new pulse generator: Keysight M8195a
      - 64 Gsample/sec, 8-bit arbitrary bitstream generator

- www.nist.gov/sri/sri-6011-josephson-arbitrary-waveform-synthesizer



2 V SRI system
NIST
Gaithersburg

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 59, May 2025. Presentation given at 22nd Biennial U.S. Workshop on Superconductor Electronics, Devices, Circuits, and Systems Santa Fe, New Mexico, April 6-10, 2025.

NIST Josephson Voltage Standard Dissemination

NIST Systems & Technology

60 Conventional JVS (incl. Hypres, Inc. up to 2015)

26 PJVS Systems + 20 Cryopackages since 2010

8 JAWS Systems + 2 Cryopackages since 2010

4 Johnson Noise Thermometer

Measurement Labs

National Measurement Institutes: international

National Laboratories: NASA, Sandia, ORNL

Industry: HP, Lockheed, Fluke, Keithley, Keysight, Boeing

DOD: Army, Navy, Air Force

DOE: Sandia & Oak Ridge Nat. Labs

NIST

Search NIST

Menu

STANDARD REFERENCE INSTRUMENTS

Standard Reference Instruments

SRI 6000 Series Programmable Josephson Voltage Standard (PJVS)

SRI 6002 Multi-Junction Thermal Converter

SRI 6003 Series Portable Vacuum Standard

SRI 6006 Precision Micro-machined Apertures

SRI 6008 Ozone Standard

SRI 6011 Josephson Arbitrary Waveform Synthesizer

The Josephson arbitrary waveform synthesizer (JAWS) is an instrument that synthesizes ac voltage waveforms and dc voltages whose metrological accuracy results from pulse biasing thousands of series-connected superconducting Josephson junctions into their identical quantum states.Technical Contact: Paul Dresselhaus

Specifications Certificate (PDF Format)

The prices listed below are for the individual instrument and do not include costs related to the final measurement calibration performed before delivery or post-delivery installation and training. The related Calibration Service ID for the SRI is 68000S. To obtain a quote for the instrument and calibration services, please contact Sales and Customer Service by phone at 301-975-2200 or email at srminfo@nist.gov.

6011d	2V JAWS chip and cryopackage (standalone)	$53,100
6011f	Cryocooled 2V JAWS System (water)	$569,000
6011g	Cryocooled 2V JAWS System (water, no synthesizer)	$328,700
6011h	Cryocooled 2V JAWS System (air-cooled compressor)	$571,600
6011a	Cryocooled 1V JAWS System (water)	Discontinued
6011b	Cryocooled 1V JAWS System (air)	Discontinued
6011c	1V JAWS chip and cryopackage (standalone)	Discontinued
6011e	1V JAWS Cryopackage with Liquid Helium Cryoprobe	Discontinued

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 59, May 2025. Presentation given at 22nd Biennial U.S. Workshop on Superconductor Electronics, Devices, Circuits, and Systems Santa Fe, New Mexico, April 6-10, 2025.

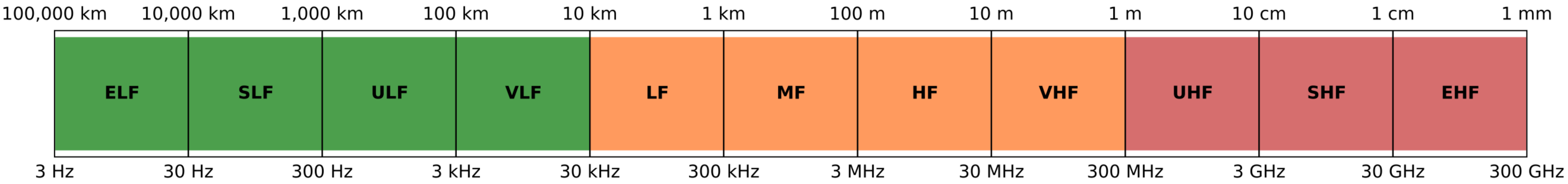
National Institute of Standards and Technology
U.S. Department of Commerce

RF JAWS
Synthesizer with Quantum-based Accuracy for RF Communications

- J. Thomas, J Hoffmann, N E Flowers-Jacobs, A E Fox, R L Johnson-Wilkke, P D Dresselhaus, S P Benz, "Cryogenic On-chip In Situ S-parameter Calibration using Superconducting Coplanar Waveguides," submitted to IEEE Trans. Micro. Theory Tech.
- J. Thomas, et al., "VHF Josephson Arbitrary Waveform Synthesizer", IEEE Trans. Appl. Supercond., vol. 34, July 2024.
- A. A. Babenko, et al., "Quantum-Based Microwave Modulated Waveforms," IEEE Trans. Microw. Theory Tech., vol. 72, Aug. 2024
- A. A. Babenko, et al., "A microwave quantum-defined millivolt source," IEEE Trans. MTT, vol. 69, Dec 2022.

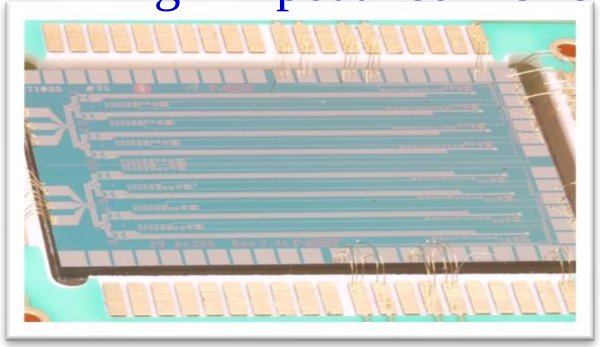
IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 59, May 2025. Presentation given at 22nd Biennial U.S. Workshop on Superconductor Electronics, Devices, Circuits, and Systems Santa Fe, New Mexico, April 6-10, 2025.

NIST JAWS Chip Types



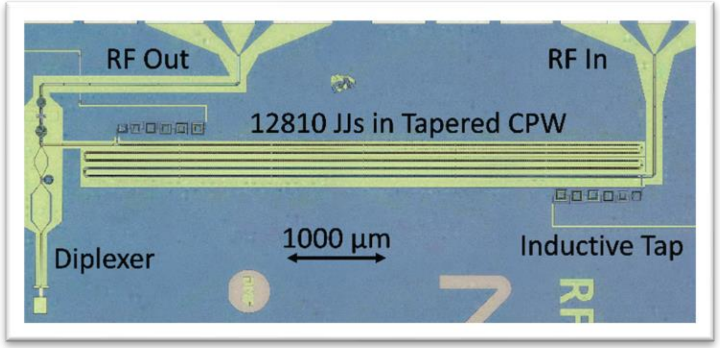
Audio JAWS

- Established: 2V, <100 kHz
  - Dividers (more arrays)
  - Impedance tapered arrays (more JJs per array)
- High impedance DUTs



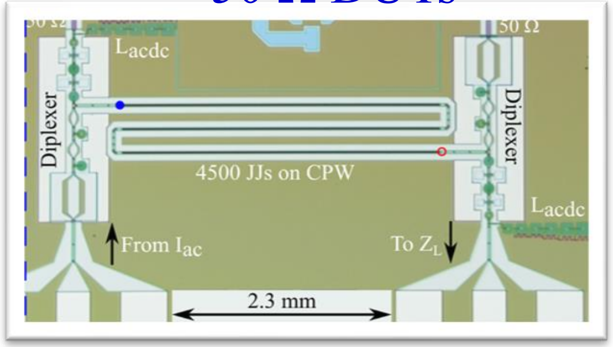
VHF-JAWS

- Goal: 0 dBm, up to 300 MHz
  - Diplexers (remove feedthrough, termination)
  - Tapered arrays
  - 50 Ω DUTs

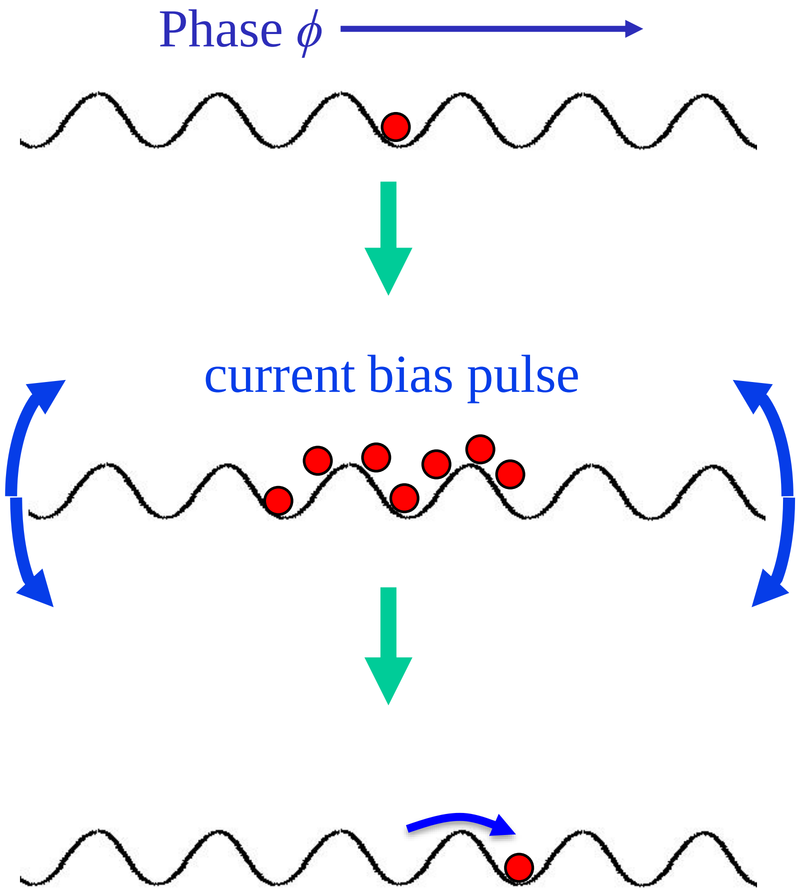


RF-JAWS

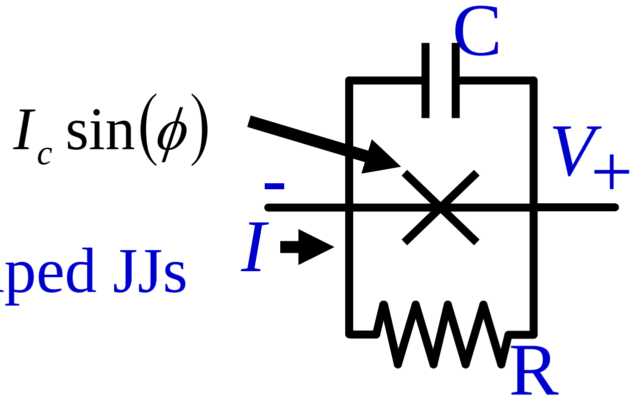
- Goal: up to 3 GHz
  - Diplexers
- Un-tapered 50 Ω arrays (λ → array length)
- 50 Ω DUTs



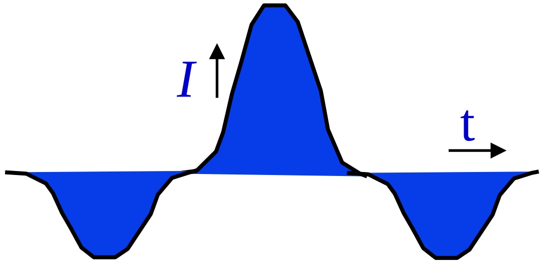
"Zero-Compensation" bias pulses



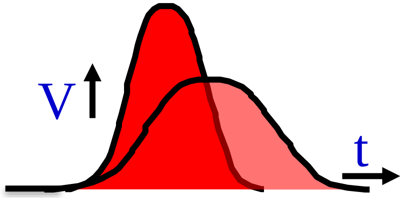
overdamped JJs



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



Imprecise *I* bias pulse



Quantized JJ *V* pulse area

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

No Compensation Bias Currents Required

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FFTs for Zero-Compensation Bias Coding

High $\Rightarrow$ 10

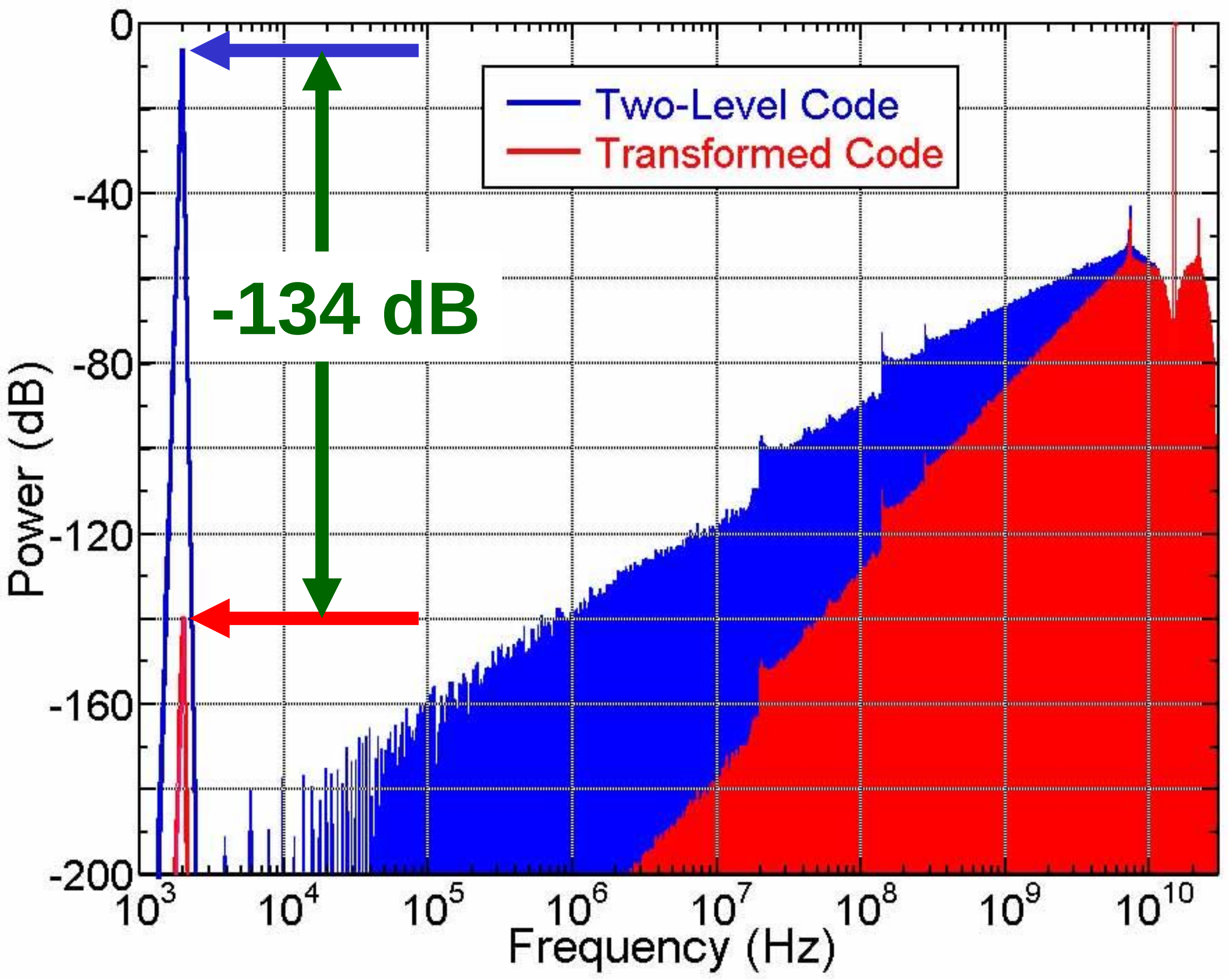
Low $\Rightarrow$ 01

Amplitude of Fundamental (Bias):

At 2 kHz is reduced ~2×10^7

At 2 MHz its reduced to $\times10^4$

- Lower Feedthrough error signals



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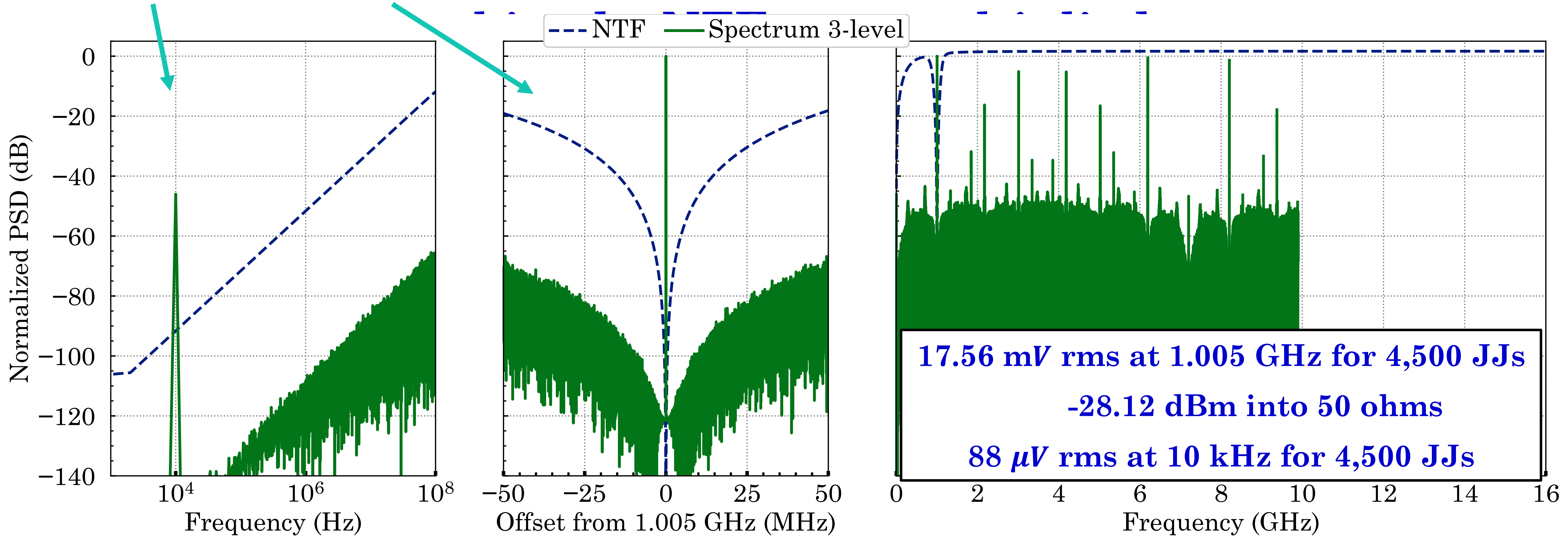
Two-Tone Delta-Sigma waveform

Low-pass and Band-pass delta-sigma modulators can be



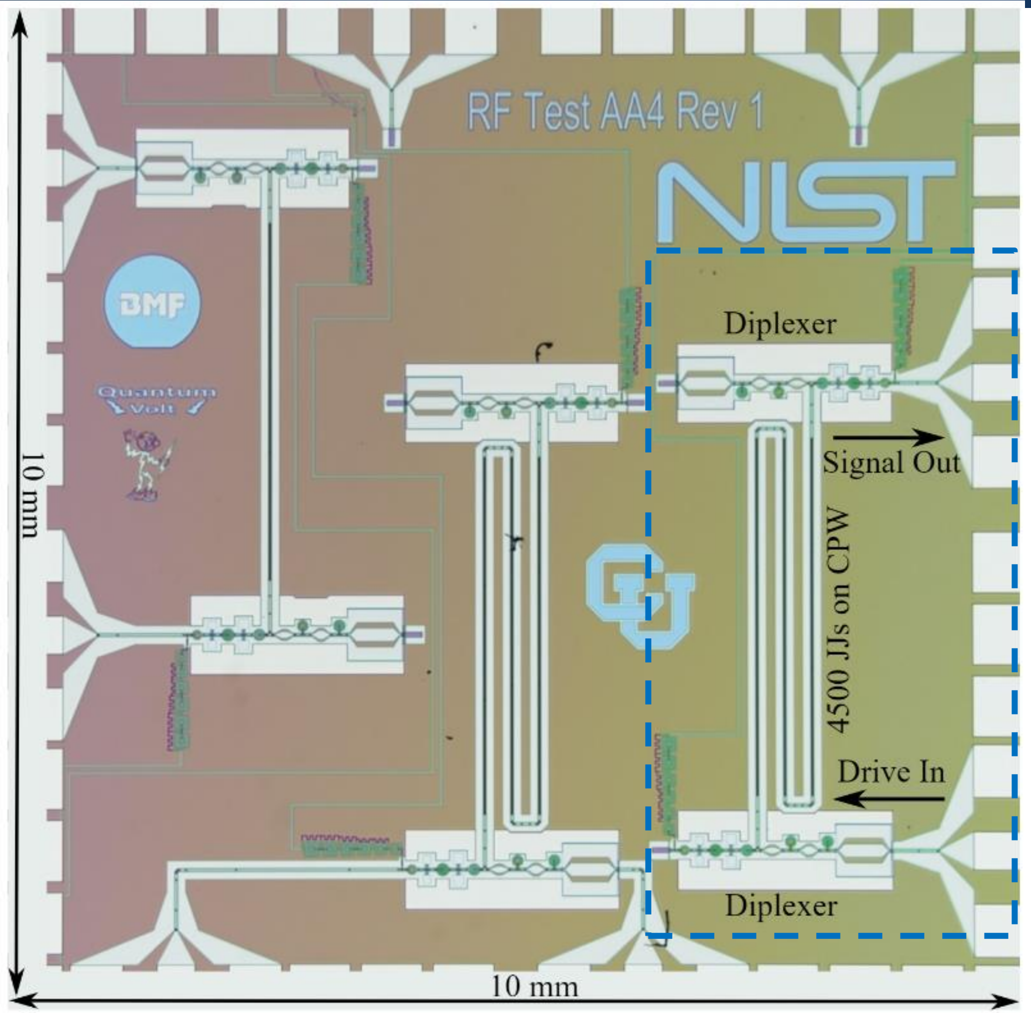
Fast measurements at 10 kHz are used to verify and optimize 1.005 GHz synthesis

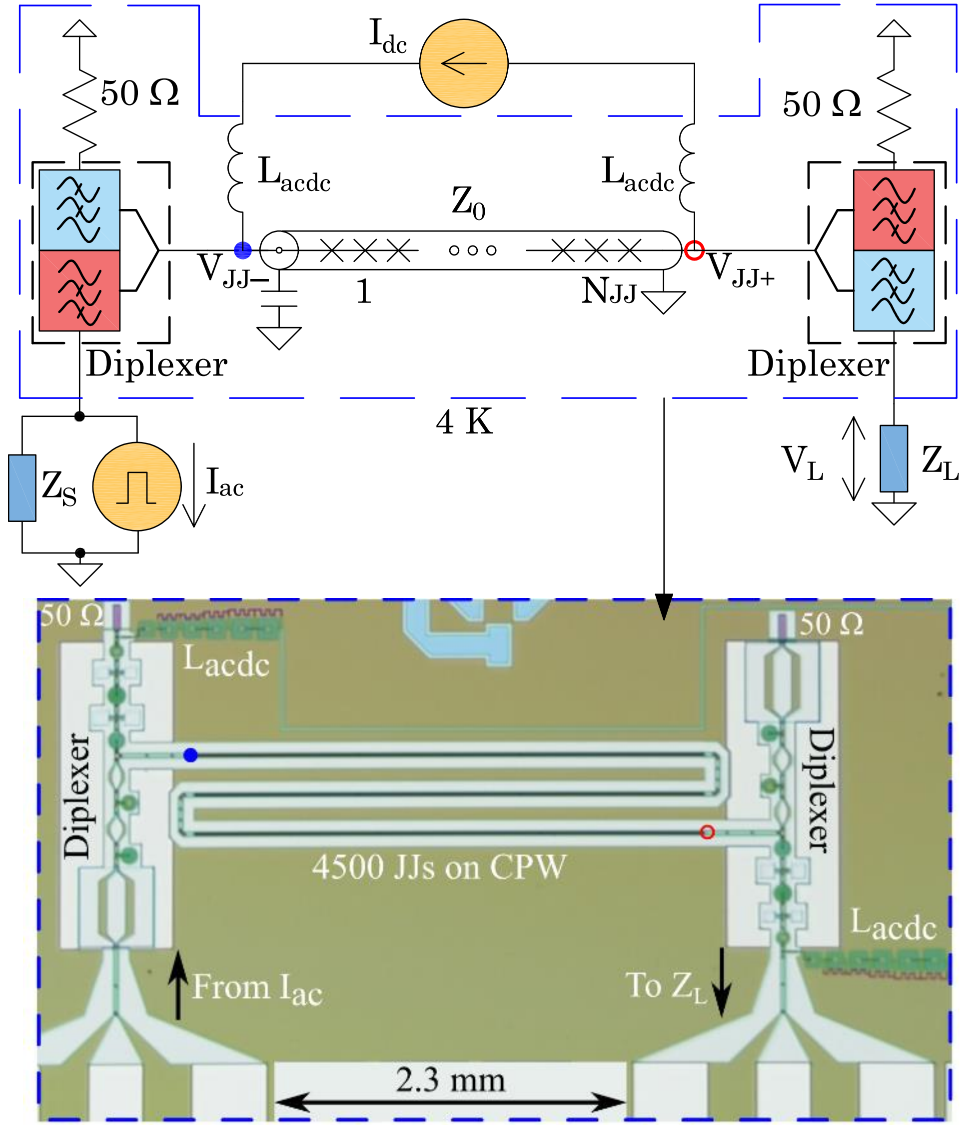
NTF – noise transfer function

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

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 59, May 2025. Presentation given at 22nd Biennial U.S. Workshop on Superconductor Electronics, Devices, Circuits, and Systems Santa Fe, New Mexico, April 6-10, 2025.

VHD- & RF-JAWS on-chip Diplexers





The diplexers reduce reflections and feedthrough for the drive current pulses along the JJ array

A. A. Babenko et al., "RF Josephson Arbitrary Waveform Synthesizer With Integrated Superconducting Diplexers", in IEEE Trans. Appl. Superconductivity (2022), 10.1109/TASC.2022.3201188

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 59, May 2025. Presentation given at 22nd Biennial U.S. Workshop on Superconductor Electronics, Devices, Circuits, and Systems Santa Fe, New Mexico, April 6-10, 2025.

Quantum-Locking Ranges up to VHF-band

What is a QLR?

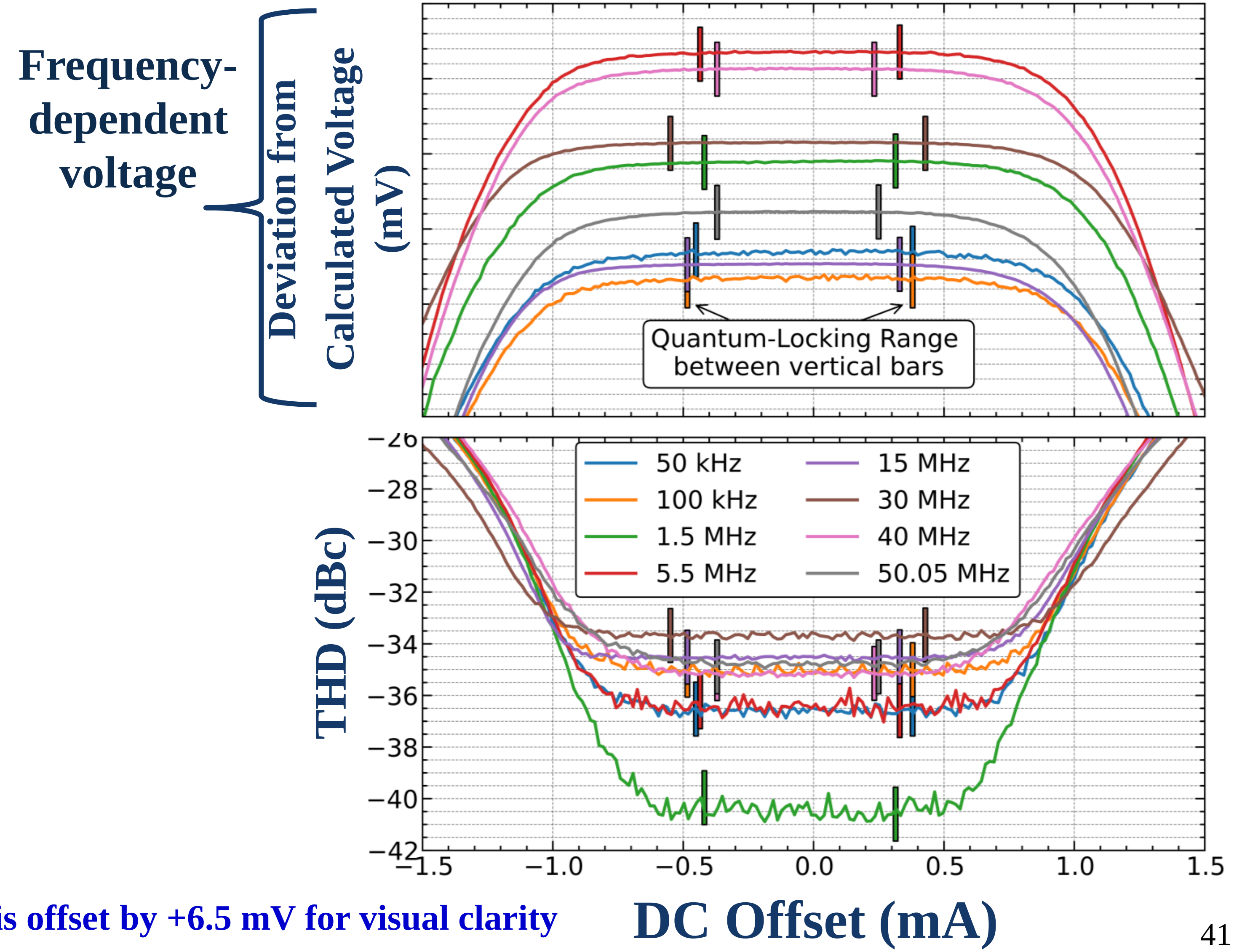
- The range over which a bias parameter can be changed while the output voltage remains constant and the Total Harmonic Distortion THD is minimized.

Why is a large QLR important?

- It demonstrates that the device can operate correctly despite changes to the bias or grounding conditions.

How can we use the QLR?

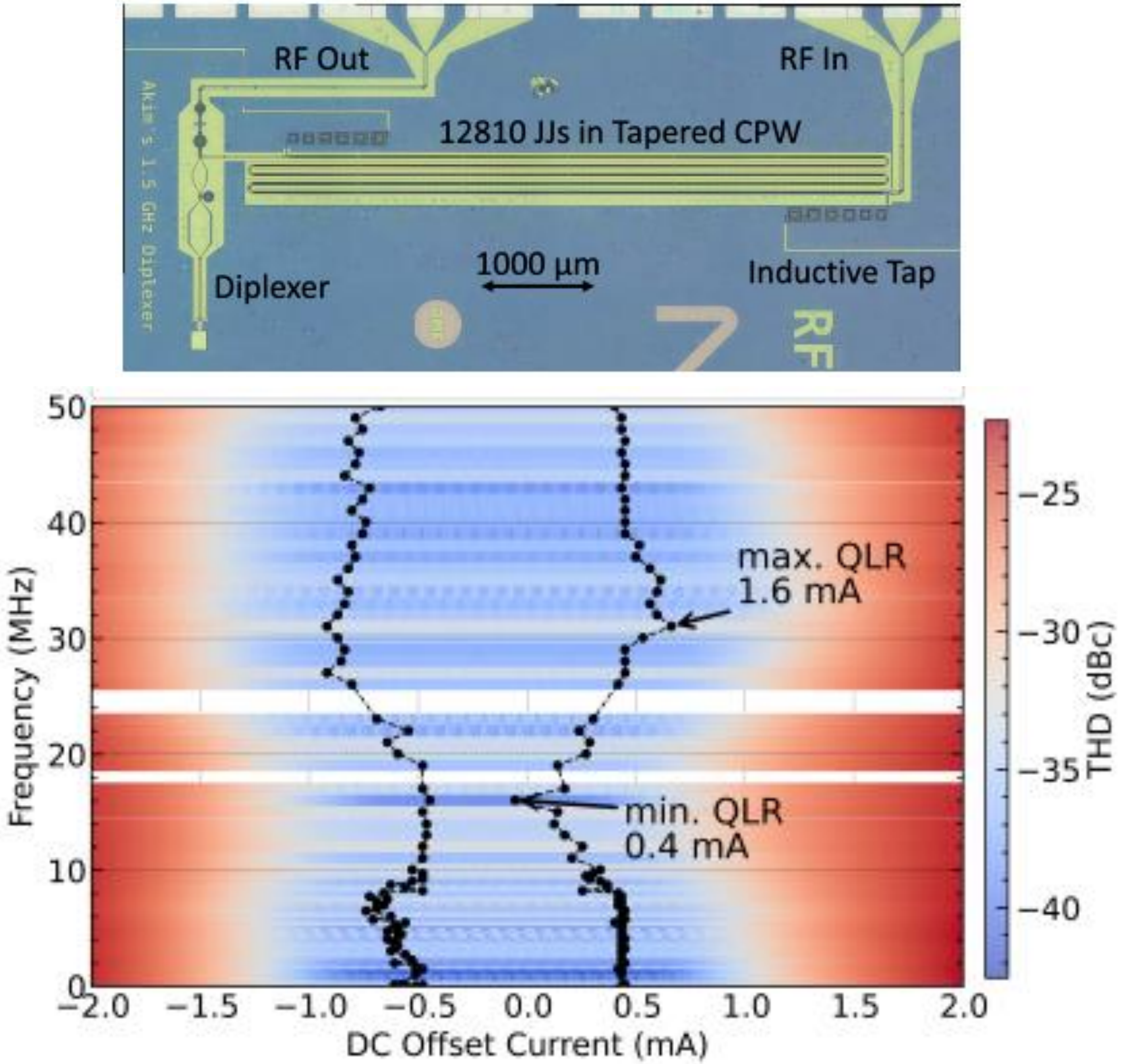
- Optimize pulse shape with FIR filters to optimize QLR
- Important tool for investigating systematic sources of error

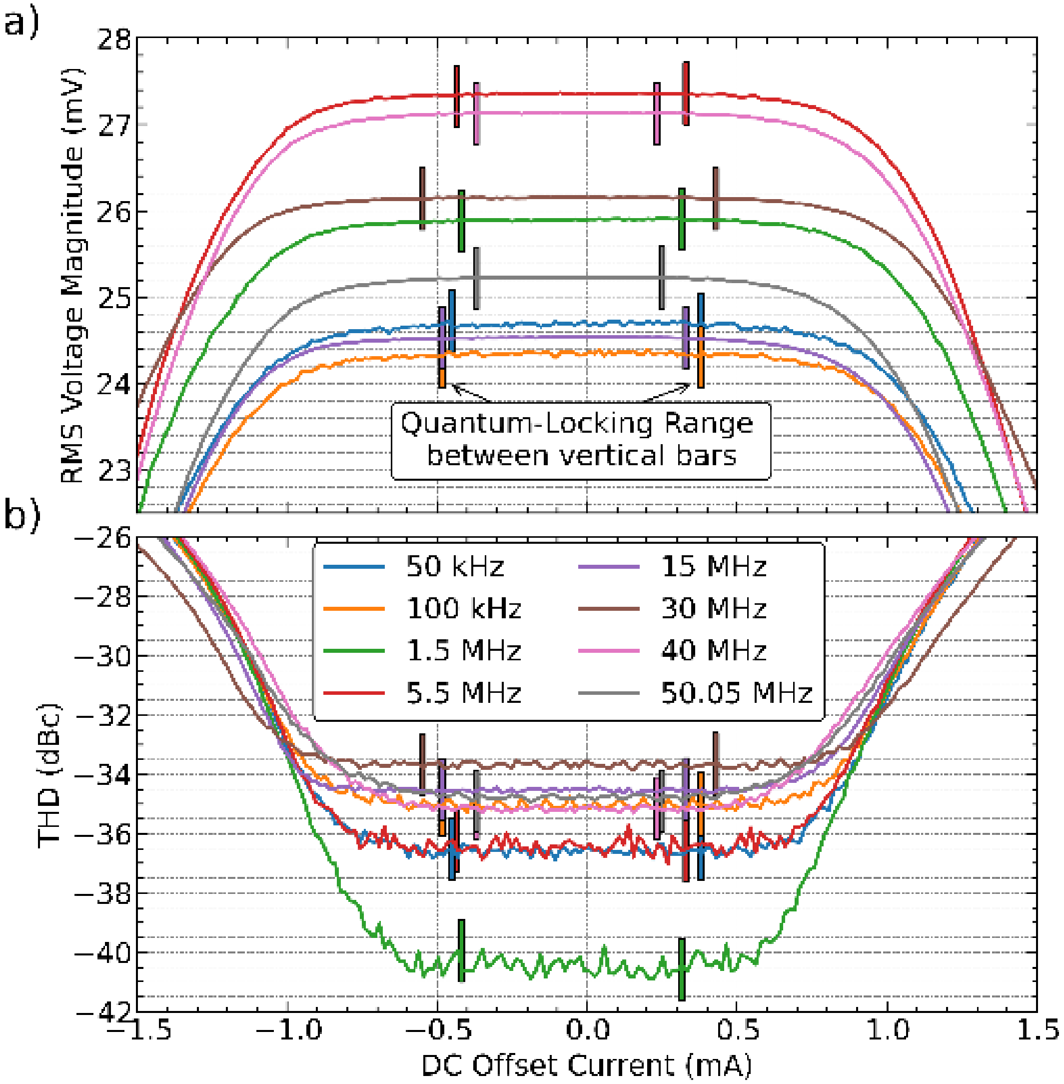


30.05 MHz voltage is offset by +6.5 mV for visual clarity

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 59, May 2025. Presentation given at 22nd Biennial U.S. Workshop on Superconductor Electronics, Devices, Circuits, and Systems Santa Fe, New Mexico, April 6-10, 2025.

VHF-JAWS 50kHz to 50 MHz





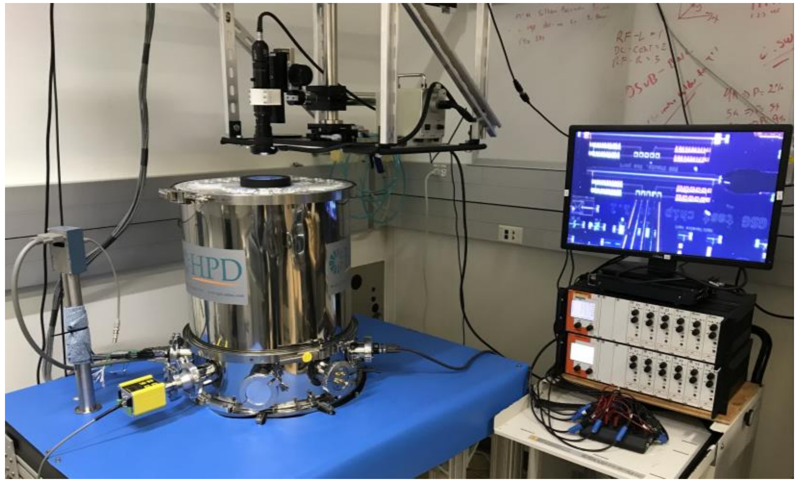
J. Thomas, et al., "VHF Josephson Arbitrary Waveform Synthesizer", IEEE Trans. Appl. Supercond. vol. 34, July 2024

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 59, May 2025. Presentation given at 22nd Biennial U.S. Workshop on Superconductor Electronics, Devices, Circuits, and Systems Santa Fe, New Mexico, April 6-10, 2025.

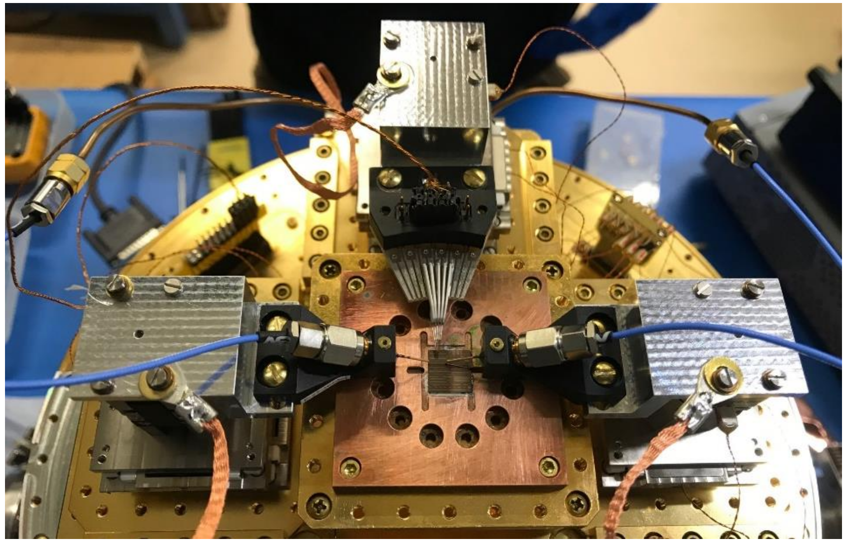
NIST

Voltage is accurate only on chip

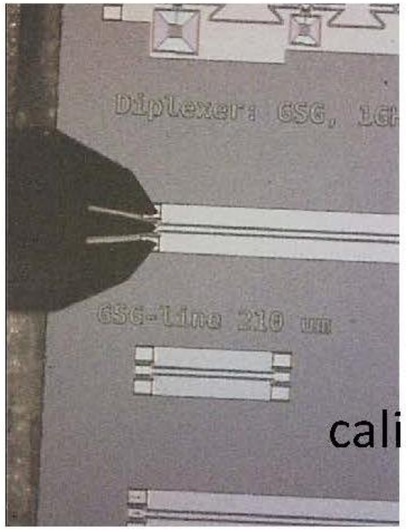
- Calibrate transfer function of room-to-chip leads at cryogenic temperatures



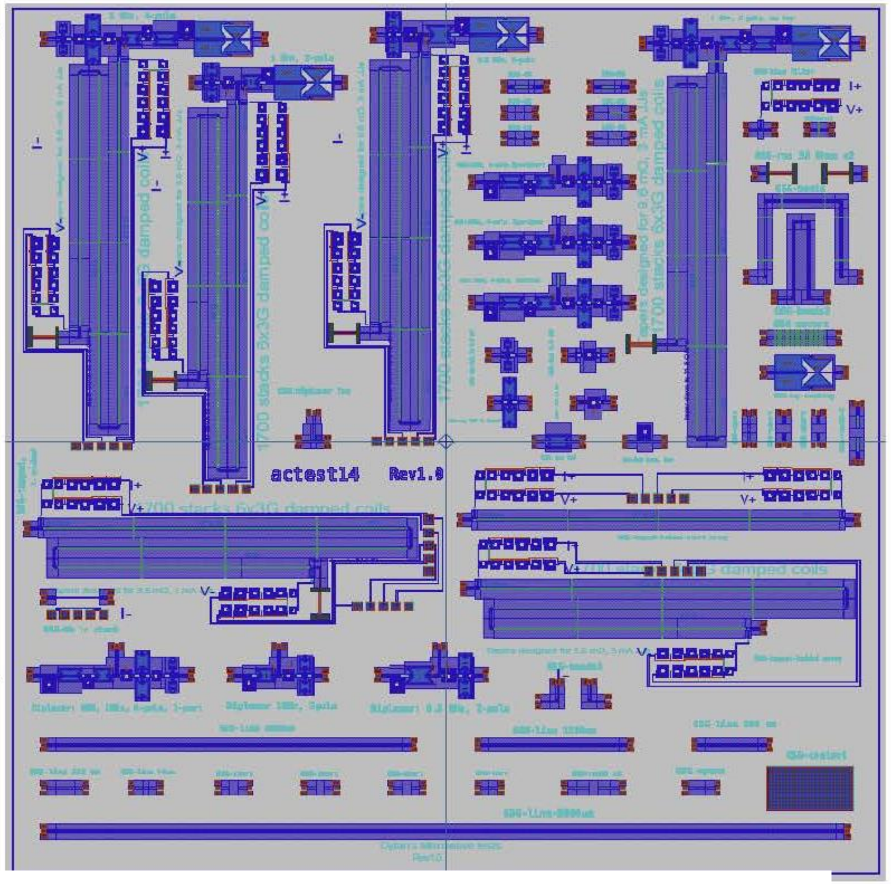
4 K Probe Stage with JJ Devices & Standards



JJ arrays for NIST Josephson arbitrary waveform synthesizer (JAWS)



TRL calibrations



Dylan Williams 2016 ASC Conference

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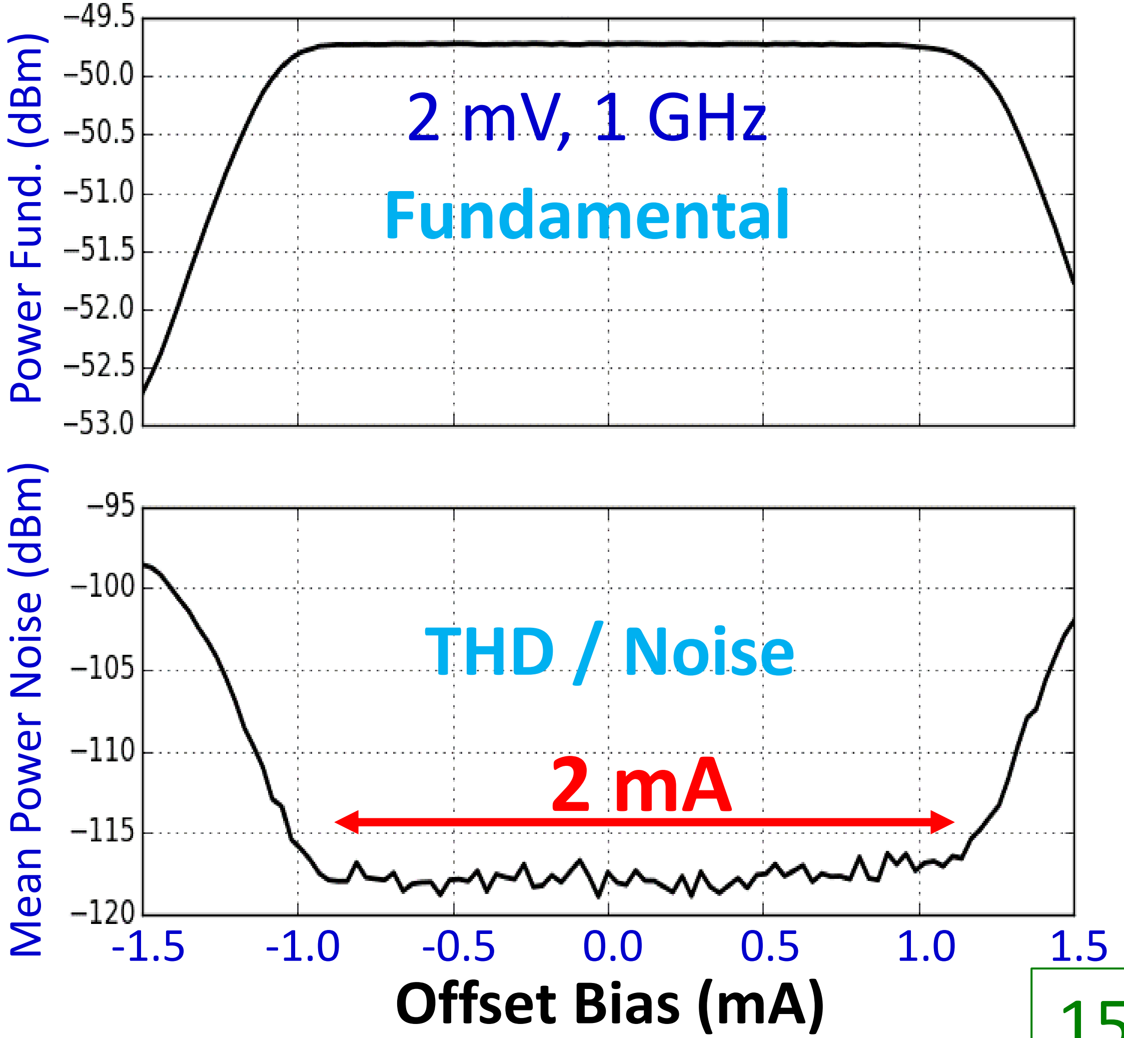
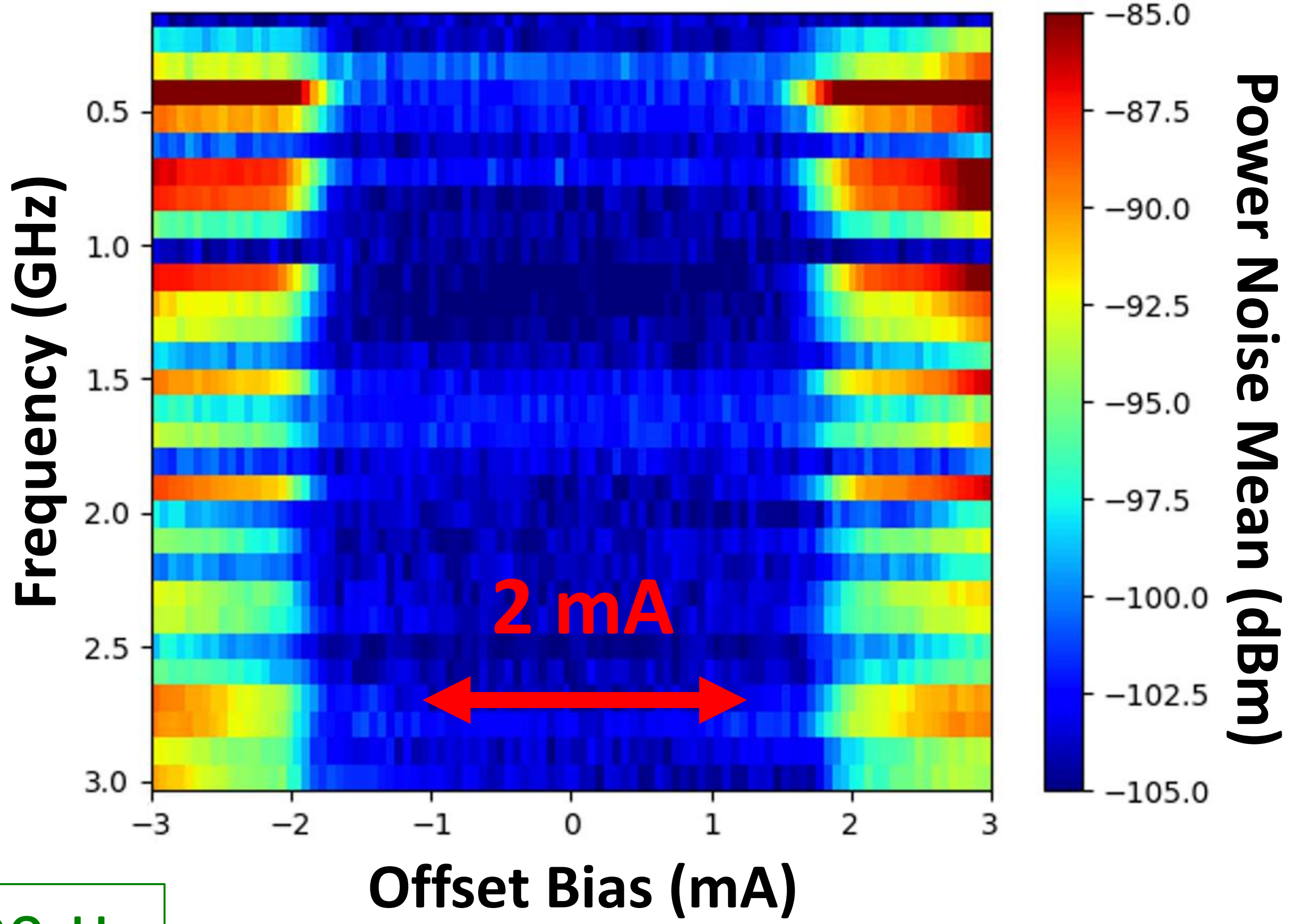
RFJAWS Quantum Locking Range at 1 GHz

NIST



1500 JJs

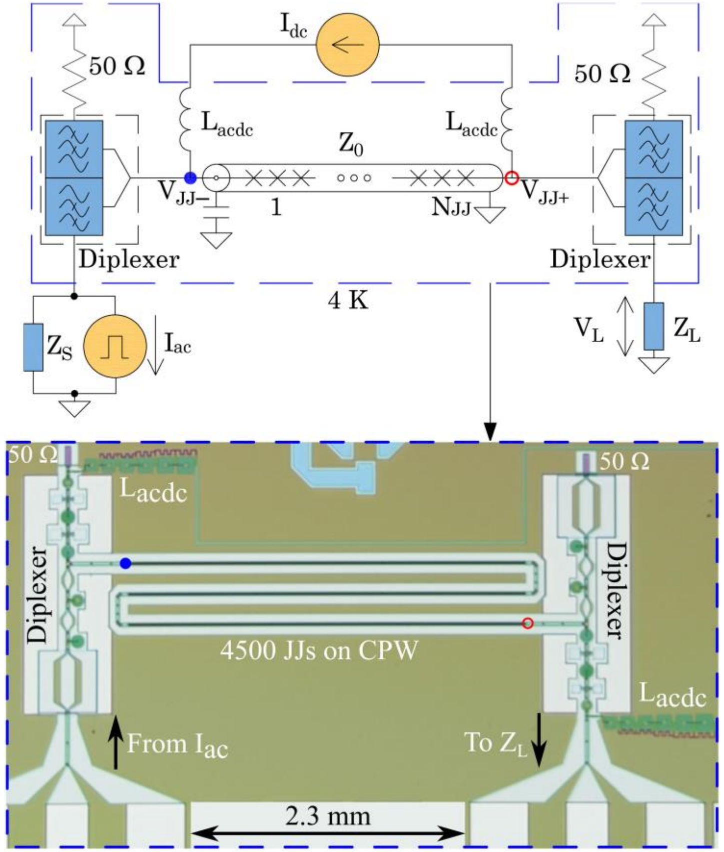


N Flowers-Jacobs, CPEM, Wellington, NZ 2022

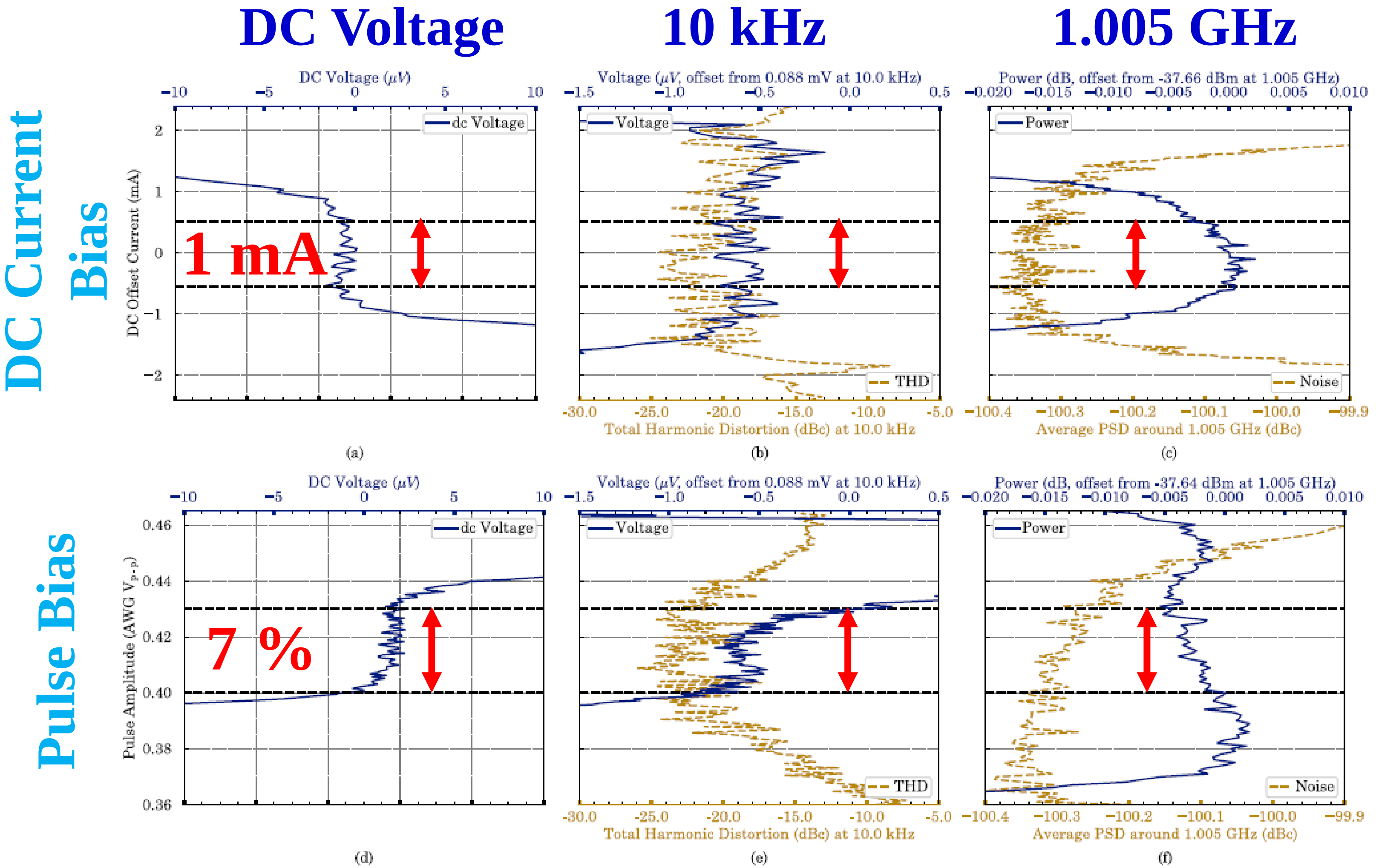
IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 59, May 2025. Presentation given at 22nd Biennial U.S. Workshop on Superconductor Electronics, Devices, Circuits, and Systems Santa Fe, New Mexico, April 6-10, 2025.

Record 22 mV rms RF JAWS Quantum Locking Ranges

RF-JAWS circuit with 4500 Junctions



Record 22 mV rms (−26.18 dBm) at 1.005 GHz

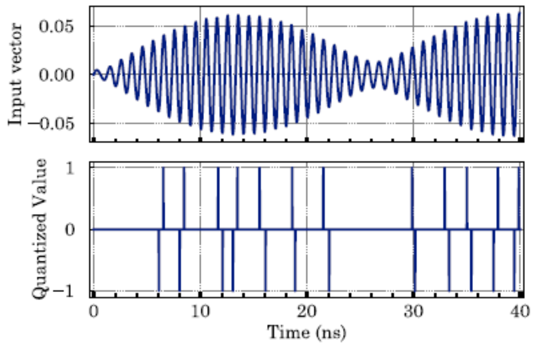


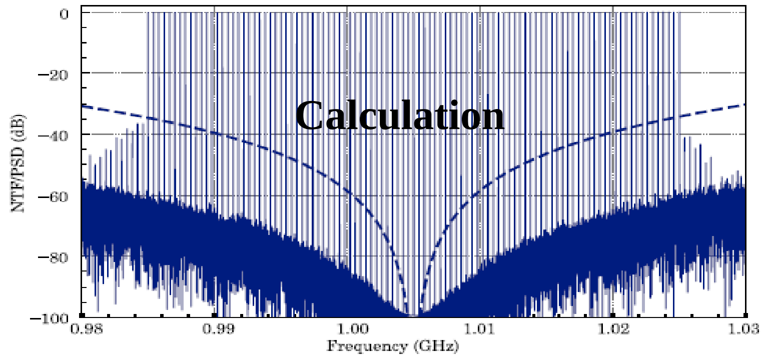
A. Babenko, et al., IEEE Trans. Appl. Supercond., Nov. 2022.

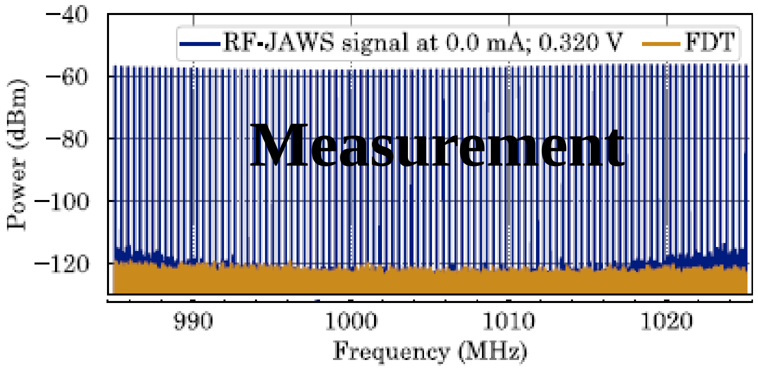
IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 59, May 2025. Presentation given at 22nd Biennial U.S. Workshop on Superconductor Electronics, Devices, Circuits, and Systems Santa Fe, New Mexico, April 6-10, 2025.

Quantum-Based Modulated Microwave Waveforms

101-Tone Chirp Signal

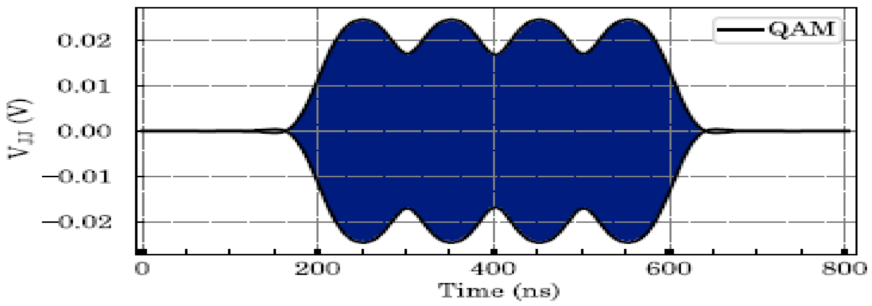


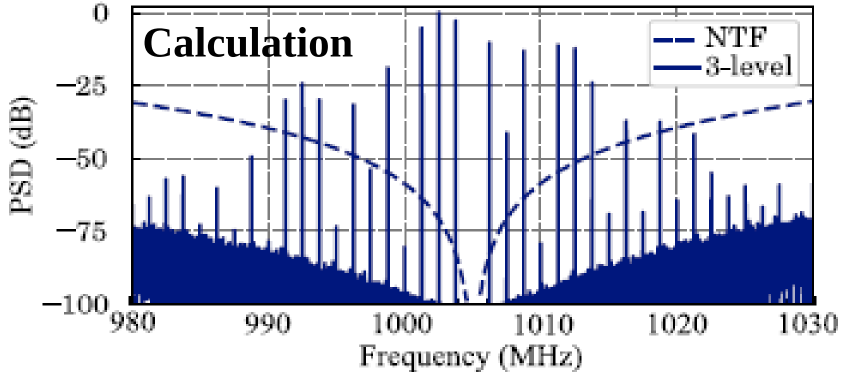


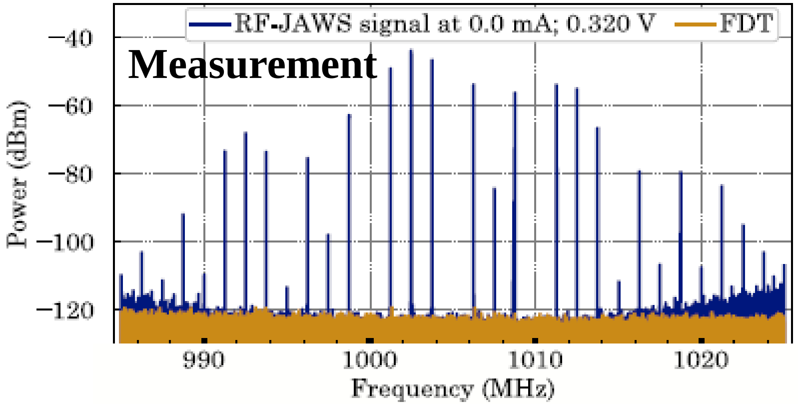


Both waveforms on a 1.005 GHz carrier

10 MHz QPSK Signal







A. Babenko, IEEE MTT

April 2024

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Conclusion

- PJVS and JAWS are quantum-based voltage sources
  - Available as NIST Standard Reference Instruments (SRI)
- VHF- & RF-JAWS are in development
  - Linearity and waveform purity are primary features
  - Single sinewaves for power/phase calibrations
  - Multi-tones and pulses for measuring DUT non-linearities