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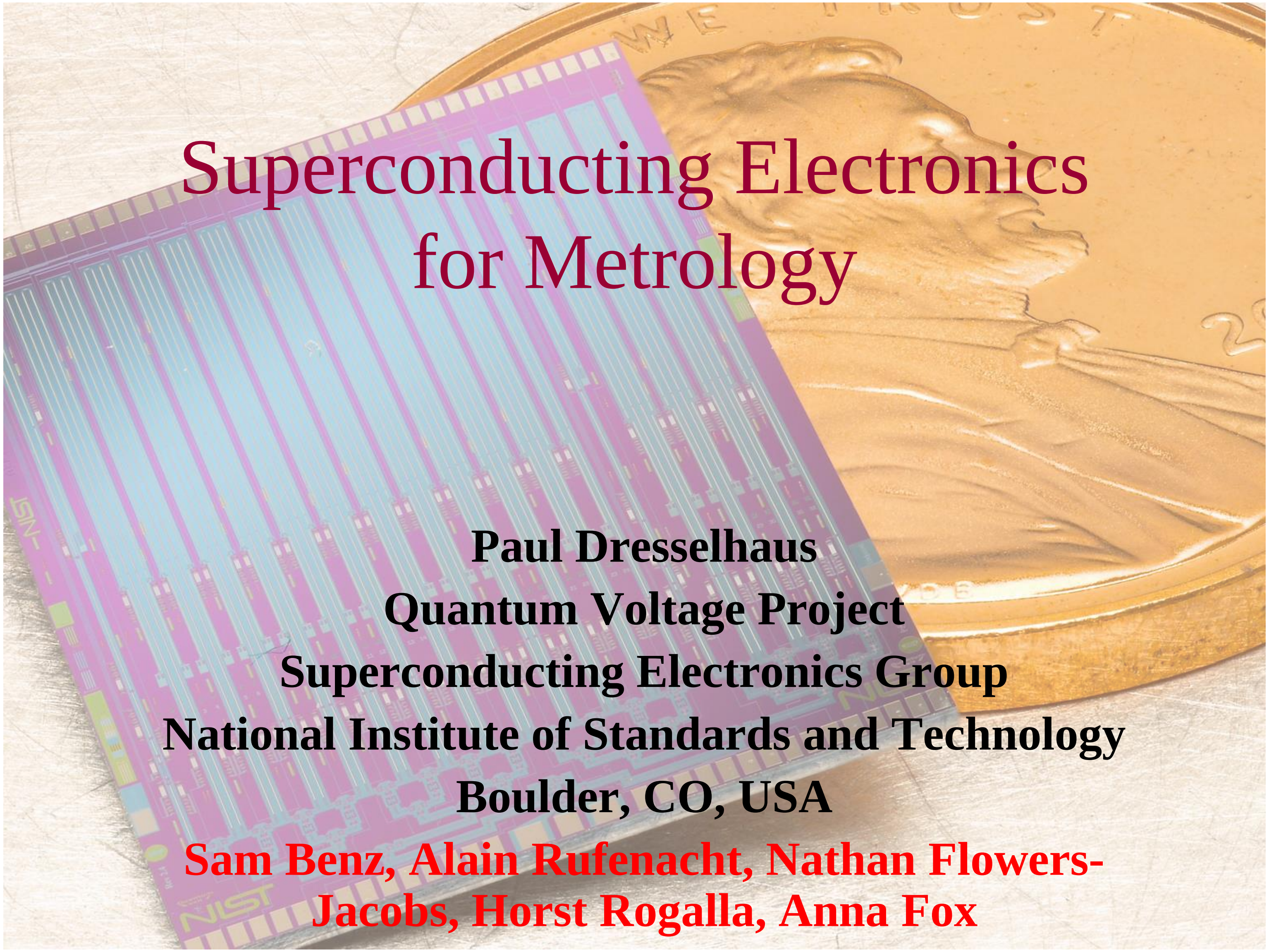
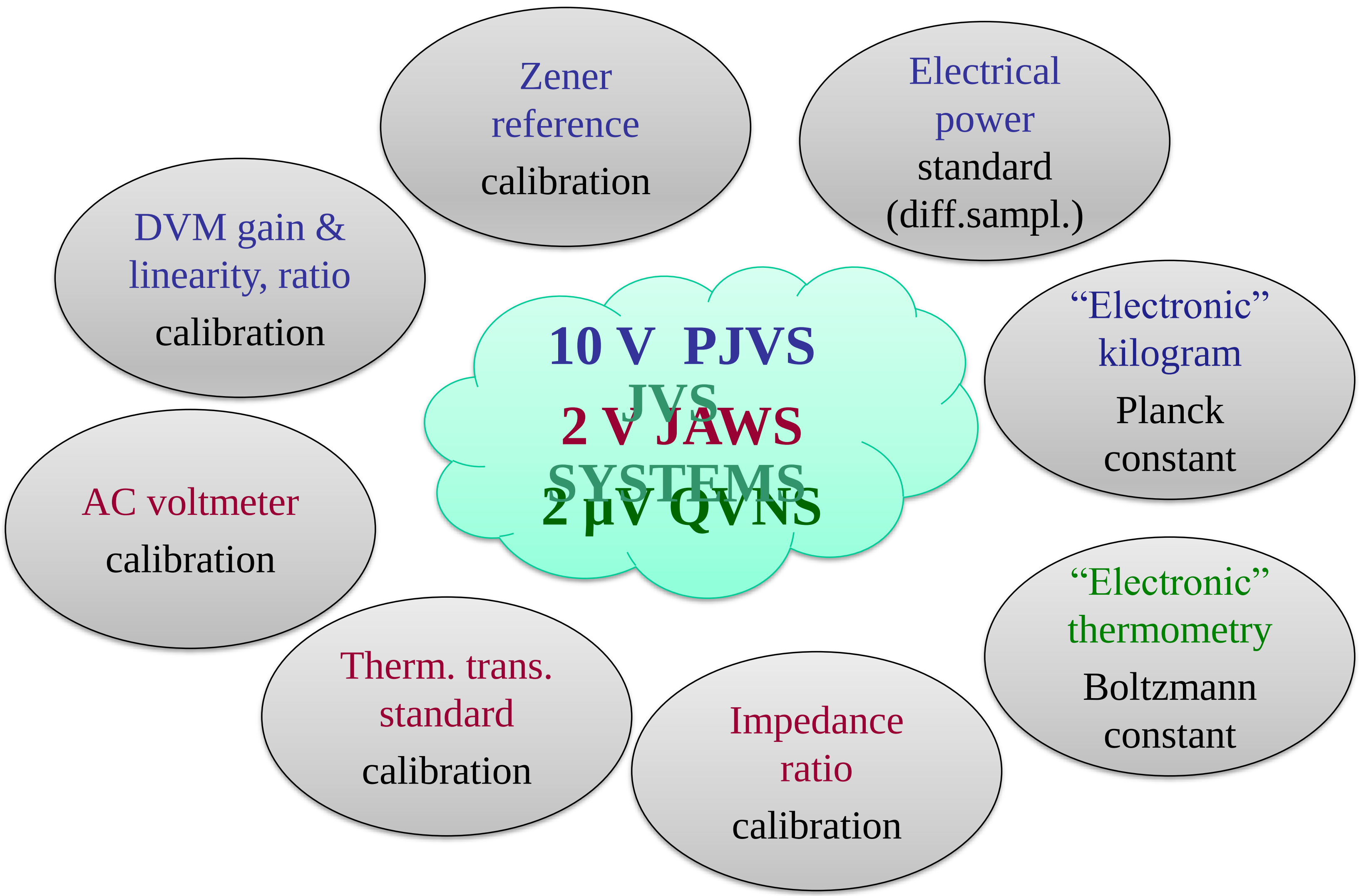


Superconducting Electronics for Metrology

Paul Dresselhaus
Quantum Voltage Project
Superconducting Electronics Group
National Institute of Standards and Technology
Boulder, CO, USA
Sam Benz, Alain Rufenacht, Nathan Flowers-Jacobs, Horst Rogalla, Anna Fox

June 16, 2017

Applications of JVS systems



New proposed SI

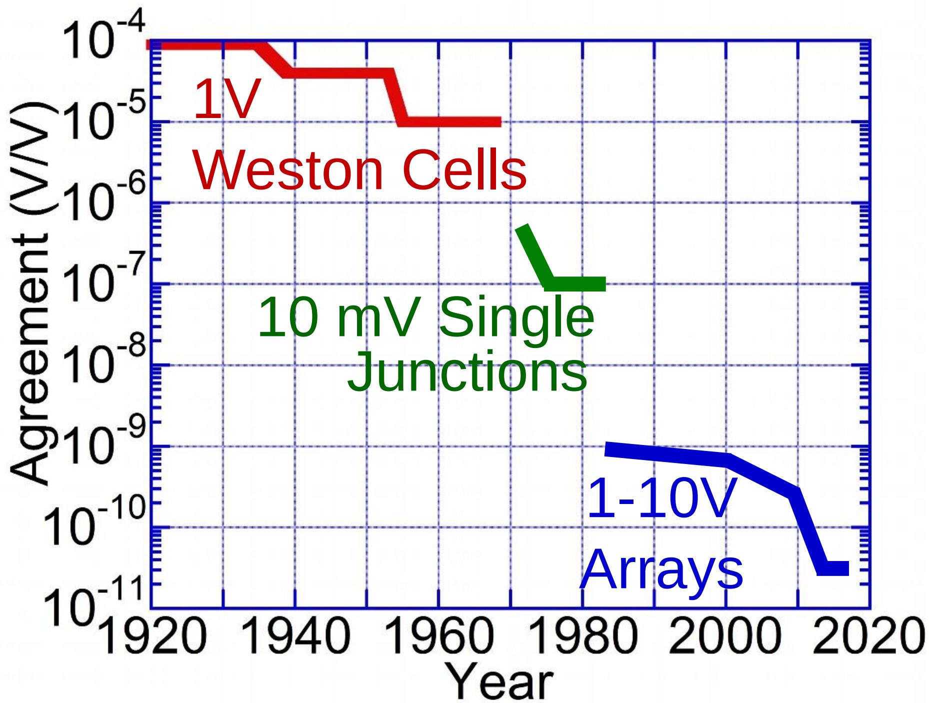
Unit		Actual SI	NEW SI	
second,	s	$\Delta\nu(^{133}Cs)_{hfs}$	$\Delta\nu(^{133}Cs)_{hfs}$	Cs hyperfine transition
meter,	m	c	c	Speed of light
kilogram,	kg	$m(K)$	h	Planck constant
ampere,	A	μ_0	e	Elementary charge
kelvin,	K	T_{TPW}	k	Boltzmann constant
mole,	mol	$M(^{12}C)$	N_A	Avogadro constant
candela	cd	K_{cd}	K_{cd}	Light source intensity at a frequency of 540 THz

Features of a Quantum Voltage Standard

- Intrinsic accuracy is based on quantum behavior
  - Josephson effect defines the electrical properties of superconducting Josephson junctions
- Always produces an accurate voltage
  - Regardless of environmental conditions or location, which is in contrast to "artifact" standards, and
  - Over a range of all bias parameters and operating conditions, called "flat spots".
- Voltage is only correct on-chip
  - Systematic errors must be removed or characterized
  - Measurement leads & circuit parasitics ("leakage" R, L and C) have thermal voltages & error currents

Artifact Standards for DC Voltage Replaced by Josephson Voltage Standards

Weston Cell, electrochemical battery cell



10 volt Josephson array chip

Varies in time & with environmental conditions

Intrinsically accurate based on quantum behavior of Josephson junctions

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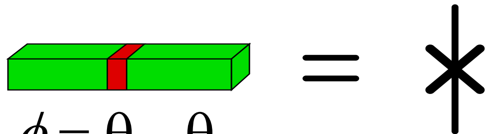
Quantum Behavior of Josephson Junctions



$$\phi = \theta_2 - \theta_1$$

- Phase quantization ensures quantized voltage pulses

$$V(t) = \frac{h}{2e}\frac{1}{2\pi}\frac{d\phi}{dt}$$

- One voltage pulse for every 2π phase change

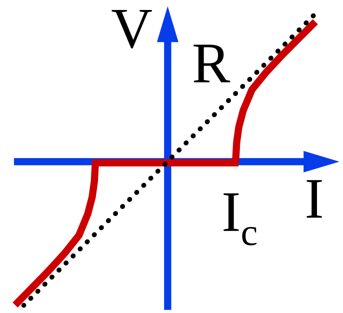
$$\int_0^\infty V(t)dt = \frac{h}{2e}\frac{1}{2\pi}\int_0^{2\pi}\phi\, dt = \frac{h}{2e}$$

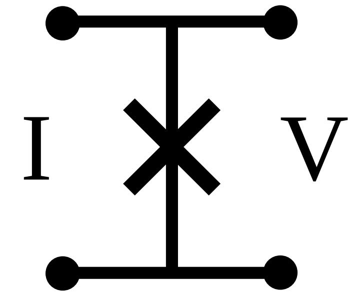
- Pulse area is always EXACTLY one flux quantum

$$\Phi_0 = \frac{h}{2e} = \frac{1}{K_J} = \frac{1}{0.4835979\, GHz/\mu V}$$

Driven Damped Josephson Junction

- DC current bias, *I*

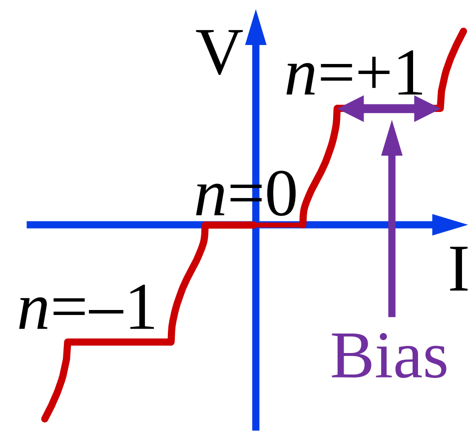




- Continuous microwave or periodic pulse bias
  - Supercurrent oscillations entrain to the drive frequency *f*
  - Lock at harmonic integers *n*
  - Generate constant DC voltage steps V_n

$$V_n = n \frac{h}{2e} f$$

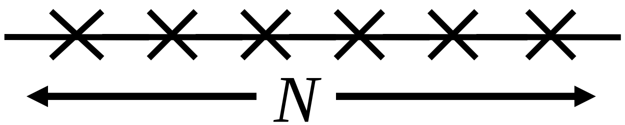
  - Over a dc bias current range or **flat spot**



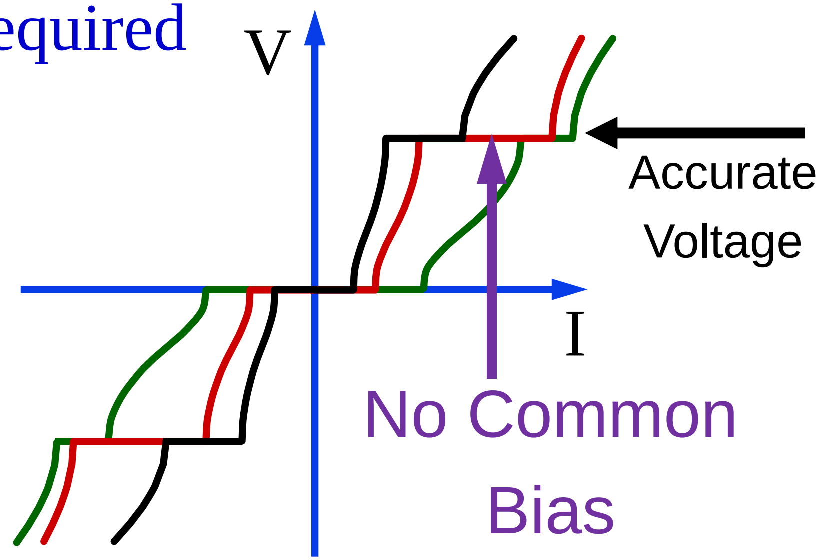
Practical Voltages Require Series Arrays

- Single junction voltages ≈ 20 μV
- 10 V is desired output voltage
- Large series arrays are required

$$\frac{h}{2e} \approx 2\mu V / GHz$$



$$V_n = \frac{h}{2e} nNf$$



- Uniform junctions
- Uniform microwave power

Practical Voltages Require Long, Uniform Series Arrays

clock

Programmable Josephson Voltage Standard

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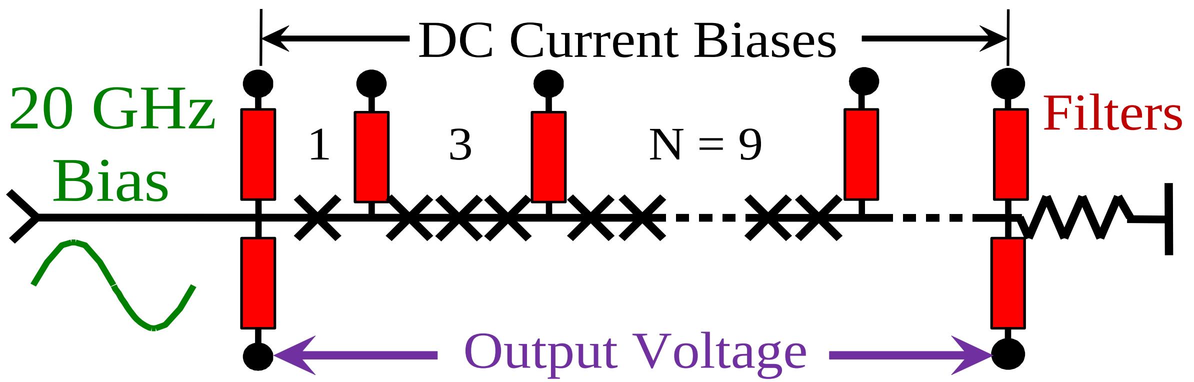
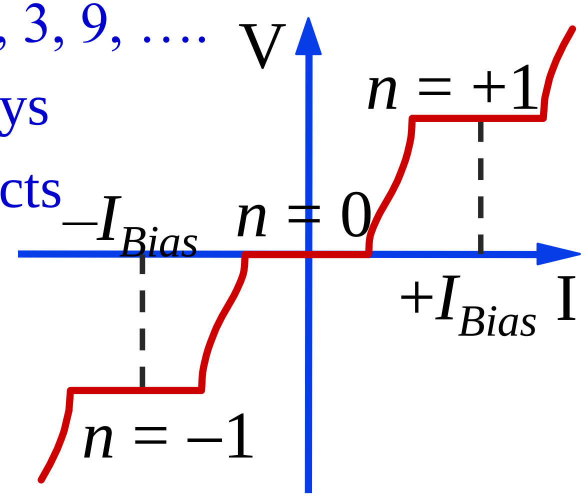
Programmable Josephson Voltage Standard



- Sub-array JJs in **ternary** sequence N=1, 3, 9, ….
- 20 GHz **microwave bias** to all sub-arrays
- **DC current bias** to each sub-array selects one of three voltage steps, n



$$V_{Array} = nN\frac{h}{2e}f$$

Hamilton, Burroughs and Kautz, 1995

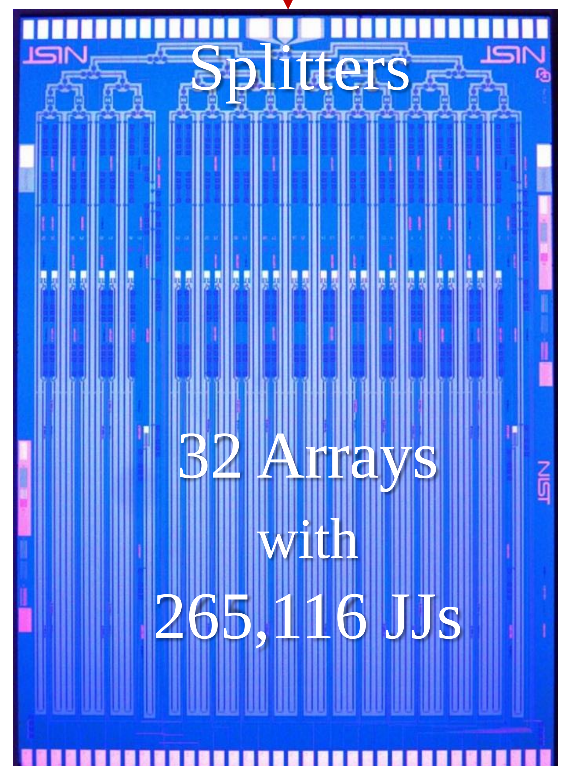
Fabrication & Design of Superconducting Circuits

- Boulder Micro-Fabrication Facility

- Superconducting integrated circuits
  – Uniform junctions, barrier materials, low-defect fabrication
- Microwave circuit design
  – Lumped element inductors & capacitors, power splitters, coplanar waveguides, simulation & modelling

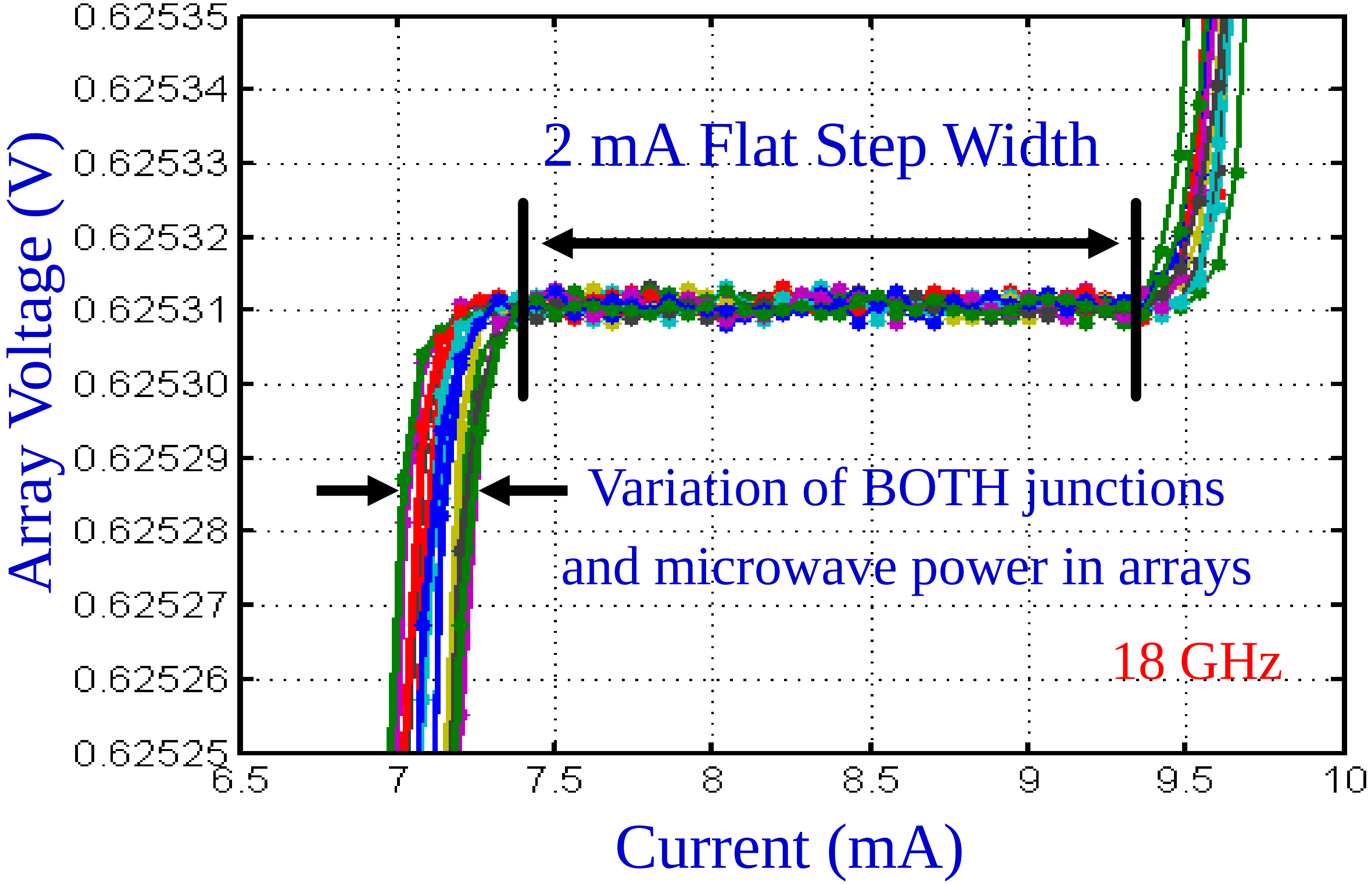
(12 x 17) mm^2 PJVS Chip

Microwave Input



DC Input/Output Pads

Flat Spots of 16 Arrays with 16800 Junctions

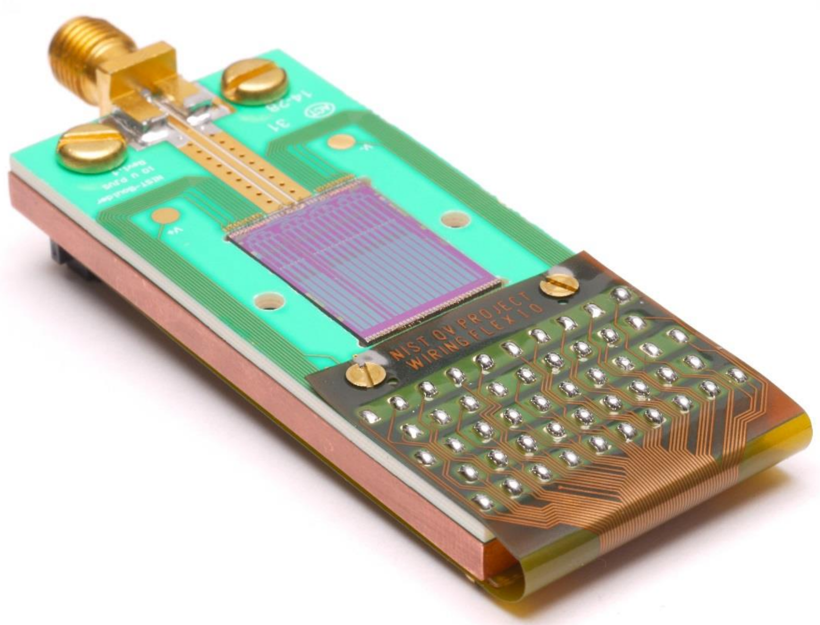


Uniform junctions and microwaves

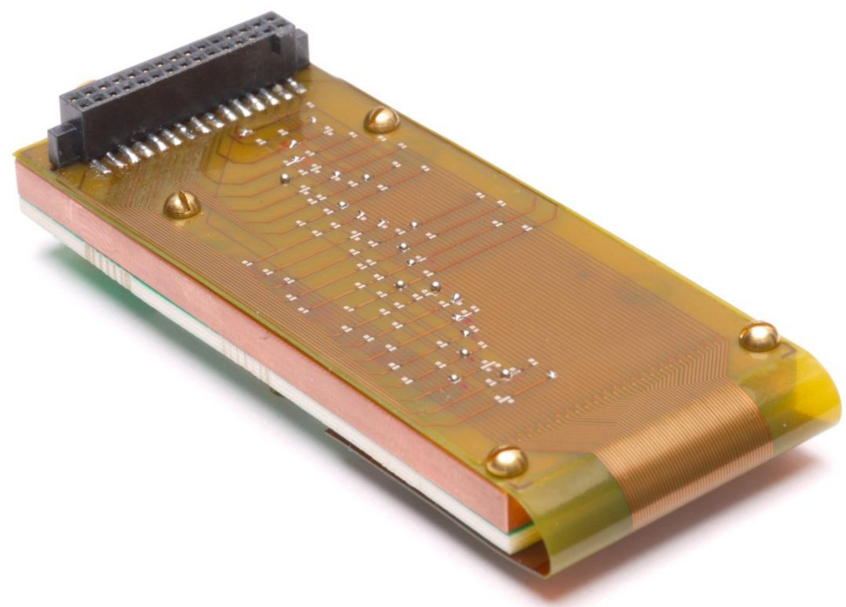
PJVS Cryopackage

- Optimized microwave, thermal and cryogenic design
- Interchangeable operation in liquid helium probes or cryostat
- Connectorization enables solder-free, fast mounting
- Reconfigurable sub-array with flex matrix bias leads

Top



Bottom



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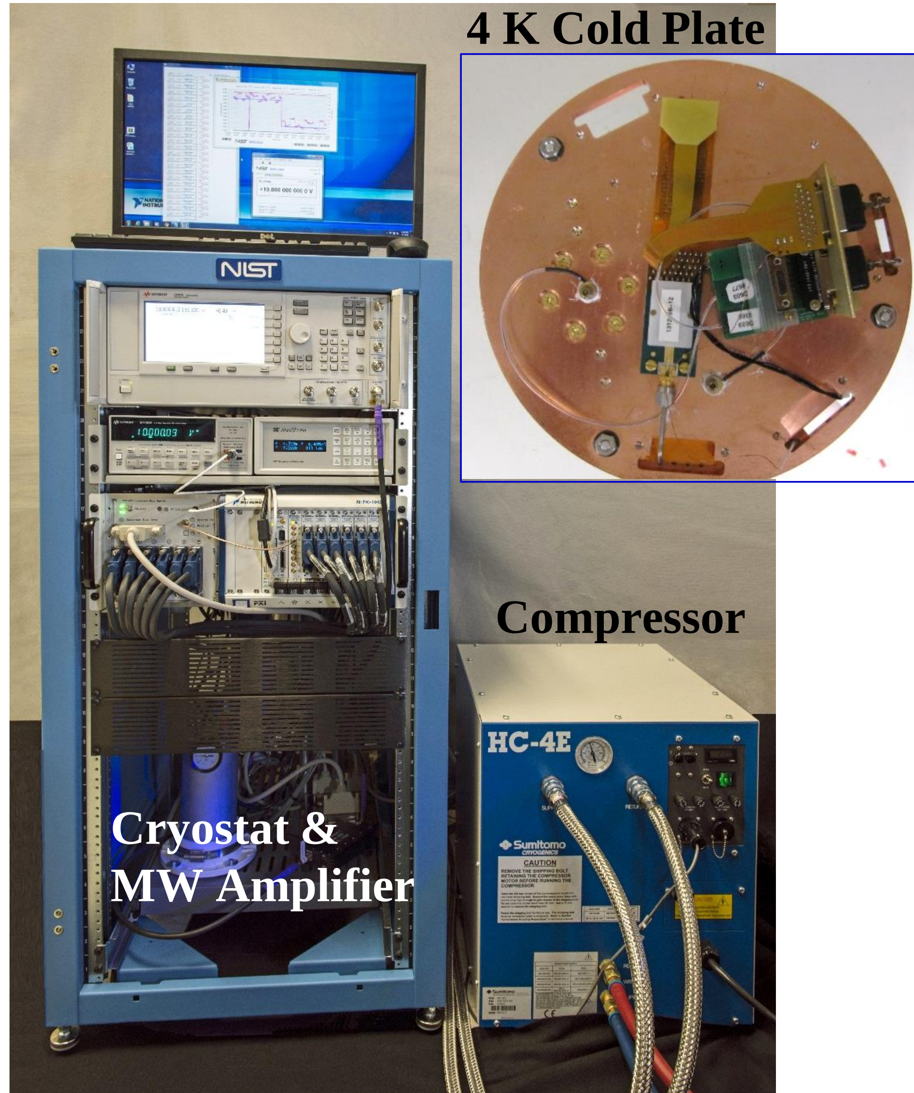
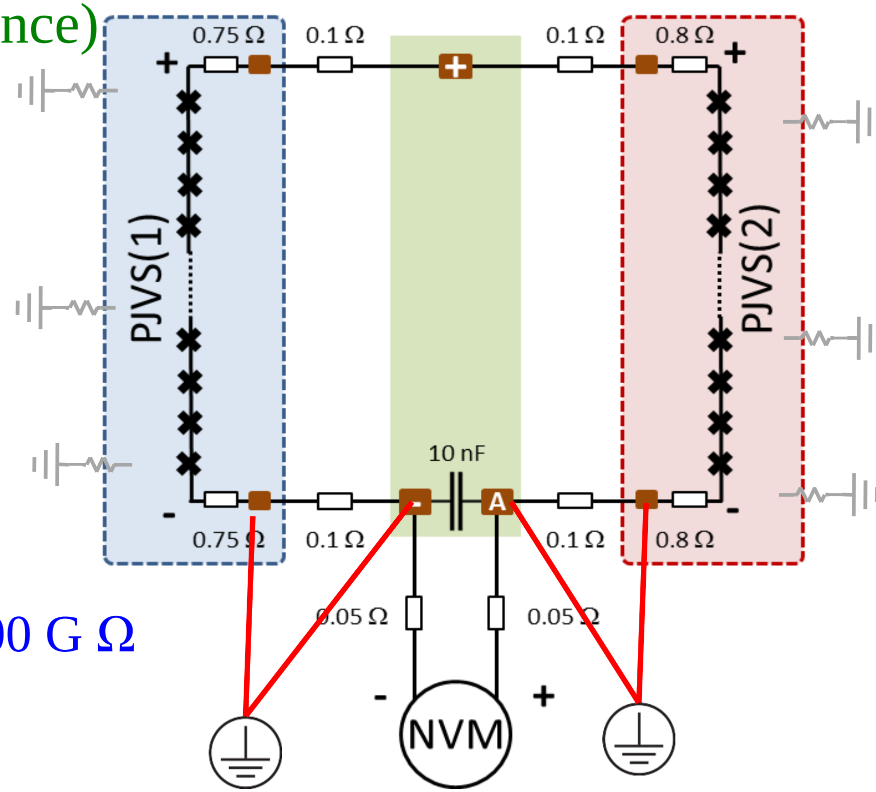
NIST Cryocooled PJVS System

- Integrated system
  - Bias electronics DC & MW
  - Cryogenics
  - Superconducting devices
  - Turn-key integrated system
  - Automation software
    - Optimize & check quantum states, flat spots
    - Performs measurements
- Specific measurement techniques needed for different applications



Leakage currents in the PJVS system

- Need high Leakage impedance (CJB& ALR)
  - PJVS (dc leakage resistance)



- 10 V/10 G Ω = 1nA
- 1 nA * 1 Ω = 1 nV
  - 1 part in 10^{10} at 10 V

Leakage resistance should be ~> 100 G Ω

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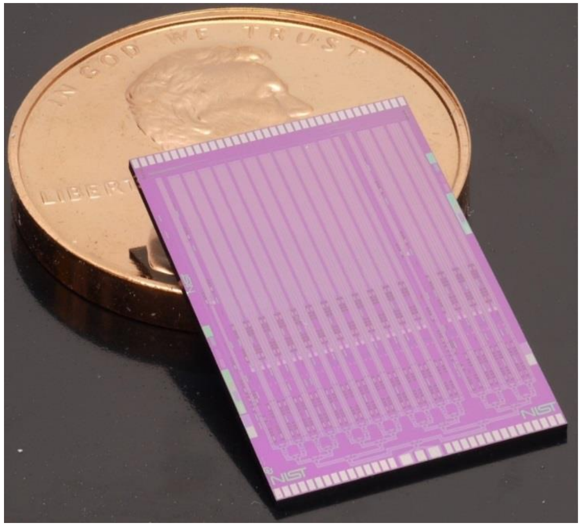
PJVS Applications & Best Results

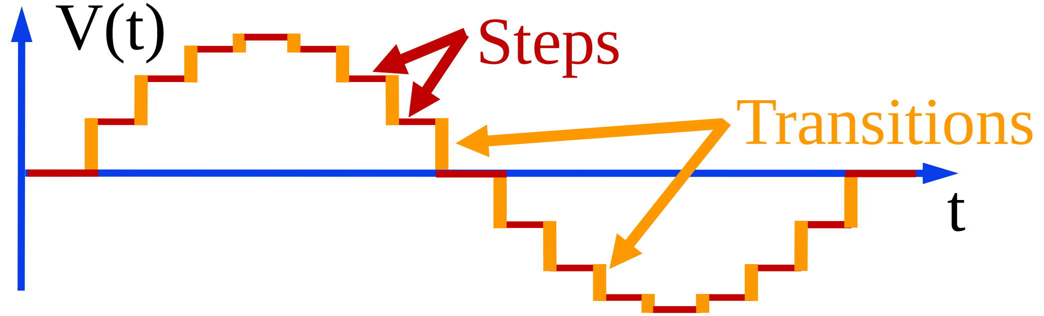


- Stable DC & stepwise AC voltages
  - Calibrate:
    - Zener reference standards
    - DVM gain, linearity
    - Calibrators
    - Power meters
  - Precision Measurements:
    - Electronic kilogram for measuring Planck's constant, *h*
- Uncertainty for different measurement techniques
  - DC to DC comparison of PJVS: 3×10^{-11}
  - Differential sampling frequencies < 500 Hz: < 1 µV/V

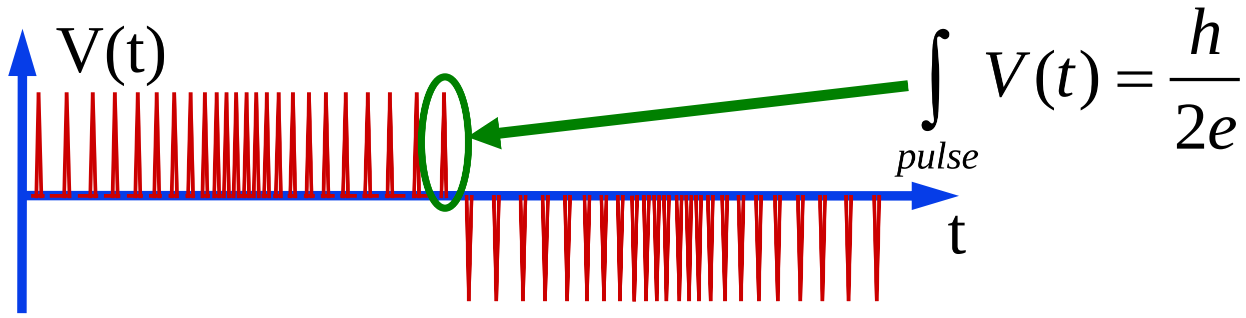
Intrinsically Accurate AC Synthesis

AC Voltage Standards & Arbitrary waveform Synthesizers

- Step-wise approximated sine waves
  - Transitions between steps compromise accuracy

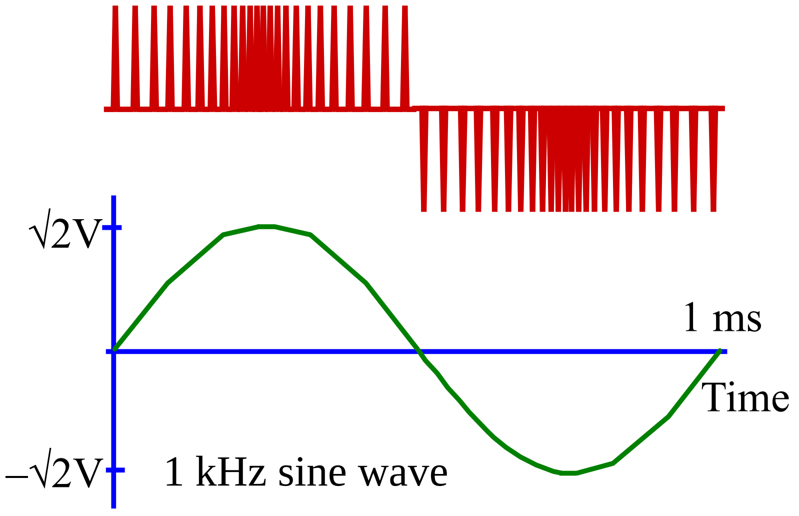


- Direct digital synthesis with current pulse sequences
  - Intrinsically accurate by controlling every quantized pulse



Pulse-Driven Voltage Synthesis

- Arbitrary voltage waveforms
- **Pulse biased**
- Directly control every JJ pulse
  - Digital signal provided by high-speed pulse generator
- Waveform synthesis
  - Timing and polarity precisely determine the voltage waveform
- Intrinsically accurate
  - Pulse density determines voltage
  - JJ pulses are perfectly quantized



Control 3 quantum states (+, 0, – pulses) for each junction to produce bipolar waveforms

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

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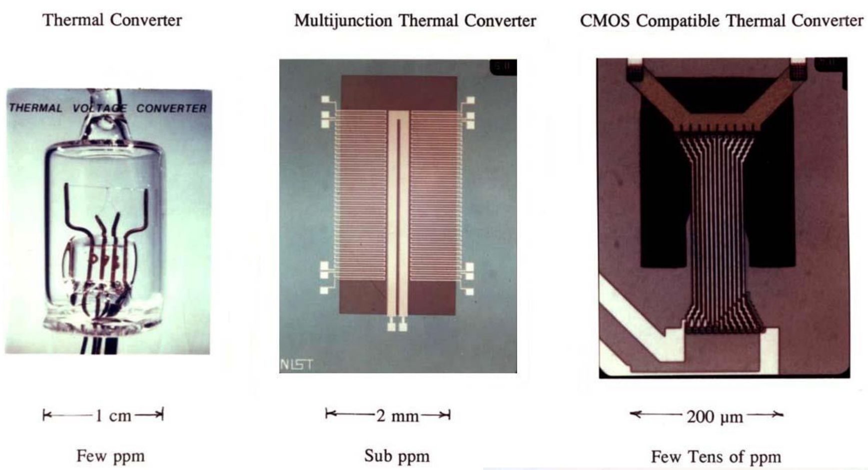
"Artifact" Detectors vs. "Quantum" Sources

- Conventional AC standards are RMS detectors
  - Thermally AC ←→ DC voltage signals
  - "Artifact" standards have similar performance, but <u>NOT identical</u>



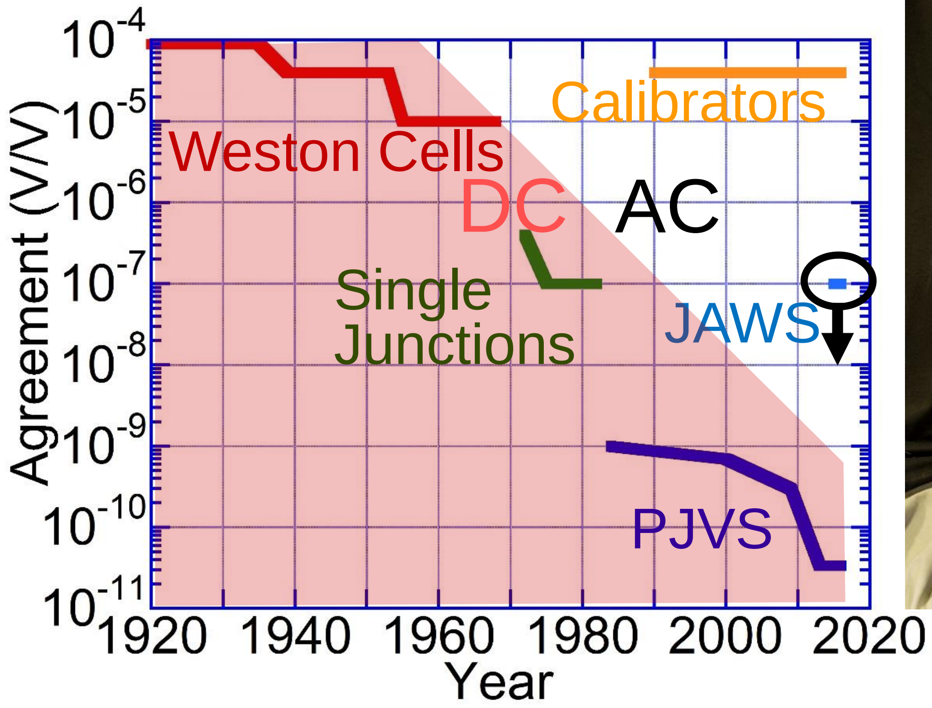
Thermal Converters

Transfer Standards

- Provide a source based on quantum effects

First Comparisons of 1 V AC Josephson Voltage Standard Sources

Commercial Voltage Calibrators

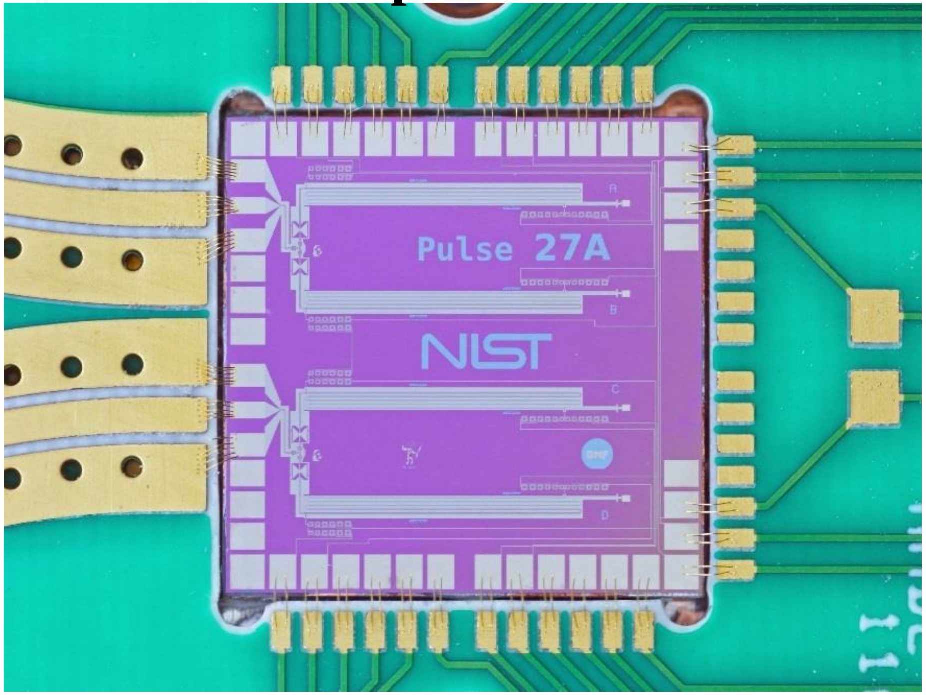


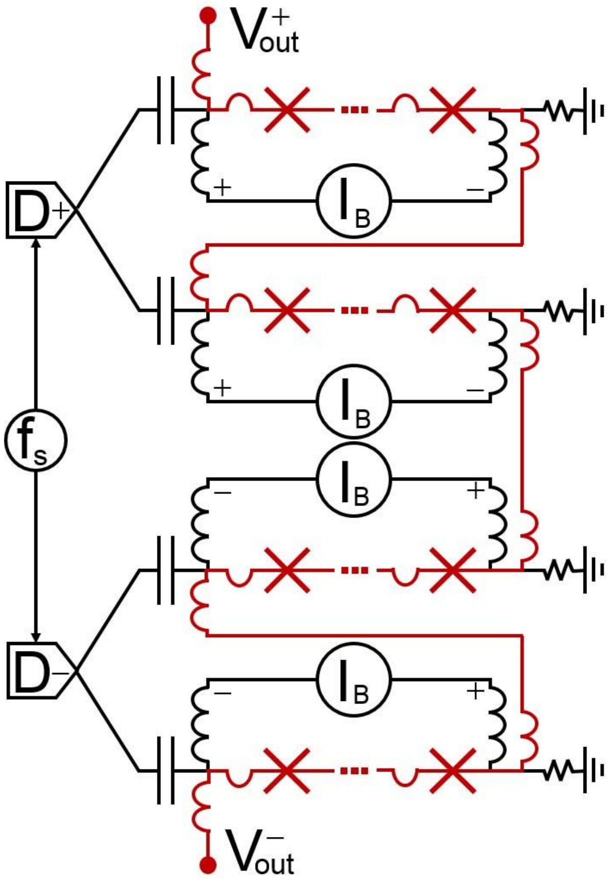
1 V JAWS

- Statistical uncertainty of first intercomparisons of 1 V AC JAWS voltages are now below 0.1 μV/V
- Systematic errors are ~1 μV/V for kilohertz frequencies

1V rms JAWS Chip and Circuit

1 cm x 1 cm Chip

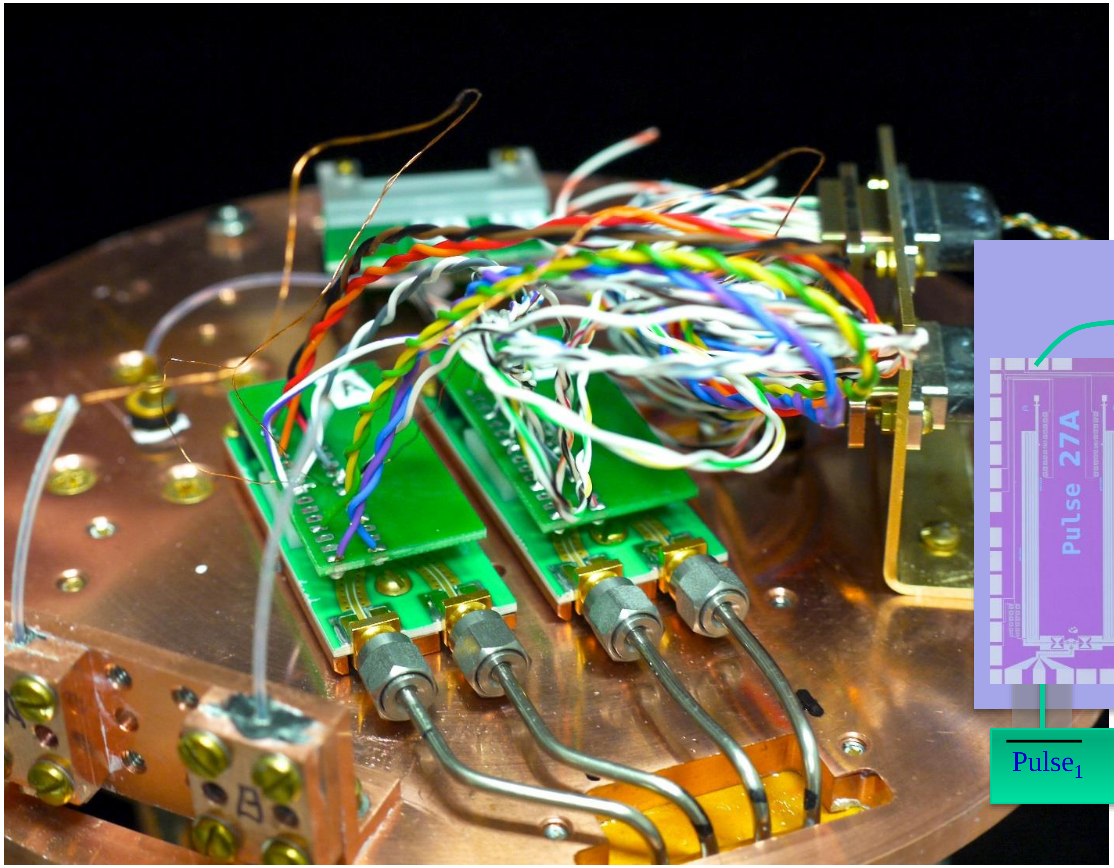




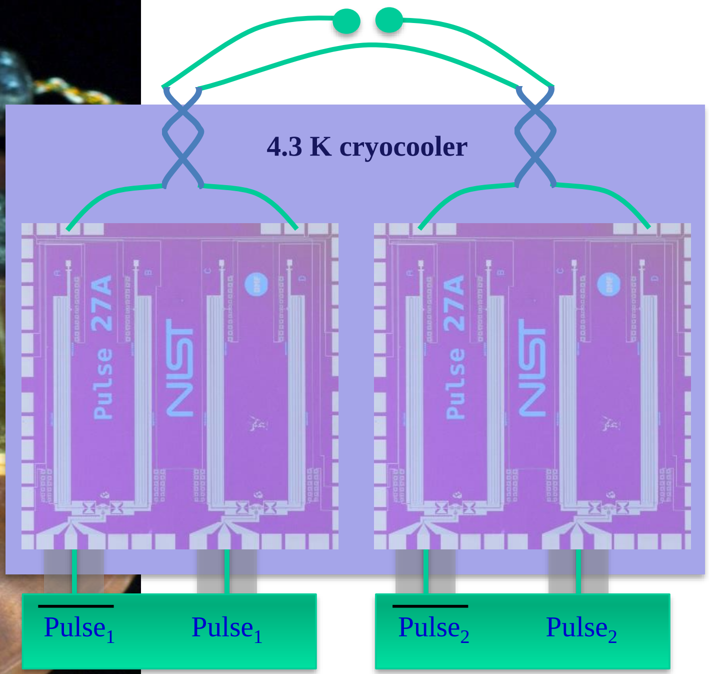
- 51,240 total junctions in 4 arrays
- 2 pulse biases and 4 low-speed biases
- Clocking pulses at 15 GHz = 770x10^{12} quantum states/s
- Measure spectra with a 24-bit ADC digitizer

Advances in the JAWS system

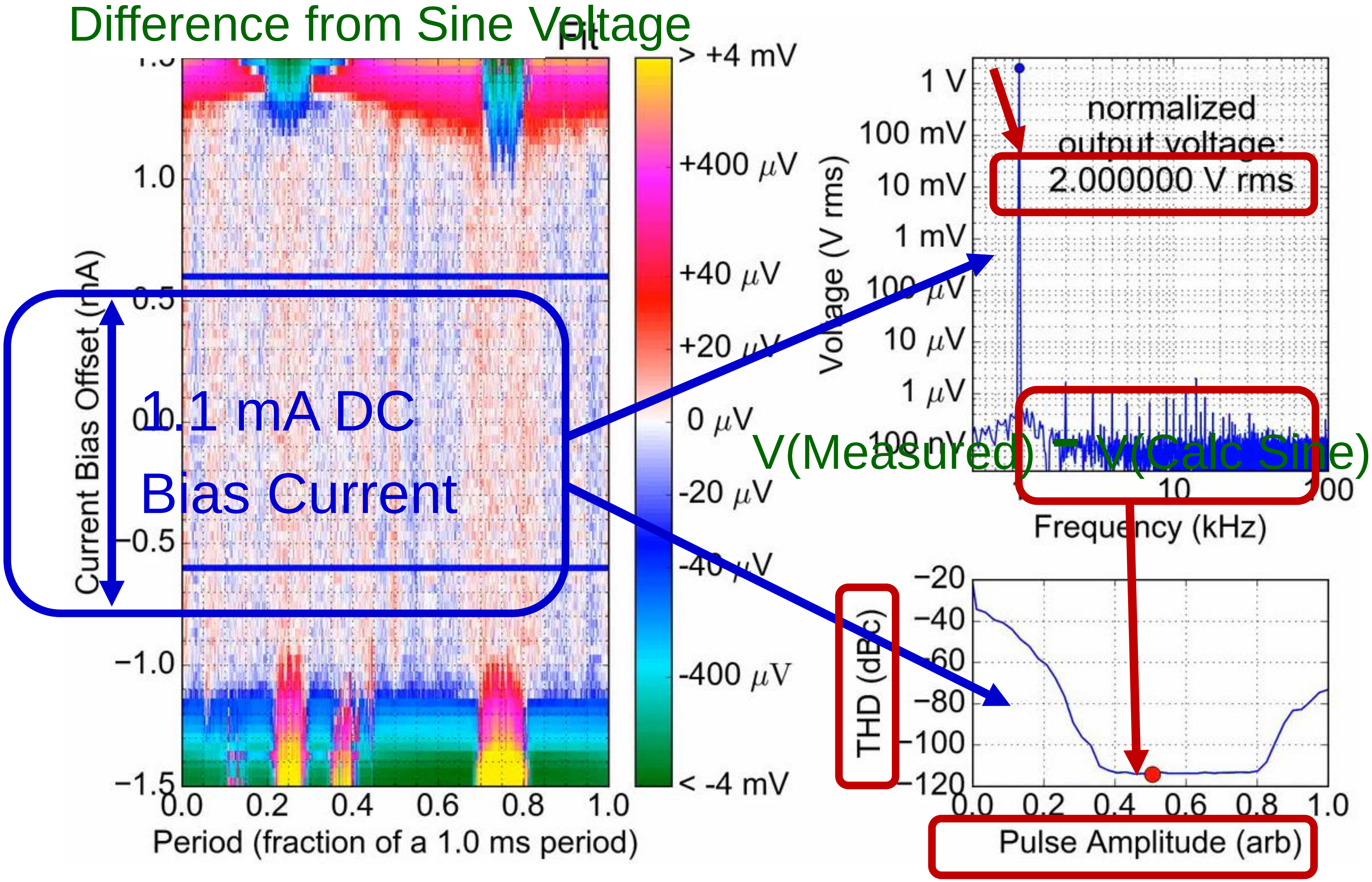
2016: **2 V** cryocooled system,
4 pulse channels (2 sets of bias electronics)



1 V ± 1 V output

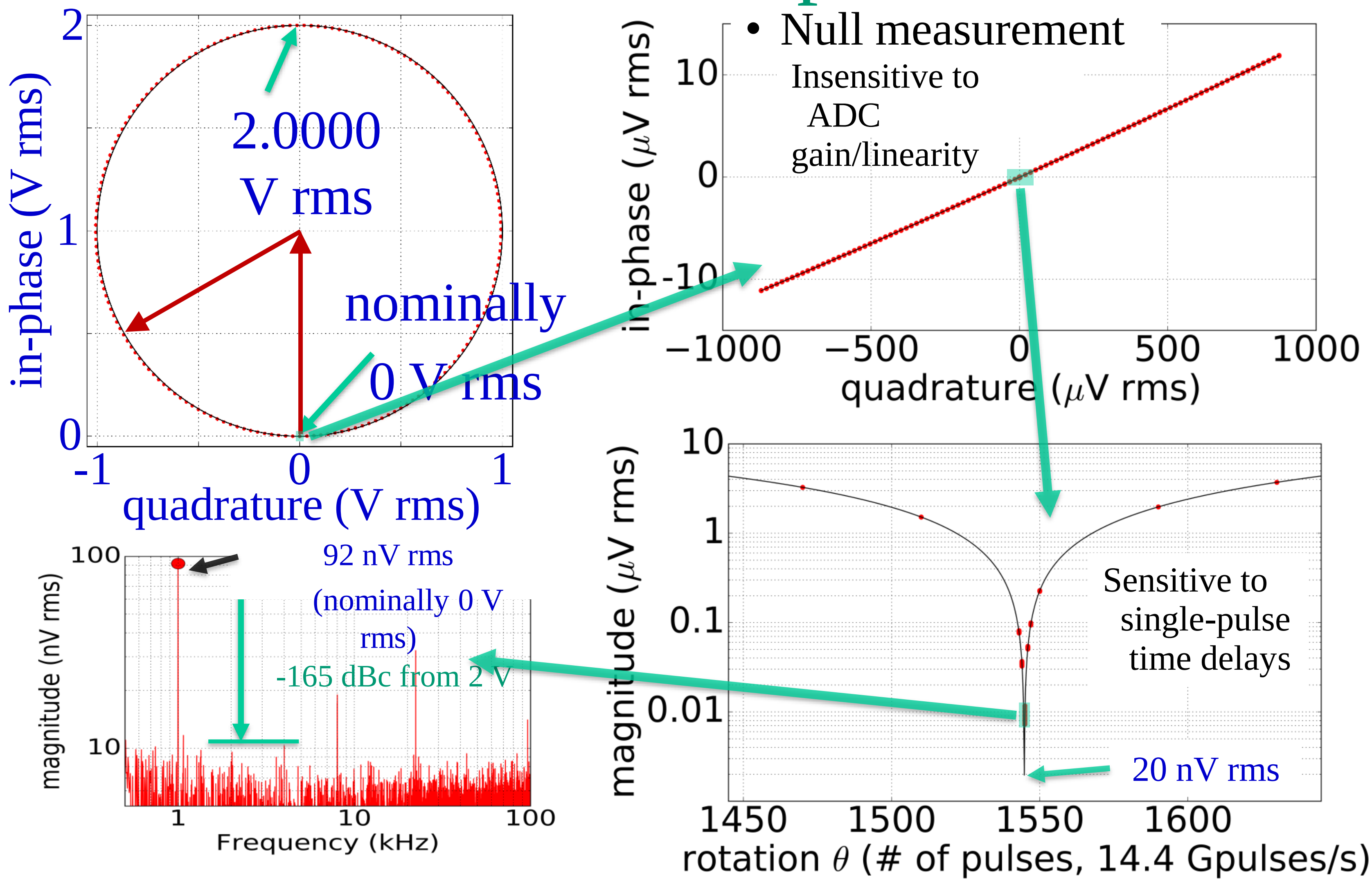


Flat Spot of Quantum States



Nathan Flowers-Jacobs, 2016

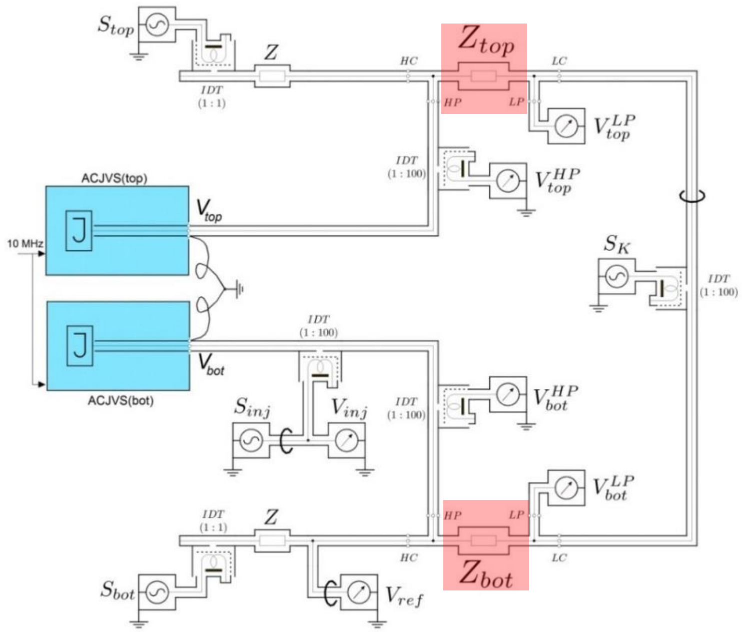
1 V ± 1 V JAWS comparison at 1 kHz

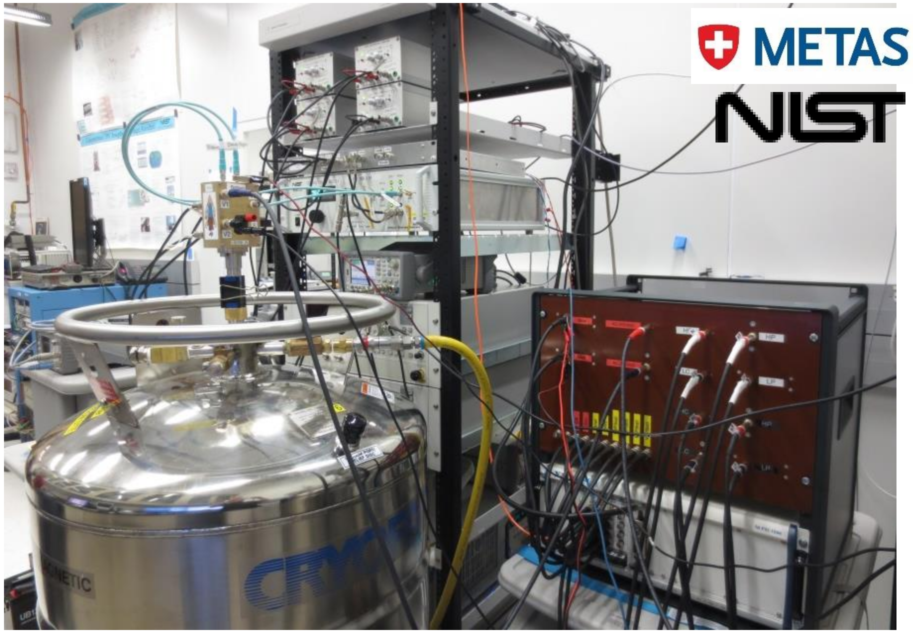


JAWS Applications

- Calibrations:
  - Voltage calibrators
  - AC-DC transfer standards
  - Thermal converters
    - May require trans-impedance amplifier
- Characterizing analog and digital electronics:
  - Gain, linearity, and distortion of analog-to-digital converters (ADCs) and amplifiers
- Impedance comparisons (*New)

Josephson-Based Full Digital Bridge for high-accuracy impedance comparisons





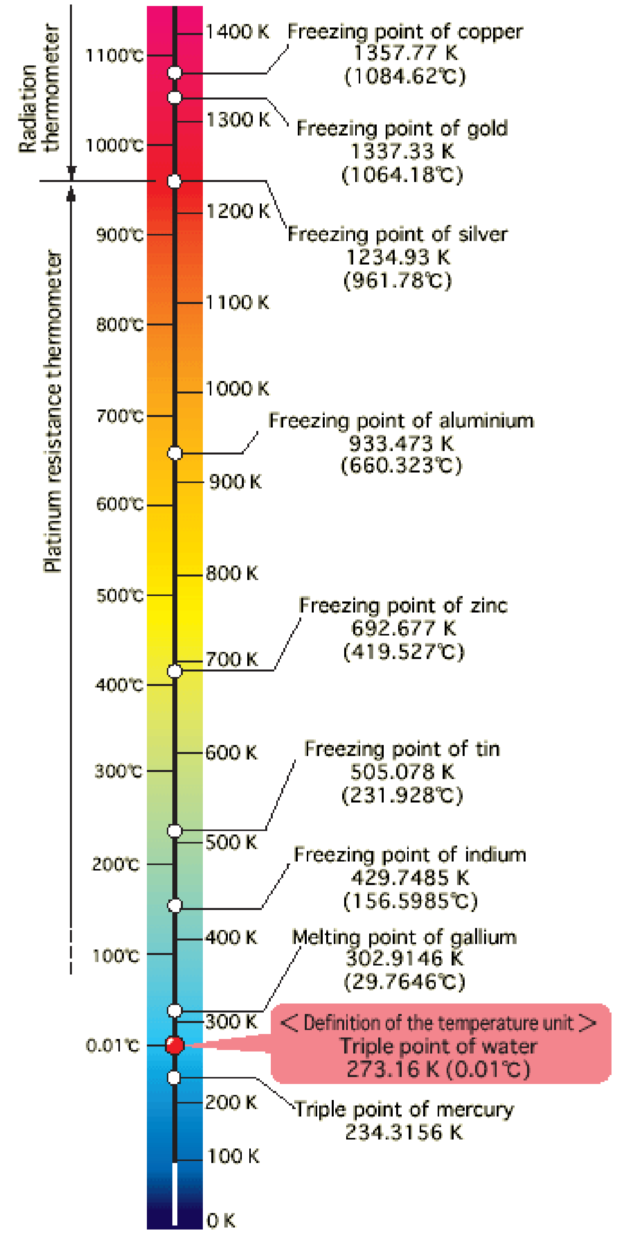
- Voltage ratio can be set to any desired value and frequency
  - Don’t need different transformers to match different impedance ratios
  - Allows direct comparison between the decadal scale and AC-QHE, 10:12.906
- Any impedance in the complex plane can be calibrated
  - Because the phase between the JAWS sources can be adjusted to any value

Overney et al., Metrologia, June 2016

Quantum Voltage Noise Source

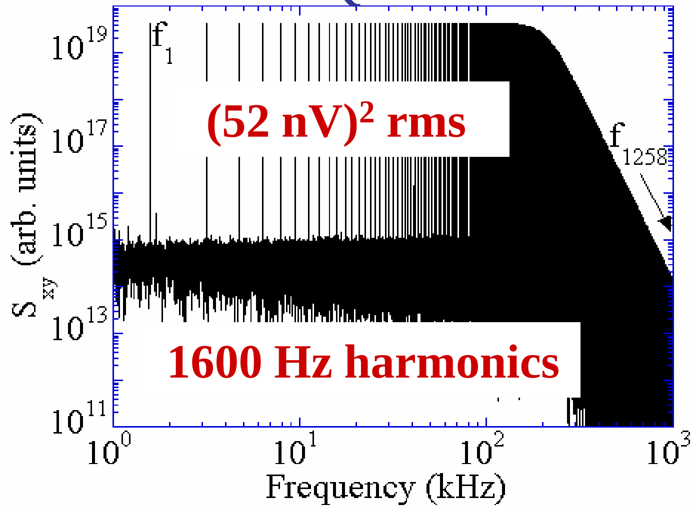
Artifact Standards in Thermometry

- ITS-90 scale of fixed points
- K defined by triple point of water
- Scale is designed to "represent" thermodynamic temperature
- Interpolation required for temps between fixed points



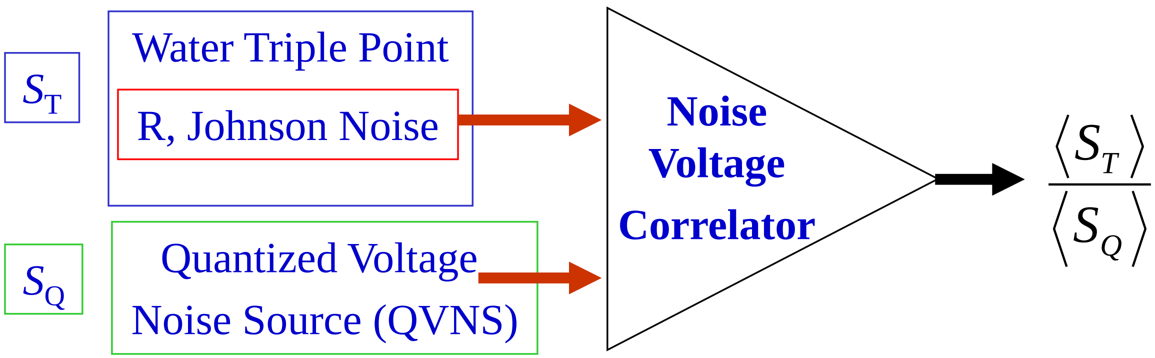
Johnson Noise Thermometry with a Quantized Voltage Noise Source

- Fully electrical measurement of thermodynamic temperature
- Measure Johnson noise voltage of a 100 Ohm resistor at different temperatures $\langle V_T^2 \rangle = S_T \Delta f = 4kTR\Delta f$
- SMALL 2 nV/√Hz noise voltage ≈ amplifier noise voltage
- Requires cross-correlation measurement techniques
- Calibrate electronics with quantum-accurate "pseudo-noise" voltage synthesized with a QVNS



Johnson Noise Thermometry

- Compare thermal and electrical noise powers

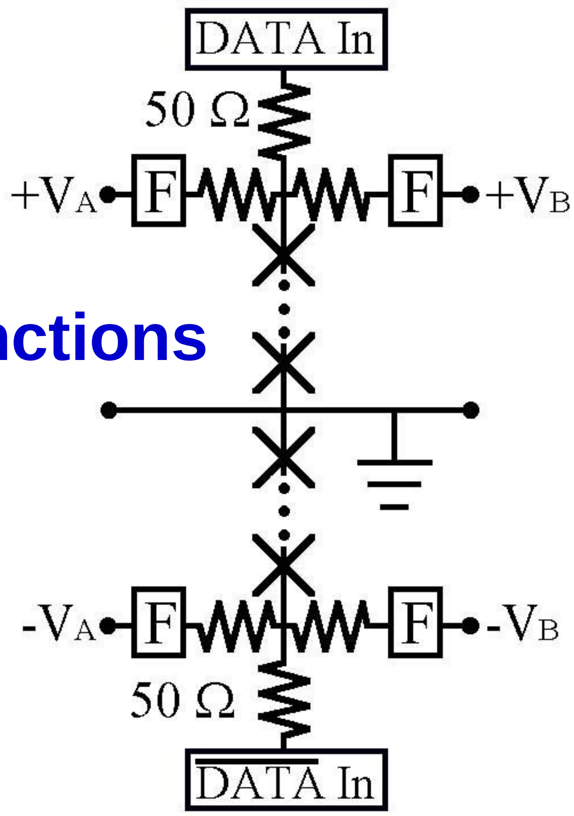


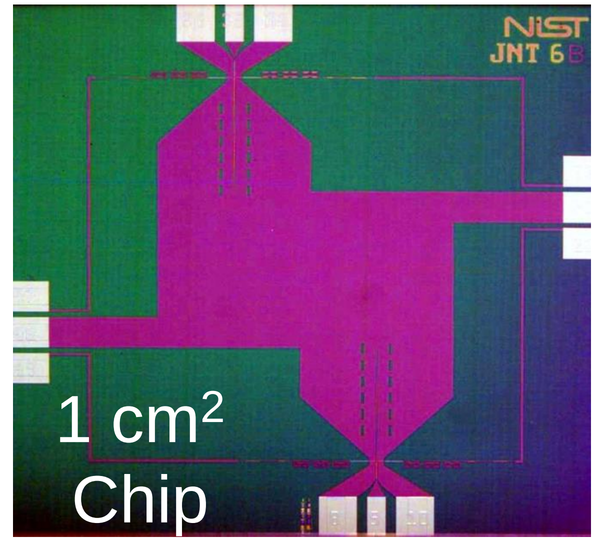
- Temperature is determined by noise ratio, measured resistance *R*, fundamental constants *h*, *k* and R_k, and QVNS constants *D*, *N*, f_{clock} and *M*)

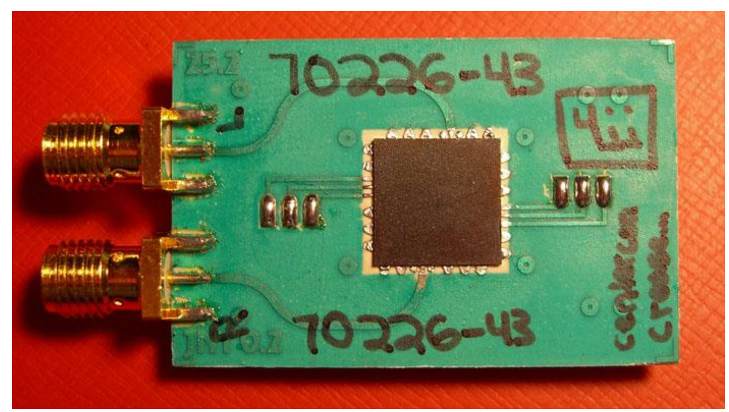
$$T = \frac{h}{k} \frac{\langle S_T \rangle}{\langle S_Q \rangle} \left(\frac{R_k}{R} \right) f_{clock} \frac{D^2 N^2 M}{16}$$

Quantum Voltage Noise Source QVNS

8 junctions

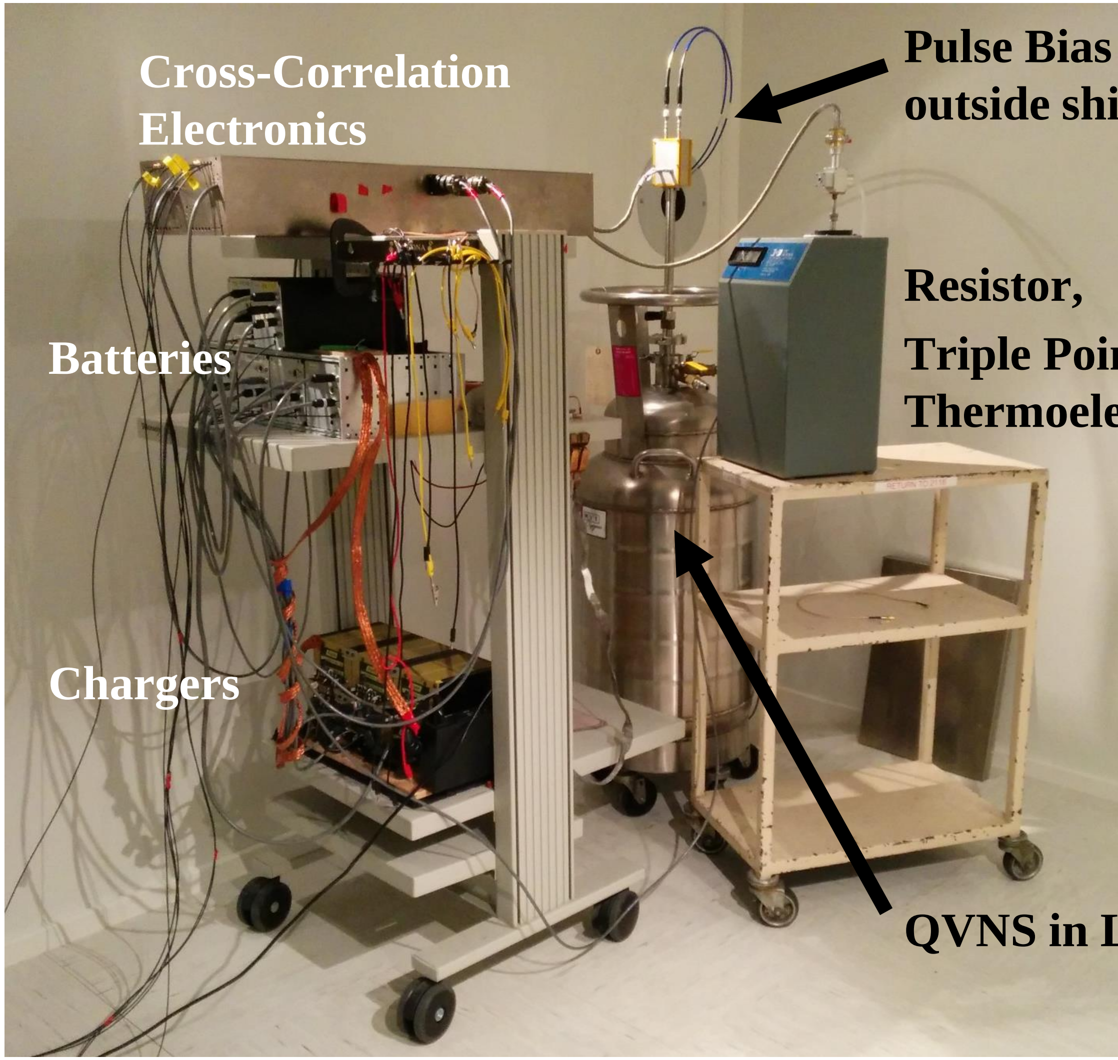






Cryopackage

NIST Johnson noise thermometer



Johnson Noise Thermometry Results

- Electronic determination of Boltzmann's constant, k

$$\frac{k}{h} = \frac{\langle S_T \rangle}{\langle S_Q \rangle}\left(\frac{R_k}{R}\right)\frac{f_{clock}}{T_{TPW}}\frac{D^2 N^2 M}{16}$$

  - Uncertainty results
    - 12×10^{-6} (5ppm Type A in 10 days) NIST USA, 2010
    - 4×10^{-6} (3ppm Type A in 34 days) NIM China, 2015
    - (9ppm Type A in 7 days) AIST Japan, 2016
  - $< 3\times10^{-6}$ is the goal for SI redefinition
- Primary "thermodynamic" thermometer
  - Measured Sn, Ga and water on ITS-90 temperature scale
  - Perfect voltage and temperature linearity has potential to increase knowledge of ITS-90 fixed-point "artifacts" and eliminate interpolation between temps

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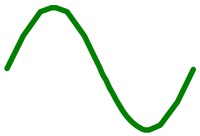
Summary

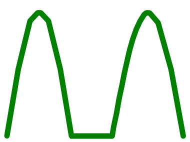
- Programmable Josephson Voltage Standard (PJVS)



Microwave Bias

  - **Intrinsically accurate DC** voltages
  - ±10V peak stepwise-approximated AC waveforms
  - Requires differential sampling on steps to realize quantum accuracy
  - Applications: DC voltage, AC voltage < 200 Hz, AC power

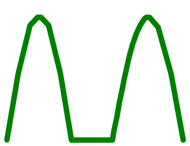
- Josephson Arbitrary Waveform Synthesizer (JAWS)



Pulse Bias

  - **Intrinsically accurate AC** waveforms
  - 2 V RMS sine waves, or 5.6 V peak-to-peak arbitrary waveforms
  - Challenge is sourcing current to low-impedance meters
  - Applications: DC voltage, AC voltage, AC power, Impedance

- Pulse-driven Quantum Voltage Noise Source (QVNS)



  - **Intrinsically accurate arbitrary** waveforms
  - 2 μV peak arbitrary waveforms of harmonic combs
  - Applications: Johnson noise thermometry, primary thermometry

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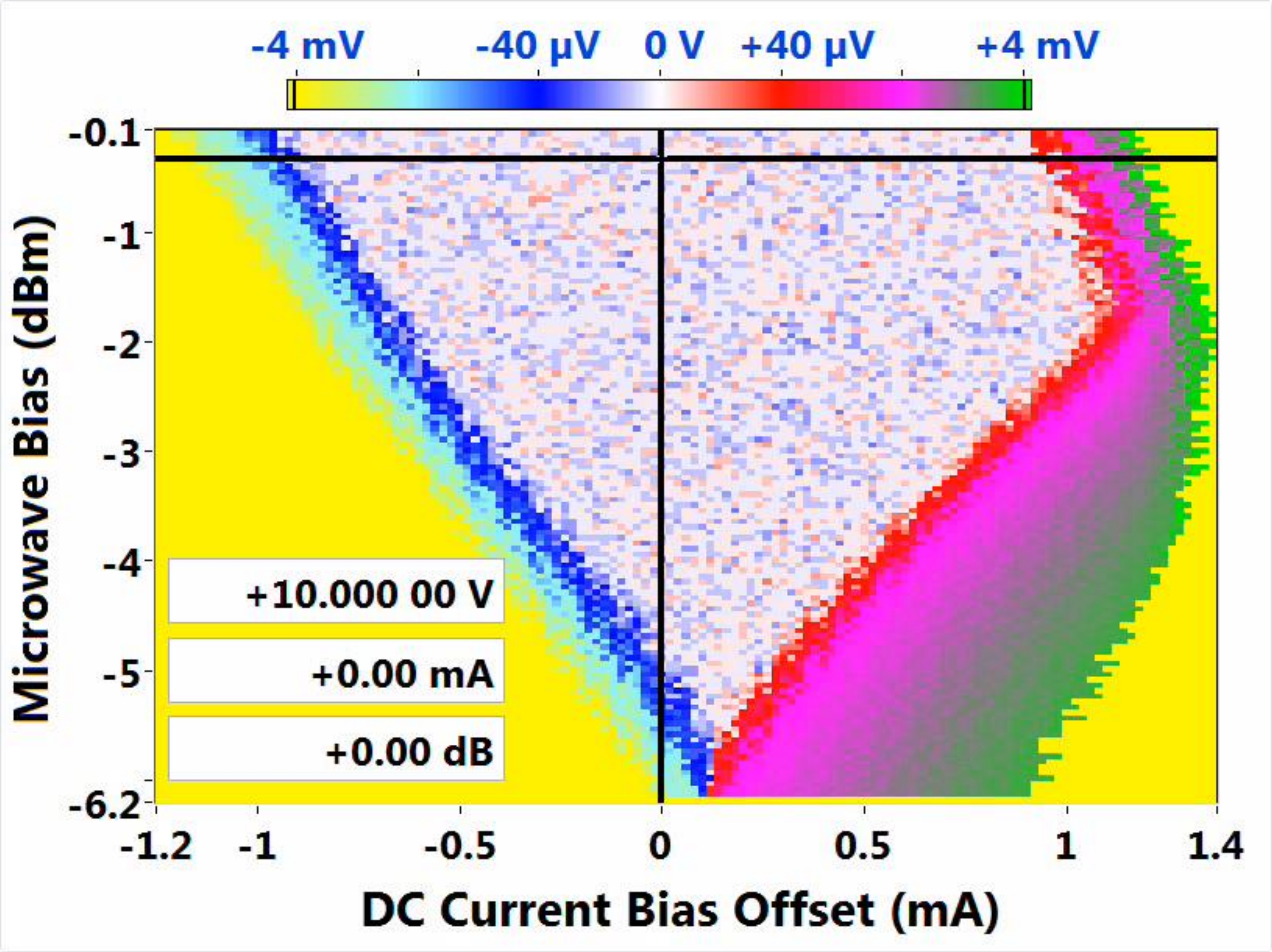
Future of JVS for SCE

- Quantum voltage standards continue to:
  - Improve in performance (V, margins, frequency)
  - Replace artifact standards (DC, AC, temperature)
  - Be applied in precision measurement that require quantum accurate performance (kg, h, k, impedance, RF metrology and perhaps quantum computing).

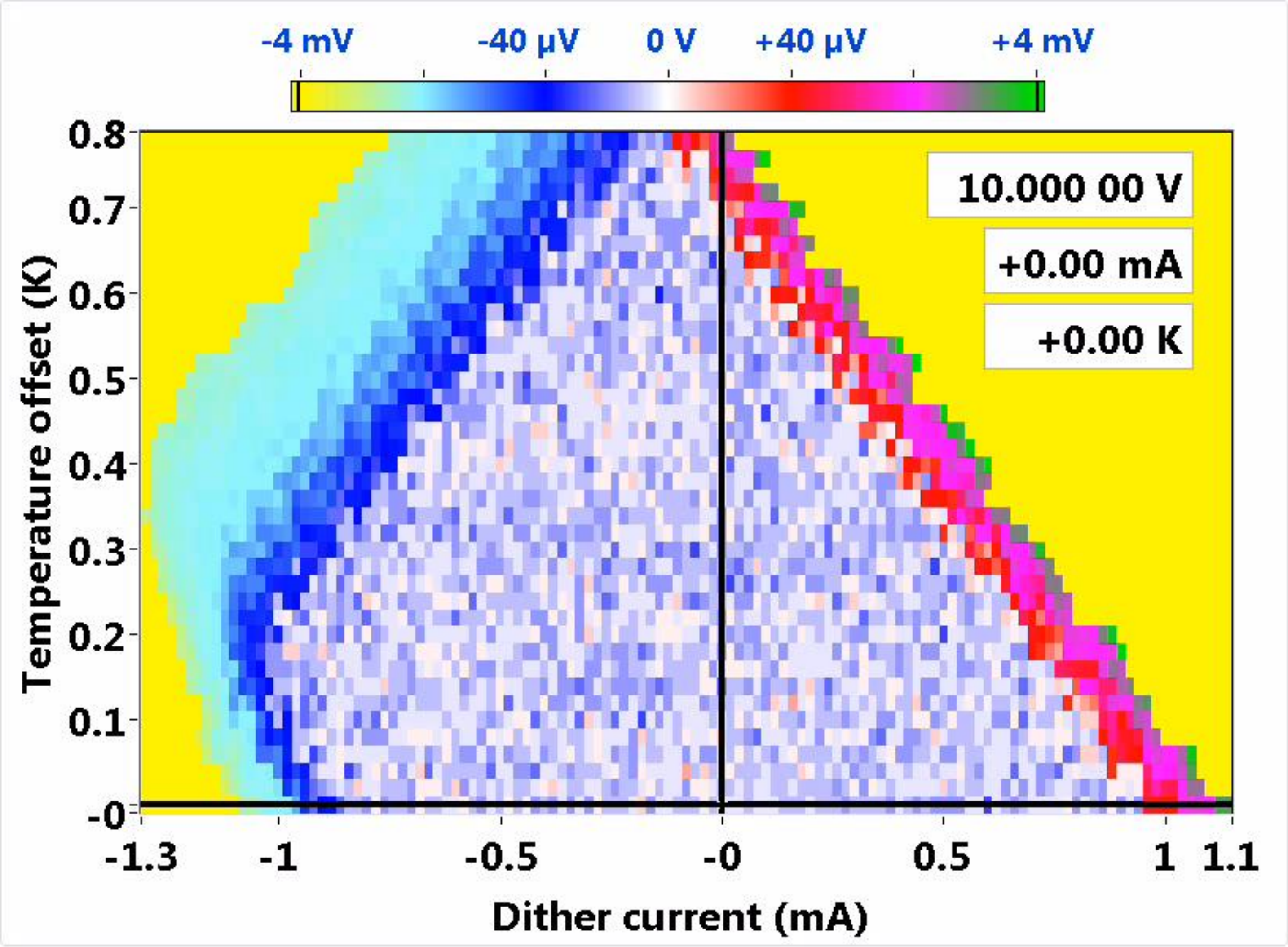
Superconductive Electronics Group in Boulder, Colorado

Flat Spots at 10 V



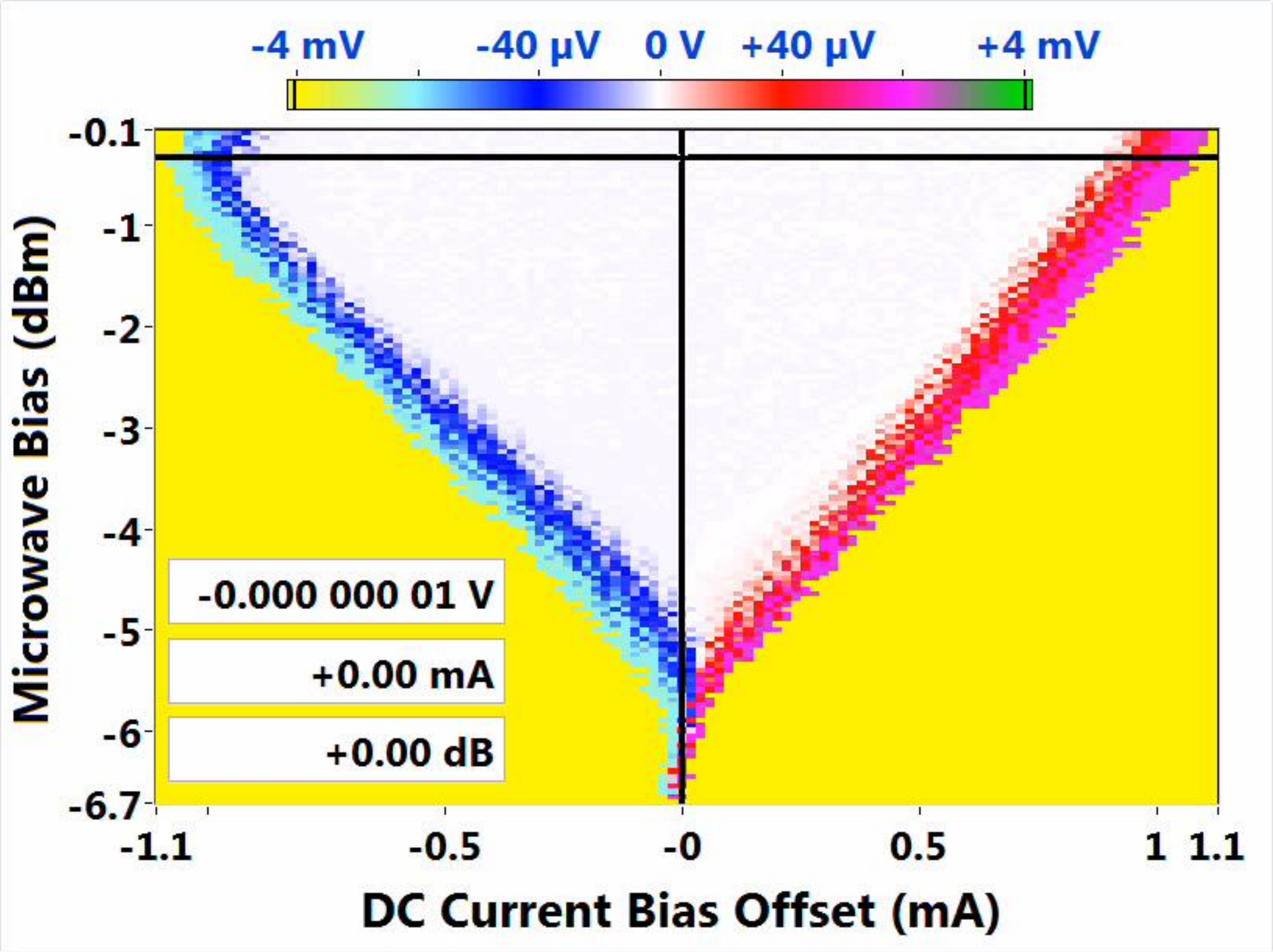
Alain Rufenacht, 2016

Flat Spots at 10 V



Alain Rufenacht, 2016

Flat Spots at 0 V (+5 V and –5 V)



NIST Voltage Standard Systems and Circuits

Systems & Circuits

60 Conventional JVS (incl. Hypres, Inc.)

18 Programmable JVS

8 Josephson Arbitrary Waveform Synthesizer

4 Johnson Noise Thermometer

Measurement Labs

National Measurement Institutes: international

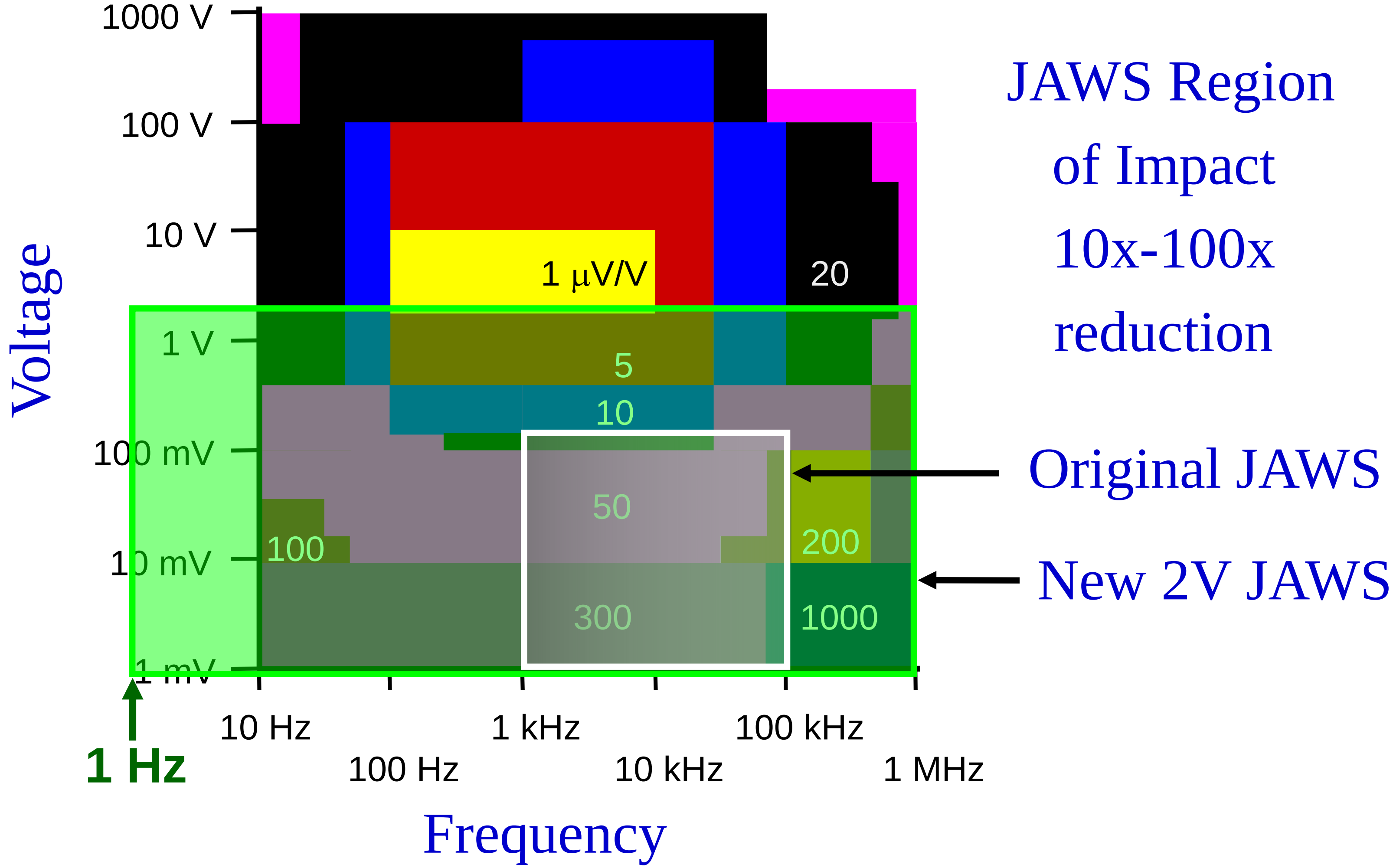
National Laboratories: NASA, Sandia

Industry: HP, Lockheed, Fluke, Keithley, Boeing

DOD: Army, Navy, Air Force

DOE: Oak Ridge Nat. Lab.

Uncertainty of RMS Detector-based Calibrations



Tom Lipe, 2005