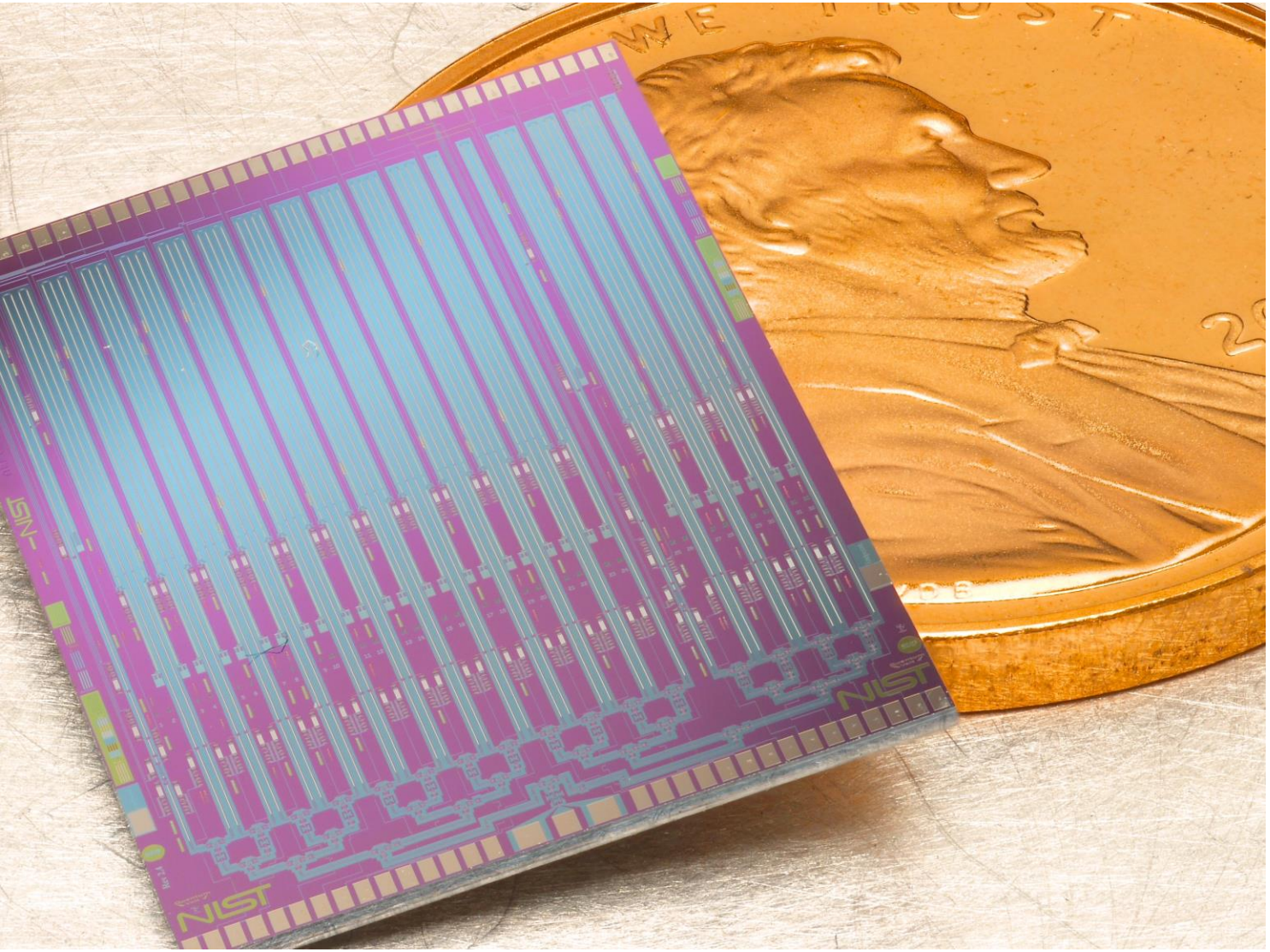
Quantum Voltage Standard Developments at NIST



Sam Benz

Superconductive Electronics Group

National Institute of Standards and Technology

Boulder, CO, USA

10 August 2017

EUCAS 2017, Geneva, Switzerland

Applications of Josephson Voltage Standard Systems

10 V PJVS
JVS
2 V JAWS
SYSTEMS
2 µV QVNS

Zener voltage references calibration

Electrical power standards calibration

DVM gain & linearity, ratio calibration

"Electronic" kilogram Planck constant

AC voltmeters calibration

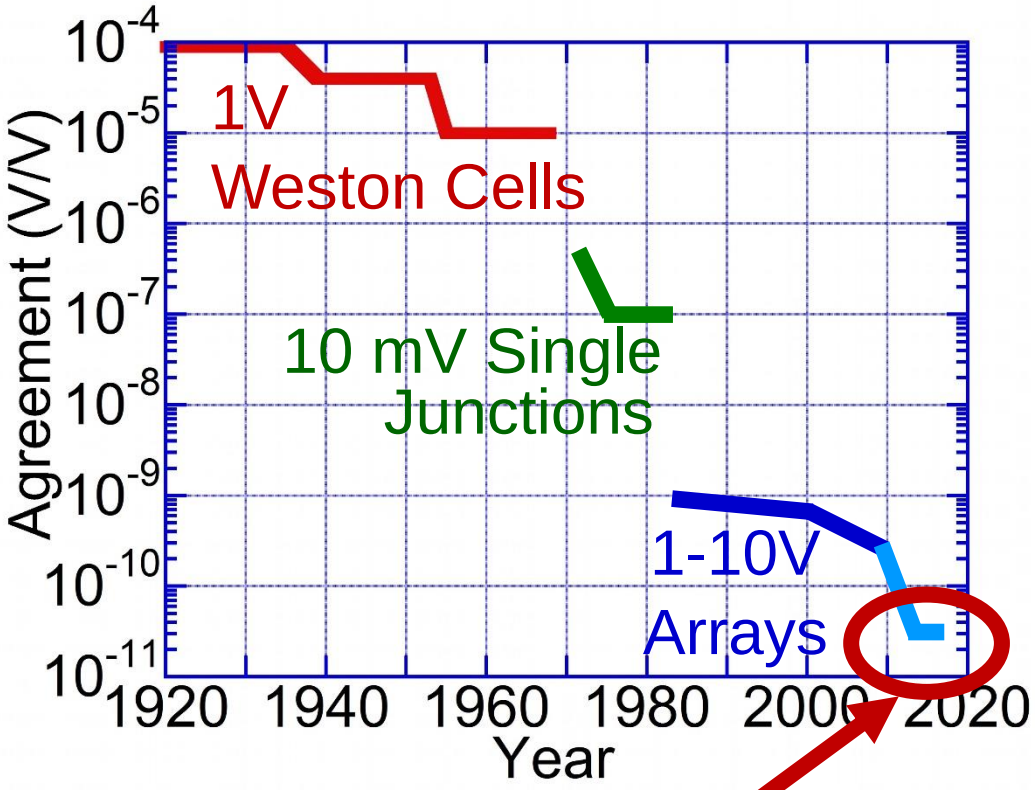
"Electronic" thermometry Boltzmann constant

AC voltage standards calibration

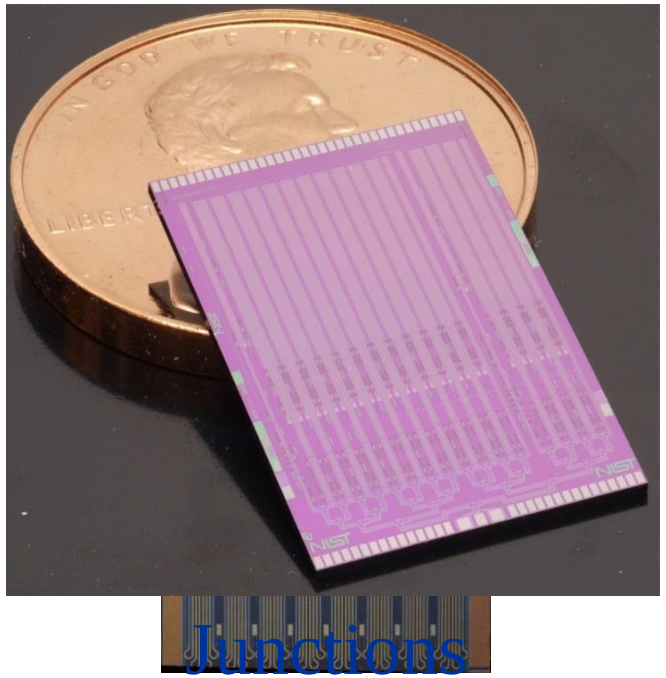
Impedance L, C, R calibration

DC Voltage Artifact Standards Replaced by Josephson Standards

Electrochemical Battery
Weston Cell
Vary in time & with environmental conditions

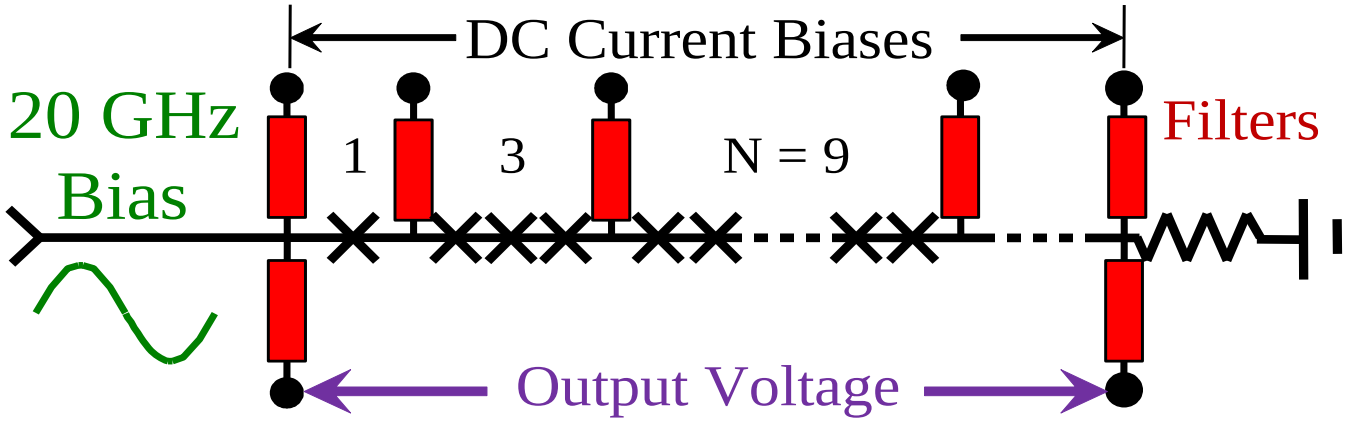


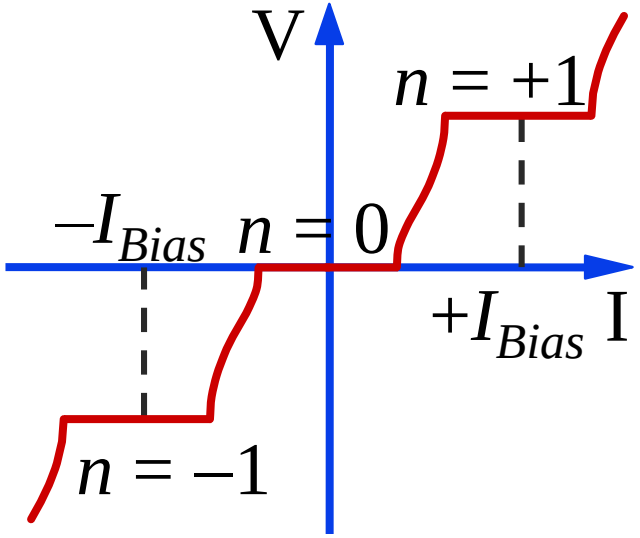
PJVS DC to DC comparison: 3×10^{-11}



Conventional JVS
Programmable JVS
Intrinsically accurate & based on quantum effects

Programmable Josephson Voltage Standard





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

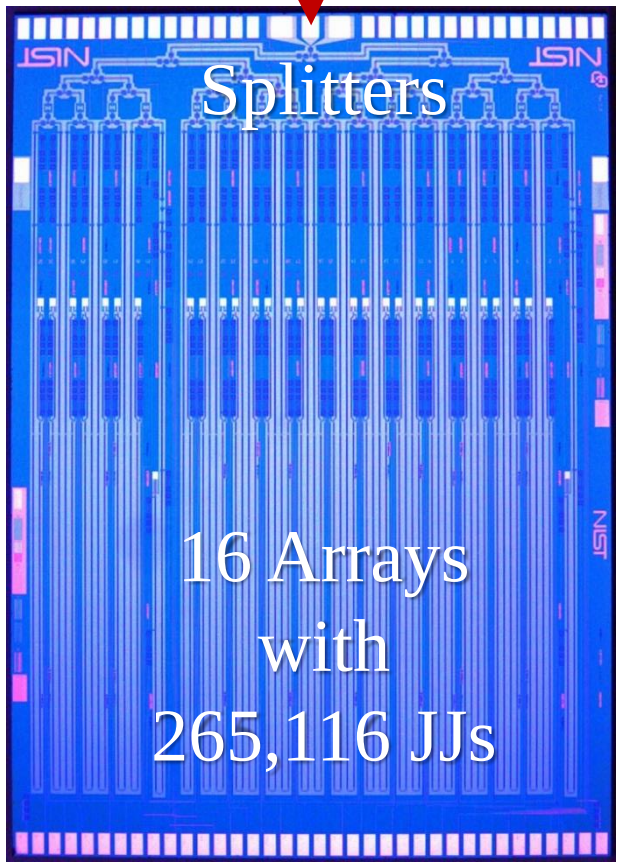
Hamilton, Burroughs and Kautz, 1995

Fabrication & Design of Superconducting Circuits

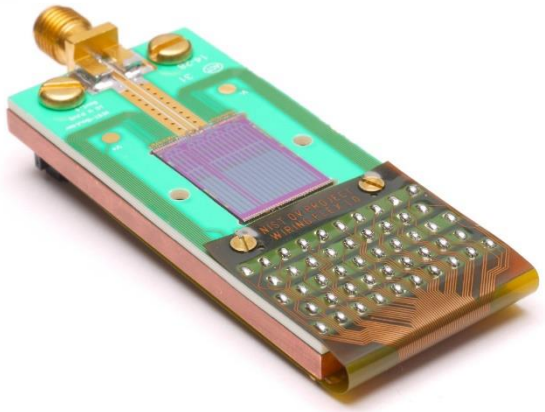
- Uniform junctions & barrier materials
  - Nb JJs with Co-sputtered *a*-Nb_xSi_{1-x} Barriers
- Microwave circuit design
  - Lumped element inductors & capacitors, power splitters, coplanar waveguides
- Packaging
  - Electrical and thermal power management

(12 x 17) mm^2 PJVS Chip

Microwave Input



DC Input/Output Pads

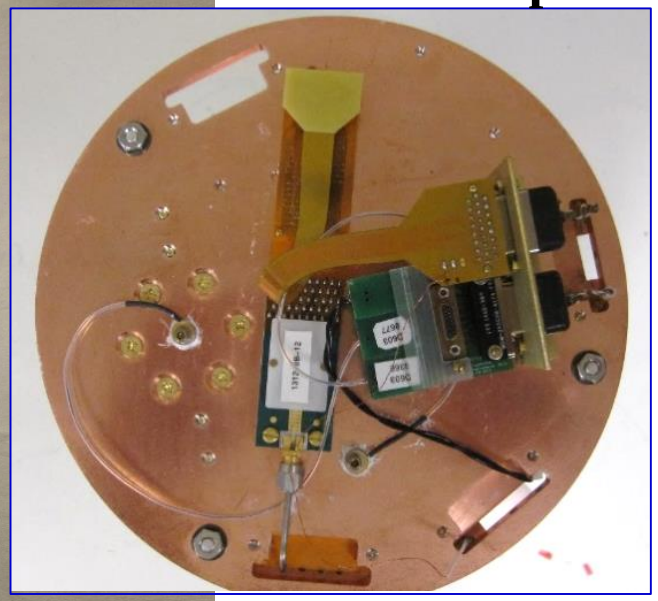


Olaya, IEEE Trans. Appl. Supercond. June 2009

Fox, IEEE Trans. Appl. Supercond. June 2015

Cryocooled PJVS System

- Integrated system
  - Bias electronics DC & microwave
  - Cryogenics
  - Superconducting devices
  - Turn-key integrated system
  - Automation software
    - Optimize & check quantum states, locking ranges
    - Performs measurements

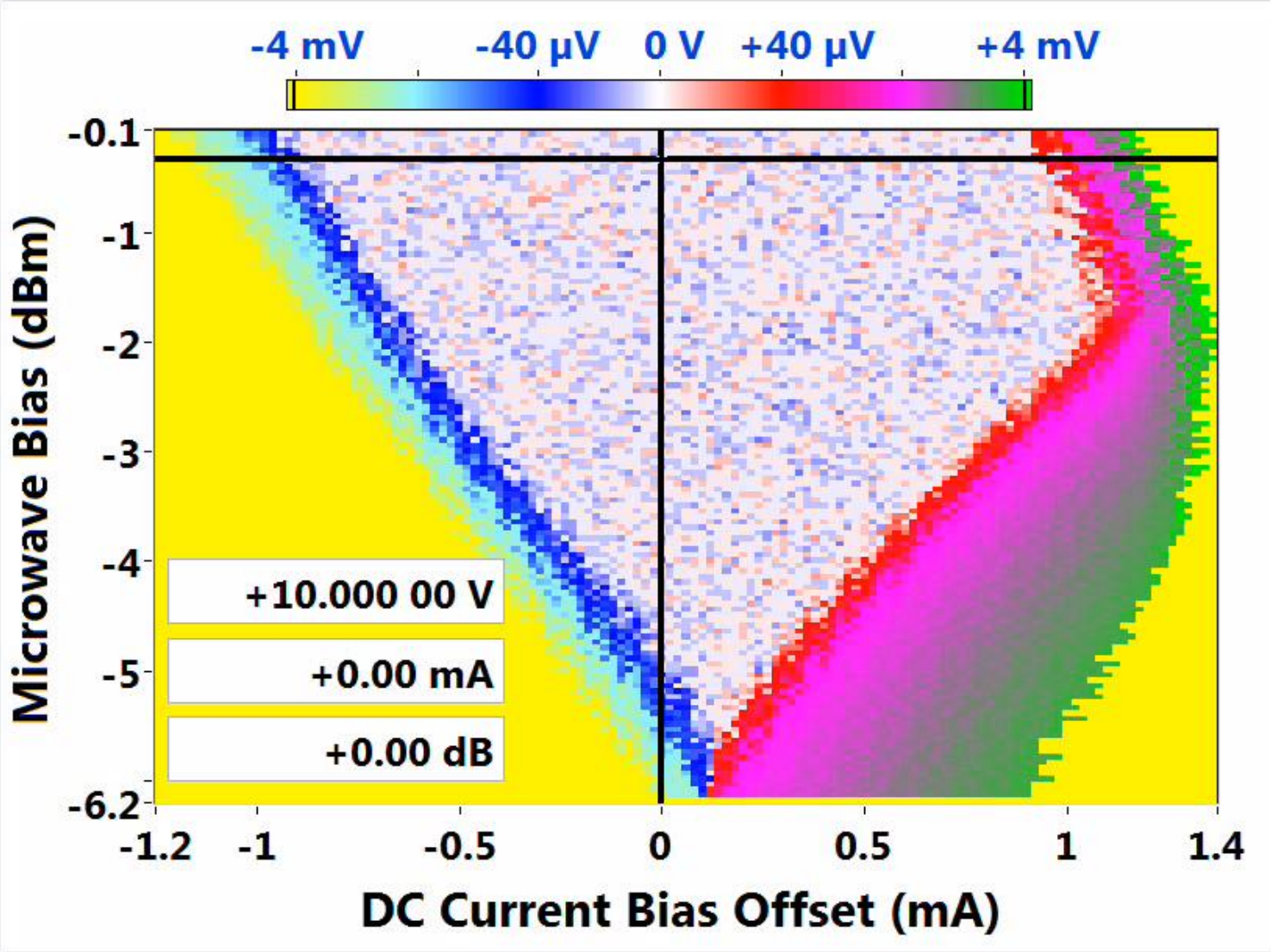


4 K Cold plate

Compressor

Rüfenacht IEEE Trans. Inst. Meas., June 2015

Quantum Locking Ranges at 10 V

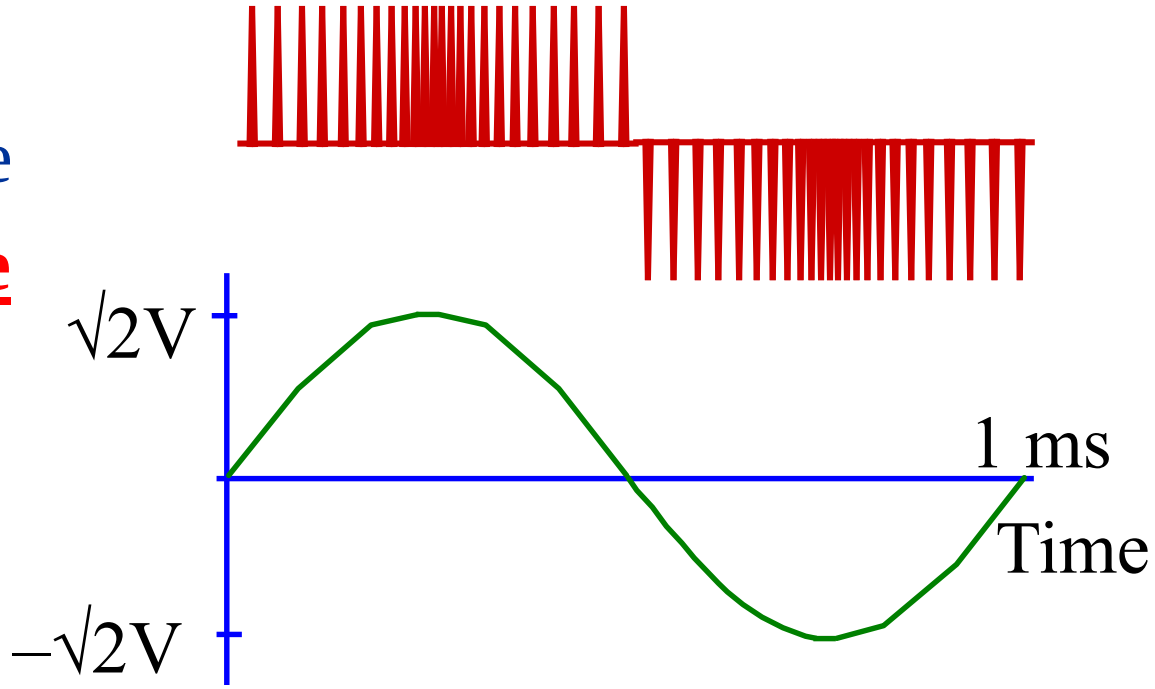


Alain Rufenacht, 2016

Josephson Arbitrary Waveform Synthesizer

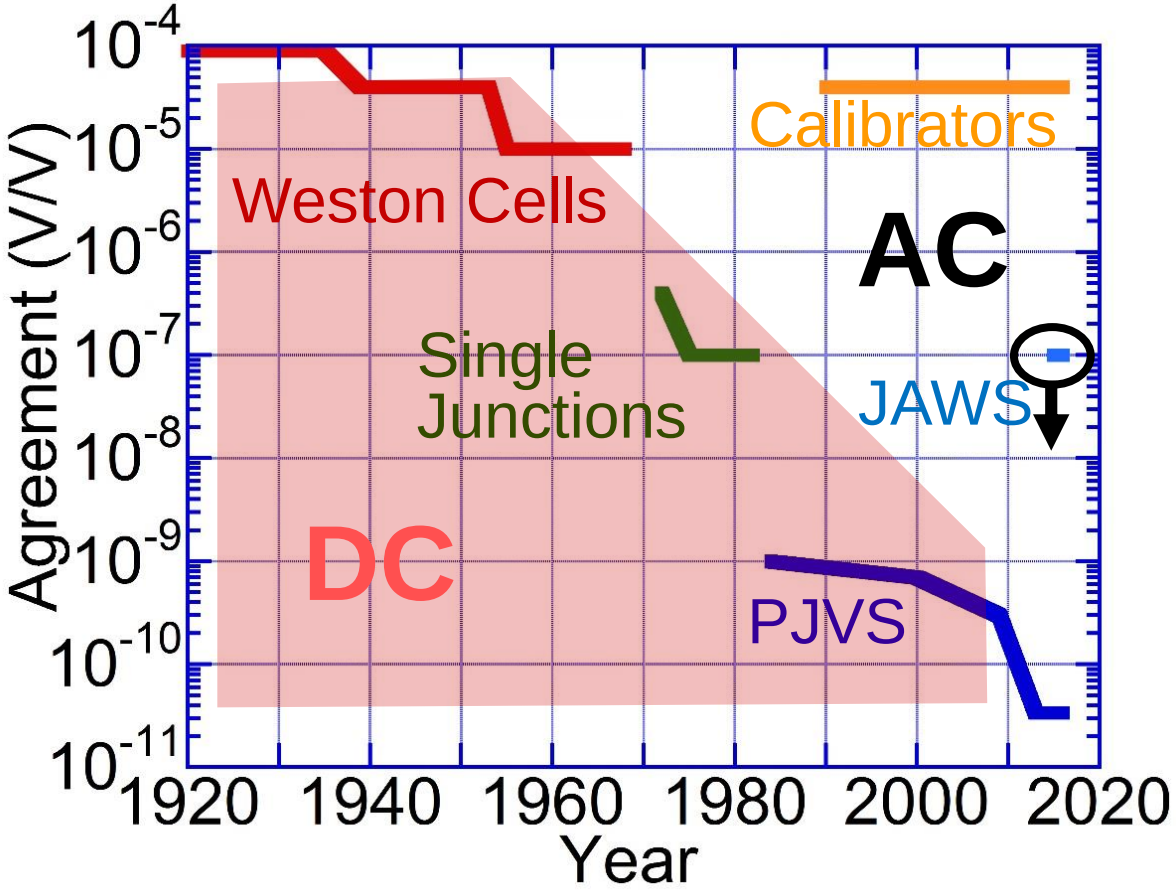
- Digital-Analog converter
- Pulse biased
- Directly control every JJ pulse
- Bipolar waveforms with **three** quantum states:
  - +1, 0, –1 pulses

- 1 kHz sine wave



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

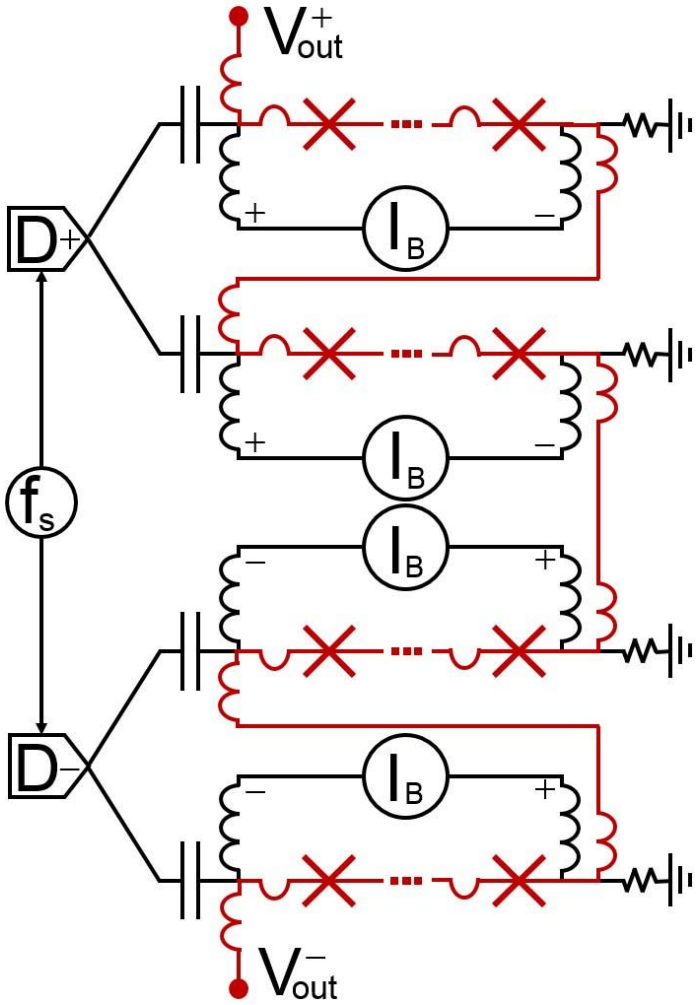
Replace Voltage Calibrators with JAWS Sources



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

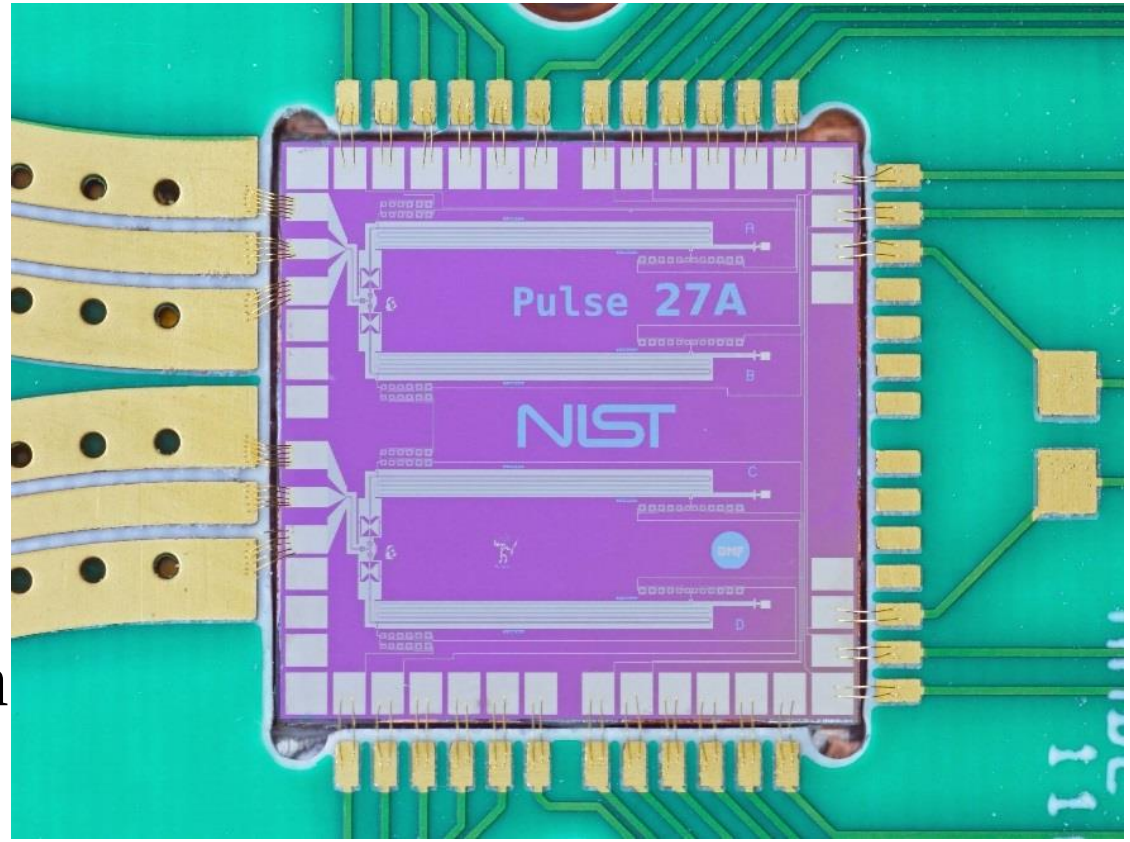
Systematic errors are ~ 10^{-6} for frequencies > 10 kHz

1V RMS JAWS Chip and Circuit



51,240 total junctions in 4 arrays

1 cm x 1 cm Chip

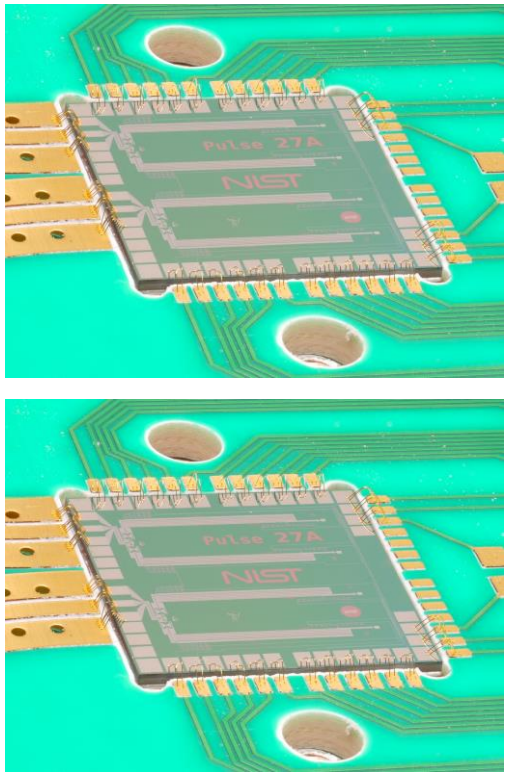


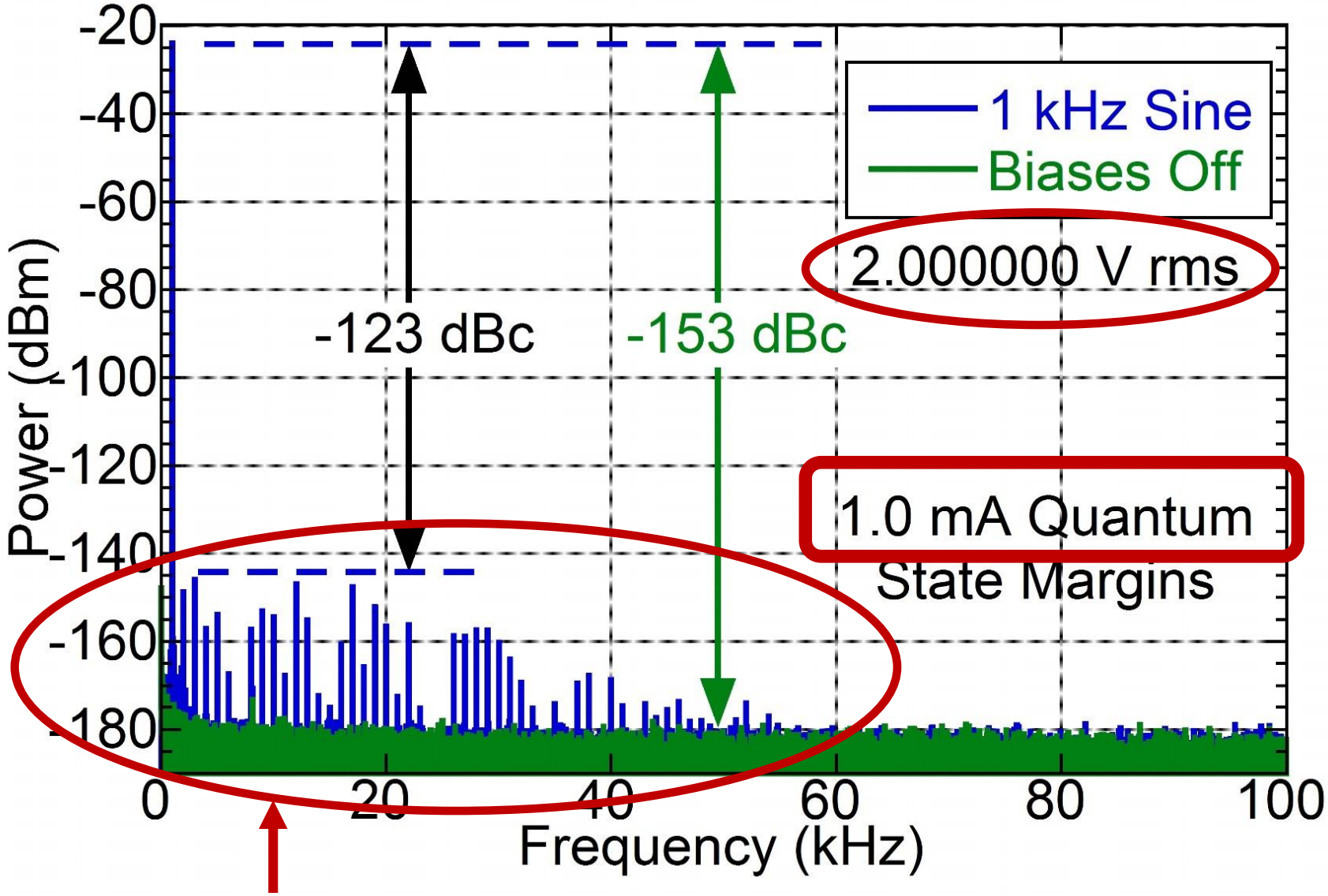
- Pulses clocked at 15 GHz
- Synchronizes 770 x 10^{12} quantum states/s
- Measure spectra with a 24-bit ADC digitizer

JAWS 2 V RMS Sine Wave

1 kHz sinewave

102,400 JJs with 2 chips



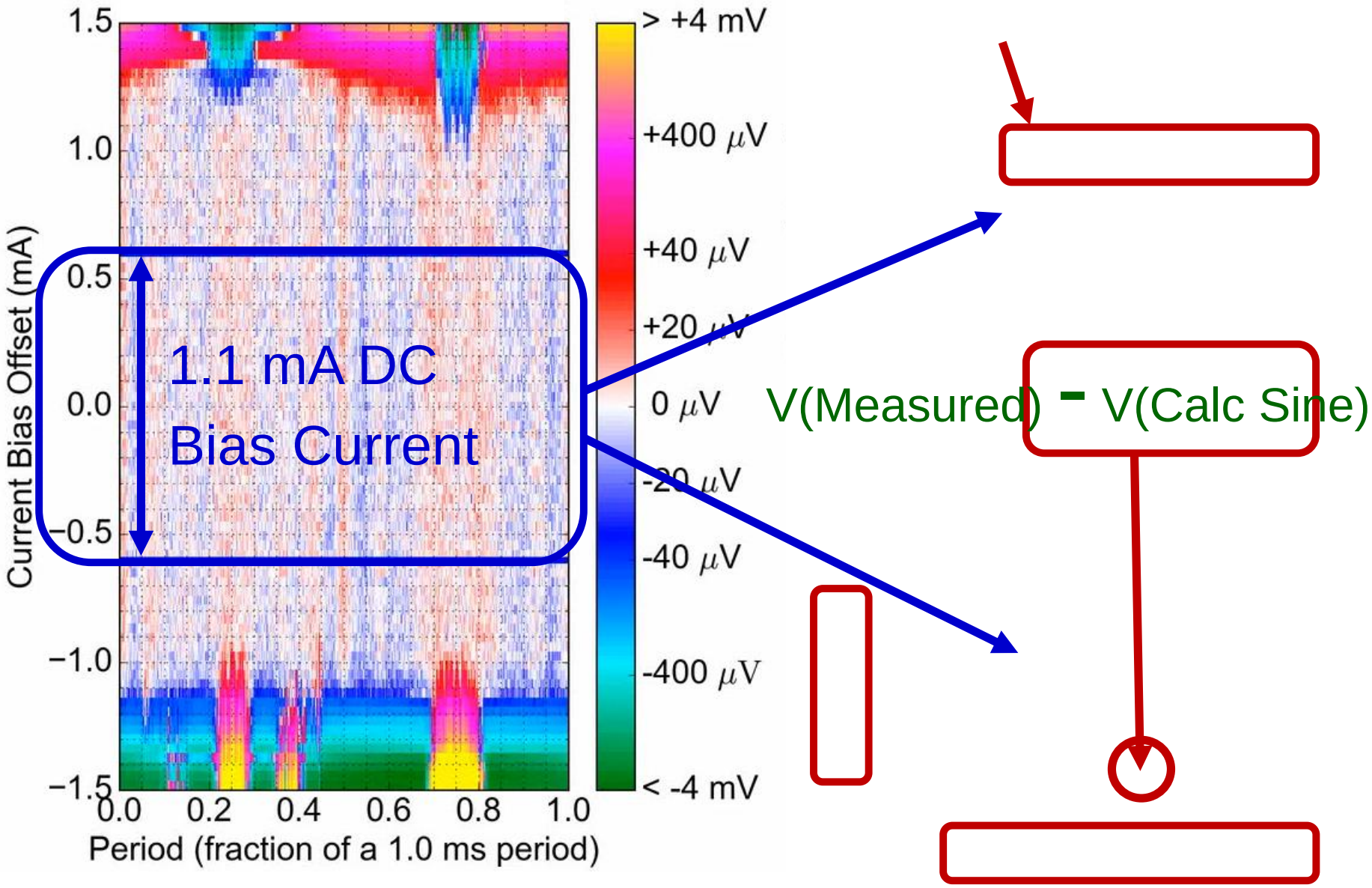


Nathan Flowers-Jacobs et al., IEEE Trans. Appl. Supercond., Feb. 2016

Non-linearities of the ADC Digitizer

Locking Range of Quantum States

Difference from Sine Voltage

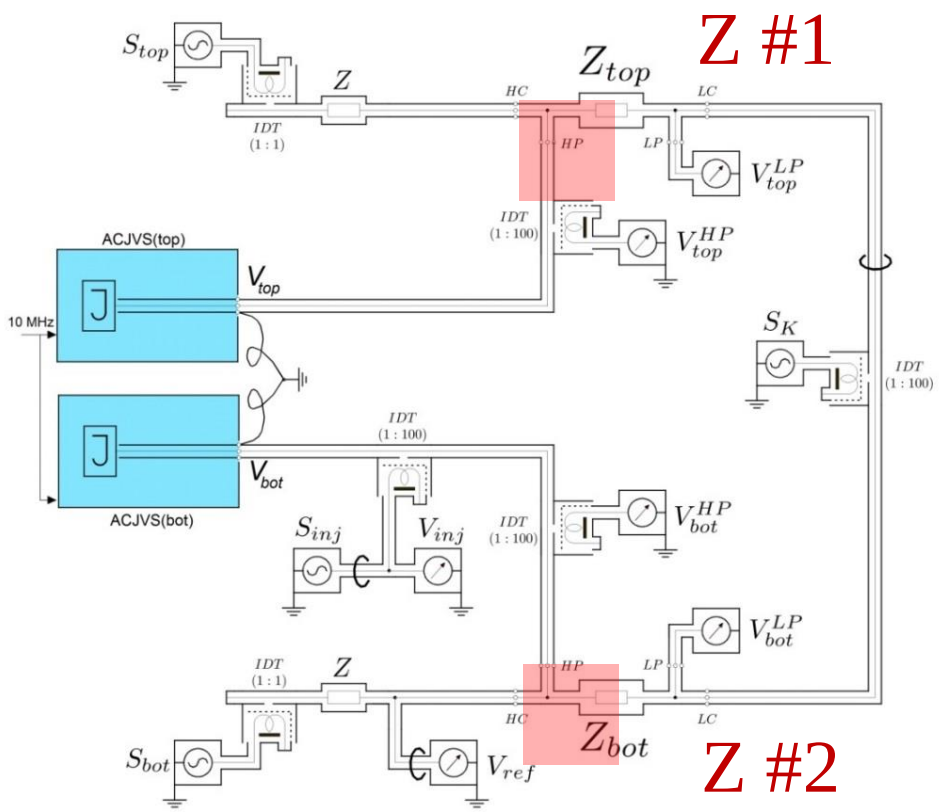


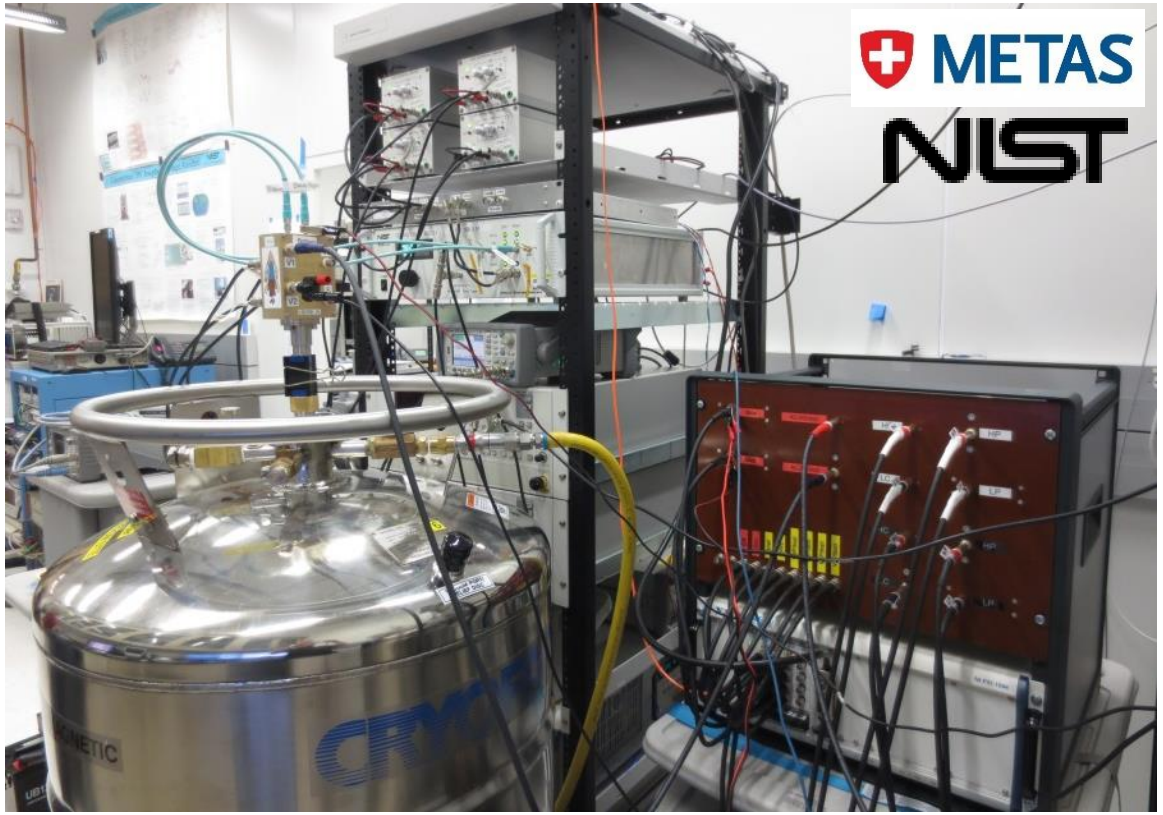
N. Flowers-Jacobs et al., IEEE Trans. Appl. Supercond., Sept. 2016

Impedance Comparisons with 2x JAWS Sources

JAWS #1

JAWS #2

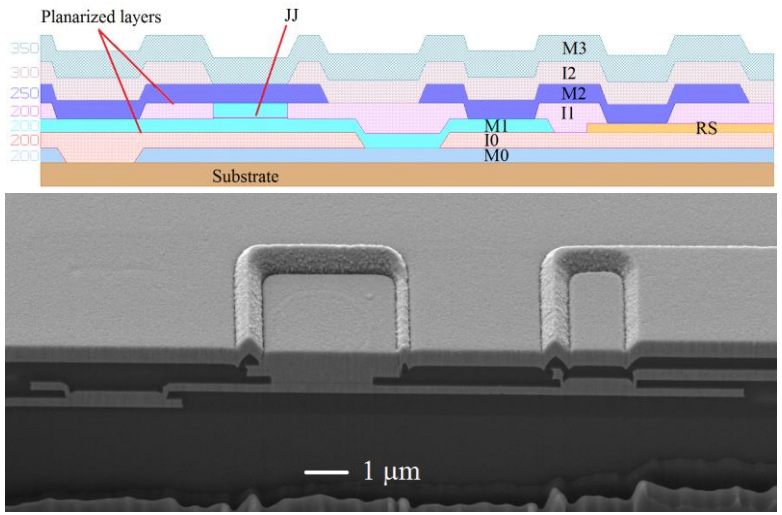




- Voltage ratio can be set to any desired value and frequency
  - Eliminates many different transformers to match different impedance ratios
- Any impedance in the complex plane can be calibrated
  - Because the JAWS phases and amplitudes are programmable

Metrology for Communications and Advanced Computing

Christine Donnelly	1EP1-10	Nonlinear response of RF JAWS
Adam Sirois	4EP2-04	Metrology for Single Flux Quantum Electronics
Justus Brevik	4EP2-24	RF Waveform Synthesis with JAWS
Manuel Castellanos-Beltran	4EO1-08	SFQ RF synthesizer



Cross-section cartoon and FIB-SEM image of 4 metal layer process with M3 ground plane. Process optimization of M2-to-M1 via is in progress.