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Recent Developments in ac-dc difference measurements at Sandia's Primary Standards Laboratory

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NCSLI Workshop and Symposium 2021

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Outline

- Overview of AC Lab at PSL
- ac-dc difference station improvements
- Multi-junction thermal converters (MJTC) efforts
- Josephson Arbitrary Waveform Synthesizer (JAWS)

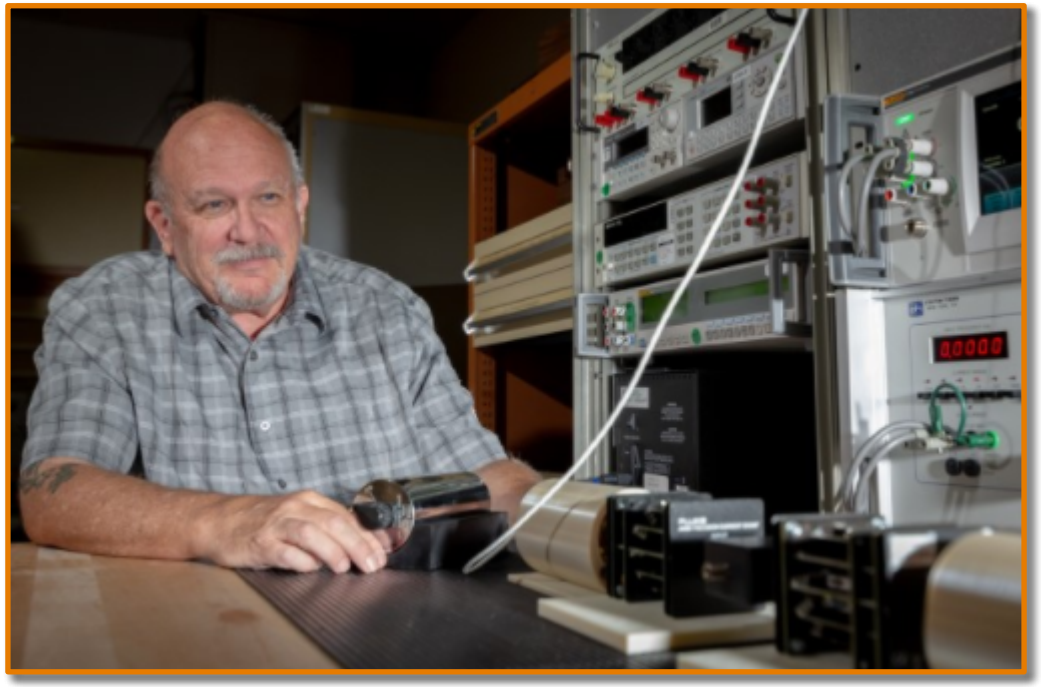
Sandia's Primary Standards Laboratory (PSL)

Mission Assignment to coordinate a system-wide Standards and Calibration Program for **Department of Energy/National Nuclear Security Administration** (NNSA) and its contractors by providing technical guidance, training, and consultation

- Develop and maintain primary standards, intrinsic standards, and measurement systems
- Provide primary and reference standard calibrations for Contractor Standards Laboratories (>1,400 in FY15)
- Ensure measurement assurance through consultation and support to product realization teams
- Provide guidance and technical training to support Contractor Standards Laboratories' calibrations throughout the NSE
- Perform technical surveys, proficiency testing, and measurement audits
- Provide a Research and Development (R&D) program in the area of measurement technology

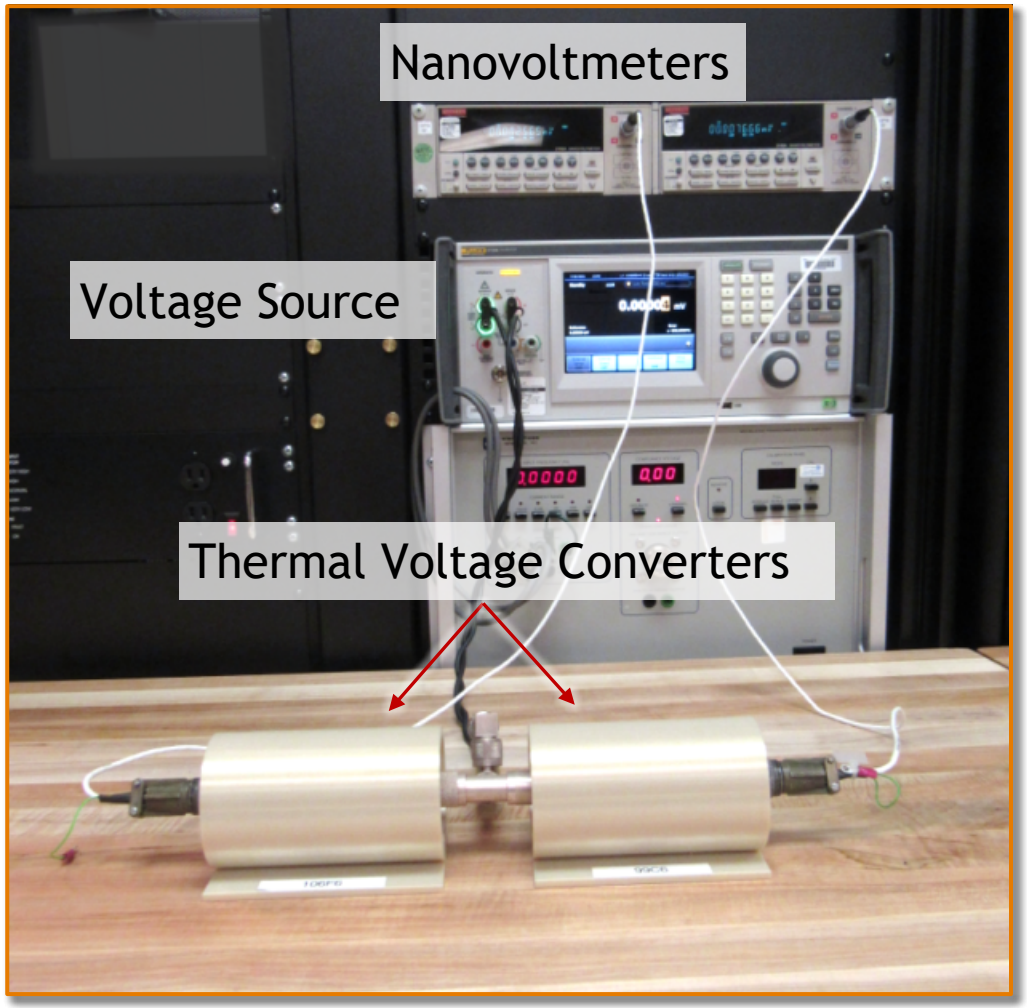
PSL AC Lab Capabilities

- Alternating Current (AC) voltage and current
- Impedance (AC resistance, inductance, and capacitance)
- Ratio Transformers/AC voltage division
- Ultra-high current
- Time and Frequency
- Voltage pulses (up to 300 kV)
- Current pulses (up to 10 kA)



ac-dc Difference Station at PSL

- Recently resurrected ac-dc difference measurement station at PSL
- ~100 Calibrations per year
- NVLAP accredited for AC current shunts (1mA to 100 A up to 100 kHz)
- **In progress**: NVLAP accredited for AC voltage



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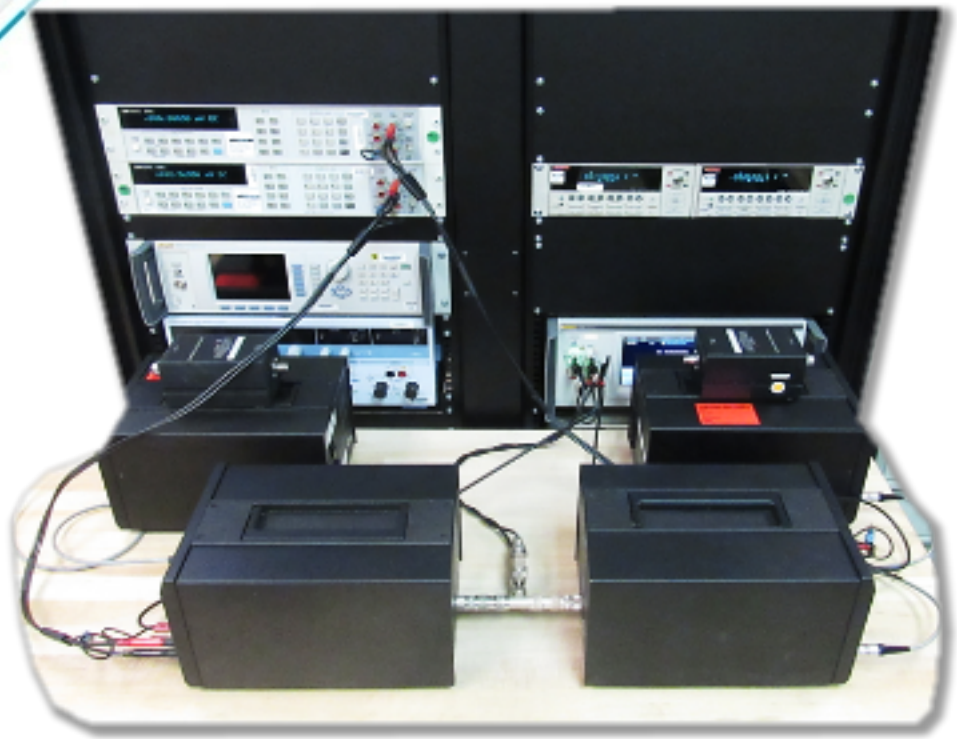
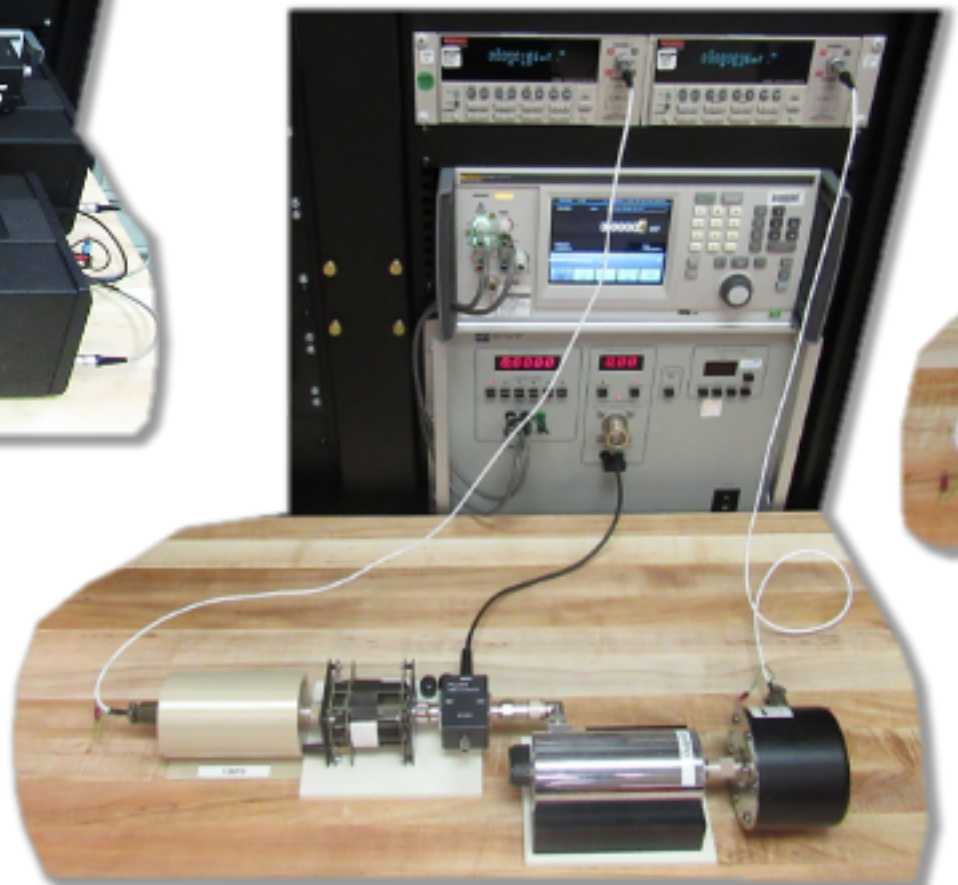
ac-dc Station Setup

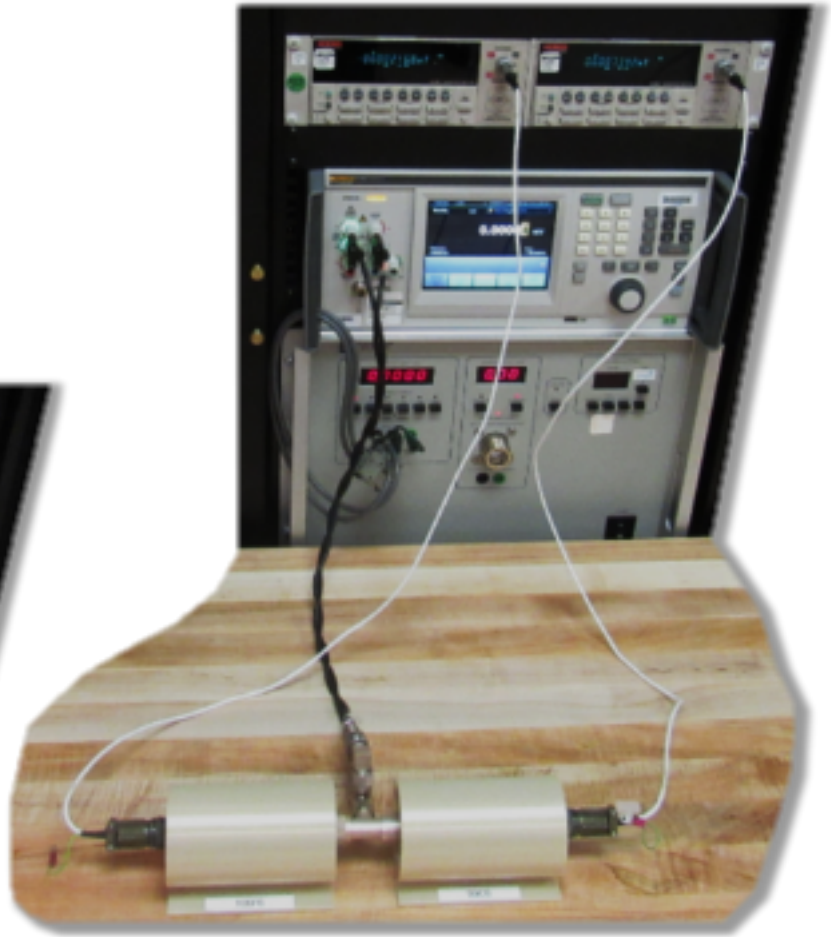
792A Calibrations (voltage + rf)



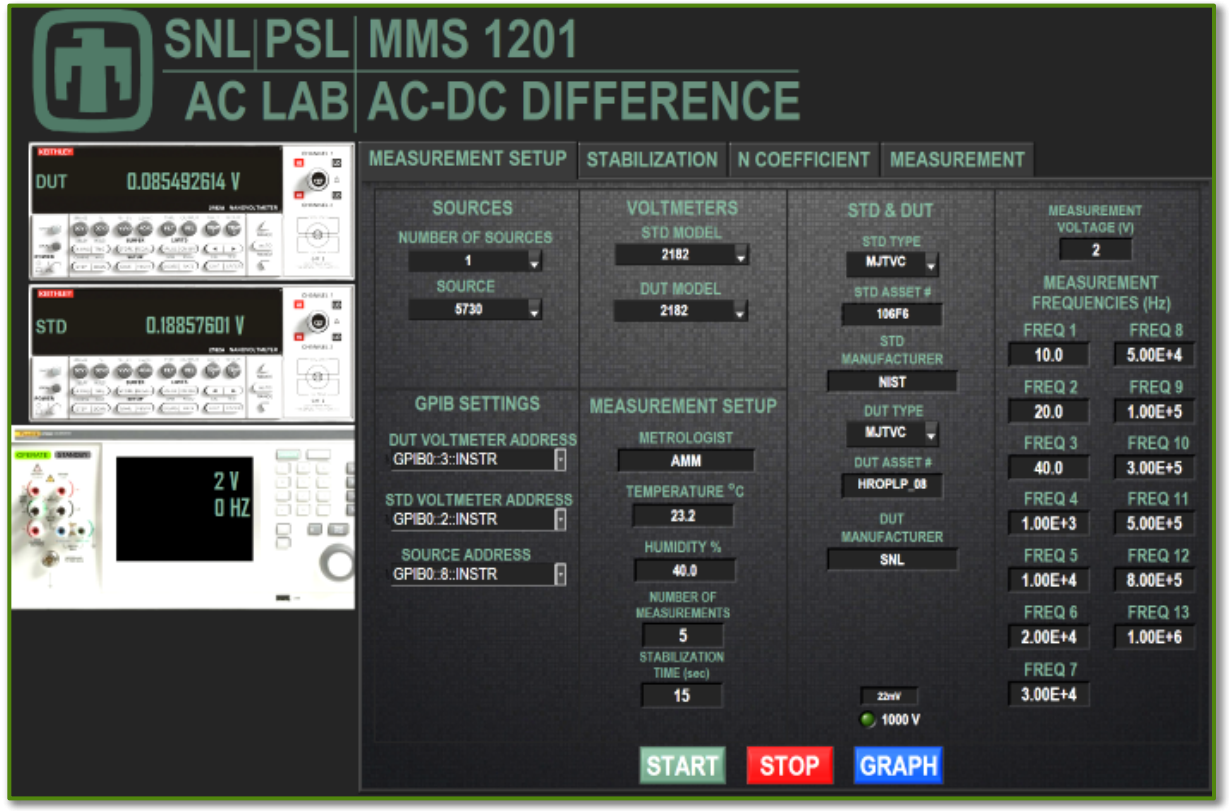
Current Calibrations



Voltage Calibrations



ac-dc Difference Software



- Completely automated (LabVIEW) software
- Real time measurement visualization
- Software can switch between different sources
- Data is sent into shared drive (can access from any computer)
- User determined wait times
- 13 frequency inputs
- Error trapping to remove statistical errors
- HTML output – can cut and paste into Excel, Word, control charts, etc.

→ All this aids in processing of calibration certificate

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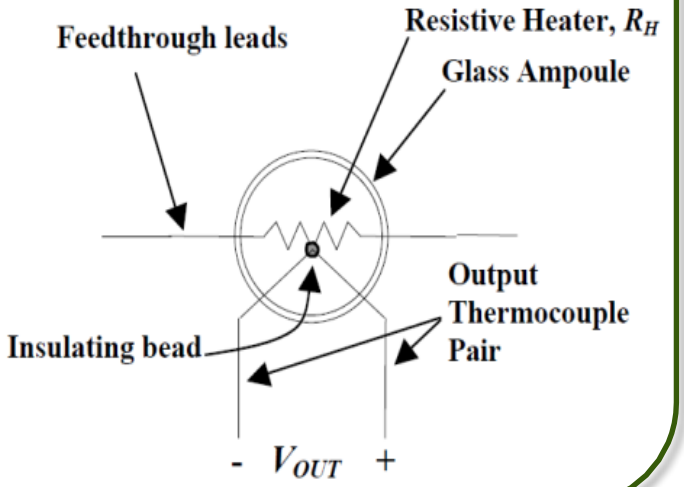
Single and Multi-Junction Thermal Converters

Single Junction Thermal Converter

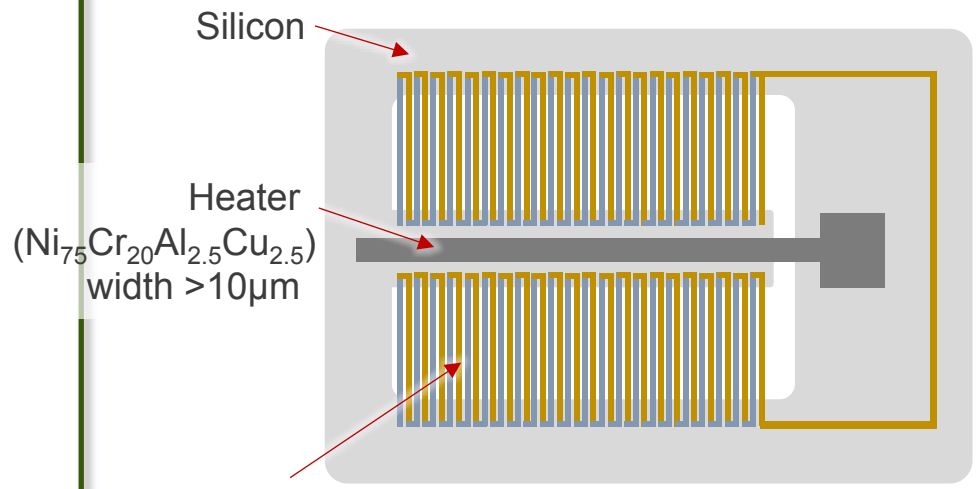


- ✓ Simple design
- ✓ Conventional AC transfer standard since 1950's
- ✗ Extremely fragile
- ✗ Small operating range
- ✗ Low output (mV)

$$\delta = \left.\frac{V_{ac} - V_{dc}}{V_{dc}}\right|_{E_{dc}=E_{ac}}$$

δ = ac-dc difference
V_{ac}, V_{dc} = Input ac and dc voltage
E_{ac}, E_{dc} = Output ac and dc emf

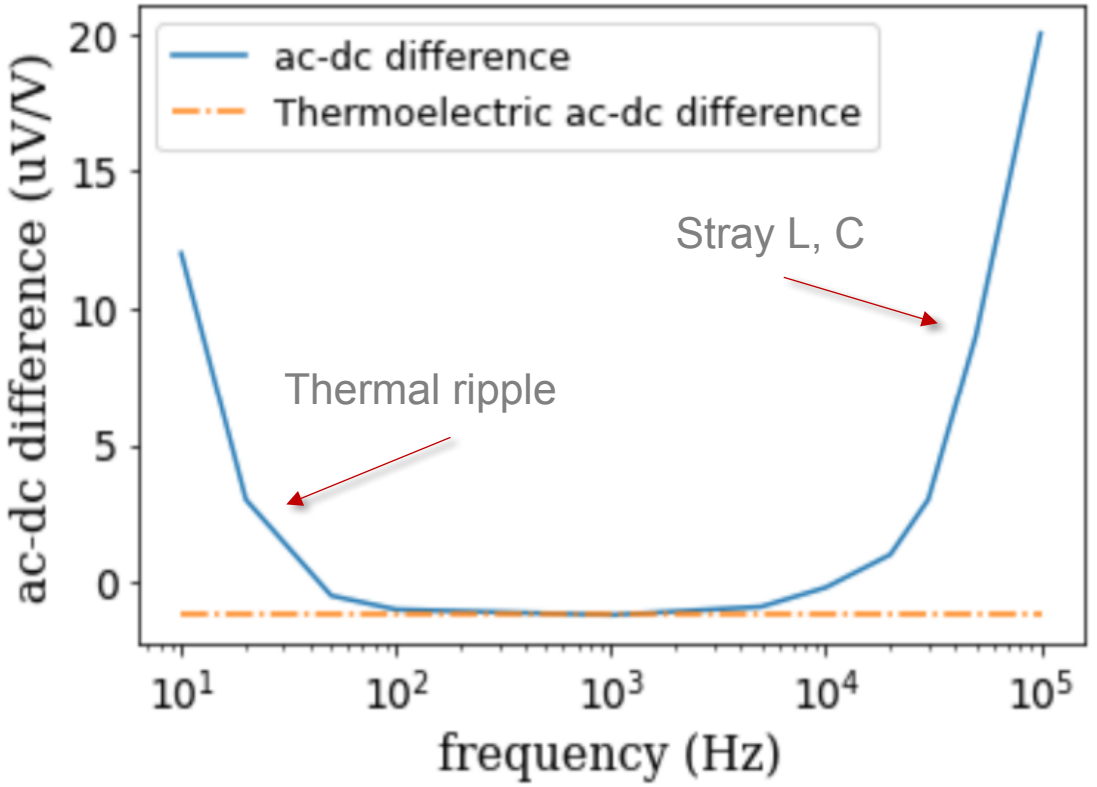
Multi-junction Thermal Converter



- ✓ Increased output voltage
- ✓ Low uncertainty (~1-2 ppm, depending on range)
- ✓ Larger operating range than single-junction
- ✗ High uncertainties at low voltages and high/low frequencies (10-100s μV/V)
- ✗ High resistance of thermocouple output

MJTC Motivation

- The MJTC substrate can have significant impact on device performance
- **Problem**: Silicon has relatively large permittivity and loss
  - Leads to capacitive coupling between the heater and thermocouples and the obelisk at high frequencies
- **Solution**: use high resistivity substrates
  - NIST – fused silica
  - PTB – quartz
  - Japan – polyimide/alumina
- **Goal**: build upon SNL process developed by Wunsch and fabricate MJTC devices on high resistivity silicon wafers
- No need to change Si etching steps



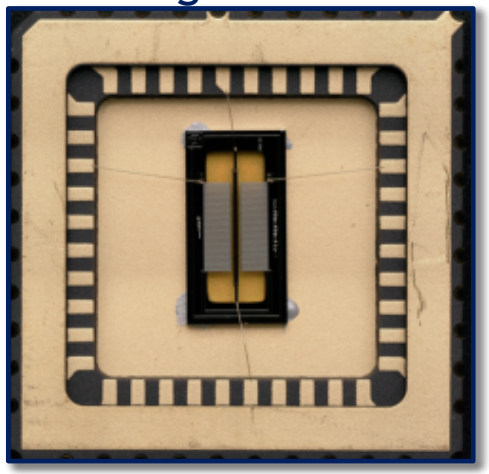
NIST; Fujiki (2015)

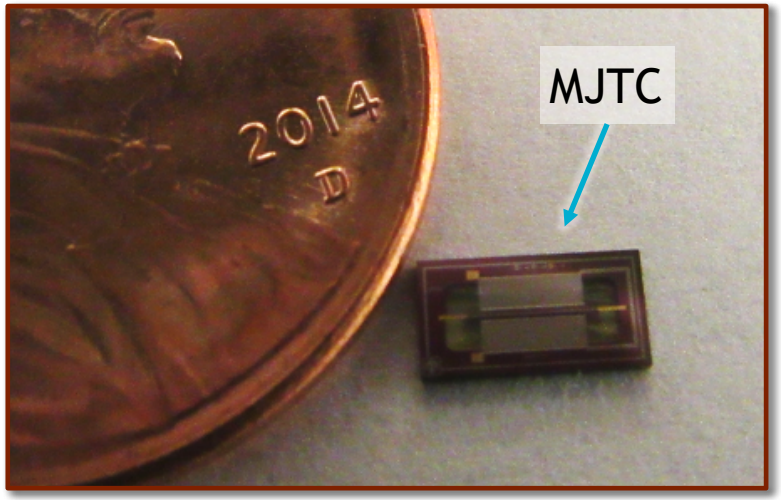
SNL - First MJTC device in two decades

All fabrication steps performed at SNL

- Initially repeated steps from 2001 process
- Metallization, deposition, patterning, etching
- Chips were wire bonded and packaged under vacuum
  - 23 devices initially tested
  - Only 2 failed devices at 1 kHz, 2V

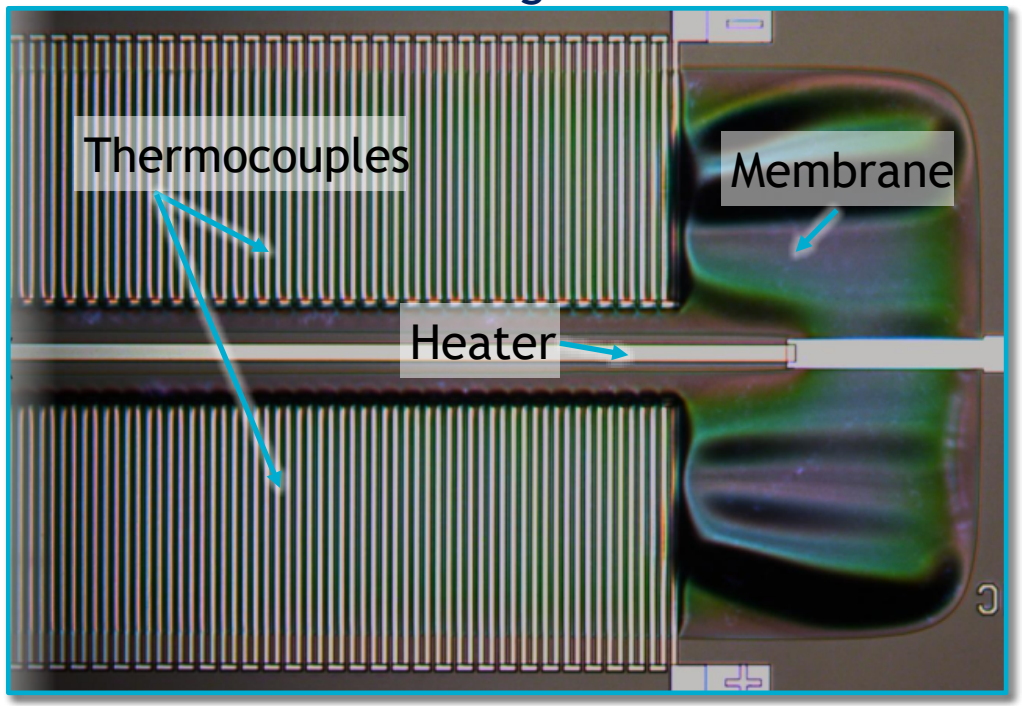
Packaged device





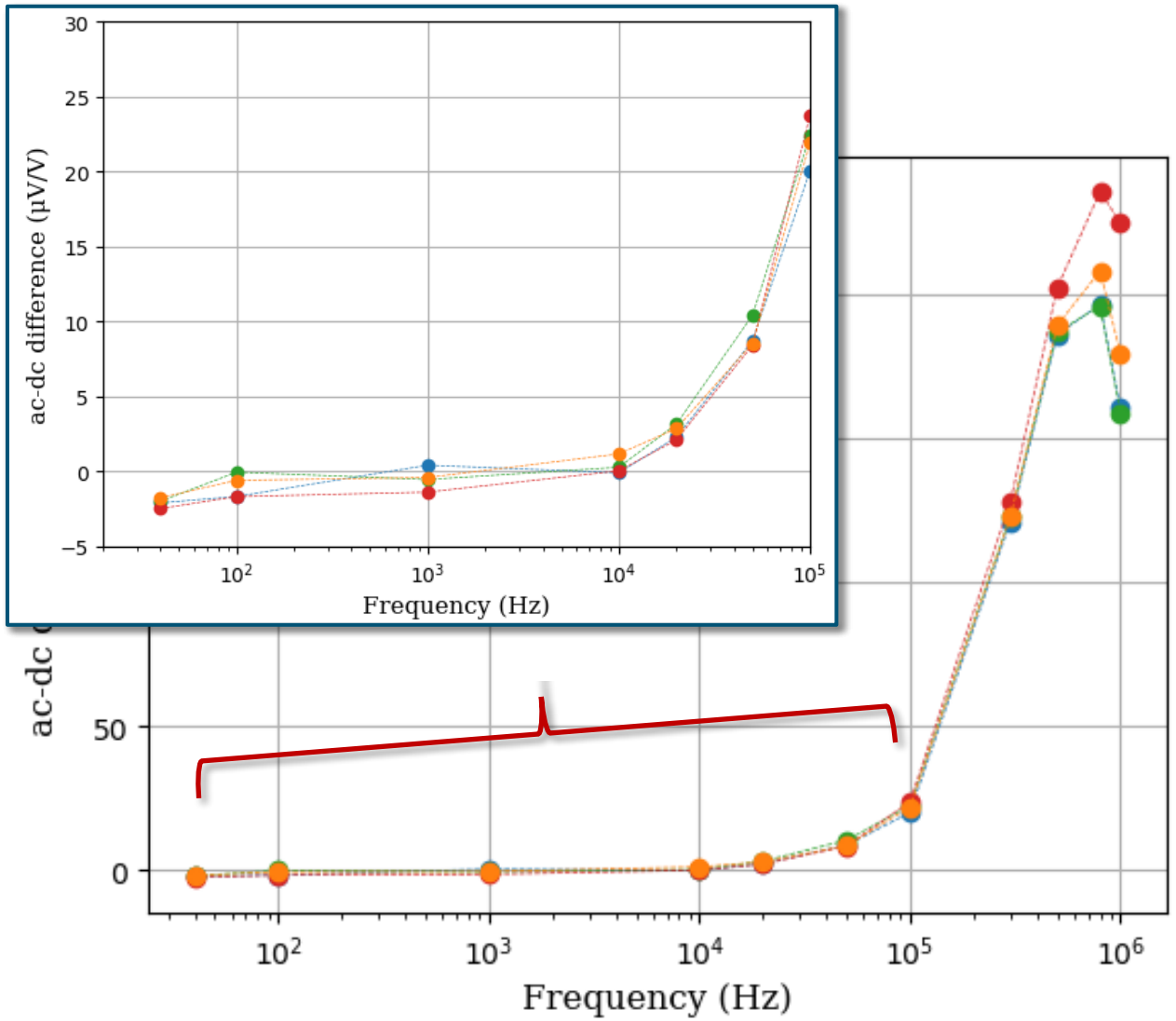
One MJTC device

Zoomed in image of MJTC device



Initial electrical results

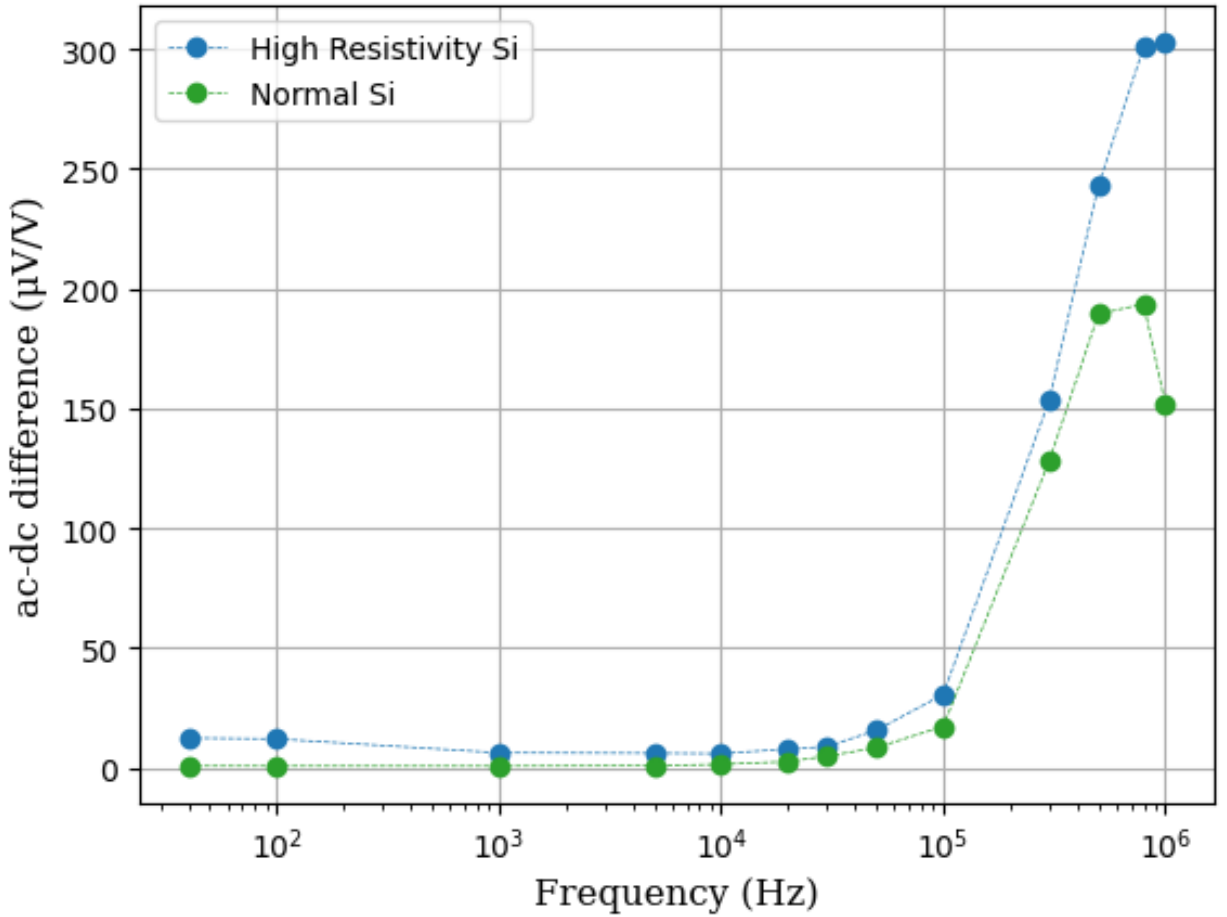
- Very reproducible results
- Sub 2 μV/V ac-dc difference up to ~50 kHz
- As expected, observed larger ac-dc difference at high frequencies
- Comparable results from 2001



Heater resistance = 140 Ω – 170 Ω

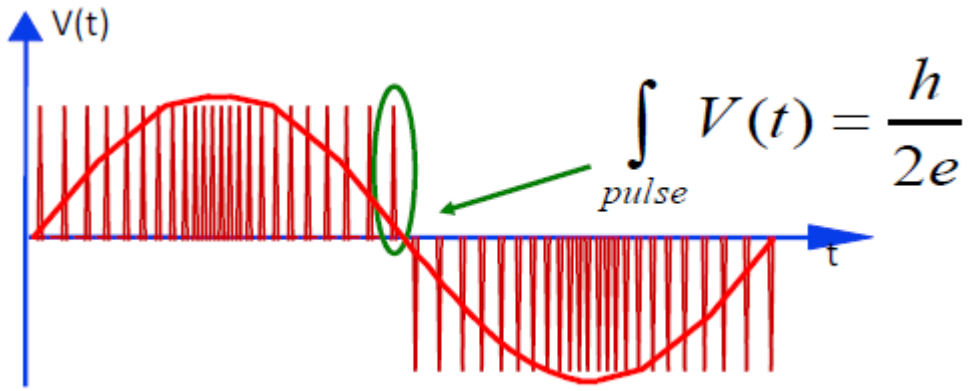
High resistivity silicon results

- ac-dc difference results using high resistivity silicon wafer
- Very first wafer!
- ac-dc difference increased at high frequencies rather than decrease
  - Fabrication issues that could have damaged the devices
  - High failure rate indicating devices were damaged during process



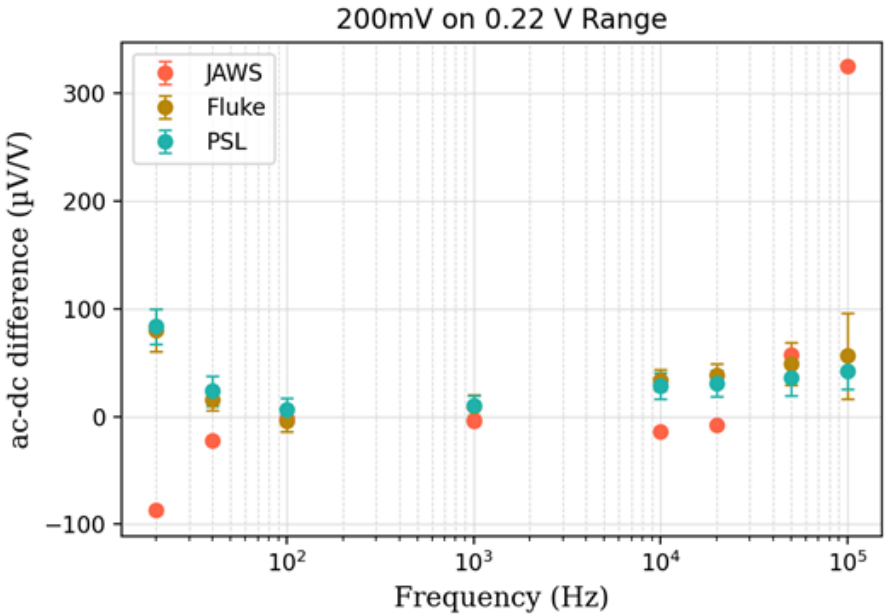
JAWS – Josephson Arbitrary Waveform Synthesizer

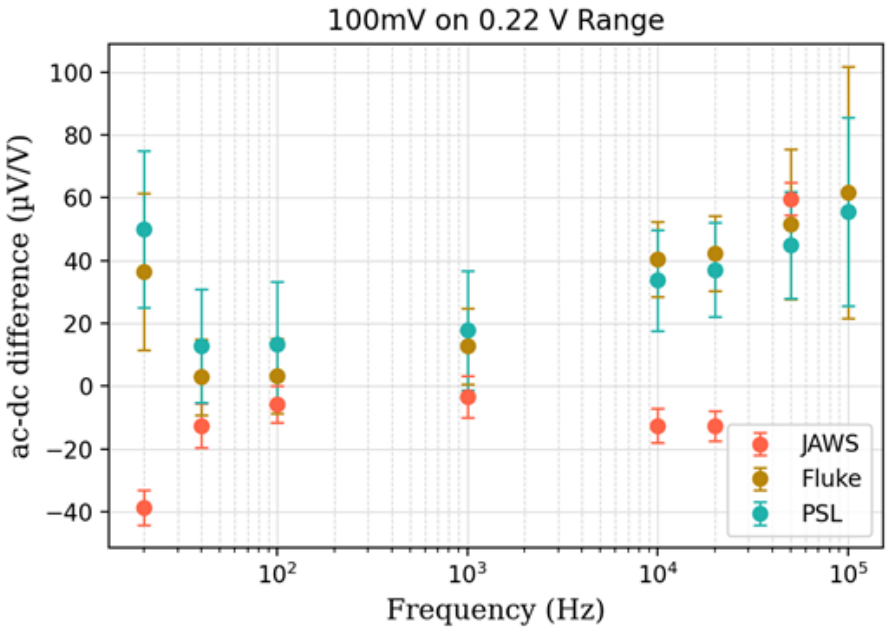
- Traditional ac calibrations are performed with a **transfer** standard
- JAWS is a quantum standard for ac voltages
- Analogous to JVS for DC voltage
- Pulse-driven Josephson Junctions
- PSL recently procured JAWS system for ac voltage calibrations
- Initial setup stages and optimization of system

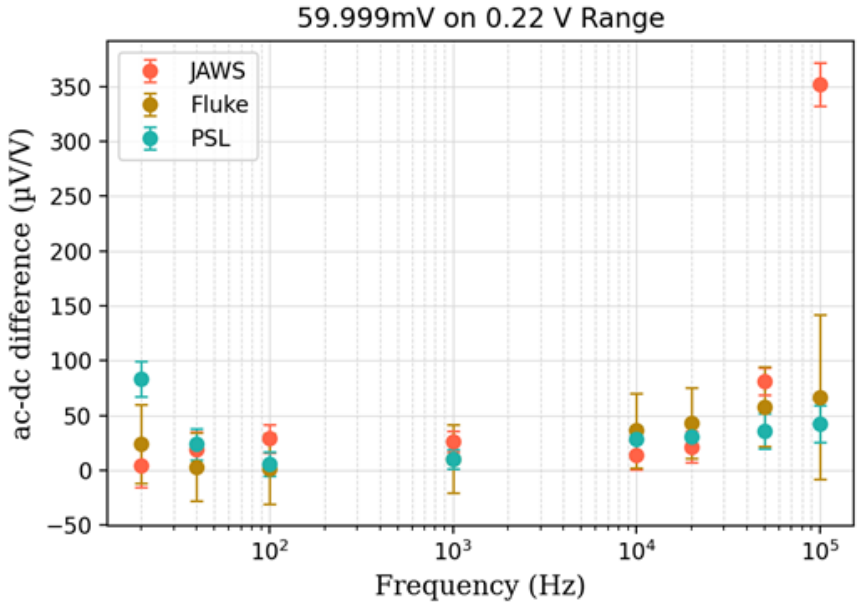


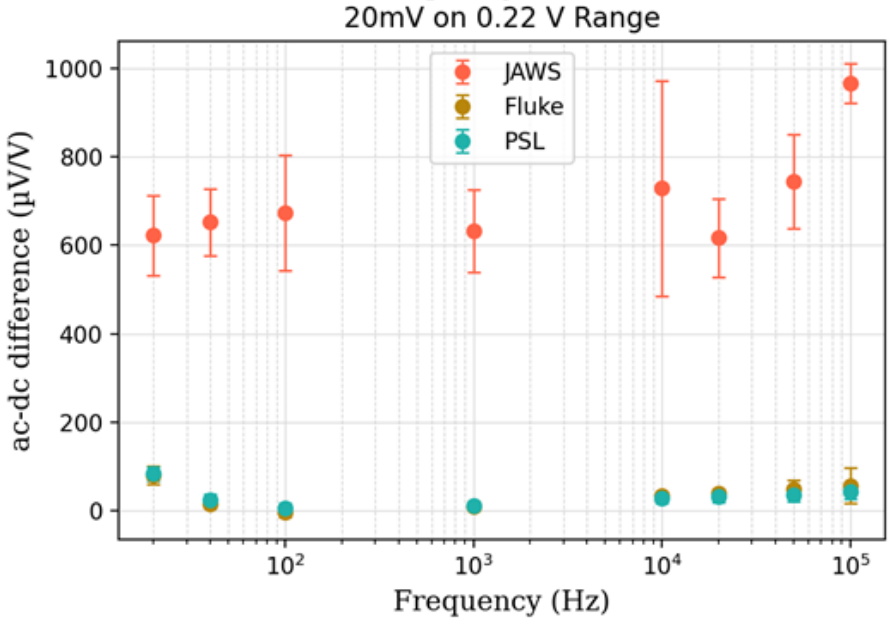
JAWS 792 Measurements

Fluke 792A data; compared to Fluke and PSL certificates for same device









Conclusions

- AC Lab at the PSL has made great strides in recent years in creating state-of-the-art ac-dc difference measurement capabilities
  - ac current, ac voltage, and 792A calibrations
- MJTC device design and fabrication
  - Investigating high resistivity substrates for high frequency applications
- JAWS procurement and initial measurements
  - 792A measurements/calibrations

Questions?

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JAWS – 5790A-B Measurements