Microwave Measurements at Cryogenic Temperatures

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Outline:

- **Introduction**
  - **acknowledgements**
  - **motivation**
- Cryogenic systems for microwave measurements
  - cooling
  - vacuum
  - thermal design, control and measurement
  - microwave connections and cabling
- Connectorized devices
  - apparatus
  - calibration and measurement issues
- On-wafer/chip (probing)
  - apparatus
  - calibration and measurement issues
- Conclusions

Acknowledgements:

- Jim Booth, et. al. (NIST)
- Robert Romanofsky, et.al. (NASA-Glenn)
- Walter Kruppa, et.al. (NRL)

Issues this talk covers:

- Information for those developing microwave cryogenic electronics who need to perform microwave measurements at cryogenic temperatures :
  - emphasis on using common equipment and instrumentation
  - understanding the limitations and sources of error
  - assumes that metrology is not your primary interest
  - applicable to HTS and cryogenic semiconductor measurements
- Discuss practical infrastructure issues:
  - cryogenic test chambers
  - thermometry
  - cabling and feedthroughs
- Connectorized device characterization:
  - scattering parameter measurements
  - noise figure measurements
  - measurements of nonlinearities
- On-wafer/chip characterization:
  - scattering parameter measurements
  - noise figure measurements
  - measurements of nonlinearities

Measurements of Devices and Systems at Cryogenic Temperatures:

- Cryogenic component or subsystem integrated in dewar with cooler:
  - ports are at room temperature so standard measurement techniques and limitations apply

- Cryogenic measurements of connectorized devices
  - ports are at cryogenic temperatures
  - calibration of measurement system up to those ports is a very difficult problem due to cryogenic induced thermal gradient and vacu um environment
  - open or closed cycle system as vibration usually not an issue

- Cryogenic measurements of patterned circuits on substrates:
  - on wafer/chip measurement using cryogenic probe station
  - can measure properties without the influence of packaging parasitics
  - calibration of system is nontrivial
  - packaging is a major issue which is often the hardest part of the design problem, especially for high-Q filters
  - usually open cycle system as vibration isolation is very important

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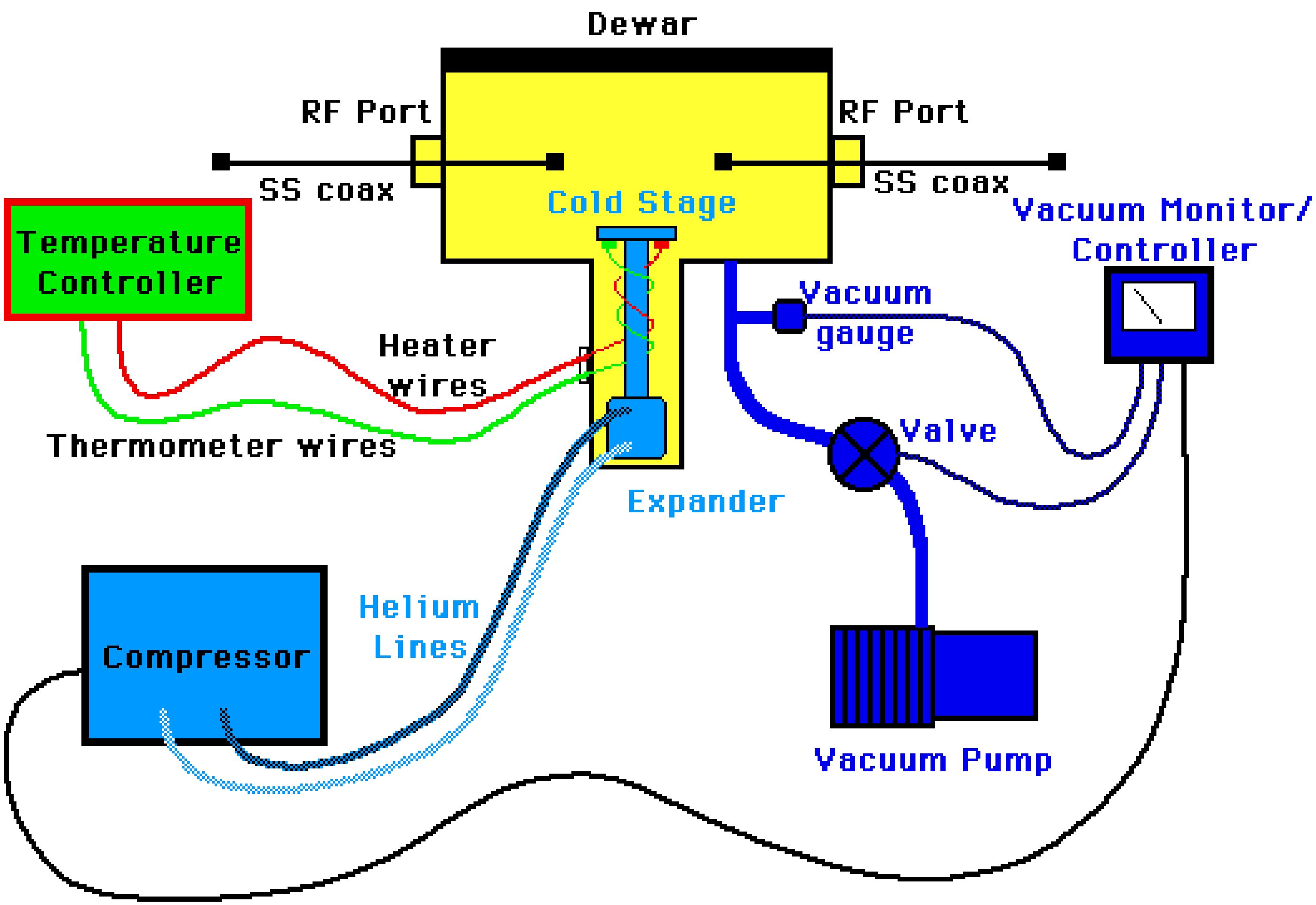
Cooling Options:

- Closed-cycle refrigerator with vacuum insulated cold finger
  - vibration can be a problem — microphonics
  - self contained — no transfer of cryogenic fluids
  - reliable — many based on cryopumps found in vacuum systems
  - not cheap
  - ensuring an isothermal environment is more difficult
- Open cycle with vacuum insulated cold finger
  - Nitrogen is cheap and easy to handle but can't get to ~ 77K
  - Helium requires expertise in handling, expensive, can get to ~ 4K
  - with either cryogen, if you want temperature control over wide range you approach complexity of closed cycle system
- Immersion in cryogenic fluid (liquid Nitrogen or Helium)
  - good if you can immerse in LN and are happy with one temperature and can stand condensation on device, very cheap
  - complicated vacuum insulated immersion cryostats for liquid He

The Basic Subsystems of a General Purpose Cryogenic Microwave Test System



Vacuum Considerations:

- With decent cooling capacity a rough pump down to ~100 milliTorr is sufficient. The cold head will then act as its own cryopump.
- Since the cold head is a better vacuum pump than a roughing pump, "backstreaming" of oil into the chamber can be a problem
  - oil can coat the chamber, DUT and cabling — a mess at best
  - solutions:
    - valve off roughing pump
    - use turbo pump to evacuate chamber
- With a good roughing pump and large refrigerator, virtual leaks, out-gassing and very small leaks are usually not a problem.
- Vent with dry Nitrogen to eliminate condensation on cold stage/DUT

Thermal design, control and measurement:

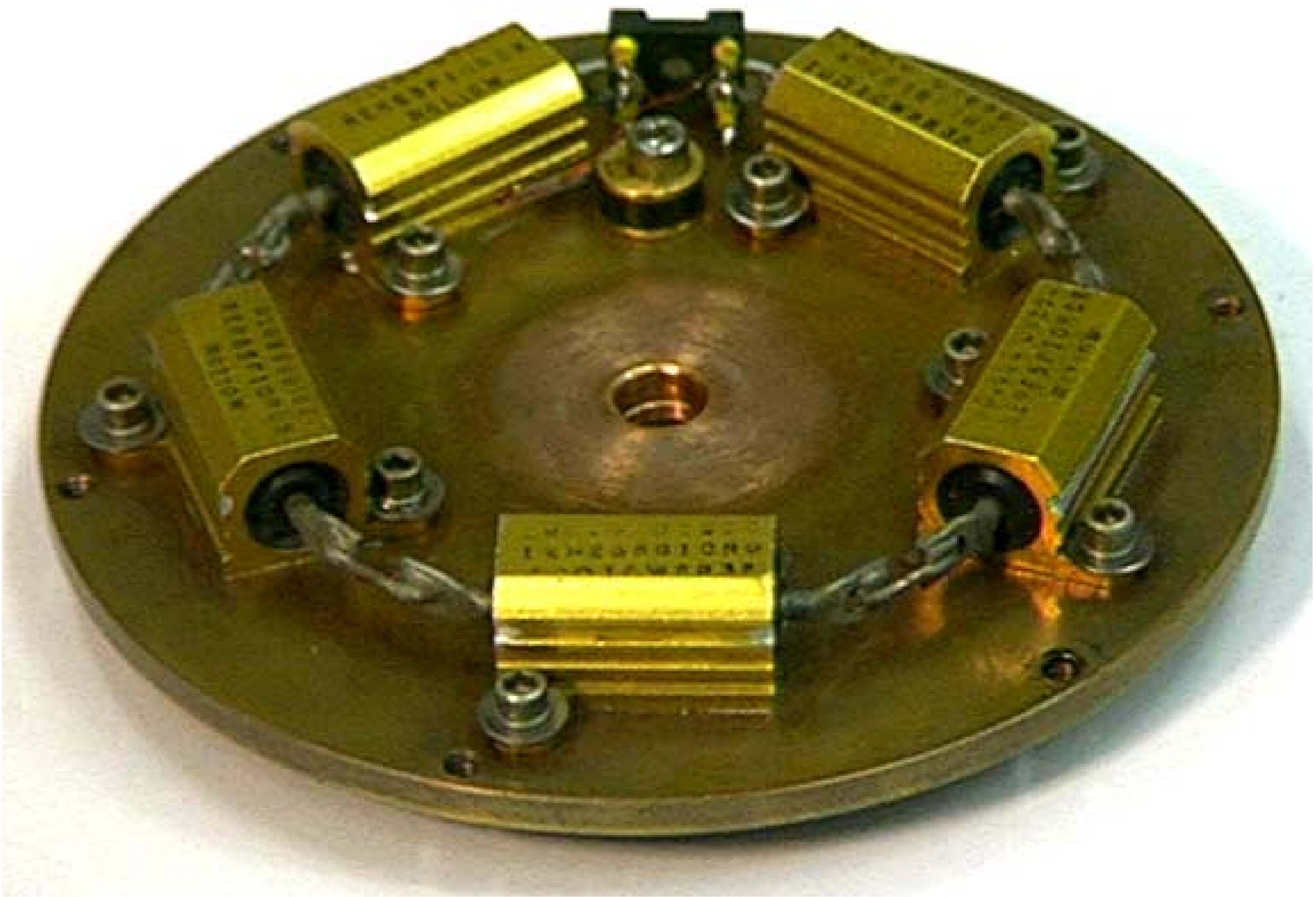
- Minimize number of interfaces that heat must cross.
- Utilize materials with good thermal conductivity at all temperatures (e.g. OFHC) in the cold finger and DUT/sample mounting platform
  - not easy to machine
  - particularly important below 77K
  - connectorized devices require good thermal package design
- Most systems provide constant cooling and use heaters in conjunction with thermometers and a controller to provide a stable environment
- Standard practice is to use two or more thermometers
  - Temperature control – mounted close to the heater
  - Sample temperature – mounted on or near the DUT/sample
  - ΔT of thermometers is a good measure of thermal design
- To provide good control at all temperature
  - heater power > cooling power at all temperatures
  - aluminum housed axial lead wirewound resistors are robust heater
  - autotuning “PID” controllers offer good performance

Thermal design, control and measurement (cont.):

- Thermal sensor types:
  - diode: fast response, interchangeable, standard calibration
  - resistor: larger, mounting strain induced errors, PTC and NTC
  - capacitor: drift and thermal cycling problems, immune to **H** fields
  - thermocouple: errors due to temperature gradient of wire
- Recommendation:
  Unless **H** fields are part of your experiment use 4-wire Si diode
- Once the chamber is under vacuum, thermal contact of DUT/sample to cold stage must be ensured. Options include:
  - thermal grease — Apeizon Type N or equivalent — messy
  - rubber cement — particularly good for small sample where concern about use of solvents exists
  - Indium foil — more difficult to use — may “stick” to sample and be destroyed in removing — expensive
  - Au foil/indium foil — even more expensive — Au is inert

The Heater Resistors and Control Sensors

(This is the underside and mounts directly on the cold finger)



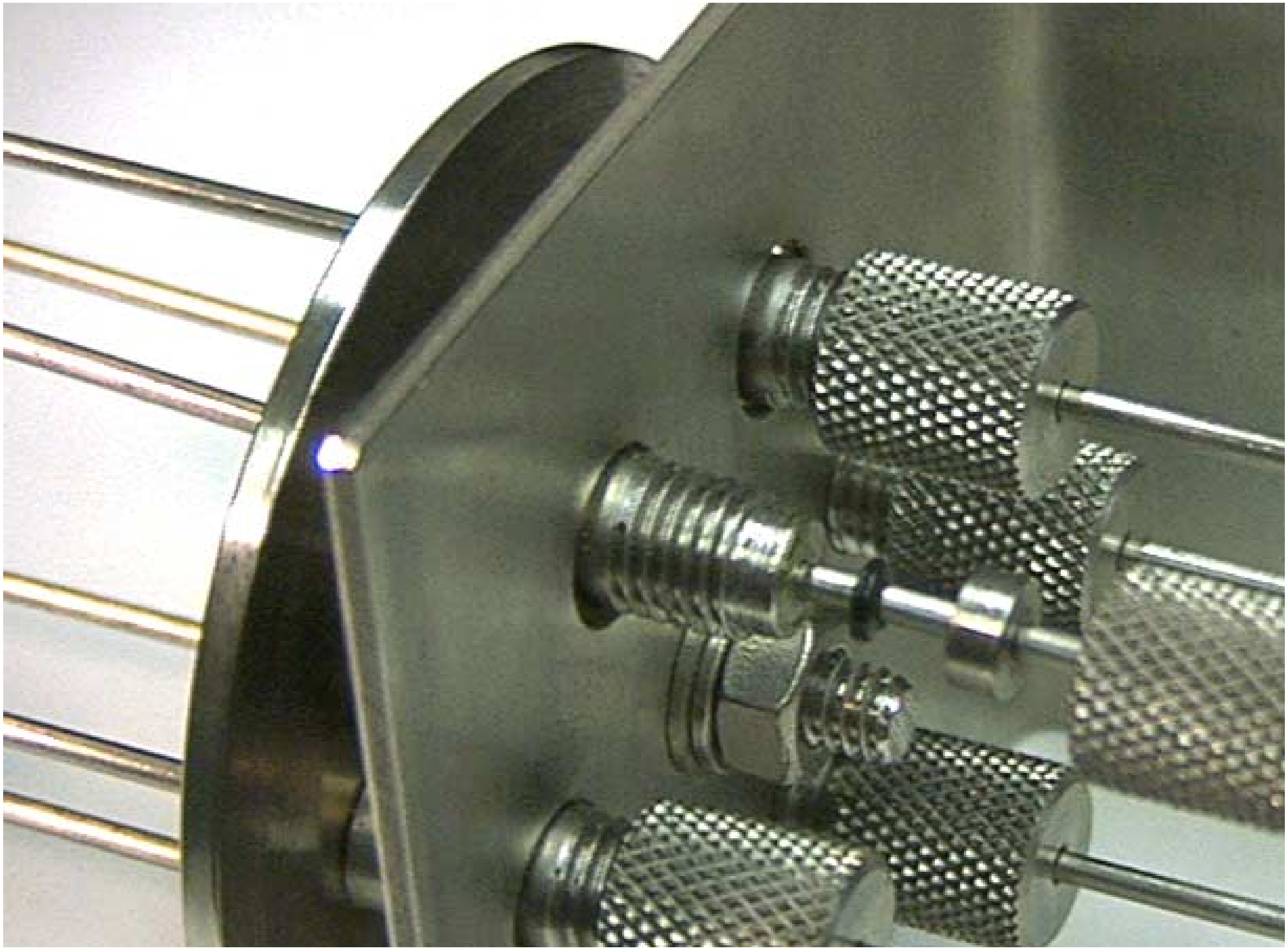
Microwave Connections and Cabling:

- Heat leaks along coax dumps heat directly into the critical region of the DUT/sample leading to higher temperature uncertainty.
- Balance the issues of attenuation versus heat leak.
  - long cables improve thermal isolation but degrade measurement
  - short cables ease measurement at the expense of heat load
- Stainless steel coax is popular option compared to Cu

Cable Type	Thermal load (W•cm)	Insertion Loss (dB/cm)
0.085 Cu	14.97	0.022
0.141 SS	1.77	0.028
0.085 SS	0.90	0.048

- Teflon has high coefficient of thermal expansion
  - gaps can occur at low temperatures – gives reflections
  - prefer coax with special dielectric with matched coefficient of thermal expansion
- Hysteresis in teflon creep can lead to problems:
  - “captured center pin” connectors for long straight cables.
  - measurement repeatability and, hence, calibration problems
- Any of the standard coax connector series (SMA, K, OS-50) can be used — individual connectors within a series may be suboptimal

Close-up of 6-port Sliding Coax Feedthrough



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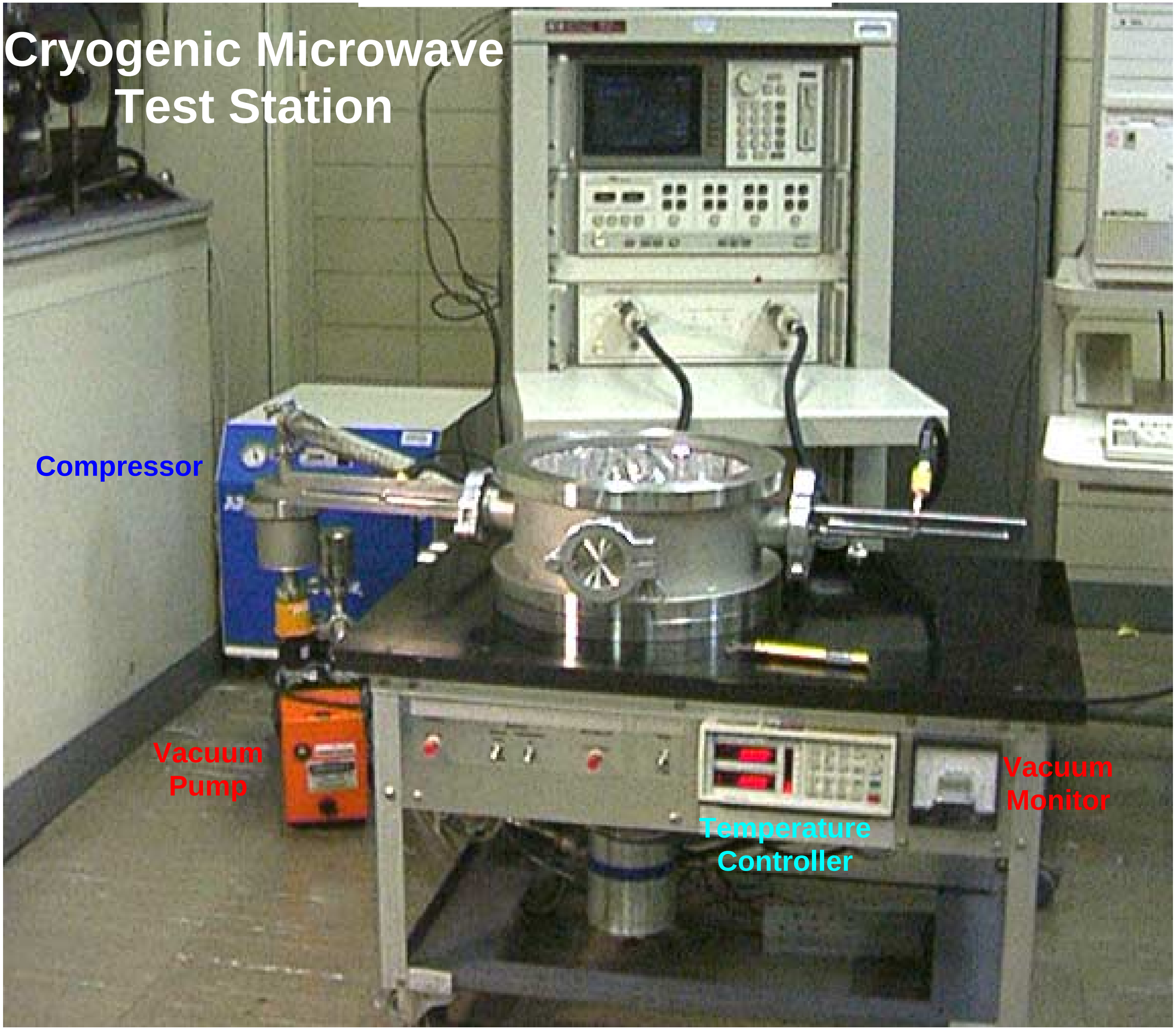
Cryogenic Microwave Test Station



The Chamber, Microwave Feedthrough and Temperature Controller

S-Parameter Measurement and Calibration Issues:

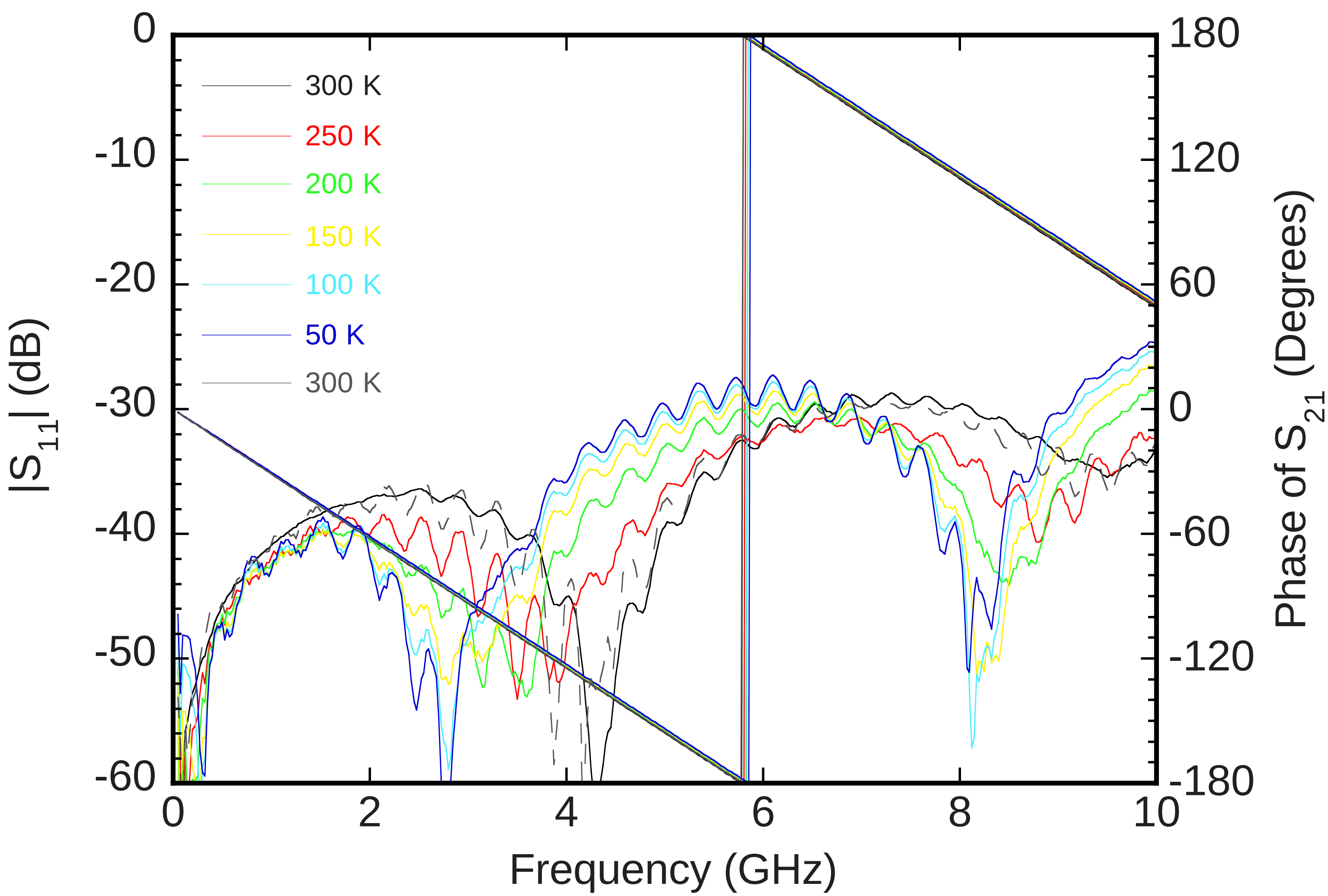
- Network analysis calibration is an issue. as temperature decreases:
  - physical lengths contract (usually) resulting is decreased cable electrical lengths
  - electrical conductivity increases (usually) resulting in decreased insertion loss of coax
  - characteristic impedance of coax may change
  - thermal cycling hysteresis (may be nonrepeatable) can negatively affect any calibration scheme

- Room temperature calibration
  - reduced accuracy
  - easy — same as always
  - some first order correction for IL can be made in some cases

- Cryogenic calibration
  - standards, particularly loads, have temperature dependence themselves — TRL preferable
  - tedious — unless a matched network using switches is used, a cryogenic cycle is needed for each standard

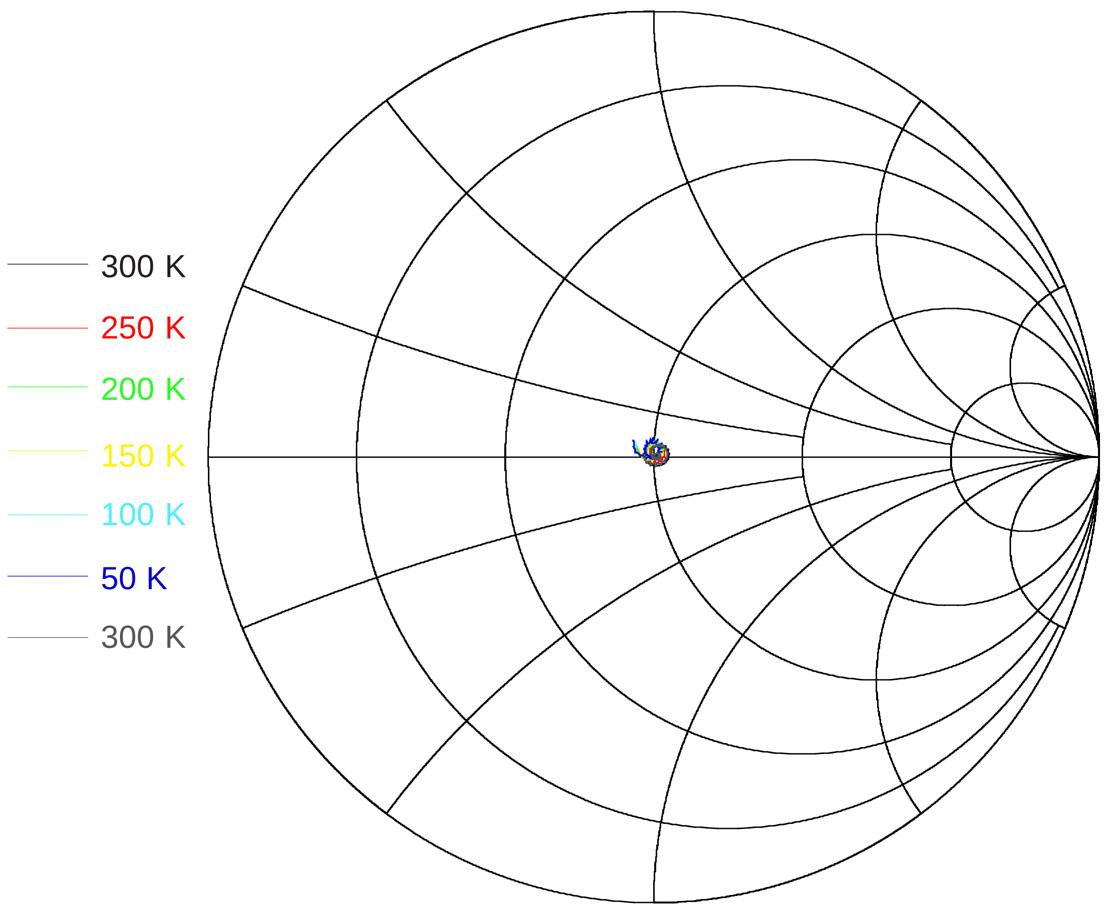
Measurement at Various Temperatures of an SMA F-F Bulkhead Adapter After Room Temperature Calibration

(using HP 85052D (SOL) 3.5mm economy cal kit)



Measurement at Various Temperatures of an SMA F-F Bulkhead Adapter After Room Temperature Calibration

(using HP 85052D (SOL) 3.5mm economy cal kit)



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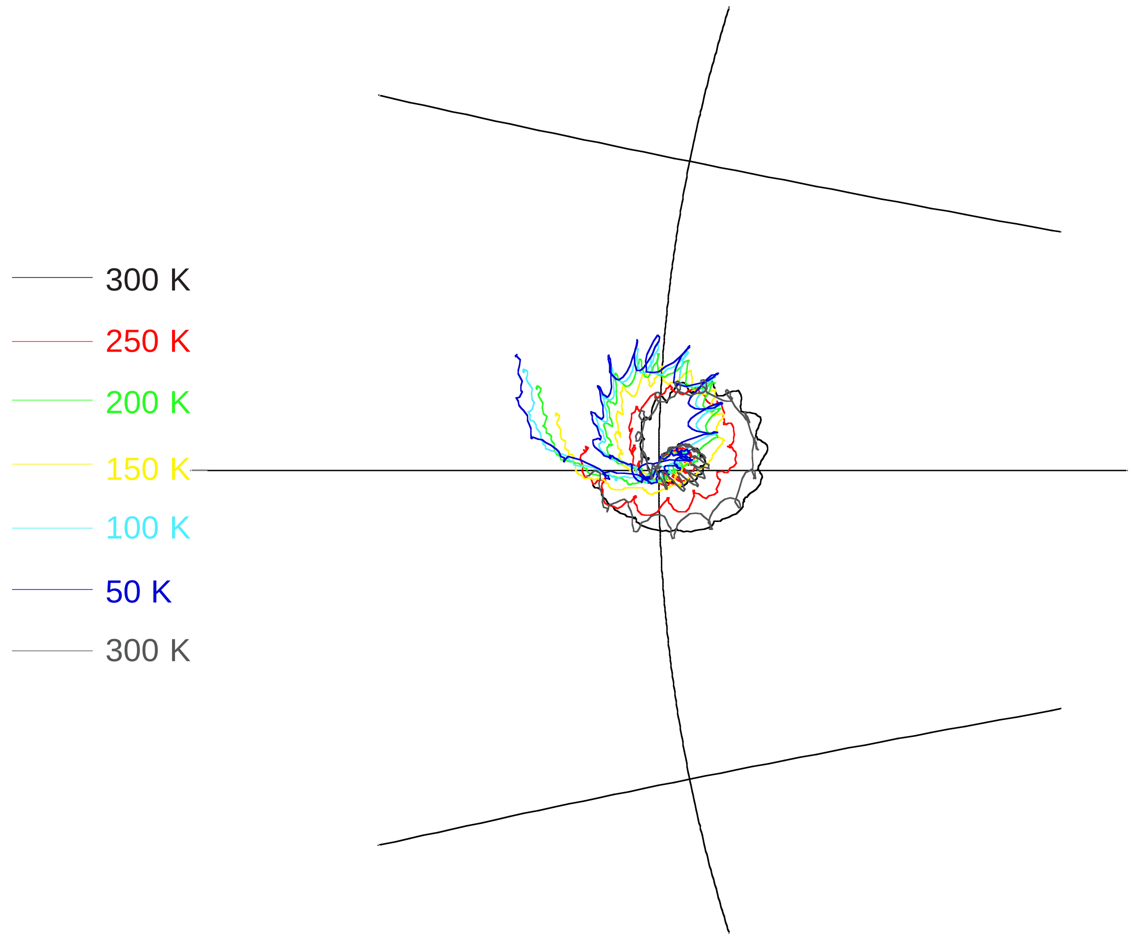
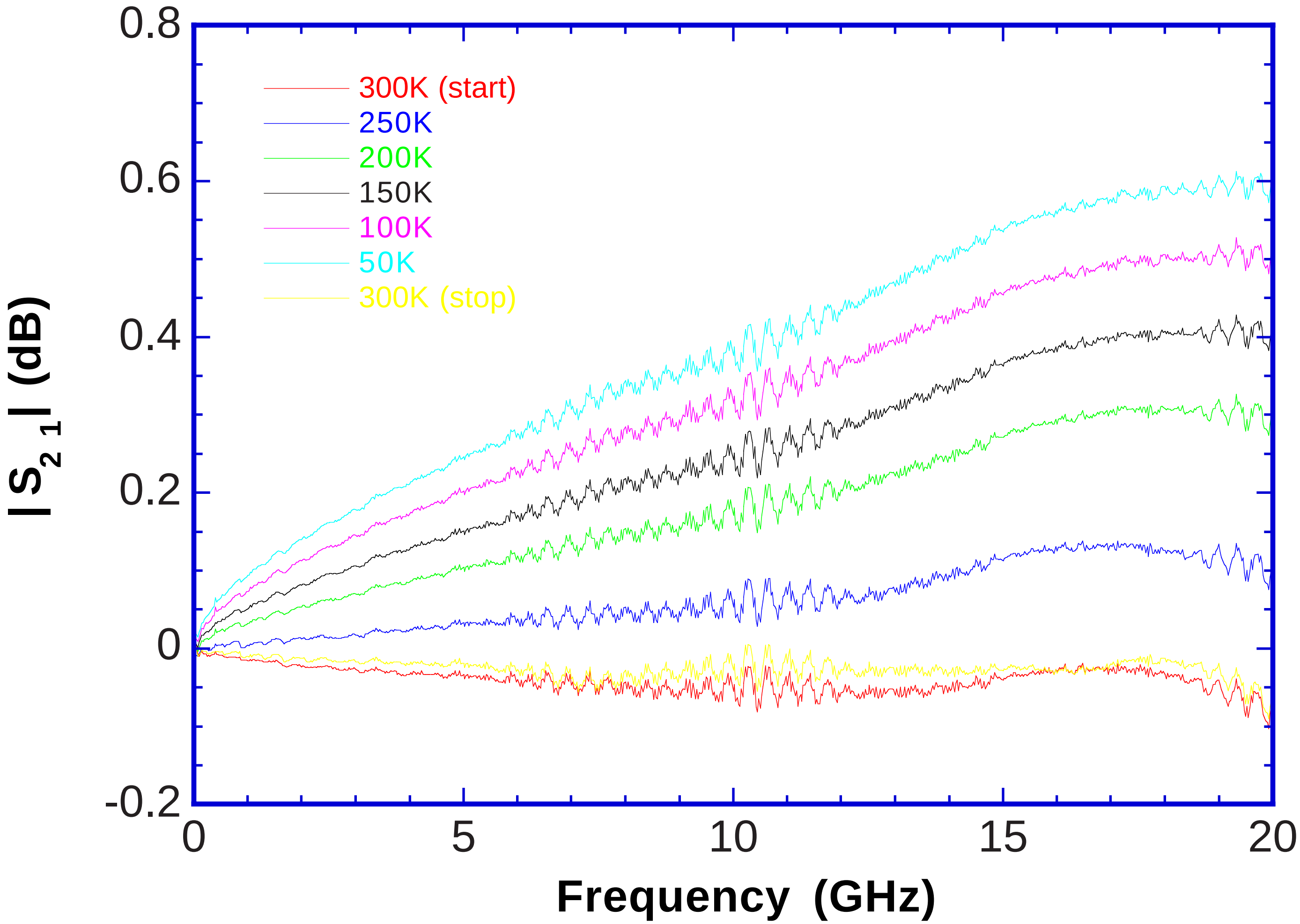


Measurement Error at Various Temperatures Illustrated by Measurement of an SMA F-F Bulkhead Adapter After Room Temperature Calibration

(using HP 85052D (SOL) 3.5mm economy cal kit)



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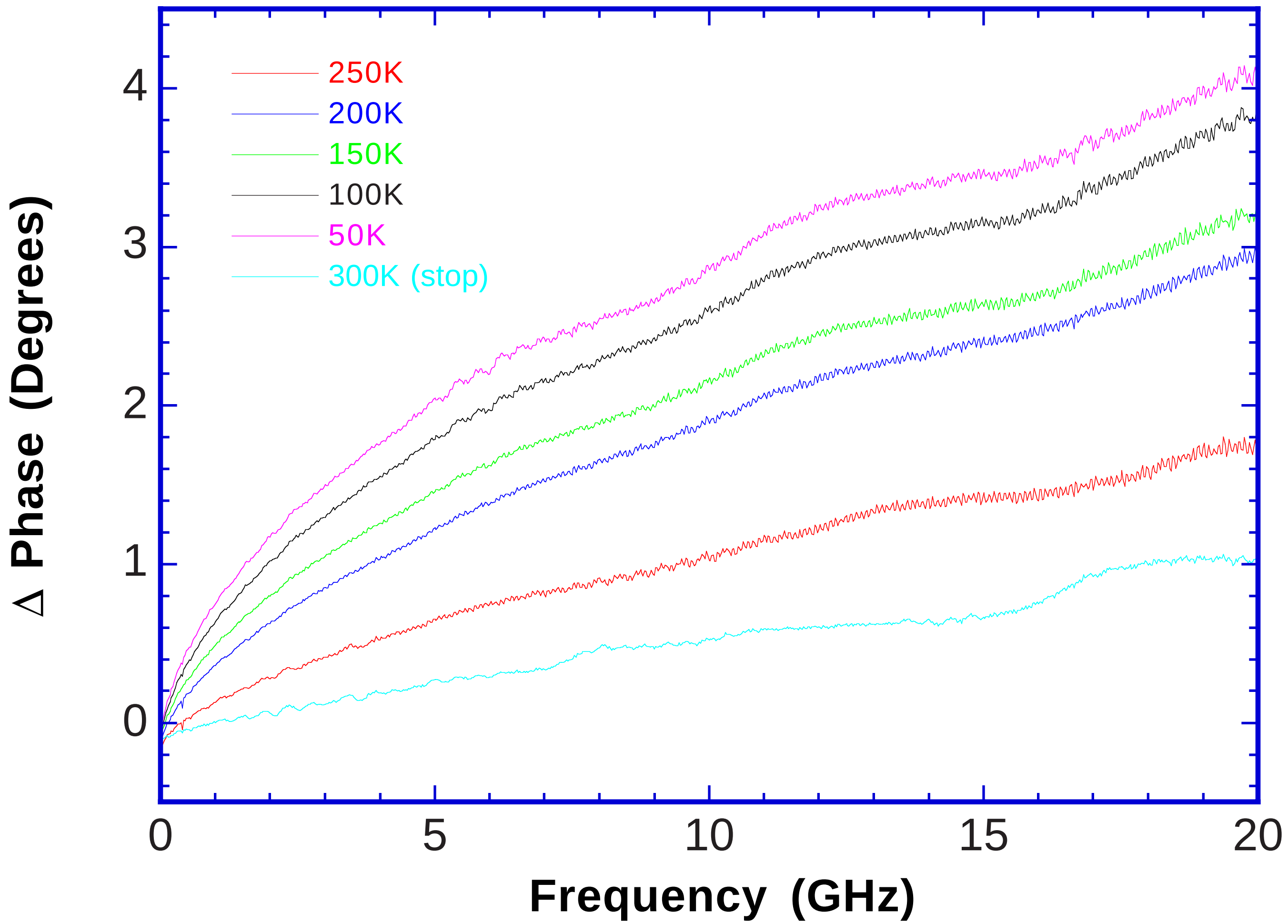
(using HP 85052D (SOL) 3.5mm economy cal kit)



S-Parameter Measurement and Calibration Issues (cont.):

- The previous example was a worst case in many ways:
  - The cable length subject to a thermal gradient was at a maximum (~20 cm)
    - IL can be reduced by ~2X by using 0.141
    - Use shorter cables — 5 cm of 0.141 cable would have a 0.5 Watt thermal load but would reduce IL by ~4X
    - phase error would, similarly, be reduced by ~4X
  - Based on measurements shown in previous graphs, these modifications should result in IL error <~0.1 dB and phase error <~0.5 degrees

- Possible complications:
  - Thermal design of DUT/sample becomes more of an issue since more heat is entering the DUT coaxial connectors.
    - minimize layers and interfaces in DUT package
    - place sample temperature sensor near coax connector
    - more sample temperature sensors to monitor ΔT of DUT
  - May need to customize coax feedthroughs to optimize this performance for each DUT

Noise Figure Measurements:

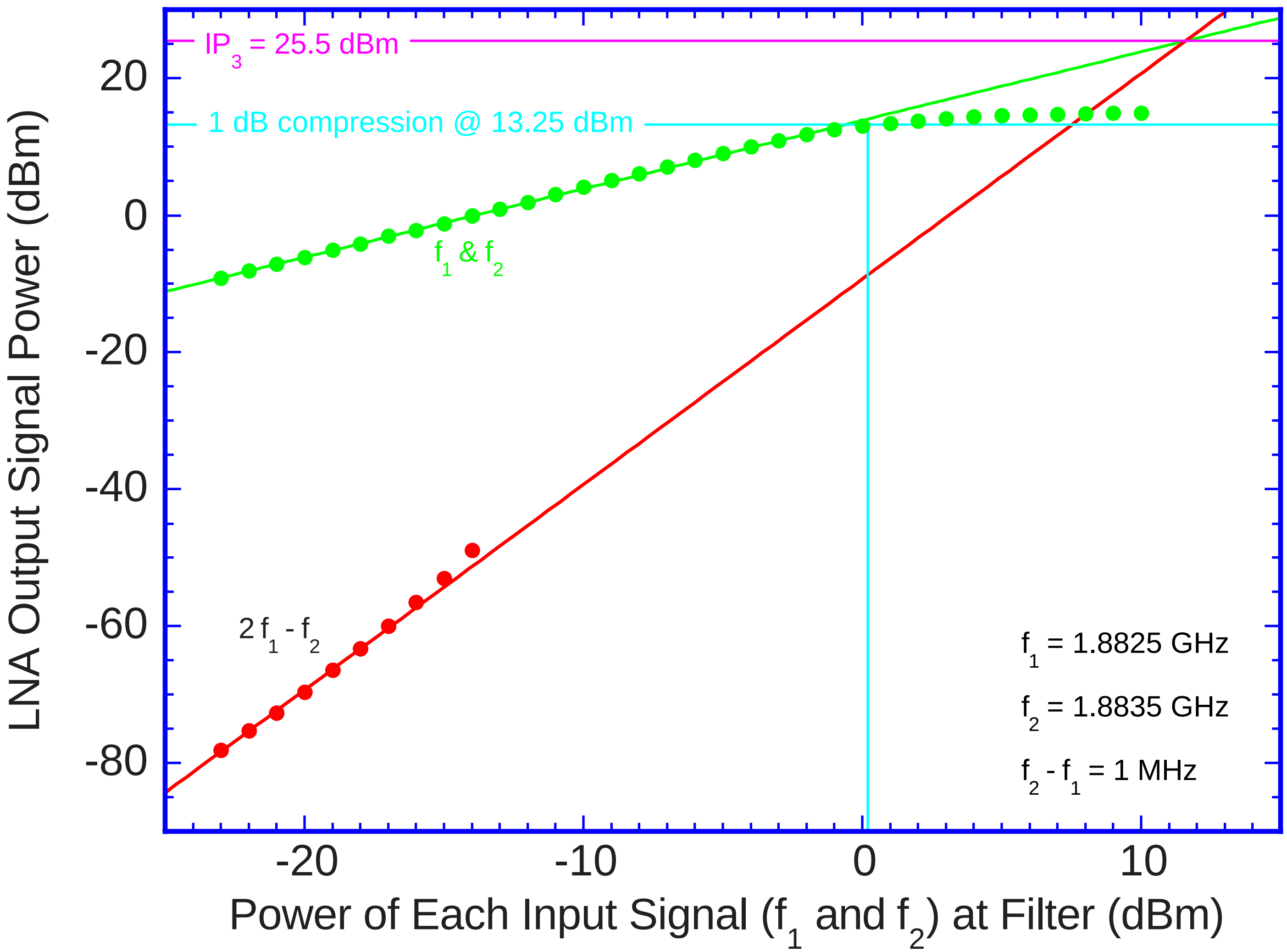
- Difficulties encountered using standard noise figure meters:
  - assumes that both ports of the DUT are available – not true in a cryogenic system
  - they are scalar instruments — hence have problems with electrically long low-loss devices
  - cryogenic feedthroughs represent such a problem — temperature dependence of electrical length and loss are a complication
  - will happily report negative Noise Figures
  - meter has an internal bandwidth that may be wider than a narrow band HTS filter – thus you also measure noise on the filter skirts
- Proceed carefully from first principles
  - even deembedding from the cascade doesn't really solve the problem due to reflections
  - an isolator can help with the reflection problems and make de-embedding more accurate in some cases
- Low Noise Figure is one of the primary reasons cryogenic operation is so promising yet it is a measurement area where standard commercial RT techniques seem least applicable

Noise Figures for a Cryogenic Receiver:

	130 K	300 K
LNA:	0.4 dB (deembedded)	0.75 dB (measured)
Filter:	0.25 dB (calculated)	0.85 dB (calculated)
Receiver:	0.7 dB (calculated)	1.6 dB (calculated)
Receiver in Dewar:	1.0 dB (measured)	1.9 dB (measured)

- NFs were measured with an HP 8970B and 8971C Noise Figure measurement system. The measurement bandwidth of this system is on the order of the filter bandwidth and since the frequency increment is 1 MHz an accurate measurement can not be obtained.
- NFs of the filter are calculated from the insertion loss.
- NFs of the receiver are calculated from the measured LNA NF and filter insertion losses.
- Values given for the receiver integrated in the Dewar are direct measured values and are estimated to be 0.25 dB high by direct measurement of the filter at 300 K.

Measured Cryogenic Receiver Nonlinearities
IP_3 and 3 dB Compression Point at 130K
(nonlinearities are consistent with LNA specifications)



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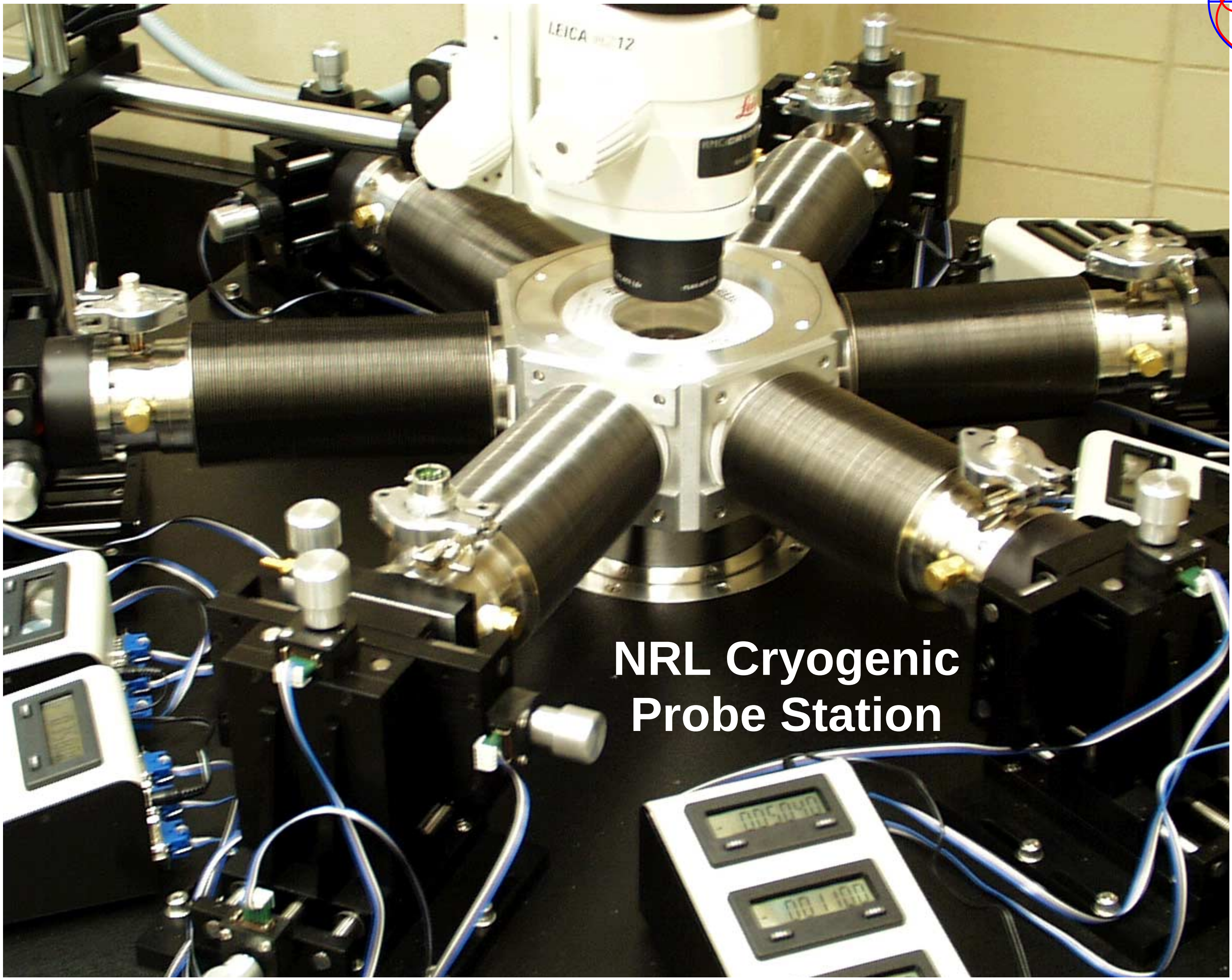
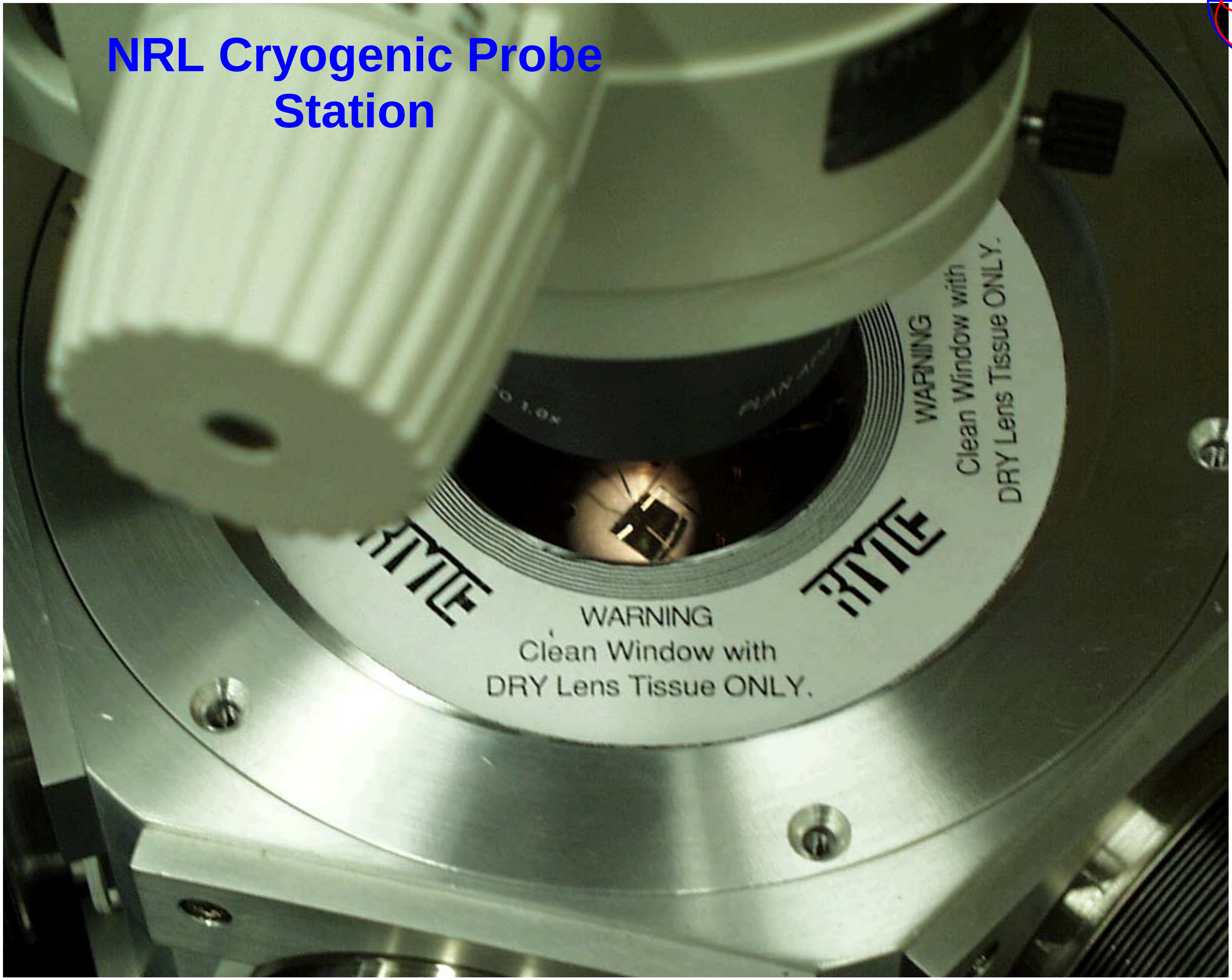
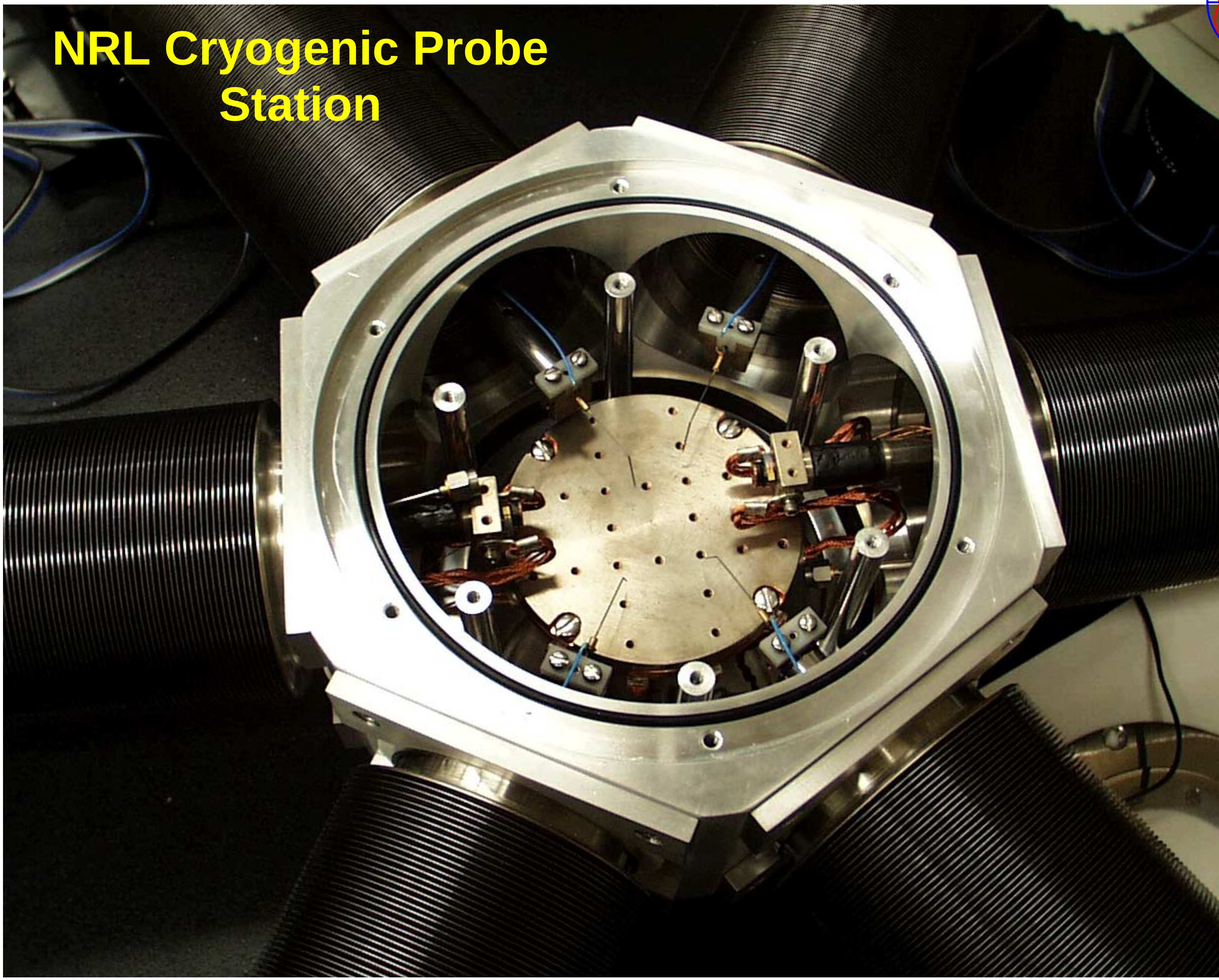

LEICA
NRL Cryogenic
Probe Station

NRL Cryogenic Probe Station

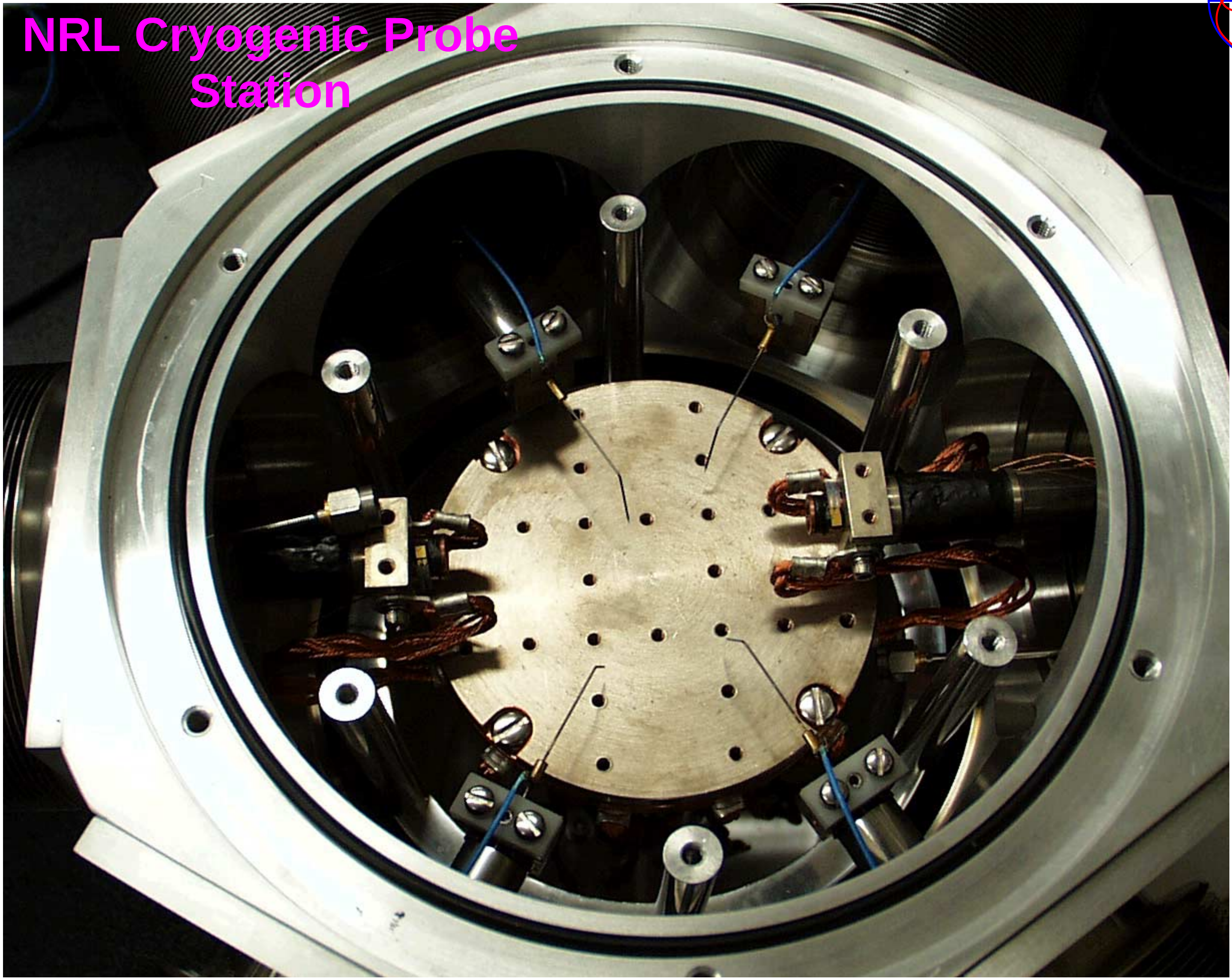
NRL Cryogenic Probe Station



NRL Cryogenic Probe Station



NRL Cryogenic Probe Station



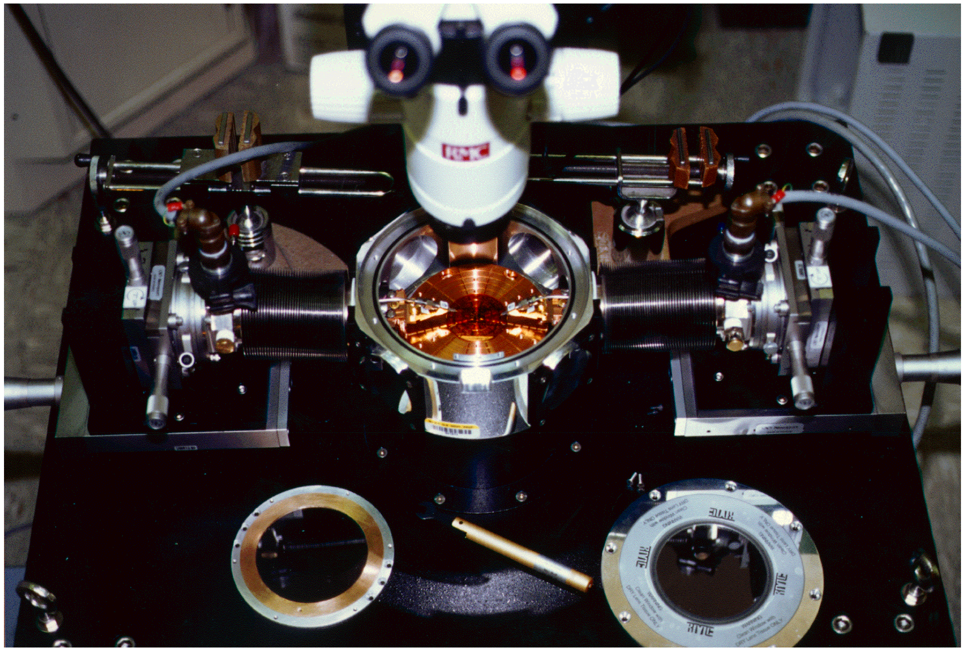
Cryogenic Wafer Probe Station at NIST, Boulder

Allows for on-wafer calibrations and measurements of coplanar devices at cryogenic temperatures

Current Experimental Programs at NIST:

1. Characterization of HTS materials at microwave frequencies
2. Measurement of nonlinear effects in HTS microwave devices
3. Evaluation of tunable ferroelectric materials

- Two microwave probes (dc - 40 GHz)
- 2” wafer capability
- Liquid helium cooled (sample base temperature 10K)
- ±180˚ sample rotation



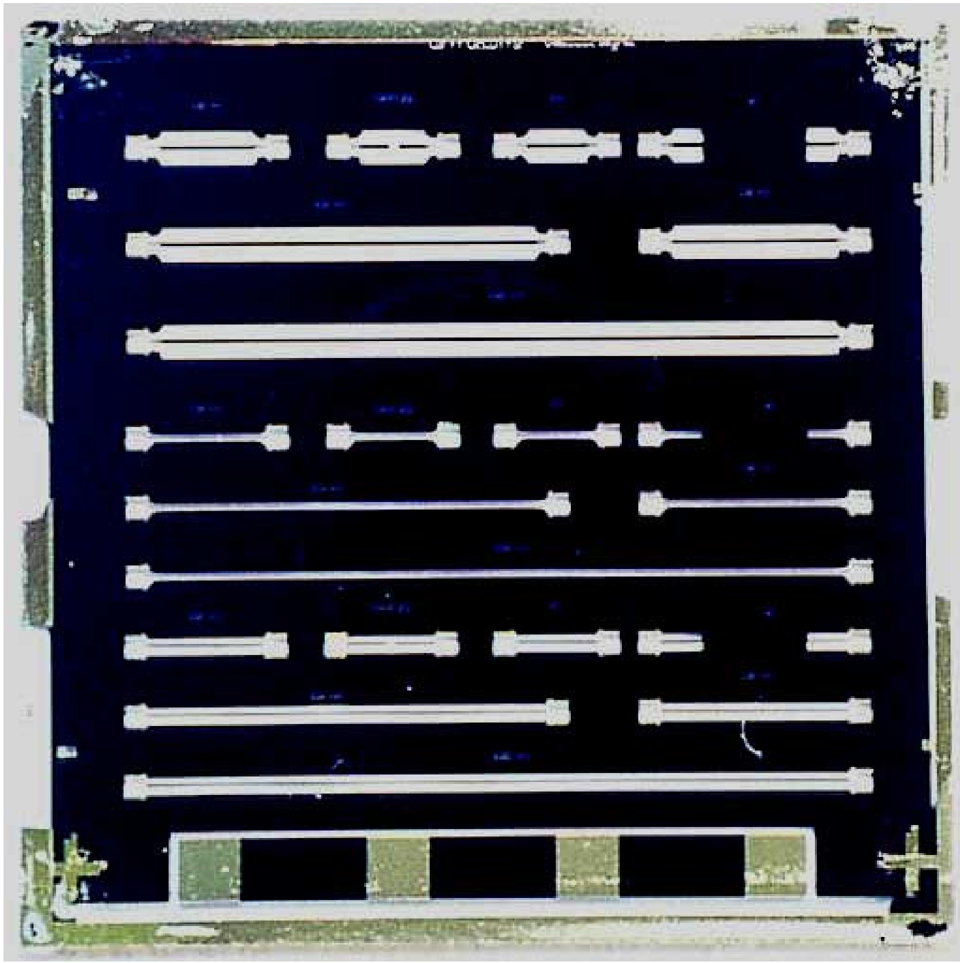
NIST
High-T_C Electronics Project

CPW Transmission Lines Fabricated from YBCO Thin Films

- Typical HTS experimental configuration:

  3 complete TRL calsets, each with a different center conductor linewidth/gap spacing (all nominally 50 Ω)

- Can fabricate many different cpw devices on the same thin film sample



105 μm Center Conductor

21 μm Center Conductor

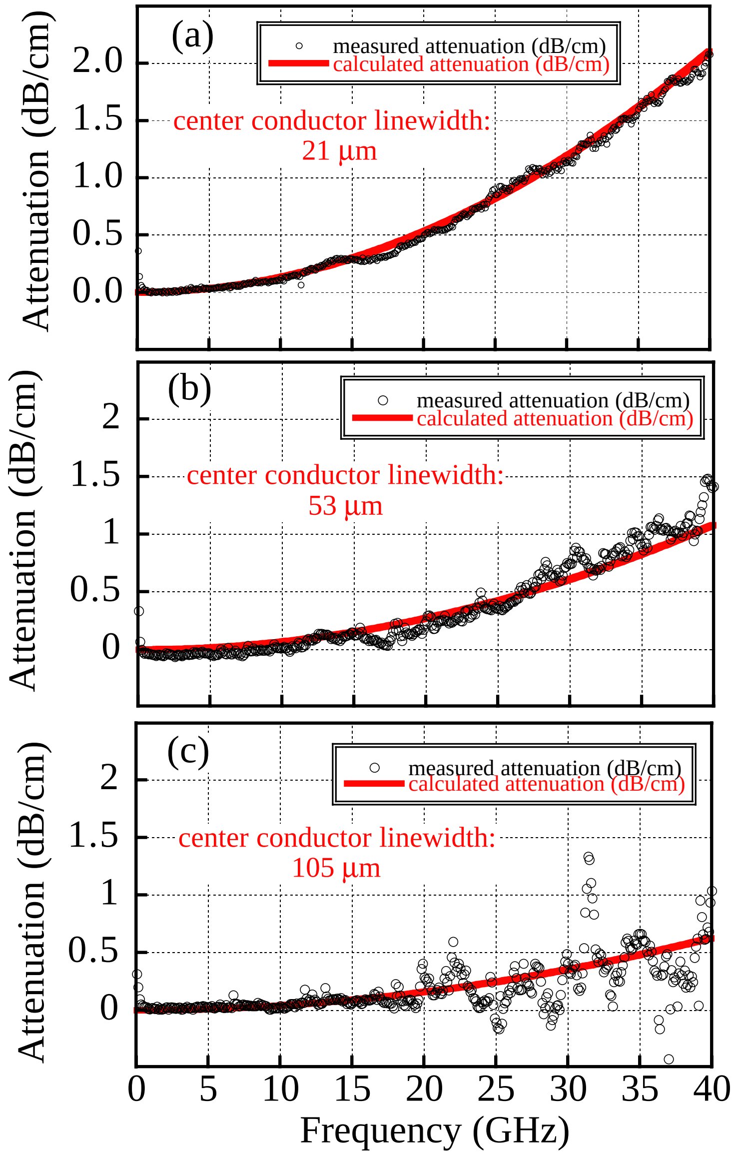
53 μm Center Conductor

15mm

Calculations of Conductor Loss in Superconducting Planar Circuits

- Attenuation constant extracted from multiline TRL calibration
- Calculation based on material properties measured on unpatterned HTS films using sapphire dielectric resonator
- Calculation and measurement show good agreement for 50nm YBCO at 76K for different geometry CPW transmission lines

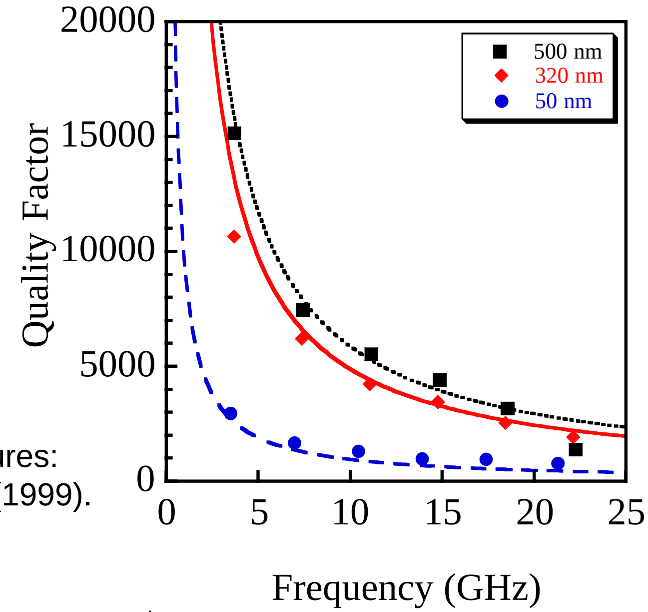
J.C. Booth and C.L.Holloway, "Conductor Loss in Superconducting Planar Structures: Calculations and Measurements," IEEE Trans. Microwave Theory Tech. **47**, 769 (1999).



CPW Resonator Measurements

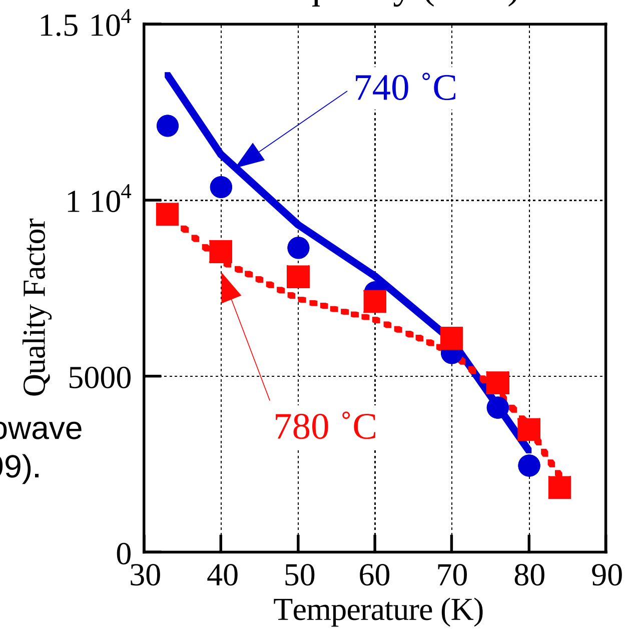
- **Calculated and measured Q-values for YBCO resonators agree for different film thicknesses**
  - CPW resonator
  - YBCO films on $LaAlO_3$ substrate
  - Temperature = 30 K
  - 21 µm center conductor linewidth
  - 11.35 mm length
  - 3.7 GHz fundamental

J.C. Booth and C.L.Holloway, "Conductor Loss in Superconducting Planar Structures: Calculations and Measurements," IEEE Trans. Microwave Theory Tech. **47**, 769 (1999).



- **Experimental comparison of 400 nm YBCO thin films grown at different deposition temperatures**
- **Solid line is calculation of CPW resonator Q based on measurements of unpatterned thin films**
  - CPW resonators
  - YBCO films on $LaAlO_3$ substrate
  - 21 µm center conductor linewidth
  - 11.35 mm length
  - 3.7 GHz fundamental

James C. Booth et al., "Simultaneous Optimization of the Linear and Nonlinear Microwave Response of YBCO Films and Devices," IEEE Trans. Appl. Supercond. **9**, 4176 (1999).



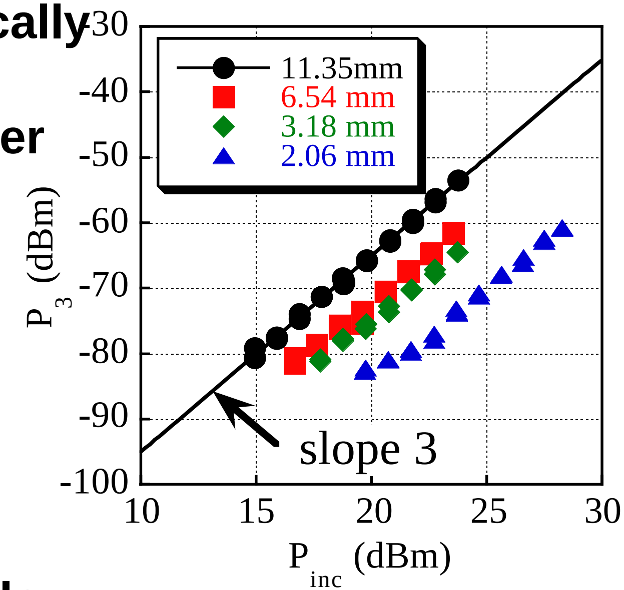
NIST
High-T_C Electronics Project

Nonlinear Measurements of HTS Microwave Devices

- **Measured third harmonic signal changes systematically for different length cpw transmission lines**
- **Nonlinear measurements lead to model for third order intercept point IP_3 in HTS devices**

320 nm YBCO on $LaAlO_3$ substrate
Temperature = 76 K
Center conductor linewidth = 21 µm

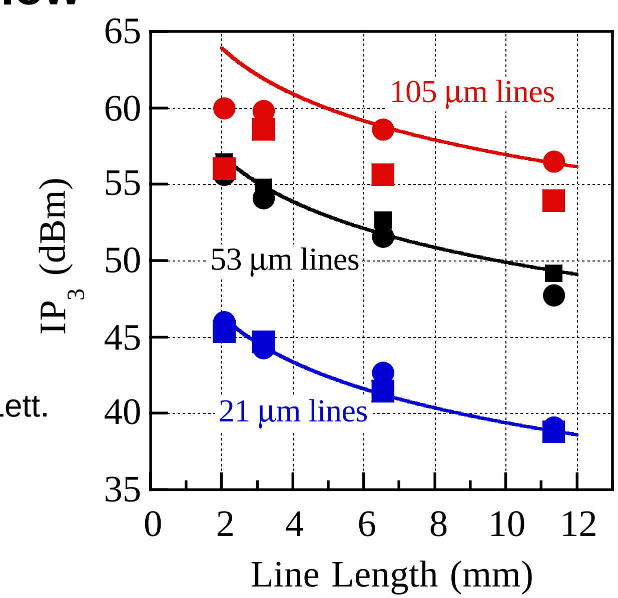
James C. Booth et al., "Geometry Dependence of Nonlinear Effects in High Temperature Superconducting Transmission Lines at Microwave Frequencies," J. Appl. Phys. **86**, 1020 (1999).



- **Relevant nonlinear model parameters confirmed by low-frequency measurements of the current-dependent penetration depth λ(J)**

50 nm YBCO on $LaAlO_3$ substrate
Temperature = 76 K
Solid lines are model predictions for IP_3 based on low-frequency inductive measurements

J.C. Claassen et al., "Nonlinear inductive response of high temperature superconducting films measured by the mutual inductance technique," Appl. Phys. Lett. **74**, 4023 (1999).



High-T_C Electronics Project

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Conclusions:

- Cryogenic microwave measurements needs have not yet been addressed by the commercial market
  - need network analyzer calibration equipment and procedures for cryogenic temperatures
  - need techniques and equipment for quantifying noise performance at cryogenic temperatures
  - need phase-stable, low-loss, high-thermal-isolation rf I/O
- Individual laboratories and institutions often have their own practices that “work” for their particular needs
- Solutions to a particular measurement problem are often dictated by the specifics of the device/circuit whose performance is being investigated and the test and measurement equipment available
- Awareness of the sources of error is the best way to design a set of measurements that will obtain an accurate characterization of the device of interest