Cornell Laboratory for
Accelerator-based Sciences and Education (CLASSE)

Superconducting-Niobium Accelerator Cavity Second-Sound Defect Localization and Repair

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Collaborators:

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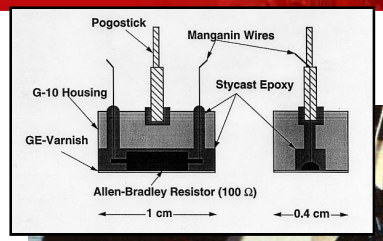
Georg Hoffstaetter	Cornell SRF Group

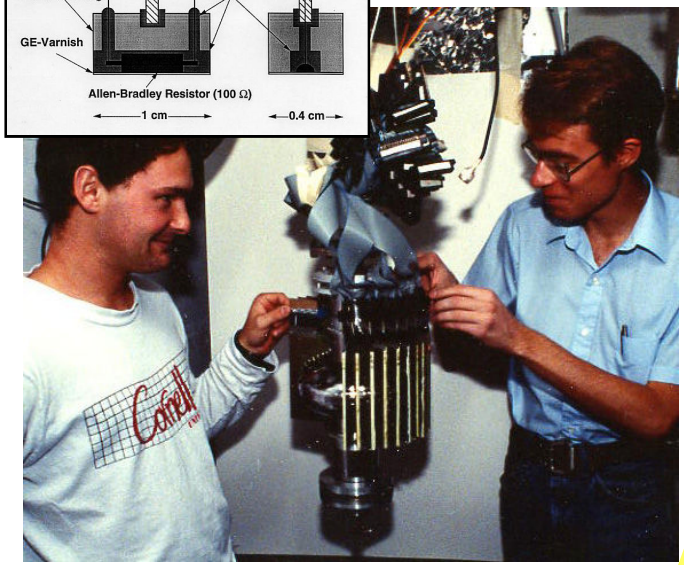
Why We Care

- **Many SRF projects need high-accelerating-gradient (E_{acc} > 10 MV/m) SRF niobium cavities.**
  - **International Linear Collider (ILC, E_{acc} = 31.5 MV/m)**
  - **Cornell ERL Project (5 MV/m < E_{acc} < 25 MV/m)**
  - **FNAL Project-X**
  - **Lot's More**
- **Not all superconducting radio-frequency (SRF) cavities reach their design goal**
- **Only 1 cavity (Cornell) has reached the maximum achievable surface magnetic field of 200 mT, 5 years ago**
- **In my experience many (75%) are limited by surface defects to peak surface magnetic fields (B_{peak}) in the range of 40-100 mT which corresponds to 5 MV/m < Eacc < 25 MV/m (ILC specs)**
- **Locating and repairing these defects is critical to producing SRF cavities for accelerator projects.**
  - **So the accelerators can deliver the specified beam to experimenters**
  - **To avoid throwing away $50k-$200k accelerating cavities devices**

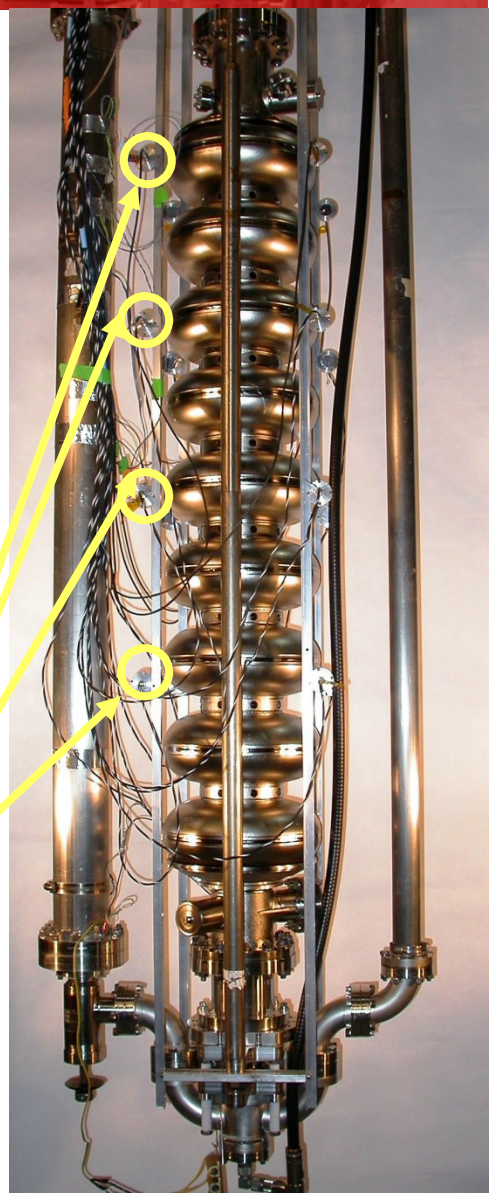
Quench-Spot Location

- **Thermometry**
  - Full temperature map of the cavity at various field levels
  - Required for a detailed understanding of the cavity performance
  - Requires thousands of precisely aligned and positioned transducers
  - Requires 2-3 cavity tests





- **Second Sound**
  - Requires a few transducers (e.g. 8)
  - Simple
  - Fast
  - Accurate
  - Only locates the quench-spot
  - Convenient for the rapid testing/repair of cavities



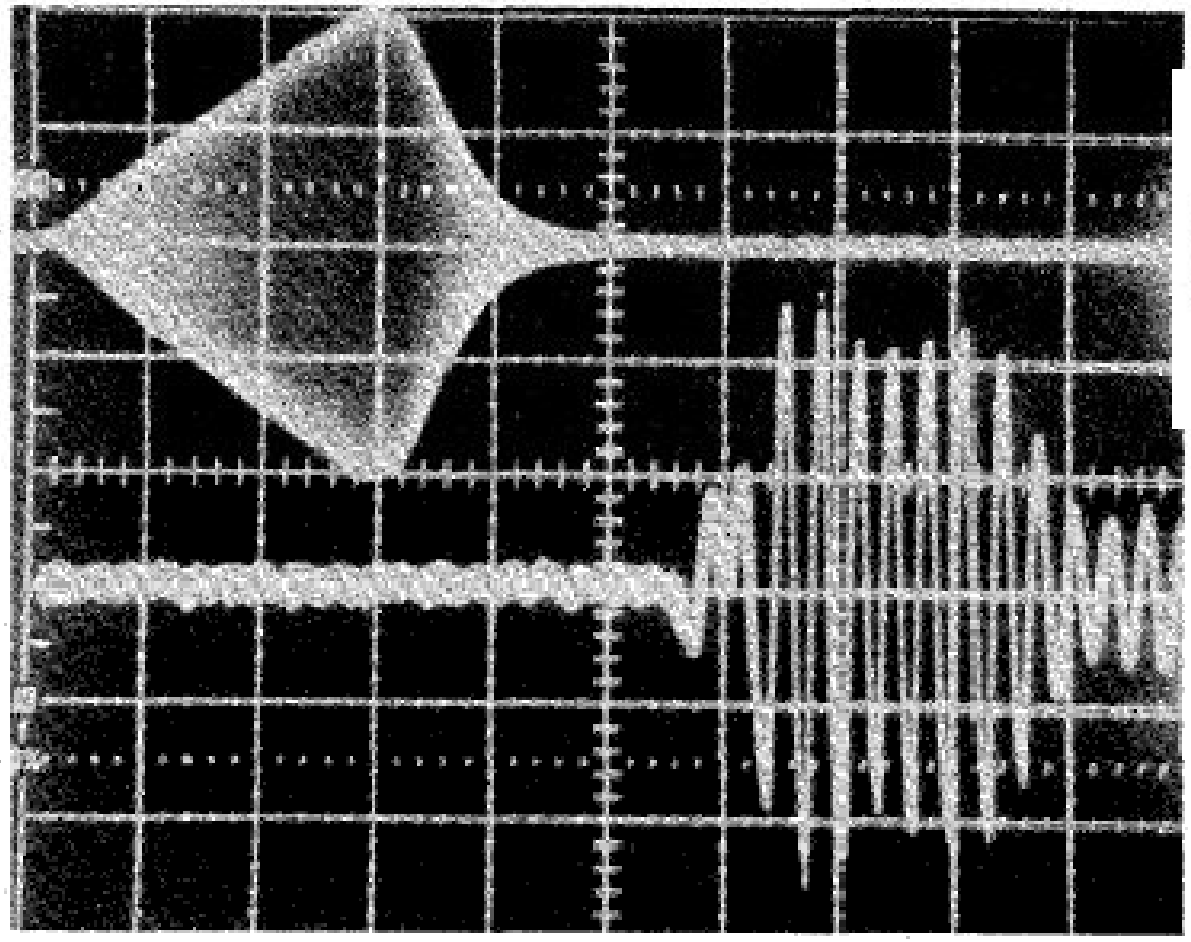
Outline

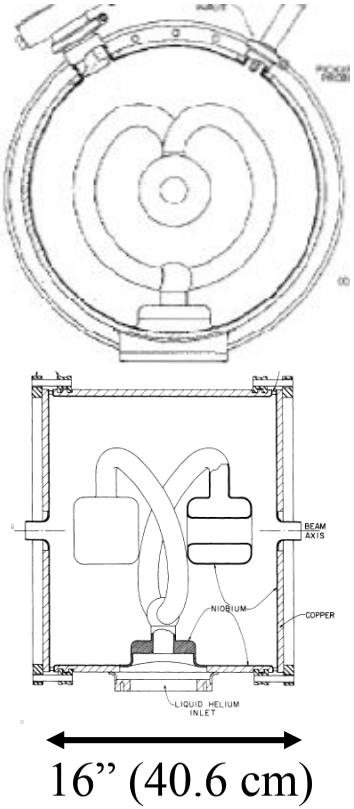
- Brief One Slide History
- Waves in Liquid Helium
- Elliptical-Cell Cavities
- Second Sound Quench-Spot Location
- Cornell Results
- Summary

A Brief History

Cavity Field

Second-Sound
Wave Detection



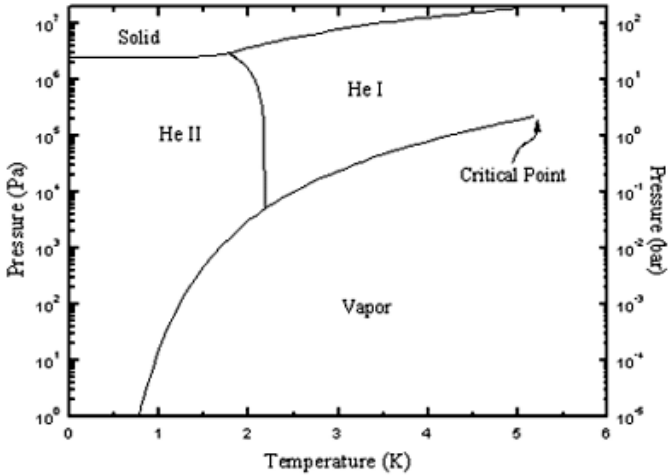


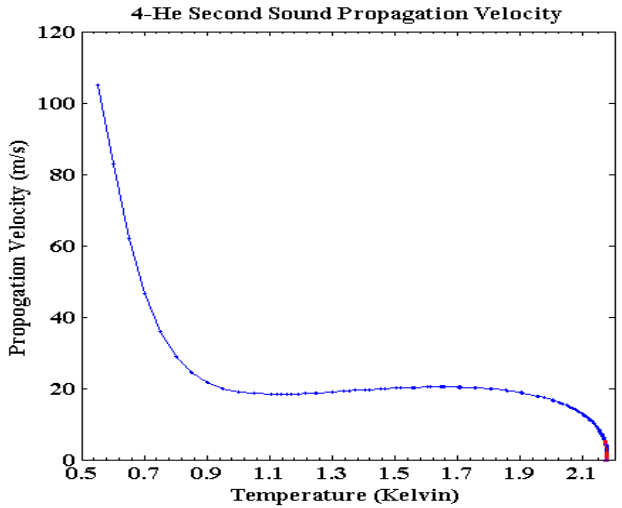
16” (40.6 cm)

1.9 K (v_s = 18.8 m/s), Vertical Scale = 10 ms/div

K.W. Shepard et. al, IEEE Trans. Mag, Vol. mag-15, No. 1, January 1979, Pg. 666

Properties of Liquid Helium





Russel J. Donnelly and Carlo F. Barenghi, "The Observed Properties of Liquid Helium at the Saturated Vapor Pressure." J. of Phys. Chem. Ref. Data, vol. 7, Issue 6, Pg. 1217 (1998).

- Wave Propagation in LHe
  - Normal P-ρ wave = 1st Sound, with velocity = ~ 220 m/s
  - Below the lambda point a T-S wave can propagate = 2nd Sound, with velocity = ~ 20 m/s
  - Superfluid ρ-T wave = 4th Sound, with velocity = ~ 200 m/s
- The detector response time can be around 0.1 msec which implies a spatial uncertainty of 2 to 4 mm if
  - The start time (initiation of cavity RF field collapse) can be determined to the same timing uncertainty
  - The arrival of the second sound wave at the detector can be determined to the same timing uncertainty

Second Sound Quench-Spot Location

- Simple defect localization schemes can be implemented by exploiting the properties of superfluid He, e.g. second sound waves.
- When a cavity quenches, typically several joules of thermal energy are transferred to the helium bath in a few milliseconds.
- If the cavity is operated at $T < 2.17$ K, the helium bath is a superfluid and a second-sound wave propagates away from the heated region of the cavity.
- By locating several transducers in the helium bath around the cavity, the second sound wave front can be observed. The time of arrival of the second sound wave at a given transducer is determined by the time of flight from the heated region, which is centered on the defect causing quench.
- Measuring the time of flight to 3 or more uniquely located transducers, unambiguously determines the defect location.

Next Topics

- Quench-Spot Location
  - Why second-sound?
  - How does it work?
- A complete example of how we find, visually identify, and repair a second sound located defect.
- The nature of cavity quench and its relation to second sound triangulation. We are still learning.

Second Sound Detectors

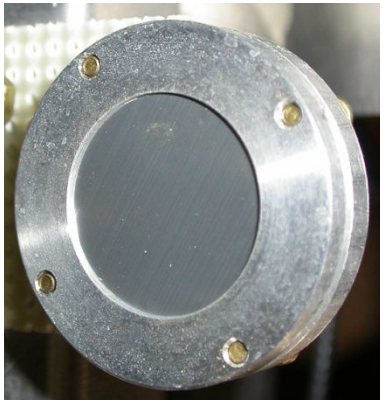
- Second sound waves are temperature/entropy waves

- Any resistor with a large temperature coefficient between 1.6 and 2.1 K can be used to measure the temperature variation
  - Germanium (ANL, Ken Shepard previous slide and M. Kelly TUPPO032 @ SRF 2009)
  - Cernox (NHMFL @ FSU)
  - Graphite (NHMFL @ FSU, Cornell)

- Oscillating Superleak Transducers (OST)
  - Sense only second sound
  - Provide a much more sensitive and selective detector in noisy environments (see R.A. Sherlock and D.O. Edwards, "Oscillating Superleak Second Sound Transducers," Rev. Sci. Instrum. 41, Pg. 1603 (1970).
  - OST operation is analogous to a Helmholtz resonator.

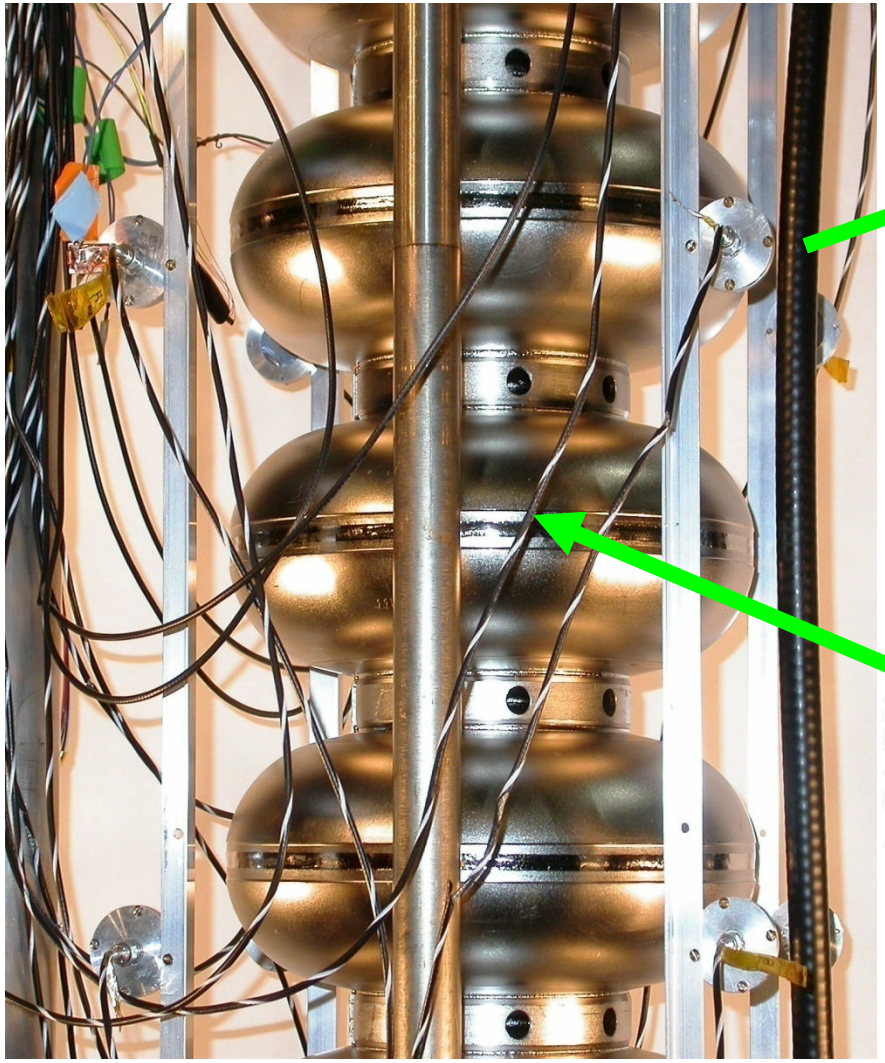
RTD

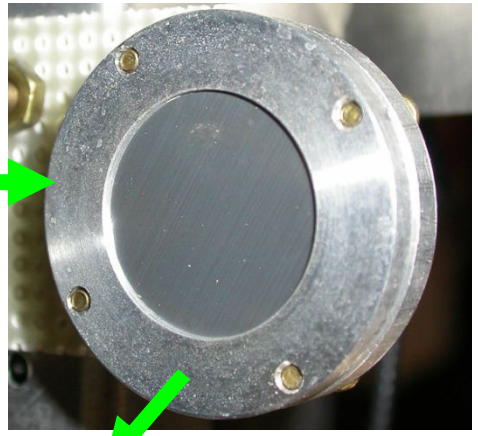
0.39" (1mm)

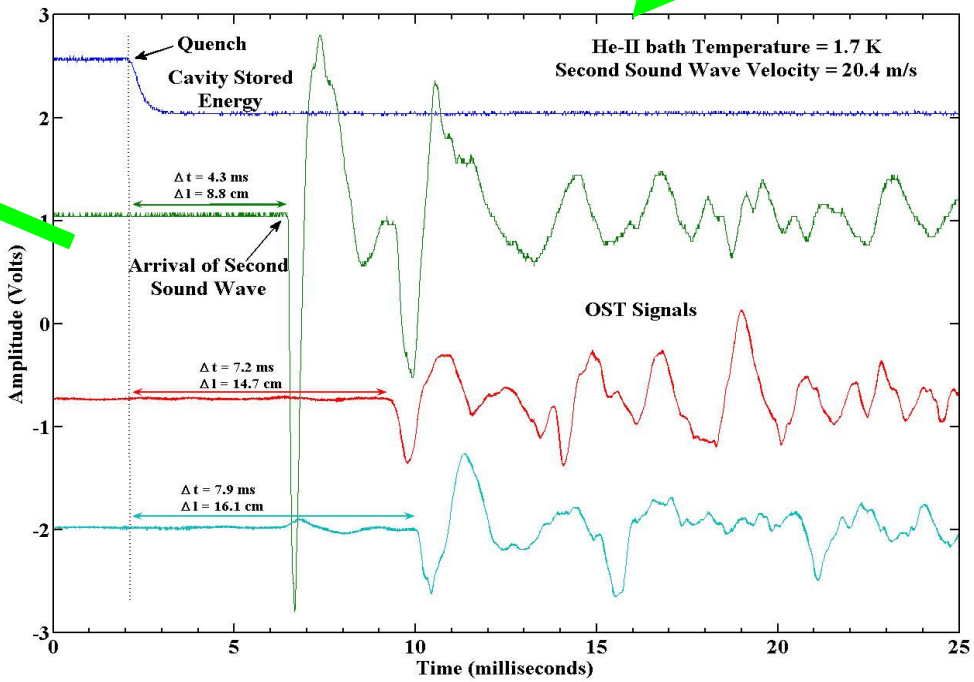


1" (2.5 cm)
(smaller version
in development)

How to Find The Quench Location





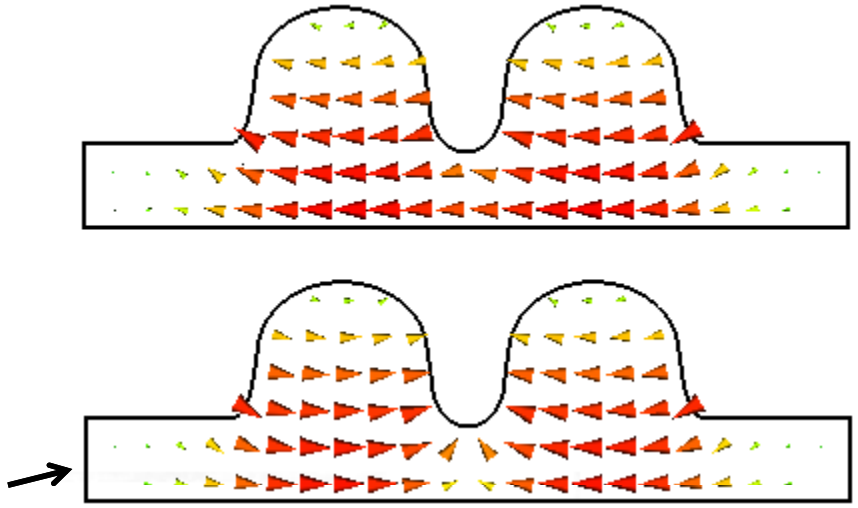


Results Overview

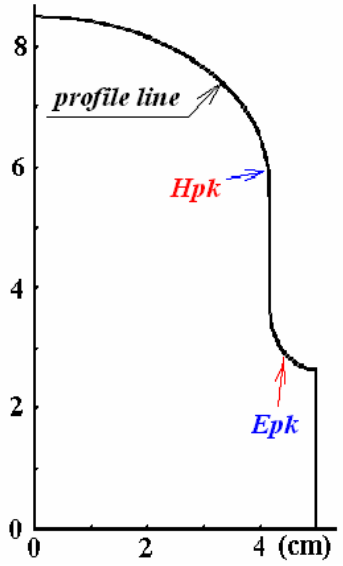
- First successful results with OSTs, reentrant 9-elliptical-cell cavity defect location and repair
- Further development work
  - More temperature-maps and examples…
  - Defect location and repair examples
  - Multi-mode excitation to find multiple quench locations works
  - More on the fundamentals of second sound quench location
- Then I will make a few closing comments

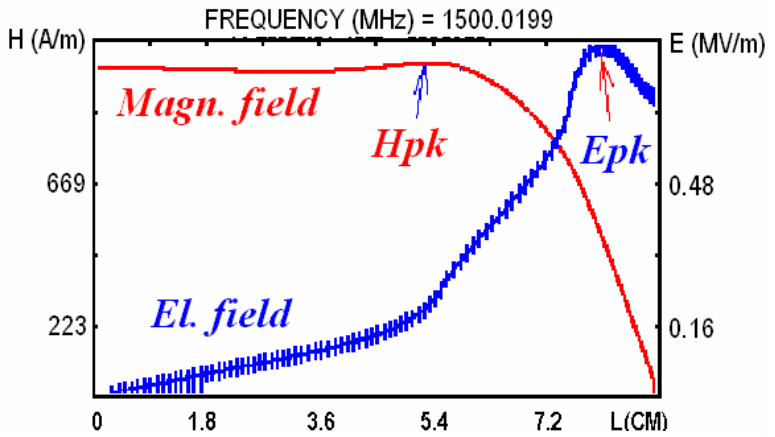
Elliptical Cell Cavities

- **In This Presentation**
  - All cavities tested are designed for particles traveling at approximately the velocity of light, $\beta = 1$.
  - All of the cavities have an elliptical cross section, and are referred to as elliptical-cell cavities.



- **Cavity Fields**
  - The surface magnetic field is concentrated by the equator weld
  - The surface electric field is concentrated at the iris
  - Cavity heating is concentrated by the equators

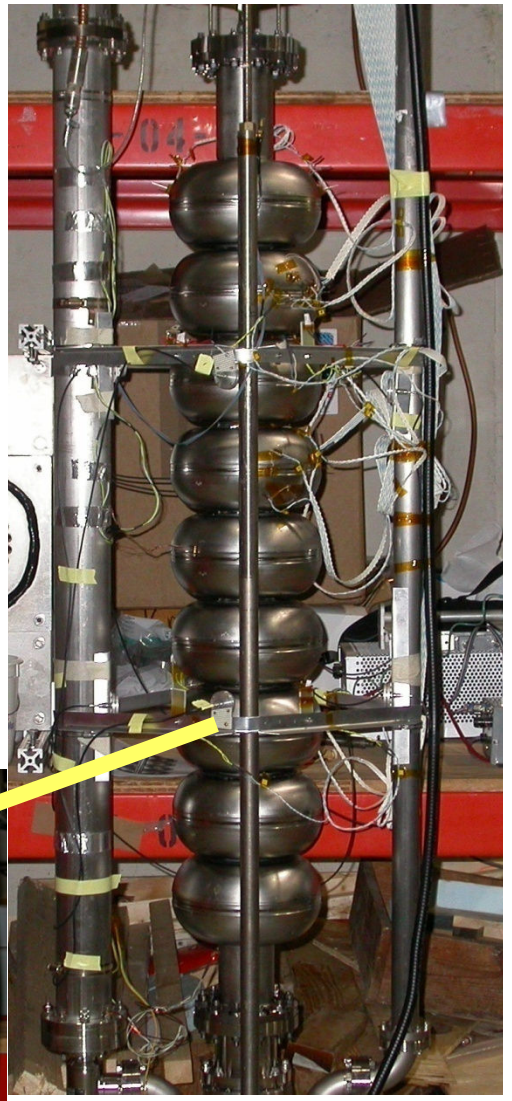


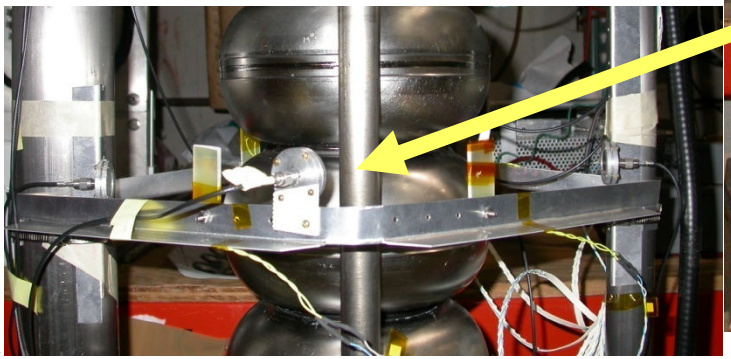


Figures Courtesy of Sergey Belomestnykh and Valery Shemelin

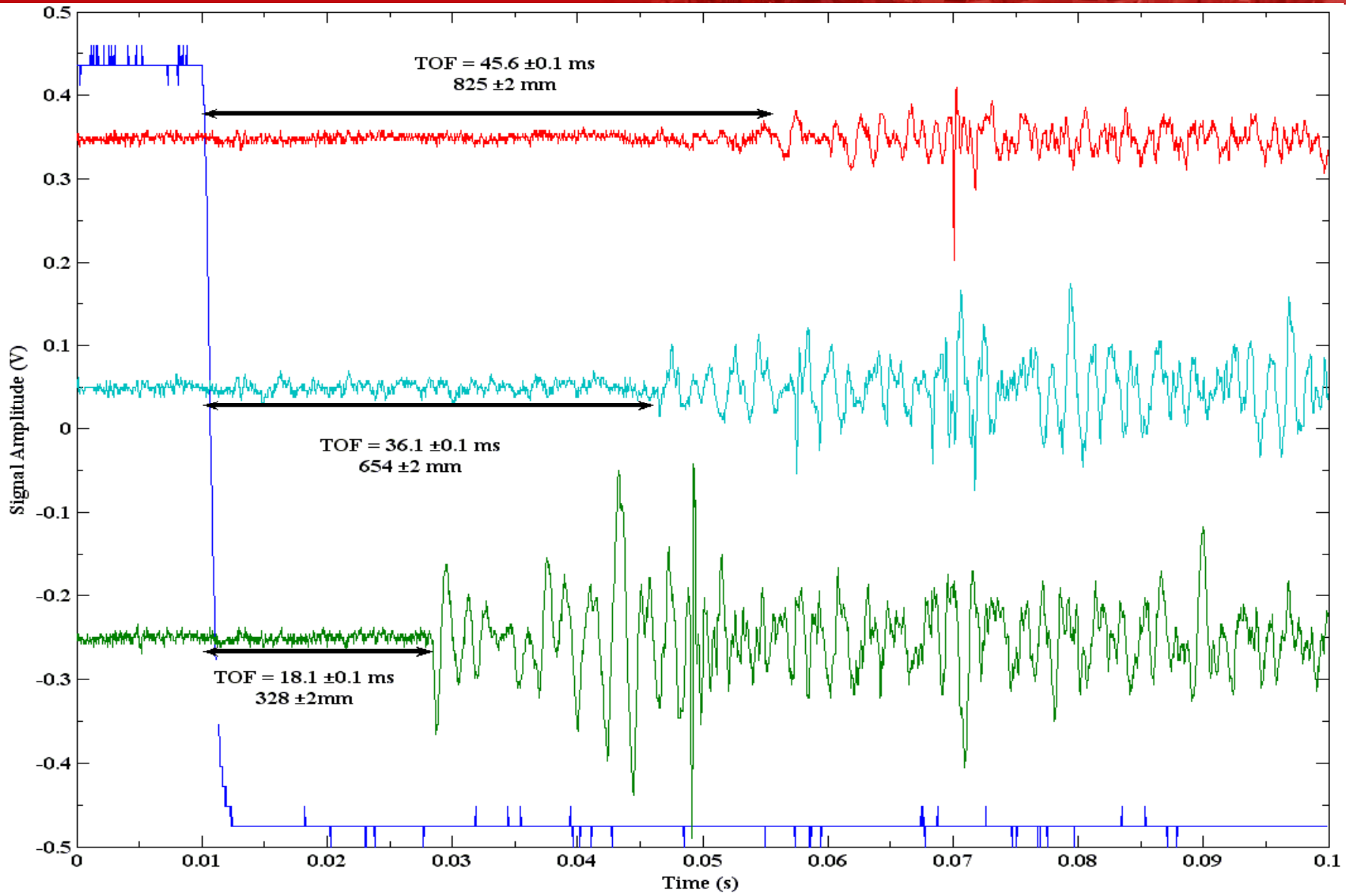
AES 9-Cell Cavity Defect Location

- To locate the defect limiting the performance of the AES reentrant 9-cell cavity we used 8 OSTs.
- During cool-down the sensor closest to the quench location shorted to ground.
- This cavity was tested at 2.05K, where the velocity of second sound is strongly temperature dependent.
- We found that the signals did not converge on a single point but all came within ~1” of a central point.
- We used the second sound velocity as a free parameter to find the point where the signals converged

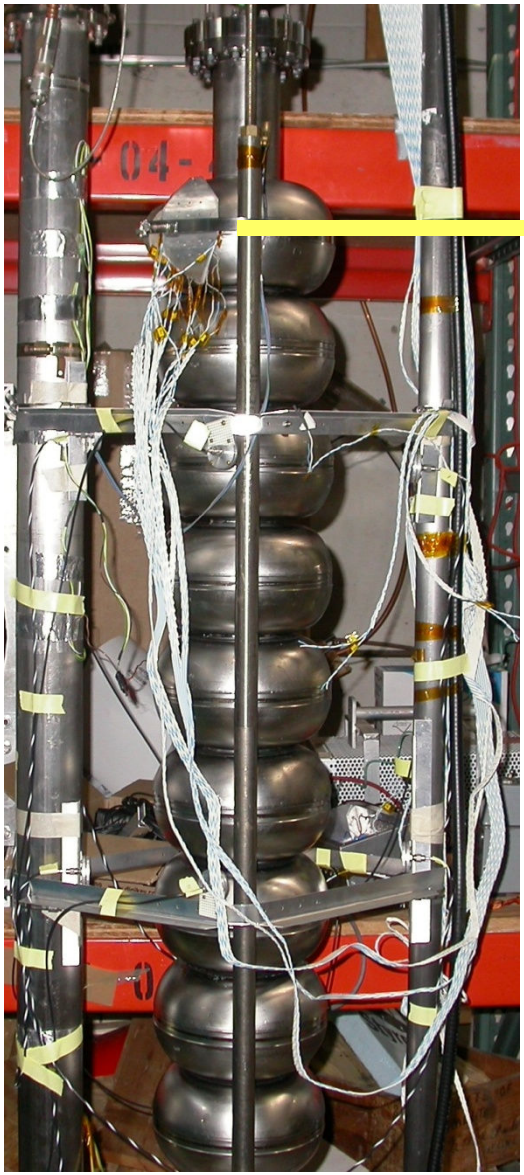


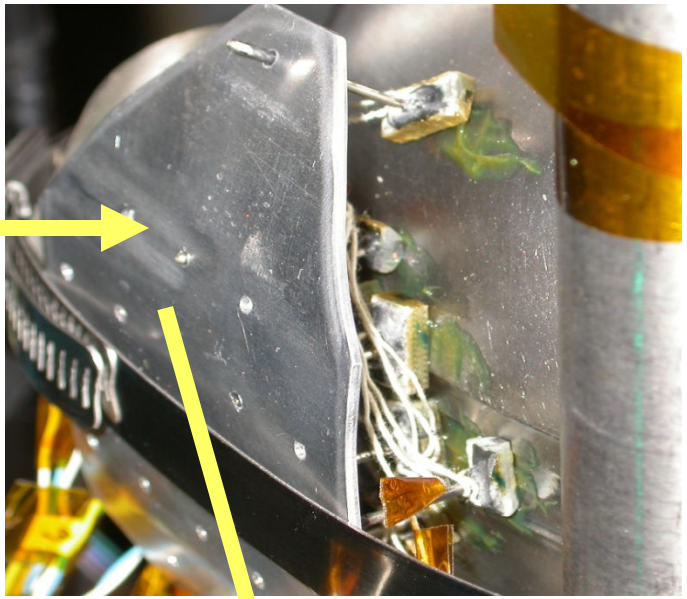


AES 9-Cell Cavity Defect Location

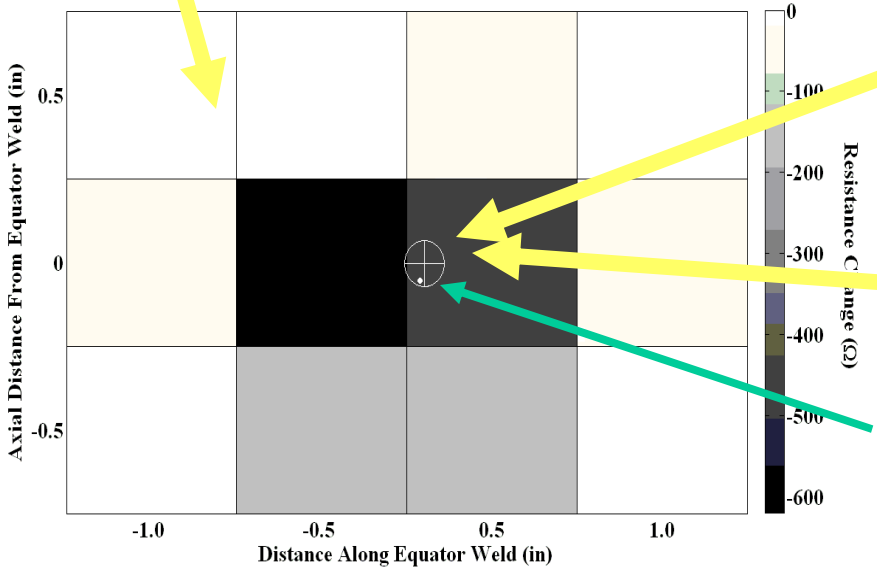


Results Making Sure This Works





Comparison of fixed thermometer heating, 2nd sound location and Optical location. Defect heating is about 50 mK at 8 MV/m



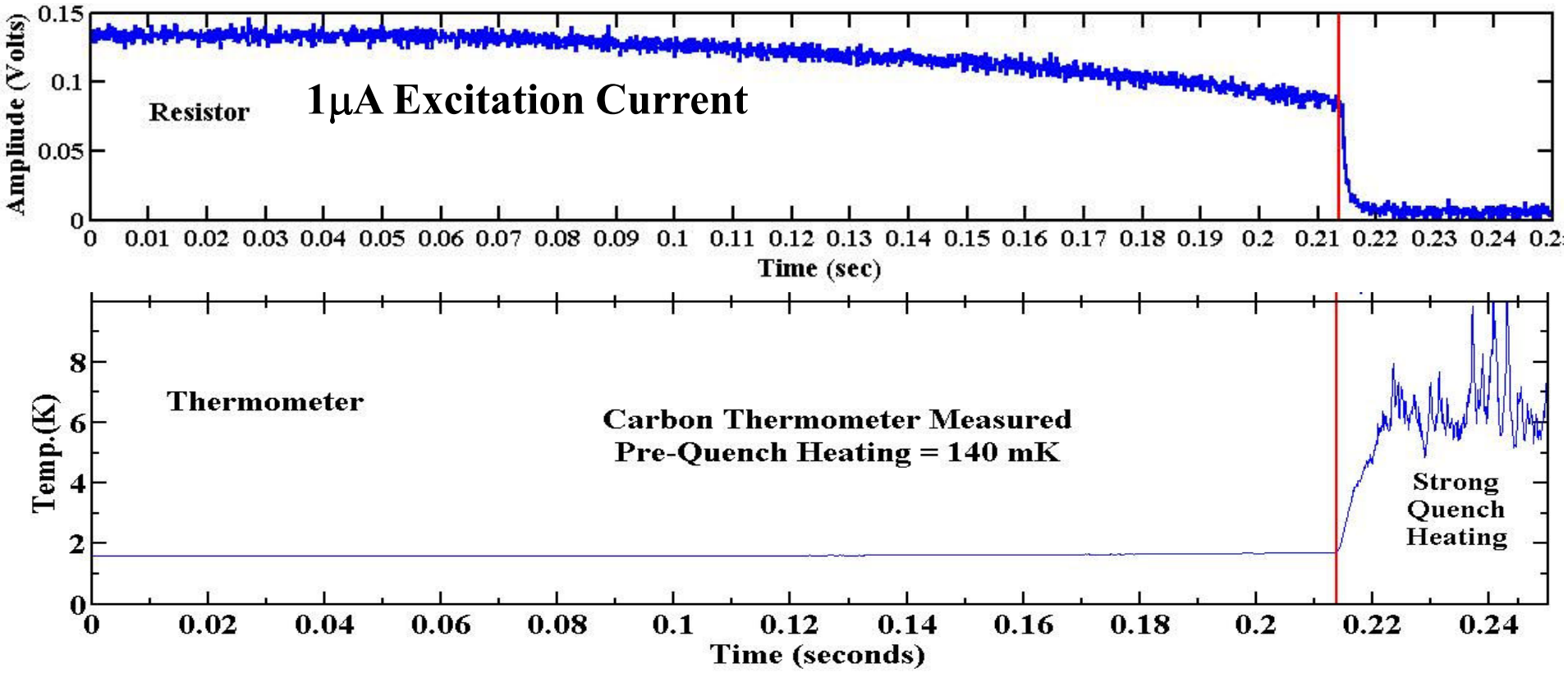
2nd Sound Defect Location

3mm radius circle around 2nd sound result

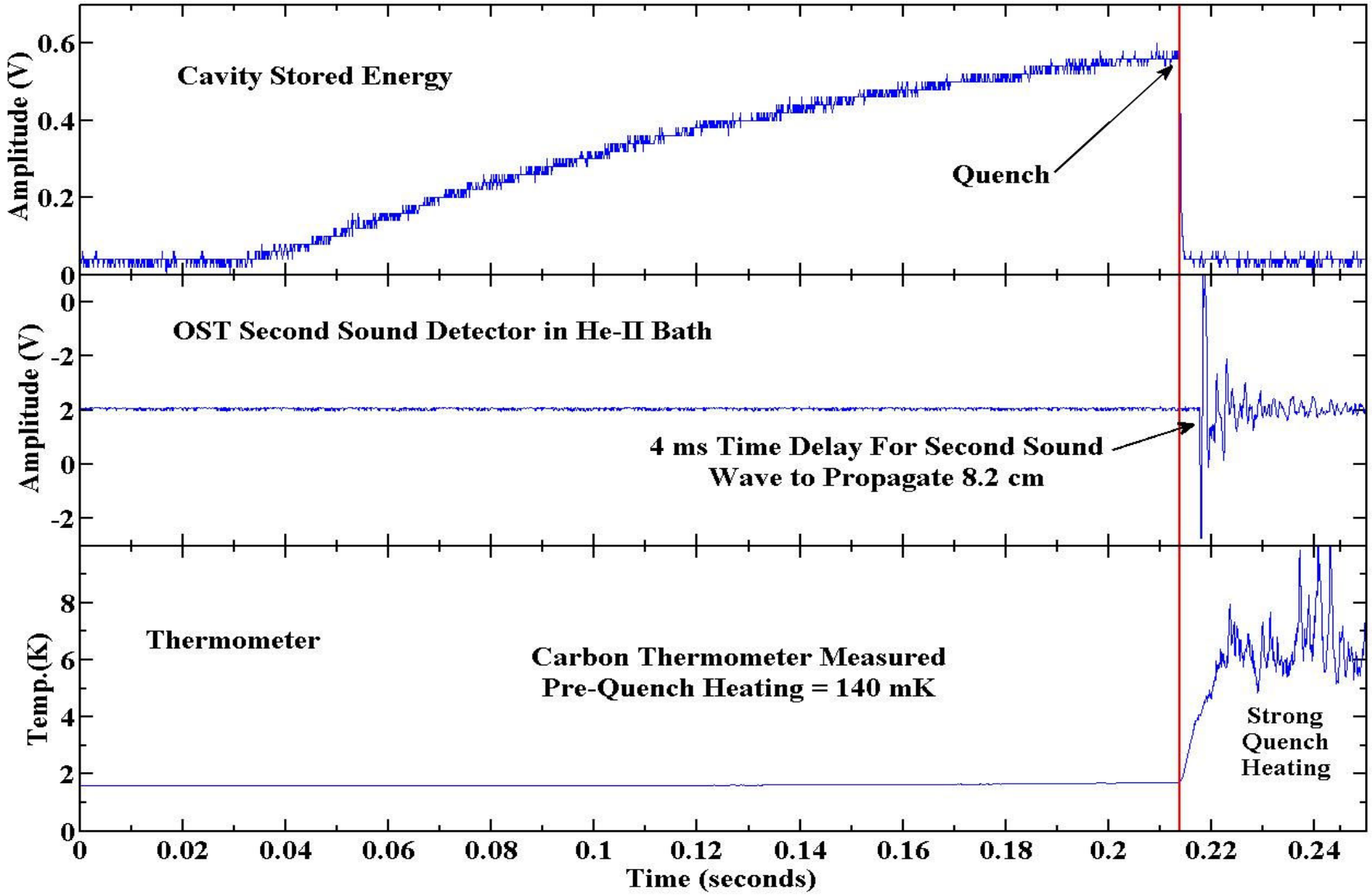
Optically Located Defect

Results Making Sure This Works

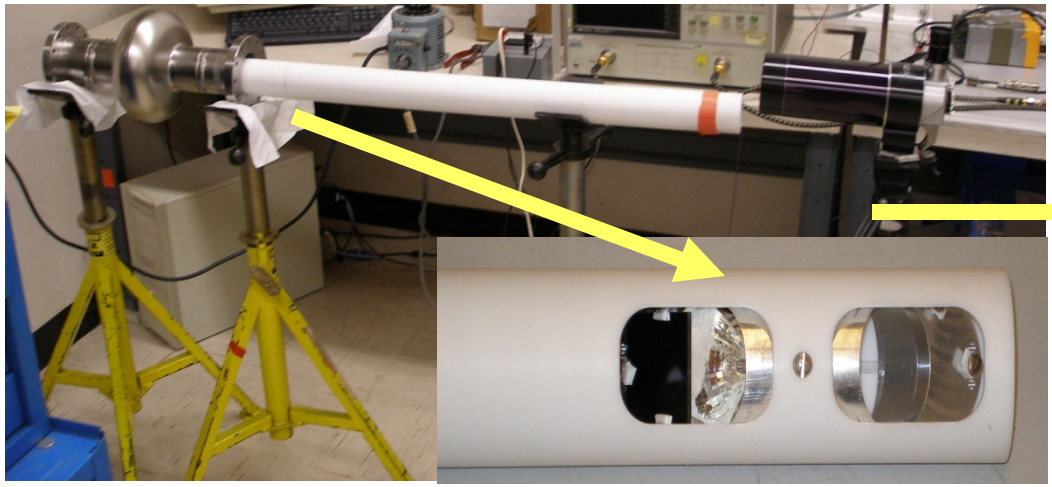
- How the thermometry works
  - Temperature Calibrated Resistor
  - Excite the resistor with a constant current and measure the dynamic voltage.
- The top figure is the data and the lower figure is the temperature

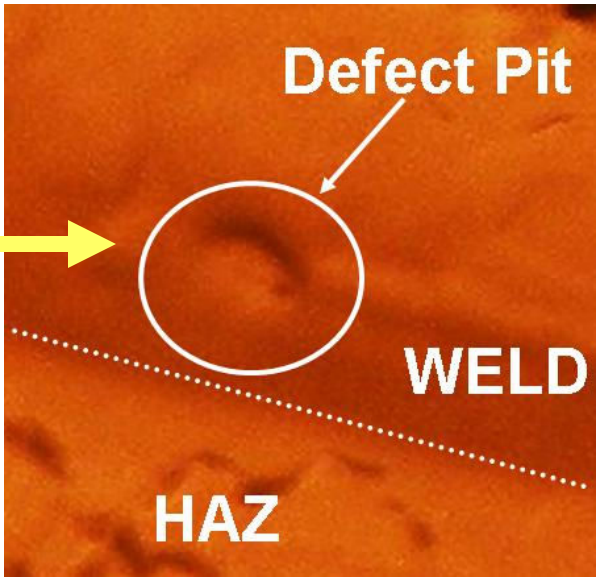


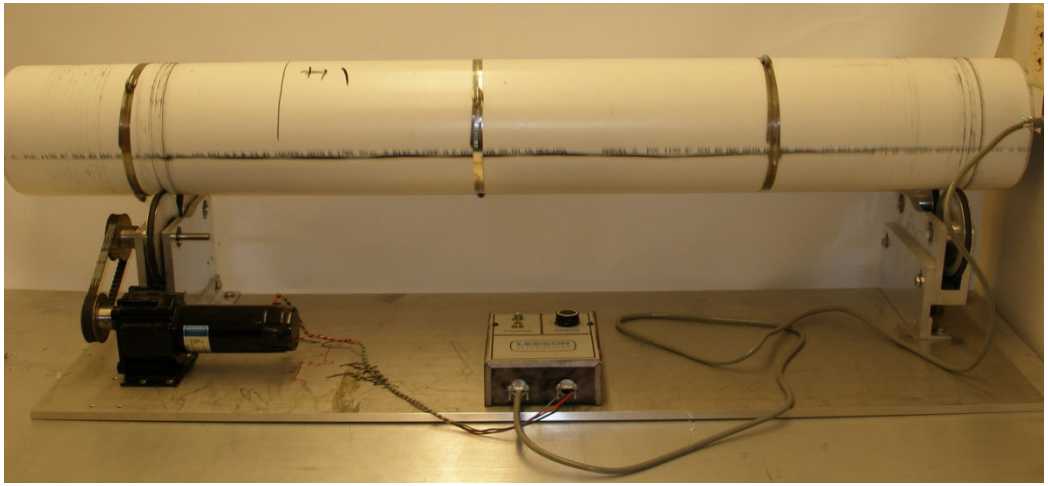
Niowave/Roark



AES Fabricated 9-Cell Cavity Weld Pits Repaired

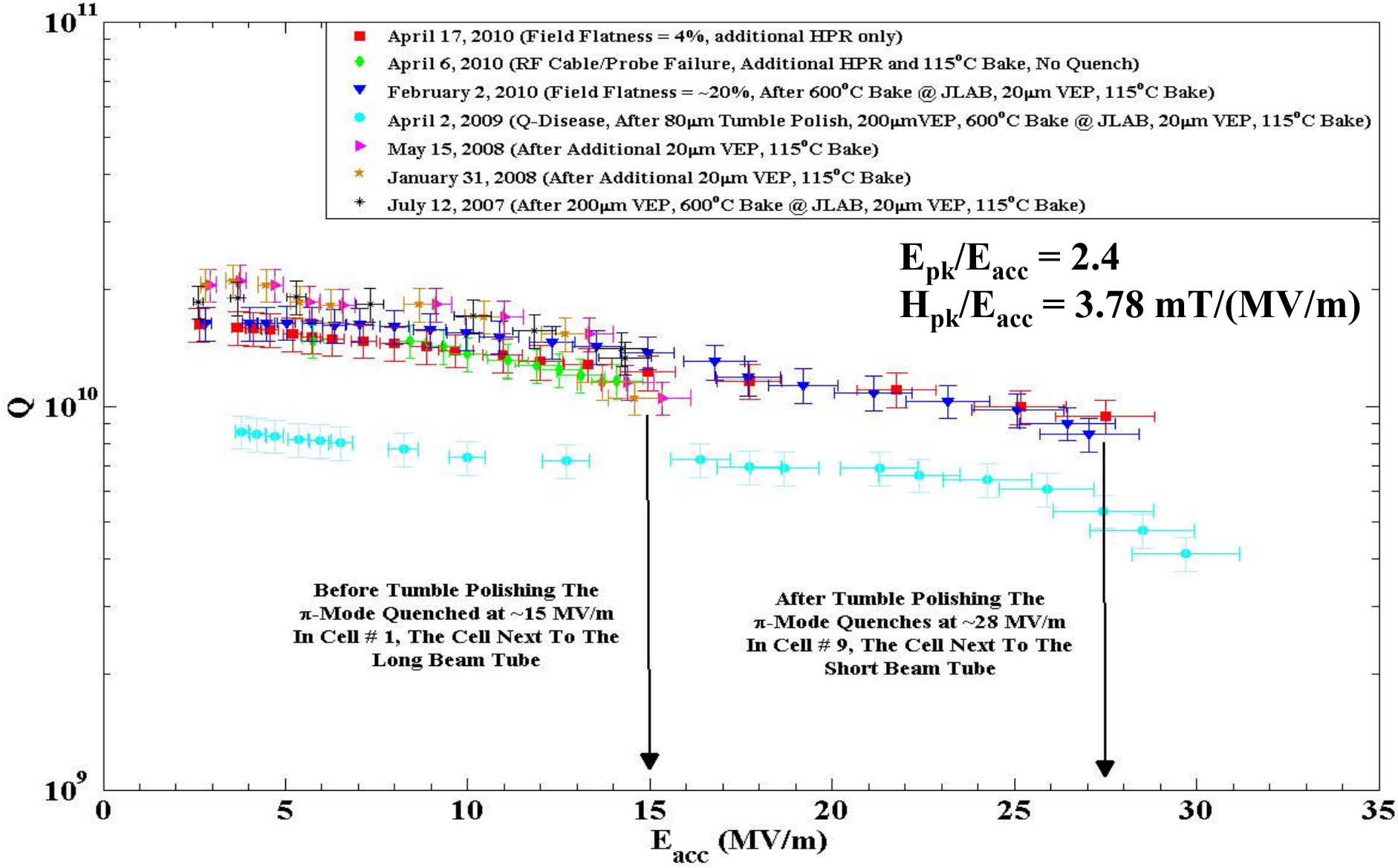




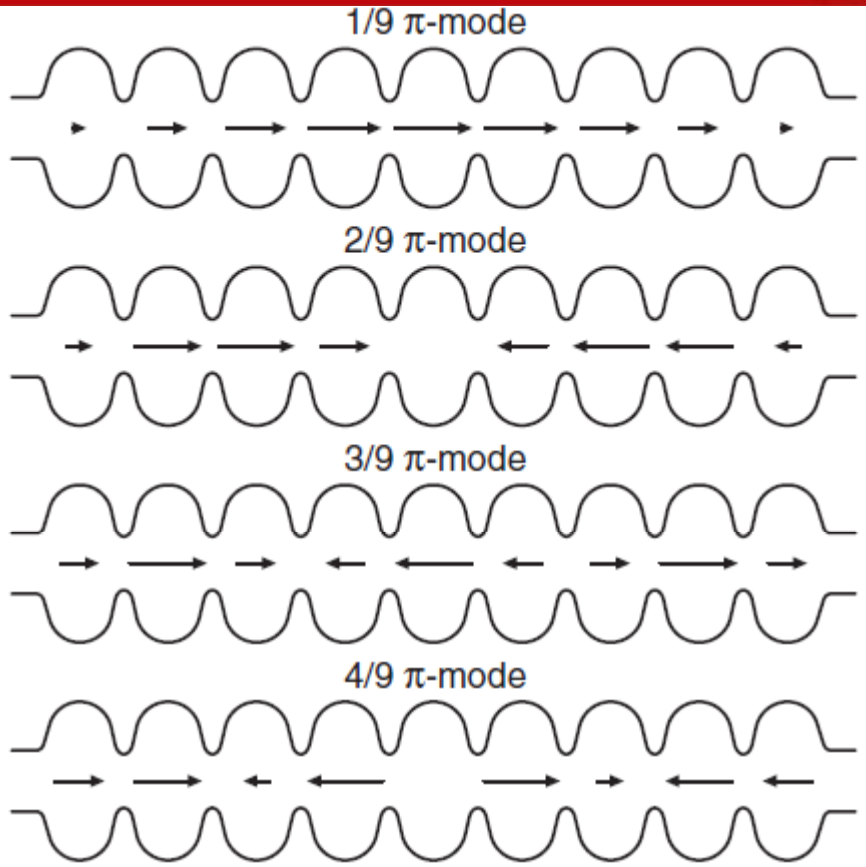


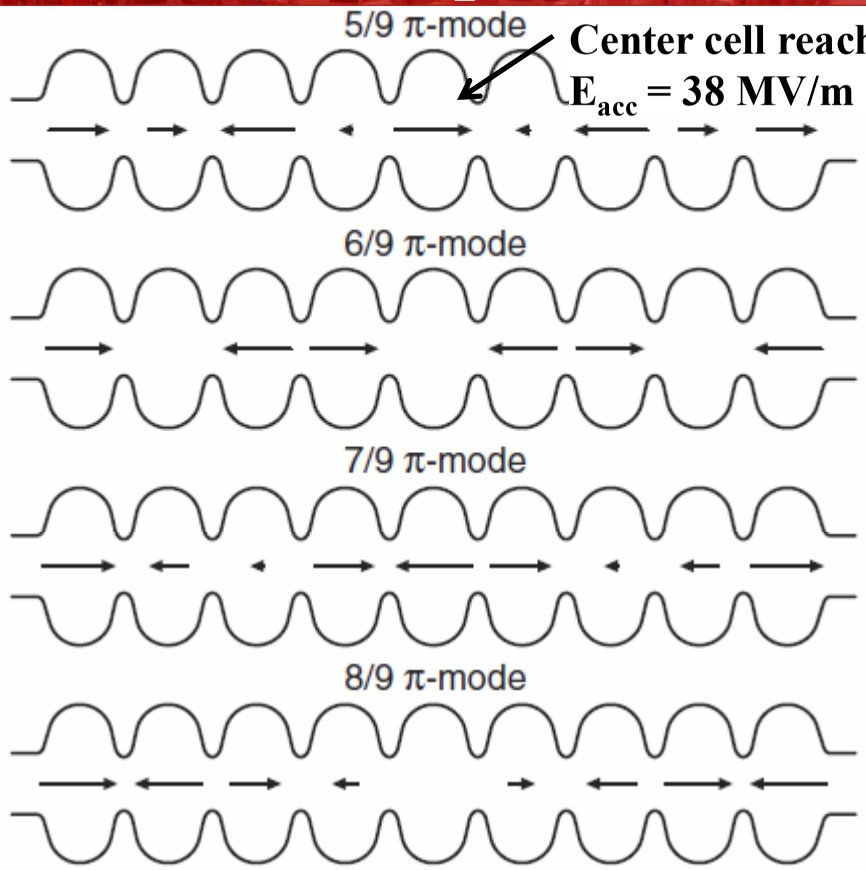
Tumbling media residue removed with HPR

Test Results

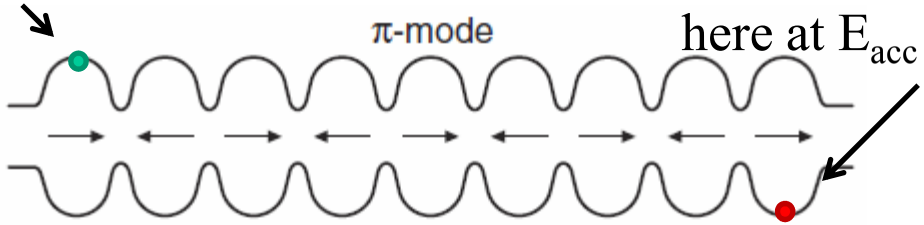


AES Fabricated 9-Cell Cavity Weld Pits Repaired





Initially the cavity quenched here at E_{acc} ~ 15 MV/m, tumble polishing improved this to E_{acc} ~ 30 MV/m.



Now the quench-spot is here at E_{acc} ~ 28 MV/m.

AES Fabricated 9-Cell Cavity Weld Pits Repaired

- **This cavity originally quenched at E_{acc} = 15 MV/m (60 mT, 35 MV/m is the goal) in the accelerating mode at a weld pit in cell #1.**
- **After tumbling and reprocessing the π-mode E_{acc} = 28 MV/m (100 mT). The measurement was limited by the available RF power the cavity did not quench.**
- **When excited in a different eigenmode (the 5π/9-mode) peak fields of 89 MV/m and 140 mT were reached in the center cell. This corresponds to E_{acc} = 37 MV/m in the center cell.**
- **These tests demonstrated that tumbling is an effective repair option for pits.**
- **Similar procedures are now routine at Cornell to improve cavity performance, single- and five-cell cavities have reached E_{acc} > 35 MV/m.**

Further Development Work

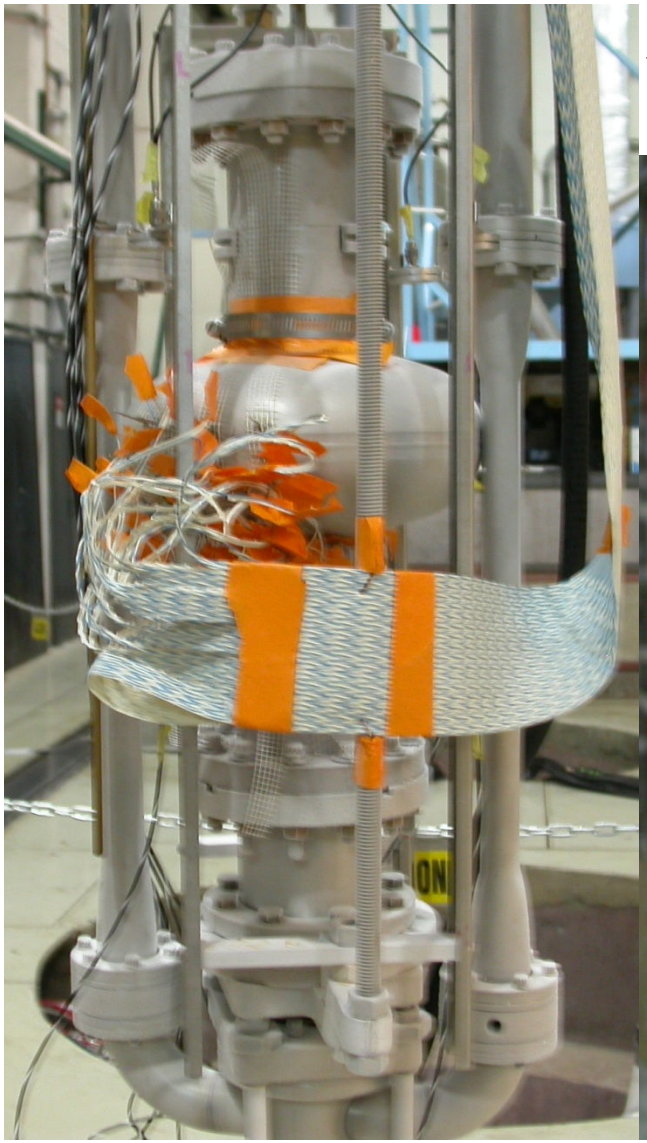
- Niowave/Roark Single-Elliptical-Cell Cavities
  - Defects found and repaired
  - Repair example

- Pulsed Reentrant-Single-Elliptical-Cell Cavity Tests
  - Fundamentals of Second Sound Location
  - Second sound waves only propagate if the energy density does not exceed ~1 W/cm^2
  - How second sound location converges on a point (almost, aka circle of confusion (~1" radius) is now the circle of understanding)

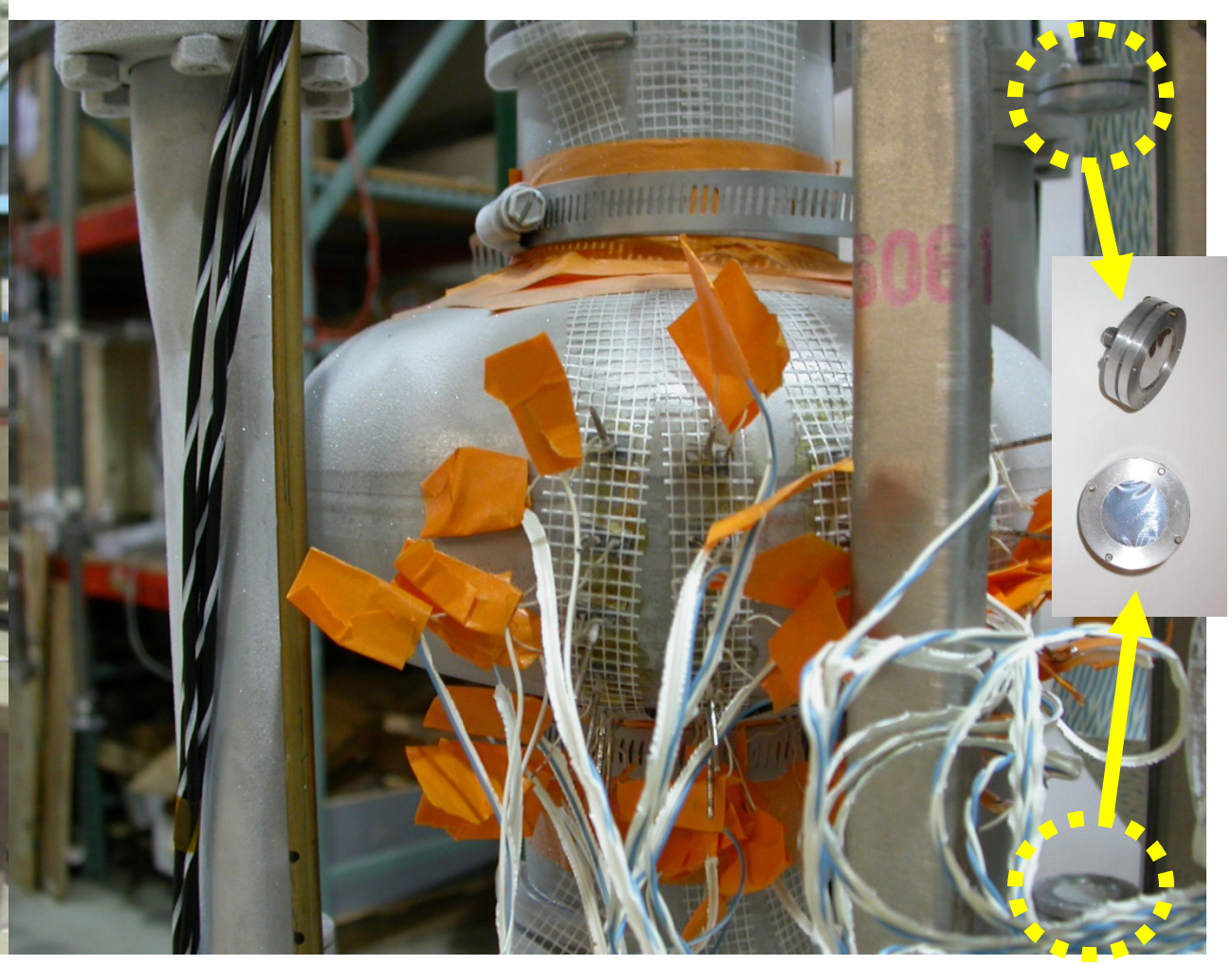
Niowave/Roark

- Cornell and FNAL collaborated on the pre-qualification of a new ILC cavity vendor: a collaboration of Niowave (Lansing, MI) and C.F. Roark Welding & Engineering Company (Brownsburg, IN)
- Niowave/Roark fabricated 6 single-cell TESLA-style cavities which were BCP treated and tested at 2 K to determine if the cavities were limited to quench fields below 25 MV/m by surface defects
- This was very useful in refining and confirming the usefulness of the 2nd sound diagnostic technique
- Initially the cavities were quenching at E_{acc} = 15 MV/m (60 mT)

Niowave/Roark

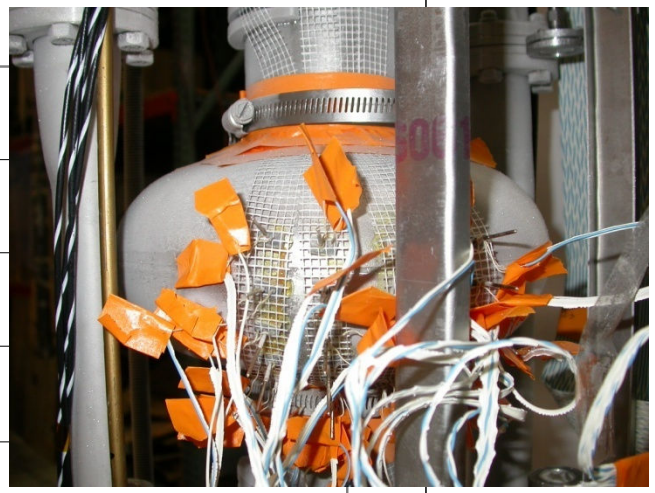


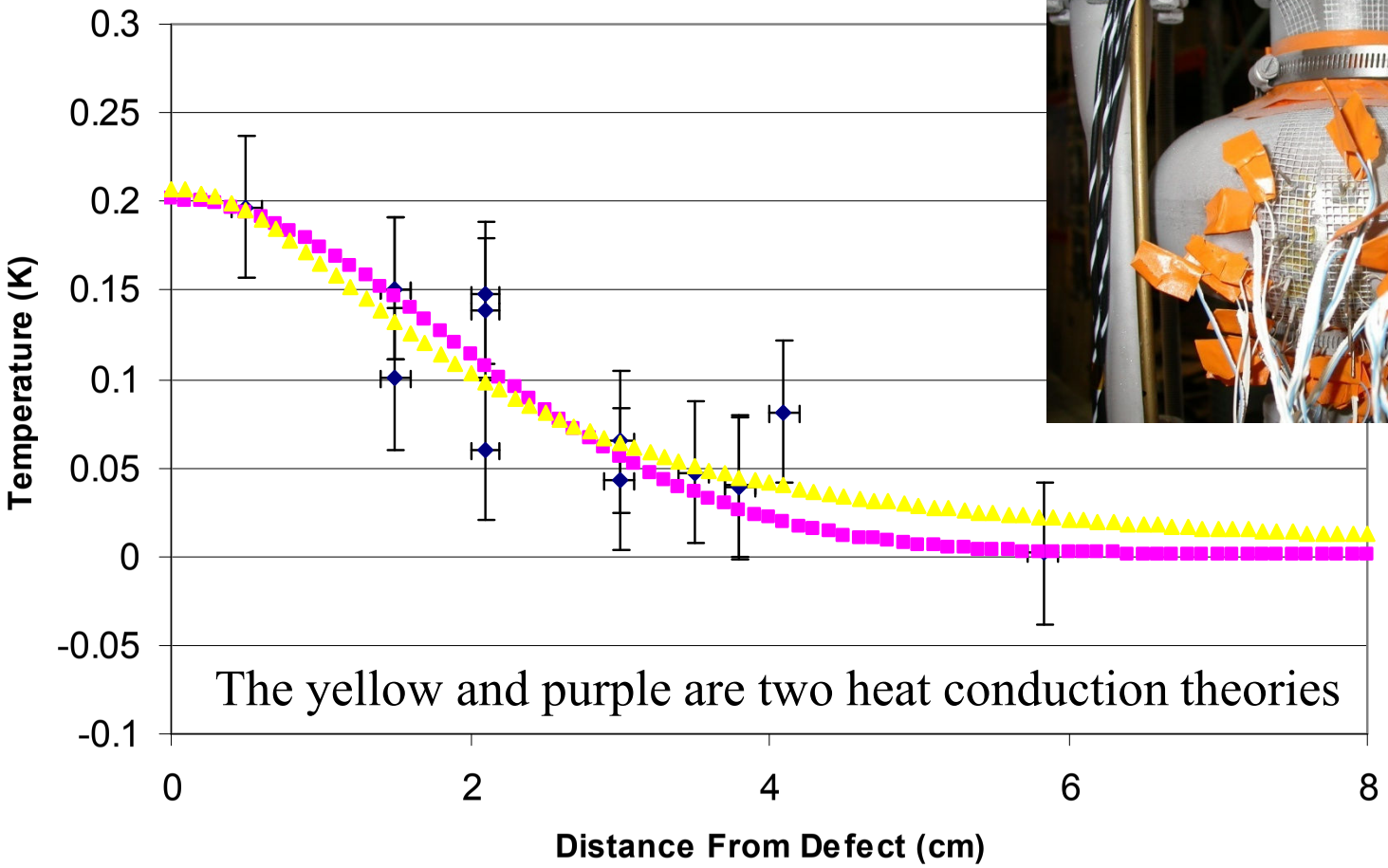
Niowave #3 with OSTs and a thermometer array



Niowave/Roark

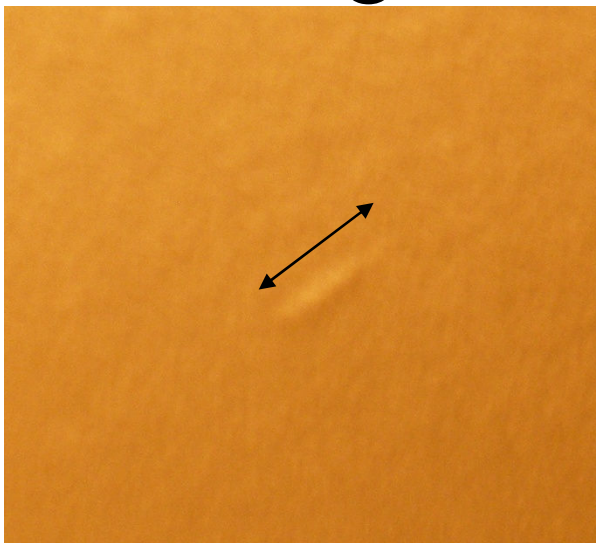
Heating Measured Just Before Quench ($E_{acc} = E_{quench} - 1$ MV/m)



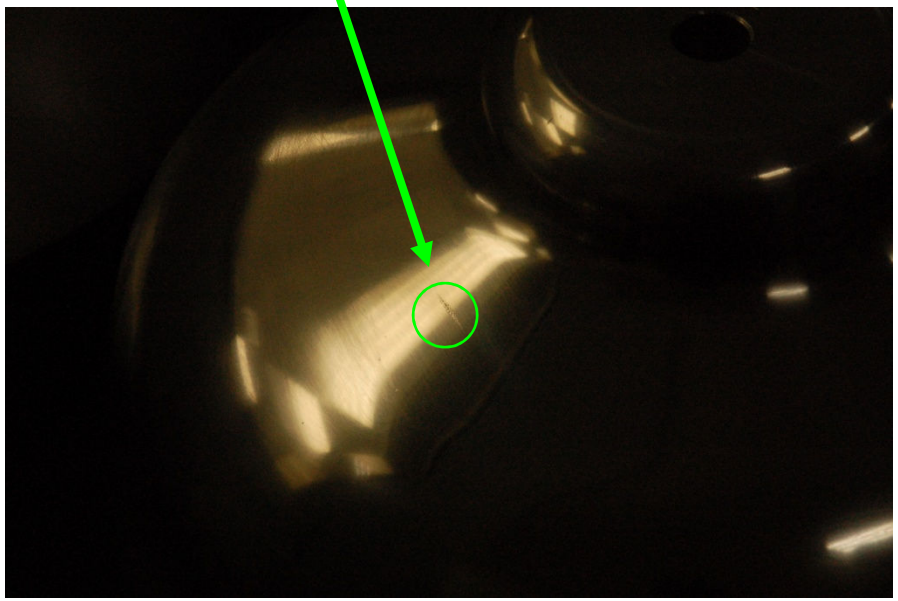


Niowave/Roark

~2mm Long Defect



Chip in Male Die

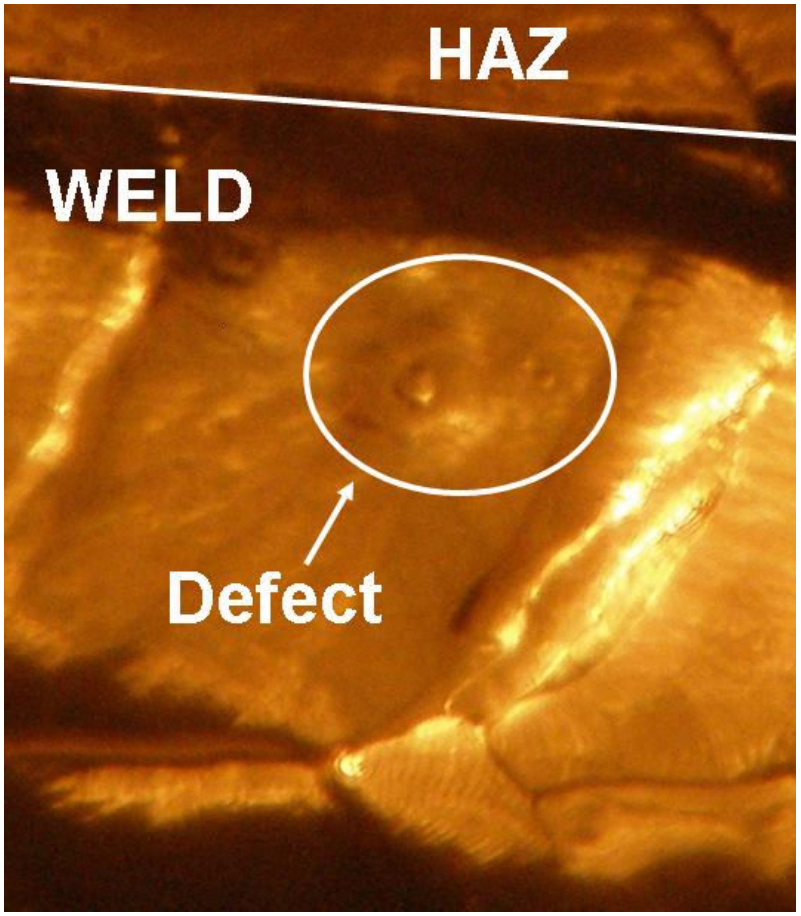


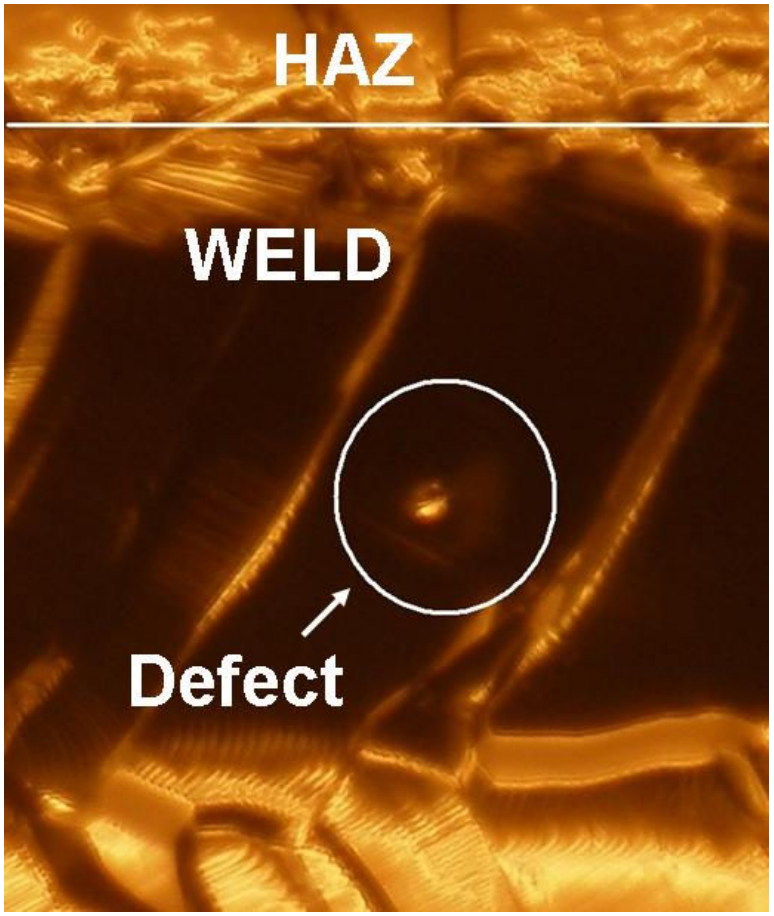
Right-hand picture courtesy of Charles Reece (JLAB)

and Genfa Wu (FNAL)

Niowave/Roark

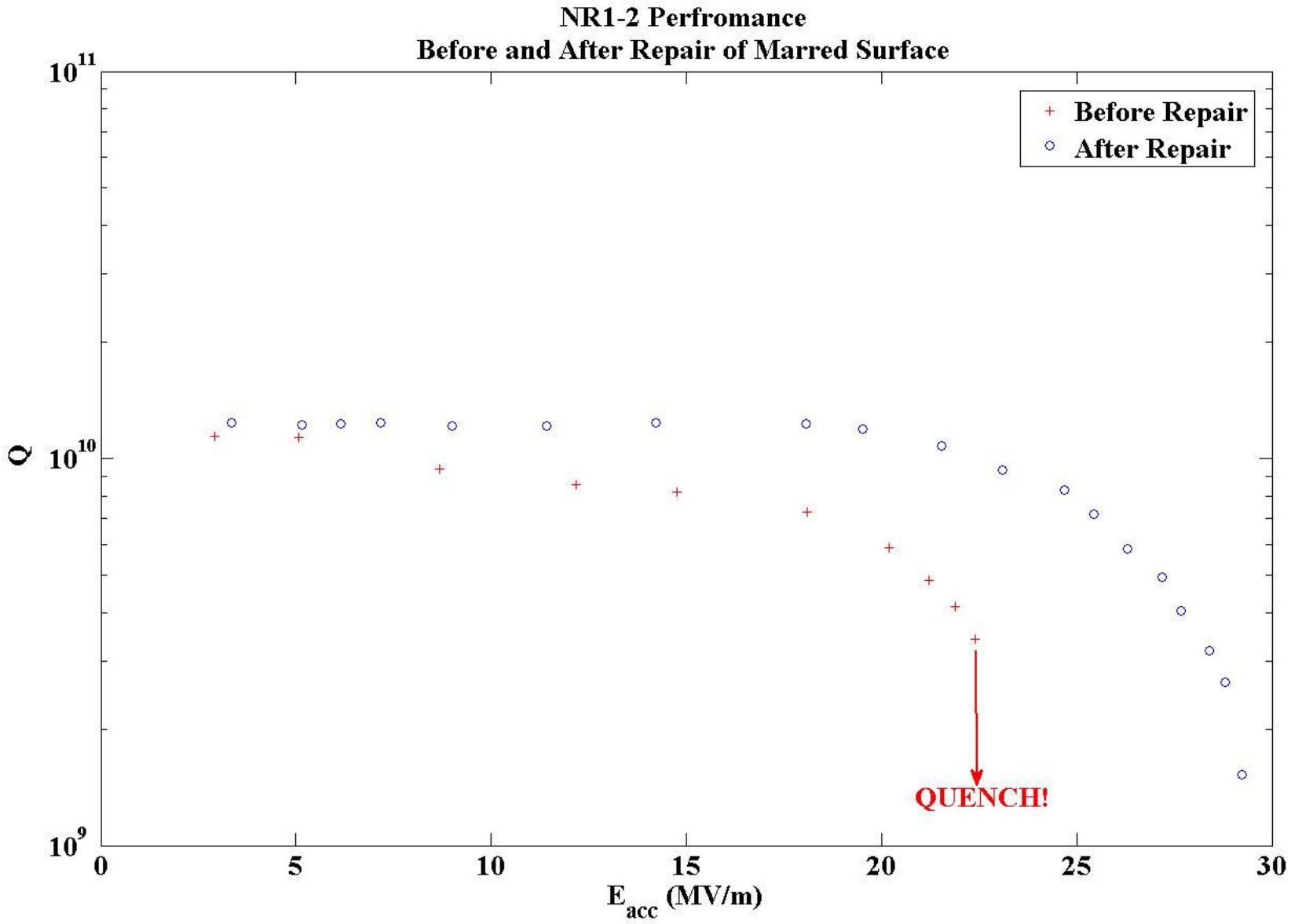
- After the bump/die problem was fixed we found more quench locations at higher fields, 20 MV/m < E_{acc} < 30 MV/m





Artifact of BCP etch of weld, R.L. Geng, SRF99, TUP021

Niowave/Roark



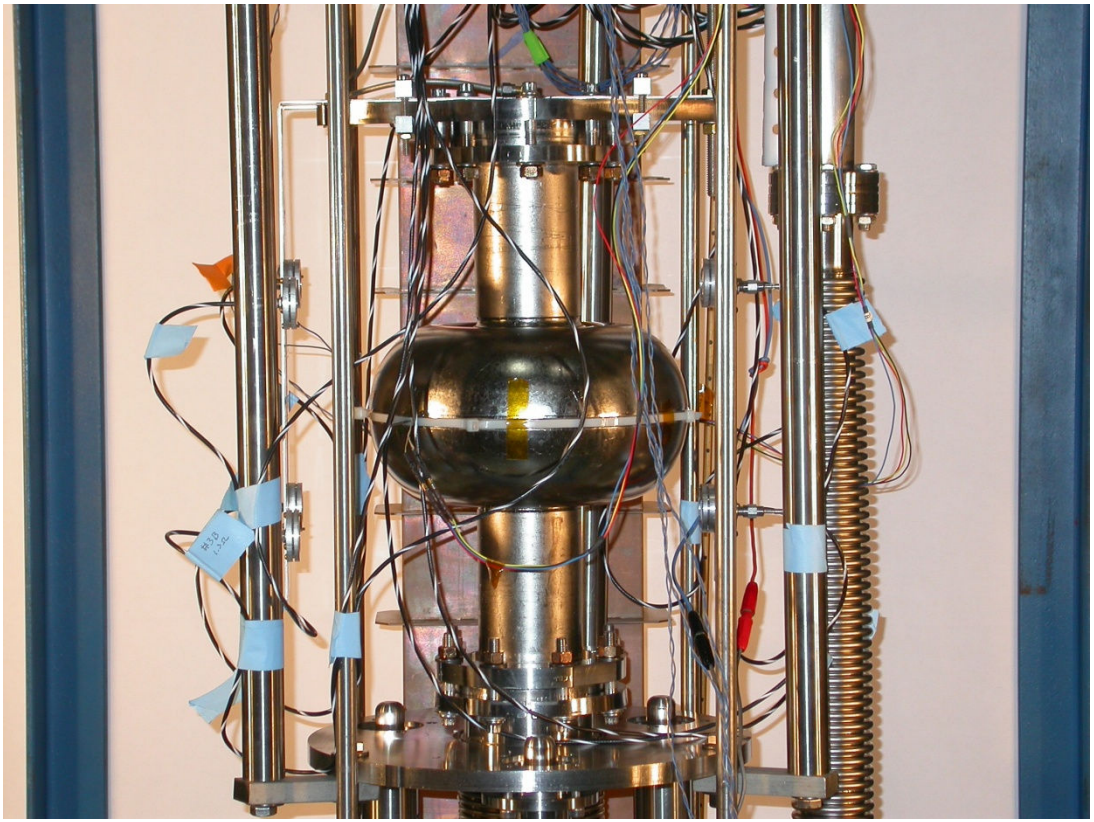
Pulsed Single Cell Results

- Prior to the pulsed measurements we had a "circle of confusion"
  - Are we observing pre-heating?
  - Are we observing thermal transport in the bulk Niobium?
  - Are we observing first/second sound wave coupling?
  - Were we confused? YES

- We tried rapidly exciting/quenching the cavity in 100-200μs to:
  - See if pre-quench heating was generating the detected second-sound wave front.
  - See if anything else was going on.

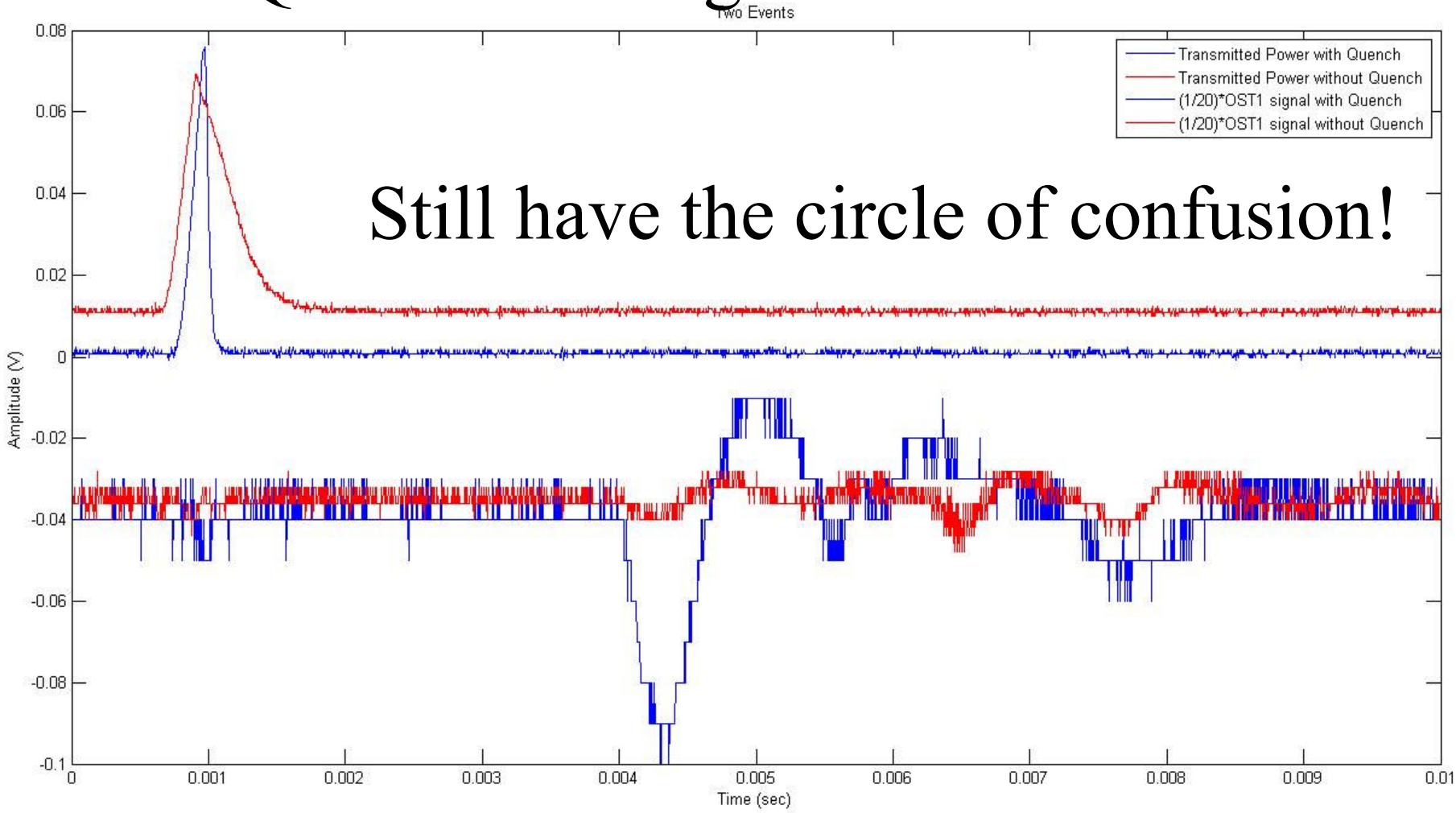
Pulsed Single Cell Measurements

Reentrant Cavity with OSTs on the Klystron Test Stand



Pulsed Single Cell Results

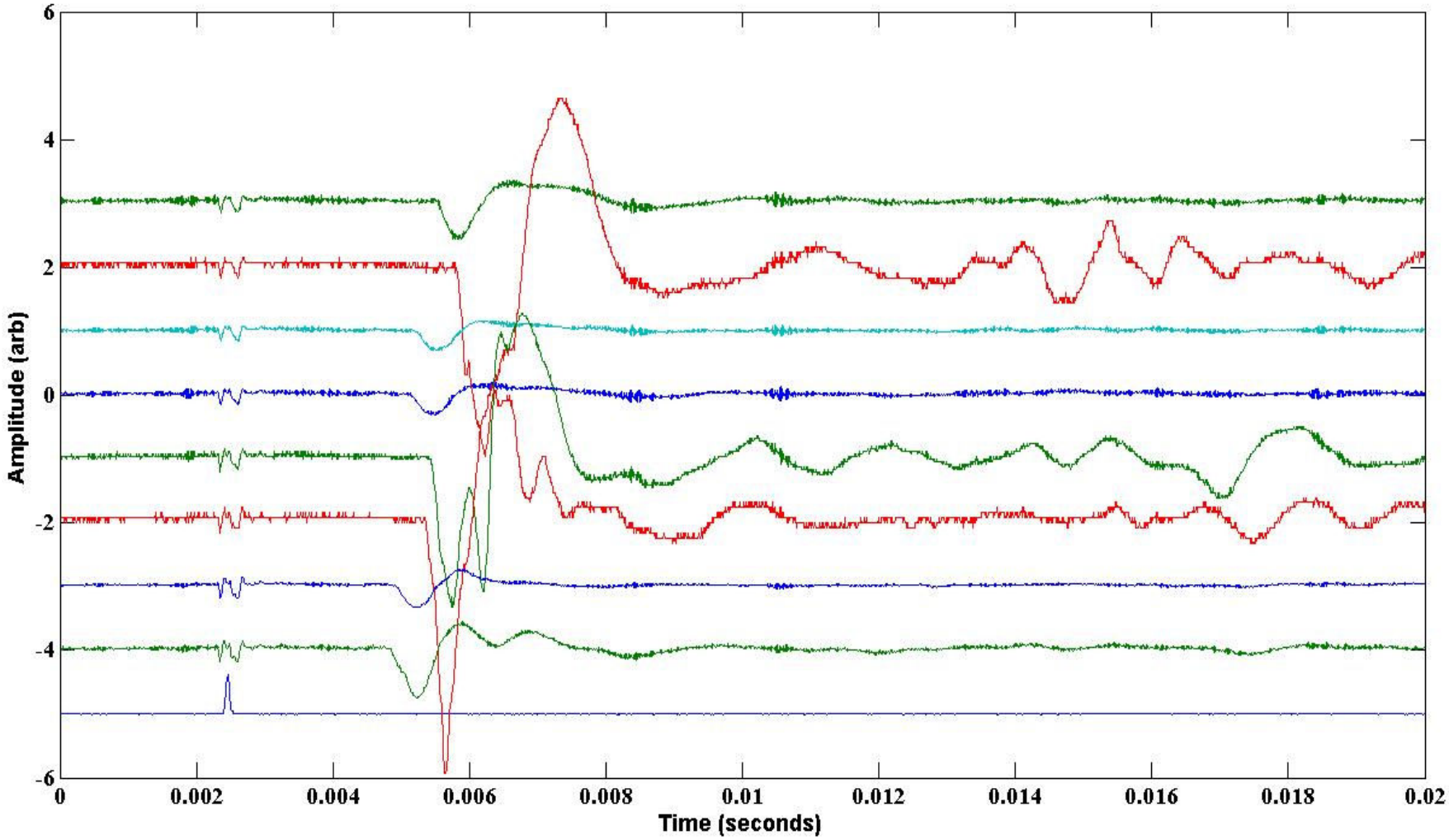
Pre-Quench Heating Has Been Observed



Still have the circle of confusion!

Pulsed Single Cell Results

Global Thermal Breakdown Has Been Observed

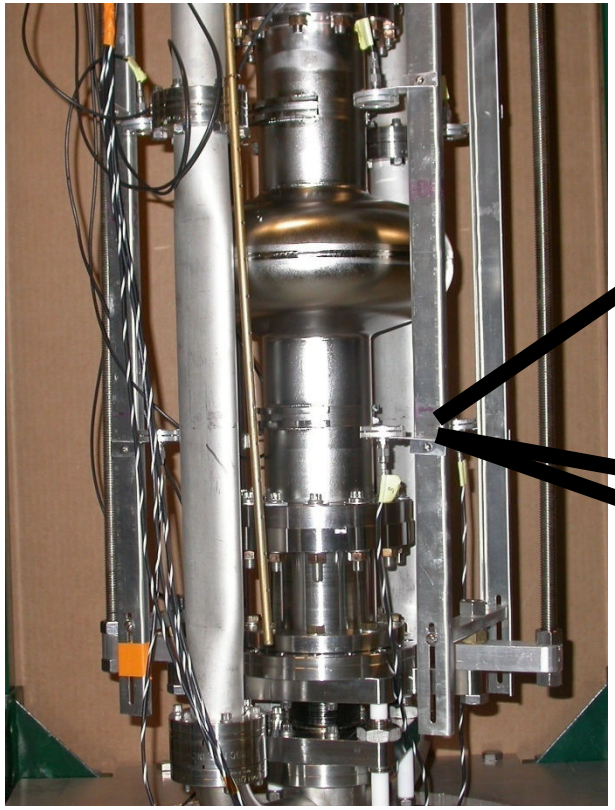


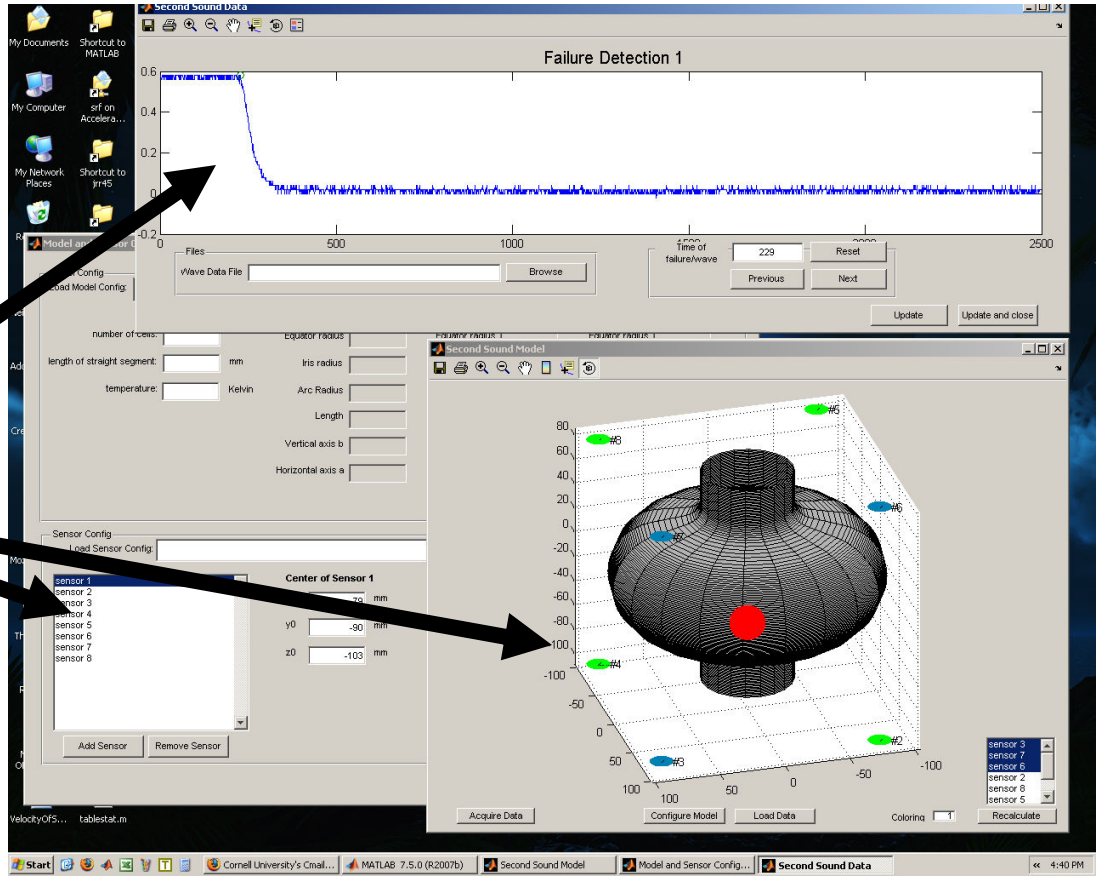
Circle of Confusion

- What is the physical origin of the circle of confusion
  - Is it due to an incomplete understanding of thermal propagation in He-II?
    - When the thermal flux exceeds ~1.5 W/cm^2 second sound cannot transport the heat (chimney limit in cryomodules)
    - Does the thermal energy couples to a first sound wave?
    - Once the thermal flux deceases to a level below ~1.5 W/cm^2 the thermal energy can again couple to a second sound wave.
  - Is it thermal propagation in the bulk-niobium? Fast (1-10 μs resolution) thermometry may be coming online in 2 months.
- If the heat travels as a first sound wave for ~0.1ms we find 0.1 ms*220m/s = 2.2 cm ~ the circle of confusion
- If the heat travels conductively through the bulk niobium for ~0.1ms we find 0.1ms*400m/s = 4 cm ~ the circle of confusion
- The circle of confusion's radius is highly correlated with the level of stored energy at the quench field level.

Future Plans

- Detect Pre-Quench Heating (Quench Protection, in cavities and in SC magnets)
- Computer modeling
- Fast Thermometry & linear spacing between transducers

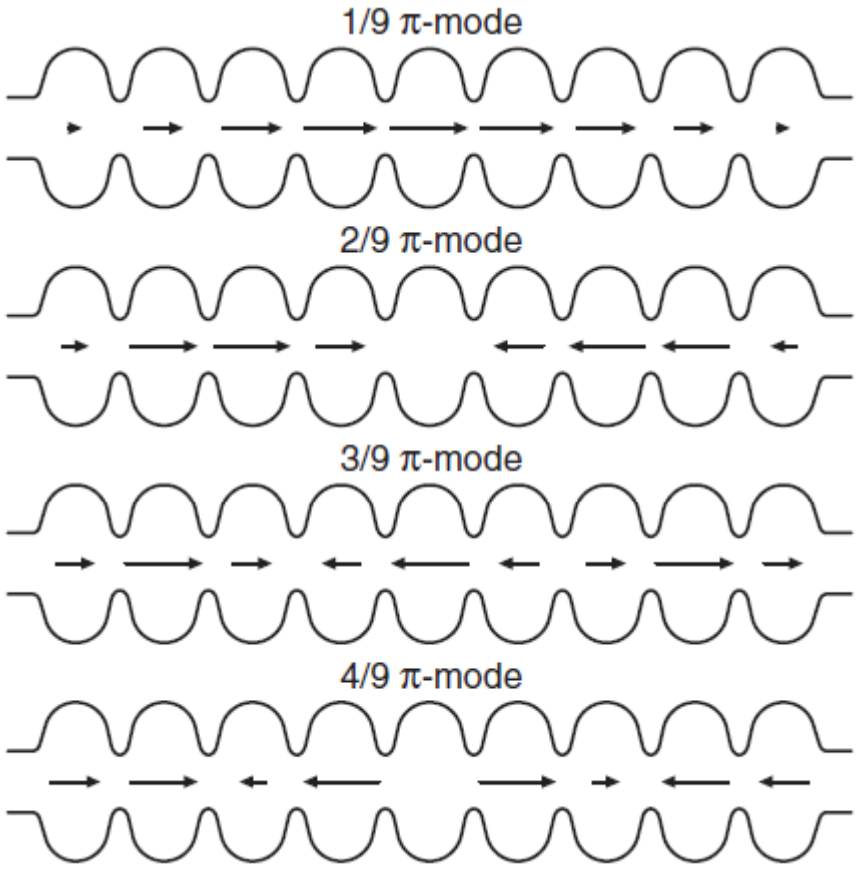


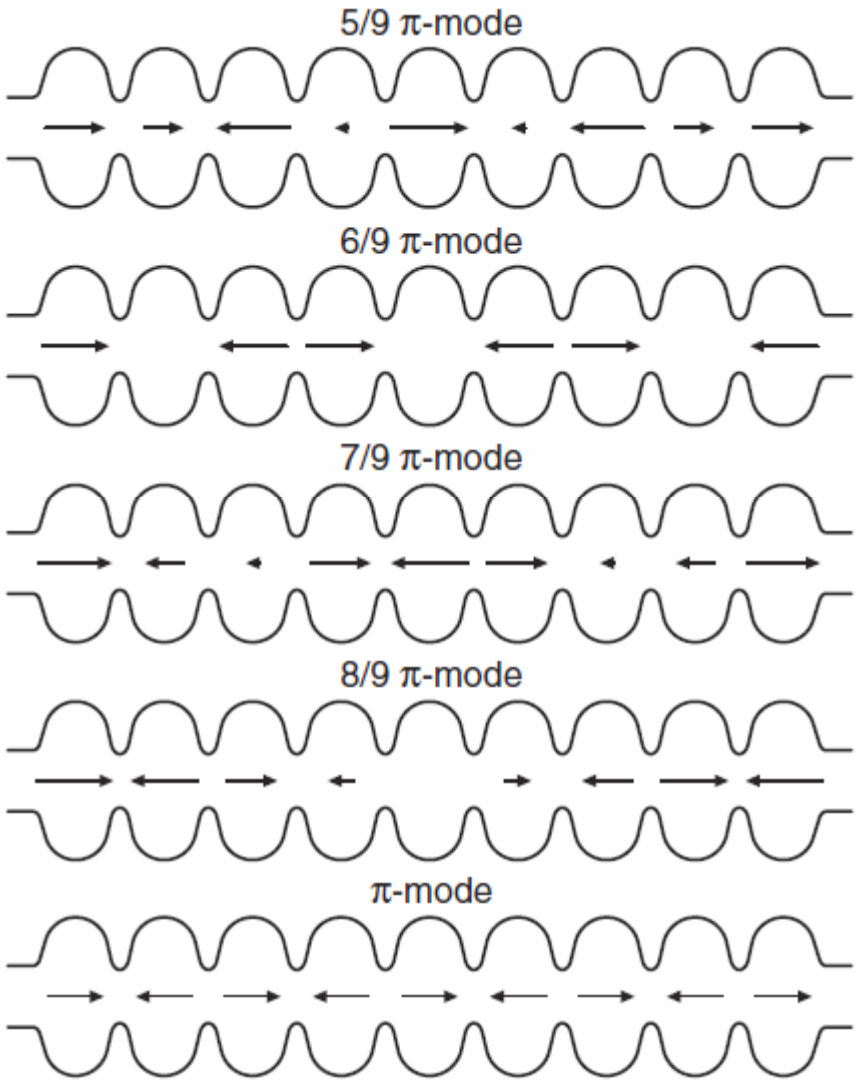


Summary

- 2nd sound quench location provides a simple, efficient, and reliable method of determining the location of quench-spots.
- 6-8 sensors per cavity test are employed versus thousands of resistors. This saves time, money, and frustration.
- The second sound quench-spot location technique would benefit any SCRF institution which wants to rapidly test/repair cavities, many are now coming online (DESY, CERN, Daresbury, JLAB, FNAL, KEK, CEA-Saclay, CEA-Orsay, U. of Toronto, Cornell, and the grandfather ANL).

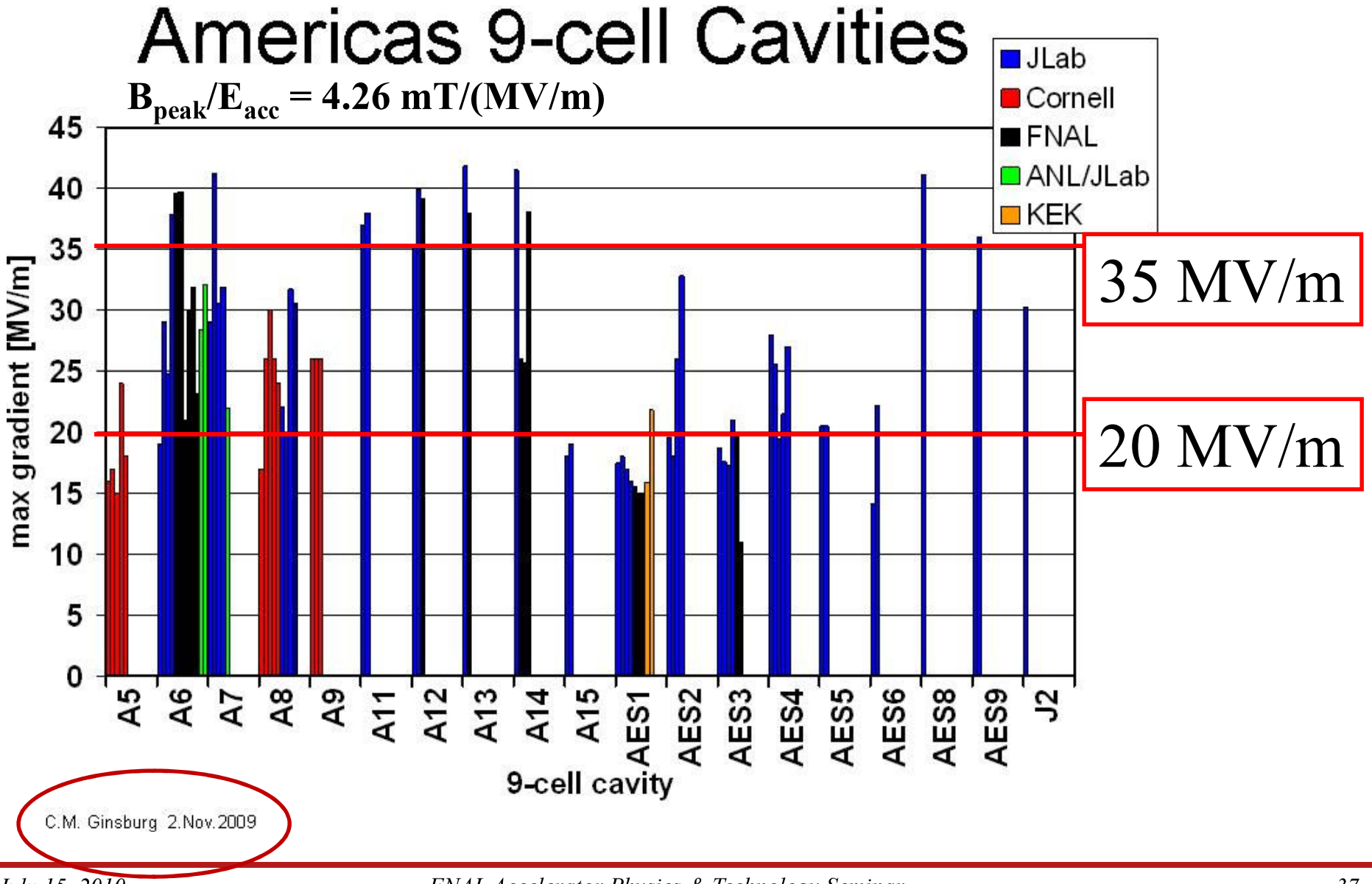
Quenching Multi-Cell Cavities



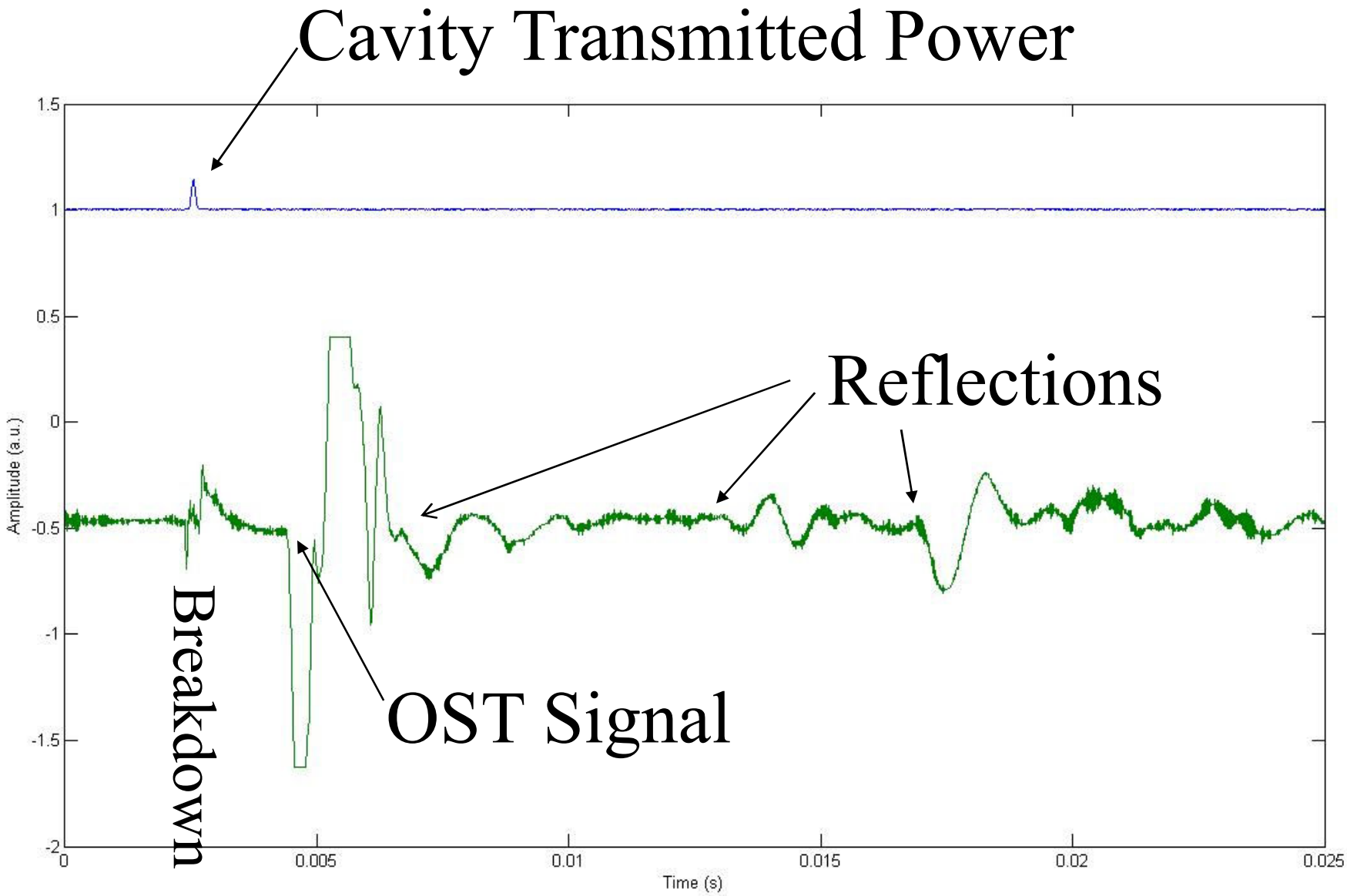


The measured second-sound-time-of-flight varies slightly you quench at the same spot but in different eigenmodes (different stored energies).

Why Do We Care?



Pulsed Single Cell Results

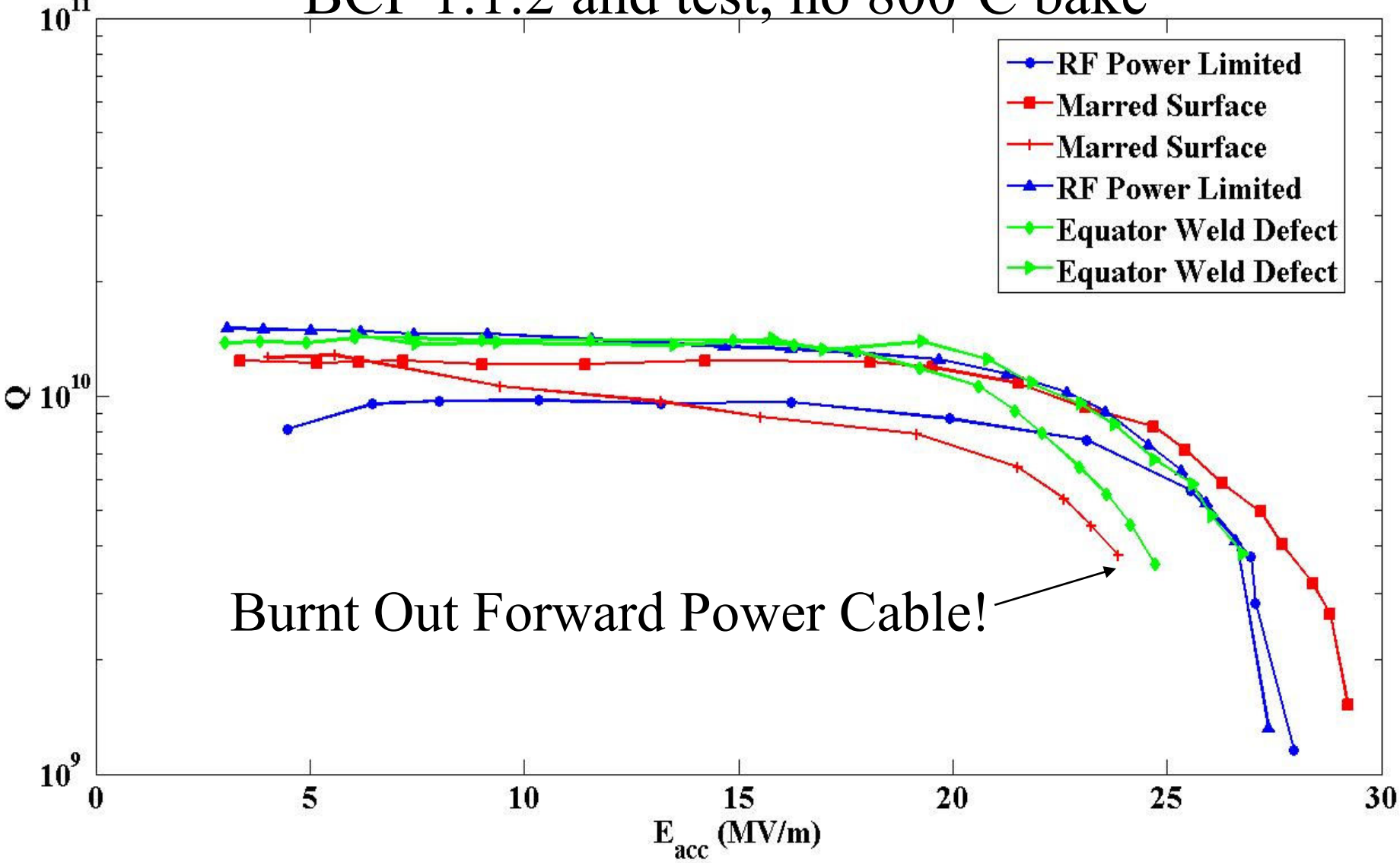


Why We Care

- We see many ILC cavities which quench at peak surface magnetic fields (B_{peak}) of 40 to 80 mT which are being improved via second sound quench location.
- Cornell sees all of its ERL prototypes quench at B_{peak} = 40 to 130 mT, two of which were repaired with the aid of second sound..
- Cornell wants to operate the ERL injector and drive linac cavities at B_{peak}(maximum) = 86 mT
- The ANL FRIB multi-spoke cavity prototypes quench at B_{peak} =
- The proposed ANL quarter-wave cavities ($\beta = 0.077$) are proposed to operate B_{peak} = 75.5 mT
- The MSU FRIB half- and quarter-wave cavities are proposed to operate with B_{peak} = 40-60 mT
- All if this is where second sound quench location can help.

Niowave/Roark

BCP 1:1:2 and test, no 800^{0}C bake



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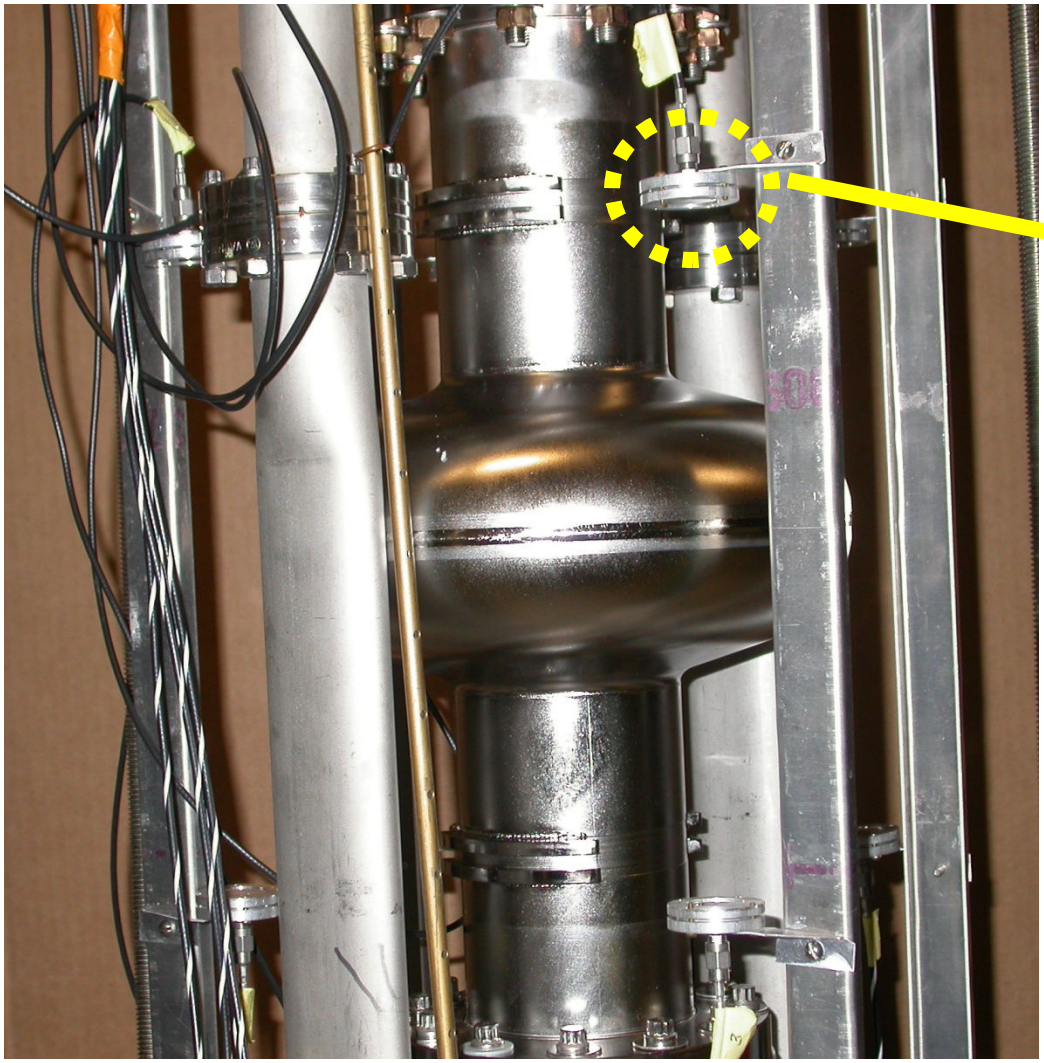

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Why We Care

- **Not all superconducting radio-frequency (SRF) cavities reach their design goal or the maximum aceivable surface magnetic field of 200 mT**
- **Many are limited by surface defects to peak surface magnetic fields (B_{peak}) in the range of 30-80 mT**
- **Locating and repairing these defects is critical to all high volume production of SRF cavities:**
  - **So the accelerators can deliver the specified beam to experimenters**
  - **To avoid throwing away $50k-$200k devices**

Development	Cavity Type	B_{peak} @ Operation Gradient
SRF Development	Many	Quench Between 30-80 mT
Cornell ERL Injector	$\beta = 1$; Elliptical-Cell	<80 mT
Cornell ERL Main Linac	$\beta = 1$; Elliptical-Cell	<100 mT
MSU FRIB/ReA3	$\beta = 0.041$ & 0.085; $\lambda/4$ $\beta = 0.285$ & 0.57; $\lambda/2$	40-60 mT
ILC	$\beta = 1$; Elliptical-Cell	>130 mT (only 25% reach this)
ANL FRIB	$\beta = 0.5$ & 0.62; TSR	Quench at ~100 mT

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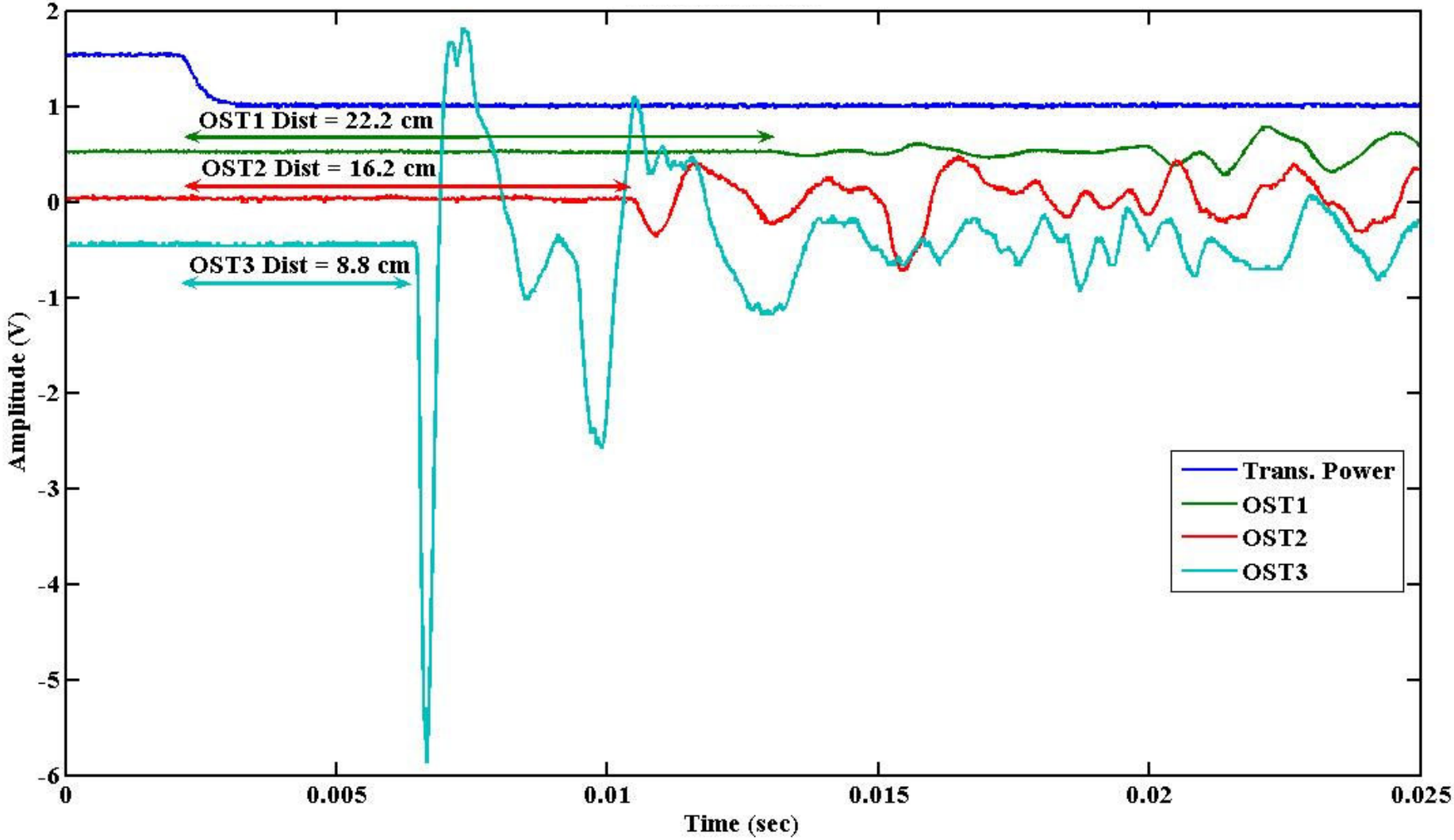

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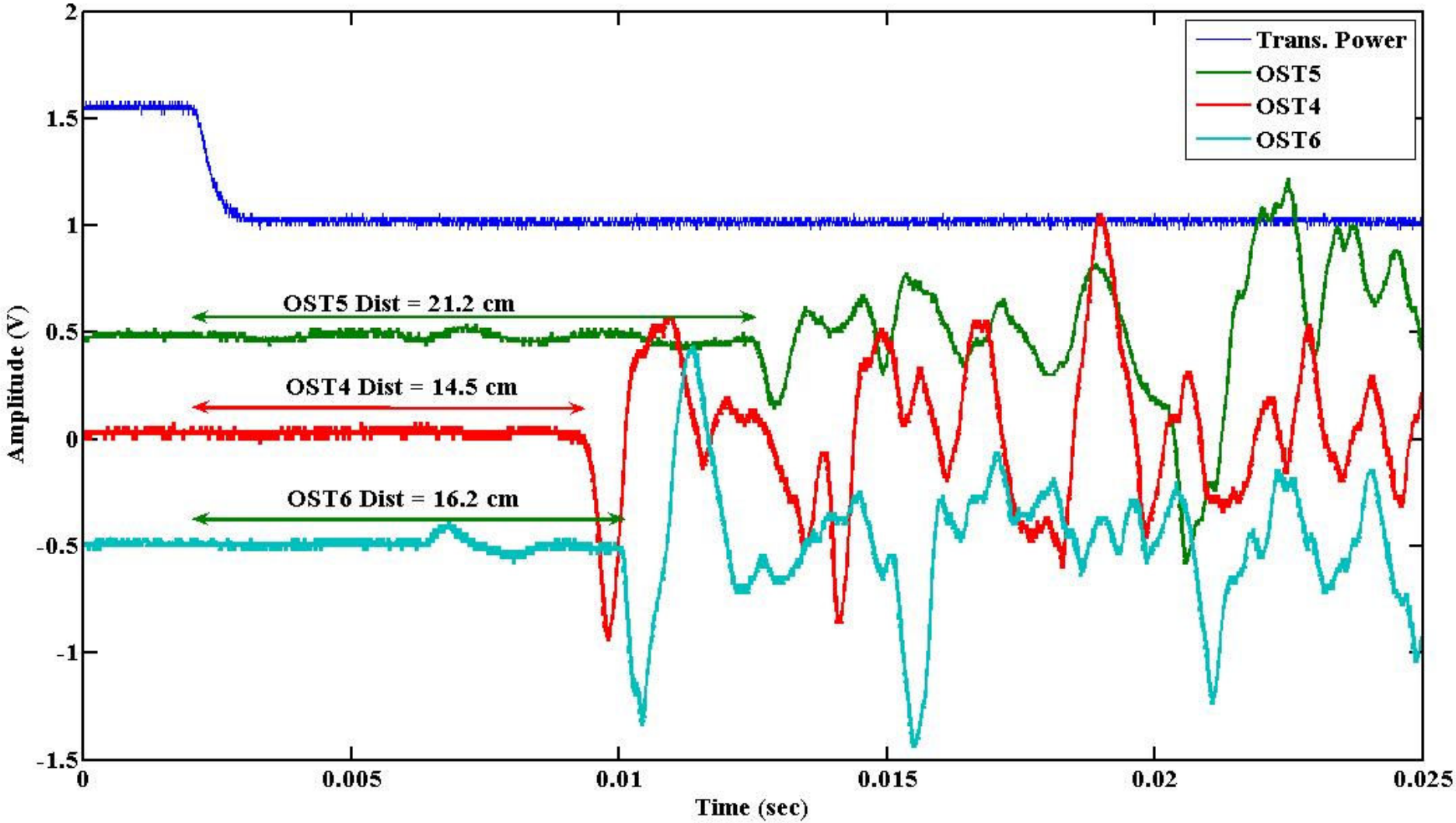

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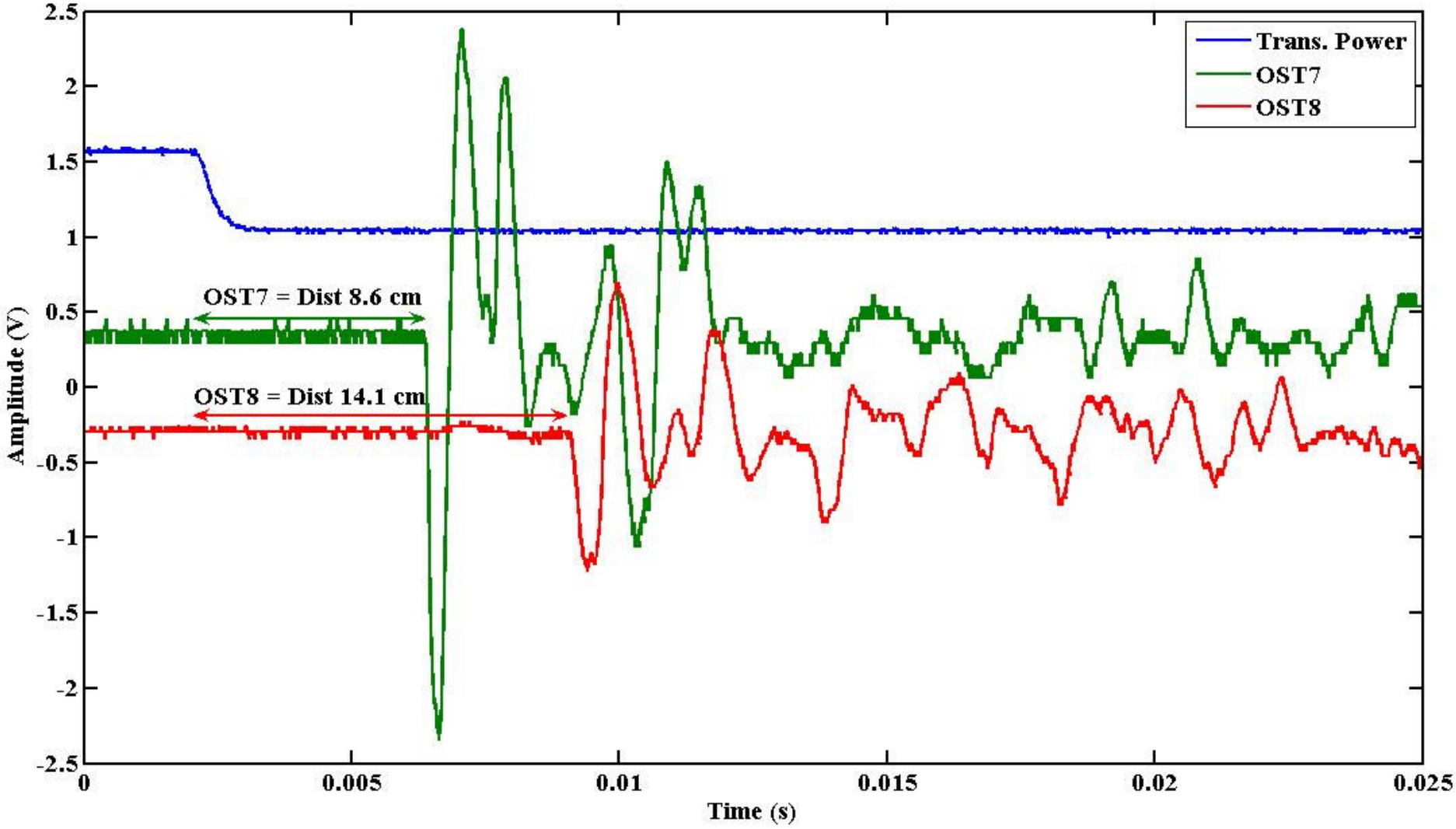
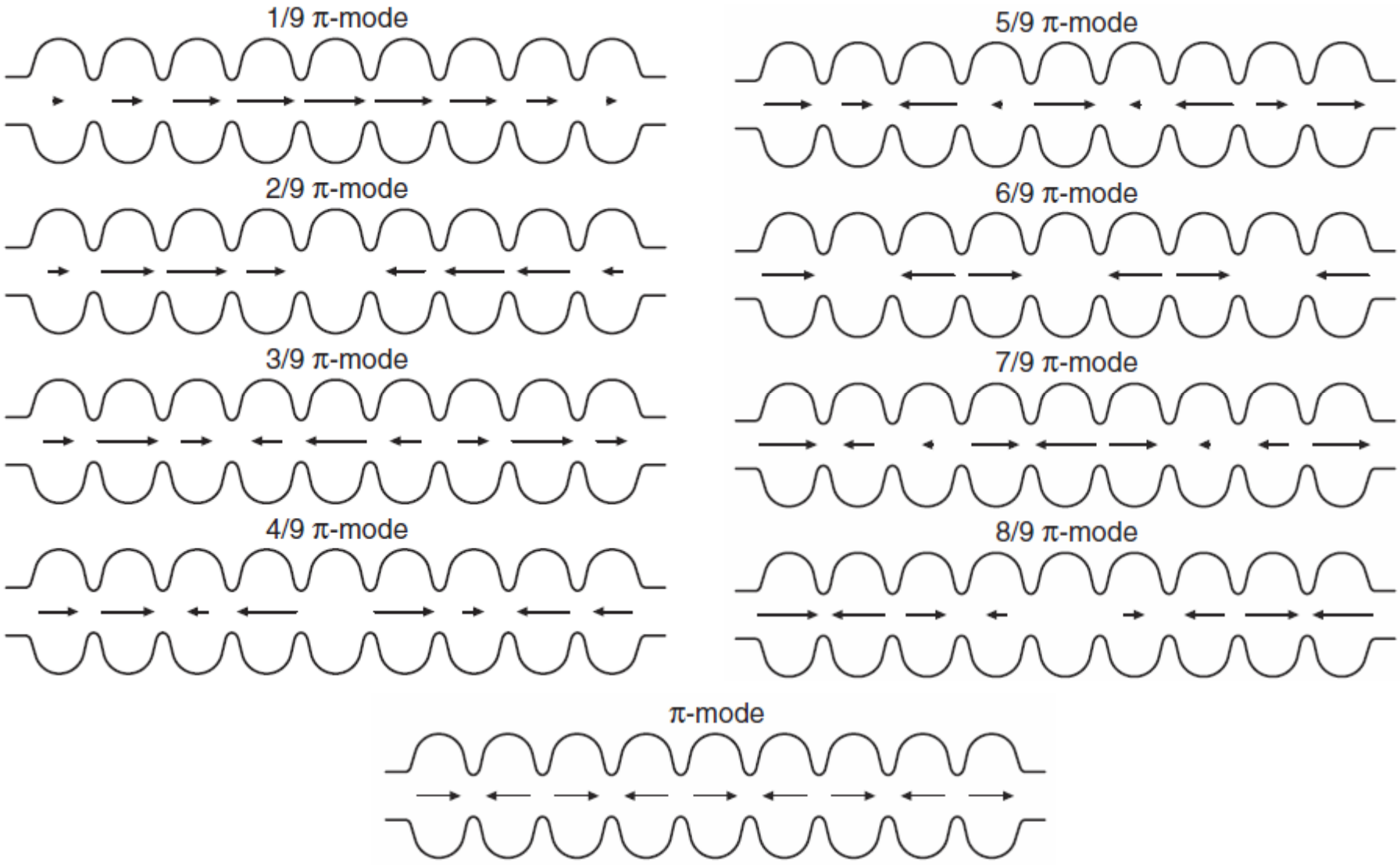
9-Cell Cavity TM_{010} Eigenmodes