Ultra-High Gradient Experiments with Cryogenic Normal-Conducting Cavities

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Outline

- Motivation
  - Single Cell Accelerating Structures
  - Properties of Cryogenic Copper
- Cryo RF Experiments
  - Understanding dynamic Q_0
  - RF Pump Probe
  - Breakdown Rates at 45 K
- Conclusions

Single Cell SW Accelerating Structures

Goals:

- We want to study rf breakdowns in practical accelerating structures:
  - dependence on circuit parameters, materials, cell shapes and surface processing techniques.

Difficulties:

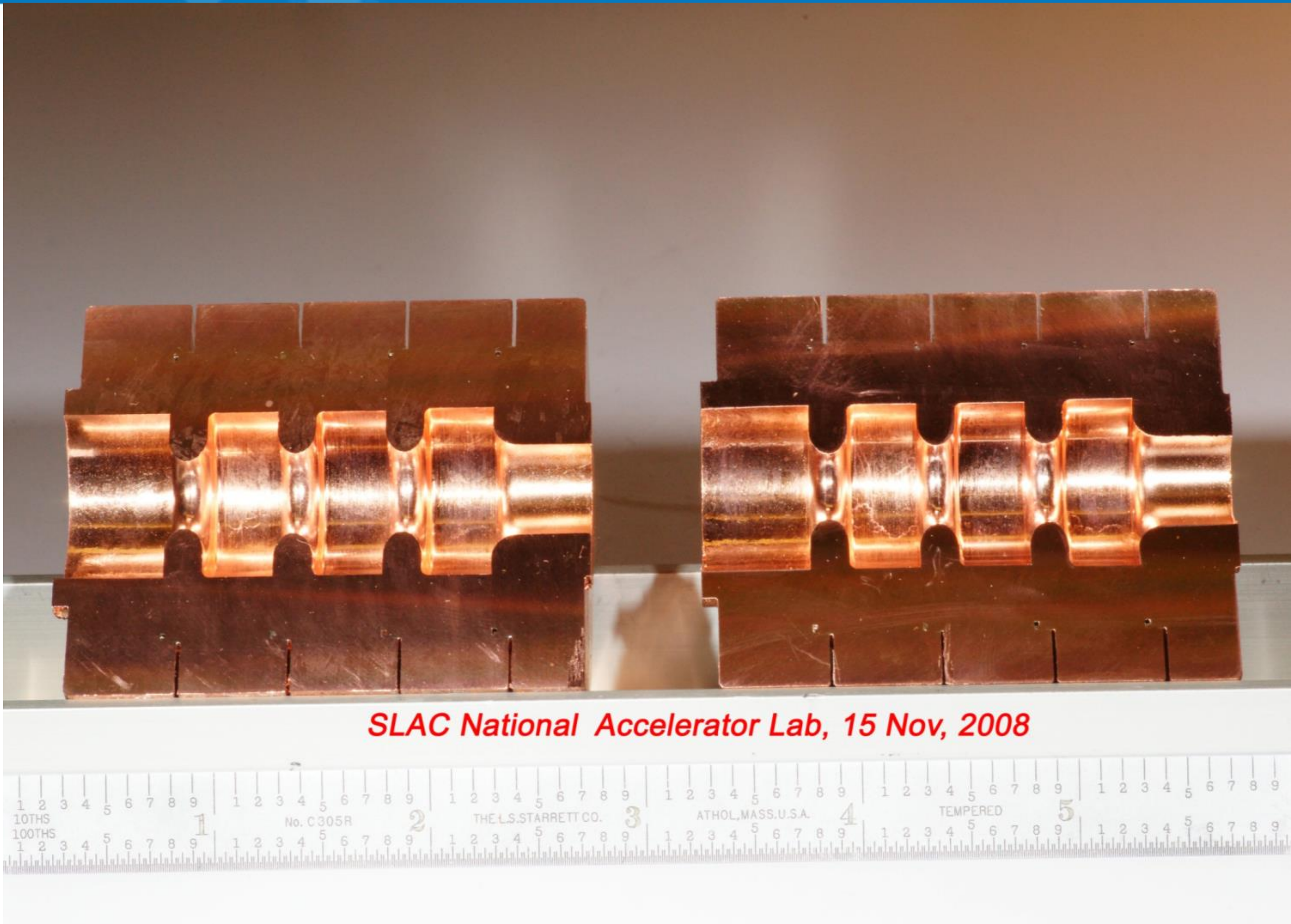
- Full scale structures are long, complex, and expensive

Solution:

- Single cell standing wave (SW) structures with properties close to that of full scale structures
- Reusable couplers

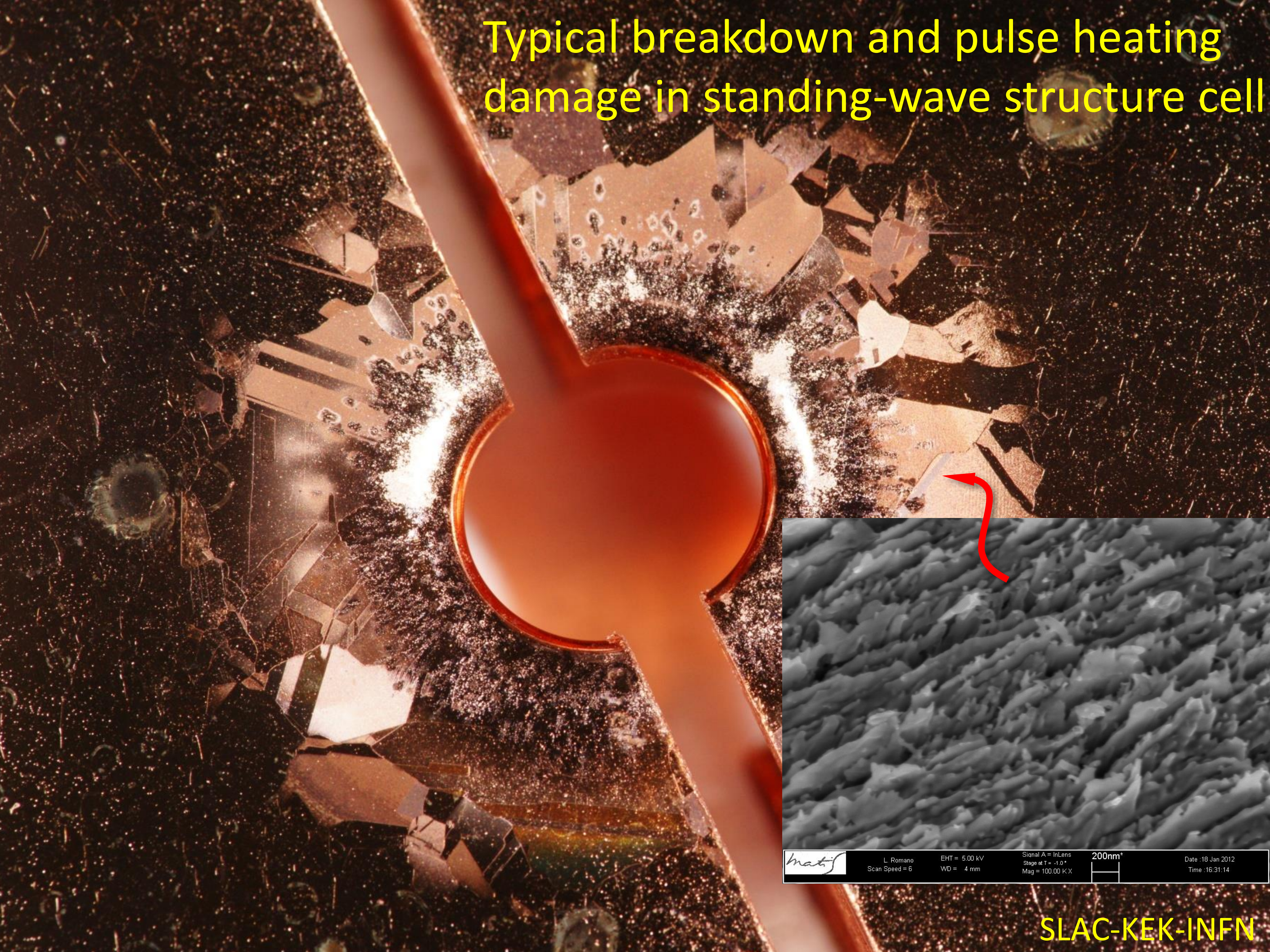
Single Cell SW Accelerating Structures

- The fields are highest in middle cell. Breakdowns occur within that cell



SLAC-KEK-INFN

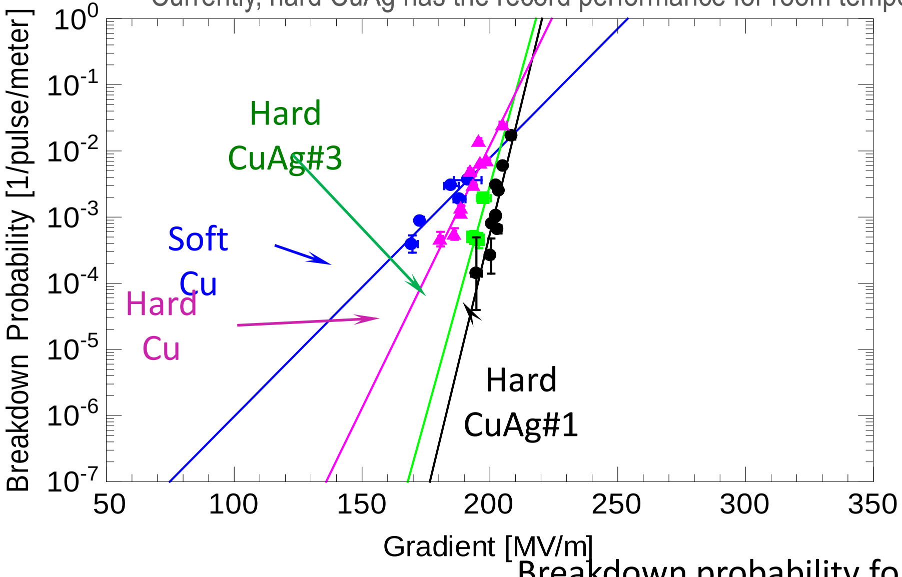
Typical breakdown and pulse heating damage in standing-wave structure cell

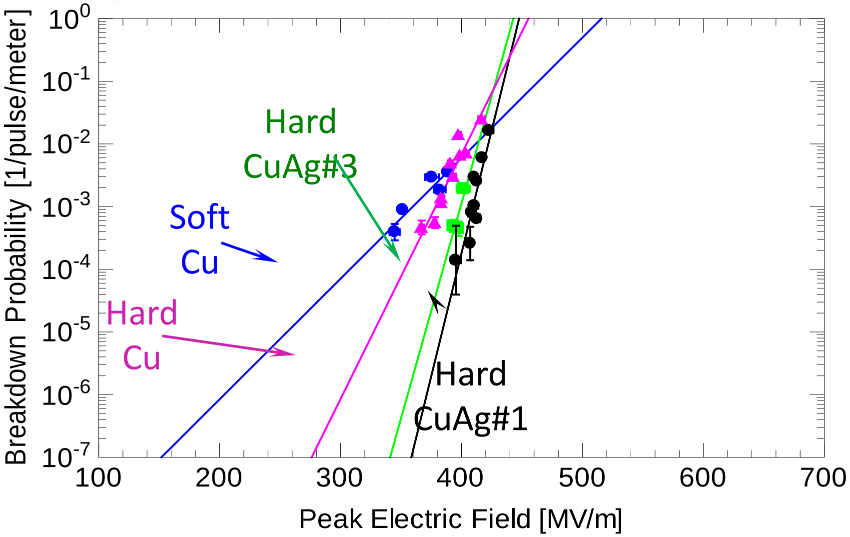


SLAC-KEK-INFN

State of Art at SLAC: Room Temeprature

- Breakdown rate is correlated with fields inside the accelerating structure.
  - We found peak pulse heating to be a good predictor of the breakdown rate in simple disk-loaded-waveguide type geometries.
  - We found the "modified Poynting vector" to be a practical predictor of the breakdown rate in more complex geometries.
- We conjecture that the breakdown rate is linked to movements of crystal defects induced by periodic stress. Pulse heating may create some or, possibly a major part of this stress. By decreasing crystal mobility and increasing yield stress we will reduce the breakdown rate for the same gradient.
- Motivated by correlation of peak pulse heating and breakdown rate we study hard cooper alloys and methods of building structures out of them.
  - We found that hard Cu and hard CuAg have better performance than soft heat-treated copper.
  - Currently, hard CuAg has the record performance for room temperature structures.



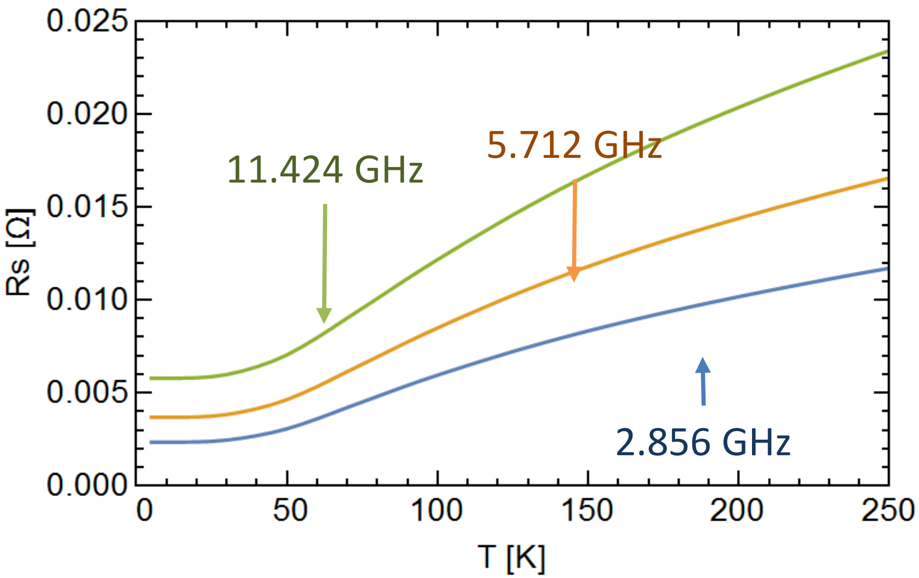


Breakdown probability for four, one made of made of soft–heat treated Cu, one hard Cu, and two hard CuAg, 150 ns shaped pulse

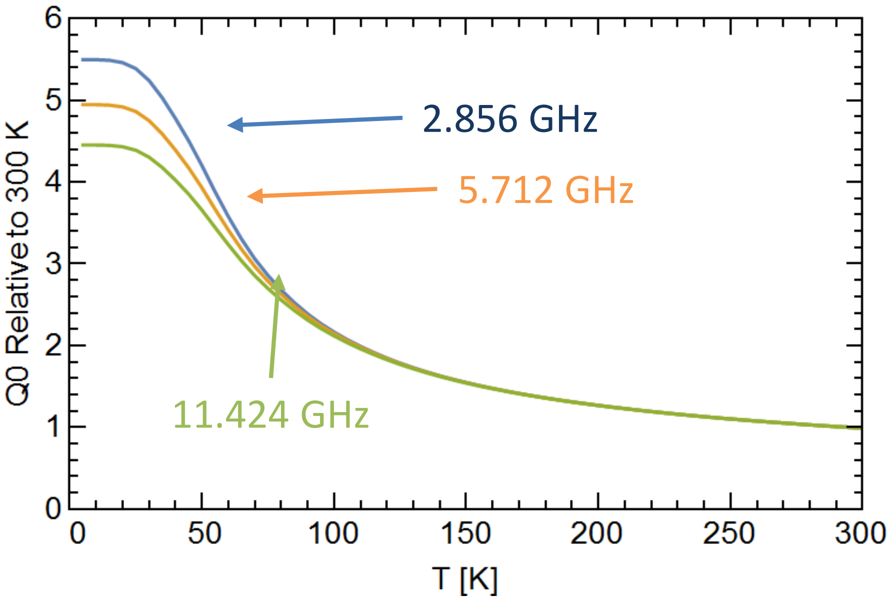
Dolgashev EAAC15

RF Surface Resistance Decreases

- As the temperature decreases, the electron conductivity increases
  - RF surface resistance decreases by a factor of over 4 for 11.424 GHz
- Less rf power is required, and less rf pulse heating is created, for a given accelerating gradient.



Theoretical RF surface resistance of Cu. RRR=400, σ=2.97x10^8 S/m²

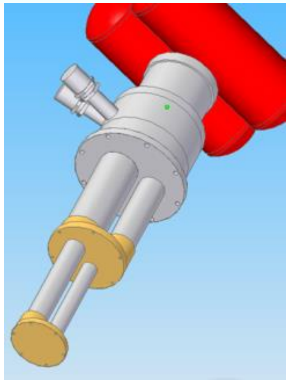


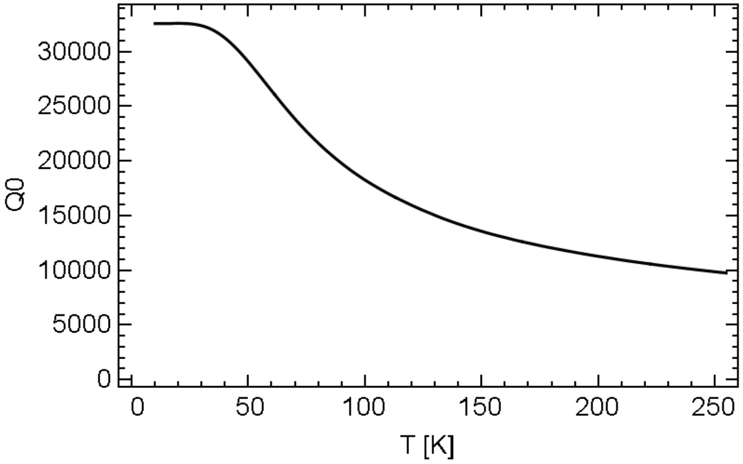
Q0 vs T in a Cu cavity; relative to Q_0 at 300 K

TE_0 Dome Cavity

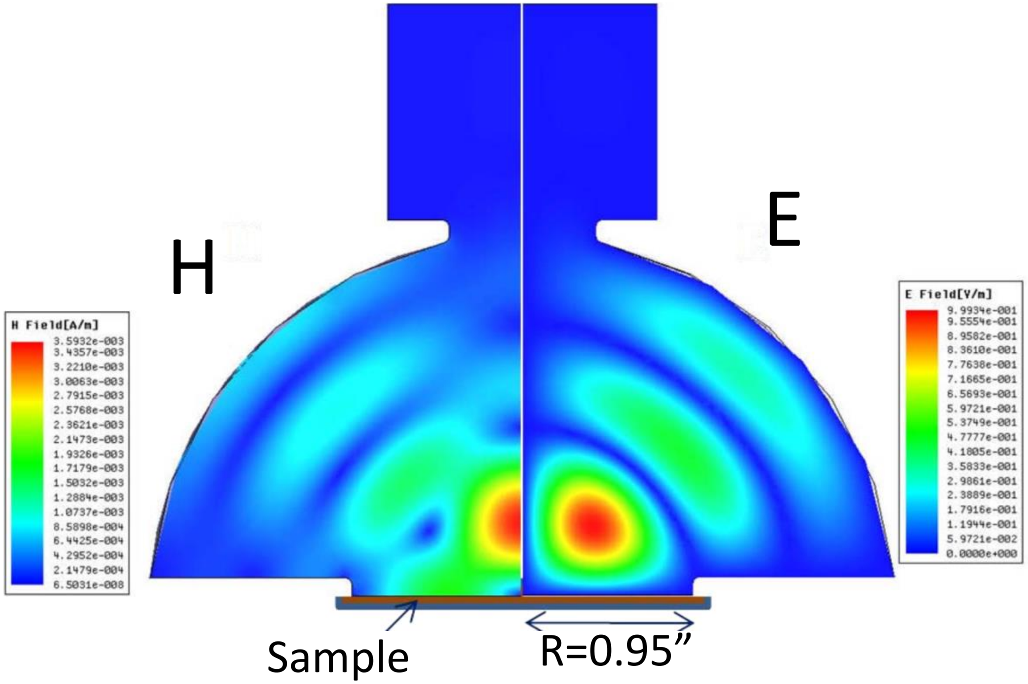
- Flat copper samples of varying purity and grain size.
- Goes down to ~4K.
- Q_0 increases by factor of 4.1 at 11.4 GHz

Cryomech CH40415





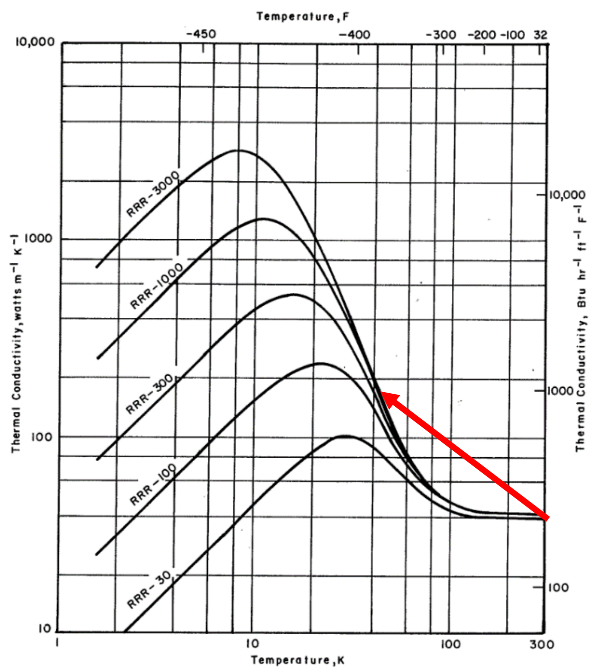
J Guo et al. Cryogenic RF Material Testing with a High-Q Copper Cavity AIP conf Proc 2010



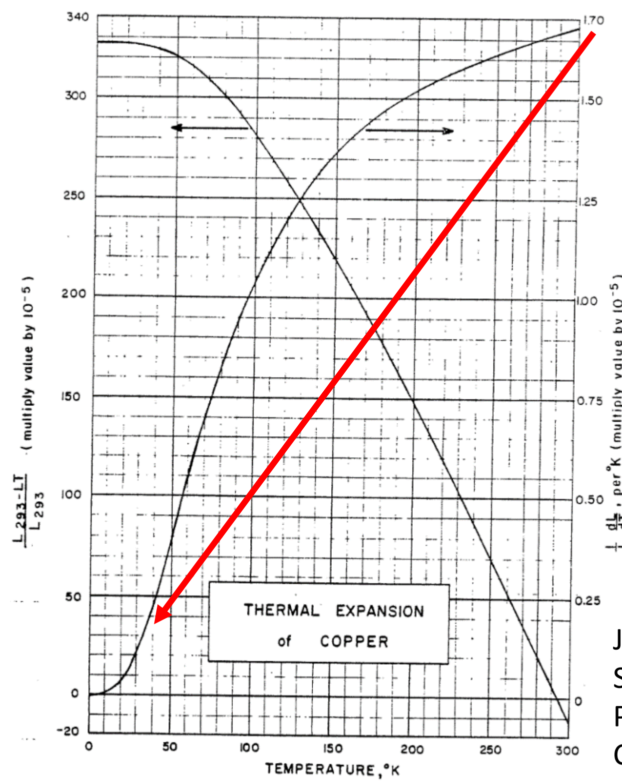
Thermal Stress and rf Pulsed Heating Reduced

- Thermal conductivity is larger at 30 K, rf pulsed heating is decreased by about a factor of 2 from room temperature for same gradient.
- As the thermal expansion coefficient decreases, thermal stress, proportional to αΔT, also decreases.

Depending on purity, thermal conductivity increases by factor of 5



THERMAL CONDUCTIVITY VERSUS TEMPERATURE FOR COPPER



Coefficient of thermal expansion decreases by order of magnitude

J. Jensen, W. Tuttle, R. Stewart, H. Brechna, A. Prodell BNL Selected Cryogenic Data Notebook

Normal Conducting Cryo Structures

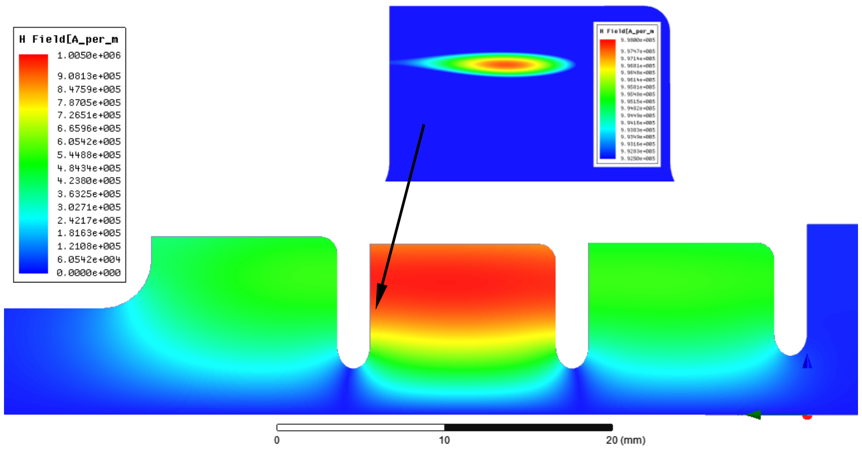
Pros:

- Decreased rf losses
- Harder material
  - Yield Strength and Young's Modulus increase
- Decreased thermal stress from rf pulsed heating
- Vacuum pumping is improved

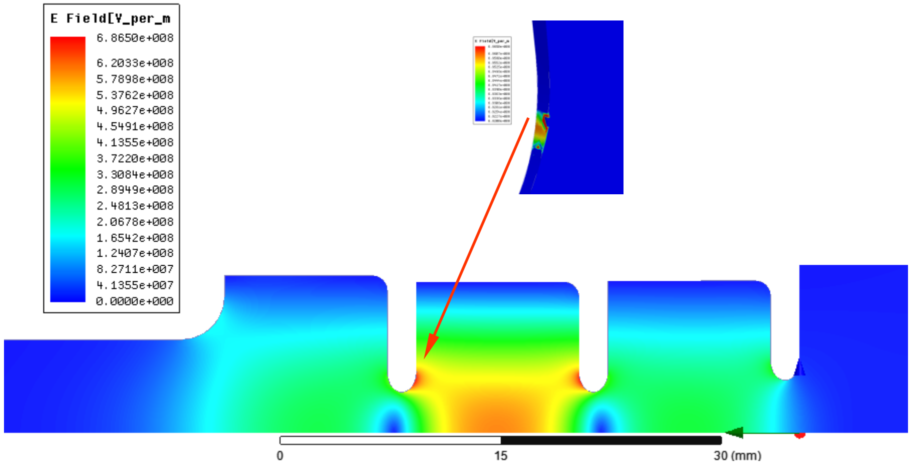
Cons:

- Since the cavity acts as a cryogenic vacuum pump any vacuum leak or other source of gasses could contaminate high field surfaces.
- Due to reduced cooling efficiency at low temperature, overall efficiency of the system is decreased. High repetition-rate operation is problematic.

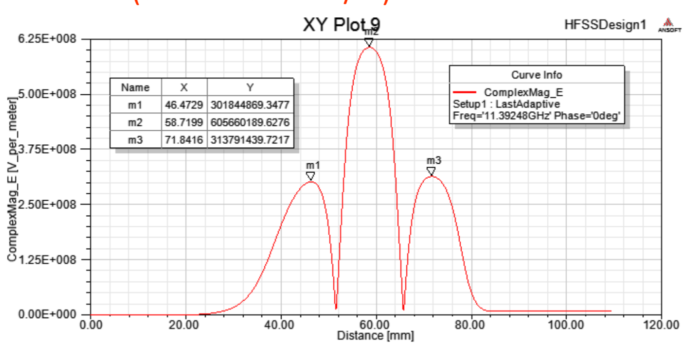
1C-SW-T2.75-A2.0-Cryo-Cu, 11.3925 GHz: 10 MW rf Input



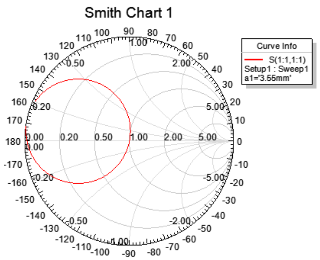
Maximum magnetic field 992.5 kA/m
(SLANS 993.2 kA/m)



Maximum electric field 686 MV/m
(SLANS 678 MV/m)



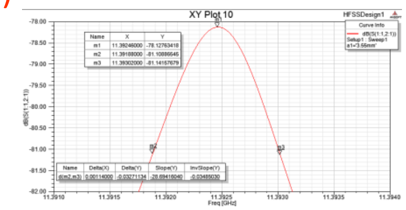
Coupler-cell on-axis field is ~4% high vs. end-cell field,
Peak field on axis 605.7 MV/m (SLANS 605.7 MV/m)

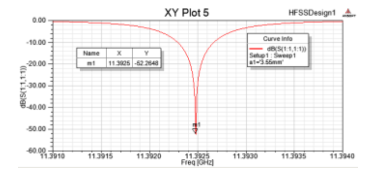


Slightly over coupled with beta= 1.00488

$$Q := \frac{11.394}{0.00114}$$

$$Q = 9.995\times 10^{3}$$

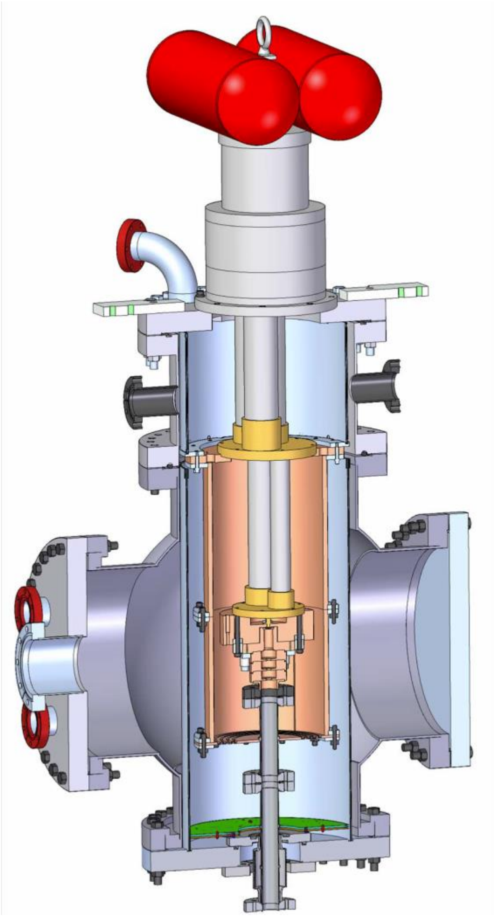




F=11.39**25** GHz (SLANS 11.93**40** GHz)

V.A. Dolgashev, SLAC, 14 March 2011

Cryo Structure Setup: rf Vacuum Isolated from Cryo Vacuum



Cryostat assembly

cold head

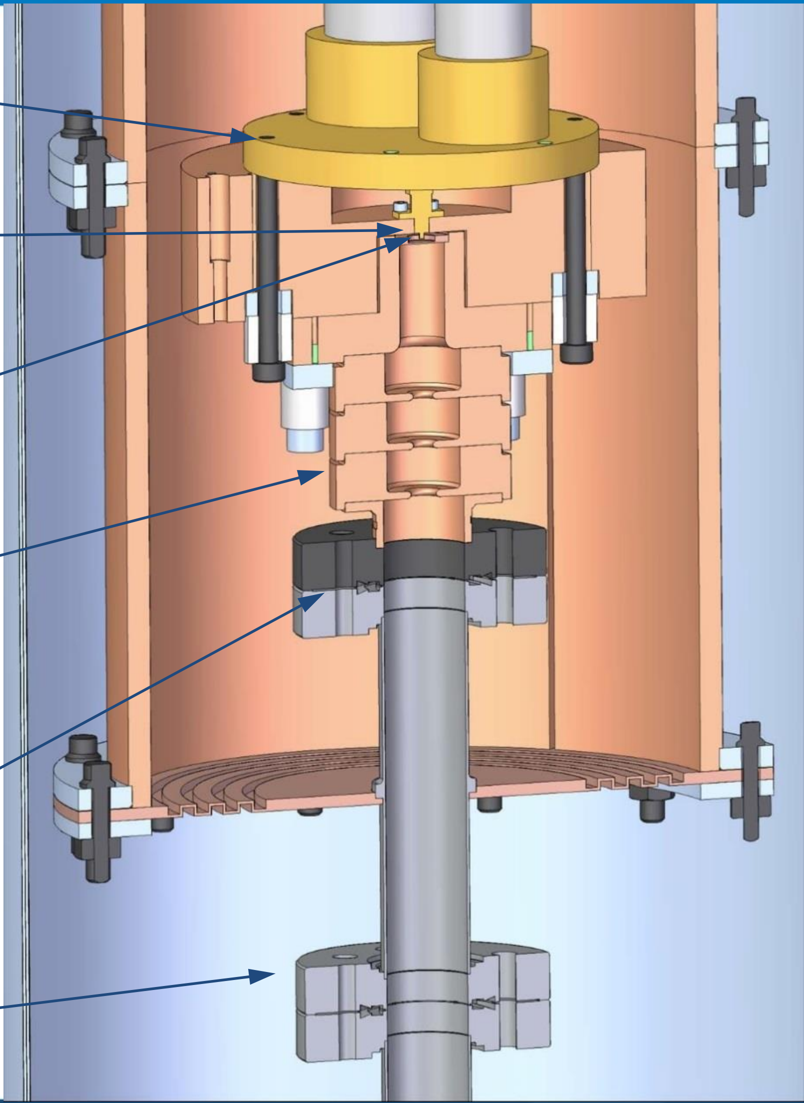
dark-current monitor

brazed-in metal foil

accelerating structure

rf flange with crashed metal gasket

stainless steel TM01 waveguide

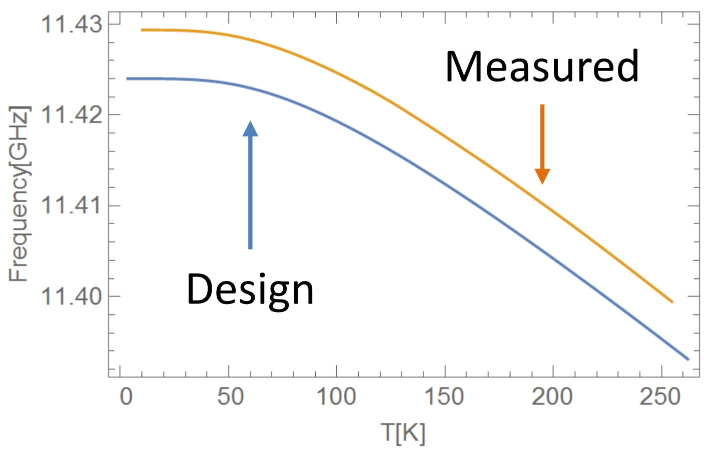


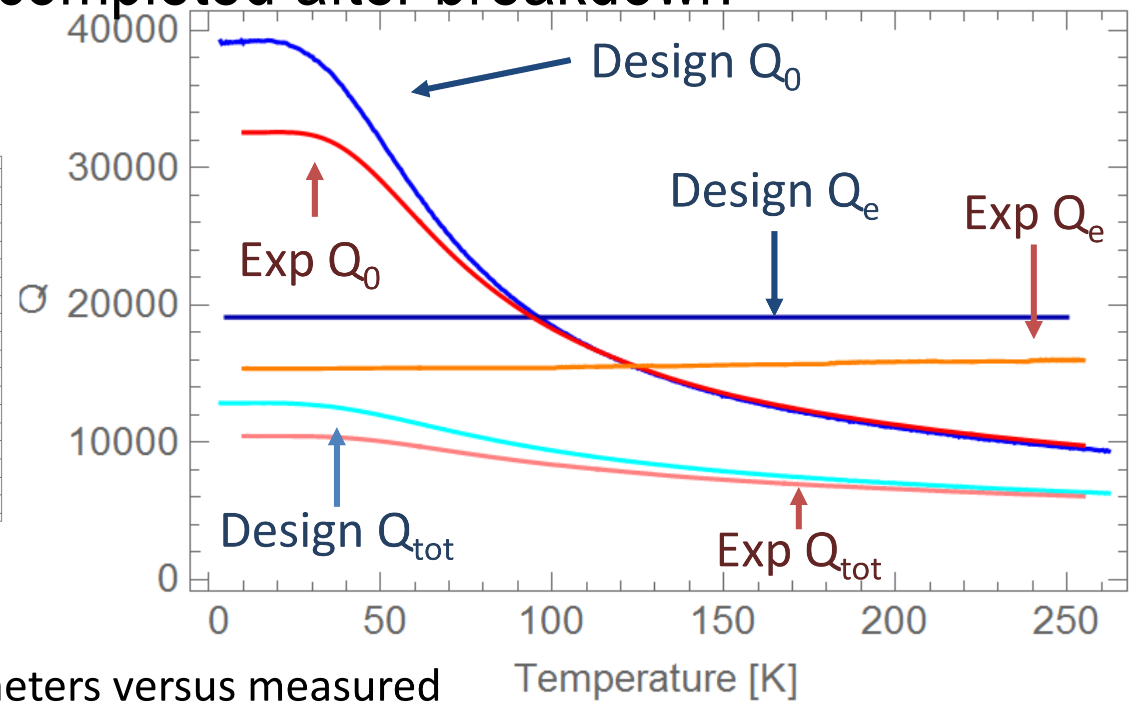
Discrepancies in High Power data

- We were not able to match the rf and dark current signals using the design static Q_0. We hypothesized that the Q_0 was changing during the rf pulse.
- We improved accuracy and dynamic range of rf diagnostics.
- Used a Network analyzer down to cryo temperatures.
- We build a circuit model of the whole rf network, from klystron to cavity to understand its behavior.
- To understand the changing Q_0 effect, we systematically measured Q_0 at a range of klystron power vs. temperature, repetition rate, and pulse length.

Network Analyzer Measurements

- 1C-SW-A2.75-T2.0-cryo-cu-SLAC-#2: Q_0 improvement in accelerating structure is lower than that of dome cavity.
- This measurement was completed after breakdown statistics data.

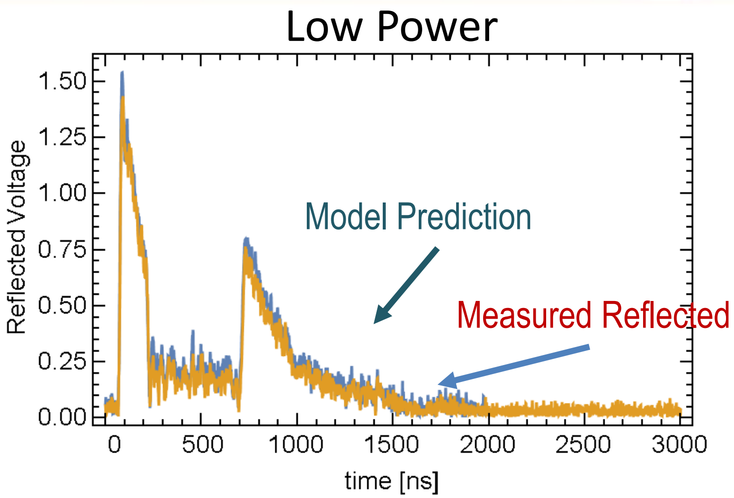


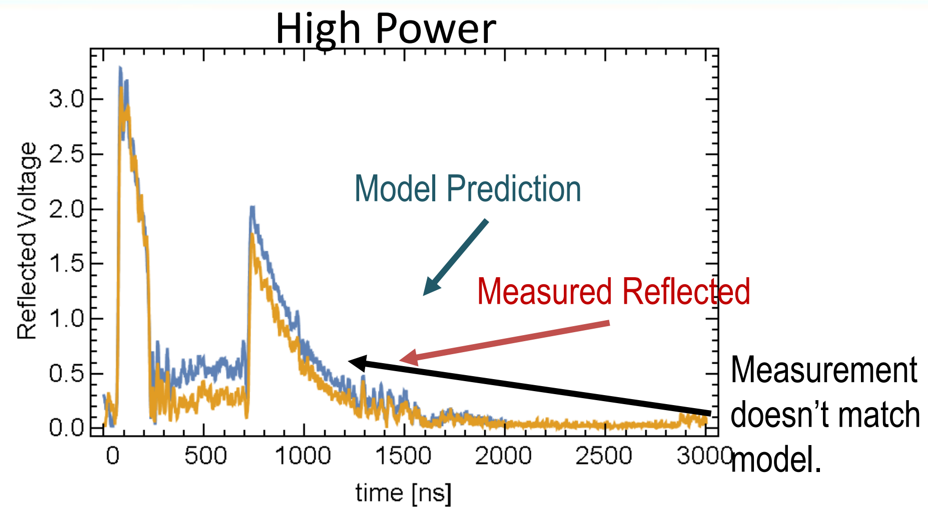


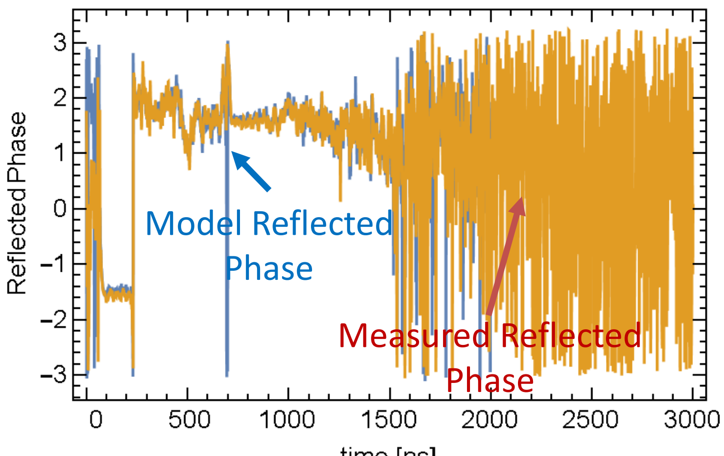
Matt Franzi,
Jim Lewandowski

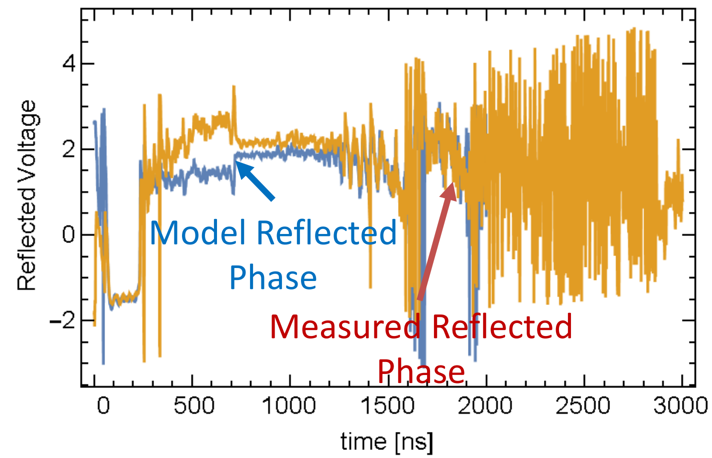
Design parameters versus measured

Low power data matches constant Q_0 circuit model; high power disagreement









Blue is the calculated response from the input rf pulse. Orange is measured reflected signal.
At low power they match. At higher power they differ. 25 K, 10 Hz, 500 ns pulse length.

A.C. et al. "Quality Factor in High Power Tests of Cryogenic Copper Accelerating Cavities" NAPAC 16

Calculating accelerating gradient with time-dependent Q0

- Q0 and w0, the resonant frequency, are allowed to vary in time during the rf pulse.
- The differential equation describing the electric field:

$$\frac{d\tilde{E}}{dt}\left(\frac{\omega_0}{Q_E} + \omega\left(\frac{1}{Q_0} - 2i\right)\right) + \tilde{E}\left((\omega_0^2 - \omega^2) - i\omega\left(\frac{\omega}{Q_0} + \frac{\omega_0}{Q_E}\right)\right) = \sqrt{\frac{8P_{\text{in}}\omega_0^3}{\mu_0 Q_E}}$$

- Magnitude of the Q_0 decay is chosen to match the measured dark current and rf signal.
  - **Dark current is exponentially dependent on electric field, accurately measures gradient**.

Equation modified from D. Pritzkau RF Pulsed Heating. 2001

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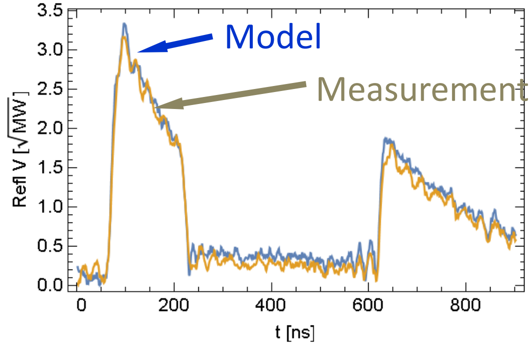
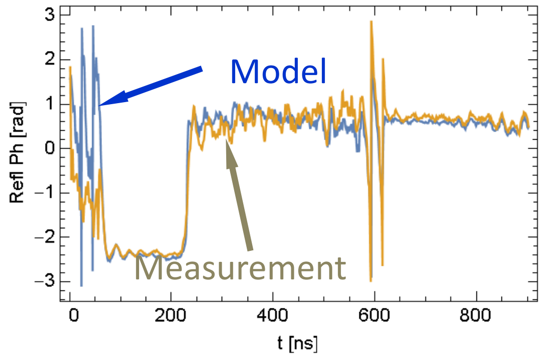
Example: Model fit for shaped pulse with flat part 400 ns, T=45 K

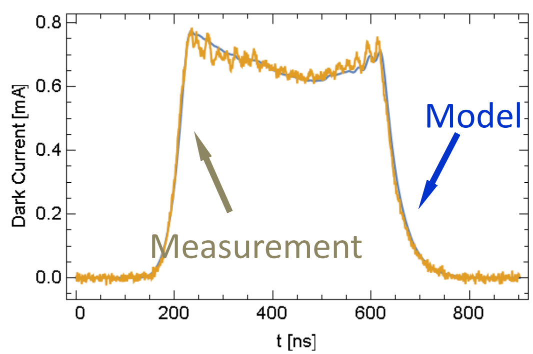
Reflected voltage

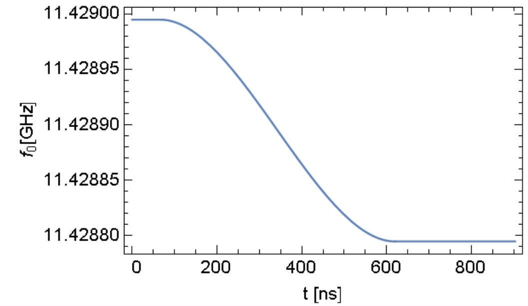


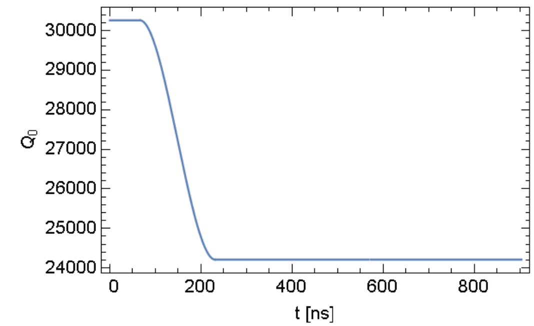
Reflected phase



Dark current







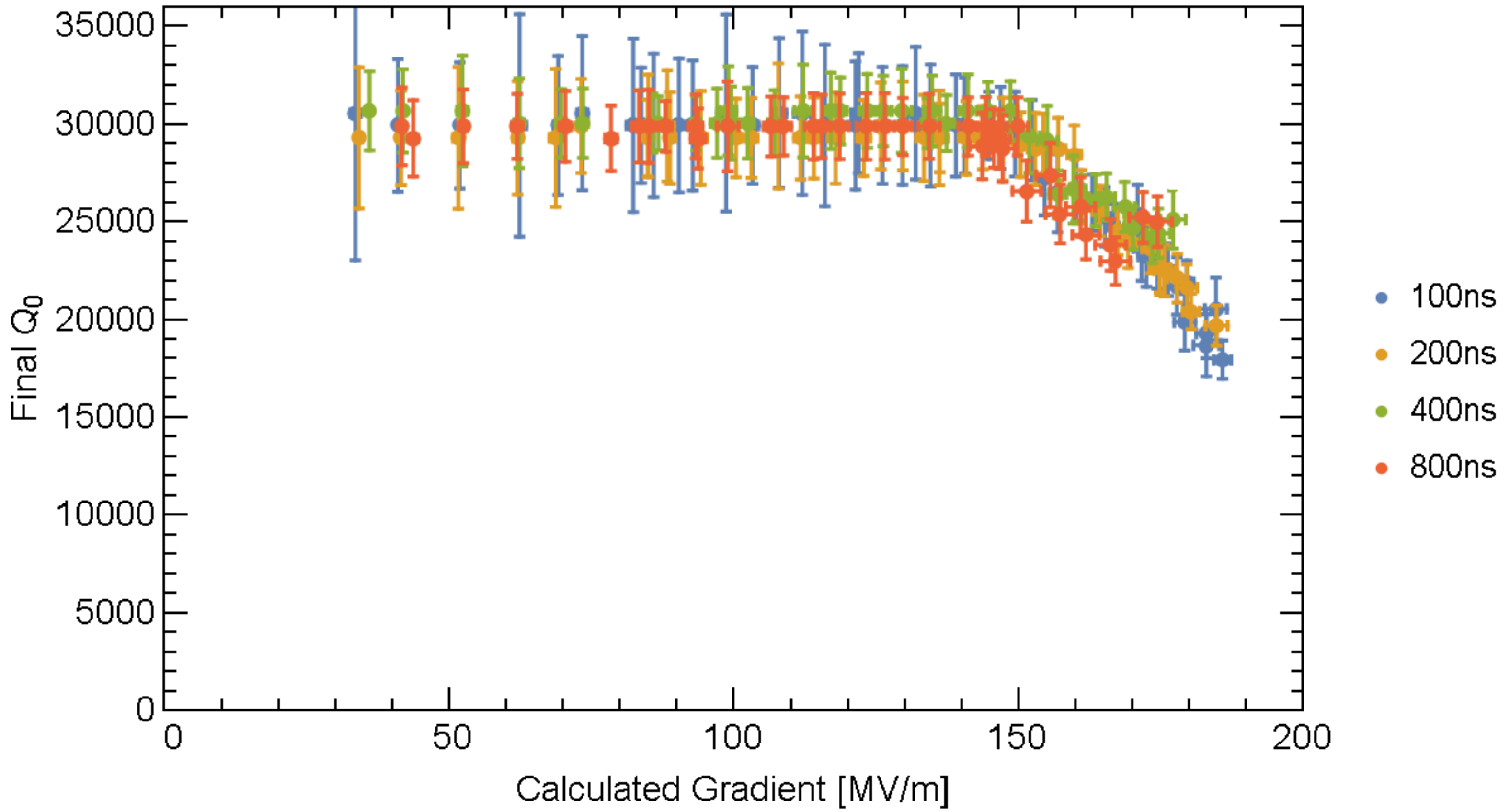
Q_0 and ω_0 vs. time

We found that the best fit came when:

- Q_0 changed very quickly as the field increased.
- The frequency changed slowly across the rf pulse

No Obvious Dependence of *Final* Q_0 on Pulse Length

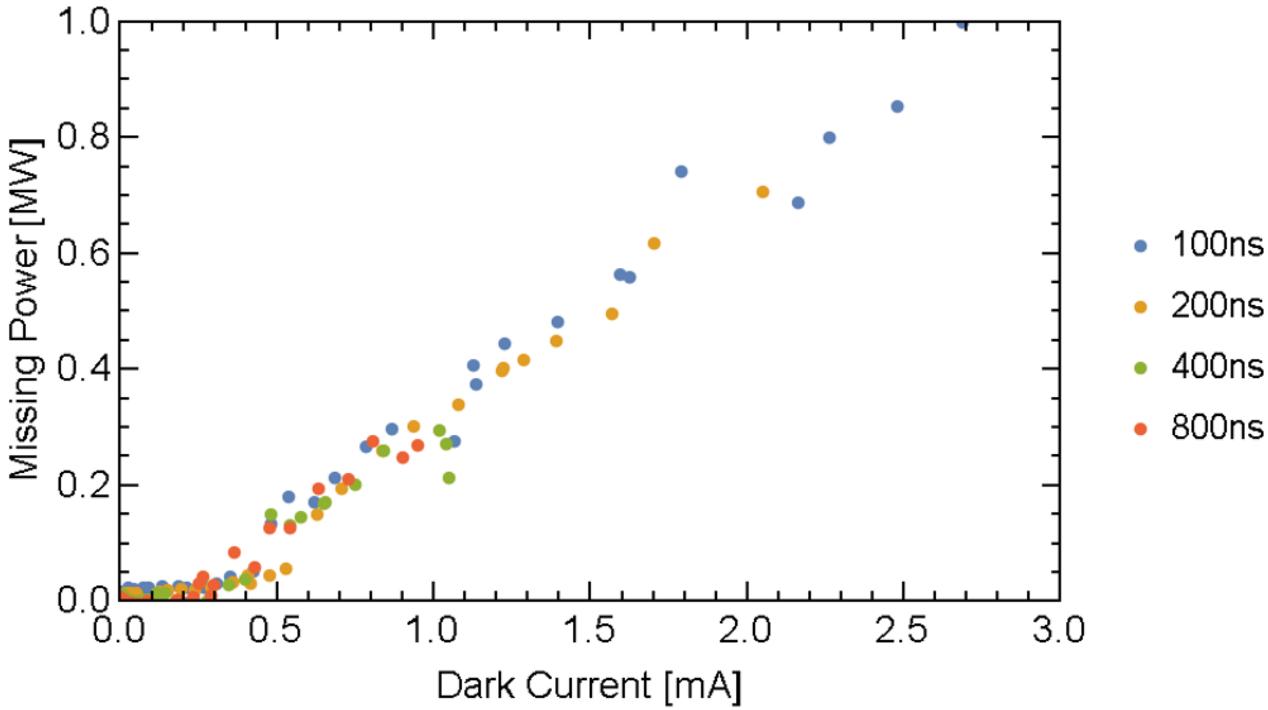
- Final Q0, is the value used to match the measured rf and dark current signals
- Data for 45 K, 30Hz, with varying flat top gradient.



Dark Current Correlated to Missing Power

The missing power is the amount of power lost not explained by the linear circuit model.

We conjecture the change in Q0 is consistent with dark current beam loading.



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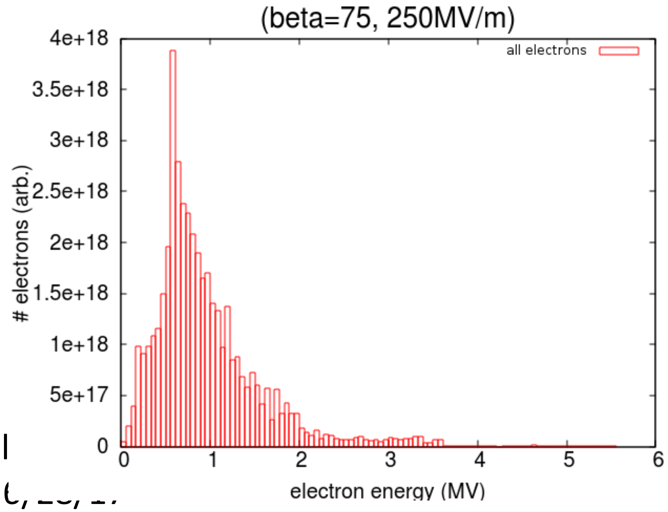
Field Emission Simulation

- Distribution of field emitted electrons
  On metal wall, up and down stream ends
- Energy spectrum of electrons when they hit a surface
- Fowler Nordheim Field emission

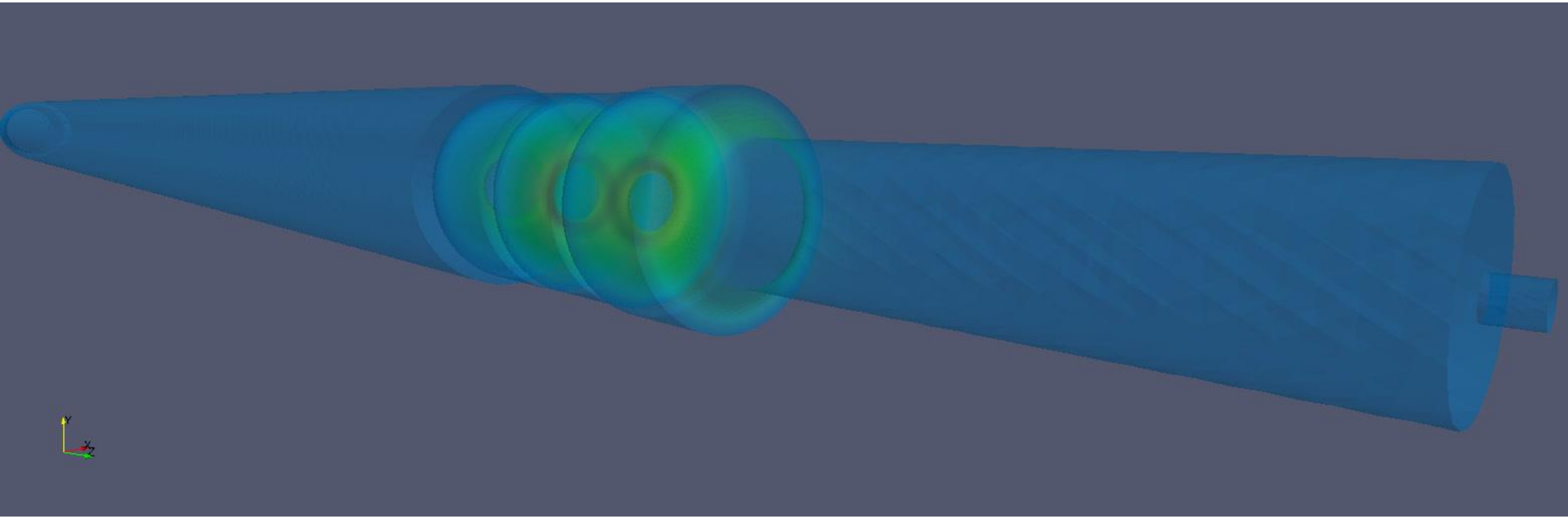
$$J(r,t) = 1.54\times10^{\left(-6+\frac{4.52}{\sqrt{\varphi}}\right)}\frac{(\beta E)^2}{\varphi}e^{\left(\frac{-6.53\times10^9\varphi^{1.5}}{\beta E}\right)}$$

- ~1% of total field emitted electrons reach current monitors
- Average power in the dark current beam predicted by this simplified model is about factor of 3 smaller than measured from Q degradation.



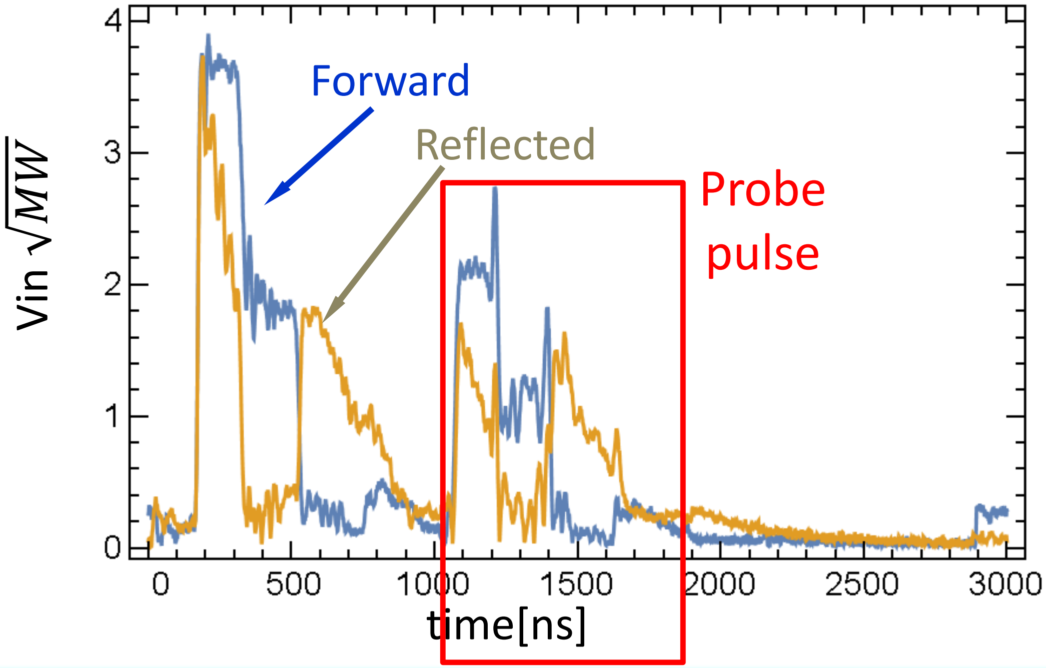
XBand Cryo Cavity - Fiel Calculation Z. Li

Time Evolution of Field Emitted Electrons

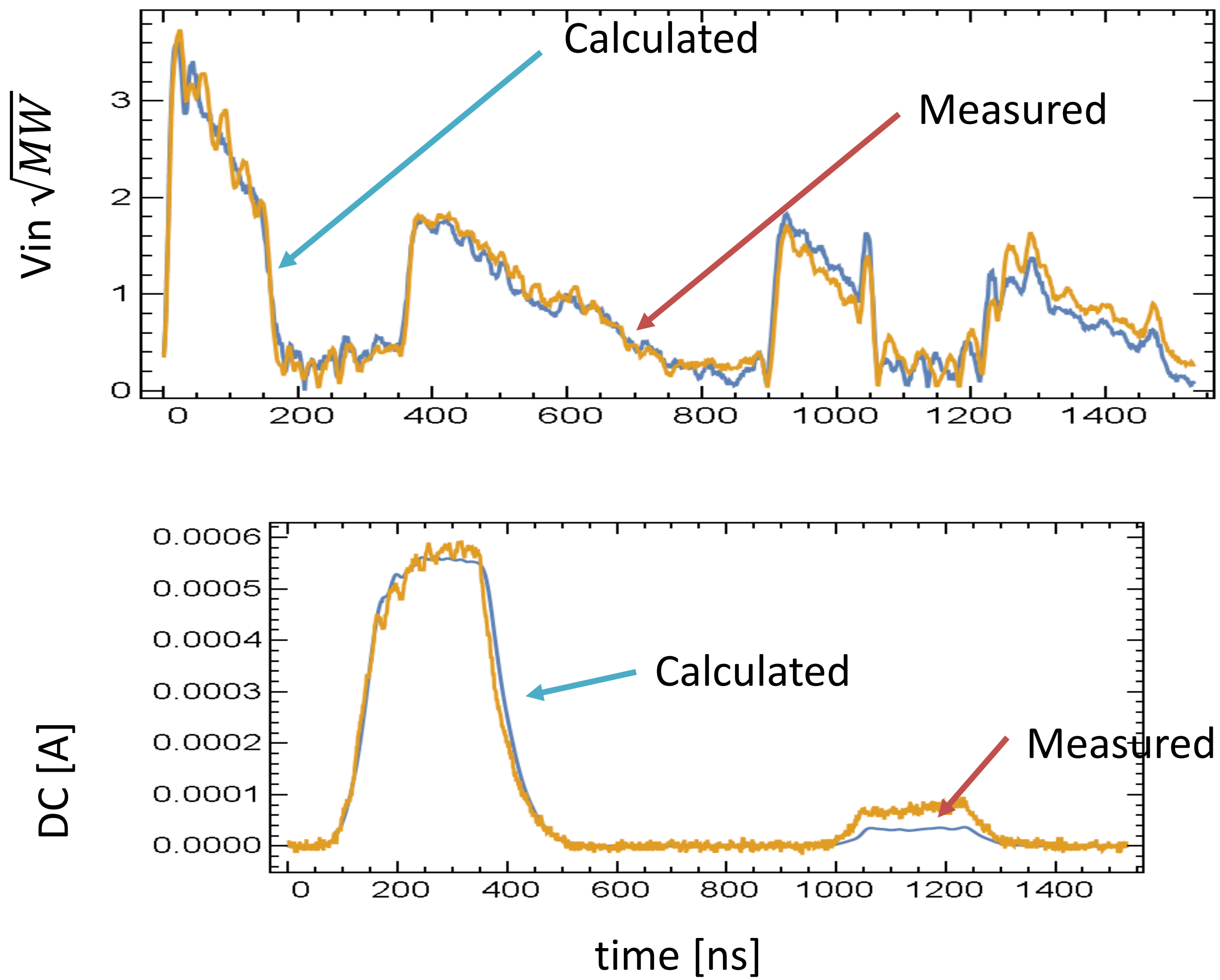


RF Pump Probe

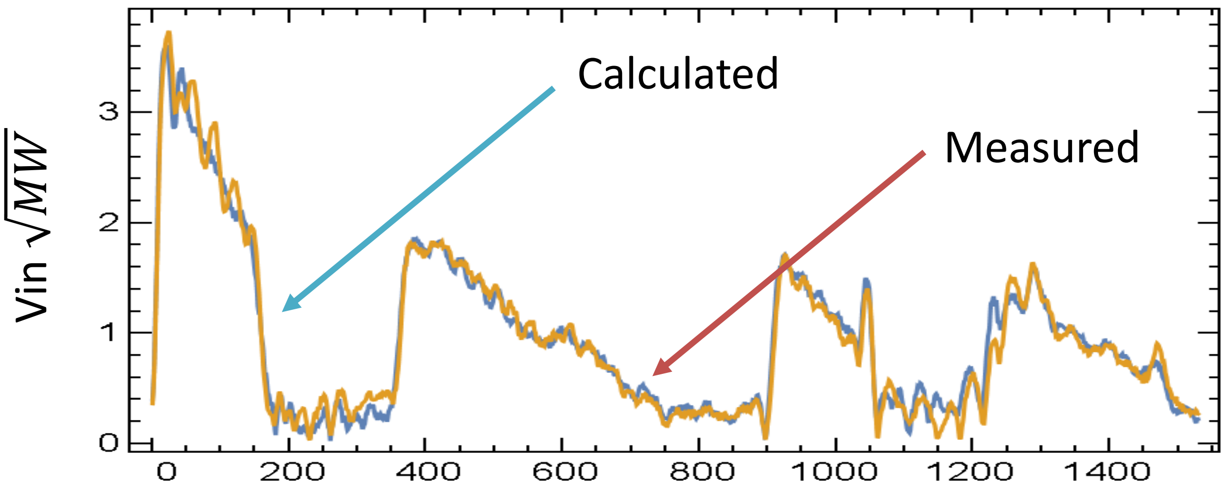
- We want to investigate how Q_0 changes after rf input pulse ends.
  - Since field is small, it is difficult to measure the value of Q_0 in that region.
- Investigate by creating two rf pulses spaced close together.

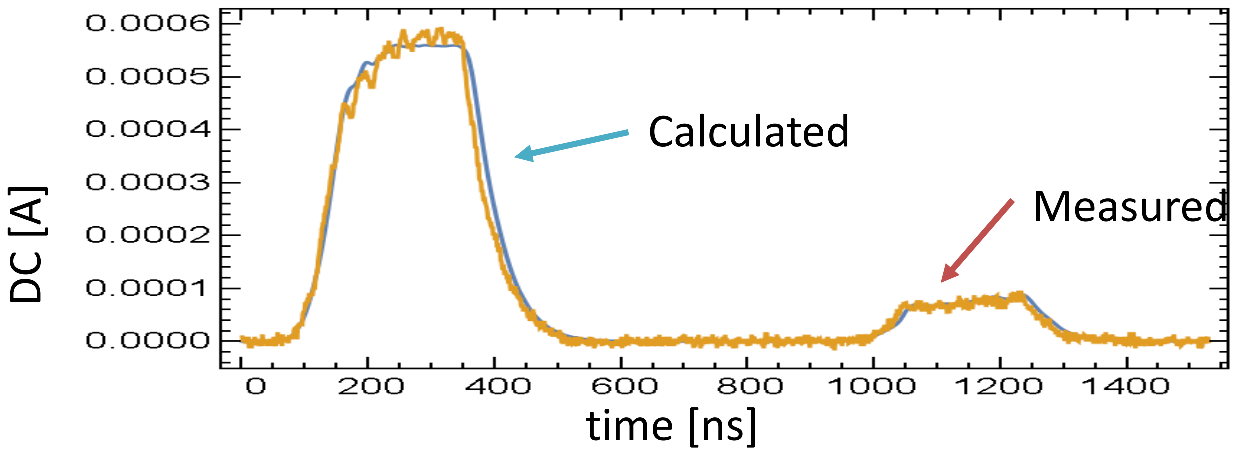


Initial Fit with Q0 that decreases and then stays at final value



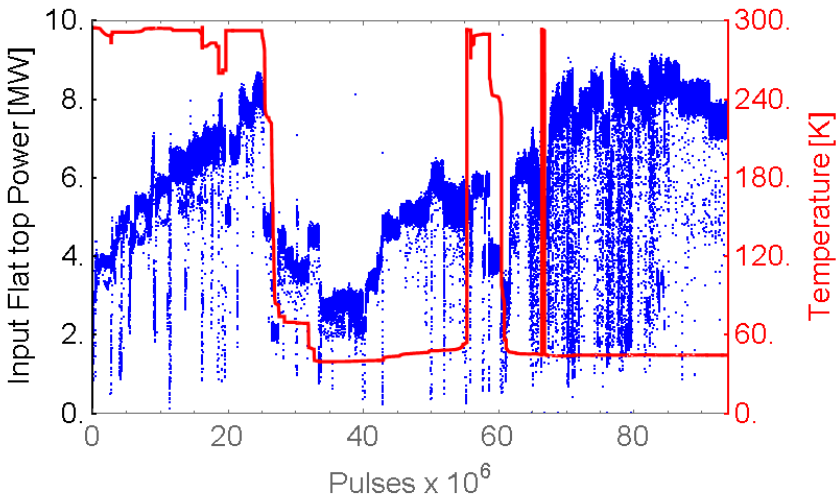
Initial Fit with Q0 that decreases and then returns to Original Value

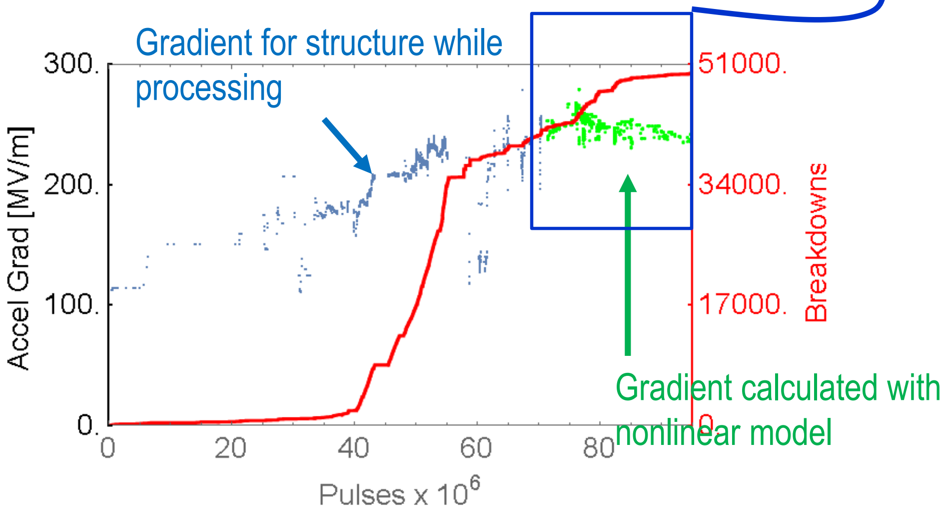


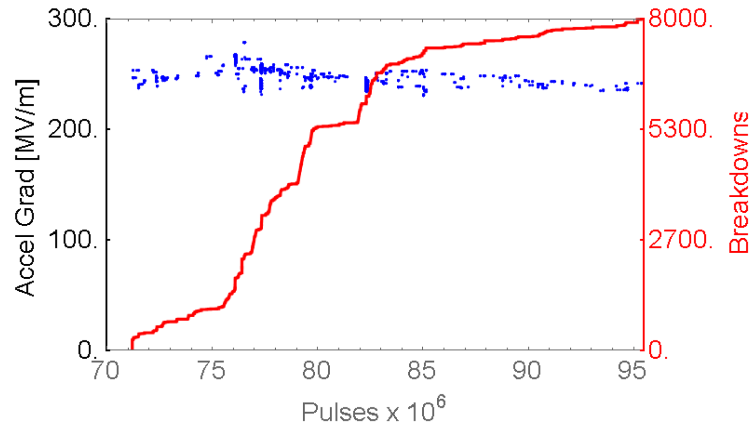


- Better fit when Q_0 returns to the large value from before rf input pulse (the cold test Q_0)

Processing History of 1C-SW-A2.75-T2.0-cryo-cu-SLAC-#2





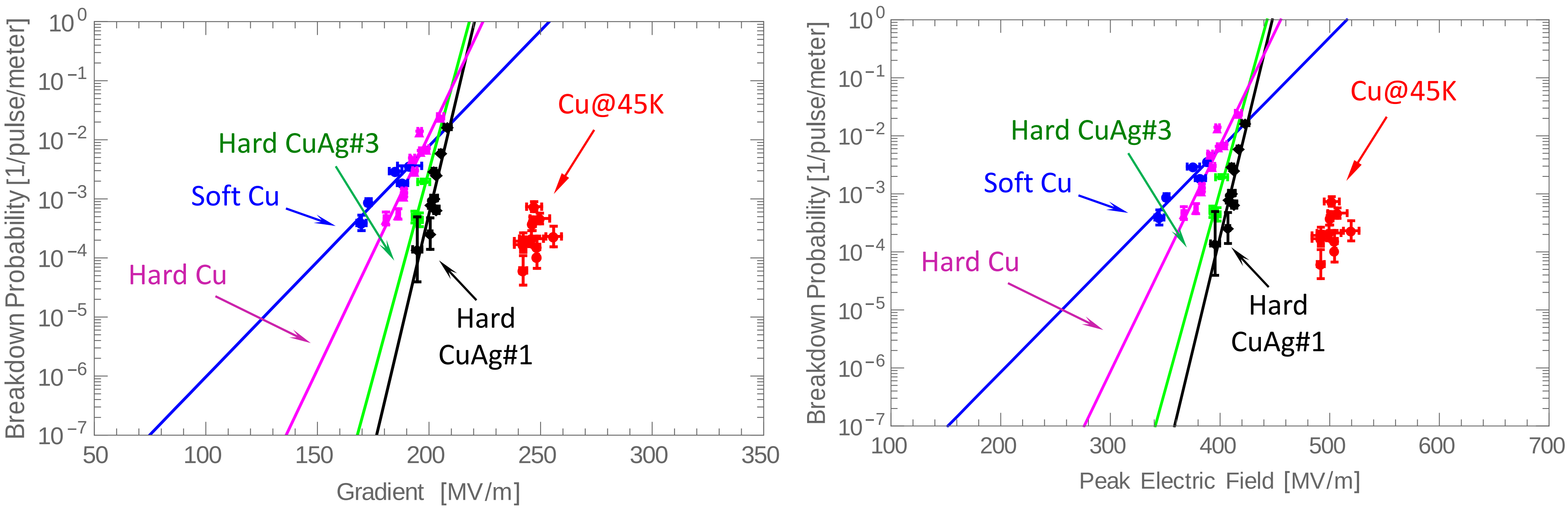


Zoom in of the data used to calculate rf breakdown statistics

AC et al. **Ultra High Gradient Breakdown Rates in X-Band Cryogenic Normal Conducting Rf Accelerating Cavities.** IPAC 17

Breakdown Rate Results

- Breakdown rate vs. gradient and peak surface electric for first rf breakdowns, 1C-A2.75-T2.0 structures, shaped rf pulse with 150 ns flat part



AC et al. **Ultra High Gradient Breakdown Rates in X-Band Cryogenic Normal Conducting Rf Accelerating Cavities.** IPAC 17

Conclusions

- Cryogenic Copper accelerating structures exhibit ultra-high gradients up to 500 MV/m peak surface electric fields with low breakdown rates.
  - We need to explore the intra-pulse change in Q_0 further, but evidence is currently consistent with beam loading due to dark currents.
  - It is possible that the other mechanisms of rf losses (i.e. resistivity increase with temperature) are also present, but the strong dependence of dark current from surface fields, likely dominates.
- We plan to apply this technology to an rf Photoinjector
- Second X-Band Structure to be tested in the coming months
  - Gradient Dependence of breakdown rate
  - Temperature dependence
- We are designing a cryostat for a S-band high gradient test

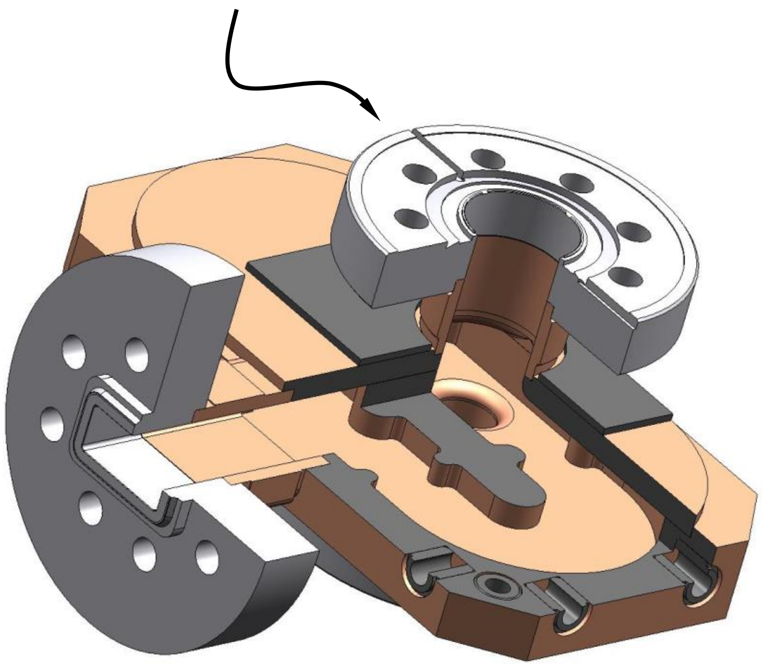
Acknowledgments

- Thanks to the DOE Office of Science Graduate Student Research (SCGSR) Program and the NSF Center for Bright Beams for funding my research at SLAC

- I would like to thank those who have contributed to this work:
  - J.B. Rosenzweig, V. Dolgashev, G. Bowden, J. Eichner, M. Franzi, A. Haase, J. Lewandowski, S. Tantawi, S. Weathersby, and C. Yoneda

BACKUP SLIDES

Reusable coupler: TM_{01} Mode Launcher



Cutaway view of the mode launcher

Two mode launchers

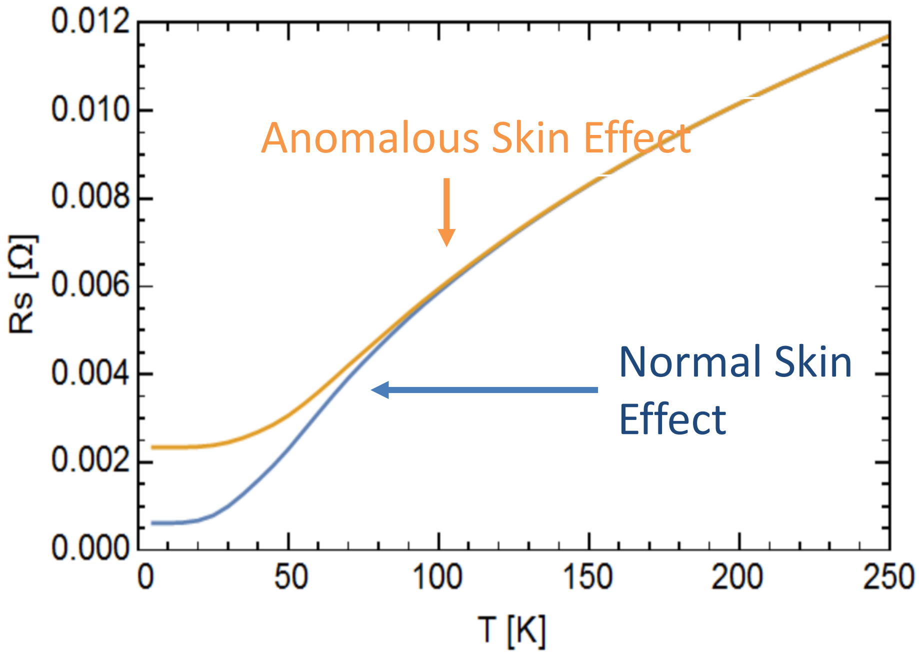
Surface electric fields in the mode launcher
E_{max}= 49 MV/m for 100 MW

V. Dolgashev, S. Tantawi, C. Nantista

RF Surface Resistance Decreases

- As the mean free path approaches the skin depth in magnitude Ohm's law no longer holds.
  - Boltzmann's equation can be numerically integrated.
- In the limit $l \gg \delta$ the surface resistance approaches a limit independent of conductivity.
  - Does not depend on the purity or RRR of the copper.

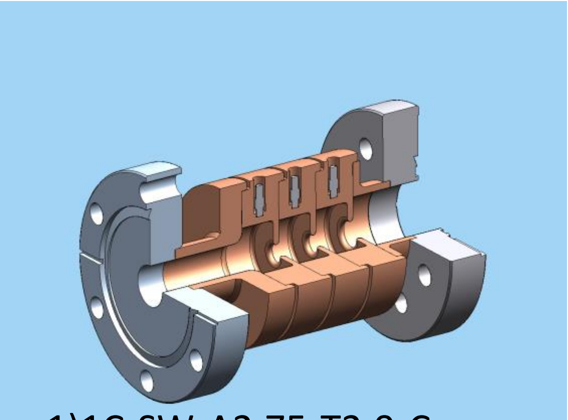
$$Z_\infty = \left(\sqrt{\frac{3\pi\omega^2 m_e^* v_d}{ne^2}}\right)^{1/3}(1+\imath\sqrt{3})$$



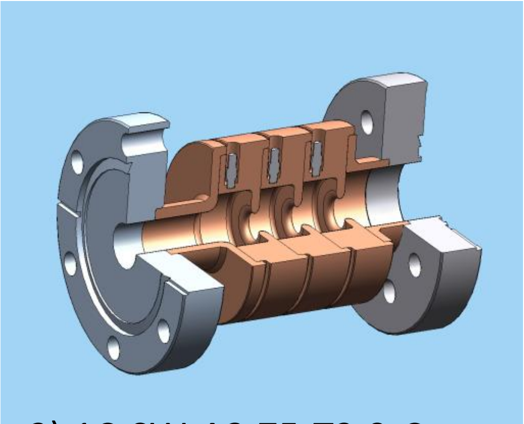
Comparison of surface resistance in NSE and ASE cases. f=2.856 GHz, σ_{room}=7.42 x 10^9 S/m, RRR=400

- Less rf power is required, and less rf pulse heating is created, for a given accelerating gradient.

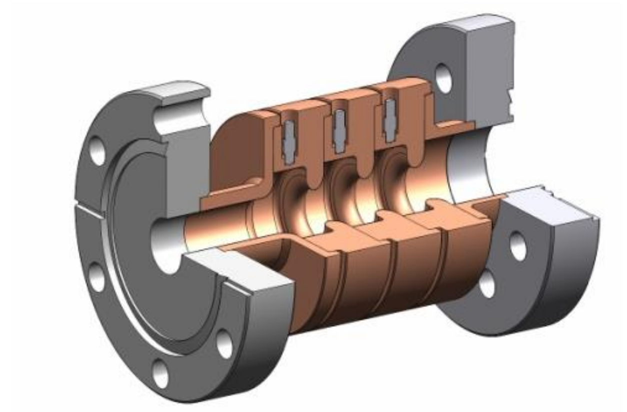
Geometrical Studies
Three Single-Cell-SW Structures of Different Geometries



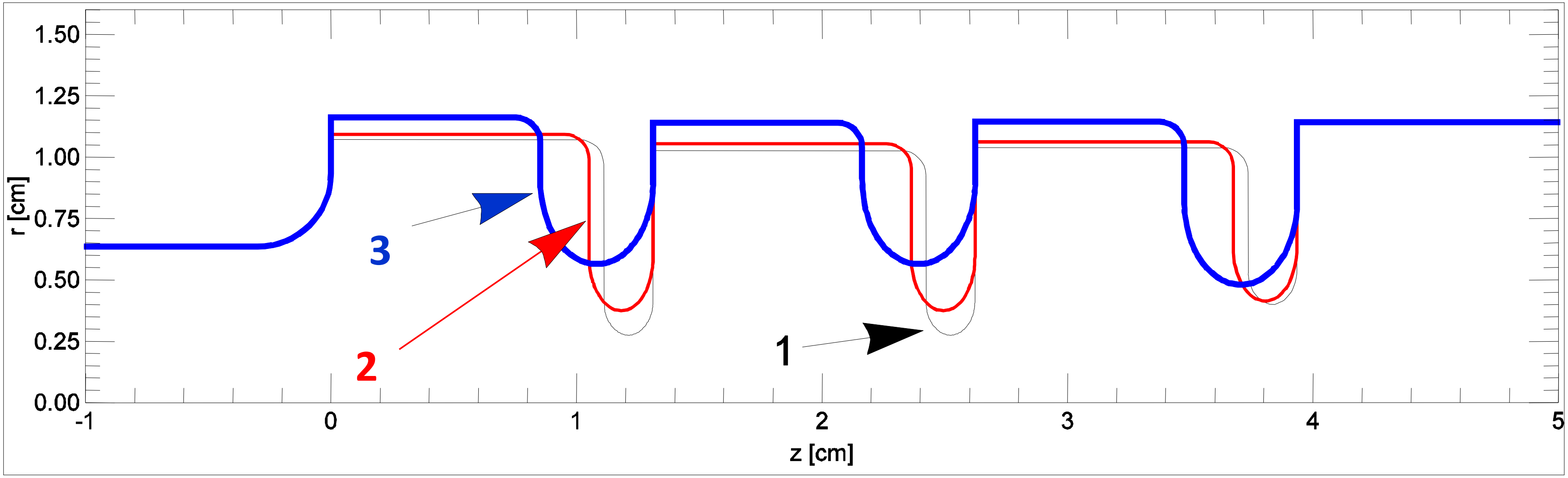
1)1C-SW-A2.75-T2.0-Cu



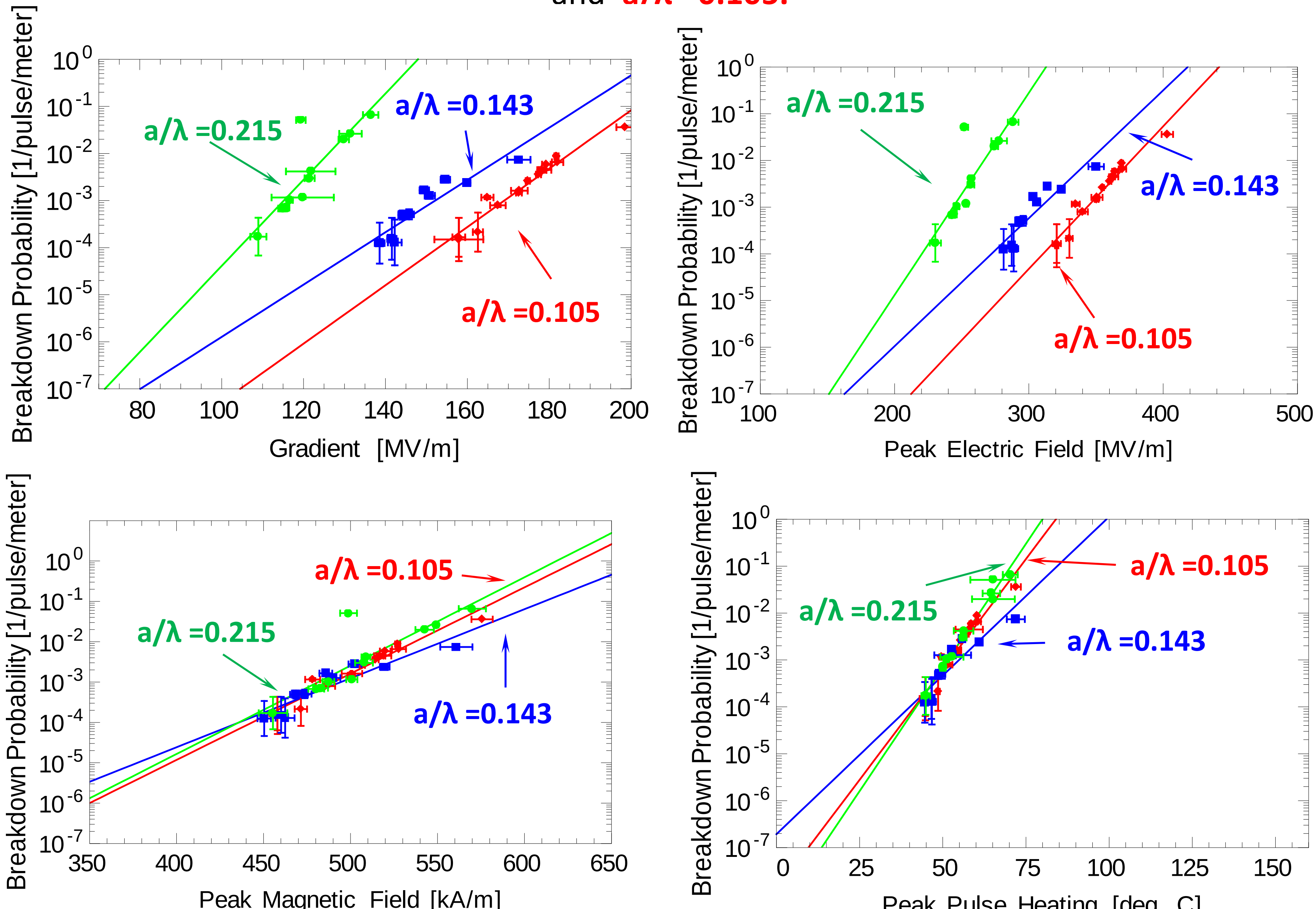
2) 1C-SW-A3.75-T2.0-Cu



3) 1C-SW-A5.65-T4.6-Cu



Standing-wave structures with different iris diameters: a/λ =0.215, a/λ =0.143, and a/λ =0.105.



Geometry and material properties plays a major role in determining the accelerating gradient and breakdown performance:

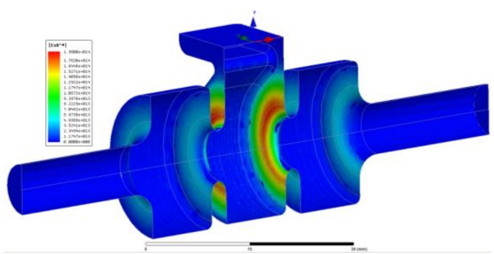
Local electric field seems to have less importance than magnetic field

Consequences :

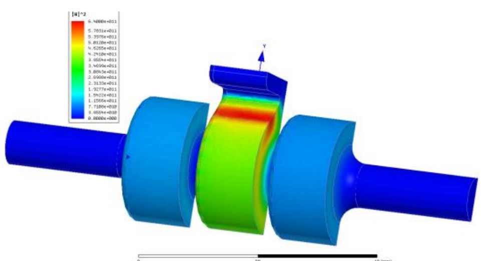
- New geometries optimized for low pulse heating
- Experiments that uncouple rf electric and magnetic fields
- Dedicated study of pulse heating
  - Lisa Laurent et al., *Experimental study of rf pulsed heating,* Phys. Rev. ST Accel. Beams 14, 041001 (2011)
  - S. Heikkinen, *Study of High Power RF Induced Thermal Fatigue in the High Gradient Accelerating Structures, Ph.D. thesis,* Helsinki University of Technology, Finland (2008).
- Hard copper allows resistant to pulse heating damage
- Clad materials
- Cryo-experiments with normal conducting structures
- Methods of building structures without extreme heat treatment

Structures that have different ratio between peak Poynting vector and peak H^2

1C-SW-A3.75-T2.6-1WR90-Cu



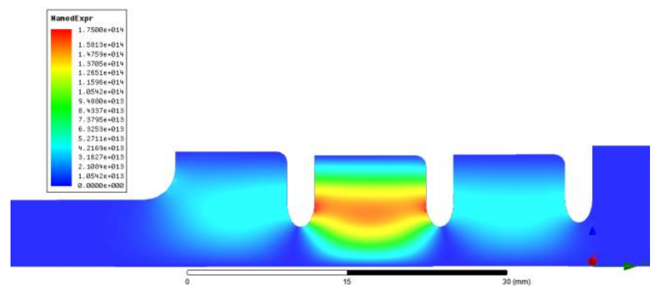
Max. Poyning Vector
1.93 e14 W/m^2



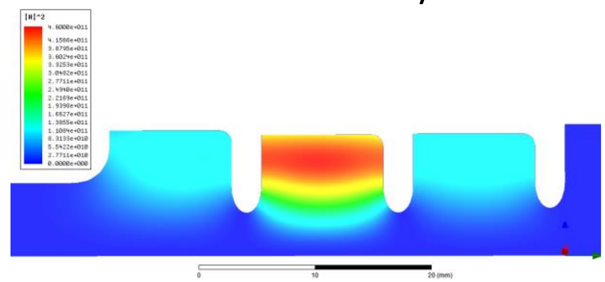
Max. |H^2| 6.4e11 (A/m)^2

Ratio is **301 Ohm**

1C-SW-A3.75-T2.6-Cu



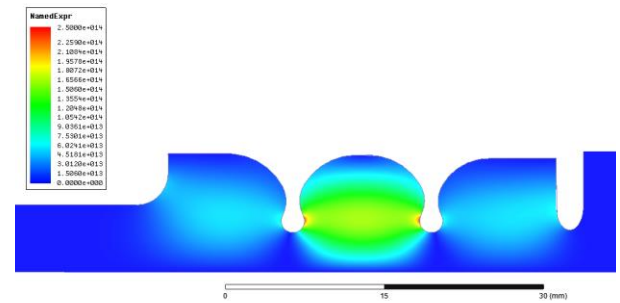
Max. Poyning Vector
1.73 e14 W/m^2



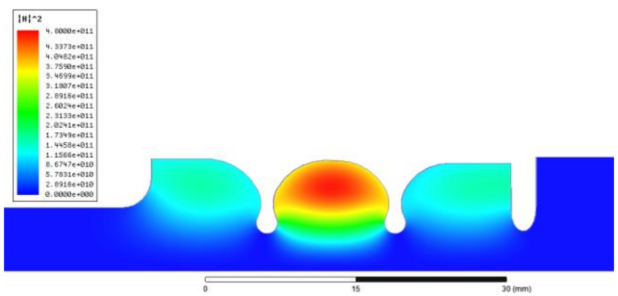
Max. |H^2| 4.44e11 (A/m)^2

Ratio is **390 Ohm**

1C-SW-A3.75-T2.2-Cu



Max. Poyning Vector
2.4e14 M/m^2



Max. |H^2| 3.8e11 (A/m)^2

Ratio is **632 Ohm**

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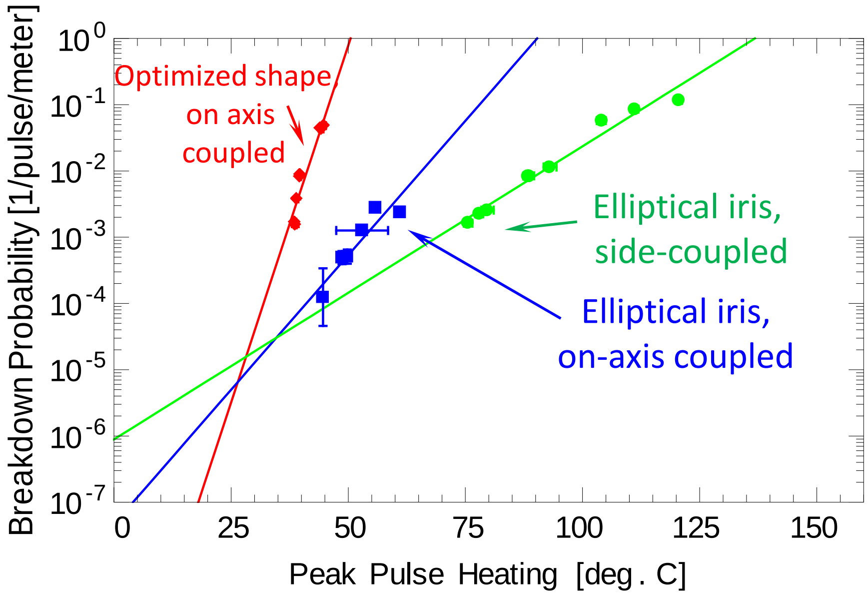
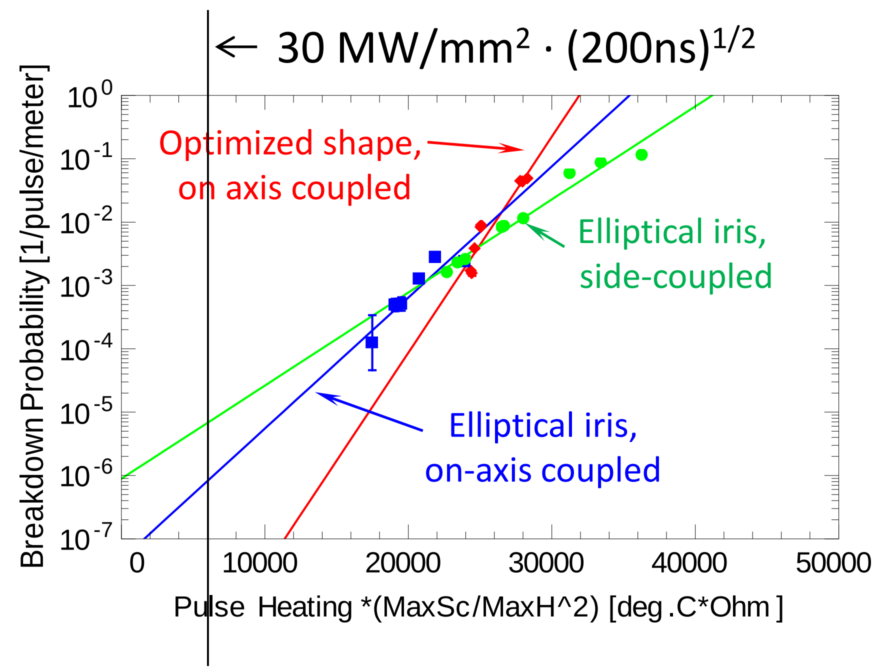
Pulse heating vs. Poynting vector

Comparison of two on-axis coupled structures and one side-coupled structure of 3.75 mm aperture, shaped pulse with 200 ns flat part





For structures of significantly different geometries breakdown rate better correlated more with peak Poynting vector than with peak surface pulse heating.

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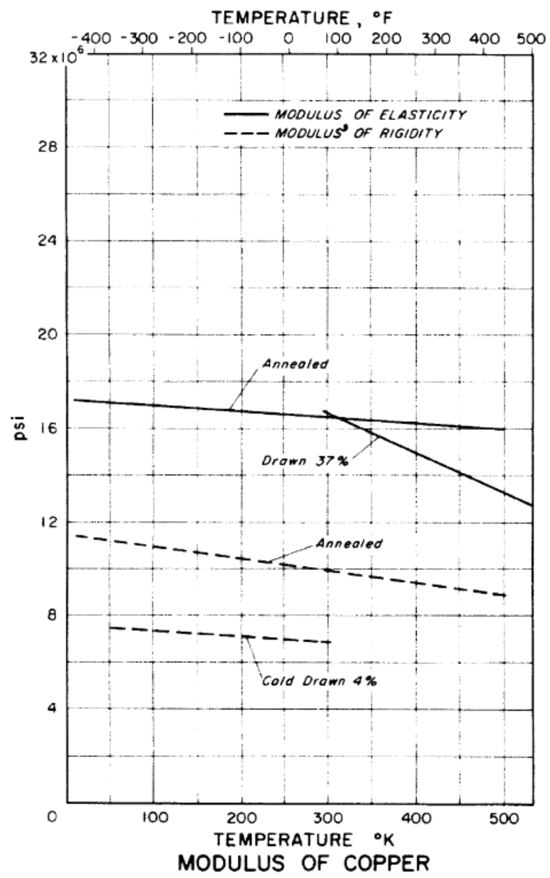
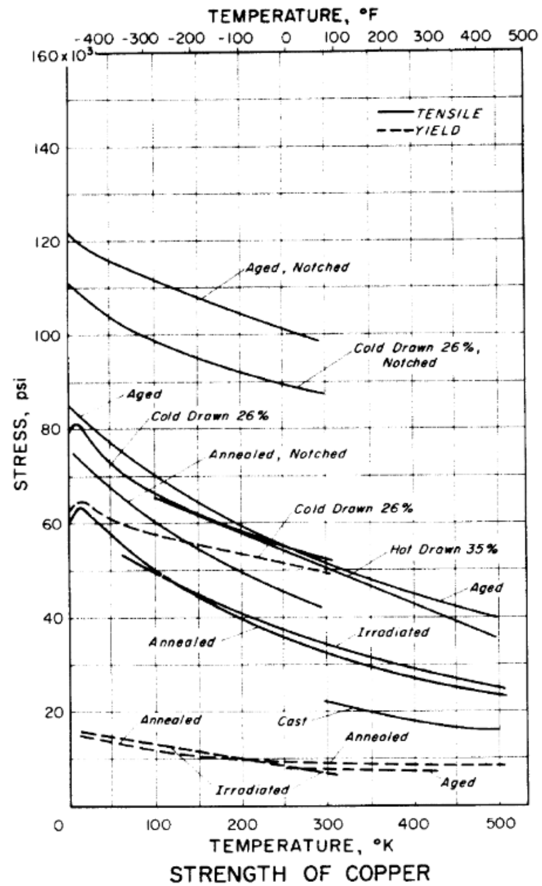
Copper is Harder at Cryogenic Temperatures

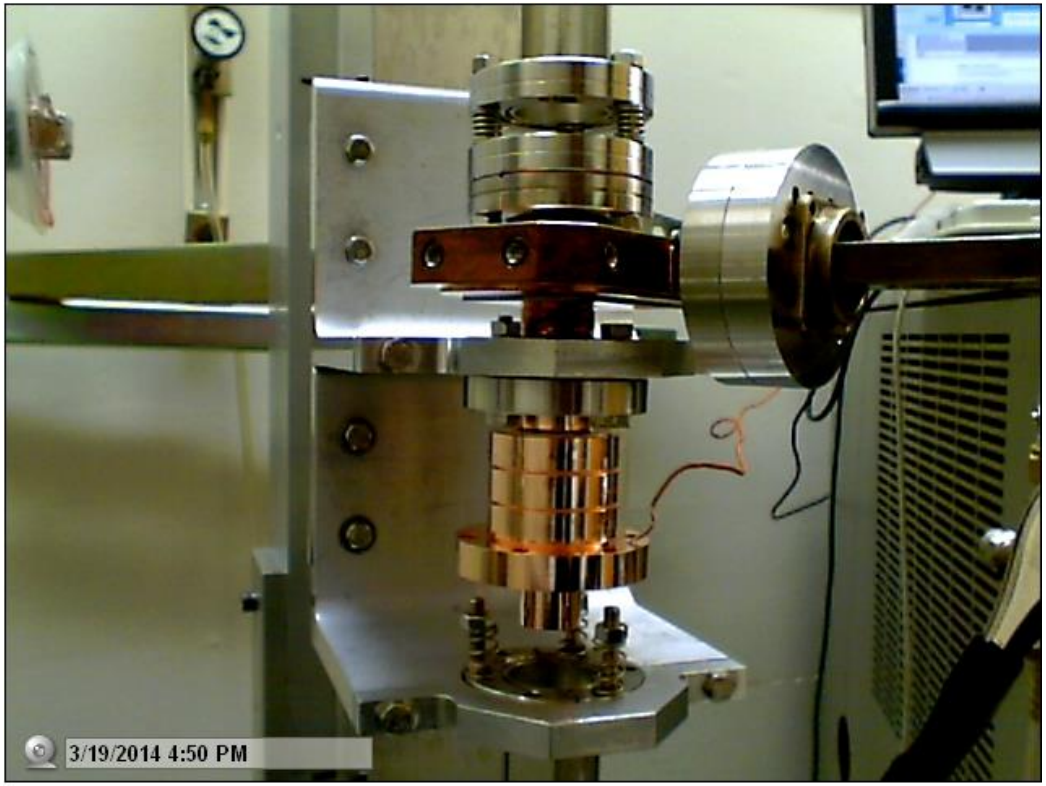
- The increased Yield strength shows that the material is harder.
- Young's modulus also increases.

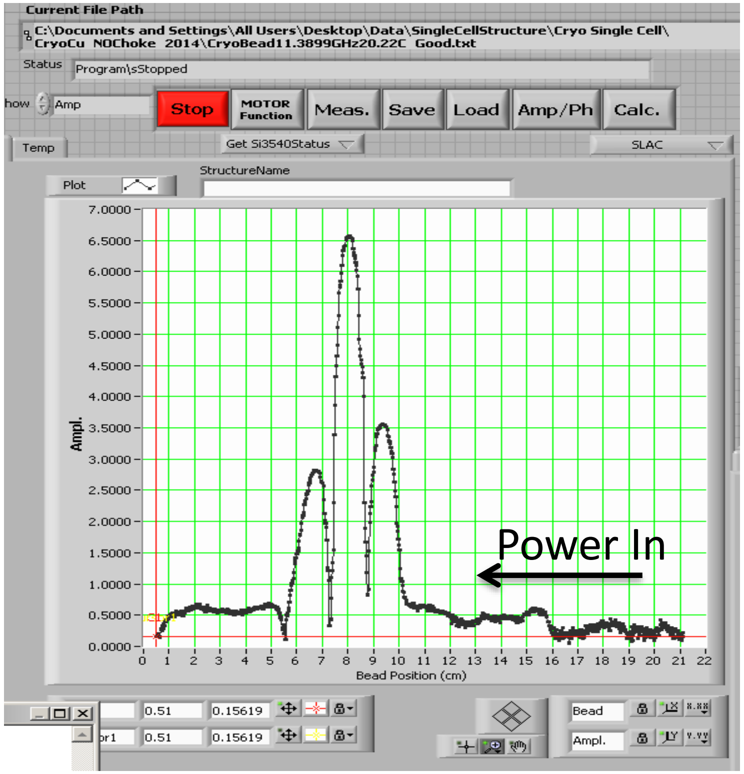




NBS Monograph 101:
Low Temperature Mechanical Properties of Copper and Selected Copper Alloys. R. Reed and R. Miksell. NBS

Beadpull of 1C-SW-T2.75-A2.0-Cryo-Cu-#2



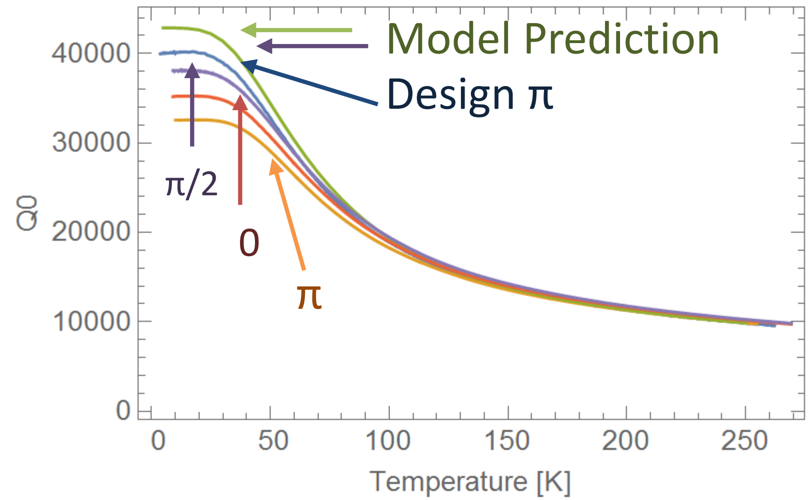


Beadpull setup

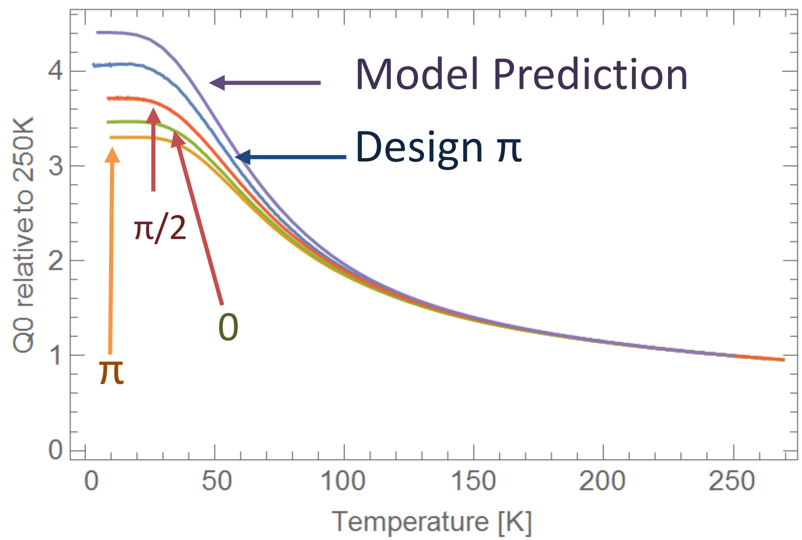
Measured on-axis field profile

Q_0 Different for Different Modes

- The increase in Q_0 with temperature varies between the three modes (0, π, π/2) of the Cryo Cavity.
- We hypothesize this is due to damage during or after high power experiments: the π mode has highest field in center cell and has lowest Q_0, π/2 has nearly no field in center cell and has the highest Q_0



Q_0 values in cryo cavity compared to copper in TE dome cavity and analytic value for max Q_0 value

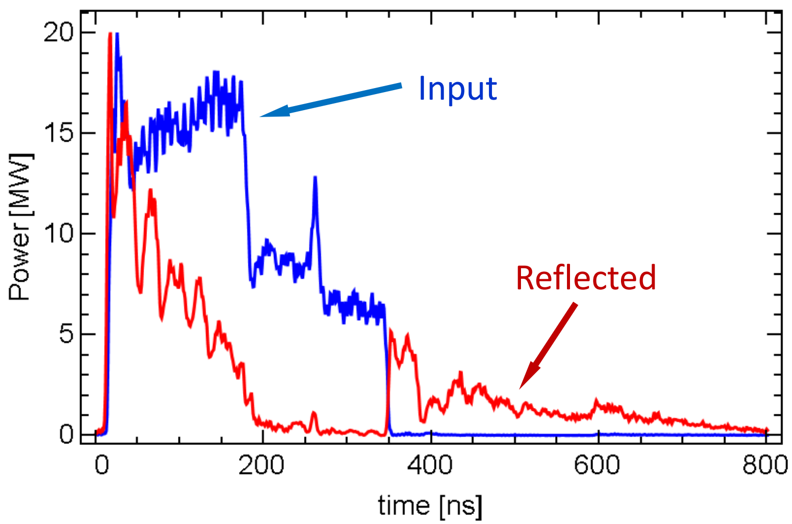


Data from above plot normalized to Q_0 value at 250K to illuminate trends

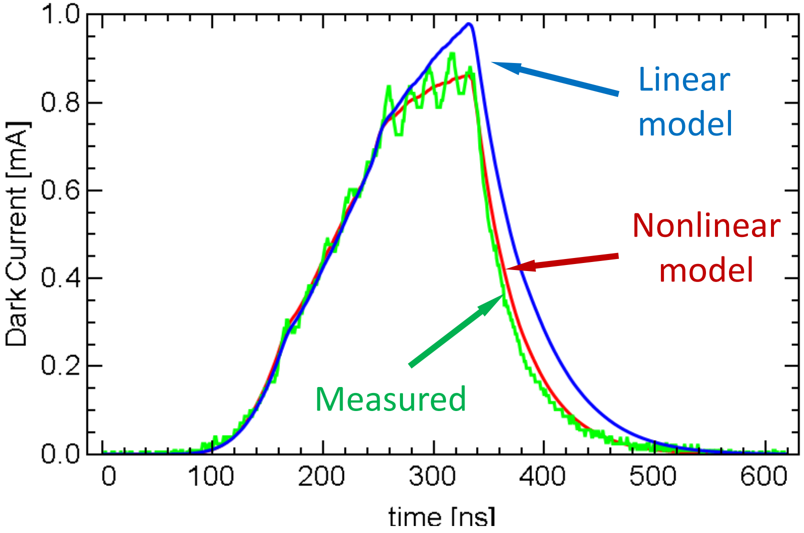
Matt Franzi,
Jim Lewandowski

Example Pulse From Breakdown Rate Test

Shaped pulse with 150 ns flat part. Cavity temperature is 45 K.
Average power during flat part of the pulse: 7.6 MW.
Qo decreases from 30,400 to 19,700.
Accelerating Gradient: 247 MV/m for linear model and 237 MV/m for model with dynamically changing Qo.



RF power vs. time



Dark current signal vs. time