Materials Testing With a High-Q RF Cavity

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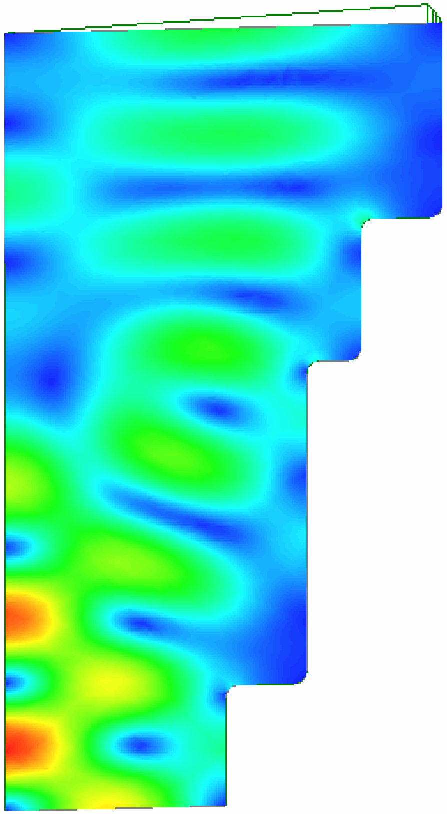
Abstract

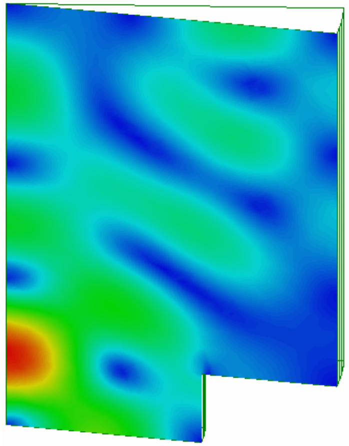
Superconducting rf is of increasing importance in particle accelerators. We have developed a resonant cavity with high quality factor and an interchangeable wall for testing of superconducting materials. A compact TE_{01} mode launcher attached to the coupling iris selectively excites the azimuthally symmetric cavity mode, which allows a gap at the detachable wall and is free of surface electric fields that could cause field emission, multipactor, and rf breakdown. The shape of the cavity is tailored to focus magnetic field on the test sample. We describe cryogenic experiments conducted with this cavity. An initial experiment with copper benchmarked our apparatus. This was followed by tests with Nb and MgB_2. In addition to characterizing the onset of superconductivity with temperature, our cavity can be resonated with a high power klystron to determine the surface magnetic field level sustainable by the material in the superconducting state. A feedback code is used to make the low level RF drive track the resonant frequency. We will also use our resonant cavity design to study the effects of high power pulsed heating on normal conducting surfaces.

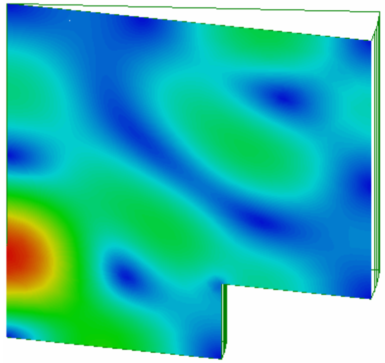
Finding the Right Cavity Shape

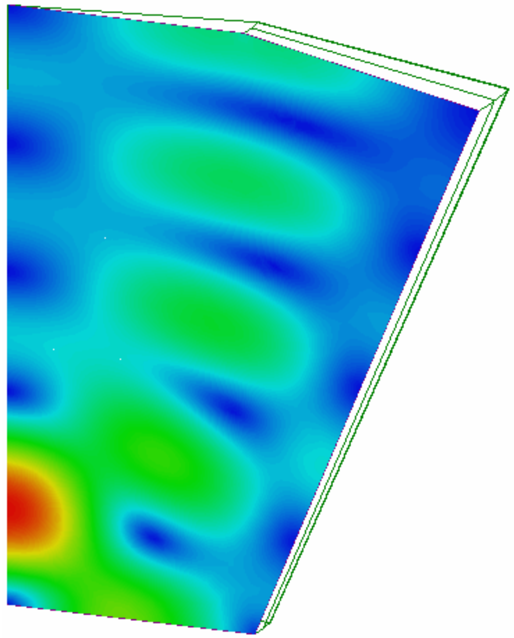
TE$_{01n}$ pillbox

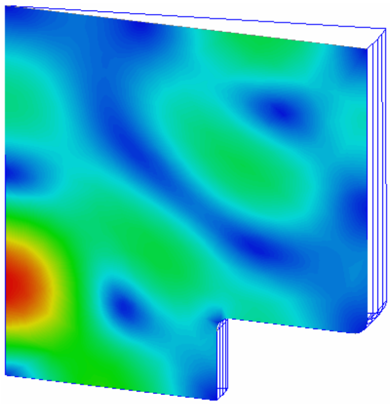
(field same on top and bottom)

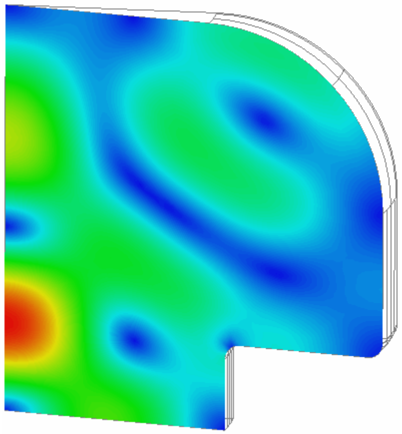


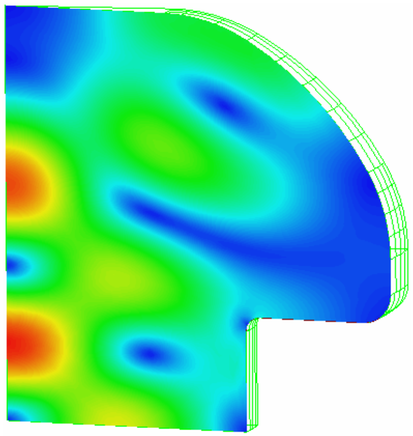




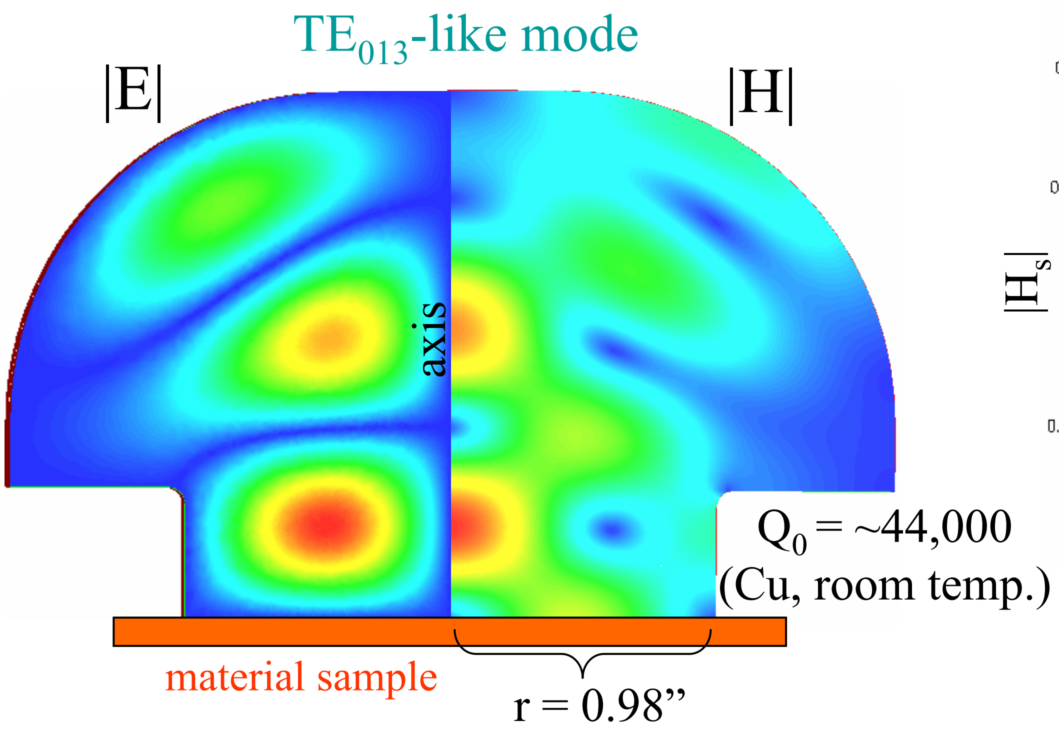


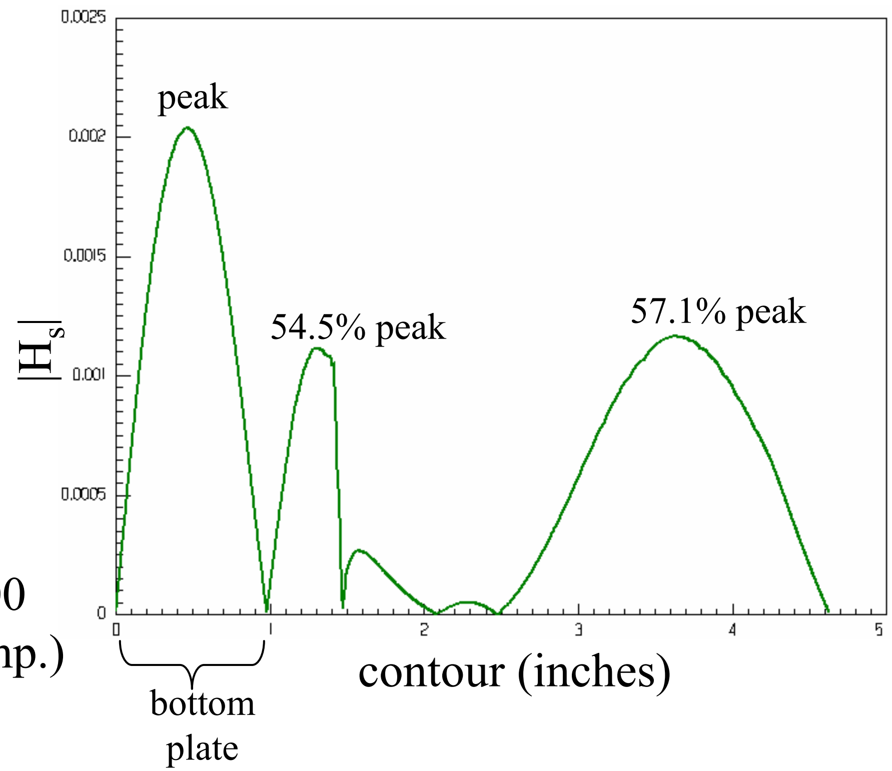






The Mushroom Cavity





Why X-band (~11.424 GHz)?:

- high power & rf components available
- fits in cryogenic dewar
- small (3”) samples required

Features:

- No surface electric fields (no multipactor)
- Magnetic field concentrated on bottom (sample) face (75% higher than anywhere else)
- Purely azimuthal currents allow demountable bottom face (gap).

Other Nearby Resonance Modes:

6.8% mode separation for axisymm. TE modes.

	Frequency (GHz)
Mode 1	(9.45389e+000, 0.00000e+000)
Mode 2	(1.14234e+001, 0.00000e+000)
Mode 3	(1.22026e+001, 0.00000e+000)

4.0% mode separation from axisymm. TM mode.

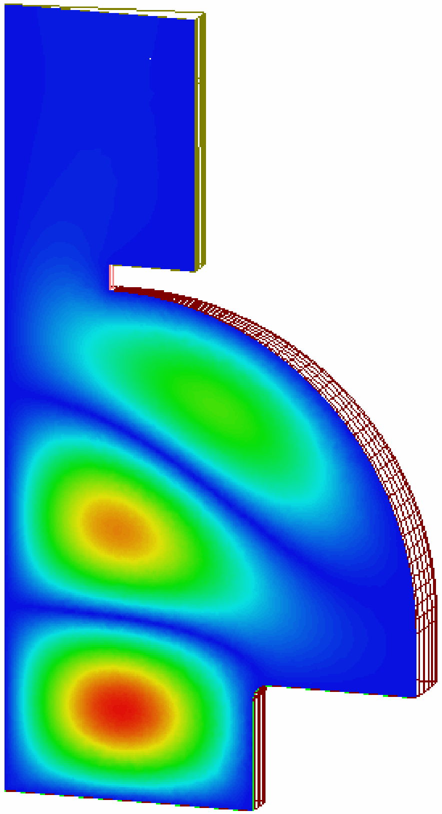
	Frequency (GHz)
Mode 1	(1.09513e+001, 0.00000e+000)
Mode 2	(1.18826e+001, 0.00000e+000)
Mode 3	(1.28660e+001, 0.00000e+000)

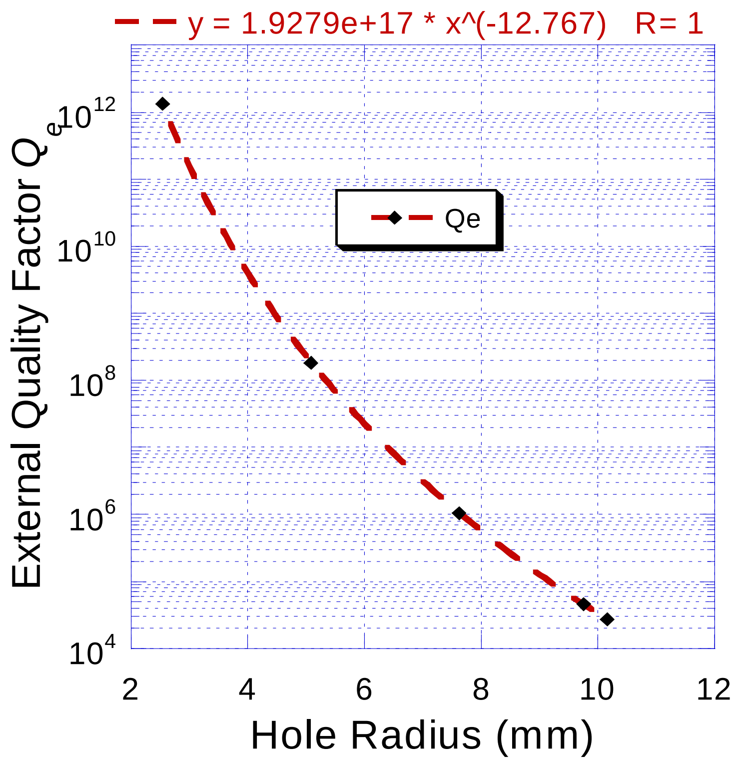
1.4% mode separation from non-axisymm. mode.

	Frequency (GHz)	
Mode 1	(1.10167e+001, 0.00000e+000)	TE_{131}
Mode 2	(1.15877e+001, 0.00000e+000)	$TM_{32?}$
Mode 3	(1.15983e+001, 0.00000e+000)	

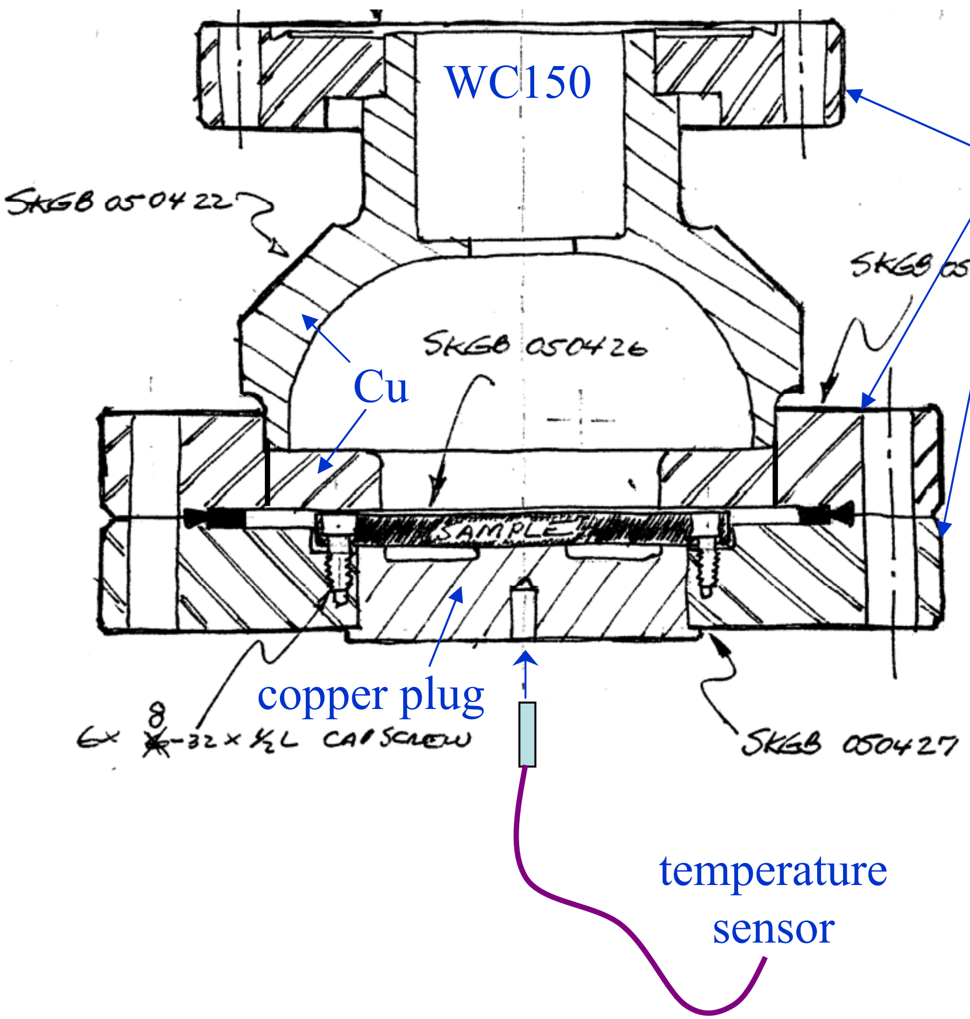
Couple on axis with pure axisymmetric tranverse electric mode TE_{01} in circular waveguide.

WC150
(3.81 cm diam.)

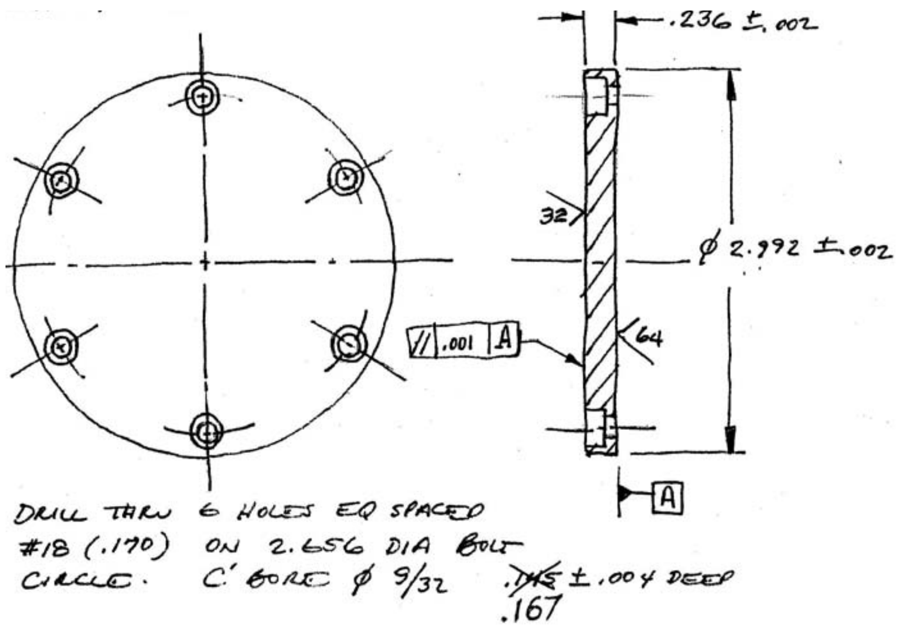




Mechanical Design

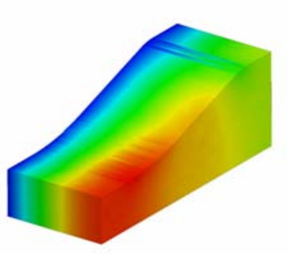


Sample Dimensions

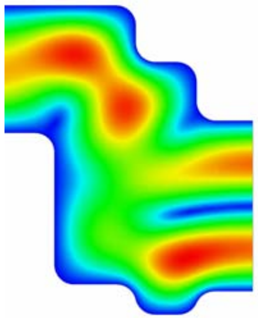


WR90-WC150 Compact High-Purity TE_{01} Mode Launcher

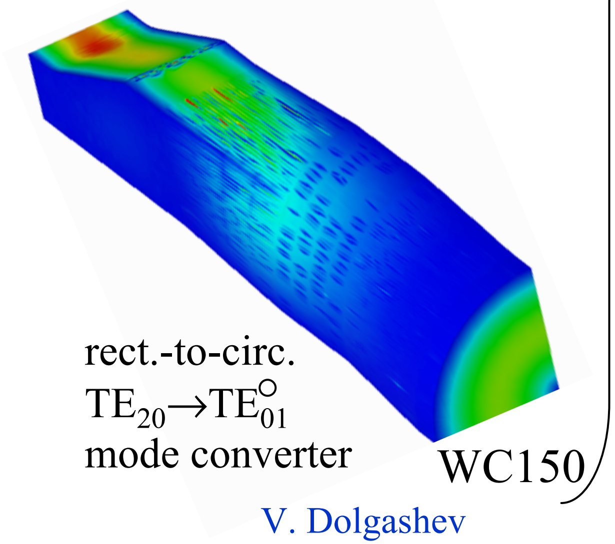
WR90



height taper (.400”→.800”)



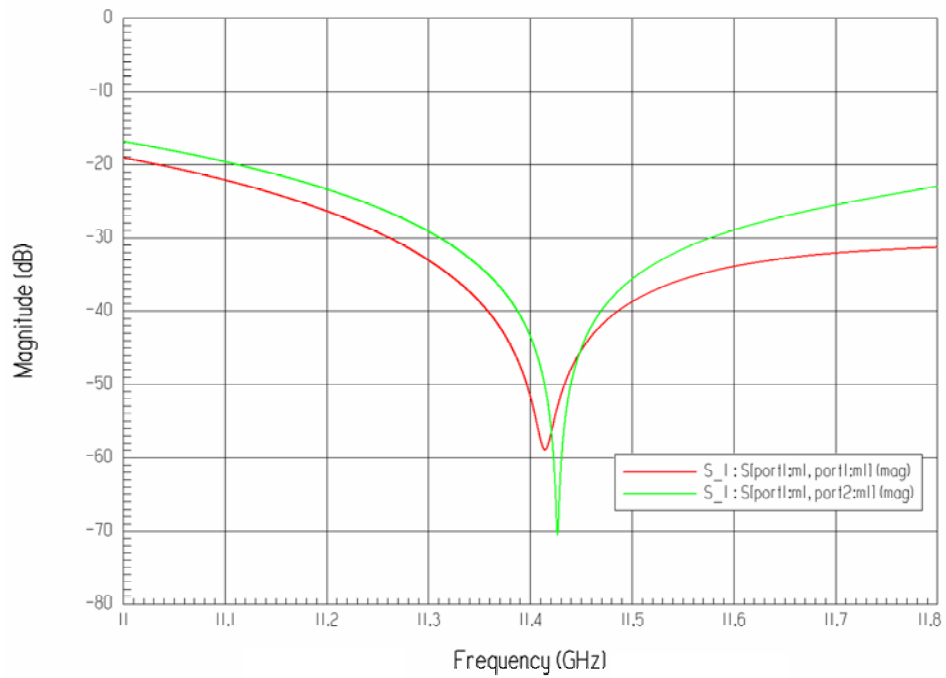
planar TE_{10}→TE_{20} converter



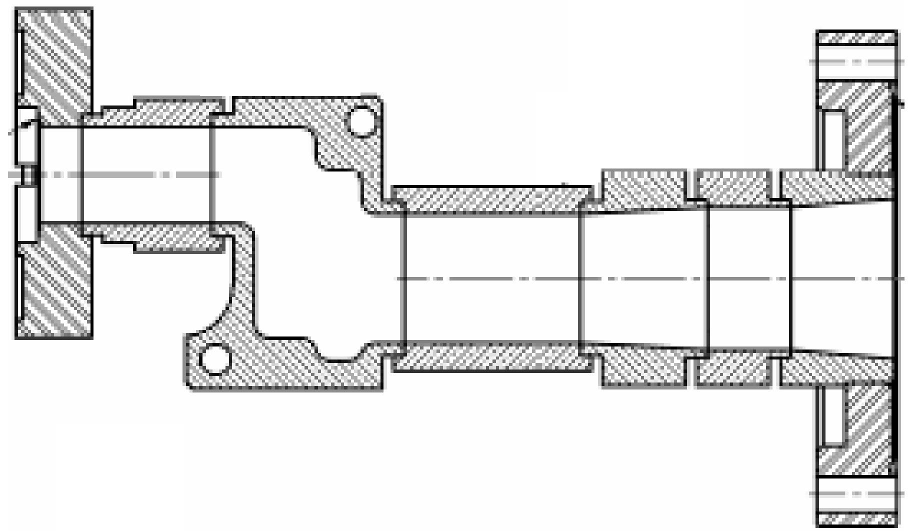
rect.-to-circ. TE_{20}→TE°_{01} mode converter

WC150

V. Dolgashev

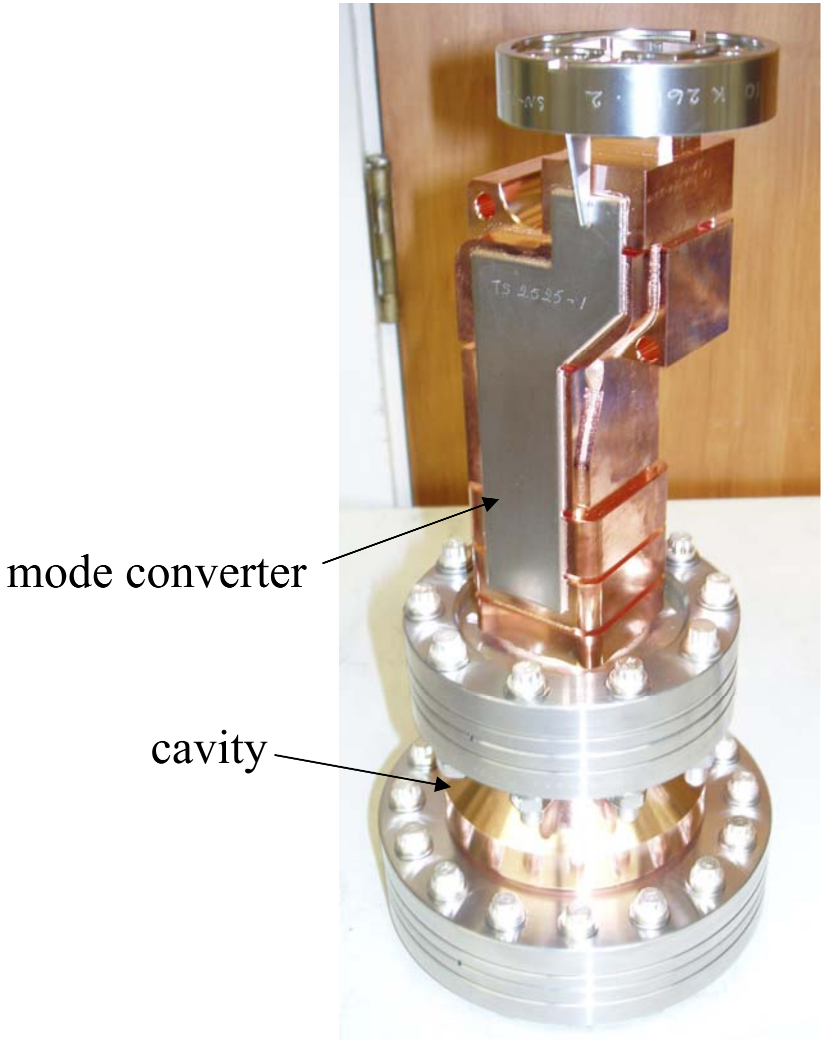


TE_{10}

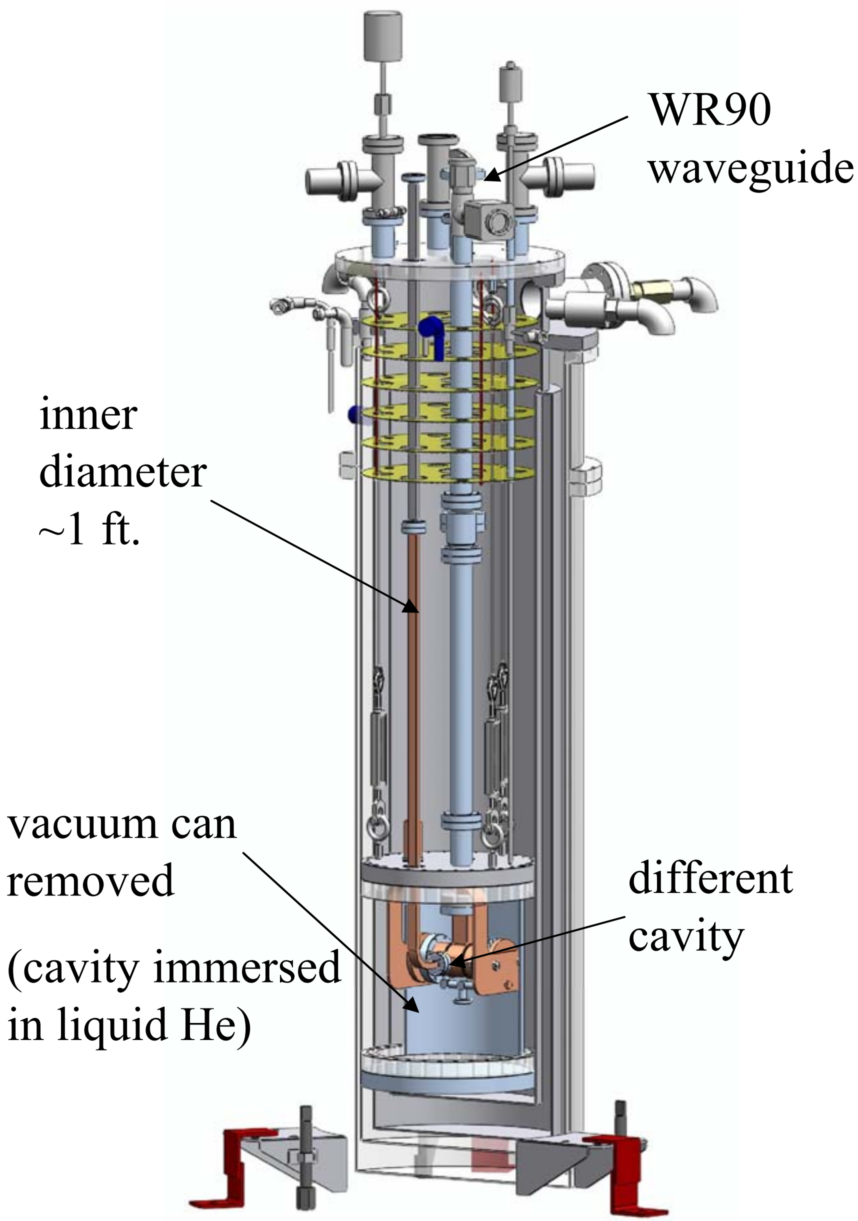


TE°_{01}

Assembly



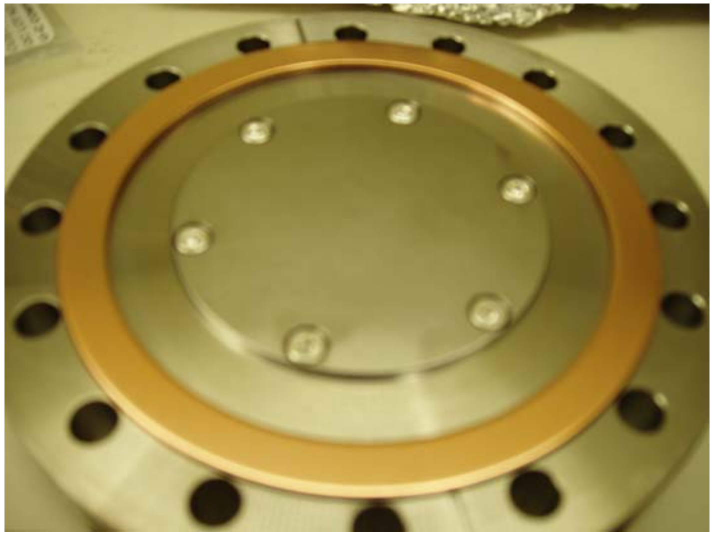
Cryogenic Dewar



“Cold” Tests (Room Temperature)

room temp. measurements

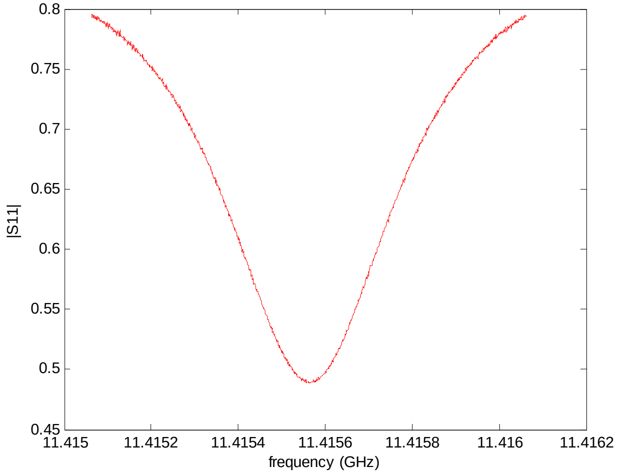
	HFSS (Cu)	Copper	Niobium
f_r	11.424	11.4072	11.4061
Q_L	30,991	29,961	20,128
β	0.4383	0.4611	0.2728
Q_0	44,575	43,775	25,619
Q_e	101,694	94,944	93,906

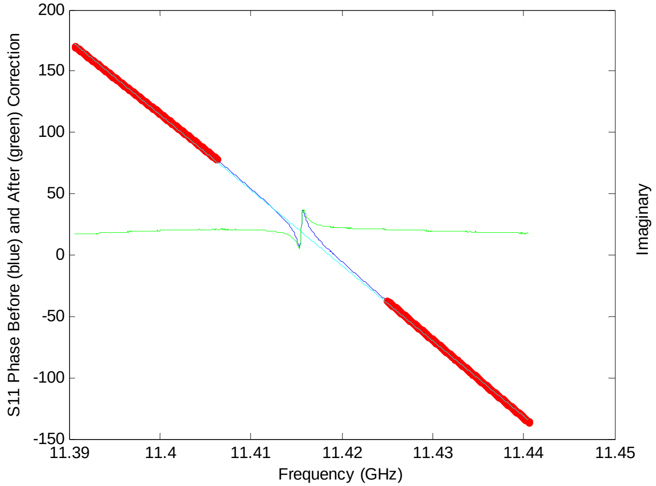


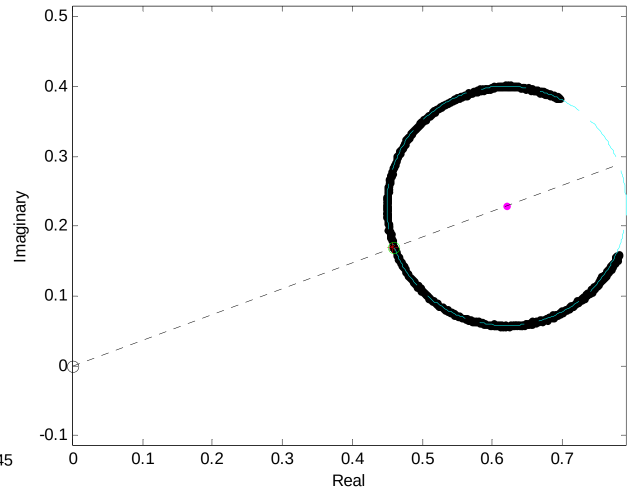
Nb sample mounted in bottom flange

HP 8510C Network Analyzer

Processing Cold Test Data







Complex S_{11} is measured with 1601 points in 1 megaherz around resonance.

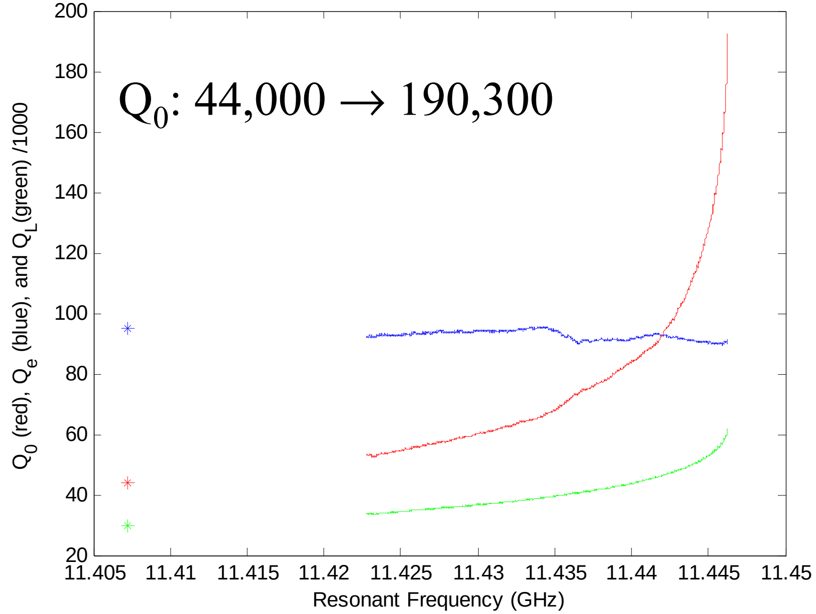
Phase slew due to input waveguide, determined from a 50 MHz measurement is subtracted from 1 MHz data.

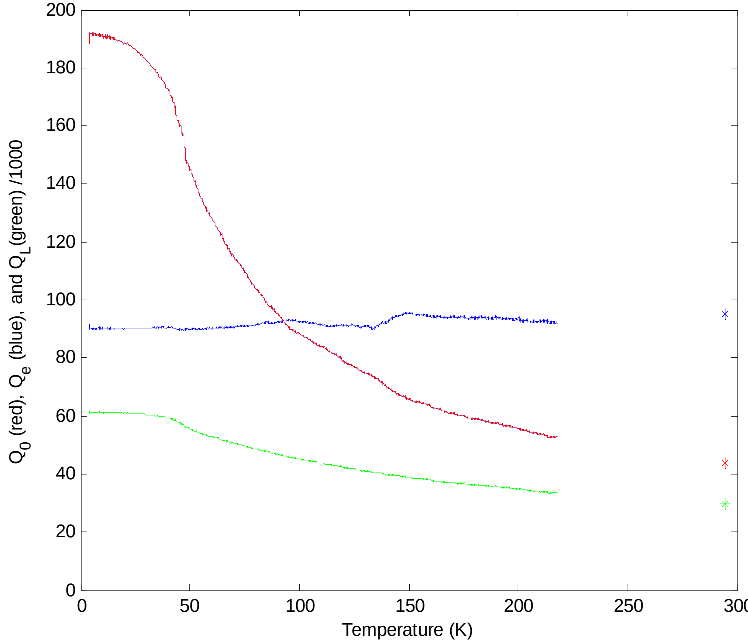
A “Q circle” is fit to the corrected S_{11} data in the complex plane to determine f_r, β, and Q_L are determined.

From these Q_0 and Q_e are derived.

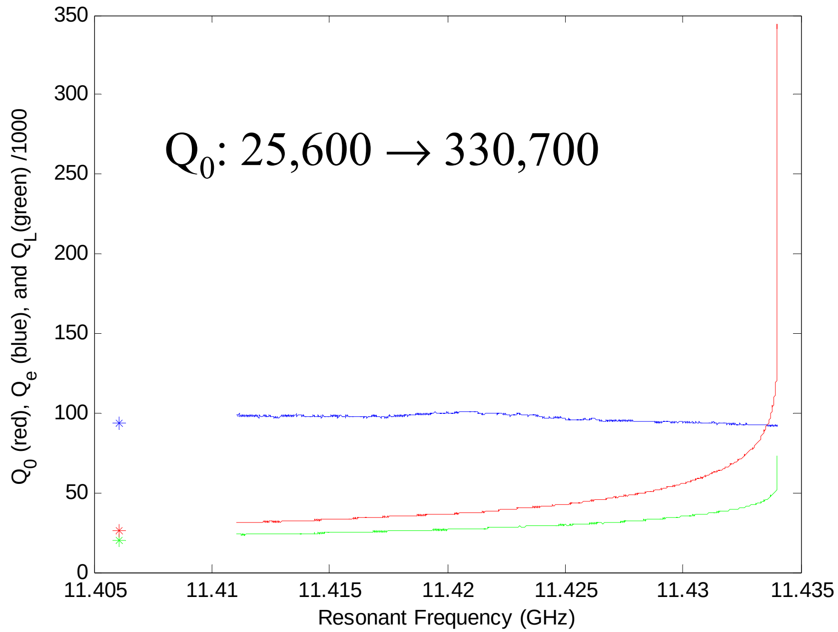
Temperature measured with a carbon-glass resistor (low end) inserted into a hole in bottom of cavity and from frequency shift (higher temperatures).

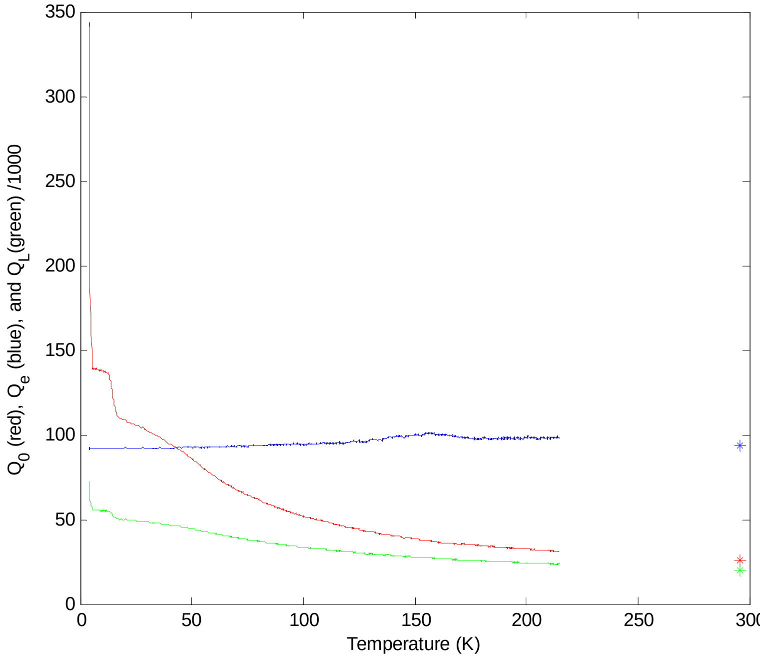
Copper Sample



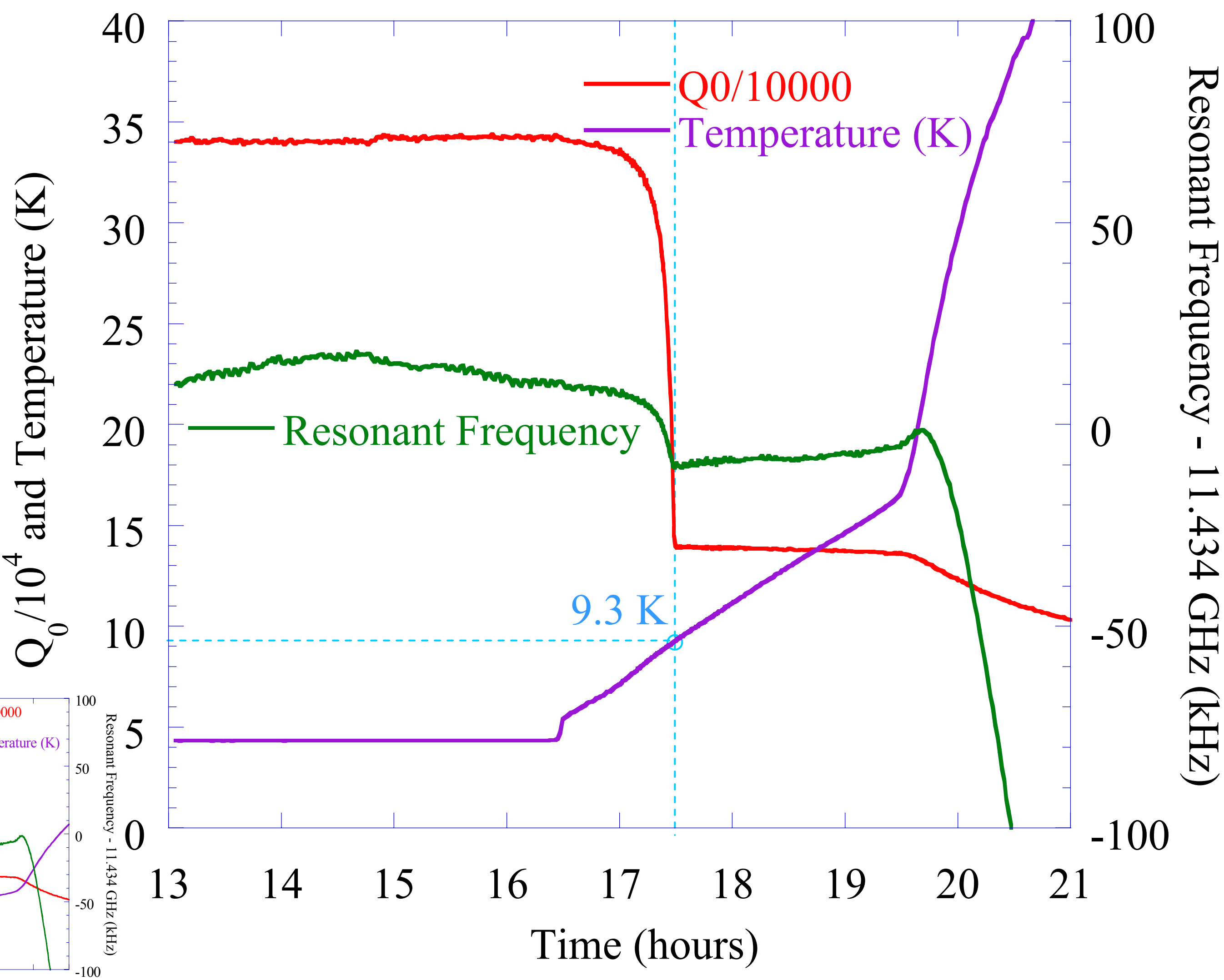


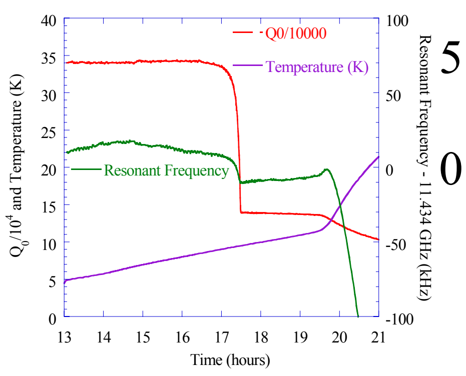
Niobium Sample



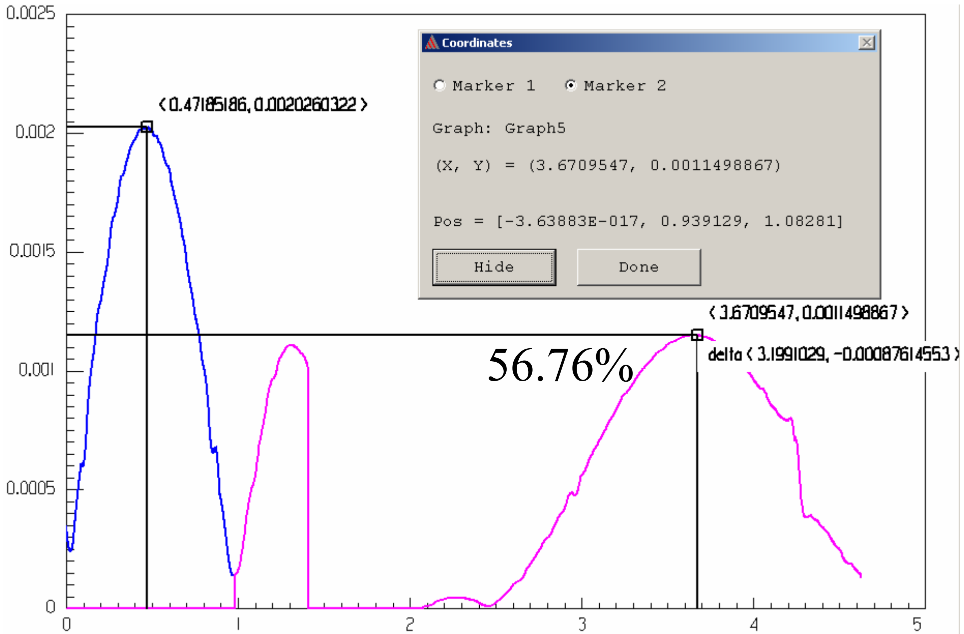


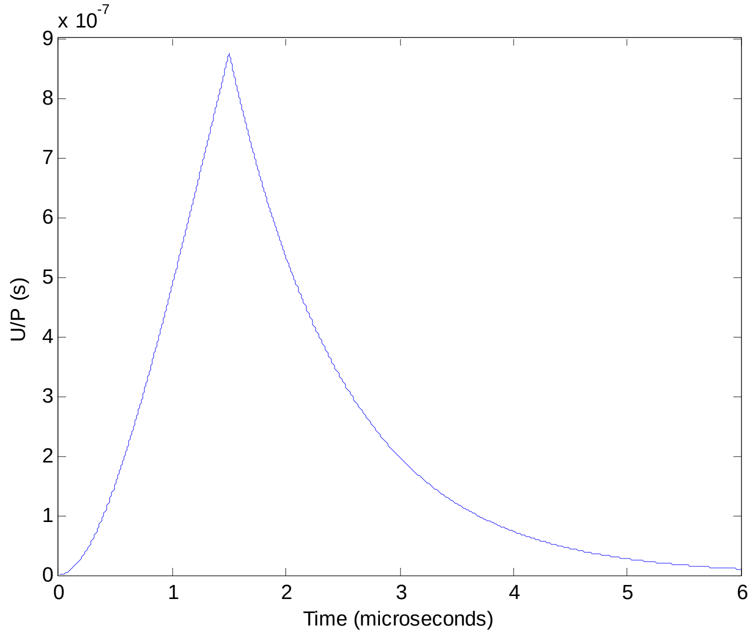
Transition of Cavity Q During Warmup from Liquid He Temperature





Needed Power





H field along radius of bottom face

$U = 8.72265 \times 10^{-17}$ J

$|H_{max}|^2 = 4.1048 \times 10^{-6}$ A^2/m^2

$|H_{max}|^2 = AU$

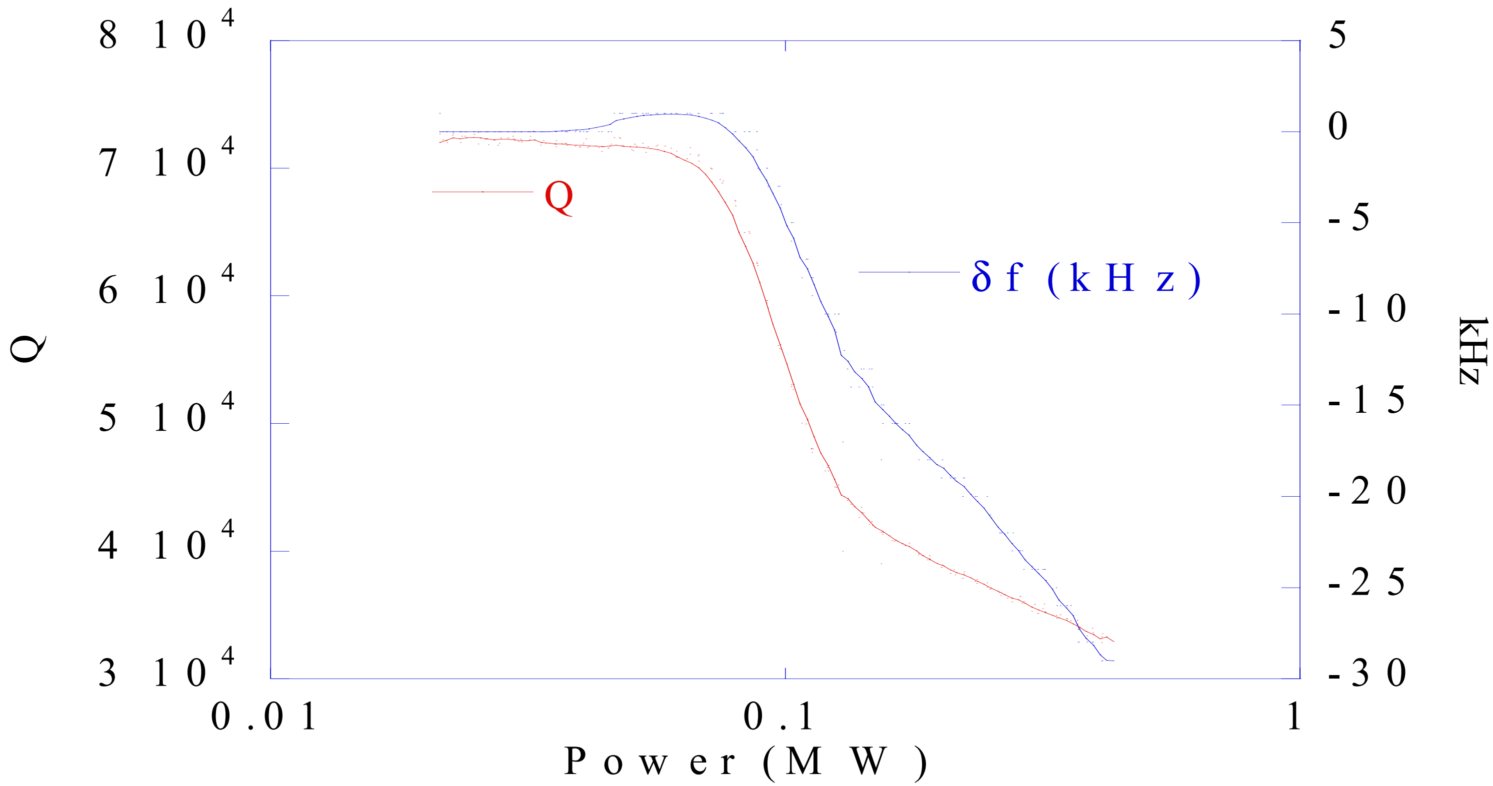
$\rightarrow A = 4.7059 \times 10^{10}$ A^2/m^2/J

If $|B_c|$=180 mT, then $|H_c|$=143.25 kA/m,

$\rightarrow U_c \approx 0.43607\text{J} = 8.754 \times 10^{-7}\text{s } P_c$ for a 1.5 µs flat input pulse.

$\rightarrow P_c \approx$ 498 kW

High Power Test of Niobium at 4.2K



New test setup for inexpensive accurate characterization of high-field RF properties of materials and processing techniques

High Power Testing

An initial high power experiment was performed, but data has not yet been fully analyzed.

A feedback code is used to make the low level RF drive track the resonant frequency by flattening the phase during cavity discharge.

Quenching of Nb sample seen as a roll off of Q as power was raised.

Our experimental setup is still maturing. We will add a high-power circulator to isolate the klystron from the cavity reflection. We will also add a silicon diode and a Cernox temperature sensor.

We will soon test a sample of MgB_2 provided by T. Tajima et al. of Los Alamos. This material is supposed to have an order of magnitude lower surface resistance than niobium at 4K and a critical temperature of ~40K, compared to 9.2K for niobium.

Pulsed Heating

Our cavity design also recommends itself to pulsed heating experiments (á la Pritzkau and Siemann).

We will conduct a set of such experiments, using a second cavity designed to be nearly critically coupled at room temperature.

These will be done in collaboration with W. Wuench, et al. of CERN, who will provide samples of copper, copper zirconium, etc.

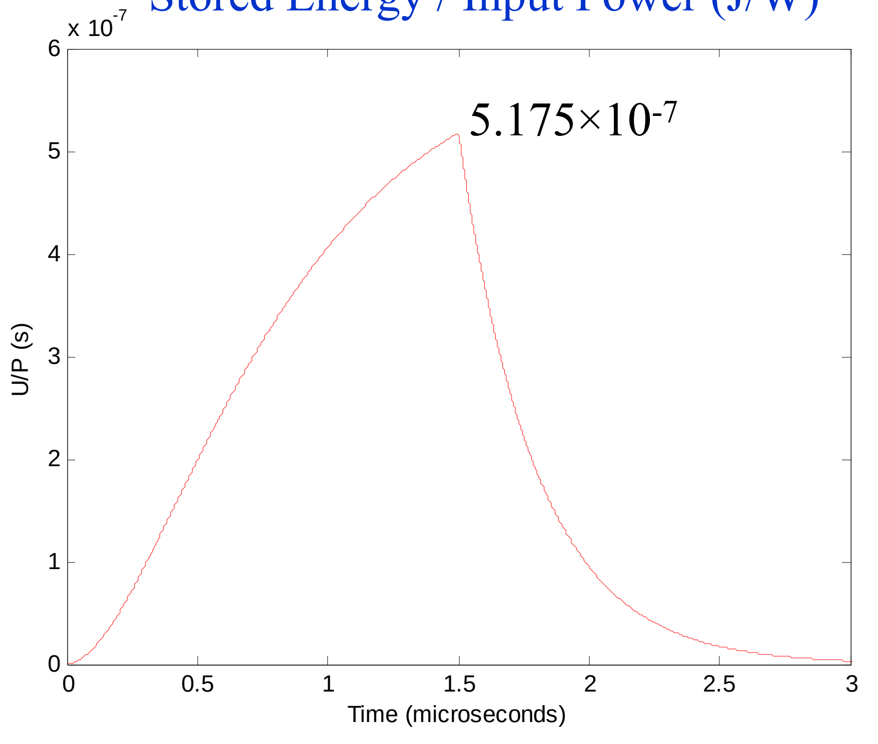
Room Temperature Design

	HFSS	Meas.
f	11.424	11.4073
Q_L	22,544*	21,197
β	1.0015*	1.0659
Q_0	45,123	43,791
Q_e	45,054	41,084

$\rightarrow \alpha=1.032$,

$\rightarrow T_c=0.5915\mu s$

Stored Energy / Input Power (J/W)



$$T(z=0,t) = T_0 + \frac{2}{\rho c_\varepsilon}\int_0^t dt' \frac{dP(t')}{dA}\frac{1}{\delta}\exp\left(\frac{4\alpha_d(t-t')}{\delta^2}\right)\mathrm{erfc}\left(\frac{2}{\delta}\sqrt{\alpha_d(t-t')}\right) \quad \text{(Pritz. (3.34))}$$

$$\frac{dP(t)}{dA} = \frac{1}{2}R_s\left|\mathbf{H}_{\|}\right|^2$$

ρ = density = 8930 kg/m^3

c_ε = specific heat at constant strain = 392.6 J/kgK (@350K)

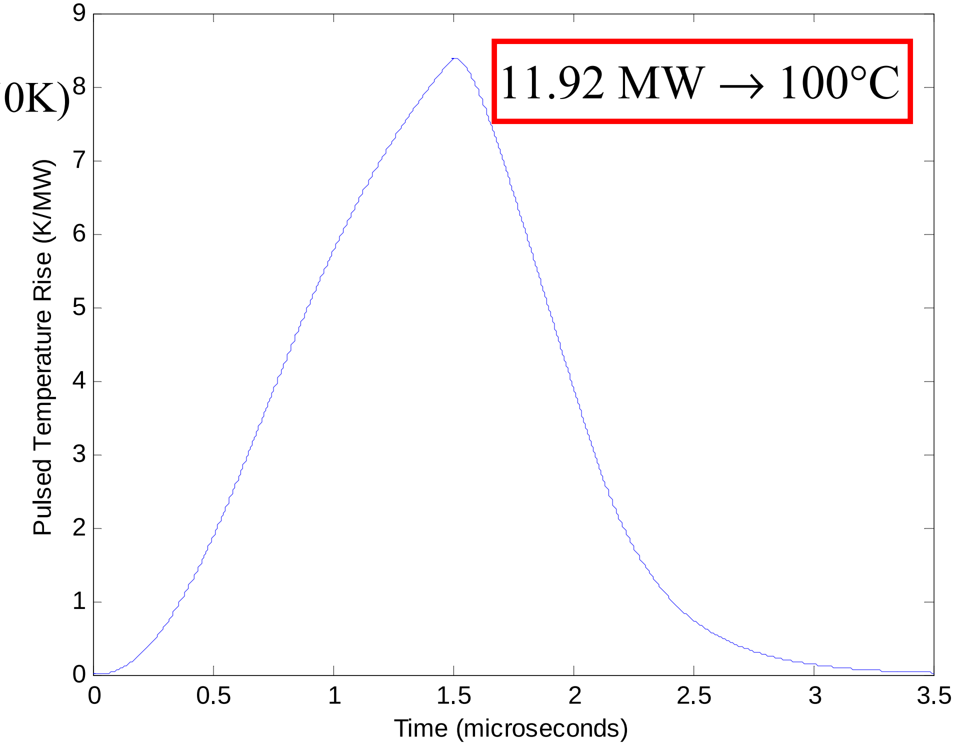
δ = skin depth = $\sqrt{\dfrac{2}{\mu\omega\sigma}}$ = 0.618μm

α_d = thermal diffusivity = 1.127×10^{-4} m^2/s (@350K)

R_s = surface resistance = $\dfrac{1}{\sigma\delta} = \sqrt{\dfrac{\mu\omega}{2\sigma}}$ = 0.0279 Ω

$\left|\mathbf{H}_{\|}\right|^2 = AU, \qquad A = 4.7059\times10^{10}\ \mathrm{A^2/m^2/J}$

Cu parameters held constant in this calculation.



We have plenty of power to create pulsed heating temperature rises on the order of 100 °C.

Conclusions

•We have designed and fabricated a compact, high-Q rf cavity optimized for economically testing the rf properties of material samples and their dependence on temperature and field by means of frequency and Q monitoring.

•We've performed low power cryogenic tests with copper and niobium samples.

•High power tests are under way.

•A similar cavity will be used for pulsed heating material testing.