SLAC's Test Bed for Superconducting Materials: System Description and Preliminary Results

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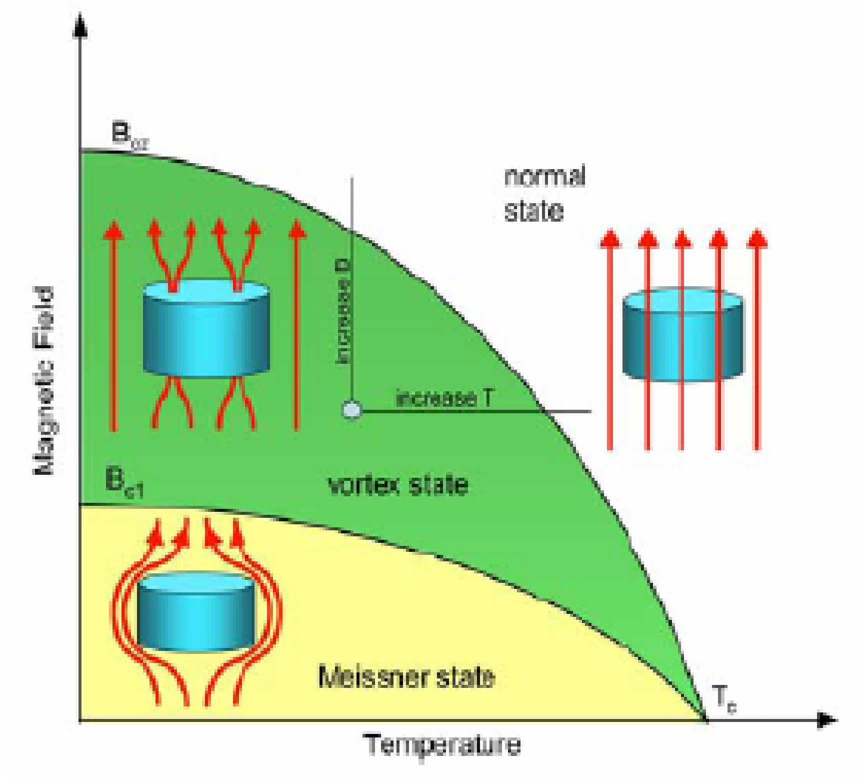
  - Superconducting RF (SRF)
  - System Description
  - Results
- Cavity Model
  - Pulse Dependence
  - Critical Magnetic Field
- Results vs Model
  - Discussion and Future Tests

Overview: SRF

- Magnetic critical fields



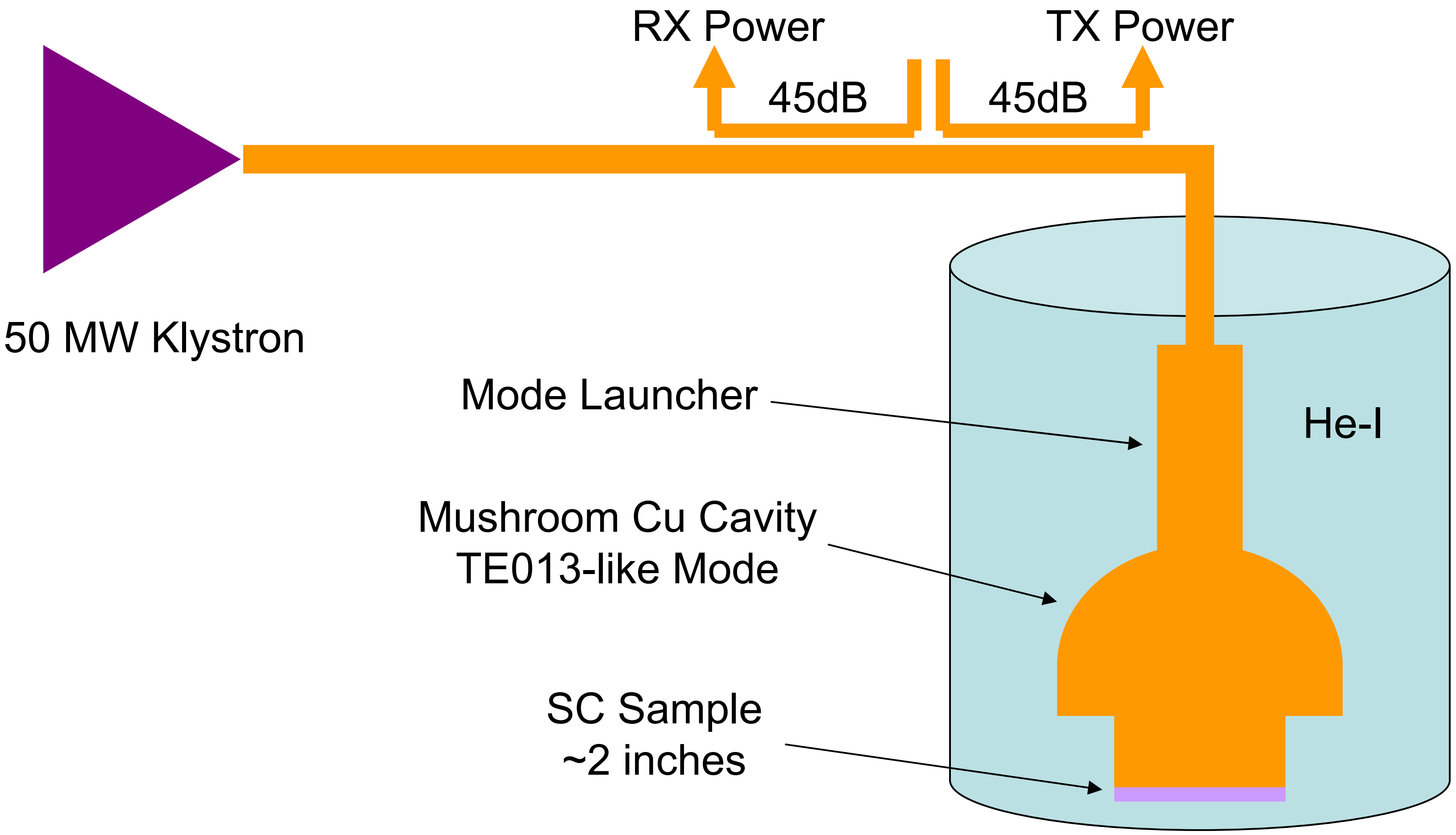
$$H_{c1} = \frac{\phi_0}{4\pi\mu\lambda_L^2}\left(\ln\frac{\lambda_L}{\xi} + 0.5\right)$$

$$H_{c2} = \frac{\phi_0}{2\pi\mu\xi^2}$$

$$H_c = \frac{\phi_0}{2\sqrt{2}\pi\lambda_L\xi}$$

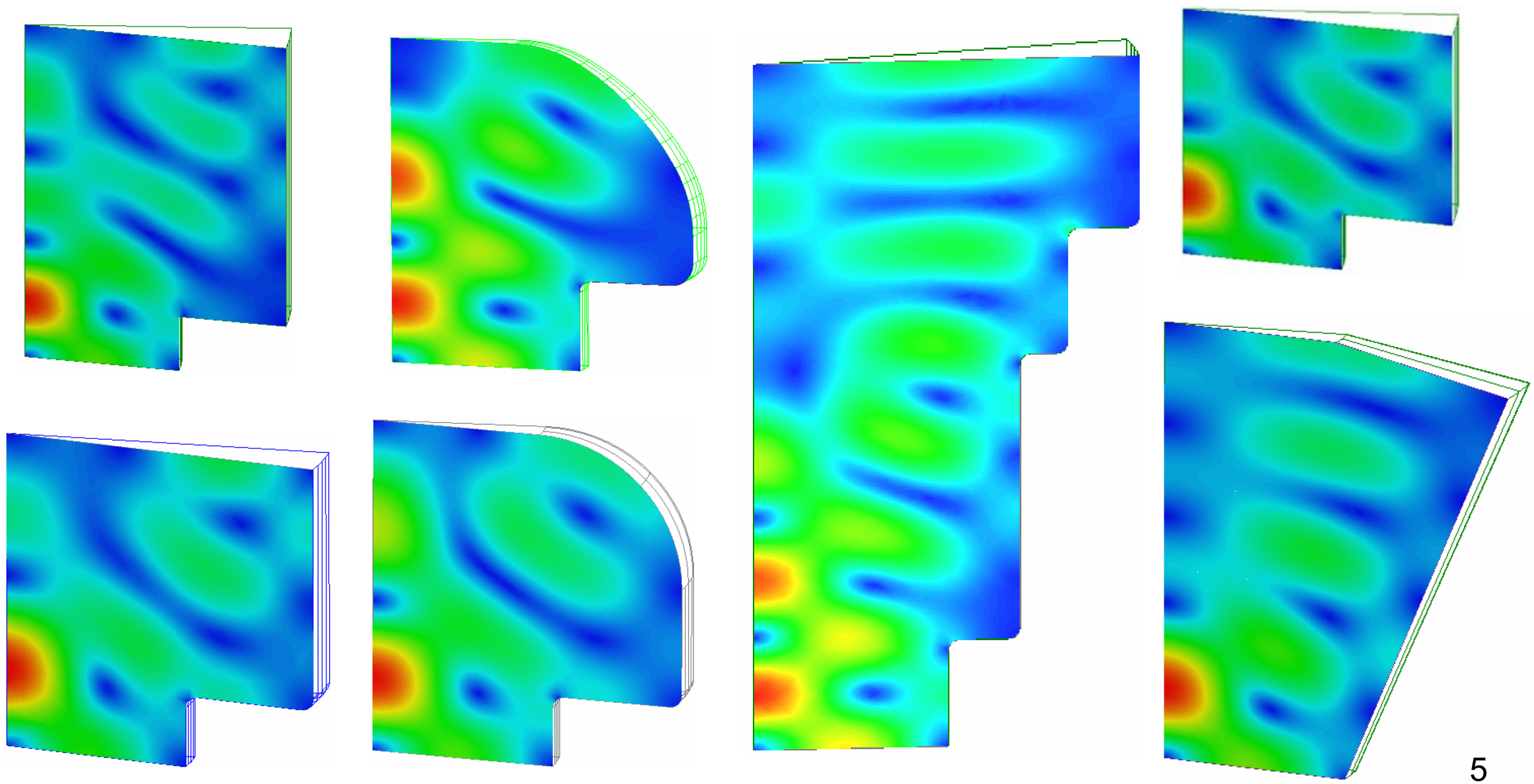
$$H_c^{RF} = ????$$

Overview: System Description



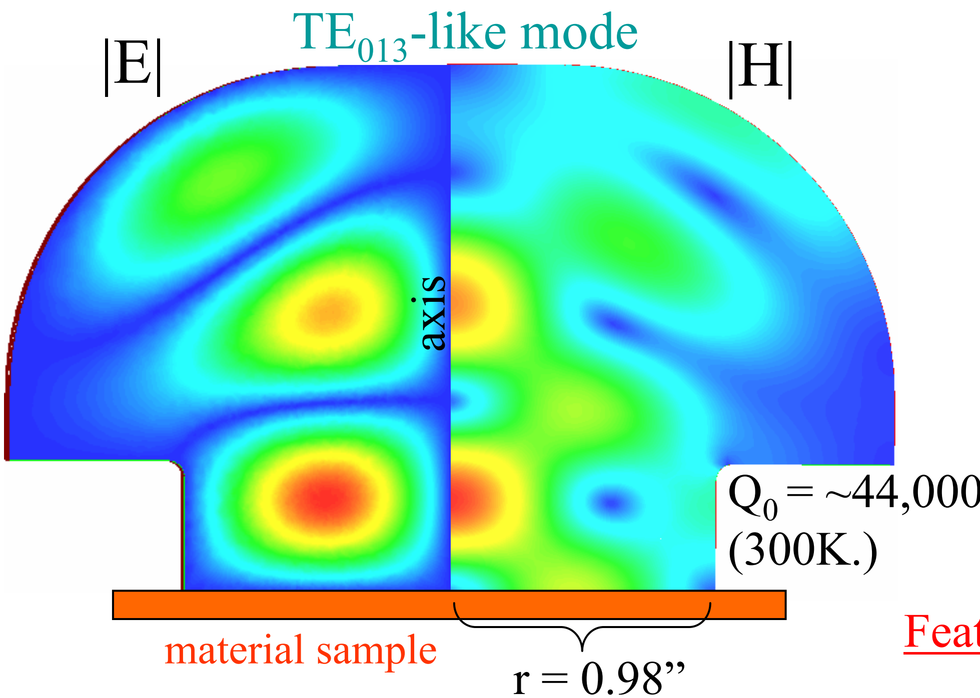
Overview: System Description

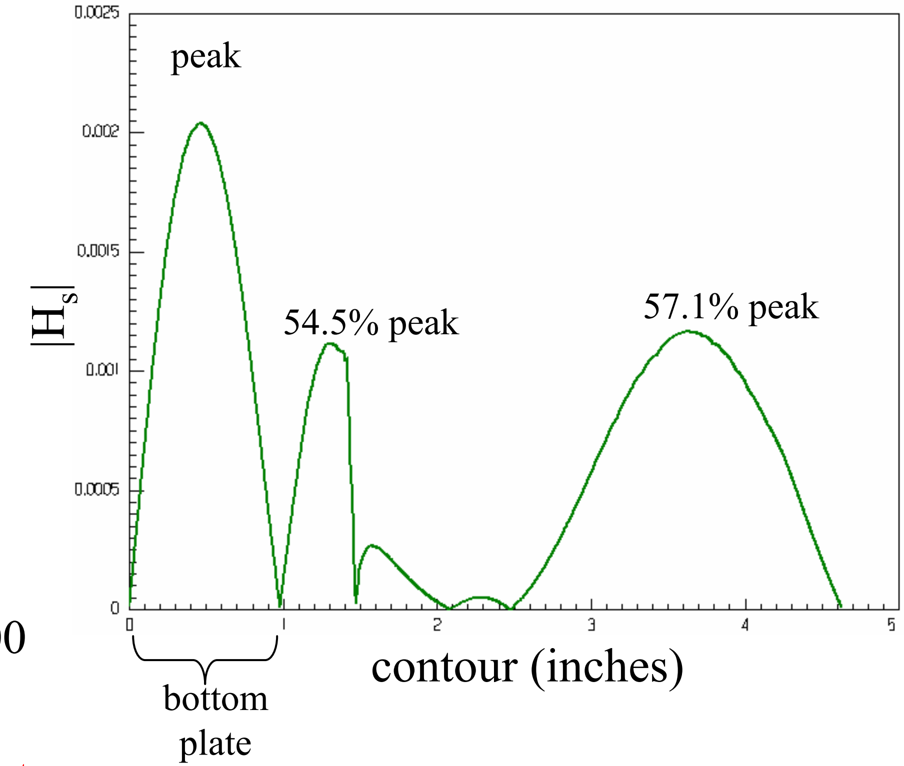
- Cavity shape
  - TE01n pillbox (same field on top and bottom)



Overview: System Description

- Mushroom cavity





Why X-band (~11.424 GHz)?:

•High power & RF components available

•Fits in cryogenic Dewar

•Small (3”) samples required

Features:

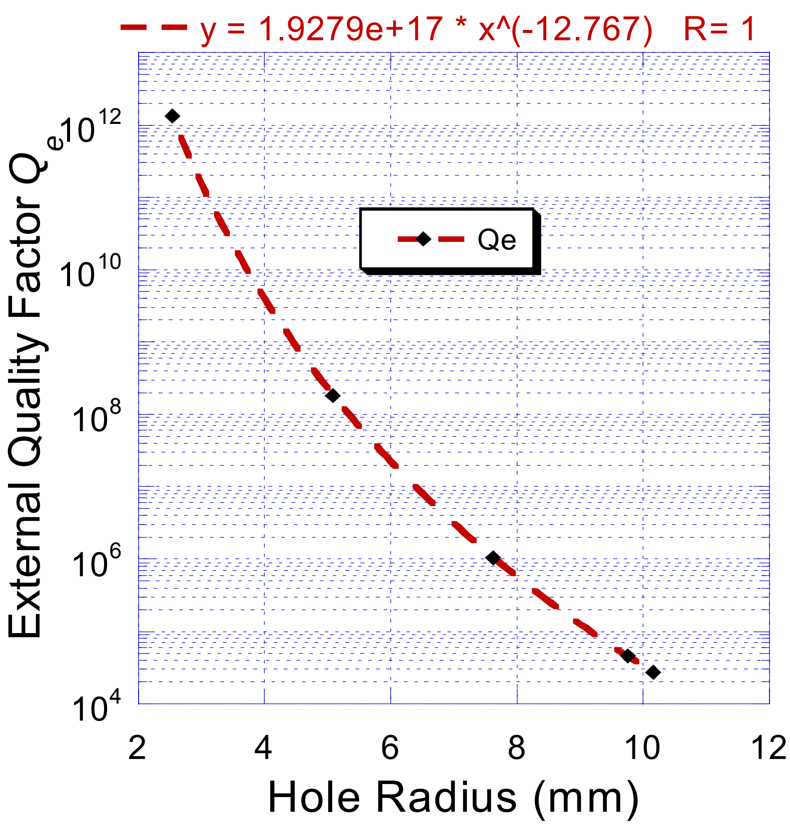
•No surface electric fields (no multipactor)

•Magnetic field concentrated on bottom (sample) face (75% higher than anywhere else)

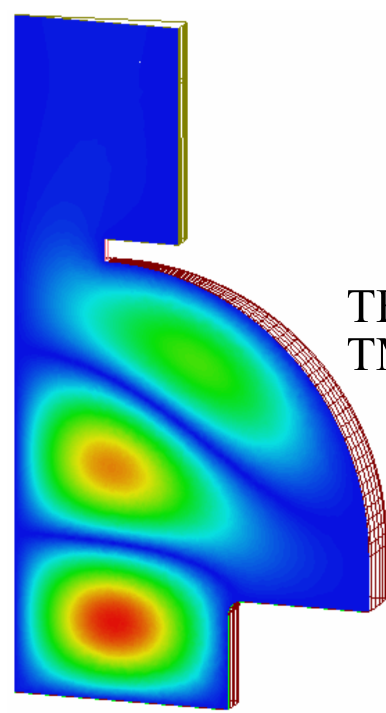
•Purely azimuthal currents allow demountable bottom face (gap).

Overview: System Description

- Other nearby resonant modes
  - Couple on axis with pure axisymmetric transverse electric mode TE01 in circular waveguide.



WC150
(3.81 cm diam.)



TE_{131}
$TM_{32?}$

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.

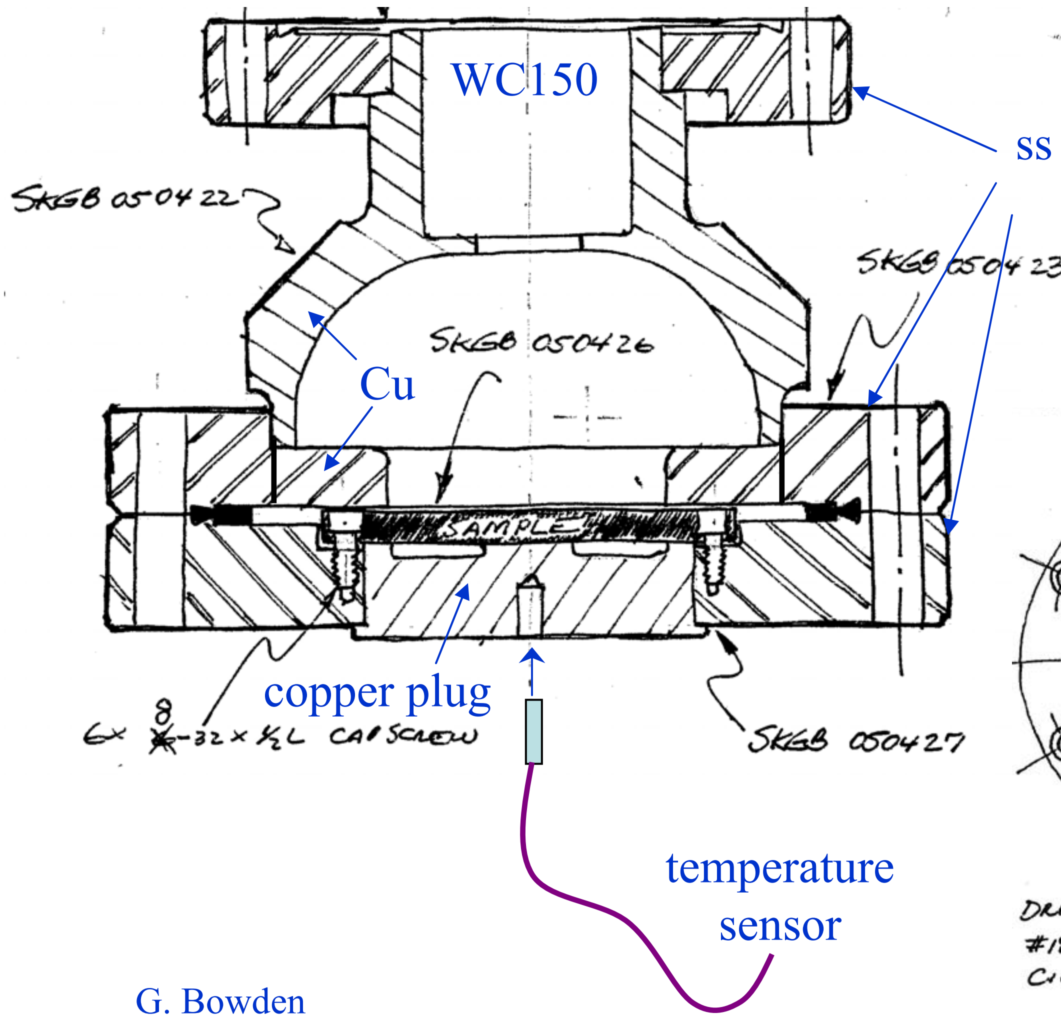
	Frequency (GHz)
Mode 1	(1.09513e+001, 0.00000e+000)
Mode 2	(1.18826e+001, 0.00000e+000)
Mode 3	(1.28660e+001, 0.00000e+000)

1.4% mode separation from non-axisymm. mode.

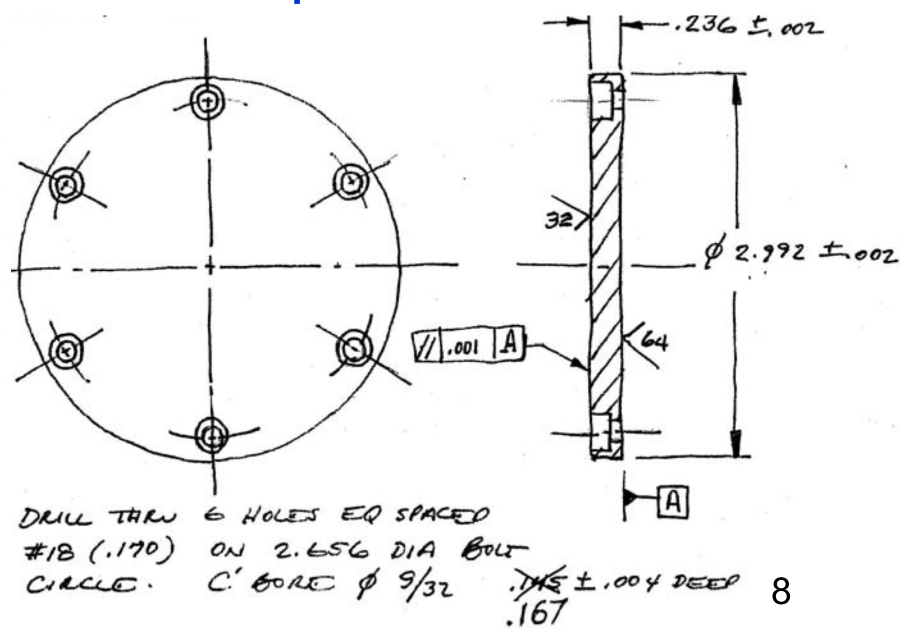
	Frequency (GHz)
Mode 1	(1.10167e+001, 0.00000e+000)
Mode 2	(1.15877e+001, 0.00000e+000)
Mode 3	(1.15983e+001, 0.00000e+000)

Overview: System Description

- Mechanical Design



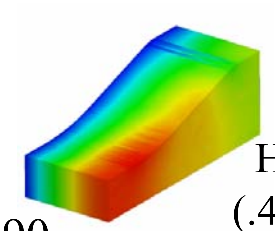
Sample Dimensions



Overview: System Description

WR90-WC150 Compact High-Purity TE01 Mode Launcher

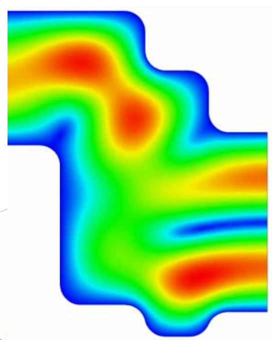
- Mode launcher

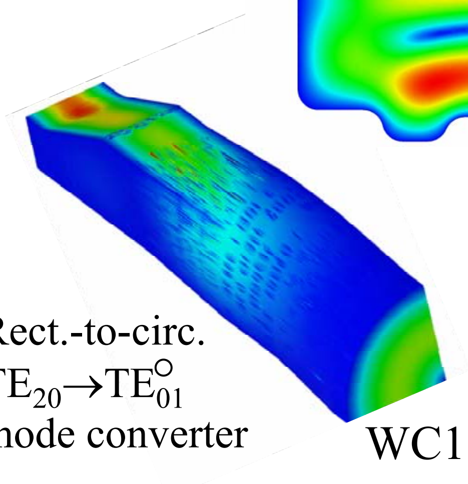


WR90

Height taper (.400”→.800”)

TE$_{10}$→TE$_{20}$ converter

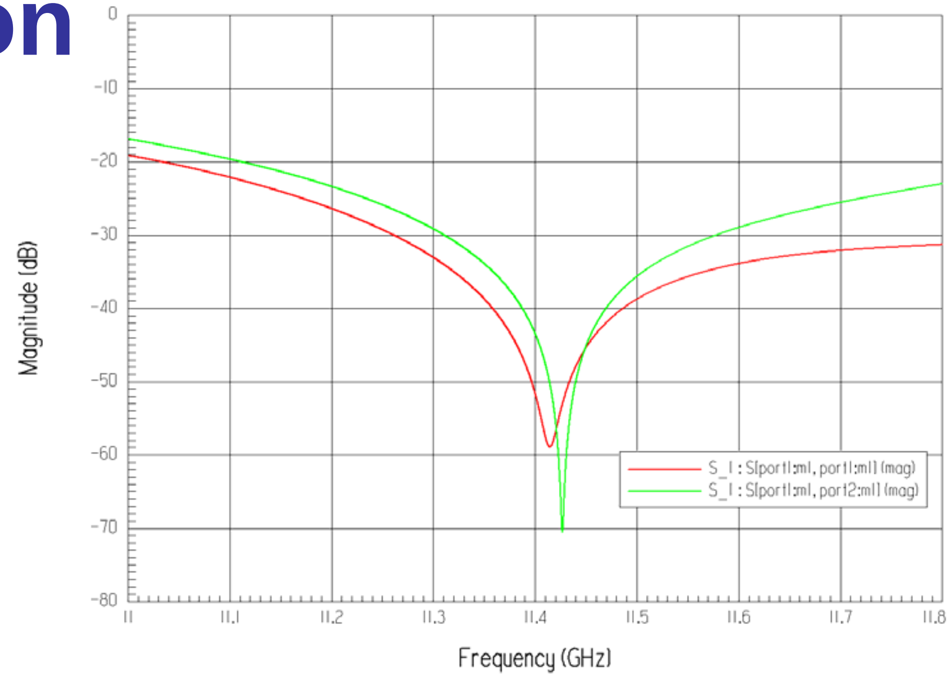




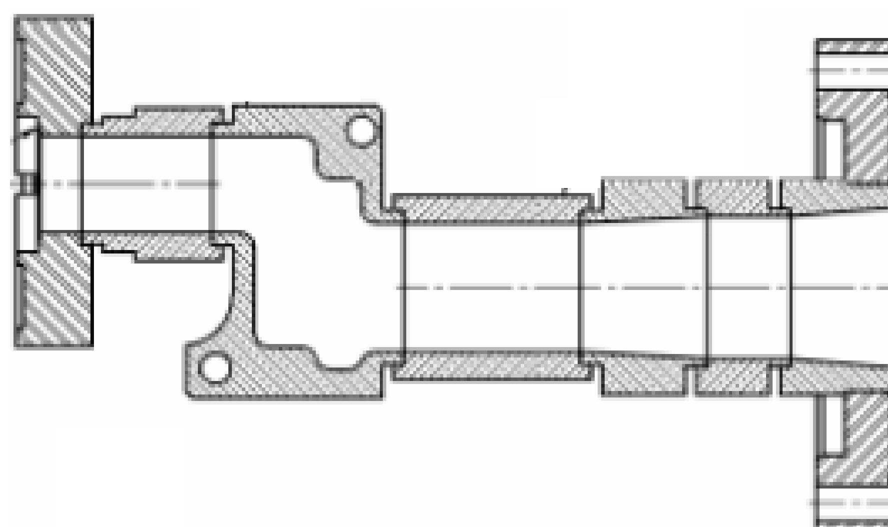
Rect.-to-circ. TE$_{20}$→TE$^{\circ}_{01}$ mode converter

WC150

V. Dolgashev

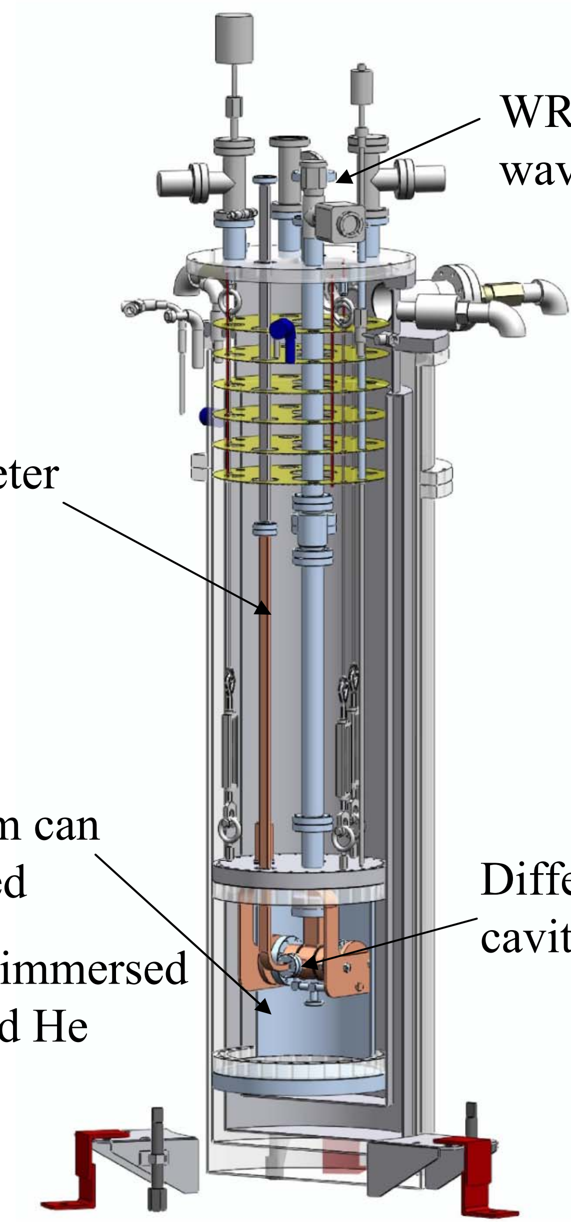


TE$_{10}$



TE$^{\circ}_{01}$

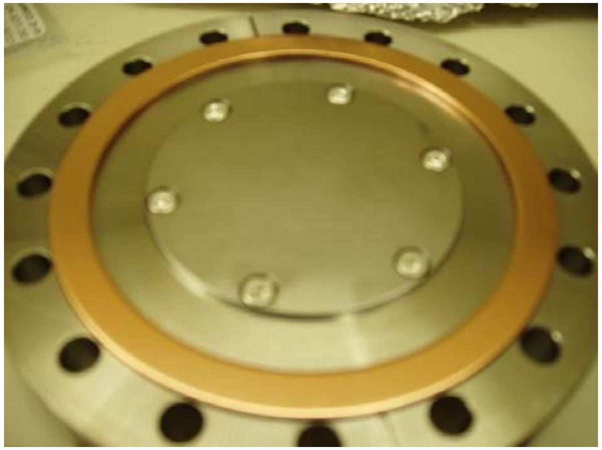
Overview:
System Description

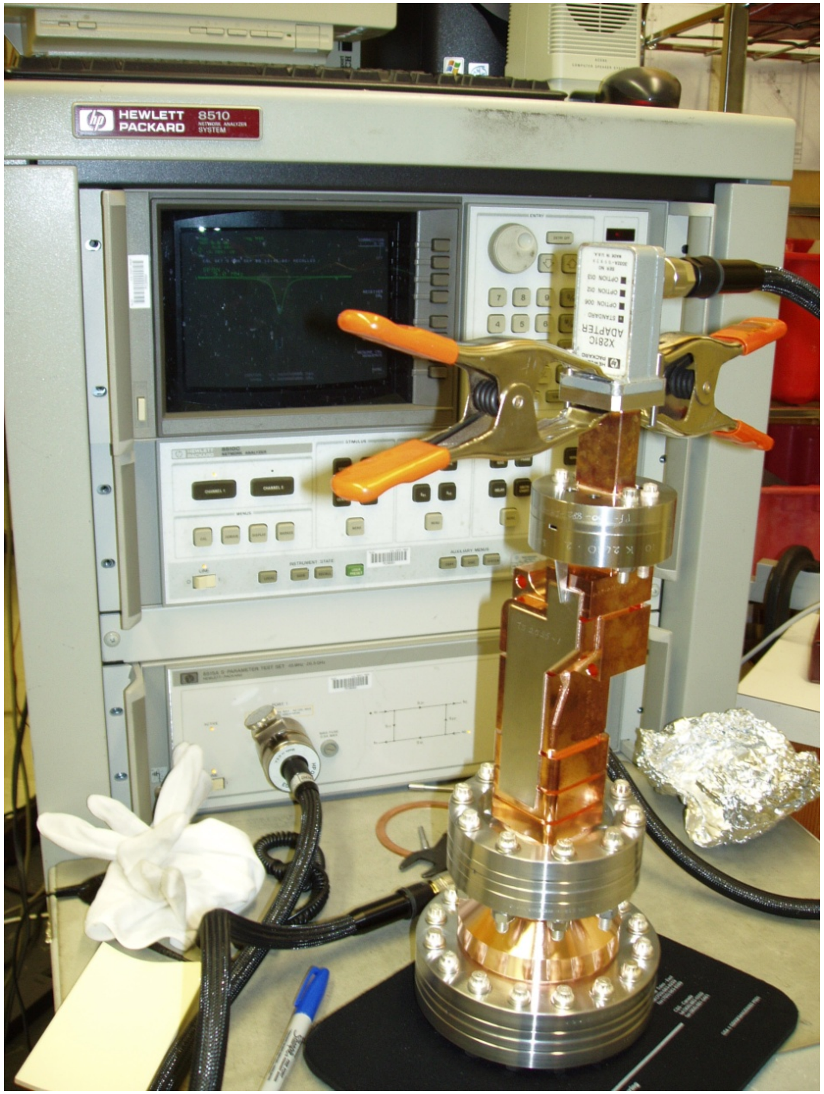


Overview: System Description

Room Temperature Tests

	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

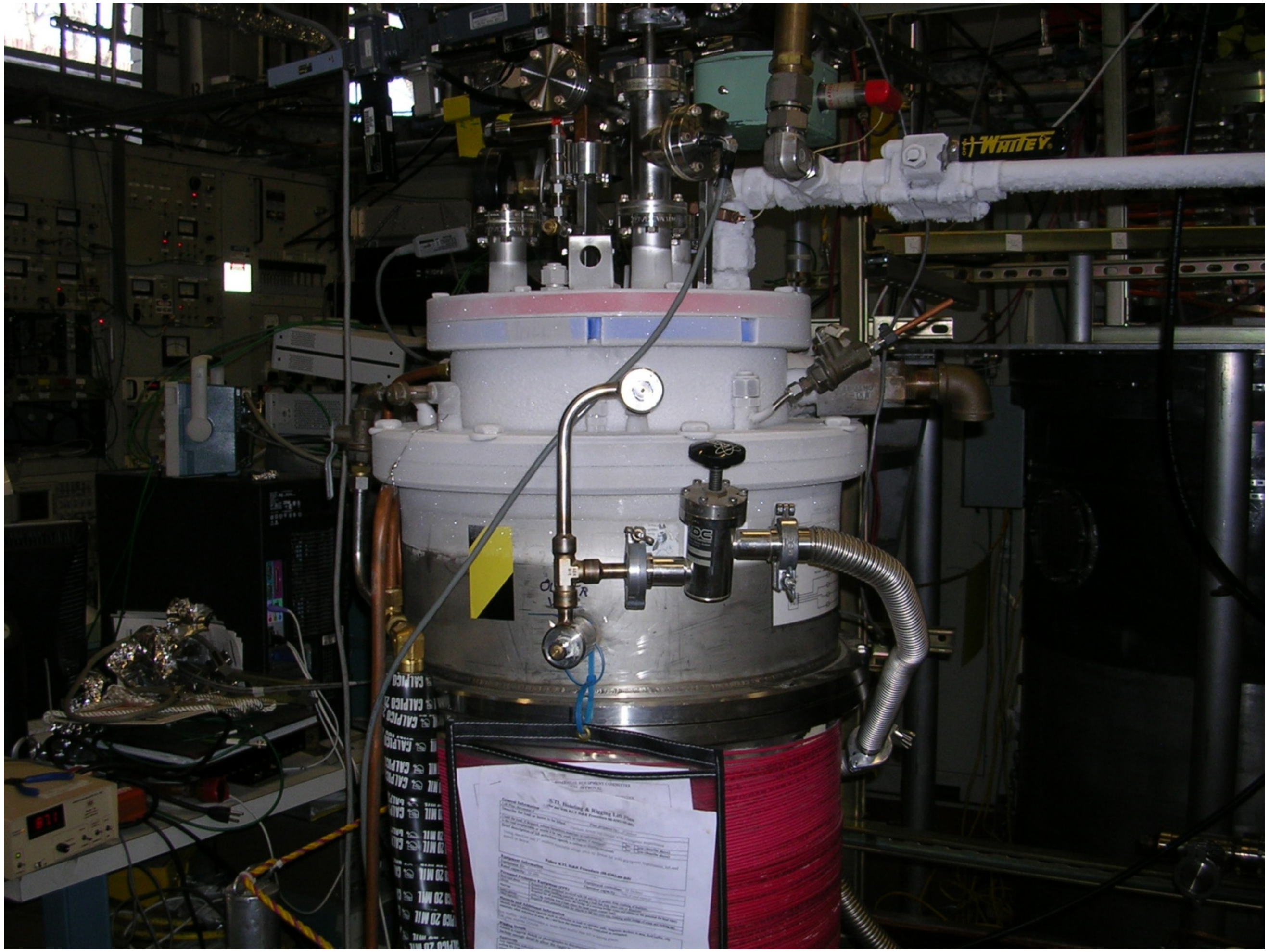

Nb sample mounted in bottom flange



HP 8510C Network Analyzer

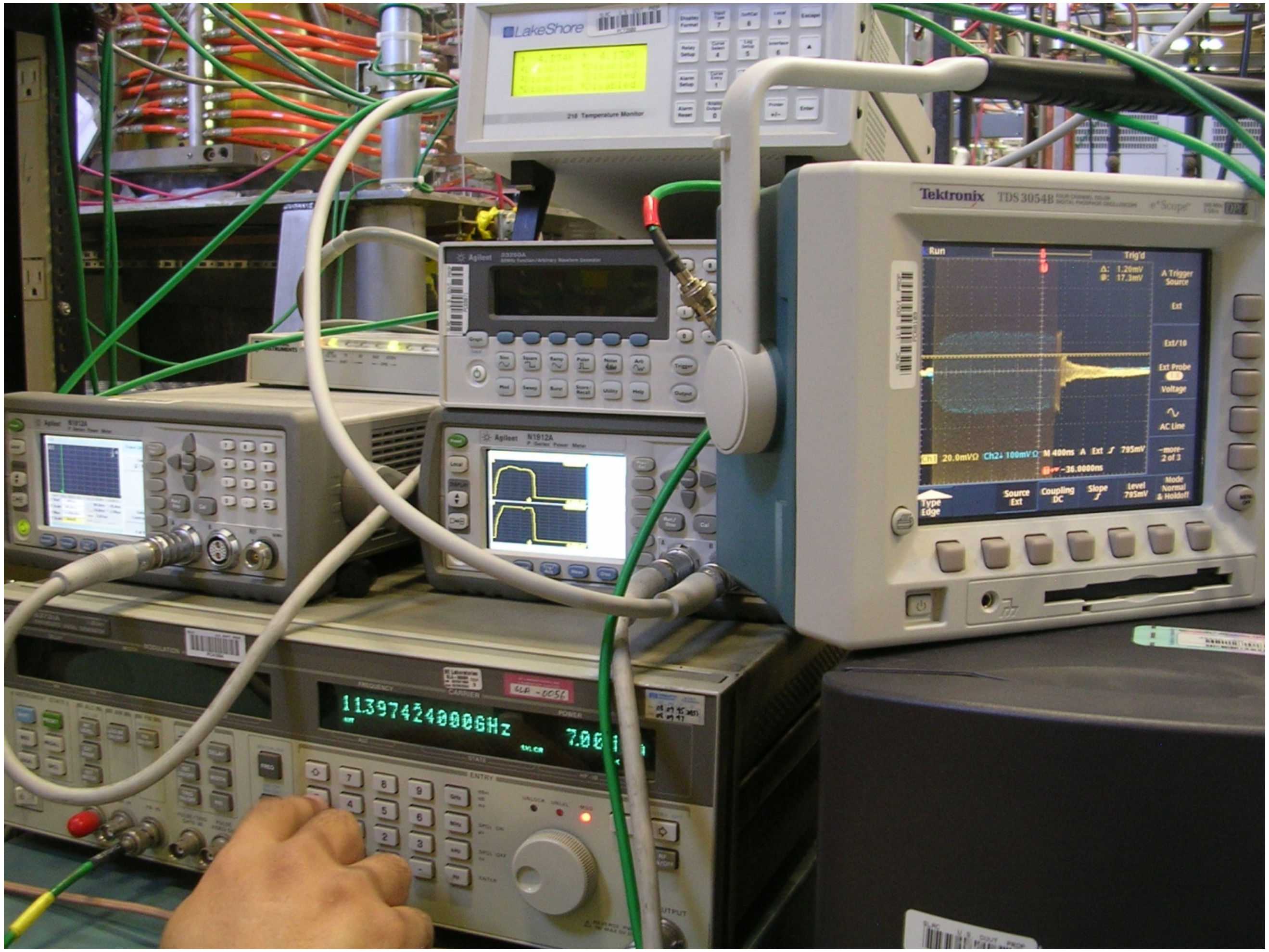
Overview: System Description

- Photographs



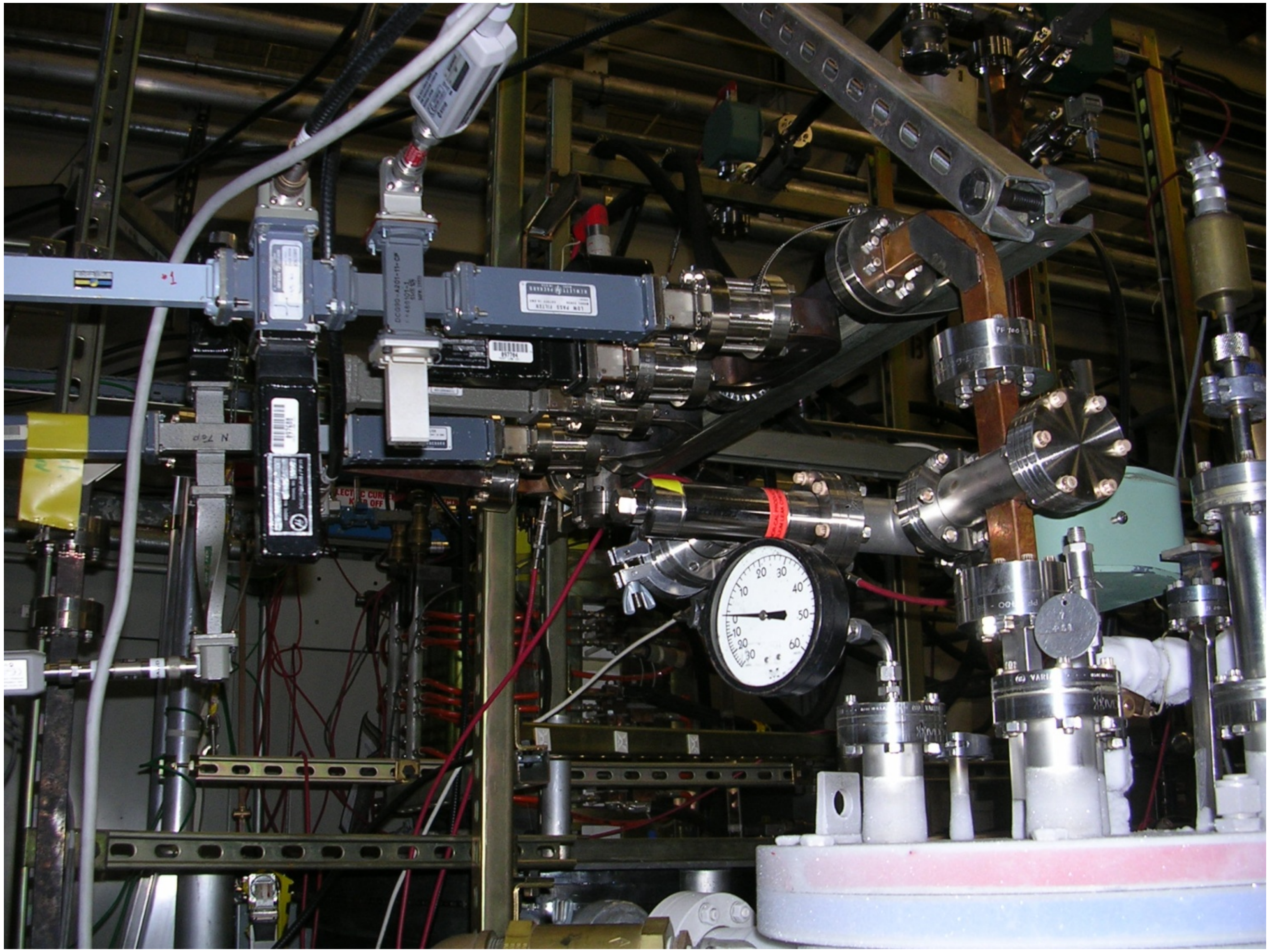
Overview: System Description

Photographs



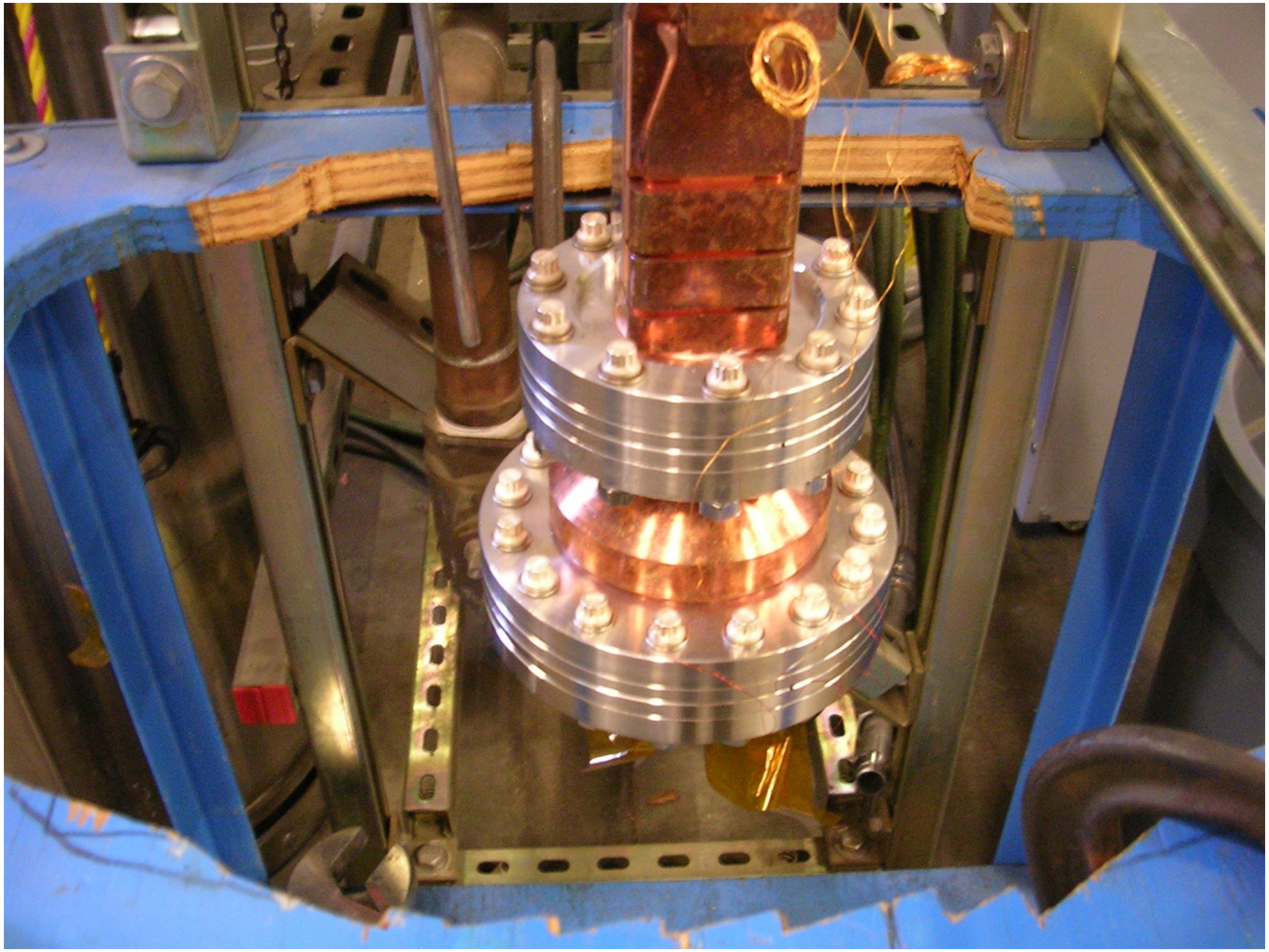
Overview: System Description

Photographs



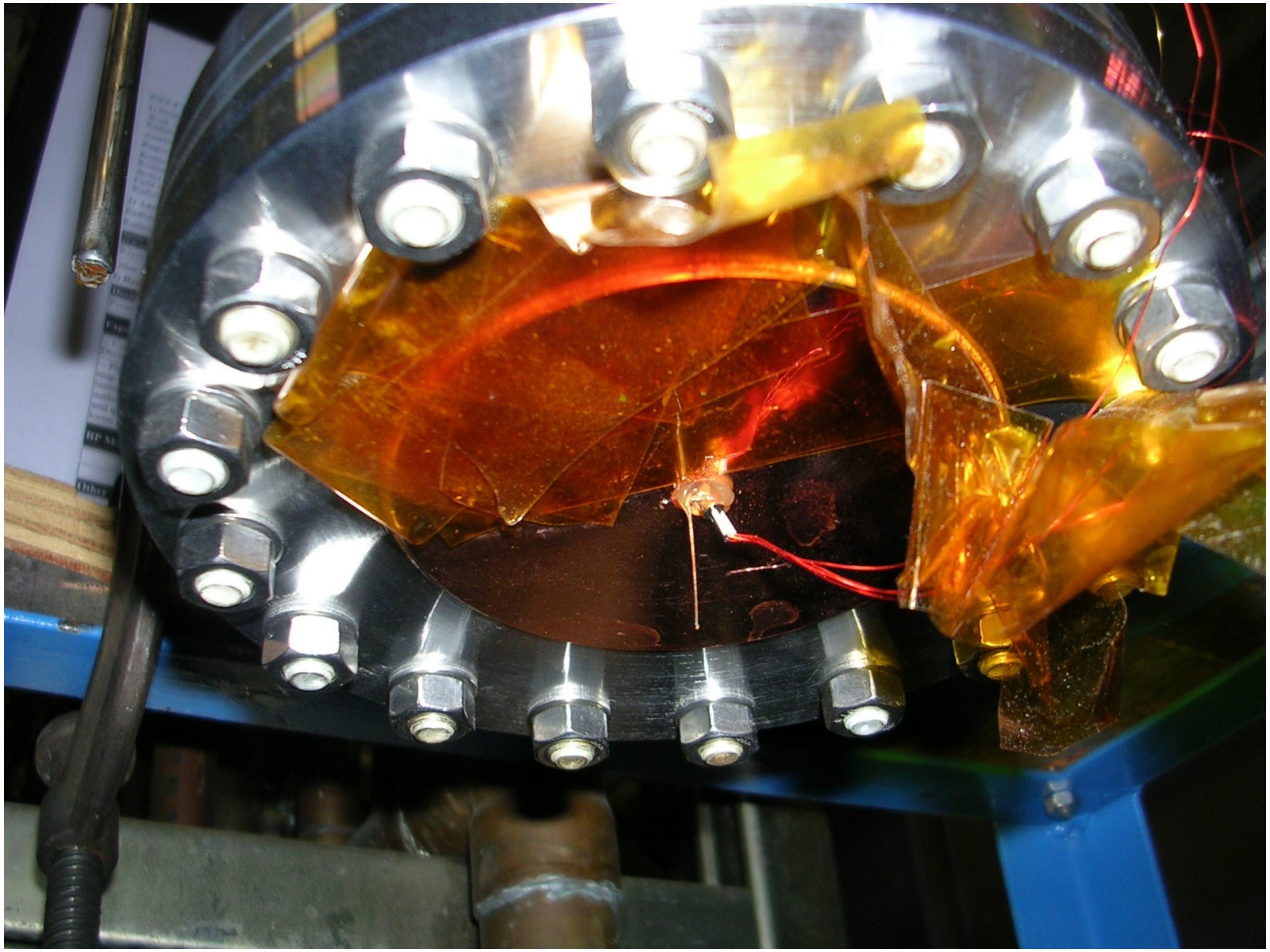
Overview: System Description

Photographs



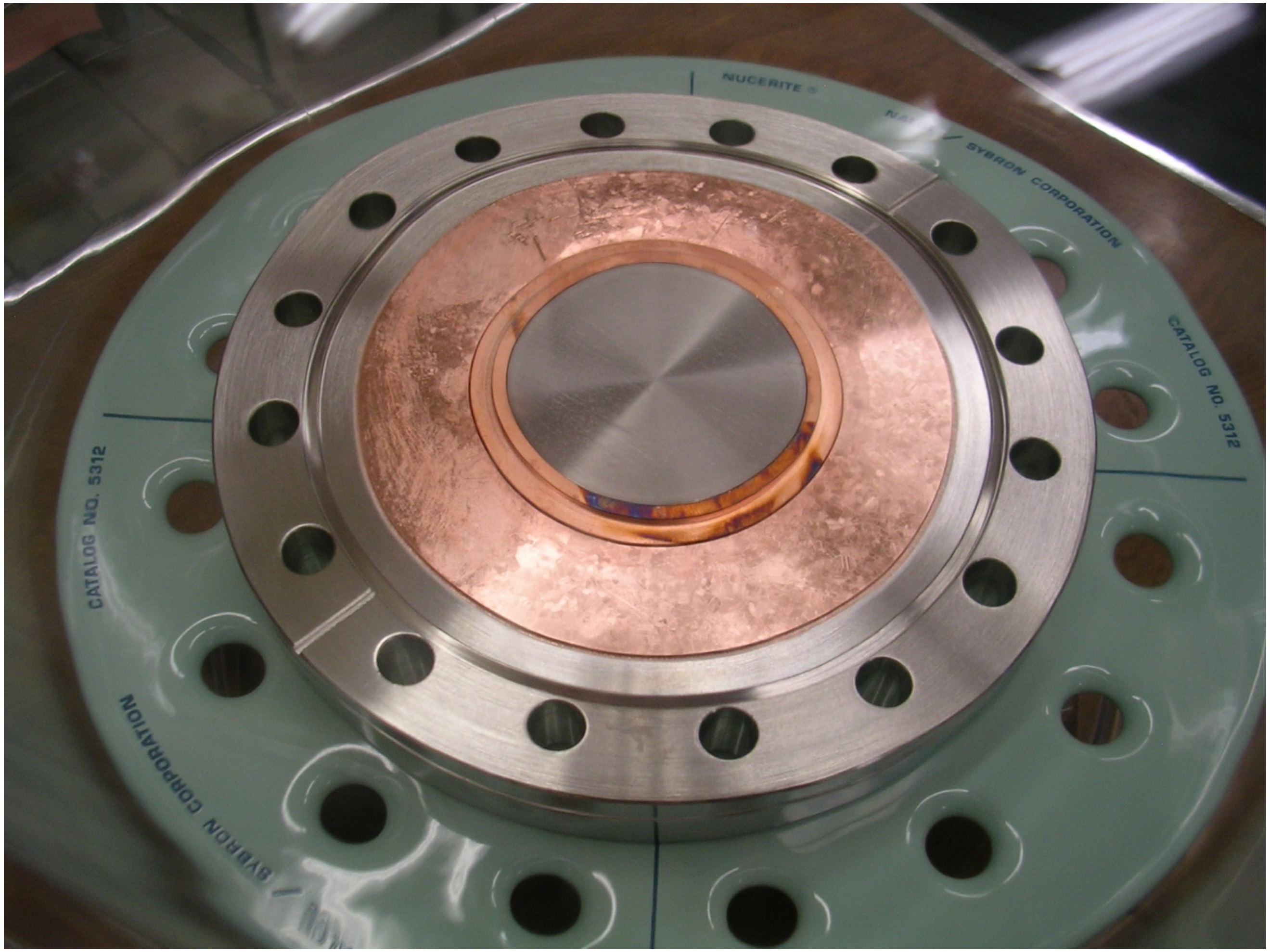
Overview: System Description

Photographs



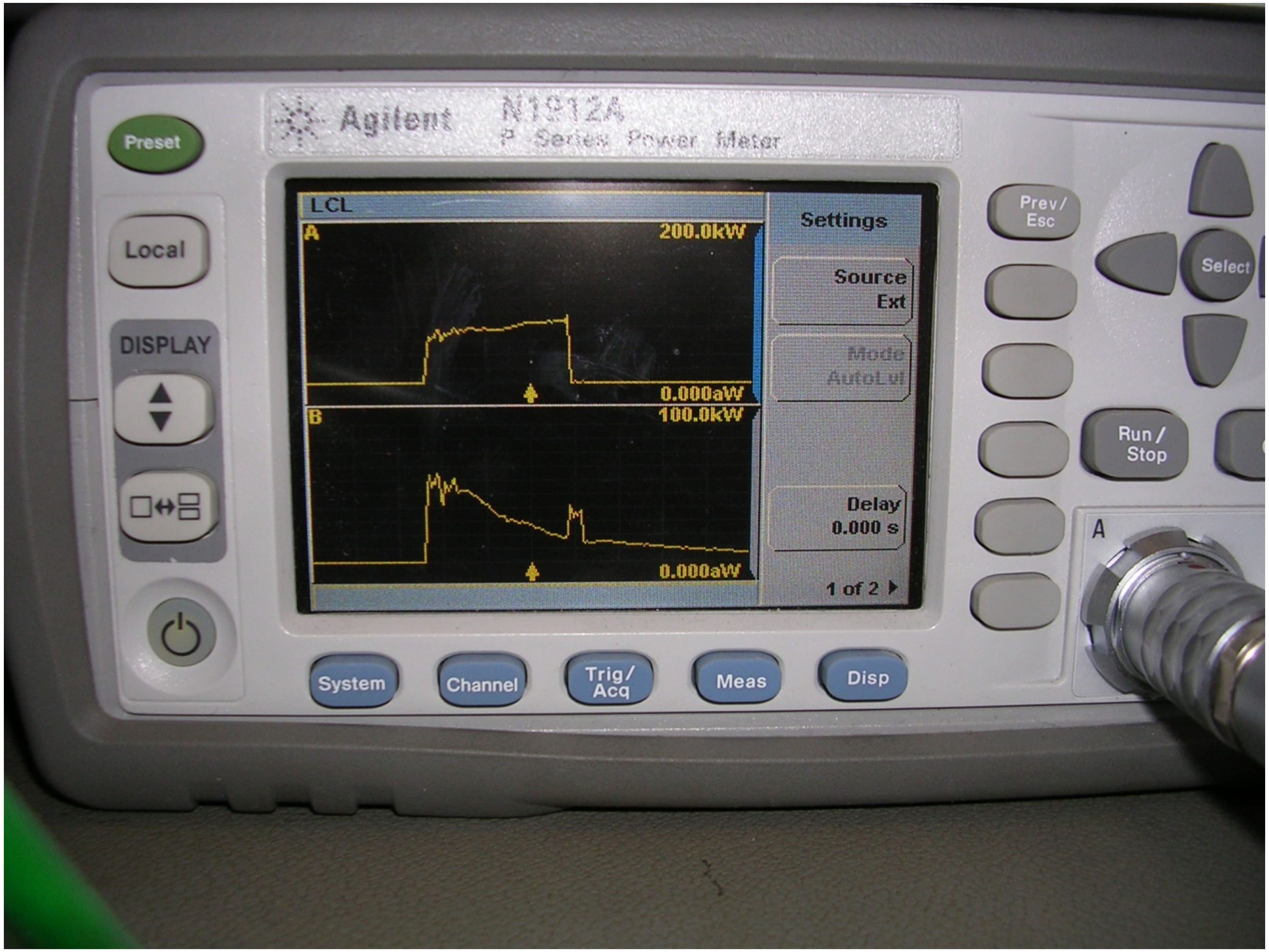
Overview: System Description

Photographs



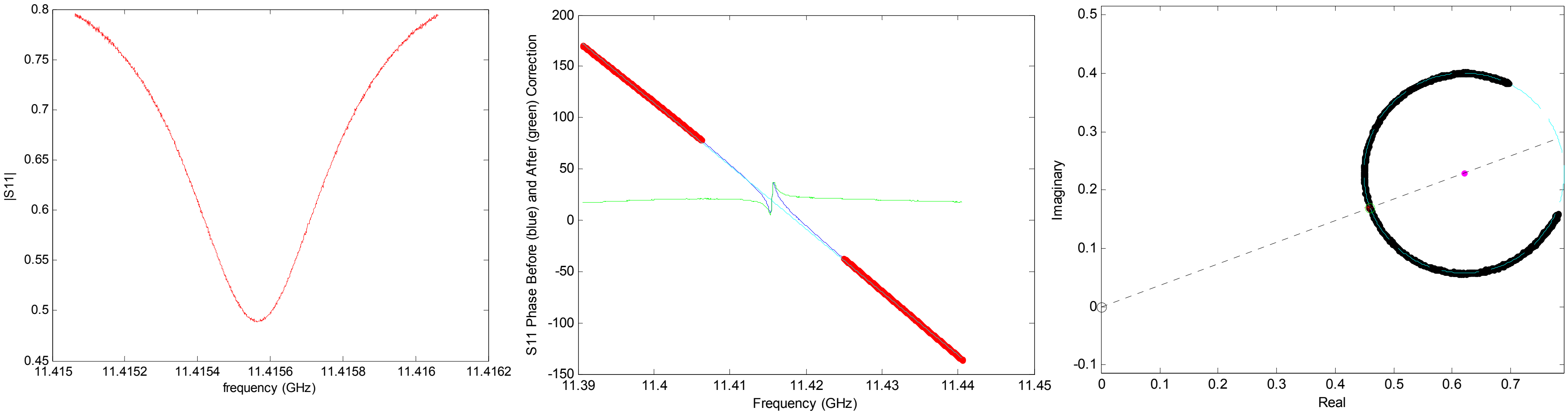
Overview: System Description

Photographs



Overview: System Description

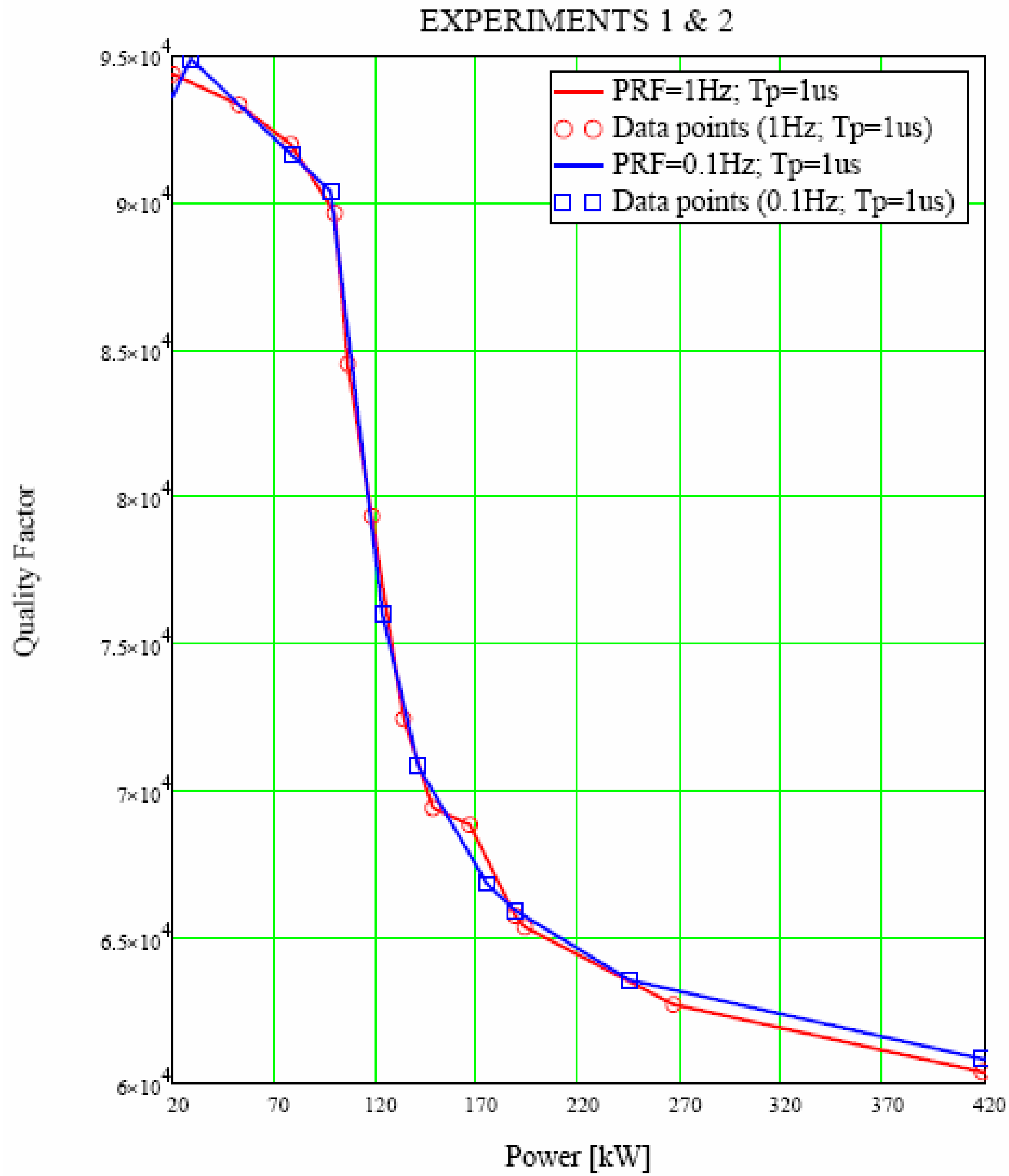
- Data Processing (room temperature)



- Complex S_{11} is measured with 1601 points in 1MHz 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 $\mathbf{f_r}$, **b**, and $\mathbf{Q_L}$. From these $\mathbf{Q_0}$ and $\mathbf{Q_e}$ 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).

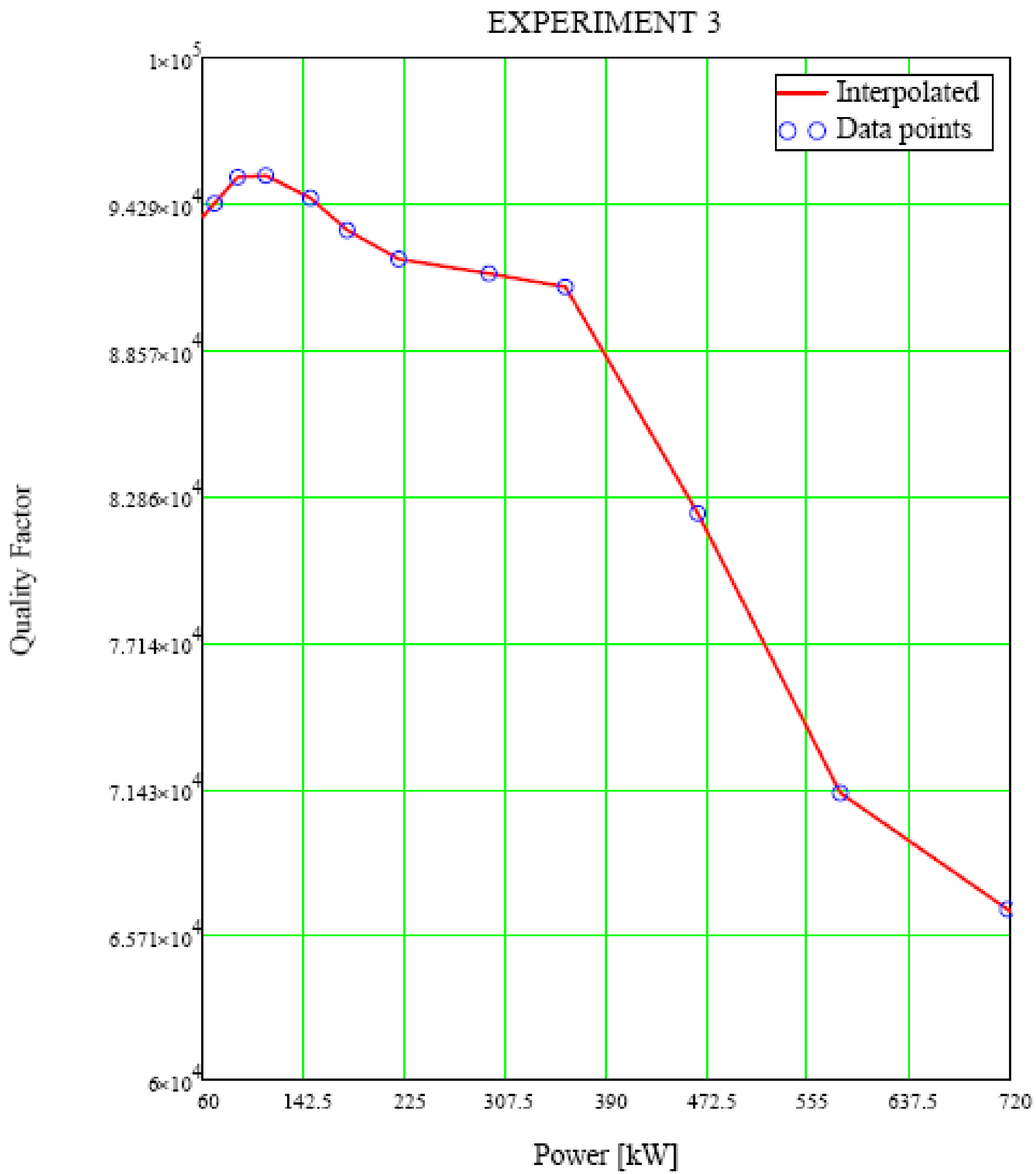
Overview: Results

Nb: RRR = 250



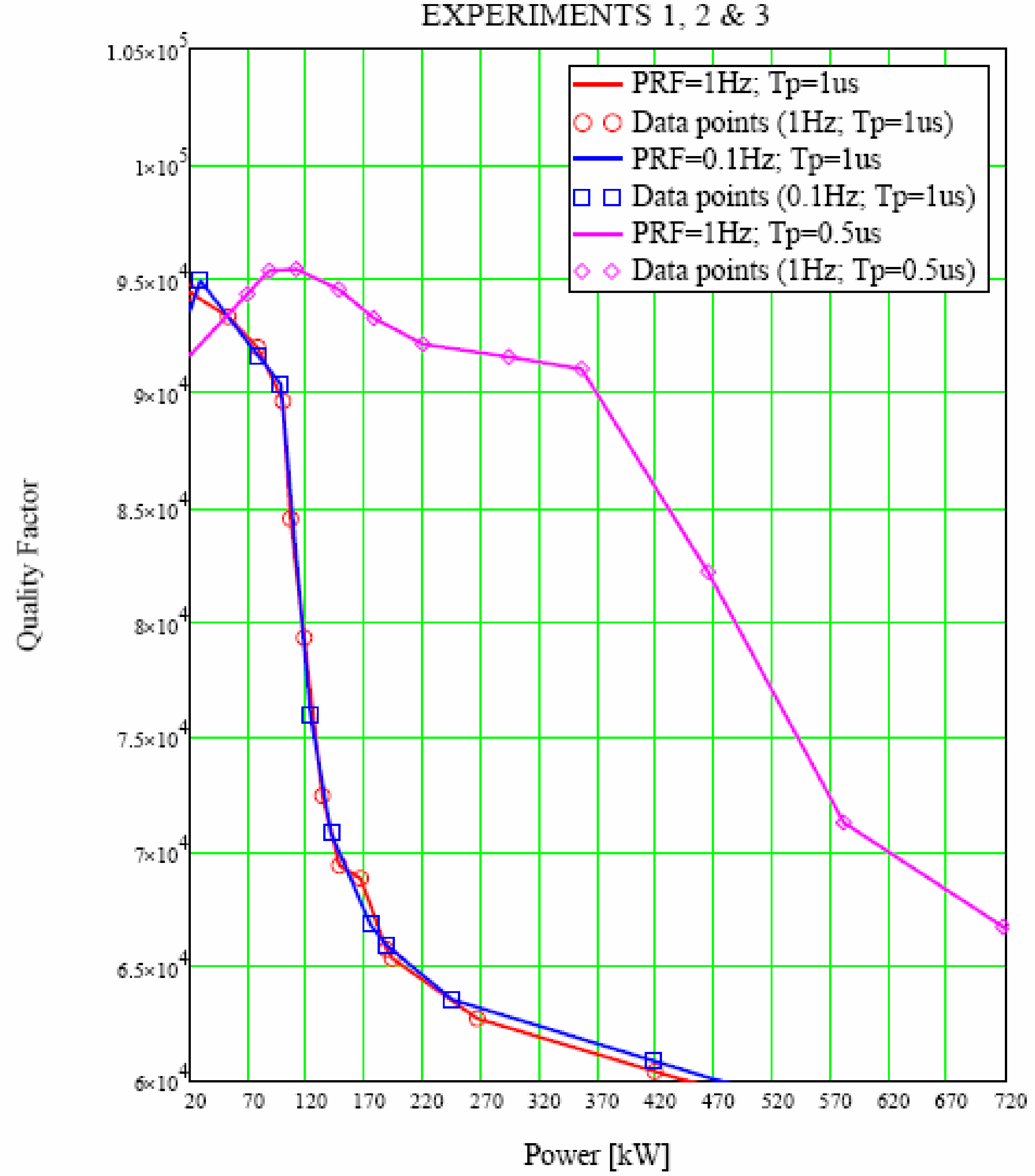
Overview: Results

Nb: RRR = 250



Overview: Results

Nb: RRR = 250



Overview: Results

- How does the pulse width depends upon input power at a given Q_L?

- How do we translate the incident power to critical magnetic field?

- How does the sample quench?

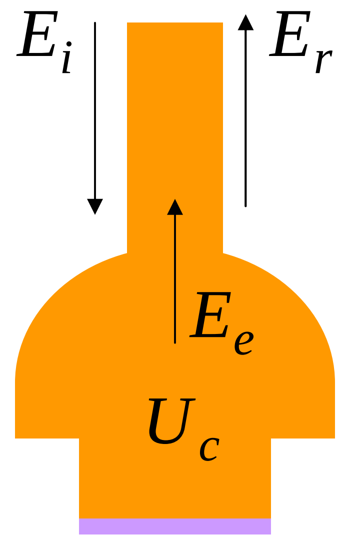
Cavity Model: Pulse Dependence

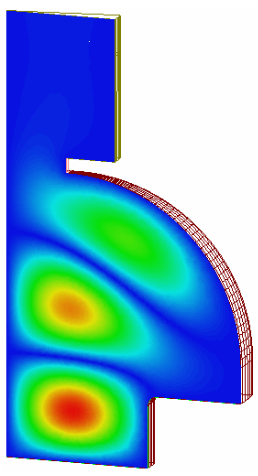
- Power balance equation

$$-\frac{dU_c}{dt} + P_i - P_r - P_L = 0$$

$$E_r = E_e + \Gamma E_i$$

$$-\frac{dU_c}{dt} + E_i^2 - \left(E_e + \Gamma E_i\right)^2 - P_L = 0$$





$$U_c = \alpha E_e^2$$

$$P_L = \xi U_c$$

Cavity Model: Pulse Dependence

- Power balance equation

$$-\frac{dU_c}{dt}+E_i^2-\left(E_e^2+\Gamma^2E_i^2+2E_e\Gamma E_i\right)-\xi U_c=0$$

$$-\frac{dU_c}{dt}+E_i^2\left(1-\Gamma^2\right)-E_e^2-2E_e\Gamma E_i-\xi U_c=0$$

$\Gamma\approx-1$

$$\frac{dU_c}{dt}+E_e^2+\xi U_c=2E_eE_i$$

$$\frac{d\alpha E_e^2}{dt}+E_e^2+\xi\alpha E_e^2=2E_eE_i$$

Cavity Model: Pulse Dependence

- Power balance equation

$$2\alpha \cancel{E_e} \frac{dE_e}{dt} + E_e^{\cancel{2}} + \xi\alpha E_e^{\cancel{2}} = 2\cancel{E_e} E_i$$

$$\boxed{\frac{dE_e}{dt} + \left(\frac{1+\xi\alpha}{2\alpha}\right) E_e = \frac{E_i}{\alpha}}$$

Recall

$$U_c = \alpha E_e^2$$

$$P_L = \xi U_c$$

$$\beta = \frac{P_e}{P_L} \Rightarrow Q_0 = \frac{\omega_0 \beta U_c}{E_e^2} \Rightarrow U_c = \frac{Q_0}{\omega_0 \beta} E_e^2 \Rightarrow \boxed{\alpha = \frac{Q_0}{\omega_0 \beta}}$$

$$Q_0 = \frac{\omega_0 U_c}{P_L} \Rightarrow P_L = \frac{\omega_0}{Q_0} U_c \Rightarrow \boxed{\xi = \frac{\omega_0}{Q_0}}$$

Cavity Model: Pulse Dependence

- Power balance equation

$$\frac{1+\xi\alpha}{2\alpha} = \frac{\omega_0}{2Q_0}(1+\beta)$$

$$\frac{1}{\alpha} = \frac{\omega_0 \beta}{Q_0}$$

$$\frac{dE_e}{dt} + \frac{\omega_0}{2Q_0}(1+\beta)E_e = \frac{\omega_0 \beta}{Q_0} E_i$$

Given $Q_L = \dfrac{Q_0}{1+\beta}$

$$\frac{2Q_L}{\omega_0}\frac{dE_e}{dt} = \frac{2\beta}{1+\beta}E_i - E_e$$

Also

$$\beta = \frac{Q_0}{Q_e}, \; Q_L = \frac{Q_0}{1+\beta}$$

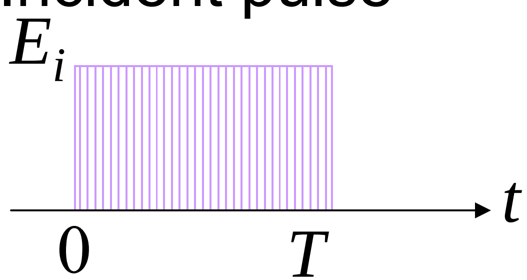
$$\frac{2\beta}{1+\beta} = \frac{2Q_L}{Q_e}$$

Cavity Model: Pulse Dependence

- Power balance equation

General solution: $E_e = \dfrac{2Q_L}{Q_e} E_i \left(1 - \mathrm{e}^{-\frac{\omega_0 t}{2Q_L}} \right)$

Incident pulse



$$E_i = \begin{cases} \sqrt{P_i} & 0 \le t \le T \\ 0 & t > T \end{cases}$$

$$E_e = \frac{2Q_L}{Q_e} \sqrt{P_i} \left(1 - \mathrm{e}^{-\frac{\omega_0 t}{2Q_L}} \right) \qquad 0 \le t \le T$$

$$E_e = \frac{2Q_L}{Q_e} \sqrt{P_i} \left(1 - \mathrm{e}^{-\frac{\omega_0 T}{2Q_L}} \right) \mathrm{e}^{-\frac{\omega_0 (t-T)}{2Q_L}} \qquad t > T$$

Cavity Model: Pulse Dependence

- Reflected field

Recall

$$E_r = E_e + \Gamma E_i \Rightarrow E_r = E_e - E_i$$

$$E_r = \frac{2Q_L}{Q_e}\sqrt{P_i}\left(1 - \mathrm{e}^{-\frac{\omega_0 t}{2Q_L}}\right) - \sqrt{P_i} \quad 0 \le t \le T$$

$$E_r = \frac{2Q_L}{Q_e}\sqrt{P_i}\left(1 - \mathrm{e}^{-\frac{\omega_0 T}{2Q_L}}\right)\mathrm{e}^{-\frac{\omega_0 (t-T)}{2Q_L}} \quad t > T$$

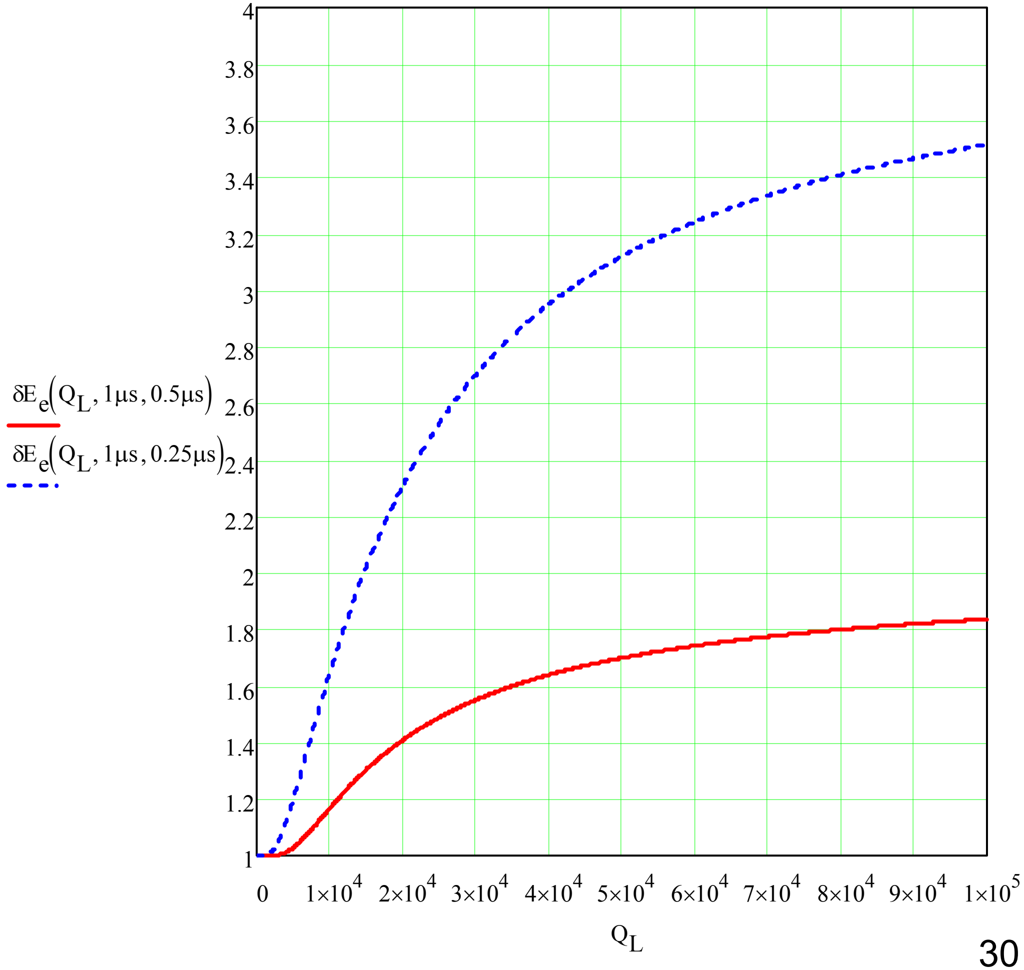
Cavity Model: Pulse Dependence

- Maximum exiting field

$$E_e^{\max}(T = T_1) = \frac{2Q_L}{Q_e}\sqrt{P_i}\left(1 - e^{-\frac{\omega_0 T_1}{2Q_L}}\right)$$

$$E_e^{\max}(T = T_2) = \frac{2Q_L}{Q_e}\sqrt{P_i}\left(1 - e^{-\frac{\omega_0 T_2}{2Q_L}}\right)$$

$$\delta E_e(Q_L, T_1, T_2) = \frac{\left(1 - e^{-\frac{\omega_0 T_1}{2Q_L}}\right)}{\left(1 - e^{-\frac{\omega_0 T_2}{2Q_L}}\right)}$$



Cavity Model: Pulse Dependence

- Reflected power

$$P_r = E_r^2 = \left[\frac{2Q_L}{Q_e} \sqrt{P_i} \left(1 - \mathrm{e}^{-\frac{\omega_0 t}{2Q_L}} \right) - \sqrt{P_i} \right]^2 \qquad 0 \le t \le T$$

$$P_r = E_r^2 = \left[\frac{2Q_L}{Q_e} \sqrt{P_i} \left(1 - \mathrm{e}^{-\frac{\omega_0 T}{2Q_L}} \right) \mathrm{e}^{-\frac{\omega_0 (t-T)}{2Q_L}} \right]^2 \qquad t > T$$

Cavity Model: Pulse Dependence

- Reflected power

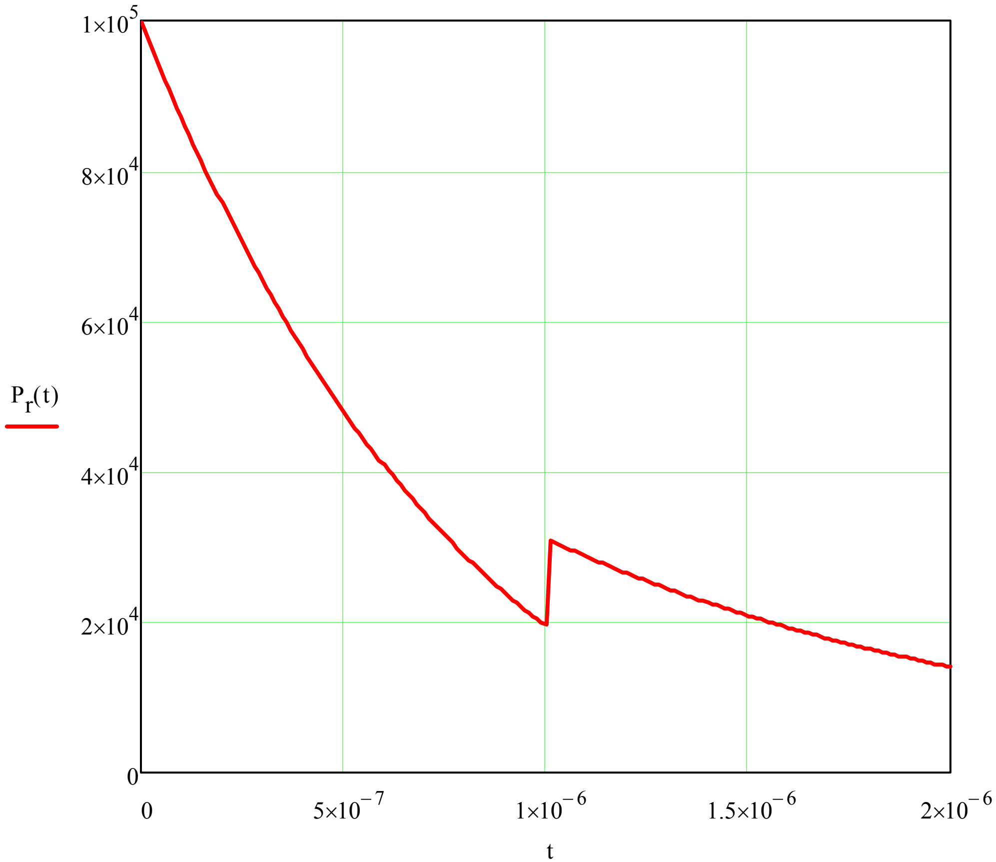
$$Q_e = 106000$$

$$Q_L = 90000$$

$$f_0 = 11.4\text{GHz}$$

$$\mathrm{P_i} = 100\text{kW}$$

$$T = 1\mu\text{s}$$



Cavity Model: Pulse Dependence

- Power in the cavity

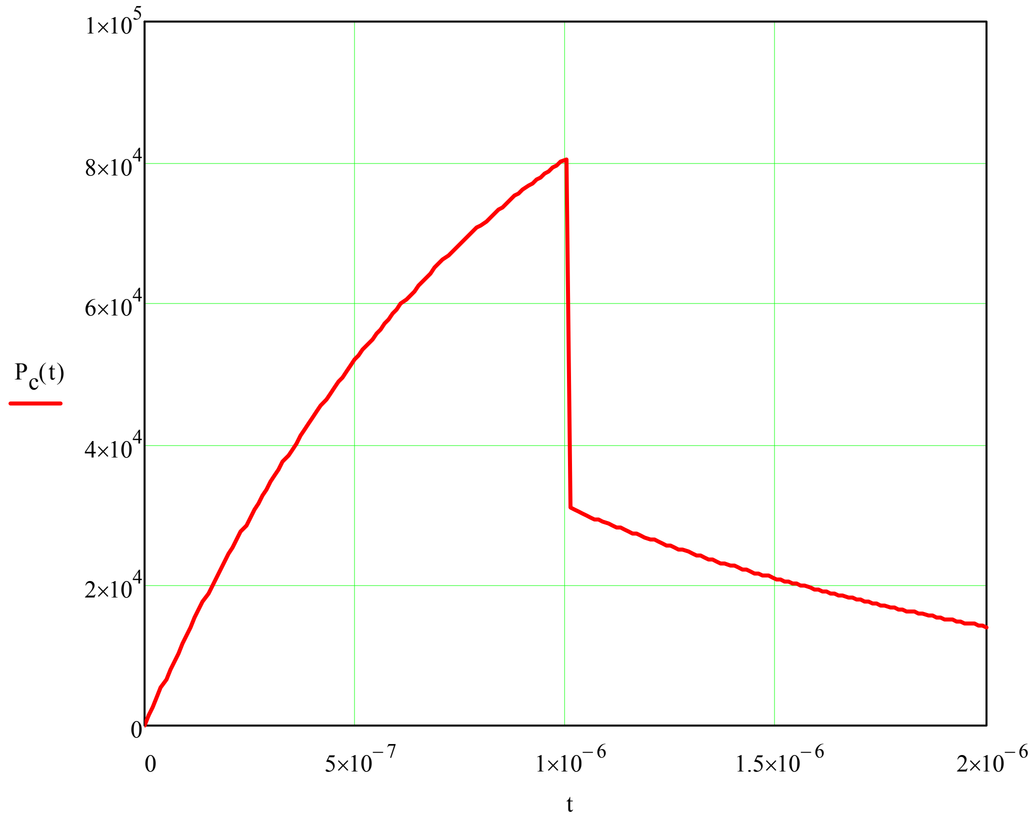
$$P_c = P_i - P_r$$

$$P_c = P_i - \left[\frac{2Q_L}{Q_e} \sqrt{P_i} \left(1 - \mathrm{e}^{-\frac{\omega_0 t}{2Q_L}} \right) - \sqrt{P_i} \right]^2 \qquad 0 \le t \le T$$

$$P_c = \left[\frac{2Q_L}{Q_e} \sqrt{P_i} \left(1 - \mathrm{e}^{-\frac{\omega_0 T}{2Q_L}} \right) \mathrm{e}^{-\frac{\omega_0 (t-T)}{2Q_L}} \right]^2 \qquad t > T$$

Cavity Model: Pulse Dependence

- Power in the cavity



$$Q_e = 106000$$

$$Q_L = 90000$$

$$f_0 = 11.4\text{GHz}$$

$$\text{P}_\text{i} = 100\text{kW}$$

$$T = 1\mu\text{s}$$

Cavity Model: Pulse Dependence

- Maximum power in the cavity

$$P_c^{\max}\left(T = T_1\right) = P_i - \left[\frac{2Q_L}{Q_e}\sqrt{P_i}\left(1 - \mathrm{e}^{-\frac{\omega_0 T_1}{2Q_L}}\right) - \sqrt{P_i}\right]^2$$

$$P_c^{\max}\left(T = T_2\right) = P_i - \left[\frac{2Q_L}{Q_e}\sqrt{P_i}\left(1 - \mathrm{e}^{-\frac{\omega_0 T_2}{2Q_L}}\right) - \sqrt{P_i}\right]^2$$

$$\delta P_c\left(Q_L, T_1, T_2\right) = \frac{P_c^{\max}\left(T = T_1\right)}{P_c^{\max}\left(T = T_2\right)}$$

Cavity Model: Pulse Dependence

- Maximum power in the cavity

$$P_c^{\max}\left(T=T_1\right)=P_i-\left[\frac{2Q_L}{Q_e}\sqrt{P_i}\left(1-\mathrm{e}^{-\frac{\omega_0 T_1}{2Q_L}}\right)-\sqrt{P_i}\right]^2 \Rightarrow$$

$$\Rightarrow P_i-\left[\frac{4Q_L^2}{Q_e^2}P_i\left(1-\mathrm{e}^{-\frac{\omega_0 T_1}{2Q_L}}\right)^2+P_i-P_i\frac{4Q_L}{Q_e}\left(1-\mathrm{e}^{-\frac{\omega_0 T_1}{2Q_L}}\right)\right]\Rightarrow$$

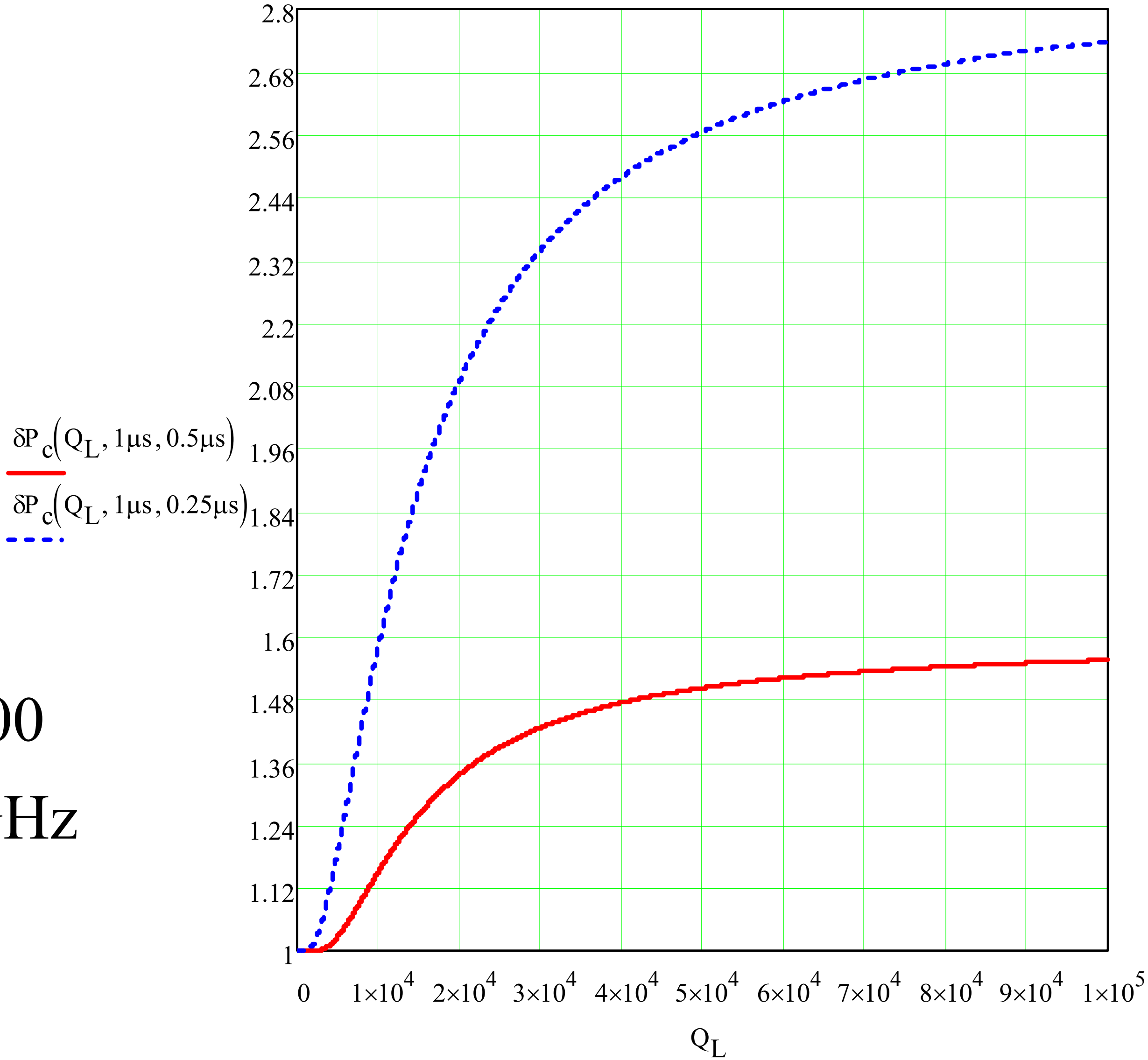
$$4P_i\frac{Q_L}{Q_e}\left(1-\mathrm{e}^{-\frac{\omega_0 T_1}{2Q_L}}\right)\cdot\left[1-\frac{Q_L}{Q_e}\left(1-\mathrm{e}^{-\frac{\omega_0 T_1}{2Q_L}}\right)\right]$$

Cavity Model: Pulse Dependence

- Ratio of maximum power in the cavity for different pulse lengths

$$\delta P_c\left(Q_L,T_1,T_2\right)=\frac{\left(1-e^{-\frac{\omega_0 T_1}{2Q_L}}\right)\cdot\left[1-\frac{Q_L}{Q_e}\left(1-e^{-\frac{\omega_0 T_1}{2Q_L}}\right)\right]}{\left(1-e^{-\frac{\omega_0 T_2}{2Q_L}}\right)\cdot\left[1-\frac{Q_L}{Q_e}\left(1-e^{-\frac{\omega_0 T_2}{2Q_L}}\right)\right]}$$

Cavity Model: Pulse Dependence

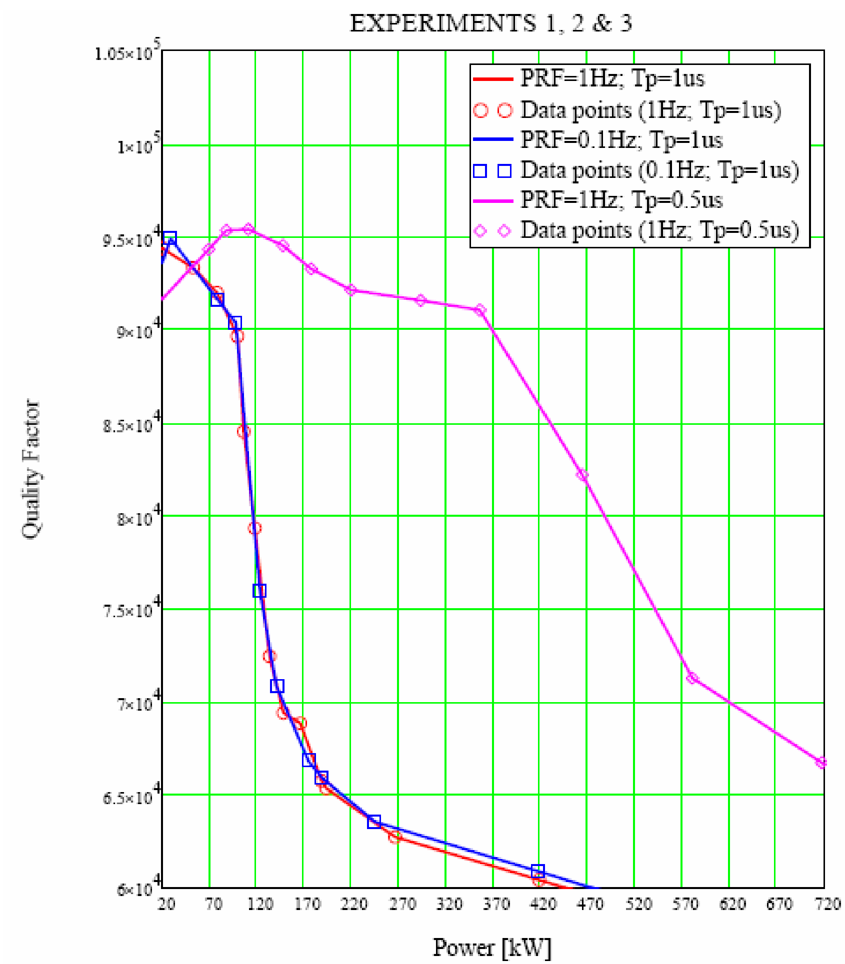


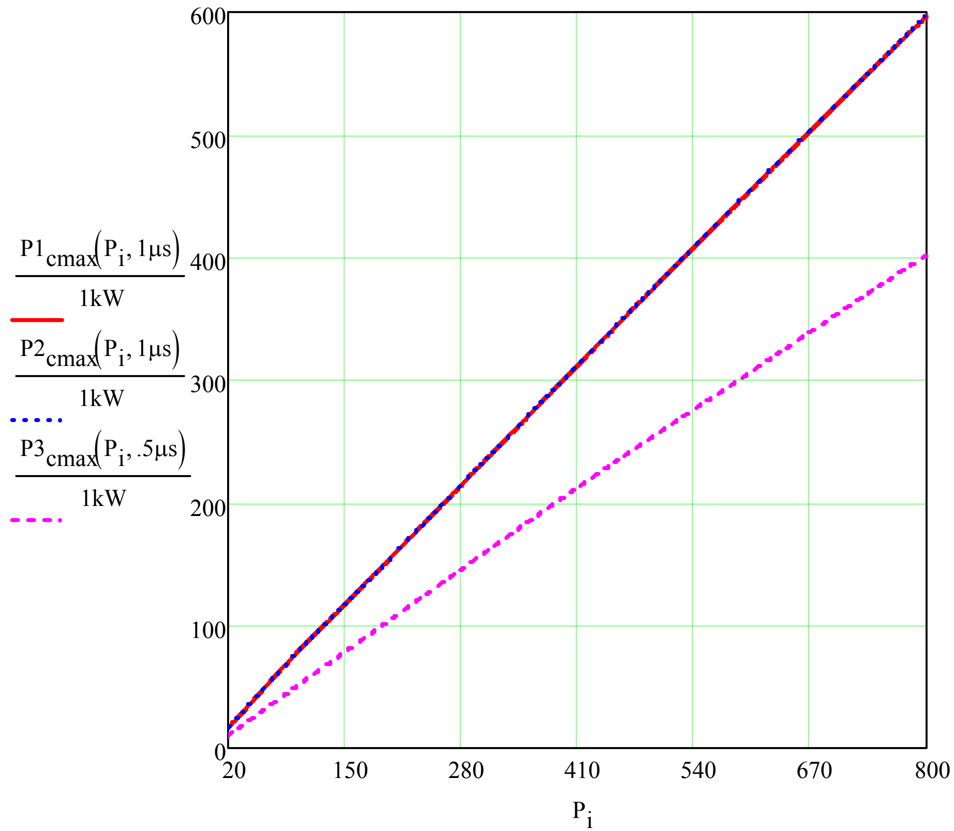
$$Q_e = 106000$$

$$f_0 = 11.4\text{GHz}$$

Cavity Model: Pulse Dependence

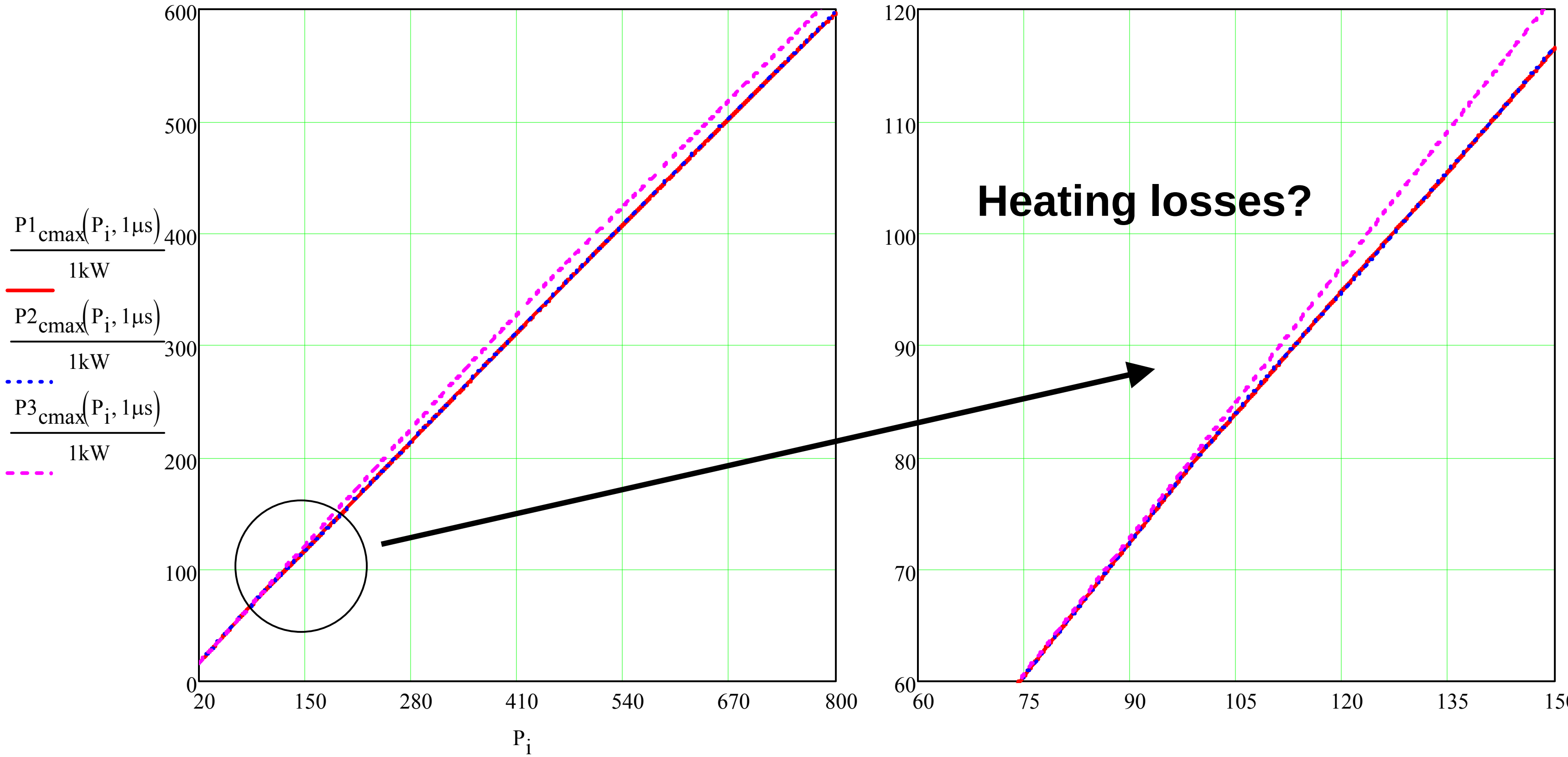
- Maximum power in the cavity for the three experiments versus P_i





Cavity Model: Pulse Dependence

- Maximum power in the cavity for the three experiments versus P_i
  - If experiment 3 were 1μs, P_c should be similar to those in experiments 1 & 2.

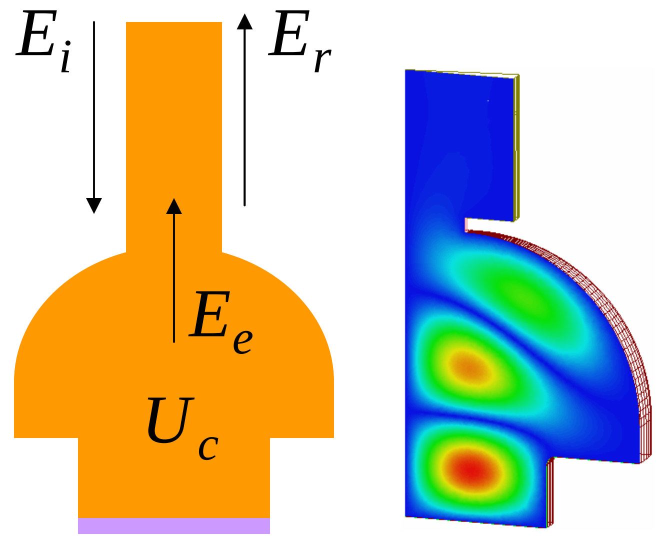


Cavity Model: Critical Magnetic Field

- Quality factors

$$\frac{1}{Q_L} = \frac{1}{Q_e} + \frac{1}{Q_c} + \frac{1}{Q_s}$$

External (aperture) Copper Sample



- Fully superconducting sample

$$Q_s = \infty \Rightarrow \frac{1}{Q_L} = \frac{1}{Q_e} + \frac{1}{Q_c} \Rightarrow \frac{1}{Q_c} = \frac{1}{Q_L} - \frac{1}{Q_e}$$

Cavity Model: Critical Magnetic Field

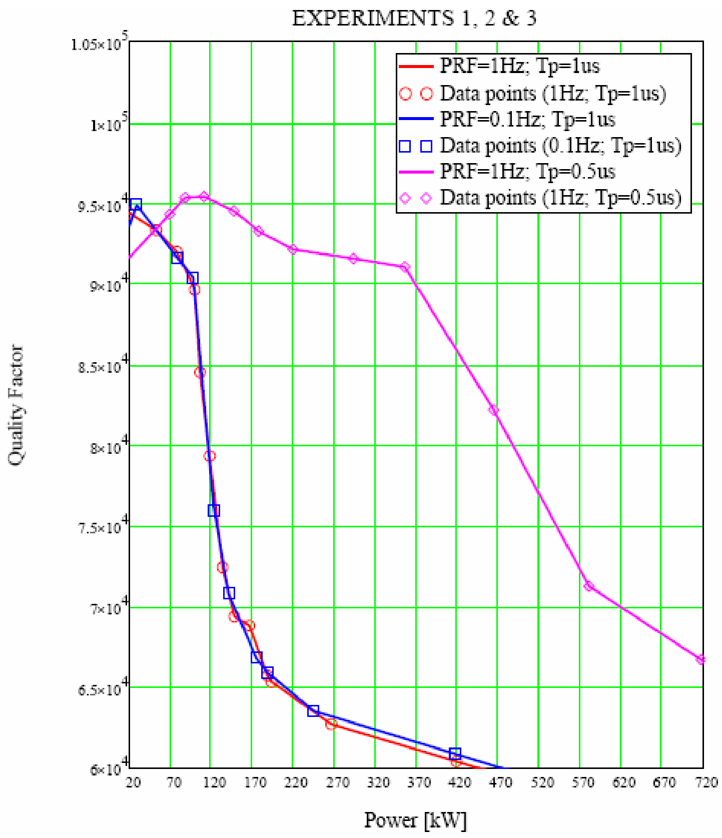
- Quality factor in normal conducting state
  - Fully superconducting

$$Q_L \approx 95000 \Rightarrow Q_c = 915455$$

  - Fully normal conducting

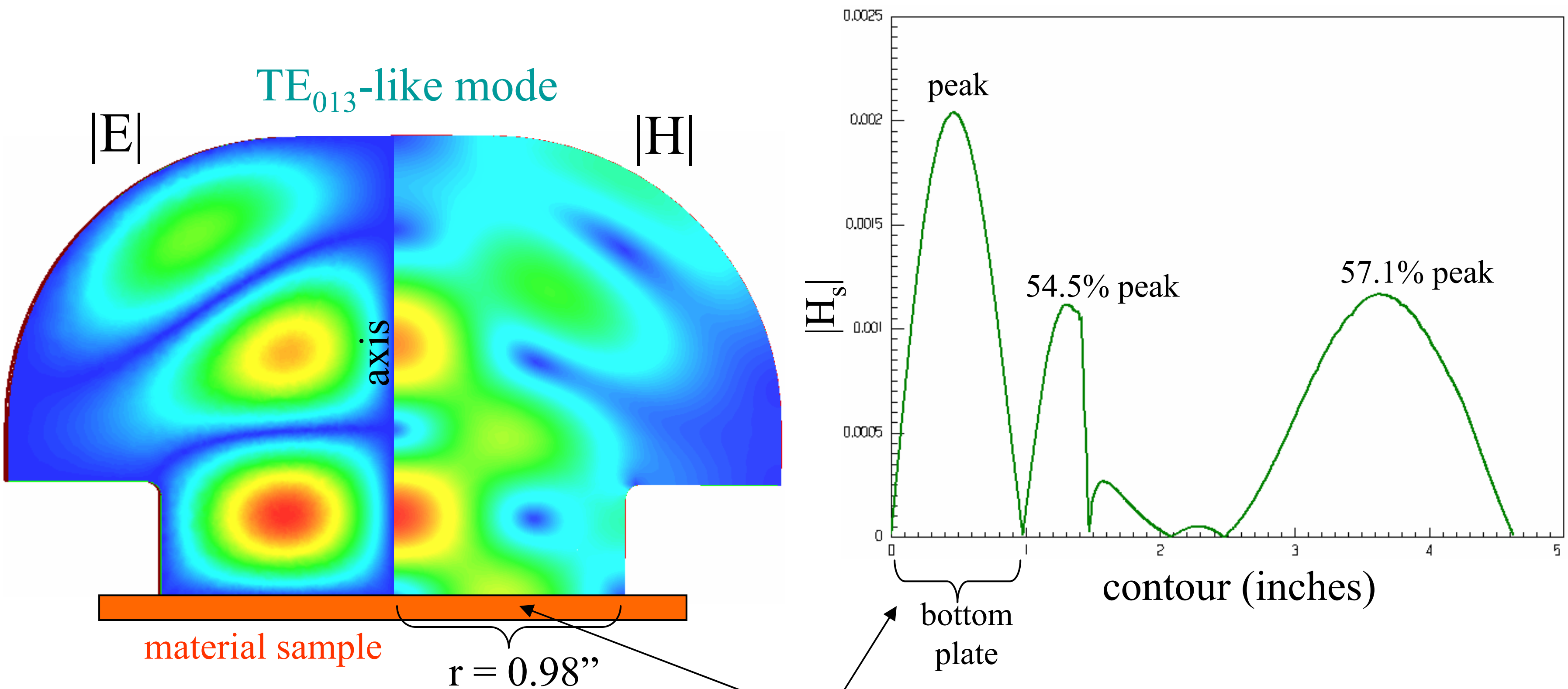
$$\frac{1}{Q_s} = \frac{1}{Q_L} - \frac{1}{Q_e} - \frac{1}{Q_c}$$

$$Q_L \approx 60000 \Rightarrow Q_s^{nc} = 162857$$



Cavity Model: Critical Magnetic Field

- Surface magnetic field



Bessel function of 1st order of the 1st kind, $J_1(x)$

Cavity Model: Critical Magnetic Field

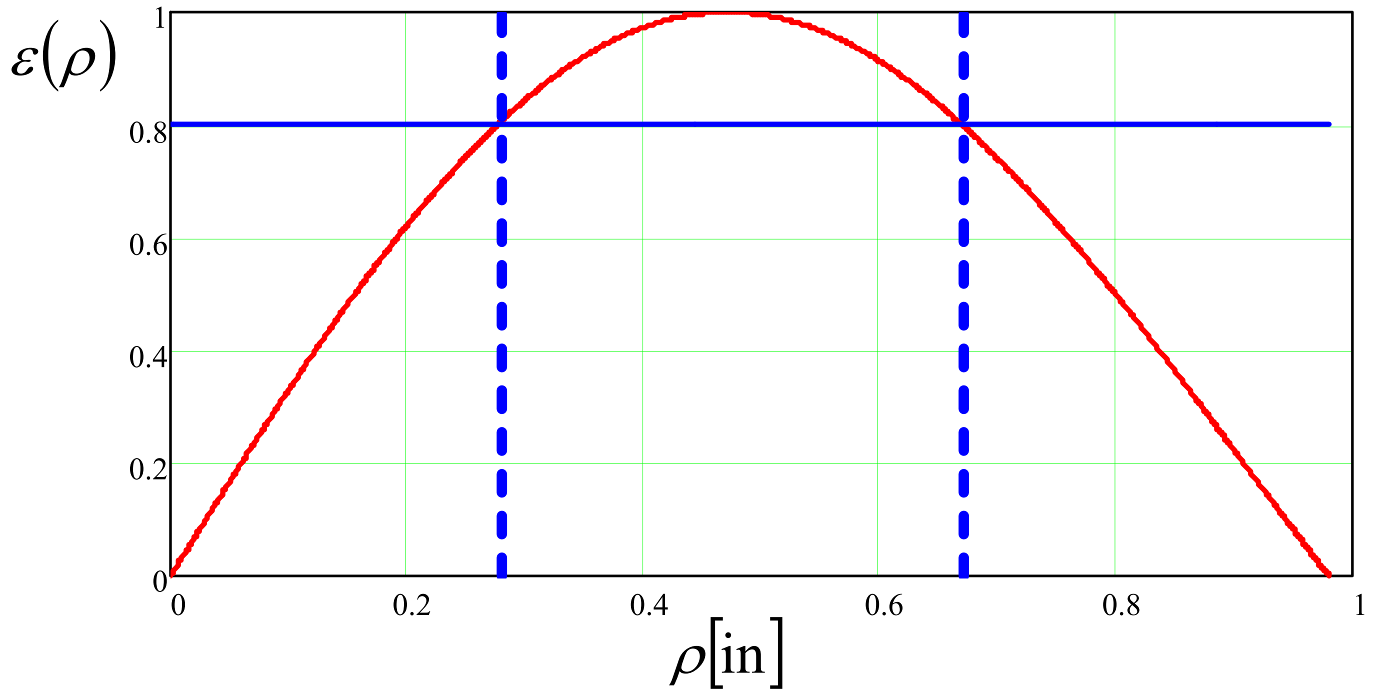
- Surface magnetic field

$$\text{radius } a = 0.98''$$

$$H_s(\rho) \propto J_1\left(\frac{3.8317\rho}{a}\right)$$

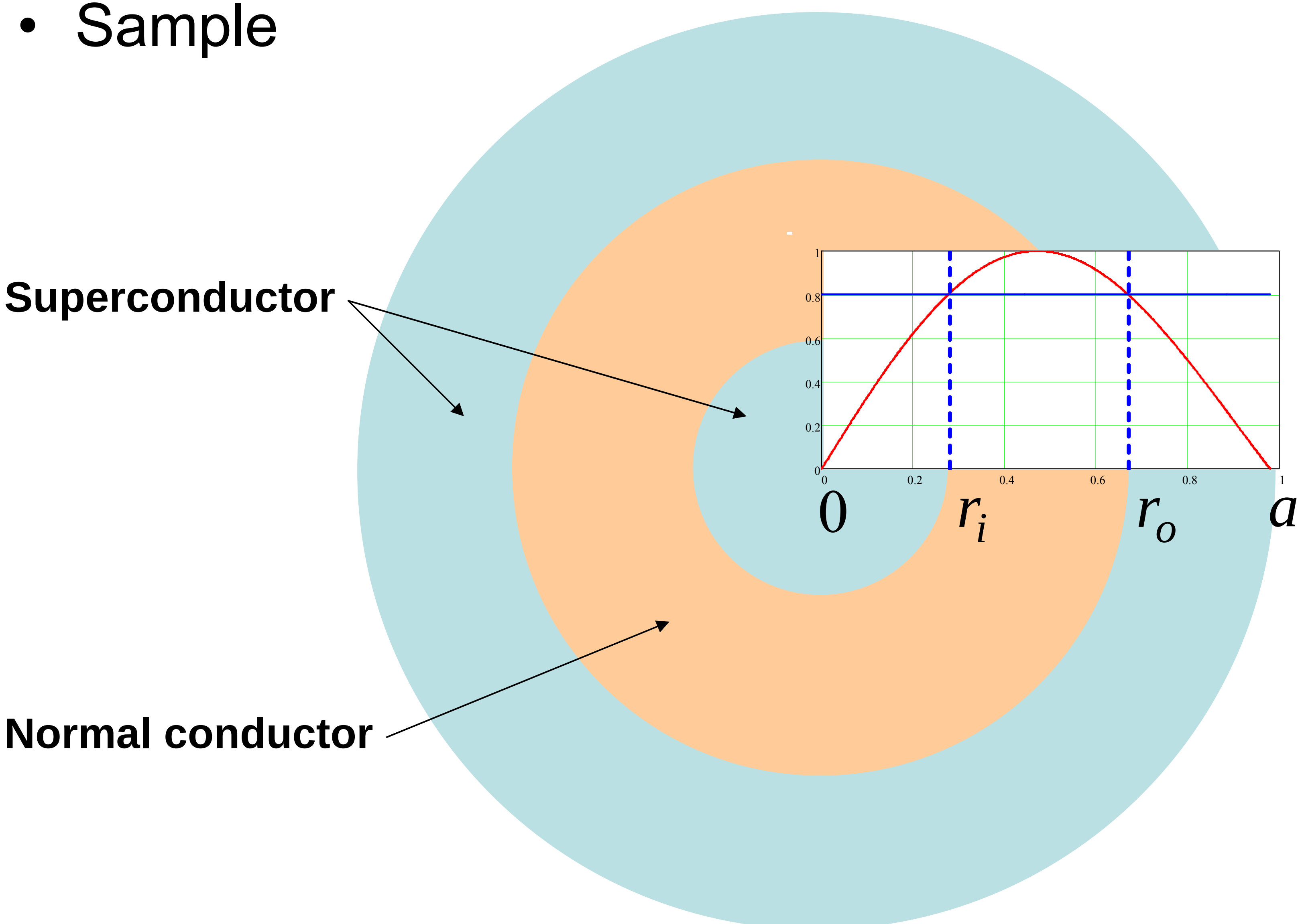
$$\varepsilon(\rho) = \frac{H_s(\rho)}{\max\left[H_s(\rho)\right]}$$

Normalized field



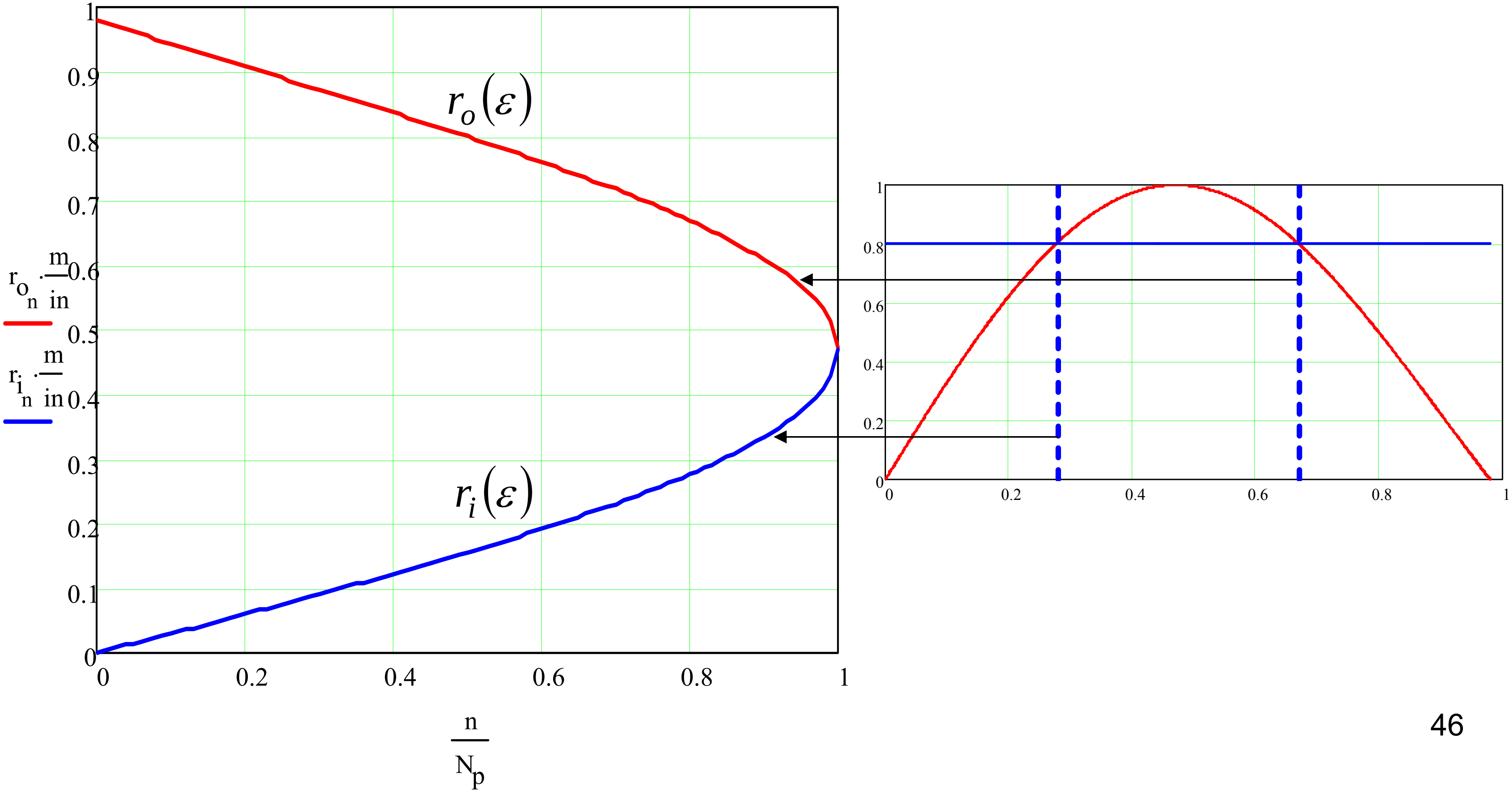
Cavity Model: Critical Magnetic Field

- Sample



Cavity Model: Critical Magnetic Field

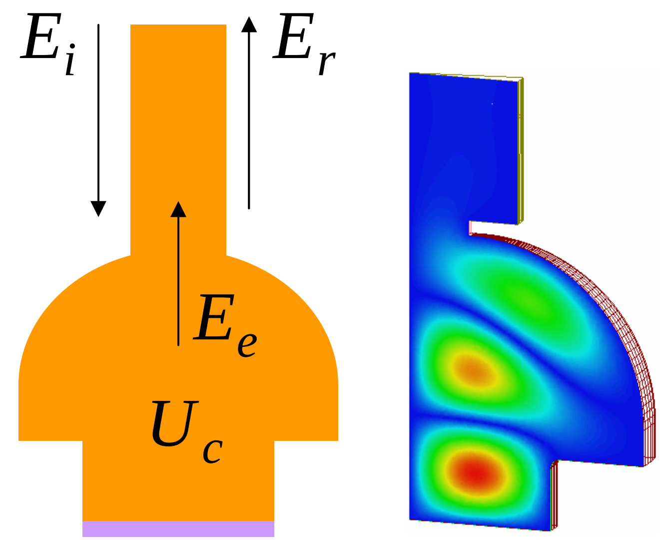
- Inverse Bessel function



Cavity Model: Critical Magnetic Field

- Quality factors

$$\frac{1}{Q_L} = \underbrace{\frac{1}{Q_e}}_{\text{External (aperture)}} + \underbrace{\frac{1}{Q_c}}_{\text{Copper}} + \underbrace{\frac{1}{Q_s}}_{\text{Sample}}$$



$$Q_s = \frac{\omega_0 U_c}{R_s P_L^s} = \frac{\omega_0 \mu_0 \iiint_v \left|\varepsilon(\rho)\right|^2 dv}{R_s \iint_s \left|\varepsilon(\rho)\right|^2 ds}$$

$$Q_s = \frac{\omega_0 \mu_0 \iiint_v \left|\varepsilon(\rho)\right|^2 dv}{R_s \int_{r_i}^{r_o} 2\pi\rho \left|\varepsilon(\rho)\right|^2 d\rho}$$

Cavity Model: Critical Magnetic Field

- Sample quality factor

$$Q_s = \frac{\omega_0 \mu_0 \iiint_V |\varepsilon(\rho)|^2 \, dv}{R_s \int_{r_i}^{r_o} 2\pi\rho |\varepsilon(\rho)|^2 \, d\rho} \cdot \frac{\int_0^{\rho=a} 2\pi\rho |\varepsilon(\rho)|^2 \, d\rho}{\int_0^{\rho=a} 2\pi\rho |\varepsilon(\rho)|^2 \, d\rho}$$

$$Q_s = Q_s^{nc} \cdot \frac{\int_0^{\rho=a} 2\pi\rho |\varepsilon(\rho)|^2 \, d\rho}{\int_{r_i}^{r_o} 2\pi\rho |\varepsilon(\rho)|^2 \, d\rho} = Q_s^{nc} \cdot \frac{9.322 \cdot 10^{-4}}{\int_{r_i}^{r_o} 2\pi\rho |\varepsilon(\rho)|^2 \, d\rho}$$

Cavity Model: Critical Magnetic Field

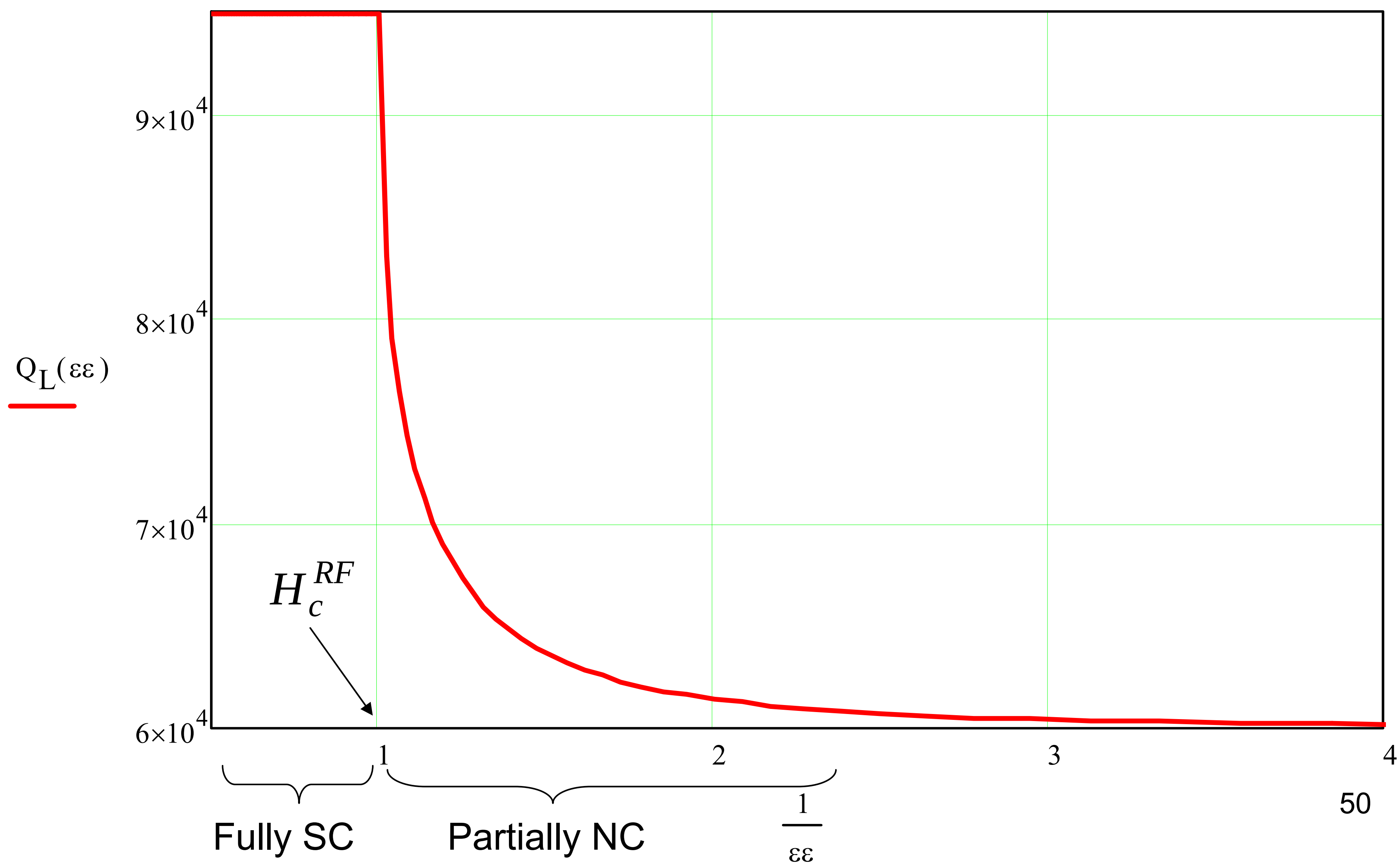
- Putting all together

$$\frac{1}{Q_L} = \frac{1}{Q_e} + \frac{1}{Q_c} + \frac{\int_{r_i}^{r_o} 2\pi\rho\left|\varepsilon(\rho)\right|^2 d\rho}{Q_s^{nc} \cdot 9.322 \cdot 10^{-4}}$$

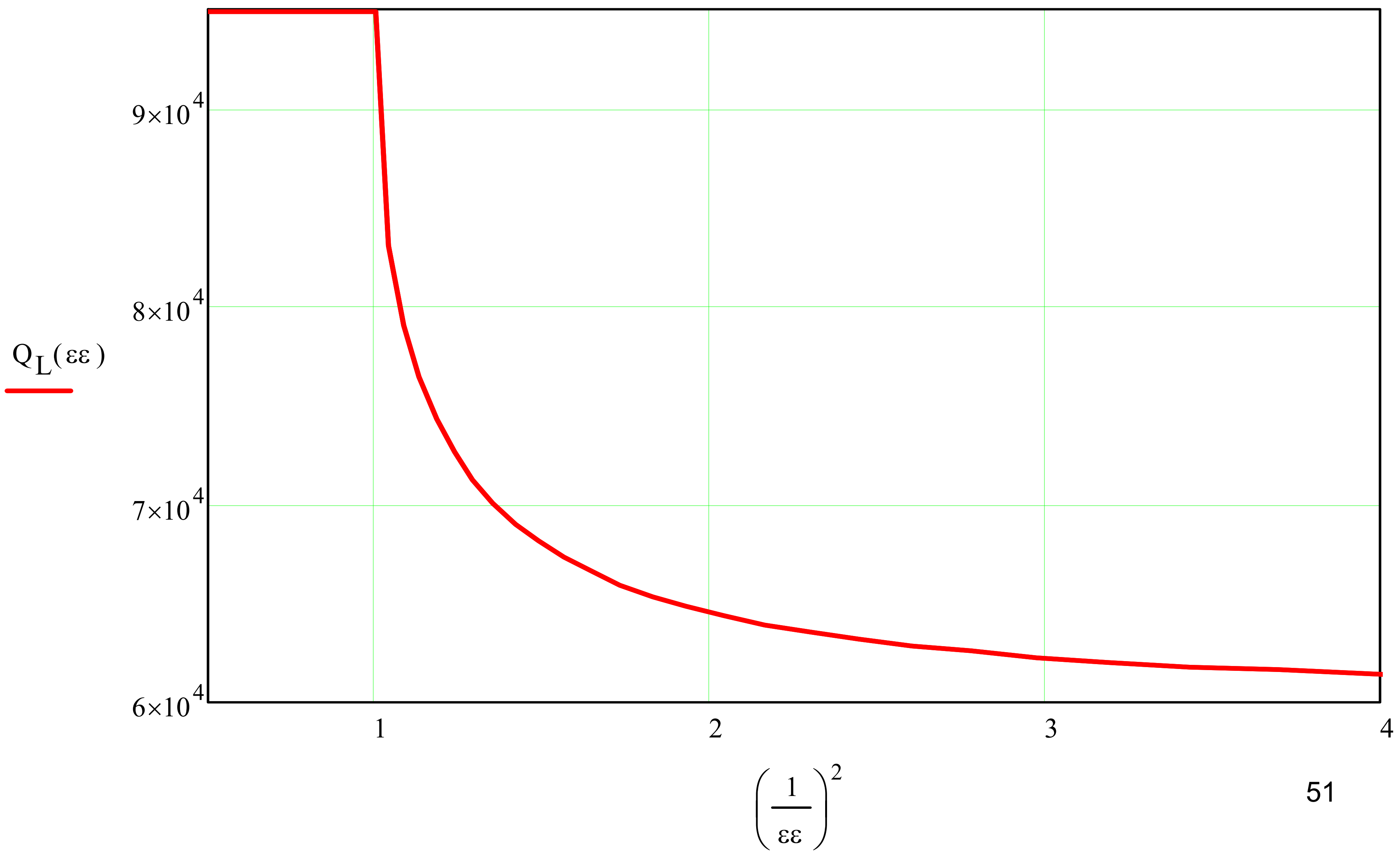
$$Q_L(\varepsilon) = \left[\frac{1}{Q_e} + \frac{1}{Q_c} + \frac{\int_{r_i(\varepsilon)}^{r_o(\varepsilon)} 2\pi\rho\left|\varepsilon(\rho)\right|^2 d\rho}{Q_s^{nc} \cdot 9.322 \cdot 10^{-4}}\right]^{-1}$$

$$P \propto H_{\max}^2 \propto \left(\frac{H_c}{\varepsilon}\right)^2 \propto \left(\frac{1}{\varepsilon}\right)^2$$

Cavity Model: Critical Magnetic Field

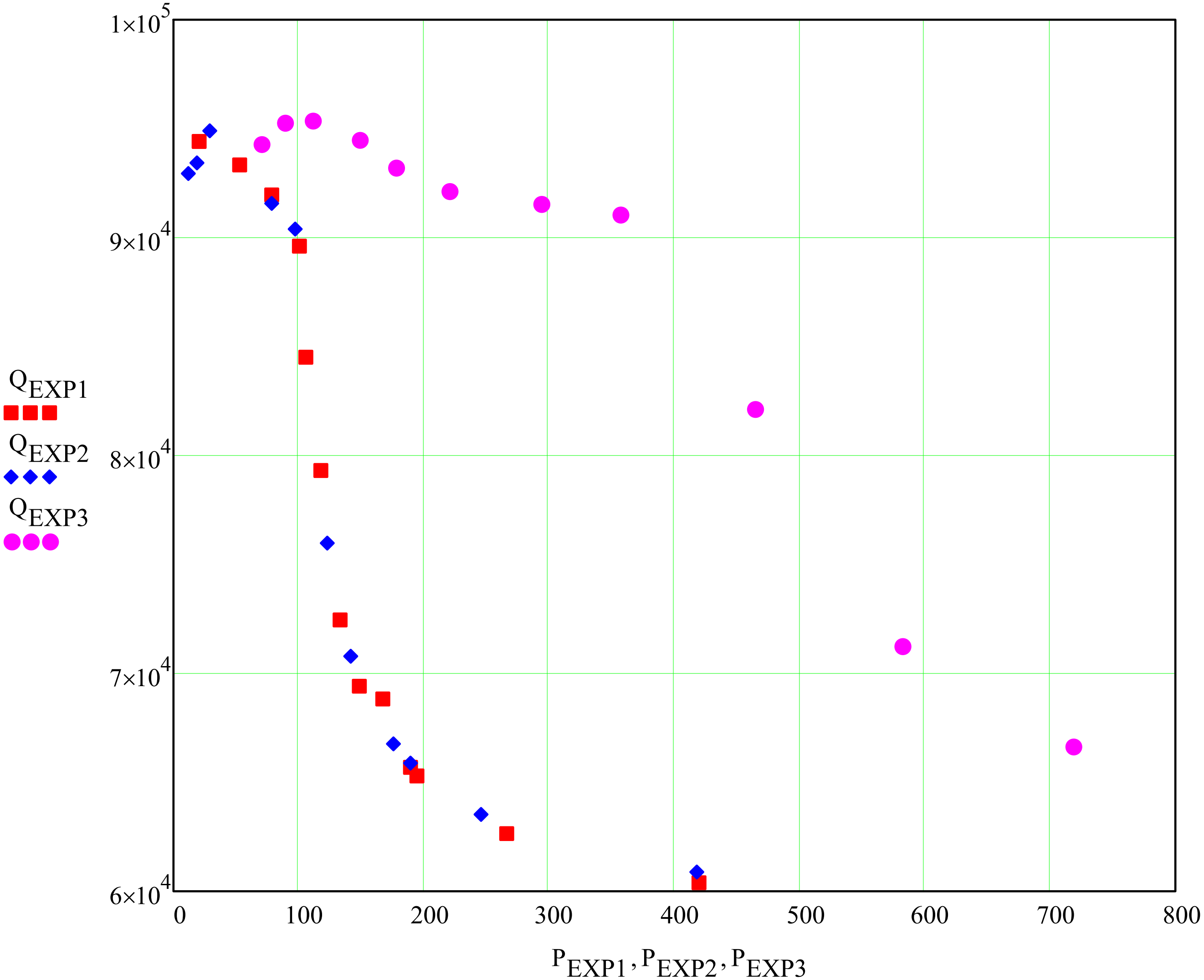


Cavity Model: Critical Magnetic Field



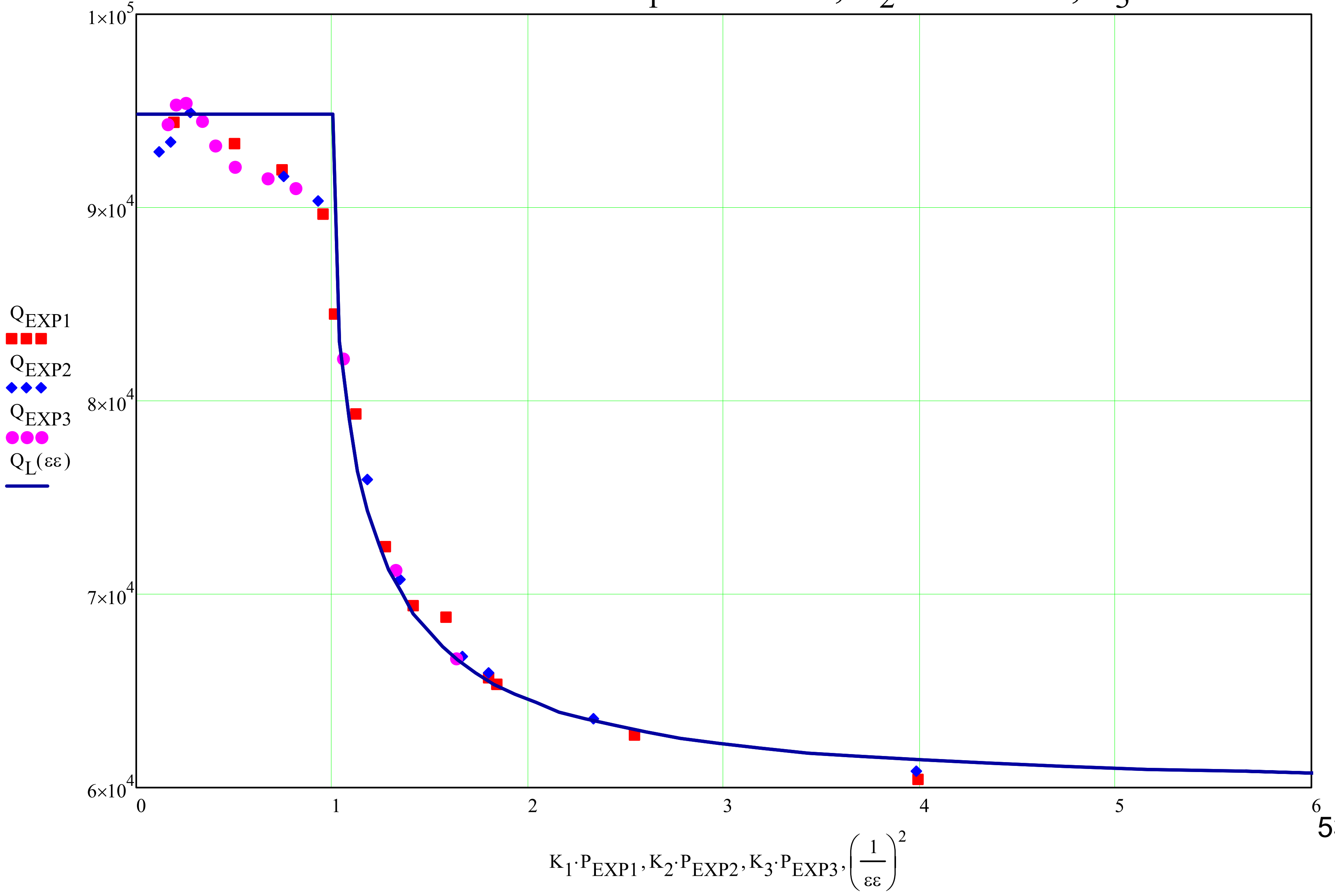
Cavity Model: Critical Magnetic Field

- Experimental Data



Cavity Model: Critical Magnetic Field

$$P_1 \to 1/105,\ P_2 \to 1/105,\ P_3 \to 1/440$$



Cavity Model: Critical Magnetic Field

- Stored energy in steady state
  - From HFSS (Sami Tantawi)

$$U_c = 8.72265\times10^{-17}\,\mathrm{J} \Rightarrow \left|\mathrm{H}_{\max}\right|^2 = 4.1048\times10^{-6}\,\frac{\mathrm{A}^2}{\mathrm{m}^2}$$

$$\left|\mathrm{H}_{\max}\right|^2 = \zeta U_c \Rightarrow \boxed{\zeta = 4.7059\times10^{10}\,\frac{\mathrm{A}^2}{\mathrm{m}^2\mathrm{J}}}$$

  - From MWS (Frank Krawczyk)

Good agreement!

$$U_c = 1\mathrm{J} \Rightarrow \left|\mathrm{H}_{\max}\right|^2 = 4.614\times10^{10}\,\frac{\mathrm{A}^2}{\mathrm{m}^2}$$

$$\left|\mathrm{H}_{\max}\right|^2 = \zeta U_c \Rightarrow \boxed{\zeta = 4.614\times10^{10}\,\frac{\mathrm{A}^2}{\mathrm{m}^2\mathrm{J}}}$$

Cavity Model: Critical Magnetic Field

- Maximum U_c

$$U_c = \alpha E_e^2 = \frac{Q_o}{\omega_0 \beta} E_e^2 \Rightarrow U_c = \frac{Q_e}{\omega_0} E_e^2$$

$$U_c = \frac{4Q_L^2}{\omega_0 Q_e} P_i \left(1 - \mathrm{e}^{-\frac{\omega_0 t}{2Q_L}} \right)^2 \qquad 0 \le t \le T$$

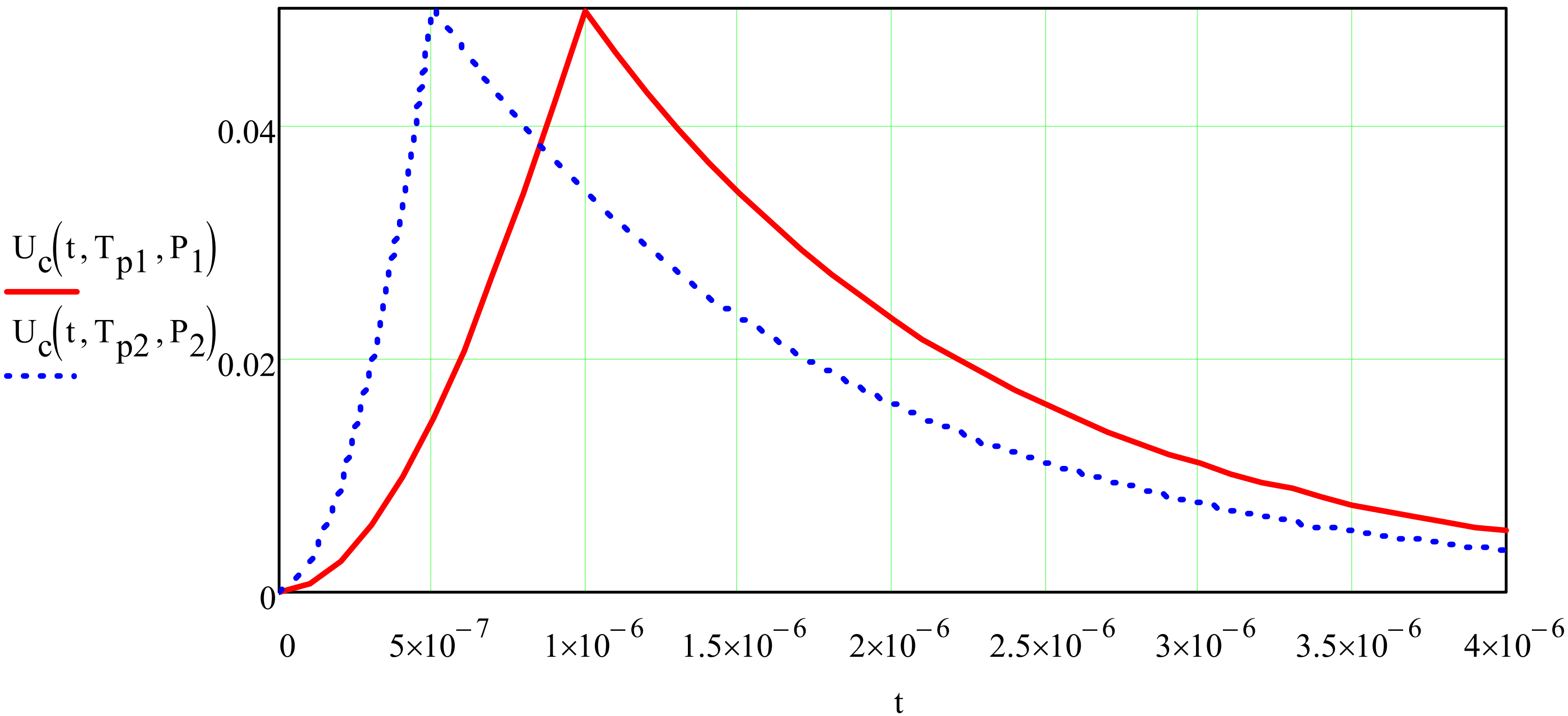
$$U_c = \frac{4Q_L^2}{\omega_0 Q_e} P_i \left(1 - \mathrm{e}^{-\frac{\omega_0 T}{2Q_L}} \right)^2 \mathrm{e}^{-\frac{\omega_0 (t-T)}{Q_L}} \qquad t > T$$

Cavity Model: Critical Magnetic Field

- Maximum U_c

1μs pulse: $T_{p1} := 1\mu s$ $P_1 := 106kW$

.5μs pulse: $T_{p2} := .5\mu s$ $P_2 := 356kW$



Cavity Model: Critical Magnetic Field

- Critical Magnetic Field

1μs pulse:

$U_c(T_{p1}, T_{p1}, P_1) = 0.05J$ $\quad H1_m := \sqrt{\zeta \cdot U_c(T_{p1}, T_{p1}, P_1)}$ $\quad H1_m = 4.789 \times 10^4 \frac{A}{m}$

$B(H1_m) = 60.186\,mT$

.5μs pulse:

$U_c(T_{p2}, T_{p2}, P_2) = 0.05J$ $\quad H2_m := \sqrt{\zeta \cdot U_c(T_{p2}, T_{p2}, P_2)}$ $\quad H2_m = 4.801 \times 10^4 \frac{A}{m}$

$B(H2_m) = 60.331 \cdot mT$

Results vs Model

Discussion

- Nb should have a H_c^{RF} of at least **~180mT**
- Possible causes
  - Pulsed heating not into account

    Solution: Use smaller and smaller pulses… available power is not an issue
  - Temperature in the RF surface is not 4.2K

    60mT, assuming 180mT being the real critical field implies T=7.5K

    This could explain why other samples "never" became superconducting…

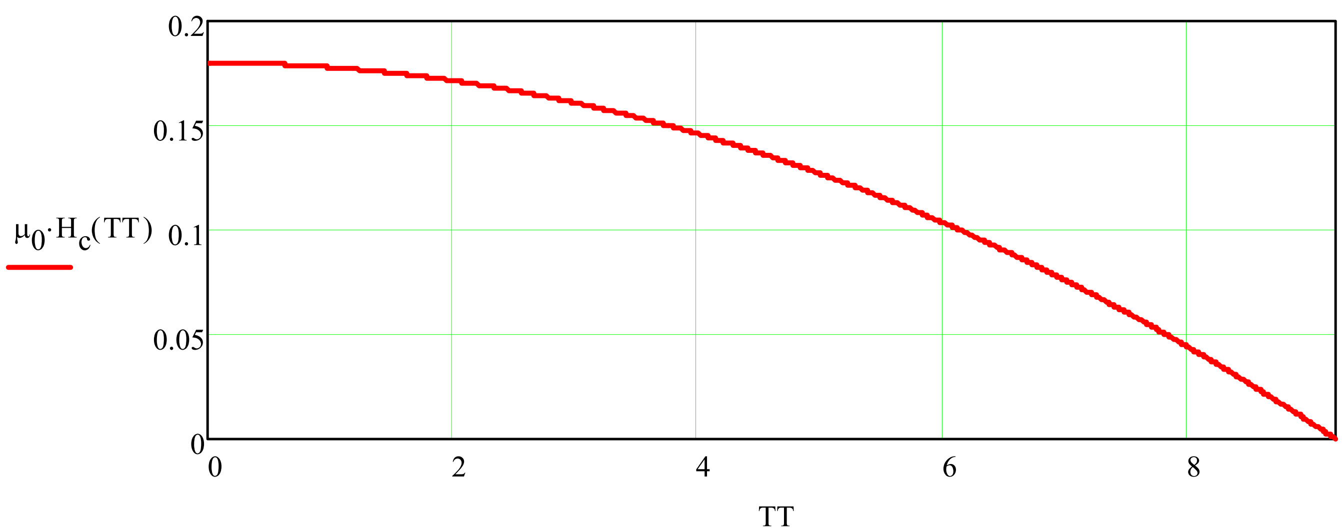
Results vs Model

Discussion

$B_{cNb} := 180mT \qquad H_{cNb} := \frac{B_{cNb}}{\mu_0} \qquad H_{cNb} = 1.432 \times 10^5 \frac{A}{m}$

$T_{cNb} := 9.2K$

$H_c(TT) := H_{cNb} \cdot \left[1 - \left(\frac{TT}{T_{cNb}}\right)^2\right] \qquad \mu_0 \cdot H_c(7.5K) = 60.376\,mT$



Results vs Model

- **Future Tests**
- New holder: better thermal contact between the copper and the superconducting sample.
- There is no thermal insulation between the cavity and the klystron. Only vacuum ~nTorr.
- Radiation heat?
- Low power test with the new holder with samples that did not become superconducting: single crystal Nb from Dessy.
- Future experiments will test very small pulses to avoid possible pulsed heating