Design and project of a Surface Impedance Characterization system (SIC) for thin film of advanced superconductors

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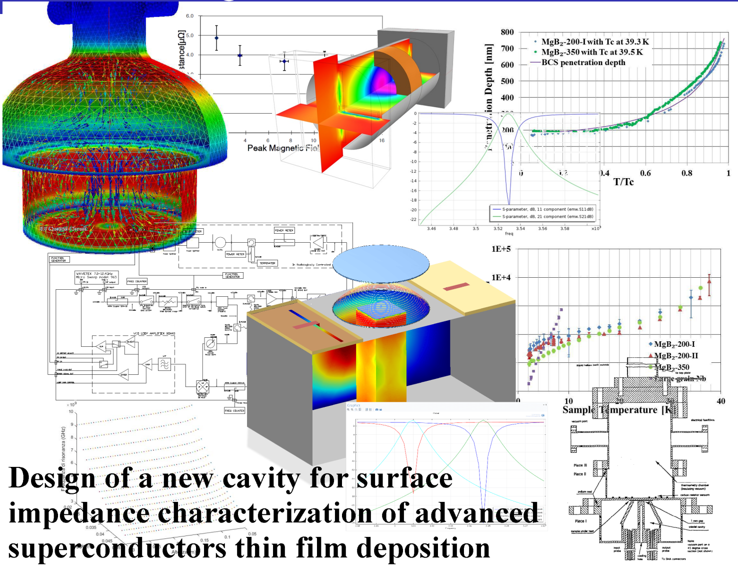
What are we doing here in Fermilab?

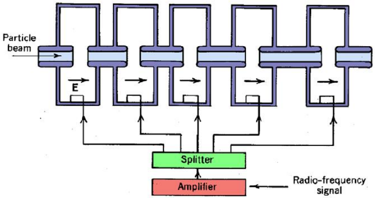


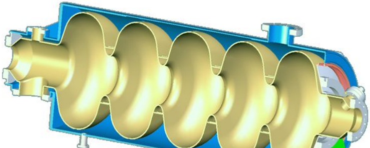
Design of a new cavity for surface impedance characterization of advanced superconductors thin film deposition

SRF Cavity: what is it?

For resonant cavity we intend a close space region, limited by perfect conducting walls and filled with a certain linear, homogeneus isotropic and non dispersive medium.

- Store huge amount of electromagnetic energy
- High efficiency in energy transmission
- High quality factor Q $=\frac{Energystored}{Energydissipated}$
- The energy dissipation depend on the surface impedance (AC current) Geometry factor $G = R_s * Q$, doesn't depend on R_s



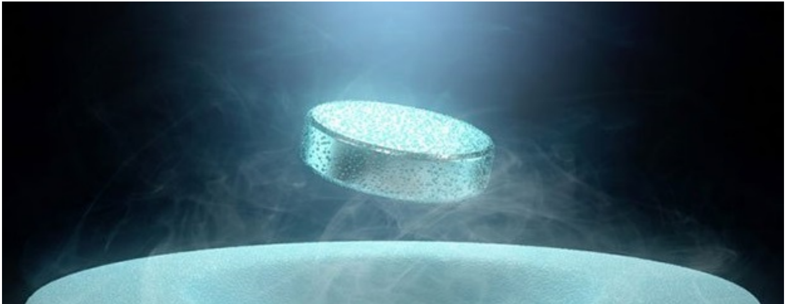


Why do we need to investigate on those phenomena?

- Development of SRF technology
- Material characterization of advanced SC
- Quantum structural matter properties of SC

SIC with Round disk sample:

-> Easy to build
-> Easy to characterize



How does a SIC work?

A SIC is a host cavity that allows to study the impedance properties.
There are two method to measure the surface impedance.

1. Quality Factor
2. Power dissipation on Sample

RF Measurments

- With RF techniques we measure $Q_i = \dfrac{\omega U}{P^i_{tot}}$ of the system
- $Q_{TOT} = (\sum \frac{1}{Q_i})^{-1} \Rightarrow$ *All*
- Q_1 Nb sample $\neq Q_2$ SC sample
- Measuring $Q_{1,2}$ of the whole system you can show that
  $$R_s = \frac{G}{\eta}\left(\frac{1}{Q_2} - \frac{1}{Q_1}\right) + \frac{G}{Q_1}$$

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Calorimetric Technique

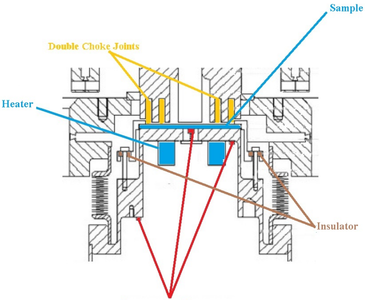
- A thermal circuit takes the heat lost on the sample by RF
- Along this circuit you measure the heat with thermal sensors
- Under the sample there is an Heater
- Meanwhile the RF is ON you insert heat with the heater for reach a steady T
- Repeat the measure disabling the RF.
  Inserting heat on circuit and reaching the same T will give information on Q and so R_s

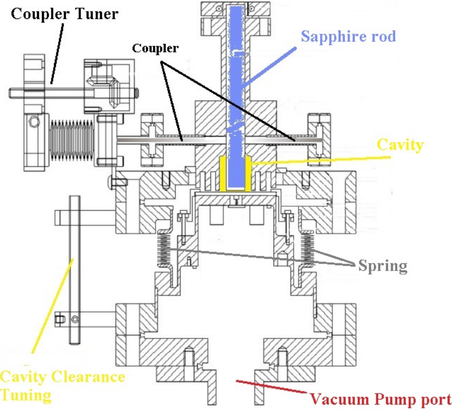
Goal of the *Summer Internship*

- Simulate the apparatus found in licterature with COMSOL©
- Study of a new improved design for host cavities
- Make simulations with COMSOL© of the new cavity

"Standing on the shoulder of giants" Bernard of Chartres, XII A.C.

- Surface Impedance of Superconducting Radio Frequency (SRF) Materials, Bingping Xiao
- RF surface impedance characterization of potential new materials for SRF-based accelerators,B. P. Xiao
- Commisioning of the SRF surface impedance characterization system at JLAB,B. P. Xiao
- A Sapphire Loaded TE011 Cavity for Surface Impedance Measurements–Design, Construction, and Commissioning Status, L. Phillips





Cavity improvement and goals

Specs

- Decrease the eigenfrequency
- Increase $Ratio = \frac{B_{pk,sample}}{B_{pk,cavity}}$ ($R > 1$ is better)

Cost of apparatus

- Design that allows to machine easily the Nb
- The Sapphire cost! Moreover, it reduces the performance of the cavity

Measurements

- Improve the RF measurements
- Improve the calorimetric technique
- Try to implement new techniques

Radio Frequency Simulation

Two candidate designs for the host cavity

Pillbox Cavity

- Xiao's and our cavity:
  - Analitic model, Eigenfrequency;
  - Coupling power sensitivity;
  - Sapphire Losses;
  - Fine simulation with optimized parameters;

$3.9\,\mathrm{GHz}$ based design

- Our cavity:
  - Eigenfrequency;
  - Coupling power;
  - Sapphire Losses
  - Fine simulation with optimized parameters;

A new Cavity: Analitic model TE_{plm} solutions

Maxwell's equations in cylindrical coordinates for a simple pillbox cavity with appropriate boundary/continuity conditions have been solved:

$$\vec{\nabla} \cdot \vec{D} = 0 \qquad \vec{\nabla} \times \vec{E} = i\omega \vec{B}$$

$$\vec{\nabla} \cdot \vec{B} = 0 \qquad \vec{\nabla} \times \vec{H} = -i\omega \vec{D}$$

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The solution is a function with separate variables
$W(\rho, \phi, z) = R(\rho)\Phi(\phi)Z(z)$

Solving the differential equation system:

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Solving the differential equation system:

- p,l,m integer for TE_{plm}
- $J_m(x)$,$Y_m(x)$ first and second order Bessel's equation
- k_A,k_B wave number in Sapphire and vacuum

$$\begin{cases} Z(z) = Z_0 sin(\frac{p\pi}{L} z) \\ \Phi(\phi) = \Phi_0 cos(m\phi) \\ R(\rho) = \begin{cases} A_0 J_m(k_A \rho) & \text{if } 0 \leq \rho < R_{sapph} \\ A_1 J_m(k_B \rho) + A_2 Y_m(k_B \rho) & \text{if } R_{sapph} \leq \rho \leq R_{cav} \end{cases} \end{cases}$$

A new Cavity: Analitic model Eigenmodes

With the continuity conditions on EM fields the values of k_A and k_B are calculated by writing a $\mathrm{MatLab}^{©}$ script (non-linear equations)

This provides the analitical eigenmodes!

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$$k_B = \sqrt{\left(\frac{k_A^2}{\epsilon_r}\right) + \left(\frac{p\pi}{L}\right)^2 \left(\frac{1}{\epsilon_r} - 1\right)}$$

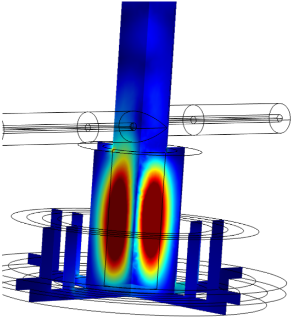
k_A Follows from continuity of solutions and their derivatives

$$\Downarrow$$

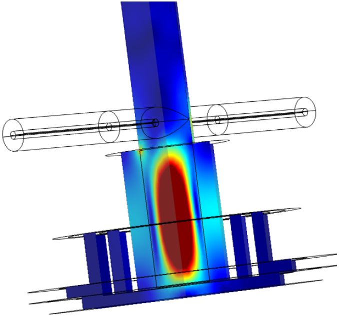
$$f_{plm} = \frac{c}{2\pi\sqrt{\epsilon_r}} \sqrt{\left(k_A(\chi'(l,m))\right)^2 + \left(\frac{p\pi}{L}\right)^2}$$

Where $\chi(l,m)'$ are the first roots of the derivative of the Bessel function J_m

Simulations and results with COMSOL©: Xiao's Pillbox



Coupled E field



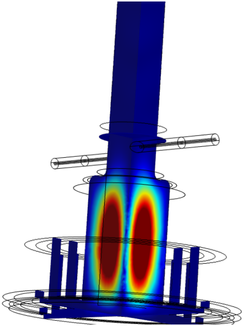
Coupled B field

$Cavity Diameter$	$20\,\mathrm{mm}$
$Cavity Length$	$22\,\mathrm{mm}$
$Sapphire Diameter$	$12\,\mathrm{mm}$
$Sapphire Length$	$169\,\mathrm{mm}$

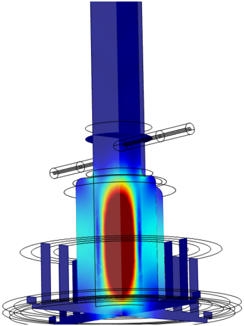
$$Ratio \approx 0.31$$

$$f \approx 7.4289\,\mathrm{GHz}$$

Simulations and results with COMSOL©: Our Pillbox



Coupled E field



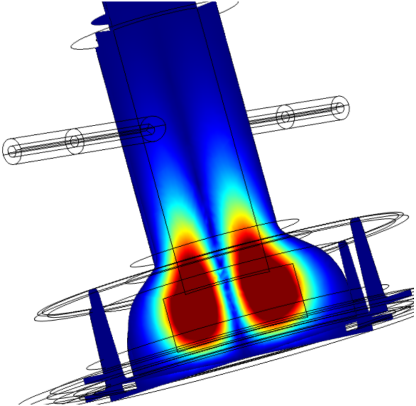
Coupled B field

$CavityDiameter$	50 mm
$CavityLength$	60 mm
$SapphireDiameter$	30 mm
$SapphireLength$	180 mm

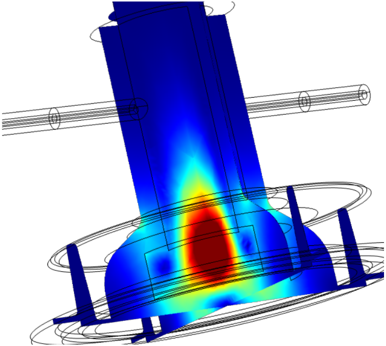
$Ratio \approx 0.55$ (EM fields in sapphire)

$f \approx 2.95\,\mathrm{GHz}$

Simulations and results with COMSOL$^{©}$: $3.9\,\mathrm{GHz}$ Based Cavity



Coupled E field



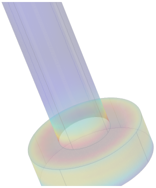
Coupled B field

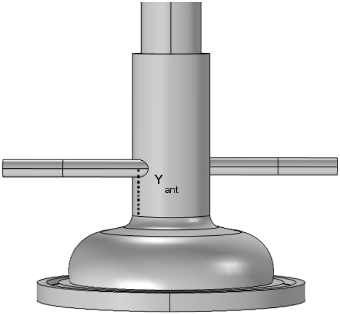
$\boxed{Ratio \approx 1.23}$

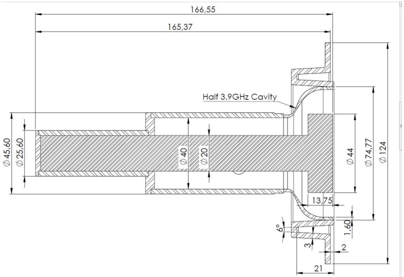
$\boxed{f \approx 3.1375\,\mathrm{GHz}}$

Sapphire and cavity Geometry of 3.9 GHz based cavity

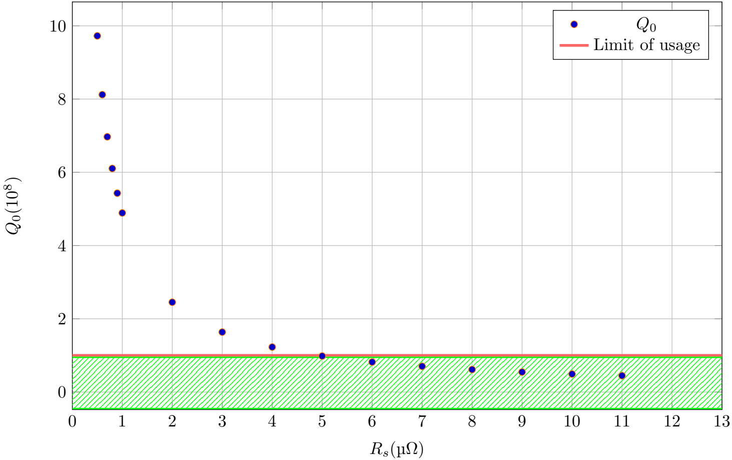
$3.9 - Cut$ Geometry	
Inner Iris Diameter	40 mm
Outer Iris Length	74.77 mm
Little Sapphire Diameter	20 mm
Little Sapphire Length	166.55 mm
Big Sapphire Diameter	44 mm
Big Sapphire Length	13.75 mm







Sapphire Losses and quality factors of



We have a big limitation due to the quality factor of the sapphire!

f[GHz]	$Q_{Ti,Clamp}$	$Q_{Sapphire}$	Q_{SSteel}	Q_{gap}
3.1375	$1.37 \cdot 10^{12}$	$4.80 \cdot 10^{8}$	$4.45 \cdot 10^{12}$	$2.32 \cdot 10^{11}$

Final Comparison

Pillbox Cavity

- Low $f \approx 2.9586\,\mathrm{GHz}$ ✓
- $Ratio < 1$ ✗
- Total-know geometry ✗
- High cost for Nb bulk ✗
- High cost of machinery ✗
- High Cost sapphire ✗
- Sapphire limitate accurancy ✗

Cutted $3.9\,\mathrm{GHz}$

- Low $f \approx 3.1357\,\mathrm{GHz}$ ✓
- $Ratio > 1$ ✓
- Well-know geometry ✓
- EB welding required ✗
- Nb parts difficult to build ✗
- High Cost sapphire ✗
- Sapphire limitating accurancy ✗

Next steps...

To do list..

- Verification of RF model
- Study of *Multipacting*
- Possible improvment of measurement techniques
- Possible design without sapphire