Design and project of a *Surface Impedance Characterization System* (SIC) of thin film deposition of advanced superconductors

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1 Introduction

Superconducting radio frequency (SRF) technology is widely adopted for the scientific potential of past and current particle accelerators. Superconducting RF is the key technology for many future accelerators because of the outstanding efficiency of this technology. Accelerators as XFEL(Hamburg) or ILC will certainly need the highest performance allowed by the state of art of the SRF cavities.
Actually SRF cavities made out of niobium are now approaching their theoretical superheating field limit. Alternative materials such as Nb_3Sn and MgB_2 are predicted to have significant higher fields and are very interesting for next generation SRF cavities. In order to to this we need to investigate on the quantum structure of matter of all the superconductors for a better comprehension of the intrinsic nature and differences between superconductors ($1^{st} - type$, $2^{st} - type$ or high critical temperature). Moreover, is necessary to investigate on the macroscopic properties as Surface Impedance or critical parameters.
A high field and high sensitivity sample host cavity will be an ideal tool for studying various field-dependent loss phenomena and to explore the ultimate performance of these new types of rf superconductors. In this report, we will present our work during a Summer Intership in Fermilab, that consist in project and design one of those cavities starting from the PhD. thesis of Dr. Bingping Xiao (Jafferson Lab) and that one of Dr. Yie Xie (Cornell University).
An host cavities used for this purpose is meant to measure the surface impedance using the sample as the bottom plate of the cavity. This means that changing the sample the RF and thermic properties change as well of the cavity itself, so it's possible to measure the physical parameters from a comparison method using first a calibrated and well know sample in Nb and then that sample of interest.
We will see that there are both RF and thermal method of measurments in our casus, and finally we will compare our cavities with figure of merit and performance of the other cavities.
We will present the path we followed starting by reviewing of bibliography till the final project with mechanical and electronic systems that we chosen with the our Supervisors Prof. Emanuela Barzi and Ing. Daniele Turrioni.

2 Superconductivity Radio-Frequency Fundamentals (SRF)

2.1 Definition of a cavity

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. In the real dielectric actually it's impossible to avoid totally the losses and could be anisotropus, so even the calculation of the chosen field in the cavity had to be properly considered.
The electromagnetic fields are particular solutions of Maxwell's equations and are the oscillations modes of the cavity. The theory states that there are an infinite number of discrete modes of oscillation, since a resonant cavity has an infinite number of discrete eigenvalues.
Generally the high-field superconductors can carry large currents distributed over their whole cross-section. These body currents are lossless when steady, exactly as are the surface currents of soft superconductors. However, for timevariant currents this may no longer be true. Variations in the current distribution are equivalent to modulation of the self-inductance and this can be shown to lead to losses. This brings with it the interest for studies on surface resistance of supeconductors.

2.2 How does it works

Electromagnetic fields are excited in the cavity by coupling in an RF source with an antenna as an RF source. When the RF frequency fed by the antenna is the same as that of a cavity mode, the resonant fields build to high amplitudes. The resonant frequency driven in SRF cavities typically ranges from 200 MHz to 200 GHz, depending on the particle species to be accelerated in casus of accelerating cavities, meanwhile in other cavities it depends just by what's the goal of the studies.
The most common fabrication technology for such SRF cavities is to form thin walled (1-3mm) shell components from high purity niobium sheets by stamping. These shell components are then welded together to form cavities. A simplified diagram of the key elements of an SRF cavity setup is shown in Figure 2. The

Figure 1: A SRF 3.9 GHz cavity

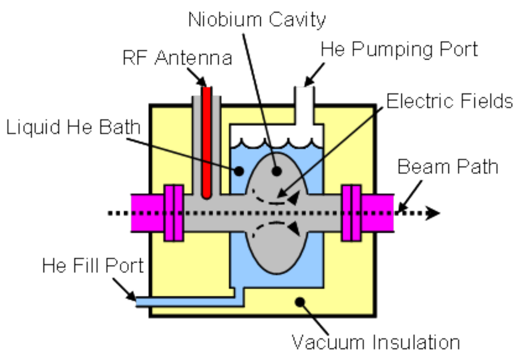


Figure 2: Schematic diagram of SRF cavity system

cavity is immersed in a saturated liquid helium bath. Pumping removes helium vapor boil-off and controls the bath temperature. The helium vessel is often pumped to a pressure below helium's superfluid lambda point to take advantage of the superfluid's thermal properties. Because superfluid has very high thermal conductivity, it makes an excellent coolant. In addition, superfluids boil only at free surfaces, preventing the formation of bubbles on the surface of the cavity, which would cause mechanical perturbations. An antenna is needed in the setup to couple RF power to the cavity fields and, in turn, any passing particle beam. The cold portions of the setup need to be extremely well insulated, which is best accomplished by a vacuum vessel surrounding the helium vessel and all ancillary cold components.
The physics behind the SRF cavities would require much more than few pages, but with the help of few simple approximation and simple models we can fulfill the preliminar knowledge of the subject.

2.3 Resonance in an series RLC circuit

An SRF cavity at frequencies nearby a resonance mode, it can be modeled as an RLC circuit [4]. In a series RLC circuit we have a resistor R, a capacitor C and an inductor L, and the physical meaning could be thought as it follows:

- The resistor R comes from the surface resistance of the walls
- The capacitor C comes from the electric field between metallic plates of the cavity
- The inductor L comes from the surface currents flowing in the walls

Writing the equation of the AC voltage $V(t) = V_0 e^{i\omega t}$ applied on a series RLC circuit we obtain:

$$RI + L\frac{dI}{dt} + \frac{1}{C}\int I dt = V_0 e^{-i\omega t}$$

$$I(t) = \frac{V_0}{\sqrt{R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2}} e^{i(\omega t - \phi)}$$

The impedance is defined as the ratio between voltage and current, we obtain:

$$Z = \frac{V(t)}{I(t)} = \sqrt{R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2} e^{i\phi} = R + i\left(\omega L - \frac{1}{\omega C}\right) \tag{1}$$

The real part of impedance is called resistance and the imaginary part is reactance. In RLC circuit , for a given voltage with a given amplitude, the current has the maximum amplitude at frequency $\omega = \frac{1}{\sqrt{LC}}$, which is the resonant frequency of this RLC circuit.
Now, at this frequency the reactance shrinks to 0 and the impedance shows only resistance, the total stored energy is $U = L\frac{V_0^2}{Z_0^2}$, while the power dissipation is $P_{diss} = U\frac{R}{L}$
In physics and engineering we define the quality factor Q_0 as a dimensionless parameter that describes how under-damped an oscillator or resonator is, as well as characterizes a resonator's bandwidth relative to its center frequency. Higher Q_0 indicates a lower rate of energy loss relative to the stored energy of the resonator; the oscillations die out more slowly. Resonators with high quality factors have low damping so that they ring longer. With our notation we define Q_0 as:

$$Q_0 = \frac{1}{R}\sqrt{\frac{L}{C}} = \frac{\omega U}{P_{diss}}$$

This means that the peak voltage on the capacitor is $V_C = Q_0 V_0$, so the AC voltage results as high as Q times of the input voltage.
Now, we need to take into account of the surface impedance of a conducting materials. This is defined as the ratio between the E field and the H field parallel to the material surface [3] and we need to represent the total impedance of a SRF cavity as it follows:

$$Z_{total} = R + i\omega L + i\omega L_V - i\frac{1}{\omega C_V} \tag{2}$$

The first two terms are representive of surface resistance while the last two terms represent the inductance and capacitance of the vacuum space in the cavity, which is defined by the geometry of the cavity.
The tipical parameters becomes now:

$$\omega = \frac{1}{\sqrt{(L + L_V)C_V}} \qquad U = (L + L_V)\frac{V_0^2}{Z_0^2}$$

$$P_{diss} = U\frac{R}{L + L_V} \qquad Q = \frac{1}{R}\sqrt{\frac{L + L_V}{C_V}}$$

2.4 Figures of Merit

The stored energy, power dissipation and quality factor also satisfy:

$$U = \frac{1}{2}\mu_0 \iiint\limits_V |H(x,y,z)|^2 \, d\tau \qquad P_{diss} = \frac{R}{2} \iint\limits_s |H(x,y,z)|^2 \, ds \qquad Q_0 = \frac{1}{R}\frac{\iiint_V |H(x,y,z)|^2 \, d\tau}{\iint_s |H(x,y,z)|^2 \, ds}$$

Let's define now G a factor dependent only by the geometry, in fact:

$$G = RQ_0 = \frac{\iiint_V |H(x,y,z)|^2 \, d\tau}{\iint_s |H(x,y,z)|^2 \, ds}$$

Those parameters are called *Figures of Merit* and are fundamentals for the characterzation and the design of a cavity. Afterwards we will briefly present a comparison of some host cavities built for those experiments and we will compare to our cavity.
In the real system if the system is coupled to an external load, the mode dissipate some power on the cavity and some on the load, so this means $P_{tot} = P_{diss} + P_i + P_t$[1]. In this way we need to define a factor Q_L which represent the quality factor in a whole:

$$Q_L = \frac{\omega U}{P_{tot}}$$

Let's now define

$$Q_i = \frac{\omega U}{P_i} \qquad\qquad Q_t = \frac{\omega U}{P_t}$$

It's easy to see that, combining the Q definition we have

$$\frac{1}{Q_L} = \frac{1}{Q_0} + \frac{1}{Q_i} + \frac{1}{Q_t} \tag{3}$$

If we says that $\beta_i = \frac{Q_0}{Q_i}$ and $\beta_t = \frac{Q_t}{Q_t}$ we have

$$Q_0 = Q_L(1 + \beta_i + \beta_t) \tag{4}$$

A parameter important as well is the Q_{ext}, that is not in the balance of the quality factor. Is a coupling parameter, studied for the coupling of antennas and defined as a relation between the power dissipated on the cavity and the power inserted in the external port, therefore

$$Q_{ext} = \frac{\omega U}{P_{ext}}$$

From the microwave theory we know that $|\Gamma|$, the VSWR is connected to β factors with:

$$|\Gamma| = \left|\frac{\beta - 1}{\beta + 1}\right|$$

This means that with a normal Network Analyzer we can obtain all the information we need for the measurments of the quality factors.
The only critical point is the sign of β, and this could be obtained knowing if $\beta < 1$ or $\beta > 1$. Knowing this one could obtain his value from [2]:

$$\beta = \begin{cases} \dfrac{1+\Gamma}{1-\Gamma} & \text{if } \beta > 1 \\ \dfrac{1-\Gamma}{1+\Gamma} & \text{if } \beta < 1 \end{cases}$$

[1] Where P_i is the power in input and P_{out} is the transmitted power.

[2] For understand a priori if *beta* is greater/less than 1 we could examinate how does the module of gamma change with the frequency. If the radius who describes the resonance contains the origin $\beta > 1$ otherwise $\beta < 1$. If the radius intersecate the origin $\beta = 1$. We respectively talk of *over-coupling*, *under-coupling* and *critical coupling*.

A really important spec for those devices is the Ratio R that says what is the ratio between maximux field on sample and maximum field on cavity, so this means:

$$R = \frac{B_{max,sample}}{B_{max,cavity}}$$

Obviuosly we want $R > 1$ because this would allow to reach higher magnetic fields for the measurments, and the cavity would quench when the $B_{pk,sample}$ is $B_{pk,sample} = R \cdot B_{pk,cavity}$.
We want to end this part saying that there are several way to measure Q of the cavity but we'll discuss only the method that uses a NA and the scattering matrix parameter of a linear system.

3 Review of literature

For many years, a variety of sample test cavity systems have been developed with the aim of RF testing material samples in-situ. Actually this is the easier way to test and study the properties of thin film deposition. For example, for test advanced superconductors as the MgB_2 for SRF cavities, build an apposite prototype would be impossible for the techniques we nowaday know, so RF test on little sample would be easier.
In the table 1 we show an incomplete list with their maximum field, area of sample, surface resistance sensitivity and operating frequency.

Performance cavities				
f(GHz)	Sample area(cm^2)	R_s(nΩ)	Maximum sample field (mT)	Reference
8.6	0.9	104	Very low	Allen et.al., 1983
5.7	40	∼103	15	Laurent et.al., 1983
3.5	127	1	2	Kneisel et.al., 1986
5.95	20	1.5·104	Unknown	Moffat et.al., 1988
0.17∼1.5	∼1	2.0·103	64	Delayen et.al., 1990
10	1	104	Unknown	Taber et.al., 1990
34	35	2.0·106	Unknown	Martens et.al., 1991
1.5	4.9	1	25	Liang et.al., 1993
0.403	44	1	25	Mahner et.al., 2003
11.4	19.6	>104	> 150	Nantista et.al., 2005
5.95	35	2.0·103	45	Romanenko et.al., 2005
7	1	104	0.15	Andreone et.al., 2006
0.6∼10	<0.1	<100	≤50	ats et.al., 2006
3.54	22	Unknown	50	Ciovati et.al., 2007
0.4∼1.2	44	Unknown	51	Junginger et.al., 2009
7.5	20	< 100	< 12	Xiao et.al., 2012
5.88	154	20	48	Xie et.al.,2013
5.02	314	5	62	Xie et.al.,2013
4.78	254	1	64	Xie et.al.,2013

Table 1: Host cavities comparison

3.1 *Standing on the shoulder of giants*

The starting point of our experience it has been study and follow the path draw by two articles we had [1] [2]. We undestood how does an host cavity work and what are the reason why some choice have been made; why the TE_{011} has been chosen? Why a Nb cavity is better than a Cu cavity?
Those and other technical aspects are presented in this section.

3.1.1 Cavities Geometries

In both articles are presented different geometries with which has been built a SIC. In [1] Dr. Binping Xiao presents the simple *Pillbox Cavity* that is a sapphire loaded cylindrical simmetric cavity with radius R and height L operating at TE_{0lm} mode[1]. In those modes the electric field lines are simple self-closing around the resonator axis and his amplitude vanish on cavity walls as well as on the sample. Moreover, in this way, no RF currents crosses the joint between the sample and the cavity and, with no surface-normal electric fields, electronic problems such as multipacting and heating due to dark current may be avoided[2]. This cavity it's the simplest for the analitic model and for the building both, but it's not the best choice for some parameters as the eigenfrequency or the Ratio.

In [2] we have two different geometries analyzed. First of all the simple Pillbox, then a *Mushroom cavity*. Except from the different geometric properties of the cavities the simple pillbox of Dr. Yi Xie has the same advantages and disadvantages of that one of Dr. Xiao. The other geometry is mushroom shaped and actually this type of cavity focuses the peak magnetic field on a sample at the root of the mushroom. A TE_{0lm} mode is still used, moreover it would significantly increase the Ratio R lowering the operation eigenfrequency. Actually this requires a more careful study on his geometry and on other critical aspects respect on the simple pillbox but would give more interesting results[3].
What we have choose as geometry will be fulfill explained on the next section 4 on page 10 and 5 on page 18.

3.1.2 Choice of measuring techniques

As we told we should write the surface impedance Z_s in two parts; the real part is R_s the surface resistance and the imaginary part X_s is the surface resistance.
The methods for measure the resistance in literature are actually the following:

- ✓ RF measurments;
- ✓ Calorimetric techniques;
- ✓ Thermal Mapping;

RF Measurments We already mentioned about the quality factor and how the total quality factor is summed as the reciprocal of the single Q_i. Those values are strongly dependents on the surface resistance, and while in the simulation we assume R_u as uniform inside the system, it's obvious that it is not. Let's define:

$$\eta_i = \frac{Q_t}{Q_i} \qquad\qquad G_i = Q_i R_u$$

Where η is the filling factor, and G indicates a parameter that is only geometrical dependent[4].
Let's note with Q_1 the whole system quality factor with the reference sample and Q_r the quality factor of the reference sample; let's denote with Q_2 the whole system factor with the sample to measure and Q_s

[1]The sapphire use will be better understood later
[2]Actually in the real system double choke joint are needed for minimize the RF losses on the interface between sample and cavity. This work even as an electromagnetic closing for the cavity
[3]Multipacting for example would be more tricky to treat respect of the normal pillbox
[4]The total geometry factor of the resonant system is $G = \sum G_i$

the quality factor of the measuring sample[5].
The portions of the system are the same during these two measurements so we have:

$$\frac{1}{Q_1} - \frac{1}{Q_r} = \frac{1}{Q_2} - \frac{1}{Q_s}$$

With those osservation we can definitely observe that the surface resistance of the sample will be:

$$R_s = \frac{G}{\eta}\left(\frac{1}{Q_2} - \frac{1}{Q_1}\right) + \frac{G}{Q_1} \tag{5}$$

The measuring error of R_s can be represented as:

$$\Delta R_s = \sqrt{\left[\frac{G}{\eta}\frac{\Delta Q_2}{Q_2^2}\right]^2 + \left[G\left(1-\frac{1}{\eta}\right)\frac{\Delta Q_1}{Q_1^2}\right]^2}$$

This explain why a superconducting cavity (Nb) would be more efficient than a normal conducting cavity (Cu), in fact the error would be significantly reduced as much as Q_i increases[1].
Operetionally the measure is a comparative method based on using two different sample and measuring the quality factor of the cavity with two different sample[2].

Calorimetric Technique The calorimeters built by Dr. Xiao in his project are actually two, and are able to deal with peak power of few µW to more than one hundred W. This tecnique actually is based on power compensation for measure the induced heat on the sample.
The calorimeter portion provides a controlled thermal conduction path from the sample to the liquid helium bath to offer a means of measuring the RF power dissipation on the sample. The heat generated by the RF field on the sample G can be conducted away to the bath only via a thermal path[3].
For obtain the heat flowing through the thermal path we nned to measure the temperature with high precision thermal sensors[4]. those sensors are mounted on the back of the sample and along the thermal path. The measure works with the following procedure:

- ✓ A heater located under the sample is turned on with a power that allows to reach an equilibrium temperature T_1 of the sample;
- ✓ With the thermal sensors one measure temperature and heat flux through the path;
- ✓ The heater is turned down and the RF power turned on reaching an equilibrum termperature $T_2 \neq T_1$;
- ✓ After this the heater is switched on again for reach $T_3 = T_1 \neq T_2$ so that one could compare the missing power needed for reach T_3;
- ✓ With the right amount of heat one can find out what the surface resistance is from the quantity $P = \frac{1}{2}R_s \iiint_V |H(x,y,z)|^2 \, d\tau$

[5]Usually the reference sample uses the same material as the cavity so the filling factor is $\eta = \frac{Q_1}{Q_r} = \frac{G}{G_r}$ and $Q_s = \frac{G_r}{R_s}$

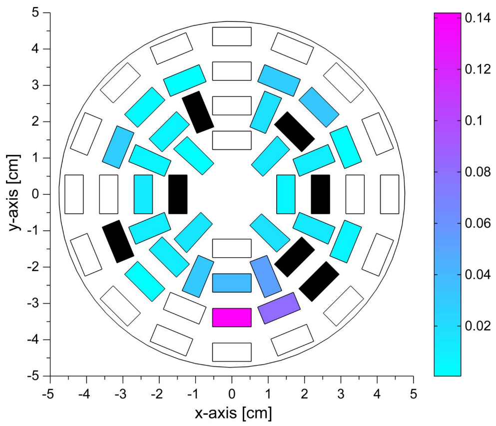
[1]For example a Cu cavity has $Q_{Cu} \approx 2 \cdot 10^5$ with $\Delta R_S \approx 0.14\,\mathrm{m\Omega}$ and $Q_{Nb} \approx 2 \cdot 10^8$ with $\Delta R_S \approx 140\,\mathrm{n\Omega}$

[2]As we mentioned before usually RF tecniques are used, and Network Analyzer and power meters are the instruments for this purpose

[3]Actually those paths are of different materials if the heat to conduct is different, for example Copper or Stainless Steel

[4]For example Lakeshore Cernox thermal sensors

Thermal Mapping This method is not used by Dr. Xiao and Dr. Xie neither, neverthless would be an interesting and very precise method for investigate on non uniform RF loss mechanism on sample. We can see an example of this in [6]. Usually, several carbon Allen-Bradley resistors with $100\,\Omega$ and 8% accurancy at room temperature are used for this purpose. Each resistor is insulated by a $G10$ housing and mounted on the sample holder. Once calibrated using a niobium sample plate prepared with the same recipe as the cavity, the T-Map is capable of detecting areas of increased surface resistance with resolution of $1\,\mathrm{n}\Omega$ and a spatial resolution 0.5 cm. In 3.1.2 we have an example of the dispotion of resistors.



3.2 Goal of the summer internship

We need to project, design and finally commission a host cavity that can be used for characterize RF properties of thin film deposition of advanced superconductors. After the studies on literature we stared a new project with several goals. In the followings items we want to show what our intention are, even for show how the project has grown up and how we get in this final design.

Cryostat Our cavity will be dip in a cryostat with $\Phi \approx 140\,\mathrm{mm}$. This is a big constraint for the geometry of the apparatus but this will allow us to use a cryostat that can reach about 2 K thanks to a λ-fridge inside the cryostat[1].

Eigenvalues We want to reach lower frequencies for the eigenvalues using TE_{0lm} modes, optimizing the cost of materials and cavity itself. The electronics would be cheaper and easier to deal with, respect of more complex and expansive instrumentation for VHF. Even if the R_s does not depend by the frequency, lower frequencies will reduce thermodinamic problems or RF losses.

Design We want to design a cavity that it's easy to tune and coupling and that has a reasonable short time of sample changing[2].

Measurments techniques Both the RF and calorimetrc techniques are quiet well know and efficient. We'll see that a changing in the calculation of R_s should be done in certain casu. A future improvement could be done with a thermal mapping, in fact this will be great for the repeatability of the experiment and the velocity in the measurments[3]. Actually several problems could arise from the cooling or for the calibration in every thermal sensor but those are only technical aspects that could be thought once that one has the final design.

The sample The sample could be really expensive, so we will take care on the repeability of measurements taking care of the sample. Its clamping and positioning will be fundamental for the parameters of the cavity and for the figures of merit themselves.

[1]A lambda point refrigerator is a device used to cool liquid helium, typically around a superconducting magnet or for low temperature measurements, from approximately 4.2 K to temperatures near the lambda point of helium (approximately 2.17 K), the temperature at which normal fluid helium (helium I) transitions to the superfluid helium II. Cooling is achieved by pumping the liquid helium in the bath through a cooling coil via a needle valve and vacuum pump.

[2]The comparative methods requires to change the sample

[3]The comparative method will be not anymore necessary

The Ratio We want to improve the Ratio[4] because of the performance of cavity. We'll see that in one of the design we reach this goal, changing in this way even the measurements technique.

Dielectric We mentioned about a Sapphire loading in the project presented in [1], and that's because a dielectric as the sapphire would low down the Eigenvalue of the cavity with a factor $\frac{1}{\sqrt{\epsilon r}}$. Moreover, the presence of a dielectric would concentrate the B-field on the sample.
Actually Sapphire is very expensive and we want to find a geometry that will optimize the cost and the Ratio both. Another improvment could be done using a different dielectric but for this internship we had no enough time for make any research on it.
We will see that is possible to do all this but we will also show that the sapphire limits the performance of the cavity because of his losses. In Appendix A.2 on page 38 we'll see what are the fundamental reasons that bring us to look for a path without sapphire.
Unlucky this Intership has not given us enough time to prove differents paths, but remove the sapphire and think about other design would be a useful task for the optimization of the project, both cost and performance.
With this short presentation of our goal we have also outlined how our report is gonna be structured. We will follow the path that first starts from the constraint we have, than continue through the choise of our cavity, and final will present some detail on the optimization.

[4] $R = \frac{B_{peak,sample}}{B_{peak,cavity}}$

4 A new Cavity - The Twofold Way: Pillbox cavity

In this Chapter we will show the path we followed for design a simple pillbox cavity and we will show all the choices and simulations results we had that allow us to make the best choice for operating with a host cavity. A simple pillbox as mentioned before is a cylindrical simmetrical cavity really easy to realize and even to describe by analitic calculations.
In [1], this geometry has been chosen because of the properties and direction of EM field inside the cavity[1], and because the electric field has not component crossing the choke joints[2].
We first start with studies on Dr. Xiao cavity getting the right results obtained by simulations made by COMSOL©, then we studied the analitical model of our cavity with a cylindric dielectric sapphire load and we studied with COMSOL© all the eingenvalues and parameters needed for optimize the cavity.

4.1 Analitic Model

For obtain an analitical model of a simple pillbox cavity it's enough resolve the Maxwell's equations with the right bounday conditions:

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

The boundary conditions actually follows from the continuity conditions of surface's fields, and remembering that our sapphire is anisotropus we can write his permittivity tensor as:

$$\underline{\underline{\epsilon}} = \begin{bmatrix} \epsilon_r & 0 & 0 \\ 0 & \epsilon_r & 0 \\ 0 & 0 & \epsilon_z \end{bmatrix}$$

where $\epsilon_r = 9.3$ and $\epsilon_z = 11.5$.

We'll solve the Maxwell equation in two media, as it show Figure 3, and following the linear superposition of the solution we can assume that the general solution could be solved as variable separation solutions. This means that we can write:

$$W(\rho, \phi, z) = R(\rho)\Phi(\phi)Z(z)$$

With some calculation is easy to see that we can obtain three differential equation as it follow:

$$\frac{d^2\Phi}{d\phi^2} = -m^2\Phi$$

where m is an integer that is characteristic of the TE mode

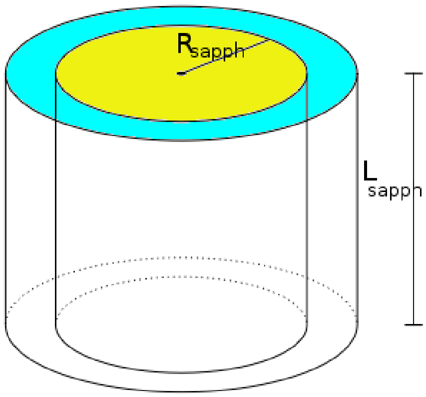


Figure 3: The yellow part is the dielectric and the light blue is the vacuum.

$$\frac{d^2Z}{dz^2} = -h^2Z$$

where $h = \dfrac{p\pi}{L}$

$$\frac{d^2D}{d\rho^2} + \frac{1}{\rho}\frac{dD}{d\rho} + \left(k_0^2\epsilon' - h^2 - \frac{m^2}{\rho^2}\right)D = 0$$

[1]The electric field lines are simple self-closing around the resonator axis, and they vanish on the cavity walls.
[2]This component would imply currents and multipacting phenomena

where $k_0 = \sqrt{\mu_0 \epsilon_0}\omega$ and $\epsilon' = 1$ in vacuum $\epsilon' = 9.3$.
The last is a Bessel differential equation that will give us two different solutions because of the two different media[3].
Tho solutions of the differential equations are the following:

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

where $k_A = \sqrt{k_0^2 \epsilon_r - h^2}$ and $k_B = \sqrt{k_0^2 - h^2}$.

4.2 Simulations

The simulations we made about the pillbox cavities are several because we fully characterized the cavity of Dr. Xiao finding all the results he presented on [1], after this we repeat the same work for our cavity. In order to do this we follow a schedule as it follows[1]

- Parametric eigenvalue studies for find out what will be the frequency of our mode;
- Parametric studies for a fine tuning of the cavity (geometry and measures of the cavity-geometry and measures of the sapphire-position and misalign of the sample);
- Parametric coupling studies of the cavity in frequency domain for find the right position for excitate the right mode in the cavity;
- Final simulation of the cavity for calculation of figures of merit and ratio;
- Thermal circuit;
- Multipacting;

We'll shortly present the cavity built by Dr. Xiao in our simulation and afterward we'll discuss on the design of our project.

4.2.1 Dr. Xiao Pillbox cavity

The pillbox cavity has the following geometric parameters:

$CavityDiameter$	20 mm
$CavityLength$	22 mm
$SapphireDiameter$	12 mm
$SapphireLength$	169 mm

In his design is possible to change the gap between the choke joint and the sample, on purpose to tune the cavity itself and optimize certain parameters. Is even possible to tune the antennas for RF power inside the dewar.

Eigenvalues First of all we found the right eigenvalue in the pillbox cavity and as the following can show(Figure 4 on the next page and Figure 5 on the following page) we found the TE_{011} mode at 7.4289 GHz[2].
Any simulation about the fine tuning has been made because it was completly determined by Dr. Xiao so we just tried his geometry.

[3]Sapphire/Dielectric and Vacuum
[1]For the 3.9 GHz geometry the simulations followed the same schedule.
[2]In [1] the value reportes is 7.6594 GHz

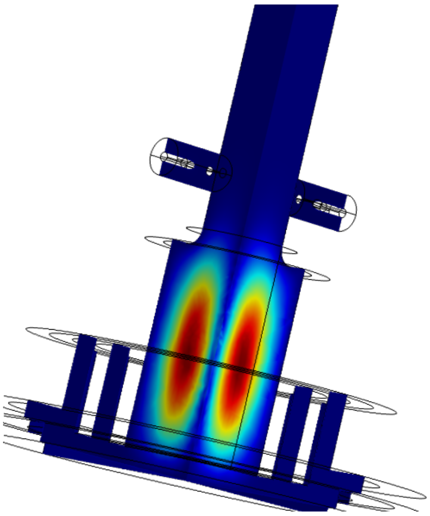


Figure 4: The electric Field in TE_{011} mode

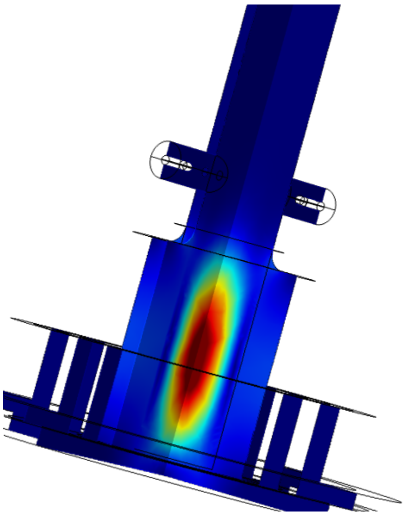


Figure 5: The magnetic Field in TE_{011} mode

Coupling We used H loop antennas for coupling the RF power with the cavity. We made simulation varying the position the antennas in a certain precise point of the waveguide who brings RF power to the mouth of the pillbox.
In Figure 6 on the next page and Figure 8 on the following page we should see the position of antennas[3,4].

Figure of merit and Ratio We find out that the figures of merit we simulated for the Dr. Xiao pillbox are perfectly in accord with the results he presented as we can show in Figure 10[1]. Varying the deeping of the antenna the Q factor changes and we found at least the same oder of magnitude of Dr. Xiao's one.
With COMSOL© it's really easy to calculate the Ratio $\frac{Bpeak}{Bsample}$ and what we found it's ratio of $R_{Bs/Bpk} \approx 0.31$, against a $R_{Xiao} \approx 0.21$ presented in his work[2,3].

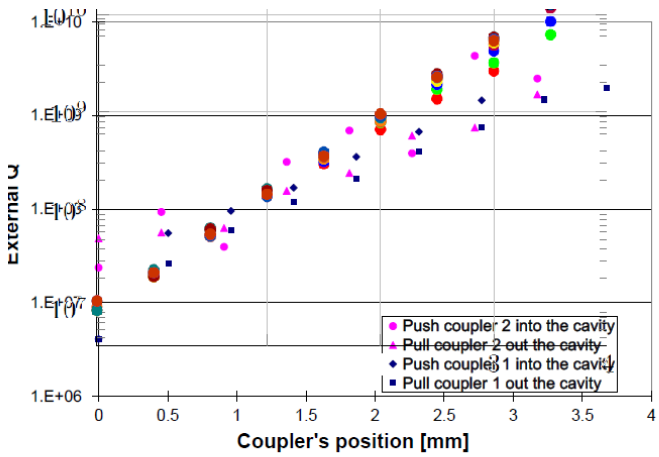


Figure 10: Overlapping of Q factors

[3] Even if the antennas look different they are the same, we just change the geometry of the cable but with same impedance for avoid mismatching

[4] The problem has not simmetry because of the power input so we expect to observe anysotropy in field distribution

[1] The big circle are our simulations and triangles and little circle are the results persented in [1]

[2] We estimated that if Dr. Xiao can't reach more than 12 mT his ratio could be around that value.

[3] In the work of Dr. Xie the $R_{Bs/Bpk} \approx 1.74$ for Pillbox and $R_{Bs/Bpk} \approx 2.35$ for the Mushroom cavity

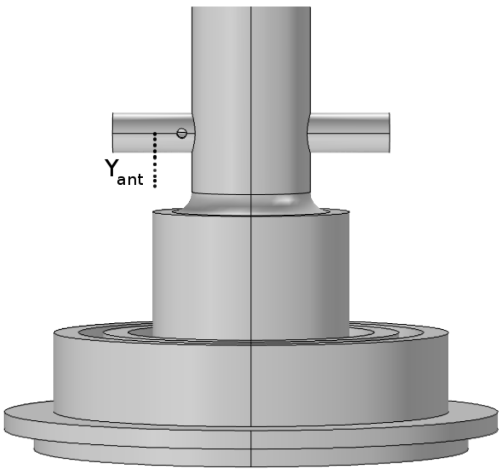


Figure 6: Section profile of the cavity ($Y_{ant} \approx 16mm$)

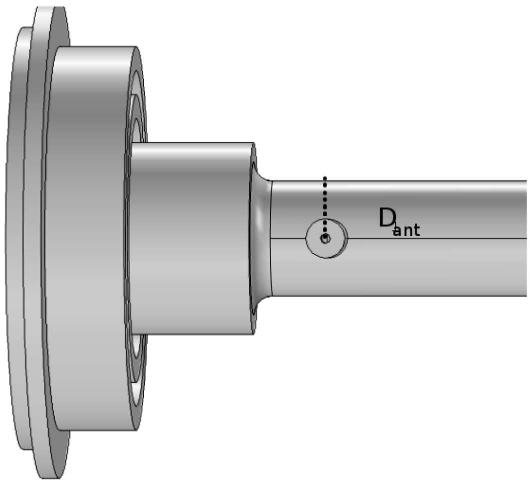


Figure 8: Another section profile of the cavity ($D_{ant} \approx 6mm$)

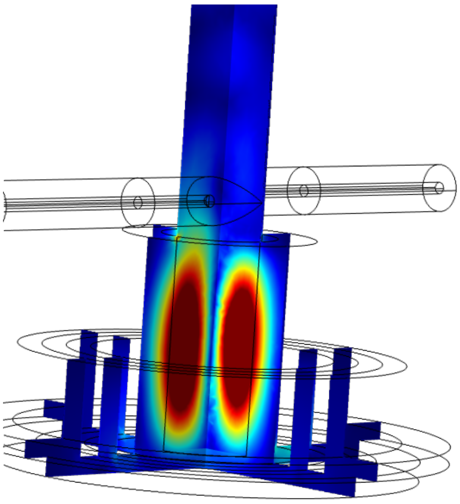


Figure 7: Coupled E field

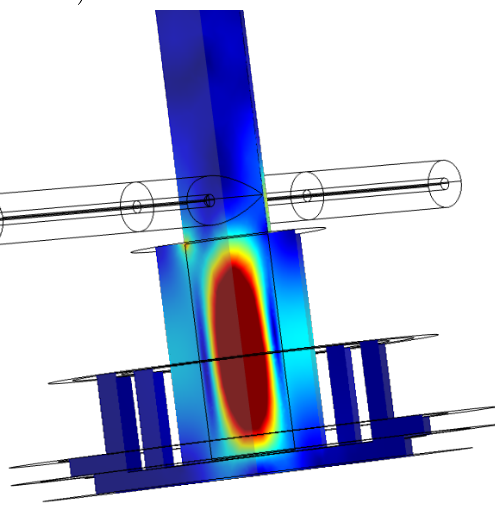


Figure 9: Coupled B field

4.2.2 Our Cavity

The simulations are the same category of that one previously told, but we tried to improve the geometry and the Ratio B on this design. We'll show now our design talking mainly about the RF characteristic and properties of our project, the choice made for some purpose or the study on sapphire. We'll take about mechanical issue and contraint later in the other chapters. Our pillbox cavity has the following geometric parameters:

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

Even in our design is possible change the gap between the choke joint and the sample. Actually is not possible to tune the antennas for RF power inside the dewar, but this as we will explain later is not a big problem.

Eigenvalues Exactly as the simulation executed on Dr. Xiao works, we found the expected eigenvalue for the pillbox cavity (Figure 11 and Figure 12).
Before to find the right value we made some fine simulation varying the geometry of our pillbox. Actually

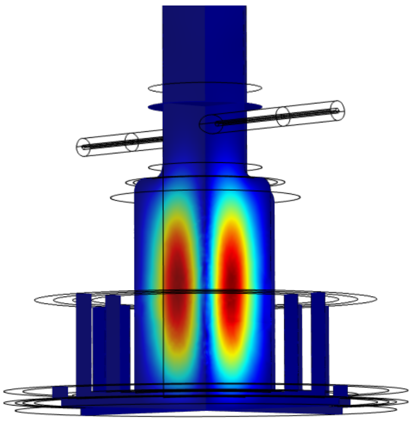


Figure 11: The electric Field in TE_{011} mode

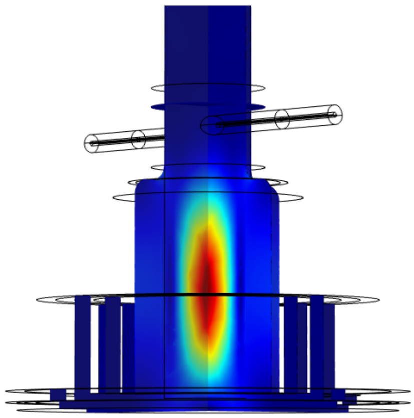


Figure 12: The magnetic Field in TE_{011} mode

we varied the R_{cavity} and L_{cavity} as the Figure 13 on the following page. Because of the mechanical constraint we had to chose strictly those values, in particular $R_c = 25\,\text{mm}$ and $L_c = 60\,\text{mm}$. This brings us to chose even the geometry of the Sapphire, and following the same issue of [1] we have $R_{sapphire} = 15\,\text{mm}$ and $L_{sapphire} = 180\,\text{mm}$ [1] that brings to a eigenvalue od $f \approx 2.95\,\text{GHz}$.

Coupling This time we choose monopole antennas for coupling the RF power with the cavity. With a parametric study of the position along the three spatials axis the best simulations gave us results that are reported in Figure 14 on page 16 and Figure 16 on page 16. Obviously those value have not to be chosen at their best, because the simulation could be better and more studies on position and feeding could be done.

Figure of merit and Ratio The figure of merit of our Pillbox cavity is the main result together with the Ratio. Simulations about Ratio have been made.

[1]The Sapphire need to be as long as the waveguide that feeds the cavity, for mechanical and RF reasons both

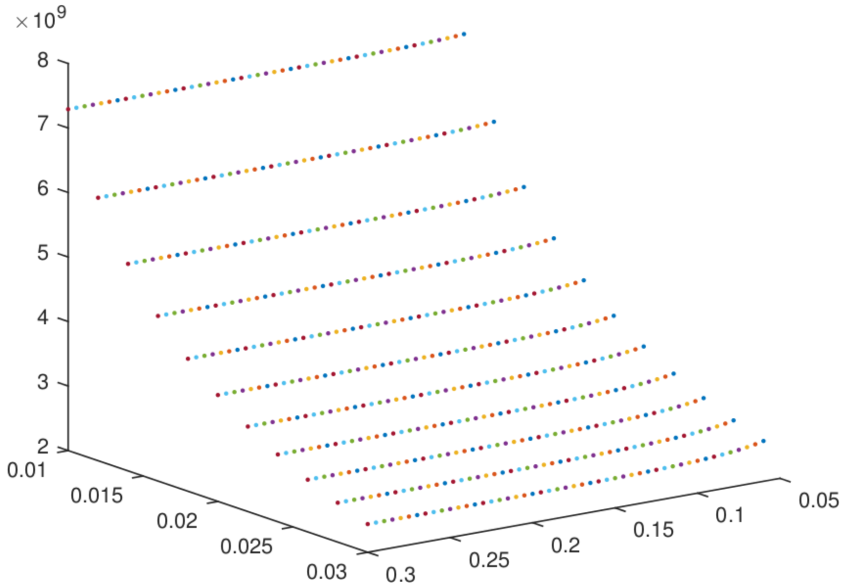


Figure 13: Plot that shows variation of eigenvalue with geometrical parameters

- We found that the Ratio of our pillbox cavity is $R \approx 0.55$
- We found that the Q_{ext} of our pillbox cavity is $Q_{ext} \approx 8.92 \cdot 10^9$

Assuming that $R_{s,Nb} \approx 100\,\mathrm{n\Omega}$ and $R_{s,Sample} \approx 50\,\mathrm{\mu\Omega}$, from the formulas seen in 2.4 on page 4 we obtain:

$$Q_0 \approx 1.32 \cdot 10^8$$

We have to notice that we are not taking in account of the sapphire here, and that *Ratio* < 1; This means that Q_0 probably would be a little lower because of the sapphire, and all the measurments would be affected by him.

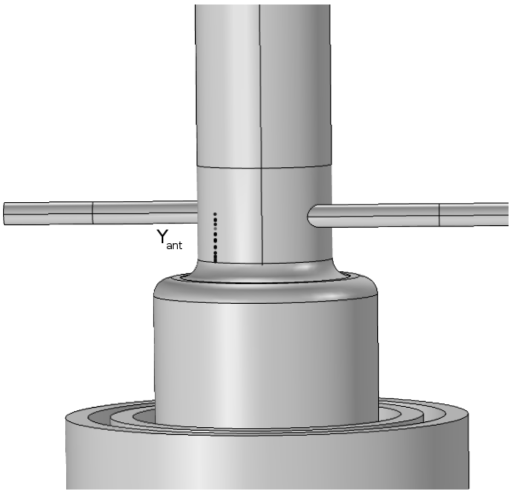


Figure 14: Another section profile of tha cavity ($Y_{ant} \approx 8.75mm$)

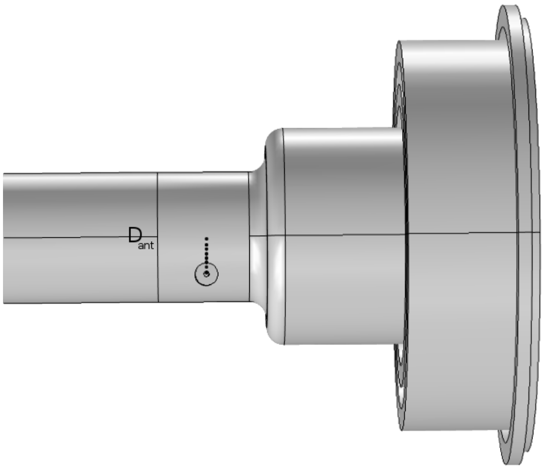


Figure 16: Section profile of the cavity ($D_{ant} \approx 14mm$)

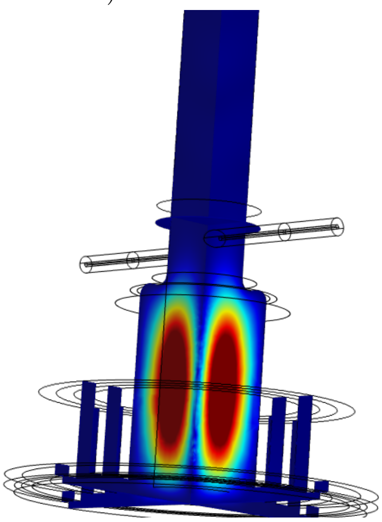


Figure 15: Coupled E field

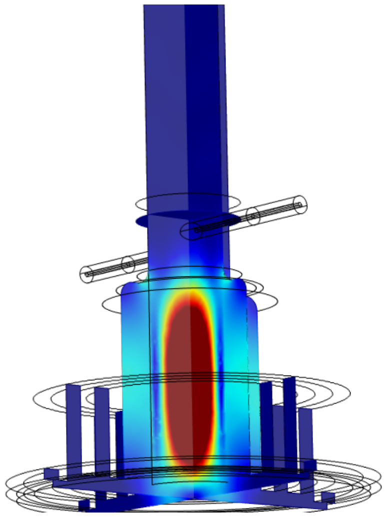


Figure 17: Coupled B field

4.3 Advanteges and Disadvantages

Let's now discuss about the advantages or disadvantage of the simple cylindrical pillbox cavity.

- We found an eigenfrequency of 2.9586 GHz that is considerable low for an host cavity, and this is even thanks to the sapphire ✓
- The double choke joint works efficiently as electromangetic closing for the cavity ✓
- His design allow us to fit in T4 and the room tuning coupling system could be upgraded to a cold tuning coupling system ✓
- His design allow us to tune the cavity, (so the eigenvalue) thanks to an external mechanical coupling ✓
- The same mechanical coupling gives a way for make the vacuum in the caviy and reach the sample with the electronic ✓
- Buy a bulk of Nb of that size, and work that design would be expansive as we will mention later ✗
- The sapphire is considerable big[1], so the cost itself would be high as well ✗
- The ratio is quiet low even if it has been improved thanks to the geometry of the sapphire ✗

[1]The $R_{sapph} = 15\,\text{mm}$ and $L_{sapph} = 180\,\text{mm}$

5 A new Cavity - The Twofold Way: $3.9\,\mathrm{GHz}$ based cavity

After some discussion with experts of the sector and further studies we decided to try a total different cavity for this purpose.
One of the most common cavity for acceleretors technology are the elliptical cavities, for example a very common design has the frequency at 1.3 GHz or 3.9 GHz. Our intention is to find a design who use those cavities, in fact it would be much more efficient for the production cost of apparatus. A little digression about those facts will be done afterwards.
Another good reason it's that with this new design we want to increment significantly the Ratio of the cavity and push it beyond one.
In this way we'll see that the sapphire itself has been reduced as well as his volume and price. Even this is thanks to the temptative of use an elliptical cavity.
Let's now talk about the simulation made for all the figure of merit and what we got of new from this design.

5.1 Simulations

5.1.1 Our Cavity

The simulation executed for this cavity are much more than the other because of the complexity and the missing of an analitical model of this cavity. We will see from the eigenvalues to che coupling of this cavity.

Eigenvalue Actually we start from a 3.9 GHz cavity for accelerators, and we decided to cut in a precise point the cavity in order to interpone at that end the sample that will act as wall of the cavity. We decided to make a simulation of sensitivity for decide where to cut our cavity, and we get the value of 1.5 cm from the bottom of the cavity.
After the mounting of the single choke joint[1] and the waveguide of the cavity we simulated the eigenvalues of this new design. The TE_{011} mode frequency without sapphire had to be a higher than 3.9 GHz, because this is the TM_{010} mode. We found that the TE_{011} is at 4.3 GHz but once the sapphire will be inserted inserted we expect that it would be lowered down.

Actually we tried to increment the ratio and lower as much as possible the eigenfrequency of the cavity so we execute simulation with several different shapes of sapphire. Starting from the simple cylinder we touch geometry as the toroid, and cones. What we found is a frequency of $\approx 3.1375\,\mathrm{GHz}$, but it's just a choice, because we still need to make sensitivity simulation[2].
In the following Figures (19 on the following page and 20 on the next page) we have an example of eigenvalues simulations.
An interesting ensemble of simulation executed are that one relative to the gap variation[3]. We want to present the results of the sensitivity simulations in the following plots.
We can see in Figure 18 that increasing the gap the frequency decrease, as we should expect in accord with the resonator theory[4]. Note that the sensitiv-

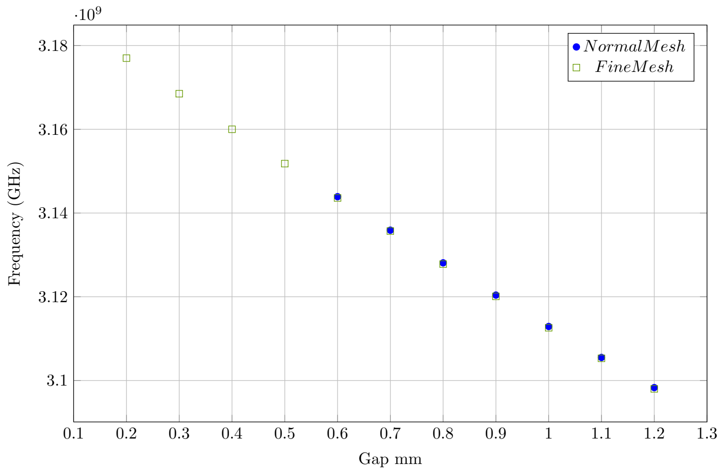


Figure 18: Frequency vs Gap.

[1] We could not use a double choke joint because of the space constraint.
[2] For example varying the gap between choke joint and sample and check how it changes the Ratio or the eigenfrequency.
[3] The distance between the choke joint and the sample
[4] Exactly like a pillbox increasing his length you'll increase the wavelength and so low down the frequency.

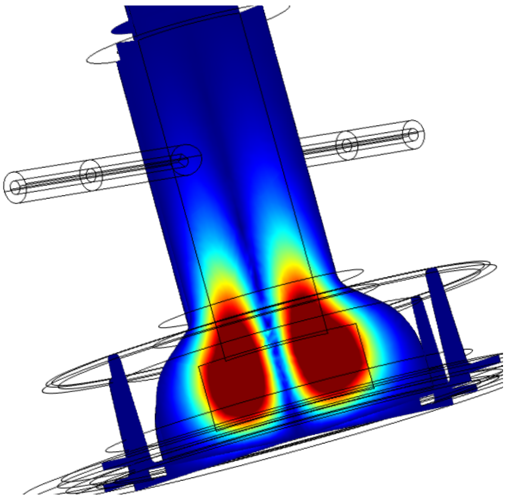


Figure 19: The electric Field in TE_{011} mode

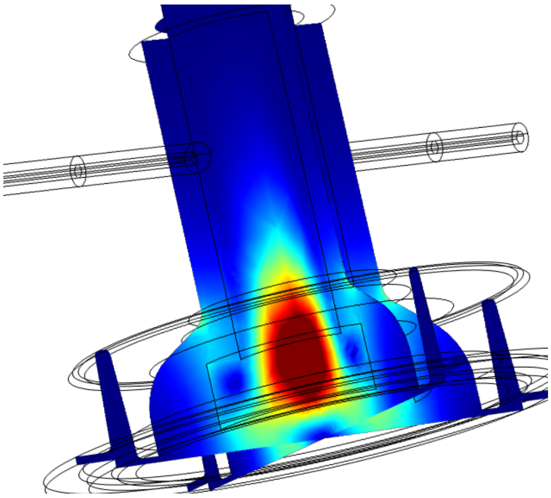


Figure 20: figure
The magnetic Field in TE_{011} mode

ity changes with a linear trend of $-80\dfrac{\text{Hz}}{\text{nm}}$.

Coupling For the coupling we should simply show that in Figure we have the Q_{ext} of the cavity in function of the distance from the geometric axis of the cavity [1].
For excitate this mode we found that for use a monopole instead of the H-loop we need to distance the monopoles antennas from the center[2]. The position along the axis will be as shown in Figure 22 on the next page. We think to build the monopole as simply Copper antennas with a $50\,\Omega$ impedance because of

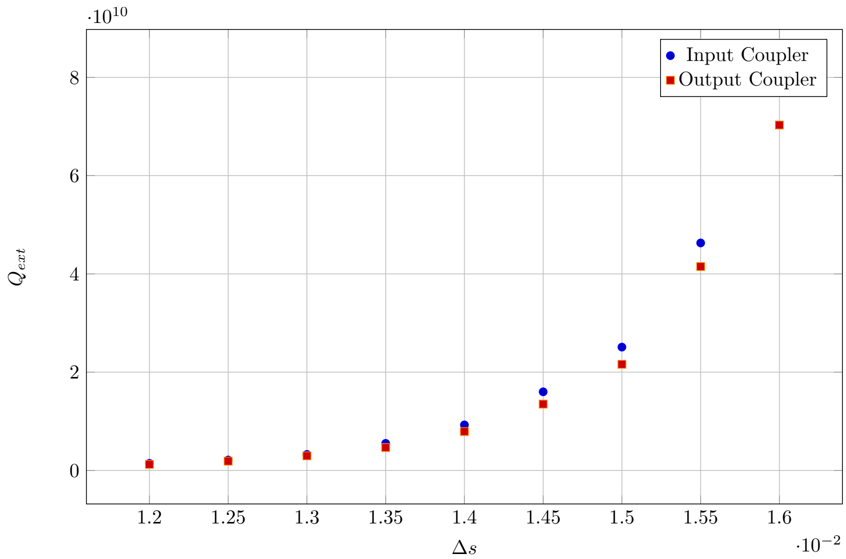


Figure 21: External Q vs the coupler's position

his matching, moreover the cannel who will surround the antennas have been simulated with *Titanium*

[1]This is the same axis of the sapphire.
[2]We made several simulations on the coupler's position along the waveguide for find the best coupling position.

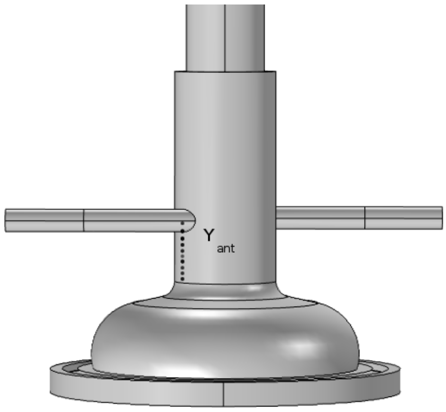


Figure 22: $Y_{ant} \approx 25\,\text{mm}$ and $12.5\,\text{mm}$ from the geometrc axis.

and *Copper*. Actually both of them are not an optimal choice because they will low down the quality factor of the cavity[3], so this menas that another material had to be chosen as channel around antennas. *Niobium* would be perfect but this will afflict even more the cost of the apparatus itself.

Figure of merit and Ratio Finally we will present briefly parameters who are significant for the performance of our cavity. The results present the Normal and Fine mesh for the simulation on COMSOL©, just for show how the FEM simulation strain to a Plateau refining the mesh itself.
First of all for the performance of the cavity it's fundamental understand how does the ratio works. Actually we can expect that the more concentred is the magnetic field on the sample the higher the ratio will be, in fact we decided for change the sapphire geometry on purpose to increase this parameter[1]. With the simulation done we found that our ratio is $R > 1$ and for this preconcept design we can be satisfied of this result. In Figure 23 we can see how does it changes the ratio with the Gap.
Finally we show in Figure 24 on page 22 an important parameter that told us the maximum magnetic

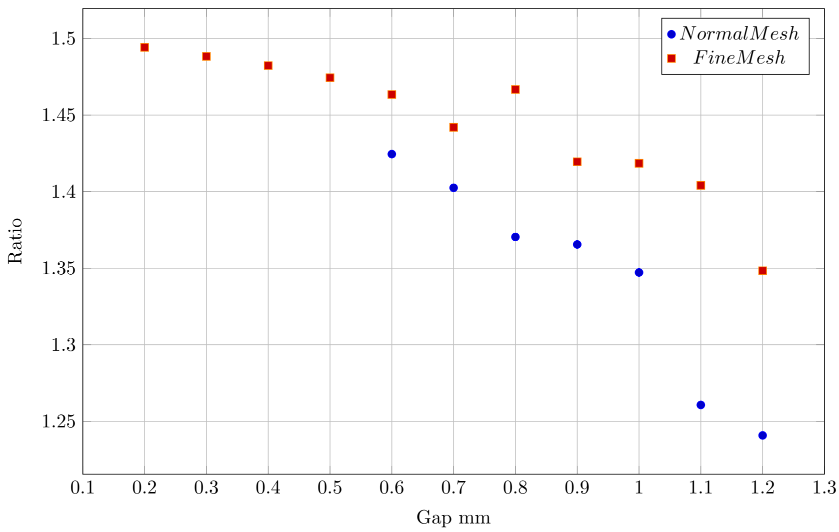


Figure 23: Ratio vs Gap

[3]Q_{Cu} and Q_{Ti} where both $\approx 10^6 10^7$ and this low down the frequency
[1]We will discuss late on Appendix A.2 on page 38

fields on the sample for unit of energy, under different gap.
What is most important for a generic cavity is actually the quality factor, that in our casus depends by different materials we have insde the cavity. Of course the Copper on the channel or on the sample holder, or the Stainless Steel that clamps the sample itself would reduce the total Q of our cavity so we need to take in account this.
Actually in our simulation we assume that the R_s of Nb cavity is about 100 nΩ and the R_s of the sample in Nb is 50 µΩ. This would bring the Sample to be the part of the cavity who weights more, so this means that even the resolution of ΔR_s will be limited by this value.
We want to show some simulation where we take in account all the materials present in the cavity, as the copper or the stainless steel in the sample holder. In the following table we have all the quality factor that have been simulated while we were studyig the coupling, and we can undersand from those data what the limitation of measurments can be, because of the limitating quality factors.
Actually in the tables is shown the main limit of our cavity: the sapphire. As we shown in the previous section usually the Q factor is calculated as the sum of the all the reciprocal Q factors present in the system. The sapphire itself and the copper channels itself seems to be the bigger limits. We will discuss later in Appendix A.2 on page 38 and in Section 7 on page 32 what this means for our design and what has to be done next after this work. In the next Section we will analyze the mechanical part of the project and we'll understand how the mechanical constraint give limits and design choice we had to do.

5.2 Advanteges and Disadvantages

Let's now discuss about the advantages or disadvantage of this new design.

- We found an eigenfrequency of 3.1357 GHz that is as the pillbox considerable low for an host cavity, and this is even thanks to the different geometry given to the sapphire ✓
- The single choke joint work as a total efficient electromangetic closure for the cavity ✓
- His design allow us to fit in T4 and the room tuning coupling system could be upgraded to a cold tuning coupling system ✓
- His design allow us to tune the cavity and consequently his eigenvalue thanks to an external mechanical coupling ✓
- The same mechanical coupling gives a way for make the vacuum in the caviy and reach the sample with the electronic ✓
- The ratio, thanks to the different geometry of the sapphire is considerable higher. ✓
- The cavity is a commercial and well know solution. We can find the design and a cavity itslef in a simpler way. ✓
- The cost would be expansive for the cutting and the electron beam technique used for solder the chocke joint. ✗
- The cost and the working of the choke would be difficult and expansive. ✗

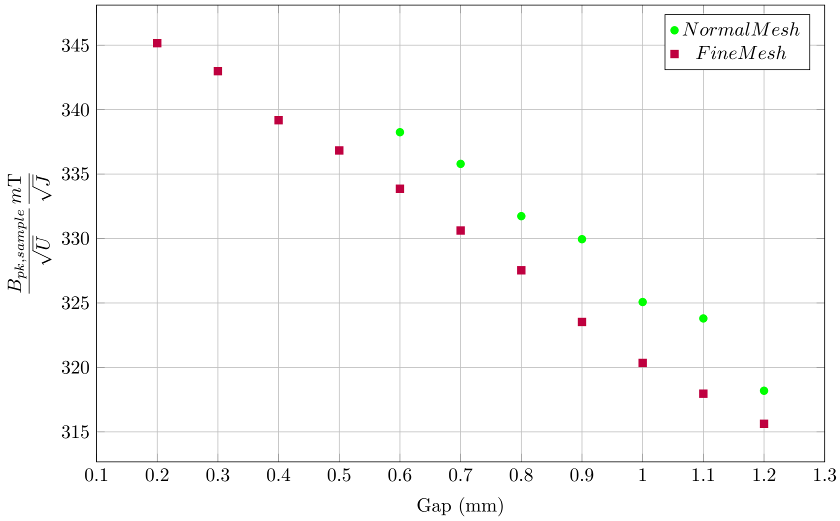


Figure 24: $\frac{B_{pj,sample}}{\sqrt{U}}$ vs Gap.

Quality factor: Varying input coupler					
ΔxAnt	$Q_{Titanium}$	Q_{SSteel}	$Q_{Channel}$	$Q_{Sapphire}$	Q_{Gap}
0.012	1.96E+12	4.46E+12	4.47E+10	4.80E+08	1.97E+11
0.0125	2.50E+12	6.97E+12	4.52E+10	4.80E+08	2.94E+11
0.013	2.88E+12	4.10E+12	4.74E+10	4.80E+08	1.92E+11
0.0135	3.54E+12	4.16E+12	4.85E+10	4.80E+08	2.02E+11
0.014	3.79E+12	3.48E+12	4.52E+10	4.80E+08	1.72E+11
0.0145	2.29E+12	3.72E+12	4.33E+10	4.80E+08	1.81E+11
0.015	2.83E+12	3.94E+12	4.60E+10	4.80E+08	2.06E+11
0.0155	2.86E+12	3.25E+12	4.42E+10	4.80E+08	1.70E+11

Quality factor: Varying output coupler					
ΔxAnt	$Q_{Titanium}$	Q_{SSteel}	$Q_{Channel}$	$Q_{Sapphire}$	Q_{Gap}
0.012	7.07E+11	3.86E+12	4.31E+10	4.80E+08	1.74E+11
0.0125	8.26E+11	3.98E+12	4.34E+10	4.80E+08	1.94E+11
0.013	1.03E+12	4.07E+12	4.48E+10	4.80E+08	2.37E+11
0.0135	1.37E+12	4.45E+12	4.58E+10	4.80E+08	2.36E+11
0.014	1.58E+12	4.29E+12	4.43E+10	4.80E+08	2.18E+11
0.0145	3.78E+12	2.88E+12	4.21E+10	4.80E+08	1.49E+11
0.015	3.04E+12	4.27E+12	4.41E+10	4.80E+08	2.27E+11
0.0155	6.40E+12	4.19E+12	4.30E+10	4.80E+08	2.21E+11

6 Cavity geometry and production

The first geometry is a pillbox cavity is described in figure 25, this cavity is made by drilling a niobium bulk.

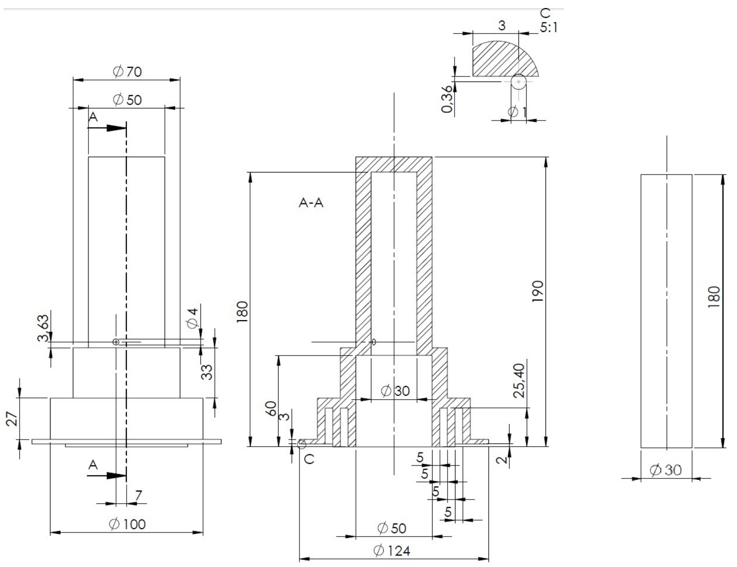


Figure 25: PillboxCavity and relative sapphire Drafting

This total customized Pillbox cavity would cost a lot because of the labour work/hour cost. In fact is not common and this could take to a higher cost of the apparatus, we estimate that only the work would cost 1145$ [1] .
Moreover, the amount of material is totally different between a single elliptical cavity and a Nb bulk of pure Nb. We need in fact a realy high purity Nb and this means that with the pillbox we will need a volume of:

$$V = (\pi R_{bulk}^2) \cdot L_{bulk} \approx (2.5\,\mathrm{cm})^2 \cdot (6\,\mathrm{cm}) = 1.178 \cdot \mathrm{m}^3$$

the cost of our bulk would be entirely defined by the foundry that will produce the bulk. The total amount of the only cavity would be probably greater than 10000$. Actually an elliptical cavity would be better instead of the pillbox because it would be much more easier to find due to the high usage in research.

The second possible geometry of the cavity is described in figure 26 on the following page
This second geometry is based on a 3.9GHz niobium cavity, all the other part are welded to it, eventually some part can be made by titanium in order to lower the cost (the top cilinder and the chocke joint). The geometry of the sapphire is maded to optimize the magnetic ratio.
Two possible geometry for the cavity are defined therefore it's possible to start with the mechanical design, actually we will present the concept design, the solution proposed in this chapter are not totally verified due to the little available time. When the solution is not verified we will focus the attention on that and will be written in *italic.*
The first things to take in consideration are the constraint originated by the equipment avaliable in the laboratory and the requirement of our setup.

[1] We had a consult with an expert who use to work on Nb who told us that would cost $82\frac{\$}{hour}$ and the first design would take $14 hours$ of work

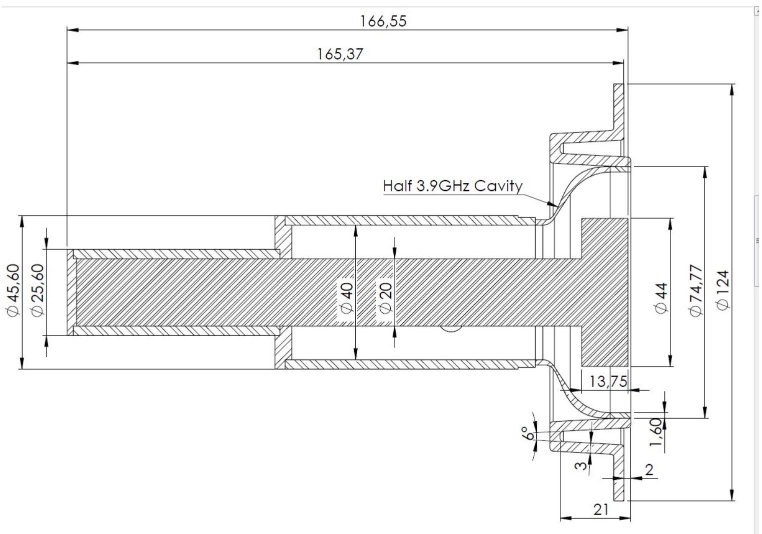


Figure 26: 3.9 Welded Cavity

6.1 Requirement of our setup

The requirements come from the study of the cavity and the papers of others realization.

- It's necessary to make ultravacuum in the volume of the RF Cavity.
- The Niobium part and the end of the thermal circuit need to be in contact with liquid Helium.
- The coupler position need to be tunable at room temperature. In particular Q_{ext} is the same at different temperature, it doesn't depend from the behaviour of the cavity.
- Also the position of the sample should be tunable, better if the setup is provided for tune the sample at Liquid Helium temperature. This means that the cavity will not be closed during the operation.

6.2 Constraint

In the desing of all the mechanical structure we need to take in consideration the following problems:

- In the laboratory there are two cryostat T3 and T4. The first as an aperture of ϕ152mm, the second ϕ252 mm. T3 as a λ -fridge and can reach 2,3K whereas the T4 can reach only 4K.
- The matherial-dependent thermal contraction of the structures. The combination of different material with different thermal contraction can cause the loss of the vacuum seals and/or the induction of high stresses in the material structure.
- Materials at cryogenic themperature have a brittle behaviour except for some paste or special material, the induction of high stresses can easly bring the material to a brittle fracture.
- In high vacuum no oil or grease can be used because they will evaporate.
- LHe tend to penetrate inside the cristalline structure of the materials.
- In high vacuum two pieces maded by similar material can weld toghether. It's important to couple different material to avoid the microwelding.
- It's common to provide a system for the separation of two flanges. For example in the picture 27 on the next page a threaded hole is made in the upper flange in order to screw a screw and force the flanges to separate .

6.3 Mounting of the sapphire

The sapphire has some electric losses that produce heat, we need to convey this thermal power through his clamp into the Helium Bath. In order to do this we can mount the sapphire with a little interference in the cavity.
To calculate the power dissipation we can start from the magnetic field on the sample assuming that the niobium surface will not quench till the magnetic field reach $B_{NiobiumTransition} = 200mT$:

$$B_{sample} = Ratio \cdot B_{NiobiumTransition} = 1,2 \cdot 200\,\mathrm{mT} = 240200\,\mathrm{mT}$$

This is the maximum reachable magnetic field magnitude on the sample. Using the factor $K = \frac{B_{sample}}{\sqrt{U}}$ to calculate the energy stored in the cavity U and then the power using the Q factor of the sapphire:

$$U = \left(\frac{B_{sample}}{K}\right)^2 = 0.53\,\mathrm{J}$$

$$P_{sapphire} = \frac{2\pi f U}{Q_{sapphire}} = 2,2 \times 10^{-8} W$$

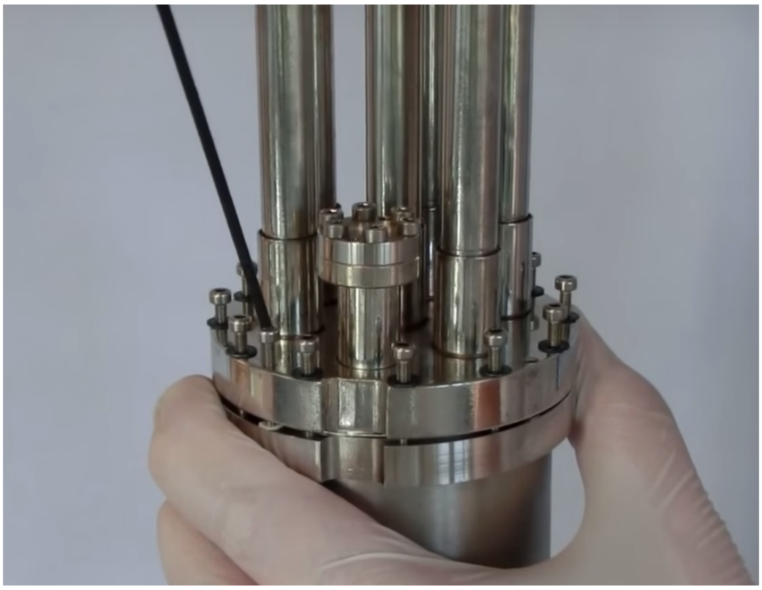


Figure 27: Unnmounting system

The power dissipated is very low, however the sapphire is in vacuum and the only way to extract the heat is form the surface contact with the niobium walls and bottom of the cavity. The contact pressure in the bottom of the cavity is negligible and so the heat transfer on this interface. We can decide the contact pressure between the walls and the sapphire and desing the tolerance of the two component.
Comparing Lambert and Fletcher model and Antonetti, White and Simons model the contact pressure needed is obtained, then the tolerance is calulated using the Lame 's plate theory. For the sapphire in the welded 3.9GHz cavity, which has a diameter of 20mm the interference minimum at mounting is $0\mu m$ and the maximum interference is $100\mu m$.
The tolerance can be 20^{+50}_{+0} for the sapphire and 20^{+0}_{-50} for the housing. In ISO tollerance it can be 20 H8/s8 (or even H9/x8).

6.4 Cryogenic Seals

To maintain the vacuum inside the cavity volume and around the thermal circuit we need to seal the system from the liquid Helium, and avoid any leak. To do this we will use welded structure and sealed flange, the flange are needed to acces part of the apparatus.
The LHe tend to penetrate inside the cristalline structure of the materials. Though there are some materials that has a very little permeability to He, some example are Fe, Nb, In, Copper, Au and Ag. Therefore steel is a very good structural material for making the vessels. However for making the seals we want a material that is highly deformable and that would not bind with the steel flange. If the seal can chemically combine with steel the sealing would be more efficient but it's also very important that the seal need to be removed and substituded without damaging the seal housings.
Three solution are taken in consideration for the design:

- Commercial Copper seals.
- Indium seals.
- Silver diamond seals.

The reference properties are listed in the table 2 on the following page token by [11]

- E is the young modulus

Materials	E (293K)	E (4K)	ν	σ_y(293K)	σ_y(4K)	ε_{el}	ε_{T-4K}
304/304L	193 GPa	200 GPa	0,3	241 MPa	448 MPa		$-0,296 \cdot 10^{-3}$
316/316L	184 GPa	213 GPa	0,3	238 MPa	610 MPa		$-0,297 \cdot 10^{-3}$
Nb	104 GPa		0,35	60 MPa			$-1,43 \cdot 10^{-3}$
In	10 GPa			2,5MPa		2 %	$-7,06 \cdot 10^{-3}$
Brass (70% Cu, 30% Zn)	103 GPa	110 GPa	0,31	473 MPa	506 MPa		$-3,84 \cdot 10^{-3}$
Ti - 6Al - 7Nb	105GPa			800 MPa	1600 MPa		$-1,51 \cdot 10^{-3}$
OFHC-Cu (annealed)	128GPa	139 GPa		75 MPa	90 MPa		$-3,16 \cdot 10^{-3}$
G10 Normal	28 GPa	36 GPa		414 MPa	758 MPa		$-7,06 \cdot 10^{-3}$
G10 Warp							$-2,41 \cdot 10^{-3}$

Table 2: Properties of Materials

- σ_y is the yield stress
- ε_{el} is the maximum elastic strain
- ε_{T-4K} is The thermal contraction from 293 K to 4 K. Defined as follow: $\varepsilon_{T-4K} = \dfrac{l(4K) - l(293K)}{l(293K)}$
- ν is the poisson's modulus

Alluminum diamond seals Silver diamond seals are Developed in Technical Division at FermiLab, and they are very reliable and easy to mount, the seal housings consist in two coupled plane surface. The diamond-shaped toroid is compressed and deformed, the seal is guaranteed from the contact between the diamond shape and the two plane surface in the flanges. However, this solution don't use less space than the other seals method and it's not cheaper either. Also this solution is in the R&D phase then a commercial solution would be better.

Commercial Copper seals Copper seals are made also for cryogenic applications, they can be built in many different shapes and they need a lot of space to work properly. They can easily be mounted on CF flange and they are very cheap. We will use CF flange with copper seals for the coupler where we have enough space for them. Also CF flange are easy to couple with Stainless Steel bellows.

Pure Indium seals Indium seals are very used in this field of cryogenic desing. These seals are made by pure indium wire slotted in cilindrical toroidal housing as can be seen in the figure 28. This wire can also be made in the laboratory of TD division. Some example of this kind of seals can be found in literature presented in [12]. Indium is a very soft material, his properties are listed in the table 2.

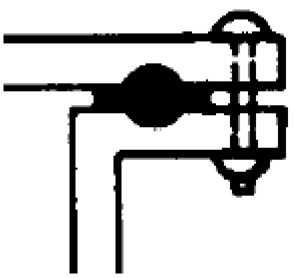


Figure 28: Indium Seals Housing

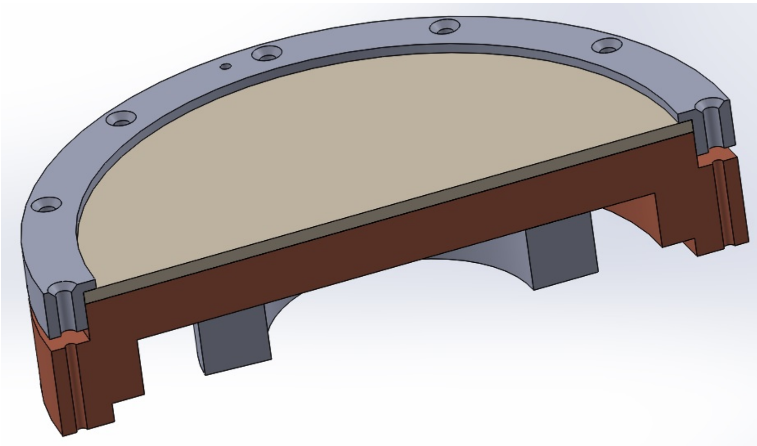


Figure 29: Sample holder and clamp

The most used technique in this application is to use two steel flanges connected by Brass Fasteners. The point of using Brass Fasteners is to compensate the contraction of the indium wire. The Indium has a very high contraction compared to the steel 2 on the previous page.
This kind of seals are very compact in space and can fit in our cryostat, though we desing our own seals. The design and the study of the mechanical system is reported in Appendix A.1 on page 35.

6.5 Sample holder

For the sample we decided to use a 94mm diameter sample with a thickness variable from 1mm to 5mm. The sample is mounted on a copper sample holder with a clamp in Aisi 304 Stainless Steel, between the sample and the holder a thin film of Kapton or teflon is needed to electrically insulate the sample. Eventually a cryogenic grease can be interposed to improve the thermal conductivity. The Cad model is reproduced in figure 29.
Under the sample holder a copper heater is glued in order to make tests at different temperature and/or comparative calorimetric tecnique.

6.6 Thermal Path

In order to make calorimetric measurements we need to desing the thermal path from the sample to the liquid helium. The thermal path need to be isolated from the cavity and the vaccum vessel. In order to do that the sample holder is mounted with 4mm clearence in the stainless steel structure, actually it's sustained by the copper/steel structure that actually build the thermal path.
The thermal conductivity of the path is a compromise between the necessity to dissipate heat in order to cool down the sample and the precision of the calorimetric measurement. Two different path are designed, one for high power dissipation and the other for high quality measurement.
Two discs are designed to have a thermal path with a thermal conductivity of 1mW/K and 1W/K. They are rappresented in figure 30 on the following page meanwhile the thermal path, with the copper disc, is represented in figure 31 on the next page

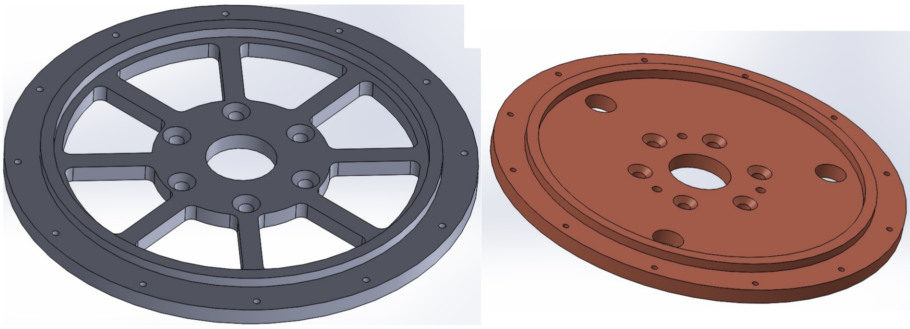


Figure 30: Thermal Resistance Disc, On the right the copper one that is used for the 1W/K thermal path. On the left the stainless steel one that is used for the 1mW/K thermal path.

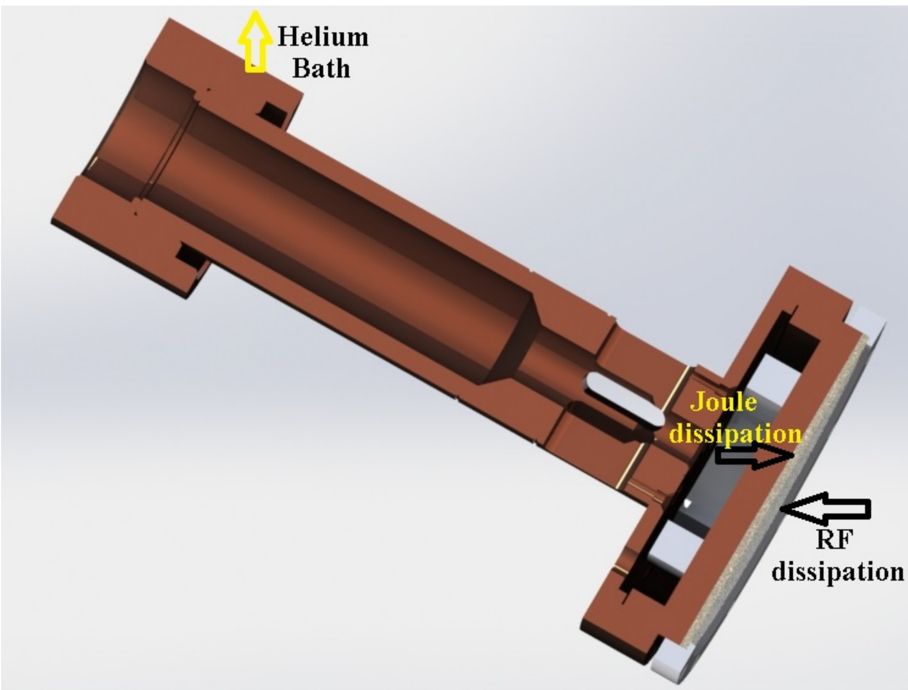


Figure 31: Thermal Path

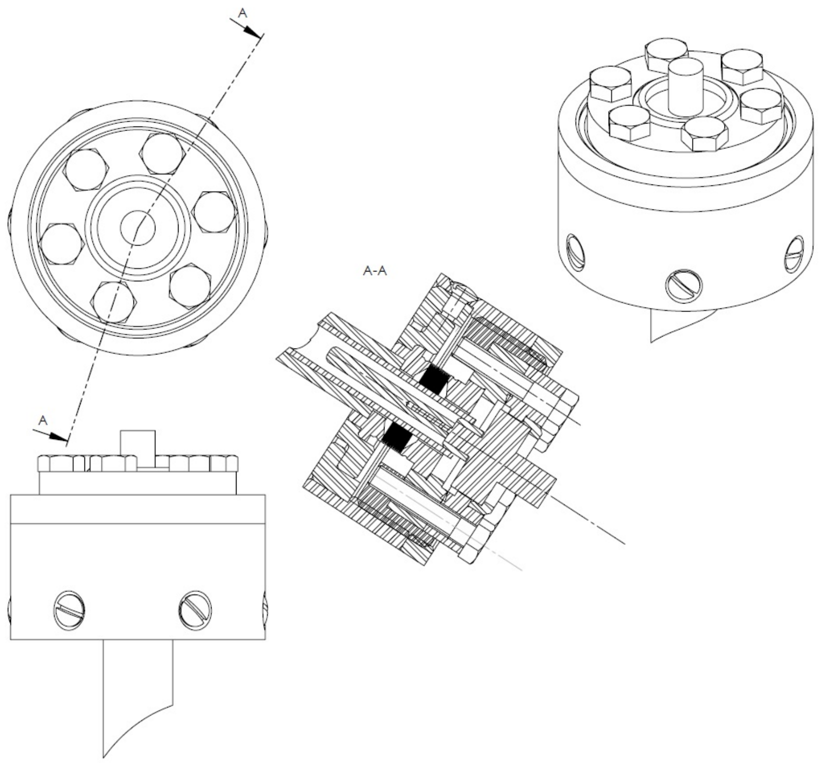


Figure 32: Tunable Coupling system

6.7 Coupler

The antennas need to be adjusted at the start of each new test, fortunately the tuning of the coupling can take place at room temperature since the Q_{ext} doesn't change from room temperature to cryogenic enviroment.
The antennas will be mounted on the side of the cavity and as we told, we will use monopole with the axis of the antenna that doesn't cross the axis of the cavity. Due to the very small space avaliable the tuning system need to be design properly. The flanges used are commercial DN 16 mounted with the proper vacuum-cryogenic seals (VATSEAL).
In order to tie the antenna with the coaxial cable a single SMA coaxial feedthrough is used, then to tune the antenna we have a screw and a threaded control knob, to block the antenna in place there is a locknut. The channel of where the antenna stay is maded by copper in order to limitate the suface RF losses, while the sealing and the structural resistance is provided by a bigger cilinder in titanium that can be welded to the niobium and the stainless steel.
The solution however is not completely verified, the problem to take in consideration is the coaxiality between the antenna and the channel. The only thing that actually can guarantee the coaxiality is a cilinder of dielectric that is put between the antenna attachment and the channel, but this is not a rotable joint, it's a single support. First of all the effect of the misalignment of the antenna should be coumputed with FEM analysis than decide what to do change in de mechanical design. Maybe the adjust screw can be used as a reference. The system is represented in figure 32.

6.8 Vacuum pipe and cables

The coaxial cable will be placed in the helium bath mounting 2 coaxial SMA feedthrough in the flange at the top of the cryostat. The cables for the heater and the temperature probes will be fitted in the vacuum

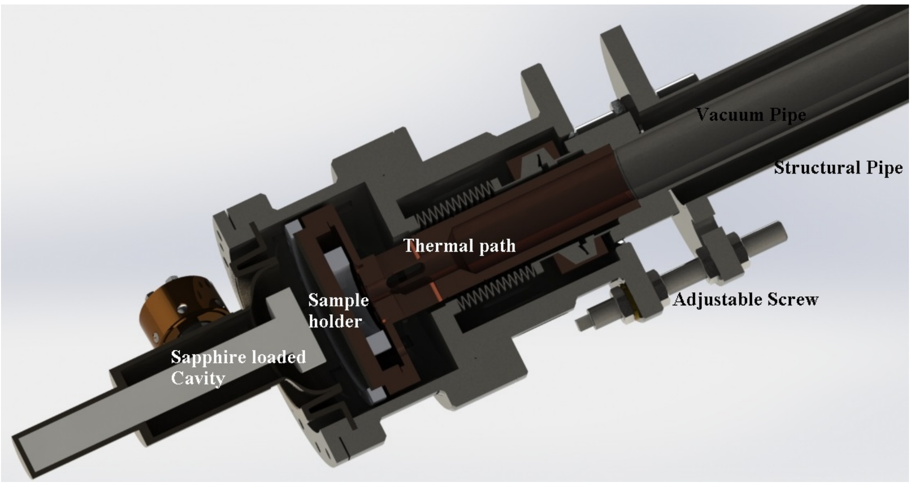


Figure 33: Apparatus

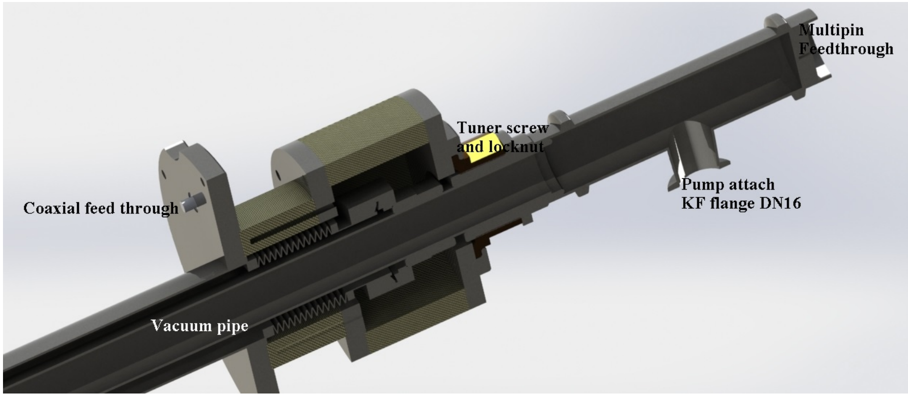


Figure 34: topflange

pipe. The vacuum pipe will be mounted with a bellow on the steel structure in order to allow his axial movement and the sealing of the cavity and the volume above it, use the figure 33 as a reference.
Notice that the vacuum pipe has three purpose:

- It's need to pump out the air and make the vacuum.
- It's part of the thermal path.
- It's used for holding and moving the sample holder.

It's clear that the vacuum pipe and the thermal path need to be mounted coaxial with the cavity in order to have the sample holder in a specific position. As a design constraint the sample holder can't be in contact, at any time, with the steel structure, also the angle between the axis of the sample and the cavity can't be more than 5°. This condition is not verified, the design allow to adjust the positions of the sample holder using the adjusting screw but some technician should be consulted.
The position of the vacuum pipe can be adjusted by the screw that is placed on the main flange.
The vacuum pump attachment is made with standard KF flanges pieces. To fit the cables for the thermal sensors and the heater a multipin feedthrough can be bought welded on a KF flange. The solution is represented in figure 34 .

7 Comparison and Final design

We can finally compare the two design, saying that the 3.9 GHz *based* design is the more interesting and convenient to study and commission. Most of the parameters we simulate are more efficient in this design respect of the pillbox, and the cost of building could be probably higher than the cutted one [1].
In the simulation made with the cavity of Dr. Xiao we had the confirmation of the problems who affects this kind of measurments. In [1] no data are reported about Q_0, but after a brief contact we had with him we know that he had problem reaching a quality factor higher than $Q_0 \approx 3 \cdot 10^7$. The simulation of his cavity shows the following results in the table 7.

f[GHz]	$Q_{Ti,Channel}$	$Q_{Sapphire}$	Q_{SSteel}	Q_{gap}
7.43	$1.682 \cdot 10^8$	$8.08 \cdot 10^{11}$	$9.60 \cdot 10^8$	$1.767 \cdot 10^8$

Table 3: Xiao's Design

From the results it's clear that the Titanium channels and the losses on the sapphire will not permit his cavity to reach performance higher than that value, in fact:

$$Q_{tot} \approx \left(\frac{1}{Q_{Ti}} + \frac{1}{Q_{Sapph}} + \frac{1}{Q_{Nb}} + \frac{1}{Q_{Sample}} \right)^{-1} = 9.108 \cdot 10^7$$

In our casus we avoided the titanium as channels, but we still have the sapphire. In the following datas we can see that he has the Q that weights more.

f[GHz]	$Q_{Ti,Clamp}$	$Q_{Sapphire}$	Q_{SSteel}	Q_{gap}
3.13	$1.37 \cdot 10^{12}$	$4.80 \cdot 10^8$	$4.45 \cdot 10^{12}$	$2.32 \cdot 10^{11}$

Table 4: Our Design

Now, discussing about G, another figure of merit, we know that this parameter is not dependant by the material and the resistance itself but only by the geometry. How we can see in the casus of Xiao cavity, $G_{Sample} >> G_{Cavity}$ and this brings to have a Ratio $R < 1$[2] and that the resolution of the surface resistance cavity is leaded by the cavity and his quality factor. In our casus is the opposite situation, in fact because of the definition of G we have that the sample weights more than the cavity, and even than the sapphire itself.

Cavity	G_{Sample}	G_{Cavity}
Xiao	15329	826.9
Our	491.9	1372

As we can see assuming $R_{s,Nb} \approx 100\,\mathrm{n}\Omega$ and $R_{s,Sample} \approx 50\,\mu\Omega$ we obtain a $Q_0 \approx 10^6$, that is quiet low for a Q factor of a cavity.
Let's claim that this is not a normal cavity but wants to be a host cavity for studies on the samples, and

[1] We cannot give a precise estimate because it depends if the single cell will be built or if it's possible to recycle an old 3.9 GHz.
[2] G is proportional to Q so higher it is G higher Q will be.

we think that this can be a good feature of our design, even if we had to make an estimation about what is the limit of reliability of our cavity. As we told in fact the values used for the R_s are assumed and token by articles found in literature, and we can simply plot how does it changes Q_0 with $R_{s,Sample}$;
in this way we will find a value where $Q_0 \approx 10^8$ and up by that value we know that the Sapphire will weight more than everything, so every measure will be not anymore affordable. In Figure 35 we can see that we have a good resolution if $R_s >> 5\,\mu\Omega$. This can suggest different things, and give us a defenitive

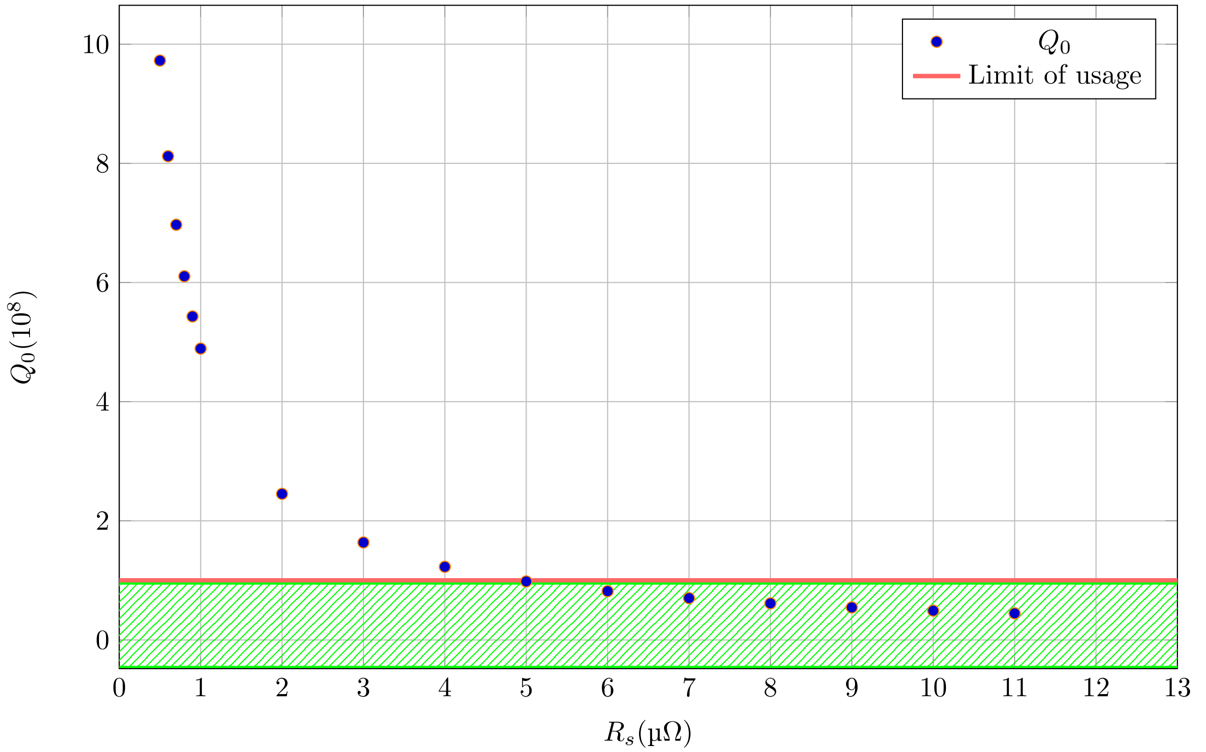
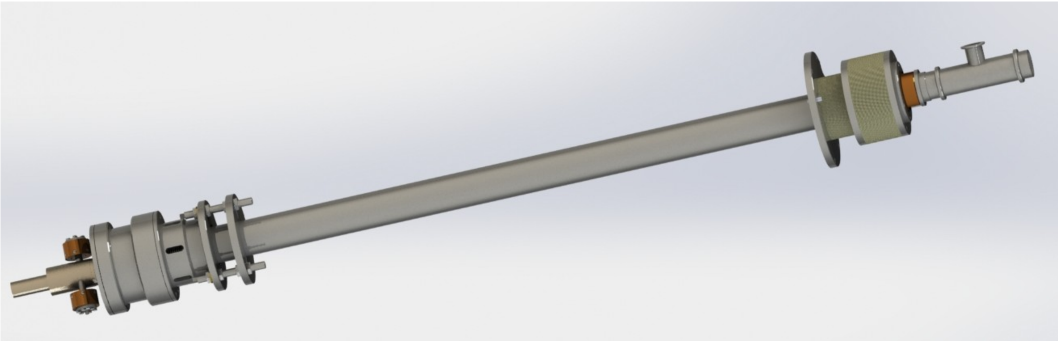


Figure 35: How Q_0 changes with $R_{s,Sample}$

point of view of our project, that we will summarize in the next section.

8 Conclusion



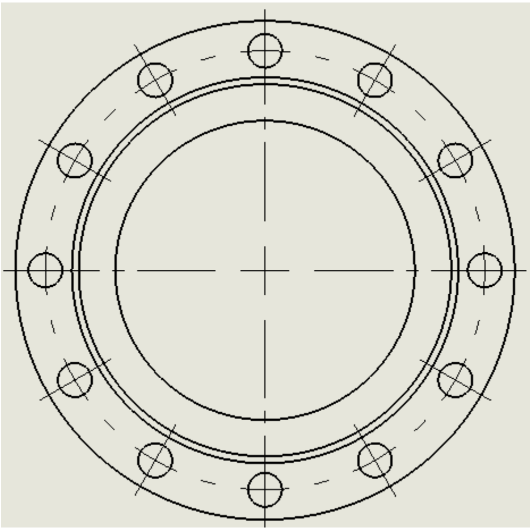
Let's now summarize what we have done and what we have still to do. We started studying the state-of-art of host cavities of different types for a better knowledge of this branch, and the main inspiring prjoect are those in [1] and [2].
After the simulation we made for take confidence with the subject we started to think to different cavities that were possible to design taking in account of the mechanical constraint and the cost of all the parts. As we mentioned the final design we chosen is a 3.9 GHz based cavity cutted at a certain precise highness from the inner iris of the cavity. This allow us to buy an already built cavity or to simply order a single cell cavity.
In order to build that cavity we'll also need other parts in Nb as that one for the Choke Joint, and overall we'll need to weld them together with the Electron Beam Welding, that had to be done in apposite company.
For the electronic measurments we'll need Radio Frequency instrumentation as the Network Analyzer or the Signal Generator, we'll need thermal sensors and instrumentation for acquiring datas from them.
Advanced LabView scripts need to be done, together with other scripts for interfacing to the laboratory instruments.
For calorimetric techniques more simulations need to be done and the thermal circuit could be improved. We can tune with a good sensitivity the eigenvalue of the cavity itself, but for mechanical reasons [1] is not possible to put couplers that can be tuned from outside. They are variable but can be tuned only at room temperature, and this is not important for the Q_0 of the cavity but for the coupling could be important.
Although a lot of major problem are solved, a lot of details need to be defined and the mechanical design need to be rewied, verified and improved. A system to move the apparatus need to be mounted, like a hook mounted on the top flanges. The cavity sealing solution presented is very easy to unmount in order to change the sample, this is very important because this kind of operation is made inside a clean room and the time spent in clean room costs.
In our results we show how the Sapphire is both the problem and the leading edge. The problem linked to this dielectric are actually ineluctable because of his fundamental role in this design. Is not only the part of the cavity that allow us to low down the frequency but it's even that one who help us to concentrate most of the field on the sample, giving him the highest weight between the quality factors.
Now, this dielectric is even the best for cryogenical and RF purpose, because of his low loss tangent, in fact other dielectric wuold loose too much power. Even with those features the sapphire is the main limit to the cavity because means that once we'll have sample with quality factor higher than that one of the sapphire our resolution would be limited. Remove the sapphire would means destroy the ratio and distrubute the TE_{011} mode on all the cavity and not in the sapphire.
The only way to escape removing the sapphire is to reproject and redesign a total new cavity with another mode; a triaxial cavity or a Mushroom cavity [2] can be a good point of starting.

[1] In our cryostat there is not space.
[2] As reported in [2]

A Appendix

A.1 Desing of Indium Seals

To understand what's going on in the seal gap we need to study the mechanical system. The housing of a 1mm diameter indium wire is represented in figure 36.



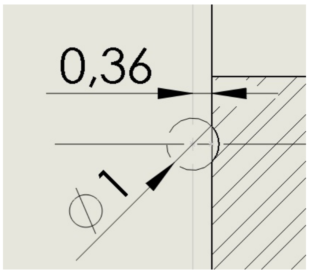


Figure 36: Housing Geometry and dimensions

While bolting the flanges with the fasteners the indium wire is compressed , we can compute the deformation and the force by using the flow stress theory in [5].
We define the quantities not in the figure 37 on the following page as follow:

- P is the medium force applied to the material. It's a force over a length because we need to multiply for the thickness of the matherial in the direction normal to the plane. P is the average value of p over the x-thickness.
- A is the area of the material. In plastic deformation, as the one we are working on, A is costant. $A = b \cdot h$.
- Y is the yield stress of the material.
- $m^*$is a coefficient that is related to friction. In this case where there's no lubrificant is $m^* = 1$.

To compute the P we will use the equation:

$$P = Y \left[1 + \frac{m^* \cdot b}{4h} \right] b \tag{6}$$

Using $A = b \cdot h$and $m^* = 1$ we obtain:

$$P = Y \left[1 + \frac{A}{4h^2} \right] \frac{A}{h} \tag{7}$$

In the chart 38 on page 37 we can see the dependence between the indium thickness and the force P with a 1mm diameter-wire, the same wire of the example in figure 36. In the example 36 the force made by the fasteners is $100N/mm$, the indium wire is compressed to a layer $0,14mm$ thick, the result can be seen in figure 39 on page 37.
When we cool down the entire system to 4K, the indium wire, the flanges and the screws contract, we will spend a few word to analyze the behaviour of the commercial solution in order to desing our seal. We

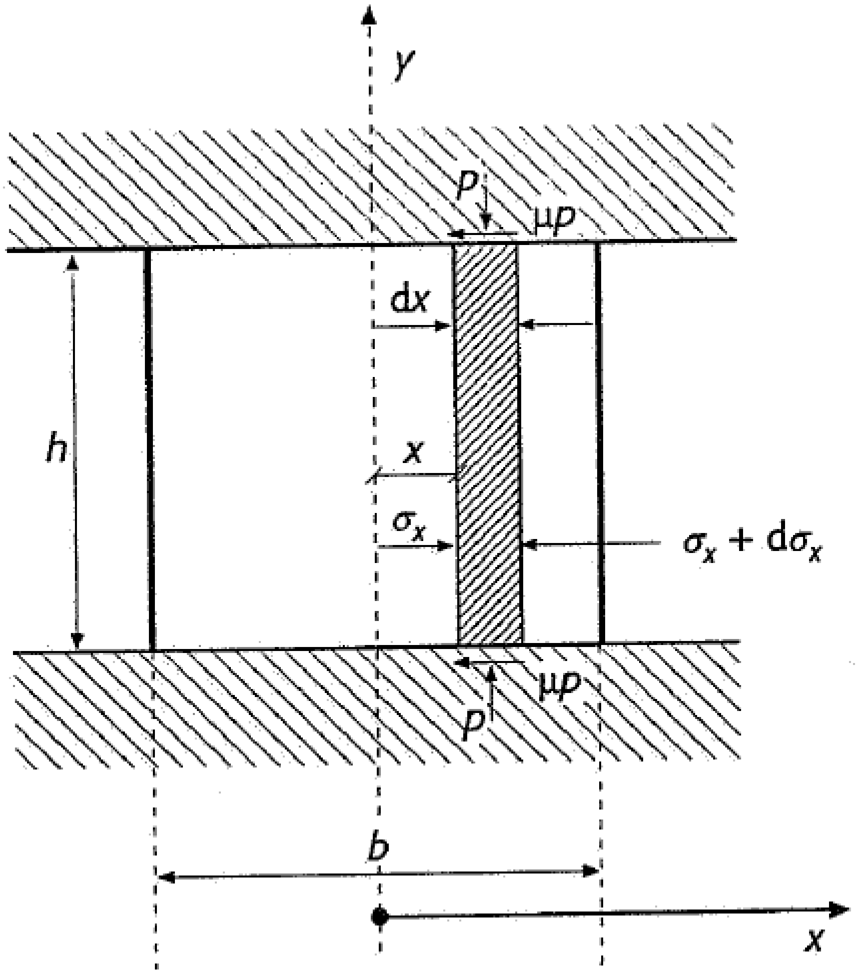


Figure 37: Definition of geometrical quantities

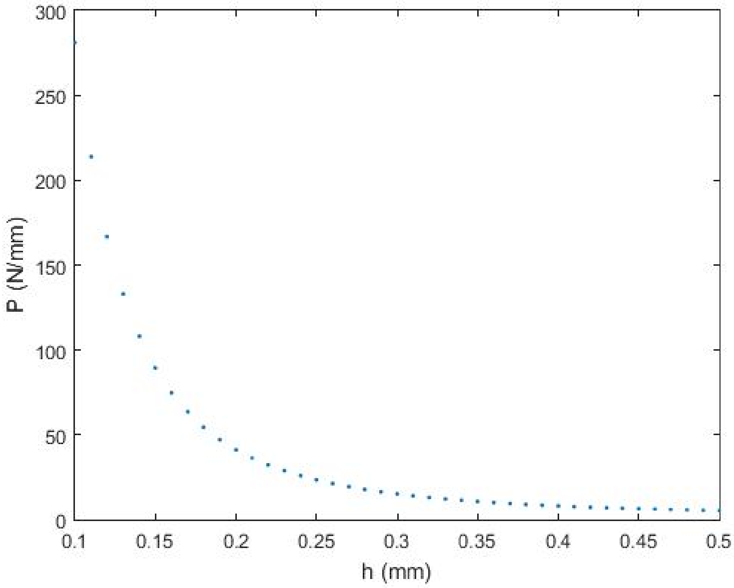


Figure 38: Force-Thickness

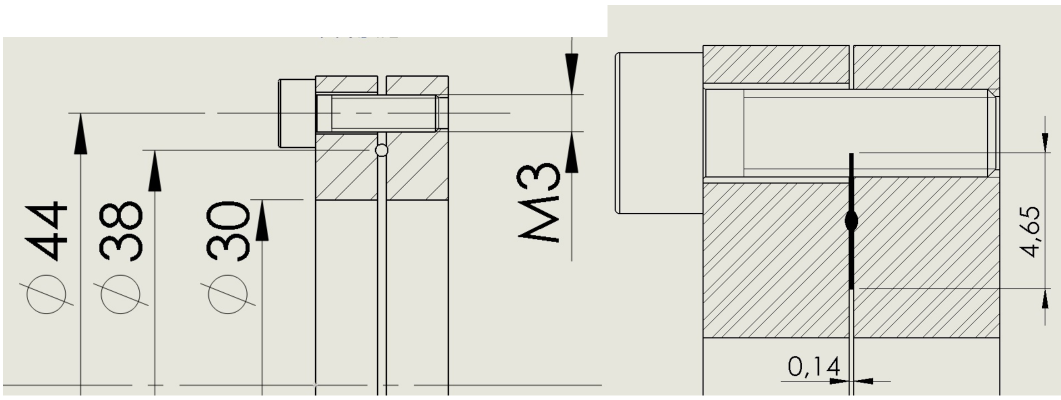


Figure 39: Uncompressed and compressed Indium Seal

will consider the stiffness of the flange negligible and the wire is plastically deformed if it's compressed more and will have an elastic return we copressed less.

- Start: the flange is closed and the force P is $100N/mm$, the indium wire is compressed to a layer $0,14mm$ thick.
- Cooling down to 4K: the flange contracts of $0,0148mm$, the brass screws contract of $0,0192mm$ and the Indium wire contracts of $0,001mm$.
- The screws is constrained to deform in traction thanks to the thermal contraction, in fact we have a differential elastic strain of $\frac{(0,0192-0,0148-0,001)mm}{5mm} = 6,82 \cdot 10^{-4}$, which increase P of $34N/mm$. So $P = 134N/mm$.
- The indium wire is compressed to $0,13mm$ thick, this is negligible compared to the deformation of the Screws.
- We are in Cryogenic condition and the contact between flanges and Indium is guaranteed by the brass screws that contract more than the Steel and compress the indium wire even more.
- If we heat all the system up we have that the flange expands of $0,0148mm$, the brass screws expand of $0,0192mm$ and the Indium wire expands of $0,001mm$.
- The condition are different than the mountig condition because when we heat up the wire can't be deformed plastically as in the cooling. Infact considering the indium we can see that it can't "grow" elastically more than 2% and it's stiffness is negligible in the system (Flange, Indium and Brass screws can be represented as spring in series, the Brass Screws has the smallest stiffness). We can calculate that the P is decreased by $47,3N/mm$ and the contact is not interrupted.

We designed our own seal as described in figure 40 on the next page, it's esay to verify the operating condition as the example above.

A.2 Sapphire

Work In Progress

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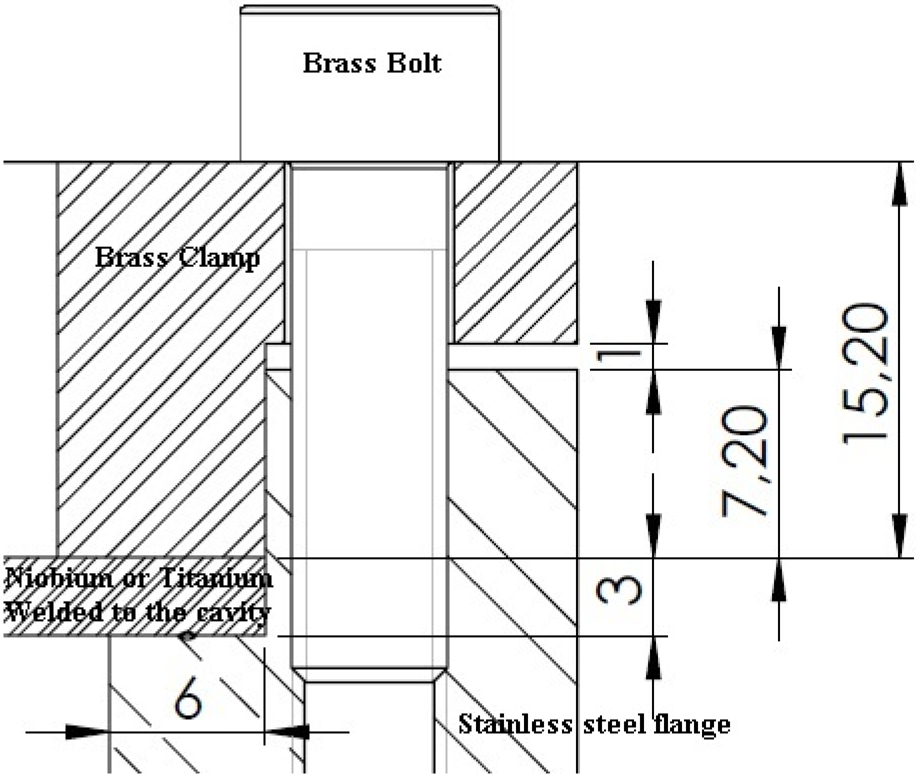

Figure 40: Indium seal design

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